

Conceptual Design of the DEMO NBIs: Main Developments and R&D Achievements

P. Sonato^a, P. Agostinetti^a, U. Fantz^b, A. Fassina^a, T. Franke^{b,c}, I. Furno^d, C. Hopf^b, I. Jenkins^e, E. Sartori^a, A. Simonin^f, M.Q. Tran^d, L. Zanotto^a

^aConsorzio RFX, Euratom-ENEA association, Corso Stati Uniti 4, 35127 Padova, Italy

^bMax-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany

^cEUROfusion Consortium, Boltzmannstr. 2, 85748 Garching, Germany

^dEcole Polytechnique Federale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

^eCulham Centre for Fusion Energy, Science Centre, Abingdon, Oxon, OX14 3DB, UK

^fCEA-IRFM, F-13108 Saint-Paul-Lez-Durance, France

E-mail contact of main author: piergiorgio.sonato@igi.cnr.it

Abstract. The objectives of the nuclear fusion power plant DEMO, to be built after the ITER experimental reactor, are usually understood to lie somewhere between those of ITER and a “first of a kind” commercial plant. Hence, in DEMO the issues related to efficiency and RAMI (Reliability, Availability, Maintainability and Inspectability) are among to most important drivers for the design, as the cost of the electricity produced by this power plant will strongly depend on these issues. In the framework of the EUROfusion Work Package Heating and Current Drive (WPHCD) within the Power Plant Physics and Development (PPPT) activities, a conceptual design of the Neutral Beam Injector (NBI) for the DEMO fusion reactor has been developed by Consorzio RFX in collaboration with other European research institutes. In order to improve efficiency and RAMI aspects, several innovative solutions have been introduced in comparison to the ITER NBI, mainly regarding the beam source, neutralizer and vacuum pumping systems.

1. Introduction

DEMO (DEMONstration Fusion Power Plant) is a proposed nuclear fusion power plant that is intended to follow the ITER experimental reactor. While in ITER the goal is to demonstrate the possibility to obtain a plasma able to sustain the fusion nuclear reaction, in DEMO the main objective is to prove the industrial feasibility of fusion by showing the electricity production from the fusion reaction, the safety aspects and the Tritium self sufficiency.

The injection of high energy neutral beams is one of the main tools to heat the plasma up to fusion conditions. In the framework of the EUROfusion Work Package Heating and Current Drive (WPHCD) within the Power Plant Physics and Development (PPPT) activities, a conceptual design of the Neutral Beam Injector (NBI) for the DEMO fusion reactor [1][2] has been developed by Consorzio RFX in collaboration with other European research institutes and integrated into the DEMO1 reference design, as shown in *FIG. 1*.

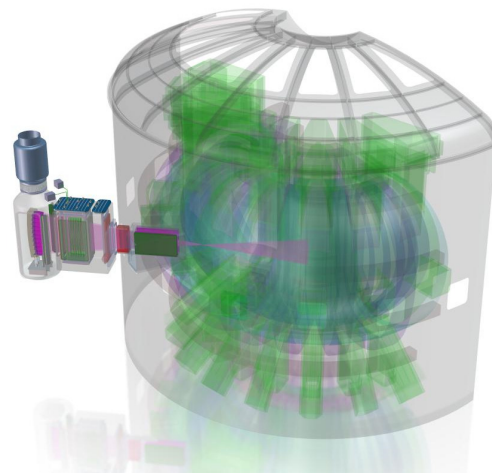


FIG. 1: Integration of the Heating Neutral Beam in the DEMO1 pre-conceptual design.

High efficiency and low recirculating power, which are fundamental requirements for the success of DEMO, have been taken into great consideration for the conceptual design of the DEMO NBI. Moreover, essential is the design of a system with the highest reasonably achievable Reliability, Availability, Maintainability and Inspectability (RAMI).

2. Implementation of efficiency and RAMI enhancements

A large R&D effort is implemented in Europe to maximize the efficiency and obtain the most effective system with respect to the RAMI analysis meeting the requirements for the DEMO power plant. In particular with respect to the state-of-the-art negative ion based neutral beam injector (NNBI) under construction for ITER the following aspects have been identified for efficiency and RAMI improvements.

(i) In ITER the neutralizer component is foreseen to have an efficiency of 55%, defined as the ratio between the power flux of neutral particles at the exit of the neutralizer and the negative ions at the entrance. To increase efficiency of the neutralizer up to 70% or more for DEMO, innovative concepts of this component, based on Photo-Neutralization (PN), are being considered for DEMO. These concepts take into account the results of the studies and NB R&D that is in progress by various laboratories throughout Europe, working on the “closed recirculating cavity with nonlinear gating” or RING concept [5] (RFX Padova/Italy), and on the Fabry-Pérot cavity (Siphore injector concept at CEA/France [6] and a proof-of-principle test facility HOMER at IPP Garching/Germany [7]).

The conceptual design of a neutralizer based on the RING concept has been implemented as one option in the DEMO NBI conceptual design. Nevertheless, as the PN feasibility and reliability are still to be demonstrated, the DEMO NBI has been designed to be compatible both with a PN and a gas neutralizer similar to the one foreseen for ITER. This approach aims at minimizing the development risks, by keeping more optional solutions to be selected in a later design stage.

(ii) Another possibility to increase the overall efficiency of a NBI system (of about 15% compared to ITER NBI, according to the present calculations) is to decrease the beam losses in the beam duct, which is the part that connects the NB injector with the tokamak chamber. This is particularly critical in DEMO because the duct is several meters long. To reduce re-ionization losses, the NB duct has been designed with a high performance vacuum pumping system, allowing to significantly decrease the gas pressure in that region.

(iii) To increase availability, the beam source for the DEMO NBI has been designed with 20 sub-sources in parallel (two adjacent columns of 10 sub-sources each) rather than a single one, following a modular design concept. Each sub-source features its Radio Frequency (RF) driver, designed following the research carried out by IPP Garching on the negative ion source BATMAN [8][9]. Alternative concepts for the ion sources are being studied at CEA (the Cybele source [6], which is based on a high power Helicon antenna developed at SPC [10]) and IPP Garching [11]. The modular solution provides an optimized alignment among the corresponding apertures of the accelerator grids, since the modules have a significantly smaller size than the whole accelerator, leading to reduced horizontal and vertical deformations of the grids compared with a non-modular solution.

(iv) An additional improvement introduced in this conceptual design compared with the existing machines is the blade-like shape of the beam. In fact, the ion beam is formed by two “blades” with large height (about 3.7 m) and small width (76 mm). Each of these blades is formed by 10 sub-beams, one per sub-source. The blades are strongly convergent in the vertical direction, with a fan shape. This solution is both compatible with the PN and the gas neutralizer with reduced/optimized vacuum conductance. It also permits to obtain a simpler shape of the residual ion dump compared to the ITER design.

(v) Moreover, the accelerator has been designed and optimized to maximize the vacuum pumping to achieve reduced stripping losses. This goal has been reached by adopting an

increasing size of the apertures in the accelerator, with three main layouts of the apertures (circular apertures, slotted apertures and frame-like apertures for each sub-source) and a design of the supporting frames that permits an optimal lateral pumping. In order to increase reliability of the vacuum pumping system, Non-Evaporable Getter (NEG) pumps are an option instead of cryopumps to provide the required vacuum pumping. This solution is under R&D phase in RFX Padova, KIT Karlsruhe Germany and industrial contributions [12]. Compared to the cryopumps, NEG pumps present numerous advantages, i.e. they are more resistant to neutron radiation, they do not need liquid helium (and nitrogen) to maintain cryogenic temperatures and they imply a lower investment and operative cost. This solution is very attractive for the future fusion devices, but its effectiveness is under validation in present R&D programme. An alternative solution, under development at KIT within the EUROfusion WPTFV (Work Package on Tritium Fuelling and Vacuum), is represented by the mercury diffusion pumps [13].

3. Definition of DEMO NBI requirements

The main requirements of the DEMO NBI, developed within the EUROfusion WPHCD activities in comparison with the ITER NBI are reported in *TAB. 1*.

TAB. 1: Main requirements for the DEMO NBI, with a comparison to the ITER NBI.

Species	ITER NBI	Advanced DEMO NBI
	H ⁰ /D ⁰	D ⁰
Beam energy [keV]	1000	800
Accelerated current [A]	40	34
Max. ion source filling pressure [Pa]	0.3	0.2
Beamlet divergence [mrad]	<7	<7
Beam on time [s]	3600	7200
Extracted e ⁻ /D ⁻ fraction	<1	<1
Neutralization efficiency	not specified*	>0.70**

*This value was not a requirement for ITER; it is foreseen to be about 0.55 for ITER.

**Theoretically obtainable with PN.

These requirements refer to the case “Advanced DEMO NBI”, while the requirements for an “ITER-like DEMO NBI” are identical to those of ITER, except for the duration of the beam on time. In fact, in this last case the DEMO NBI would be an up-to-date version of the ITER NBI, taking into account the DEMO operating scenario.

It can be noted that the requirements of the advanced DEMO NBI are similar but not identical to the ones of the ITER NBI. Namely, it can be observed that:

- In the DEMO NBI, only Deuterium negative ions (D⁻) are considered, whereas ITER NBI is required to operate with hydrogen negative ions (H⁻) in hydrogen discharges. A beam made of deuterium neutrals (D⁰) is the final goal also in both NBIs.
- The beam energy requirement has been slightly decreased in the DEMO NBI compared to ITER (from 1 MeV to 800 keV) to improve the overall reliability of the NBI system integrated into the reactor. The voltage holding of 1 MV DC potential in presence of magnetic fields can be obtained only with optimal conditions of the electrode surfaces, in terms of smoothness and vacuum conditions [14].
- The maximum ion source filling pressure has been decreased, to increase efficiency. In fact, the beam losses in the accelerator are strictly linked to the gas density in the accelerator, that in turn is proportional to the pressure in the ion source.
- The maximum divergence of the beamlets must be very small in both cases; allowing a large fraction of the particles to reach the plasma inside the main chamber.
- The required total accelerated current has been decreased of about 15%, to increase availability of the NBI. Presently, high values of accelerated currents are obtainable only in the case of a perfect set up of the ion source, that is likely to be obtained only in particularly optimised operating conditions.

- The extracted e^-/D^- fraction (or e^-/H^- fraction if the operations are with hydrogen ions) must be in both experiments kept lower than 1. A low ratio permits to limit the heat loads on the extraction grid and to increase the efficiency of the extraction/acceleration system. It requires a good conditioning of the ion source [8].
- The neutralization efficiency requirement has been introduced, differently from ITER, because it is one of the main tools to decrease the recirculating power of the plant and to increase the reliability and availability of the injector.
- The beam-on time is doubled with respect to ITER (two hours instead of one hour), to cope with the so-called DEMO 1 requirements a non-continuous fusion power plant.

4. Choice of the main design parameters

Based on the requirements described in Sec. 3, a set of functional parameters was proposed by the design team and is reported in TAB. 2, where also the corresponding parameters of the ITER NBI are reported for comparison.

TAB. 2: Main parameters assumed for the advanced DEMO NBI, with a comparison to the ITER NBI.

	ITER NBI	Advanced DEMO NBI
Extracted current density [$A\ m^{-2}$]	293	200
Aperture radius [m]	0.007	0.007
Number of aperture columns per source	20	4
Number of aperture rows per source	64	15
Number of sub-sources	1	20
Total extraction area [m^2]	0.197	0.185
Extracted Current [A]	57.7	36.9
Acceleration voltage [kV]	1000	800
Auxiliaries/extraction overall efficiency	0.9	0.9
Gross Power [MW]	64.1	32.8
Stripping/halo current losses efficiency	0.7	0.9
Accelerated current [A]	40	33.3
Beam source transmission efficiency	0.95	0.98
Neutralizer efficiency	0.55	0.7*
Beam line/duct transmission efficiency	0.8	0.92
Power released to the plasma [MW]	16.7	16.8
Injector overall efficiency	0.26	0.51
Number of injectors	3	3
Overall NBI power to the plasma [MW]	50.2	50.4

*theoretically obtainable with PN.

Generally, the efficiencies of the main components are increased in DEMO NBI compared to the ITER NBI values. This is achievable mainly by changing the working principle of the neutralizer (from gas to photo-neutralization), re-designing all the main components and decreasing the density of the background gas in the accelerator, in the beam line components and in the duct. All of these contribute to decrease the beam losses generated by the stripping and re-ionization reactions. In the advanced DEMO NBI, the power consumption of the neutral beam would be approximately half than the ITER one (32.8 MW instead of 64.1 MW), while having the same nominal power injected to the plasma. This would represent a large advantage in terms of recirculating power reduction and efficiency of the whole DEMO.

5. Development of the conceptual design

The present conceptual design of the advanced DEMO NBI, shown in FIG. 2, features the following main components:

- A negative ion beam source, composed of 20 sub-sources (two adjacent columns of 10 sub-sources each). The dimension of each sub-source is approximately $0.4 \times 0.4 \times 0.4\ m^3$. Each sub-source features 4×15 apertures (4 in the horizontal direction, 15 in the vertical direction) with 20 horizontal \times 22 vertical mm steps, like in the SPIDER [15] and MITICA [16]

experiments. The ion beam is formed by two “blades” with large height (about 4 m) and small width (about 70 mm). The blades are strongly convergent in the vertical direction, with a fan shape, to focus the entire beam to the opening in the Breeding Blanket (BB), where it enters in the main chamber.

- A PN based on the (RING) concept, but compatible with other options.
- A Residual Ion Dump (RID) featuring a flat water-cooled CuCrZr plate.
- A beam source vessel, containing the entire beam source with the related NEG pumps.
- A beam line vessel, containing the complete neutralizer and RID structures.
- A duct connecting the beam line vessel to the tokamak chamber. The duct features a large NEG pump (to reduce gas density and re-ionization losses) and two heat dumps (to dump the heat loads by re-ionization).

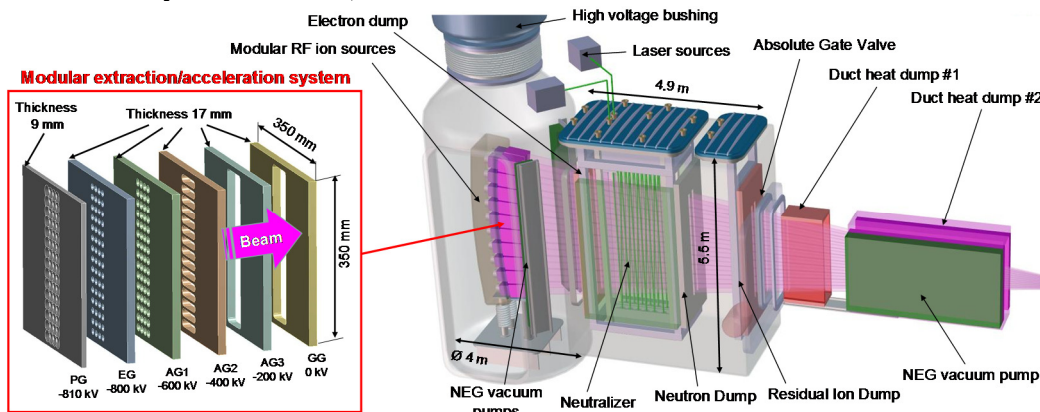


FIG. 2: Overview of the DEMO NBI with the main components and a sketch of the grids of the modular extraction/acceleration system.

The modular solution for the beam source is found to have the following main advantages:

- A better alignment between the corresponding apertures of the grids, also in presence of thermal expansion. Each module has a significantly smaller size than the whole accelerator, hence the horizontal and vertical deformations are also reduced compared with a non-modular solution. In ITER NBI, for instance, the modularity is only in the vertical direction (where there are four separated modules) but not on the horizontal one, introducing a quite difficult alignment and a significant thermal sensitivity for the alignment of both grids and beamlets.
- A more uniform magnetic filter field inside each sub-source, because magnets and/or coils can be put among the two columns of sub-sources; magnetic filter field is a primary factor for the performance of negative ion source [8]. A more uniform magnetic filter field could be an advantage considering the helicon ion sources [10][11], that operate with a higher field (around 12 mT) than the classic IPP-type RF drivers.
- An increased neutralization efficiency, considering the present choice of RING PN, but also considering a gas neutralizer. This modular solution with two blade-like beams is the most convenient to limit the width of the neutralizer channels minimising the gas throughput thanks to a reduced neutralizer vacuum conductance.
- A higher availability during the operations in DEMO; if some sub-sources do not work properly, the remaining ones can in any case provide the negative ion beam.
- The R&D phase can be carried out using a small beam source, which is more flexible and less expensive than a full size prototype. Once optimized, the sub-source can be replicated to form a cluster in the DEMO NBI.

On the other hand, there are also some drawbacks:

- A more complex construction of the ion sources, because there are 20 small ion sub-sources rather than a single large one.

- A more complex construction of the extraction/acceleration system, because the 20 grid segments composing each grid must be supported by a single frame structure that has to cope with high voltage and cooling issues.

The PN, based on the RING concept [5], uses two lasers with 35 kW power each, 1.5 μm wavelength (infrared), 100 ps pulse length and 1 μs interval between pulses. By means of a second harmonic generator, only the 2nd harmonic is circulated in the PN, having a wavelength of 0.75 μm , half of the initial one injected by the laser. The 2nd harmonic remains trapped in the mirror system, given by a certain number of upper/lower mirrors (6 in the presented design) and additional 4 mirrors with a 45° angle. The negative ion beam must have enough intersection (limited to 76 mm for laser technological limitations). Additionally the laser has to intercept the beam in a sufficient number of times (14 in the presented design), so that a suitable neutralization power of the ion beam can be provided.

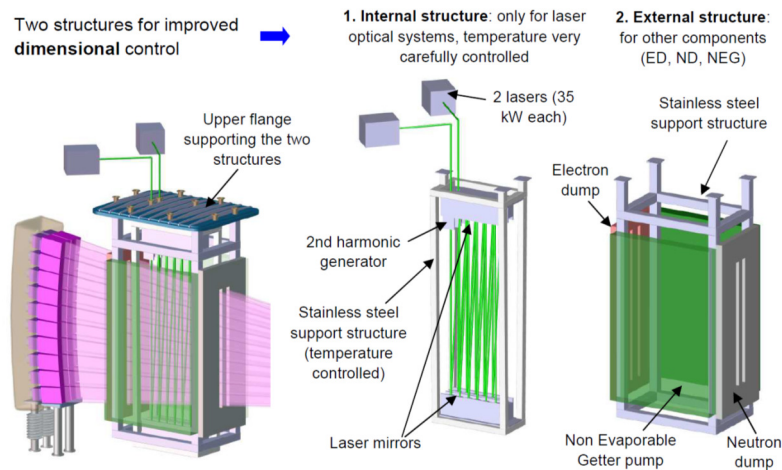


FIG. 3: Neutralizer conceptual design.

In order to have a sufficient precision on the position of the mirrors, a double frame design is proposed as shown in FIG. 3. The internal structure supports the laser optical systems, while the external structure supports the other auxiliary components, subjected to significant thermal loads (electron dump, neutron dump and NEG pumps). The electron dump stops the electrons accelerated together with the negative ions out of the accelerator, while the neutron dump stops the neutrons coming from the tokamak chamber. The NEG pumps keep a high vacuum in the region minimizing the gas density inside the beam line vessel and consequently the stripping and re-ionization losses. In fact, the density of background gas can be much lower than with gas neutralizer, because the efficiency of the neutralizer with photo-neutralization is not depending on the background gas density. This represents a significant advantage of the PN with respect to the gas neutralizer.

The connection of the optical systems to the upper flange permits to regulate the mirrors when they are outside the beam line vessel and then put the system in the operating position. The dedicated cooling for the internal structure permits to carefully control the temperature of this structure during operation. On the other hand, the thermal expansion of the external structure is not so delicate hence; all the high heat load components are mounted on this structure.

The interface between the NBI and the BB is critical for several reasons:

- The reduction of TBR (Tritium Breeding Ratio) due to the presence of the NBI opening on the BB. This has been minimised by focusing the neutral beam at the center of the opening corresponding to the removed BB. This permits to have minimum aperture on the BB and consequently a small impact on the TBR.
- The amount of neutron radiation reaching the NBI components from the tokamak, depending on the dimension of the NBI aperture and on the injection angle.

- The interaction of the beam with the plasma (and walls, because of shine-through) inside the tokamak, depending on the injection angle.
- The layout of the port region, that is critical because of the interface between several critical components, like BB, NBI, toroidal field (TF) coils etc.
- The local modifications on the design of the BB needed around the aperture zone.

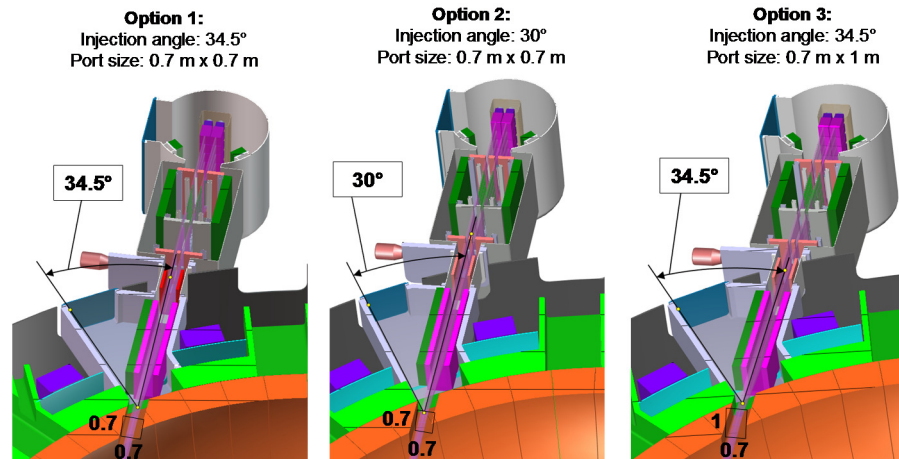


FIG. 4: Interface with breeding blanket: comparison between the three design options.

Regarding this critical aspect, three design options have been proposed, as shown in FIG. 4). A feedback has involved different EUROfusion groups working on the BB (WPBB) and on the remote maintenance (WPRM), the CCFE group studying the neutronic aspects and the CIEMAT group designing the Dual Coolant Lithium Lead (DCLL) BB. Option 2 was identified as the reference design. In fact, thanks to the reduced injection angle of 30° , this option requires no modification of the vacuum vessel (VV) due to the reduced injection angle. For the same reason, the clearance with the TF coils is larger. On the other hand, the neutronic load on the NBI components The neutronic loads on the NBI components are insignificantly larger for option 2 compared to option 1. Studies on the influence of the injection angle on the interaction between the injected neutral beam and the plasma inside the tokamak are also foreseen in the next future.

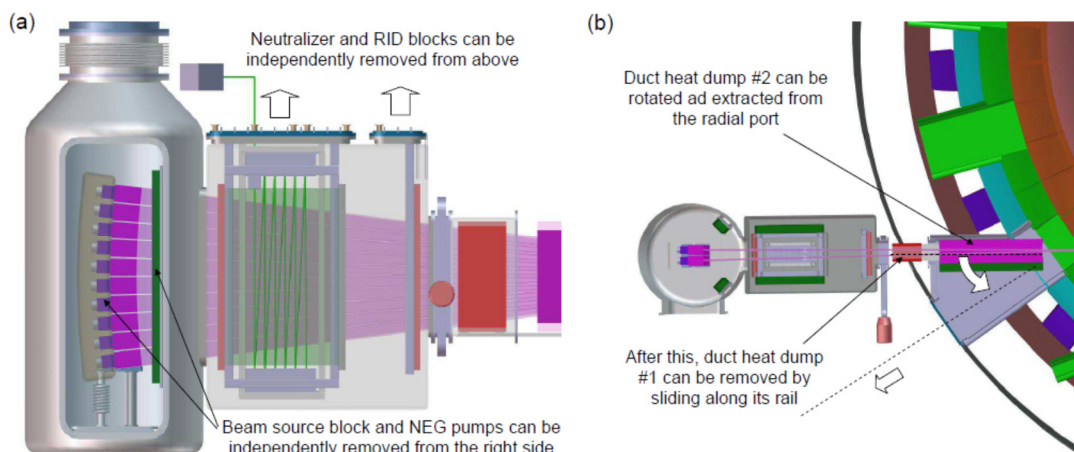


FIG. 5: Maintenance strategy: (a) beam source and beam line components; (b) duct components.

To increase the maintainability of the fusion power plant, the DEMO NBI has been designed in such a way that all the main components can be substituted without removing other components. For example, the beam source can be removed from the lateral opening of the beam source vessel (see FIG. 5a), the neutralizer and the residual ion dump from the dedicated upper flanges (see FIG. 5a), and the duct components from the radial port close to the NBI tangential port (see FIG. 5b).

6. Conclusions

The conceptual design of the DEMO NBI has been developed in the framework of the EUROfusion activities on the heating and current drive (HCD) systems aiming to increase the efficiency (>50%) and better coping with RAMI requirements. The design features a modular approach for the beam source and is ready to adopt the photo-neutralisation concept.

The main components of the DEMO NBI have been drafted, based on the present knowledge and on the R&D currently being carried out in various European Research Institutes. The design of most components will be further studied and developed within EUROfusion.

In future, the various NB injector concepts under development (ITER-like and DEMO-like), could be tested, after demonstrating their feasibility and performances in the different facilities throughout Europe, in the neutral beam test facility PRIMA hosted in Padova (Italy).

Acknowledgements and disclaimer

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

- [1] GIRUZZI G., et al., “Modelling of pulsed and steady-state DEMO scenarios”, Nucl. Fusion 55, 073002 (2015).
- [2] FRANKE T., et al., “On the Present Status of the EU DEMO H&CD Systems, Technology, Functions and Mix”, poster SP13-63 presented at 26th SOFE conference, Austin, Texas USA (2015).
- [3] TOIGO V., et al., “Progress in the realization of the PRIMA Neutral Beam Test Facility”, Nucl. Fusion 55 (2015) 083025.
- [4] MARCUZZI D., et al., “Final Design of the Beam Source for the MITICA Injector”, Rev. Sci. Instrum. 87, 02B309 (2016).
- [5] FASSINA A., et al., “Feasibility Study of a NBI Photoneutralizer Based on Nonlinear Gating Laser Recirculation”, Rev. Sci. Instrum. 87, 02B318 (2016).
- [6] SIMONIN A., et al., “R&D around a photoneutralizer-based NBI system (Siphore) in view of a DEMO Tokamak steady state fusion reactor”, Nucl. Fusion 55 (2015) 123020.
- [7] RAUNER D., et al., “Comparison of measured and modelled negative hydrogen ion densities at the ECR-discharge HOMER”, AIP Conf. Proc. 1655, 020017 (2015).
- [8] FANTZ U., et al., “Physical performance analysis and progress of the development of the negative ion RF source for the ITER NBI system”, Nucl. Fusion 49 (2009) 125007.
- [9] KRAUS W., et al., “Long pulse large area beam extraction with a rf driven H-/D- source”, Rev. Sci. Instrum. 79, 02C108 (2008).
- [10] FURNO I., et al., “A novel helicon plasma source for negative ion beams for fusion”, in preparation for Nucl. Fusion.
- [11] BRIEFI S. and FANTZ U., “Investigation of Helicon discharges as RF coupling concept of negative hydrogen ion sources”, AIP Conf Proc. 1515, 278-283 (2013).
- [12] BONUCCI A., MANINI P., SIVIERO F., SONATO P., “Getter pumping system”, WO Patent App. PCT/IB2015/054,728 (2015).
- [13] GIEGERICH T. DAY C., “Conceptuation of a continuously working vacuum pump train for fusion power plants”, Fusion Eng. Des. 88 (2013) 2206-2209.
- [14] PILAN N., et al., “Magnetic Field Effect on Voltage Holding in the MITICA Electrostatic Accelerator”, IEEE Tran. Pla. Sci. Vol. 42 No.4 (2014).
- [15] AGOSTINETTI P., et al., “Physics and engineering design of the Accelerator and Electron Dump for SPIDER”, Nucl. Fusion 51 (2011) 063004.
- [16] AGOSTINETTI P., et al., “Detailed design optimization of the MITICA negative ion accelerator in view of the ITER NBI”, Nucl. Fusion 56 (2016) 016015.