The 5th International Symposium on Negative Ions, Beams and Sources

12th – 15th September 2016

St. Anne’s College, Oxford UK

Programme and Book of Abstracts

www.nibs2016.org
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Introduction

The 5th International Symposium on Negative Ions, Beams and Sources (NIBS’16) will be held in St. Anne's College, Oxford, UK on the 12th – 16th September, 2016. The symposium is jointly organized by the Science and Technology Facilities Council (STFC) and the Culham Centre for Fusion Energy (CCFE).

When it began in 1977, as The Symposium on Production and Neutralization of Negative Ions and Beams, the symposium was for accelerator and fusion applications. The current form of the symposium welcomes contributions on any aspect of the use of negative ions in basic or applied research. NIBS’16 will cover all areas of science and technology related to negative ion production and use. The symposium will present results obtained from experimental investigations as well as theoretical modelling. The symposium is also an ideal setting for new researchers to establish contacts and see first-hand the latest developments in the field of negative ion research.

Scope and Topics

The aim of the symposium is to exchange information on science, technology, engineering, and operational experiences in all areas relevant to negative ions by providing a forum for discussion. Contributions from a wide variety of fields, such as: fusion, accelerators, material science or industrial applications are expected. The main topics of the symposium are:

1. Fundamental processes and modelling
2. H− and D− sources for fusion, accelerators and other applications
3. Other negative ion sources
4. Beam formation and low energy transport
5. Beam acceleration and neutralization
6. Beam lines and facilities
7. Applications
Symposium Venue

NIBS’16 will be held at St. Anne’s College in Oxford for the first three days of the symposium (Monday to Wednesday), the symposium will then move to STFC Rutherford Appleton Laboratory on Thursday and CCFE Culham on Friday. Transport will be provided on Thursday and Friday between Oxford and the laboratories.

St. Anne’s College

The St. Anne’s part of the symposium will take place in the Mary Ogilvie Lecture Theatre. Poster sessions will take place in Seminar Room 8 on Monday and Tuesday. Coffee breaks will be in Seminar Room 9 and lunch will be provided in the Dining Hall.
Rutherford Appleton Laboratory

On Thursday, coaches will leave from St. Anne’s main entrance at 08:00 sharp and head to the Rutherford Appleton Laboratory (RAL). Talks will take place in the Pickavance Lecture Theatre in building R22, with coffee breaks in the R22 foyer. A finger buffet lunch will be provided in the R18 visitors centre.

Tours of the ISIS, FETS and VESPA negative hydrogen ion accelerator facilities at RAL will take place after the afternoon coffee break, before coaches will return the group to St. Anne’s in Oxford.

The ISIS Pulsed Spallation Neutron and Muon Facility was the first of its kind, having been operational since 1984. With 29 instrument stations divided between two target stations, ISIS has the greatest scientific output of any pulsed neutron source in the world, with around 600 journal papers published annually. A powerful proton beam is accelerated to 800 MeV by a rapid-cycling synchrotron (RCS) before colliding with tantalum-clad tungsten targets to generate neutrons. The RCS is fed by a Penning ion source at the start of a 70 MeV H⁻ linac. The accelerator will be operational during NIBS’16, but Target Stations 1 & 2 (TS1 & TS2) will be open for tours.

The Front End Test Stand (FETS) is being constructed in building R8 at RAL as a demonstrator for a high intensity chopped H⁻ linac for future ISIS upgrades. An upgraded ISIS-type Penning H⁻ ion source delivers a 60 mA, 10% duty-factor beam to a 3 MeV radio-frequency quadrupole and chopping line.

A Vessel for Extraction and Source Plasma Analyses (VESPA) is operational in building R2 at RAL for detailed ion source R&D. The VESPA aims to modernise the Penning ion source with a view to achieving loss-less beam transport and extending the source lifetime for ISIS operations.
Culham Centre for Fusion Energy

On Friday, coaches will leave from St. Anne’s main entrance at 08:00 sharp and head to the Culham Centre for Fusion Energy (CCFE). Talks will take place in the HOW room, with coffee breaks and a finger buffet lunch will be provided in the HOW room foyer.

Tours around the JET tokamak will take place after the afternoon coffee break, before coaches will return the group to St. Anne’s in Oxford.

An additional coach will leave CCFE at lunchtime, returning to Oxford those participants who need to catch early flights. Sign-up sheets for this extra coach will be available throughout the week.

The tour of the Culham facilities will include:

- The JET control room
- The remote handling control room, where the robotic MASCOT is used for in-vessel activities during shutdowns
- The JET Assembly Hall, a maintenance area for large JET components, and also the location of the full size mock-up of the vessel, known as the In-Vessel Training Facility (IVTF).
- The JET Torus Hall (subject to any operational restrictions), where JET itself is located, with 2 Neutral Injection Boxes (NIBs) capable of 35MW total deuterium beams.
- The Neutral Beam Test Bed (NBTB) Hot Cell, where a full sized JET NIB is used with a single PINI and increased diagnostics to condition and characterise all JET PINIs before use on JET
- The Small Negative Ion Facility (SNIF), CCFE’s negative ion source experiment, initially presented at NIBS 2012.
**Presentation Information**

The symposium will consist of contributed papers in oral and poster sessions to encourage close contact between researchers and to generate intense discussions. Papers that are accepted after the usual review process will be published in the AIP conference proceedings.

**Oral**

Most papers are allocated a time of 20 minutes for the presentation and 5 minutes for questions and discussion. Invited talks are allocated 25 minutes, plus 5 minutes for questions. All lecture theatres at St. Anne’s, RAL and CCFE are equipped with Windows PCs with MS Office 2010 and Adobe Acrobat X. Supported presentation formats are Microsoft PowerPoint and PDF.

Although a variety of standard video codecs are supported, speakers are strongly advised to provide video files separately and not only embedded in the presentation. Please be prepared to have your presentation on a portable USB flash drive and hand it out to the audio-visual assistant at least one session before the start of our talk. To ensure efficient movement between talks, your presentation file should be named:

```
NIBS2016_<dayofweek>_<lastname>
```

Where `<dayofweek>` is to be replaced with the weekday of the presentation and `<lastname>` with the last name of the presenter.

**Poster**

There are two poster sessions. The first session is on Monday, September 12th and the second session on Tuesday, September 13th. Both begin at 15:30 and are located in Seminar Room 8 near the Mary Ogilvie lecture theatre. Each presenter will be allocated 90 cm by 120 cm (approximately portrait A0) and given adequate mounting supplies. The posters should be mounted in the morning of the session and removed by the next morning.
Social Programme

Reception

From 18:30 on Monday the 12\textsuperscript{th} of September, drinks and canapés will be served accompanied by a string quartet in the Sheldonian Theatre, Oxford, to celebrate the start of the symposium.

Excursion

Lunch will be provided on Wednesday at St. Anne’s college before an afternoon excursion. Participants may choose between a visit to historic Blenheim Palace or a relaxing voyage up the River Cherwell in a traditional Oxford punt. After the excursion, both groups will reconvene at the Cherwell Boathouse for an enjoyable barbeque dinner and drinks.

Banquet

A symposium banquet will take place in the beautiful dining hall of Trinity College in Oxford in the evening of Thursday the 15\textsuperscript{th} of September, beginning at 19:30.
NIBS Award

The NIBS Award will be presented for recent innovative and significant achievements in the fields of the physics, theory, technology and/or applications of sources, low energy beam transport, and/or diagnostics of negative ions.

The first NIBS Award was presented at the NIBS’14 Symposium in Garching to the IPP plasma physics group for their outstanding work on large negative ion sources, including the recent ELISE test rig.

The second NIBS Award, donated by D-Pace Inc., will be presented at NIBS’16. It will consist of a certificate and CA$5,000.

The International Program Committee will choose the winning nomination and the award will be announced at the conference banquet.

International Programme Committee

M. Bacal, UPMC, France
Y. Belchenko, INP, Russia
D. Boilson, ITER Organisation, France
D. Faircloth, STFC, UK
G. Fubiani, LAPLACE/CNRS/Univ. of Toulouse, France
Y. Hwang, SNU, Korea
A. Holmes, Marcham Scientific, UK
M. Kashiwagi, JAEG, Japan
W. Kraus, IPP, Germany
J. Lettry, CERN, Switzerland
R. McAdams, CCFE, UK
Y. Mori, Kyoto University, Japan
M. Stöckli, ORNL, USA
Y. Takeiri, NIFS, Japan
O. Tarvainen, Univ. of Jyväskylä, Finland

Local Organizing Committee

Dan Faircloth (STFC, Chairman)
Roy McAdams (CCFE)
Scott Lawrie (STFC)
Jamie Zacks (CCFE)
Alison Black (CCFE)
Trudi Gurney (STFC)

Secretary

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Abingdon, Oxfordshire,
OX14 3DB,
United Kingdom.
admin@nibs2016.org
www.nibs2016.org
**Sponsors**

We warmly thank the generous contributions from our sponsors:

![D-Pace](image1.png)

![John Adams Institute for Accelerator Science](image2.png)

![Swagelok](image3.png)

![Kurt J. Lesker Company](image4.png)

![Glassman Europe](image5.png)

![Hiden Analytical](image6.png)

![ANDOR](image7.png)

![IOP Institute of Physics Plasma Physics Group](image8.png)
## Monday 12\textsuperscript{th} September

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<td>09:00 – 09:15</td>
<td><strong>D. Faircloth</strong></td>
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<td></td>
<td>Welcome</td>
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<td>09:15 – 09:45</td>
<td><strong>K. Tsumori</strong></td>
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<td>MonO1</td>
<td>Physics-Based Investigation of Negative Ion Behaviour in a Negative-Ion-Rich Plasma using Integrated Diagnostics</td>
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<td>09:45 – 10:15</td>
<td><strong>J. Lettry</strong></td>
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<td>MonO2</td>
<td>CERN’s Linac4 Caesiated Surface H\textsuperscript{+} Source</td>
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<td>10:35 – 11:05</td>
<td><strong>D. Wünderlich</strong></td>
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<td>MonO3</td>
<td>Long Pulse, High Power Operation of the ELISE Test Facility</td>
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<td>11:05 – 11:30</td>
<td><strong>R. Hemsworth</strong></td>
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<td>MonO4</td>
<td>Neutral Beam Injection for Fusion</td>
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<td>11:30 – 11:55</td>
<td><strong>U. Fantz</strong></td>
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<td>MonO5</td>
<td>Operation of Large RF sources for H\textsuperscript{−}: Lessons Learned at ELISE</td>
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<td>11:55 – 12:20</td>
<td><strong>Y. Belchenko</strong></td>
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<td>MonO6</td>
<td>Extracted Currents in the Inductively Driven Surface-Plasma Negative Hydrogen Ion Source</td>
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<td>13:30 – 13:55</td>
<td><strong>W. Kraus</strong></td>
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<td>MonO7</td>
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<td>Improvements of the Versatile Multi-aperture Negative Ion Source NIO1</td>
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<td>14:20 – 14:45</td>
<td><strong>N. Umeda</strong></td>
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<td>MonO9</td>
<td>Long Pulse and High Power Density H\textsuperscript{−} Ion Beam Accelerations for ITER</td>
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<td><strong>K. Pandya</strong></td>
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<td>First Results from Negative Ion Beam Extraction in ROBIN in Surface Mode</td>
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<td>MonP1–MonP28</td>
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<td>18:30 – 21:00</td>
<td>Welcome Reception</td>
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| 13:00 – 19:00| Punting                                                                |        |
| 19:00 – 21:00| Groups #1 & #2 Re-combine for Dinner  
Cherwell Boathouse                          |        |
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<td>Coach to Rutherford Appleton Laboratory (RAL)</td>
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<td>A. Pimazzoni</td>
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<tr>
<td>MonP3</td>
<td>E. Sartori</td>
<td>Development of an energy analyser as diagnostic of beam-generated plasma in negative ion beam systems</td>
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Abstracts
MonO1

Physics-based Investigation of Negative Ion Behavior in a Negative-ion-rich Plasma using Integrated Diagnostics

K. Tsumori\textsuperscript{1,2}, Y. Takeiri\textsuperscript{1,2}, K. Ikeda\textsuperscript{1}, H. Nakano\textsuperscript{1,2}, S. Geng\textsuperscript{2}, M. Kisaki\textsuperscript{1}, M. Wada\textsuperscript{3}, K. Sasaki\textsuperscript{4}, S. Nishiyama\textsuperscript{4}, M. Goto\textsuperscript{1,2}, M. Osakabe\textsuperscript{1,2} and K. Nagaoka\textsuperscript{1,2}

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Total injection power of 16 MW had been successfully achieved using three Neutral Beam Injectors (NBIs) for the Large Helical Device (LHD). Detailed mechanism from production through extraction of hydrogen negative (H\textsuperscript{−}) ions are still yet to be clarified and the understanding is essential for further improvement of NBI. We have presented the production of negative-ion-rich plasma and H\textsuperscript{−} behavior in the beam extraction region of a large-scaled negative ion source with use of an integrated diagnostic system [1-5]. The plasmas has been investigated further for two-dimensional electron, positive ion and H\textsuperscript{−} flows in the extraction region. Figure 1 shows the H\textsuperscript{−} flow during beam extraction. The flow pattern indicates the existence a stagnation region, where the H\textsuperscript{−} flow changes the direction, near z =20 mm in the figure. The pattern also suggests that H\textsuperscript{−} comes from plasma grid (PG) surface and the flow turns toward an extraction aperture. The flow change before and after beam extraction shows the similar tendency of H\textsuperscript{−} flow. The stagnation region is located at a region of the magnetic layers induced by filter and electron-deflection magnetic (EDM) fields indicating that the EDM field strongly affects the H\textsuperscript{−} flows.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{flow_pattern.png}
\caption{H\textsuperscript{−} flow pattern near plasma grid (during beam extraction).}
\end{figure}

References

Linac4 cesiated surface H⁺ sources are routinely operated for the commissioning of the CERN’s Linac4 and on an ion source test stand. Stable current of 40-50 mA are achieved but measurement of the transmission through the LEBT were below expectations and triggered additional beam characterization. The H⁺ beam divergence, profile and emittance are measured and compared to beam simulation. The impact of the puller dump and of the accelerating einzel lens voltages are reported.

The status of ongoing development work is described; H⁺ and D⁻ beams produced with the linac4 cesiated surface ion source measured at the test stand are presented.
The ion source of the ELISE test facility (0.9×1.0 m\textsuperscript{2} with an extraction area of 0.1 m\textsuperscript{2} ) has half the size of the ion source foreseen for the ITER NBI beam lines. Aim of ELISE is to demonstrate that such large RF driven negative ion sources can achieve the following parameters at a filling pressure of 0.3 Pa and for pulse lengths of up to one hour: extracted current densities of 28.5 mA/cm\textsuperscript{2} in deuterium and 33.0 mA/cm\textsuperscript{2} in hydrogen, a ratio of coextracted electrons to extracted ions below one and deviations in the uniformity of the extracted beam of less than 10%.

In the first experimental campaigns of ELISE successfully routine operation in short pulses (10 s beam phases within plasma pulses of 20 s) was demonstrated. Next step is a stepwise extension of the pulse length up to one hour at low RF power (20 kW/driver) with the final goal of performing long pulses with high RF power (up to 80 kW/driver). The most crucial factor limiting the source performance during such pulses – in particular in deuterium – can be a steady increase of the co-extracted electron current.

The magnetic filter field plays a key role in the suppression of the co-extracted electrons. External permanent magnets – strengthening the standard magnetic filter field (generated by a current flowing through the plasma grid) and significantly modifying the field topology – have been added to ELISE. By this measure the amount and the temporal instability of the co-extracted electrons is strongly reduced. Performing long pulses with high power was, however, accompanied by technical issues that had to be solved first: a premature pulse termination could be caused by an increase of the temperature of components in the driver containment, resulting in a strong pressure increase, or by breakdowns occurring randomly in the driver containment.

The contribution focusses on the latest results achieved at ELISE in long pulse, high power operation both in hydrogen and deuterium. Presented are measured current densities (extracted negative ions and co-extracted electrons) as well as results of beam diagnostics, indicating the beam homogeneity.
Neutral Beam Injection for Fusion

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Abstract:

Neutral beam injection (NBI) has been the most successful heating scheme applied to fusion devices, the majority of which have been based on the acceleration and neutralization in a gas target of accelerated positive ions. For large fusion devices such as ITER, DEMO and fusion reactors, beam energies of the order of 0.5 MeV per nucleon or higher are required to penetrate deeply into the fusing plasma, and thus to heat the plasma in the most important region, i.e. near the poloidal axis of the device and to drive current in the plasma. Because the efficiency of neutralization of positive ions in a gas target becomes unacceptably low at energies above \( \approx 100 \text{ keV/nucleon} \), future injectors will be based on the neutralization of negative ions, either in a gas target, by photons or in a plasma target. So far only two systems based on negative ions have been used on fusion devices, at JT-60U and at LHD, both based on neutralization in a gas target. The injectors for ITER will also use a gas target, but the energy and operating environment are both reactor and DEMO relevant. Also, unlike previous NBI systems, the ITER injectors will have to operate for pulse lengths, orders of magnitude higher, than most previous NBI systems. In this paper the R&D required for an NBI system for a reactor is considered against the background of the ITER NBI system development, and the main drivers for the required R&D are identified. In addition, likely routes to success are considered and a strategy for the required R&D suggested.
The goal of the ELISE test facility is to demonstrate that large RF driven negative ion sources can achieve the parameters required for the ITER beam sources in terms of current density and beam homogeneity at a filling pressure of 0.3 Pa for pulse lengths of up to one hour. The ion source of the ELISE test facility (0.9×1.0 m² with an extraction area of 0.1 m²) has half the size of the ion source foreseen for the ITER NBI beam lines. Stable extracted current densities of 28.5 mA/cm² D⁻ and 33.0 mA/cm² H⁻ have to be achieved using maximum RF power of 90 kW/driver for each of the four drivers powered by two RF generators. The ratio of co-extracted electrons to extracted ions must be always below one and deviations in the uniformity of the extracted beam of less than 10% are allowed.

ELISE is operational since three years interrupted by seven months maintenance phase for source inspection. To demonstrate the performance of the beam source a stepwise approach has been chosen starting with short pulse operation (10 s beam during a 20 s plasma phase) at low RF power (20 kW/driver) towards long pulses which means plasma phases up to one hour with pulsed extraction of 10 s (limited by the available HV power supply) at higher RF power.

The experience gained regarding operation, maintenance, relevant technical issues of such large RF sources will be discussed together with the consequences for operation of the ITER beam sources.
Extracted Currents in the Inductively Driven Surface-Plasma Negative Hydrogen Ion Source

Yu. Belchenko, A. Ivanov, A. Sanin, O. Sotnikov

Budker Institute of Nuclear Physics, Novosibirsk, Russia

The data on long-pulsed operation of BINP RF surface-plasma source [1] will be presented. The source regularly produces the H- ion beam with current >1A, energy ≥90 keV and pulse duration ≥2 s. The total H- beam current, transported to the distant Faraday cup and the currents in the circuits of ion-optical system elements were measured. The composition of accelerated current was clarified.

Fig.1 shows the dependencies of beam current $I_b$, of extraction electrode current $I_{EG}$, and of acceleration electrode current $I_{AG}$ vs acceleration voltage $U_{ac}$ (at constant extraction voltage 12 kV). The gradual increase of $I_b$ current and the decrease of $I_{EG}$ current confirm the improving of beam focusing with the acceleration voltage growth. The $I_{AG}$ current is maximal at $U_{ac} = 20$ kV. The residual $I_{AG}$ current ~ 0.5 A, recorded at $U_{ac}$ level of 60-75 kV is mainly caused by electrons, co-accelerated with negative ion beam, while the current of co-extracted electrons, intercepted to the extraction electrode has value of about 0.3 A.

References

Performance of the BATMAN RF Source with a Large Racetrack Shaped Driver

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The negative ion sources for the ITER NBI will be equipped with 8 cylindrical drivers for plasma generation from which the plasma expands into the source volume. This concept is based on the small prototype source with only one driver developed at IPP Garching. Each two horizontally arranged drivers are supplied by one RF generator. In order to increase the RF efficiency and the operational reliability of the source it could be favourable to substitute two drivers by a large one which needs significantly less power for the same negative ion current.

For this purpose a large driver with a race-track shaped base area - the prototype RF source for the ASDEX Upgrade NBI - is currently being tested at the BATMAN test facility. The volume of this source of $32 \times 19 \times 58 \text{ cm}^3$ (width $\times$ height $\times$ length) is much larger than that of the cylindrical drivers of the prototype source and of the ELISE source (diameter 24.5 cm and 28 cm respectively, height 14 cm). The latter is a half-size ITER source equipped with four drivers. In order to keep the total source depth unchanged the "race-track driver" is mounted onto an expansion volume which is shorter than that of the prototype source (14 cm instead of 19 cm). In the driver a six turn RF coil surrounds a 6 mm thick quartz insulator, which is mounted inside a vacuum chamber to avoid a cracking by the atmospheric pressure. The Cs oven is mounted in a central position onto the drivers back plate. The magnetic filter field is kept the same as in the prototype source.

The conditioning characteristics and the results of beam extraction experiments are reported and compared to that achieved with the previous source design. Possible improvements of ITER size sources based on these investigations are discussed.
Improvements of the Versatile Multiaperture Negative Ion Source NIO1

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The ion source NIO1 (Negative Ion Optimization 1) was developed and installed as a reduced-size model of multi-aperture sources used in neutral beam injectors. NIO1 beam optics is optimized for a 130 mA H⁻ current (subdivided in 9 beamlets) at a Vₛ=60 kV extraction voltage, with an electron-to-ion current ratio Rᵢ up to 2. In an initial phase, NIO1 was operated with Vₛ=0 to verify the coupling of radiofrequency (rf) power Pᵣ to plasma. The distinction between capacitively coupled plasma (E-mode, consistent with a low electron density plasma nₑ) and inductively coupled plasma (H-mode, requiring larger nₑ) was clearly related to several experimental signatures, especially for air or nitrogen plasmas, where E to H transition was observed with Pᵣ about 0.5 kW (with hysteresis). In hydrogen, the same transition may require about 1 kW, so that air cooling of the rf window was improved. Beams of H⁻ and O⁻ were separately extracted (using pure gases as input); since no caesium is yet introduced into the source, the expected ion currents are typically lower than 10 mA; this requires a lower acceleration voltage Vₛ (to keep the same perveance). Operation at lower voltages and current (as appropriate in this phase) is possible, but use of weaker deflection magnets in the extraction grid (EG) or use of heavier gases (oxygen) is then advisable. Preliminary experiments indicate the need of increasing the ampere-turns in magnetic filter and the bias voltage to reduce Rᵢ (still very large, about 150 for oxygen), in qualitative agreement with theoretical and numerical models. In a separate test stand, NIO1 caesium oven was tested, with deposition on a molybdenum substrate, and advanced Cs dispensers are in development.
High power negative ion beam acceleration of 1 MeV, 40 A (current density of 200 A/m²) for 3600 s is required for the ITER neutral beam (NB) system. In the MeV-class test facility of QST, the ITER prototype multi-aperture and five-stage (MAMuG) electrostatic accelerator called MeV accelerator has been developed to demonstrate ITER relevant negative ion beam. One of targets in the MeV accelerator is to accelerate the H- ion beam up to 1 MeV with 200 A/m² for 60 s, where the pulse duration is limited by the present power supply. To achieve the target, the accelerator has been improved step by step. Initially, excess high grid heat load of more than 30% of the total beam acceleration power was one of critical issues to achieve 1 MeV beams. To reduce the grid heat load, the aperture offset and the field shaping plate were applied to compensate beam deflections due to residual magnetic field and the space charge repulsion between beams [1]. Then, 1 MeV beam was achieved, but the pulse length was still limited around 1 s. The extraction grid was modified to have high cooling capability and to enlarge aperture diameter at the exit to prevent beam interception on the grid. These modifications led to reduce grid heat load from 13% to 10% and to achieve beam acceleration of 0.68 MeV, 100 A/m² for 60 s [2]. Remaining issues to achieve the target were to stabilize arc discharge in the negative ion source for high power and long pulse operation and to optimize the beam optics. In the high power and long pulse arc discharge, a critical issue is damage on the filament due to arcing. Based on the fundamental experiment, the shape and the location of the filaments have been modified. To optimize the beam optics, the shape of the extractor has been modified and the first acceleration gap has been tuned by reducing from 112 mm to 108.6 mm. As the result, the H- beam of 0.97 MeV, 190 A/m² (263 mA) from 9 apertures of 14 mm in diameter has been accelerated for 60 s stably without breakdowns. The temperature of the cooling water was saturated. This is a breakthrough to assure the ITER accelerator.

References

MonO10

First Results from Negative Ion Beam Extraction in ROBIN in Surface Mode

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ROBIN, the first step in the Indian R&D program on negative ion beams has reached an important milestone, with the production of -ve ions in the surface conversion mode. In the present set-up, negative hydrogen ion beam extraction is effected through an extraction area of ~ 73.38 cm² (146 apertures of 8mm diameter). The extraction and acceleration system for ROBIN are based on three grid electrostatic accelerator system which are fed by high voltage DC power supplies (Extraction power supply: 11kV, 35A and Acceleration power supply 35kV, 15A).

The surface mode of ROBIN operation is initiated with the injection of Cesium (Cs) vapour into the source. The immediate signature of surface mode operation is the considerable reduction of co-extracted electron current. The increase of negative ion current depends on various other parameters (e.g. plasma grid temperature, plasma grid bias, extraction to acceleration voltage ratio, impurity level, Cs recycling etc.) of the source. Presently the surface mode operation has resulted in reduction of co-extracted electron current by a factor of 5-6 compared to volume mode. However, the enhancement of the negative ion current is observed as ~1.5 times correspondingly, which is expected to be improved further after ongoing optimization of operational parameters. In addition, to control over impurities Cryopump (14,000 l/s for Hydrogen) is installed along with a Residual Gas Analyzer (RGA) in ROBIN. For characterization of ROBIN, negative ion beam extraction experiments have been performed by varying different experimental parameters e.g. RF power (30-70 kW), source operational pressure (0.6 – 0.3 pa), plasma grid bias voltage, plasma grid temperature, extraction & acceleration voltage combination. First assessments indicate that best performance of ROBIN is achieved at pressures of 0.5 Pa. Linear scaling of negative ion current density with input RF power is also observed. Further, perveance scan establishes that optimum extraction voltage for ROBIN is ~ 5 kV for a beam accelerated to 22 kV. To characterize the beam a thermocouple based instrumented differential calorimeter has been installed and put into operation in ROBIN. The results obtained from ROBIN will enrich the database on RF based ion sources for upcoming Fusion Devices. The paper will present the results of parametric study of ROBIN operation and beam optimization in surface mode.
Recent Performance of and Extraction Studies with the Spallation Neutron Source H\textsuperscript{+} Injector


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Over the past year the Spallation Neutron Source has operated with proton beam powers near 1.4 MW with good availability. However, a recent premature target failure led to a power reduction to 1 MW for a ~20-week target service cycle, before changing the target and increasing the power to 1.2 MW. If all goes well, the power may be restored to 1.4 MW in less than a year. While the Hinjector is normally able to deliver the 35 mA linac beam current required for 1.4 MW, higher beam currents are desired to achieve more margin that can compensate for potential deficiencies. And eventually, for the second target station the ~50 mA - demonstrated in 2010 - needs to be restored. This is expected when the new RFQ is installed to replace the old RFQ with its heavily compromised transmission [1].

In the meantime methods that promise to increase the RFQ output current are being explored. We started to apply positive high voltages to the extractor to increase the extraction field. The e-dump voltage is scaled proportionally to maintain the uniformity of the extraction field, which is important, as seen earlier [2]. As seen in Fig.1, the LEBT output current does not increase with the extraction field, suggesting an emission limited extraction. However, the RFQ output current increases by roughly 10% when the extractor voltage is increased from 0 to 15 kV and lens 1 is lowered while lens 2 is increased. This is consistent with a lower beam emittance in the LEBT, which increases the transmission through the RFQ.

References

World Brightest (Class) J-PARC RF-Driven H⁻ Ion Source for High Energy Accelerators

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The J-PARC (Japan Proton Accelerator Research Complex) cesiated rf-driven H⁻ ion source [1,2,3] has been successfully operated satisfying the J-PARC second stage requirements of an H⁻ ion beam of 60mA within normalized emittances of 1.5πmm•mrad both horizontally and vertically, a flat top beam duty factor of 1.25% (500µs×25Hz) and a life-time of longer than 1000 hours about 2 years. In this paper, the empirically discovered effective modifications to minimize the transverse emittances and produce the world brightest (class) H⁻ ion beam on a test-stand are presented. The normalized rms emittance of 95% 66mA H⁻ ion beam is evaluated as $\epsilon_{rmsm95\%}=0.23\pi\text{mm•mrad}$, which is about 20% improved from $0.29\pi\text{mm•mrad}$ measured in the previous setting.

References

Linac4 is a 160 MeV H⁺ linear accelerator part of the upgrade of the LHC injector chain. Its cesiated surface H⁺ source is designed to provide a beam intensity of 40-50mA. It is operated with periodical Cs-injection at typically 30 days intervals [1] and this implies that the beam parameters will slowly evolve during operation.

Autopilot is a control software package extending CERN developed Inspector framework [2]. The aim of Autopilot is to automatize the mandatory optimization and cesiation processes and to derive performance indicators, thus keeping human intervention minimal.

Autopilot has been developed by capitalizing on the experience from manually operating the source. It comprises various algorithms running in real-time, which have been devised to:

- Optimize the ion source performance by regulation of H₂ injection, RF power and frequency.
- Describe the performance of the source with performance indicators, which can be easily understood by operators.
- Identify failures, try to recover the nominal operation and send warning in case of deviation from nominal operation.
- Make the performance indicators remotely available through Web pages.

Autopilot is at the same level of hierarchy as an operator, in the CERN infrastructure. This allows the combination of all ion source devices, giving to Autopilot the required flexibility. Autopilot is executed in a dedicated server, ensuring unique and centralized control, yet allowing multiple operators to interact at runtime, always coordinating between them. Autopilot follows the doctrine of flexibility, adaptability, portability and scalability, and can be extended to other components of CERN’s accelerators.

In this paper, a detailed description of the Autopilot algorithms is presented, along with first results of operating the Linac4 H⁺ Ion Source with Autopilot.

References

RF Negative Hydrogen Ion Source Development in China Spallation Neutron Source

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China Spallation Neutron Source (CSNS) is now running a penning negative hydrogen ion source \cite{1}, which has a life time of several weeks with occasional sparks of extract-electrode. To improve the life time of the ion source and prepare for the CSNS-phase II, we are trying to develop a RF negative hydrogen ion source with external antenna.

![Configuration of the external antenna RF ion source under development at CSNS.](image)

The configuration is shown in Fig. 1, which is similar to the DESY external antenna ion source developed by Jens Peters \cite{2} and SNS ion source developed by R. F. Welton and M. Stockli \cite{3}. However several changes are made attempting to improve the stability and life time. Firstly, Si\textsubscript{3}N\textsubscript{4} ceramic with high thermal shock resistance, high thermal conductivity is used for plasma chamber, which can endure an average power of 2000W. Secondly, the water-cooled antenna is brazed on the chamber to improve the energy efficiency. Thirdly, cesium is injected directly to the plasma chamber if necessary, to simplify the converter and extraction. Area of stainless steel exposed to plasma is minimized to reduce the sputtering and degassing. Instead Mo, Pt coating and Ta material are used to face the plasma.

References

Demonstrating H⁻ Beam Focussing Using An Elliptical Electrostatic Einzel Lens

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H⁻ ion source research is being performed at the ISIS spallation neutron and muon facility on a dedicated Vessel for Extraction and Source Plasma Analyses (VESPA) [1]. The ion extraction and optics system presently being used on ISIS is centered on a combined-function sector dipole magnet [2]. This traps cesium vapor escaping the ion source; mass-separates co-extracted electrons and stripped neutrals, and weak-focusses the highly asymmetric slit-shaped ion beam. Unfortunately the added drift length through the magnet under strong space-charge forces means up to 50% of the beam is collimated on the magnet. The VESPA has shown [3] that the ISIS ion source actually produces 80 mA of beam current at standard settings, but because of magnet collimation only 55 mA is injected into the solenoid Low Energy Beam Transport (LEBT). A new purely electrostatic post-extraction system incorporating an einzel lens with an elliptical aperture is currently under test. This allows much greater flexibility of pervance and phase space matching for injection into the LEBT and Radio Frequency Quadrupole (RFQ). This paper discusses high voltage breakdown mitigation strategies and presents the first results of the novel elliptical transport system. So far, 70 mA of beam has been transported through the new system with a normalized transverse RMS emittance of 0.4 π mm mrad.

References

The \( \text{H}^+ \) injector for the RFQ accelerator at the Spallation Neutron Source consists of an RF-driven, multi-cusp, Cs-enhanced \( \text{H}^+ \) ion source and a 2-lens electrostatic low energy beam transport (LEBT). The second lens is split into four electrically isolated quadrants for beam steering and chopping. There is no space in the 12-cm-long LEBT section for a beam current torroid; steering the beam on to the isolated RFQ entrance aperture ring is the only way the LEBT-output and the RFQ-input beam current can be measured. Our method and procedure have recently been refined to improve reliability and accuracy. The new measurements suggest that earlier measurements tended to underestimate the currents by \( \sim 0.2 \) mA, but essentially confirm \( \text{H}^+ \) beam currents of 50-60 mA being injected into the RFQ during routine operation. However, the RFQ output current is usually only \( \sim 35 \) mA due to its degraded transmission that occurred a few years ago. A spare RFQ was acquired and is being prepared for testing with an almost identical \( \text{H}^+ \) injector coupled to it. In this work, 1) the beam currents measured on the RFQ entrance aperture ring will be compared with beam current monitor (BCM) and faraday cup measurements, and 2) beam emittance measurements with an improved device and improved methodologies will be presented.
Improvements and Plasma Analysis of PKU Microwave Driven Cs-free H⁻ Ion Source

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H⁻ beam currents of 35 mA in pulsed mode with 100Hz/1ms and 25 mA in CW mode had been obtained from PKU No. 4 microwave driven Cs-free H⁻ ion source. Its duty factor can be changed from 1% to 100% variously. In order to improve the performance of H⁻ ion source, several optimizations of the source were carried out: more water-cooling around the source body, optimized deflect magnet configuration and operating parameters. After above improvements a 45 mA pure H⁻ current in pulsed mode with 100Hz/1ms had been extracted in 35 keV with 2100 W RF power from No.4 H⁻ Source, and a 29 mA H⁻ current was extracted in CW mode with RF power of 1000 W. To further understand the plasma processes within a microwave driven volume H⁻ source, a comparison beam extraction of H⁻ beam and the positive hydrogen ions beam of H⁺, H₂⁺, H₃⁺ has been launched through inverting the polarities of the high voltage power supplies and that of 90° dipole analyzer magnet power supply with No. 4 PKU H⁻ source under different RF power and operation gas pressure. The experimental results showed the pure H⁻ current and the percentages of H⁺, H₂⁺, H₃⁺ were increased and that of H₃⁺ and the ratio of H⁻/e were decreased with the increasing of RF power. When the pressure of the source increased, the pure H⁻ current and the percentage of H⁺ kept constant, while that of H₂⁺ was decreased and that of H₃⁺ was increased. The pure H⁻ current variation trend was strong related with the percentage of H⁺ ion species. The details of experiments and will be showed in the article.

References

The U.S. Spallation Neutron Source (SNS) now operates with ~1 MW of beam power to target with the near-term goal of delivering 1.4 MW and a longer-term goal of delivering ~2.8 MW to support a planned second target station. Presently, H\textsuperscript{-} beam pulses (~35mA, ~1 ms, 60 Hz) from an RF-driven, Cs-enhanced, multi-cusp ion source are injected into the RFQ (Radio Frequency Quadrupole) and accelerated to 2.5 MeV before being injected into the linac. The recently acquired spare RFQ structure has been incorporated into a newly constructed Beam Test Facility (BTF). The purpose of the BTF is to validate the RFQ as a ready spare for the SNS, to perform 2.5 MeV beam dynamic and neutron moderator studies as well as to test and develop ion sources. If the emittance and the beam energy measurements meet requirements and the transmission shows considerable performance improvements over the existing SNS injector we will swap the SNS and BTF injectors as early as 2017. This report describes the ion source systems for this facility as well as the first LEBT and RFQ beam current measurements performed at the BTF with both the baseline internal and external antenna SNS ion sources. The relative performance of both SNS and BTF injectors are discussed as well as the injectors capabilities to deliver the ~50mA (~1 ms, 60 Hz) required to support the original and the second target station.
A new high duty factor (50 Hz 2 ms), scaled Penning surface plasma source is being developed at RAL [1]. Early tests resulted in an overheating anode, caused by poor thermal contact at elevated temperatures [2]. After a thorough analysis of the anode to source-body fit at different temperatures and different combinations of mechanical tolerances, a new anode with modified tolerance has been manufactured.

This paper details commissioning results at full duty cycle. Beam currents and emittances are detailed.

References

Influence of the cusp field on the plasma parameters of the Linac4 H⁻ ion source

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Currently the Linac4, a 160 MeV H⁻ linear accelerator is being built at CERN within the framework of the LHC injector upgrade project. The ion source of Linac4 relies on inductive RF coupling with an external coil for discharge generation (RF frequency 2 MHz, maximum RF power 100 kW). It can be operated in two modes: the first one where H⁻ ions are generated in the plasma volume via vibrationally excited hydrogen molecules and the second one where the H⁻ ions are produced from hydrogen ions and atoms impinging on a low work function surface which is created by evaporating caesium into the source. For optimizing the H⁻ yield in both operation modes with respect to the operational parameters like RF power and pressure but also with respect to fundamental ion source design properties, detailed knowledge of the plasma parameters and the processes taking place in the discharge is mandatory.

The performed investigations focused on the influence of the cusp field on the discharge parameters without evaporating caesium into the source. The magnetic cusp field which aims at confining the electrons and therefore reducing the energy loss is generated via NdFeB permanent magnets arranged in an octopole Halbach configuration. In order to gain insight in the plasma parameters, high-resolution optical emission spectroscopy (OES) measurements have been carried out at the Linac4 ion source test stand at CERN. The OES measurements of the atomic Balmer series radiation and the molecular Fulcher emission (d ³Πu → a ³Σg⁺ transition, located between 590 and 650 nm) have been evaluated with the collisional radiative models Yacora H and Yacora H₂. The obtained discharge parameters like the electron density and temperature as well as the vibrational and rotational temperature of the hydrogen molecules are compared for the cases with and without cusp field magnets installed at the ion source test stand for varying pressure and RF power.
High density plasma calculation of J-PARC RF negative ion source


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From September 2014, operation of Cs-seeded, multi-cusp, Radio Frequency (RF), hydrogen negative ion source (J-PARC source) has been started [1-3]. The operation for 1,000 hours of J-PARC source has been achieved with H- beam current 45 mA and duty factor of 1.25% (0.5 msec and 25 Hz) [3]. In the present study, mechanisms of hydrogen plasma ramp-up and H- production/transport processes in the steady state (which lasts for few 100 us) are investigated by numerical modeling for RF plasma [4,5]. In the simulation, charged particle (e, H+, H2+, and Cs+) transport, time variations of inductive and capacitive electromagnetic field, collision processes between charged and neutral (H, H2) particles are solved simultaneously. The model is applied to KEK parallel computation System-A with 32 nodes and 256 GB memory in order to solve high density RF plasma up to around 10^{18} m^{-3} with adequate statisticity. In the presentation, time variations of plasma density distributions and average energy are shown with electromagnetic field variations.

References

**WedO1**

**Coupling between magnetic filter and extraction in ITER-relevant negative ion source**

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A strong interplay between magnetic filter and plasma grid bias voltage leads to the co-extracted electron current in ITER-relevant negative ion source. In addition, the filter field itself creates strong plasma dis-homogeneity along the plasma grid inducing different conditions (from classical electron-ion to complete ion-ion plasma) at the apertures. For this reason, a 2.5D PIC-MCC model (the losses in the third dimensions along the magnetic filter lines are taken into account with a simple loss model) of the full scale ITER-relevant negative ion source has been developed keeping the single cell small enough to resolve in detail the extraction dynamics till the second extraction grid. Results (see Figs. 1 where the plasma potential and electron density structures in the expansion and extraction regions have been reported) have shown the presence of fine structures in the direction perpendicular to magnetic filter and the strong dis-homogenous plasma conditions at the entrance of every extraction aperture.

![Figure 1. Two dimensional map of (a) electric potential $\phi(V)$ and (b) electron density $n_e(m^{-3})$ in the expansion region of ITER-relevant negative ion source.](image)

**References**


Numerical simulation of the RF plasma discharge in the Linac4 H⁻ ion source

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Linac4 is the new H⁻ linear accelerator currently being commissioned at CERN as part of the upgrade of the LHC injector chain. Its cesiated ion source is required to deliver an H⁻ beam of 40-50 mA within an RMS emittance of 0.25 mm x mrad in pulses of 500 µs and a repetition rate up to 2 Hz [1]. H⁻ ions are created in a Radio-Frequency (RF) inductively coupled plasma operated at 2 MHz, where two modes of H⁻ production are known to take place: volume production by dissociative attachment of vibrationally excited molecules H₂(v) [2], and surface conversion of protons H⁺ and atoms H⁰ impinging onto a cesiated surface [3].

We have developed a Particle-In-Cell Monte Carlo Collision code [4] to self-consistently simulate the coupling between the RF coil and the plasma. Our goal is to investigate the influence of the RF plasma heating on the H₂(v) population and the H⁺/H⁰ fluxes onto the cesiated surface. The simulated plasma includes a kinetic description of the charged particles (e⁻, H⁺, H₂⁺, H₃⁺ and H⁻) as well as the neutral populations of H⁰ and H₂(v). Output from these simulations represent crucial inputs for the modelling of the beam formation [5].

In this paper we present a detailed description of the plasma discharge at the nominal Linac4 operational conditions (40 kW RF power at 3 Pa H₂ pressure) including spatio-temporal variations of the population densities and temperatures, dissociation degree and H⁺/H⁰ fluxes onto the cesiated surface. Variation of RF power and H₂ pressure are investigated to assess their effect on the plasma parameters. Simulation results are compared to optical emission spectroscopy measurements performed on a dedicated test-stand at CERN.

References

Modelling of caesium dynamics
in the negative ion sources BATMAN and ELISE

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The knowledge of Cs dynamics in negative hydrogen ion sources is a primary issue to achieve the ITER requirements for the NBI systems, i.e. one hour operation with an accelerated ion current of 40 A of D− and a ratio between negative ions and co-extracted electrons below one. The efficiency of negative ion production depends on converter surface work function, which for good conditioning approaches the one of bulk Cs. To avoid the work function degradation it is necessary to maintain a sufficient flux of Cs onto the converter surface during the beam pulse. Cs transport and redistribution is influenced by many parameters, such as the Cs nozzle position and orientation, the evaporation rate, the plasma parameter profiles and the source wall condition, i.e. the surface temperature and the presence of impurities (due to the high reactivity of Cs). For the investigation of Cs transport inside the RF ion sources, the Monte Carlo transport code CsFlow3D was developed [1]: the provided outputs are the Cs fluxes and coverage onto the source walls, both in vacuum and during the plasma pulse, while a key input parameter is the sticking coefficient of the walls and of the converter surface. The code was updated to calculate also line average density of neutral Cs along specific lines-of-sight; these values can be then directly compared with the laser absorption spectroscopy data, a diagnostic used to determine neutral Cs density both during vacuum phase and during the plasma pulse. Simulations were performed for the operation of the negative ion sources at BATMAN (1/8 of the ITER source) and ELISE (half of the ITER source) test facilities. In particular, the simulated time traces of neutral Cs density in relation with the Cs nozzle configuration, the plasma parameter profiles and the duty cycle will be presented, as well as the comparisons between simulations and laser absorption spectroscopy measurements for both the test facilities BATMAN and ELISE.

References

Modelling of negative ion and co-electron extraction from high brightness magnetized plasma sources

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Negative ion and co-electron extraction from a magnetized high power tandem type Inductively-Coupled-Plasma (ICP) negative ion source is modelled using a 3D Particle-in-Cell (PIC) algorithm with Monte-Carlo Collisions (MCC). As an example, we model the particle extraction from the multi-aperture ITER prototype negative ion source (BATMAN) [1]. The effect of biasing the plasma electrode (PE), which separates the ion source plasma from the electrostatic accelerator, is analysed in details. We show that the extracted negative ion current is maximized when the PE is floating (i.e., an equal amount of positive and negative charges are impacting the electrode) while the co-extracted electron current is monotonically decreasing as the bias voltage is increased. This is confirmed by experimental measurements [2].

The potential in the extraction region increases along with the bias, while its amplitude inside the driver (discharge area) remains unaffected. This is due to the fact that the electron current flowing onto the PE remains a small fraction of the total losses collected on the other surfaces. Most of the electron current impacts the driver walls or the back of the expansion chamber (second chamber next to the driver). The magnetic field barrier does in effect separate the driver from the rest of the ion source. The plasma potential flattens as the floating condition is approached on the PE. In addition, the gap between the bias voltage and the plasma potential in the extraction region decreases which explains why the co-extracted electron current is sharply decreasing (the electrons are collected by the PE instead). For bias voltages ($V_{PE}$) above floating PE conditions, the plasma potential profile along (Ox) reverses locally, that is $\phi < V_{PE}$. Furthermore, the bias voltage lowers the positive ion flux on the PE surface. The fraction of negative ions inside the extracted beamlet which were produced by positive ions is consequently decreasing as well. Lastly, we will show that the extracted negative ion current which comes from negative ions produced inside the ion source volume via dissociative attachment with an hydrogen molecule also peaks when the PE is floating (i.e., a flat plasma potential profile inside the expansion chamber).

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Support from CEA and from the French Fédération de Recherche sur la Fusion Magnétique is acknowledged. This work was granted access to the HPC resources of CALMIP supercomputing centre under the allocation 2013-P1125.

References

Multi-fluid Simulation Models for Inductively Coupled Plasma Sources

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A numerical simulation model for Inductively Coupled Plasma (ICP) sources and its implementation in the USim fluid-plasma software is presented. The primary objective of the simulation model is to evolve plasma from a neutral gas and its coupling to externally imposed electromagnetic fields. This model is being developed to analyze the potential for antenna failures in the Spallation Neutron Source negative hydrogen ion source [1].

In this paper we demonstrate this model by simulating plasma generation and dynamics in a benchmark ICP device. An RF current at a frequency of $f = 13.6$ MHz is used to generate ions from argon gas with gas pressure $\sim 10$ mTorr. An electric field in the plasma due to the RF current in external antenna coils is obtained by solving a vector potential equation given by:

$$\nabla^2 A + \omega^2 \mu \varepsilon A = -\mu J.$$ 

The dielectric constant $\varepsilon$ is given by $\varepsilon_0 - i\sigma/\omega$, where $\omega = 2\pi f$, and $\sigma$ is the plasma conductivity. Using the induced electric field, power deposition in the argon gas is estimated and a set of reacting multi species fluid-plasma equations are solved to predict the plasma density, temperature, and velocity. Figure 1 shows preliminary results of the electron temperature and electric field of the argon plasma. In this sample simulation, plasma was assumed sationary and only the azimuthal component of the electric field $E_\theta$ is considered. Electrons and ion/neutral energy equations are solved considering RF power deposition, thermal conduction and collisional heat transfer between the electrons and heavy particles. We describe our model for plasma chemistry that controls the plasma generation, and present here results for heating of plasma electrons and ions, as well as investigating plasma dynamics and derivations of the dominating physical processes at different physical length and time scales.

References

Study of energy relaxation processes of the surface produced negative ions by using 3D3V-PIC simulation

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To improve the H− beam optics in the Cs-seeded H− ion sources, it is necessary to understand the energy relaxation processes of surface produced H− ions. In the surface H− production, since the Frank-Condon H atoms or the accelerated H+ ions through the sheath are converted to H− ions, the surface produced H− ions are considered to be launched with the initial energy of a few eV.

Our previous study by using the 2D3V-PIC (two dimensions in real space and three dimensions in velocity space particle in cell) model shows that the beam optics of the extracted H− ion beam is strongly affected by the energy relaxation process via the Coulomb collision [1]. This process is verified by using the 3D3V-PIC model. The temperatures of the background H+ ions and the surface produced H− ions are assumed to be 0.25 eV, and 1.5 eV, respectively. The velocity distribution functions of H− ions, which are perpendicular to the direction of H− extraction (x-axis), are shown in Fig. 1. These velocity distribution functions are obtained at the location of 3 mm away from the plasma grid. In Fig. 1, \(v_{ih,e}\) is the electron thermal velocity at 1 eV. It is shown that the temperature of H− ions is reduced from 1.5 eV to 0.6 eV due to the Coulomb collision. In the conference, another energy relaxation processes such as the charge exchange collision with the H atoms, and the effect of the energy relaxation processes on the H− beam optics will be presented.

Figure 1. The velocity distribution functions of H− ions perpendicular to the direction of H− extraction.

References

Impact due to Impurity Contamination upon Cs Consumption of a Negative Hydrogen Ion Source

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Introduction of Cs into a negative hydrogen (H⁻) ion source reduces work function of the plasma grid to be less than 2.0 eV [1], a value realized by Cs coverage on metal thinner than a monolayer. Unlike bulk Cs, metallic Mo, material commonly used for a plasma grid or a color of a negative hydrogen ion source, should hold adsorbed Cs with large binding energy corresponding to reduction of work function. Thus, with the energy acquired from the plasma potential in the ion source, hydrogen ions cannot sputter out Cs on the plasma grid surface leaving the plasma grid work function to stay low. It is often observed that vacuum leak of an ion source reduces the amount of H⁻ current extracted from the ion source [2]. There are two possibilities to make the work function of the plasma grid to be higher. One is adsorption of oxygen on the plasma grid with Cs, forming a high work function plasma grid surface. The other is direct sputtering of Cs atoms from the plasma grid by oxygen ions that reduces the Cs coverage below thickness of low work function.

In this study, a surface collision cascade simulation program ACAT (Atomic Collisions in Amorphous Target) was run to estimate the Cs sputtering yield against oxygen and carbon for the conditions that Cs atoms are coadsorbed on the Mo plasma grid surface with hydrogen, oxygen and carbon. Figure 1 is an example for Cs sputtering yield from Cs and hydrogen coadsorbed Mo surface. As can be seen from the figure, the sputtering yield becomes sizable at less than 5 eV oxygen impact energy. Effects due to coadsorption upon Cs sputtering yields for different incident ion species are discussed.

References


Figure 1. Cs sputtering yield by O⁺ ion impact from Cs and hydrogen adsorbed Mo.
SPIDER experiment, the full size prototype of the beam source for the ITER heating neutral beam injector, has to demonstrate extraction and acceleration to 100 kV of a large negative ion hydrogen or deuterium beam with co-extracted electron fraction $e^-/D^- < 1$ and beam uniformity within 10%, for up to one hour beam pulse.

Main RF source plasma and beam parameters are measured with different complementary techniques to exploit the combination of their specific features. While SPIDER plant systems are being installed, the different diagnostic systems are in the procurement phase. Their final design will be described with a focus on some key solutions and most original and cost effective implementations, following the conceptual design reported in [1,2].

Thermocouples used to measure the power load distribution in the source and over the beam dump front surface will be efficiently fixed with proven technique and acquired through custom electronics. Spectroscopy needs to use well collimated lines of sight and will employ novel design spectrometers with higher efficiency and resolution and filtered detectors with custom built amplifiers. The electrostatic probes will be operated through electronics specifically developed to cope with the challenging environment of the RF source. The instrumented calorimeter STRIKE will use new CFC tiles, still under development. Two linear cameras, one built in house, have been tested as suitable for optical beam tomography. Most of these components are being prototyped or are under test before final production and installation, which will be completed before start of SPIDER operation.

References

SIPHORE is a potential photo neutraliser based system for Neutral Beam Injection (NBI) on the future nuclear fusion demonstration reactor DEMO. SIPHORE accelerates 100 keV pre-accelerated negative ion beams in a single step to around 1 MeV. These 1 MeV beams are then efficiently photo neutralised and drift into the DEMO tokamak.

Research into a novel type of compact bushing for this system is being conducted through the HVIV (High Voltage holding In Vacuum) partnership between CEA-Cadarache, GeePs-CentraleSupélec, LPGP and LCAR. It aims to concentrate the high electric field inside the bushing itself, rather than in the vacuum tank. Hence the field emission current is also concentrated inside the bushing and it can be attempted to suppress this so-called dark current by conditioning the internal surfaces and by adding gas.

LCAR have performed theoretical quantum mechanical studies of electron field emission and the role of adsorbates in changing the work function. LPGP studied the ionisation of gas due to field emission current and the behaviour of micro particles exposed to emissive electron current in the vacuum gap under high electric fields. Experiments at Geeps have clarified the role of surface conditioning in reducing the dark current. Geeps also found that nitrogen gas is much more effective than helium in reducing the field emission.

Finally, IRFM have performed experiments on a single stage test bushing that features a 36 cm high porcelain insulator and two cylindrical electrode surfaces separated by 40 mm vacuum or low-pressure gas. Applying voltage to a brand new set of electrodes results in dark current which then releases gas that stabilises the dark current. Conditioning allows to increase the voltage. The system appears to condition to ~115 kV without dark current and/or gas release. This conditioning is then partially lost overnight. Using 0.1 Pa N₂ gas, the voltage holding exceeded 185 kV without dark current. Above this voltage, exterior breakdowns occurred over the insulator, which was in air.

The project will finish with the fabrication of a 2-stage compact bushing, capable to withstand 400 kV. On the transmission line side, the bushing is kept in SF₆, on the other side the bushing is in vacuum.

The paper will describe the work performed for this project and the design for the 2-stage bushing that should be in fabrication by the time the Conference takes place.
Prototype High voltage bushing (PHVB) is a scaled down configuration of DNB High Voltage Bushing (HVB) of ITER. It is designed for operation at 50 kV DC to ensure operational performance and thereby confirming the design configuration of DNB HVB. Two concentric insulators viz. Ceramic and Fiber reinforced polymer (FRP) rings are used as double layered vacuum boundary for 50 kV isolation between grounded and high voltage flanges. Stress shields are designed for smooth electric field distribution. During ceramic to Kovar brazing, spilling can not be controlled which may lead to high localized electrostatic stress. To understand spilling phenomenon and precise stress calculation, quantitative analysis was performed using Scanning Electron Microscopy (SEM) of brazed sample and similar configuration modeled while performing the Finite Element (FE) analysis. FE analysis of PHVB is performed to find out electrical stresses on different areas of PHVB and are maintained similar to DNB HV Bushing. With this configuration, the experiment is performed considering ITER like vacuum and electrical parameters. Initial HV test is performed by temporary vacuum sealing arrangements using gaskets/o-rings at both ends in order to achieve desired vacuum and keep the system maintainable. During validation test, 50 kV voltage withstand is performed for one hour. Voltage withstand test for 60 kV DC (20% higher rated voltage) have also been performed without any breakdown. Successful operation of PHVB confirms the design of DNB HV Bushing. As a next step, permanent vacuum sealing configuration has been designed. In this paper, configuration of PHVB with experimental validation data will be presented.
Investigation of plasma parameters at BATMAN for variation of the Cs evaporation asymmetry and comparing two driver geometries

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The Neutral Beam Injection (NBI) system for ITER requires large scale sources for negative hydrogen ions. BATMAN (Bavarian Test Machine for Negative Ions) is a test facility attached with the prototype source for the ITER NBI (1/8 source size of the ITER source), dedicated to physical investigations due to its flexible access for diagnostics and exchange of source components. The required amount of negative ions is produced by surface conversion of hydrogen atoms or ions on caesiated surfaces. Several diagnostic tools (Optical Emission Spectroscopy, Cavity Ring-Down Spectroscopy for H\(^-\), Langmuir probes, Tunable Diode Laser Absorption Spectroscopy for Cs) allow the determination of plasma parameters in the ion source. Plasma parameters for two modifications of the standard prototype source have been investigated:

Firstly, a second Cs oven has been installed in the bottom part of the back plate in addition to the regularly used oven in the top part of the back plate. Evaporation from the top oven only can lead to a vertically asymmetric Cs distribution in front of the convertor surface. Using both ovens, a symmetric Cs distribution can be reached – however, no significant change of the extracted ion current has been determined for varying Cs symmetry if the source is well-conditioned.

Secondly, BATMAN has been equipped with a much larger, racetrack-shaped RF driver (area of 32x58 cm\(^2\)) instead of the cylindrical RF driver (diameter of 24.5 cm). The main idea is that one racetrack driver could substitute two cylindrical drivers in larger sources with increased reliability and power efficiency. It is expected that one racetrack driver requires less RF power than the sum of two cylindrical drivers for achieving similar plasma parameters in the driver and thus a similar extracted negative ion current. The racetrack driver is equipped with one Cs oven in the center of the driver back plate. A detailed comparison of the plasma parameters in the driver as well as close to the plasma grid will be presented.
Ion source development for a Photoneutralization based NBI system of Fusion reactors

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The specifications required to operate an NBI system on DEMO are very demanding. The system has to provide a very high level of power and energy, (~100MW of D\textsuperscript{0} beam at 1MeV), including high wall-plug efficiency ($\eta > 65\%$). For this purpose, a new injector concept, called Siphore, is under investigation between CEA and French universities. Siphore is based on the stripping of the high energetic negative ions by photo-detachment provided by several Fabry-Perot cavities implemented along the D\textsuperscript{\textsuperscript{+}} beam. The beamline is designed to be tall and narrow in order that the photon flux overlaps the entire negative ion beam. The paper will describe the present R\&D at CEA which addresses the development of an RF ion source for Siphore, the main goal being to produce an intense negative ion beam sheet. Cybele is based on a magnetized plasma column where hot electrons are emitted in the source center. A cylindrical RF 1MHz driver has been implanted on the bottom extremity of the Cybele source. The plasma transport with or without magnetic field in the source volume is characterized using Langmuir probes; the present experimental results will be presented.

Cybele source: Left: principle of the plasma confinement and implantation of the RF driver.
Right: Photo of Cybele on the testbed
Efficiency of Cs-free materials for negative hydrogen ion production

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Present high current negative hydrogen ion sources use the surface conversion mechanism at a low work function surface for efficient negative ion production. For that purpose caesium is evaporated into the ion source which after various ad- and desorption processes covers the converter surface and lowers its work function significantly. However, the chemically highly reactive surface layer is subject to impurities from the background gases during vacuum phases and to the interaction with the hydrogen discharge during plasma phases. While the former leads to degradation of the work function, the latter results in complex redistribution processes of Cs within the ion source including possibly extensive modifications of the converter surface conditions. Hence, maintaining a stable and homogeneous low work function surface and thus a high source performance is quite demanding and requires moreover continuous evaporation of Cs into the ion source. Especially in prospect of negative ion based neutral beam heating at a future fusion power plant and the associated RAMI issues (reliability, availability, maintainability, inspectability) alternatives to caesium for efficient negative hydrogen ion formation are thus desirable. Fundamental investigations on promising Cs-free materials are performed at the flexible laboratory experiment HOMER (Homogeneous Electron Cyclotron Resonance Plasma) \cite{1}. The setup is designed as a tandem source and provides comparable plasma parameters to the conditions close to the converter surface in negative ion sources. Sample surfaces up to sizes of 8.5 x 6 cm\textsuperscript{2} are investigated. The influence of the sample material on the negative hydrogen ion density is measured locally above the surface via a laser photo detachment system. Investigated materials include tantalum and tungsten, non-doped and boron-doped diamond (BDD) as wells as materials with inherent low work function like LaB\textsubscript{6} or lanthanum-doped molybdenum (MoLa). The negative hydrogen ion density is measured depending on the hydrogen pressure, the distance to the sample surface, the bias potential applied to the surface and the sample temperature. 0-dimensional modelling is applied \cite{2} to discuss the respective formation and destruction processes of H– within the plasma volume. Focus is laid on the rating of the materials regarding H– production in comparison to the two reference cases of a bare and a caesiated stainless steel surface.

References

Preliminary studies for a beam-generated plasma neutralizer test in NIO1

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The deployment of neutral beam injectors in future fusion plants is beset by the particularly poor efficiency of the neutralization process. Plasma neutralizers, originally proposed in the 80s, promise consistent efficiency improvement with respect to baseline scenarios based on gas neutralizers. Halfway between these solutions, beam-driven plasma neutralizers have been considered by Surrey [1], which might offer an improved neutralization at a minor technological cost. Anyway, since plasma formation is to be obtained by a special configuration of magnetic fields, preferably obtained by permanent magnet only, some trial experiments with reduced-size prototypes are necessary. The test of such a system in the small negative ion beam system NIO1 is discussed in this paper. The proposal also moves from the fact that there are limited experimental measurements of the neutralizer plasma parameters in a negative ion beam systems for fusion. This test would contribute also to study fundamental physics that has direct implications also in beam optics, beam transport, operation of electrostatic residual ion dumps, and long pulse operations with indirect heating of mechanic components not in direct view of the particle beam. The required gas target thickness, and possible magnetic confinement solutions are presented. Integration in NIO1 is also discussed, with the impact on the pumping system and the setup for measuring the residual beam fractions. An estimate of ionization degree and neutral yield is given for this design. This work was set up with partial financial support of EUROPfusion.

References

ONIX results: Comparison of grid geometry (Batman - ELISE - flat grid)

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The neutral beam injection (NBI) system for ITER should deliver 40A of D\textsuperscript{0} with an energy of 1 MeV for heating and current drive. Before being accelerated and further neutralized, the negative ions produced in the large area ion source via the surface conversion process or via production in the plasma volume must be extracted properly (\textit{i.e.} low emittance) in order to have a suitable beam. This constitutes one of the most crucial steps for NBI transmittance and efficiency.

The beam characteristic is affected directly by the geometry of the apertures (flat or chamfered), the extraction potential, the grid bias voltage, the plasma density, the negative ion emission rate due to surface processes, the magnetic filter field and the deflection field for co-extracted electrons to name only the main of them.

During the last years, the 3D PIC-MCC ONIX (Orsay Negative Ion eXtraction) code has been dedicated to the modelling of the extraction of negative hydrogen ions and co-extracted electrons. The code is benchmarked with direct comparison to experimental results obtained at the negative ion test facility BATMAN (BAvarian Test MAchine for Negative ions) which is equipped with the ITER prototype source. The insights provided by ONIX allowed us to understand the physics of negative ions extraction \cite{ref1}.

In parallel, the design of the extraction system of the test facility ELISE (Extraction from a Large Ion Source Experiment) is finished corresponding to the one of the ion source for ITER. Therefore, the ONIX code has been recently adapted and used for the modelling of negative ion extraction at ELISE.

The presentation focusses the comparison of the main characteristics of the extraction of negative ions and co-extracted electrons for the two grid geometries of BATMAN and ELISE.

References

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Study of negative ion surface production in cesium-free H\textsubscript{2} and D\textsubscript{2} plasmas

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Negative ion surface production in plasmas is of a primary interest for neutral beam injection devices in fusion. D\textsuperscript{−} current density of 200 A/m\textsuperscript{2} is required for ITER. The only up-to-date solution to reach such a high D\textsuperscript{−} negative-ion current is the use of cesium (Cs). Deposition of Cs on the negative-ion source walls lowers the material work function and allows for high electron-capture efficiency by incident particles and high negative ion yields. However, severe drawbacks to the use of Cs have been identified, hence a strong reduction of Cs consumption or its elimination from the fusion negative-ion sources is highly valuable. We are working on H\textsuperscript{−}/D\textsuperscript{−} negative-ion surface production in Cs-free H\textsubscript{2}/D\textsubscript{2} plasmas.

In our experiment a sample is placed inside a low pressure plasma reactor PHISIS, facing a mass spectrometer (MS). The sample is biased negatively with respect to the plasma potential. Negative ions formed on the sample surface upon positive ion bombardment are accelerated by the sheath towards the plasma, cross the plasma and reach the MS where they are detected according to their energy. Under this configuration, negative-ions are self-extracted from the plasma. To gain insight into negative-ion surface production mechanisms, it is of primary importance to derive from the measured Negative-Ion Energy Distribution Function (NIEDF) the characteristics of the negative-ion emission from the surface. We have developed a model \cite{1,2} allowing to compute from the measured NIEDFs the energetic and angular characteristics of the negative-ions emitted by the surface. The model has been validated by comparison with the experiment. Based on this methodology, we are studying negative-ion surface production on different materials, including highly oriented pyrolytic graphite, single crystal and microcrystalline diamond (either B-doped or non-doped), gadolinium. In order to enable the study of negative-ion production on surfaces of insulating materials a pulsed bias method has been developed. The influence of surface temperature, bias and plasma exposure time on negative-ion yield is investigated.

Diamond is a promising candidate to enhance surface production of H\textsuperscript{−}/D\textsuperscript{−}. Given its low or even negative electron affinity and variable wide energy band gap (depending on the doping), diamond may exhibit a relatively high total electron emission yield. We have previously demonstrated a significant enhancement of negative-ion yield on diamond at elevated temperatures \cite{3}. We observe that in order to optimize the negative-ion production on diamond one has to work with a less degraded surface. This can be obtained either by heating the surface to 400°C–500°C, which allows restoring intrinsic properties of diamond, or by working at lower surface bias of 10–20 eV.

In this contribution we present the methodology used to study negative-ion surface production. We show results on relative negative-ion yields for various diamond films including single crystals. With the aim of working in conditions closer to negative-ion sources in terms of positive ion energy, we present some recent measurements obtained at low surface bias.

References

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Negative Ion Formation from a Low-Work-Function Nanoporous Inorganic Electride Surface

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Recently, Hosono and his coworkers have found that a kind of nanoporous inorganic oxide can be transformed to an electride \cite{1,2}. This new material is air-stable, mechanically robust and machinable. It shows electrically conductance and has a low work function of 2.4 – 2.8 eV. Possible applications of the material include an electron emitter operated in medium temperature range. In the present work, we investigate the characteristics of this electride experimentally from the view point of H\textsuperscript{-} production.

The material surface was exposed to an atomic hydrogen (H\textsubscript{0}) flux and the negative current from the surface was measured as a function of H\textsubscript{0} flux. Electrons and positive ions from the atomic hydrogen source were eliminated by a pair of neodymium-iron magnets, and the negative charge produced at the electride surface was detected. Similar measurement was carried out with a low-work-function bi-alkali material covered molybdenum surface (~2.3 eV). Under the same condition of atomic hydrogen exposure, nearly the same negative current was observed. The temperature dependence and the photoelectric response of the material will be reported.

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Features of Radio Frequency surface plasma sources with solenoidal magnetic field

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Operation of Radio Frequency Surface Plasma Sources (RF SPS) with a solenoidal magnetic field are described. RF SPS with solenoidal and saddle antennas are discussed. Dependences of beam current and extraction current on RF power, gas flow, solenoidal magnetic field and filter magnetic field are presented.

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Benchmark of single beamlet analysis to predict operational parameter for ITER in Japan - Italy joint experiments

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The negative ion accelerators for the ITER neutral beam system has been designed by using the conventional beam codes for the positive ion accelerators because mechanism of meniscus formation of negative ions has not been clarified well. In this way, the operational window of the negative ion accelerators can be simply predicted, but the grid heat loading by peripheral beam (beam halo) could not be simulated. To understand the applicable range of the conventional codes to the negative ion accelerators, and then to understand the negative ion meniscus consequently, the benchmark tests between the conventional codes (BEAMORBT (BO) [1] and SLACCAD (SC)[2]) and the experiments have been performed under a joint experiment by RFX and QST on the Negative Ion Test Stand in Naka.

Figure 1 shows one numerical results as an example with the grid configuration. The extraction voltage ($V_{ext}$) is applied between the plasma grid (PG) and the extraction grid (EXG). The acceleration voltage ($V_{acc}$) is applied between EXG and the grounded grid (GG).

Figure 2 shows the beam divergence angle as a function of $V_{ext}$ at $V_{acc}$ of 20 kV. $V_{ext}$ with the minimum divergence angle are shown around 4.0 kV both in the numerical codes and the experimental result. The operational window can be predicted in the numerical codes. However, the absolute values of the divergence angle of the experiment was larger than those of the numerical result. One of reasons will be that the numerical code cannot represent the beam halo. Even in the numerical results, the divergence angle in the BO is slightly lower than that of the SC. To understand the meniscus effect to the beam divergence, the relationship between meniscus depth $\Delta z_{menis}$ and beam divergence in the numerical results was compared as shown in Figure 3. The details are reported in the paper.

References
Effect due to Plasma Electrode Adsorbates upon the Negative Ion Current and Electron Current Extracted from a Negative Ion Source.

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The intensity of negative hydrogen ion (H⁻) current and that of electron current extracted from a negative ion source show different characteristics against the change in plasma electrode bias depending upon the material covering the plasma electrode surface. The knowledge of these characteristics is of importance for a proper design of an efficient H⁻ ion source. This paper discusses the effect based upon two kinds of experiments: i) experiments with a caesium covered plasma electrode ii) experiments with plasma electrodes covered with tungsten or tantalum evaporated from filaments made of these metals. The tantalum and caesium covered plasma electrode lead to an enhancement of the extracted H⁻ ion current by a factor of 2 compared to the tungsten coverage on the plasma electrode. The electron current is also affected by the material covering the plasma electrode. The reasons for observing these characteristics are elucidated.

References

Experimental validation of an innovative deflection compensation method in a multi-beamlet negative-ion accelerator

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In multi-beamlet negative ion accelerators for fusion applications, the required transverse magnetic field for the suppression of co-extracted electrons is generated by permanent magnets arranged in parallel arrays, embedded in the Extraction Grid. However, such configuration also produces an undesired “criss-cross” deflection of ion trajectories, which can downgrade the overall beam optics. This deflection is traditionally counterbalanced by electrostatic means, i.e. by introducing a small offset in the axis of the grid apertures.

During the final design of MITICA, which is the prototype of the ITER Heating Neutral Beam Injector presently under construction in Padova [1], an innovative magnetic configuration called ADCM (Asymmetric Deflection Compensation Magnets) has been conceived [2] and adopted, offering several advantages in terms of operational flexibility compared to the traditional solution. In the framework of a research collaboration between RFX and QST, the new concept has been experimentally tested for the first time in 2016 by a joint RFX–QST team. A new ITER-like [3] Extraction Grid (designed and built at RFX) was mounted on the existing NITS device at the QST lab in Naka. For direct comparison, half of the Extraction Grid was provided with the new ADCM configuration, whereas the rest of the grid had standard magnets with no compensation. A target made of monoaxial carbon-carbon fibre composite and an infrared camera were used for accurate beam optics measurement. The results obtained have confirmed the effectiveness of the ADCM concept for the compensation of the criss-cross ion deflection. Some discrepancies in the scaling of ion deflection with respect to 3D simulations were also evidenced and investigated. The paper presents the main results obtained during the experimental campaign on NITS at QST, which lasted in total six weeks, together with a discussion of the first data analysis results.

References

Study of electron transport across the magnetic filter of NIO1 Negative ion Source

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In the framework of the accompanying activities in support to the ITER NBI test facility a relatively compact radiofrequency (RF) ion source, named NIO1 (Negative Ion Optimization, phase 1) was developed in Padua, Italy, in collaboration between Consorzio RFX and INFN. Negative hydrogen ions are formed in a cold, inductively coupled plasma with a 2MHz, 2.5 kW external antenna.

A cooling of the electron energy distribution is necessary to increase the survival probability of negative ions in the proximity of the extraction area. This goal is accomplished by means of a transversal magnetic field, confining the high energy electrons better than the colder electrons. In NIO1, this filter field can cover different topologies, exploiting different set of magnets and high current paths. In this contribution we study the property of the plasma in the vicinity of the extraction region for different B field configurations. For this experiment the source was operated in pure volume conditions, in hydrogen and oxygen plasmas. The experimental data, measured by spectroscopic means is interpreted also with the support of finite element analysis simulations of the magnetic field and a dedicated numerical model for the electron transport across it, including Coulomb and gas collisions.

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The extraction of negative carbon ions with volume-cusp ion sources

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The production of negative carbon ions with volume-cusp ion source is being investigated. Using acetylene as the injection gas in our filament-powered source [1], up to 250 $\mu$A of beam with more than 20\% of C$_2^-$ was extracted. The beam composition is analyzed as a function of the tuning parameters and plasma properties are studied through optical emission spectroscopy. The 13.56 MHz RF RADIS ion source [2] is also being commissioned for the production of H$^-$ and negative carbon ions. This allows for direct comparison with the filament-powered source. Beam composition and plasma properties are studied with the RF powered source. Carbon dioxide is also being tested as an injection gas for the production of negative carbon ions. It is expected that the use of CO$_2$ will give higher C$^-$ yields than acetylene.
FriO7

**PIP-II Injector Test’s Low Energy Beam Transport: Commissioning and Selected Measurements**

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The Proton Improvement Plan II (PIP-II) at Fermilab is a program of upgrades to the injection complex. As presently envisioned, the PIP-II program is centered around a new 2 mA, 800 MeV H\(^-\) CW superconducting linac working initially in a pulse mode (0.55 ms, 20 Hz).

To validate the concept of such machine’s front-end, a test accelerator (a.k.a. PIP-II Injector Test) is under construction [1]. It includes a 15 mA DC, 30 keV H\(^-\) ion source, a 2 m-long Low Energy Beam Transport (LEBT), a 2.1 MeV CW RFQ, followed by a Medium Energy Beam Transport (MEBT) that feeds 2 cryomodules increasing the beam energy to ~25 MeV, and a High Energy Beam Transport section (HEBT) that takes the beam to a dump. The ion source and LEBT, in its initial straight configuration, have been commissioned to full specification parameters. This paper introduces the LEBT design and presents some of the commissioning results.

**References**

A novel helicon plasma source for negative ion beams for fusion

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In DEMO reactor to produce electricity, a total installed power up to 150 MW is considered. In the heating mix, neutral beam (NB) injectors of high neutral particle energy (0.8-1 MeV) with high wall-plug efficiency ($\eta$ in the range of 50\% to 60\%) will be required. Present design considered a NB system delivering in total 50 MW. In the Siphore NB concept [1], one of the promising candidates to meet these challenging requirements, negative ions will be extracted from a long, thin ion source 3 m high and 15 cm wide, accelerated and subsequently photo-neutralized. This requires the development of a new generation of negative ion sources. At the Swiss Plasma Center (SPC), a novel helicon plasma source, based on a resonant network antenna, is currently under study. The source delivers up to 10 kW at 13.56 MHz, and is installed on a linear (1.8 m long, 0.4 m diameter) vacuum vessel, allowing for full plasma characterization. In this work, the principles of operation of resonant antennas as helicon sources will be introduced, and absolute spectroscopic, Langmuir probe and interferometry measurements will be presented to characterize the performance of the source in terms of hydrogen/deuterium dissociation and negative ion production as a function of the input power at low gas pressure (0.3 Pa) and moderate magnetic field (~100 Gauss), as required by Siphore.

References

Powerful neutral beam injectors (NBI) are required as heating and current drive systems for tokamaks like ITER. The development of negative ion sources and accelerators (40A; 1MeV D⁻ beam) in particular, is a crucial point and many issues still require a better understanding. In this framework, the experiment NIO1 (9 beamlets of 15 mA H⁻ each, 60 kV) operated at Consorzio RFX has started operation in 2014 [1]. Both its RF negative ion source (up to 2.5kW) and its beamline are equipped with many diagnostics Error! Reference source not found.. For the early tests on the extraction system, oxygen has been used as well as hydrogen due to its higher electronegativity, which allows reaching currents large enough to test also the beam diagnostics even without caesium injection. In particular a 1D-CFC tile is used as a calorimeter to determine the beam power deposition by observing the rear surface of the tile with an IR camera; the same design is applied as for STRIKE [3], one of the diagnostics of SPIDER, the ITER-like ion source prototype [4], whose facility is currently under construction at Consorzio RFX. From this diagnostic it is possible to assess also the beam divergence and thus the beam optics. The present contribution describes the characterization of NIO1 particle beam by means of temperature and current measurements with different source and acceleration parameters.

References

The RF negative ion source NIO1[1], built at Consorzio RFX in Padua (Italy), is aimed to investigate general issues on ion source physics in view of the full-size ITER injector MITICA [2-3] as well as DEMO relevant solutions, like energy recovery and alternative neutralization systems, crucial for neutral beam injectors in future fusion experiments.

NIO1 has been designed to produce 9 H⁻ beamlets (in a 3x3 pattern) of 15mA each and 60keV, using a three electrodes system downstream the plasma source. At the moment the source is at its early operational stage [4] and only operation at low power and low beam energy is possible. In particular NIO1 presents a too strong set of SmCo co-extraction electron suppression magnets (CESM) in the extraction grid (EG) that will be replaced by a weaker set of Ferrite magnets. A completely new set of magnets will be also designed and mounted on the new EG[5] that will be installed next year, replacing the present one.

In this paper, the finite element code OPERA 3D is used to investigate the effects of the three sets of magnets on beamlet optics. A comparison of numerical results with measurements will be provided where possible. Both operations in oxygen and hydrogen gases will be compared in the investigation. This work was set up with partial financial support of F4E/EUROfusion.

References

[4]: M. Cavenago et al. *First experiments with the negative ion source NIO1*, Rev. Sci. Instrum. 87, 02B320 (2016).
Development of an energy analyzer as diagnostic of beam-generated plasma in negative ion beam systems

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The measurement of the plasma potential and the energy spectrum of secondary particles in the drift region of a negative ion beam offers an insight into beam-induced plasma formation and beam transport in low pressure gases. Plasma formation in negative-ion beam systems, and the characteristics of such a plasma are of interest especially for space charge compensation, plasma formation in neutralizers, and the development of improved schemes of beam-induced plasma neutralizers for future fusion devices. All these aspects have direct implications in the ITER Heating Neutral Beam and the operation of the prototypes, SPIDER and MITICA, and also have important role in the studies for NBI systems in Demo, while at present experimental data are lacking.

In this paper we present the design and development of an ion energy analyzer to measure the beam plasma formation and space charge compensation in negative ion beams. The diagnostic is a retarding field energy analyzer (RF EA), and will measure the transverse energy spectra of plasma molecular ions. The calculations that supported the design are reported, and a method to interpret the measurements in negative ion beam systems is also proposed. Finally, results of RFEA experimental test in a magnetron plasma are presented.

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MonP4

Does viscous and transient effects, dissociation, heating and surface scattering play a role in the gas density distribution along SPIDER accelerator?

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SPIDER is the full-scale beam source prototype of the ITER heating neutral beam. To support the incoming operation, we study for the first time a number of aspects linked to the presence of background gas in the multiaperture accelerator, which may occur in the early phase of SPIDER operation. In high filling pressure operations (1Pa), viscous effects will probably play a role. In short pulse operation, transients might introduce variability in the conditions seen by the beam. Dissociation, with the ensuing presence of atomic hydrogen along the extractor and accelerator, constitutes an additional gas target for the ion beam, exhibiting higher stripping probability. Gas heating is possible by indirect effects, due to beam-gas or beam-surface interaction. Finally, gas evacuation from the ion source may be favoured by non-diffuse scattering at surfaces, possible in non-isothermal gas flows. These aspects are studied by a 3D Direct Simulation Monte Carlo method, recently implemented in the Avocado code. The implementation is validated first by comparison against cases available in bibliography. The described effects are studied by parametric analyses.

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Control, Interlock, Acquisition and Data Retrieval Systems for the Negative Ion Source NIO1

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The NIO1 (Negative Ion Optimization, phase 1) experiment is a versatile test bench operated by Consorzio RFX and INFN in the framework of the activities aimed at the enhancement of negative ion sources for production of large ion beams for plasma heating in nuclear fusion devices and accelerator applications. The nominal beam current of 135mA at -60kV is divided into 9 beamlets, with multi-aperture extraction electrodes. The plasma is continuously sustained by a 2MHz radiofrequency power supply, with a standard matching box. A High Voltage Deck (HVD) is placed inside the lead shielding surrounding NIO1 and is fed by an insulation transformer installed in a nearby box. It contains the radiofrequency generator, the gas control, electronics and power supplies for the ion source. A closed-circuit water cooling system was installed for the whole system, with a branch towards the HVD.

The present contribution describes the control, interlock, acquisition and data retrieval systems for NIO1. Control and data acquisition system implementation require versatility and flexibility for an experiment such as NIO1; for example, new hardware components (e.g. Raspberry PI board, Arduino board, homemade hardware acquisition board) and different types of serial communication (RS232, GPIB, Ethernet) should be rapidly integrated in the communication network (Ethernet switches and electro-optical media-converters), while optical fibre uplinks are implemented to interconnect devices operating in the HVD. The software solution was to adopt Labview as the core of the control and of the acquisition systems (with the development of a synoptic panel) and MDSplus (including the most recent features, like support for long pulse discharge and MDSplus-Labview integration) for data archiving, distribution and visualization. A description is also given of the interlocks that are presently implemented to protect NIO1 against failures of the cooling system and to detect high voltage breakdown occurrences and over-temperatures. A Relational Data Base (based on PostgreSQL) is used to store time-averaged (summary) data for subsequent efficient data analysis in any programming language via standard connectors.

This work was set up with partial financial support of EUROfusion.
Test of 1D carbon-carbon composite prototype tiles for the SPIDER diagnostic calorimeter


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Additional heating will be provided to the thermonuclear fusion experiment ITER by injection of neutral beams from accelerated negative ions. In the SPIDER test facility, under construction at Consorzio RFX in Padova (Italy), the production of negative ions will be studied and optimised. To this purpose the test bed will require the assessment of beam characteristics.

STRIKE (Short-Time Retractable Instrumented Kalorimeter Experiment) is a diagnostic used to characterise the SPIDER beam during short operation (several seconds) and to verify if the beam meets the ITER requirements regarding the maximum allowed beam non-uniformity (below ±10%). The most important measurements performed by STRIKE are beam uniformity, beamlet divergence and stripping losses.

The major components of STRIKE are 16 1D-CFC (Carbon matrix-Carbon Fibre reinforced Composite) tiles, observed at the rear side by a thermal camera. The requirements of the 1D CFC material include a large thermal conductivity along the tile thickness at least 10 times larger than in the other two directions; low specific heat and density; uniform parameters over the tile surface; capability to withstand localised heat loads resulting in steep temperature gradients. So 1D CFC is a very anisotropic and delicate material, which is not commercially available, and prototypes are being specifically realised.

This contribution gives an overview of the tests performed on the CFC prototype tiles, aimed at verifying their thermal and thermo-mechanical behaviour. The spatial uniformity of the parameters and the ratio between the thermal conductivities are assessed by means of a power laser at Consorzio RFX, while the thermo-mechanical properties are investigated in the GLADIS facility at IPP (Max-Plank-Institut für Plasmaphysik) Garching. Dedicated linear and non-linear thermal finite-element simulations are carried out to interpret the experiments and to estimate the thermal conductivities; these simulations are described and the comparison of the experimental data with the simulation results is presented.

This work was set up with partial financial support of F4E.
Influence of the magnetic filter field topology on the beam divergence at the ELISE test facility

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The ELISE test facility hosts a RF negative ion source, equipped with an extraction system which should deliver half the current foreseen for the ITER Neutral Beam Injector, keeping the ratio of co-extracted electrons to ions below 1. An important tool for the suppression of the co-extracted electrons is the magnetic filter field, produced by a current flowing in the plasma grid, the first grid of the 3 stage extraction system. To boost the source performances new concepts for the production of the magnetic filter field have been tested, combining the existing system with permanent magnets attached on the source walls [2]. The topologies of these new magnetic configurations modify the space charge distribution in the extraction region, with consequences for the beam optics. These effects will be characterized in this article by studying the angular distribution of the beam particles, as measured by the Beam Emission Spectroscopy (BES) diagnostic. The behavior of the beam will be studied also through the measurements of the currents flowing on the grounded grid (the third grid) and on the grid holder box surrounding its exit. The main finding is that the broader component of the beam increases when the magnetic field is strengthened by permanent magnets, i.e. in the cases in which the co-extraction of electrons is more suppressed.

References

Electron density and temperature in NIO1 RF source, operated in oxygen and argon

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The NIO1 experiment [1], built and operated at Consorzio RFX, hosts an RF negative ion source, from which it is possible to produce a beam of maximum 130 mA in H\textsuperscript{-} ions, accelerated up to 60 kV. For the preliminary tests of the extraction system the source has been operated in oxygen, whose high electronegativity allows to reach useful levels of extracted beam current. The efficiency of negative ions extraction is strongly influenced by electron density and temperature close to the Plasma Grid. To support the tests these parameters have been measured by means of the Optical Emission Spectroscopy diagnostic. This technique [2] has involved the use of an oxygen-argon mixture to produce the plasma in the source. The intensities of specific Ar I and Ar II lines have been measured along lines of sight close to the Plasma Grid, and have been interpreted with the ADAS package [3] to get the desired information. This work will describe the diagnostic hardware, the analysis method and the measured values of electron density and temperature, as function of the main source parameters (RF power, pressure, bias voltage and magnetic filter field).

References

Preliminary Results of Radio Frequency ion source with two types of matching units

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The Experimental Advanced Superconducting Tokamak (EAST) is one of the fully superconducting tokamaks to study the physics of steady-state operation for nuclear fusion sciences. A neutral beam injector (NBI) was installed on the EAST for the plasma heating and driving. An arc based ion source was employed on EAST-NBI. In order to support scientific research of the next generation of fusion devices, the radio frequency (RF) was studied in the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP).

A simple RF ion source test bed was developed for performance test of RF ion source (Fig. 1). The RF ion source contains a RF driver with diameter of 200 mm and depth of 130 mm, a six turns of antenna with diameter of 227 mm, and an expansion region with depth of 240 mm. The RF power with fixed frequency of 1 MHz can be transferred to the antenna through a matching unit. The maximum power is 50 kW. A RF-compensated Langmuir probe was installed in the bottom of expansion region to measure the plasma parameters.

The matching unit is used to coupling the RF power into plasma. There are two types of matching units. One is only use the capacitors and other is use the transformer and the capacitors. The transformer was designed to insulate the high voltage from RF ion source during beam extraction, so, the RF generator can works in the ground potential. The preliminary results of RF plasma generation with two type of matching units were tested, including the RF power transfer efficiency, characteristic of marching units and the plasma parameters.
Preliminary Results of Radio Frequency Drived Plasma for the Negative Ion Sources

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The Experimental Advanced Superconducting Tokamak (EAST) is one of the fully superconducting tokamaks to study the physics of steady-state operation for nuclear fusion sciences. Neutral beam injector (NBI) is an effective plasma heating and driving method for fusion sciences research. The ion source is the most precision and important part of NBI.

A radio frequency (RF) ion source has been developed in the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). The RF ion source contains a RF driver with diameter of 200 mm and depth of 130 mm, a six turns of antenna with diameter of 227mm, and an expansion region with depth of 240 mm. The RF power with fixed frequency of 1 MHz can be transferred to the antenna through a matching unit. The maximum power is 50 kW. A RF-compensated Langmuir probe was installed in the bottom of expansion region to measure the plasma parameters.

A simple RF ion source test bed was developed, which is shown in Fig.1. In order to ignite the initial plasma, the start filament and higher initial gas pressure were used. So, the gas pressure was much higher and decrease to about 1Pa to hold the plasma. The plasma density and temperature was investigated with different RF power, gas pressure, and type of matching unit. The performance of plasma ignited by RF power was analyzed. The details of experimental results were presented when the matching unit with and without transformer. In the future, we will change the filtering magnet in the expansion region, and measure the negative ion parameters without and with cesium. And the negative ion beam will be extracted with different type of accelerators.

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{image1.png}
  \caption{Picture of RF ion source test bed}
  \label{fig:rfsource}
\end{figure}
MonP11

High currents Negative Ion source with a Planar ion Funnel extraction system

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High current large negative (H-, D-) ICP ion sources will produce the neutral beams needed for fusion plasma heating in ITER. To reach very high negative ion beams a cesium coated surface of the plasma grid is usually used. The cesium coating however, poses some problem in the maintenance and operation of the ion source and for that alternative ways to enhance the ion current extraction should be investigated. An alternative way to enhance the beam current could be the use of a Planar Ion Funnel (PIF) extraction system recently proposed for applications where a very high extraction efficiency are required [1]. In this contribution the idea of applying the PIF extraction on an ICP negative ion source to further increase the ion current extracted will be discussed and some simulation to better show the goodness of this proposal will also be presented.

References

An axisymmetric system to recover beam energy from partially neutralized $H^-$ beams was recently proposed, for a given beam acceleration voltage $V_s$ [1]. In the case of ion source NIO1, $V_s$ may range from 20 to 60 kV. A first nominal $H^-$ beam for simulation was assumed having 60 keV and 20 mA with a 4 mm radius and 0 mrad divergence. A second more realistic beam with 3 mrad divergence, and a composition of 25 : 50 : 25 of $H^-$, $H^0$ and $H^+$ has also been considered. The collector works by decelerating the $H^-$ ions (into a system similar to a Faraday cup provided with an exit hole electrode), so that they are radially deflected by space charge and anode lens effects, and collected to a low kinetic energy $K_c$ (less than 1 keV), while neutral and $H^+$ ions can pass through the exit hole electrode. A following collector can recover $H^+$ energy. Several tools were compared for simulations, from commercial programs to user prepared codes, which are challenging for highly nonlinear problem and for a possible (numerically unstable) virtual cathode phenomena; stabilization techniques are compared. Limits for local perveance are discussed. Also mesh asymmetry effects and the related transverse oscillations of $H^+$ beam may be observed. Efficiency over 90% can be reached in typical conditions. The secondary yield (which is low thanks to low impact energy $K_c$ and Faraday cup concept) is estimated.

References

ROBIN is an inductively coupled plasma (ICP) based negative hydrogen ion source, operated with a 100kW, 1MHz Tetrode based RF generator (RFG). Inductive plasma ignition by the RFG in ROBIN is associated with electron seeding by a hot filament and a gas puff. RFG is triggered by the control system to deliver power just at the peak pressure of the gas puff. Once plasma is ignited due to proper impedance matching, a bright light, dominated by $\text{H}_\alpha$ (656nm wavelength) radiation is available inside RF driver which is used as a feedback signal to the RFG to continue its operation. If impedance matching is not correct, plasma is not produced due to lack of power coupling and bright light is not available. During such condition, reflected RF power may damage the RFG. Therefore, to protect the RFG, it need to be switch off automatically within 200ms by the control system in such cases. This plasma light based RFG interlock is adopted from BATMAN ion source. However, in case of vacuum immersed RF ion source in reactor grade NBI system, such plasma light based interlock may not be feasible due to lack of adequate optical fiber interfaces because of material damage and its maintenance issues. The present demonstration of RFG interlock by Bias Current (BC) in ROBIN testbed gives an alternate option in this regard. In ROBIN, a bias plate (BP) is placed in the plasma chamber near the plasma grid (PG). BP is electrically connected to the plasma chamber wall of the ion source and PG is isolated from the wall. A high current ~10 A direct current (DC) power supply of voltage in the range of 0 - 30V is connected between the PG and the BP in such a way that PG can be biased positively with respect to the BP or plasma chamber. This arrangement is actually made to absorb electrons and correspondingly reduce co-extracted electron current during beam extraction. However, in case of normal plasma operation, BC rises due to the presence of plasma electrons, almost in the same timescale as plasma light detection system, and so BC signal can also be used as RFG interlock. The BC signal transmission is through optical isolation to reduce noise interference with the signal. The response of the current monitoring signal available from the PG power supply of ROBIN is quite slow (in the order of few tens of milliseconds). Therefore, a fast response current detection electronic circuit having the ability to generate a PG current detection pulse with adjustable threshold set point has been developed and integrated with ROBIN, and the above concept has been demonstrated in ROBIN recently. The present paper will discuss this experimental activity and its results.
Investigation of the RF-efficiency of inductively coupled hydrogen plasmas at 1 MHz

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Plasma generation of RF-driven sources for negative hydrogen ions is based on inductive coupling. As the optimum source performance is typically achieved for very high RF powers up to 100 kW, likewise high demands are posed on the RF circuits and generators in such an operating regime. Therefore, an improvement of the coupling efficiency of RF-plasma generation is highly desirable, in terms of reducing the totally consumed RF-power while preserving plasma parameters which are favourable for $^1$H production.

The coupling efficiency of RF-plasma generation is fundamentally investigated at the small lab experiment CHARLIE. Due to its flexibility and comprehensive set of diagnostics, different setups for RF-plasma generation can be directly compared. Additionally, the possibility to apply a weak external magnetic field allows for the investigation of promising alternatives to ICP such as Helicon coupling [1].

In this contribution, the investigation of a conventional ICP utilizing a helical coil is presented. A continuous wave driven hydrogen plasma is generated at 1 MHz and a RF power up to 1 kW for a pressure range of 0.3 to 10 Pa. Via in-line RF-voltage, current and phase angle measurement of the applied generator, as well as the indirect measurement of the RF-current directly running through the plasma coil via a current transformer, the coupling efficiency is quantified. The key parameters of the generated plasma are determined via electrical probes and emission spectroscopy, the latter in combination with collisional radiative modelling. In order to gain detailed insight into the heating mechanism, the measured plasma parameters are compared to modelled parameters provided by an electromagnetic Particle-In-Cell Monte-Carlo collision method simulating the RF-heating of the plasma based on the real experiment geometry [2,3].

References

Study of Back Streaming Ion using a Slot Type Grounded Grid in Hydrogen Negative-ion Source

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We installed a multi-slot type grounded grid (MSGG: slot width = 14 mm) replaced a multi-aperture grounded grid (MAGG: aperture diameter = 16 mm) to enhance current efficiency extracted from the negative ion source and to reduce conditioning time in 3rd beam line (BL3). From the performance evaluation test for MSGG in the year 2016, we confirmed the decreasing of electric breakdowns in the beam energy over 170 keV. We quickly achieved 180 keV beam acceleration with 80 A beam current used two ion sources with the new MSGG by a small number of shots. The total number of breakdowns on MSGG was reduced to less than half times of MAGG in the last two seasons. We consider that lower thermal loads on the MSGG due to high-transparency is effective in the growth of beam power. The high-transparency MSGG received lower thermal loads by collision of the peripheral portion of beam. This will also contribute a safety beam operation.

We also observed increase of beam current with low Cs consumption in the MSGG experiment used same arc discharge chamber. We have observed large elongate back-streaming spots on the back plate inside of the arc chamber. In this experiment, we installed an optical emission spectroscopy (OES) diagnostic in the discharge region of the negative hydrogen ion source. We observed the large increase of neutral Cs spectrum ($\lambda = 522$ nm) during beam extraction due to the thermal load on the back plate surface by back-streaming positive ions. This behavior weakly related to the beam energy, but strongly related to the beam power with constant focal condition. It is considered that the production of negative hydrogen ion was improved by the active Cs recycling which evaporate from the back plate due to the heat load by back-streaming positive ions. We also find huge increase of Cs intensity and large thermal loads on the MSGG in out of beam focus. We discuss the relation between beam focusing condition and the distribution of back streaming ions using the numerical calculation.
Determination of the energy and angle distribution functions of negative ions produced on the surface in hydrogen plasmas using mass spectrometry

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Negative ion surface production in cesium (Cs) seeded hydrogen plasmas is of primary interest for the present neutral beam injection systems; development of Cs-free negative ion sources would be highly valuable for the future systems. This work focuses on the understanding of the mechanisms of the surface production of negative-ions H\textsuperscript{−}/D\textsuperscript{−} in low pressure Cs-free plasmas of H\textsubscript{2}/D\textsubscript{2}.

In the experiment reported here, negative ions are produced on a sample which is immersed into hydrogen plasma and negatively biased with respect to plasma potential. The negative ions created under the positive ion bombardment are accelerated towards the plasma, self-extracted and detected according to their energy and mass by a mass spectrometer (MS) placed in front of the sample. The shape of the measured negative-ion energy distribution function (NIEDF) strongly differs from the NIEDF of the ions emitted by the sample because of the limited acceptance angle of the mass spectrometer. To gain insight into the production mechanisms, we propose two methods to compute the distribution functions in energy and angle (NIEADFs) of the negative-ions emitted by the sample.

The first method is based on an \textit{a priori} determination of the NIEADF and on an \textit{a posteriori} validation of the choice by comparison of the modelled and experimental NIEDFs. SRIM code provides a good \textit{a priori} choice of the NIEADF if the surface ionization probability is constant [1]. Modelling of the corresponding NIEDF measured by MS has shown a remarkable agreement with experiment for highly oriented pyrolytic graphite (HOPG). Moreover, we showed by tilting the sample that this validation concerns the whole distribution of emitted ions in terms of energy and angle [2]. However, the input parameters for SRIM may be unknown in general case and the surface ionization probability may depend on the ion energy and the angle of emission. For this reason we propose the second method: a reconstruction of the distribution of negative ions leaving the surface in energy and angle based on the NIEDF measurements at different tilt angles of the sample. The reconstruction algorithm does not depend on the negative-ion production mechanism, so it can be applied to any type of surface and/or negative ion. In this contribution we present this new method and show some results obtained for HOPG and gadolinium (low work-function metal) materials.

References

High effective neutralizer for negative hydrogen and deuterium ion beams on base of nonresonance adiabatic trap of photons.

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Photo neutralization of the neutral beams is considered as alternative of gas target for enhancement injection efficiency. Significant power density of photons in steady state is needed for this aim. This requires certain radiation storage. As a rule authors consider different analogs of Fabry-Perot cell (see for example [1]), which have sufficiently strong limitations such as laser beam quality, optic elements stabilization and other. In [2] a new concept of open adiabatic photon trap has been suggested. Possibility in principle adiabatic photon confinement in simple system was shown in work [3]. This paper presents the results of experiments on photoneutralization of hydrogen and deuterium negative ions beams.

Photon storage trap is designed as a system of parallel placed mirrors 25 cm long, consisting of individual cylindrical and spherical mirrors with a characteristic transverse dimension of 50 mm and a radius of curvature of 250 mm. The effectiveness of this approach is mainly determined by the quality of the reflecting surface. It is practically independent from the quality of the injected radiation and does not require high precision alignment of optical elements. In such a system, the photons undergo multiple reflections. Experiments were carried out using an injector with a beam energy 6-12 keV and a current of 1 A, the laser power up to 2 kW. Neutralization coefficient obtained for negative hydrogen ions is ~90% and ~98% for deuterium (See fig.1). These results demonstrate the high efficiency of this method and opportunities of the photon detachment target for powerful beams of negative ions neutralization.

References

Cs density measurement in arc driven negative ion source by means of laser absorption spectroscopy

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The Cs plays an important role on the hydrogen negative ion sources because the negative ion production is significantly enhanced due to the reduction of the work function on the plasma grid (PG) covered with the Cs. On the other hand, the maintenance interval for the ion source is limited by the Cs consumption rate and the Cs could cause the electrical breakdown when it enters the gap between the PG and the extraction grid (EG).

To understand the Cs behavior and optimizing the Cs consumption, we installed the laser absorption spectroscopy system to the 1/3-scaled negative ion source (NIFS-RNIS), where the plasma is produced by the arc discharge with filaments. The Cs density has been measured in various discharge conditions. In the paper, we will discuss the correlation with the Cs density to the negative ion density, electron density, and beam quality.
Simultaneous measurements of work function and H− density including caesiation of a converter surface

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Negative hydrogen ion formation can occur via a volume or a surface mechanism. The negative hydrogen ion source for the neutral beam injection system of ITER relies on the more efficient surface production regime, especially at a pressure of 0.3 Pa. The negative ions are created by conversion of atomic hydrogen and positive hydrogen ions at the converter surface. The H\textsuperscript{−} yield dominantly depends on the surface work function. By caesiation, the work function is lowered, enhancing this way the negative hydrogen ion formation. The work function is indeed a key parameter for the performance and temporal stability of negative ion sources, but there not directly accessible.

Hence, the correlation between work function of caesiated surfaces and H\textsuperscript{−} density is investigated at the laboratory experiment ACCesS (Augsburg Comprehensive Cesium Setup) [1,2]. The plasma parameters of the low temperature planar inductively coupled plasma are close to the ones of ion sources, with a background pressure of 10−6 mbar. A Cs dispenser oven is used to evaporate caesium into the experimental chamber [3]. The experiment is equipped with several diagnostic systems, which can be operated simultaneously. The work function of sample surfaces is evaluated by means of the Fowler method [4], while the negative hydrogen ion density is measured by a cavity ring-down spectroscopy system.

The work function of caesiated samples is monitored and its influence on the H\textsuperscript{−} density is investigated. Due to caesiation, the work function decreases as expected. However, in vacuum phase the presence of background gases leads to the formation of Cs compounds. This results in a higher work function at the surface with respect to pure Cs layers. Furthermore, in plasma phase the interaction with the hydrogen plasma also modifies the Cs layer, affecting the work function of the surface: while the impinging ions and UV radiation clean the Cs layer, the adsorption of particles from the plasma itself and the erosion of the Cs layer lead to a degradation of the layer. Because of the Cs dynamics in plasma operation, simultaneous measurements are mandatory and first results will be presented.

References

Beam characterization at BATMAN for variation of the Cs evaporation asymmetry and comparing two driver geometries

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The properties of the negative hydrogen ion beam produced at the BATMAN testbed (BAvarian Test MAchine for Negative ions) were investigated by means of dedicated beam diagnostics: an array of telescopes for Beam Emission Spectroscopy (BES) and a copper calorimeter. BES is employed for measuring the $\text{H}\alpha$ light-spectrum produced by the interaction between the beam and the background gas in the drift region: five horizontal lines-of-sight provide information about the vertical beam profile, divergence and inhomogeneity for varying source parameters. The calorimeter is composed of a water-cooled copper panel with 29 thermocouples embedded and arranged as a cross, measuring the horizontal and vertical beam profiles from the temperature difference ($\Delta T$) on each thermocouple between the start and the end of the beam. The negative ions are produced by the conversion of hydrogen atoms and ions on the cesiated plasma grid. The standard prototype source consists of a Cs oven located on top of the testbed and a cylindrical RF driver. The vertical beam profile shows a drift up because of the magnetic beam deflection and the asymmetric Cs evaporation. Two modifications to the prototype were investigated in this work. The first consists in the addition of a second oven at the bottom of the testbed for symmetric Cs evaporation inside the source. Using the beam diagnostics at this set-up it was possible to compare the profile of the beam measured with Cs evaporation from the top, the bottom and both ovens for the same source parameters and for increasing extracted ion current during conditioning. The second modification consists in replacing the cylindrical driver with a larger racetrack-shaped RF driver and placing the Cs oven in a central position at the back. The resulting beam characteristics are discussed and compared with those obtained with the previous source design.
A negative ion beam source has been established in Korea Atomic Energy Research Institute (KAERI) [1]. The source is mainly composed of an RF inductively coupled plasma source and a beam extraction grid system. The plasma source is equipped with an actively water-cooled Faraday shield which enables the RF power loading up to 10 kW and stable long-pulse operations. The RF power coupling efficiency to plasmas was estimated about maximum 80% at high RF powers with the current measurements of an RF antenna. A magnetic filter field (MFF) was realized with the permanent magnets to enhance the volume production of negative ions by reducing the electron temperature near the plasma grid. Probe measurements with an RF-compensated single Langmuir probe near the plasma grid showed the electron temperatures are below 1 eV at relatively high RF powers, confirming the MFF’s performance. An electron deflection field (EDF) was also realized by placing the permanent magnets in the extraction grid to suppress the co-extracted electrons. In the beam extraction experiments, however, the ratio of co-extracted electrons to negative ions were controlled dominantly by the plasma grid bias voltage with respect to the expansion chamber. Together with the experimental research, a global model analysis was conducted by solving a set of non-linear particle balance equations. The negative ion densities were calculated by the global model based on the plasma parameters obtained by the probe measurements. The calculated results show a reasonably good agreement with negative ion densities measured by the photo-detachment method with a Nd:YAG laser.

References

Experimental investigation of the relation between plasma parameters and impedance in the Linac4 H⁻ source

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CERN’s new particle accelerator Linac4 is part of the upgrade the LHC accelerator chain. Linac4 is required to deliver 160 MeV H⁻ beam to improve the beam brightness and luminosity in the Large Hadron Collider (LHC). The cesiated surface Linac4 ion source must deliver 40-50 mA, 45 keV H⁻ beam.

The power transfer efficiency between the RF generator (100 kW from 1.9 MHz to 2.1 MHz) and the ion source plasma is one of the most important parameters that determine the extracted H⁻ beam current [1]. The optimization of the power transfer to an ordinary load can readily be achieved by equalizing the impedance of the load to that of the RF generator, which is realized by the insertion of a matching circuit between the load and the generator. In the case of the Linac4 H⁻ source RF system, however, the optimization during the plasma pulse cannot be done by the matching circuit alone and is achieved by variation of the RF-frequency because the impedance of the load depends on the plasma parameters’ evolution during the pulse.

In the previous work at CERN, it has been shown that the tuning of RF frequency dynamically during the discharge is necessary to improve RF-coupling to the plasma [2]. The tuning is by now automated, however, the complex relation between the power transfer efficiency, discharge parameters, hydrogen pressure and plasma impedance deserves further investigation.

The aim of our study is to clarify the dependence of the plasma impedance on the plasma parameters. The dependence will be experimentally investigated varying RF-power and H₂ gas pressure. The experimental results will be discussed comparing the theoretical model of plasma impedance [3-5].

References

A RF-driven negative hydrogen ion source test facility has been constructed at HUST, it is operated at the pressure of 0.1~1Pa, RF power of 1MHz and 5-20 kilowatts, with discharge pulse of up to 10 seconds. In order to diagnose plasma parameters and evaluate the source performance, a RF compensated Langmuir probe system was developed autonomously. High side current detection was applied to measure drawn current by probe, which makes up the shortage of extra probe voltage compensation for low side current detection. For processing the experimental data, a computing program was developed to automatically calculate plasma density, electron temperature and electron energy distribution function, numerical techniques including digital filtering, nonlinear fitting, numerical interpolation and integration were implemented and various methods of interpretation of probe data were analyzed and compared. Discharge and diagnosis experiments in the driver region were carried out, results would be presented and discussed in the paper.

![Figure 1. Data processing of a typical hydrogen discharge in the driver at pressure of 0.3Pa, power of 10kW.](image)

**References**


In most ray tracing simulation codes [1], the extraction region of a negative ion source is treated by simplified empirical models, in complete analogy with a positive ion source, which makes two-dimensional (2D) and 3D three-dimensional simulations possible. Anyway the values of initial parameters (energy at plasma electrode potential, plasma potential, distribution of transverse momenta of electrons and negative ions) needs to be carefully adjusted in order to make the simulation to converge; often a good fit to experimental result is obtained with parameter values which are unexpected according to the parameter definition and meaning. This is related to effects (like collisions and plasma diffusion) which may be negligible in the beam and in the ray tracing, but quite relevant in the plasma before the extraction layer. From a reduced one-dimensional (1D) integrodifferential model of a simplified kinetic equation (in two velocity components) including magnetic field and effective collisions, recently analytically described [2], the expected trends of most extraction parameters are here discussed and compared with simpler fluid models of extraction layers and with ray tracing models.

References

Negative hydrogen ion sources have a wide range of applications, such as accelerator for high-energy particle physics\(^1\), medical use\(^2\) and fusion plasma heating\(^3\). The common issue of developing the negative ion sources is to produce high current negative ion beams with good beam optics.

In order to develop such a negative ion source, it is necessary to clarify the extraction mechanism. Recently, various 3D kinetic particle codes have been developed to study the extraction mechanism\(^4-7\). Nevertheless, the direct comparison between each other has not yet been done.

Therefore, we have carried out a code-to-code benchmark activity to validate our codes. In the present study, the progress in this benchmark activity will be shown. More specifically, temporal evolution of extracted current densities, profiles of electric potential and density will be compared with each other. At the moment, this comparison has been performed in the case of the plasma consisting of only electrons and positive ions as a first step.

References

Inductively coupled plasma (ICP) negative ion sources are of fundamental importance for ITER-like Neutral Beam Injection (NBI) systems, because poor performances of the ion source result in a lower yield of the full fusion machine. A versatile cylindrically symmetrical ICP-RF source named NIO1 (Negative Ion Optimization phase 1) is now operating in Padua, built by Consorzio RFX and INFN. The driver of ITER and ITER-like ion sources is usually built as a cylindrical gas-filled vessel around which a RF-current driven coil is wound. In spite of the wide diffusion of RF sources, a complete understanding of the mechanisms regulating the RF-coupling of the plasma is still lacking and self-consistent simulations of the system are highly advisable.

For this reason we developed a 2.5D Particle-In-Cell Monte-Carlo-Collision (PIC-MCC) model of a cylindrical ICP-RF source, keeping the grid spacing and time step of the simulation small enough to respectively resolve the Debye length and the plasma frequency scales. Results of these simulations are here reported with details about the computational side and future developments.
Analysis of the Spatial Non-Uniformity of Negative Ion Production in Surface-Produced Negative Ion Sources

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To improve the spatial uniformity of the negative ion (H\textsuperscript{–}) production is one of the most important issues for large negative ion sources. In these sources, the surface-produced H\textsuperscript{–} ions are formed via the H\textsubscript{0} atom flux onto the Plasma Grid (PG). H\textsubscript{0} atoms are produced by electron impact collisions of H\textsubscript{2} molecules with high-energy electrons (E>20eV). Thus it is essential to study the electron energy distribution function (EEDF) and the spatial distribution of the electrons to analyse and to understand the mechanisms of the spatial non-uniformity of H\textsuperscript{–} ions.

In this study, KEIO-MARC code (Kinetic Electron transport simulation of IOn source plasmas in the Multi-cusp ARC discharge) \cite{1} has been applied to the JT-60SA negative ion source with 1.2 m in length and 0.5 m in width. In Ref. \cite{2}, it is shown that the magnetic drift of the electrons in one direction is the main cause of the non-uniformity in the long negative ion source with a MC-PGMF (Multi-Cusp and PG Magnetic Filter) configuration. Thus, in the JT-60SA negative ion source, instead of the MC-PGMF configuration, a TNT-MF (TeNT Magnetic Filter) configuration has been adopted to improve the uniformity. The TNT-MF configuration enhances the plasma rotation inside the chamber and improves the spatial uniformity. However, an asymmetric feature was still observed, because the plasma rotation was not enough especially at the end wall in the longitudinal direction. In order to obtain further improvements of the uniformity, a modified TNT-MF configuration has been applied. The results from the KEIO-MARC code shows that the plasma rotation can be enhanced by this magnetic configuration. The numerical results are confirmed in the experiments \cite{3}, and the improvement of the spatial uniformity has been observed. In addition, we are currently modelling H\textsuperscript{–} ion transport to analyse how the H\textsuperscript{–} ions are transported to the PG aperture and extracted as H\textsuperscript{–} beams. Further results will be presented in details.

References

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Influence of the configuration of the magnetic filter field on the discharge structure in the RF driven negative ion source prototype for fusion

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The influence of the magnetic field strength and topology on the plasma parameters in the RF prototype negative ion source for ITER is investigated numerically. A previously developed 2D fluid plasma model [1] has been extended to take into account the complex structure of the magnetic field in the source. A new feature of the model is that the presence of magnetic fields in the driver, i.e. the plasma generation volume, can be taken into account. This is the case both in the prototype source (where the magnetic field is produced by external permanent magnets) used at the BATMAN test facility [2], and in the ELISE source (where the magnetic field is produced by a current flowing through the plasma grid) [3]. In these two cases the primary role of the magnetic filter is the same, namely to reduce the amount of coextracted electrons. Thus, and in order to reduce the computational effort, both configurations of the magnetic filter are studied for the geometry of the prototype source. For the magnetic field configuration used at BATMAN, the axial position of the filter has been varied according to the experiment when external magnet frames are used. For the magnetic field produced by the plasma grid current (corresponding to ELISE) the bias applied to plasma grid and the strength of the field has been varied. The obtained results show that in the two configurations of the magnetic filter the plasma in the entire source volume is magnetised, affecting the electron and electron energy fluxes from their origin in the driver region, resulting in an asymmetrical discharge structure. Shifting the position of the magnetic filter towards the plasma grid leads to reduction of the electron current at plasma grid.

References

Numerical modeling of the Negative Hydrogen Ion Production in the Ion Source for Cyclotrons

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Negative hydrogen ion ($H^-$) sources are used for many kinds of applications, such as medical applications, the fusion plasma heating systems and the high energy accelerators. In these applications, to enhance the $H^-$ production in the $H^-$ sources is one of the most critical issues. To analyze the $H^-$ production in the ion sources, a systematic study of the EEDF (Electron Energy Distribution Function) has been conducted by KEIO-MARC code (Kinetic modeling of Electrons in the Ion source plasmas by the Multi-cusp ARC-discharge code) \cite{1}. In the previous study, the dependencies of the EEDF and the $H^-$ production on the arc-discharge power have been investigated \cite{2}. However, it was shown that the NPDD (Neutral Particle Density Distribution) could play a key role in the more accurate EEDF analysis. The purpose of this study is to clarify the effects of the NPDD on the EEDF and the $H^-$ production with our Advanced KEIO-MARC code, which solves the electrons and the neutral particles transport self-consistently.

To validate Advanced KEIO-MARC code, the analysis of the EEDF and the volume $H^-$ production has been started for the DC arc-discharge $H^-$ ion source for medical applications of Sumitomo Heavy Industries, Ltd \cite{3}. Furthermore, the effects of design parameters, such as the gas pressure, the position of the gas injection port and the magnetic field configuration, are going on to be analyzed based on the parameter survey with Advanced KEIO-MARC code.

References

Cesiation is a small admixture of cesium in a gas discharge that increases negative ion emission and decreases electron emission [1,2]. Cesiation decreases the surface work function and increases the probability of escaping back scattered and sputtered particles as negative ions. It is difficult to control the surface work function during the discharge. A positronium negative ion is a bound system consisting of a positron and two electrons that is created when an escaping positronium atom from a metal captures an electron from the surface. As in the case of H- formation, the probability of positronium negative ion formation strongly depends on the surface work function. The positronium negative ion creation rate can be determined by measuring the shift of the annihilation gamma ray spectrum from accelerated positronium negative ions. In this report it is proposed to use the emission of positronium negative ions to monitor the surface work function. The surface to be monitored is first irradiated by positrons from a positron emitter (for example radioisotope $^{22}$Na). The emitted positronium negative ions are then accelerated by an electric field. Gamma rays produced by the annihilated electron and positron are registered by a proportional detector (for example pure Germanium). The number of Doppler shifted gamma rays generated by the accelerated positronium negative ions [3] can then be used to determine the surface work function.

References

Recent progress in the development of advanced negative ion sources has been connected with the optimization of cesiation in surface plasma sources (SPS). The cesiation effect is a significant enhancement of negative ion emission from gas discharges with the decrease of the co-extracted electron current below the negative ion current following an admixture of small amount of cesium. It was observed for the first time in 1971 at the Institute of Nuclear Physics (Novosibirsk, Russia) [1,2] by placing into the discharge a compound with one milligram of cesium. Key experiments, clarifying the mechanism of efficient generation of negative ions in gas discharges will be discussed. Subsequent developments of SPS for highly efficient negative ion production caused by the interaction of plasma particles with electrodes on which the adsorbed cesium reduced the surface work-function are described. We consider it appropriate to analyze the past and current experiments in which the surface-plasma mechanism for negative ion production can be clearly identified. In the last 45 years, the intensity of negative ion beams has increased by cesiation up to $10^4$ times, from three milli-Amperes to tens of Amperes.

References


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Negative Ion Formation by Proton Reflection from a Molybdenum Surface at a Shallow Incidence Angle

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Recent Fundamental processes of hydrogen-isotope negative ion formation on a surface are of importance for development of ion sources for nuclear fusion and accelerators, and attract theoretical investigation. Lots of works had been done by experiments, on alkali metals, single-crystal, polycrystalline, and amorphous surfaces\cite{1,2}. Normal incidence, or an incidence angle less than 70° from the normal was chosen in most of these experiments. In an ion source or a fusion device under magnetic field, ions sometime impinge at a shallow angle. This motivates us to study the particle reflections at shallower incidence angles. Theoretical studies showed that the negative ion formation coefficient from reflection (or secondary emission) is proportional to the product of the reflected particle flux, a negative ion formation probability, and a survival probability\cite{3}, and the formation probability has a maximum at the outgoing perpendicular velocity (v\textsubscript{⊥}) around 0.02 atomic unit, while the survival probability increases as v\textsubscript{⊥} increases\cite{4}.

In this research, the angle-resolved energy distribution function of positive/negative ions produced from Mo and Mo-alkali-complex surfaces was measured by using the beam-surface interaction apparatus at National Institute for Fusion Science. A proton beam of 0.3, 0.5 and 1 keV was injected on the target with an angle of 80°, 70°, 60°, 50°, 40° from normal. For each setting of the target angle, the energy analyzer for the measurement of reflected ions was moved from 86° to ~ 40°. The magnetic field of the analyzer was scanned from -4 keV to +4 keV continuously, and only H\textsuperscript{–} and H\textsuperscript{+} peaks at energy of 60 – 100% of injection energy were observed.

A numerical simulation calculation, Atomic Collision in Amorphous Target (ACAT), has been carried out to get the angular distribution of total reflection particle flux. Experimentally the reflected H\textsuperscript{–} ion intensity takes maximum at smaller angle than the calculated total flux, showing that the negative ion reflection probability has a maximum at v\textsubscript{⊥} of 0.04 atomic unit.

References

Study of Negative Hydrogen Ion Production at Low Work Function Material Surface using a Hydrogen Atom Source

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It was experimentally demonstrated that negative hydrogen ion (H\textsuperscript{−}) current from an ion source can be enhanced by introduction of Cs into the source [1]. Work function of the plasma grid was confirmed to be an important parameter for H\textsuperscript{−} production [2] [3]. As the surface adsorption is affected by the temperature, work function and thus the H\textsuperscript{−} ion yield can be affected by the plasma grid temperature. In this study, temperature of a target under irradiation of atomic hydrogen flux is changed to see the effect onto H\textsuperscript{−} production.

In this research, a hydrogen atom source that produces hydrogen atoms by thermal dissociation is used to investigate the relation between the production rate of H\textsuperscript{−} and the temperature of the surface. The chamber is made of copper gasket flanges and has 7 ports (Figure 1), which enable the irradiation of hydrogen atoms, target heating with infrared radiation, a laser beam injection to measure the target work function by photoelectric effect and H\textsuperscript{−} detection using a Faraday cup. Two turbo molecular pumps evacuate the chamber to realize a vacuum better than 10\textsuperscript{−5} Pa, which is necessary for stable surface diagnostics by photoemission. Five lasers of different wavelength at 325 nm, 405 nm, 450 nm, 532 nm and 632.8 nm are directed to the target and the work function are determined by Fowler’s theory [4].

References

The Characteristics of DC Laser Photodetachment Signals in a Hot Carbon Cathode Discharge

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Carbon thin films such as diamond-like carbon can be utilized in various fields for their functionality. One way to form such films is to use carbon containing plasma, in which the fundamental behavior of negative ions affects the quality of the formed film. In this experiment, carbon negative ions are measured using the laser photodetachment method.

Photodetachment signals excited by a DC laser were detected by a Langmuir probe immersed in carbon containing plasma. By using a semiconductor laser and changing the position of a Langmuir probe, the spatial distributions of electrons detached from the negative ions were detected. A high temperature carbon filament served as a cathode for producing a carbon containing discharge with Ar filling gas. A discharge current of the order of 10 mA produced a plasma in a volume of 150 mm diameter and 200 mm height. In this experimental geometry, carbon negative ions can be formed by both surface and volume processes as the electron affinity of carbon is as large as 1.27 eV. The photon energy of the laser was chosen to 940 nm or 1.32 eV and the laser can deliver up to 1.0 W power. Photodetachment signals were dependent upon the gas pressure, the value of discharge current, and the laser modulation frequency. Electrons produced by photodetachment are confined around the wall of the plasma source by the magnetic field. The optical emission spectrum indicated the existence of C\textsubscript{2} molecules. These molecules are to form carbon negative ions through electron attachment processes.

Hydrogen gas can interact with carbon filament to produce hydrocarbon molecules having large negative ion affinities. Species composition in a plasma with hydrogen gas operation is investigated.

References

Beam Production of a Laser Ion Source with a Rotating Hollow Cylinder Target for Low Energy Positive and Negative Ions

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A laser ion source utilizing a hollow cylinder graphite target is being investigated for the objective of narrowing the energy distributions of the produced positive and negative ions. The laser ablation process inside the hollow cylinder produces and expands the plasma within the narrow volume and pushes out of the target. Plasma characteristics obtained from the Langmuir probe analysis of the laser produced plasma at the target exit show the electron temperature to be 0.5 eV which is suitable for negative ion production. Time-of-flight measurements using a Faraday cup observed a positive burst followed by a longer duration of a negative current peak which corresponds to electrons or negative ions. The time constant calculated from the decay at the end of the Faraday cup current signal increased as the target surface accumulated up to 12,000 laser shots. To resolve the current signal depletion from the localized surface deterioration due to repeated laser irradiation, a rotational target has been designed for continuous beam operation. Beam extraction experiments for positive and negative ions as well as diagnostics using time-of-flight spectroscopy are currently being carried out to understand the beam characteristics caused by the rotating hollow cylinder target geometry.

Figure 1. Design of the rotating hollow cylinder target for the continuous operation of the laser ion source.

References

Spectroscopic Study of Molecular Hydrogen Concentration at the Vicinity of Metal Surfaces

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An appropriate choice of wall materials for a negative hydrogen ion (H\(^-\)) source is known to increase H\(^-\) current and reduce electron extraction current. To date, it has been reported that tantalum covered wall enhances the negative ion production possibly due to its high atom-wall recombination coefficient [1]. Bacal et al. showed that tantalum covered wall of a multicusp ion source increased the negative ion density by 60-90% from the original density in a non-tantalum covered vessel [2]. They also confirmed the presence of vibrationally excited H\(_2\) molecules in the ion source for the tantalum covered wall, while the spectral shape and intensity did not differ largely from those of tungsten covered wall [2].

In this study, we investigate the Fulcher-α band spectra at the vicinity of refractory metal materials including tantalum, molybdenum and tungsten to see the fundamental processes behind the wall-formation and destruction of hydrogen molecules. A monochromator of 0.3 Å wavelength resolution observes the Fulcher-α band spectra near the refractory metal target, which is bombarded with a linear magnetized hydrogen plasma produced by a DC tungsten hot cathode discharge. A manipulator equipped with a target holder can change the target position along the direction of magnetic field lines. This allows a measurement of spatial dependence of spectral intensity distribution upon the distance from the target surface. Figure 1 shows the intensities of the first five vibrational bands in Q branch and Balmer-α line plotted as functions of distance from the tantalum surface. The intensity of molecular spectra decreases as the distance from the surface increases, while the Balmer-α intensity increases against the distance. The result suggests that the tantalum surface can be the source of vibrationally excited hydrogen molecules that are to be converted to H\(^-\) ions upon capturing low energy electrons.

References

Metal negative ions are produced through both surface and volume production processes [1] [2]. In a RF driven negative ion source, negative ions can be produced by both processes, but should have different energies depending upon how they are produced in the source. The surface produced components are produced at the target potential. On the other hand, the ions produced in plasma are expected to have a plasma potential. Measurements of a beam energy spectrum can distinguish which component predominates the extracted ion beam due to their energy difference.

The ion source has 80 mm inner diameter and 90 mm length. Eight rows of permanent magnets arranged at the side of the cylindrical chamber enhance plasma confinement. Together with this magnets, a ring magnet and a cylindrical magnet at the center of end flange form magnetron magnetic field configuration. The 72 mm diameter planer sputter target made of 2 mm thick Cu disk is attached at the end flange. Radio frequency power at 13.56 MHz is directly supplied to the target to maintain plasma discharge and induce self-bias to the target for sputtering. The direct extraction of metal negative ions causes frequent break down at extraction electrode due to fresh metallic Cu adhesion on the extraction electrode. A pair of permanent magnets for further suppression of electron current are added at the plasma electrode. Beam extraction geometry suitable for electron separation [3] is being investigated.

References

A 14 GHz electron resonance (ECR) ion source with conical magnetic filter field structure has been developed to realize an efficient extraction of volume produced negative hydrogen (H⁻) ions [1]. This magnetic field structure diverges toward the extraction hall and produces both a magnetic field region with the intensity required for the ECR condition and a low electron temperature region which is indispensable to the volume production. This ion source can produce a high density plasma because of the reduced size of the discharge chamber driven by shorter wavelength the microwave at 14 GHz. The results showed the H⁻ ion beam current reached about 0.6 mA/cm² with about 40 W microwave power as an optimum value. The observed VUV signal corresponding to the production rate of vibrationally excited hydrogen molecular showed a spatial distribution of the signal with higher intensities near the microwave inlet [2]. In this study, to clarify production process of H⁻ in this type of ion source, a 2.45 GHz ECR ion source was constructed with the same magnetic field structure to reduce the power density for diagnosing the plasma with the methods such as a Langmuir probe.

In this newly assembled ion source, a Nb-Fe-B permanent magnet produces a conical magnetic filter field at the top of a 110 mm diameter 100 mm height alumina discharge chamber. The magnetic field region with the intensity larger than 875 G, corresponding to the ECR condition for 2.45 GHz, is located up to the point 26 mm from the chamber wall. A microwave for ECR is introduced into the chamber through waveguides attached to both sides of the ion source. The measurement of the extracted H⁻ ion beam current by a Faraday cup will be composed to the plasma parameters.

References

Experimental study of H atom recombination on different surfaces in relation to H$^-$ negative ion production

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Volume production of H$^-$ negative ions is mostly attributed to the dissociative attachment (DA) of electrons to ro-vibrationally excited molecules [1,2]. Apart from the main formation path for enriching the plasma with these molecules (i.e. radiative decay of singlet states excited by collisions with energetic electrons, i.e. EV excitation) [3], an additional formation process refers to recombination of hydrogen atoms on the surface of materials which face the plasma [4,5]. In this work, the importance of the later process is evaluated by considering various materials. Pyrex, Stainless Steel, Highly Oriented Pyrolytic Graphite - HOPG, and Yttrium, are sequentially tested in the ECR-driven H$^-$ negative ion source ROSAE III. This source is specially designed to promote as much as possible surface recombination only on the surface of the specimen under test, limiting at the same time the formation of ro-vibrational states via other processes (e.g. EV excitation). Optical emission spectroscopy does prove a high degree of dissociation in this source. Furthermore, electron and negative ion densities are measured by means of electrostatic probe and laser photodetachment [6], respectively. The effectiveness of the above materials for the production of ro-vibrational states is thus evaluated indirectly, i.e. by comparing the values of the produced negative ion densities, assuming H$^-$ production through DA mainly. The results suggest that, under the present conditions, the formation of ro-vibrational states is apparently dominated by process other than surface recombination.

References

VUV emission spectroscopy combined with H− density measurements in the ion source Prometheus I

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Prometheus I is a volume H− negative ion source, driven by a network of dipolar electron cyclotron resonance (ECR) sources (2.45 GHz) [1-3]. The vacuum-ultraviolet (VUV) emission spectrum of low-temperature hydrogen plasma is potentially related to molecular and atomic processes involved directly or indirectly in the production of negative ions [4]. In this work, VUV spectroscopy has been performed in the above source, Prometheus I, both in the ECR zones and the bulk plasma. The acquired VUV spectra are correlated with the negative ion densities, as measured by means of laser photodetachment [5], and the possible mechanisms of negative ions production are considered. The well-established H− formation process of dissociative attachment to vibrationally excited molecules [6] is evaluated, while additional production paths (e.g. neutral resonant ionization [7,8]) are tested. The obtained results indicate that for the source Prometheus I, the dominant formation process is dissociative attachment.

References

Photoelectron emission experiments with ECR-driven multi-dipolar negative ion plasma source

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Photoelectron emission measurements have been performed using a 2.45 GHz ECR-driven multi-dipolar plasma source [1] in a low pressure pure hydrogen discharge. Photoelectron currents induced by light emitted from ECR zone and $\text{H}^-$ production region are measured from Al, Cu, Mo, Ta, and stainless steel (SAE 304) surfaces as a function of microwave power and neutral hydrogen pressure. The total photoelectron flux from the plasma chamber wall is estimated from the measured photoelectron currents by taking into account the geometry of the experimental setup. The photoelectron emission is correlated with the $\text{H}^-$ production in the ECR source, as measured by means of laser photodetachment under the same operating conditions [2]. The results are compared to those obtained in a filament-driven multicusp arc discharge volume production $\text{H}^-$ ion source [3].

References

Development of a cesium-free negative hydrogen ion source using sheet plasma

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We have development of negative hydrogen ions in cesium-free discharge using the magnetized sheet plasma. The negative hydrogen ion density $n_{H^-}$ are measured by Omegatron mass-analyzer and negative hydrogen ion-beams are extracted from the sheet plasma. Negative hydrogen ions are formed by volume-production, that is, the dissociative attachment of low energy electrons ($T_e = 1\text{-}2$ eV) to highly vibrationally excited molecules, which are attributed to the electron-impact excitation of molecules by high energy electrons ($T_e > 10$ eV) in the plasma column. Under a small amount of secondary hydrogen gas entering the hydrogen plasma, $n_{H^-}$ is localized in the periphery (10-20 mm), where there are low-energy electron from the edge of the sheet plasma. The hydrogen negative ions density are detected using an Omegatron mass-analyzer. The electron density and temperature are measured using a Langmuir probe. Ion beams are extracted through the small hole with an extraction voltage of 2 kV. The maximum negative hydrogen ion beam current density is about $15 \text{ mA/cm}^2$ at a neutral gas pressure of 0.3 Pa and discharge current of 50 A.

References

A Pulsed RF Discharge for a Cs-Free H⁻ Ion Source

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Fusion NBI ion sources of the future will require alternatives to caesium for H⁻ surface production. Ion sources currently being developed for use in damage free plasma etching of future Ultra-Large Scale Integrated circuits make use of temporally filtered RF discharges for high density volume production of negative ions [1]. The H⁻ ion source developed at the University of Liverpool aims to demonstrate a high volume H⁻ density using a time modulated pulsed RF hydrogen discharge, for comparison with conventional magnetically filtered fusion H⁻ ion sources. The source will also be used for testing plasma grid materials which have shown promise as Cs alternatives for H⁻ surface production, such as HOPG and diamond and other carbon based materials [2].

References


Comparison of Plasma Properties for Different Antenna Designs in the Spallation Neutron Source Negative Hydrogen Ion Source

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Internal antenna negative hydrogen ion sources can fail when plasma heating causes ablation of the insulating coating due to small structural defects such as cracks. During this process, plasma ions impacting the surfaces of rf antennas causes heating of the coating, which can melt or ablate, thus exposing conducting surfaces to the plasma. Reducing antenna failures that reduce the operating capabilities of the Spallation Neutron Source (SNS) accelerator has been one of the top priorities of the SNS H- Source Program at ORNL.

We have been utilizing numerical modeling of internal antenna negative hydrogen ion sources in order help optimize antenna designs in order to reduce antenna failures. We have implemented a number of fluid models with electromagnetics using the simulation tool Usim and applied them to modeling the SNS internal antenna negative ion source. We report here on results comparing two different antenna designs. The baseline design, as is currently in use in the SNS source, and a wide-leg design, that has been tested, and may replace the baseline design if it can reduce antenna failures while still maintaining source performance. The wide-leg antenna is designed to move the antenna supports out of the high-density plasma regions, in order to decrease the possible negative effects of ion bombardment. We model the plasma evolution using a single-fluid MHD model with an imposed magnetic field due to the rf antenna current and the confining multi-cusp field for both the baseline and wide-leg antenna configurations. We find that the maximum plasma velocity near the antenna surfaces is reduced by nearly 50\% in the wide-leg configuration, and that overall the bulk plasma velocity is reduced for this configuration. In addition, although we measure a small increase in the maximum plasma flux on the antenna surface for the wide-leg design, we see a broad-based reduction of plasma flux on the antenna in the regions where the antenna is mostly exposed to the plasma, corresponding to where failures are likely to occur.
A one-dimensional ion species model for an RF driven negative ion source

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A one-dimensional model for an RF driven negative ion source has been developed based on a planar inductive discharge. The model differs from traditional filament and arc ion sources because there are no primary electrons present, and is simply composed of an antenna region (driver) and a main plasma discharge region. However it does include the plasma transport equations for particle energy and flow, which have previously worked well for modelling DC driven sources. The model has been developed primarily to model the Small Negative Ion Facility (SNIF) ion source at CCFE, but may be easily adapted to model other RF sources for neutral beam systems. Currently the model considers the hydrogenic isotope ion species, and provides a detailed description of the plasma parameters along the source axis, i.e. plasma temperature, density and potential, as well as current densities and species fluxes. The inputs to the model are the RF power, the magnetic filter field, the source gas pressure and the bias voltage for the plasma grid. Results from the model are presented and where possible compared to existing experimental data from SNIF, with varying RF power, source pressure and bias voltage.
Characterisation of the SNIF Ion Source

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Measurements have been made of the extracted H⁻ current and co-extracted electron current from the SNIF negative ion source. The dependence of these currents on RF power, plasma insert bias voltage and source filling pressure have been measured. In all cases the ratio of co-extracted electron current to negative ion current is less than unity. During parameter scans data was collected using a high resolution spectrometer viewing the extraction region of the non-caesiated source in order to attempt to understand the low ratio of co-extracted electrons to negative ions. Data was collected for the atomic Balmer series and in the molecular Fulcher range. A coronal model and a collisional radiative model have both been applied to this data to improve understanding of the conditions in the extraction region from calculated gas and electron temperatures. The results are presented here. Plans for further diagnostic improvements on SNIF are also discussed.

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TueP18

Design of a small extraction area negative hydrogen ions source at HUST

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The development of a radio frequency driven negative hydrogen ions source for the neutral beam heating devices of fusion experiments has been carried out at Huazhong University of Science and Technology. In 2014 the plasma was motivated in a $\Phi 284$mm RF driver successfully. A complete test facility with extraction system is planned to be built to assemble and test the negative hydrogen ions.

The test facility will be operated with a current density of 300 A·m$^{-2}$ H-and a pulse length of 4s. The extraction is on the small size ($46cm^2$) due to the existing $\Phi 500$mm cavity vessel. The design of the extractor grids for a 30kV system is presented. Various metals would be adopted for the plasma grid to research the generation efficiency of negative ions. The grids with ITER-like grid system, namely 5×6 apertures ($\Phi 14$mm), are designed according to the constraints set by the heat power density and the cooling channels. In order to get an optimal magnetic filter field in front of the plasma grid, an alterable electric current driven through the grid vertically will be available. The Caesium evaporator is also considered in the test facility to enhance the negative ions generation effect.

References

Two operation modes of RF system for RF negative ion source experimental facility at HUST

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A RF-driven negative ion source experimental facility has been built at Huazhong University of Science and Technology (HUST) since 2011 to research relevant key technologies. To study behaviors of RF system in different operating modes, RF power supply could run in fixed-frequency or auto-tuning operation modes[1]. In fixed-frequency mode, it outputs a set power in a fixed frequency. In auto-tuning mode, it adjusts the RF frequency to seek and track the minimum standing wave ratio (SWR) operation condition. The variation range of the frequency for auto-tuning operation mode has been estimated before RF power supply manufacture. In order to achieve flexible frequency adjusting, the RF signal source adopts a direct digital synthesizer (DDS). The trend of power reflection coefficient $|\rho|^2$ with different forward power $P_f$ at a fixed frequency is present in Fig.1. The experiments in auto-tuning mode fail due to screen grid current trip in practice. The possible reason and solution will be discussed in the full paper.

![Graph](image)

Figure 1. Peak power reflection coefficient with different forward power levels at $f = 1.02$ MHz and peak gas pressure 1.5Pa.

References

Development of a 20 mA Negative Hydrogen Ion Source for Cyclotrons

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A cesiated DC arc-driven H\textsuperscript{−} source has been developed for 30 MeV medical cyclotrons in Sumitomo Heavy Industries, Ltd. In the Cs-seeded operation, H\textsuperscript{−} current increases in proportional to the arc-discharged power. Continuous H\textsuperscript{−} beam current of 22 mA is obtained at an arc power of 2.6 kW [1]. In order to improve the beam stability for the long-term operation, an optimized plasma electrode and a beam current control system have been developed. A cesium injection system has also been modified for easy maintenance and operation.

In the Cs-free operation, H\textsuperscript{−} beam current saturates as the arc power increases. The H\textsuperscript{−} current dependences on arc-discharge condition with different magnetic filter field strengths and the H\textsuperscript{−} saturation mechanism at higher arc power have been investigated both by experimental measurements and a numerical analysis with KEIO-MARC code (Kinetic modeling of Electrons in the Ion source plasmas by the Multi-cusp ARC-discharge) [2]. At the optimum magnetic field strength which gives the highest arc efficiency (the ratio of the H\textsuperscript{−} beam current to the arc power), 14.1 mA H\textsuperscript{−} beam is obtained at an arc power of 4.5 kW. The maximum H\textsuperscript{−} beam current of 15.2 mA is obtained by another magnetic field strength at an arc power of 6.5 kW.

References

Linac4 cesiated surface negative ion source is required to produce 40-50 mA of $\text{H}^-$ ions within a transverse rms emittance of $0.25\pi \text{ mm}\cdot\text{mrad}$[1]. In order to achieve the requirements, it is necessary to understand the $\text{H}^-$ extraction mechanism and optimize the $\text{H}^-$ beam extraction from Linac4 negative ion source. Recently, the extraction region of Linac4 ion source has been modeled by Particle in Cell (PIC) simulation in Ref. [2] to clarify the $\text{H}^-$ extraction mechanism. However, the dependences of the beam current and divergence on the operation parameters (e. g. extraction voltage) in Linac4 negative ion source have not been investigated.

Therefore, the purpose of this study is to clarify the operation parameters which can control the negative ion beam current and divergence by using the 2D3V (two dimension in real space and three dimension in velocity space) PIC model in which volume production and surface production of $\text{H}^-$ are taken into account [3-4]. More specifically, the effect of the puller-electrode voltage will be focused on, and its effects on the following items will be studied; (1) plasma meniscus formation, (2) extracted $\text{H}^-$ and electron beam current, and (3) $\text{H}^-$ beam divergence.

References

Emittance Evaluation Admissible as Standard Method of J-PARC RF-Driven H⁻ Ion Source

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The J-PARC (Japan Proton Accelerator Research Complex) cesiated rf-driven H⁻ ion source [1,2,3] has been successfully operated satisfying the J-PARC second stage requirements of an H⁻ ion beam of 60mA within normalized emittances of $1.5\pi$mm•mrad both horizontally and vertically, a flat top beam duty factor of 1.25% ($500\mu$s×25Hz) and a life-time of longer than 1000 hours about 2 years. In this paper, the evaluation method of the transverse emittances, which is admissible as the standard, is presented. By compensating the unpredictably observed slight base-line sift to opposite signal probably due to the positive ions of the beam plasma, the rms emittances of 95% beam, which are necessary to compare the source performance with other sources operated in other facilities, are evaluated as accurate as possible.

References

Operation Status of the J-PARC RF-Driven H- Ion Source


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A cesiated RF-driven negative hydrogen ion source [1-4] was started to operate in September 2014 in response to the need for upgrading J-PARC’s linac beam current. A schematic of the ion source is shown in Figure 1. The ion source mainly comprises a stainless-steel plasma chamber, a beam extractor, and a large vacuum chamber with two turbo molecular pumps of 1500 L/s for differential pumping. The ion source has been successfully providing the required beam current to the accelerator without any significant issues other than a single-incident antenna failure occurred in October 2014. Continuous operation for approximately 1,000 h was achieved with a beam current and duty factor of 45 mA and 1.25% (0.5 msec and 25 Hz), respectively. In this paper, we will present the some operation parameters and the beam stability through the long-term user operation.

Figure 1. Schematic of the J-PARC H- ion source

References

Two main erosion processes of the hot cathode in the \( \text{H}^+ \) surface converter ion source are discussed: thermal evaporation and plasma sputtering. In several filaments V-I heating measurements we observed an increase of the erosion rates after the cesium transfer, following a change in cesium oven temperature or following a change to the arc discharge voltage. The filament lifetime analysis based on the simplified thermal evaporation was no longer applicable [1, 2]. Basic phenomena of the liquid-vapor phase transition were used to estimate the density of cesium atoms. A simple model of the arc discharge was used to estimate main plasma parameters and calculate the sputtering yield of tungsten atoms. Light hydrogen ions (\( \text{H}^+, \text{H}_2^+ \)) have no influence on the tungsten filament sputtering, because their maximal kinetic energies are below the ion sputtering threshold energies. The dominant mass loss mechanisms used in the new filament model are: the thermal evaporation and plasma sputtering caused by heavy ions (\( \text{Cs}^+ \) and \( \text{W}^+ \)). We will discuss a set of experiments to separate and measure the different mass degradation contributions due to the thermal evaporation and the heavy ion plasma sputtering. In order to reduce the plasma sputtering effect, a new ion source tuning with reduced arc discharge voltage will be proposed.

References

Overview of recent studies and design changes for the FNAL magnetron ion source.

D.S. Bollinger, A. Sosa

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

This paper will cover several studies and design changes that will eventually be implemented to the Fermi National Accelerator Laboratory (FNAL) magnetron ion source. The topics include tungsten cathode insert, solenoid gas valves, current controlled arc pulser, cesium boiler redesign, gas mixtures of hydrogen and nitrogen, and duty factor reduction. The studies were performed on the FNAL test stand described in [1], with the aim to improve source lifetime, stability, and reducing the amount of tuning needed.

References

Recent Operation of the FNAL Magnetron H- Ion Source

P.R. Karns, D.S. Bollinger, A. Sosa

Fermi National Accelerator Laboratory, Box 500, MS 307, Batavia, Illinois, 60510

This paper will detail changes in the operational paradigm of the Fermi National Accelerator Laboratory (FNAL) magnetron H\(^-\) ion source due to upgrades in the accelerator system. Prior to November of 2012 the H\(^-\) ions for High Energy Physics (HEP) experiments were extracted at \(~18\) keV vertically downward into a 90 degree bending magnet and accelerated through a Cockcroft-Walton accelerating column to 750 keV. Following the upgrade in the fall of 2012 the H\(^-\) ions are now directly extracted from a magnetron at 35 keV and accelerated to 750 keV by a Radio Frequency Quadrupole (RFQ). This change in extraction energy as well as the orientation of the ion source required not only a redesign of the ion source, but an updated understanding of its operation at these new values. Discussed in detail are the changes to the ion source timing, arc discharge current, hydrogen gas pressure, and cesium delivery system that were needed to maintain consistent operation at \(>99\%\) uptime for HEP, with an increased ion source lifetime of over 9 months.
Performance characterization of a solenoid-type gas valve for the H⁺ magnetron source at FNAL

A.G. Sosa, D. Bollinger, P.R. Karns and C.Y. Tan

Fermi National Accelerator Laboratory, Batavia, USA

The magnetron-style H⁺ ion sources currently in operation at Fermilab use piezoelectric gas valves to function. This kind of gas valve is sensitive to small changes in ambient temperature, which affect the stability and performance of the ion source. This motivates the need to find an alternative way of feeding H₂ gas into the source. A solenoid-type gas valve has been characterized in a dedicated off-line test stand to assess the feasibility of its use in the operational ion sources. H⁺ ion beams have been extracted at 35 keV using this valve. In this study, the performance of the solenoid gas valve has been characterized measuring the beam current output of the magnetron source with respect to the voltage and pulse width of the signal applied to the gas valve.

References

The next generation of fusion reactors requires a high level of additional plasma-heating power ranging between 100 and 150 MW. The talk will present the concept and potential performances (high efficiency and high neutral power) of a new neutral beam system based on photoneutralization. The concept lies on the duplication of several MW range Fabry-Perot recycling cavities implemented along the energetic negative ion (D-) beam to attain a high photodetachment rate ($\eta \gg 80\%$). The development of such high power optical cavities and their implantation in a fusion machine would benefit for the major part from the gravitational wave detectors proven technology. The second part of the talk will be focused on the photoneutralizer implantation: in order to protect the high-reflectivity mirrors against the reactor and injector aggressive environments (mechanical vibrations, gas, pollutants and radiations), the optical cells containing the cavity mirrors are set up in the technical galleries outside the bioshield, 15 metres above and below the injector tank (see Fig. 1). The mirrors are sustained within the optical cell by dedicated mechanical-vibration mitigation systems (super-attenuators) equipped with magnetic actuators able to control the mirror alignments. To keep the mirrors in a high and clean vacuum ($P_{\text{optical cell}} \sim 10^{-6}$ Pa), a specific pumping system is implemented along the pipes between the optical cells and the injector. The optical cells and pipes are shielded against the remaining radiations of the technical galleries. Furthermore, this specific photoneutralizer arrangement facilitates the maintainability by remote handling of the optical components.
The operation of H⁻ ion source for CSNS

H. F. Ouyang¹,², S. J. Liu, T. Huang, Y. C. Xiao, K. J. Xue, Y. J. Lv, X. X. Cao, W. D. Chen and F. X. Zhao

¹ China Spallation Neutron Source, Institute of High Energy Physics, CAS, China
² Dongguan Institute of Neutron Science, China

The Penning Surface Plasma (PSP) ion source as ISIS ion source is adopted as the ion source for CSNS. For CSNS phase I, the beam requirements for the ion source are as follows. The output energy and pulsed current is 50keV and 20mA, respectively, with a rms emittance of 0.2πmm.mrad. While the maximum repetition rate and pulse length is 25Hz and 500μs, respectively. During the beam commissioning of the front end last year, the H⁻ ion source could provide about 50mA H⁻ beam current in total and 20mA beam current within a rms emittance 0.2πmm.mrad. The maximum beam current got at exit of RFQ is up to 28mA at 1Hz and 100μs, more than 15mA at 25Hz and 500μs. But the stability is not satisfactory at present. The ion source stability is only dependent on the beam pulse length. With the beam pulse length less than 150μs, the ion source is stable. When the pulse length is larger than 150μs, the extraction spark occurs at a frequency depending on the pulse length. In case of 500μs, the spark frequency is about 4 times per hour. The spark happens between the discharge chamber and the extractor, or between the discharge chamber and the bending magnet poles. As you know, the ion source is a cesium added ion source, and cesium is easily deposited on the extractor and the bending magnet poles. When the extracting electrons strike on the extractor or the poles, the spark easily occurs. To avoid the sparking between the discharge chamber and the extractor, we can adjust the extracting gap and the extracting slit width. The spark between the discharge chamber and the bending magnet poles is avoided by adjusting the structure of the extractor and changing the electron download position. After many experiments, now the ion source stability is highly improved.
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<th>Tuesday 13th September</th>
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