First NBI configuration study for FAST proposal

M. Baruzzo[1], M. Schneider[2], V. Basiuk[2], A. Cardinali[3], M. Marinucci[3], J. F. Artaud[2], O. Asunta[4], T. Bolzonella[1], F. Crisanti[3], R. Dumont[2], G. Giruzzi[2], F. Imbeaux[2], P. Mantica[5], M. Valisa[1], F. Zonca[3]

[1]Consorzio RFX, Associazione EURATOM-ENEA, Corso Stati Uniti 4, 35127 Padova, Italy
[2]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[3]Associazione Euratom-ENEA sulla Fusione, CP 65-00044 Frascati, Rome, Italy
[4]Helsinki University of Technology, Association Euratom Tekes, PO Box 4100, 02015 TKK, Finland
[5]Istituto di Fisica del Plasma 'P.Caldirola', Associazione Euratom-ENEA-CNR, Milano, Italy

Introduction

FAST is being proposed as part of the European strategy in support to ITER operations and towards DEMO studies [1]. The main mission of this new device will be the exploitation of integrated burning plasma physics issues within a medium size machine, with particular attention to confinement properties of ITER relevant populations of fast particles. To this purpose, the addition of neutral beam injection has been recently proposed for FAST to complement ICRH, LH and ECRH for plasma heating, current drive and fast particle production. In the paper the first results of a Neutral Beam Injection study for FAST tokamak proposal will be presented. The aim of the study is to verify the feasibility of a high energy tangential NBI for the present FAST design and to figure out the effects of the injection on passing and trapped fast particle populations, and on macroscopic discharge parameters in standard FAST H-mode scenario.

FAST NBI conceptual design

The reference H-mode scenario in FAST features a single-null diverted, 6.5 MA of plasma current, 7.5 T of toroidal magnetic field and 30MW of total input power [1], with a central electron density of about $2.5 10^{20} m^{-3}$. The main physics requirements for a beam on FAST are that in order to be relevant to burning plasmas the beam generated fast particles have to be super-Alfvenic and their pressure of the order of a few per cent of the magnetic pressure. In addition, the beam energy must be high enough to assure deep penetration in the dense FAST plasma and also drive preferentially electron heating to emulate alpha heating in a reactor. The associated power has to significantly contribute to the total required input power. Momentum input and current drive capabilities are important ingredients as well, useful for microturbulence and MHD stability and advanced scenarios studies. Beam steering is also desirable to extend the study to different profiles of fast ions densities and power deposition. Such a kind of NBI has to be coupled to a relatively compact (R=1.82 m, a= 0.64 m) high magnetic field device, taking into account the narrow space available between toroidal field coils [1]. A preliminary configuration for this injector has been conceived, with the criterion of being as close as possible to actual ITER design. The considered beam energy ranges between 700keV to 1MeV, with two different injected species Hydrogen and Deuterium, and a total input power of 10MW. Given the prescribed ion energy, the overall dimension of the NBI optics has to be kept similar to the ITER ones. The smaller power required though permits to reduce the source area, to produce a narrower beam and easier to fit inside FAST narrow portholes. For this reason the ITER NBI source geometry has been reduced to two hyperbeamlets columns, giving an overall number of 2 times 4 hyperbeamlets. The source-plasma distance is about 24m, and each hyperbeamlet is horizontally focused at a distance of 23.4m, for the beam to be as narrow as possible inside the duct. For the same reason the same horizontal and vertical focus distances are used for the overall 8 hyperbeamlets focusing. The injection is tangential, as required by the compact machine dimensions and by the high beam energy, with a tangency radius of 1.283m, the largest permitted by the port geometry. The source retains the possibility of tilting the vertical angle as the ITER source, though the tilting angle is reduced to 0.797°, which is already enough to give a very off-axis injection, given the distance to the plasma and the compact size of the device.

FAST NBI simulation using NEMO and SPOT

The effect of this NBI configuration on the standard FAST H-mode scenario has been initially simulated using the NEMO code [2]. NEMO calculates the NBI fast ion birth profiles starting from the cross sections of all of the ion generation processes and given plasma shape, plasma density, ion and electron temperature profiles. It also takes into account the NBI parameters as the 3D configuration of the injector, the injected species and the ion energy. The plasma shape, density and temperature profiles used were taken from a CRONOS simulation [3] of FAST H-mode standard scenario with 30MW of injected ICRH power, where heat diffusion equations were solved using Bohm/gyro-Bohm diffusivities with prescribed electron and ion densities. The input ion and electron temperature and density profiles are plotted in Figure 1. The output 2D fast ion birth rate ($m^{-3}s^{-1}$) for a standard case of on-axis injection of 1MeV deuterons is plotted in Figure 2. The ion birth profile is then used in SPOT [4], a Monte Carlo code which generates test particles according to the birth distribution given by NEMO, and follows their path along magnetic field lines until they thermalize. The simulation is performed in time, taking into account the evolution of NBI fast ions population at each time step, and it ends when the fast ion population reaches the equilibrium state. The output of this step are the fast ion kinetic quantities, such as the equilibrium fast ions distribution in energy space, pitch angle and real space. Also important NBI related quantities are calculated, such as NBI driven current, deposited power and injected torque. The output power densities deposited on electron and ions are plotted in Figure 3. Using this code an extensive

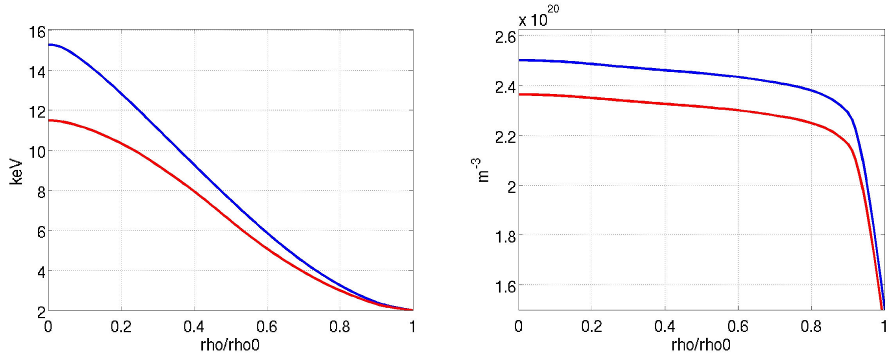

Figure 1: Ion (red) and electron (blue) temperature and density profiles as a function of normalized radius

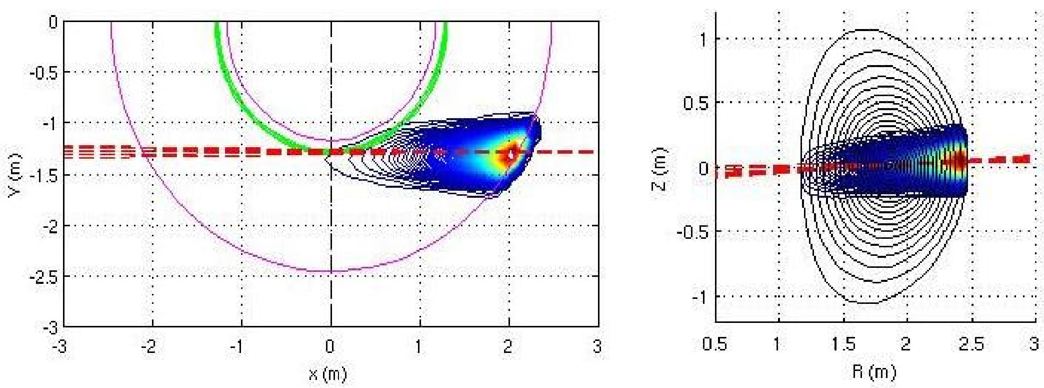

Figure 2: 2d NB deposition for on axis injection, top view (left) and poloidal view (right). Hyperbeamlets axes are overplotted as dashed red lines.

parametric scan has been performed varying ion energy, ion species, beam divergence and injection angle, to evaluate the most effective configuration to fulfil the NBI scientific requirements for FAST. Explored parameters are shown in Table 1. The results of the scan are plotted in Figure 4 for the deuterium injection case. First of all a large difference in the profiles can be noticed between on-axis injection (blue red) and off-axis injection (green, cyan), in fact in the first case both fast ion density and the driven current are steep and peaked in the center, while the second case profiles are centred around ρ=0.4, much broader towards the edge and almost zero in the center. The peaked profiles for the on-axis case are compatible with the edge deposition in Figure 2 taking into account the volume effect. The effect of a larger divergence (dashed lines) is of blurring the beam and making the deposition profile less localized. This can be important in the center, because it lowers the central fast ion density of 20% in the on-axis case, or makes it different from zero in the off-axis case. The reduction of injection energy from 1MeV to 700KeV has the effect of enhancing the ion generation towards the edge-middle ρ zone, lowering the central fast ion density in the on-axis case, while it has little effect in the off-axis case. The results with hydrogen injection are qualitatively similar to the deuterium ones, with similar ion density and driven current profiles.

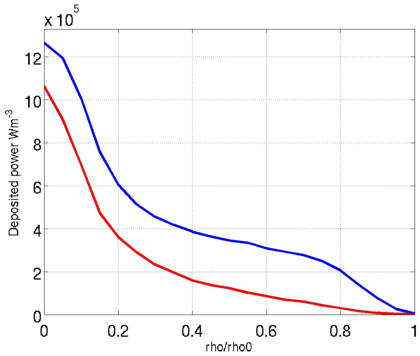

Figure 3: Deposited power on electrons (blue) and ions (red) as a function of normalized radius.

	Isotope	E(MeV)	Divergence	Direction
SCAN1	D	1,00	5,00E-03°	On axis
SCAN2	D	1,00	5,00E-03°	Off axis
SCAN3	D	0,70	5,00E-03°	On axis
SCAN4	D	0,70	5,00E-03°	Off axis
SCAN5	H	1,00	5,00E-03°	On axis
SCAN6	H	1,00	5,00E-03°	Off axis
SCAN7	H	0,70	5,00E-03°	On axis
SCAN8	H	0,70	5,00E-03°	Off axis
SCAN9	D	1,00	7,00E-03°	On axis
SCAN10	D	1,00	7,00E-03°	Off axis
SCAN11	D	0,70	7,00E-03°	On axis
SCAN12	D	0,70	7,00E-03°	Off axis
SCAN13	H	1,00	7,00E-03°	On axis
SCAN14	H	1,00	7,00E-03°	Off axis
SCAN15	H	0,70	7,00E-03°	On axis
SCAN16	H	0,70	7,00E-03°	Off axis

Table 1: Performed parametric scan for FAST NBI

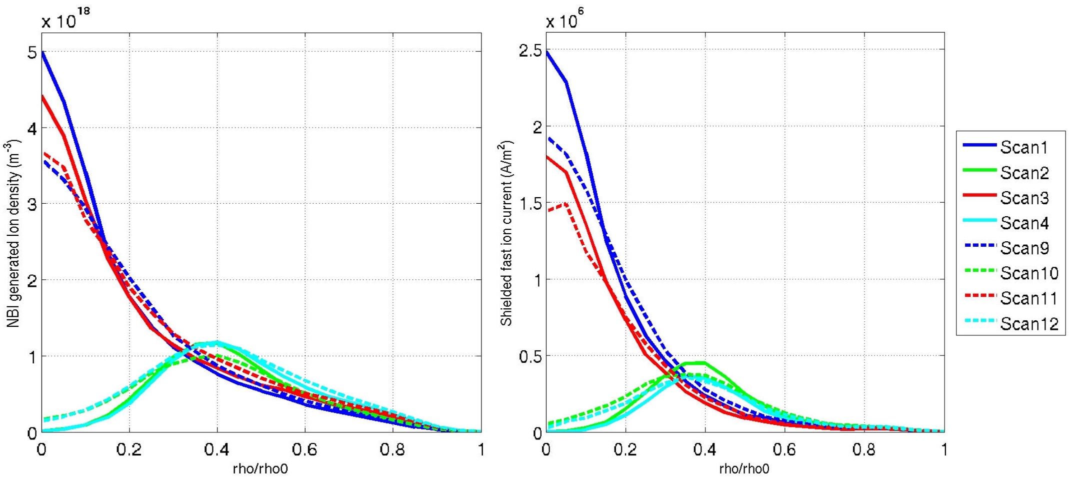

Figure 4: Fast ion density (left) and beam driven current as a function of normalized radius for the parametric scan in the deuterium injection case

CRONOS SIMULATIONS

A full scenario simulation has been also performed using NEMO coupled to CRONOS, to simulate FAST H-mode scenario with a plasma current of 6.5 MA, 30MW ICRH input power and 10MW NBI power. In this case the ICRH deposition profile was calculated offline using TORIC full wave code, and it is peaked at ρ=0.25. In this simulation heat diffusion equations were solved using Bohm/gyro-Bohm diffusivities with prescribed electron and ion densities, as in the initial one.

In Figure 5 the NBI impact on temperature profiles can be seen for a case with the same NBI parameters as SCAN1. In blue the temperature profiles without NBI are plotted, while the profiles with NBI are over-plotted in green. An enhancement of about 2keV can be seen in both ion and electron temperatures for ρ<0.4. In both cases ion temperature is higher than electron temperature at ρ=0.25 given the ICRH deposition mentioned above.

In Figure 6 the difference between offline calculated (blue) and self-consistent (green) radial profiles are shown for fast ion density (top) and NBI driven current density (bottom). In both cases self consistent quantities are slightly larger than the offline calculated quantities for ρ<0.6. This might be due to the higher current drive efficiency for larger electron temperatures for the driven current profile. While the larger fast ions density in the center might be due to the smaller electron ionization cross section for larger electron temperature, which leads to inner deposition and in turn smaller losses towards the edge. The obtained profiles are similar to the ones calculated with the offline version of NEMO, giving the evidence that the parameter optimization performed offline still holds for the self-consistently simulated scenario, and it can be used as a starting point for a more refined optimization using CRONOS. The overall NBI setup gave promising results and it is worth to be analyzed further with more refined CRONOS simulations and a technical feasibility study.

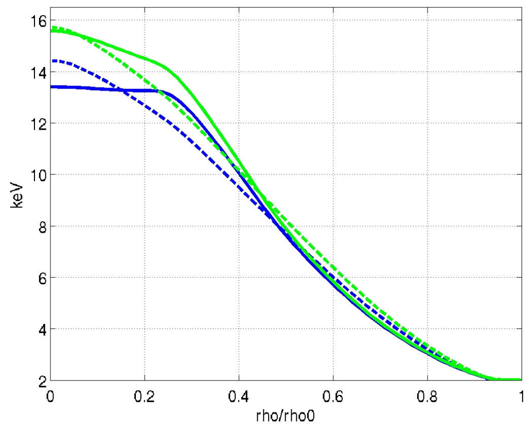

Figure 5: Electron (dashed) and ion temperature (filled) as a function of normalized radius without NBI (blue) and with NBI (green).

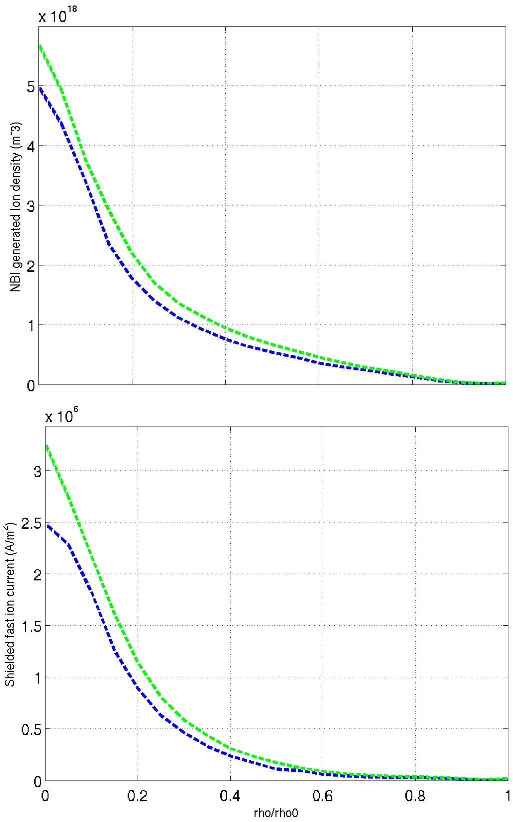

Figure 6: Fast ion density radial profile (top plot) and fast ion current (bottom plot) in the offline case (blue) and in the self-consistent simulation (green).

[1] G. Calabrò *et al* 2009 *Nucl. Fusion* **49,** 055002
[2] M. Schneider *et al to be submitted to Nucl. Fusion*
[3] J.F. Artaud *et al* 2010 *Nucl. Fusion* **50** 043001
[4] M. Schneider *et al* 2005 *Plasma Phys. Control. Fusion* **47**, 2087-2106