BEAM FUNNELING IN THE FACILITY FOR RARE ISOTOPE BEAMS*

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Abstract

The Facility for Rare Isotope Beams (FRIB) will provide intense beams of short-lived isotopes for fundamental research in nuclear structure and nuclear astrophysics. Operation of the facility requires intense uranium primary beams. At the present time acceleration of two simultaneous charge states of uranium from a single ion source is needed to achieve the required intensity. In case the intensity of the accelerated beam from the ion source is not sufficient, several scenarios are considered for beam funneling. One option is based on the utilization of an RF kicker for merging of bunched beams extracted from ECR ion sources. Another one implements the idea of utilizing an RFQ for beam merging [1], which can be used after preliminary acceleration of both beams. The third approach assumes utilization of RF kicker for accelerated beams. Parameters of all three schemes are compared and analyzed.

BEAM FUNNELING IN λ/2 RF KICKER

Operation of FRIB requires high intensity primary beams. The proposed operating mode requires the simultaneous acceleration of two charge states from a single ion source. In this paper we study alternative ways of obtaining the same intensity from two different ion sources. Beam funneling is an effective way to increase beam intensity. When two beams are preliminary bunched at the frequency *f*, they can be merged by an RF deflector to the same axis to provide final beam bunched at the double frequency *2f*, and with double intensity. Experience with beam funneling [2] indicates successful operation of merging process. The key problem in beam funneling is to keep emittance growth of both beams at the reasonable level to prevent further beam losses.

As a first option, we consider funneling of primary heavy ion beams obtained from two ECR sources (see Fig. 1). After extraction, each beam is bunched in a multi-harmonic buncher at the frequency of $f = 40$ MHz. With the typical extraction voltage of 100 kV, and velocity of $^{238}U^{33+}$ particle of $\beta = 5.43\times10^{-3}$, bunches are separated by the distance of $\beta\lambda = 4.05$ cm. Application of a standing wave λ/2 RF kicker for beam merging of the length of $\beta\lambda/2 = 2$ cm and with the vertical gap of $g = 4$ cm with applied field $E(x,y,z)\cos(\omega t + \varphi_o)$ is considered (see Fig. 2). Change of slope of particle trajectory after passing through the standing wave kicker is described by

$$\Delta y' = \frac{qE\lambda}{mc^2}\,\frac{\cos\bar{\varphi}\,\sin\frac{\theta}{2}}{\pi\beta\gamma}\,, \qquad (1)$$

where E is the field amplitude, λ is the wavelength, $\bar{\varphi}$ is the RF phase of the center of the bunch in the middle of RF kicker, and θ is the transit time angle. Parameters of the structure and beam parameters are presented in Table 1. Simulations indicate transverse beam emittance growth of $\varepsilon_f/\varepsilon_o = 1.58$ due to large aberrations in field distribution. Fig. 3 illustrates beam merging and final particle distribution in merging plane. Large transverse emittance growth makes this approach unacceptable for application in funneling of heavy ions.

Table 1: Parameters of Setup for Funneling of the Beams Extracted From ECR Ion Sources

Ion	$^{238}U^{33+}$
Beam voltage	100 kV
Particle velocity	5.43×10^{-3}
Initial transverse emittance	0.065 π cm mrad
Transverse beam emittance growth	1.58
Longitudinal beam emittance	0.56 keV/u nsec
RF frequency	40 MHz
RF kicker length	2 cm
Vertical gap	4 cm
Voltage	± 250 kV
RF bunch length	80^o
Energy spread	± 1.5%
Initial beam angle	± 0.072 rad

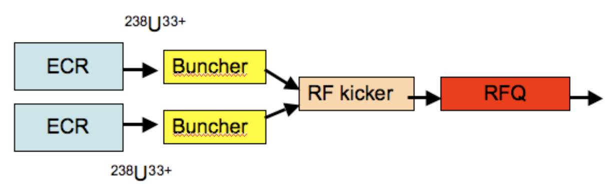

Figure 1: Schematic layout of funneling of bunched beams extracted from ECR sources.

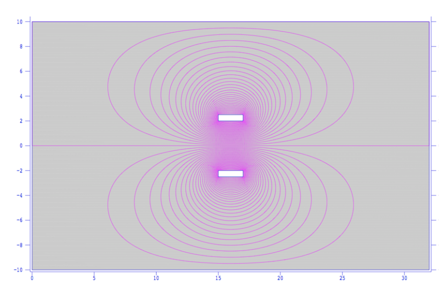

Figure 2: Field distribution in RF kicker for beam funneling.

FUNNELING OF 300 KEV/U BEAM IN RF KICKER

Smaller emittance growth in beam merging can be obtained if RF kicker is placed after pre-acceleration of two beams (see Fig. 4). Fig. 5 illustrates 3D field

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distribution in the kicker originally designed for beam distribution for the MSU-RIA driver linac [3]. Kicker has sizes of $X \times Y \times Z$ = 15 cm x 5 cm x 9 cm. Both beams enter the kicker at the angle of ± 67 mrad.

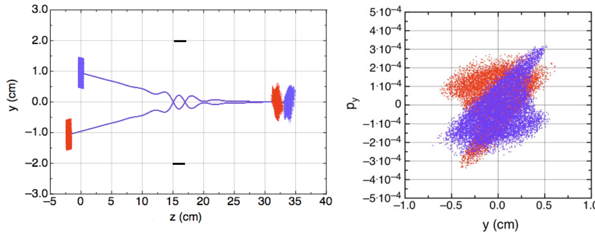

Figure 3: Funneling of 13.8 keV/u $^{238}U^{33+}$ beams in RF kicker. The beam oscillation outside the kicker are produced by the fringe fields.

Parameters of setup are given in Table 2. Figs. 6, 7 illustrate process of beam funneling, final transverse phase space of the overlapped beams, and initial and final longitudinal beam distributions. Effect of small deceleration is visible because of presence of longitudinal component in field distribution of RF kicker (see Fig. 5). This system provides small transverse beam emittance growth of $\varepsilon_f / \varepsilon_o$ = 1.1, which makes it acceptable for application.

Table 2: Parameters of Funneling of Accelerated Beams by RF Kicker

Ion	$^{238}U^{33+}$
RF frequency	40 MHz
Beam energy	300 keV/u
Particle velocity	0.0252874
Bunch length	0.5 cm
Energy spread	± 0.8%
Initial transverse beam emittance	0.04 π cm mrad
Transverse emittance growth	1.1
Longitudinal beam emittance	0.78 π keV/u nsec
Longitudinal emittance growth	1.23
Entrance angles	± 0.067
Vertical gap	5 cm
Length	9 cm
Width	15 cm
Electrode voltage	500 kV

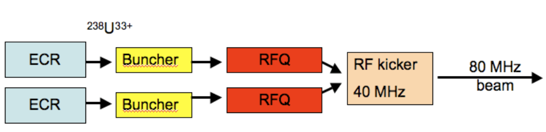

Figure 4: Beam funneling with post-RFQ kicker.

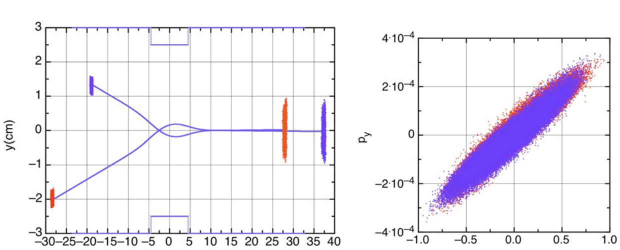

Figure 5: Funneling of 300 keV/u $^{238}U^{33+}$ beams in $\lambda/2$ RF kicker and final beam overlapping.

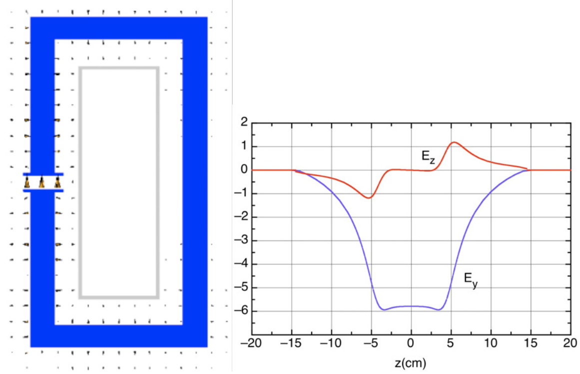

Figure 6: RF kicker and field distribution at 1 cm from median plane.

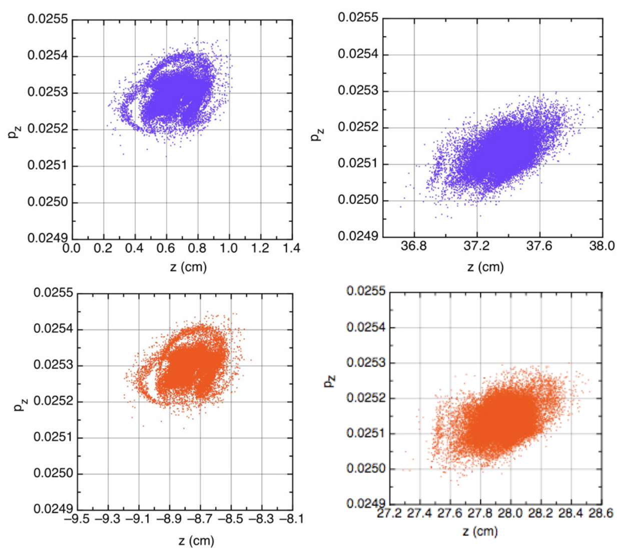

Figure 7: Longitudinal particle distribution before (left) and after (right) funneling.

BEAM FUNNELING IN MODIFIED RFQ

Application of RF kicker to beam funneling requires large voltage of 500 kV (see Table 2). As an alternative approach, we considered an interesting proposal on beam funneling which was done in Ref [1]. It was suggested to use the modified Radio Frequency Quadrupole (RFQ) structure to combine both beam merging and continuous periodic transverse focusing of both beams. The electrode configuration is changed with respect to conventional RFQ to provide additional dipole component of electric field. Potential of the modified RFQ is given by

$$U = \frac{V}{2}\left[C\left(\frac{x^2 - y^2}{a^2}\right) + D \sinh kx \cos kz \right] \sin(\omega t + \varphi_o). \quad (2)$$

Pole tips are described by equating the potential function, Eq. (2) to constant value $U = V/2$:

$$\frac{C}{a^2}(x^2 - y^2) + D \sinh kx \cos kz = 1 . \quad (3)$$

Coefficients C, D in the potential function are expressed via electrode modulation parameter m, aperture of the structure, a, and wave number $k = 2\pi/\beta\lambda$ by

$$D = \frac{m^2 - 1}{m^2 \sinh ka + \sinh mka}\,, \qquad (4)$$

$$C = 1 - D \sinh ka\,. \qquad (5)$$

Analysis of particle dynamics shows, that motion in x - and y - directions are not symmetrical. While motion in y - direction is purely oscillating, single particle trajectory in the x-plane is a combination of oscillation with dipole component, which is used for beam funneling:

$$\frac{d^2x}{dt^2} + \frac{qCV}{ma^2}\left(x + \frac{ka^2D}{2C}\cosh kx \cos kz\right)\sin(\omega t + \varphi_o) = 0 \qquad .(6)$$

Solution of equation of motion in x - direction can be written as:

$$x = x_o \sin \Omega t + x_1 \sin \omega t + x_d\,, \qquad (7)$$

where Ω is the frequency of smoothed oscillations, and x_d is the beam axis offset:

$$\Omega = \frac{1}{\sqrt{2}}\frac{\omega_o^2}{\omega}\,, \qquad x_d = \alpha\left(\frac{\omega}{\omega_o}\right)^2\,, \qquad (8)$$

where

$$\omega_o^2 = \frac{qCV}{ma^2}\,, \qquad \alpha = -\frac{ka^2D}{2C}\sin\varphi\,. \qquad (9)$$

Eqs. (7) - (9) indicate that selection of $\varphi = \pm 90^o$ and $m > 1$ provides two stable beam axis shifted by $\pm x_d$ where two bunched beam can oscillate around. Then, gradual decrease of the vane modulation coefficient from the nominal value to $m = 1$ brings both axis together with beams eventually merging around central axis of RFQ.

Table 3 and Fig. 9 illustrate results of calculation of beam merging in RFQ for the beams with energy 300 keV/u following described recommendations. Both bunches enter the structure at the angle of approximately $\pm$ 4x10^{-2} shifted longitudinally by $\Delta z = \beta\lambda/2$. Chosen value of intervane voltage of U = 253.8 kV provides structure with the ratio of parameters, Eq. (8), $\Omega/\omega = 0.18$. Initial modulation electrode parameters $m = 1.2$ is selected to have initial beam separation of $x_d = \pm$ 2 cm. The funneling is provided by reducing the modulation coefficient m from 1.2 to 1, which, in turn, reduces the coefficient D in pole tips profile from the nominal value of $D = 0.05488$ to zero, eventually providing beams offset to zero. Beam funneling is accompanied by small transverse emittance growth $\varepsilon_f/\varepsilon_o = 1.1$, which make this system attractive for practical application. Finally, let us note, that funneling can be provided for two charge state beams as well. Fig. 10 illustrates funneling of $^{238}U^{33+}$, $^{238}U^{34+}$ beams in the same structure.

Table 3: Parameters of RFQ Funneling

Ion	$^{238}U^{33+}$
RF Frequency	40 MHz
Beam energy	300 keV/u
Particle velocity	0.0252874
Bunch length	0.5 cm
Energy spread	± 0.8%
Initial transverse beam emittance	0.04 π cm mrad
Transverse emittance growth	1.1
Longitudinal beam emittance	0.78 π keV/u nsec
Entrance angles:	- 4.86x10^{-2}, 4.48x10^{-2}
Cell length, $\beta\lambda/2$	9.4238 cm
Voltage, V	253.8 kV
Aperture radius, a	3 cm
Length	75.391 cm (8 cells)
Modulation coefficient, m	1.2

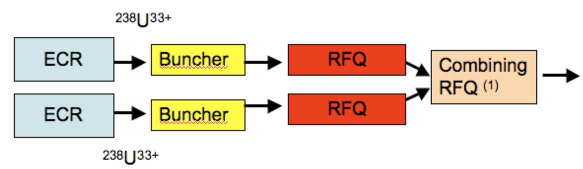

Figure 8: Beam funneling based on combining RFQ.

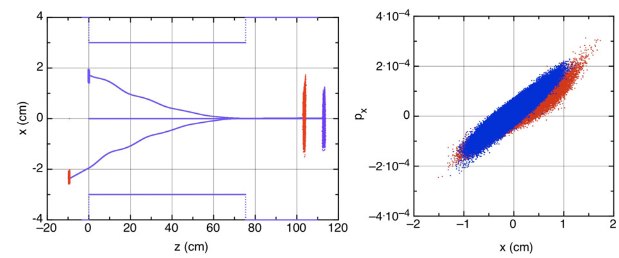

Figure 9: Funneling of 300 keV/u $^{238}U^{33+}$ beams in modified 40 MHz RFQ.

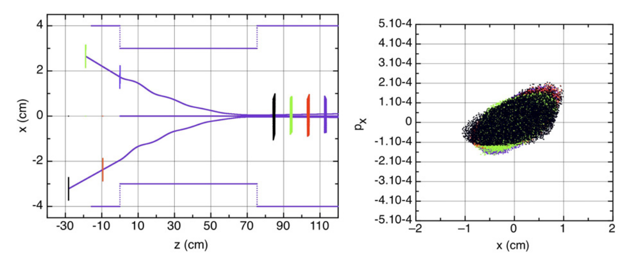

Figure 10: Funneling of two charge state bunches: (blue, red) $^{238}U^{33+}$, (green, black) $^{238}U^{34+}$.

REFERENCES

[1] R. H. Stokes and G. N. Minerbo, AIP Conference Proceedings 139 (1985), p. 79.

[2] A. Schempp, NIM-A 464 (2001), p.p. 395 – 399.

[3] M. Doleans et al., Proceedings of the LINAC 2006, Knoxville, Tennessee, (2006), p.106.