Status of energy recovery, cooler and ion source experiments

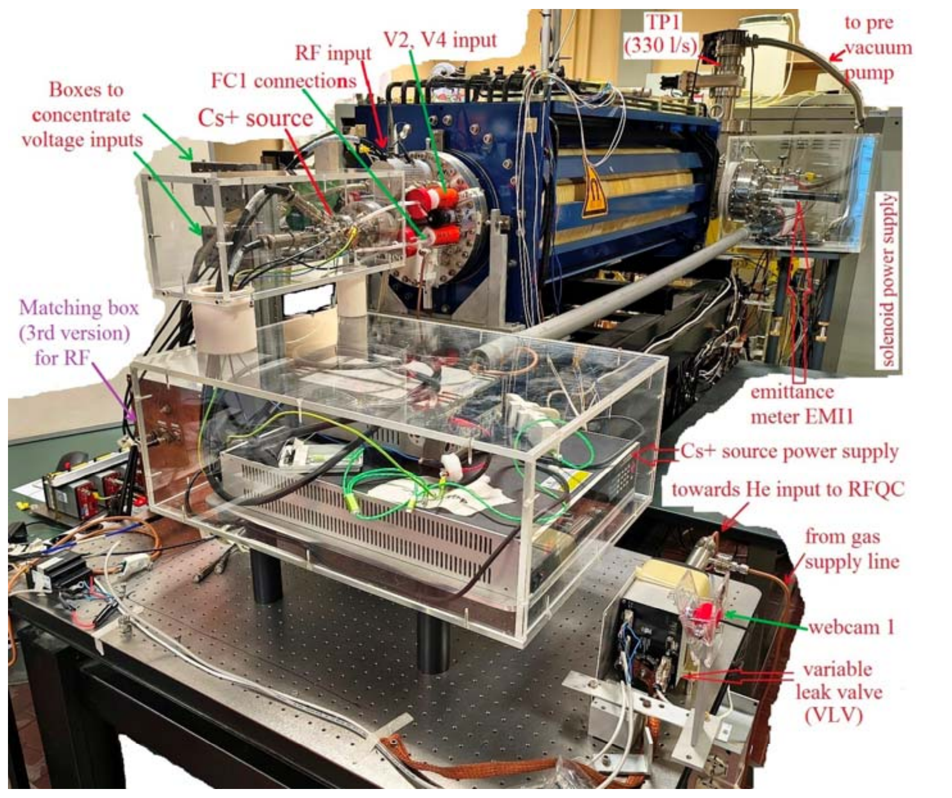
Presented on 5th Feb 2026 as poster at CPI2026 , 3-6 Feb 2026, Frascati, Italy

1° Conferenza Italiana Plasmi

M. Cavenago[a], M. Barbisan[b], R. S. Delogu[c], A. Ruzzon[a], G. Maero[d], M. Romé[d], G. Castro[e], V.Variale[f], P. Agostinetti[c], C. Baltador[a], M. Comunian[a], L.Celona[e], G.D'Agostino[e], D. Dell'Olio[f], A. Galatà[a], M. Maggiore[a], N. Pilan[c], D. Ravarotto[c], F .Taccogna[b,f], V. Valentino[f], 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. Milano and INFN-MI, v. Celoria 16, 20133, Milano, Italy; [e] INFN-LNS, v. S. Sofia 62, 95123 Catania, Italy ; [f] INFN-BA, v. Orabona n. 4, 70126 Bari, Italy

Abstract: The integrated experiment Plasma4beam2 addresses some innovative experiments in accelerator physics, in part described in this work. In neutral beam injectors (NBI) for tokamak heating or diagnostics, radiofrequency (RF) negative ion sources are used and residual ion beams (both D+ and D-) are produced; recovering their energy may improve net NBI efficiency and reduce heat load on walls. Voltage holding is also challenging. A 20 keV prototype suitable for test with TRIPS (H+) or NIO1 (H-) is being finally assembled on a test line near the former source. While NIO1, a 2MHz RF source is currently in shutdown, higher frequencies (4 MHz) and/or Faraday shields and Langmuir probes for it are being studied. Finally an RF Quadrupole ion Cooler RFQC (where He is the buffer gas) is presented, with the status of all subsystem development; for the limited RF power needed, 4 MHz is a suitable working frequency.



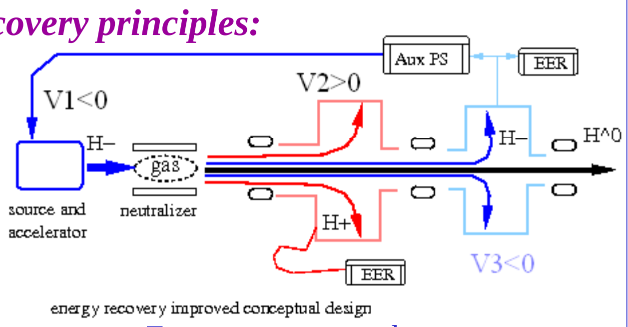
Overview of RFQC setup, note Cs+ source and He leak valve VLV

1. INTRODUCTION

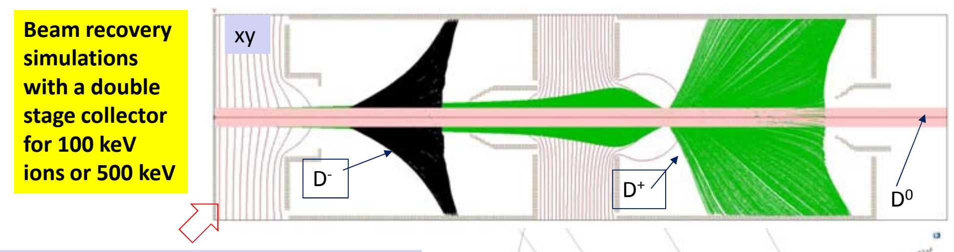
Fusion reactors will surely benefit from energetically efficient Neutral Beam Injectors [J. Pamela, PPCF, 37 A325 (1995)], which may be improved with energy recover (ER) systems, for which we proposed a new solution (decel-axcel transport). Other aspects to be improved are negative ion source (NIS) stability and HV holding, in the perspective of 20 years running. The compact ion source NIO1 was capable of more of 10^4 s beam on target time/day, discovering the gas conditioning effect (here summarized) in Cs free regimes after 4 years of operation, while operation in Cs based regimes is possibly more intriguing (and currently in shutdown for man power limitations at Consorzio RFX). Principles, progresses with ER test stand at LNL and with HV design are here briefed, as well as a companion experimental activity (also in Plasma4beam2) of Radiofrequency Quadrupole Cooler (RFQC) also requiring decel-axcel transport and gas control. RFQC are used or planned to cool exotic ion beams, as in the LNL SPES project at LNL .

1.2) beam energy recovery principles:

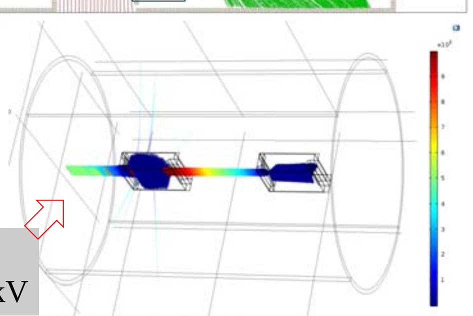
For 500 keV ions, the energy recovery efficiency ε is a little bit lower (ε =98%) from COMSOL simulations than ε the SIMION ones (>99%) ; in both cases, the charge collection efficiency η is practically 1.



Energy recovery scheme



Simion: For E_{ki}=100 keV with V_{g1}=-99350 V; V_{c1}=-99400 V; V_{r1}=-100800 V; V_{g2}= 99200 V; V_{c2}= 99250; V_{r2}= 100800 V

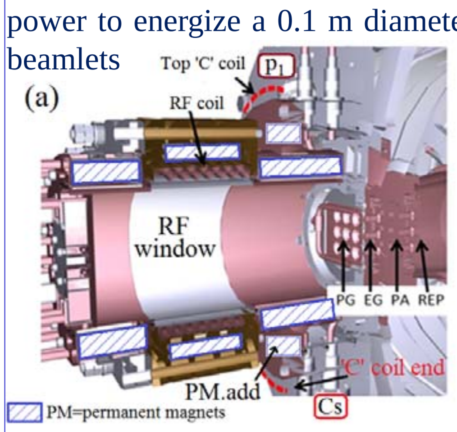


Comsol 3D View: V_{c1}=497 kV; V_{r1}=508 kV; V_{c2}= 490 kV; V_{r2}= 509 kV

Both D^- and D^+ ions are recovered with a collection efficiency of 100% . The D^+ ions are recovered, in average, with a higher residual energy. Neutral beam (D^0) is also shown.

1.3) NIO1 (negative ion optimization 1) recall

NIO1 was described elsewhere: it uses only 2.5 kW 2 MHz CW RF power to energize a 0.1 m diameter 0.2 m long plasma with 9 extracted beamlets



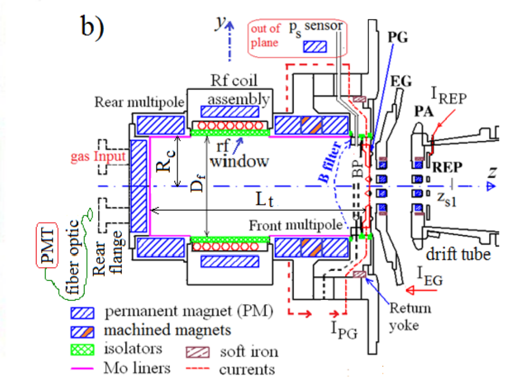
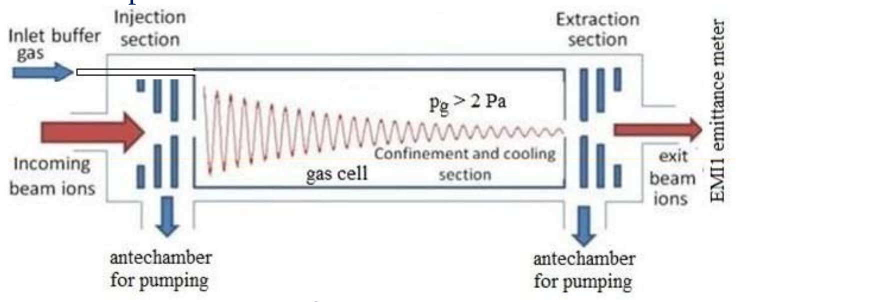


Fig: a) View of NIO1 plasma chamber and grids (see labels), with a cut parallel to plane xz; 'p1' marks the gauge flange, and 'Cs' the oven one; b) NIO1 yz section: note bias plate (BP), plasma grid (PG) and extensive permanent magnet (PM) installation.

Due to its reduced size, possible upgrading to 4 MHz or to 5 kW RF (and 25 beamlets) may be reasonably feasible and should be studied.

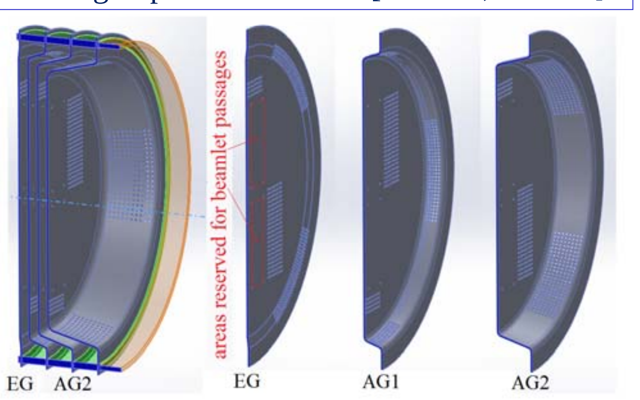
1.4) RFQC principles

Ion beam (with axis z) is first decelerated and then cooled by collisions with gas. To avoid diffusion in x,y, ions [Ruzzon et al 2025 JINST 20 P11023] are confined by a radio-frequency quadrupole field, which generates a ponderomotive potential

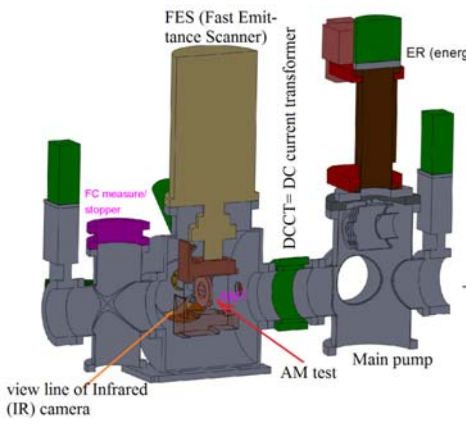


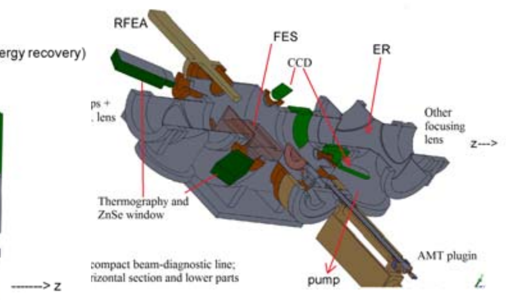
Moreover, an additional confinement can be provided by a solenoid magnetic field, as in Eltrap RFQC installation, whose status is reported. For Eltrap and Penning-Malmberg traps see elsewhere [G. Maero, this conf.]

INFN/LNL+BA design of venting holes for 510 kV accelerating columns of NBI, diameter about 3 m as DTT [F. Romanelli et al 2024 Nucl. Fusion **64** 112015]. Note x=0 plane symmetry and most beamlet holes omitted (to simplify graphs and simulations)

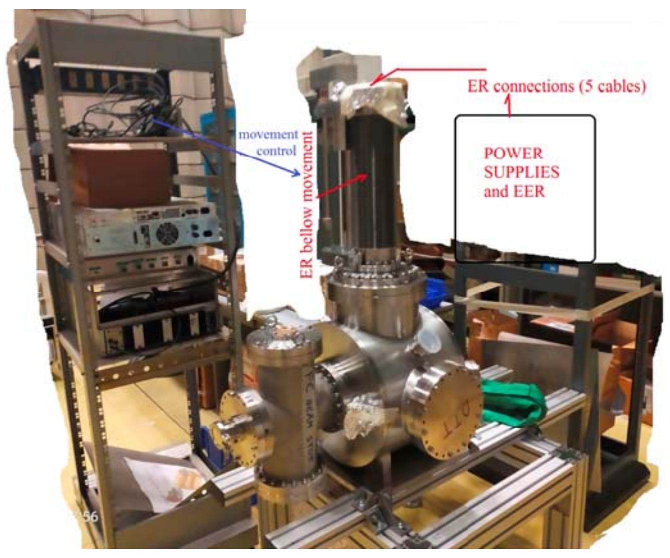


2) ENERGY RECOVERY TESTS: design and status





The ER and fast emittance scanner (FES) integrated test beamline: design overview and horizontal section



ER suspended to its plug-in movement

Overview of test installation status (near TRIPS)

CF40 Retarding Field Energy Analyzer plug-in

ER [Variale et al 2024 JINST 19 C10006] with 3 decel electrodes

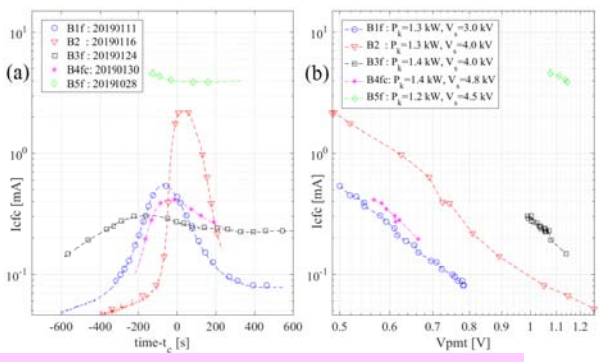
Possible installation flange of ER on TRIPS simplified beamline; note current transducer

ER with steering electrodes

3 NIO1 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 [Cavenago et al 2023 JINST 18 C09009]. Recent improvement in analysis allow to present here an overview of 2018-2019 transients:

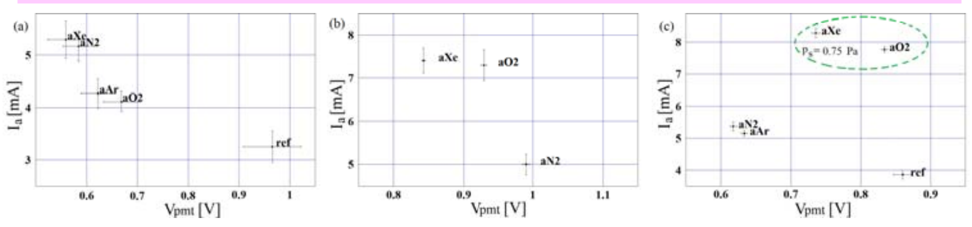
2019: More transients B1 to B4 towards stabilization; case B5 is stabilization after first O_2 conditioning: (a) current I_{cfc} vs time t with t_c a time shift, at fixed control parameters. In labels, as B4fc, 'f' means filter current I_{pg} ≥300 A; 'c' means cryopumps on; (b) I_{cfc} vs V_{pmt} for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

'Gas conditioning' consists <u>in alternating one day</u> of NIO1 run with a gas (as N_2 or heavier) <u>and several days</u> 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'.

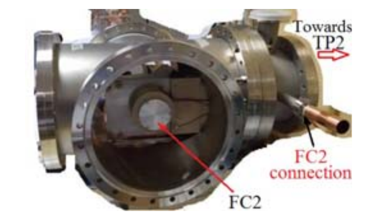


Residual anti-correlation of I_a vs V_{pmt} in gas conditioning phases (from 'ref'=after long summer break, to 'aXe' = after Xe conditioning phase) at cryo off and source major control parameters: (a) P_k = 1.2 kW, p_s = 0.75 Pa, V_s = 8 ± 0.2 kV; (b) P_k = 1.4 kW, p_s = 0.9 Pa, V_s = 7.6 ± 0.4 kV; (c)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

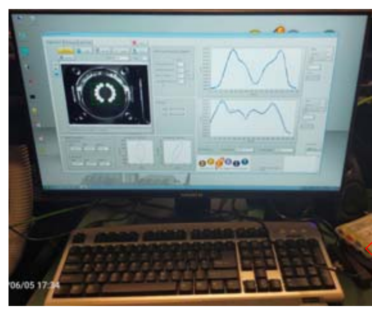
The effectiveness of gas conditioning is a robust proof that surface effect matters also in Cs-free regimes. Noble gas mixing (similar to ECRIS) to be studied in NIO2

The 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, and noble gas conditioning and noble gas mixing may be useful for Cs regimes. In the perspective of 25 beamlet extraction (instead of 9) and aiming to increase RF power from 2 to 5 kW, a Faraday Shield (FS) is advisable to protect RF window (see other poster for some simulations): a removable addictive-manufacturing-made FS is promising, 4MHz operation may also improve RF compensation in Langmuir probes (see ICIS 2025).

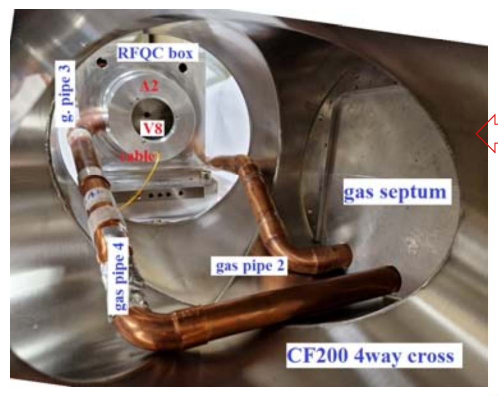
4. RFQC Setup and initial beam results



End Faraday cup FC2, its connections and surroundings

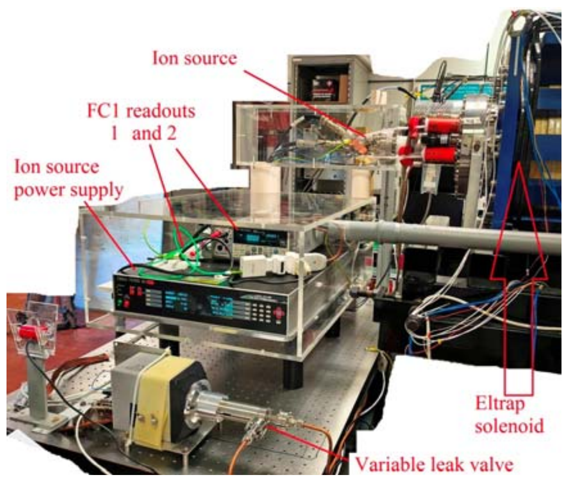


Test of EMI1 communication via fiber optic uplinks, user and OEM softwares

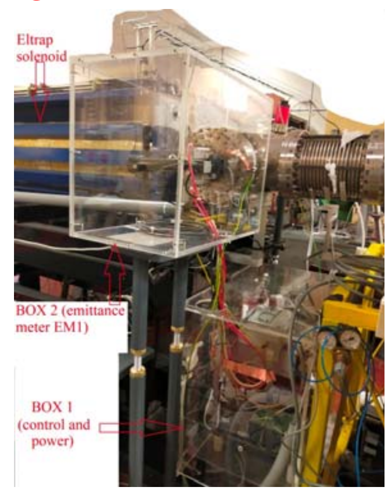


View of gas pipes and septum inside the 4way CF200 cross, with electrodes V9 and V10 dismounted from antechamber A2 to show V8.

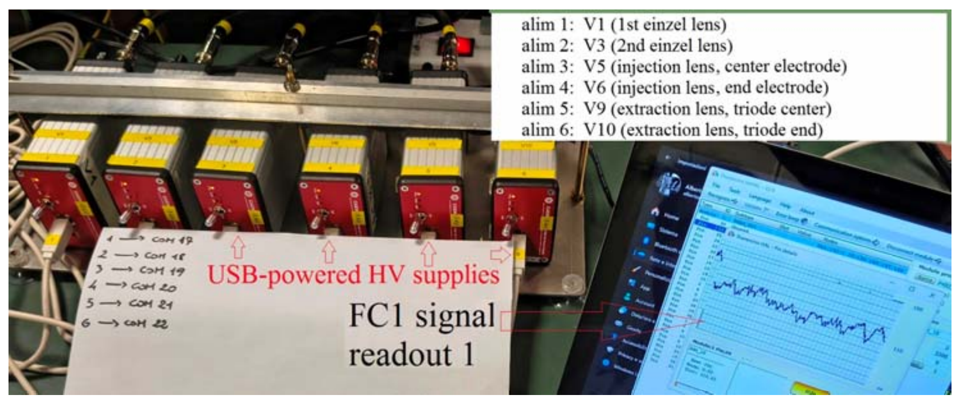
A differential gas pumping (using two turbopumps) is used to maintain RFQC box at p_g > 4 Pa, and high vacuum elsewhere



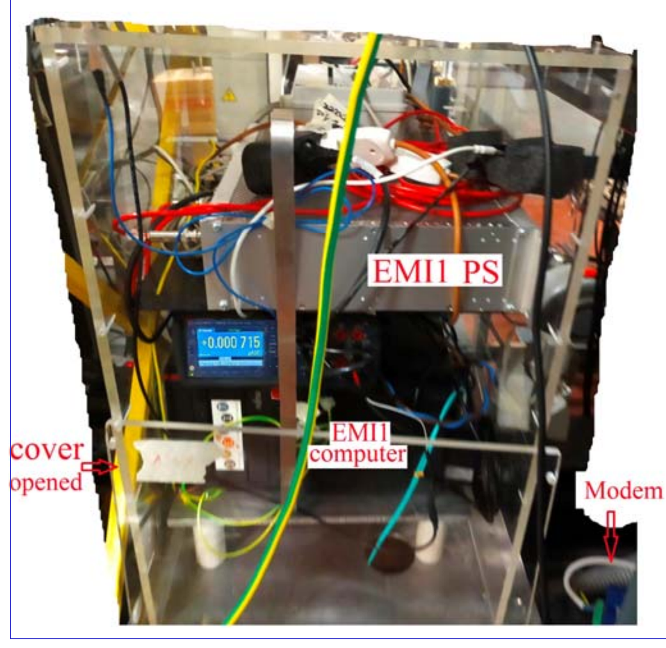
View of RFQC/Eltrap input setup, note leak valve, its tubes, and source turn on.



Eltrap output, with EMI1, Box1 and 2. The bellow to TP1 is visible; pump TP2 (550 l/s, sized for He flow) is covered.



An array of some HV supplies for beam lenses (usually needing more voltages each, but for the so-called einzel lenses); their regulation allows to focus current as required or in FC1 (wireless readout shown, but a nano-ammeter reading is available: we got a 95% transmission to FC1)



Commissioning of beam extraction diagnostic (densely packed and in progress). The fixed faraday cup FC2 is readout with a 6.5 digit multimeter (wifi optional); a retractable pepper pot emittance meter EMI1 is also included, with its HV supply and controlling computer (note double green fiber optic link)

Conclusions: The installation of the ER 20 kV prototype was recently begun at LNL as described: works on connections and ER plug-in movement is progressing. Some results obtained by NIO1 (gas conditioning) have been illustrated here and an institutional effort to promote it is certainly necessary and valuable, especially considering that NIO1 is capable of steady-state operation and cost-effective 4 MHz enhancement tests. The RFQC installation in the Eltrap had to implement several HV einzel and immersion lenses, with complex cabling and control; also ion source control requested some care. A remarkable milestone of 95 % transmission to the first FC was finally reached, with most of the electronics for the 2nd FC installed; verification of decel/axcel transport feature is well progressing. As final political remark, experiments of this scale are necessary for a validation of concepts to be later extended, and need a stronger support.