PD-01

NEXT-STEP ECRIS AND 2m LENGTH 4.52 GeV ADVANCED ACCELERATOR: Novel Extraction of Trapped Ions and their Acceleration-Final Focusing by Nonneutral and Neutral Plasmas

Masanobu NIIMURA, Takahide NAKAGAWA, Akira GOTO, and Yasushige YANO

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

Abstract For more efficient extraction of high-charge state (HCS) ion beams and for much shorter pulse beam production than presently achievable, we propose a pulsed, electric (E-) field to be induced inside an ECR ion source. Advantages over conventional upgrading technologies, right range of the E-field intensity, and low-emittance extraction hardware are described. It is shown that the E-field method can extract only HCS ions with a drastically high upgrading factor surpassing the e-beam method, without disturbing the rf-heated hot electrons inside ECR ellipse. Further, in order to accelerate heavy ion beams to a GeV/u energy (case: U238, Z=60) and to focus it to a submillimeter beam size we present preliminary studies on a high-acceleration gradient (9GeV/m peak) nonneutral plasma accelerator and a neutral plasma final beam focuser, respectively. A novel 4.52GeV accelerator coupled with a neutralizing and focusing z-pinch plasma seems feasible in an elliptical chamber of 2m length.

1. Introduction

The ECR ion source (ECRIS) has readily established its position as the most efficient HCS ions injector for heavy ion linacs and cyclotrons. This paper searches a way of further improvement of the performance not only in CW but also pulsed operations, so that it can evolve useful source for also synchrotrons. The work is based on our recent discovery of the physical scenario for upgrading the extraction efficiency of HCS ion beams in ECRIS1), the concept of which prompt us to design not only the next-step ECRIS but also an advanced accelerator.

As a positive use of the space-charge potential has let ECRIS grow as the best HCS ions injector, this paper suggests deepening and tailoring of the space-charge potential for accelerator applications. Concept of the heavy ion plasma accelerator (HIPAC) can be found in the literature2) and the experiments have been performed since 1970's. A radial potential difference of 300 kV was practically measured3) inside a toroidal chamber, whose minor radius a=8cm, by filling it with electrons at the density $n_e=10^{10}$ cm^{-3}. Electrons are no need to be hot for the potential formation as long as they are confined in a chamber during the ion acceleration. They all used a toroidal chamber for acceleration and trapping of ions inside a topologically closed potential-well which can be formed with magnetically confined electrons. This paper describes a novel extraction and focusing of accelerated beams, which is impossible with a toroidal chamber but possible with an elliptical one.

2. Review of Upgrading Physics

The HCS ion beam current from an ECRIS is known to enhance significantly by employing so-called upgrade technologies such as (i) electron (e-) beam injection, (ii) wall-coating, and (iii) gas-mixing. The upgrading factor, η defined by the ratio of extracted ion beam-current 'with' to 'without' an upgrade technology increases sharply together with charge-state, Z. The physical scenario of upgrading mechanism was discovered based on the experimentally and numerically observable facts: (1) Remarkable similarity among the effects of (i)~(iii), (2) Experimental η that scales by exp Z, but only for the Z's above a critical one, Z_o; existence of a potential-well which can trap the otherwise-lost HCS ions for a time enough for charge multiplication, (3) Parametric study of simultaneous rate-equations has indicated that the charge state distribution (CSD) may become anomalous, meaning that the HCS ion density increases with Z, only if the diffusion loss becomes negligible along with the charge exchange loss from a given system; existence of a negative potential.

Thus we were forced to draw a conclusion that the major role of all those upgrading technologies (i) ~ (iii) is to help-tapping the HCS ions otherwise-trapped quasi-indefinitely inside the potential-well. We have identified the mechanism to be the local lowering of potential barrier (LLPB) or bitten dog-food bowl (BDFB), by which the cw endloss current can locally increase its magnitude in the range of HCS. Here, the terminology of 'endloss' refers the leakage flown out of potential-end. In 3D-picture, 'potential-end' corresponds the surface of an ECR ellipse. On the other hand, 'local' refers a part of the potential-end. This paper will show that the LLPB tends to occur preferentially along the axisymmetric axis of ECR device even for the cases of (ii) and (iii).

2.1 Physical Proof of Experimental Results

The present day ECRIS's in the CW mode of operation are all tapping the endloss current, relying on an imperfection of the electrostatic confinement. The trapped ions at the charge state Z and energy kT_{iZ} can leak out of a potential-well of depth $\Delta\phi$ with probability exp $(-Ze\Delta\phi/kT_{iZ})$. Zero probability ($\Delta\phi \to \infty$, $kT_{iZ} \to 0$) is ideal for production of highly HCS ions and low emittance beams, but such a perfect confinement is not good as an ion source which should extract the maximum possible ion beam current, $I_b \equiv ZeS_p\Gamma_s$:1)

$$I_b = I_o \exp\left(-\frac{Ze\Delta\phi}{kT_{iZ}}\right), \qquad I_o \equiv 0.61 ZeS_p v_B n_Z(0) \qquad (1)$$

Here, the expression of I_o is obtainable from the flux conservation, $S_{end}\Gamma_{end} = S_p\Gamma_s$. The CW endloss current of n_Z ions is $I_Z \equiv ZeS_{end}\Gamma_{end}$, where S_{end} is the ion escaping surface at the potential-end. All the loss current, $S_{end}\Gamma_{end}$ was assumed to be extracted eventually via the sheath surface, S_p near the plasma electrode located at ECRIS exit. Γ_s is the ion flux at the sheath edge and known to be $\Gamma_s \equiv v_B n_s$, where $v_B \equiv (kT_e/m_i)^{1/2}$ is the Bohm velocity and the sheath edge density is $n_s \approx 0.61 n_o$. Here, n_o is the density of HCS ions of interest in the peripheral plasma, which is assumed uniform with the endloss density just leaking out at the potential-end, $n_Z(L_p/2) \equiv n_Z(0)\exp[-Ze\Delta\phi/ kT_{iz}]$.

Suppose the hight of $\Delta\phi$ was lowered locally by an e-beam injection to $\Delta\phi - \Delta\phi_{eb}$, Eq. (1) gives

$$I_{eb} = I_o \exp\left[-\frac{Ze\Delta\phi}{kT_{iz}}\left(1 - \frac{\Delta\phi_{eb}}{\Delta\phi}\right)\right] \qquad (2)$$

This expression indicates that I_{eb} should increase as $\Delta\phi_{eb}$ increases. This is consistent with experimental observation: the ion (i-) beam current enhanced as the e-beam current was increased. Thus, the e-beam must be lowering the $\Delta\phi$ or increasing the magnitude of $\Delta\phi_{eb}$.

If we take the ratio of Eq.(2)/Eq.(1) we have

$$\eta \equiv I_{eb}/I_{eb} = \exp\left[\frac{Ze\Delta\phi_{eb}}{kT_{iz}}\right] \sim \exp[Z] \qquad (3)$$

This result agrees well with a number of experimental results where $\eta \sim \exp[Z]$ is evident. Since $\eta \geq 1$ in the region $Z \geq Z_o$, Eq. (3) would be better expressed by

$$\eta(Z) = \exp\left[\frac{e\Delta\phi_{eb}}{kT_{iz}}(Z - Z_o)\right], \qquad (Z \geq Z_o) \qquad (4)$$

Here, Z_o is the threshold with which the confinement time is long enough for producing HCS ions of interest; $kT_{iz} \leq Z_o e\Delta\phi_{eb}$. Z_o increases proportionately with the ionization time needed for the Z of the atom of interest.

2.2 Wall-Coating and Gas-Mixing to Form an e-Beam Like Electron Channel on Axis

The wall-coating works similar way as an e-beam gun. Secondary electrons (n_{es}) can be generated when HCS ions approach the wall which is coated with low work-function material like MgO. They are accelerated by the positive plasma potneital towards the circumference of ECR-zone and there they tend to stagnate. Those n_{es} pointing the ECRIS axis will be 'beamed' along the axis due to joining with incoming n_{es} together with MMF focusing effect; the n_{es} is thus at least two-times denser on axis than the circumference of ECR zone. This is a formation of quasi-stationary 'e-beam', which can lower $\Delta\phi$ near the axis.

Gas mixing too can behave an 'e-gun' by two steps. Step 1: Completely stripped ions of the lighter gas such as O_2 and H_2, fed either internally from oxidized-wall or externally by gas-mixing, can cool T_{iz} of the higher Z ions as they 'evaporate' out of ECR zone. The lowered T_{iz} can guarantee to become highly HCS ions. Such highly HCS ions only can generate a number of n_{es} to exceed the own Z-number as they approach the (oxidized) wall surface. Step 2: The n_{es} emitted from the wall would follow the same process as the case of wall-coating.

3. Novel Extraction of Trapped HCS Ions

Conventional technologies (i)~(iii) are a destructive extraction in terms of the original hight of ECR heated potential-well. We search a non-destructive but efficient way of extraction. The problem can be solved if only the trapped ions are accelerated by an axial electric field E_Z inductively induced inside the ECR zone, without loosing the ECR heated hot electrons from the zone.

3.1 Theory of E-Field Extraction

Here we estimate a right range of the E-field intensity for the novel extraction technology proposed.

3.1.1 Motion of Charged Particles Inside a Magnetic Bottle First, we study if the electron cloud can be contained magnetically even after the application of an external E-field. Consider an electron gyrating around the axisymmetric **B**-field which increases slowly parallel to the direction of +z axis. Then, in the cylindrical polar coordinates, B_r is always pointing z-axis. The direction of gyration is anti-clockwise if seen towards +z axis from the back of the plane which is perpendicular to the z-axis. Writing the linear velocity of gyration by $v_{\perp e}$, the $v_{\perp e} \mathbf{x} B_r$ is in the negative (or -z) direction. Therefore, the Lorentz force can be expressed by $\mathbf{F} = -e[\mathbf{v}\mathrm{x}\mathbf{B}] = ev_{\perp e}B_r$. Here, $B_r = -(r_L/2)(\partial B_z/\partial z)$ which is a Maxwell equation, $\nabla \bullet B = 0$ expressed in the axisymmetric system $(\partial/\partial\theta = 0)$, provided that $\partial B_z/\partial z$ is approximately constant with r over the distance of Larmor radius, $r_{Le} \equiv v_{\perp e}/\omega_{ce}$. Since $\omega_{ce} \equiv eB/m$, the axial motion of electrons can be expressed by

$$m\frac{dv_z}{dt} = -e[v_{\perp e} \mathbf{x} B_r] = -\mu_e \frac{\partial B_z}{\partial z}, \qquad \mu_e \equiv \frac{1}{2} m v_{\perp e}^2/B \qquad (5)$$

This Eq.(5) states that electrons experience a -z directed force $F_z = \mu_e(\partial B_z/\partial z)$ in the region where $\partial B_z/\partial z \geq 0$. F_z is proportional with the electron magnetic moment, μ_e. This means that electrons can be safely confined inside a pair of MMF even after an E_z was applied, if $eE_z << \mu_e(\partial B_z/\partial z)$.

Since the total kinetic energy $W \equiv mv^2/2 \equiv W_z + W_\perp$ is constant $(dW/dt=0)$, Eq. (5) gives the invariance of μ or $d\mu_e/dt = 0$. The invariance of μ tells that at the turning point $B = B_R$ and $W_\perp = W$ so that $\mu_e = W/B_R$. However, B_R should equal B_{ECR} at the ECR surface since there produces the largest perpendicular energy $W_{\perp max}$. Should a particle move along the **B**-field line to a location $B \geq B_{ECR}$, there $W_\perp$ should be higher than $W_{\perp max}$ from the invariance of μ, which is unlikely. If $B_m = 10$kG and $B_o \approx B_R$ in a 10 GHz ECRIS ($B_{ECR} \approx B_R = 3.57$ kG), we have $\Delta B/B_R = 1.80$, $\Delta z = 10$ cm, and $mv_e^2/2 = 500$ eV so that

$$E_z << \frac{1}{2e} m v_e^2 \frac{\Delta B}{B_{ECR}} \frac{1}{\Delta z} = 90 \text{ V/cm} \qquad (6)$$

is the safe electric field to keep the ECR zone in position.

On the other hand, ions are not difficult to extract from a magnetic bottle since they are usually not well confined anyway due to the fact that $r_{Li}/r_{Le} \approx (M/m)^{1/2}/Z > 1$ under $T_i = T_e$ unless Z is very large. However, ECRIS ions are high-Z and kT_{iz} may be very low inside the space charge potential of electrons in the steady state. This can create the situation $r_{Li} \approx r_{Le}$. Then, $F_z = -\mu_i(\partial B_z/\partial z)$, but $\mu_i \equiv Mv_{\perp i}^2/2B = kT_i/B_{ECR}$. Thus $\mu_i << \mu_e$, and the condition $ZeE_z \geq \mu_i(\partial B_z/\partial z)$ determines the minimum E_z:

$$E_z \geq \frac{1}{2Ze} M v_i^2 \frac{\Delta B}{B_{ECR}} \frac{1}{\Delta z} = 0.90 \text{ V/cm} \qquad (7)$$

Here, $mv_i^2/2 = 50$eV and $Z=10$ was assumed. Right E-field should thus be within the range, $0.90 \leq E_z(\text{V/cm}) << 90$.

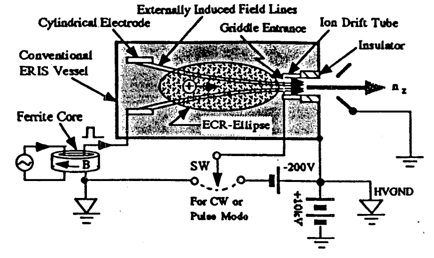
3.1.2 Motion of Charged Particles Inside an Electron Space Charge Potential of ECR Ellipse

Here, we study if heavy ions can indeed be extracted out of an ECR ellipse by applying an electric field. The original electron space charge potential inside of ECR ellipse is filled by ions but only partially, since the peripheral ions are aheading outward walls from the time of the formation of potential well. Therefore, the potential barrier needed to cross for trapped ions is the $\Delta\phi$ generated by the excess charge density, $e(n_e - \Sigma Z_z n_z)$. In the energy wise, $Ze\Delta\phi \geq kT_{iz}$ for high-performance ECRIS's and $kT_{iz} \leq 50$eV for typical devices. The e-beam injection at LBL lowered the hight of positive plasma potential V_p which is same to lower $\Delta\phi$ by $\Delta\phi_{eb}$=10eV to obtain $\Delta\phi$-10V. Their experiment can be explained well by the set of parameters: Z=10, $\Delta\phi$=20eV, kT_{iz}=50eV. For this we need an extra E_z to satisfy $ZeE_z l_p \geq 20$eV, where $l_p \approx 5$cm is the useful length of acceleration which is one half of the length of a typical ECR ellipse. Thus, for Z=10 ions we need $E_z \geq 0.4$ V/cm. We choose E_z= 4 V/cm which satisfies also the above condition $0.90 \leq E_z(\text{V/cm}) << 90$. A drastic improvement in η is evident with the E-field method. **Table I** compares the η with the e-beam case.

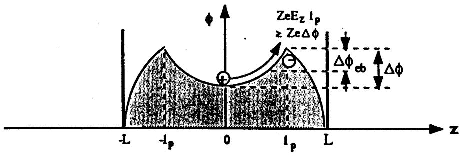
Table I: Improved η by E-field method

E_z = 4V/cm	Z=10	Z=15
η (e-Beam)	7.39	19.9
η (E-Field)	24.5	169

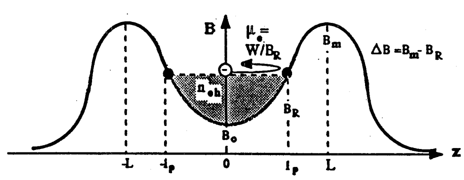
Fig. 1 shows schematic drawings of the next-step ECRIS proposed. The emittance is expected good because of the use of drift tube with a griddle front and due to the fact that E-field method can extract highly HCS ions whose T_{iz} is likely zero4) due to their location of confinement close to the bottom of parabolic potential.



(a) E-Field Induction Circuit for Fast-Pulse Ion Beam Extraction.



(b) Principle of E-Field Extraction of Ions from Potential-Well.



(c) Magnetically Trapped Hot Electrons n_{eh}, if $eE_z << \mu_e (\partial B/\partial z)$.

Fig.1. E-field extracting, efficient ECRIS schematics.

4. Nonneutral Plasma Advanced Accelerator and Neutral Plasma Beam Focusing

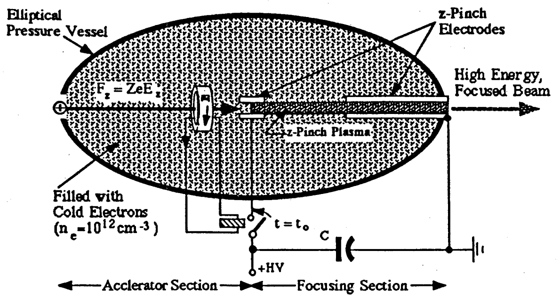
The axis of a cylinder of radius a=1 m filled with 100% electrons at density $n_e = 10^{12}$ cm^{-3} is holding a negative electric potential against grounded wall given by

$$\Delta\phi \equiv \frac{n_e e}{4\varepsilon_o} a^2 = 4.52 \times 10^{-9} \, n_e(\text{m}^{-3}) \, a(\text{m})^2 = 4.52 \text{ GeV} \quad (8)$$

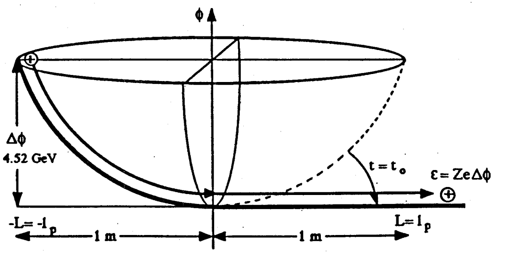
Such a charge cylinder contains a huge acceleration gradient, E_r=9.04GeV/m at the wall, although zero at r=0.

This paper proposes a utilization of such space charge field for an economical alternative of heavy ion accelerators. We will use a fat elliptical chamber of length 2m filled with only electrons. In the both midplanes of its depth as well as of its length the electric potential distribution should be similar to the one for circular cross section of charge cylinders. If for an example, ^{238}U ions at Z=60 were injected at one end of the ellipse, they would attain the energy 1.14 GeV/nucleon at the midplane of ellipse. What is difficult is to extract particles right at the bottom of the potential-well. Our innovative idea of achieving this is to flatten the potential in the decerelation section by using a z-pinch plasma. A high energy, focused beam may be extracted from the other end of ellipse.

Fig.2 shows a z-pinch device to be set along the axis starting from the midplane. The plasma will be fired at the moment when a bunch of ions impinged in to the first electrode. The metallic gas needed for producing solid-density plasma will be generated itself from electrode surfaces when flashes over. Inside the plasma the self defocusing effect of ion beam can be neutralized and thus the IxB self-focusing effect may become effective before reaching the relativistic speed. However, our calculation shows that force density of the self-focusing is much smaller than the kinetic pressure of pinch plasma. With moderate to solid-state z-pinch densities, $n_e = 10^{24} \sim 10^{28}$ m^{-3} (kT=1 keV), we obtain p= nkT=1.6x10^3 ~1.6x 10^7 atm. Sumbillimeter focus size can thus be expected.



(a) Nonneutral Plasma Accelerator and z-Pinch Plasma Beam Focuser.



(b) Plasma Tailoring Electron Space-Charge Potential-Profile at $t \geq t_o$.

Fig.2. A 2m, 4.25GeV advanced accelerator schematics.

1) M. Niimura, T. Kageyama, T. Nakagawa, A. Goto, and Y. Yano, Proceedings of ECR-12, INS-J-182, p.141 (1995).
2) G.S. Janes et al., Phys. Rev. **145**, 925 (1966).
3) W. Clark et al., Phys. Rev. **37**, 592 (1976).
4) A. Irani and N. Rostoker, Particle Acc. **8**, 107 (1978).