BEAM OPTICAL DESIGN OF A MULTI CHARGE ION RECIRCULATOR FOR CHARGE BREEDERS

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Abstract

Ions of high charge states as required for both stable and radioactive beams in order to optimally profit from the accelerating voltage provided can be produced by means of charge state breeders. However, the energy increase obtained is accompanied by an intensity decrease due to the low efficiency of the charge breeding process itself. With respect to the production of radioactive beams an enhancement of the breeding efficiency would be most desirable to avoid a high power primary beam as yet inevitable to counteract the loss in intensity. For this purpose the beam optics of an ion recirculation capable to separate the desired charge state and to reinject the remaining charge spectrum has been designed. The ions, potentially extracted from both sides of the charge breeder, are focused by means of electrostatic quadrupole doublets and bent by two 180° dipole magnets resulting in a racetrack-like shape. After one revolution the optics realises horizontally and vertically a point-to-point image independent from the charge state of the ions. The second order geometric aberrations as well as most of the chromatic aberrations vanish. The non-zero energy dependant aberrations are compensated by the charge dependant aberrations leading to an effectively achromatic system up to the second order. The beam optical calculations have been carried out with the arbitrary order beam physics code COSY INFINITY and been validated with the beam envelope code TRANSPORT.

INTRODUCTION

The efficiency of charge breeders is essentially limited by two effects. On the one hand the ions are generated in a broad spectrum of different charge states where most of them are lost in a post-source spectrometer. On the other hand, caused by the symmetric potential distribution of ECR ion sources, often applied for charge breeding, the ions are not only extracted in the forward but ineluctably also in the backward direction. As a consequence the efficiency yields obtained by high performance sources do not exceed 2-7% for metal ions and approximately 10% for gaseous elements [1]. Following an idea by E.A. Lamzin [2] the possibility of reinjecting the undesirable ions from both sides of the booster would solve both deficiencies and would lead to a tremendous increase of the charge breeding efficiency. In RIB-facilities, high power primary beams with their challenges in respect of operational safety and radiation protection could thus be avoided. It should be mentioned that such an ion recirculation has never been technically realised.

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GENERAL LAYOUT

In contrast to reference [2] where the ion recirculation is obtained by means of an electrostatic ring and the expansion of the charge states by a separated magnetic spectrometer the setup proposed here combines ion recirculation and charge state separation by applying two 180° dipole magnets with field index $n = 0$. Electrostatic elements are solely used for beam focusing. For this purpose four quadrupoles (EQ01, EQ02, EQ03, EQ04), arranged in doublets, are placed between the ion source and each of the dipoles. Due to the charge dispersion the backstraight is exempt from focusing elements.

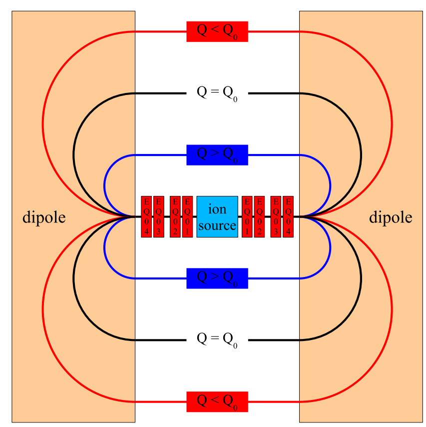

Figure 1: Racetrack shaped ion recirculator. Q: arbitrary charge; Q_0: reference charge; EQ: electric quadrupoles.

To achieve the design goal of recirculating a spectrum of $^{140}_{54}\mathrm{Xe}^q$ ranging from $q = 1+$ to $q = 40+$ with a bending radius of the reference charge state $q_0 = 20+$ of $R_{q_0} = 0.5$ m and a spacing between the closest charge states ($q = 39+, 40+$) of at least $\Delta x = 1.0$ cm the width of the two magnets reaches 10.0 m and the depth 3.0 m (each with margin included). The distance between the two dipoles defined by the minimum space necessary for the insertion of the ion source and the electrostatic quadrupoles amounts approximately to 4.0 m. With this, the whole arrangement has a quadratic shape of 10×10 m^2. However, these dimensions could be diminished by choosing less ambitious design parameters.

Regarding the slowest particle ($q = 1+$) and assuming an extraction voltage of $U_{ext} = 20$ kV we find a time-of-flight between charge breeder extraction and reinjection of $\tau \approx 130$ μs which is much less than the fastest confinement times obtained for state-of-the-art ECR sources lying in the range of several tens of milliseconds [3] and moreover far below the half-life of $^{140}_{54}$Xe, $T_{1/2} = 13.6$ s.

BEAM OPTICAL CALCULATIONS

The beam optics envisaged with the described setup is a combined point-to-point, parallel-to-parallel image, resulting in a waist-to-waist image, in both transversal planes from the source extraction to the reinjection. Except for the vertical parallel-to-parallel image this optics is independent from the ion charge. The settings of the electrostatic quadrupoles are symmetric with respect to the charge breeder but uncoupled at each side. They deliver four free parameters for the minimisation of the transfer matrix elements R_{12}, R_{34}, R_{21} and R_{43} in first order calculations and the transverse beam envelopes Σ_{21} and Σ_{43} or the end positions and angles of rays for higher orders. Two different set of parameters, referred to as optics 1 and optics 2, which fulfill the conditions with sufficient accuracy have been elaborated. Both Optics exhibit a transversal waist in the beam line between charge breeder and dipole magnet: optics 1 in the vertical plane, optics 2 in the horizontal plane. Horizontal waists within the bending section and a double waist at half optical path length on the back straight are common to both optics and could serve as recirculator injection and extraction points by means of electrostatic septa. The input parameters for the calculations can be taken from table 1. As we deal with an electrostatic acceleration the particles have all the same electric rigidity $E\rho = 2 \cdot U_{ext}$ but due to $B\rho = p/Q$ different magnetic rigidities. The initial beam parameters are typical values obtained for ECR charge breeders [3].

Table 1: Input parameters for the beam optical calculations.

Parameter	Value
Particle	
mass number	$A = 140$ (e.g. $^{140}_{54}$Xe)
charge	$Q = +20, +1, +40\,e$
kinetic energy	$E_{kin} = 400.0, 20.0, 800.0$ kV
electric rigidity	$E\rho = 40.0$ kV
magnetic rigidity	$B\rho = 0.054, 0.241, 0.038$ Tm
Beam	
radius	$R = 4.0$ mm
opening angle	$\alpha = \pm 10.0$ mrad
emittance	$\varepsilon = 40.0\ \pi$mm·mrad

COSY INFINITY SIMULATIONS

COSY INFINITY [4] (in the following reffered to as "COSY") is an arbitrary order beam physics code. It is based on differential algebra and adapted for the study and design of beam physics systems including accelerators, spectrometers and beam lines. It offers the option to simultaneously simulate particles with different masses or charges states, the latter being of especial interest for the problem at hand.

The calculations presented here have been carried out in 3rd order. The quadrupoles settings could be optimised by means of the built in algorithms. In fig. 2(a) the horizontal beam optics 1 of the charge states $q = 16+$ (red), $q = 20+$ (black) and $q = 24+$ (blue) is shown in a 2D-rays-illustration. Apparently this optics is independent from the charge state, as the longer trajectory in the dipole magnet is compensated by the likewise increased weak focusing. The vertical optics 1 (parallel and point rays) of the reference charge $Q_0 = 20\ e$ is presented in fig. 2(b). For charges $Q \neq Q_0$, not included in fig. 2(b), no compensation of variations in the trajectory length takes place in this plane due to the absence of the vertical focusing forces at the dipole edges (wedge angle $\varphi = 0°$) and the vertical waist on the backstraight is consequently shifted downstream for charges $Q > Q_0$ respectively upstream for $Q < Q_0$. In the latter case this entails a strong blow up of the beam towards the end of the circulation but the envelope remains within a radius of 6.0 cm. To prevent beam losses the aperture R of the electrostatic quadrupoles has therefore been chosen to $R = 10$ cm.

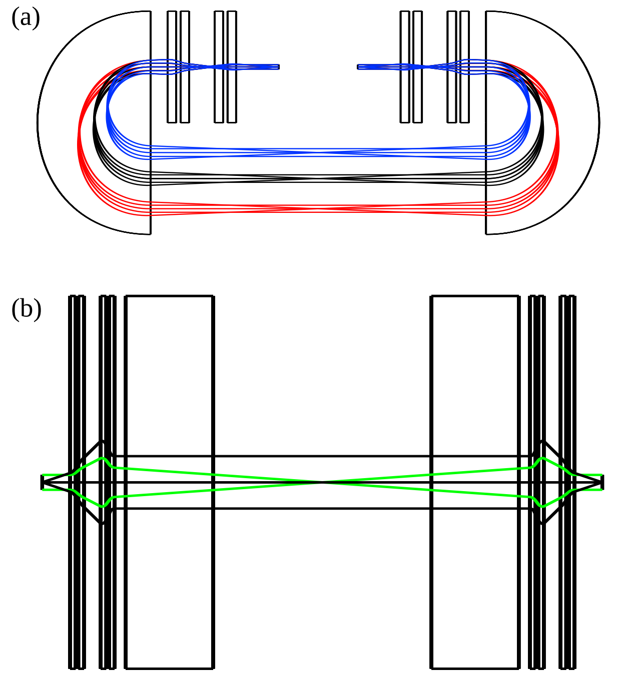

Figure 2: Optics 1 calculated with COSY in 3rd order. (a): Horizontal 2D-illustration for $Q = 16\ e$ (red), $Q = 20\ e$ (black) and $Q = 24\ e$ (blue). (b): Vertical rays of the reference charge $Q_0 = 20\ e$ (black, green).

TRANSPORT SIMULATIONS

So far the influence of space charge effects has been omitted in our calculations even though the beam current may reach values of several 100 μA [3]. The main contribution of the current originates from impurities consisting of the support gas of the ion source such as ^{4}He or ^{16}O. Although having different masses than the desired beam these ions posses the same electrostatic rigidity. They are hence transported up to the dipole magnet where they are finally separated from the beam due to their different mag-

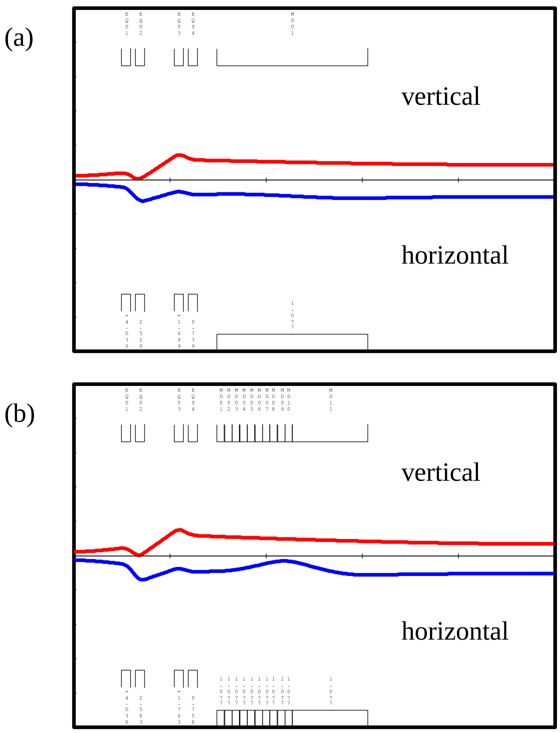

Figure 3: Beam envelopes of optics 2 for one symmetry element calculated with Graphic TRANSPORT in 2nd order without space charge (a) and in 1st order for a beam intensity of $I = 1.0$ mA (b).

netic rigidity. To simulate this effect which is not a priori negligible the code TRANSPORT [5] has been consulted. The PSI version "Graphic TRANSPORT" [6] does not only offer a user friendly graphical user interface but in particular a first order space charge calculation realised by a series of thin lenses placed at user defined intervals.

The beam optics has been calculated only for half of a revolution, i.e. two quadrupole doublets, one dipole magnet and half of the backstraight, corresponding to the symmetry element of the ion recirculator. This implies a point-to-parallel and a parallel-to-point image which again implies a waist-to-waist image. Both optics already observed with COSY have been confirmed by the TRANSPORT optimiser. The result of this simulation for beam optics 2 is presented in fig. 3. The calculation without space charge effects, cf. fig. 3(a), has been carried out in 2nd order which is the maximum order implemented in the PSI version. Using the space charge option the calculation is limited to the 1st order. The result for a beam intensity of $I = 1.0$ mA is shown in fig. 3(b). The decay of the beam intensity in the dipole magnet due to the beam separation has been approximately imitated by cutting the magnet into segments and decreasing the beam intensity behind each segment according to an exponential law. The simulation proves that a modification of the beam line arrangement due to space charge effects is dispensable as the desired optics can be restored by simply readjusting the quadrupole voltages.

COMPARISON AND CONCLUSION

The beam optics of an ion recirculator for charge breeders consisting of two 180° dipole magnets and eight electrostatic quadrupoles has been investigated with the codes COSY and TRANSPORT. The comparison of the results is resumed in table 2. An agreement in the per cent range is observed between COSY and TRANSPORT ($I = 0$ mA). The voltages necessary to focus a space charge beam with $I = 1.0$ mA rest within reasonable limits according to the TRANSPORT simulation. The concept is promising and the work should be continued to arrive at a technical realisation.

Table 2: Comparison of the quadrupole pole tip voltages obtained with COSY (reference) and TRANSPORT (with and without space charge).

Quadrupole		**EQ1**	**EQ2**	**EQ3**	**EQ4**
Optics 1					
COSY ✓3rd order	kV	10.9	-2.3	-8.4	8.4
TRANSPORT ✓2nd order	%	-0.3	-7.6	+2.4	+0.2
TRANSPORT ✓1st order ✓space charge	%	+4.3	+4.3	+5.5	+5.2
Optics 2					
COSY ✓3rd order	kV	-20.1	12.5	-8.4	3.6
TRANSPORT ✓2nd order	%	+0.4	+1.5	+0.7	+2.0
TRANSPORT ✓1st order ✓space charge	%	+0.5	+3.7	+4.5	+4.6

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