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Proposal to the INTC Committee

An Energy Upgrade of REX-ISOLDE to 3.1 MeV/u and Acceleration of Heavier Masses up to $A = 150$

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Summary

With an additional 9-gap resonator, operated at 202.56 MHz, the maximum beam energy of REX-ISOLDE will be increased from 2.2 MeV/u to 3.1 MeV/u. This enlarges considerably the range of mass numbers of projectiles reaching the Coulomb barrier for nuclear reactions. Acceleration of heavier projectiles, however, requires longer charge breeding times leading to smaller pulse repetition rates. Thus EBIS developments aiming at shorter breeding times by using higher electron beam current densities are foreseen. Moreover, longer breeding times require longer accumulation times and larger ion storage capacities in REXTRAP to maintain the beam intensities, which will be reached by using new cooling techniques. Although various optimization steps can be performed with ion sources local to REX-ISOLDE, a commissioning of the modified REX-ISOLDE with ISOLDE beams of heavier masses with 15 shifts is requested.

1 Introduction

To make full use of the broad range of isotopes available at ISOLDE an energy upgrade of REX-ISOLDE to 3.1 MeV/u is being prepared and a further future upgrade to 4.3 MeV/u is under consideration. Presently the maximum beam energy of REX-ISOLDE is 2.2 MeV/u, where the Coulomb barrier significantly limits the mass A and nuclear charge Z of the projectiles that can be used to induce nuclear reactions. The maximum useful mass and charge number is limited by the requirement

$$\frac{A + A_{\text{target}}}{A \cdot A_{\text{target}}} \cdot \frac{Z \cdot Z_{\text{target}}}{A^{1/3} + A^{1/3}_{\text{target}}} \leq \frac{E}{A} \text{ [MeV/u]}, \tag{1}$$

which is obtained considering head-on collisions and approximating the interaction radius by $1.44(A^{1/3} + A^{1/3}_{\text{target}})$ fm [1]. Assuming $A \sim 2.5\,Z$ this leads for beam energies of 2.2 MeV/u and a deuterium target to a maximum projectile mass number of $A = 55$ and for an approximately symmetric projectile–target system to $A = 50$. With an increase of the beam energy to 3.1 MeV/u these numbers increase significantly to 90 and 85, respectively, and for 4.3 MeV/u to $A = 140$ for both cases.

However, this upgrade requires further developments to reach higher efficiencies for heavier beams in REX-ISOLDE. We therefore plan to increase the storage times and ion bunch intensities in REXTRAP, which hopefully will result in two orders of magnitude higher beam currents (up to 10 pnA) than presently available. While reasonable charge breeding times are reached for light ion beams, heavier beams require more intense electron beams in REX-EBIS. Presently only 150 A/cm^2 are used, while the system was designed for 250 A/cm^2, which will be reached in the near future. Moreover, other cathode designs are now available, which would allow for 500 A/cm^2 [2] e. g. by magnetically compressing the electron beam. Since the breeding times are proportional to the current density a significant shortening of the breeding times and a successful operation with heavier beams is foreseen. Also pushing the energy of the present REX-LINAC to a maximum value of 2.3 MeV/u allows for a maximum beam energy of 3.1 MeV/u with the new resonator. Though many properties can be optimized with ion sources local to REX-ISOLDE the combination of all improvements has to be tested in commissioning runs with beams from ISOLDE.

2 Technical developments

2.1 REX-LINAC

In order to overcome the present mass limit of $A \approx 40$ for the investigation of nuclear reactions, an energy upgrade using a 9-gap IH-resonantor is planned for the next shutdown period. In Fig. 1 the layout of the LINAC upgrade is shown. The new cavity will be set-up in the drift space between the last quadrupole lens of the 7-gap resonators and the big bending magnet. The required 100 kW 202.56 MHz amplifier will be located in the amplifier room separated from the 101.28 MHz amplifier rows. The new resonator has a resonance frequency of 202.56 MHz and operates with a maximum duty cycle of 10 %. The synchronous particle velocity is 7.4 % of c, corresponding to a cell length of 55 mm. The high shunt impedance of this structure of about 300 MΩ/m results in a total resonator

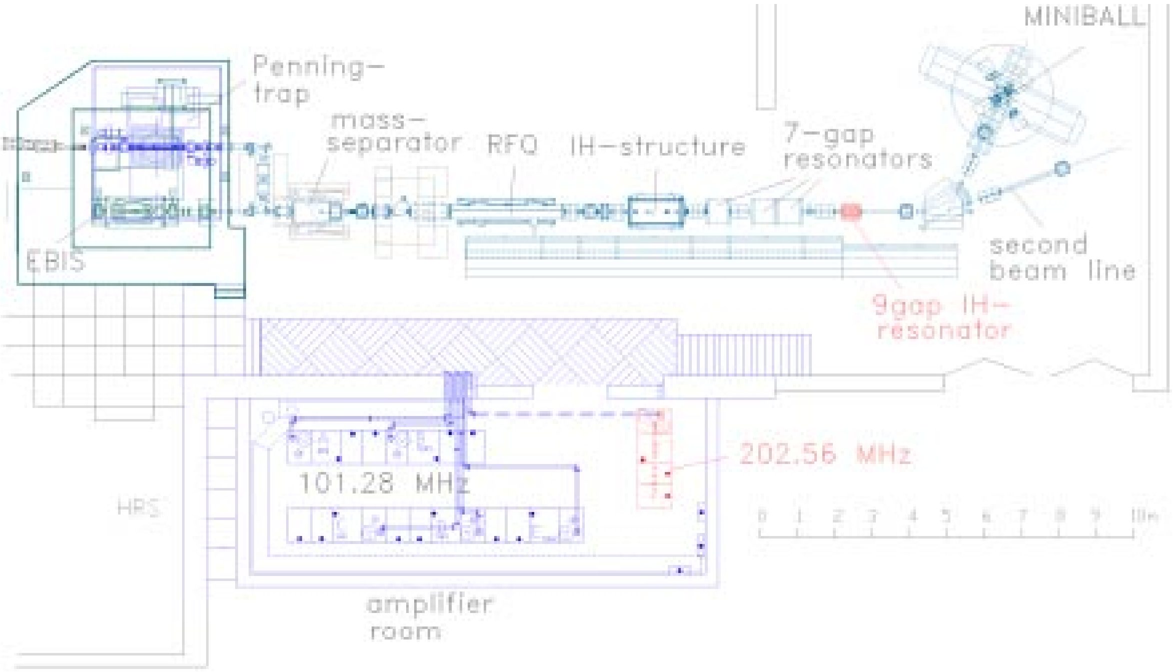

Figure 1: *Layout of REX-ISOLDE, including the new 9-gap resonator.*

voltage of 3.7 MV for 90 kW rf-power fed into the cavity. Assuming a transit time factor of 0.9 for the cavity at 0°-synchronous phase and an $A/q = 4.5$ of the radioactive ion beam a maximum energy gain of 0.74 MeV/u is possible. Operating the three 7-gap spiral resonators of REX-ISOLDE at 0°-synchronous phase an energy of 2.3 MeV/u for $A/q = 4.5$ can be achieved, which is the injection energy for the following 9-gap IH-resonator. Due to the higher resonance frequency of 202 MHz all dimensions of the resonator are reduced by roughly a factor two in comparison to the 101 MHz booster cavity of the REX-ISOLDE LINAC. Thus a space-saving, energy efficient upgrade solution, similar to the LINAC3 of CERN, becomes possible.

Fig. 2 shows details of the resonator tank with the upper and lower half lids and a central support frame. The plunger on top is used for fine tuning of the resonator frequency. Originally, the tank was planned as a 7-gap resonator for the Munich fission fragment accelerator MAFF. However, due to delays in getting the permission to run the Munich FRM-II reactor, the original 6 drift tubes were replaced by 8 new drift tubes to adjust it to the needs of REX-ISOLDE. Due to the delay of the reactor start-up a long term usage at CERN can be foreseen, allowing to gain operational experience with these kind of accelerator structures.

A 1:1 model of the 7-gap resonator was used to determine the relevant rf- and geometrical data of the new IH-resonator. Meanwhile the power resonator is in production (see Fig. 3) and final frequency tuning measurements have been carried out with both drift tube structures. Measurements of the resonance frequency with both structures have shown a small difference of only 100 kHz in the resonance frequency. Due to the smaller drift tubes the shunt impedance of the 9-gap resonator, however, is expected to be significantly increased, which could be verified in corresponding measurements as well.

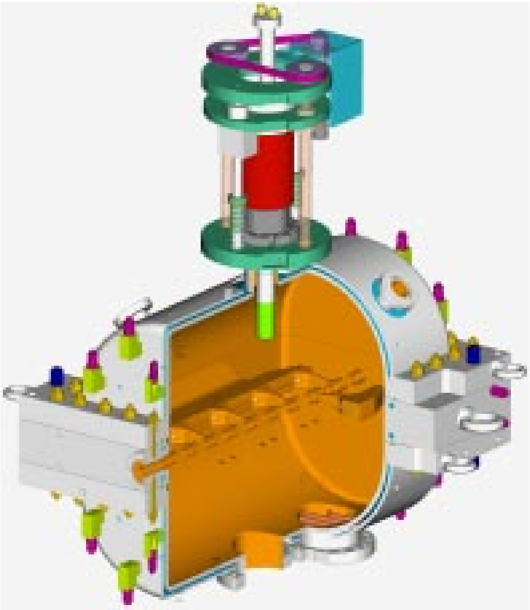

Figure 2: *Technical Drawing of the new 9-gap resonator. The inner tank length is 0.5 m.*

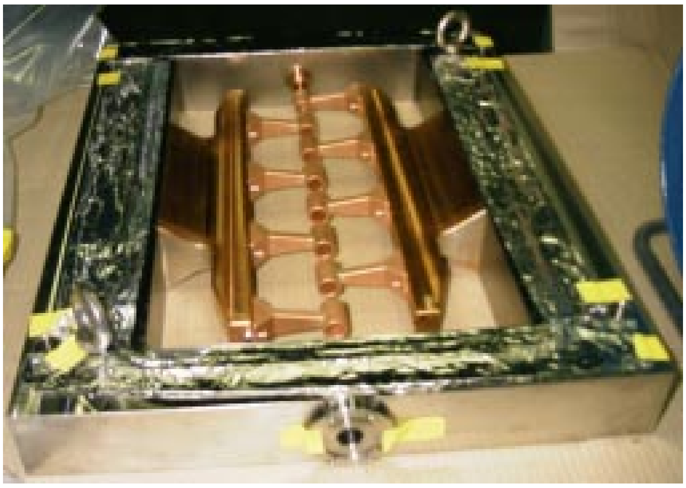

Figure 3: *Central frame of the power resonator with 8 drift tubes.*

2.2 REXEBIS

The maximum A/q value of 4.5 for the radioactive ions, which can be accelerated via the REX-LINAC, requires charge breeding of the heavier masses to higher charge states up to 30 in REXEBIS [3]. The breeding time for a given mass and charge state can be estimated by the following relation:

$$t_q = \frac{e}{j_e} \sum_{i=1}^{q-1} \frac{1}{\sigma_{i \to i+1}(E_e)} \tag{2}$$

Here j_e is the electron beam current density and $\sigma_{i \to i+1}$ is the ionisation cross section from charge i to $i + 1$, which is energy dependent. A well suited expression for the energy dependence of the cross section is given by the semiempirical Lotz formula [4]:

$$\sigma_{i\to i+1}(E_e) = 4.5 \cdot 10^{-14} \sum_{nl} \frac{\ln(E_e/E_{i,nl})}{E_e \cdot E_{i,nl}} \ [\mathrm{cm}^2] \tag{3}$$

Here E_e is the electron beam energy in eV and $E_{i,nl}$ are the ionization energies for removable electrons in all nl orbitals in eV. Assuming an electron beam current of 250 A/cm^2 and a beam energy of 5 keV, the breeding time for mass A = 120–150 increases significantly to about 100–160 ms and the repetition rate of the breeding cycle would have to be decreased from 50 Hz to 5–6 Hz.

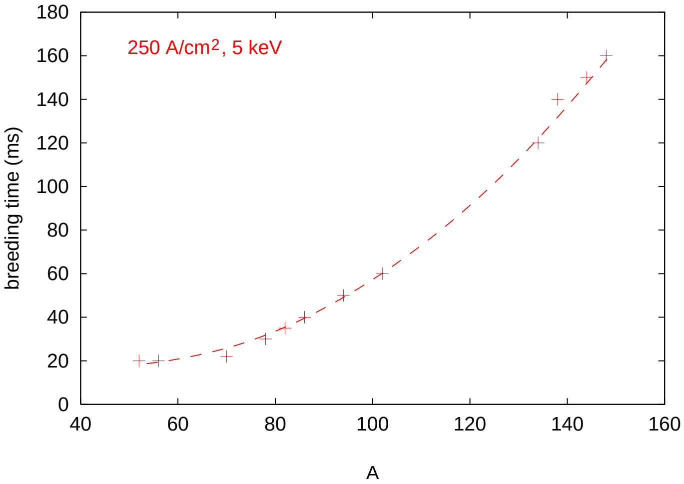

Figure 4: *Charge breeding times for neutron-rich nuclei to reach a mass to charge ratio A/q of 4.5. The design values for the electron beam of the EBIS (250 A/cm^2 and 5 keV) were assumed.*

Fig. 4 shows the breeding time as a function of the mass number A for the electron beam parameter given above. For the heaviest nucleus considered (^{148}Ba) with charge state 33$^+$ the ionization energy for the last electron is 2.1 keV. Since the Lotz formula for ionization shows a maximum of the ionization cross section for electron beam energies of about 3-times the ionization energy the available electron beam energy of 5 keV is sufficient. On the other hand, an increase of the electron beam current density of the REXEBIS by a factor of two would reduce the breeding times below 100 ms [2].

The study of breeding of heavier masses can easily be done using La-ions desorbed from the LaB$_6$ cathode used in the REXEBIS. For the breeding of radioactive ions a potential barrier usually prevents La ions from the cathode to reach the breeding region. Avoiding the potential barrier, a typical charge state spectrum of La-ions obtained after 20 ms of breeding is shown in Fig. 5. The maximum yield is observed for charge state $\sim 20^+$ after 20 ms breeding time. In contrast to charge state spectra obtained after injection from REX-TRAP the continuous injection of lanthanum leads to a much broader charge state distribution.

2.3 REXTRAP

A reduced repetition rate of the breeding cycle requires a longer accumulation and cooling cycle of REXTRAP. This could deteriorate the beam intensity as the maximum number of

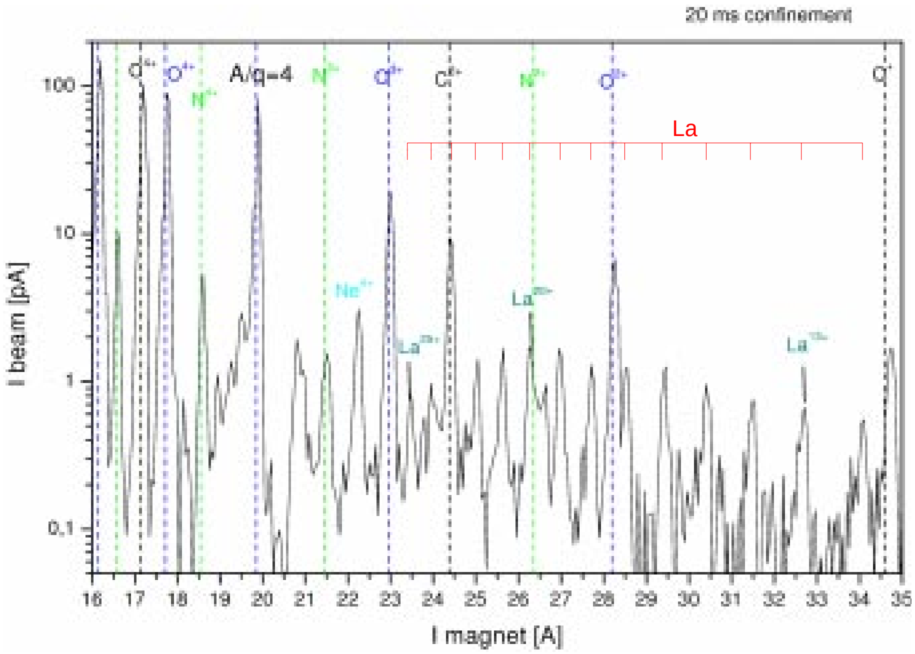

Figure 5: *Picket fence charge state spectrum of lanthanum ions after 20 ms confinement produced after elevated filament heating of the LaB*$_6$ *cathode. In contrast to charge state spectra obtained after injection from REXTRAP the continuous injection leads to a much broader charge state distribution.*

ions in REXTRAP is limited by space charge effects and storage halflife.

So far the ions in REXTRAP were cooled via the buffer-gas side-band cooling scheme [5, 6]. The reduced cyclotron motion (ω_+) and the magnetron motion (ω_-) are cooled by the buffer gas. As shown in Fig. 6a the amplitude of the cyclotron motion for an individual ion is reduced, while the radius of the magnetron motion will slowly increase without side-band cooling. Combining the rest gas cooling with a rf quadrupole electric field in the plane vertical to the B-field at a resonance frequency $\omega_+ + \omega_- = \Omega_c$, however, a coupling between the cyclotron and the magnetron motion occurs leading to a centering of the ion in the trap as shown in Fig. 6b.

If we consider a number of singly charged ions in excess of 10^5 space charge effects become important and the resonance frequencies for driving the different motions start to shift [6]. For ^{23}Na$^+$-ions the cyclotron resonance Ω_c (= 12.58 MHz) was applied with a quadrupole E-field to the four-fold segmented central electrode located in a 3 T magnetic field. Simulations for a cloud of 10^7 ions of ^{23}Na$^+$ showed that the ion cloud rotates as a whole with $\omega_{\rm rot} \sim 38$ kHz, a value which can be extracted also from measured shifts in the cyclotron resonance frequency when side-band cooling is applied [7, 6].

For a large rigid rotating cylindrical ion cloud in a homogeneous magnetic field B the three forces: (i) the Coulomb space charge force, (ii) the centrifugal force and (iii) the focusing $v \times B$ force balance:

$$\frac{n \cdot e^2 \cdot r}{2\epsilon_0} + m \cdot \omega_{\rm rot}^2 \cdot r = e \cdot \omega_{\rm rot} \cdot r \cdot B \qquad (4)$$

Introducing the plasma frequency $\omega_p^2 = \frac{e^2 \cdot n}{\epsilon_0 \cdot m}$ and the cyclotron frequency $\Omega_c = \frac{e \cdot B}{m}$ with

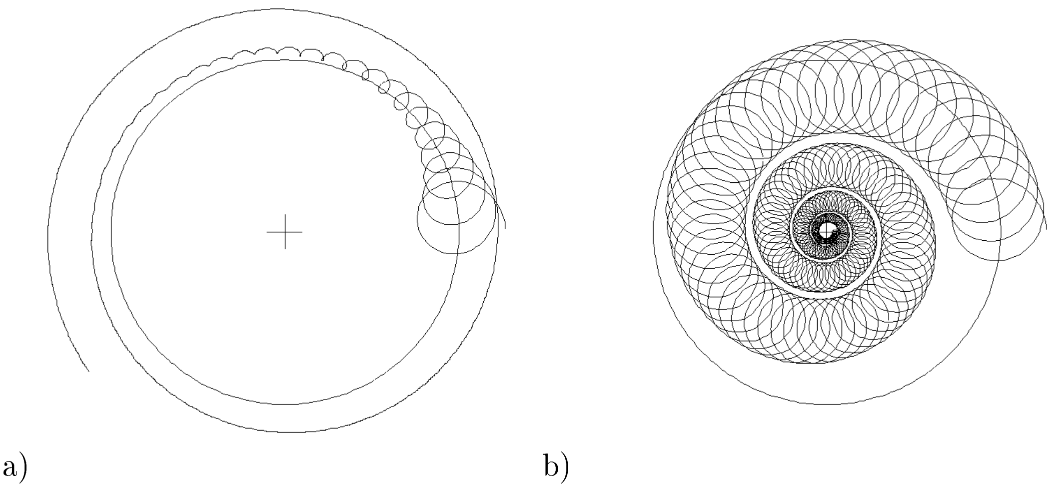

Figure 6: *a) Rest gas cooling of an ion in a Penning trap, showing the orbit in a plane perpendicular to the magnetic field with the fast damping of the cyclotron motion and the slow blow up of the magnetron motion. b) Side-band cooling of an ion in a Penning trap, where both the cyclotron and magnetron radii decrease.*

the ion density n and ion mass m, we obtain a quadratic equation in $\omega_{\rm rot}$ with the two solutions $\omega_{\rm rot\pm}$ [11]:

$$\omega_{\rm rot\pm} = \frac{\Omega_c \pm \sqrt{\Omega_c^2 - 2\omega_p^2}}{2} \tag{5}$$

These solutions are shown in Fig. 7. The rotational frequency allowing for the maximum plasma frequency $\omega_p = \Omega_c/\sqrt{2}$ is $\Omega_c/2$. From this relation we obtain the Brillouin limit for the maximum ion density:

$$n_{\rm max} = \frac{B^2\epsilon_0}{2m} = \frac{1}{A}\cdot(\frac{B^2\epsilon_0}{2m_u}) \tag{6}$$

leading to $n_{\rm max} = \frac{1}{A}\cdot 2.4\cdot 10^7[1/({\rm mm})^3]$ for our field of 3 T.

In the future we therefore want to apply a new cooling scheme: the so called “rotating wall” scheme [8, 9, 10, 11, 12]. The idea is to balance the plasma expansion of the rotating plasma by a “rotating wall” electric field, which spins up the ion cloud and causes via the $v \times B$ force a plasma compression close to the Brillouin limit. This has been studied for $\rm Mg^+$ ions with laser diagnostics [10] as well as for electron plasmas [13] and positron plasmas [9]. The heating produced by the applied rotating electric field has to be compensated by some cooling mechanism. For ions laser cooling and neutral buffer gas has been applied. For electrons and positrons cyclotron cooling in the strong magnetic field or neutral buffer gas cooling has been used.

Fig.8 shows eight azimuthally segmented electrodes to which the rotating multipole E-field of multipole order m is applied. The field can be derived from the potential given in cylindrical coordinates:

$$\Phi(r,\Theta) = A_m(\frac{r}{a})^m \cos(m(\Theta - \omega_{\rm rot}\cdot t)) \tag{7}$$

The electric field components are:

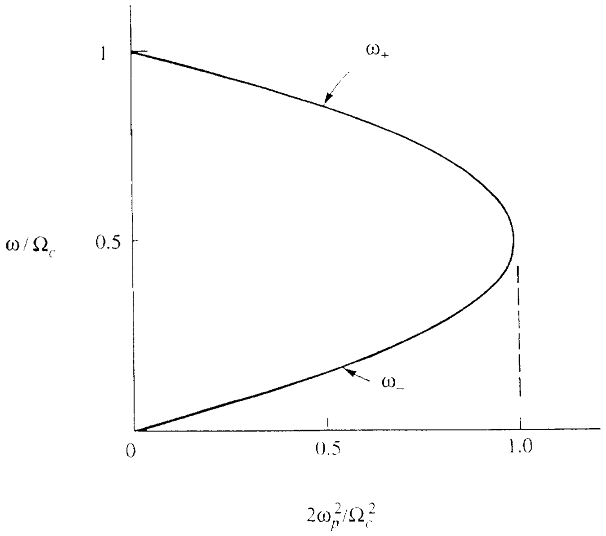

Figure 7: *Plasma rotation frequency* ω_{rot} *as a function of plasma frequency* ω_p *and the cyclotron frequency* Ω_c*, which depends on the magnetic field strength [11].*

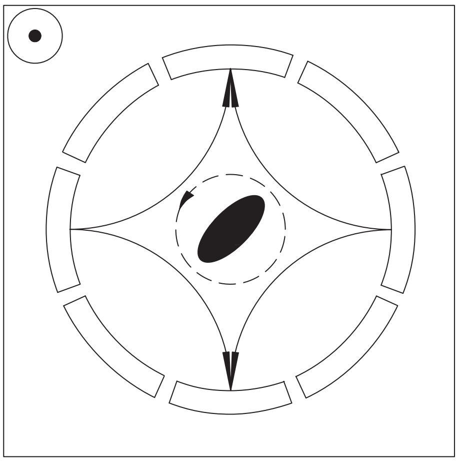

Figure 8: *E-field configuration for rotating wall cooling with an eight-fold segmented electrode.*

$$E_r(r,\Theta) = E_m(\frac{r}{a})^{m-1}\cos(m(\Theta - \omega_{\mathrm{rot}}\cdot t)) \tag{8}$$

$$E_\Theta(r,\Theta) = -E_m(\frac{r}{a})^{m-1}\sin(m(\Theta - \omega_{\mathrm{rot}}\cdot t)) \tag{9}$$

In Fig. 8 a rotating quadrupole field with $m = 2$ is shown. Since the tangential friction by the buffer gas for rigid rotation is given by $\frac{e}{\mu}\cdot r\cdot\omega_{\mathrm{rot}}$, where μ is the ion mobility, a quadrupole field ($m = 2$) with a radially linear increasing E-field appears most appropriate. For the application of such an E-field an eight-fold segmented central electrode will be installed in REXTRAP in the next weeks.

For first tests a rotating electric dipole field was applied to the presently existing four-fold segmented electrode. When a rotating frequency ω_{rot}= 396 kHz was used for Na$^+$-ions an increase in the stored ions per bunch from about 10^7 with side-band cooling to

$5 \cdot 10^7$ with rotating wall cooling was observed. The expected increase by the factor 10 ($\sim 396\,\mathrm{kHz} \,/\, 38\,\mathrm{kHz}$) was not reached because the injected ion intensity was not sufficient. For this rotating wall scheme also an increase of the storage time from formerly 200 ms was observed. Thus the ion loss by radial expansion was suppressed.

In the future we want to spin up the ion cloud close to the to the maximum rotational frequency $\Omega_c/2$ with an axial rotating quadrupole E-field. With this a total increase in ion density and bunch intensity by a factor of about **80**, compared to the former cyclotron resonance side-band cooling scheme, is expected. Special rotating Trivelpiece-Gould (TG) plasma mode resonances, which correspond to transversly running Langmuir waves, may increase the efficiency to induce rotation [13]. The rigid rotation of the ion cloud with friction and energy loss in the rest gas and its balance with the driving force of rotation has to be studied. Also the time required to spin up the ion cloud to its maximum rotational frequency has to be investigated, as well as the emittance after extraction from the Penning trap solenoid. In this way REXTRAP may be capable of handling much higher intensities of up to 10^{10} ions/s.

3 Requested beam time

These new breeding scenarios require tests of REXTRAP with longer accumulation and cooling times for the new “rotating wall” scheme, tests of the ion injection of heavier masses into the REXEBIS and measurements of charge state spectra from masses up to $A = 150$. Tests with local ion sources of REX-ISOLDE are already planned und will be performed beforehand, using intense heavy mass beams with mass number A up to 150. Our experience with several surprises (e. g. stray magnetic fields) with lighter beams from ISOLDE taught us, that we should request **15 shifts of stable and radioactive parasitic beams from ISOLDE** for commissioning these developments. Beam from the test ions sources are solely alkali metals.

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