

MULTIGRID NEGATIVE ION SOURCE TEST AND MODELING

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Abstract

Negative ion sources are a fundamental ingredient of neutral ion beam injectors for tokamaks, like the ITER project[1] and beyond. While detail of formation of negative ions and meniscus of the plasma beam interface at source extraction is still debated, reasonable modelling of the beam extraction is well possible. A project of a small source (up to 9 beamlets of 15 mA each of H^- , 60 kV acceleration voltage) is here described, and relevant modeling tools are reviewed. Flexibility and modularity was emphasized. The extracted beam is directly useful for calorimeter tests and code benchmarking.

INTRODUCTION

The inductively coupled plasma (ICP) ion sources emerged as a reference design for the neutral beam injectors (NBI) included in the ITER project, for the reliable heating of the plasma (based on a few MHz radiofrequency) and for the reasonable current density of H^- extracted ($j_{H^-} = 280 \text{ A/m}^2$). Negative ions are accelerated by a 1 MV voltage in a $0.4 \pm 0.1 \text{ m}$ distance depending from accelerator design[2] and after a 1.6 m drift enter inside a neutralizer. Source works with a gas pressure of 0.3 Pa, while neutralizer works at 0.1(8) Pa (average) and the drift is pumped down to 0.02 Pa by cryopumps. Large experimental facilities (ion current $\geq 40 \text{ A}$, ion energy up to 1 MeV) are being planned at RFX; we here report only on some supporting activities in modelling and on small scale experiments.

A scheme of an rf negative ion source is shown in fig 1, with z as the beam axis. Electrons heated to about $T_e = 4 \text{ eV}$ [3] are confined (by a magnetic filter field B_x) in the rear of source (region 1), while a lower temperature plasma $T_e = 1 \text{ eV}$ diffuses in region 2 towards the source exit, named plasma grid electrode (PG). An intermediate and optional electrode named bias plate (BP) returns to the plasma a large flow of electrons, necessarily lost on PG.

Both mechanisms of negative ion formations need the two plasmas: a) ion formed on the PG walls by the fast neutrals produced in the 4 eV plasma can propagate (and be reflected toward exit) only in the 1 eV plasma (destruction cross section increases with T_e); b) H_2 must be vibrationally excited in the hotter plasma to undergo a dissociative attachment of a cold electron (affinity 0.7 eV). We assume that electron density reduces near PG by the effect of B_x and of the space charge of H^- , so that coextracted current density j_e of electrons is reasonable ($j_e/j_{H^-} \geq 2$).

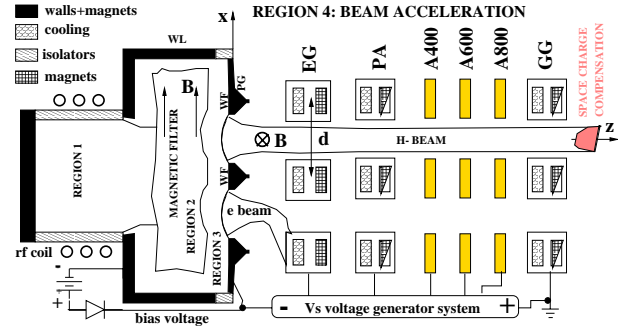


Figure 1: Scheme (not to scale) of a negative ion source and acceleration: additional grids A400, A600 and A800 exist only in MAMUG concept

The extraction grid electrode (EG) has smaller holes than PG has, to accommodate cooling and permanent magnets (PM), and it must stop most of the coextracted electrons below a 10 kV energy. Magnetic remanence B_r of PM can reach 0.96 T. The following electrode (PA) has different functions, names and voltages in different design: in SINGAP (SINGLE GAP), it preaccelerates the beam at 60 kV before injection in the main gap[2]; in MAMUG (Multiple Aperture MULTIPLE GRID) it is the first out of five 200 kV acceleration gaps[4]; in low voltage test facilities (60 to 100 kV) it coincides with the grounded grid (GG). We find convenient to refer to the second acceleration electrode as the preacceleration electrode in any case. After GG, acceleration terminates and space charge compensation occurs[5, 6]. Depending from this compensation, we speculate that an auxiliary electrode may be placed after the end of the accelerator to prevent ion backstreaming.

Many codes exist, or are being developed, to model parts of the negative ion accelerator, and an incomplete summary is here attempted. The electrostatic potential ϕ is solved from

$$\Delta\phi = -\rho/\epsilon_0 \equiv -(e/\epsilon_0)[N_p - N_n - N_e] \quad (1)$$

where N_n (respectively N_p and N_e) is the number density of negative ions (respectively of positive ions and electrons) and ρ is the total space charge. It is generally agreed that existing simulation tools, even if extremely valuable, are not sufficient for a complete understanding of the extracted beam and an accurate prediction of electron orbits; and that code improvement must be continued to fully include the plasma sheath region, where $\rho \neq 0$, with a thickness of about $10\lambda_D$, where $\lambda_D = (\epsilon_0 T_e / N_0 e^2)^{1/2}$ with $N_0 = N_e + N_n$ is the Debye length (about 0.02 mm).

In the design usual procedure, several numerical codes are used, as SLACCAD[2], the recently developed

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EAMCC[7], and some commercial codes as NIGUN[8], SCALA[9], KOBRA3D[10] and PBGUNS[11].

SLACCAD[2] solves eq. 1, calculating N_n by ray tracing in a cylindrical geometry with coordinate (r, z) . Inside plasma, total space charge ρ is set to zero; plasma boundary is defined by the $\phi = -d_1$ equipotential where d_1 is a positive negligible quantity, for example $d_1 = 0.1$ V. The 2D geometry allows to appreciate finer geometry details. Moreover, the model account for stripping losses of the ion beam, which affects ϕ through N_n . At this stage, clearly flawed designs can be rapidly rejected.

EAMCC[7] serves as a second filter in this procedure: the $\phi(r, z)$ previously computed is mapped to a 3D geometry; similarly the magnetic field is taken from a file or from analytic formulas. The particle collision (with gas or wall) are fully accounted with a MonteCarlo technique, and secondary particles are also followed. Even if, due to ramification of the cascade of particles, large fluctuation can exist in the local thermal load, the load integrated onto any electrodes is reasonably precise, and can be used as a design criteria.

Two dimensional PIC (Particle in Cell) and 3D ray tracing codes were developed to study ion motion inside plasma[12], in particular to get the probability that a H^- generated on the PG wall is deviated towards extraction: this ranges from 0.2 to 0.4, increasing with the transverse magnetic field.

In the next section, preliminary results of a selfconsistent code (provisionally called BYPO16) will be shown. Using a planar geometry (z, x) , this code can consider an external magnetic field B_y , and calculate the selfconsistent field ϕ including the contribution of the electron density, which is enhanced before the EG, see Fig. 2. BYPO16 provides also an hoc model of the sheath and of the transverse ion temperature, so that beam halos and/or ion beam hitting the EG are often observed. In the last section, we describe the conceptual design of the a small 60 kV negative ion source (NIO1) which can address four issues: a) to benchmark code results about increasing B_y strength and ion temperature effects; b) to provide some optical diagnostic near to the bias plate and the PG; c) to test calorimetric beam profile monitors, and simple emittance meters; d) to optimize rf coupling to plasma (in the 1-60 MHz range at low power).

A MODELING TOOL

Principles of a selfconsistent code including plasma sheath and beam simulation in a moderate magnetic field were discussed elsewhere[13]. This code evolved with NIO1 design and is based on multiphysics environment[14]. User input is fully parametric, and is contained in a 'struct' data variable, as common in modern programming concept; either one beamlet or an infinite array of beamlet is simulated. Magnetic field is given by analytical solutions for a PM infinite array.

By definition the $z = 0$ plane cuts the PG electrode; in

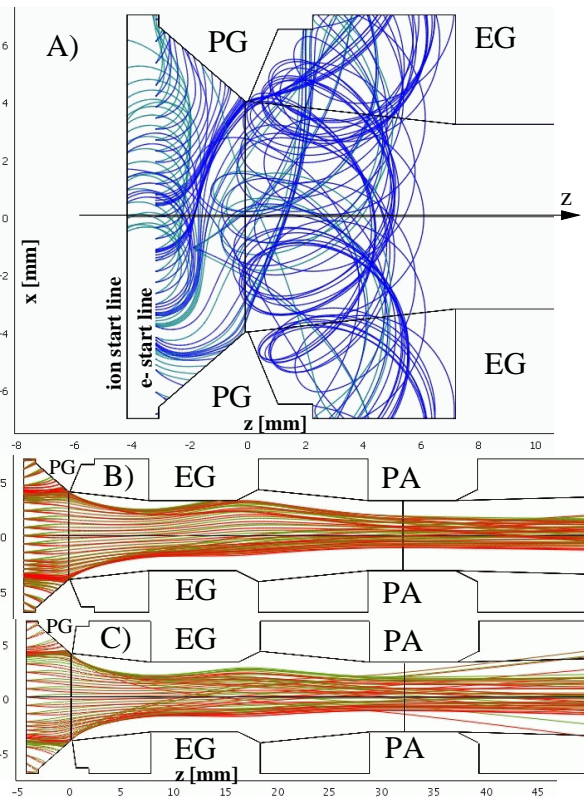


Figure 2: Bypo16 sample outputs: A) electrons for $B_r = 0.96$ T case; B) ions for $B_r = 0.96$ T; C) ions for $B_r = 0.48$ T.

$z < 0$ we leave the inner face, exposed to plasma, and the extraction hole; in $z > 0$ we have the focus electrode profile. This is useful to separately optimize the two PG faces. On the ion start line (fig 2) a nonlinear mixed boundary condition is used for ϕ and its z -derivative $\phi_{,z}$, using the typical dependence between ϕ and $\phi_{,z}$ borrowed from the well known Tonk and Langmuir complete plasma equation [15], with some fitting for numerical stability and speed.

Mesh density is automatically increased inside plasma to allow resolution of λ_D size. We can define a scaling parameter S as the ratio of j_H^- in the actual source and j_H^- assumed as input in the simulation. Plasma density scales as S^{-1} and $\lambda_D \propto S^{1/2}$, so that preliminary simulation can run within reasonable memory size (1 GB RAM) using $S \cong 200$. External voltages scale as $S^{-2/3}$ to keep permeance constant and magnetic field scales as $S^{-1/3}$. Verification of this approximate scaling in 2D will open the way to 3D plasma-beam simulation.

Typical plots of electron and ion trajectories are shown in Fig. 2, for a slightly overdeflected case $B_r = 0.96$ T. Note that electrons which exit from the upper border are reinjected in the lower border. This proves that electron orbits may have many reflections in the acceleration gap (with consequent enhancement of the electron space charge). Unfortunately orbit computation time increases proportionally. In the ion beam, a refinement technique

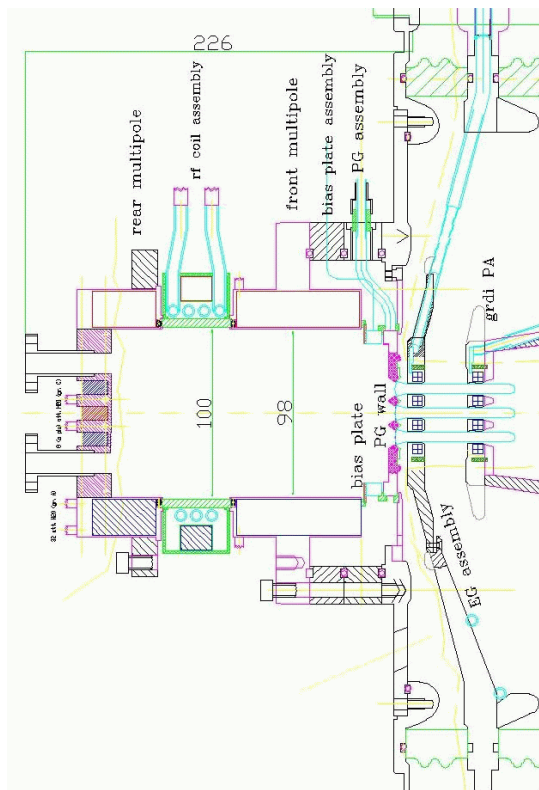


Figure 3: Conceptual design of a small negative ion source

is visible: ray spacing is decreased near the PG edges, so that a precise determination of the extracted beam size is possible even when ray spacing is fairly large in the core beam (where rays interpolation techniques can be used). It should be noted that edge rays usually have much more aberration than core rays, thus refinement is useful for a realistic picture of emittances and halos.

Several code applications and improvements are well in progress. The most important will require a description of the presheath of a negative ion plasma, for which some numerical [12] and analytical studies exists[16].

THE NIO1 PROJECT

The small source conceptual design (called NIO1, for Negative Ion Optimization 1, see Fig. 3) emphasizes modularity, for quick repair of parts, so that source is a tower of disk assemblies (connected by O-rings). Rotation of parts of 90° is possible, to test the better direction of the source magnetic filter (crossed or parallel to the EG field). Consequently we have 9 beam holes in a 14 mm spacing square pattern; hole diameter is 7 mm (maximum 8 mm). Requiring $j_{H^-} \geq 280 \text{ A/m}^2$ (equivalent to 200 A/m^2 of D^- , which is the ITER design value), total extracted ion current is in the order of 100 mA (an economic limit); nominal source voltage is $V_s = -60 \text{ kV}$, with isolators up to $V_s = -100 \text{ kV}$. Square pattern has other advantages: a) we get more elliptic aberration on the lateral beams, so simulating NBI systems for ITER closely; b) permanent mag-

net placement seems easier. Magnetic field was carefully equalized between holes, using some iron shimming; all simulations were done in same multiphysics environment used by BYPO16 as well [14]. Due to the small size, manufacturing the EG electrode (movable along z) will be a technical test.

The PA design include removable PMs also, to improve beam alignment, and for generality. Operation is limited to clean H_2 . A quickly removable Cs oven was also proposed. Source has an $m = 7$ multipole field (14 poles), so to merge smoothly with the B_x dipole field. Two lines of view pass between multipole bars.

Plasma is inductively coupled to an external rf antenna[17], wound over a 47 mm long ceramic tube. Some effort was put to make operation without a Faraday shield possible: antenna is water cooled and a jacket around the ceramic allows for air cooling of it. Additional PM behind the coil to supplement plasma confinement are being evaluated. Several advanced matching techniques for rf circuitry are also being studied; main frequency is $2 \pm 0.2 \text{ MHz}$, but low power experiment between 1 and 60 Mhz will be possible. Modular design easily allows to use to a longer rf antenna (as usual) and a Faraday screen, if needed.

Among other innovations to be tested we list: wall material effects; extended bias plate in the ion source; and many beam diagnostic systems, including calorimetric profile monitors and Alison scanners to measure emittance.

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