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# HOLLOW BEAM FORMATION IN THE EXTRACTION REGION OF ECRIS

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## Abstract

Beam optics in the extraction system of an ECR ion source (ECRIS) are examined both analytically and numerically, by taking nonlinear effect due to aberrations of einzel lens into account. It is shown that this effect can cause hollow beam formation. Simple analytical criteria to keep the good beam quality in the focusing system are given.

## 1. Introduction

Beam quality of a high-intensity heavy-ion accelerator is mostly defined by the extraction region of the ion source where nonlinearity due to space charge and focusing field are significant. At the RIKEN Accelerator Research Facility an 18-GHz ECR ion source (ECRIS) is under construction for the heavy-ion linac. This new ECRIS is expected to produce higher-charge states of heavy-ions so that the acceleration performance of the linac can be further upgraded. The extraction system of this ECRIS consists of an extraction gap and an einzel lens as shown in Figs.1 and 2. After passing the einzel lens, the extracted beam has to be focused onto a spot with a diameter of 10 mm to be matched with the following beam transport system. The purpose of this study is to examine nonlinear beam-optics effects of the einzel lens which can influence the beam profile and emittance shape of the extracted beam.

## 2. Beam Emittance

In an ECRIS charged particles are born in a strong longitudinal magnetic field $B_Z$ fulfilling the ECR resonance condition $2\omega_L=\omega_{RF}$ where $\omega_L=eB_Z/2m_e$ is Larmor's frequency of electrons and $\omega_{RF}$ is a microwave frequency. The effective phase space area occupied by the ensemble of particles is described by the value of root-mean-square (RMS) normalized beam emittance defined in canonical-conjugate coordinates:

$$\varepsilon=\frac{4}{m\,c}\sqrt{<x^2><P_x{}^2>-<xP_x>^2}\ , \qquad (1)$$

where m, x, and $P_X$ are a mass, a transversal Cartesian coordinate and a canonical-conjugate momentum of a particle, respectively, and c is the speed of light. For particles in the ECRIS one can put $<xP_X> = 0$. Canonical momentum of a particle $P_x = p_x - qA_x = p_x - qB_z\,y/2$ in the longitudinal magnetic field is a combination of mechanical momentum $p_X$ and $qA_X$ where q is an ion charge and $A_X$ is an x-component of vector potential of the magnetic field . The RMS value of canonical momentum is given by:

$$<P_x^2> = <p_x^2> - q\,B_z<p_x\,y> + \frac{q^2\,B_z^2}{4}<y^2>\ . \qquad (2)$$

The first integral in eq. (2) describes the thermal spread of mechanical momentum of charged particles in the ECR plasma. Therefore, the RMS value of mechanical momentum is given by $<p_x{}^2> = <p_{th}{}^2> = mkT_i$ where $T_i$ is the ion temperature and k is Boltzmann's constant. The middle integral equals zero because there is no correlation of $p_X$ and y. The last integral is proportional to the RMS value of transverse coordinate $<y^2>$. For most of the beam distributions $\sqrt{<y^2>} = R/2$ where R is a beam radius comprising around 90% of particles. Finally the RMS value of canonical momentum is $<P_x^2> = <p_{th}^2> + (q\,B_z\,R\,/\,4\,)^2$. Combining the obtained value of $<P_X{}^2>$ with equation (1) the normalized beam emittance ε is given by:

$$\varepsilon=2\,R\sqrt{\frac{kT_i}{mc^2}+\left[\frac{\omega_L\,R}{2\,c}\right]^2}\ . \qquad (3)$$

The formula (3) is usually used for estimation of the emittance of the beam with an ambient magnetic field on the cathode [1]. In the case of the 18-GHz ECRIS the resonant value of magnetic field is $B_Z$=0.637 T. The normalized beam emittance of, for example, an $Ar^{5+}$ beam with the ion temperature $kT_i$ =3eV is $\varepsilon = 2{\cdot}5{\cdot}10^{-3}\sqrt{0.8\ \ 10^{-10}+10^{-9}} = 3.3{\cdot}10^{-7}$ π·m·rad.

## 3. Numerical Study of Beam Optics

Numerical calculation of particle trajectories in the extraction region was performed with the computer program BEAMPATH [2]. Particle trajectories obey the equations of motion derived from a single particle Hamiltonian in Cartesian coordinates:

$$H=\frac{1}{2\,m}\left[(P_x-qA_x)^2+(P_y-qA_y)^2+(P_z-qA_z)^2\right]+q(U_f+U_c), \qquad (4)$$

where $U_c$ is a space charge potential of the beam and $U_f$ is a potential of the focusing field. The space charge potential is calculated from 2D Poisson's equation in Cartesian coordinates on the mesh 256 x 256. The 2D electrostatic potentials in the extraction gap and in the einzel lens are calculated by using the program POISSON.

Numerical study was performed for $Ar^{5+}$-ion beam with current of 100 eμA. The following parameters were varied so as to find the optimal matching conditions for the extracted beam with the beam transport system downstream: the extraction gap was varied from 3 cm to 4 cm; the distance of einzel lens from the extraction hole from 25 cm to 35 cm; and the voltage at the central electrode of einzel lens from 10 kV to 14 kV. The results are presented in Table 1 and in Figs. 1-4.

It is noted that in Fig. 4 the beam forms hollow structure at the waist point of beam envelope. The same phenomena were experimentally observed in the high perveance electron guns [4] and in the short solenoid electron lenses with large aberrations [5]. For understanding more details of these phenomena, let us consider the following analytical model.

## 4. Hollow Beam Formation

After being extracted from the ECRIS particles pass through the focusing lens and then move in a drift space.

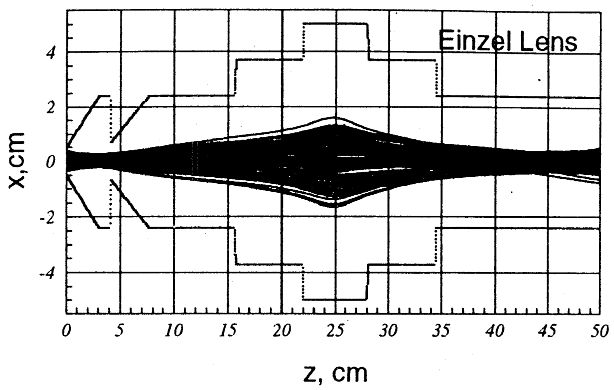

Fig. 1 Particle trajectories in the extraction region of the ECR ion source: extraction gap 4cm, lens voltage 14 kV, position of lens center 25 cm, coefficient $C_\alpha R^2 = 0.15$.

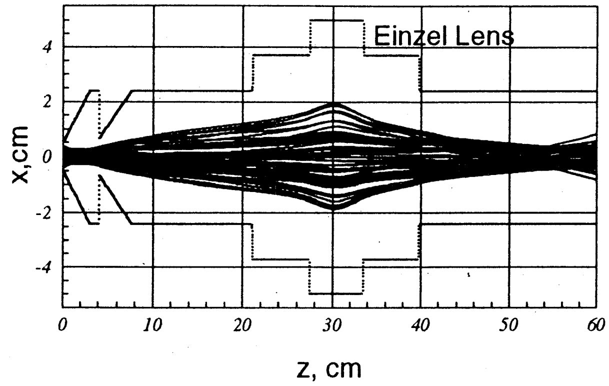

Fig. 2. Particle trajectories in the extraction region of the ECR ion source: extraction gap 4cm, lens voltage 12.5 kV, position of lens center 30.4 cm, coefficient $C_\alpha R^2 = 0.3$.

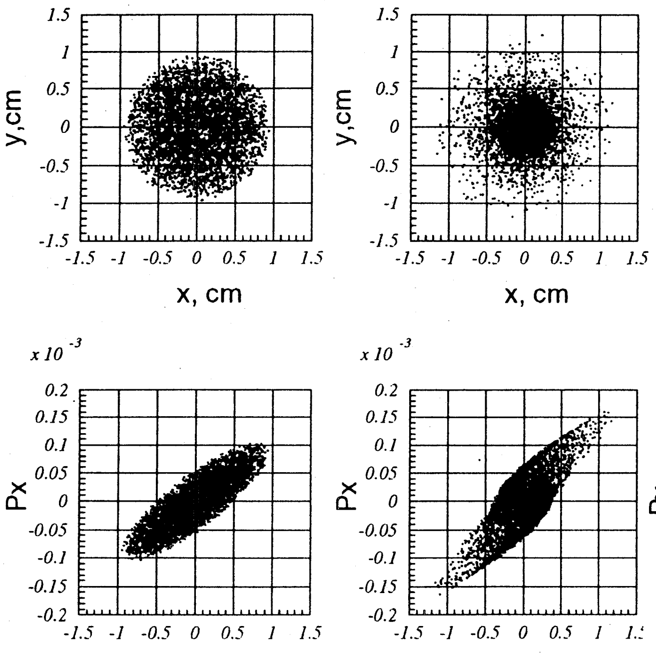

Fig. 3. Cross sections of the beam (top) and phase space projections of particles (bottom) at z= 14 cm (left column) and at z=51 cm (right column) for the extraction system presented in Fig. 1. RMS emittance growth is $\varepsilon_f/\varepsilon_0 = 1.15$.

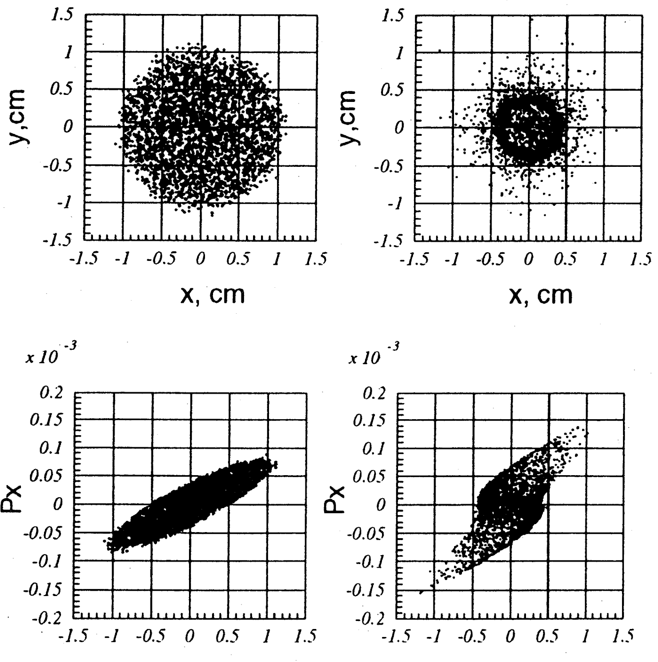

Fig. 4. Cross sections of the beam (top) and phase space projections of particles (bottom) at z=16 cm (left column) and at z = 60 cm (right column) for the extraction system presented in Fig. 2. RMS emittance growth is $\varepsilon_f/\varepsilon_0 = 1.3$.

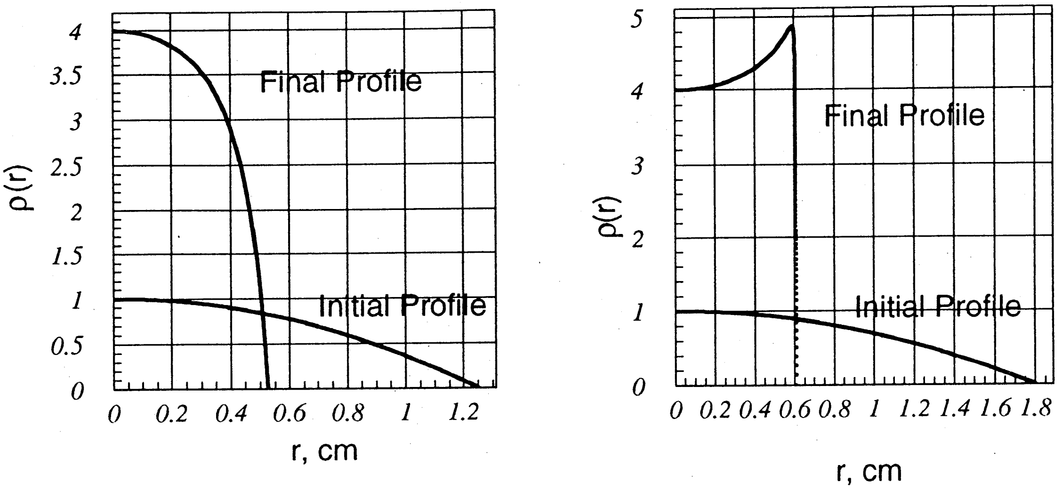

Fig. 5. Beam profile conservation in weak nonlinear field $C_\alpha R^2 = 0.15$ (left) and hollow beam formation in strong nonlinear field $C_\alpha R^2 = 0.3$ (right), calculated from formula (7).

For particles born in the magnetic field of ECRIS the value of azimuthal component of canonical momentum $P_\theta = (1/2)\, q\, B_z r_o^2$ is conserved. The electric field of the einzel lens provides focusing effect which can be described by a linear term as well as higher order terms. The radial equation of motion of a particle in this region is given by

$$\frac{d^2r}{dt^2} = \frac{P_\theta^2}{m^2 r^3} - \frac{q}{m}\left[\frac{r}{2}\frac{\partial E_z}{\partial z} - \frac{r^3}{16}\frac{\partial^3 E_z}{\partial z^3} + \ldots\right] . \qquad (5)$$

After passing through the thin lens initially parallel particles with radial displacement $r_o$ are converged with slope of $r_o' = -(1 + C_\alpha r_o^2)\, r_o / f$, where f is a focal length of the lens and $C_\alpha$ is a spherical aberration coefficient. The equation of motion (5) can be integrated in drift space to obtain the relationship between the initial and the final radii of particle:

$$r^2 = r_o^2 \{ [1 - \tau (1 + C_\alpha r_o^2)]^2 + \eta^2 \} , \qquad (6)$$

where $\tau$ (= z/f) is a dimensionless drift distance and $\eta$ (= $\omega_L t$) is a dimensionless time of particle drift. To find the beam density redistribution, let us take it into account that the number of particles dN inside a thin ring (r, r+dr) is kept constant during the drift of the beam, and hence the particle density $\rho(r) = dN/(2\pi r dr)$ at any z is connected with the initial density $\rho(r_o)$ by the equation $\rho(r)\, dr^2 = \rho(r_o)\, dr_o^2$, or

$$\rho(r) = \frac{\rho(r_o)}{[1-\tau\ (1 + C_\alpha r_o^2)]^2 + \eta^2 - 2 r_o^2 \tau C_\alpha [1 - \tau (1 + C_\alpha r_o^2)]} . \qquad (7)$$

From this relationship changing of the beam profile is observed when a spherical aberration is significant. The linear focusing lens ($C_\alpha$=0) conserves the beam profile and changes only sizes of the beam. Nonlinear component of electrostatic field increases focusing of particles in comparison with the linear component only [6]. It results in a beam profile with a more particle-populated boundary than the central region (see Fig. 5).

This hollow beam formation is accompanied by emittance growth of the beam. In the case considered the effective RMS emittance can increase by 1.3 times (see fig. 4). Such effect of the nonlinearity on beam intensity redistribution can be controlled by the product of spherical aberration coefficient and square of beam radius $C_\alpha R^2$. Analysis of the formula (7) shows that the beam profile is conserved if $C_\alpha R^2 < 0.2$ . For the lens considered $C_\alpha = 0.1$ cm$^{-2}$, and hence the beam radius R in the lens should be kept smaller than 1.4 cm. The numerical calculations confirm this limitation to keep the quality of the beam (see Figs. 1-4).

Table 1. Parameters of 100 eμA Ar $^{5+}$ ion beam in the extraction region of the 18-GHz ECRIS.

| Extract. gap, cm | Lens voltage, kV | Center of of lens, cm | Beam waist, cm | Waist radius, cm | Emittance growth, $\varepsilon_f/\varepsilon_o$ |
|---|---|---|---|---|---|
| 3 | 10 | 30.4 | 34 | 1.6 | 1.1 |
| 4 | 12.5 | 30.4 | 59 | 0.5 | 1.3 |
| 4 | 13 | 30.4 | 60 | 0.6 | 1.1 |
| 3 | 13 | 30.4 | 56 | 0.4 | 1.3 |
| 4 | 13 | 35.5 | 60 | 0.5 | 1.4 |
| 4 | 14 | 25 | 48 | 0.5 | 1.1 |

## 5. Conclusions

Nonlinear effect associated with the hollow beam profile formation in the extraction region of ECRIS was examined through both the numerical particle tracking and the analytical treatment. Simple formula has been derived to estimate the significance of spherical aberrations on the beam profile redistribution. This study is important in the design of the low-energy part of heavy-ion accelerators.

## 6. References

[1]. I.Ben-Zvi, Proceedings of the PAC95, Washington D.C., (1993), 2962.
[2]. Y.Batygin, Proceedings of the EPAC92, Berlin, (1992), 822.
[3]. J.Kim, J.Whealton and G.Schiling, J. Appl. Phys. 49 (2) (1978), 517.
[4]. M.Reiser, "Theory and Design of Charged Particle Beams", Wiley, New York, 1994.
[5]. P.Loschialpo et.al., J. Appl. Phys., 57, (1985),10.
[6]. J.D.Lawson, "The Physics of Charged Particle Beams", Clarendon Press, Oxford, 1977.