BTR Application for Beam Slowing-down Analysis

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Abstract. BTR code, which is generally used for neutral beamlines design and optimizations, is applied to calculate the injected beam stopping in plasma, beam ionization and current drive in a fusion neutron source DEMO-FNS. Beam-plasma model implements a detailed spatial and angular distribution of the injected beam with account of multi-channel injector geometry and operation parameters. The beam ionization incorporates the stopping cross-section fits by Janev-Suzuki. The beam instant 3D deposition in plasma is compared for various beam geometries. The beam losses and detailed shine-through images are obtained with account of beam aberrations in 3D plasma target. The fast ions current profiles are evaluated with a simple slowing-down procedure. The influence of beam size, beamlets focusing and inner divergence is proved to be essential for beam deposition and current drive efficiency. The aberrations of tangential beam decay in toroidal plasmas lead to beam profiles asymmetry, which can be potentially critical for the current drive - especially when *thick* and *divergent* beams are injected *off-axis*.

INTRODUCTION

Neutral beam injection (NBI) is one of the main sources of heating and non-inductive current drive in fusion devices, including fusion neutron sources (FNS) [1]. When the level of injected power is high, the heat loads from the beam can be potentially dangerous for tokamak first wall, especially in the presence of non-axisymmetric perturbations of the magnetic field. Neutral beam injection is a source of plasma rotation, which can also destabilize plasma operation. Therefore, reliable and accurate 3D simulation of NBI is important for any fusion device using NBI. To achieve NBI high performance, a detailed numerical study has to provide the beam power deposition in plasma, the current sources distribution and shine-through imprints. In the earlier stages of fusion it was assumed that tokamak plasmas are toroidal symmetric [2]. In practice, the axis-symmetry of the magnetic field is broken: one of the reasons is the finite number of toroidal field coils, the periodicity can be destroyed also by external magnetic perturbations. A tokamak first wall (FW) is also three-dimensional. Finally, the spatial and angular beam structure can play important role for the beam capture and the beam driven effects, such as current drive, heating and rotation. In FNS device the beam geometry has a strong impact on the fast ions energy distribution, leading to lower neutral yields, than evaluated by simplified beam models. In order to measure these deviations from simplified cases, the beam-plasma models and numerical tools should be able to consider a full 3D geometry of the system, including the injector and plasma configuration.

BTR code [3] is one of these tools allowing a comprehensive and accurate 3D modelling of NBI geometry, the injected beam structure, and plasma configuration. BTR standard beamlet-based model is currently applied to the beam stopping and slowing-down calculations. The model accepts the magnetic surfaces geometry with plasma parameters, and calculates the beam ionization imprints in the plasma volume. The beam ionization is not limited by magnetic separatrix, but can include the region outside the last closed flux surface (or SOL). The data can be used next for particles following (slowing-down) in plasma. Classical BTR is stand-alone Windows application, i.e. an independent tool, but it could be also used in a combination with other codes, which are ready to treat a highly detailed 6D beam statistics. BTR statistics (10^7-10^{12}) is needed to obtain high resolution profiles of beam deposition, shine-through maps, fast ions energy distributions, and current profiles. The beam slowing-down method presented is based on several simple assumptions, e.g. the plasma geometry and profiles are fixed, the orbit effects are neglected. However, this approach is still informative for 3D studies of beam effects, and the results can be easily verified analytically for many cases. The main purpose of the paper is to highlight the beam *geometry effects* on the beam relevant quantities, such as beam deposition and current drive (CD). All the comparisons and verification procedures are not discussed here.

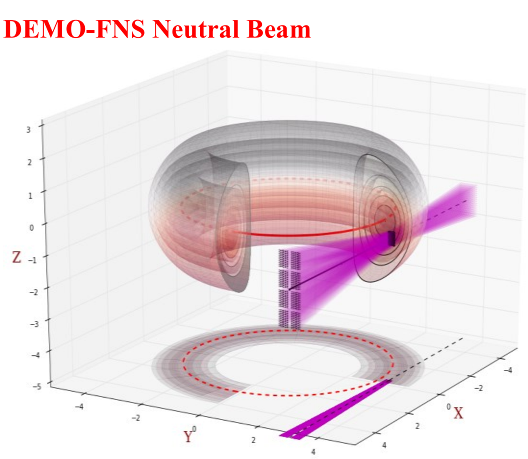
The structure of the paper is as follows. First, the target NBI used for the calculations is described. Next, BTR beamlet-based model is introduced, and simple methods to beam stopping and slowing-down are discussed. Finally, the conclusions are made on the model feasibility.

NBI for DEMO-FNS

Intense fusion neutron sources (FNS) [1] are of interest for many technology and scientific applications, including transmutation of elements, nuclear fuel production and material science. Neutral beam injection, based on deuterium beams, is particularly important in FNS systems, as it provides a comprehensive method for a steady state heating, particles fueling for fusion, current generation and control. High efficiency of beam driven effects is ensured when the beam penetration to plasma is enough to be captured by plasma core. NBI is considered as the most efficient current source, since the beam generated fast ions directly produce the current parallel to the magnetic field. This beam driven current (NBCD), together with bootstrap current can fully replace the inductive current in plasma, making possible the steady-state operation. The best CD efficiency is typically achieved for highest electron temperatures and lowest densities of plasma, and when the beam energy is close to the critical energy [4]. Beam penetration and shine-through losses can also limit the choice of available parameters.

Steady-state operation of fusion neutron source DEMO-FNS [1] will be only possible with additional heating and current drive supplied by fast neutral beams. The entire NBI layout includes six injectors (with four in operation any time). The injected power in a steady-state mode is 30MW (deuterium) with energy E = 500 keV. The NBI concept and main components are similar to ITER heating NBI, with both systems implementing the same ion source. Due to DEMO-FNS dimensions, the nominal injected beam energy is 2 times lower, than that for ITER HNB. This leads to the shorter beamline, with total length 20m, and reduced port size 0.4x0.8m. The beam array structure is optimized to 2 channels (ITER HNB has 4 channels). The injection geometry (Figure 1) is supposed to be off-axis, with the tangential point position R = 3.5m, Z = 0.5m, with no beam tilting.

In FNSs' plasma the neutrons are mainly generated in D-T reaction between the hot injected beam particles and core plasma ions. The high density of injected power in DEMO-FNS leads to specific operation scenarios with a relatively high fraction of fast particles, high rotation velocity, and low collisions rates. Since DEMO-FNS performance is mainly defined by the neutron flux yield of beam-plasma fusion, it should be highly sensitive to the fast ions energy distribution. The most effective current generation in steady-state operation also depends on the beam deposition profile in plasma, and can be achieved only for limited range of parameters. The search of optimum operational window is made with account of the restrictions on shine-through beam losses.



R, m	**3.2**
a, m	**1**
R/a	**3.2**
k	**2**
Z_{eff}	**1-1.5**
T_e, keV	**10 - 15**
n_e, m^{-3}	**0.5 - 1e20**
B, T	**5**
NB power, MW	**30**
Target point Rt/Zt, m	**2.8 … 3.5/ -0.5**
Inclination, deg	**0**
Beam Source	**D-**
Energy, keV	**500**
Window W x H, m	**0.4 x 0.8**

FIGURE 1. DEMO-FNS parameters and Neutral Beam geometry

BTR Beam for Plasma

BTR code ([3], *"Beam Transmission with Re-ionization"*) has been routinely used for NBI beamlines design and optimizations since 2005. BTR model of the neutral beam is the most comprehensive (Figure 2), it calculates a detailed beam geometry and footprints (3D space + 3D velocity) in axial and normal cross-sections, including the plasma entrance. The source beam (i.e. emitted from ion source) multi-beamlet structure is accurately reproduced, and each beamlet is described by individual bi-gauss angular distribution. The beam 6D shape, calculated at the injection port, also accounts for the source ions deflection before neutralization, the beam passing through the injector channels and ducts, and all the beam losses during the transmission path to plasma.

The injected beam is finally represented by 10^5-10^9 neutral particles (or any unlimited amount). Their further ionization in plasma produces the ensemble of 10^7-10^{12} ionized test particles (fast ions). All of the ions can be further slowed down until thermal velocities in 3D magnetic geometry of plasma. No limits are imposed on the spatial geometry of plasma – it is not necessarily axis-symmetric. With unlimited fast particles statistics BTR can deliver high resolution profiles of beam deposition, shine-through maps, fast ions energy distributions, and beam driven current profiles. BTR is completely independent (stand-alone) Windows application, still BTR beam model can be applied as input for other particle following codes, perhaps for future 3D plasma modeling.

Compared to simplified NB models, the detailed BTR beam can be more informative for plasma study. First, it applies the detailed magnetic 3D geometry of plasma when simulating the neutral beam ionization, this leads to a most accurate 6D distribution (positions + velocities) of fast ions source. This becomes important if truly 3D magnetic fields and 2D plasma profiles are available. Besides, BTR offers a great flexibility in the geometry input, so the same approach can be used for NBI geometry study for any plasma device.

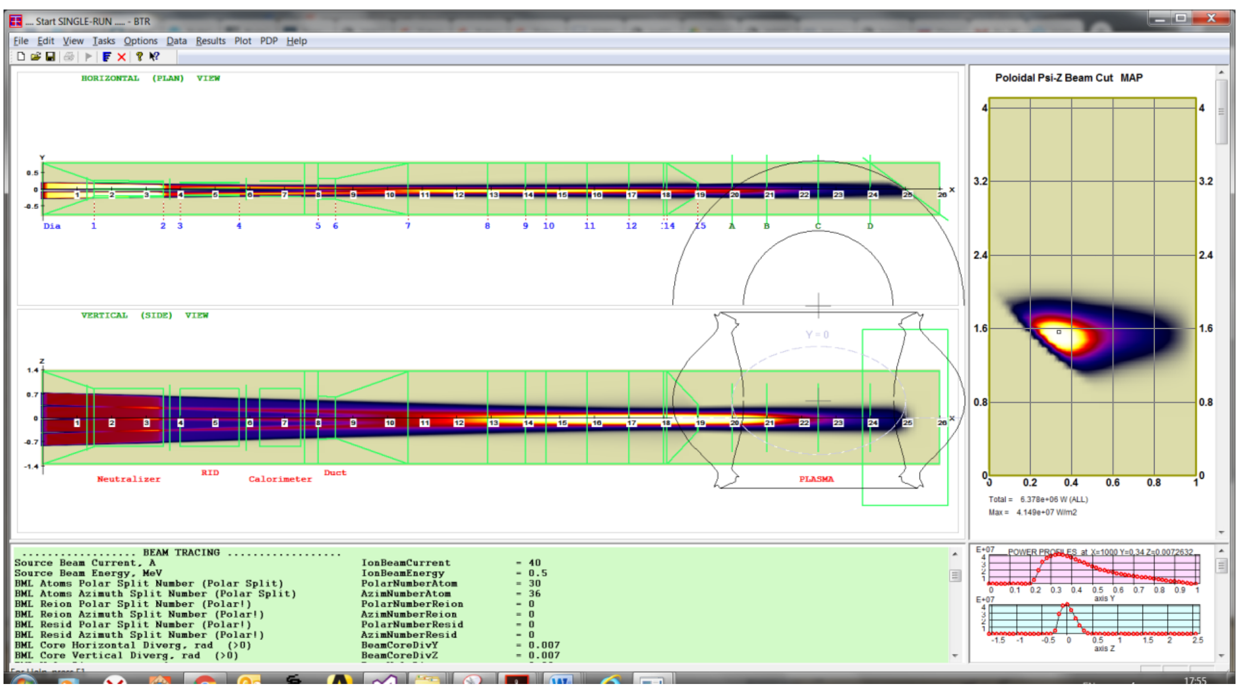


FIGURE 2. BTR-code Screen with the beam power cuts in horizontal and vertical planes (DEMO-FNS NBI)

Beam Stopping Calculations

NB penetration in plasma is accompanied by neutral beam current decay (or beam *stopping*) and fast ions generation. The result ions instant deposition (6D) can be used next for beam-driven effects evaluation: current drive efficiency, momentum source (torque), heating, beam-plasma fusion, neutron yield, etc. Non-ionized fraction of the beam forms the shine-through losses and power load to FW. The plasma profiles ne/Te/Zeff can be either delivered from plasma equilibrium codes, or taken from experimental data available. For parametric studies of DEMO-FNS scenarios, we basically used the profiles delivered by ASTRA, and next – various analytical profiles.

The general results of BTR stopping analysis included: the beam integral decay and ionization profile along the injection axis, the detailed maps of fast ions immediate distribution, and the shine-through power load maps at the first wall. Also we studied the influence of injected beam injection geometry and angular structure, variation of beam target point, beam axis inclinations, and the entire range of possible scenarios. Throughout the calculations, three main beam geometry options are compared: thin beam, rectangular (parallel rays), and focused (converged beamlets axes with inner angular divergence). The detailed beam geometry (3^{rd} beam option) is provided by BTR code, after running it in a real NBI configuration and physical environment.

The basic calculation procedure is described below. The results of beam ionization are shown for one scenario, and illustrate the comparison of two beam shapes: parallel and focused. For thin beam model, all the profiles of beam decay are evident and are easily verified analytically (not shown). All the dependencies on the beam energy, plasma density and temperature, which are obtained by other beam stopping models, are well reproduced by BTR too. Again, these are not shown here.

The NB penetration model implements the analytical fits of cross-sections proposed by Janev [5], and next corrected by Suzuki [6], with account of multistep enhancement.

Beam Ionization: cross-sections

For the special purposes of beam stopping and ionization, a servicing code in Python (BTOR) implements the effective stopping cross-section fits by Janev from [5]:

$$\sigma_z(cm^2) = \sigma_H[1 + (Z_{eff} - 1)S_z]$$

$$\sigma_H(cm^2) = \frac{10^{-16}}{E}\exp\left\{\sum_{i=1}^{2}\sum_{j=1}^{3}\sum_{k=1}^{2} A_{ijk}\varepsilon^{i-1}[\ln N]^{j-1}\,U^{k-1}\right\}$$

$$S_z = \sum_{i=1}^{2}\sum_{j=1}^{3}\sum_{k=1}^{2} B_{ijk}\varepsilon^{i-1}[\ln N]^{j-1}\,U^{k-1}$$

Where: $\varepsilon = \ln(E)$, $N = \frac{ne}{10^{19}}$, $U = \ln(T_e)$.

The improved formula by Suzuki for hydrogen plasma [6] is also included to BTOR:

$$\boldsymbol{\sigma_H(cm^2)} = A_1\frac{10^{-16}}{E}(1 + A_2\varepsilon + A_3\varepsilon^2)\{1+[1 - \exp(-A_4 N)]^{A_5}(A_6 + A_7\varepsilon + A_8\varepsilon^2)\} \times (1 + A_9 U + A_{10}U^2)$$

BTOR delivery is shown in Figure 3. For DEMO-FNS scenarios the effective cross-section value is ~ $1\cdot10^{-20}$m^2.

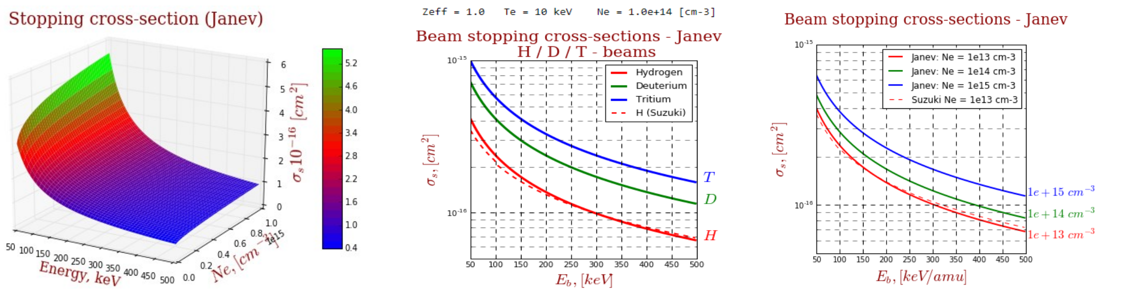
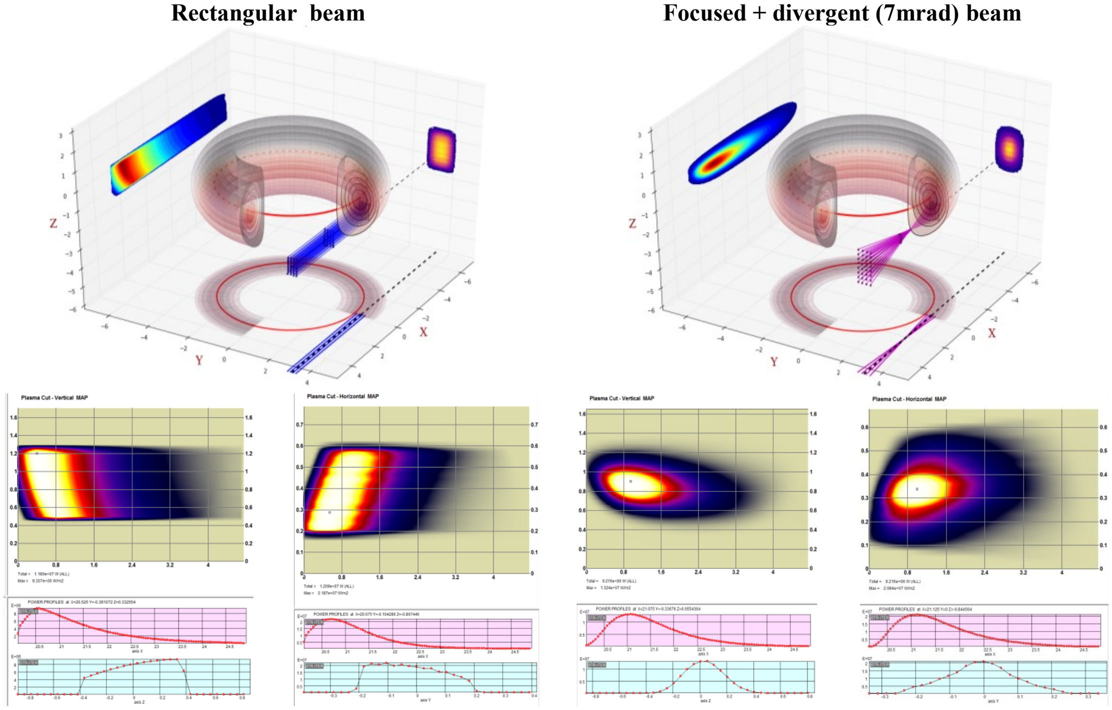


FIGURE 3. Effective stopping cross-section calculated by BTOR (Python). DEMO-FNS: $\boldsymbol{\sigma_s = 0.9 - 1.2 \times 10^{-20} m^2}$

Beam Geometry effect

Figure 4 shows the ionization imprints - for two beam models with finite size, obtained with BTOR cross-sections. Rectangular beam model, represented by parallel rays, is often applied for beam-plasma calculations (especially by MC models), as it is more realistic than thin model (single ray). However, if compared with a detailed beamlets model with focusing and divergence applied, the fast ions imprints in plasma, produced by a rectangular beam, differ essentially from the realistic case, as it is evident from the vertical and horizontal beam cross-sections shown in Figure 4. As the beam driven current depends on the fast ions immediate distribution, the detailed model can correct the expected current drive efficiency. For DEMO-FNS plasma with off-axis injection, the realistic (BTR) beam model gives lower values of total beam current (-20%), than other codes predict. Hence, these effects should be studied more thoroughly.

Rectangular beam **Focused + divergent (7mrad) beam**



Vertical plane **Horizontal plane** **Vertical plane** **Horizontal plane**

FIGURE 4. Comparison of beam 3D deposition (ionization) for basic neutral beam shapes

For transport analysis and magnetic equilibrium reconstruction, the fast ions distribution function caused by neutral beam is essential. It defines the heating profiles, current-drive, and other quantities, which can be next coupled to real-time transport and equilibrium codes. Beyond real-time applications, this knowledge is also essential for design studies or discharge planning. BTR model can be used to calculate it as well.

Fast Ions Slowing-Down

The NBI fast-ion distribution is normally calculated by solving the kinetic equation with a source term (given by the beam), and the collision operator (including fast ions slowing-down and pitch angle scattering). Multiple models, which calculate NB instant fast ion distribution, are currently known and show good agreement with experiments, e.g. NUBEAM [7]. Like all Monte-Carlo models, its accuracy depends (as N^3) on the test particles amount, the beam model in NUBEAM is not beamlet-based, although it is one of the most accurate. There also exist many fast and reduced models, but they usually make quite strong approximations.

Within BTR approach, the neutral beam stopping and fast-ion birth profiles are calculated first, by using the methods described above, with beam shape and angular spectra included. Next, the fast ions (FI) parallel velocity is followed along *thermalization* path in toroidal direction. The velocity profiles for the entire fast ions ensemble (10^7-10^{12} test ions) can be compiled to the result density and energy distribution function, and also give the result radial profile of current produced. This fairly simple model can give the upper limit of the beam driven current (I_{NBCD}) in a steady-state operation, and next can be applied for other beam-plasma effects study, including heating and torque. Here are the basic model assumptions and reductions:

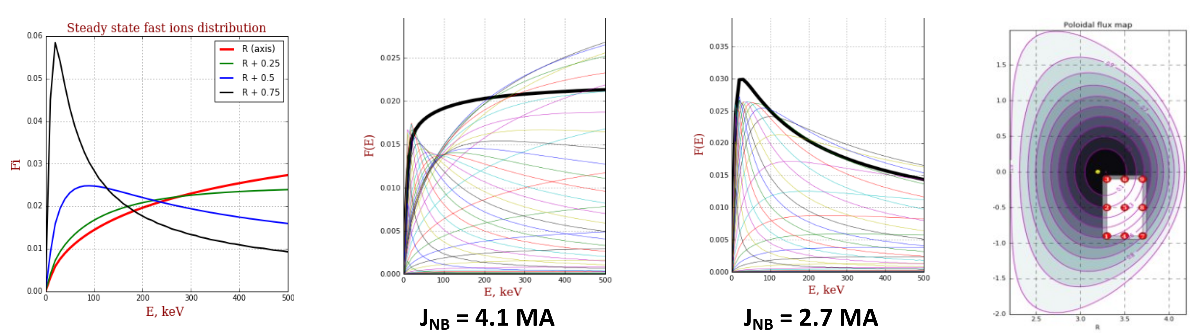
- Each test particle (or FI) slows-down until thermal velocity: $V / V_0 = 0.2$, and stays within layer $\rho = \rho 0$, where ρ is any radial coordinate used for plasma profiles definition (can be a magnetic flux surface, ψ);
- toroidal current produced by FI is defined by its parallel velocity;
- charge-exchange losses, velocity radial diffusion, pitch angle scattering, electron screening, trapped orbits -- are ignored; $I_{NBCD} = I_{NBFI.}$

The characteristic time for beam ions slowing down to the thermal energy, including the drag force on plasma ions and electrons, is taken from [4] as:

$$\tau_s = \frac{\tau_{se}}{3} \cdot ln\left[1 + \left(\frac{Eb}{Ec}\right)^{3/2}\right],$$

Where $\tau_{se} = \text{Coeff} \cdot Te^{3/2} / n_e$ stands for the slowing down on electrons (or Spitser time), see 5.4.3 in [4],
$E_c = 14.8 \cdot A_b / A_i^{3/2} \cdot T_e$ -- is critical energy.

By using this approach, a distribution function can be calculated for each selected group of test particles within the radial plasma layer $\rho = \rho_i$ (partial distribution). Next, to get the total distribution for the beam, all these partial distributions are added with weight of the instant current produced (w_i). The results for partial and total distributions are shown in Figure 5. According to our model, the final distribution function for realistic NB geometry is mainly defined by two factors: the radial current weight (i.e. the instant radial NB deposition profile), and the range of tangent points covered by the beam cross-section (or *NB target window*), see Figure 5-d. The result NB current profiles should also depend on the beam-plasma relative geometry, and this will be shown next.



a b c d

FIGURE 5. Fast ions energy distributions in DEMO-FNS ($n_e = 5 \cdot 10^{19} m^{-3}$, T_e = 15keV): a – partial distribution for fast ions born at different tangent points (red – plasma axis, black – plasma periphery); b – total distribution for BTR beam injected ON-AXIS (R_t/Z_t = 3.2 / 0m); c – total distribution for BTR beam injected OFF-AXIS (R_t/Z_t = 3.5 /-0.5m); d – NB *window*

NB injection produces a current of fast ions circulating around the torus. The fast ions current stacks up during the injection period, and a steady state is reached when the build-up rate of current due to stacking is balanced by the loss rate due to slowing down through collisions with plasma electrons and bulk ions, or to charge exchange of the fast ions with neutral atoms [4]. We assume, that each fast ion carries a current, which decreases along its slowing-down, and the overall toroidal NB current is created by the parallel velocity component of the supra-thermal ions. We neglect the trapped banana orbits, which can reduce the current, especially in low collisions plasma operation, as well as the electron screening; therefore the CD net value is $I_{NBCD} = I_{NBI}$. These approximations allow for *the best case* evaluation (overestimated) of beam driven current and other quantities. It is stated that real CD values *should not exceed* these values, since the electron screening and real orbits can only decrease the fast ions current.

The fast ions current profiles, generated by the beam injected to DEMO-FNS, are shown in Figure 6. The beam 6D shape is calculated by BTR at NBI exit plane, while the target point in plasma is varied. These results confirm the strong link of beam deposition with the driven current and the need of careful matching of beam-plasma parameters to obtain a required CD efficiency. The illustration of NB *current build-up* due to stacking is given also in Figure 7, where the current profile is *followed in time*. The comparison of on-axis and off-axis injection shows an essential difference in CD efficiency (up to 1.5-2 times) between the two options.

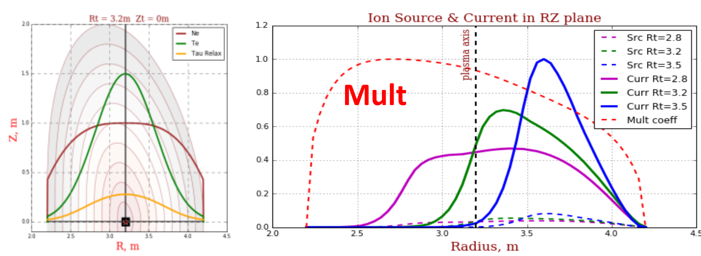


FIGURE 6. NBCD calculations for DEMO-FNS plasma: a - plasma profiles (green – Te, brown – ne, yellow – τ_s); b – instant radial current profiles (dashed curves) and result current profiles (solid lines) obtained for different beam target points (R_t = 2.8, 3.2, 3.5m). Red dashed curve - the effective current multiplication factor, defined by the slowing down time and the circulation radius (number of turns before thermalization).

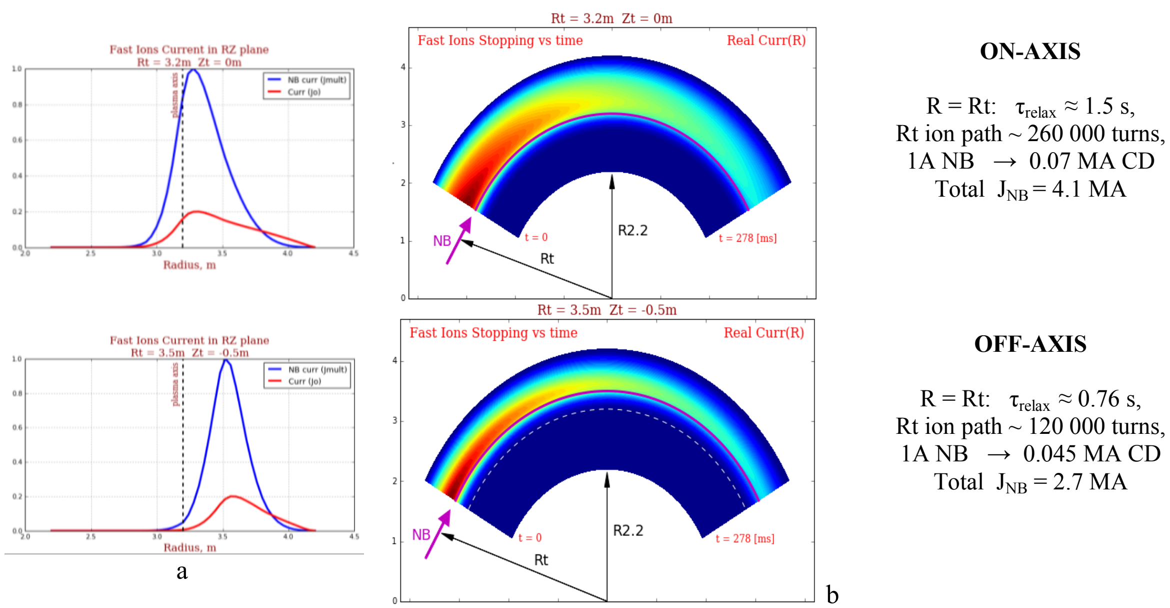


FIGURE 7. Current circulation in DEMO-FNS: a - the instant current (red line), the total current (blue); b – the current profile evolution in time: the time is *evolved* along the toroidal direction φ clockwise. Upper – on-axis, lower – off-axis injection.

CONCLUSIONS

NBI performs the maximum current drive efficiency among all the heating and CD systems. The NBCD radial profiles, as well as other beam driven effects in plasma, strongly depend on the beam 3D deposition in plasma, the latter being sensitive to the beam structure, beam energy, the injection geometry (tangent point and tilting), plasma density and temperature profiles. These parameters should be matched and optimized to achieve the desired plasma scenarios and profiles, and to get maximum available NB efficiency for a given power injected.

In fusion neutron sources NBI is particularly important, as it provides a reliable method for a steady-state heating, particles fueling, current generation and control. In DEMO-FNS, the main source of neutrons is beam-plasma fusion, and this leads to a specific requirement for the fast particles distribution function – to have a relatively high fraction of hot ions in the spectra. NB capability to drive off-axis current is especially interesting from the perspective of steady-state operation in FNS tokamaks.

The neutral beam penetration and the hot ions distributions (in volume and velocity space) in plasma can be calculated by BTR code with high accuracy. The calculations of beam deposition and slowing-down show, that for a given beam energy the optimum *window of plasma parameters* and the overall current drive efficiency can vary in a wide range – when the beam 6D shape or aiming are varied. The off-axis injection in general produces lower current than on-axis. Moreover, the off-axis beam in general is more sensitive to small deviations of plasma parameters or beam aiming, than on-axis. For DEMO-FNS, the values of beam current, predicted by BTR model for off-axis beam, are *~20-30% lower*, than calculated by NUBEAM for similar conditions – this result is rather unexpected, as BTR model should *overestimate* the current generated by the beam ions.

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REFERENCES

1. Kuteev et al., Nuclear Fusion, vol. 57, p. 076039, 2017
2. O. Asunta, J. Govenius, R. Budny, M. Gorelenkova, G. Tardini, T. Kurki-Suonio, A. Salmi, S. Sipilä, Modelling neutral beams in fusion devices: Beamlet-based model for fast particle simulations, Computer Physics Communications 188 (2015) p33
3. BTR-webpage https://sites.google.com/site/btrcode/
4. J.Wesson, Tokamaks, 4th Edition 2011, Oxford: Oxford University Press
5. R.K. Janev et al, Penetration of energetic neutral beams into fusion plasmas, 1989 Nucl. Fusion 29 p2125.
6. S. Suzuki et al, “Attenuation of high-energy neutral hydrogen beams in high-density plasmas” Plasma Phys. Control. Fusion, 1998, vol. 40, p. 2097.
7. A Pankin, D. McCune, R. Andre, G. Bateman, A. Kritz, The tokamak Monte Carlo fast ion module NUBEAM in the national transport code collaboration library, Computer Physics Communications 159 (3) (2004) p157
8. M. Singh et al. 2017 New J. Phys. 19 055004