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OPTIMIZATION OF MASS RESOLUTION PARAMETERS COMBINED WITH ION COOLER PERFOMANCE

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Abstract

High resolution mass spectrometers (HRMS) for separation of exotic ion species in nuclear physics experiments request a low emittance and small energy spread (with ΔE the peak-to-peak value, and σ_E the rms value) for the input beam, so that ion cooler devices, as Radio Frequency Quadrupole Coolers (RFQC), are typically envisioned. The SPES (Selective Production of Exotic Species) project at LNL requests $M/\Delta M \cong 20000$, rms normalized emittance ϵ_x^N in the order of 2 nm (see definitions later), and in the case of 160 keV ions, $\sigma_E \cong 1$ eV. The relevant collisional data are reviewed, in particular for Cs^+ against He, whose pressure ranges from 3 Pa to 9 Pa, in Milan test bench optimization. Practical consideration on gas pumping, voltage stability σ_{Va} and magnet design are also included. Typical limits of RFQC and HRMS performances are discussed, and relevant formulas are implemented in easy reference tools.

INTRODUCTION

Cooling [1,2] of secondary beams is often necessary to accelerator based nuclear and sub-nuclear physics, with beams ranging from exotic nuclei ions (like $^{132}Sn^{1+}$), as in the SPES (Selective Production of Exotic Species [3,4]) project at LNL, to positrons e^+, muons $\mu^\pm$ [5] and antiprotons, for the respective collider facilities. In the latter cases, emittance reflects the phase space necessary to decay and/or efficient production reactions; so transverse momentum is large, also exceeding the MeV/c range. In SPES project a conveniently limited H^+ primary beam (from a cyclotron) induces fission reactions in a hot target, with products first stopped into the target, then diffused and singly ionized in sources IS of several kinds [6,7], which have to cope with the heat and radiation produced by the primary beam; so source voltage and ion kinetic energy K_i are limited, say $K_i \cong 40$ keV. Emittance and rms energy spread σ_{E1} of the secondary beam depend on source kind; we consider the worst case of plasma sources: we have $\sigma_{E1} \cong 5$ eVrms (so much smaller than $\mu^\pm$ one), which allows beam transport to a (less-shielded) re-accelerator; total current can be reduced to < 25 nA by a suitable Wien filter. Anyway, this beam still contains many nuclear species, so that most experiments require a High Resolution Mass Spectrometer (HRMS) [8], whose design relies on colder beams, as obtained in so-called coolers, for example a Radio Frequency Quadrupole (RFQ) Cooler (RFQC) [2], see Fig. 1.a.

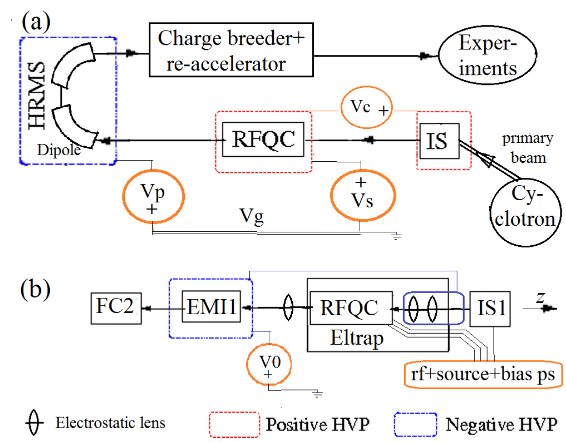

Figure 1: Block diagrams (not to scale) of: (a) interdependence of ion source IS, cooler and HRMS, as a zoom in the SPES project; (b) ion source IS1, cooler and emittance meter EMI1 in the Eltrap machine; beam stops at Faraday cup FC2. Some power supplies (ps) are sketched.

Cooling of particles X (that is the reduction of the momentum variance of ion population) is accomplished with two opposing processes, one involving collisions where particles X exchange energy and momentum with a colder beam [9] or gas, the other is a reacceleration, where all X particles receive an equal additional energy (by small bias voltages V_i^s in our case). A condition for cooling is that faster X particles loose more energy than slower ones in collisions; to obtain this, careful design, simulations and experimental verification of coolers are required.

OVERVIEW OF MAJOR COMPONENTS

In an RFQC [10–12], which is a kind of linear ion trap, ions are decelerated, and enter inside a gas cell, typically filled with He at a pressure from $p_g = 3$ Pa to 9 Pa, which contains an RFQ with rods divided in N sections; so ions are slowed down by this buffer gas and are confined by the RFQ voltages; the RFQC is usually enclosed in a box, at a voltage V_s with respect to ground, to maintain the gas pressure. By applying adequate drift voltages V_i^s (from 10 V to 100 V, respect to that box) to the RFQC sections $i = 1, \ldots, N$, ions are reaccelerated to one box end, where they are extracted. A previous LNL RFQ test prototype (with $N = 10$ sections [2,6]) was installed into the Eltrap facility (a Penning-Malmberg trap with a 1.5 m long solenoid) at Milan University, see Fig 1.b, to study the combined confinement

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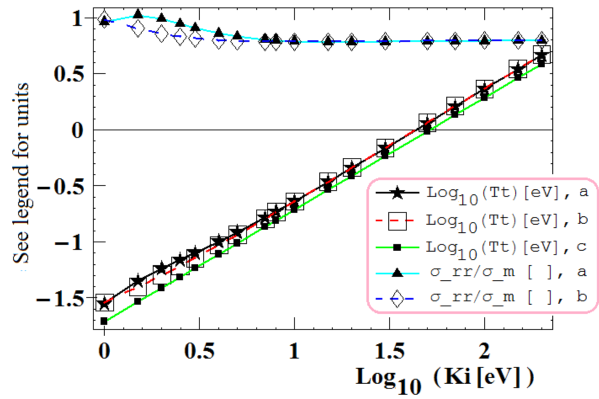

Figure 2: Cs^+-He collision results vs ion kinetic energy K_i (up to 200 eV); see just after Eq. 6 for T_t expression; case 'c' is the hard sphere model with 2.5 Å radius, case 'a' and 'b' use different inter-atomic potentials (see text).

of the RFQ and of a $\mathbf{B}^s$ magnetic field [11], and the injection and extraction phases. In this test, natural $^{133}Cs^{1+}$ ions are provided by a commercial surface ion source IS1.

As regard to general requirements and notations, let xyz be a local reference frame with z axis tangent to beam; since axial velocity $v_z \neq 0$, each ion path can be written $x(z)$, $y(z)$ and $x'(z) = v_x/v_z$; rms geometrical emittances ϵ^g are most naturally defined by $\epsilon^g_x = (\langle x^2\rangle\langle x'^2\rangle - \langle x\,x'\rangle^2)^{1/2}$ with $\langle\rangle$ the beam or statistical average, and similarly for y, when x and y motions are uncorrelated (see Ref. [13] for coupled xy motion). Ion source rms geometrical emittances are $\epsilon^g_{x1} = \epsilon^g_{y1} \leq 9$ mm-mrad $= 9 \times 10^{-6}$ m at ion energy $K_i = 40$ keV, so that rms normalized emittance $\epsilon^N_{x1} = \beta\gamma\epsilon^g_{x1} \cong 7\times10^{-9}$m; energy spread is in the order 10 eVpp, so conservatively we set its rms spread $\sigma_{E1} \cong 4$ eVrms as initial value at IS1. Exotic ions (for example ^{100}Nb and ^{100}Tc) need a high resolution mass spectrometer HRMS [3], with resolution goal 1:20000. In SPES project, a HRMS design requests a High Voltage platform HVP to rise $K_i \cong 160$ keV and an emittance about $\epsilon^N_x \cong 1.5 \times 10^{-9}$ m with $\sigma_E \cong 1.5$ eV, to be provided by the RFQC ion cooler inserted between IS and HVP [4, 14].

High Voltage Platform

The ion accelerating voltage V_a (at HRMS input), as shown in Fig. 1, is the sum of V_p (HV platform), V_s (RFQC reference voltage) and of differences (or fluctuations) in their ground connection V_g, which cannot be neglected at required accuracy:

$$V_a = V_s + V_p + V_g \tag{1}$$

Note that ion source low voltage V_c with respect to reference V_s needs to be regulated for injection see Fig. 1.a, with other possible fluctuations, which can be included in the σ_{E1} value and are assumed to be mostly damped by the RFQC itself. In other words, RFQC box exit is the virtual ion source (where ion kinetic energy eV_i is few eV), where tracing of ions to HRMS should begin.

Current design values are $V_p = 120$ kV, $V_s = 40$ kV and $V_g = 0$ (possibly requesting a thick aluminum plate, drawn as a double line in Fig. 1). Suppression of corona and other HV microdischarges is necessary, as implemented by carefully rounded platform edges and spacings [15]; in particular, ion acceleration and deceleration columns need care. Moreover, balancing of loads on the three phase main network inside platform is recommended, to reduce V_p ripple; it is often argued that V_p and V_s ripples can be anti-correlated (by very careful engineering), but this may be considered as further improvement option. In any case, the rms voltage spread σ_{Va} must include ripples and correlation of Eq. 1 terms.

Gas Collisions

Let m_i be the ion mass, with charge equal to the proton charge e, m_g be the mass of gas, with density n_g and ϕ_s be the electrostatic potential; we express temperatures in energy units, and gas temperature $T_g \cong 0.026$ eV is neglected. Let $\mathbf{v}$ be ion velocity (in the laboratory system), averaged on a rf period; confining effect of rf can be expressed by a so-called ponderomotive potential ϕ_p [10,17]. Many gas collisions are needed to change $\mathbf{v}$ significantly, since $m_g/m_i = 0.03 \ll 1$; Langevin-style equations can model both the first m_g/m_i order effect, which is a friction force $-m_i\nu_m\mathbf{v}$ and the 2nd order straggling effect

$$\mathrm{d}_t\mathbf{v} = \frac{e}{m_i}\left(\mathbf{E}_s + \mathbf{E}_p + \mathbf{v}\times\mathbf{B}^s\right) - \nu_m\mathbf{v} + \boldsymbol{\eta} \quad , \tag{2}$$

$$\langle\boldsymbol{\eta}\rangle = 0\,, \quad \langle\eta^k(t)\eta^n(t')\rangle = D^{kn}\delta(t-t') \tag{3}$$

where $\nu_m(K_i)$ is the collision frequency, $\mathbf{E}_p = -\nabla\phi_p$, $\mathbf{E}_s = -\nabla\phi_s$, notation $\langle\rangle$ indicates the statistical average, $\boldsymbol{\eta}$ is a random kick, with 2nd order moment given by diffusion tensor $D(K_i)$, and $k, n = 1, 2, 3$ or x, y, z are coordinate indexes; by symmetry, ν_m can not depend from ion direction, but only on its speed $v = |\mathbf{v}|$ (or on its energy $K_i = m_i\mathbf{v}^2/2$). Let $\theta(b, E_{cm})$ be the deflection angle and E_{cm} be the collision energy in the center of mass system, while b is the impact parameter [16,17]; we have $E_{cm} = f_1K_i$ and $\nu_m = n_g f_1 v\sigma_m$ with the [momentum-transfer] cross section

$$\sigma_m = 2\pi\int_0^\infty \mathrm{d}b\, b[1-\cos\theta(b,E_{cm})]\,, \quad f_1 = \frac{m_g}{m_g+m_i} \tag{4}$$

and, in paraxial approximation $|v_x/v_z| \ll 1$,

$$D_{xx} = n_g f_1^2 v^3\sigma_{xx}\,, \quad \sigma_{xx} = \pi\int_0^\infty \mathrm{d}b\, b\sin^2\theta(b,E_{cm}) \tag{5}$$

Since D induces an emittance growth, while ν_m may give emittance decrease, their precise calculation for all K_i is basic to cooler performances, see Fig. 2, with $\sigma_{rr} = 2\sigma_{xx}$; seemingly different parameters of the He-Cs^+ inter-atomic potential $V(r)$ with r the ion-atom distance are given in Refs. [17] and [18]; anyway we obtain similar results for the ratio $\sigma_{rr}/\sigma_m \cong 0.8$ when $K_i \geq 5$ eV. Let $\tilde{\mathbf{v}}$ be the fluctuation of $\mathbf{v}$ and define the transverse temperature as

$$T_t = m_i\langle\tilde{v}_x^2 + \tilde{v}_y^2\rangle/2\,; \tag{6}$$

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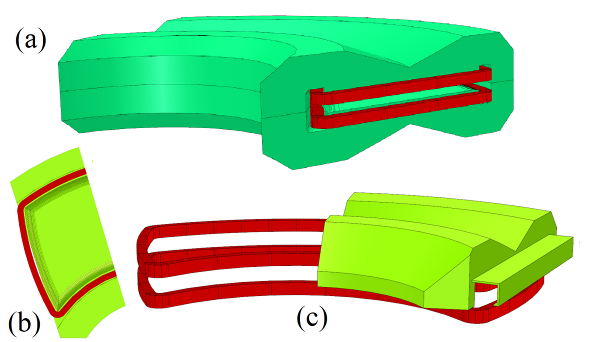

Figure 3: Optimization steps of dipoles with large bending radius (1.5 m): (a) from H-shape to yoke weight reduction; (b) adding Rogowsky edge with curved boundary (radius $R_e \cong 2$ m to 3 m) of pole shoes; (c) view of coils, a field external clamp and a final chamfer of yoke.

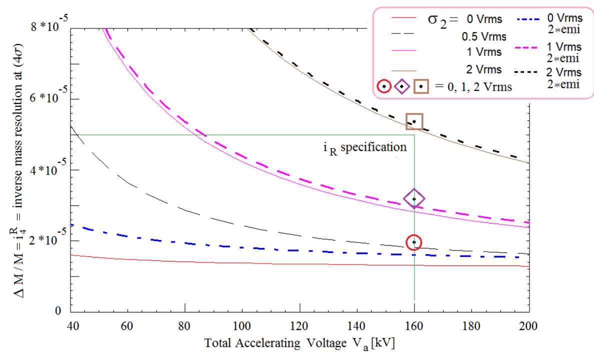

Figure 4: Inverse resolving power i_4^R vs. acceleration voltage V_a, for several σ_2 as labeled; curves from Eq. 8, at $\epsilon_x^N = 2.9 \times 10^{-9}$ m (thicker lines, '2*emi') or $\epsilon_x^N = 1.45 \times 10^{-9}$ m (thinner lines), with comparison to three points from multiparticle simulations

as a rule of thumb, in paraxial approximation, we reach $T_t = m_i D_{xx}/\nu_m \cong 1.6 f_1 K_i$, for adequate pressures ($p_g > 6$ Pa to 9 Pa in Eltrap case), as shown in Ref. [13]; we then obtain $\sigma_E \cong 0.5$ eVrms. This confirms [2] design and choices of V_i^s, where K_i goes down from 20 to about 3 eV in last two RFQC sections, as a compromise between transmission and cooling, so that T_t from 0.2 eV to 1 eV. Note also that $T_t \gg T_g$, confirming the gas at rest assumption.

Studies and Highlights on HRMS

Ion mass ratio is $M = m_i e/m_u|q|$ with q and m_i the charge and ion mass, and m_u the atomic mass unit; eg. $M = 99.9071$ for $^{100}Tc^{+1}$ and $M = 99.9136$ for $^{100}Nb^{+1}$, which SPES aims to separate [3]. A typical beamline with two 90 degree dipoles (Fig. 3) is used: the maximum resolving power $M/\Delta M$ is related to ion bending radius r_b, nominal bending radius R_m and maximum beam envelope size $\pm x_M$; so a magnet pole width greater than $2x_M$ is needed. First, neglecting voltage and magnetic field B_y variations, the inverse resolving power i_4^R at $\Delta M = 4\sigma_M$ separation is

$$i_4^R \equiv \frac{\Delta M}{M} = 4\frac{x_w}{D_i} = \frac{x_w}{R_m} = \frac{\epsilon_g}{x'_d R_m} = f_0 \frac{\epsilon_g}{x_M} \qquad (7)$$

with x_w the waist rms spot, $D_i = 4R_m$ the dispersion function, x'_d the rms divergence in the input or object point related to $\epsilon_g = x_w x'_d$, and to envelope size by $x_M = f_0 x'_d R_m$ with $f_0 = 2\sqrt{5}/3$ from beam transport matrices, as used in steps above. Second, ion bending radius satisfies $r_b^2 = M(V_a + V_i)2m_u/eB_y^2$, with $E_i = eV_i$ the residual ion energy at RFQC exit; differentiating it, solving for dM/M, and adding rms spread σ_{V_i}, σ_{By}, σ_{Va} effects to Eq. 7 we get

$$i_4^R \cong 4\sigma_1, \quad \sigma_1^2 = 4\frac{\sigma_{By}^2}{B_y^2} + \frac{\sigma_{Va}^2 + \sigma_{Vi}^2}{(V_a + V_i)^2} + f_1 \frac{\epsilon_g^2}{x_M^2} \qquad (8)$$

with $f_1 = (f_0/4)^2 = 5/36$ for consistency with Eq. 7. We can define $\sigma_2 = \sqrt{\sigma_{Va}^2 + \sigma_{Vi}^2}$ to group RFQC and HRMS electrical performance in one critical parameter; sensitivity of i_4^R respect to V_a and σ_2 is shown in Fig. 4, for $\sigma_{By}/B_y \cong 1.5 \times 10^{-6}$ and $x_M = 0.25$ m, with curves from above theory and points from multiparticle simulations [8]; at $V_a = 160$ kV design goal needs $\sigma_2 < 1.8$ Vrms, that implies $\sigma_{Vp}/V_p \cong 10^{-5}$, considered well feasible with some margin. Doubling the emittance has a large effect when $\sigma_2 = 0$, but difference reduces to less than 1.9% when $\sigma_2 = 2$ Vrms, as plotted.

Similarly, multiparticle simulations (with error about as the plotted marker size) give a larger i^R because they include the effect of B_y changes near pole boundaries, but also this difference is only about 3% when $\sigma_2 = 2$ Vrms. Note that dipole fringe field is important; edge curvature $R_e \cong 2.9$ m is required to avoid excessive nonlinear (sextupole) effects, as calculated from magnet simulation and confirmed by this multiparticle simulations. Nonlinear theoretical studies are well in progress and outside this paper scope. Note that thicker lines in Fig. 4 corresponds to $c\epsilon_x^N \cong (\langle x^2\rangle\langle v_x^2\rangle)^{1/2} \cong 0.9\ m^2/s$ at RFQC exit, that is $T_t = 0.5$ eV and a 1.8 mm rms radius, well consistent with RFQC box exit.

CONCLUSION

Cooling of heavy exotic ions in RFQC is feasible down to $c\epsilon_x^N < 1\ m^2/s$ (rms value, depending also on collision physics) and $\sigma_E \cong 0.5$ eVrms, which gives some margins for voltage stability of HV platforms or other errors.

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