Neutral beam injection for DEMO alternative scenarios

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Within the current EU pre-conceptual design activities, the reference demonstrative fusion power plant concept relies on ITER-like, pulsed H-mode plasmas (“DEMO1”) [Federici G. et al., Nucl. Fusion 59 (2019), 066013]. Simultaneously, alternative design options are being considered. An example is “Flexi-DEMO”, which is designed for steady-state plasma discharges, but can also be run pulsed at the same fusion power with the same auxiliary heating systems if the plasma confinement time turns out to be not sufficient for non-inductive operations [Zohm H. et al., Nucl. Fusion, 57 (2017), 086002]. Preliminary investigations have started also for ELM-free regimes, such as I-mode or QH-mode, due to the issues encountered in ELMs active control at reactor scales [Siccinio M. et al, Fusion Eng. Des. 156 (2020), 111603].

Neutral beam injection (NBI) is one of the candidates for a DEMO heating and current-drive system. Depending on the system design, NBI can be optimized for e.g. central heating (as for DEMO1), current-drive (as for Flexi-DEMO) or even to provide torque to the plasma (which may favour the access to ELM-free QH-mode regime [Garofalo A. et al., Nucl. Fusion 51 (2011) 083018]).

In the present contribution we describe the main NBI features in terms of design parameters (NBI energy, injection geometry) that would optimize these alternative DEMO plasma scenarios, in particular regarding Flexi-DEMO and QH-mode regime. Wide-range parametric scans through METIS numerical simulations of DEMO plasmas indicate the optimal design windows for NBI system in each plasma configuration. These results need however further validations against technical constraints, available technology limits and detailed plasma transport simulations.

Keywords: DEMO; NBI; H&CD; plasma scenarios; Flexi-DEMO; QH-mode;

1. Alternative scenarios: Flexi-DEMO and QH-mode DEMO

Currently, the European DEMO reactor concept relies on a baseline H-mode plasma (DEMO1). Its plasma current is mainly inductive, and the scenario is affected by large ELMs [1], which require active suppression methods. Alternative plasma scenarios are also being studied, with the aim of solving particular issues which can be seen as possible showstoppers.

One of these alternative concepts has been developed to aim at stationary plasmas, and it is called Flexi-DEMO [2]. It is a flexible machine, designed for steady-state plasmas, but which can be also run pulsed at the same fusion power and auxiliary heating power if the plasma confinement turns out to be non-sufficient. In the design of the fully non inductive target plasma scenario, heating and current drive (H&CD) systems play a critical role. Neutral Beam Injection (NBI) is a good candidate for Flexi-DEMO due to the potential high current drive efficiency, especially when injected off-axis.

From recent studies, it has been demonstrated that even a few type-I ELMs are not tolerable in DEMO1 [3]. A possible solution is to rely on ELM active control systems, although this concept is hardly scalable to reactors. Therefore, in the last years, ELM-free scenarios became more and more attractive for DEMO. For example, QH-mode shows indeed absence of ELMs, while maintaining H-mode confinement properties. In DIII-D tokamak, it has been shown that to access and maintain this regime, a certain edge electric field shear is needed [4]. In order to generate this shear, a possible candidate is NBI induced rotation.

NBI can be therefore used as scenario actuator for the aforementioned alternative DEMO concepts, either to induce plasma current or rotation.

The paper is structured as follows. In section 2, the goals of the work are presented, together with the methodology, based on plasma discharge simulations by a simplified transport model. Section 3 describes the results for NBI optimization on Flexi-DEMO scenario, while section 4 describes NBI capabilities for QH-mode access in DEMO. Section 5 presents conclusion and the foreseen future work.

2. Goals and methodology of the work

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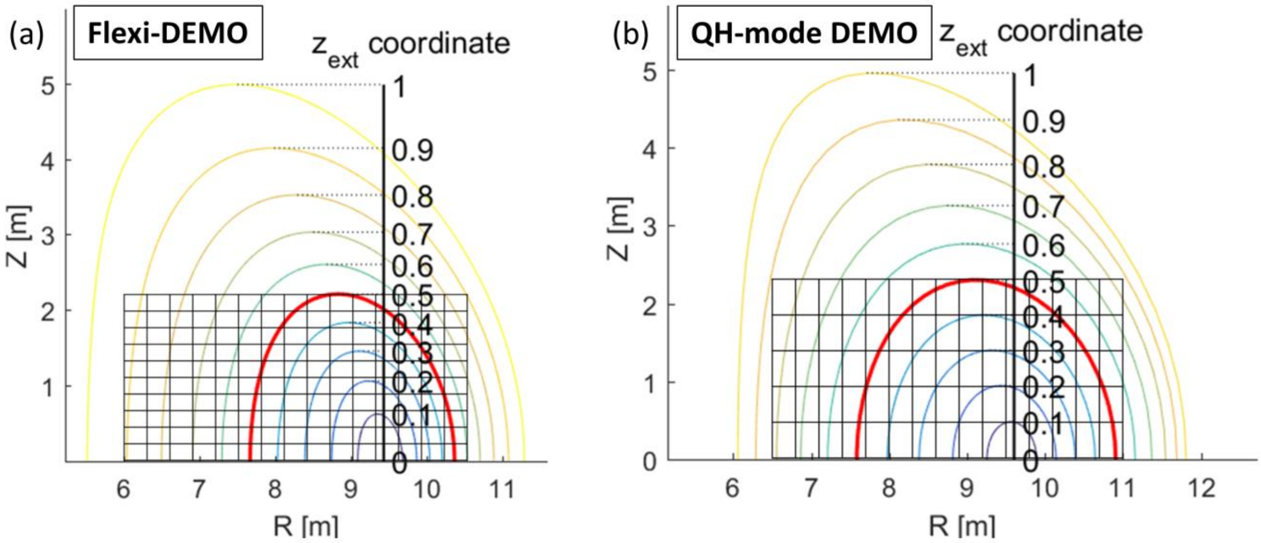

Figure 1: Grid of (R_{tang}, z_{ext}) points representing the different beam injection trajectories simulated in the present work for Flexi-DEMO (a) and QH-mode DEMO (b) scenarios. Flat-top plasma equilibria are also represented for reference in the poloidal plane.

H&CD systems have to be carefully designed according to the objective of the machine. Producing a steady-state, fully non-inductive plasma sustained by H&CD systems (as for Flexi-DEMO), or generating an edge velocity shear to enable the operation in QH-mode regime (QH-mode DEMO) require precise, but different, auxiliary system characteristics. The most important degrees of freedom for a NBI system, from a point of view of the interaction with the plasma, are the injection geometry and energy. The injected species is supposed to be deuterium, as for DEMO1 reactor. The aim of this work is to investigate the NBI parameter space, in order to find whether there is an optimal region in terms of Flexi-DEMO and QH-mode DEMO scenario requirements. This work does not discuss the system feasibility from machine-integration and technology point of view: this is a prelaminar investigation to evaluate ideal system characteristics from a plasma scenario standpoint.

The work goal is achieved through wide parameter scans, by numerical simulations with METIS 0.5D integrated transport code [5]. METIS is capable of simulating a full tokamak discharge, solving the transport of energy, momentum and particles, and taking into account plasma current diffusion. It uses analytical models and scaling laws that allow fast computation times. It calculates the 2D plasma equilibria and evolves plasma kinetic profiles, according to actuators input as NBI. The NBI system is described by the specification of the injected species (D), the power waveform, the injection energy and geometry (included if co- or counter-current injection). In particular, the beam tangency radius (R_{tang}) is required, together with the beam vertical tilt, described by a normalized parameter (z_{ext}) which is 0 for equatorial injection and increases to 1 for injections aiming at the uppermost point in the poloidal plane (maximum METIS z_{ext} = 0.5). In the following work, the (co-current only) injection geometry has been varied exploring the grid of (R_{tang}, z_{ext}) points illustrated in fig. 1 both for Flexi-DEMO and QH-mode DEMO. At the moment, counter-current injection option has been excluded due to the foreseen large fast particle orbit losses, considering the high NBI power.

3. NBI parameter scans for Flexi-DEMO

Flexi-DEMO upper operational point, i.e. the target steady state scenario, has been designed within EUROfusion activities. The main parameters are: major / minor radius R = 8.4 m / a = 2.9 m, magnetic field at the axis B_T = 5.8 T, plasma current I_p = 14.5 MA, fusion power P_{fus} = 1.55 GW. Stationary flat-top profiles of plasma density and temperature representing the METIS working point are illustrated in fig. 2.

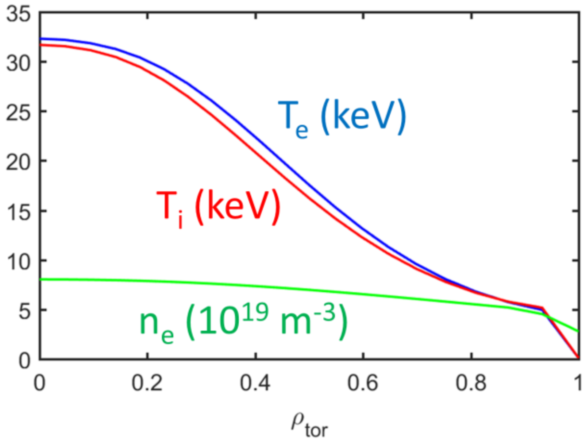

Figure 2: Flexi-DEMO profiles of electron, ion temperatures and density as a function of the normalized toroidal flux.

The nominal NBI parameters are: injected power P_{NBI} = 130 MW (in addition to electron cyclotron resonance heating), particle energy E_{NBI} = 1 MeV, R_{tang} = 7.5 m and

z_{ext} = 0.2. For METIS simulations, NBI parameters have been varied, in particular the injection geometry (see fig. 1) and energy (0.8, 1, 1.5 and 2 MeV), keeping P_{NBI} at the reference value, for a total of 704 simulated cases.

A figure of merit of Flexi-DEMO scenario is the non-inductive fraction (f_{ni}) of the total plasma current, which should reach 1 for the target scenario. Non-inductive current sources come from the aforementioned H&CD systems and from bootstrap current, which depend on plasma pressure gradients (and hence affected also by kinetic profile changes due to e.g. NBI). The result of the beam injection geometry scan is illustrated in fig. 3 for E_{NBI} = 1 MeV case, with a plot of the achieved f_{ni} value for each analysed injection case. Off-axis beam injection (large R_{tang}) at the nominal power can sustain fully non-inductive operations. It is interesting to see that for strongly off-axis trajectories, the nominal P_{NBI} can be lowered, since f_{ni} > 1. Increasing injection energy ensures higher NBI current-drive efficiency, and less power required to reach f_{ni} = 1 target scenario.

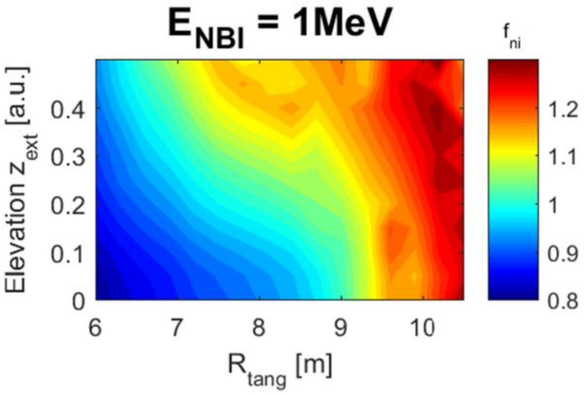

Figure 3: Fraction of non-inductive current (f_{ni}) achieved for Flexi-DEMO as a function of beam injection line geometry. Flexi-DEMO target is f_{ni} = 1. Values f_{ni} > 1 indicates that nominal NBI power (130 MW) can be lowered.

METIS estimates also negligible fast particle losses (both shine-through and first orbit losses), unless increasing injection energy to 1.5 or 2 MeV at largely off-axis injection geometries. For the current case analysed, E_{NBI} = 1 MeV, shine-through losses are represented in fig. 4. It is clear that, for the target flat-top density, shine-through is negligible for Flexi-DEMO for most of the parameter space investigated. It is interesting to notice that only the tangency radius influences the amount of losses, while a vertical tilt change is almost irrelevant.

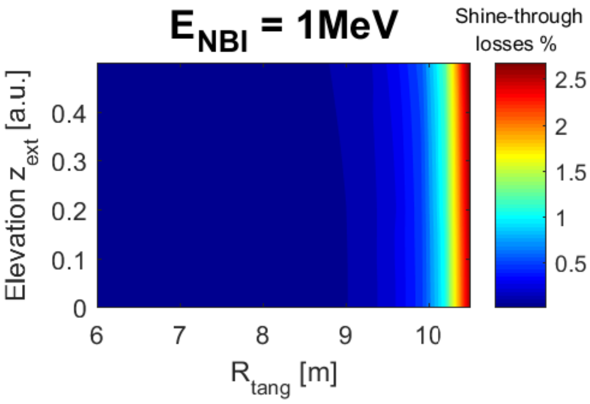

Figure 4: Flexi-DEMO NBI shine-through losses, for different injection geometries, at E_{NBI} = 1 MeV.

METIS estimates the first orbit loss channel counting the newly born fast ions which are generated into an orbit within a gyro-radius from the separatrix. For this reason, only peripheral, largely off-axis, injections (both in horizontal and vertical directions) show an increased first orbit loss ratio, up to a few percent, while most of the simulated NBI geometries show losses less than 2%. Fig. 5 depicts Flexi-DEMO first orbit losses, for the analysed injection lines, at E_{NBI} = 1 MeV.

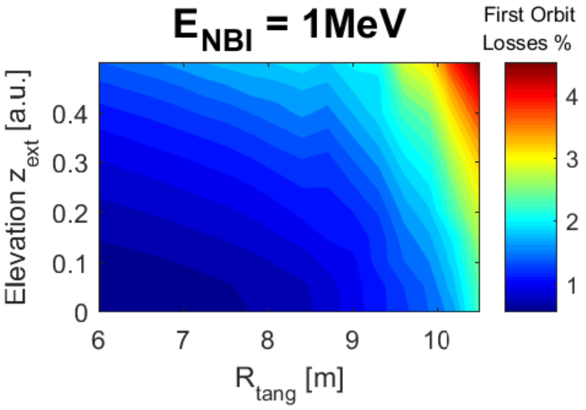

Figure 5: Flexi-DEMO NBI first orbit losses, for different injection geometries, at E_{NBI} = 1 MeV.

NBI parameter variation has a strong impact also on plasma scenario. METIS indeed simulates the whole integrated plasma discharge: moving the injection line from plasma core to edge affects e.g. the plasma temperature, as illustrated in fig. 6 for the core electron temperature (E_{NBI} = 1 MeV). Consequently, also fusion power decreases for more off-axis injections, up to -10 %. This is a parameter which has to be carefully evaluated in the economy of a fusion reactor.

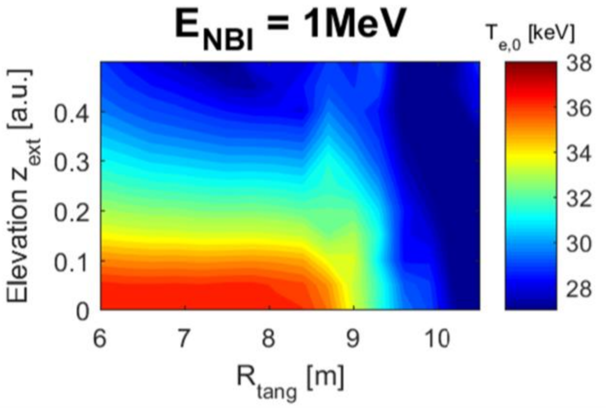

Figure 6: Flexi-DEMO core electron temperature for different NBI injection geometries, at $E_{NBI} = 1$ MeV.

4. NBI parameter scan for QH-mode DEMO

QH-mode DEMO is a machine which is similar to DEMO1 as dimensions and main parameters (R = 8.94 m, a = 2.88 m, BT = 5.74 T, Ip = 18.21 MA, Pfus = 1.87 GW). The METIS working point for this plasma scenario is represented in fig. 7.

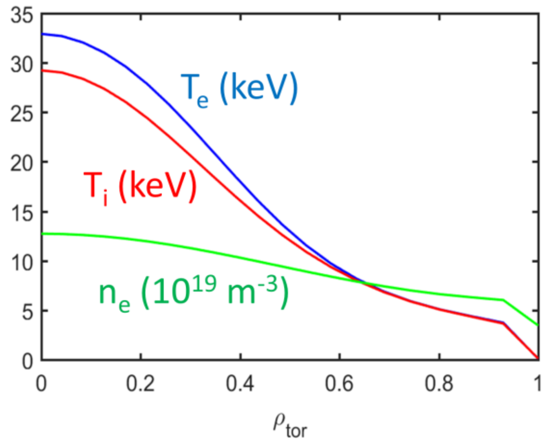

Figure 7: QH-mode DEMO profiles of electron, ion temperatures and density as a function of the normalized toroidal flux.

In order to access QH-mode regime, a certain edge shear in the radial electric field frequency $\omega_E = E_r/(RB_\theta)$ is required. The QH-mode threshold has been identified for DIII-D tokamak as $\frac{\Delta\omega_E/\Delta r}{\omega_A}\Big|_{edge} \sim 0.25\, m^{-1}$ [4], where $\Delta\omega_E/\Delta r$ is the electric field frequency variation in the outer half of the pedestal region and ω_A is the Alfven frequency. In order to evaluate QH-mode access in a reactor-like machine as DEMO, we decided to normalize this parameter to the DIII-D minor radius, resulting in a normalized QH-mode threshold of:

$$a \cdot \frac{\Delta\omega_E/\Delta r}{\omega_A}\Big|_{edge} \sim 0.17 \qquad \text{(eq. 1)}$$

The nominal NBI parameters (equal to DEMO1 ones) are: P_{NBI} = 76 MW, E_{NBI} = 1 MeV, R_{tang} = 7.09 m and z_{ext} = 0. METIS simulations have been run for different injection options (with geometries described in fig. 1 and E_{NBI} = 30, 50, 70, 90, 100, 300, 800, 1000 keV), for a total of 768 cases. The resulting normalized QH-mode threshold strongly depends on the injection energy, being higher for low E_{NBI} (< 100 keV). NBI indeed is supposed to be capable of producing an electric field shear in the edge, if it provides rotation to the plasma, and the NBI momentum input increases with decreasing E_{NBI}. Since the electric field shear has to be generated in the plasma edge region, off-axis injection is preferable. Fig. 8 shows the values of the normalized achieved plasma QH-mode threshold as defined in eq. 1, for different beam line trajectories at E_{NBI} = 30 and 100 keV (resp. fig. 8a and 8b).

It is possible to see that, at the nominal P_{NBI} (76 MW), the plasma almost reaches the QH-mode threshold value (~0.17), only for a limited parameter area. The values of the optimal NBI parameters imply however a peripheral beam ionization, which results in considerable orbit losses. This can be seen in fig. 9, which shows first orbit loss estimation for E_{NBI} = 30 keV (fig. 9a) and 100 keV (fig. 9b). Peripheral injection and edge fast ion generation due to lower beam penetration at lower injection energy implies that, according to METIS estimation, a large number of fast ions are lost in their gyro-motion, due to likely crossing of the separatrix. Passing from core to edge injection, first orbit losses double, up to > 10% and > 15% respectively for 100 and 30 keV options. Moreover, fusion power production is also affected by NBI energy variation, with a decrease of

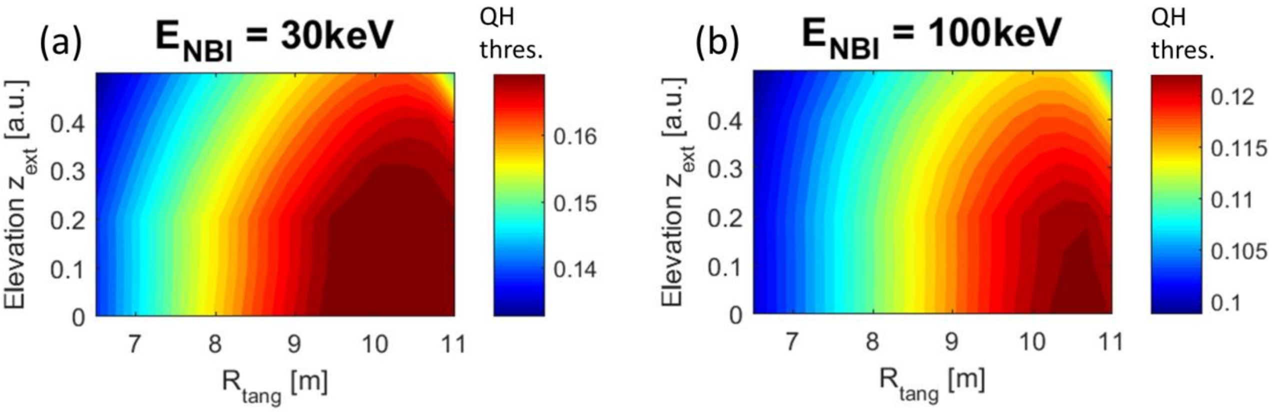

Figure 8: Normalized QH-mode access threshold value (as defined in eq. 1) for different beam injection line geometries, at E_{NBI} = 30 (a) and 100 (b) keV. QH-mode can be reached for threshold values >~ 0.17, according to DIII-D experience [4].

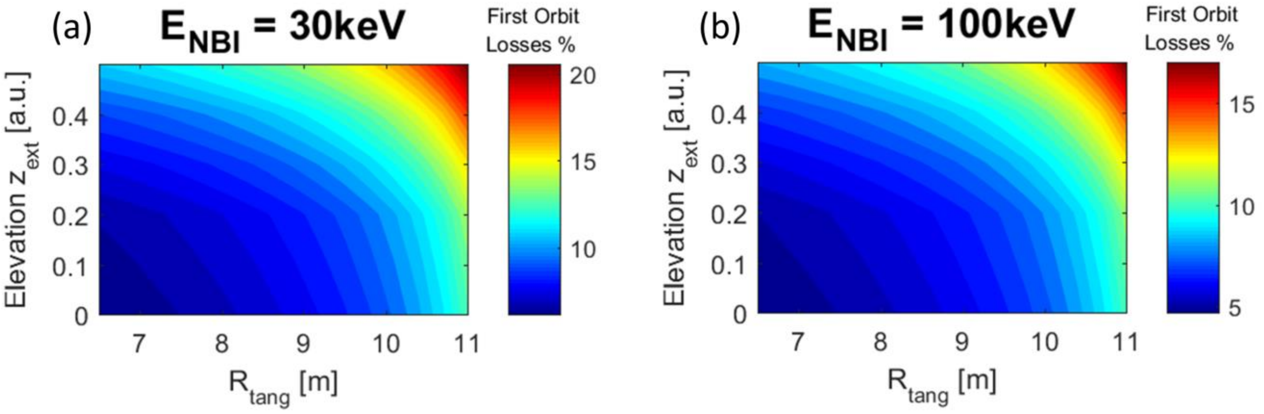

Figure 9: METIS estimation of first orbit losses ratio to injected P_{NBI}, for ENBI = 30 keV (a) and ENBI = 100 keV (b).

~ 10% for 100 keV option with respect to 1 MeV injection. QH-mode for DEMO plasma can be therefore hardly reached only by a NBI system, due to the large required injection power only for plasma rotation, and the large resulting fast particle losses. Anyway, other methods can be used to generate the necessary electric field shear, as static, non-axisymmetric, non-resonant magnetic fields [4].

5. Conclusion and future work

DEMO alternative scenarios are being studied within EUROfusion, in addition to the baseline H-mode pulsed DEMO1 plasma. The aim of these studies is to secure the road towards a fusion power plant, by investigating different plasma scenarios. Among these options, Flexi-DEMO [2] has been proposed as a flexible machine designed with a target steady-state, non-inductive plasma. In order to solve the ELMs issues in DEMO1, ELM-free regimes, such as QH-mode, gained particular interest in DEMO community [3]. Both steady-state and QH-mode plasmas relies on a substantial power input from H&CD systems. The present work analysed the possible contribution of co-current NBI to reach Flexi-DEMO and QH-mode DEMO target scenarios, through wide NBI parameter scans by means of METIS [5] simulations. In particular NBI energy and injection trajectory have been varied at constant injected power to evaluate the optimal NBI parameter region for each plasma scenario. Flexi-DEMO has to achieve fully non-inductive plasma, by means of bootstrap currents and external current drive. Off-axis injection with an energy of 1 MeV satisfies this requirement, even at a reduced P_{NBI} with respect to the nominal value of 130 MW. Increasing the injection energy would increase the NBI current drive efficiency and the total driven current. Changes in injection energy and trajectory have an impact on the whole plasma, as for instance on plasma temperature and fusion power output. With a strongly off-axis injection, fusion power can decrease up to 10%. Fast particle losses are estimated to be negligible for Flexi-DEMO, increasing only for largely off-axis injections. The access to QH-mode regime is not fully understood, and this work is based on the findings of DIII-D tokamak [4]. In DIII-D, a QH-mode access threshold has been identified, depending on the radial electric field frequency shear in the outer half of the pedestal. This value has been scaled to DEMO dimensions, through normalization by the minor radius. Only very low energy (< 100 keV) NBI with off-axis aiming can barely reach the necessary QH-mode threshold, at the nominal NBI power for QH-mode DEMO (76 MW). Orbit losses could though represent an issue, due to the peripheral beam ionization. For QH-mode access, counter-current injection option (not analysed in this work) could also represent an interesting solution to increase the radial electric field shear, although we can expect considerable fast particle losses. These results must anyway be confirmed through focused transport simulation with more detailed codes. The optimal NBI parameter region has then to be evaluated from a machine-integration and technology feasibility point of view, which has not been done yet. In conclusion, if NBI results an attractive system for steady-state scenarios thanks to high current-drive efficiency, a sufficient rotation shear by NBI for QH-mode access may hardly be reached unless with higher injected power and considerable fast particle losses.

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References

[1] Federici G. et al., Nucl. Fusion 59 (2019), 066013.
[2] Zohm H. et al., Nucl. Fusion, 57 (2017), 086002.
[3] Siccinio M. et al, Fusion Eng. Des. 156 (2020), 111603.
[4] Garofalo A. et al., Nucl. Fusion 51 (2011) 083018.
[5] Artaud J.F. et al Nucl. Fusion 58 (2018) 105001.