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Volume and surface effects in Cs-free regimes in NIO1

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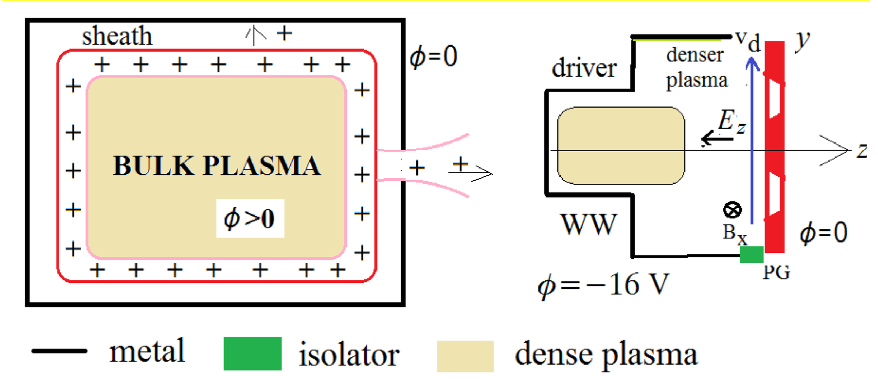
Abstract: NIO1 (Negative Ion Optimization phase 1) is a compact multiaperture radiofrequency H- ion source whose design was optimized for sustainable prolonged beam on target (BOT) operation; installation economy implied a drastic scaling as respect to fusion device D- sources. The latter, in a consistent view for energy production request a beam on tokamak (BOT) span of 20 years, that is 6 10^8 s. Even if Cesium improves H- production as well known, also Cs-free regimes (and intermediate regimes) well deserve some development effort, in view of avoiding long term contamination of the accelerator and for use as cleaning procedure. Data collected by NIO1 in a true Cs-free regime (before 2020) are thus very important, and need a through statistical analysis, with special attention to the technique of gas conditioning that was discovered in NIO1 and to the issues concerned with long term operation. Gas conditioning macroscopically proves the importance of surface effects, even when the final production of H- happens in the source volume. As regards to the Electron Cyclotron Resonance Ion Sources (ECRIS), exchange of ideas and concepts, such as 'electron starvation' and biased disks, liners and wall coatings, is discussed. H- ion sources differ in terms of surface to volume ratio (over 10^2 m^{-1} in matrix ion sources), practically achievable BOT (from 10^4 s to 10^6 s per year) and working frequency (from GHz in the ECRIS case down to 1 MHz) is reviewed. Gas mixing, conditioning and surface material perspectives are envisioned.

I. INTRODUCTION

Negative ions (eg. H^-) production and extraction include much more complex systems ([12]) than positive ions do. Fusion applications add the major challenges: large current feasible only with multiaperture source; 2) CW operation time longer than hours; source life beam on target time BOT = 6 10^8 s (20 years)

I.a BEAM FORMATION



As well known [Tonks, 1929] a positive ion plasma (say in a metal box) develops a positive ambipolar potential (normal sheath), which propels ions to walls. Piercing a hole in the box is enough for extraction. On the contrary, H- beams need: 1) formation of a so called inverted sheath near plasma grid (PG), with one V_b or more bias voltages [see Variale, Cavenago, poster 21]; 2) a magnetic filter field B^f.

I.b H^- production

H_2 dissociation and H+ production (by impact ionization) needs over 15 eV electrons, that is electron temperature T_e > 4 eV (driver region). This plasma will destroy H-, so a colder plasma (extraction region) near PG is obtained with filter Bf to store H-; filter Bf indeed

Dissociative attachment (DA) volume production :

$$e\ (\text{cold}) + H2^* \rightarrow H- + H$$

H2* = vibrationally excited molecule, also produced by >15 eV electrons.

Charge exchange on cesiated wall:

$$H\ (\text{fast}) + Cs + e\ (\text{wall}) \rightarrow H- + Cs + \text{wall}$$

In Cs-based regimes, wall importance is obvious. In NIO1 true Cs-free regimes were studied until 2019; still we find wall effects, mainly gas conditioning.

Some symbols: p_s source pressure; p_2 vessel pressure, P_k forward rf power, I_{pg} current in plasma grid PG electrode , j_i H^- current density, j_e e^- current density

II. SET-UP and development

NIO1 has a modular setup, and achieved H- beam runs longer than 10^4 s, trying to open worldwide a new window in fusion researches on source transient and stability effect. Achieved BOT < 10^6 s/year limited by support.

II.a Overview

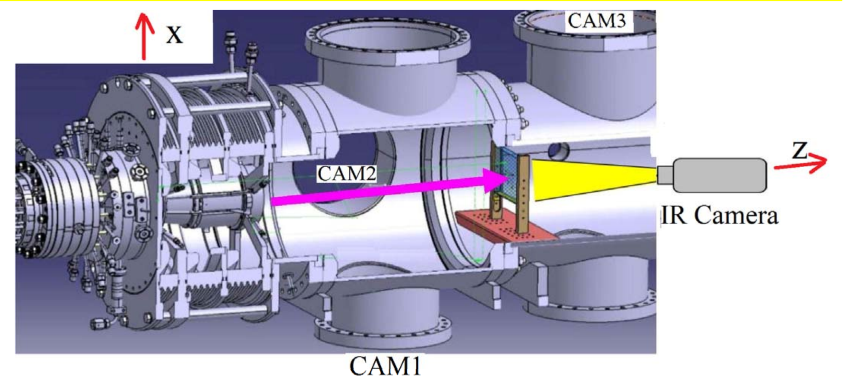
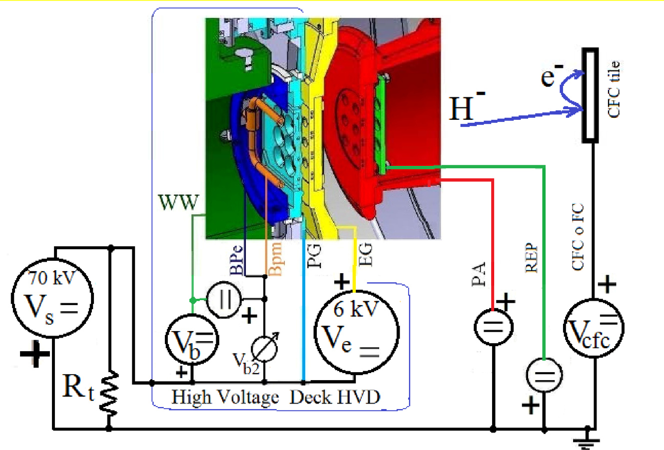


Figure 2. Overall 3D cut view, showing part of NIO1 accelerating electrodes; note CAM1, CAM2 and CAM3 placement; CFC tile recently moved after CAM3 position

II.b Main connections



Nio1 major electrodes and connections; V_s is total acceleration voltage , V_e the extraction voltage, V_b the main bias, V_{cfc} = CFC polarization voltage (absolute values). Corrected ion current is

$$I_a = I_s - (V_s/R_t)$$

power supply current I_s

II.c Transients

Transients (seen from 2017) are a spontaneous change of extracted ion current without major power supplies change. As a first remedies to get back to good current we develop: 1) improved rf window air cooling; 2) change of p_s. So we observed anti-correlation

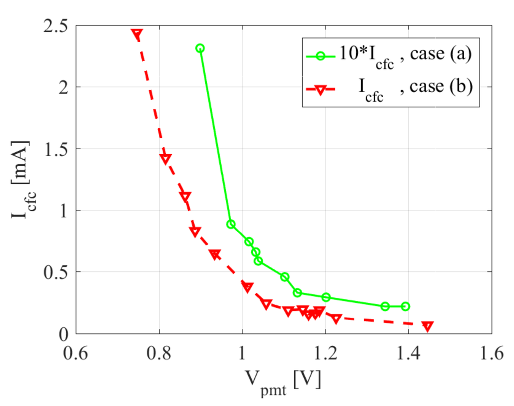
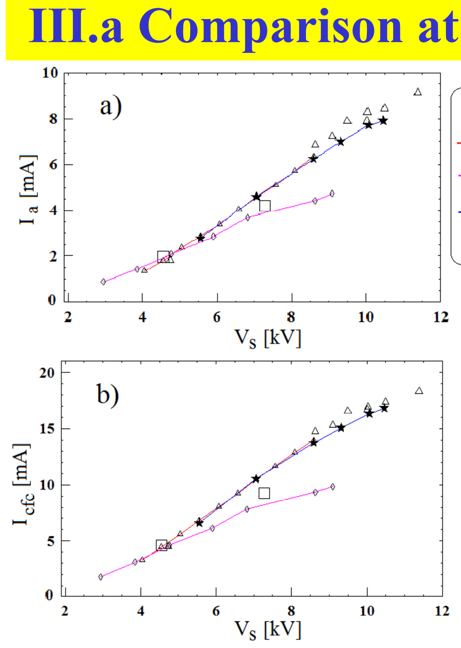


Fig 4: Anti-correlation of I_{cfc} and V_{pmt} during transients, for several fixed conditions:(a) at fixed control parameter as P_k=1.2 kW, I_{pg}≈0 , p_s=0.75 Pa, beam voltage V_s=4 kV, extraction voltage V_e=0.5 kV, compare [5]; (b): P_k=1.3 kW, p_s=0.9 Pa, filter current I_{pg}=400 A with configuration 'f3' [13]; V_s=4 kV and V_e=0.45 kV for better stability). Curve 'a' multiplied by 10; typical error 5 %

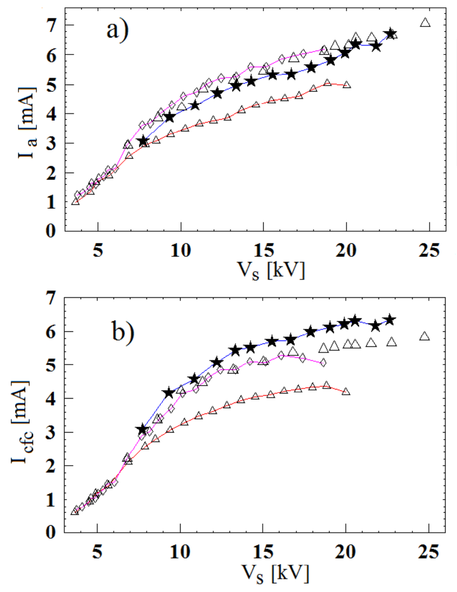
III. Systematic experiments

NIO1 support gas was O_2 or air and then H_2 (2015). In 2017 we see unexpected transients. To suppress them, at last we try gas conditioning: one day O_2, then H_2 again for a week, repeating. Gas conditioning with O_2 was very successful[13]; here we add results with selected other gases, as N_2 (suggested for comparison to air), Ar (used in many rf sources), Xe (mass similar to Cs). For busy schedule, Kr and Ne were unfortunately omitted. To cancel previous conditioning, we run source for several days, result for H- of last two days are the set 'ref'. Then we run with Ar for one day; results for H- in following two operation days are set 'aAr' (after Ar in brief). We repeated with N2 calling the H- result the set 'aN2'. Similarly for 'aO2' and 'aXe'.

III.a Comparison at selected pressures

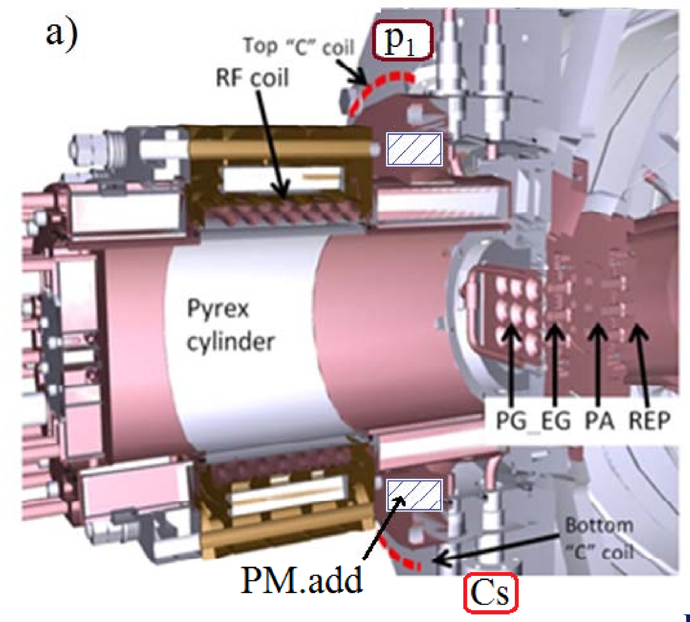


Comparisons at given P_k=1400 W of H^- current indicators I_a (panel a) and I_{cfc} (panel b) vs the total acceleration voltage V_s, at p_s=0.75 Pa, with cryopumps off, so p_2=0.21 Pa; here V_s/V_e, with V_e the EG extraction voltage, is about 9



As figure above, but p_s=0.9 Pa, with cryopumps on, so p_2=26 mPa, which allow to use larger Vs, where gas conditioning is needed so that source can provided adequate current ('aO2' and 'aXe' are better). At low voltages, all the curves coalesce, since current is space charge limited as $V_s^{3/2}$

All tested gas conditionings show some improvement



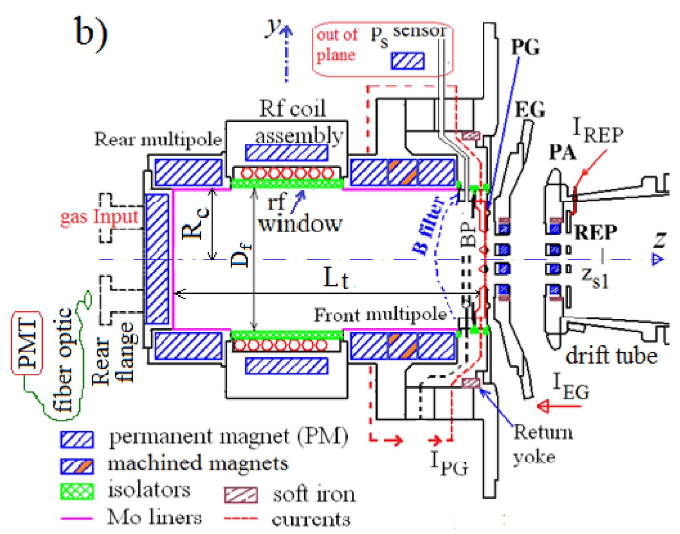
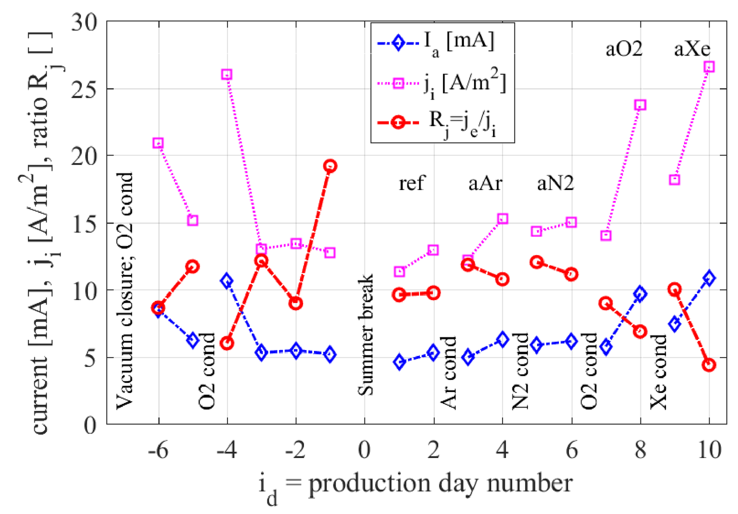
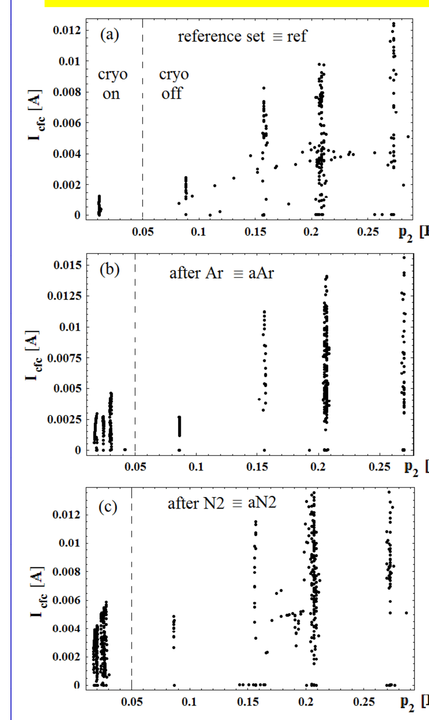


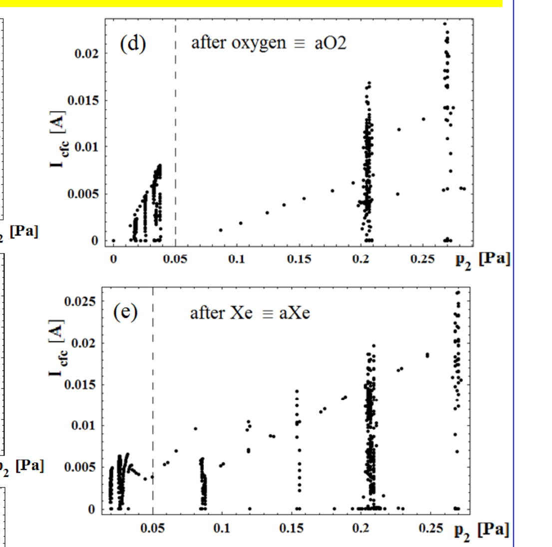
Figure 1: a) View of NIO1 plasma chamber and grids (see labels), with a cut parallel to plane xz; 'p1' marks the gauge flange, and 'Cs' the oven one; b) NIO1 yz section: note bias plate (BP), plasma grid (PG) and extensive permanent magnet (PM) installation.



Summary of typical daily results for I_a, j_i and R_j vs index i_d, which enumerates the H^- production days, eg. set 'ref' is i_d= 1,2, set after argon 'aAr' is [3,4], set 'aXe' id= 9,10; days i_d\<0 are before summer break; other line breaks are conditioning ('cond') days; typical 2\σ error is 10 %.

III.b Overall comparisons



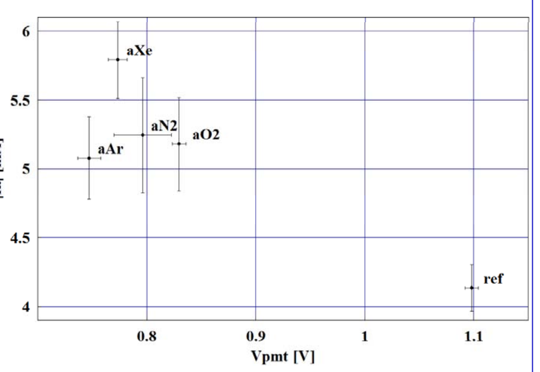


Note: cryo on and off regions are separated by a dashed line; data pile up at frequently obtained pressure p_2

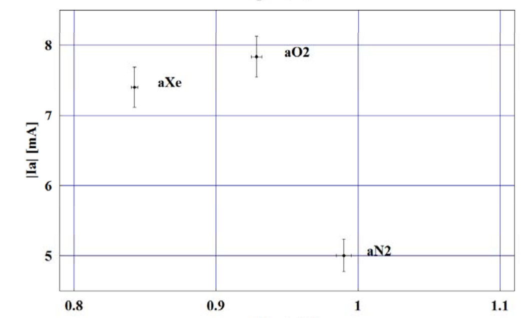
Overall set surveys : a) scatter plot of I_{cfc} vs p_2 for H_2 reference set (no conditioning='ref'), with P_k\= 1400 W; b) same plot after Ar conditioning, set 'aAr' ; c) same plot after N2, set 'aN2'; d) same plot after 'c' and O2= set 'aO2' ; e) same after Xe, 'aXe'.

III.c Anti-correlation of I_a and V_{pmt}

Comparison of I_a vs PMT signal for gas conditioning as labeled, averaged near V_s=7.55± 0.2 kV and 2nd bias currrent I_{b2}=0.4± 0.1 A, with rf power Pk=1.4 kW, p_s=0.75 Pa and cryopump off (so p_2 =0.21 Pa); as before 'aN2' means 'after N2conditioning', while 'ref' is before any conditioning



Comparison of I_a vs PMT signal as fig above, but with V_s=7.7± 0.3 kV, I_{b2}=0.5± 0.2 A, p_s=0.9 Pa and cryopump off (so p_2 =0.27 Pa)



I_a vs V_{pmt} anti-correlation is an outstanding feature (explained in talk 7).

Efficacy of gas conditioning is a robust proof that surface effect matters also in Cs- free regimes

III.d Beams (see also poster P30)

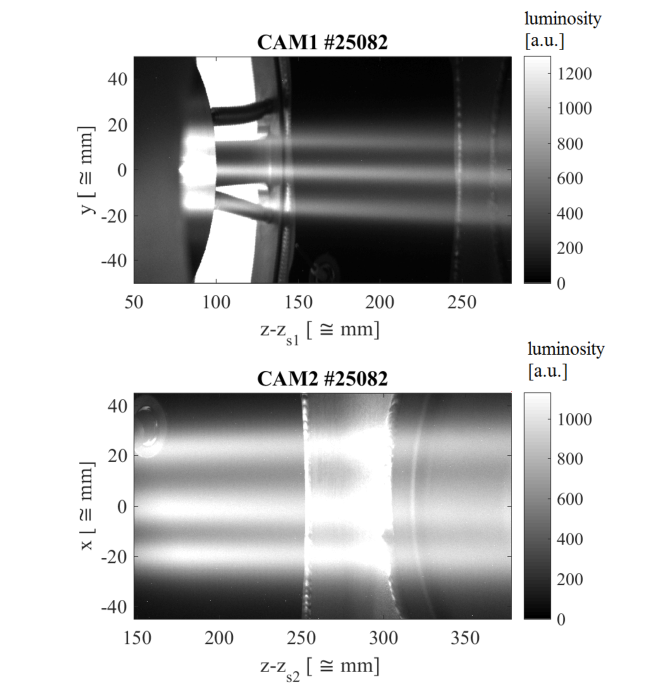
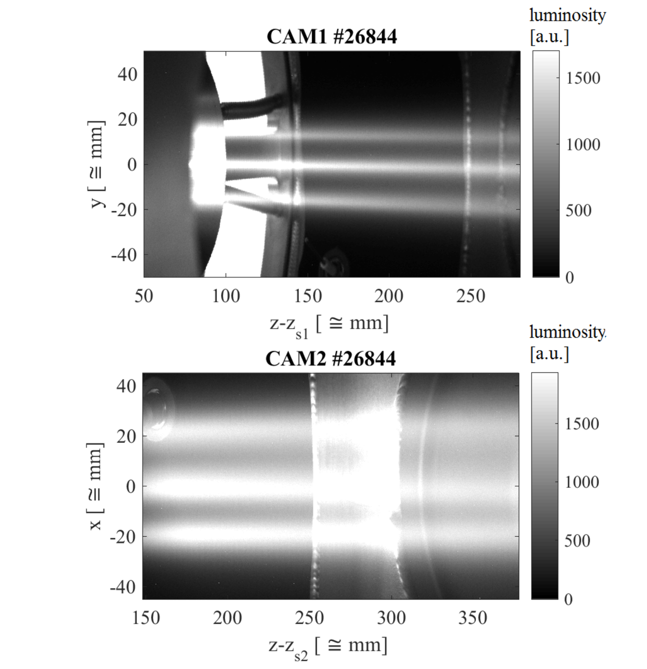


Figure 8. Projections of the H- beamlet matrix as seen from two lateral cameras; one example after Nitrogen conditioning 'aN2', with V_s=5.4 kV (limiting I_a to 2.5 mA), V_s/V_e ≈ 10 , p_s=0.9 Pa, and I_{pg}=400 A; labels show camera name and dataset index dsn.



As Figure 8, but with I_a=4.1 mA, requiring V_e=0.75 kV and V_s=8.1 kV for reasonable optics; an example after Xenon conditioning 'aXe'

V. Conclusion and perspectives

The H^- production can be improved in Cs-free regime, in a repeated way, with a gas conditioning technique, which also cancels the undesired transient fluctuation noted in previous works. Some fluid model is well in progress [see talk ID 7 this conf.]; analogies with gas mixing and other effects in ECRIS[7, 19, 20] are noteworthy. In perspective, gas conditioning with Ar or Xe can be helpful in Cs-based regimes, or after Cs-based operation, both for cleaning[11] and for lowering the extraction plasma temperature T_e^a ; and it may be a valuable integrative method for H− ion sources.

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