Improvements of the Versatile Multiaperture Negative Ion Source NIO1*

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1) Introductory remarks on NBI (neutral beam injectors)
2) NIO1 setup
3) NIO1 electron clouds in EG gap?
4) Experimental results
5) Conclusions.

*see also posters MonP1, P2, P5, P8, P11a, P23 and P25, and orals Thu07 and Fri05.
Neutral Beam Injectors (NBI) [typical injector MITICA (Megavolt ITer Injector Concept Advancement) specification are 1 MV, 1280 beamlets, total 55 A of D- beam] , which need to be strongly optimized in the perspective of DEMO reactor, request a thorough understanding of negative ion sources and of the multi-beamlet optics. A relatively compact RF ion source, named NIO1 (Negative Ion Optimization 1), with 9 beam apertures for a total H- current of 130 mA, 60kV acceleration voltage, was installed at Consorzio RFX, including a high voltage deck and a X-ray shield, to provide a test bench for source optimizations in the framework of the accompanying activities in support to the ITER NBI test facility. NIO1 operation has started in July 2014, at zero extraction voltage. NIO1 status and plasma experiments with many filling gases are described, up to a 1.7 kW rf power. Transition to inductively coupled plasma is reported in the case of air and hydrogen and pure or doped oxygen. Beams of H- and O- were separately extracted; since no caesium is yet introduced into the source, the expected ion currents are typically lower than 5 mA; this requires a lower acceleration voltage $V_s$ (to keep the same perveance). Beam extraction up to $V_s=25$ kV, bias and filter effects are discussed.
1) Introductory remarks on NBI (neutral beam injectors)
For fusion reactors like ITER or DEMO, many (3) neutral beam injectors are needed for: 1) heating; 2) current drive. A test facility is being built in Padua at RFX.

Design of building PRIMA-MITICA (from P. Sonato, RFX, 2009) and building view (from V. Toigo, 2015)

- Covered surface: 7050 m²
- Height: 26 m

MITICA = 1 MV/40 A beam
SPIDER = 100 kV/55 A system
Beam current $D^-$ 40 A
Kinetic energy $D^- e D^0$ 1 MeV
Pulse Length 400 a 3600 s
off time between pulses <3 hours

length about 20 m

NBI (neutral beam injectors)

D- ion source

MITICA (Megavolt ITer Injector Concept Advancement)

3D view of a neutral ion injector [adapted from P. Sonato, RFX, 2009]; MAMUG = MultiAperture MUlti Grid.

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2) NIO1 experimental set-up

NIO1 source (0.5 m diameter, 60 kV, nominal beam power 8 kW) delivered to RFX in May 2013

Vacuum tightness improved (with ceramic cleaning) in November 2013

Source support completed in December 2013 and aligned in January

Calorimeter/beam dump (INFN) delivered to RFX in January 2014

First source operation in July 2014

Hydrogen supply line installed (2014)

New closed water cooling system installed Sept.-Nov. 2014; rf 2.5 kW generator repaired 2014. Water from technical plant enough for full power operation in April 2015

60 kV holding verified in January 2015 (at source off)
2.1) general setup and concept

Figure: Isometric view of NIO1 and HVD (high voltage deck)

Figure: Overview of lead box enclosing NIO1 source, acceleration column and diagnostic chamber (as labelled); HVD cover removed to make source head visible.

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Simple explanation of coupling modes
2.2) the 2016 setup

Figure: Cut view of NIO1 pumping cross, showing CFC tile

Figure: (a) horizontal zy section of NIO1 source and electrode; note filter position; (b) isometric view of NIO1 vacuum vessel

NOMINAL VALUES

- \( V_s = -V_{PG} < 60 \text{ kV} \)
- \( V_e = V_{PG} - V_{EG} < 9 \text{ kV} \)

require better pumps: another TP is now in use
2.3) new C-conductors

It is noted that $|I_e|$, the extracted electron current typically decreases when we rise the magnetic filter current (from 10 to 400 A); this is beneficial, but 400 A is kind of a technical limit. So we change circuit to get more field integral, at least

Figure: (a) field $B_x$ vs $z$, with $I_{PG}=100$ A (b) old circuit; (c) circuit using C-conductors

Figure: reversing 5% of the multipole magnet volume (d2) gives 160 G. This mimics 1600 A effect

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2.4) new bias wirings

Figure: The bias configurations; note that I-II are with filter $\alpha$, and III to VI with the new C conductors, that is filter $\beta$; from July 2016 power supply BIASBP was added, so 2 independent voltages are available:

$$V_b = V_{PG} - V_{WW}$$

$$V_v = V_{PG} - V_{BPe}$$

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2.5) general HVD setup

(a) NIO1 installed, with source covered by high voltage deck, rf matching box in the foreground, acceleration column, diagnostic chamber in the background. Two doors of Pb shielding were opened to make photographs


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(a) view of PA; (b) source rear opened for alignment; (c) water to HVD; (d) screen of control system (see poster MonP5)
2.6) special accessories

Figure: NIO1 cesium oven, partially dismounted, and removed from its test stand, where it is covered by a thermal insulation

Figure: monitor of electric potential in drifting beam + secondary plasma (preliminary density estimate $5 \times 10^{11}$ m$^{-3}$ [E.Sartori])

Figure: design of the second Cs evaporator for NIO1, using solid pellets
2.7) upgraded vacuum chamber electrode: Mo liners and new EG

Figure: Front multipole walls covered by Mo liners; during this maintenance also mounting studs were improved

Figure: Rear cover and multipole covered by Mo liners; note a liner also protects O-ring

Figure: The new EG (see poster C Baltador et al. NIBS2016, paper Veltri et al. NIBS014, Cavenago et al. PSST 2014)
OLD STATUS OF source walls and rf window: After operation at rf power 1.7 kW, a vacuum loss appeared (probably for elastic bolts unbalanced loosening, possible with vibration; finer mechanical adjustments are in progress). The opening of the source makes some observation possible: some wall deposit is apparent; two conductive rings appears at rf window ceramics ends. This suggests periodical inspection of source (opening rear cover) and use of Mo liners.

Figure 4 (a) the front multipole with bias plate and PG beam extraction holes; (b) the rf coil module with the rear multipole attached. Since NIO1 has a closed B-mod magnet configuration (as an ECRIS) the pattern of deposit is hardly surprising, but is of course worth of investigation too.

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3) The possible electron cloud in the PG-EG gap

The voltage

\[ V_{ep} = \frac{e}{2m} \left( \frac{I_A}{\exp(\pi d_a/L_y)} + \frac{I_C}{2 \cosh(\pi d_a/L_y)} \right)^2 \]

with \( I_A \) and \( I_C \) the field integral constant of ADCM and CESM magnets, expresses the order of voltage of magnetic insulation in a 1D planar diode (a); qualitatively also collision-less 2D simulation show spiraling. Anyway discharges are an issues.

for magnetic field and drift, see posters MonP2 and MonP23 and oral FriO5
4) Results: 4.1 rf matching

(a) Plasma of O/N at 2 Pa, rf forward about 200 W, $B_z$ about 10 G

(b) Very accurate rf model seems possible.

Experience at LNL MetAlice test-stand (a) transition from E to H coupling and low pressure operation routinely achieved; (b) Very accurate rf model seems possible.

Low voltage (no plasma) matching of NIO1 (note here some differences between model and measurement)
4) Results: 4.2: clear transition with rf power for air

Increasing rf power, a typical jump in luminosity is observed for air on 3 different diagnostics:

Luxmeter
Fiber+PMT
Spectrometer (low res 1nm)

At this jump, air show decreasing Te, as expected for E-H transition.

Figure: Plasma luminosity $L_x$ vs forward rf power $P_f$ at $p_1=0.9$ Pa; also shown $P_{pmt}$ (1 a.u. = 10 mW) and $M_{394}$ (1 a.u. = $10^{17}$ ph/s/m$^2$) and apparent electron temperature $T_e$; typical error +/- 10%
Figure: Plasma luminosity $L_x$ vs source pressure $p_1$ (air) at constant net(*) rf power $P = P_f - P_r = 0.47kW$; also shown $P_{pmt}$ (1 a.u. = 10 mW) and $M_{394}$ (1 a.u. = $10^{17}$ ph/s/m$^2$) and $T_e$; typical error +/- 10%

(*) For each pressure, $P_f$ was decreased, to get E-mode, and then raised until net power $P$ reached set level

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Hydrogen vs air

For both gases, plasma emission jumps at some power

H2 requires more rf power and gives less light

Spectra analysis of air is simply (here) based on nitrogen; H2 analysis seems more difficult

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4) New result 4.3) the rf power $P_t$ for E-H transition

With Mo liners
no sputter on rf window
$\therefore P_t$ has decreased

Old result (Alumina rf Window) $P_t=550$ W for air decreasing with pressure, 1500 W for H2

New result: (a) air $P_t=300$ at very low pressure $p_1<0.5$ Pa; (b) 400 W for O/Ar mixture (90:10 mole fractions) at comparable pressure $p_2=0.5$ Pa; (c) hydrogen $P_t=800$ W at $p_1=2.3$ Pa.

Note: more systematic work for transition at different pressure is now needed for the new setup with Mo liners and two turbopumps.

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4 result 4.4) optimal $V_s/V_e$ ratio

Temporarily it is assumed that ion current is

$$I_i = I_{PA} + I_{REP} + I_{CFC}$$

with the sum referring to absolute values (and current measured with a secondary emission suppression) is the ion current passing the EG and electron current (or bad current) is

$$I_e \approx |I_{EG}|$$

Figure above: BES (beam emission spectroscopy) with $V_s=7.5$ kV and $V_e=1.2$ kV

Figure (left): the demerit figure $I_{PA}/I_{CFC}$ is used to optimize $V_e$ (alias EG voltage) at fixed $V_s$ (alias AG voltage)
Images of the beam on the CFC tile. Beamlet divergence (and heat diffusion) masks beamlet structure. See **poster MonP1** for detail.
Conclusion 1: rising bias is beneficial, so the 30 V power was installed (but not yet used).

Conclusion 2: install filter current circuit β.

Summary of beams
For O⁻
$I_i \leq 3 \, mA$ but $I_e/I_i \approx 170$
For H⁻
$I_i \leq 2 \, mA$ but $I_e/I_i \approx 40$ (also lower in some cases)

Figure: $|I_e|$ vs bias $V_b$

$V \text{ bias} = V_p = 12 \, V$, other conditions as above:

Filter current circuit α

Figure: $|I_e|$ vs $I_{PG}$

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4) preliminary result 4.6) ion current using two bias voltages, $V_b$ and $V_v$

**Figure:** the bias plate voltage as function of bias plate current $I_v$; note that $I_v > 0$ require that configuration 6 is used (red line), while $I_v < 0$ requires conf. 5 (blue line). Accidentally a lower rf power $P_f$ was used after switching to conf. 6. The floating voltage of bias plate where lines join is thus not so dependent on $P_f$

**Conditions held fixed:** $V_b=20$ V, $I_{PG}=400$ A, $V_s=5$ kV, $V_e=0.75$ kV.

Effect of 2nd bias is interesting, but further experiments are necessary.

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5) Conclusions

Versatile ion sources (kW beams) like NIO1 are necessary for detailed physical understanding of negative ion sources (MW beams), even if some optimization depends on source scale.

Some theoretical and experimental understanding of electron clouds in PG-EG gap was pursued.

NIO1 was operated with many filling gases, including air and hydrogen and oxygen. After confirming the distinction between E and H modes, improving the experimental procedure for hydrogen, the beam extraction was investigated at moderate acceleration power and rf current. Bias and magnetic filter configuration were improved, with increases of the ion extraction current, not yet saturated.

Several bias and magnetic configuration were tested and improved; other important upgrades to do are EG\textsubscript{2} installation and new filter permanent magnets, and cryogenic pumps.

Thank you for attention

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