Laboratori Nazionali di Legnaro (Istituto Nazionale di Fisica Nucleare)

Presented on 11th Sept '25 as poster at ICIS2025, 8-12 Sept. 2025, Oxford, UK

Commissioning of a combined RFQ Cooler with axial magnetic field in Eltrap

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Abstract: Cooling of secondary beams is often critical to accelerator based nuclear and sub-nuclear physics, as discussed elsewhere. In the SPES (Selective Production of Exotic Species) case at LNL, radiofrequency quadrupole coolers (RFQC) are often necessary to cool the beam produced by fission sources (a mixture of exotic ion species like $^{132}Sn^{1+}$) both in energy spread σ_E and normalized transverse emittance ϵ_N, in order to match the acceptance of high resolution mass spectrometers for exotic nuclei selection (rms roughly σ_E = 0.5 eV and ϵ_N < 3 nm). Cooling is obtained with ion-gas collisions, against He gas, whose pressure ranges from 2 to 6 or 9 Pa, but collision energy must be in the order of 10 eV, to avoid heating by collisions; so the ion beam energy (K_s = 40 keV in SPES) has to be reduced before RFQC injection. Beam transport inside RFQC may be facilitated by an axial magnetic field as in Eltrap machine, where an RFQC prototype is now installed and being commissioned, with a challenging beam optics; results from several computational codes are recalled. This provides a versatile test bench for several RFQC technical optimizations, including differential gas pumping and RF voltage distribution to RFQC electrodes. In Eltrap RFQC, we limit K_s ≤ 5 keV and ion kind to $^{133}Cs^{+}$, to use a commercial ion source (installed on a suitable voltage platform) as injector. Beam diagnostics include a Faraday cup FC1 before RFQC injection, and, after extraction, another Faraday cup FC2 and a pepperpot emittance meter EMI1 (also on a suitable platform). Commissioning status is reported, including the elaborate final wiring of RFQC electrodes and the differential pumping system, the tuning of extraction optic and the communication between different hardware, especially with EMI1. Beam dynamics and energy analysis capabilities of FC2 (and/or its necessary updates to an energy spread analyzer) are also noted.

1. INTRODUCTION

Cooling of particle beams is an advanced topic of accelerator physics, since ordinary BTE (beam transport element) are based on Hamiltonian H mechanics. When ion source or production target has a too large spread of produced particle distribution momentum (in the beam direction, that is an energy spread, or in the transverse direction, that is emittance, or in both) for the following BTE and detectors, we need a cooler transport element. To obtain cooling we need interaction with other systems, be it a gas (as in our application, or muon cooling), or a colder electron beam (electron beam cooler) or special noise pickup and feedback system.

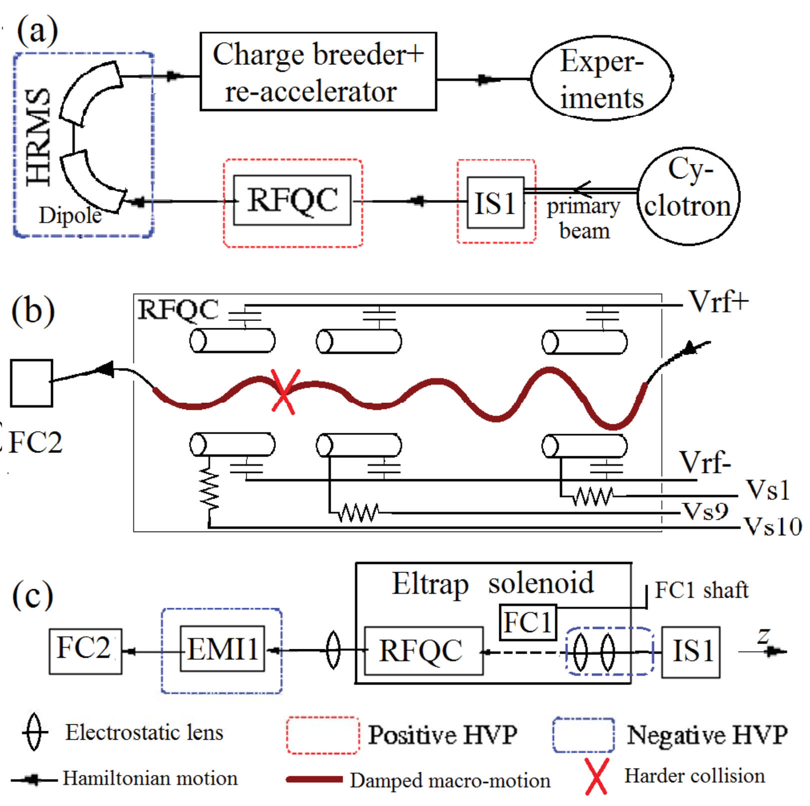
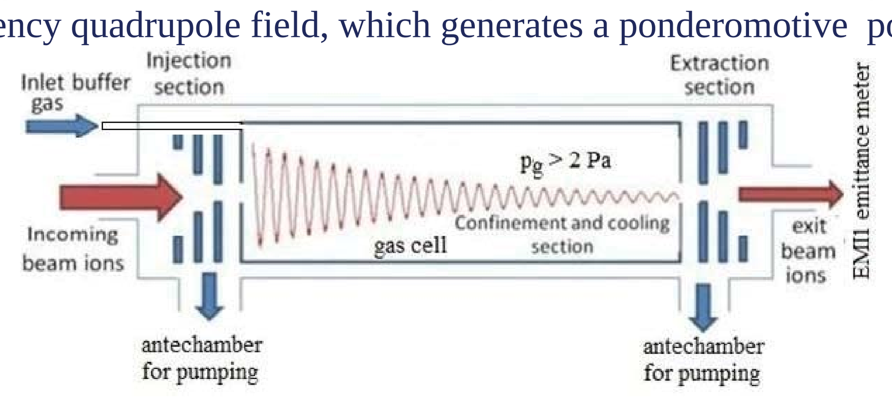


Figure 1. (a) relation of RFQC with the SPES project; (b) principle of RFQC confinement and cooling, with some electrodes, voltages and parts shown; (c) the Eltrap machine RFQC installation, note emittance meter EMI1, ion source IS1 and Faraday cups FC1 and FC2

Cooler size and detailed shape depend from the spread amount to cool. For muon cooling spread is 100 MeV/c order so cooler length is 100 m order. In the case of exotic ions, produced by a fission target and the following plasma ion sources, the rms energy spread is in the 5 eVrms order, so cooler length is about 1 m.

1.1 principle of RFQ coolers

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



Ions drift to extraction thanks to a small electrostatic field; four RFQ rods are divided in 10 or 18 segments each. After RFQC, ions are reaccelerated with electrostatic fields towards the emittance meter.

1.2 ion-gas collision physical outline

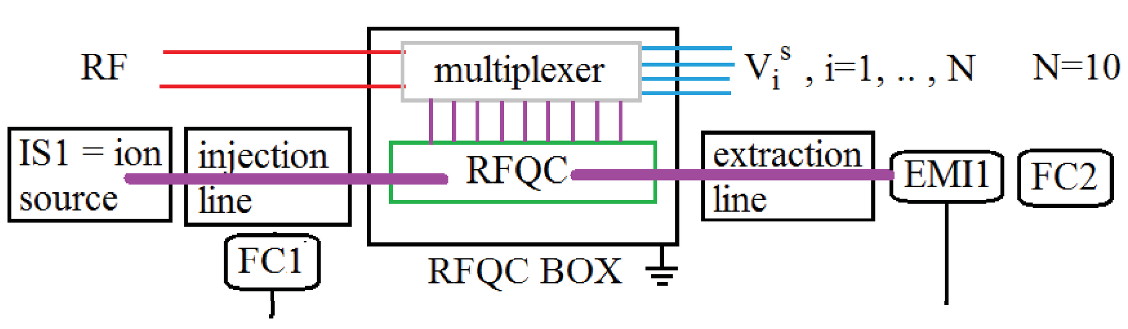
Many collisions with light gas molecules can cool a heavy ion with kinetic energy Ki, since rms spread after collision is (at most) of the order of the center of mass energy E_{cm}

$$E_{cm} = f_1 K_i \qquad f_1 = \frac{m_g}{m_g + m_i}$$

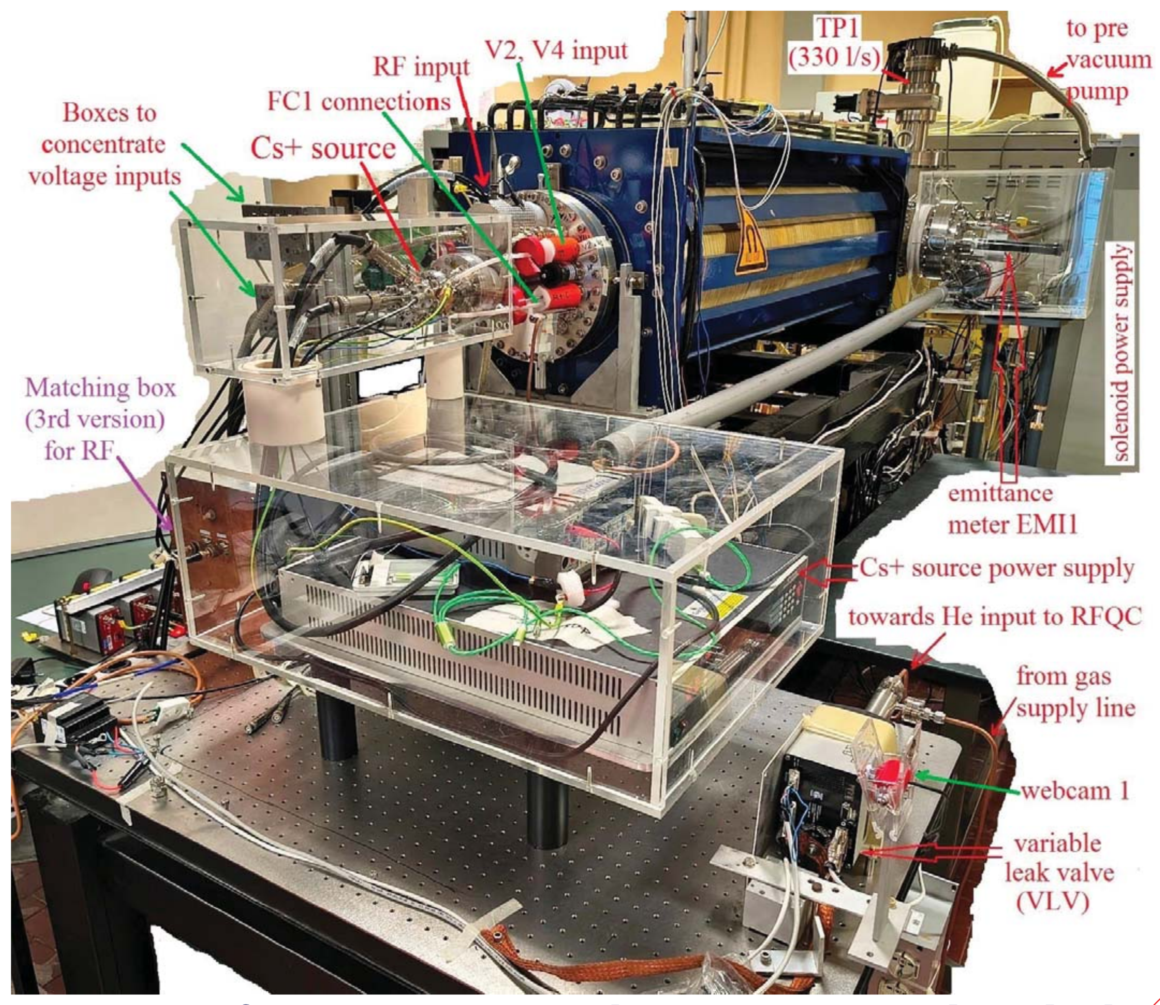
m_i ion mass
m_g gas (molecule) mass

Taking f1 as small as possible, that is f1<0.05, we need to decelerate a beam to K_i = 10 eV, where RF quadrupole focusing is one of the few effective focusing method. An even stronger RF confinement is needed if ion are trapped inside RFQC, with K_i in the 1 eV order. After cooling ion must be extracted and reaccelerated, with adequate beam transport optics, avoiding focusing mismatches that will again heat the beam. Figure 1.b sketches the damped motion inside RFQC, and the Hamiltonian motion (no gas, no collisions) outside.
THIS COMPLEX PHYSICS is worthwhile detailed investigation in itself, to the extent possible in a dedicated test bench. Our test bench in the Eltrap machine (figure 1.c) also provides B_z magnetic field for additional focusing, with z the beam axis.

1.3 RFQC test major components

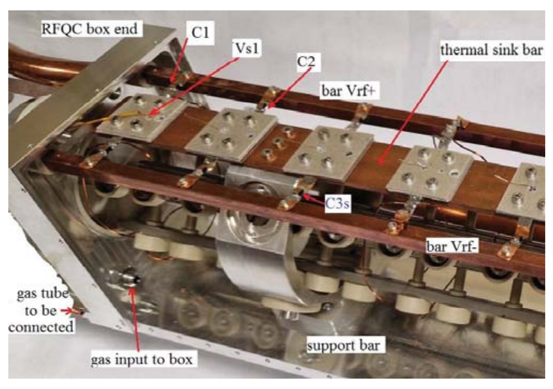


Block scheme of RFQC test parts (Eltrap setup); a multiplexer distributes RF and DC bias voltages to each RFQC electrode

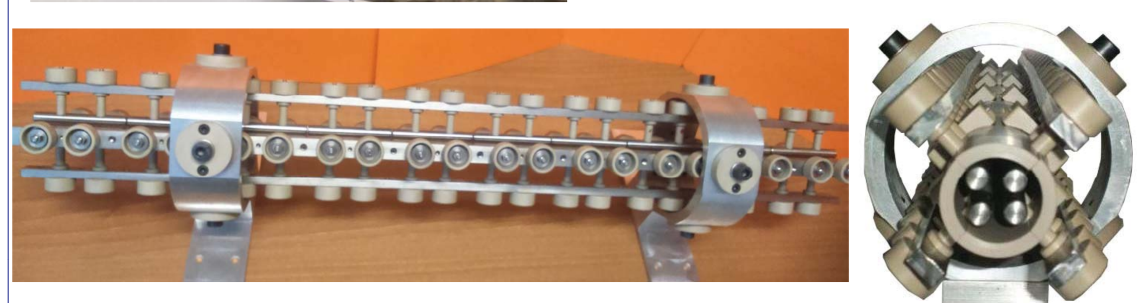


Overview of setup status , with Cs+ source and He leak valve VLV in the foreground (see also views on the right)

2.detail on setup intermediate steps and parts

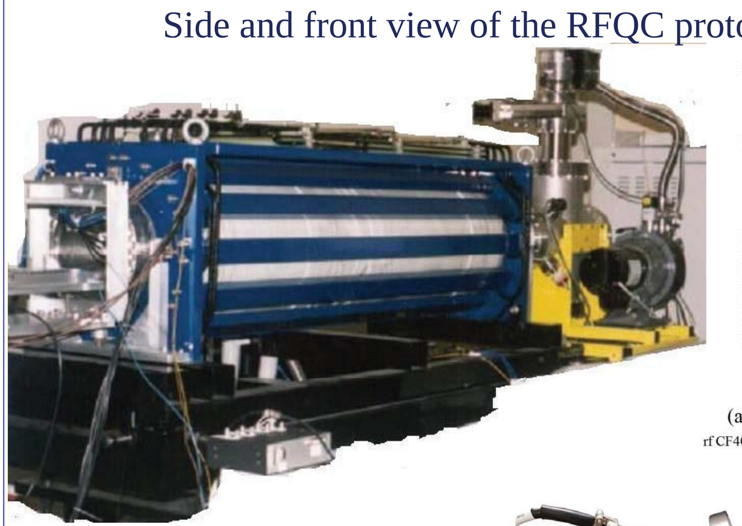


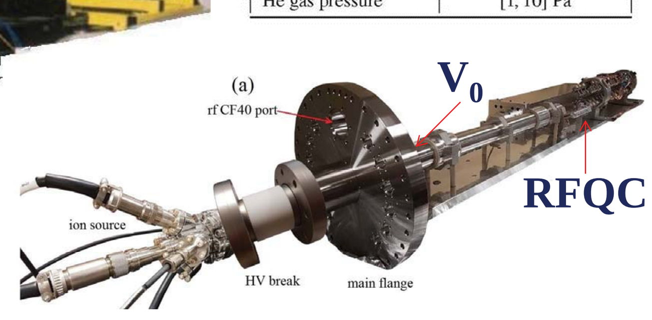
Detail of RF multiplexer (gas-tight RFQC cover removed); the resistors are sandwiched between mica foils for heat disposal towards a large copper bar; capacitors as C1, C2 and C3s stay in He gas region.



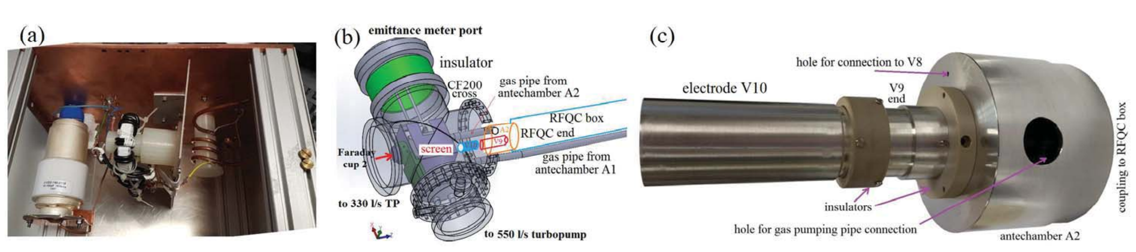
Side and front view of the RFQC prototype

Frequency	4 MHz
Peak rf voltage	200 V
Maximum B_z	0.2 T
Injection line length	1.058 m
RFQC length	0.72 m
RFQC aperture	9 mm
Extraction line length	0.388 m
Beam current	[0.1, 1] μA
Beam temperature	0.3 eV
Beam emittance	5 πmm-mrad at 5 keV
He gas pressure	[1, 10] Pa

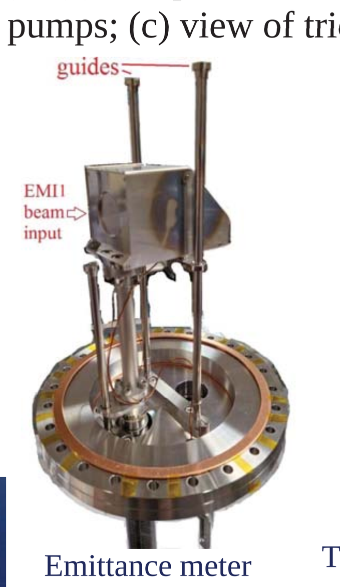




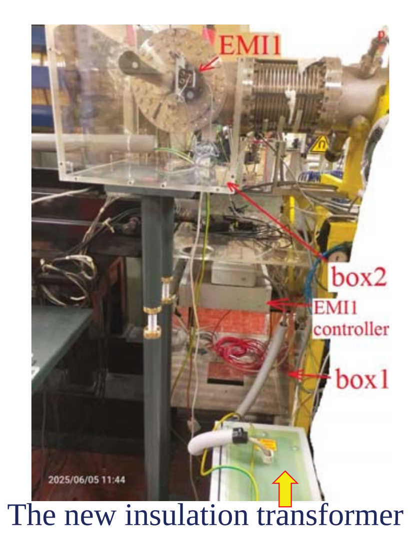
The Eltrap machine, preliminary parameters and assembly of RFQC plugin



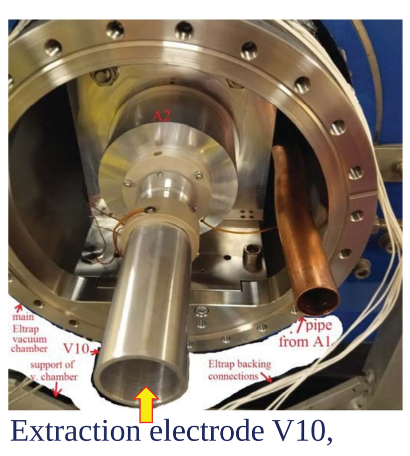
RFQC (from JPCS2022) : (a) low power matching box; (b) scheme of emittance meter and pumps; (c) view of triode extraction line



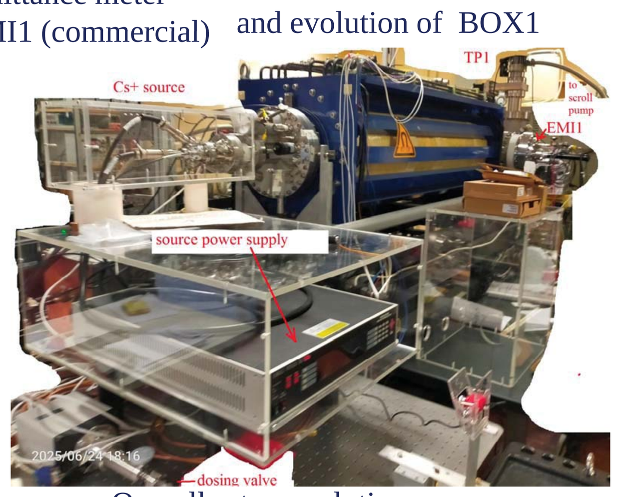
Emittance meter EMI1 (commercial)



The new insulation transformer and evolution of BOX1

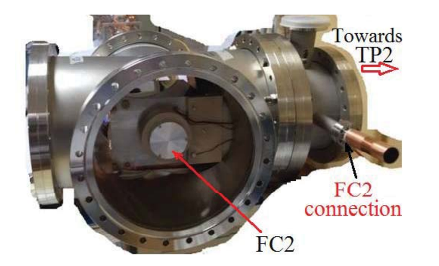


Extraction electrode V10, supported by puller electrode V9 and second antechamber A2, before its gas pipe installation. Note gas pipe from the 1st antechamber A1.



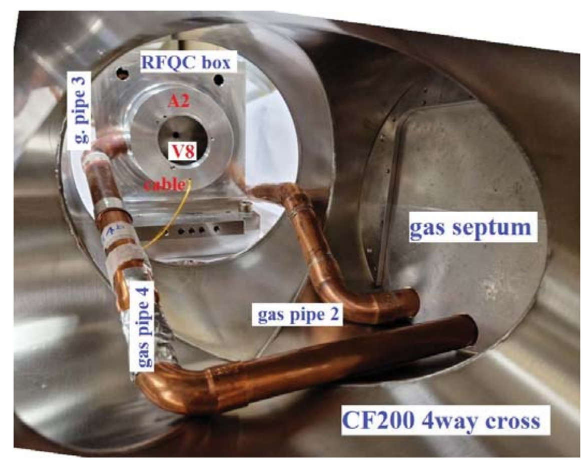
Overall setup evolution

3. Setup-status and initial beam results



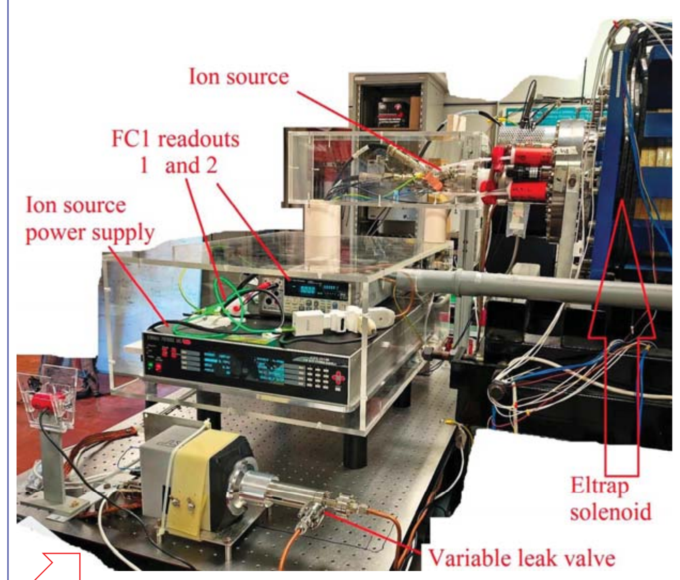
End Faraday cup FC2, its connections and surroundings

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

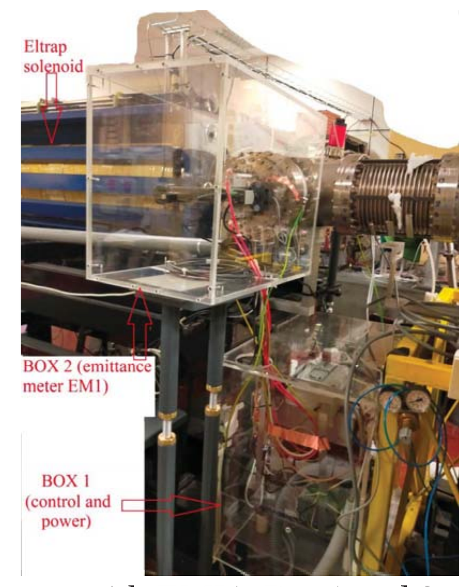


View of gas pipes and septum inside the 4way CF200 cross, with electrodes V9 and V10 dismounted from antechamber A2 to show V8.

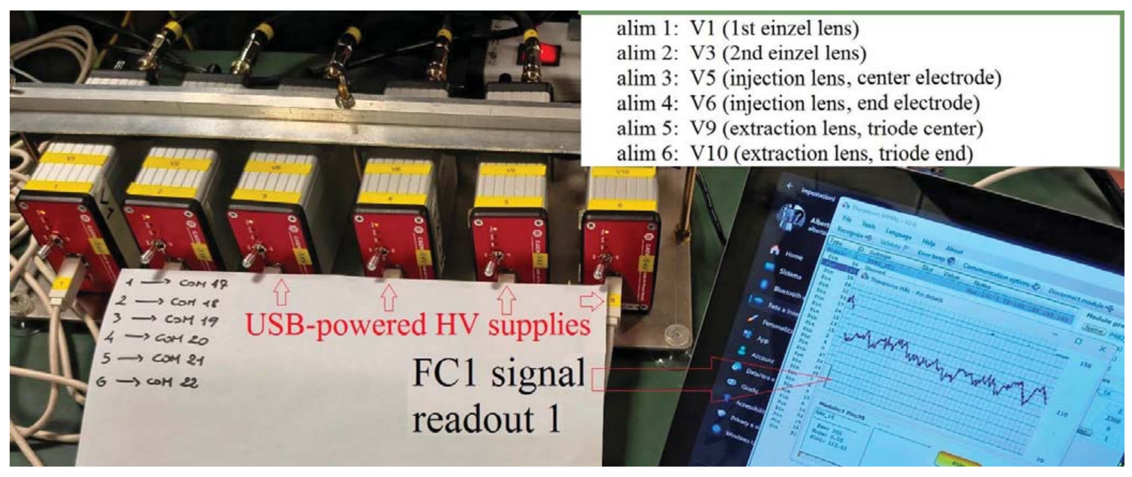
A differential gas pumping (using two turbopumps) is used to maintain RFQC box at pg > 4 Pa, and high vacuum elsewhere



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



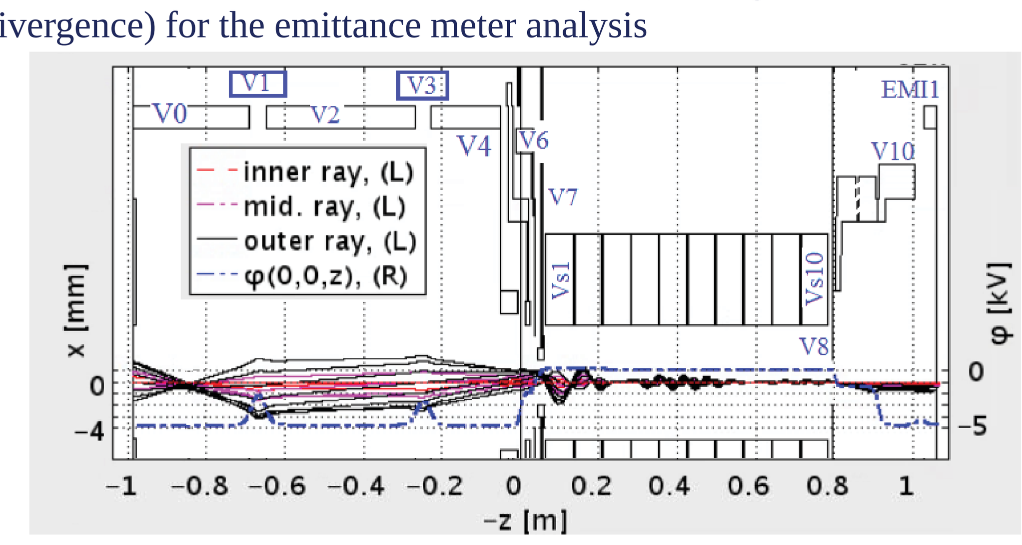
Eltrap output, with EMI1, Box1 and 2. The bellow to TP1 is visible; pump TP2 (550 l/s, sized for He flow) is covered.



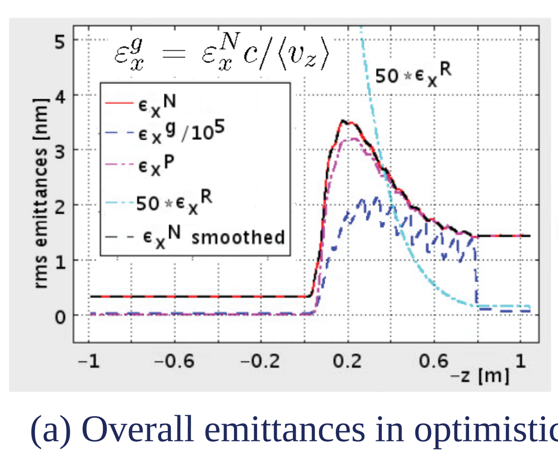
An array of some HV supplies for beam lenses (usually needing more voltages each, but for so-called einzel lenses); their regulation allows to changes slightly current in FC1 (wireless readout shown)

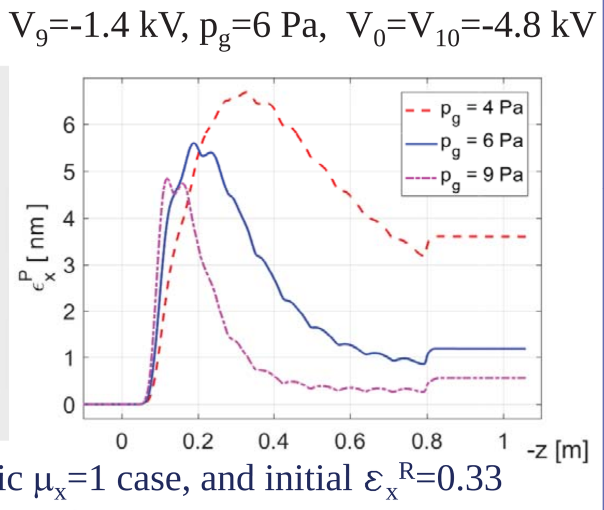
4. Theory+ Simulation summary. with ray tracing and restarting at extraction

A starting tool was the ray tracing: we make sure that beam from ion source IS1 is correctly focused by einzel lenses into RFQC input pupil and that extracted beam is suitable (considering its rms radius and divergence) for the emittance meter analysis



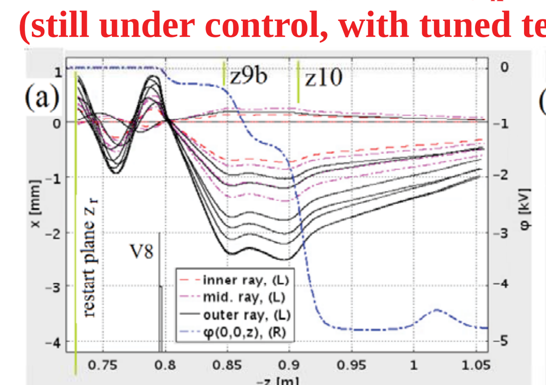
Overall tracing for reference triode V_9=-1.4 kV, p_g=6 Pa, V_0=V_{10}=-4.8 kV

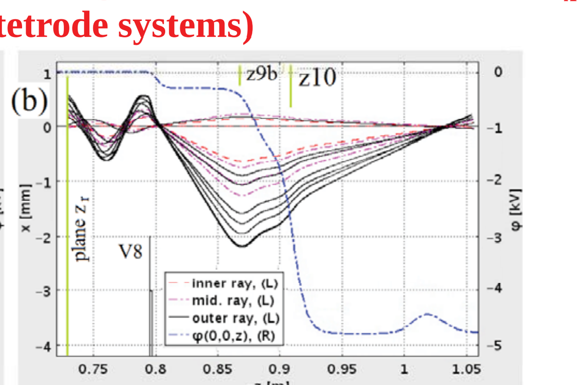




(a) Overall emittances in optimistic μ_x=1 case, and initial ε_x^R=0.33 nm for p_g=6 Pa; (b) pencil emittances for several p_g

Note that at extraction ray emittance is completely damped, but pencil emittance is not. It is thus convenient to restart rays with a multiplicative safety factor μ_x > 2, to get a more realistic value of ε_x^N (still under control, with tuned tetrode systems)





Restarted rays for (a) second and (b) first tetrode design, with V_9=-300 V and V_{9b}=-1.4 kV, and μ_x=2 . Other resampling methods in development

RFQC beams with <0.5 eVrms energy spread (ICIS2021) are thus possible

In conclusion these computations indicate good transmission and output emittances, in typical conditions. Test bench will allow to verify technical solutions for RF multiplexer, gas control, and source/accelerator operation

Work set up in collaboration and financial support of INFN-Group 5, exp. Ion2neutral and div. Acceleratori INFN-LNL