Improved Conceptual Design of the Beamline for the DTT Neutral Beam Injector

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***Abstract*—The Divertor Test Tokamak facility (DTT) will be a new experimental facility located at Frascati, Rome, Italy, whose main goal will be to have a a better understanding on hot plasma interactions with Plasma Facing Components (PFC) and aid in the development of ITER and successively DEMO. The improved conceptual design of the beamline for the DTT Neutral Beam Heating system is here overviewed, with a particular focus on the technical solutions adopted to fulfill the requirements and to maximize beamline performances. The proposed system features a beamline providing deuterium neutrals (D^0) with an energy of 510 keV and an injected power of 10 MW. Various design options have been considered, and a comprehensive set of simulations has been carried out using several physics and engineering codes to drive the choice of the most suitable design options and optimize them, aiming at finding a good compromise among different design requirements.**

***Index Terms*— DTT, NBI, neutral, beam, injector**

I. INTRODUCTION

T

HE main purpose of the Divertor Tokamak Test facility (DTT) is to study solutions to mitigate the issue of power exhaust in conditions relevant for ITER and DEMO [1], aiming at exploring alternative power exhaust solutions for the machines that will follow ITER [2][3], in particular the demonstrative power plant DEMO that is currently in the conceptual design phase [4].

In this context, the principal objective of DTT is to mitigate the risk of a difficult extrapolation to a fusion reactor of the conventional divertor based on detached conditions, which will be tested in ITER. The task implies the study of the completely integrated power exhaust problems and the demonstration of how the possible implemented solutions (e.g., advanced divertor configurations or liquid metals) could be integrated in the DEMO device and other fusion reactors.

The key feature of such a study is to equip the machine with a significant amount of auxiliary heating power in order to test innovative divertor concepts. DTT will be able to explore various magnetic divertor configurations and in order to reach a reactor relevant power flow to the divertor, 45 MW of auxiliary power will have to be coupled to the plasma using the following systems: Electron Cyclotron Resonant Heating (ECRH), Ion Cyclotron Resonant Heating (ICRH) and Neutral Beam Heating (NBH) [5].

In this framework, the conceptual design of the beamline for the DTT Neutral Beam Heating system, based on negative ions, is overviewed, with a particular focus on the technical solutions adopted to fulfill the requirements and maximize beamline performances.

The proposed system features a beamline providing deuterium neutrals (D^0) with an energy of 510 keV and an injected power of 10 MW. Regarding the effect of the NBI in DTT, recent studies are reported in [6] and [7].

An overview of the current conceptual design of the beamline for the DTT Neutral Beam Injector (NBI) is given in Fig. 1, while Tab. 1 reports the main functional parameters.

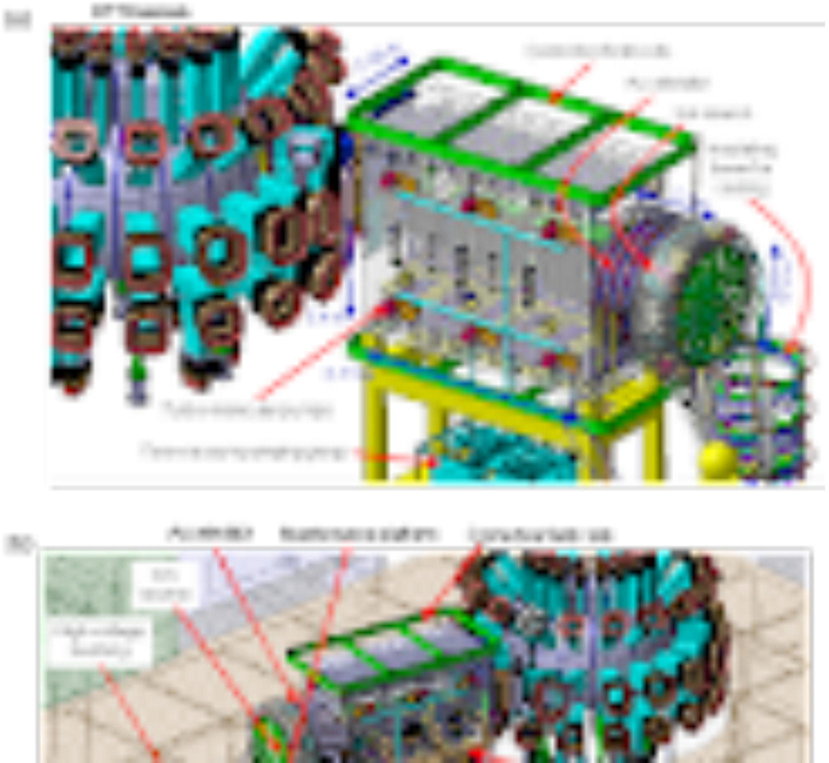
Parameter	Value
Injected power	10 MW
Beam Energy	510 kV
Accelerated D^- current	40 A
Extracted D^- current density	> 239 A m^{-2}
Ion source filling pressure	≥ 0.3 Pa
Extracted current uniformity	±10%
Beam on time	50 s
Co-extracted electron fraction (e^-/D^-)	< 0.5
Beamlet divergence	< 7 mrad
Auxiliaries/extraction efficiency	0.9
Accelerator efficiency	0.8
Beam source/neutraliser entrance transmission efficiency	0.95
Neutralizer efficiency	0.55

Beam line/duct transmission efficiency	0.95

Tab. 1 - Main functional parameters of the DTT NBI.

Similarly to the NBIs of JT60 [8] and LHD [9], a design with an air-insulated beam source is adopted for DTT NBI, i.e. the accelerator and ion source assemblies are connected to the rear part of the vacuum vessel, as shown in Fig. 1a. This solution was selected because it maximizes the Reliability and Availability indexes (evaluated as in [10]), by improving the beam source accessibility and simplifying the design. The DTT NBI design differs from the Japanese scheme in the choice of the ion source: in fact it is proposed to use the same Radio Frequency source concept adopted for ITER, mainly developed by IPP Garching [11]. The Beam Line Components (BLC), i.e. the Neutralizer, the Residual Ion Dump (RID) and the Calorimeter, will be ITER-like too, whereas the vacuum vessel will not include any large flanges (differently from ITER) to reduce cost and weight. For the vacuum pumping, it is foreseen to have a system based on turbo-molecular pumps located on the side walls of the vessel and Non-Evaporable Getter (NEG) pumps [12] located on the upper and lower surfaces of the vessel.

As the NBI is quite close to the tokamak, the NBI region is interested by a strong stray poloidal field, that, if not compensated, would be detrimental for the optics of the negative ions, especially in the accelerator and neutralizer region, reducing the overall efficiency of the NBI system and increasing the heat loads on the main components. Hence, a compensation system using corrective field coils has been developed. These coils are located on the top and bottom region of the vacuum vessel, as shown in Fig. 1a and 1b. As the current levels requested in the coils with such a system are extremely high in the current conceptual design (> 500 kAturn), the design team is currently working to improve the compensation system by adding also a ferro-magnetic shield in the neutralizer region. This solution is foreseen to decrease the requirement on the current through the compensation coils.



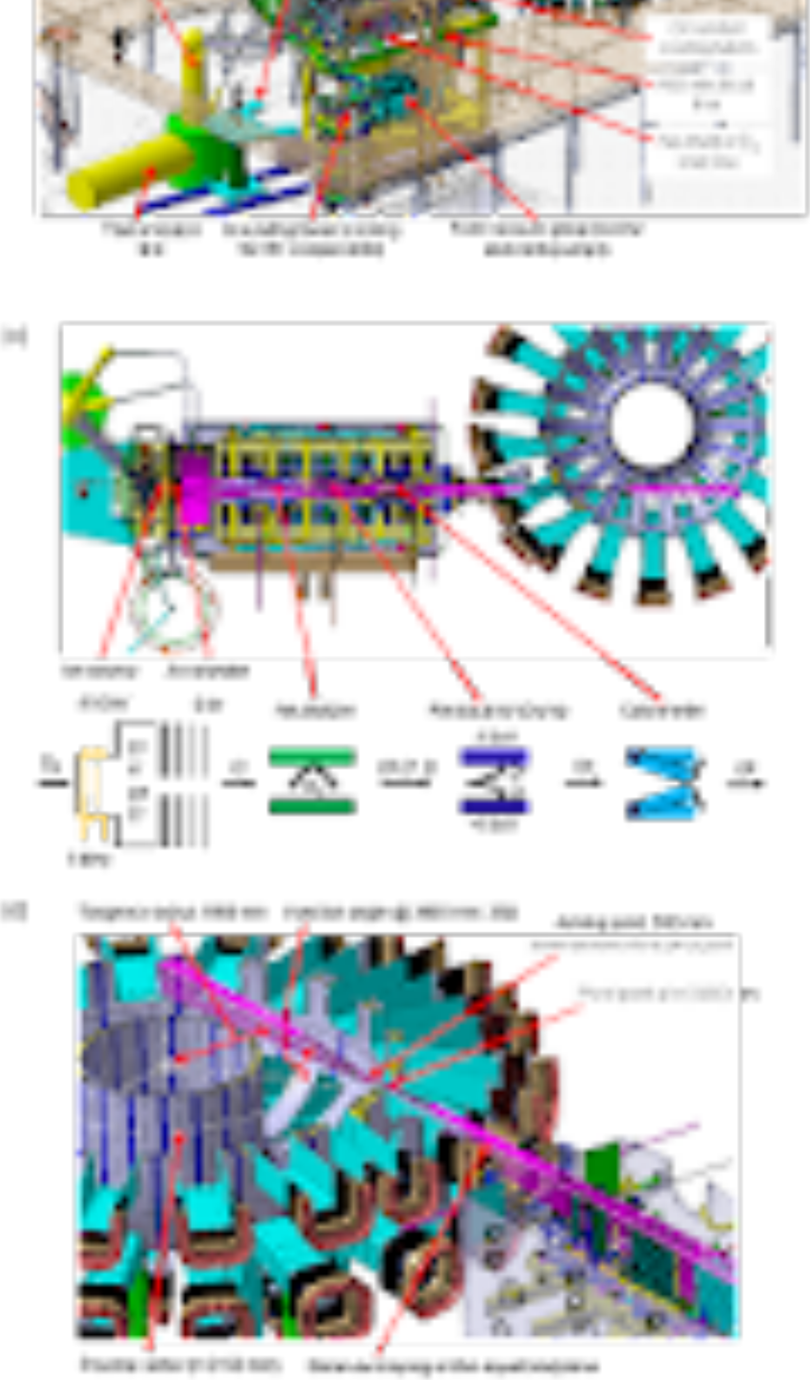


Fig. 1. Overview of the DTT NBI conceptual design: (a) overall beamline view with main dimensions; (b) overall injector view with connections to external auxiliary systems; (c) top view with functional scheme; (d) focus view on the duct region.

Only small flanges are foreseen on the vacuum vessel for pumping, diagnostics and BLCs supplies, while the BLCs maintenance is planned to be from the large circular flange of the accelerator, after removing the ion source and accelerator. Dedicated rails are hosted inside the vacuum vessel to insert and extract the BLCs, and to support them when they are in position. The maintenance of the ion source and accelerator will be carried out using a dedicated maintenance platform (shown in Fig. 1b), able to reach the critical regions of these components.

A transmission line and an insulating tower will be located at the two sides of the ion source, as shown in Fig. 1b. The transmission line will bring the electrical power to the ion source and accelerator by means of a high voltage bushing connecting the grounded transmission line to the ion voltage bushing connecting the grounded transmission line to the ion source at -510 kV, and two smaller bushings bringing the bias to the two acceleration grids. On the other hand, the insulating tower will bring the cooling water to the ion source and accelerator. To reduce to acceptable values the drain current between high voltage components and ground, the insulating tower will feature plastic tubes wound like spirals, as shown in the conceptual design of Fig. 1b.

Also the tubes bringing the deuterium gas to the ion source and the tubes for the exhaust system of the high voltage vacuum system (described in Section V) will pass through the insulating tower, as they are also connecting components at high voltage (-510 kV) with the ground.

According to the current DTT schedule, the conceptual design and R&D phase related to the DTT NBI system is foreseen to last until 2025, followed by an engineering design phase until 2027 and then by a procurement and installation phase in order to have the DTT NBI system operating in DTT in 2033.

II. Single Source Vs. Double Source solution

During 2020, the team working on the plasma physics of the DTT tokamak and diagnostic systems added the requirement that the beam must be also usable as a diagnostic beam. This implies that the beam must be located on the equatorial plane of the tokamak, otherwise the measurements of the interactions between the plasma and the beam particles would not provide the best diagnostic coverage and the best possible information.

The design previously adopted for the DTT NBI [13], featuring two beam sources and called "double source" solution in the following, could not satisfy the requirement that the beam must be also usable as a diagnostic beam. Hence, the DTT NBI team developed a new design approach featuring a single beam source. This solution will be referred to as the "single source" solution and is described in the following.

The main differences between the "single source" and the "double source" conceptual design solutions are the following:

- with the single source solution, the beam is on the equatorial plane, whereas with the double source solution the beam is formed by two sub-beams each having an angle of 5.3° with reference to the equatorial plane.
- one beam source assembly with diameter of about 3 m instead of two beam source assemblies with diameter of about 2 m.
- one neutralizer, one RID and one calorimeter instead of two neutralizers, two RIDs and two calorimeters.

The main advantages of the "single source" solution compared to the "double source" one are:

1. possibility to use the heating NBI also as a diagnostic NBI, because the beam is on the equatorial plane;
2. the correction coils are more effective in protecting the beam from the detrimental effect of the stray magnetic field from the tokamak. In fact, the beam is located in the middle between the two set of correction coils (located above and below the vessel);

3. more clearance around the beam in the duct region, with a reduction of the heat loads generated by the beam halo on the duct;

4. less components and less electrical and cooling connections, implying a better RAMI score [10] and a lower cost;

5. faster alignment procedure because the components to be aligned (accelerator grids, neutralizer, RID and calorimeter) are fewer;

6. the R&D from ITER NBI would constitute a much better reference because the ion source can be almost identical to the MITICA one, with only some minor adaptations;

7. the maintenance of NEG pumps is improved, because there is the space for dedicated ports above and below the beam source.

The main identified drawbacks of the "single source" solution are the following:

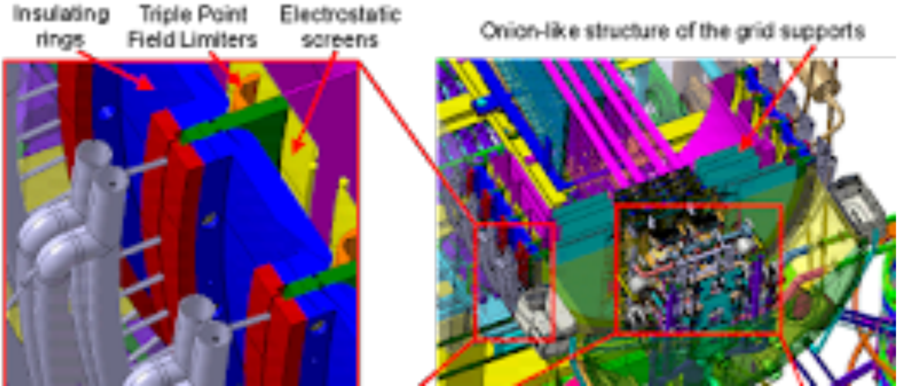
1. larger dimensions of ion source and vessel;

2. the beam footprint on the inner wall of the tokamak is on the equatorial plane instead of being slightly above and slightly below the equatorial plane as in the "double source" solution. Hence, the systems located close to the beam footprint must be better protected.

It has been evaluated that the advantages are significantly stronger than the disadvantages, hence the design team has proposed to proceed with the conceptual design activities following the "single source" solution.

III. Ion Source and Accelerator

The ion source for DTT NBI, shown in Fig. 2, will be almost identical to the MITICA one [14]. In fact, the MITICA ion source was designed taking into account the return of experience from the existing ion sources and a large R&D effort was devoted at IPP Garching and RFX to validate its design and qualify its manufacturing process. On its back part, the ion source includes an electrical matching network (featuring a set of coupling capacitors to optimize the operation of the Radio Frequency coils used to ionize the gas), cesium ovens (to evaporate cesium vapour in the ion source to increase the amount of extracted negative ions) and water manifolds (to actively control the operating temperature of all the components of the ion source, which need to work at a defined temperature to reach an optimal efficiency). The adaptation of the MITICA ion source to DTT NBI mainly regards the routing of the filter field busbars and the electrical connections.



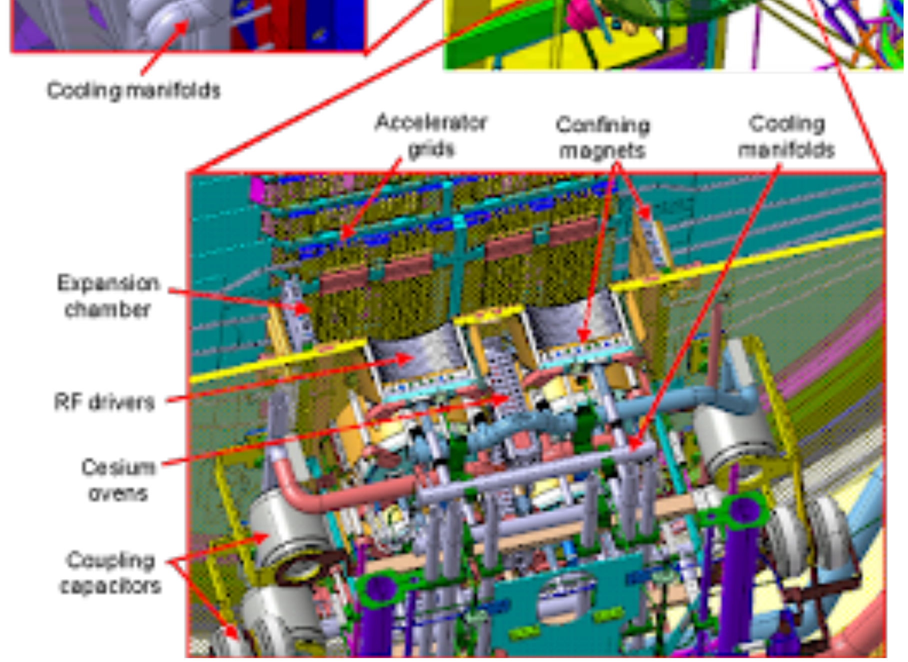


Fig. 2. Conceptual design of the ion source and accelerator for the DTT NBI.

Maximizing D^- extraction while minimizing co-extracted electrons is one of the main critical issues of an ion source for negative ion based NBIs. To do this, several methods are applied analogously to SPIDER, MITICA and ITER NBI [15][16]:

- adopting an enhanced shape of the Plasma Grid (PG) upstream surface (featuring large chamfers with a 40° angle with reference to the beam axis);
- operating the PG at high temperature (about 150 °C);
- covering the PG with a mono-layer of cesium, injected by dedicated cesium ovens mounted on the ion source;
- applying a high current flow vertically through the PG and dedicated return conductors (this generates a magnetic filter field in front of the PG).

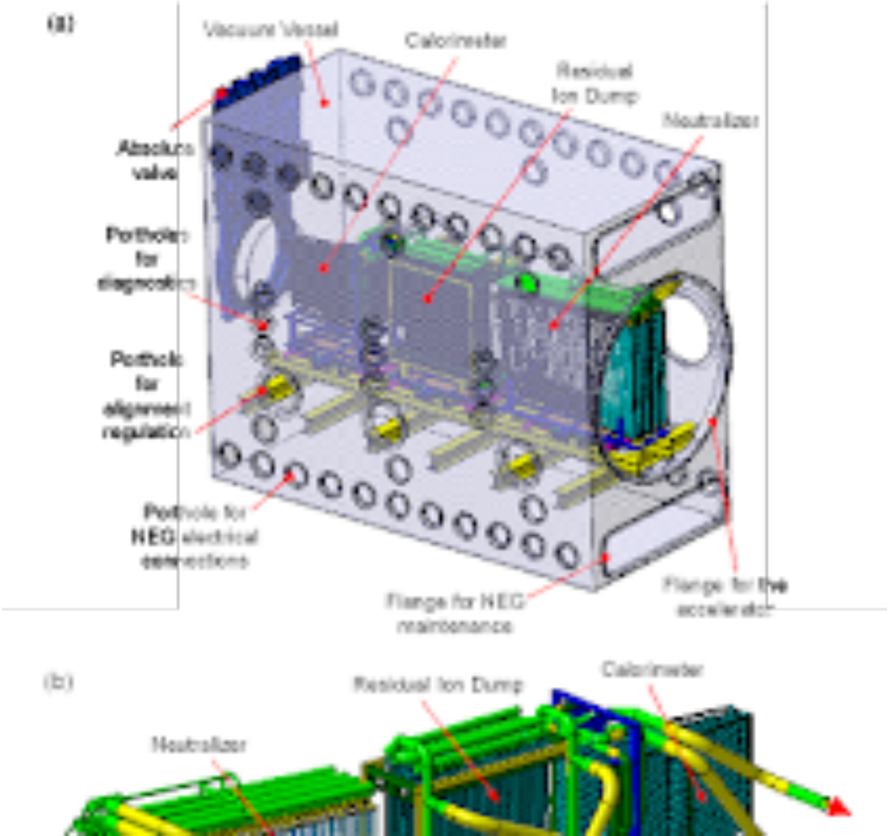
In particular, the magnetic filter field configuration is a key issue for the good operations of a negative ion source. In fact, it was experimentally found in SPIDER [17] that a large axial field in the RF drivers is giving detrimental effects, and is even capable of quenching the plasma in some conditions because the axial field lines are causing a confinement loss of the electrons which are easily lost on the driver walls. On the other hand, in ELISE it was found that operating with deuterium a higher filter field strength is advisable compared to hydrogen operations in order to stabilize the co-extracted electrons, resulting in a significant reduction of the extracted ion current in deuterium [18]. Hence, various configurations of the filter field busbars are currently under evaluation and comparison, taking into account experimental and simulations results.

The accelerator, located just downstream of the ion source (see Fig. 2), has been conceptually designed to accelerate 40 A of D^- to an energy of 510 keV. This is made by means of a set of grids biased at different potentials: a Plasma Grid (PG) operating at -510 kV, an Extraction Grid (EG) at -500 kV, a Hyperlens Grid (HG) also at -500 kV (attached to the downstream side of the EG), a first Acceleration Grid (AG1) at -333 kV, a second Acceleration Grid at -166 kV and a Grounded Grid (GG) at ground second Acceleration Grid at -100 kV and a Grounded Grid (GG) at ground potential. Detailed information on the beam optics optimization and aiming strategy is reported in [19].

Electrons, neutrals (D^0) and positive particles (D^+ and D_2^+) are generated in the accelerator by stripping and charge-exchange reactions of the D^- particles with the background gas, that is mainly D_2. These particles, as well as the D^- having a large divergence (called halo fraction of the beam), are finally impinging on the grids and on the plasma source, generating high heat fluxes on these surfaces. For this reason, all the grids and the plasma source components are equipped with high performance cooling systems able to avoid damages due to the extremely concentrated heat loads, and the density of the background gas in the accelerator is minimized by means of a high performance vacuum system.

The accelerator grid segments represent a critical component as they have a rather complex design, with very small cooling channels, apertures for the negative ions and grooves for the embedded magnets. They can be manufactured by means of copper electrodeposition on a milled base plate made of pure copper [20][21] or by brazing together two milled plates as done for all the Japanese NBIs [8][9]. An alternative manufacturing process, based on additive manufacturing, is currently being investigated by means of a dedicated R&D program [22]. Another critical R&D program is foreseen to develop and validate a manufacturing process for the FRP (fiber-reinforced polymer) rings of the accelerator. In fact, these rings are rather large (diameter of 3 m) and must fulfill various important functions, i.e. to maintain the electrical insulation between the acceleration stages and to support the beam source while being perfectly leak tight and providing a vacuum compatible surface on the internal side.

IV. Beam Line Components, Vacuum Vessel and Absolute Valve



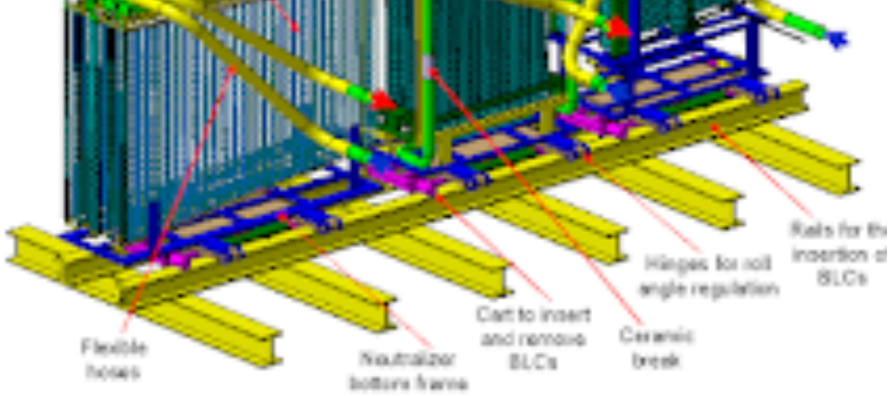


Fig. 3. Conceptual design of the Beam Line Components, Vacuum Vessel and Absolute Valve for DTT NBI: (a) overall view; (b) focus view on the BLCs.

The Beam Line Components (BLCs), shown in Fig. 3, are large components dedicated to the treatments of the beam after it exits the accelerator, namely:

- the neutralizer transforms the negative ion beam (made of D^- particles) into a neutral beam (made of D^0 particles). This is achieved by making the D^- particles interact with D_2 particles at a calibrated density in a dedicated region. This process has a maximum efficiency of about 60%, meaning that in optimal operating conditions ~60% of D^- are transformed into D^0, while ~20% remain D^- and ~20% are ionized into D^+.
- the residual ion dump (RID) diverts the residual ions exiting from the neutralizer, i.e. D^- and D^+, on suitable plates while it is transparent to D^0. In fact, D^- and D^+ would damage the vessel and the beam duct if they were not dumped by the RID.
- the calorimeter, when closed, intercepts the D^0 beam measuring its power. When open, it is transparent to the D^0 beam but protects the NBI duct from excessive heat loading.

The Vacuum Vessel (VV) is a large vessel containing the BLCs and the NEG pumps. It also supports the accelerator and the ion source (on the back side), the absolute valve (on the front side), the turbomolecular pumps and several diagnostic systems (on the lateral walls). As shown in Fig. 3, it features several portholes for diagnostics, maintenance and regulation purposes, as well as the pipes and connections for cooling water, gas and electrical power to the BLCs. The pressure inside the VV is required to be <0.02 Pa in nominal operating conditions. As there is a significant throughput of D_2 gas injected into the VV from the ion source (~2.8 Pa m^3 s^{-1}), from the neutralizer (~20.8 Pa m^3 s^{-1}) and from the duct (~0.3 Pa m^3 s^{-1}), large vacuum pumping systems are installed in the VV.

The three BLCs need to be precisely aligned with reference to the beam, because their relative positions affect several important operating parameters, in particular the NBI efficiency and heat loads. This will be achieved by observing the footprints generated on the alignment target by the optical pointers mounted on the PG and by moving the BLCs by means of movable supports, driven by in-vessel electrical actuators.

The absolute valve, located on the downstream side of the VV, has the function to separate the tokamak vacuum from the NBI vacuum when needed. An industry survey is currently on-going to select possible manufacturers and choose the most suitable technologies.

V. Gas Injection and Vacuum System

The Gas injection and Vacuum System (GVS) for the DTT NBI, shown in Fig. 4, is composed of two parts:

- A grounded section connected to the main vacuum vessel (green labels in Fig. 4). This part is made of a fore-vacuum system (given by 4 screw and 4 roots pumps) plus a UHV system based on 12 turbo-molecular pumps, located on the side walls of the vessel, and Non-Evaporable Getter (NEG) pumps, located inside the vessel on the upper and lower surfaces.

- A high voltage part connected to the ion source vessel and working at -510 kV voltage (red labels in Fig. 4). This part consists of a fore-vacuum system (given by two compact screw pumps mounted on the external surface of the ion source vessel) plus a UHV system based on 4 turbo-molecular pumps, also located on the side walls of the ion source vessel.

The design of the fore-vacuum group and turbopumps group for DTT NBI benefits from the R&D and manufacturing experience coming from SPIDER and MITICA [23], while the NEG part has been developed in collaboration with industry [12].

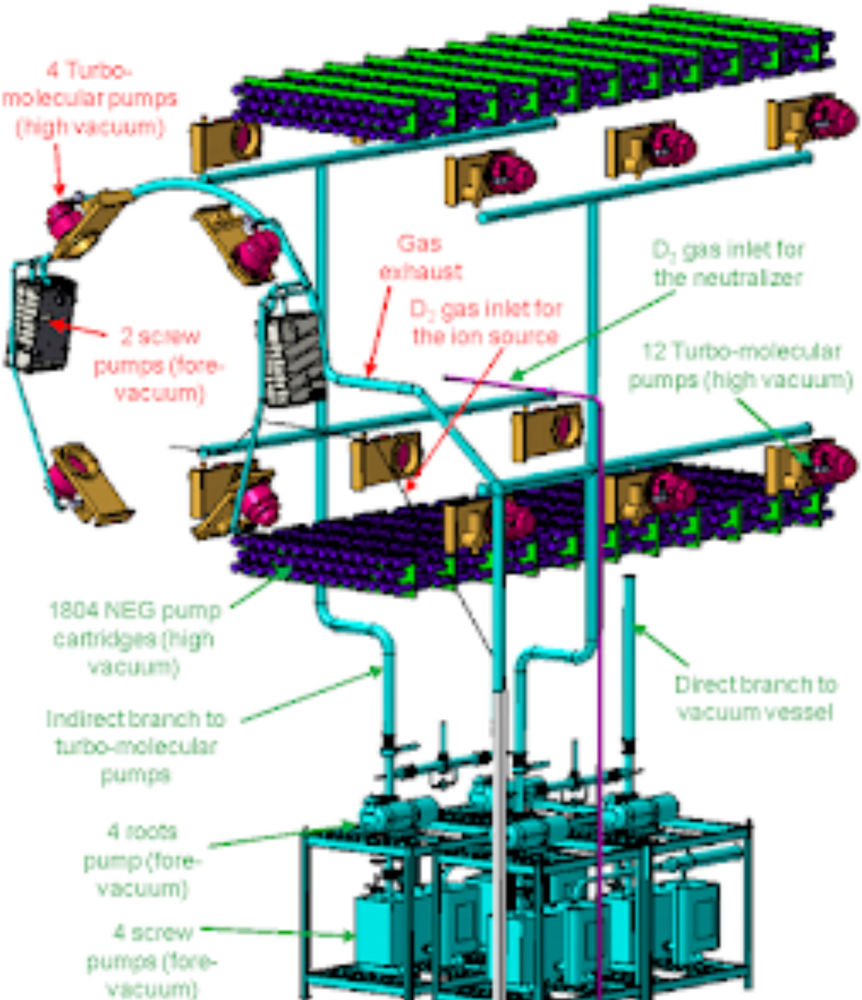


Fig. 4. Conceptual design of the Gas Injection and Vacuum System (GVS) for DTT NBI

VI. Conclusions

A complete conceptual design of the DTT NBI beamline has been developed considering 510 keV beam energy and 10 MW injected to the plasma. The main design guidelines were the return of experience from existing experiments, the reduction of cost and the maximization of the RAMI compliance of the system according to the criteria in [10].

The conceptual design has been developed in two versions, a "double source" solution [13] and a "single source" solution, the latter being the one described in the present work. After some brainstorming sessions in the design team, the "single source" solution was selected for the prosecution of the conceptual design and integration activities.

The refinement of the conceptual design, several R&D activities, the development of the engineering design and the procurement of the beamline for DTT NBI are on-going or foreseen in the near future.

References

[1] R. Ambrosino, et al., “DTT - Divertor Tokamak Test facility: A testbed for DEMO”, Fusion Eng. Des. 167 (2021) 112330.

[2] R. Albanese, et al., “Design review for the Italian Divertor Tokamak Test facility”, Fusion Eng. Des. 146 (2019) 194-197.

[3] G. Mazzitelli, et al., “Role of Italian DTT in the power exhaust implementation strategy”, Fusion Eng. Des. 146 (2019) 932-936.

[4] G. Federici et al., “Overview of the DEMO staged design approach in Europe”, Nucl. Fusion 59 (2019) 066013.

[5] G. Granucci, et al., “The Heating & Current Drive System of Divertor Tokamak Test (DTT)”, IEEE 20th Mediterranean Electrotechnical Conference (MELECON) (2020), 629-633.

[6] G. Spizzo, et al ., “Collisionless losses of fast ions in the divertor tokamak test due to toroidal field ripple”, Nucl. Fusion 61 (2021) 116016.

[7] I. Casiraghi, et al., “First principle-based multi-channel integrated modelling in support of the design of the Divertor Tokamak Test facility”, Nucl. Fusion 61 (2021) 116068.

[8] A. Kojima et al., ”Progress in long-pulse production of powerful negative ion beams for JT-60SA and ITER”, Nucl. Fusion 55 (2015) 063006

[9] Y. Takeiri et al., “High-power and long-pulse injection with negative-ion-based neutral beam injectors in the Large Helical Device”, Nucl. Fusion 46 (2006) S199-S210.

[10] P. Agostinetti, et al., “RAMI evaluation of the beam source for the DEMO neutral beam injectors”, Fus. Eng. Des. 159 (2020) 111628

[11] B. Heinemann et al., “Latest achievements of the negative ion beam test facility ELISE”, Fus. Eng. Des. 136 (2018) 569-574.

[12] F. Siviero et al., “Characterization of ZAO® sintered getter material for use in fusion applications”, Fus. Eng. Des. 146 (2019) 1729-1732.

[13] P. Agostinetti, et al., ”Conceptual Design of the Beamline for the DTT Neutral Beam Injector following a Double Beam Source Design Approach”, Plasma and Fusion Research, Vol. 16, 2405080 (2021).

[14] P. Zaccaria, et al., “Progress in the MITICA beam source design”, Rev. Sci. Instrum. 83, 02B108 (2012).

[15] P. Agostinetti, et al., “Physics and engineering design of the Accelerator and Electron Dump for SPIDER”, Nucl. Fusion 51 (2011) 063004.

[16] P. Agostinetti, et al., “Detailed design optimization of the MITICA negative ion accelerator in view of the ITER NBI”, Nucl. Fusion 56 (2016) 016015.

[17] N. Marconato, et al., “An optimized and flexible configuration for the

[17] N. Marconato, et al., "An optimized and flexible configuration for the magnetic filter in the SPIDER experiment", Fusion Eng. Des. 166 (2021) 112281.

[18] D. Wünderlich, et al., "NNBI for ITER: status of long pulses in deuterium at the test facilities BATMAN Upgrade and ELISE", Nucl. Fusion 61 (2021) 096023.

[19] F. Veronese, at al., "Performance Optimization of the Electrostatic Accelerator for DTT Neutral Beam Injector", presented af SOFE 2021 and to be published in IEEE Trans. Plasma Science.

[20] P. Agostinetti, et al., "Manufacturing and Testing of Grid Prototypes for the ITER Neutral Beam Injectors", IEEE Trans. on Plasma Science, 42 (2014) 628-632.

[21] P. Agostinetti, et al., "Investigation of the Thermo-mechanical Properties of Electro-deposited Copper for ITER", J. Nucl. Mater. 417 (2011) 924-927.

[22] M. Bonesso, et al.," Effect of particle size distribution on laser powder bed fusion manufacturability of copper", Proceedings of the 5th Metal Additive Manufacturing Conference 2020, pp. 173-18.

[23] S. Dal Bello, et al., "SPIDER gas injection and vacuum system: From design to commissioning", Fusion Eng. Des. 146 (2019) 1485-148.