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# A RFQ COOLER DEVELOPMENT[*]

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## *Abstract*

The cooling of beams of exotic nuclei (both in energy spread and in transverse oscillations) is critical to downstream mass spectrometry devices and can be provided by collisions with light gases as in the Radio Frequency Quadrupole Cooler (RFQC). As in other traps, several electromagnetic systems can be used for beam deceleration confinement and deceleration, as a radiofrequency (rf) quadrupole, a magnetic solenoid and electrostatic acceleration. Since rf contributes both to beam cooling and heating, operational parameters should be carefully optimized. The LNL RFQC prototype is going to be placed inside the existing Eltrap solenoid, capable of providing a magnetic flux density component $B_z$ up to 0.2 T, where $z$ is the solenoid axis. Setup progress and related rf component development are reported; in particular simple matching boxes are discussed; the differential gas pumping system is also described.

## INTRODUCTION

In the context of manipulation of beam of exotic (or radioactive) nuclei [1], the rms energy spread $\Delta E$ must be limited to the order of 1 eV for two reasons: the need of achieving a large mass resolving power $m/\Delta m \gg 10^4$ in order to separate isobars and the efficiency of injection into charge breeders [2], which requires a small $\Delta E < 5$ eV; see for example equation (8) in [3]. Since the typical energy spread from plasma ion sources suitable for radioactive nuclei production, under installation in the INFN-LNL project SPES (Selective Production of Exotic Species [1, 4]), is $\Delta E \in [5, 20]$ eV, a cooling device should be inserted before high resolution mass separation (HRMS), as for example a Radiofrequency Quadrupole Cooler (RFQC).

In a RFQC, ion beam with energy $E_b$ and charge state $1^+$ is stopped by collisions with gas (typically He pressure $p = 1$ to 10 Pa); the beam is maintained focused in $x, y$ by a radiofrequency quadrupole and drifts toward extraction thanks to an applied electrostatic field $E_z < 100$ V/m, to be carefully optimized. Since gas collisions are more effective at low energy, the RFQC is placed on a high voltage platform to have $E < 200$ eV (preferably 100 eV) at injection, and optics of injection and extraction needs also very challenging optimizations [5]. Therefore a RFQC prototype was built at LNL [6] and is going to be tested in the Eltrap facility of Milan University and INFN, where an axial $B_z$ is also available, further improving the transverse ion confinement. Note that HRMS requires an $xx'$ rms geometrical emittance below 0.7 $\pi$mm-mrad at 260 keV, equivalent to 2 $\pi$ mm-mrad at 25 keV. Ion source transverse rms emittance [4] is in the range [6, 20] $\pi$-mm-mrad for 25 keV $\mathrm{Ar}^{1+}$; therefore it needs to be cooled too.

Let $V_{rf}$ the peak rf voltage applied at electrodes with $r_0$ their inner radius; as well known averaging over rf cycles gives a confinement effect [7, 8], equivalent to an effective potential $V_p(r) = \frac{1}{2} m\omega_M^2 r^2/e$ with the macromotion angular frequency

$$\omega_M \equiv \frac{k_q\,\omega}{\sqrt{8}} \quad , \quad k_q = \frac{4e|V_{rf}|}{m\omega^2 r_0^2} \tag{1}$$

where $k_q$ is the Mathieu parameter; a sufficient condition for motion stability is $k_q < k_1 = 0.91$.

Even if the RFQC concept is well established since several decades, rules for quantitative design and prediction of ion transmission are still missing; the large complexity of the equipment makes development and experimental tests both necessary and challenging. Our set-up emphasizes versatility of components and diagnostic, as described in the following.

## THE ELTRAP RFQC SETUP

Except for the beam emittance meter and the second faraday cup where the RFQC output ion beam is analyzed, all other beamline elements are mounted on a rigid plugin, which can be assembled, wired, and tested outside the vacuum chamber, and then inserted into the CF250 flanged Eltrap solenoid bore. The plugin major parts (following ion travel direction, see Fig. 1 in [8]) are: the alkali metal ion source, a CF63 flanged 10 kV insulator ceramic break, a CF250/63 transition where several auxiliary flanges are provided for feedthroughs (mainly electrical connections), a machined beam where einzel lens and drift tubes are supported with insulated PEEK posts and a gas tight housing box for RFQC is placed; the plugin is about 2 m long, and slides on spheres to facilitate insertion into Eltrap.

Let $\phi$ be the electric potential with respect to the vacuum chamber, and $\phi_e = \phi(0, 0, z_e)$ the ion emitter potential, with $z_e$ the ion emitter position. To simplify RFQC connections, the ion source chassis is floated to (a negative voltage) $V_0$ respect to vacuum chamber, which is the same potential of the drift tubes electrode $V_2$ and $V_4$. Then the acceleration voltage $V(z)$ defined as

$$V(z) = \phi(0, 0, z_e) - \phi(0, 0, z) = \phi_e - \phi(0, 0, z) \tag{2}$$

is mostly due to $V_0$; for the example of a $E_b = 5$ keV beam, we plan $\phi_e = 0.2$ kV and $V_0 = -4.8$ kV. This configuration complicates source operation; but we also have the advantage that einzel lens voltages $V_1 = -0.2$ kV and $V_2 = -1.3$ kV can be conveniently produced by USB powered modules, and accuracy of the measured $\phi_e - V_1$ focussing voltage can

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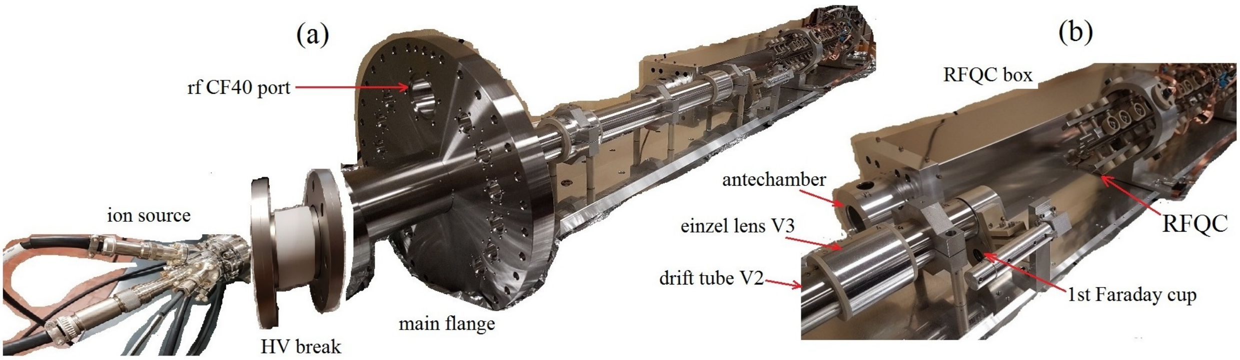

Figure 1: (a) The plugin parts: note ion source, injection beam-line and RFQC; (b) zoom on the RFQC input, with box moved aside for better visibility.

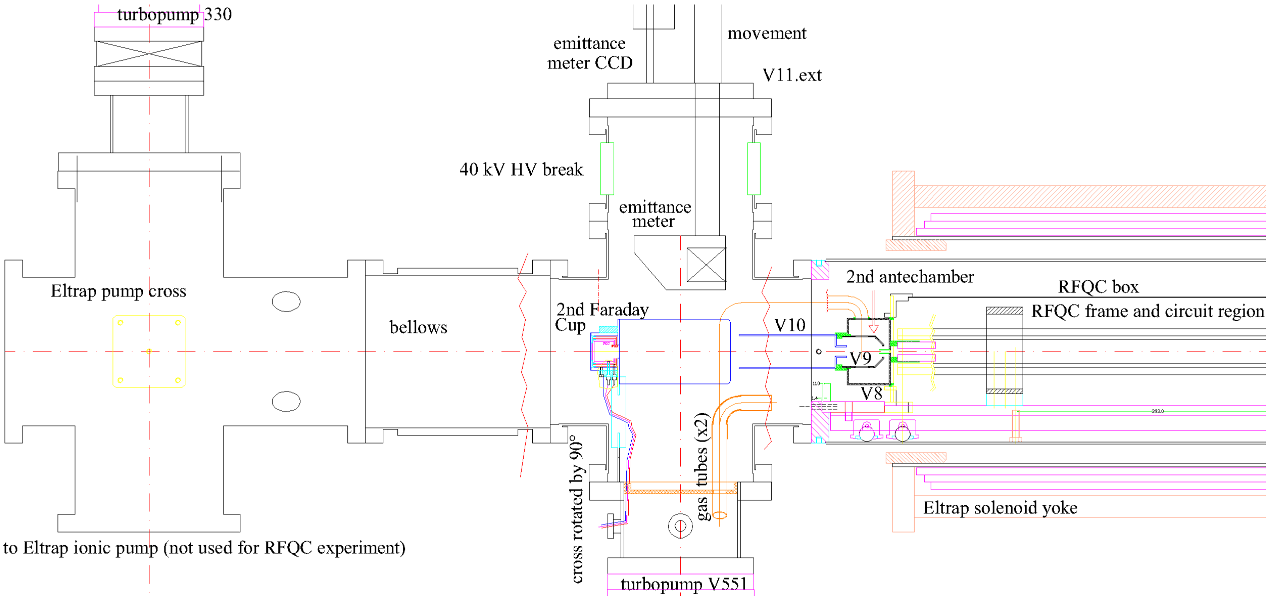

Figure 2: The extraction beam-line from RFQC, beam diagnostic and gas pumping systems

reach values below 100 mVrms (that is, $2\times10^{-5}$ parts of $V_b$). The same applies to the injection lenses $V_5$ and $V_6$. Electrode $V_7$ and $V_8$ are the end plates (within 100 V from ground) of the gas enclosure (RFQC box) of the RFQC; the rest of the RFQC box is grounded. A first faraday cup can be inserted in drift tube $V_4$; ion source can provide over $I_i = 1000$ nA of $Cs^+$ ions, even if $I_i \leq 200$ nA is a suggested limit when the emittance meter is used.

For Eltrap logistic, the more convenient insertion direction for the emittance meter results the horizontal (note the figure breaks in Fig. 2). Extraction beam line is formed by plate $V_8$, lens $V_9$, drift tube $V_{10}$, emittance meter (at potential $V_{11}$) and the second faraday cup (under construction), see fig 2. The emittance meter is mounted on a 40 kV ceramic break on a CF200 cross, so that its voltage is adjustable; anyway operation with emittance meter and drift $V_{10}$ connected to $V_0$ seems the better choice.

The alkali ion source has a negligible ion energy spread (0.4 eV) so that any ion energy $E_b$ distribution can be reconstructed by scanning $\phi_e$. It can be also argued that, by scanning the second faraday cup voltage $V_d$ and recording the current $I_o(V_d)$, a sort of discrimination of the ion energy $E_d$ after the RFQC can be obtained; in other words, the second faraday cup can approximate (or be replaced with) a retarding field energy analyzer. This ambitious plan will clearly request a long data collection phase to get the full kernel $K$ characterizing the RFQC

$$\frac{I_o'(V_d)}{\max I_o} \equiv f(V_d) = \int \mathrm{d}V_b\, K(V_d, V_b; p, V_{rf})\, g(V_b) \qquad (3)$$

where $V_b = E_b/e$ is the ion acceleration voltage, $g(V_b)$ [or $f(V_d)$ ] is the distribution of input ions in $V_b$ [or output ions in $V_d$], and $'$ indicates the derivative. Ion source estimated $xx'$ rms geometrical emittance is about $5\,\pi$ mm-mrad at 5 keV, which is equivalent to the previously stated $0.7\,\pi$ mm-mrad at 260 keV (and to an ion transverse temperature of 0.2 eV). Among heating effects in RFQC, we have gas collisions [9]: even if $Cs^+$ transfer energy (to He), collisions may contribute an increase of $v_x$ and $v_y$, that is of transverse temperature (in the sub-eV scale), so that a Monte Carlo module must be added to ray-tracing simulation [8]. The

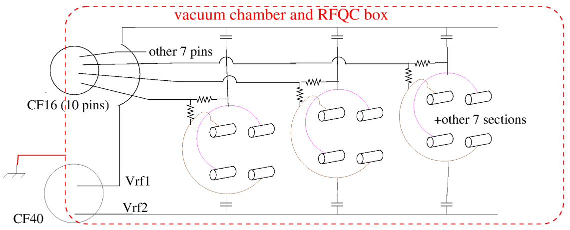

Figure 3: The multiplexer, connecting the 40 electrodes to 12 input pins; capacitors may have equal values, $C = 1$ nF in the example tested, as well as all resistors have equal resistance $R = 0.47$ MΩ.

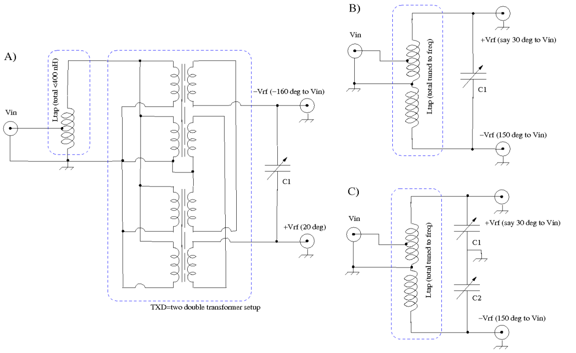

Figure 4: Some matching box schemes: A) low power, with output balance by ferrite core transformers; B) air core; C) air core, with output balance improved by two variable capacitors.

CF200 cross also connects to the 550 l/s pump for Helium differential pumping: it is envisioned that gas escaping from the V7 and V8 beam holes accumulates in antechambers (see fig 2) and is conveyed to pump region by 20 mm diameter tubes. The gas finally escaping towards beamlines is, of course, a drawback of the RFQC cooler concept, and is to be pumped by standard 330 l/s pump of the Eltrap machine. It is planned that the RQFC box be also connected to the plugin flange by two smaller tubes (gas tight): one for He injection, one for pressure $p$ measure; after suitable pre-regulation near atmospheric pressure and rupture disks, He input will be dosed by a mass flow controller, interlocked to pumps.

With the completion of the first faraday cup this March, the RFQC is almost ready for wiring test and insertion. Unfortunately the test of ion source in a separated test stand evidenced a deterioration of Cs emitter, so that installation is delayed.

## *Electric and RF Fields*

It is usually argued that rf voltage is bounded by $V_{rf} < k_1 m\omega^2 r_0^2/e$ by stability, so that the use of larger frequencies allows the use of larger voltages; actually 4 MHz is more than enough, since we get $V_{rf} < 4$ kV for our geometry ($r_0 = 4.5$ mm), while breakdown consideration suggests far lower voltages. We note that, at constant rf voltage, in order to increase the ponderomotive potential $V_p$, use of lower frequencies is advantageous, since macromotion frequency $\omega_M$ scales as $1/\omega$ thanks to eq. (1); from [8] simulations, a value $V_p(r_0) \cong 2.5$ V is sufficient in our geometry; this translates to $V_{rf} \cong 0.2$ kV at 4 MHz.

Since the RFQC has 10 sections of four electrodes each, in principle we have to supply 40 rf voltage and 40 dc bias, with 40 high voltage feedthroughs. In practice, we use multiplexing, see Fig. 3, so that only two rf voltages and 10 DC bias need to be supplied; moreover the RFQC is held near ground potential, to simplify insulation and cabling tasks; the multiplexer circuitry in vacuum consists of capacitors and resistors, with a thermal sink through mica washers and the RFQC mounting frame. This multiplexer has a flat response in the MHz range.

Note that RFQC itself is typically a largely reactive load, say an equivalent circuit $C_p = 200$ pF in parallel with $R_p = 2$ kΩ from very preliminary RFQC test cabling for each of the two multiplexer rf inputs; we can add a contribution of the order of 100 pF for the cables between RFQC and matching box MB. Note that an older design philosophy called for an oversized rf amplifier with class A output, so that the RFQC (an unmatched load) could be driven without any matching network (or box); a power rating $P_{rf} \cong 0.5$kW was envisioned. We observed that we have to supply two rf counter-phase voltages, which naturally lead to the use of transformers, and therefore of a matching box (MB). In our new design philosophy, the matching box allows to use a single output 50Ω matched amplifier to drive the two rf channels, with obvious economy in the amplifier. A MB prototype capable of providing $V_{rf} \cong 50$ V with $P_{rf} = 1$ W was developed, based on broad-band coaxial cable transformers (with small MnZn ferrites), see circuit A in figure 4. Precisely, in a test with RFQC and a multiplexer based on common resistors, with the rf generator set for 1 Vrms output on a matched load, we have input voltage $V_{rf}^0 = 0.94$ Vrms at resonance $f = 3.95$ MHz, with outputs $V_{rf}^1 = 4.58$ Vrms (phase delay $23^0$ to generator trigger) and $V_{rf}^1 = 4.69$ Vrms (phase delay -$157^0$ as requested). After disconnecting the RQFC, the resonance of MB becomes $f = 5.1$ MHz.

A more robust air-core matching box is under construction. A > 50 W rf generator seems suitable with reasonable margins. On the other hand, tuning of matching box, stability of rf voltage, and RFQC cabling becomes strongly correlated, so that the RQFC cabling should be completed and tested at low voltages, before the finalization of the full-power matching box.

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