NIO1 A VERSATILE NEGATIVE ION SOURCE*

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Abstract

The development of neutral beam injectors (NBI) for tokamaks like the ITER project requires high performance and huge negative ion sources (40 A of D- beam required); it was recently accepted that inductive plasma coupled (ICP) radiofrequency sources are the preferred option. It is therefore useful to have a moderate size source of modular design to test and verify both construction technologies and components and simulation codes; here the NIO1 design (60 kV, 9 beamlets of 15 mA H- each) and construction status are described. Source is assembled from disk shaped modules, for rapid replacement; the beamlets are arranged in 3 times 3 square matrix. Solution for strong electrodes water cooling, magnetic filter control and cesium regulation are described.

INTRODUCTION

The efficiency of neutral beam injectors (NBI) for fusion reactors, like the ITER (International Thermonuclear Experimental Reactor) project and beyond, does also depend on the negative ion source (NIS), which is the first part of the NBI system. The large current (50 A of D- beam) and the high voltage insulation (1 MV) makes it desirable to have several similar but smaller test sources, where optimization studies can be continuously pursued, as well as tests of manufacturing procedures. Here we describe the status of NIO1 project (Negative Ion Optimization phase 1, see fig 1), envisioning a 60 kV source of only H^- ions, extracting 9 beamlets of 15 mA each.

Due to the small electron H affinity (0.75 eV), two H^-production mechanisms were debated in literature[1, 2], and both require a two step sequence to work efficiently: 1) in the so called surface production, first an electron with energy $E_e > 8$ eV raises H_2 from the electronic ground state X to the electronic unstable state b, whose dissociation produces fast H^0 fragments: $e + \mathrm{H}_2(X,0) \rightarrow \mathrm{H}_2(b) + e \rightarrow 2\mathrm{H}^0 + e$. These fragments then hit walls whose work function is decreased by the presence of cesium, producing H^- via the reaction $\mathrm{H}^0 + \mathrm{Cs}^-(w) \rightarrow \mathrm{H}^- + \mathrm{Cs}(w)$; optimal conditions[2] are half a monolayer of Cs coverage, H^0 kinetic energy larger than 2 eV and a low extraction voltage material; 2) in the so called volume production, the H_2 molecule is excited by an electron with energy $E_e \geq 5$ eV to a vibrational level $\nu \geq 5$; then a slow electron $E_e \cong 1$ eV is needed by the reaction $e + \mathrm{H}_2(X,\nu) \rightarrow \mathrm{H}^- + \mathrm{H}^0$. Electrons with $E_e > 15$ eV (i.e. $T_e \geq 4$ eV) are required to ionize H_2 and form the plasma[3], but $T_e \leq 1$ is necessary for a good H^- survival, since rate of destruction $e + \mathrm{H}^- \rightarrow 2e + H^0$ increases with E_e. For these reasons, in NIS we must have two plasma regions; one hot plasma $T_e \geq 4$ eV and one cold plasma $T_e \leq 1$ eV, separated by a magnetic filter which reduces T_e and the electron density n_e.

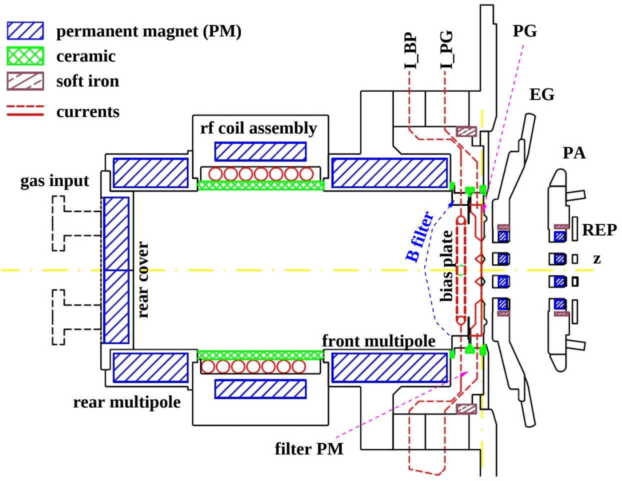

Figure 1: Scheme of NIO1 source: horizontal section (solid lines) and major connections not in section plane (dashed)

Detail of extraction and beam formation are discussed elsewhere[4, 5]; simple estimates of the extracted particle current $j_e = k_1 n_e (T_e/m_e)^{1/2}$ and $j_{H^-} = k_1 n_{H^-} (T_H/m_H)^{1/2}$ with $k^1 = (2\pi)^{-1/2}$ show that $n_e \ll n_{H^-}$ for a reasonable current ratio $R_j = j_e/j_{H^-} < 2$.

NIS were greatly improved in past years[6], and the Inductively Coupled Plasma (ICP) sources with an external rf antenna are now preferred for durability[2], but some points are still debated: 1) the calculation of the extracted beam quality, as a function of source parameter and electrode design; this affects heat load and losses inside the accelerator; 2) the uniformity of beamlet parameters and quality; 3) the long term evolution of Cs wall coverage in a steady state plasma[7]; 4) the relative importance of source magnetic confinement for source performance; 5) the minimization of the source filling gas pressure (specification is $p_1 \leq 0.3$ Pa, since diffusing gas causes beam losses into the accelerator and needs large pumping system); 6) the understanding of the rf power balance. We should note that pressure and source dimension are somewhat inversely related, so that working pressure on smaller systems may be interpreted as a worst case estimate.

Another disadvantage of smaller sources is that the size of mechanical parts (like the water cooling channels in

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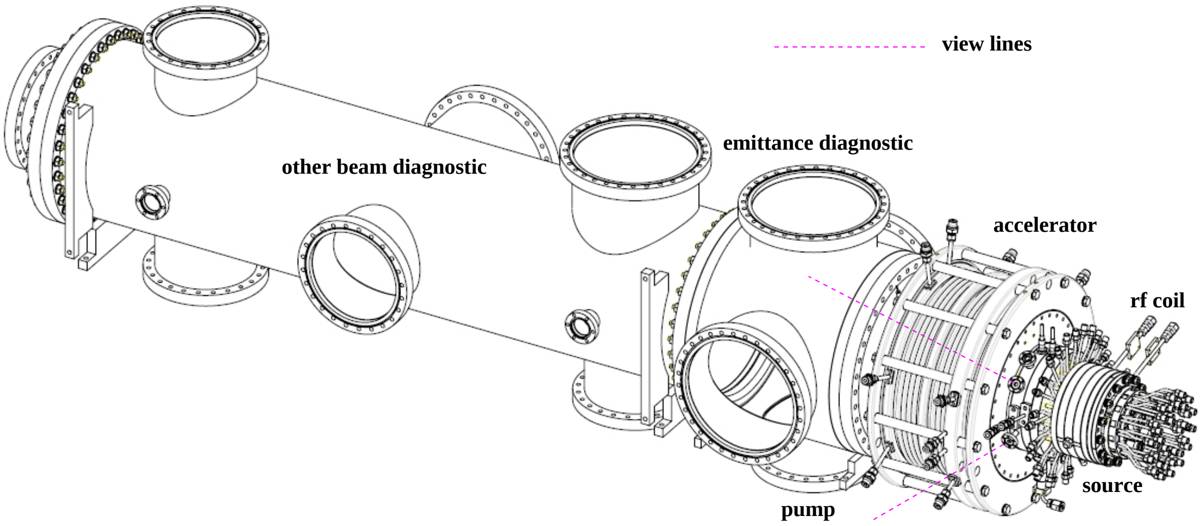

Figure 2: NIO1 global setup: the emittance meter flanges are CF250, the pump flange are CF200; accelerator insulator are sealed by O-ring; support not shown

the accelerator grids) should be proportionally reduced and calls for a precise construction. These cons are more than balanced by the capability of rapidly changing and optimizing again source parts, which makes many experimental campaigns feasible; this aspect is enhanced by the modular NIO1 design (see next section).

NIO1 CONSTRUCTION

NIO1 design was presented elsewhere in detail[8], so that it will only be briefly recalled here (see fig 1 and 2); the construction has begun; most important source issues will be critically described here, with some notes about experimental activities.

NIO1 plasma is approximately a cylinder, 98 mm diameter, 211.7 mm long. Magnetic confinement system of NIO1 can thus follow the symmetry of a $m = 7$ multipole, which can be merged with $m = 1$ dipole filter at the extraction. When all permanent magnets (PM) are assembled as designed, a minimum $|\mathbf{B}|$ configuration is obtained, where a closed surface with a constant $|\mathbf{B}|$ separates the dense central plasma from the walls; in other words we have a magnetic bottle configuration without holes. For NIS, the importance of a strong filter is evident, but the role of the other parts of the magnetic bottle is less clear (differently from other sources). By replacing some SmCo magnets (remanence $B_r = 0.96$ T) with hard ferrite magnets (available from $B_r = .3$ T to 0.38 T) or smaller magnets or non magnetic fillers, NIO1 can explore a fairly complete range of $|\mathbf{B}|$ strengths. Behind the rf coil, hard ferrite magnets (or no magnets) have to be used to reduce rf losses in magnets; moreover, in some simple plasma models, the ICP efficiency decreases with the magnetic field. Air cooling is used for rf coil magnets, while most of other magnets modules (the end cover, the rear multipole, the coil multipole, the front multipole) are strongly water cooled.

The multipole assemblies are (necessarily) electrically connected to the bulk of the ion source mounting flange; they constitute 90 % of the metal surface exposed to plasma, so playing an important reference role for the plasma average potential and wall current. The other metal surfaces that are exposed to plasma belong to the bias plate assembly and the plasma grid assembly, biased at different voltages. Let V_w and V_{BP} the voltage of multipole walls and of bias plate with respect to the PG walls. A few volt negative V_w is known to be useful, both experimentally[2] and from some simulations and models [5, 9]. We plan to cover all plasma exposed metal surfaces by a 3 μm layer of Mo to reduce sputtering[7].

The PG assembly is composed by an external flange (with several CF16 ports for actinometry, vacuum monitoring, Cs injection) and a 90 mm diameter central disk where the 9 beam extraction holes are carefully machined and two copper tubes allow for the passage of a current I_{PG} and a thermal regulating fluid; the current is guided by a copper insert in this central disk. In the construction design, these tube passages through the external flange are isolated, and sealed by Kalrez Oring, so as to withstand several source on/off cycles. The fluid (air preferred to pressurized water for simplicity) has the functions; 1) to cool the conductor; 2) to maintain the PG disk at a prescribed temperature for optimal Cs coverage, say $T_{PG} = 400$ K to fix ideas. Depending on the I_{PG} value and plasma power load, the fluid has a heating or more frequently a cooling action; in any case, only input T_{in} and output T_o temperature, not T_{PG}, can be directly measured, so that a function of T_{in}, T_o, I_{PG} and fluid flow should be the PG temperature control objective.

The bias plate (BP) assembly also features an external flange (with no ports) and an internal part where a current $I_{PB} = -I_{PG}$ is passed; we have one more insulated part, the bias plate BP itself directly exposed to the plasma and made of solid molybdenum. It can be so verified the effect

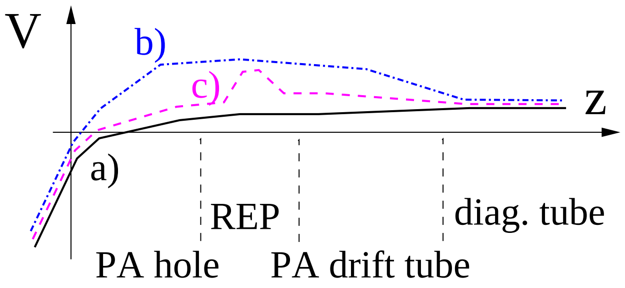

Figure 3: Active and passive back streaming control, voltage $V(z)$ respect to lab ground, for: a) PA earthed and worst case; b) PA bias positive c) PA floating, REP bias positive

V_{BP} in the ±20 V range, which was argued to be useful as the V_W is. The currents I_{PB} and I_{PG}, with a ring shaped iron return yoke provide a valuable supplement to the PM filter field. A honeycomb bias plate HBP is proposed, with two advantages: 1) a larger surface in contact with plasma and with deposition of cesium; 2) a mechanical help to the filtering of hot electrons.

The rf coil is a water cooled tube directly wound with some insulation on the ceramic rf window; an additional forced air cooling is provided for the window. It should be noted that we will try to have NIO1 work without a Faraday shield inside, both for economy of construction and for understanding the plasma rf power balance. A Faraday shield can anyway be easily inserted from the rear cover, if needed.

In general, the rf coil is the inductive part of a LCR resonant circuit. In simpler ICP models, the plasma is the secondary of a non ideal transformer where the rf coil is the primary; therefore as the plasma switches on, the inductance L_1 seen at the primary should decrease and the effective series resistance should increase from R_l to $R_l + R_p$, where R_l is due to circuit losses plus the eddy currents (in walls, coil, Faraday shield) and R_p is due to the ohmic heating of the plasma. We note that a large R_l corresponds to a less efficient rf use, but it enlarges bandwidth of LCR circuit, hindering possible mismatches, plasma variation and efficiency variation with frequency. To develop a better matching, some prototyping of matching boxes and of rf suitable probes has also begun.

In the acceleration column, a great attention is paid to electrode cooling. In the extraction grid EG we have two independent cooling circuits for the central disk (where all nine beam holes have to be strongly cooled), both to accommodate a greater flow and to reduce the pressure drop required. The external flange made of aluminum is separately cooled. The first gap length is adjustable between 5 and 7 mm, thanks to spacers and flexible water connections. Magnet and iron shims pocket are simply machined in the EG central disk, while the water cooling channels are covered by electrodeposition.

The central disk of the final acceleration assembly (called PA from post acceleration grid) is similar to the EG; this assembly includes a watercooled drift tube. The PA is isolated from the main vacuum chamber (pumping cross and beam diagnostic tube), so that it can be positively biased to avoid H_2^+ back streaming (see fig. 3). A small electrode REP can be inserted in the PA assembly: in that case, it is possible to apply this positive bias to REP only. Thanks to isolation, the beam current collected by PA can be measured. By a very firm NIO1 design choice, the magnet system in the PA is similar and roughly specular to EG one, to improve cancellation of ion deflection using the principle of homogeneous actions ("magnet deflection should not be compensated by a transverse electric field, and vice versa, since this would work only near a particular beam velocity"). It is thus possible to keep perveance and beam optics stable, even when ion source current becomes less than the design value, by simply reducing the extraction voltage.

Cesium oven prototyping

Cesium is transported from wall to wall by repeated evaporation (at the wall temperature vapor pressure) and deposition, as given by the geometrical viewing factors of a straight flight, when there is no plasma. In a plasma, Cs is readily ionized, and is transported as other ions. Cesium is also used in sputter negative sources for heavy ions (Au^- for example), where it is well known that the Cs pipe from oven reservoir to source should be heated for the whole length to avoid long term Cs sticking. Since a wrapped heater was unpractical, NIO1 design plans a heavy copper pipe overheated near 470 K at one end; reservoir temperature should be stabilized to a lower value to limit consumption and source coverage; the reservoir is closed by a valve, to help removal and refilling operation (in a glove box). Thermal stability was largely debated, concluding that most parts in air should be enclosed in metal shells and fiberglass boxes. The NIO1 cesium oven is built and going to be commissioned separately from NIO1 at first, since it can fit on a test stand at LNL. This also allows to develop the temperature stabilizing control at ground potential, before integrating it in NIO1 source electronics, and to characterize the Cs flow better.

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