Sergey S. Ananyev, E.D. Dlougach, A.I. Krylov, A.A. Panasenkov, B.V. Kuteev
NRC Kurchatov Institute; Ac. Kurchatov sq., 1/1, Moscow RU-123182, Russia

E-mail contact of the corresponding author: Ananyev_SS@nrcki.ru

KURCHATOV INSTITUTE
NATIONAL RESEARCH CENTRE

Concept of plasma heating and current drive neutral beam system for fusion neutron source "DEMO-FNS"

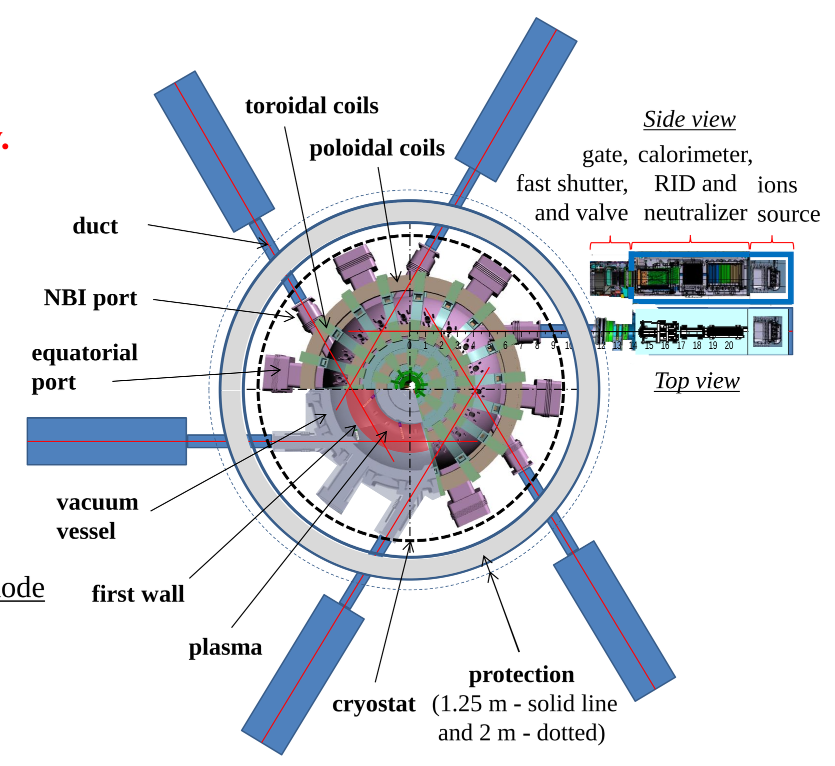
Abstract

Steady-state operation of a fusion neutron source (FNS) requires plasma heating and current drive by means of additional power delivered by neutral beams. Six neutral beam injectors (NBI) will provide DEMO-FNS machine with additional heating power up to 30 MW, with neutral particle energy 500 keV. NBI systems developed for ITER can serve as the prototype for DEMO-FNS, as both systems have similar ion source current, with accelerated beam power in ITER NBI (1MeV) being twice as large as in DEMO-FNS. The paper de-scribes the NBI system with account of its integration to DEMO-FNS tokamak complex.

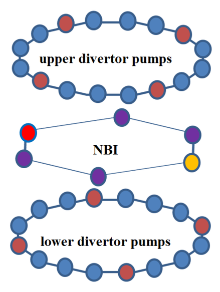
Significant differences in the design elements of injectors for DEMO-FNS are associated with smaller values of critical parameters such as injected power, the values of peak power densities on the walls along the beam path, smaller gas flows in the injector compared to the injectors being developed for ITER. At this stage, we deliberately do not consider systems that are auxiliary to the injection complex of fast atoms, but we emphasize the complexity of their design and integration into tokamak systems.

We proposed the ITER NBI parameters revision to optimize the injector and components design for the DEMO-FNS facility. Optimal beam transmission line configuration has been chosen and the loads on its elements have been calculated.

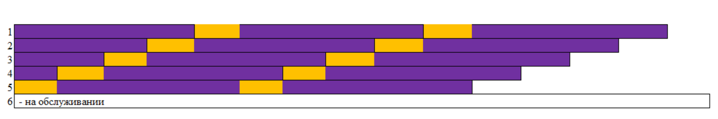
A system of six injectors should provide the possibility of steady-state plasma heating and current drive generation, thereby creating conditions for the steady-state operation of the FNS unit as a whole.



Injectors schematic placement for the DEMO-FNS facility



Divertor's and NBIs pumps



Proposed staggered NBIs pumping scheme for steady-state mode

Injection steady-state operation mode is supported by the of four injectors simultaneous operation combination, while the fifth, in turn, enters the cryopanels regeneration mode. It is envisaged that the sixth injector may be in operational reserve, planned maintenance or repair.

Fusion neutron source DEMO-FNS

The basis of a hybrid fission-fusion reactor is fusion neutron source **(FNS)** based on the tokamak. FNS with output fusion power 10-50 MW should provide steady state flow of fusion neutrons which already reached in pulse experiments of existing tokamaks JET and JT-60U.

Project DEMO-FNS is arms to demonstration of fusion and hybrid technologies and it requires technologies. This facility should demonstrate a steady state operation regimes, tests of materials and components, demonstration of tokamak enabling technologies and nuclear technologies of hybrid blanket and fuel-production plant for Pilot Hybrid Plant **(PHP)**.

Parameters of DEMO-FNS / PHP

Parameter	
Aspect ratio R/a, m	3.2/1
Toroidal magnetic field, T	5
Electron/ion temperature, keV	11.5/10.7
Beta normalized β_N	2.1
Plasma current I_p, MA	5
Neutron yield G_N, 1/s	$1.3 \cdot 10^{19}$
Neutral injection power P_b, MW	36
ECR heating power P_{EC}, MW	6
Discharge time, h	5000
Capacity factor	0.3
Life time, years	30
Consumed/generated power, MW	0.2

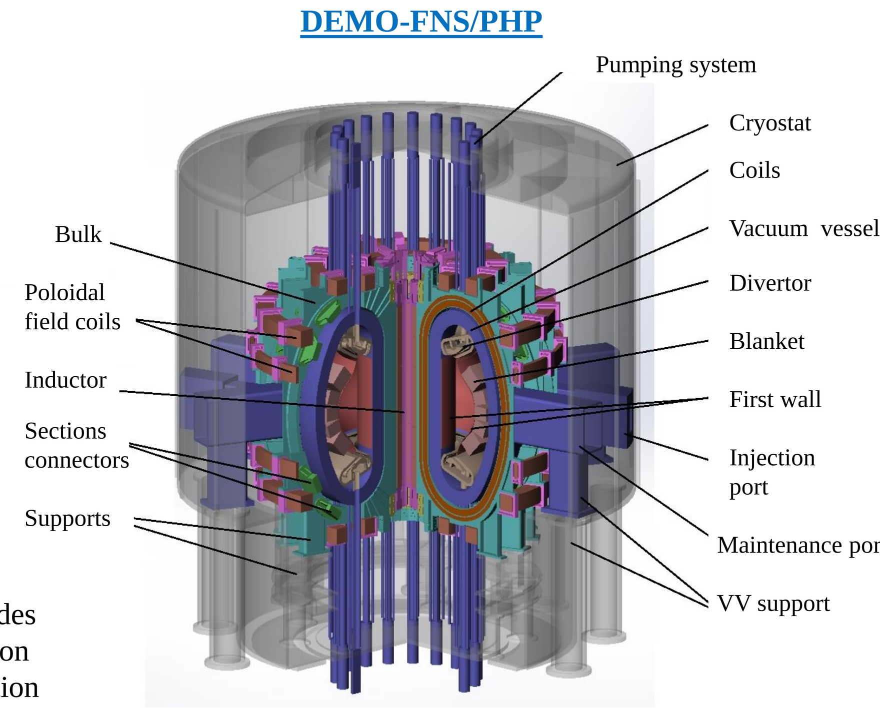
DEMO-FNS

Demonstration of:
- Tritium breeding
- Minor actinides (MA) incineration
- Fissile nuclide production
- Destruction of long life radionuclides

PHP

- Tritium breeding and production
- Destruction of MA and long life radio-nuclides
- Electric power production
- Fissile nuclides production

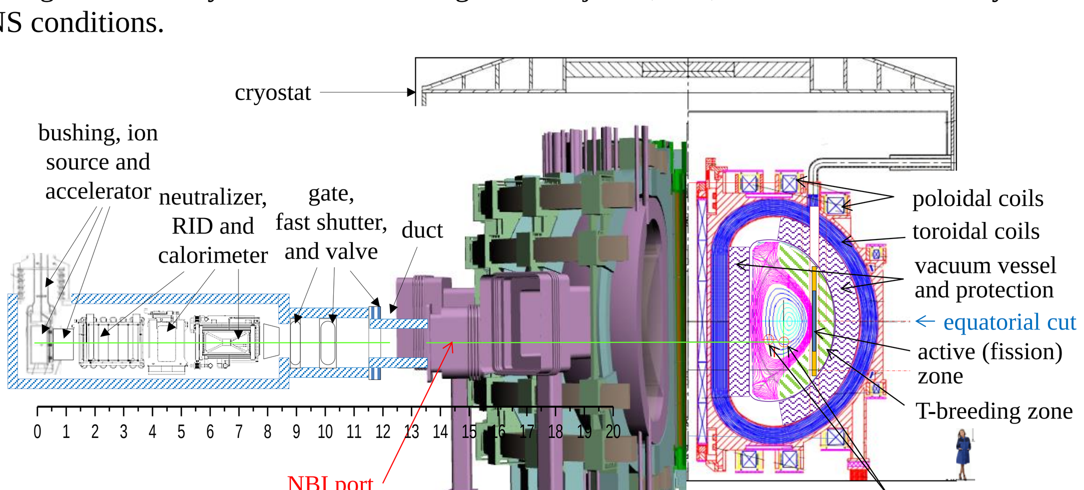
DEMO-FNS/PHP



The injectors developed for the ITER project have the energy of the initial D- ions 1 MeV and the power in the injected beam of D0 atoms to 16.7 MW. Assuming that the negative ion current at the exit from the accelerator (ion source) in the DEMO-FNS injectors will be the same as in the ITER (40 A), and the negative ions energy (NI) and atoms is half the value (0.5 MeV), it can be expected that the operating conditions of the injector FNS will be greatly facilitated. Thus, the smaller energy of the beam atoms leads to smaller values of injector parameters such as injected power, peak power densities on the walls along the beam path, smaller gas flows in the injector and other differences. A number of other parameters are expected to be similar to ITER injectors, for example, the geometric parameters of the initial beam.

The composition of the auxiliary injector systems, such as the supply and distribution of cooling water, the supply of refrigerants to the panels, the power supply in the injector, the mechanical systems for ensuring the assembly and commissioning of the injector, etc., remains fundamentally the same, but all systems require analysis and optimization for FNS conditions.

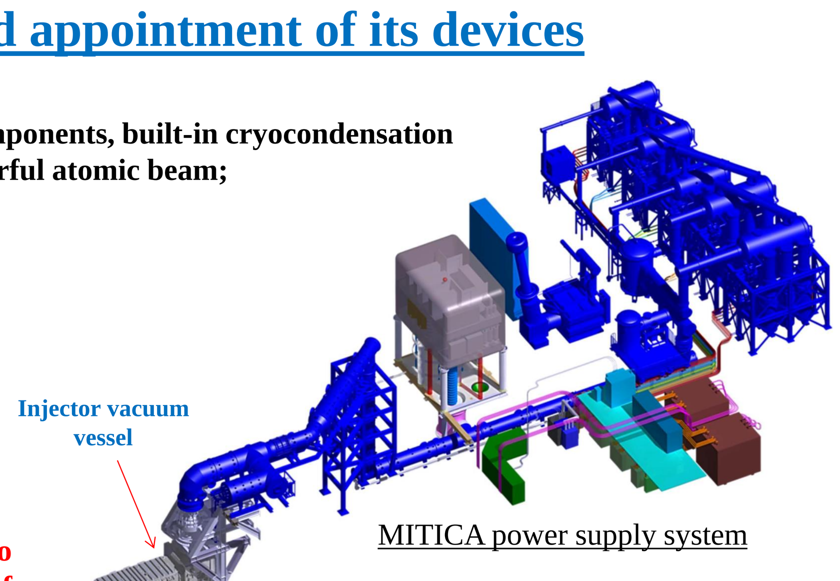
Calculations made using zero-dimensional code and NUBEAM MonteCarlo and ASTRA codes substantiated the use of 500-keV deuterium atoms beams and a total injection capacity of up to 30 MW. The energy of the atoms is chosen mainly from the condition of a sufficiently deep beam penetration into the plasma with tangential introduction, its effective heating, and the maintenance of the current near the axis of the plasma. By optimizing the plasma confinement conditions, other injection parameters were chosen: impact parameter 2.75 m, vertical displacement of injection axis 0.6 m, angle of vertical inclination 0 °, and others.



Composition of the NBI system and appointment of its devices

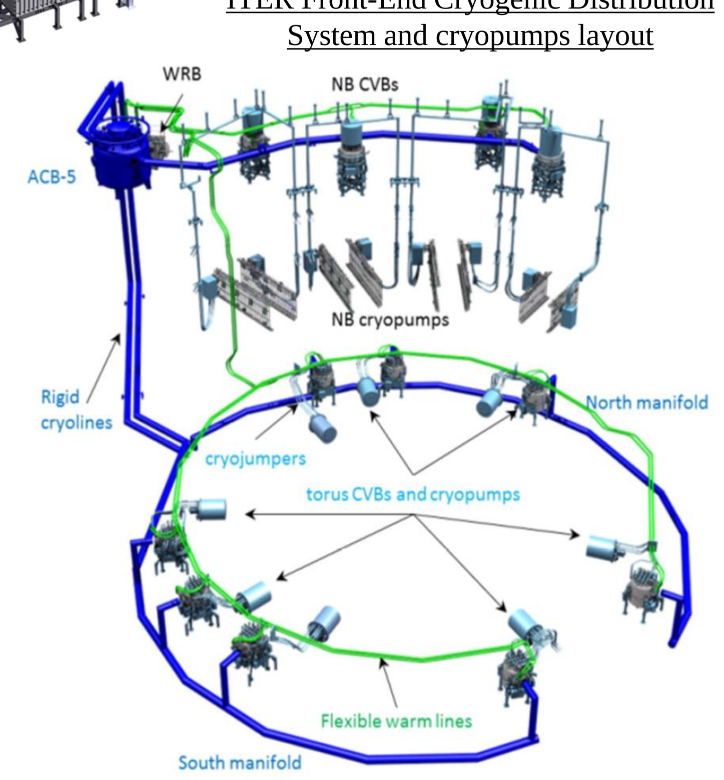
The injection heating system contains the following devices and subsystems:
- **six injectors of fast atoms, each containing an ion source, beam bundle components, built-in cryocondensation pumps and other devices necessary for obtaining and transporting a powerful atomic beam;**
- power supply system of injectors;
- system of injectors and ion sources vacuum preparation;
- water cooling system of all injector components, including components located under different electrical potentials (from zero to 1 MV);
- **gas inlet system into ion sources and neutralizers**;
- cryogenic supply system;
- automated injection control system.

At this stage, we deliberately do not consider systems that are auxiliary to the injection complex of fast atoms, but we emphasize the complexity of their design and integration into tokamak systems.

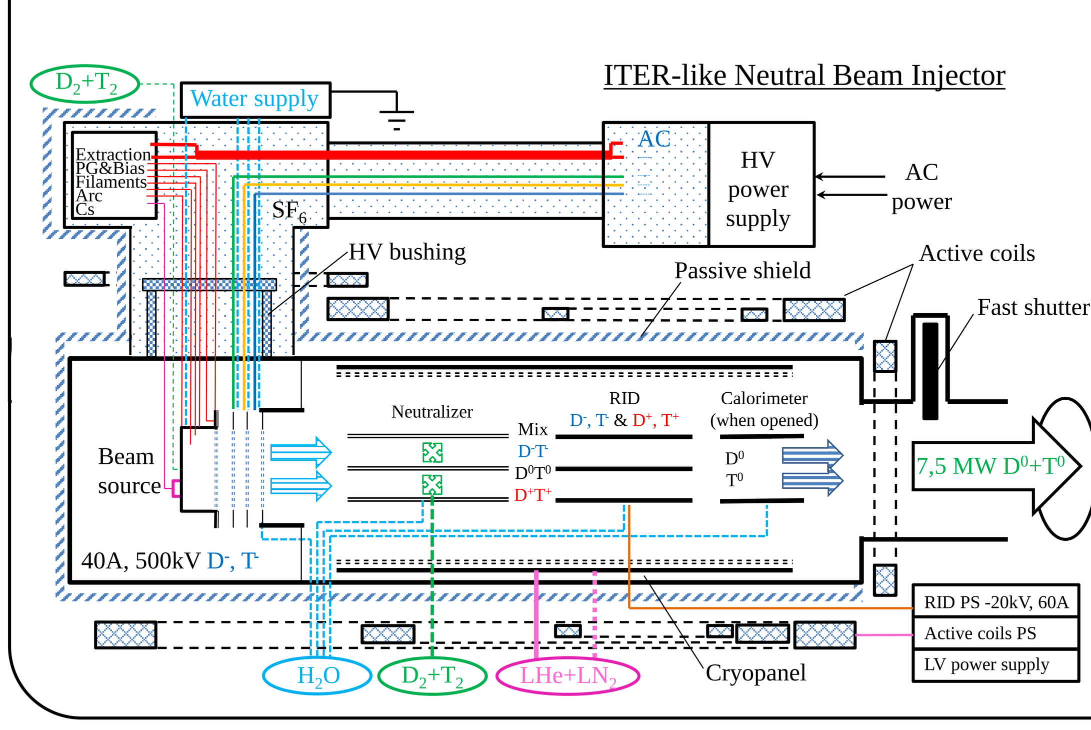


MITICA power supply system

ITER Front-End Cryogenic Distribution System and cryopumps layout



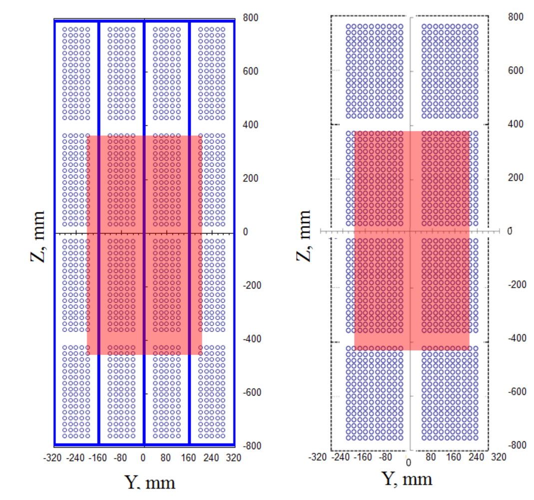
ITER-like Neutral Beam Injector



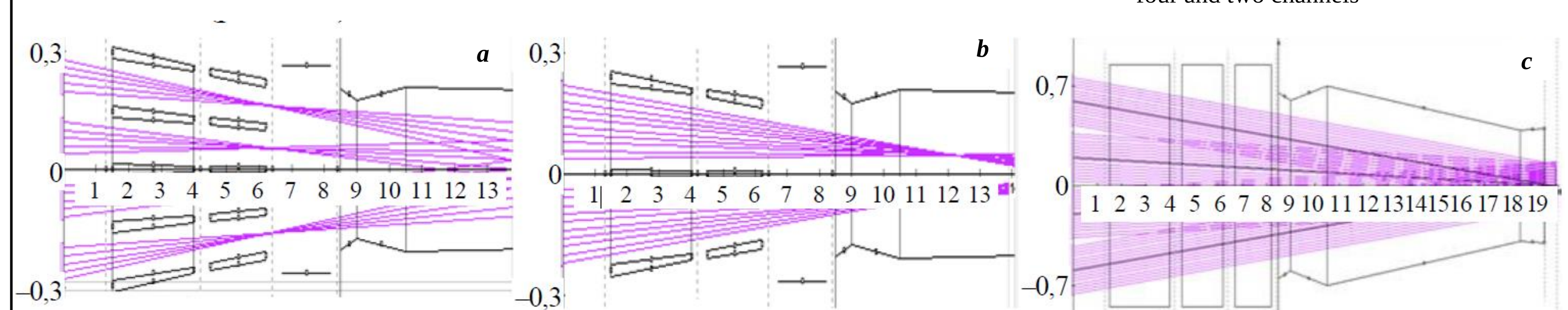
Parameters and optimization results of the injector schedule

The decrease in energy and power of ion and atomic beams in the FNS injector makes it possible to optimize the configuration and parameters of the injection path components to achieve the maximum efficiency of beam transport from the ion source to the tokamak plasma while providing acceptable levels of energy release and load power density for components and path elements.

Since the beam emerging from the source has an angular divergence, the first possibility of increasing the efficiency of transportation is the shortening of the length of the beam line. FNS configuration with its magnetic field coil, cryostat, and biosecurity limits the size of the entrance window to the chamber in a tokamak 0.4×0.8 m length and defines magnitude atom channel ≥11 m. Compared with the ITER injector is shorter by almost 4 meters and still remains the possibility of reducing the neutralizer length (the optimal thickness of the gas target is 1.75 times smaller), and the beam receiver (lower power and power density). With a decrease in the neutralizer length, to create the same target thickness, the necessary gas flow to it naturally increases. However, the losses of the atomic beam for reionization remain noticeably less than the dominant losses on the direct beam interception on the walls along the way to the tokamak (geometric losses). This leads to the need to analyse, in comparison with the prototype, a shorter neutralizer length, as well as a smaller channels number in the neutralizer and RID, in order to reduce geometric losses. The angle of inclination of each panel of the calorimeter relative to the injector axis was increased 2 times (up to 10°), which made it possible to shorten its length by 1.5 m.



Ion beam structure at the output:
- four and two channels



Beamlet focusing scheme for the DEMO-FNS injector: horizontal focusing - four channels (a), two channels (b); Vertical focusing is common for both figure (c). Vertically, within each group, the beamlet axis is parallel

FNS injector parameters with different geometric characteristics

Parameter	Four channels, width 0.1 m				Two channels, width 0.2 m			
Length neutralizer , m	1,5	2,0	2,5	3,0	1,5	2,0	**2,5**	3,0
F , m *	5,2	5,7	6,2	6,7	12	12	**12**	12
Gas in the neutralizer, Pa·m³/s	28,8	17,4	12,3	8,2	38,6	27,1	**19,9**	15,2
Geometrical beam loss	0,22	0,237	0,266	0,298	0,172	0,187	**0,203**	0,218
The beam loss for re- ionization	0,153	0,114	0,082	0,075	0,185	0,135	**0,101**	0,090
Total beam loss, fraction	0,339	0,324	0,326	0,351	0,325	0,297	**0,283**	0,288
Injected power, MW	7,93	8,11	8,09	7,79	8,10	8,44	**8,60**	8,54
Time before regeneration, h **	1,95	3,16	4,69	6,65	1,46	2,24	**3,21**	4,46

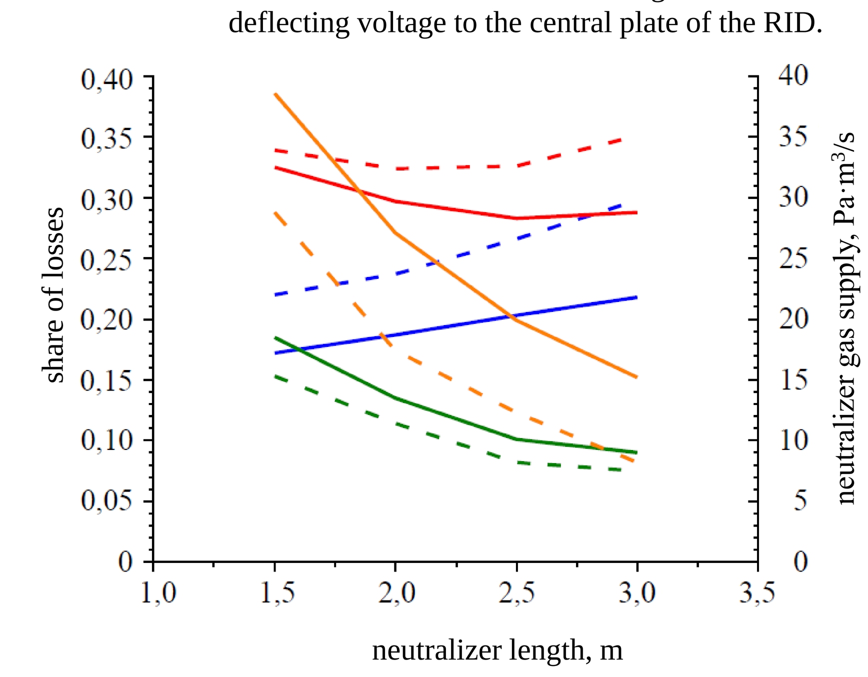
* Horizontal focus of beamlet in a group.
** Gas accumulation time: 2% of the injector vacuum chamber volume under normal conditions

As can be seen from the data given in Table (and figure), the option is attractive with two channels of twice the width and a neutralizer of 2.5 m in length. In this variant, the length of the path from the ion source to the exit from the atomic duct decreases to 19.5 m. In this case, despite the increase in the required gas flow to the neutralizer, loss on a straight line interception and reionization are less , than in the 4-channel version and the injected power is much larger. In addition, in the design of the neutralizer and especially the RID, consisting of only two channels (three plates), it is much easier to connect the cooling water and the deflecting voltage to the central plate of the RID.

The main characteristics of the beam power variation along the injection path and the distribution of loads and peak power densities thereon in a 2-channel version of the injector with a neutralizer length of 2.5 m, the power of the negative ions beam at the exit from the ion source of 20 MW (the divergence angle of 7 mrad, the inaccuracy of the angular adjustment of the beam axis horizontally 2 mrad and vertical 4 mrad.)

Beam power variation along the beamline and loads distribution

Parameter	Value
Power loads from the beam in neutralizer, MW	1,25
Peak power density at the end elements of the neutralizer, MW / m²	1,90
Peak power density at the neutralizer channel wall, MW / m²	0,21
Neutral beam power at the neutralizer output, MW	11,25
The power loss of a neutral beam in a RID , MW	0,69
The total power released in the RID (atoms + ions), MW	8,19
Peak power density at the end of the RID panel, MW / m ²	3,30
Peak power density on the RID panel, MW / m² (BTR- code)	4,00
Neutral beam power at the RID output, MW	10,56
Peak power density on the calorimeter panel, MW / m².	11,25
Neutral beam power intercepted by the scraper, MW	0,43
Peak power density on the scraper wall, MW / m²	0,50
Load power from a beam on the duct liner walls, MW	0,92
Peak power density on the side wall of the liner, MW / m²	0,37
Peak power density on the top wall of the liner, MW / m²	0,33
Neutral beam power injected into the plasma (taking into account the 10% loss for reionization), MW	8,28

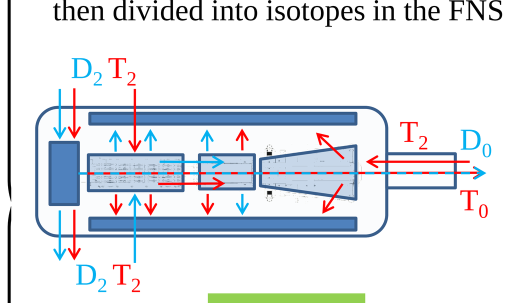


Losses (after the neutralizer) for reionization, geometric and complete, and supply of gas to the neutralizer to create an optimal target thickness of $8 \cdot 10^{19}$ m^{-2}, depending on the length of the neutralizer: solid curves for the 2-channel path; dotted curves for 4-channel; green curves - losses for reionization; blue curves - geometric losses; red curves - complete losses; orange graphs - gas flow to the neutralizer

However, there are complicating circumstances.
Thus, with a lower energy of negative ions, their sensitivity to the magnetic field along their trajectory increases, more precisely, to its vertical component, which deflects ions across the narrow direction of the channel of the neutralizer. Such a deviation results in some horizontal blurring of the atomic beam in the neutralizer, depending on how long a negative ion moved before the time of stripping.

Tritium fuel cycle

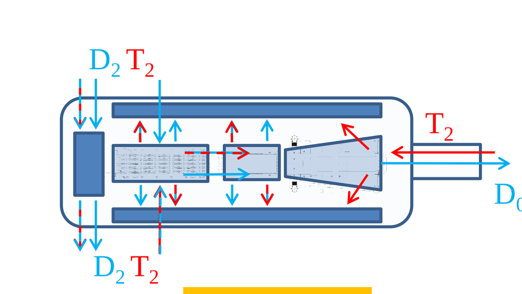
During the design of the tritium fuel cycle (FC) of the DEMO-FNS facility, several options for gas supply to NBIs were considered. In tokamak, tritium and deuterium are fed separately, and at the outlet of its divertor, the pumped gas is a mixture of D_2:T_2 about 50% by 50%. This mixture is then divided into isotopes in the FNS fuel cycle system.



I scenario D:T=1:1

With a deuterium and tritium mixture in equal parts (which allows to avoids isotopic flow separation and to reduce the accumulation of tritium in FS).

Tritium presence in the gas used is completely permissible for the operation of the source and neutralizer. By the time of regeneration due to the explosive content of deuterium (~ 2% by volume under normal conditions), less than 1 g of tritium accumulates on the cryopanels of the pump. After the regeneration of the cryopanels, containing only a small tritium admixture, can again be directly used for ions source and the neutralizer. When the tritium content in the injectors gas supply circuit mixture of the reaches a certain value (say, on the order of 5%), all this gas can be directed to the general system of separation of tritium from deuterium and replaced by purified deuterium. The advantage of the second option before the first is obvious. Disadvantage can be considered the necessity of own circuit of gas supply for neutral injection system.



II scenario D:T=1:0,05

With deuterium without tritium admixture, which implies the use of a separate gas processing loop including gas purification systems and a system for hydrogen isotopes separation to maintain tritium at a low level.

Conclusion

ITER NB injectors schemes and approach are adopted as a base for DEMO-FNS injector prototype – with the parameters review. With the extracted ion current at the beam source exit being the same, and the ion energy being a half of that in ITER NBI, we expect the similarity of both NBI systems. We propose a revised set of parameters to optimize the design of DEMO-FNS injector and its components. The proposals for the preliminary design of the key components of the injector have been worked out.

Lower values of main parameters, such as power injected. Peak power densities along the beamline, as compared with ITER NBI, allowed to reduce the number of channels to two, make the neutralizer, RID, and calorimeter shorter. As a result the total beamline length is reduced to 19.5m. Despite the raised gas flow to 2-channels neutralizer, the total losses (caused by direct interception and reionization) has proved to be less than in 4-channels option, and the injected power is higher. Besides, the design of neutralizer and RID tends facilitate. Optimum values of beam groups focusing is calculated for the chosen NBI scheme, and the result loads at the key components along the beam path for the selected beam optics: the divergence angle 7 mrad, the angular misalignments of the beam axis are 2 mrad along horizontal and 4 mrad along vertical. The acceptable level of vertical magnetic field component is evaluated. The optimal solution of gas puffing integration with DEMO-FNC FC is proposed.

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