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Laboratori Nazionali di Legnaro (Istituto Nazionale di Fisica Nucleare)

# Extraction of many H- Beamlets from Ion Source NIO1

*M. Cavenago [1,a)], G. Serianni[2], P. Veltri[1,2], M. De Muri[1,2], M. Agostini[2], V. Antoni[2], C. Baltador[2], P. Barbato[2], M. Barbisan[2], A. Barzon[2], L. Baseggio[2], M. Bigi[2], M. Brombin[2], L. Buonincontri[2], V. Cervaro[2], F. Degli Agostini[2], E. Fagotti[1], L. Franchin[2], N. Ippolito[4], K. Timur[5], B. Laterza[2], L. Lotto[2], A.Ludovici[3], G. Maero[6], M. Maniero[2], L. Migliorato[2], A. Minarello[1], P. Minelli[7], F. Molon[2], G. Moro[2], R. Pasqualotto[2], J. Palak[2], T. Patton[2], S. Petrenko[5], A. Pimazzoni[2], D. Ravarotto[2], M. Recchia[2], L. Romanato[2], M. Rome´[6], F. Rossetto[2], E. Sartori[1,3], M. Sattin[1], F. Spinazze`[3], F. Stivanello[1], F. Taccogna[7], M. Tollin[2], L.Trevisan[2], V. Variale[4], M.Ugoletti[1], M. Zanini[3], B. Zaniol[2], S. Zucchetti[2] and P. Sonato[2]*

**[1)] INFN-LNL, viale dell'Universita' n. 2, Legnaro, Italy; [2)] Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), c.so S. Uniti 4, 35127 Padova; [3)] Università Padova; [4)] INFN-BA, Bari, Italy; [5)] ITEP, Moscow, Russia; [6)] INFN-MI and Università Milano; [7)] CNR-Nanotec, Bari; [8)] Università Bologna**

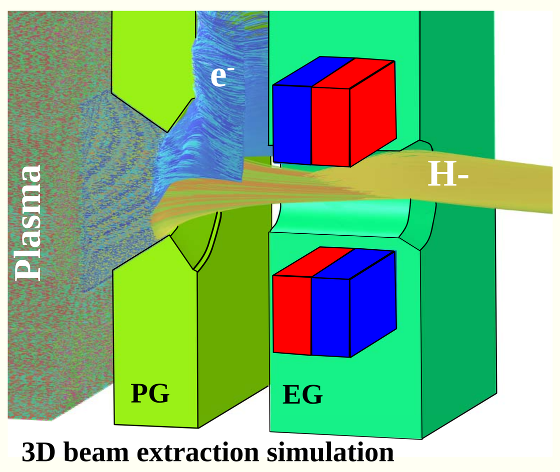
**After installation of Mo liners in the source NIO1 (Negative Ion Optimization phase 1), hydrogen plasma in a continuous regime operation (much longer than one hour) are routinely maintained over 1 kW power and 0.5 Pa pressure, allowing a systematic investigation of pure H$^-$ volume effect, which request a much lower acceleration voltage Vs about 12 kV than future Cs operations Vs about 60 kV . A new extraction grid EG was installed (replacing some eroded BN insulator) and preliminary result are compared old EG ones, especially discussing effect of different deflection field strength and need of intermediate values. Large improvements in beam diagnostics and effect of installation of cryogenic pump are also reported.**

## I. INTRODUCTION

The ion source NIO1 (Negative Ion Optimization phase 1) installed from 2013 at Consorzio RFX in collaboration with INFN-LNL has a modular design to make experimental comparison of several magnetic field configuration and source models possible[1], not only as a support activity for the test facility of the ITER Neutral Beam Injector, but also to possibly validate innovations in negative ion source design in the perspective of future reactors[2]. We describe effects on H$^-$ beams of major improvements from 2016 beginning, which included modification of external and internal magnetic filter, replacement of the extraction grid EG, installation of the first cryopump, and some diagnostics and acquisition upgrades. The cesiation[3] allows a tenfold increase of H- output ( typically to an ion current density $j_{H-} = 330$ A/m$^2$), and in some cases, effect has a moderate persistence[4]; on the other hand, in the perspective of the Demo reactor, one request is to reduce or to eliminate the use of Cs[5], even with a reduction of current density $j_{H-} \cong 200$ A/m$^2$. The Cs oven operation in NIO1 was thus delayed, to test optimal conditions for volume production.

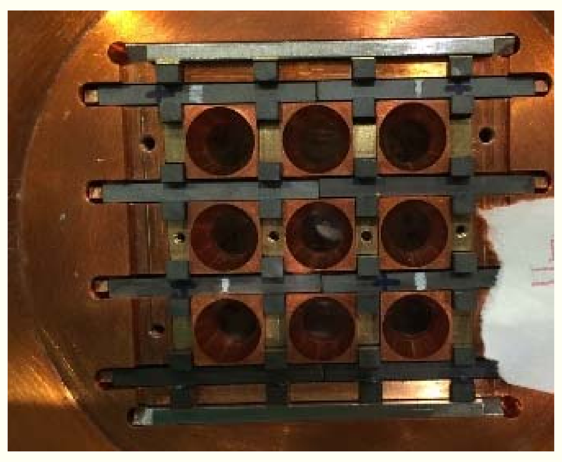
NIO1 set-up was described elsewhere[1, 6]. In the following we summarize most important effect observed.

**NIO1 original extractor**

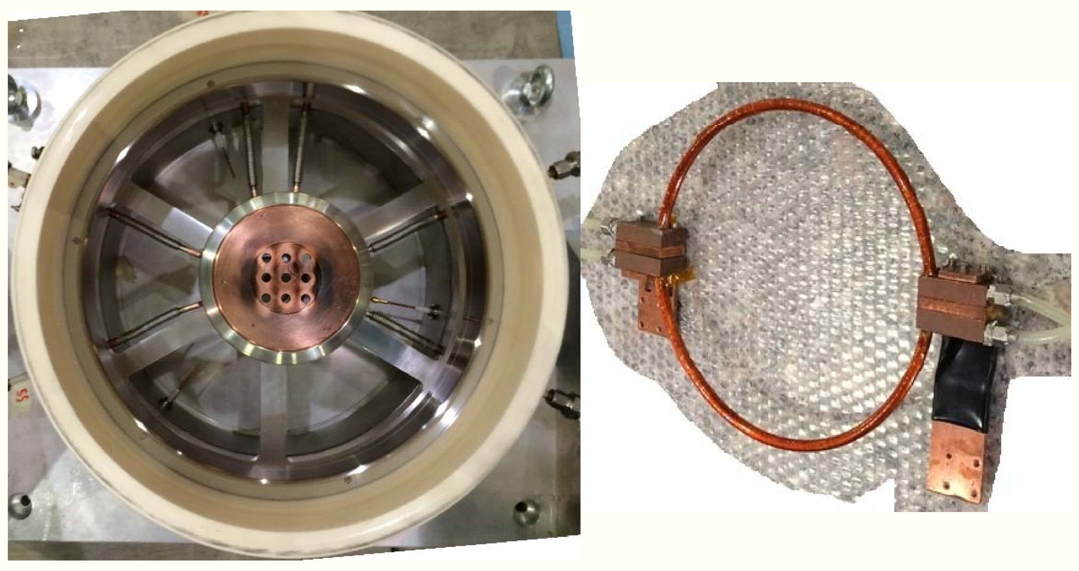



**3D beam extraction simulation**

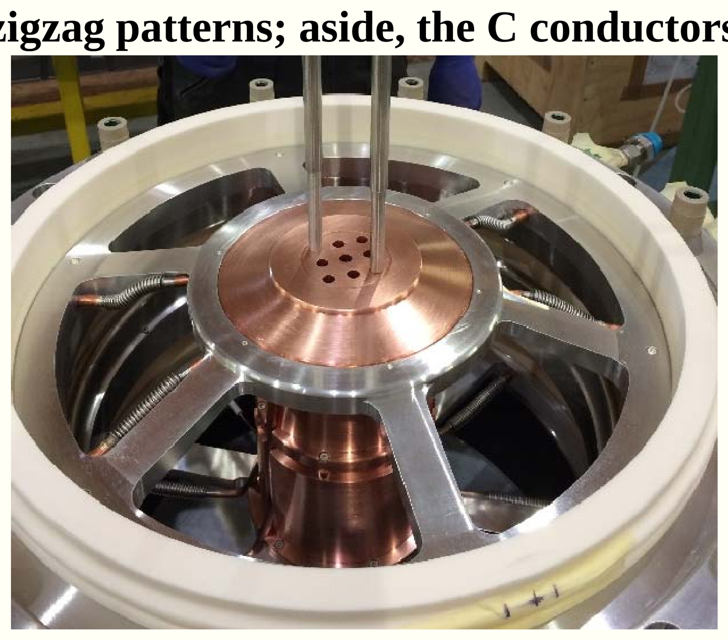
**NIO1 New EG: 40 embed magnets**



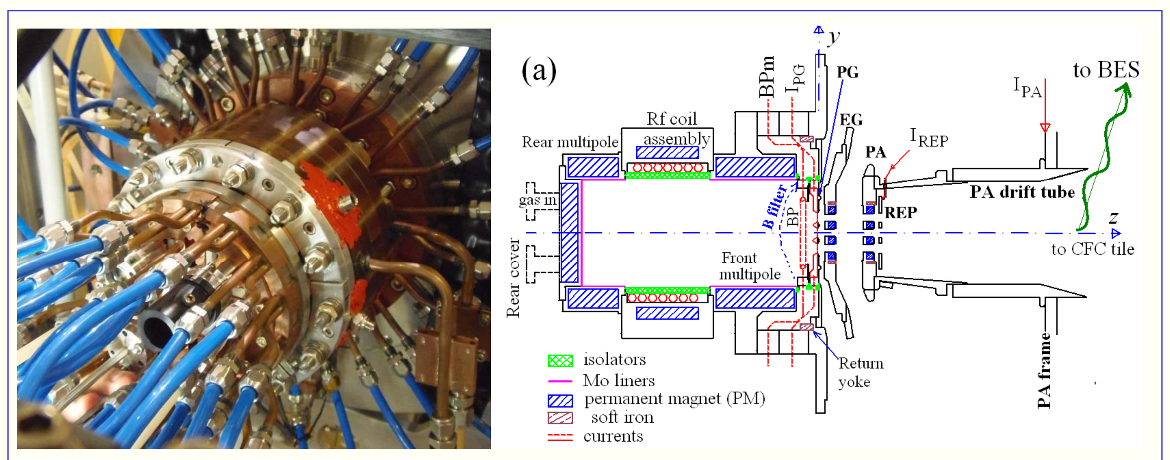
**Some comparison of the old extraction grid of NIO1 (known to tolerably deflect the ion beam from3D simulation) and the new EG grid, using many more magnets**



**May 2017 disassembly: the old EG: note burns with a zigzag patterns; aside, the C conductors**



**The new EG being aligned for tests; note also the accelerator column and PEEK bars**




**NIO1 close up of the ion source head (note strong water cooling for CW operation); (a) a section of ion source and electrode immediately following.**

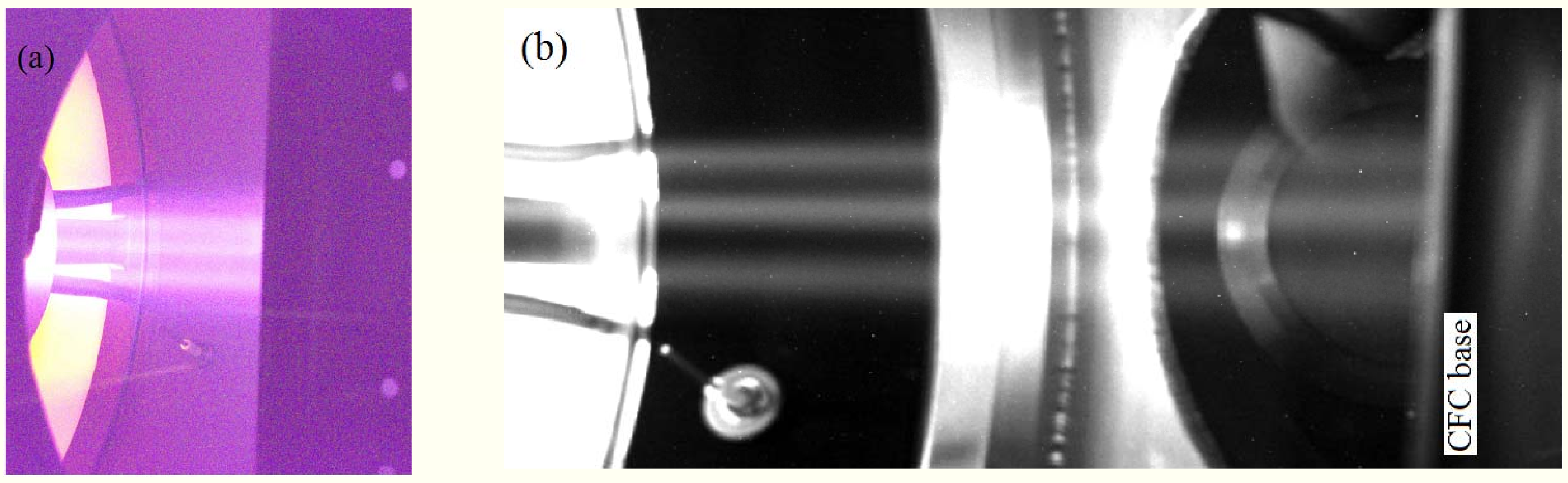



**FIGURE 1.** (a) Bottom view of beamlets extracted with old extraction grid, with visibility enhanced by reflection at $p_2 = 0.48$ Pa and $V_s = 8$ kV; (b) Bottom view of beamlets extracted at low pressure $p_2 \cong 0.03$ Pa (source $p_1 = 0.7$ Pa), low voltage $V_e = 0.3$ kV and $V_s = 2.5$ kV, new extraction grid; note CFC base was moved forward and purposely tilted to avoid direct shine-back.

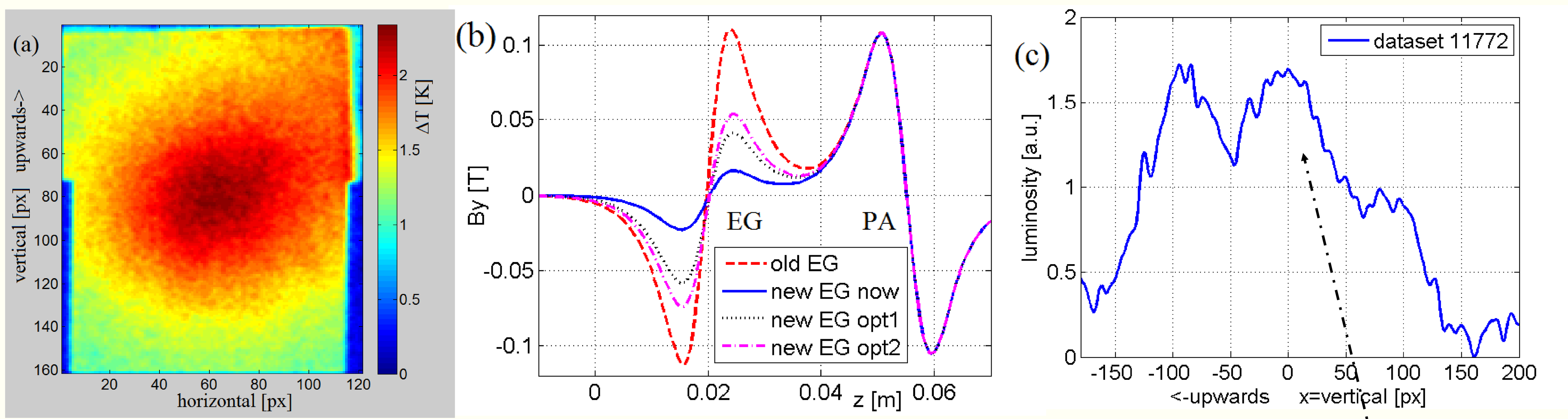



**FIGURE 2.** (a) Temperature rise $\Delta T$ on the CFC tile in 150 s, 1 px = 0.75 mm; (b) comparison of some profiles for $B_y$ on accelerator axis $z$; (c) lateral profile of luminosity; alignment and pixel conversion 1 px ≅ 0.3 mm are preliminary.

## MAJOR EXPERIMENTAL RESULTS + PERSPECTIVES

NIO1 has 9 beam circular apertures with diameter 7.6 mm and is designed for a maximum total H$^-$ current $I_-$ of 130 mA at a maximum $-V_s = -60kV$ total acceleration voltage; assuming $j_{H-} = 30$ A/m$^2$, this scale down to $I_- = 12$ mA and $V_s = 13$ kV and at equal perveance[7]. The installation of molybdenum liners in NIO1 has proven to be successful in order to largely decrease the contamination of rf window by wall sputtering; intense hydrogen plasma are thus achievable even at moderate rf power (1200 W) in a continuous regime operation (much longer than one hour), which enabled prolonged campaign at several plasma conditions; operation down to source pressure $p_1 = 0.5$ Pa is possible, while best beam currents were observed below 1.5 Pa, say $p_1 \cong 1.2$ Pa (always including the $H_2$ correction factor). Even if conductive layer deposition[1] is no longer observed, after month of operation some small decrease of plasma brightness appears, and the rf window (now made in borosilicate) is routinely cleaned at each major shutdown.

Before the installation of the new EG grid[8], database of results with H could be compared to previously results with Oxygen (and Oxygen/Argon mixtures), where a much larger coextracted electron current $I_e$ was measured as expected, and ion beam current was thus limited below 3 mA. On the contrary for H, the limited rf power used resulted in a low extracted current (6 mA), consistently with the stated limitation in voltage. The ratio of $V_s$ to $V_e$ for better beam extraction ranged from 7 to 9 depending on other conditions and optimization goal.

A camera (a visible light intensity two-dimensional imaging device, 1200 x 1600 pixels, 12 bit) looking from below shows three roughly parallel beams, with a still unexplained partial coalescence of two of them (see Fig 1.(a)). On the other hand, in a perpendicular projection (that is, a lateral view), a profile detector (one-dimensional, 2048 pixel) shows one peak only. A proposed explanation was a pile-up effect at the $z$ where detector is looking, since the strong magnets of the old EG deflects two columns of beamlets down and the central one up; this image blurring is helped by beam divergence and beam scattering from gas. The pressure was $p_2 \cong 0.5$ Pa since the two turbopumps are poorly efficient for $H_2$.

During the shutdown (May 2017) for the installation of the EG, NIO1 was fully dismounted and then realigned for the first time. The thin insulators among BP and PG and other walls show plasma related embrittlement, and were rebuilt in a more compact BN grade. Accelerator insulators needed to be cleaned. Re-assembly implied axis rotation, and required few tries of rf windows before a satisfying vacuum was achieved again. More mechanical conformal rf windows are under production.

In initial phase of operation, a large divergence of the beamlets was observed, with largely different luminosity among the three beams visible from bottom. After some optimization of source voltages and installation of additional magnet outside the ion source, we got a good working region with $V_e = 0.3 \pm 0.05$ kV and $V_s$ from 2.5 to 4.5 kV, with a satisfying beam pattern, see fig 1.(b). A reduction of working voltage was in part desired (to match the low current of an uncesiated source at low rf power) and expected, since the new EG was tested with the weaker magnet set: deflection fields $B_y$ of new EG (peak $B_y = -238$ G) is much lower than old EG one (peak -1150 G), see Fig. 2.(b). Assuming an uniform and round meniscus and that coextracted electron to ion current ration was limited $R_j \cong 2$, one-beamlet simulations predicted that new EG correctly stops electrons up to $V_e \cong 1$ kV , with ions optics reasonable up to $V_s \cong 9$ kV; so different assumptions must be searched for.

A possible explanation is insufficient $B_y$ field at all extraction holes. Also as a working hypothesis, we speculate that field $B_y$ from the filter and the EG interfere summing to zero at the central beam extraction, leaving a large electron current to flow out when $V_e > 0.4$ kV so that $R_j > 50$ and all beamlet optics are compromised. Both explanations are supported by the minor improvements observed when adding external magnets to the source body. The insertion of stronger magnets in the EG is planned around the year end shutdown, see opt1 in Fig. 2.(b).

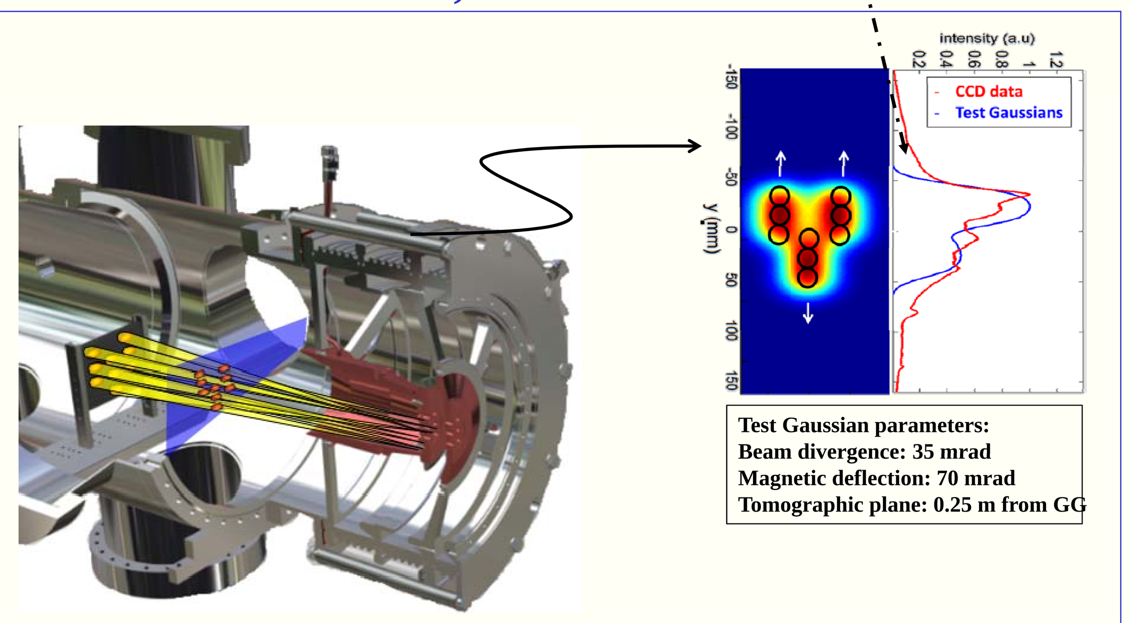
The combination of plasma grid (PG) bias voltage ($V_b$ up 45 V) and bias plate (BP) voltage ($V_{bp}$ separately controllable in NIO1) may help to balance the three beamlets, but affects the coextracted electrode current $I_e$; typical values of current to bias plate are held to $I_{bp} = 0.2$ A. Moreover with new EG at least two beamlet are visible in the lateral projection profile, see Fig 2.(c). A first cryogenic pump was installed, with possibility of improving vessel vacuum for one hour, provided that plasma is started using only turbopumps Just before cryopump input valve opening, gas dosing valve voltage is fixed so that $p_1 = 2.2$ Pa (and $p_2 = 1.35$ Pa), and $P_k = 1.2$ kW. After valve opening pressure drop to $\bar{p}_1 = 0.6$ Pa (and $p_2 = 0.025$ Pa), which still guarantee that plasma stays on. Doppler-shifted emission diagnostic[9] is well consistent with pressure and known atomic cross section profiles, as further verified with cryopump operation. Even if total beam is small in present condition a careful procedure allow to extract data from the static CFC tile: beam is kept on and off for relatively short periods ($\tau < 10^2$ s): so beam heat footprint is not completely leveled by lateral diffusion ($\tau_d < O(10)$ s), see fig 2.(a), and precise total power measure is inferable by subtracting cooling rate from heating rate (by fit or by averaging).

Effectiveness of NIO1 experiment requests a flexible and robust software acquisition, storage and retrieval of information. At the higher level, most of information is indexed by a dataset number.

With reduction of vessel total pressure due to cryogenic pump, sharper beam images are visible by the bottom camera (confirming a previOus trend), but no substantial improvement of voltage holding is apparent. For understanding the role of systematic contamination and possible erratic leaks a residual gas analysis (requiring differential pumping) is being planned, together with vacuum quality improvements (use of denser boron nitride and other high quality materials, cleaning of accelerator insulators). Two circuitry kinds are used to protect electrode; one is inbuilt in power supplies, another one is based on current spike amplitude discrimination: often more spikes are visible at $P_k = 1100$ W than at $P_k = 1200$ W. The voltage holding issue clearly will require more investigation.

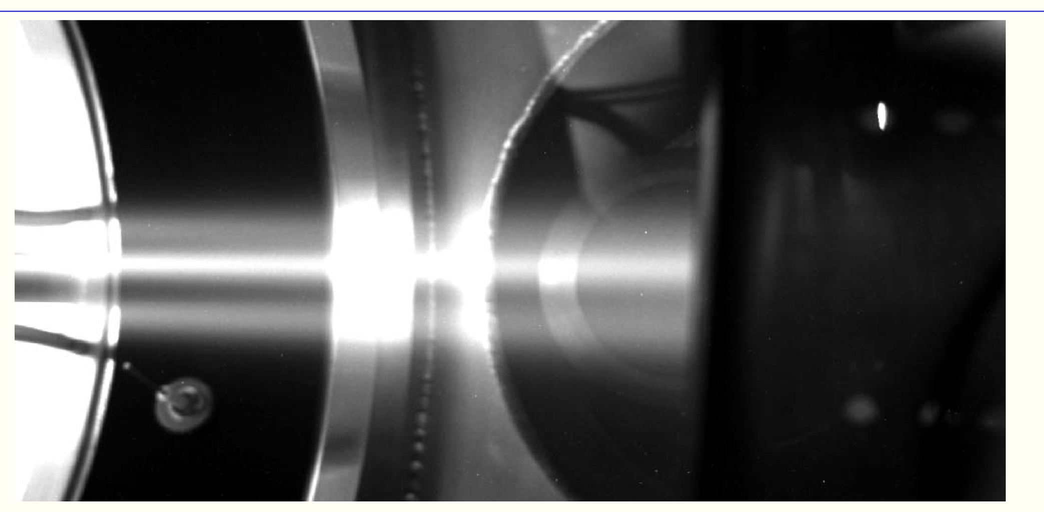
A second camera will be laterally installed (in place of the existing one-dimensional detector), to verify the better alignment of beamlet in deflection direction. In conclusion we got a preliminary confirmation (perhaps fortuitous) of the importance of having a deflection field fringe large enough (so to reduce electron current even in the plasma), and of the preference for crossed direction to filter field[1]; for pursuing a more robust proof and a research of thresholds, EG magnets field will be soon rised.

**Old EG data below, New EG data above**




**The first data show a largely asymmetric beam, whereas in principle one may expect a Gaussian profile. The asymmetry is probably induced by the Magnets in the EG: deflected beamlets (column by columns)**

**(from P. Veltri talk, p. 23, at IPAIA workshop, Bari, 3 March 2017, online at https://agenda.infn.it/conferenceDisplay.py?confId=12546)**



**As fig 1.(b) above but Ve=0.35 kV, Pk=1000 W and p2=0.3 Pa (before cryopump input valve opening)**

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