Researches on Negative Ion Sources and Neutral Beam Injectors

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Powerful NBIs (neutral beam injectors, up to 40 A of D\(^-\) and 1 MeV continuous beam[1]) are a fundamental ingredient in the ITER project, in order both to heat the fusion plasma over 15 keV and to sustain the plasma current in stationary regimes (pulse length over 400 s, specification is one hour). This capability is called ‘current drive’. For particle energies over a few hundred keV, NBIs are necessarily based on negative ion beam and sources (NIBS) [2], since the small electron binding energy of D\(^-\) (0.7546 eV, while 0.7542 eV for H\(^-\)) makes neutralization reaction very efficient even at 1MeV energies. The NBI test facility, named PRIMA (Padua Research on ITER Megavolt Accelerator) [4], was finally approved for construction at RFX, Padua, by the ITER Council in November 2009. Here we summarize the several researches on the NIBS performed in collaboration between INFN and Consorzio RFX, which are only a part of the large efforts related to NBI development.

Among theoretical researches we have: 1) the analysis of the extraction sheath formed in negative ion sources, with a transverse magnetic field to reduce electron emission[5, 6]; 2) the collection of a database of atomic cross sections of all relevant processes, including hydrogen and deuterium, resolved at least on the lower electronic levels of molecular species (X, A, B, a, c for H\(_2\) and the ground state X for H\(_2^+\)); 3) the simulation of beam extraction and propagation, both with existing codes and with purposely written codes; the latter include important physical phenomena: space charge compensation in the drift tubes, space charge of deflected electrons, and (in progress) transition from collisionless presheath to collisionless sheath at beam extraction6–8; 4) some renewed interest in modeling of high voltage insulation: model ranges from empirical to probabilistic to Monte Carlo to Fokker-Planck-style equations on two dimensional manifolds (electrode surfaces like the anode)[9].

The experimental effort includes: 1) the construction of a relatively small ion source (named NIO1, Negative Ion Optimization phase 1, envisioning a multiaperture extractor with 9 beamlets of 15 mA each of 60 keV H\(^-\) ions) for quick tests of relevant physics and for training[10–12]; source is based on an Inductively Coupled Plasma (ICP); 2) matching of radiofrequency in typical ICP conditions; 3) development of a Fast Emittance Scanner (FES), to correctly validate the emittance prediction of simulation codes[13].

CODE UPGRADES

The BYPO (named from \(B_y\) polarized) code was described elsewhere[7]; it is limited to time independent two spatial dimension (2D) geometries, in order to make possible the study of fine details, as the extraction hole edges and the Debye length \(\lambda_D\). By convention \(z\) is the beam extraction direction, while \(x\) is perpendicular to a given magnetic field \(B_z(x,z)\). Simulation region is restricted to \(x=\pm L_x/2\), where \(L_x\) is the spacing of apertures in \(x\) direction. The scaled quantities \(u=-e\phi/T\) and \(n_i=N_i/N_0\) are used, with \(T\) a typical plasma temperature (1 eV), \(\phi\) the potential electric, \(N_i\) the plasma density and \(N_i\) the i-th species particle density. Since extraction holes have generally a cylindrical symmetry, while the multiaperture system has a (discrete) square symmetry, the Poisson equation is approximately projected in 2D as:

\[
(\partial^2_x + \partial^2_z) n_i w = \frac{w(z,x) - w(z,-x)}{2x^2}
\]

where \(w(z,x)\) includes only the \(m=0\) and \(m=1\) modes of \(u\), and \(n_i = (n_H^+ - n_H^- - n_e)/\lambda_D^2\) is proportional to the net charge. Code accepts options: \(h_z = 1\) for planar geometry (without the second term on the right hand side), \(h_x = |x|\) for cylindrical geometry and \(h_z \equiv \sin(\pi x/L_x) L_x/\pi\) for multiapertures grids. Solutions are simply joined on the singular line \(x=0\) by continuity. The iterative calculation of \(n_i\) was described elsewhere[7], using interpolation and ray tracing (see fig 1). Especially from electron trajectories, it is apparent that transition from a collisional plasma to a collisionless ray tracing is the major issue to clarify in sheath studies [5, 6].

Some simulations of square and round extraction holes was also performed with standard 3D codes, with a fixed emission surface, no magnetic field and no collision.

![Fig. 1. Ray tracing for A) electrons; B) H\(^+\) ions.](Image)
The construction of NIO1 (scheduled for 2009) was delayed for budget cuts, and a limited amount of parts were finally ordered in July 2009. Design was described elsewhere\cite{10}, and only a few notes are here added.

Rf coil modules can be easily changed in the NIO1 concept, since the external rf coil is clamped between disk shaped sub-assembly; in particular the number of turns \(N_1\) of the coil can be changed. Nominal frequency is 2 MHz, in proportion to 1 MHz used in the larger sources actually planned in the NBI injector. In the first half of the year, the NIO1 design was refined: simulation of rf coupling\cite{14} to plasma showed that modules with \(N_1 \leq 5\) have very poor efficiency, so that construction of a \(N_1 = 7\) coil was preferred.

Some small model of a six turn coil source was also prepared and tested in realistic conditions, using dried air as a feeding gas for simplicity. Since the plasma should behave as a coupled rf coil, large variation of the rf matching condition limited range can pass through a second slit, placed about 10 mm after. These particles are collected by a Faraday cup with two deflection plates, so that particles whose \(V_i \leq \frac{1}{7} V_p\) have very poor efficiency, so that construction of a \(N_1 = 7\) coil was preferred.

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Using a strong linear motor (> 2500 N) and a carefully programmed acceleration and deceleration phase (0.25 s, the scanner completes a double measure (two passes into beam at a 0.3 m/s speed) within 2 s. Necessary voltage is |\(V_d\)| < 2 kV with a slew rate up to \(2 \times 10^8\) V/s, for 60 or 80 keV protons. Mechanical parts including the motor, the large bellows mounted on a CF250 flange and the measuring head (size 150 × 150 × 50 mm, including slits, deflection plate, faraday cup) were designed and ordered to the industry (see fig 2).

Data acquisition is also challenging, since \(I\) should be amplified and digitized with a 30 MHz bandwidth and at least a 12 bit accuracy. The faraday cup should be matched to the coaxial line and the amplifier. Memory depth exceeds standard oscilloscope limits, so that dedicated hardware should be planned and procured in 2010.

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Other equipments that can be tested at the NIO1 source include models of beam dumps for NBI systems, and optical spectrometers. Moreover, the accelerator column and the ion source (both generating transverse magnetic field \(B_x\) and \(B_y\) ) can rotated by 90 degree around z axis in NIO1 (in principle), so experimentally verifying the effects of their relative orientation. In summary, the perspective experimental program at NIO1 is rich and includes tests which are difficult to perform on larger sources, but requires a large effort and a consistent financing.

\[2\] W. Kraus et al., Rev. Sci. Instrum. 75 (2004), 1832
\[4\] P. Sonato et al., Fusion Eng. Des., 84, 269 (2009)
\[7\] M. Cavenago, P. Veltri, F. Sattin, G. Serianni, V. Antoni, IEEE Trans. on Plasma Science, 36, pp 1581-1588
\[9\] M. Cavenago, P. Antonini, P. Veltri, N. Pilan, V. Antoni, G. Serianni “Cascades of Secondary Particles in High Voltage Accelerators”, ibidem
\[12\] Agostinetti et al., p 325, ibidem