

# HOLLOW BEAM PROFILE IN THE EXTRACTION SYSTEM OF ECR ION SOURCE

Y.Batygin, A.Goto and Y.Yano

The Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama 351-01, Japan

## Abstract

Nonlinear optics effect of the beam extracted from ECR ion source is studied. Hollow beam formation due to aberrations of einzel lens is examined both numerically and analytically. Description of beam intensity redistribution due to nonlinear focusing field is given. The analytical relationship between the initial and the final beam distribution in the extraction region is derived.

## I. INTRODUCTION

Beam quality of a heavy ion accelerator complex is mostly defined by the extraction region of ion source where a space charge and a nonlinear external focusing field are essential. The extraction region of the 18 GHz ECR ion source which is under construction to upgrade RIKEN Accelerator Research Facility consists of an extraction electrode under the voltage of  $U_{ext}=10kV$  followed by a three-electrode Einzel lens (see fig.1). After passing the lens, the beam has to be focused into a spot with a diameter of 10 mm to be matched with the following transport system. The purpose of this study is to examine nonlinear beam optics effects which can influence the beam profile and emittance shape of the extracted beam.

## II. BEAM EMITTANCE

In ECR ion source particles are born in strong longitudinal magnetic field  $B$  fulfilling the ECR resonance condition  $2\omega_L=\omega_{RF}$  where  $\omega_L=qB_z/2m$  is Larmor's frequency and  $\omega_{RF}$  is a microwave frequency. The effective phase space area occupied by the ensemble of particles is defined by the value of root-mean-square (RMS) normalized beam emittance

$$\varepsilon = \frac{4}{m_0 c} \sqrt{\langle x^2 \rangle \langle P_x^2 \rangle - \langle x P_x \rangle^2}, \quad (1)$$

where  $x$  is a transversal Cartesian coordinate and  $P_x$  is a canonical conjugate momentum of particle. For particles in ion source one can put  $\langle x P_x \rangle = 0$ . Canonical momentum of a particle  $P_x$  in longitudinal magnetic field is a combination of mechanical momentum  $p_x$  and  $qA_x$  where  $q$  is a particle charge and  $A_x$  is a x-component of vector potential of magnetic field:

$$P_x = p_x - qA_x = p_x - q \frac{B_z y}{2}. \quad (2)$$

Calculation of RMS value of canonical momentum gives:

$$\langle P_x^2 \rangle = \langle p_x^2 \rangle - q B_z \langle p_x y \rangle + \frac{q^2 B_z^2}{4} \langle y^2 \rangle. \quad (3)$$

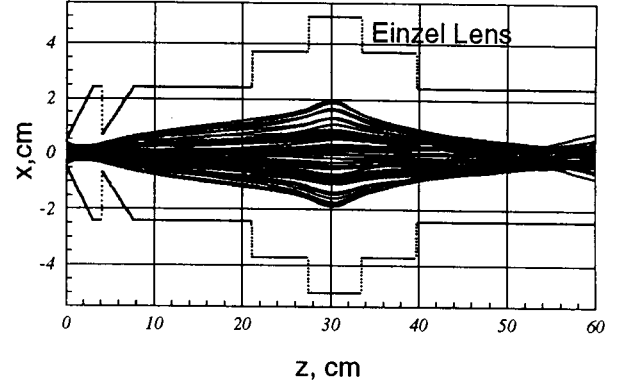


Fig. 1: Particle trajectories in the extraction region of the 18 GHz ECR ion source.

The first integral in eq. (3) describes the thermal spread of mechanical momentum of particles in plasma. The values of mechanical momentum are defined by temperature of ions  $T_i$  therefore one can put  $\langle p_x^2 \rangle = \langle p_{th}^2 \rangle = m_0 k T_i$  where  $k = 8.617 \times 10^{-5} \text{ eV} \cdot \text{K}^{-1}$  is Boltzmann's constant. The middle integral equals zero due to symmetric property of distribution function  $f$  and thermal momentum  $p_x$  with respect to coordinate  $y$ . The last integral is proportional to the RMS value of transverse coordinate  $\langle y^2 \rangle$ . For most of the beam distributions  $\langle y^2 \rangle = R^2/4$  where  $R$  is a beam radius comprising around 90% of particles. Finally the value of  $\langle P_x^2 \rangle$  is defined as follows:

$$\langle P_x^2 \rangle = \langle p_{th}^2 \rangle + \frac{(q B_z R)^2}{4}. \quad (4)$$

Combining the obtained value of  $\langle P_x^2 \rangle$  with equation (1) the value of normalized beam emittance  $\varepsilon$  is given by:

$$\varepsilon = 2 R \sqrt{\frac{k T_i}{m_0 c^2} + \left[ \frac{\omega_L R}{2 c} \right]^2}. \quad (5)$$

The formula (5) is usually used for estimation of emittance of the beam with ambient magnetic field on the cathode [1].

For the considered case of the 18 GHz ECR ion source the resonant value of magnetic field is  $B=0.637 \text{ T}$ . The normalized beam emittance of an  $\text{Ar}^{+5}$  beam with the temperature  $kT_i = 3\text{eV}$  is:

$$\varepsilon = 2 \times 5 \times 10^{-3} \times \sqrt{0.8 \times 10^{-10} + 10^{-9}} = 3.3 \times 10^{-7} \pi \text{ m rad}. \quad (6)$$

The beam emittance is mostly defined by the value of magnetic field.

### III. NUMERICAL STUDY OF BEAM OPTICS

Numerical calculation of beam extraction was performed with the computer program BEAMPATH [2]. Ion trajectories start from a concave plasma emitting surface within the beam convergence angle  $\theta$  defined by an aspect ratio  $R/d$  of extraction region and a ratio of beam perveance  $P = I/U_{ext}^{3/2}$  to Child-Langmuir perveance  $P_0 = (4\pi/9)\epsilon_0(R^2/d^2)(2q/m)^{1/2}$  of one dimensional diode [3]:

$$\theta = -0.625 \frac{R}{d} \left( \frac{P}{P_0} - 1 \right) . \quad (7)$$

For the expected value of beam current  $I=100\mu A$  of  $Ar^{+5}$  the flow of particles is not space charge dominated and therefore initial convergence of the beam  $\theta = -0.075$  is mostly defined by the focusing properties of extraction region.

Particle trajectories obey the equations of motion derived from a single particle Hamiltonian:

$$H = \frac{1}{2m} [p_r^2 + \left( \frac{p_\theta}{r} - qA_\theta \right)^2 + p_z^2] + q(U_f + U_c) , \quad (8)$$

where  $p_r$ ,  $p_\theta$  and  $p_z$  are components of momentum of the particle,  $U_f$  is a potential of the focusing field,  $U_c$  is a space charge potential of the beam and  $A_\theta = B_z r/2$  is a vector potential of the magnetic field. From computer simulation of the beam extraction problem in the ECR ion source it follows that the beam can obtain hollow structure at the point of crossover (see fig. 2). The same phenomenon is observed in high perveance electron guns [4] and under focusing of an electron beam by short solenoid lenses with large aberrations [5]. For more details, let us consider the following analytical model.

### IV. HOLLOW BEAM FORMATION

For particles born in the magnetic field of ECR ion source, the value of azimuth component of canonical momentum is:

$$P_\theta = qB_z \frac{r^2}{2} . \quad (9)$$

If the thermal spread of particle momentum is negligible the value of normalized beam emittance is connected with the maximum value of canonical momentum:

$$\epsilon = \frac{1}{m c} R \frac{P_{\theta \max}}{R} = \frac{\omega_L R^2}{c} \quad (10)$$

After extraction from ECR source particles pass through the focusing lens and then move in a drift space. Electric field of the lens provides focusing which consists of a linear term  $G$  and higher order terms. We restrict our consideration to the first nonlinear term of electric field  $G_3$ . The transverse equation of motion of a particle in this region is given by

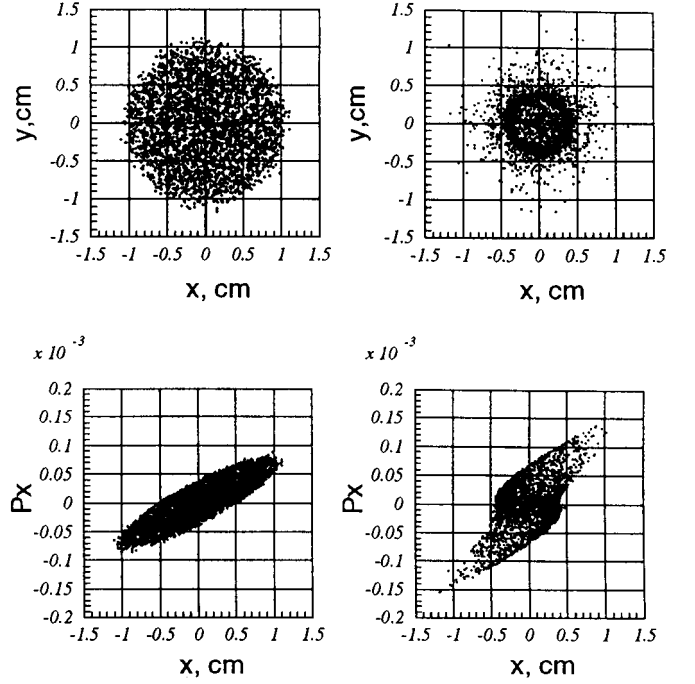


Fig. 2: Cross section of the beam (top) and phase space projections of particles (bottom) at  $z=16$  cm (left column) and at  $z=60$  cm (right column).

$$\frac{d^2 r}{dt^2} = \frac{P_\theta^2}{m^2 r^3} - \frac{q}{m} [G(z) r + G_3(z) r^3 + \dots] . \quad (11)$$

We assume the thin lens approximation which means that the length of the lens is small in comparison to the focal length. Therefore the radius of particle  $r_0$  is not changed during the time of passing through the lens  $t_L$ . Equation (8) can be integrated to obtain the relationship between the initial and the final radii of particle in the drift region:

$$r^2 = r_0^2 \{ [1 - f(r_0) \tau]^2 + \tau^2 \} , \quad (12)$$

where  $\tau = \omega_L t$  is a dimensionless time of particle drift and the following notations are used:

$$f(r_0) = (1 - \delta r_0^2) \tau_L ; \quad \delta = \frac{G_3}{G - \frac{m}{q} \omega_L^2} ;$$

$$\tau_L = \left( \frac{q}{m \omega_L^2} - 1 \right) t_L \omega_L . \quad (13)$$

To find the beam density redistribution let us take into account that the number of particles  $dN$  inside a thin ring ( $r, r+dr$ ) is constant during the drift of the beam, hence the particle density  $\rho(r) = dN / (2\pi r dr)$  at any  $z$  is connected with the initial density  $\rho(r_0)$  by the equation  $\rho(r) dr^2 = \rho(r_0) dr_0^2$  or:

$$\rho(r) = \rho(r_0) \frac{1}{\tau^2 + 2 r_0^2 \tau \tau_i \delta (\tau f - 1) + (\tau f - 1)^2} \quad (14)$$

From this relationship it follows that changing of the beam profile is observed when a nonlinear term of the focusing field is not zero ( $\delta \neq 0$ ). The linear focusing lens ( $\delta = 0$ ) conserves the beam profile and changes only sizes of the beam. Introducing the nonlinear component of focusing field results in beam intensity redistribution according to the above formula and finally in hollow beam formation (see fig.3).

The hollow beam profile formation can be understood from the fact that spherical aberration of an electrostatic lens increases focusing of particles in comparison with the ideal linear focusing [6]. As a sequence the peripheral particles in the drift region move faster to the axis than the inner beam particles. It results in a most populated boundary of the compressed beam than the core of the beam at the point of crossover.

Hollow beam formation is accompanied by emittance growth of the beam due to nonlinearity of a focusing lens. In the considered case the effective root-mean-square emittance is increased by 1.3 times (see fig. 2). For keeping the quality of the beam obtained from an ion source the nonlinearity of the focusing lenses have to be minimized.

## V. CONCLUSIONS

Nonlinear beam effect associated with hollow beam profile formation in the extraction region of ECR ion source was examined via numerical particle tracking and analytical treatment. Simple formula has been derived to control the significance of aberrations with respect to linear focusing and value of longitudinal magnetic field in ECR source. Calculations done are important in the problem of matching of the beam with accelerating structures.

## VI. 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.

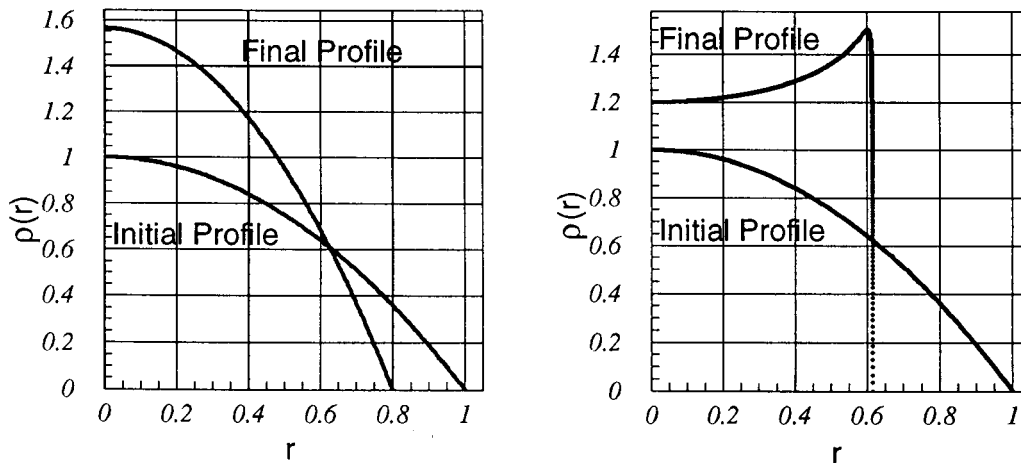


Fig. 3: Beam profile conservation in linear focusing field (left) and hollow beam formation in nonlinear field (right), calculated by formula (11).