R&D for neutral beam injectors for fusion reactors

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A fusion reactor and/or DEMO will require additional heating in order to:

1. **Increase the plasma temperature to that required to have a sufficiently high $D^+ + T^+$ reaction rate.**
2. **Drive current in a tokamak based reactor/DEMO.**
3. **Inject sufficient power to enter the H-mode.**

Today it is understood that only NBI can fulfil the current drive requirement (point 2) with the required efficiency.

NBI needs significant R&D to meet reactor requirements.

Any heating system for a fusion reactor and/or DEMO will have to:

1. **Have a global efficiency, i.e. the ratio of the power absorbed in the plasma of the reactor/DEMO to the electrical power used by the heating system, of ≥60%;**
2. **Operate continuously;**
3. **Operate in a harsh nuclear environment.**

None of the above conditions are met by any existing system. Only the heating systems designed for ITER have taken account of the need to operate in a nuclear environment.

1 Injector Efficiency

- ≥60% can only be achieved with either a photon neutraliser giving ≈90% neutralisation or a plasma neutraliser + energy recovery for both the positive and negative residual ion fractions.
- In either case a substantially reduced gas flow from the ion source and improved beamlet optics (mainly less halo) are required.

Given space restrictions and increased complexity associated with a plasma neutraliser + energy recovery, we conclude that a photon neutraliser seems the most viable concept.

1 Injector Efficiency contd.

	ITER like	Reactor J(D$^-$) 50%
	MW	MW
RF power to ion source	0.8	0.4
Electrical power to the ion source: (RF efficiency increased from ≈50% to 85% using solid state PS.)	1.6	0.5
• **Stripping loss:**	8.0	1.5
• **Back-streaming ion power:**	1.0	0.2
• **Electron power exiting the accelerator:**	1.0	0.2
• The gas flow from the ion source for reactor/Demo injector is reduced by **66%**		
Total accelerated power	**40.0**	**22.3**
Total power lost in the beam source	**10.0**	**1.9**
Power to accelerator with AC to DC conversion ≈87.5%:	**57.1**	**27.6**

1 Injector Efficiency contd.

Beamlet halo: ITER 15%, reactor/Demo 5%.	6.0	1.1
Neutral power exiting the neutraliser: ITER (gas) 56%, reactor/Demo (photon neutraliser) 90%.	19.0	19.0
Power injected, geometric loss 5%, re-ionisation 7% (ITER), 1% (reactor/Demo):	**17.2**	**18.1**
Electrical power to the residual ion dump:	1.05	0.04
Electrical power to the laser: Reactor /Demo, up to 800 kW of laser power, with 40% efficiency.	0.0	2.0
Electrical power to the active correction and compensation coils: Reactor/Demo narrower coils.	1.6	1.1
Electrical power for the cryogen supply (operation):	5.0	0.2
Electrical power for the water cooling:	0.8	0.1
Total electrical power to the injector	**67.2**	**32**
Overall efficiency	**26%**	**57%**

2 Continuous operation

There are at least 4 potential problems occurs with (quasi) continuous operation of neutral beam injectors:

2.1 Pumping;

2.2 Caesium accumulation;

2.3 Erosion and sputtering of materials;

2.4 Fatigue.

2.1 Pumping

All the existing and foreseen NBI system need massive pumping speeds (PSs), which is, for all long pulse systems, achieved with cryopumps.

All designs of future systems require high PSs, even with reduced neutraliser and source gas flows:

The ITER injectors have a PS of ≈$3*10^6$ L/s for D_2, so a reduction in the gas flow of a factor 10 would mean a PS of ≈$3*10^5$ L/s for D_2 is required – well beyond the speed of mechanical pumps.

In addition the pumps must have a pumping speed for He of several 10s of m^3/s

2.1 Pumping contd.

Cryopumps do not actually pump gas out of the injectors, but they store it locally and they need periodic re-generation.

In-situ regeneration whilst operating is neglected as not demonstrated and very difficult.

Solution: one extra injector:

2.1 Pumping contd.

Example: Injector operating time 5 h, 6 injectors installed

Time (h)	1	2	3	4	5	6
Injector 1	Regen.					
Injector 2		Regen.				
Injector 3			Regen.			
Injector 4				Regen.		
Injector 5					Regen.	
Injector 6						Regen.

Note that this scenario requires, other things being equal, a reduction in the gas flow into each injector that is 5 times lower than into an ITER HNB.

2.2 Cs accumulation

Extrapolating from the ITER beam source expected performance, ≈20 mg/h of Cs will need to be injected into the ion source.

Similar requirement in the beam source of an ion source on a reactor/Demo, >1 kg will have been injected into each source every 6 years of reactor operation.

As it has been found that most of the Cs remains in the ion source, that is very likely to cause operational problems.

2.2 Cs accumulation contd.

Therefore R&D is needed:

- To develop a technique for cleaning Cs from an ion source, **by remote means**;
- **Or** the required Cs injection rate must be reduced by about a factor 20 to allow operation for the reactor lifetime without cleaning the Cs out of the source;
- **Or** an alternative to Cs needs to be developed.

2.3 Erosion and sputtering of materials

In most areas in the injector the erosion of a component can be ‘managed’ by good design. What cannot be avoided is the sputtering from the back-plates of the ion source by back-streaming positive ions, which could cause a water leak.

Reducing the back-streaming ion current density by more than a factor 6 means that the thickness of material above the water could be 2 mm (Mo).

Extrapolating from the ITER situation suggests that such a layer would be eroded in <10 y, which is not sufficient to avoid the need to replace the back-plate during the lifetime of a reactor (40 years).

2.3 Erosion and sputtering of materials contd.

The material sputtered from the back-plates will eventually coat the PG with many monolayers with whatever material constitutes the back-plates. If some “magic” material is used to produce a low work function PG surface, that will be buried within a time that is much les than the reactor lifetime. (ITER total sputtering rate is $\approx 5 \times 10^{16}$ atoms/s. For the reactor/Demo injector it is $\approx 1 \times 10^{16}$ atoms/s.)

- **Back-plate replacement may be needed within the lifetime of a reactor.**
- **If a non-renewable PG surface is used, the sputtered material must be the same as the PG surface, or a way to remove the sputtered material in situ must be developed.**

2.4 Fatigue

All the components of an injector for a reactor or Demo will have to be designed to have a fatigue life that is longer than the life of the device (as on ITER).

The lower extracted current density, the reduced gas flow into the ion source and the use of a high efficiency neutraliser mean that the power density on the extractor and accelerator and the residual ion dump will be lower than in the ITER HNBs, and the fatigue lifetime should not be a problem.

That is not the case for the beamline calorimeter, which will see a similar current density to the ITER HNB calorimeter.

2.4 Fatigue contd.

Fatigue arises from the thermal stress change during beam on-off cycles. In a reactor/Demo that will be determined by the cryopump regeneration time.

If the pumps need to be regenerated after ≈5 h of operation, with continuous operation of the reactor, ≈600 regenerations will be needed per year, and 24000 in 40 y.

If 5 near full power pulses suffice to re-condition the injector, the number of fatigue cycles is $\approx 10^5$.

That is **only** a slightly higher than the fatigue life of the ITER HNB calorimeter, i.e. it should be OK.

But, the extracted current density cannot be increased to >50% of that from the ITER beam source.

3 Nuclear constraints

A multitude of constraints arise because the injectors of a fusion reactor/DEMO will operate in a nuclear environment; principally:

1. Materials
2. Mechanical engineering
3. Space constraints
4. Remote handling

3.1 Materials

This is a long list, but amongst those known to have had a direct effect on the design of the ITER NB injectors are:

a) No flurogenated materials inside the vacuum boundary or flurogenated gases in contact with the vacuum boundary;
b) No insulating gases in line with high neutron and gamma fluxes because of radiation induced conductivity;
c) No organic materials (e.g. insulators and O-rings) because they deteriorate and lose their mechanical properties under neutron and gamma radiation;
d) No NdFe magnets as they lose their magnetism rapidly under neutron bombardment;
e) Low activation materials (e.g. low cobalt stainless steel) must be used to minimise activation.

3.2 Mechanical engineering

All designs have to be submitted to and approved by the nuclear regulator. In the case of ITER getting approval from the regulator has meant*:

a) Following the (strict) RCCMR code for the design of the NB vessels, which severely restricts the type of welds etc.;
b) All penetrations of the vacuum boundary must be capable of being sealed with two all-metal valves in series, or a window + an all metal valve;
c) All vacuum seal must use a double seal with the interspace between the seals monitored;
d) All designs must be validated for all possible load cases. It has to be shown that the confinement boundary is not breached, e.g. in the case of a severe earthquake.

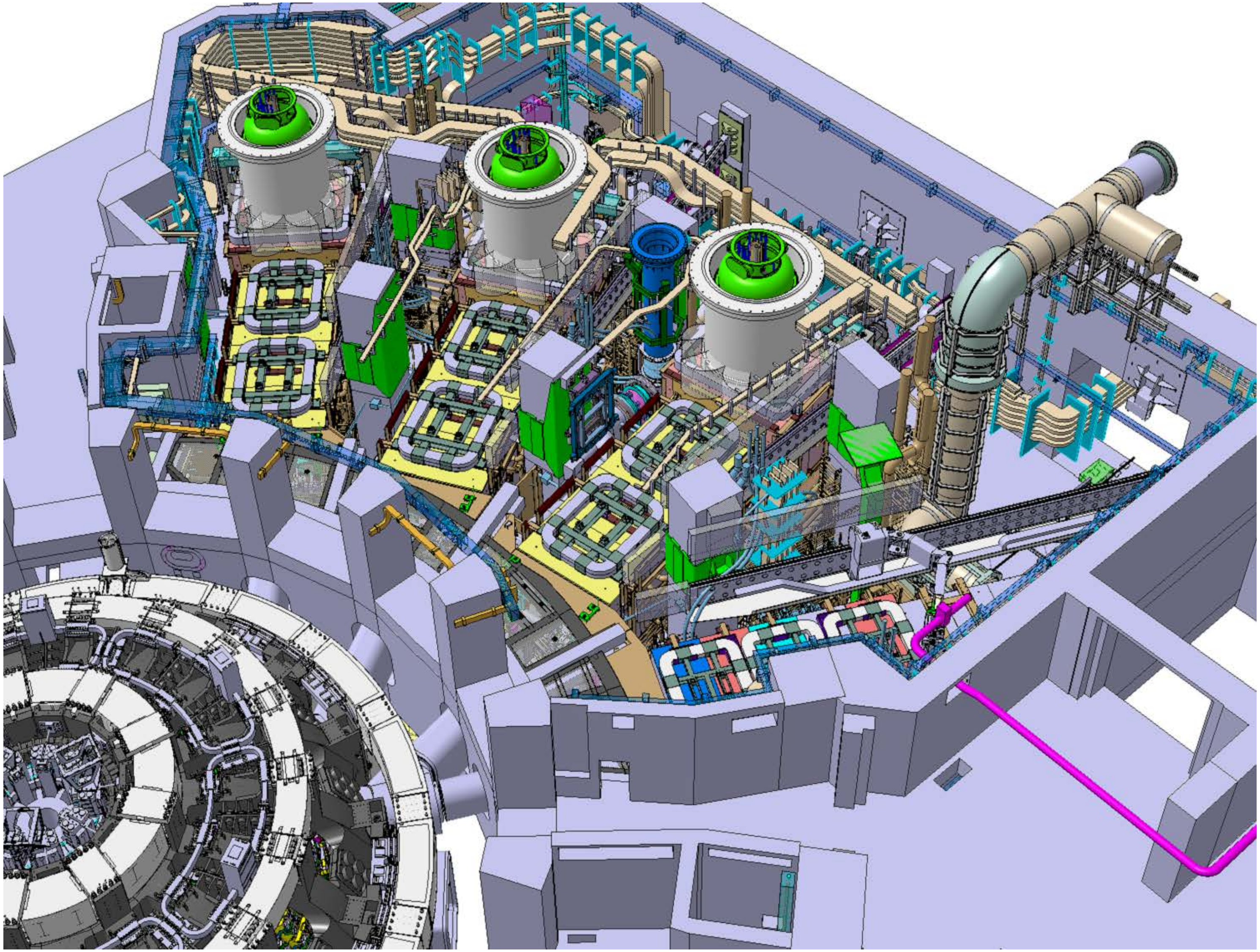
* Limited selection of examples given

3.3 Space constraints

Two considerations lead to quite severe space constraints in a nuclear environment:

1. The so-called “nuclear island” must be limited in extent. This means, for example, that windows must be close to the vacuum vessel and not located remotely at the end of a connecting tube or waveguide.
2. The injectors will become highly activated in use on the reactor/Demo, which means that all maintenance or repair must be carried out by remote means. That leads to the need for extra space both inside, and around, the injector vessel.

Computer view of the ITER NB cell equipped with 3 HNBs and the DNB. NB cell floor area >1100 m^2, volume ≈11,000 m^3.



Summary

- **Injectors for a reactor/Demo will have to have a global efficiency ≥60%. That will require a photon neutraliser and a significant reduction in the gas flow into the beam source.**
- **The continuous operation will require that the design of all components of the injector have sufficient life, taking account of erosion and fatigue.**
- **If a low work function surface for the PG is developed to replace Cs, it must tolerate the sputtering due to back streaming positive ions.**

Summary (Contd.)

- **Space constraints will be severe, especially as remote maintenance must be foreseen, requiring space for access etc.**
- **All extensions of the "nuclear island" will be limited, probably requiring windows in any extensions such as tubes for the laser of the neutraliser system.**
- **The continuous operation will require that the design of all components of the injector have sufficient life, taking account of erosion and fatigue.**
- **If a low work function surface for the PG is developed to replace Cs, it must tolerate the sputtering due to back streaming positive ions.**

Conclusions

- The experience gained from the design of the injectors for ITER must be taken into account in assessing any R&D proposal.

- Any R&D proposal must give a conceptual guide as to how the final system will be able to meet the expected conditions in a reactor/Demo.

Thank you for your attention

Extra slides

2.1 Pumping contd.

The gas from the fusion device entering the injector will contain He produced in the fusion reactions (≈10%). It is calculated that to avoid the He density significantly increasing the re-ionisation losses a PS for He of several 10s of m^3/s is required.

That might be achieved with turbo-molecular pumps, but the need for large apertures in the NB vessel and the associated auxiliary pipes and pumps makes that unlikely.

Only NEGs and cryopumps can provide the PS needed to pump D_2, but NEGs cannot pump He, so it is concluded that cryopumps with activated charcoal surfaces will be used.

The maximum neutralisation for a plasma neutraliser as a function of the degree of ionisation.

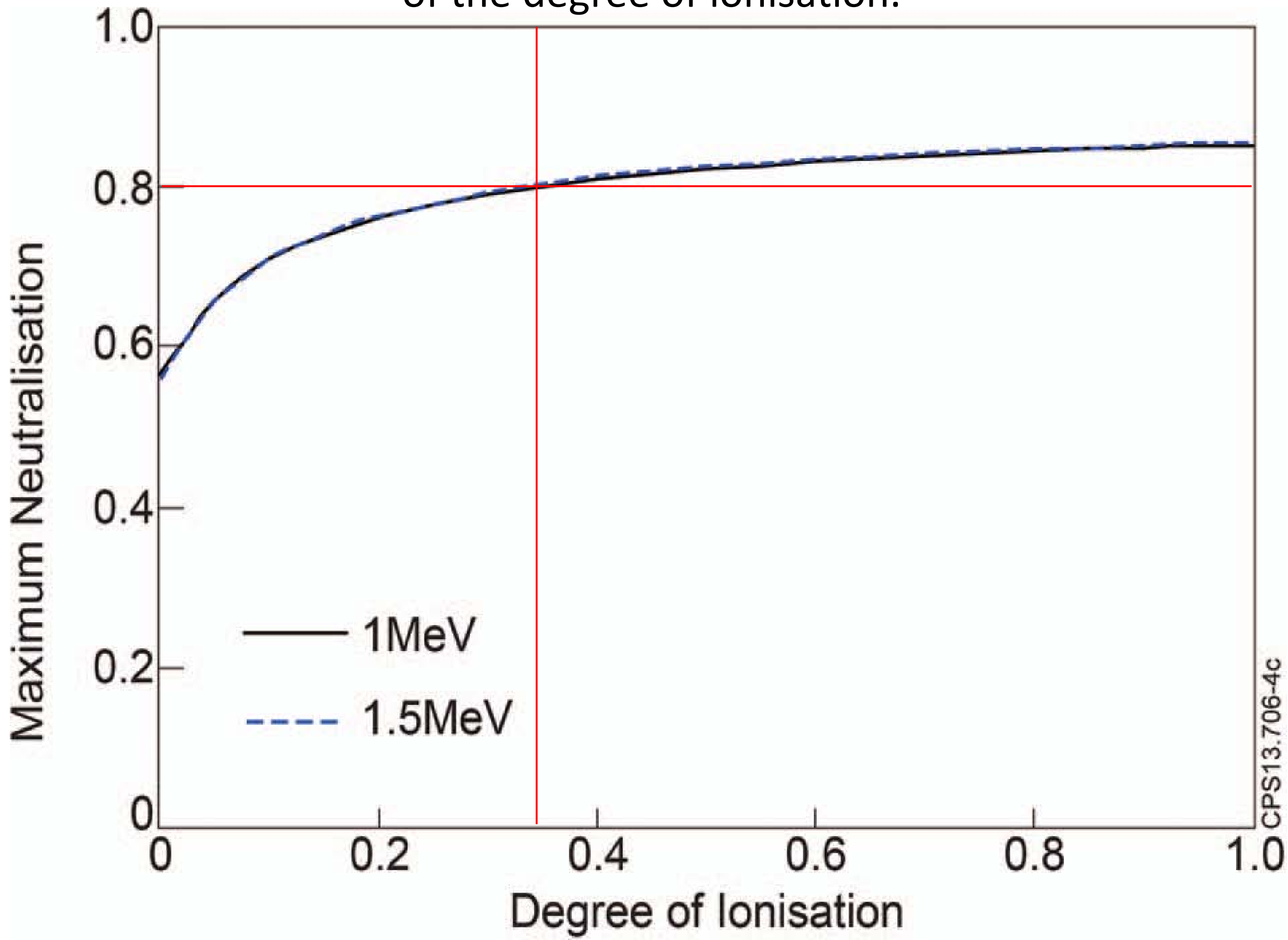
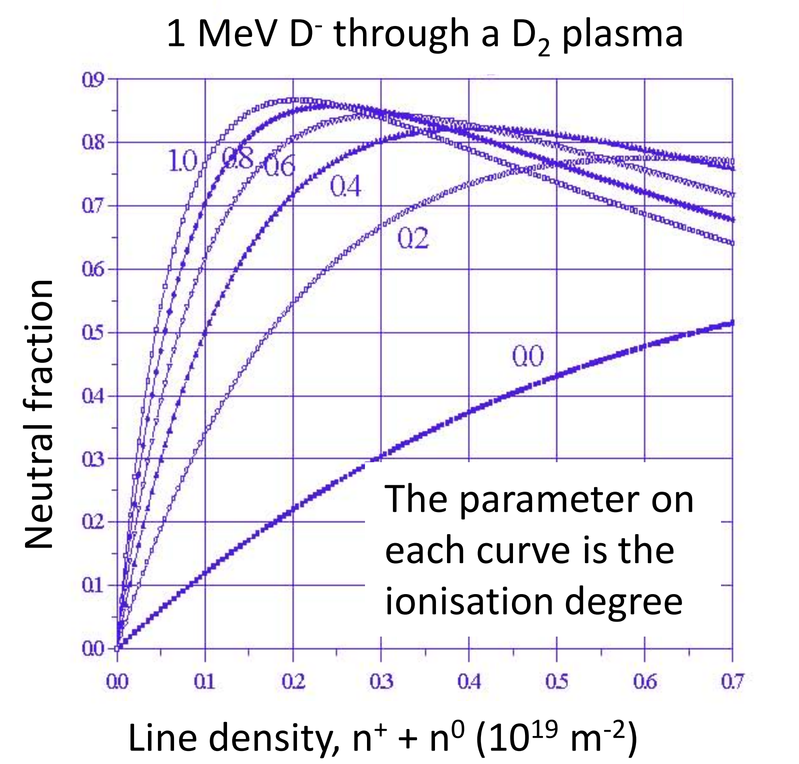
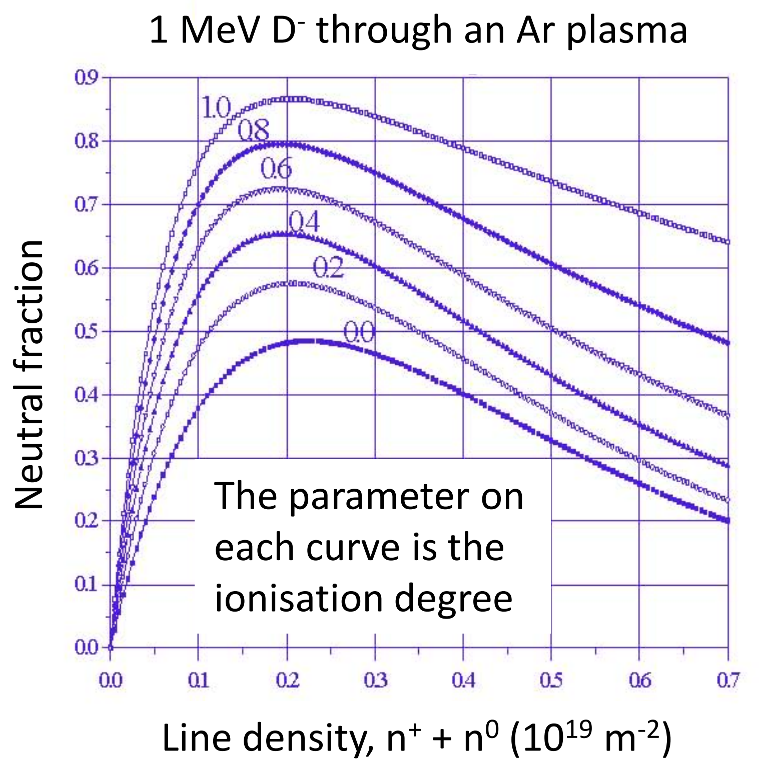


Figure taken from "Beyond ITER: Neutral beams for a demonstration fusion reactor (DEMO), R McAdams, Rev. Sci. Inst., **85**, 02B319 (2014).





Curves taken from the presentation of V Kulygin: "STATUS OF PLASMA NEUTRALIZER DEVELOPMENT ", V. Kulygin, I. Moskalenko, A. Spitsyn, A. Skovoroda, S. Yanchenkov, V. Zhiltsov, Kurchatov Institute, Moscow, Russia.