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Integration studies of a positive neutral beam injector system into the design of a volumetric neutron source

T. Franke [a,b,*], C. Bachmann [b], V. Claps [c], A. Doering [a], T. Fellinger [a], C. Gliss [b], T. Haertl [a,b], C. Hopf [a], M. Kannamüller [a,b], D. Leichtle [d], R. Mozzillo [c], J. Hun Park [d], P. Pereslavtsev [b,d], R. Riedl [a], M. Siccinio [a,b], A. Valentine [e]

[a] Max Planck Institute for Plasma Physics, Boltzmannstr. 2, Garching 85748, Germany
[b] Fusion Technology Department, EUROfusion Consortium, Boltzmannstr. 2, Garching 85748, Germany
[c] CREATE, Engineering Department of Basilicata University, Campus Macchia Romana (PZ), 85100, Italy
[d] Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany
[e] Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxford OX14 3DB, UK

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ABSTRACT

A feasibility study regarding a volumetric neutron source (VNS) is presently conducted in the EUROfusion Consortium. The VNS uses Positive Neutral Beam Injection (P-NBI) for plasma heating, current drive and particularly to drive beam-target fusion, aiming for a high neutron production (≈0.5 MW/m^2 neutron wall load in the equatorial plane). P-NBI is a reliable auxiliary heating system, widely employed in plasma devices such as ASDEX Upgrade (AUG), W7-X and JT60-SA.

The paper describes the integration of the P-NBI system into the design of the VNS. This includes the neutral beam (NB) duct from the torus vacuum vessel to the NBI box with the gate valves, the space requirements of the NB injectors in the building as well as the connections for cooling water, cryo-supplies, electrical high voltage and radio frequency (RF) cable connections. Since the VNS is a nuclear machine with lifetime doses significantly exceeding those of ITER, the requirements for remote maintenance (RM) are very different from any existing NBI design. The RM concept and the RM sequences will be discussed.

Neutronics studies for the NB duct were performed and design iterations undertaken to assure that neutron heating and lifetime fluences remain below limits at the superconducting toroidal and poloidal field coils adjacent to the NB duct.

The work considers the return of experience from AUG, ITER and some other fusion experimental machines in operation, under construction or in conceptual design such as DEMO.

1. Introduction

Within the EUROfusion Consortium a feasibility study has been undertaken for a volumetric neutron source (VNS) [1,2] to bridge a technology gap to a planned demonstration fusion reactor (DEMO) to qualify and test systems, structures and components (SSCs) and materials under fusion reactor relevant neutron fluxes and fluences.

The VNS is a small tokamak machine with a major plasma radius R_0 of about 2.5 m compared to DEMO with 8.5 to 9 m [3,4]. The neutral beam injection (NBI) of VNS has three major functions, to heat up the plasma, to drive non-inductive plasma current for quasi steady state plasma operation, and particularly to generate a beam driven fusion reaction in the burning plasma. For that, physics simulations were done to calculate the NBI parameters, leading to an NBI power to plasma demand of about 42 MW at 120 keV beam energy while shooting deuterium-beams into a tritium-dominated plasma. It is assumed a feed gas purity of about 95 % deuterium for the NBIs and the plasma has a tritium/deuterium ratio of about 80 %/20 % because of beam fuelling. Different percentages are under study too [5]. The resulting fusion rate leads to a neutron wall load (NWL) of about 0.5 MW/m^2 at equatorial plane with an expected end of lifetime (EOL) fluence of 50 dpa in 10 full power years (FPYs). The plasma fusion amplification factor Q will be less than one which means the fusion reaction would stop, when the NBI power would be switched off. Nevertheless, if only some part of the NBI

* Corresponding author at: Max Planck Institute for Plasma Physics, Boltzmannstr. 2, Garching 85748, Germany.
E-mail address: thomas.franke@euro-fusion.org (T. Franke).

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power were lost, e.g. by a malfunction of one of the NBI injectors, the VNS can still perform but with less NWL.

The operational scheme, which was developed, is that out of 4 installed NBI injectors 3 are operated at any time, while one is in the cryo-pump regeneration mode. The sequences should have on-times for the NBI injectors of 3 h and regeneration times of one hour [5,6].

In addition to the NBI auxiliary power, electron cyclotron (EC) power to plasma with 10 MW for plasma bulk heating, NTM and impurity control is foreseen and the EC system presently under design study.

The paper describes the integration of the NBI into the tokamak machine and into the buildings from an engineering point of view with accompanying neutronics studies. Also it describes the basic remote maintenance (RM) strategy, mainly showing the RM concept foreseen in the active maintenance facility (AMF) with a developed contamination control sequence.

2. Key technical challenges and necessary advancements of the VNS NBI

One major point for the VNS NBI design is the fact that the VNS shall be operated in steady state mode over long periods to allow sufficiently high displacements per atom (dpa) in the SSCs under test, which requires a high reliability and availability of the NBI system. This demands also RM since a highly neutron / gamma radiated environment means that no human access is allowed but only robotic tools can be applied. A technically mature RM concept is a key to success for the VNS.

Table 1 summarizes the maturity levels of different VNS NBI parameters / items from most critical to non-critical ones. This table lists some examples, it could be extended in future. Gaps and challenges are also addressed in [6] e.g. related to the cumulative beam on time, the operation in a nuclear environment and the consequent RM needs and in [5] for the cryo-pumping.

Table 1
Status and necessary advancement needs for the P-NBI of VNS, from red (most critical items #1, 2), over yellow (to be quantified but not deemed to be critical items #3, 4) to green (non-critical items #5–10).

#	Parameter / Item	Value / Comment	Maturity
1	System Availability	NBI ≥ 90% assumed for a VNS availability target 30-40%	not demonstrated
2	Operational time	Quasi continuous wave (3 to 6 h on / 1 to 2 h off repeatedly)	not demonstrated
3	Redundant NBI injectors at the tokamak	Assumed not to be required, plasma to be operated with less fusion power if NB sources fail	depends on final system availability, to be quantified
4	Residual ion dump (RID)	ITER-like divertor mono-block technology foreseen	RID design is underway, to be confirmed
5	Beam energy	120 keV	as in JET, proven
6	Beam power per injector / VNS total NBI power	~14 MW / ~42 MW (to achieve 30 MW fusion power with 0.5 MW/m^2 neutron wall load)	extracted current like ASDEX Upgrade / W7-X NBIs, proven
7	Ion sources	4 positive ion sources per injector with D/T injection (95% / 5%)	D-, T-beams demonstrated in JET, proven
8	Injector pumps	3 cryo-pumps per box ~2 to 8 Mio. l/s (3.7 K cryo-panels / 80 K baffles)	ITER-like, JT60SA-like, proven
9	Cooling of internal components	water, @50°C inlet, 16 bar	proven technology
10	Voltage insulation	vacuum, air, (no SF_6)	proven technology

3. NBI system description

The NBI system for the VNS is described in detail in [6] and the vacuum pumping concept for the quasi-continuous NBI operation in VNS in [5].

Each of VNS NBI injectors, cf. Fig. 1, consists of (i) the NBI box, (ii) four radio frequency (RF) ion sources on the back side, in total 4 top closure plates to have access to the internal components and (iii) front-end components (i.e. the fast shutter, the absolute valve and duct bellows) connecting the NBI injector with the NBI duct. The 4 top closure plates consist of one main closure plate to which the neutralizers, the residual ion dumps, the bending magnet and water pipes are connected, and 3 smaller closure plates for the cryo-pumps, two at each side and one in the front part of the NBI box. The cryo-pumps arrangement inside each injector box can be seen from Fig. 2, where the 3 yellow items per box are the cryo-pumps. The cryo-supply manifolds are placed outside of the NBI box and are connected to cryo-jumpers which pass through the top closure plates to supply the cryo-pumps with liquid helium. The cryo-pumps are operated at 3.7 K (cryo-panels) and 80 K (baffles), respectively. The water-cooling connection will be realized through one inlet and one outlet pipe passing through the main top closure plate and internally distributing the cooling water to the cooled components by an internal water manifold.

The top removal starts with disconnecting the cryo-jumpers and cutting off the water pipes and then bending them away, so that the top closure plates are free for access and the internal components (hanging on them) can be lifted. The top removal concept will be explained in chapter 7.

There is no calorimeter installed inside the NBI injector. The calorimeter will be installed externally in the NB test cell, see chapter 7.

Not shown in Fig. 1 is the magnetic shielding for the injector box and for the ion sources as in this stage the requirements were not yet evaluated. They could be done either by iron or by active coils and will be assessed later.

Some components like valves are just shown as placeholders, as their design will be delt with during the concept design phase.

The placeholder for the RF ion sources (green coloured) at the back of the NBI box in Fig. 1 should comprise the space required for the RF ion sources with their insulators, grid system, cable connection etc.

4. Machine integration

The main requirements for the integration of the NBI duct to the tokamak were given by the following constraints:

(a) Tangential injection to the plasma radius for high current drive efficiency.
(b) Sufficient clearance from NBI duct to toroidal field (TF) and poloidal field (PF) coils including tolerances and margins.

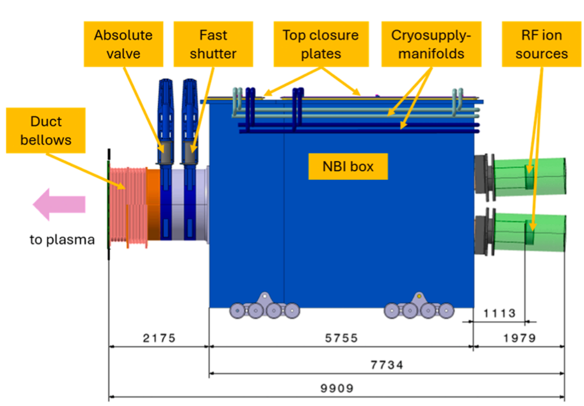

Fig. 1. Side view of one NBI injector with main components and measures.

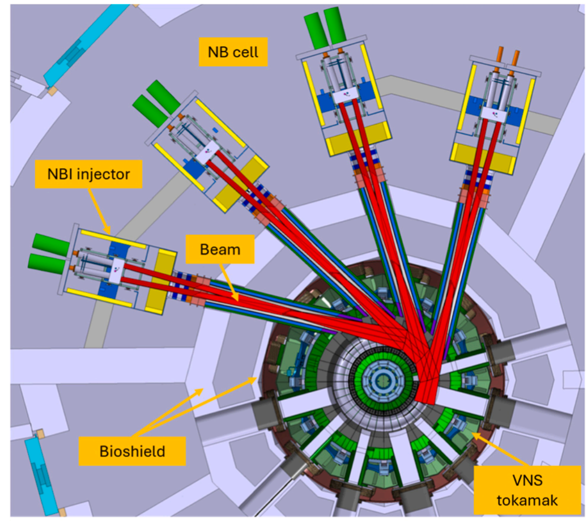

Fig. 2. Horizontal cross section of NBIs in VNS, in red the beams from the ion sources to the plasma.

(c) NBI duct neutron shielding to protect the TF and PF coils (stay below maximum nuclear heating in the winding packs (WPs) and the maximum dose in the insulators).
(d) Beam injection at equatorial port level (about midplane) for best NWL at lowest beam power.
(e) Position front-end components (valves, bellows) outside the bioshield for good accessibility.
(f) Optimize NBI duct transmission power to be better than 85 % of beam power.
(g) Reduce NBI duct reionization losses to less than 10 % of beam power.

Fig. 2 shows the VNS with 4 NBI injectors pointing with their beams to the tangential radius of the VNS plasma.

From an integration point of view, it was difficult to find sufficient space between the TF and PF coils for the NB duct. The four beams from the 4 NBI sources per injector as well as their individual beamlets are all aiming at common vertical and horizontal focal points close to the plasma, while two focal points were placed at different positions along the duct axis. The horizontal one was placed in between the TF coils, as there the horizontal space was most critical for adding the thermal shield. The vertical focus point was placed in the middle of the breeding / shielding blanket to reduce the blanket opening as much as possible. This also reduces integration problems with the blankets and reduces the neutron flux of the neutrons streaming into the NBI duct towards the NBI injector. With this design optimization, the transmission efficiency and the clearances to the coils could be kept effectual while the intersection with the blanket could be reduced. The beams and focal points are shown in Figs. 6 and 7.

The integration was done iteratively because the boundary conditions kept changing, e.g. the NBI box size varied with the design progress and with that the distance from the sources to the focal points and with those the vertical and horizontal extensions of the beam duct and consequently the clearances to the TF/PF coils and there were other challenges too. Foresightful a parametrized CATIA model of the NBI injector was implemented which automatically adapted whenever parameters were changed which saved CAD engineering resources.

Fig. 3 shows the beam intersection with the blanket, bigger cutouts are necessary in the central and lateral blanket segments. In the same figure and in Fig. 4 the layers of the NB duct can be seen. The beam duct consists of 3 layers, the high heat flux (HHF) components (40 mm thick, white coloured), which intercept the beam edge and take the heat loads of re-ionized particles, the duct shield or shield layer (160 mm thick,

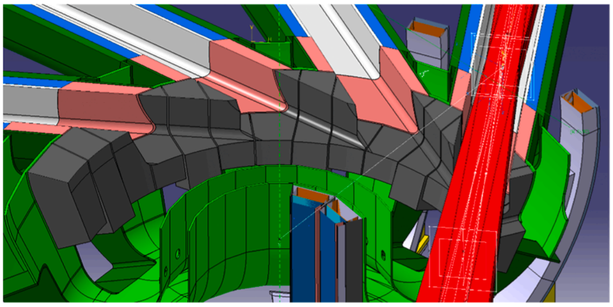

Fig. 3. Beam (dark red) intersection with the shielding / breeding blanket (black) and the interspace (light red).

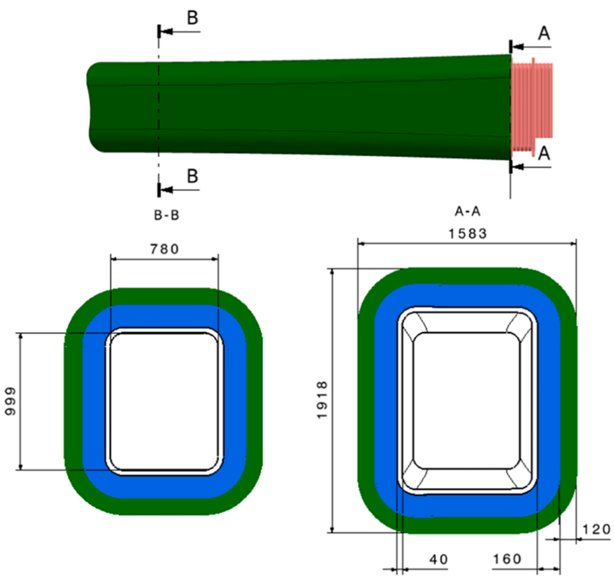

Fig. 4. NBI duct, top: side view of the NBI duct (green) with duct connection bellows (red), cf. also Fig. 6 for a cross section side view with NBI box, bottom left: at the connection to the tokamak VV, bottom right: at the connection to the NBI box.

blue coloured), which is composed of a material mix that effectively shields the neutrons from the TF/PF coils and the NBI duct walls (120 mm thick, green coloured), which provide additional shielding. The 3-layer concept for the duct was applied as originally developed for ITER [7] and foreseen in DEMO [8]. The front part of the NB liner (light red coloured) is expected to receive a neutron dose that will require replacement after a few FPYs. A customized remote handling concept must be developed for this component.

The NBI duct has a length of ~7 m and an opening of ~1 m (heights) by 0.78 m (width) at the tokamak side, cf. Fig. 4. The length from the VV stub to the grounded grid of the ion source is ≈16.1 m, cf. Fig. 6. Given the expected 1σ divergence of the Gaussian beamlets of 0.7° the beam opening still needs to be relatively big to have sufficient beam transmission. The calculated geometrical transmission is 87 % [6].

5. Neutronics analysis

Since VNS is a very compact nuclear machine with similar neutron fluxes and fluences on the equatorial plane as foreseen in DEMO, the protection of the critical systems from neutrons is important. To shield the TF / PF coils from neutrons several cases of neutron transport calculations with the Monte-Carlo n-particle transport (MCNP) code were made for different material combinations to iteratively improve the shielding design to finally stay below the limits. The two main limits for the superconducting coils are 450 W/m^3 for the WPs nuclear heating and 50 MGy/10 FPYs [9] for the dose in the insulators. The latter limit is set by the maximum dose the materials can sustain before showing mechanical or electrical degradation. The 450 W/m^3 nuclear heating limit in the WP is in between the 1000 W/m^3 as applied in ITER and the 50 W/m^3 design limit in DEMO [10]. The DEMO value was set much lower to have higher margin plus to reduce the size of the cryo-plant.

Four cases were studied in which the duct shield and the duct wall material compositions were changed, while the HHF components were not changed and are assumed as a mixture of CuCrZr 60 % / H_2O 40 %. The 4 cases are listed in Table 2. In Case 4 an additional shield plug was added between the NBI ducts and the TF coils. Fig. 5 shows the MCNP and related CAD models, in which the additional NBI shield plug is labelled.

The following results were achieved, cf. Table 3. For Case 1 the values on both criteria are much above the limits, also for Case 2, the improved duct shielding could not much improve the overall shielding performance. In Case 3 the insulator dose was below the limit (with a little margin) whereas the TF coil nuclear heating was slightly above the limit. To gain margin and to lower the TF coil heating the additional NB shield plug was applied in the design. In Case 4 both limits as defined before could be complied with sufficient margin. The additional weights to include tungsten in the neutron shielding and the additional shield plug with B4C are reported also in Table 2. They are not negligible, and so are the additional costs of the material. However, the default Case 1 did not provide sufficient shielding.

Further studies will be conducted in the future also to calculate the material damage limits in the VV sections around the NBI duct. They should not exceed the limit of 2.75 dpa/10 FPYs in the VV. Furthermore, it must be checked if the HHF components can be used until EOL operation with their present material mixture or if e.g. tungsten coating is required, as is for example foreseen in the plasma first wall.

6. Site layout and building integration

The NBI high voltage power supply building 37 is close to the tokamak building 11, and the power supply cables are routed through bridge A into the tokamak building, cf. Fig. 8 and then further to the NBI injectors inside the NB cell and trough bridge E to the NBI test stand inside the AMF.

The NBI system is large and drives the tokamak building design due to its size. The NB cell is 8.5 m high and combines the equatorial port level L1 and the level L2 (which has no machine ports) of the tokamak building to allow sufficient heights for the NBI injector installations. In Fig. 9 the tokamak NB cell is shown. The other port cells on level L1 are not visible in this view as they are below the L2 floor. They foresee port cells, 1 for EC, 2 for diagnostics and 4 for material test ports.

Due to the tangential beam inclination one neighbouring equatorial port to the NBI is blocked for the use of port plugs but hosts the vacuum vessel pressure suppression system (VVPSS) connection (violet boxes in the adjacent port cell to the NB cell in Fig. 9.)

The connection of the NB cell to the AMF, building 21 in Fig. 8, is visualized by an arrow and labelled 'AMF' in Fig. 9. At this position a connection gate to the AMF is foreseen for all NBI injectors. To allow

Table 2
Studied MCNP cases.

Case	Duct shield	Duct wall	NBI plug
1	SS316 70 % / H_2O 30 %	SS316	–
2	W 86 % / SS316 6 % / H_2O 8 %	SS316	–
3	W 60 % / SS316 30 % / H_2O 10 %	W 60 % / SS316 30 % / H_2O 10 %	–
4	W 60 % / SS316 30 % / H_2O 10 %	W 60 % / SS316 30 % / H_2O 10 %	B4C 90 % / H_2O 10 %

SS316 = stainless steel 316, *W*= tungsten, B4C = boron carbide.

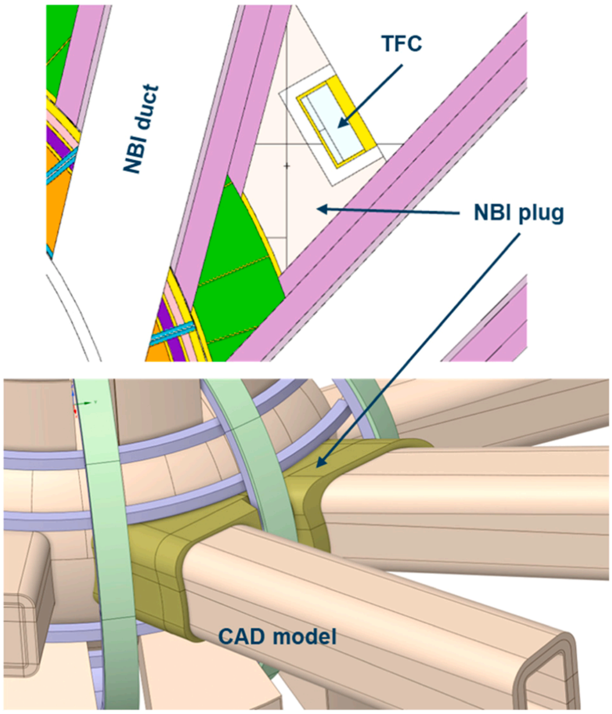

Fig. 5. VNS NB duct MCNP model (top) and simplified CAD model (bottom).

them to be transferred to the AMF through this gate 4 turntables are embedded in the L2 floor, with rails connecting them. The turntables are outside of the NB cell, in red shown the inner circular turntables with a diameter of ≈5.7 m and in orange the outer circular rotation space with a diameter of ≈10 m.

7. Remote maintenance

Reliability, availability, maintainability, inspectability (RAMI) is an important topic that will be considered during the whole project life-cycle, at foremost in the design phases. Because of the complexity of RM operations during repair and maintenance in combination with the gamma activation caused by neutrons and the T dust inside the NBI injector, no major *in-situ* repair is planned inside the tokamak building NB cell. For maintenance the whole NBI injector will be disconnected and radially shifted on a transportation system on rails. To allow the disconnection two beamline valves are foreseen in series. They would be required anyway for safety and pumping reasons and are also present in the ITER NBI [11]. These valves are an absolute valve (or gate valve) connected to the duct bellows and a fast shutter adjacent to it, connected to the NBI box. Both valves will be closed and then the flange in between them unlocked to allow separation. Fig. 10 shows the point of disconnection.

All services and supply lines have to be removed, before the NBI injector can be moved backwards.

To remove/re-assemble the services and supply lines, it is needed:

- to cut/re-weld water pipes, (optional open/close mechanical pipe connectors),
- connect/disconnect the roughing pumps,
- connect/disconnect the high voltage (HV) and RF cables from the ion sources,
- to connect/disconnect the cables for diagnostics,
- to connect/disconnect the cryo-jumpers for the cryo-pumps.

After the removal of the services and supply lines and disconnecting the two valves, the NBI injector will be transported to the AMF on rails and turntables. There it can be opened safely, and components can be removed and repaired from the top.

The AMF is next to the tokamak building and in there the NBI maintenance shall happen as the *in-situ* RM inside the tokamak building was excluded for space reasons but also not to interrupt the plasma operation while maintaining the NBIs, since some *in-situ* RM operations would take too long time. Instead, to remove one NBI and replace it with a spare NBI saves time and will help to achieve the high availability goals of the VNS. The AMF is ideal for any kind of RM activities and provides also the necessary space for RM tools.

A simplified scheme for the hot cell concept inside the AMF is shown in Fig. 11 with the non-contaminated NB maintenance cell in green and contaminated hot cell area above.

Fig. 12 shows the different cells (rooms) inside the AMF for NBI RM

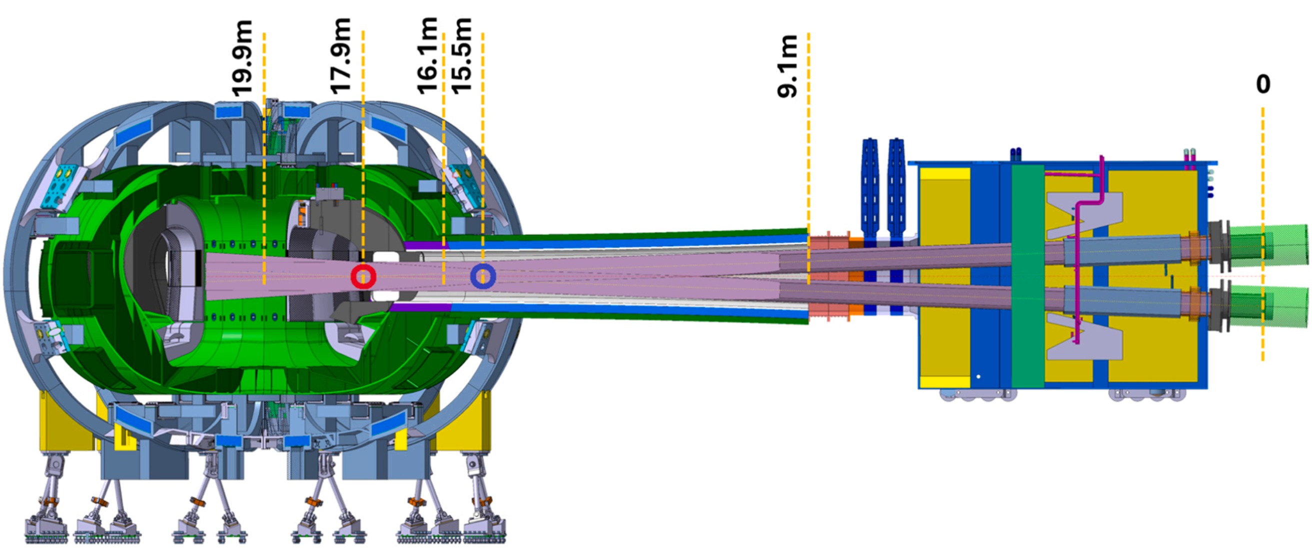

Fig. 6. Vertical cross section of one NBI injector with measures from the source grid to the machine centre (19.9 m), to the vertical focus point (17.9 m, red circle), to the horizontal focus point (15.5 m, blue circle), to the VV stub / end of NBI duct (16.1 m) and to the beginning of the NBI duct (9.1 m). The measures are taken along the beamline axis. The measures are minimally different from [6] because the position of the grounded grid was slightly corrected. The NBI box shows the internal components (in yellow the cryo-pumps, in green the bending magnet, in magenta the water pipes to the cooled components, i.e. in light grey the residual ion dumps and in dark grey the neutralizers). For more details about the NBI box cf [6].

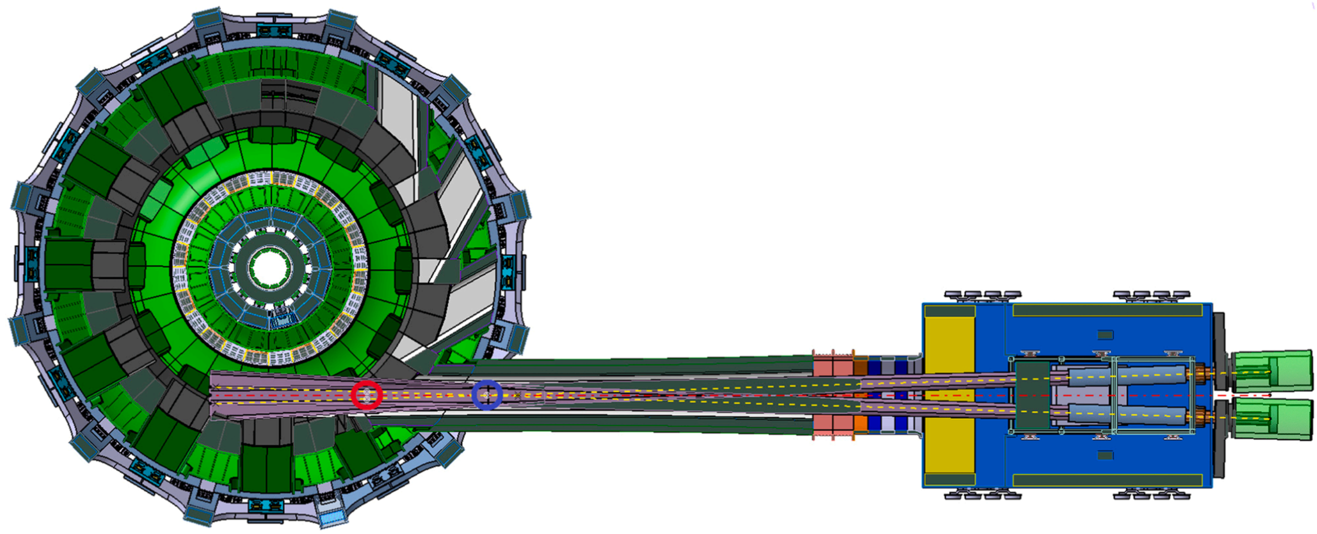

Fig. 7. Horizontal cross section of one NBI, the red circle indicates the vertical focus point, the blue circle the horizontal focus point.

Table 3
Results of the MCNP case-study.

Case	TF coil WP nuclear heating [W/m^3]	Insulator dose [MGy/10 FPYs]	Additional mass [tons/duct]
1	4660	1070	–
2	4180	962	16.3
3	650	42	16.3
4	177	10	16.3 +4 (NBI plug)

and testing. When repair or maintenance is needed, the NBI injector will be brought into the NB maintenance cell first. A top removal concept was developed and foresees that the top closure plates on the NBI box will be lifted on which the internal NB components are mounted (hanging) as mentioned before. To remove the interiors of the NBI injector without causing tritium or activated dust contamination in the maintenance cell, a docking flange attached to bellows-like confinement sleeves will be lowered before opening the top closure plates.

Inside the NB hot cell after all the RM is done, the components will be re-assembled by lowering them into the NBI box and closing the top closure plates. They will be sealed with a welded lip seal (optionally double HELICOFLEX® seals could be used).

The sequence for contamination-controlled maintenance is divided into 9 steps and shown in Fig. 13:

(1) disconnection of services (cryo, water, electr., etc.) and bending away the opened connections,
(2) placement of a local contamination protection,
(3) open the top closure plate,
(4) docking of door and confinement sleeves,
(5) component removal with the top closure plate and repair in the hot cell,
(6) component installation,
(7) component installed,
(8) removal of local contamination protection and sealing of closure plate,
(9) local decontamination and reconnection of services (cryo, water, electric, etc.).

With this contamination control sequence, it is guaranteed that the NBI injector and the maintenance cell are kept clean. In case of any accident during maintenance releasing any tritium or activated dust to

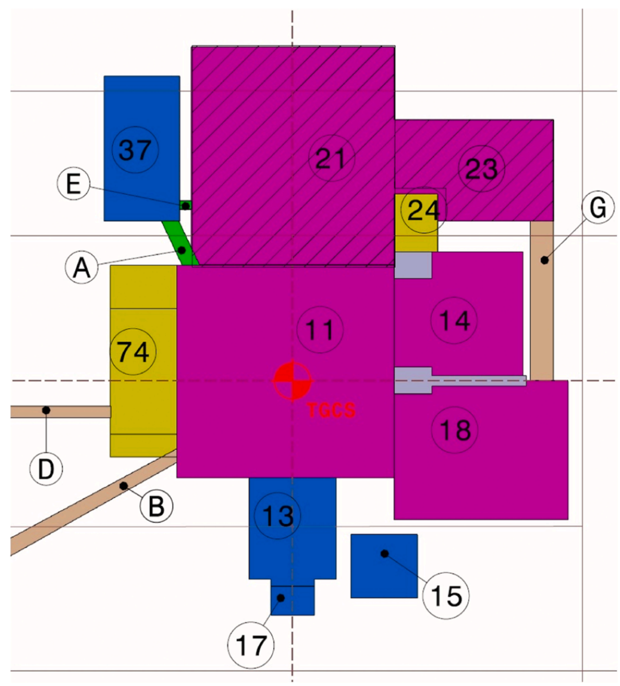

Fig. 8. Preliminary VNS site layout (partial) with 11 tokamak building, 13 assembly building, 14 tritium building, 15 RF heating building, 17 cleaning facility, 18 chemical and volume control system (CVCS) building, 21 AMF, 23 radwaste building, 24 personal access control and emergency control room, 37 NB high voltage power supply building, 74 diagnostic building, bridges A and E for the NB power supply cables to the NBI injectors and the NBI test stand, bridges D and B for the coil power supply connections to the magnet system and for cryo-lines, bridge G for the CVCS connection with the radwaste building.

the non-contaminated area the air detritiation system is activated, and additional exceptional cleaning would be needed. This case therefore should be prevented by any means.

Many different types of actions are required for maintenance and testing and the related tools need to be selected or to be developed if not available on the market. These efforts and related costs shall not be underestimated.

After RM the NBI injector is transported into the AMF NB test cell or also called test stand. There it is reconnected to the services required for

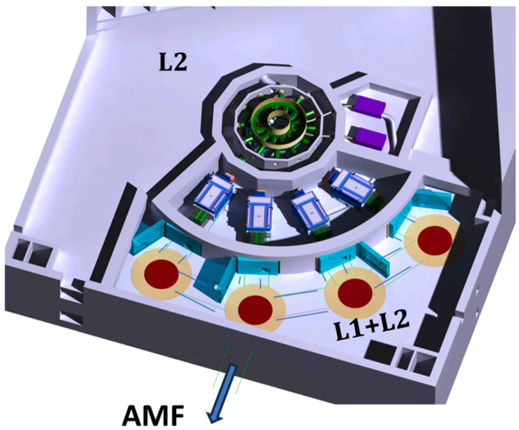

Fig. 9. Tokamak building with NB cell shown with the 4 NBI injectors.

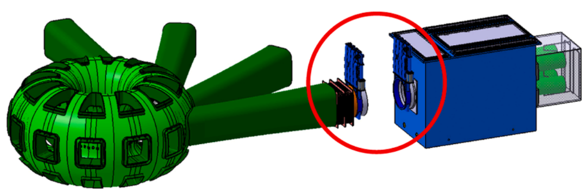

Fig. 10. Disconnection of the NBI box from the VNS tokamak and transportation to the AMF for repair, maintenance and testing, with one valve on each side (see red circle).

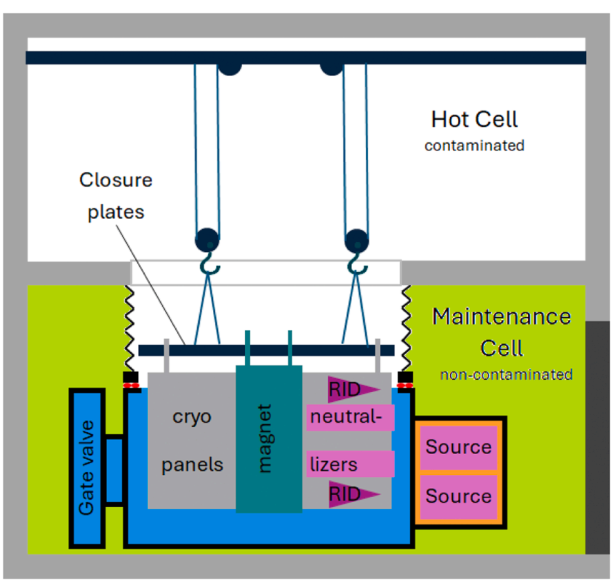

Fig. 11. Hot cell concept with top removal of components, Note that the calorimeter is placed in the NB test cell, not in this figure.

its operation and attached to a vacuum chamber in which a beam dump calorimeter is installed. The primary purposes of testing the NBI injector in the test cell are (i) high voltage conditioning, (ii) checking and correction of the beam misalignments, and (iii) functional tests of the subsystems. After successfully adjusting, conditioning and testing the injector becomes a spare injector, ready for installation at the VNS at any time another NB injector would fail or would need regular maintenance. The installation of the calorimeter at the test cell and not inside the NBI boxes is a deviation from the concept on most other existing beamlines such as AUG or ITER where a movable calorimeter is inside the NBI box. The new concept avoids movable parts inside the VNS NBI box, aiding more reliability.

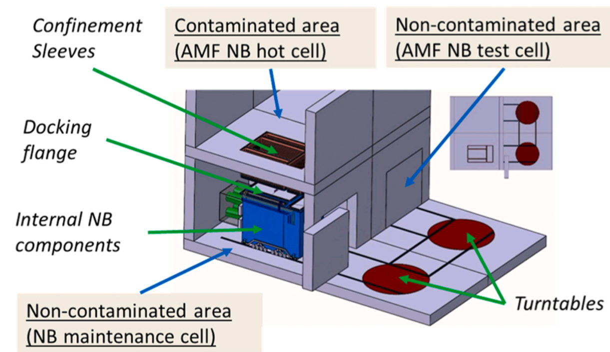

Fig. 12. AMF cells for maintenance and testing.

7.1. Availability

Existing NBI systems are operated in pulsed modes with very low cumulated on-times, e.g. the AUG NBI operated 22 h to date whereas for VNS it is expected to be operated 65,000 h in 10 FPYs [6]. Generally, P-NBI is seen as a very reliable heating method in present day and former experiments [12,13]. It operates at much lower voltages, e.g. 93 keV typically in AUG whereas negative ion source based NBI (N—NBI) as in ITER [14] or DTT concepts [15] shall operate at ≈1000 keV or ≈500 keV respectively which requires very high voltages. The issues of Cs-management of N—NBI sources and the co-extracted electrons indeed were addressed successfully recently for ITER at the NBI test lab ELISE [16,17] but these achievements need to still to be investigated further. Also other N—NBI systems are operated e.g. at JT60-SA [18] even for longer pulses with up to 100 s. Despite the big progress of N—NBIs in recent years, P-NBI is presently still at a higher technical readiness level (TRL). However, for the VNS the reliability and availability aspects are very different from existing machines, as the VNS shall operate in quasi steady state condition over long periods and not just as experiment. The goal is to design the VNS NBI to cope with the high overall availability (A) target of VNS of 25–40 %,

- operational phase 1 (OP1) with 5 dpa@20 %A in 1 FPY
- OP2 with 20 dpa@30 %A in 4 FPYs and
- OP3 with 25 dpa@40 %A in 5 FPYs

to achieve the total 50 dpa in 10 FPYs [2]. A task on RAMI for NBI has been started based on the failure mode effective analysis (FMEA) approach to support the design.

To achieve this high VNS availability goals as stated before the NBI system shall be extremely reliable, for that several strategies have to be implemented:

(1) To have spare NBI injectors as discussed before, (one or two depending on the RAMI calculations), because a spare NBI injector can be relatively quickly exchanged in a case of a failure of one of the operated NBI injectors.
(2) To have regular preventive maintenance following the determined VNS maintenance schedule.
(3) The design of the injectors shall be simplified, modular and the components of high quality.
(4) All connections shall be designed for a quick exchange, therefore cryo-jumpers, mechanical pipe connectors and other quick connection systems shall be validated for their applicability.
(5) To have a good testing strategy and a close-by NBI test stand.

The whole VNS physics concept on the other hand has to be fail proof related to NBI power shortages as mentioned in the introduction in the

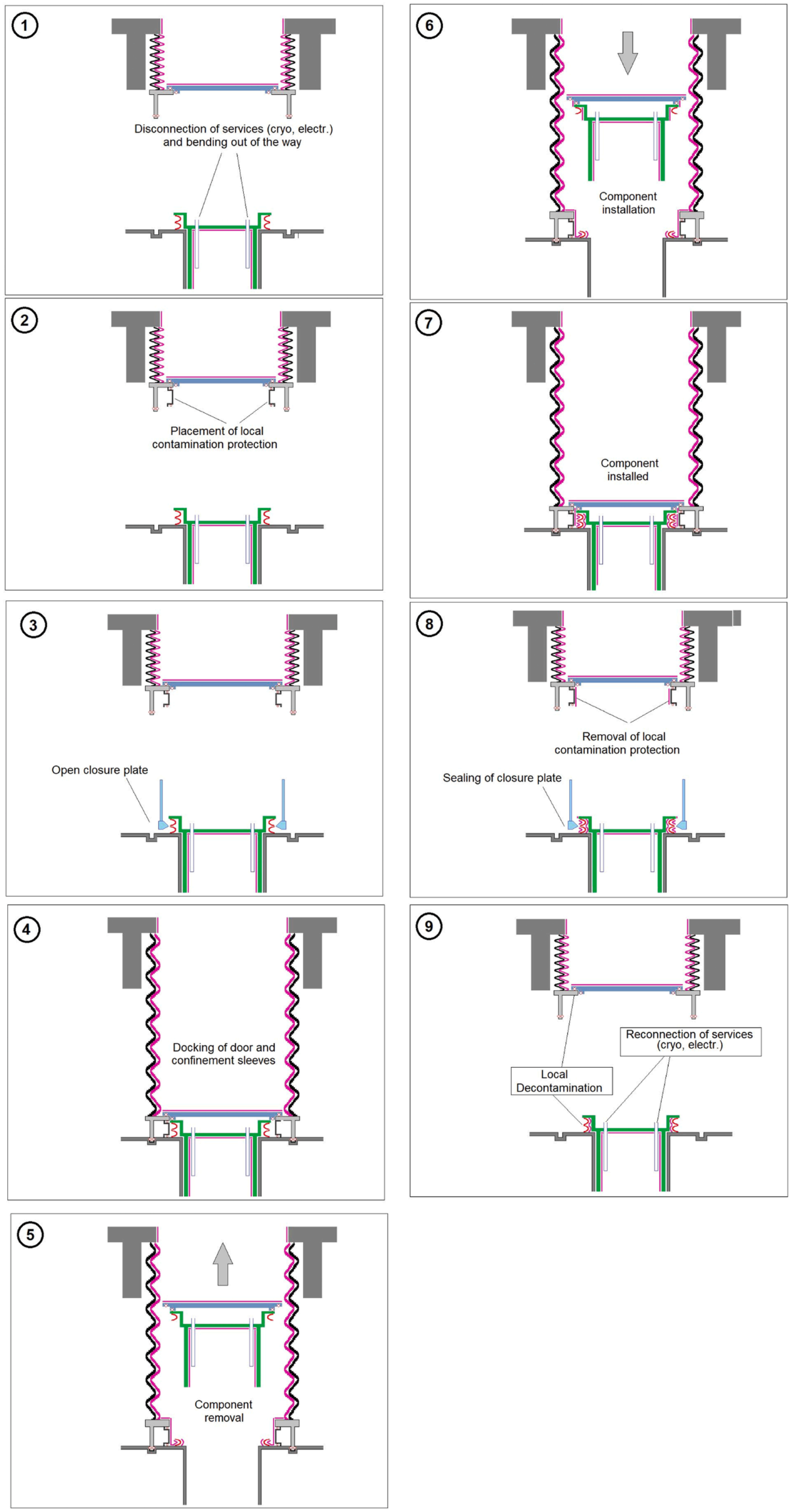

Fig. 13. Contamination control sequence inside the AMF, (the text inside the figures is written before, see 9 steps).

sense, that the failure of one NBI source or even of a whole NBI injector will not terminate the plasma and consequently also not the neutron production, but the neutron fluxes will just be lower until the system is repaired.

From operational experiences it should be noted as advantage for VNS, that HV deconditioning and related breakdowns highly occur due to long idle times, typical for present experimental machines with operational campaigns followed by longer shutdown phases e.g. for machine modifications. Continuous operation as in VNS in contrast provides advantages for keeping the HV conditioning stable.

Another important factor for achieving higher reliabilities is the testing strategy of all NBI injector sub-components before installation into the NBI injector and testing of the whole injector before operating it in the VNS. For the internal HHF components test facilities such as GLADIS [19] could be used to support this strategy. Also a test stand for long-pulse RF ion source tests to achieve high cumulative beam times is planned. Here synergies could be used as for GLADIS it is planned an upgrade to steady state operation and the sources used in there for HHF material tests are the same as the RF ion sources as used in AUG and planned for VNS.

For the whole VNS NBI injector, the construction of a (up to discussion ¼, ½ or full size) prototype beamline for integrated testing in long pulses is foreseen. This test facility also would allow to commission the NBI injector or parts of it before moving them into the VNS. In parallel to the VNS operation this test facility could be used to improve the injector design further based on the operational experience and to test design upgrades if needed.

8. Summary

The integration of the NBI system in the VNS tokamak building and the AMF NBI maintenance, hot cell and testing cells were performed. Integration issues originating from tight space as well as neutron fluxes and fluences were carefully studied and the neutronics limits achieved with sufficient margins. Tungsten as shielding material is required as well as an additional NBI shield plug with boron carbide to ensure a safe TF / PF coil operation. The maintenance concept which is of great importance for the success of the VNS in view to its high required availability was developed. Practically that means that for repair and maintenance the NBI injectors will be moved from the tokamak building to the AMF and no major *in-situ* maintenance will be done inside the tokamak building. A contamination control sequence for the AMF was developed to avoid any uncontrolled release of tritium or activated dust. Further design studies as indicated are needed, the integration work showed good progress and results, there are open challenges and uncertainties to be tackled and to be completed during the conceptual design phase of VNS.

CRediT authorship contribution statement

T. Franke: Writing – original draft, Conceptualization. **C. Bachmann:** Writing – review & editing, Conceptualization. **V. Claps:** Conceptualization. **A. Doering:** Conceptualization. **T. Fellinger:** Conceptualization. **C. Gliss:** Writing – review & editing, Conceptualization. **T. Haertl:** Writing – review & editing. **C. Hopf:** Writing – review & editing, Conceptualization. **M. Kannamüller:** Writing – review & editing, Conceptualization. **D. Leichtle:** Validation. **R. Mozzillo:** Conceptualization. **J. Hun Park:** Validation. **P. Pereslavtsev:** Validation, Conceptualization. **R. Riedl:** Investigation. **M. Siccinio:** Conceptualization. **A. Valentine:** Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] G. Federici, Testing needs for the development and qualification of a breeding blanket for DEMO, Nucl. Fusion 63 (2023) 125002.
[2] C. Bachmann, et al., Engineering concept of the VNS - a beam-driven tokamak for component testing, Fusion Eng. Des. 211 (2024) 114796.
[3] G. Federici, et al., Overview of the DEMO staged design approach in Europe, Nucl. Fusion 59 (2019) 066013.
[4] M. Coleman, et al., Definition of an EU-DEMO design point robust to epistemic plasma physics uncertainties, Nucl. Fusion 65 (2024) 036039.
[5] T. Haertl, et al., Vacuum pumping concept for quasi-continuous NBI operation at a steady state fusion machine, Fusion Eng. Des. 213 (2024) 114864.
[6] C. Hopf, et al., Neutral beam injection for a Tokamak-based volumetric neutron source, Fusion Eng. Des. 213 (2024) 114870.
[7] B. Chuilon, et al., Key enabling design features of the ITER HNB duct liner, Fusion Eng. Des. 96–97 (2015) 433–437.
[8] T. Franke, et al., Initial port integration concept for EC and NB systems in EU DEMO tokamak, Fusion Eng. Des. 146 (2019) 1642–1646. Part B.
[9] L. Giannini, et al., Conceptual design studies on the magnet system for the volumetric neutron, IEEE Trans. Appl. Supercond. 34 (2024) 5. Issue:.
[10] U. Fischer, et al., Neutronics requirements for a DEMO fusion power plant, Fusion Eng. Des. 98-99 (2015) 2134–2137.
[11] M. Urbani, et al., The ITER neutral beam front end components integration, Fusion Eng. Des. 88 (9–10) (2013) 2110–2114. Issues.
[12] D. Stork, Neutral beam heating and current drive systems, Fusion Eng. Des. 14 (1–2) (1991) 111–133. Issues.
[13] B. Streibl, et al., Chapter 2: machine design, fueling, and heating in ASDEX upgrade, Fusion Sci. Technol. 44 (Issue 3) (2003) 578–592.
[14] R.S. Hemsworth, et al., Overview of the design of the ITER heating neutral beam injectors, New J. Phys. 19 (2017) 025005.
[15] P. Agostinetti, et al., Improved conceptual design of the beamline for the DTT neutral beam injector, IEEE Trans. Plasma Sci. 50 (Issue 11) (2022) 4027–4032.
[16] U. Fantz, et al., Ion source developments at IPP: on the road towards achieving the ITER-NBI targets and preparing concepts for DEMO, J. Phys. Conf. Ser. 2244 (2022) 012049.
[17] C. Wimmer, et al., Stabilizing long pulse D^- extraction for NBI using a Cs shower, Fusion Eng. Des. (2024) submitted.
[18] Y. Ikeda, et al., Technical design of NBI system for JT-60SA, Fusion Eng. Des. 82 (5–14) (2007) 791–797. Issues.
[19] H. Greuner, et al., High heat flux facility GLADIS: operational characteristics and results of W7-X pre-series target tests, J. Nucl. Mater. 367-370 (2007) 1444–1448. Part B.