Beam extraction from the Multi-Aperture Negative Ion Source NIO1 and Related Activities of the Beam4Fusion Experiment

M. Cavenago[1], G. Serianni[2], P. Veltri[1,2], M. De Muri[1,2], V. Antoni[2], R. Pasqualotto[2], M. Barbisan[2], B. Laterza[2], L. Baseggio[2], M. Bigi[2], V. Cervaro[2], D. Ravarotto[2], G. Claps[3], G.Croci[4,5,6], P. Agostinetti[2], F. Degli Agostini[2], P. Barbato[2], M. Brombin[2], E. Fagotti[1], L. Franchin[2], G. Gorini[5,6], T. Kulevoy[1,7], F. Cavaliere[8], G. Maero[8], M. Maniero[2], D. Fasolo[9], A. Minarello[1], L. Migliorato[2], F. Molon[2], A. Muraro[4,5], F. Murtas[3], F. Taccogna[10], V. Variale[11], N. Ippolito[11], L. Romanato[2], E. Sartori[2], S. Petrenko[1,7], M. Poggi[1], M. Rebai[5,6], M. Recchia[2], M. Romé[8], M. Sattin[1], M. Tardocchi[4,5], B. Zaniol[2]

[1] INFN-LNL, Divisione Acceleratori, Legnaro, Italy, [2] Consorzio RFX , Padova, Italy, [3] INFN-LNF, Frascati, Italy, [4]Istituto di Fisica del Plasma del CNR, Milano, [5] INFN-MIB, Milano, Italy, [6] Dip. Fisica, Univ. Milano Bicocca, [7]ITEP, Moscow, Russia, [8] Dip. Fisica, Univ. Milano and INFN-MI, Milano, Italy, [9]Centro Ricerche Fusione Univ. Padova, Italy, [10] Nanotech-CNR, Bari, Italy, [11] INFN-BA, Bari, Italy

INTRODUCTION

The Neutral Beam Injectors (NBI) [1,2] are an essential plasma heating system for the International Thermonuclear Experimental Reactor (ITER) project, considering the need of long pulses operations, in order to sustain plasma toroidal current (so called 'current drive').

NBIs are necessarily based on hydrogen-isotope ion sources [3]. In the perspective of the efficiency of the DEMO reactor (the DEMOnstration power plant), NBIs and their ion sources need to be improved and strongly optimized [4].

A relatively compact radiofrequency (rf) ion source, named NIO1 (Negative Ion Optimization phase 1) [5-9], was developed by INFN and Consorzio RFX, and installed at RFX, Padua, to provide a test bench for source optimizations in support to the ITER NBI test facility, which will include two prototypes SPIDER and MITICA, under construction at Consorzio RFX [2]. These optimizations enter also in the framework of INFN experiments INFN-E (for Energy) and Beam4Fusion (Group 5), which also include development of neutron diagnostic for NBI injectors and for tokamaks [10].

NIO1 has 9 beam apertures and is designed for a total H^- current of 130 mA at -60kV extraction voltage; its operation with support gas like air (July 2014) and hydrogen (early 2015) was reported elsewhere [5-7], and together with beam operation (end 2015) are here summarized.

Among theoretical researches related to negative ion sources, this year particular attention was dedicated to critical revision of particle in cell simulation tools, of plasma sheaths and of recirculating beam optics [11-13].

NIO1 STATUS

The NIO1 ion source, described elsewhere [5-7], was delivered to Consorzio RFX in 2013 and put into operation in 2014. The first experiments (July 2014) used air as support gas, at a filling pressure p_s of some Pa inside the source and p_v inside the vessel. From 2015, after the installation according to RFX experience of a hydrogen feeding line, experiments with H_2 were also performed. Improvements in the water cooling circuit and the repair of the water cooled rf generator made experiments with 1 kW rf power or more possible. In the second semester, after installation of some additional protection circuit for electrodes, high voltage operation has progressively begun, up to now limited to source voltage Vs=-20 kV (instead of nominal -60 kV), with a proportional limitation on the voltage of extraction grid (EG). Interlock system [7] and other installation details [5, 7] are described elsewhere.

Improvements under procurement were: a) cryogenic additional pumps; b) additional filter magnet and current path, as well as an independent bias plate voltage; c) a new EG, received at year end; d) water deionizer. Their installation is planned for 2016.

NIO1 EXPERIMENTS

The most interesting result of experiment with air was the clear identification of two rf coupling regimes, the E mode (where a tenuous plasma is perturbed by coil voltage) and the H mode (where a stronger plasma significantly shields coil voltage, leaving a pure inductive coupling), with correlated signatures as discussed elsewhere [5,6]. For example a jump of light emitted is evident (see Fig. 1)

In NIO1 the post-acceleration grid is insulated, so measurement of impinging current is straightforward, see fig 2.a; with an adequate shunt, voltage V_{PA} is the volt order and over, so reducing any noise from rf parasitic rectification. An optional bias (+50 V) to collect secondary electrons is not yet applied, but it is planned for early 2016; similarly the V_{BP} voltage will be measured and driven by a dedicated power supply PBP. A CFC (Carbon Fibre Composite) tile installed as in Fig. 3 was recently insulated to measure current. Some hints of beam footprint (Fig. 2.b) are masked by local scratches to the CFC surface, to be polished at first vacuum opening.

A preliminary estimate of the current I_i of extracted ions (typically at 20 kV) is I_{PA} + I_{CFC}, as shown in Fig 4 while ion current impacting on EG should be zero (with ideal optics) or not much larger than I_i (even in worst condition for optics). It may be thus assumed that coextracted electron current I_e differs from current I_{EG} measured on EG by a quantity of order I_i or lower. Now I_{EG} is typically 300 mA (with 2 kV extraction), with small reduction when source bias or filter is optimized. Thus I_e/I_i is about 170 or larger in this experiment.

Effects of a bias current driven by PBP and of improved magnetic filter need to be investigated in early 2016.

OTHER ACTIVITIES

The beam energy recovery and recirculation for NBI was discussed in the NIO1 collaboration (LNL-BA and RFX), and a conceptual proposal for proofs of principle using the NIO1 beam was published, together with several simulation of the NIO1 physics. At the same time, innovative ideas on recirculation of beam for improving neutralizer efficiency were proposed [12]. The particle-based simulation of the full scale NIO1 source is progressing (adapting an existing code[13]) and detail of rf coupling will be merged soon. Passive neutron diagnostic can monitor the deuterium ions impinging on SPIDER calorimeter [10], using GEM (Gas electron multiplier, developed by INFN and CERN) neutron detectors to give a rapid response. GEM modules, simple and robust enough to be placed just on the back of SPIDER calorimeter, are ready for installation. Prototypes of the dedicated signal acquisition "GEMINI" ASIC chip, capable of processing signals from 16 GEM channels (or 32 channels when mounted on a mini-board compatible with the previous 8-channel CARIOCA chip), were also built, confirming the good operation of the digital part. Optimization of their analog front end is well in progress. A related application of GEM detectors is the discrimination of 2.45 and 14 MeV neutrons, for fusion plasma diagnostic, of progressively wider use worldwide.

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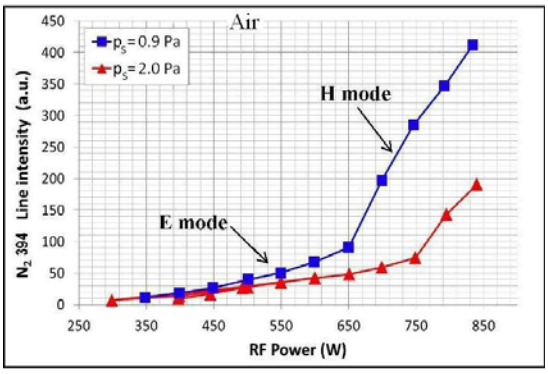

Fig. 1. Intensity of N_2 spectral line at λ=394.3 nm vs rf power (support gas is air).

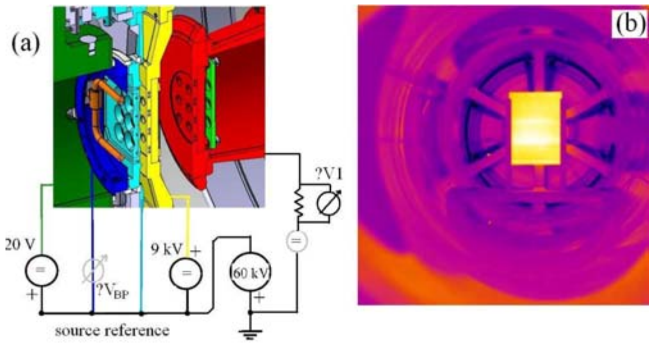

Fig. 2 (a) NIO1 extraction region and some related electronics (b) infrared image of the CFC tile

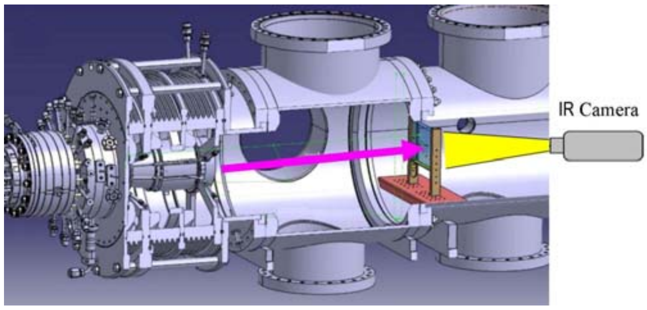

Fig. 3. Cut view of NIO1 beamline, with a temporary CFC tile intercepting the beam

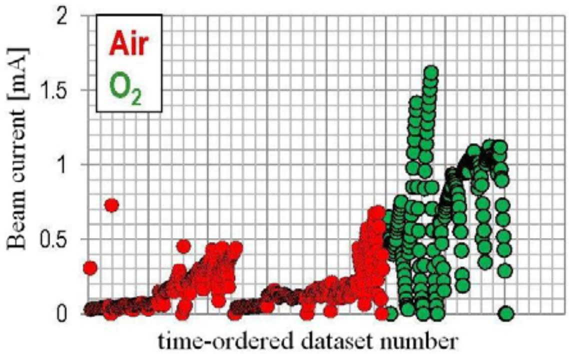

Fig. 4: Apparent beam current (estimated from PA and CFC)