Towards NIO2, a 5 kW RF compact H- ion source

Presented on 8th Sept '25 as poster at ICIS2025, 8-12 Sept. 2025, Oxford, UK

M. Cavenago[a], M. Barbisan[b], R. S. Delogu[c], C. Baltador[a], D. Martini[a], A. Muraro[b,d], D. Ravarotto[c], A. Ruzzon[a], F.Taccogna[b,e], G.Croci[b,d], G. Castro[f], L.Celona[f], G.D'Agostino[f], L.Neri[f], V.Variale[e], V.Antoni[b,c]

[a]) INFN-LNL, v. dell'Università n. 2, 35020 Legnaro (PD) Italy; [b]) ISTP-CNR, c.so Stati Uniti n. 4, 35020 Padova (PD) Italy; [c]) Consorzio RFX, c.so Stati Uniti n. 4, 35020 Padova (PD) Italy; [d]) Univ. MI-Bicocca e INFN-MIB, p.za della Scienza 3, Milano, Italy; [e])INFN-BA, v. Orabona n. 4, 70126 Bari, Italy ; [f])INFN-LNS, v. S. Sofia 62, 95123 Catania, Italy

Abstract: The negative ion sources operation of neutral beam injectors (NBI) for tokamak must be carefully optimized for low beam divergence, minimal Cs use, and related HV stability. The long term operation (LTO) is challenging, especially because not only plasma but also evolving surface wall conditions are involved in H- or D- production; moreover, in a full-size source (as SPIDER) installed RF (radio frequency) power may reach 800 kW and H gas consumption 16 mg/s with consequential pumping, so that reduced size or compact ion sources are very convenient for studying the underlying physics and for flexibility in testing innovations. The NIO1 (negative ion optimization phase 1) source was indeed operated since 2014 (in close collaboration between Consorzio RFX and INFN) as a convenient benchmark, but it is limited to 9 beamlets and about 2 kW RF power; evidence of both of fast transients and slow evolution in LTO was demonstrated. Construction of a novel FS by additive manufacturing, with an elaborate design to balance internal water flows, proved necessary and satisfactory to fit into the NIO1 source. Based on these experiences, design of a companion source NIO2 is proposed for 5 kW RF power, with a larger expansion chamber and at least 25 beamlet extraction, for better beam uniformity studies. The larger RF power implies the need of a more cooled Faraday Shield, as here discussed: in first design, total cooling was satisfactorily improved by increasing circuits branches as shown, but cooling uniformity still need some improvement. Generalization of the seamless match of magnetic filter and multipole confinement introduced in NIO1 is discussed, considering optimization of expansion backplate magnets also. The spacing between source rear plate and RF coil and the large aspect ratio length/radius of this coil (which were introduced as design rules in NIO1 and in following studies for the Divertor Test Tokamak) are maintained. Results and issues with Langmuir probe RF compensation measured in MetAlice LNL test-stand are also summarized. Improved gas and Cs injection are also proposed. The application of additive manufacturing at least to Faraday Shields (as recently build) and to the extraction grid is fostered.

1. INTRODUCTION

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

Neutral Beam Injectors NBI can help to maintain a fusion reactor as a tokamak in steady state for hours, providing both plasma heating and current drive; at least 2 NBIs (providing 16 MW each) are needed in ITER and one prototype (called MITICA) is under development in Padua (by ITER and Consorzio RFX). NBI poses challenging requirements to ion sources [1-4], as: 1) large current density j_i and total current, requiring multiaperture sources; 2) long CW operation time and life time > 6 10^8 s (20 years); 3) negative ion sources (NIS) are required, electron density j_e<j_i, but negative ions (eg. D^- or H^-) production and extraction include much more complex physics than positive ions do. Thus accumulation of experience gained with several NIS configurations is crucial, as NIO1 (which has demonstrated $2*10^4$ s beam pulse length, quick access and modifications, low total power consumption <50 kW) and NIO2 project here proposed.

Both Cs-free and Cs-enhanced production [7] were studied:
Cs free [7,10,11]: Dissociative attachment (DA) volume production :

$$e\ (\text{cold}) + H_2^* \rightarrow H^- + H$$

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

Cs-enhanced which gives larger H- current [7,12,13]: Charge exchange on cesiated wall:

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

COMPLEX SYSTEMS and NONLINEARITES [11]: 1) In both cases, the space charge of H- (or D-) accumulated near extraction helps to reduce j_e, which gives a positive feedback in j_i/j_e balance (in steady state). Also Cs+ ions affects this balance; 20 s time scale observed[8].
2) Plasma is energized by radiofrequency (RF), the denser the plasma, the better the RF absorption [6]. But to get some plasma density, you need RF absorption. This positive feedback is partly controlled by ion loss to walls, secondary electron emission (SEE) from walls, and of course, applied RF power P_k .

1.2 Summary of NIO1 setup / NIO2 project

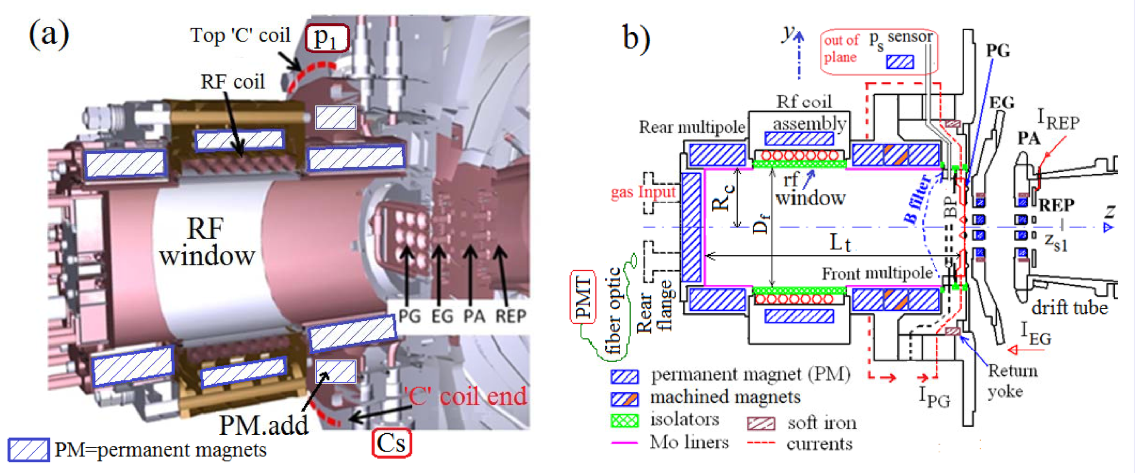
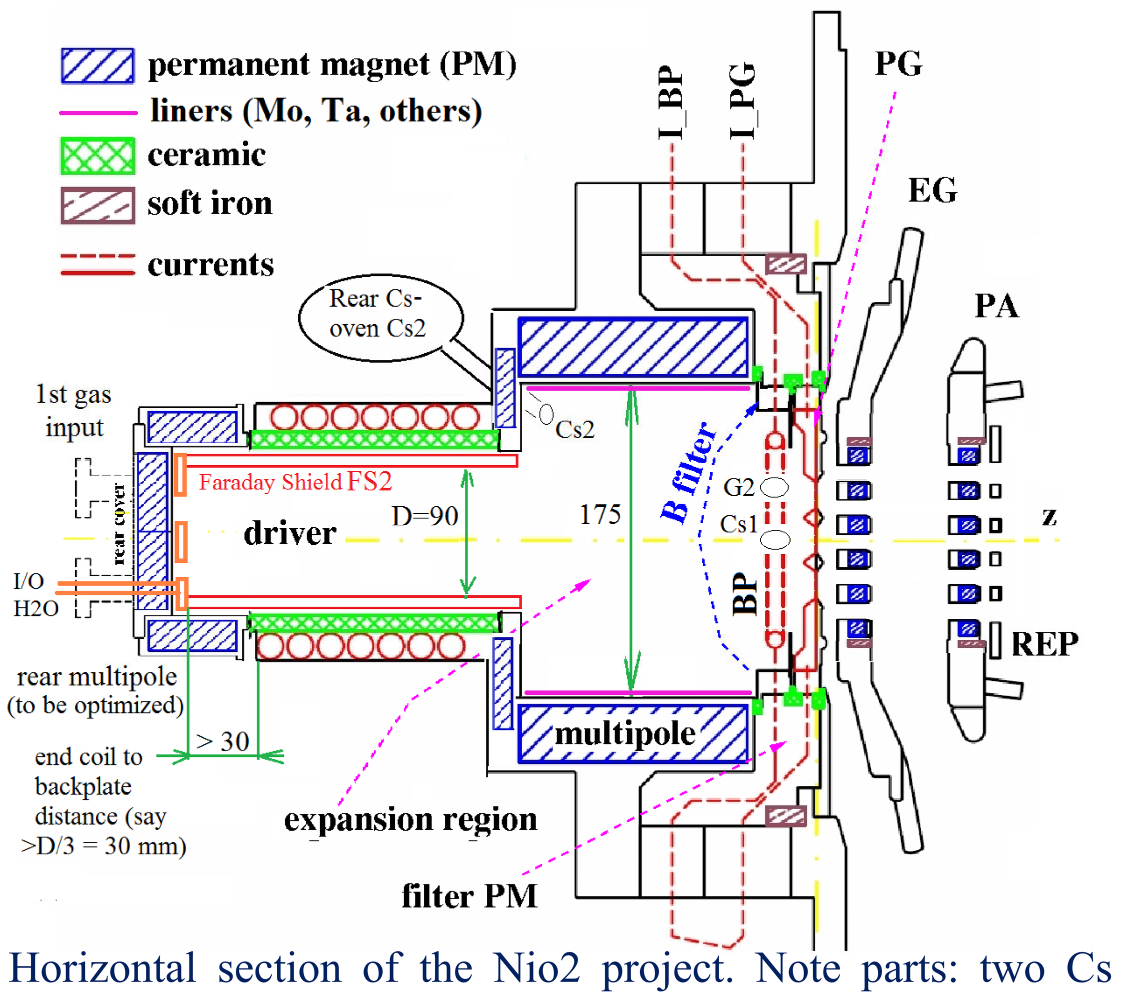
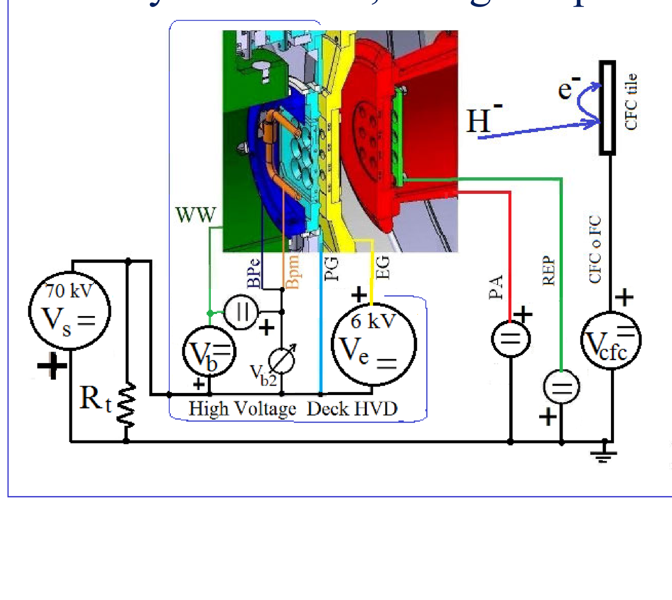


Figure 1: a) View of NIO1 plasma chamber and grids (see labels), with a cut parallel to plane xz; 'p1' marks the gauge flange, and 'Cs' the oven one; b) NIO1 yz section: note bias plate (BP), plasma grid (PG) and extensive permanent magnet (PM) installation.



Horizontal section of the Nio2 project. Note parts: two Cs inputs [Cs1 (lower side) and Cs2] are provided; the improved Faraday shield FS2; 2nd gas input G2 for gas mixing

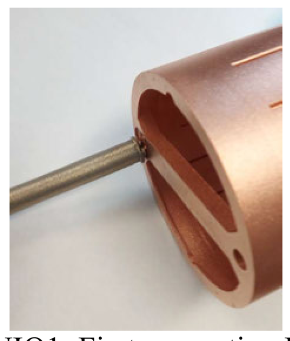


Scheme NIO1/2 major electrodes and connections; V_s is total acceleration voltage, with R_t the total parallel resistance, V_e the extraction voltage, V_b the main bias, V_{cfc} = CFC polarization voltage (absolute values). Corrected ion current I_a is

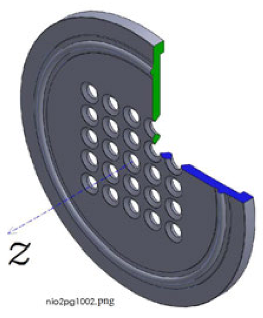
$$I_a = I_s - (V_s/R_t)$$

power supply current I_s

NIO1: copper and stainless steel parts of 1st generation FS, both built by AM (photo courtesy of AddtoShape srl)

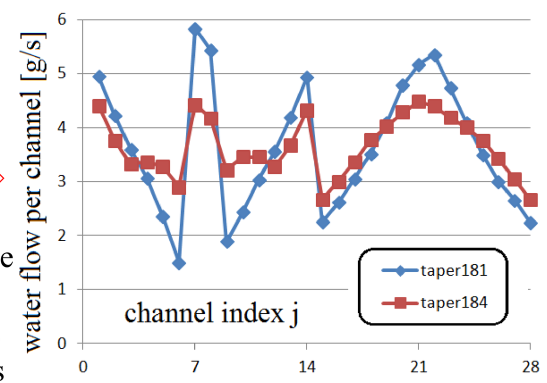


NIO1: First generation FS after surface cleaning



Cut view of NIO2 plasma grid

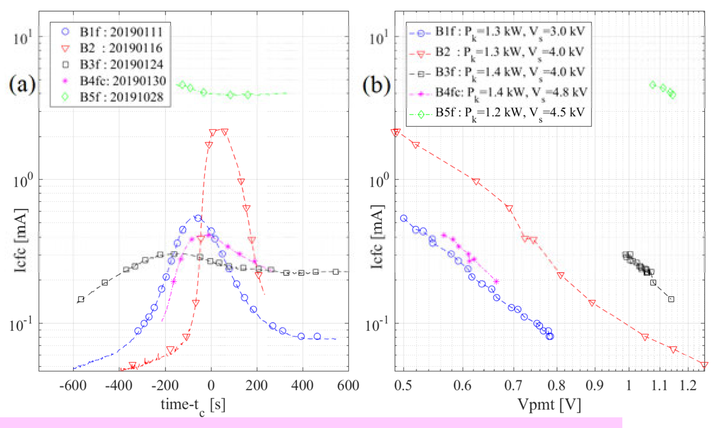
NIO2 design of FS cooling: channel networks show non uniformity of water flow, especially at large Reynolds numbers (10^4), see curve taper181. Mitigation of this effect is well progressing (see step taper184). In NIO1 FS uniformity within ± 10% was finally obtained after 20 steps



2 Transients,Cs-free regime, gas-conditioning

NIO1 Cs-free regime experience may be divided into two phases: 2015-7: optimization of the RF wall material, changed from alumina to borosilicate, so that up to P_k=1.8 kW may be applied (1.2 to 1.6 kW typical); 2018-9: observation of transients, and their stabilization with several techniques. Recent improvement in analysis allow to present here an overview of 2018-2019 transients:

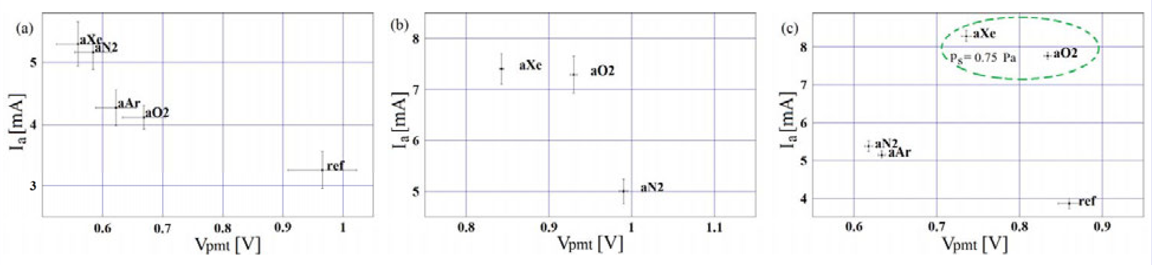
2019: More transients B1 to B4 towards stabilization; case B5 is stabilization after first O_2 conditioning: (a) current I_{cfc} vs time t with t_c a time shift, at fixed control parameters. In labels, as B4fc, 'f' means filter current I_{pg} ≥300 A; 'c' means cryopumps on; (b) I_{cfc} vs V_{pmt} for same cases, with P_k and V_s as labeled and p_s = 0.7(5) Pa.



I_a vs V_{pmt} anti-correlation is an outstanding feature[6]

'Gas conditioning' consists in alternating one day of NIO1 run with a gas (as N_2 or heavier) and several days with H_2, which then gives a larger and more stable production of H-

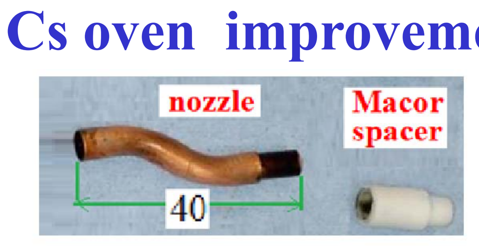
All tested gas conditionings show some improvement at fixed V_s. When cryopumps are on, higher voltages can be applied especially after O_2 or Xe conditioning[9], named phase 'aO2' and 'aXe'.

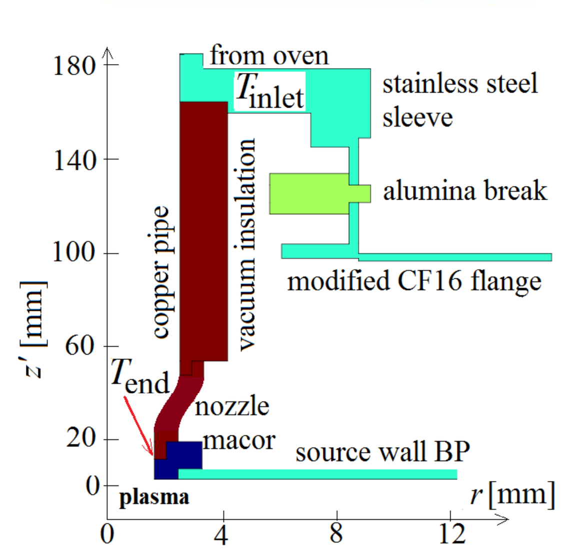


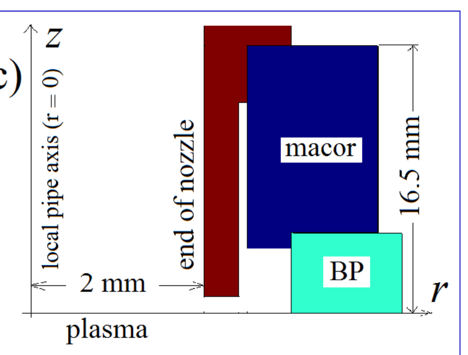
Residual anti-correlation of I_a vs V_{pmt} in gas conditioning phases (from 'ref'=after long summer break, to 'aXe' = after Xe conditioning phase) at cryo off and source major control parameters: (a) P_k = 1.2 kW, p_s = 0.75 Pa, V_s = 8 ± 0.2 kV; (b) P_k = 1.4 kW, p_s = 0.9 Pa, V_s = 7.6 ± 0.4 kV; (c) Pk = 1.4 kW, V_s = 11 ± 0.4 kV and p_s = 0.6 Pa, unless otherwise labeled

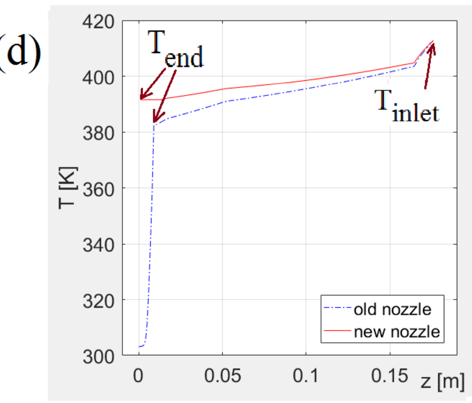
Efficacy of gas conditioning is a robust proof that surface effect matters also in Cs-free regimes. Noble gas mixing (similar to ECRIS) to be studied in NIO2

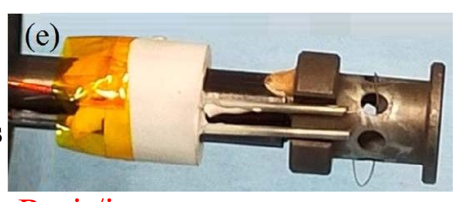
3.1 Cs oven improvements







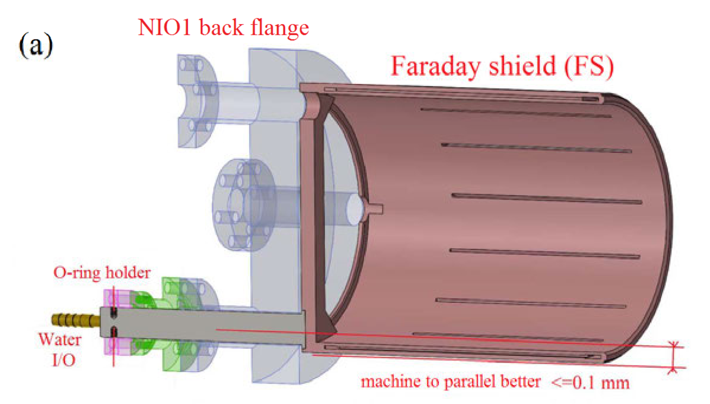




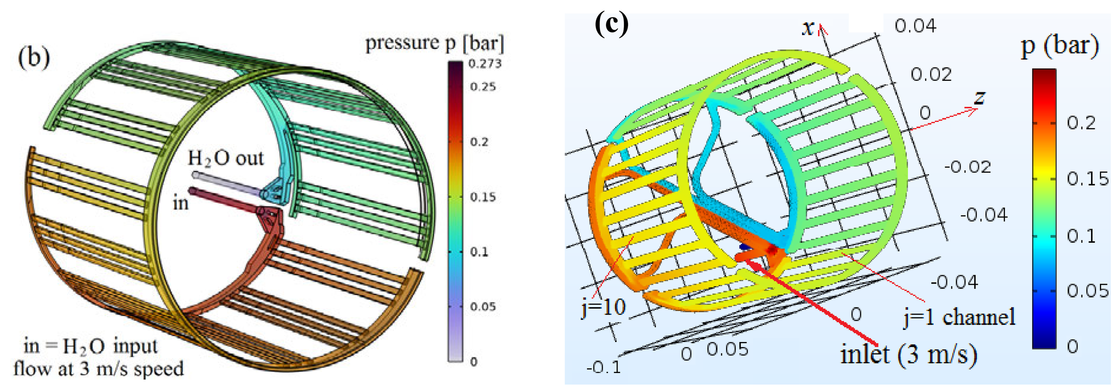
(b) old Cs nozzle scheme(not to scale) and photos of some parts; note T_{end} and T_{inlet} definitions; (c) Improved Cs nozzle design (detail); (d) simulations of T_{end}; (e) another oven exit example (SPIDER)

Tests with Cs show: 1) a very good transient result for R_j=j_e/j_i, but then over-cesiation was reached, result worsen, and recovery is only partial to now (experiment slowed for logistic reasons); 2) optimal oven (T_r) and inlet temperature (T_{inlet}) were expected 400 K from vapor pressure data, but 470 K was often required up to now. Simulations (d) shows a drop of 80 K across old macor spacer, which may explain all observed issues. Simulation (d) also shows that new nozzle design (c) has no temperature drop, so that usual Cs result (j_i=200 A/m2) are not impossible. This is 1st priority at source restart.

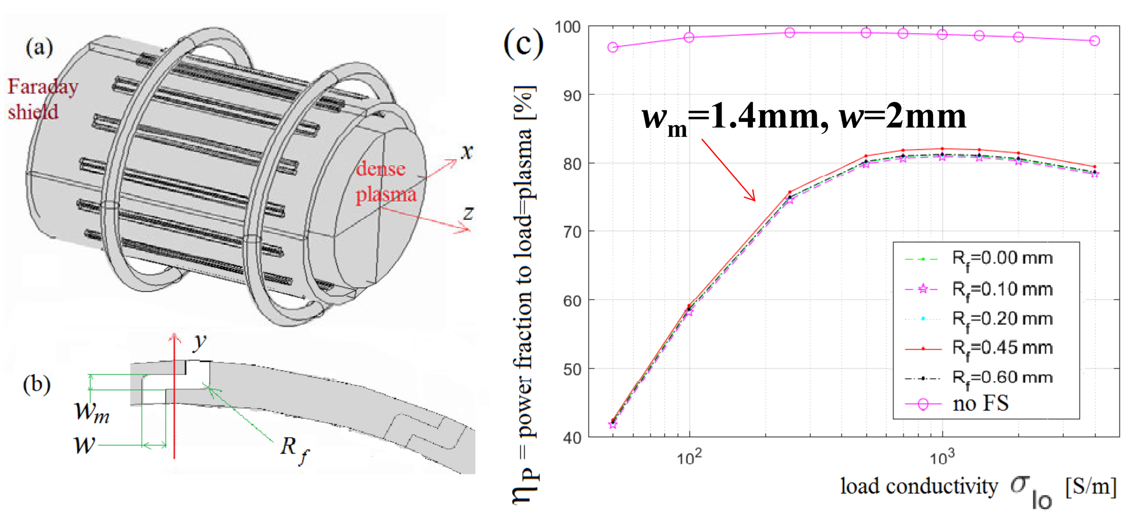
3.2 FARADAY SHIELD development in AM



a) the Faraday shield Plugin design (ID 90 mm) and its surrounding in NIO1; b) waterflow simulations, showing channels surfaces (and pressure drop on these); note I/O collectors; c) 2nd generation FS, 28 slot version (due to larger conduits, some lower pressure drop appears)



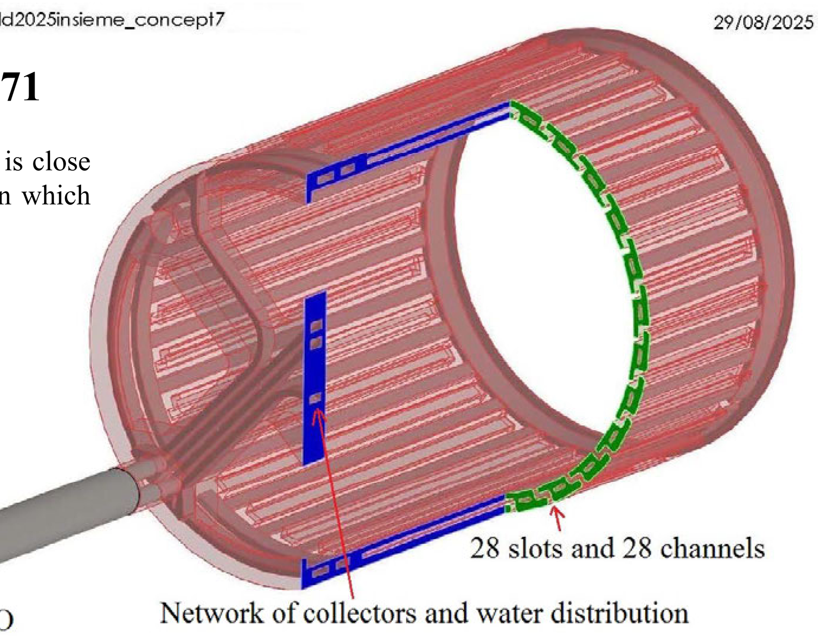
A faraday shield (FS) is not present in NIO1 up to now for: 1) study of possible increased RF efficiency, as in[5] ; 2) construction difficulty due to small overall size. But a removable FS plugin will add experience on: a) protection of the RF window, possibility improving stability of Ia and Vpmt; b) comparison with most NIS (as SPIDER) and verification of statement '1'. On the other hand, recent advancement in addictive manufacturing (AM) of copper solved issue '2' above (see design 'a' and 'b' above), and construction of a FS for NIO1 is well in progress (see photos c and d above), as well as electromagnetic simulations (below)



(a) the Faraday shield geometry, with a simplified plasma load model; coil 1st and last turn (out of 7 simulated) are shown; (b) detail of slot section, note fillet radius R_f ; (c) power fraction η_P not dissipated in coil or Faraday shield, as function of the assumed load conductivity σ_{lo}. Note η_P>0.7 for σ_{lo}>200 S/m; to estimate final efficiency η_P', multiply η_P by 0.74 to account for loss in existing NIO1 parts [6]. For reported NIO1 experiments, there is at least a 700 W margin to cover FS loss.

$$\Delta p \propto v_{in}^{1.71}$$

This simulated result fit is close to Blasius approximation which predicts a 1.75 exponent

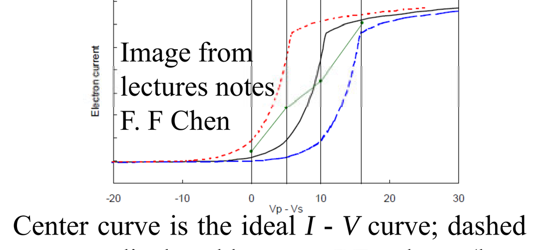


The improved cooling for 5 kW operation: only Δp ≈75000 Pa drop is needed for v_{in}=6 m/s input speed in inox I/O, which reduces at or below 2 m/s in copper walled collectors and further to 1 m/s in channels. Both a 28 slot version (above) and a 14 slot version are in procurement. Both inox and copper mass made by AM

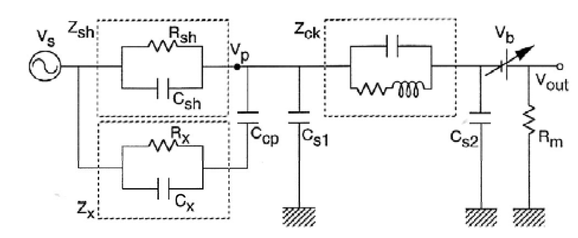
low power (2 kW) FS tests

3.3 RF compensation in Langmuir probes

Langmuir probe electron I-V curve is strongly perturbed by RF oscillations, so that special hardware (located near or into plasma region) is necessary



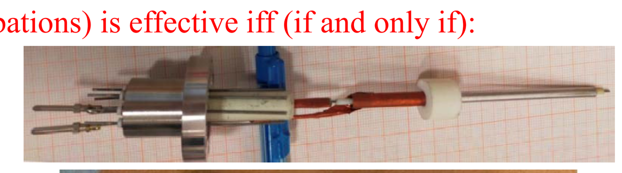
Center curve is the ideal *I - V* curve; dashed ones are displaced by some RF voltage (here ±5V). The time-average curve (green line) differs greatly from ideal curve.



Probe tip can follow V_{RF} iff effective impedance Z_{eff} of isolating inductors Z_{ck} is large compared with the larger of sheath impedances $|Z_{sh,x}|$.

RF compensation circuit (of RF perturbations) is effective iff (if and only if):

$$Z_{eff} >> Z_{sh,x} \left(\frac{e\,|\tilde{V}_{rf}|}{KT_e} - 1 \right)$$



Example of isolating inductor Z_{ck} , specially wound to minimize field leakage and parasitic capacitance (MetAlice test-stand, LNL)

Examples of Langmuir probes (LNL/S+RFX)

Conclusions: continuous beam extraction in NIO1 has made possible to observe stable and transient beam extraction regimes, opening the way to research on stabilization methods. In Cs-free regimes the gas conditioning emerged as a practical and effective method. Both noble gas conditioning and noble gas mixing may be useful for Cs regimes. Also for Cs-enhanced regime, a new nozzle design is well motivated by simulations and observed effects. Initial design of NIO2 is here shown, with 25 beamlet extraction (instead of 9), aiming to increase RF power from 2 to 5 kW, which requires a Faraday Shield (FS) to protect RF window. A removable FS is also useful for: to validate addictive manufacturing for highly reliable ion sources; for comparison (NIO1 only) of a source with and without FS. Simulations of RF transmission in FS were here shown; low power (2 kW) FS were built; design of 5 kW FS cooling is here shown. Improvement of RF compensation in Langmuir probes is also here addressed.