Requirements and modelling of fast particle injection in RFX-mod tokamak plasmas

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Abstract

The planned upgrade of the RFX-mod device is a good opportunity to widen the operational space of the machine, in both Reversed Field Pinch (RFP) and tokamak configurations. Installation of a power neutral beam injector is envisaged and a NB system compatible with RFX-mod, formerly installed in TPE-RX, is already available on site. In this work, the METIS simulator is used to study the feasibility of the injector integration in RFX-mod circular tokamak plasmas. METIS code allows the simulation of a full tokamak discharge, with the addition of the neutral beam injection (NBI) which, in METIS, is described by a decay equation applied in a simplified geometry and an analytical solution of the Fokker-Planck equation. In this work, RFX-mod scenarios with NBI have been studied, with focus on the beam absorption and plasma response to the additional heating.

Keywords: RFX-mod, NBI, fast particles, METIS, TPE-RX

1. Introduction

RFX-mod is a medium size (R = 2 m, a = 0.459 m) device capable to work in both tokamak and reversed field pinch (RFP) magnetic configuration. As the biggest operational RFP, it reached the record plasma current of 2 MA. Its advanced feedback system for MHD control has been fundamental in reaching this result. Furthermore the device can reach uncommon tokamak regimes, such as plasmas with $q(a) < 2$ [1]. Nowadays RFX-mod is under upgrade: one of the most challenging changes is the integration of the vacuum vessel in the support structure, which will make the feedback system closer to the plasma edge and thus improve the plasma control [2].
Another important planned upgrade is the integration of a neutral beam injector. Thanks to the collaboration between Consorzio RFX, Padua, Italy, and the AIST Institute, Tsukuba, Japan, the NB injector formerly operating on TPE-RX is currently available. It was designed to operate with a power of 1.25 MW, accelerating a current up to 60 A of 25 keV hydrogen positive ions for 30 ms (nominal conditions), but it can work also with deuterium (with a reduced power of ~ 0.9 MW). If necessary, the beam could operate also at 15 keV for 60 ms. The injector has a multiaperture three-grid electrostatic accelerator with the typical design adopted for the positive ion accelerator. The designed focal length is 1860 mm and the effective diameter of the extraction region is 345 mm. Close to the focal point the spot diameter of the beam trace has been measured to be $\phi \sim 36$ mm. From the beam profile data, the divergence has been estimated as $\theta \sim 0.8°$ [3].
The design of the NBI implementation has been already studied in [4],[5], assuring that the integration of such system is feasible, with an efficiency (defined as the ratio between the power injected in RFX-mod and the electrical power to the injector) $\eta > 25\%$. Due to mechanical constraints mainly linked to toroidal field coils configuration, the only possible injection is along a radial chord on the equatorial plane. In figure 1 the design of

the NB system integration can be seen.

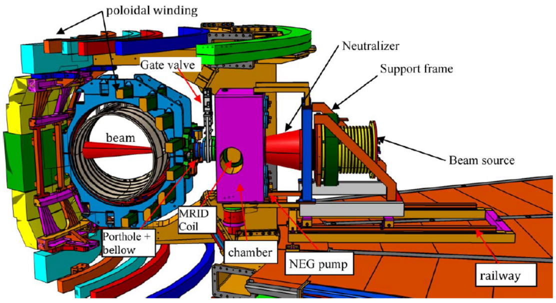

Figure 1: CAD design of the RFX-mod NB system. [4]

The NBI on RFP plasmas has already been studied in [6]. In this work, a set of requirements for an NB system to be applied to RFX-mod tokamak plasmas is analysed, carefully considering the beam shine-through for a wide range of scenarios. Finally some indications of the physical effects to be expected from NBI-plasma coupling will be highlighted, with special attention to the beam energy absorption (both in terms of time dependent quantities and of spatial profiles) and to the possibility of inducing a transition from L to H confinement modes.

2. METIS simulation of RFX-mod tokamak discharges

METIS [7] is the tool used in this work to simulate a full RFX-mod tokamak plasma. The METIS code allows simulation of a full tokamak discharge in the time-scale of few minutes on a commercial PC, using relations coming from scaling laws coupled with simplified source models. It can evaluate both the time-dependence and the radial profiles of the physical quantities. For each simulated discharge, METIS needs as an input the time dependence of plasma current and density, the geometry of the plasma (last closed flux surface shape, major and minor radius), the plasma composition and the additional heating (NBI or waves). The other parameters, such as the plasma composition, the impurities, the transport coefficients, the MHD instability parameters, the profiles shape, neoclassical effects, L-H transition coefficients, etc. have been evaluated and validated with experimental data. Although METIS has been widely used to simulate different tokamaks, a RFX-mod discharge has never been simulated with METIS so far. We therefore performed as validation a METIS simulation of

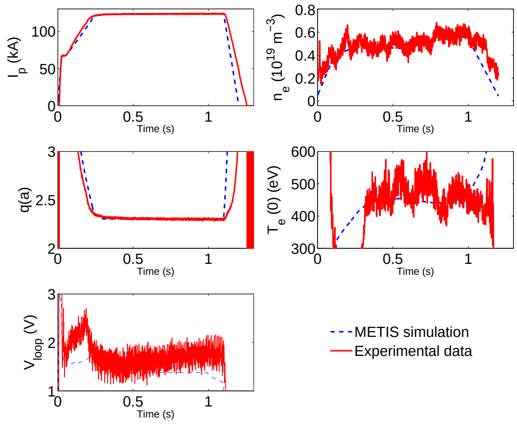

Figure 2: Comparison between experimental data and METIS simulation for shot #38688.

some reference RFX shots. Results were compared with experimental data showing a good agreement (in figure 2 an example is shown). In these simulations careful attention has been given to the flattop phase, including the sawtooth instability.
In order to include a NB system in METIS simulations, it is necessary to define the injection geometry, the beam size (considered as a pencil beam), its energy, the beam power wavefunction, the beam composition and the scaling law related to the current drive electron-shielding. Because of the foreseen normal injection of the RFX-mod NB system, the current drive effect is not considered in this work. As output, METIS can provide e.g. the power deposition to the plasma, the fast particle losses and the slowing-down time.

A set of RFX-mod circular tokamak plasmas discharges has been simulated with typical plasma current and density, as shown in figure 3. In table 1 the labels, the density and the normalised density are indicated for each shot. This database of simulations has been used in this work to study the effect of the implementation of a NB system. As it can be noted, the plasma current (thus the Greenwald density) is kept fixed all over the shots (during the flattop, $I_p = 120\,\text{kA}$, $q_a = 2.3$). The plasma composition is unvaried (main gas deuterium, with carbon and lithium as impurities) while the density profile peaking factor ($n_0/\langle n\rangle$) has been estimated. It varies between 1.1 for the UH shot and 1.3 for the UL shot.

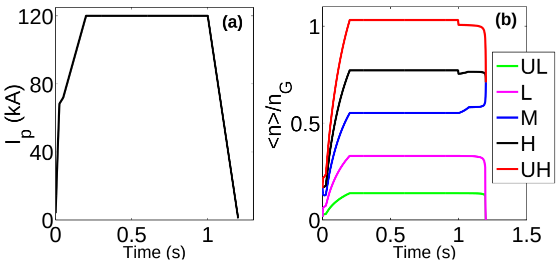

Figure 3: Plasma current (a) and normalised density (b) for the shots simulated with METIS.

Label	Name	$\langle n\rangle(10^{18}\mathrm{m}^{-3})$	$\langle n_e\rangle/n_G(\%)$
UL	Ultra-Low	2.5	13
L	Low	6	32
M	Medium	10	53
H	High	14	75
UH	Ultra-High	18.7	100

Table 1: Density parameters for the reference shots. $\langle n\rangle$ indicates the line-averaged electron density.

3. Results for $E_{beam} = 25\,$keV

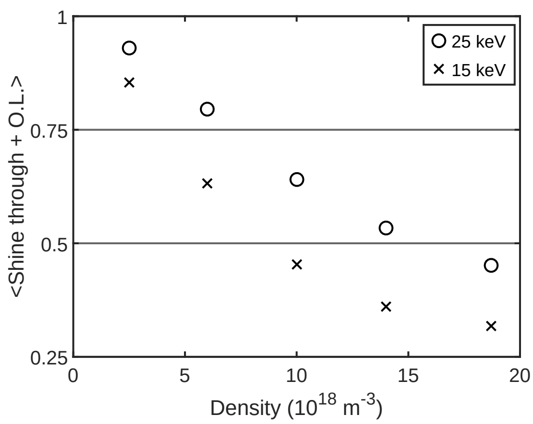

Figure 4: Shine-through as function of density. Two symbols are used for the two beam energies.

In the first part of the work the injection of a 25 keV deuterium beam at the power of 1.25 MW for 30 ms during the flattop is studied. In figure 4 the average losses of the beam energy (accounting shine-through and orbit losses) are shown: for densities below $10^{19}m^{-3}$ (M) the losses are high (above 70 %) and thus not considered in the following analysis. Figure 5 (a) shows that the central electron temperature increases during the NBI by about

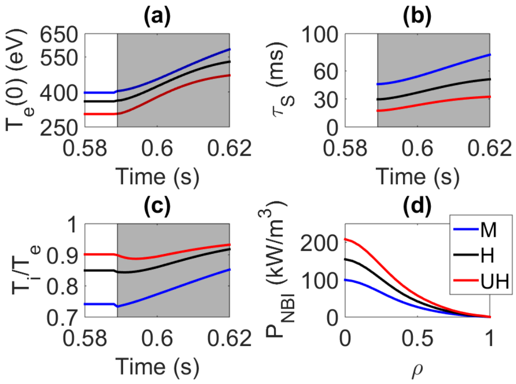

Figure 5: Case $E_{beam} = 25\,$keV: $T_e(0)$ (a), τ_S(b), T_i/T_e(c) and $P_{ABS}(\rho)$(d) for M (blue), H (black) and UH (red) shots. The shaded area is the injection time window.

50% and (b) the slowing-down time reaches at maximum $\sim 0.1\,$s, thus the fast ions can exchange all their energy before the discharge end. In panel (c) it is shown that the average T_i/T_e ratio rises up to ~ 0.9, allowing the exploration of new plasma conditions in RFX-mod tokamak. The power deposition profile is shown in panel (d), showing that the maximum of the absorption is at the center of the plasma column. The beam energy is distributed between ions and electrons depending on the ratio between the beam energy and the so called critical energy of the beam [8]: if it's greater than 1 the energy is given to the electrons, otherwise to the ions. In this case, the critical energy, and thus the energy transfer, depends mainly on the temperature, in fact for a D beam impinging on a D plasma the critical energy is $E_C[\mathrm{keV}] = 18.6\,T_e[\mathrm{keV}]$. In figure 6 the ranges of energy distribution are shown, and it can be clearly seen that most of the power is absorbed by plasma electrons.

4. Results for $E_{beam} = 15\,$keV

Since with a beam energy of 25 keV the shine-through is quite high, a study has been done also with the beam energy of 15 keV, with a duration of 60 ms. As shown in figure 4, with the medium density shot at $E_{beam} = 15\,$keV the losses are below 50 %, indicating that the scenario at reduced energy is promising in terms of shine-through. In this work, the plasma current extracted from the beam source has been assumed constant, thus the power injected in the plasma ($P = I_{ext}\cdot\Delta V_{acc}$) has been scaled linearly.

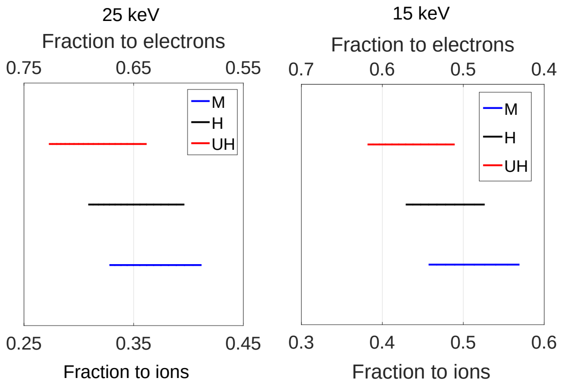

Figure 6: Range of power distribution delivered to ions (bottom) and electrons (top) during NB injection in analysed discharges.

The results of the simulations with 15 keV NBI are shown in figure 7, which can be directly compared to figure 5. It can be seen from panel (a) that the electron temperature (and consequently the slowing-down time in panel (b)) tends to saturate to a fixed value while the ion temperature (panel (c)) increases until the beam is turned-off. A really interesting feature is that the ratio T_i/T_e exceeds 1 for almost all the shots studied. This can be justified by the fact that at lower energies the energy is exchanged mainly with the plasma thermal ions. The absorption profile (d) is similar to the case of 25 keV, though the values are lower. The

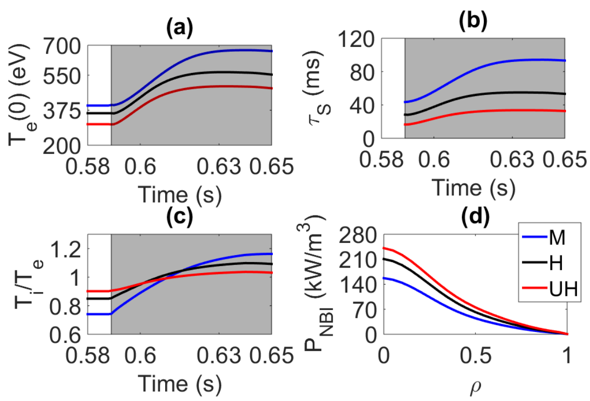

Figure 7: Case $E_{beam} = 15$ keV: $T_e(0)$ (a), τ_S(b), T_i/T_e(c) and $P_{ABS}(\rho)$(d) for M (blue), H (black) and UH (red) shots. The shaded area is the injection time window.

lowest ratio of the energy with respect to the critical energy results in a higher power deposition to the ions, shown in figure 6. Notice that the range is broader in this case with respect to the 25 keV NBI case.

5. Conclusions

In this work, the METIS program has been used to simulate the integration of a NB system in RFX-mod. The simulations have been carried on with NB energy of 25 keV and 15 keV, which are the available energies for the beam to be installed in RFX-mod and with a fixed geometry due to mechanical constraints. The results show that the NBI with $E = 25$ keV will have a high shine-through value but the power deposited to the plasma allows the exploration of different scenarios with higher T_e and $T_i/T_e \sim 0.9$. Similar results are achieved with $E = 15$ keV, leading to $T_i/T_e > 1$ with a lower shine-through.

The addition of NB power can favor the L-H transition: in usual RFX-mod tokamak ohmic discharges, the power flowing through the separatrix is close to the threshold to reach the H mode [9]. In figure 8 it is shown that during the beam injection at 25 keV the power becomes higher than the threshold power needed and thus the L-H transition occurs. At 15 keV the power of the beam alone is instead too low to induce the L-H transition. The scaling law for the threshold power used is taken from [10].

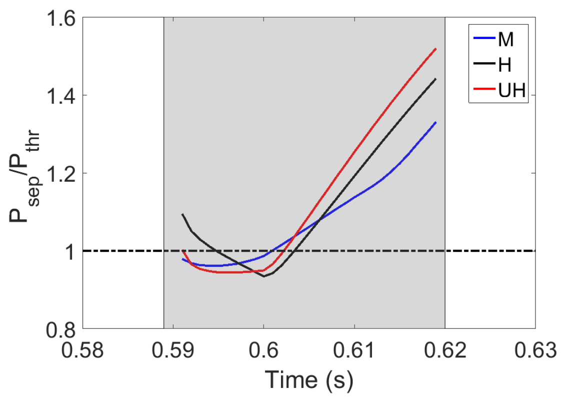

Figure 8: P_{LCFS}/P_{LH}. The shaded area represents the beam injection time window.

Further studies involve a better analysis of the L-H transition, different plasma shapes (like an X-point plasma), a deeper study on the particles orbit and particles birth profile inside a RFX-mod tokamak plasma.

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References

[1] M.E. Puiatti et al., Overview of the RFX-mod contribution to the international fusion science program, Nuclear Fusion 55 (10) (2015) 104012.

[2] Peruzzo S. et al., Design of machine upgrades for the RFX-mod experiment, in: 29th SOFT Symposium on Fusion Technlogy, 2016.

[3] Sakakita H. et al., Characteristics of high-power-density and focused neutral beam system, in: 32nd Conf. Plasma Physics Control. Fus., 2005.

[4] Dal Bello S. et al., Integration design of TPE-RX neutral beam injector on RFX-mod, Fusion Engineering and Design 86 (6–8) (2011) 772–775.

[5] Pilan N. et al., The monte carlo simulation of a 1-mw neutral beam injector on RFX-Mod, IEEE Transactions on Plasma Science 40 (4) (2012) 1042–1052.

[6] Anderson J.K. et al., Simulation of a power neutral beam injection in RFX-Mod, in: 38th EPS conference on Plasma Physics, 2011.

[7] J. F. Artaud, METIS user's guide (2008).

[8] Stix Thomas H., Heating of toroidal plasmas by neutral injection, Plasma Physics 14 (4) (1972) 367.

[9] L. Marrelli et al., Tokamak experiments in RFX-mod with polarized insertable electrode, in: 43rd EPS Conference on Plasma Physics, Leuven, 2016.

[10] Martin YR et al., Power requirement for accessing the h-mode in iter, Journal of Physics: Conference Series 123 (1) (2008) 012033.