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LATTICE STUDIES OF CRYRING

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Abstract

CRYRING[1] is a small storage and acceleration ring for very heavy highly charged ions from an EBIS type ion source (CRYSIS). The kinetic energy range is from 100 keV/u to 10 MeV/u. The functions of the ring and the respective beam optical constraints are discussed.

Introduction

A special feature of CRYRING is that it will be a multi-purpose ring: It will be operated both in synchrotron mode and in storage mode. In storage mode various kinds of experiments are planned to be made in the ring and then one usually wants to cool the beam (e^--cooling). There are, therefore, different requirements as regarding beam quality at different parts of the accelerator. However, the size of the ring itself is limited (max circumference 25-30 m - four long straight sections) due to different circumstances like financial questions (vacuum equipment) and the existing hall where the ring will be placed. Therefore, we cannot have special insertions for different functions (injection, extraction, cooling, acceleration/deceleration, merged beams, crossed beams, ...). Some functions must be combined and this calls for beam flexibility.

Extraction and Injection

At this stage of the study it is foreseen that multi-turn injection is used. To achieve a large duty cycle (30 %) slow extraction will be used and hence the operation point should be in the vicinity of a horizontal third order resonance. The resonance is excited with suitably phased sextupoles.

For injection and extraction it is good to have large horizontal ß-values. It has been planned to use electrostatic deflectors as proposed for ELENA[2]. Because the maximum rigidity of the extracted beam is 1.35 Tm, we need a relatively long septum and thus it was decided to separate injection and extraction. In principle both injection and extraction need similar properties of the beam and hence it is natural to place them on opposite sides of the ring, since it is obvious that the two other straight sections will not have the same kind of beam optics.

To have the most effective extraction, dispersion should be forced to zero. This would provide us with the possibility to place the acceleration cavity on the injection straight section. From now on the straight section for injection and acceleration is labelled as SS1 and the straight section for extraction as SS3.

More rigorous studies of injections and extraction schemes have been started.

Electron Cooling

Most experiments planned to be done in the ring need very good longitudinal and transverse energy resolution. This calls for small $\Delta p/p$ and a small emittance. To attain such a beam quality electron cooling is used. It is the transverse cooling that depends on the lattice functions. Cooling time sets the lower limit to β_y-values and the requirement of decreasing the transverse emittance sets the upper limit.

If space-charge effects are neglected, the equilibrium beam divergence θ_i can be written as

$$\theta_i = \sqrt{m/M}\,\theta_e \tag{1}$$

where m is the electron mass and M the mass of the ion. Space-charge effects and intrabeam scattering of course increase the equilibrium divergence. The transverse electron energy is a function of the electron gun cathode temperature. A cathode temperature of 850°C corresponds to an electron energy of 0.1 eV. This value has been used in the calculations as the lowest electron temperature. If one wants the transverse emittance of the ions to be decreased, the initial divergence of the beam should be larger than shown above. The maximum divergence of the beam corresponding to emittance E_y is

$$\theta(\max) = \sqrt{E_y/\beta_y} \tag{2}$$

where β_y must be taken at a symmetry point where we have an erect phase space ellipse.

From equations (1) and (2) we see that for given emittances β_y is proportional to the mass of the ion, so that the lightest ions give the lowest upper limit for β_y-values in the cooling section. The lightest ion planned to be cooled is Ar. It has been planned to decelerate beams to as low energies as 100 keV/u. This energy corresponds to an electron divergence of 43 mrad which leads to an Ar-beam divergence of 0.16 mrad. If we now require the cooling to act at least on the "outer" 30 % of the beam (Gaussian distribution) we get the maximum permissible β_y-values from

$$\beta_y < E_y/4\theta_i^2 \tag{3}$$

where E_y is given in units (π m rad). If one assumes as small initial emittance as 1 π mm mrad, one gets

$$\beta_y < 9.8 \text{ m} \tag{4}$$

This is not a bad assumption, since in some of the experiments planned to be done in the ring the final emittance must be smaller than 1 π mm mrad.

The cooling time is proportional to

$$\tau \propto (\theta_e^2 + \theta_i^2)^{3/2} \tag{5}$$

Thus an ion divergence 20 % smaller than the electron divergence gives only a factor 2 compared to zero ion divergence. We want that at least 95 % of the beam has smaller divergence than 80 % of the electron divergence also with the highest beam energies. This requirement is fulfilled if β_y is larger than 0.5 m. So, we have the condition

$$0.5 \text{ m} < \beta_y < 9.8 \text{ m} \tag{6}$$

If there is no dispersion and the transverse emittances are not too large all particles will be cooled longitudinally i.e. $\Delta p/p$ will be decreased. If the dispersion and the initial momentum spread are large enough, there is a certain portion of ions whose momentum will be increased over the optimal value whereas the other ions will be cooled normally (and even faster than

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without dispersion). The electron velocity as a function of distance from the symmetry axis is a parabola due to electron beam space charge. The ion velocity distribution follows a line whose slope is $1/D_y$. These can be seen in Figure 1.

In longitudinal cooling the velocity of the ions tends to approach the electron velocity. Hence, the ions in the stable region move towards the crossing of the curves and the ions in the unstable region move away from the beam axis making up a tail in the momentum distribution. This tail may be a useful tool to overcome the Keil-Schnell limit for microwave instability (see later in the text).

Merged Beams

One of the most interesting (and most difficult) experiments planned to be done in the ring is an experiment with two merging ion beams. In such a situation it is possible to achieve very low center-of-mass energies, below 1 eV may be possible (with certain restrictions). Very low center-of-mass energies call for a very good energy resolution, both longitudinal and transverse. Hence one must have as small $\Delta p/p$ and beam divergence in both beams as possible. Small divergence means a small transverse emittance and/or large β_y-values. The properties of the external beam are determined by the injection line and therefore we discuss only the focusing of the stored beam.

The center-of-mass energy is determined by the velocities of the two beams and the possible angle between them. Even if the two beams were absolutely parallel we should, however, get some contribution from the transverse motion, since it is not possible to have zero emittance. If we assume that the angle between the two beams stays constant and is very small, we get a contribution to E_{cm} only and not to ΔE_{cm}. The normal transverse motion of the ions in the beam due to a non-zero emittance increases both E_{cm} and ΔE_{cm}.

In a typical merged beams experiment the required center-of-mass energy is of the order of 1 eV. The specific energies of the beams would then be of the order of 100 keV/u. In these cases we need extremely good energy resolutions ($\Delta p/p = 10^{-4} - 10^{-5}$) and very small beam divergences to achieve small ΔE_{cm}. The energy resolution mentioned should be possible to get via electron cooling whereas that for the external beam is relatively easy to achieve with electrostatic acceleration (HV platform). In merged beams experiments the beam must be cooled and the cooling gives equilibrium divergences (eqs. 1 and 2), i.e. E_y/β_y, in the cooling section. So, we see that β_y-values in the merging region should be "normalized" to the values in the cooling section and thus one can say that the betatron amplitude functions in the merged beams interaction region should be at least as large as in the cooling section.

We have decided to do merged beams experiment in the same straight section as extraction. Approximative calculations show that it is possible to achieve ΔE_{cm} as small as 0.05 eV (rms) when the beam energies are of the order of 100 keV/u. However, this calls for very small emittances (divergences) and it is clear that it is not allowed to have any quadrupoles in the interaction region. This is a relatively strict constraint on the lattice but necessary for merged beams experiments.

The Lattice

In the lattice calculations the program MAD has been used. The aim was to find a lattice that would fill all (or most) of the beam optical requirements set by the different functions of the ring. Due to the limit of maximum circumference (about 30 m) it has been chosen to have four long straight sections. Two of these should have no quadrupoles (SS1 and SS3). It has also been chosen to use rectangular laminated dipoles with zero gradient for many reasons (easy to manufacture, fast cycling, injection of the negative ions into the merging region, reaction product analysing especially in the merged beams experiments). We also want to have zero dispersion in SS1 and SS3. These conditions together with the constraints on β_y-values somewhat limit our possibilities to choose the operating point. One possible lattice is shown in Fig. 2 and the lattice functions of one quadrant in Fig. 3. The operation point of the ring is $Q_x = 1.40$ (1.333 during the extraction) and $Q_z = 2.40$. Table 1 gives the main parameters of CRYRING.

Operation Limits

Space charge limit

Tune shift due to space charge sets a limit for maximum number of stored ions in the ring which is proportional to A/q^2 and for non relativistic particles to kinetic energy. Table 2 gives the space charge limit for the injection energy and for the lowest planned energy corresponding to tune shift $\delta Q=0.1$ with different emittances.

Keil-Schnell limit

For a given momentum spread the Keil-Schnell criterion[3] gives us the maximum number of ions that we can have in the ring without getting the microwave instability. For low energies the space charge component is dominating in the longitudinal coupling impedance and thus there is not much to be done to increase the K.S.-limit. In this case the limit can be written as

$$\left(\frac{\delta p}{p}\right)^2 > \frac{(q/A)\ I\ r_o\ 4\pi\varepsilon_o\ Z_o\ g}{|n|\ \gamma\ \beta^2\ e\ \ 2\ \beta\ \gamma^2} \tag{7}$$

where $\delta p/p$ is the FWHM value of the momentum distribution

$Z_o = \mu_o\, c = 377\ \Omega$

$g = 1 + 2\ln(b/a)$

b = radius of the vacuum tube

a = average radius of the beam

In the case of CRYRING (7) can be reduced to

$$N_{K.S.} < \frac{A}{q^2}\beta^2 \left(\frac{\delta p}{p}\right)^2 R\ 1.3\cdot 10^{17} \tag{8}$$

Above we have left γ^3 out since for energies in CRYRING it is ≈ 1. R is the average radius of the ring. Again, we have $(A/q^2)\beta^2$ dependence, which does not favour highly charged ions with low energy.

Table 3 gives $N_{K.S.}$ for three different beam energies corresponding to different $\delta p/p$.

In merged beams experiments one needs $\Delta p/p$ of the order of 10^{-4} and hence at the first sight it does not seem very promising from the intensity point of view. There are, however, some theoretical predictions for cases where $N >> N_{K.S.}$ that this condition could lead to a non-destructive instability with a "stabilizing tail" in the momentum distribution[4]. The momentum distribution would consist of a very narrow peak and a tail which contains N(tail) > 0.67 · N(total) · (ReZ/ImZ) particles (Z is the longitudinal coupling impedance). One could get this stabilizing tail by electron cooling if there is enough dispersion as mentioned before. For the beam energies in CRYRING the imaginary part of Z is of the order of some kΩ's (space charge component) and the resistive (real) part is usually 50 Ω at the most. Therefore only a minor part of the ions has to be in the tail of the momentum distribution.

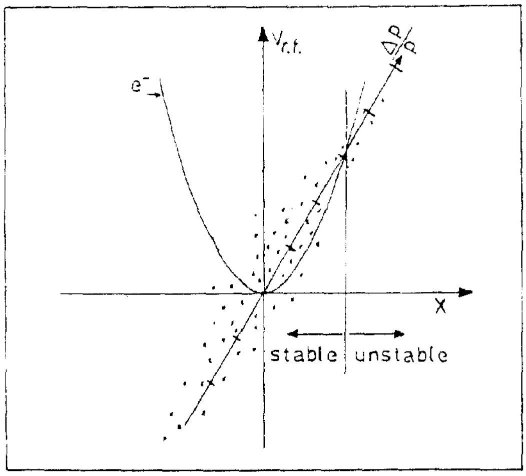

Figure 1. Ion and electron (rest frame) velocity distributions.

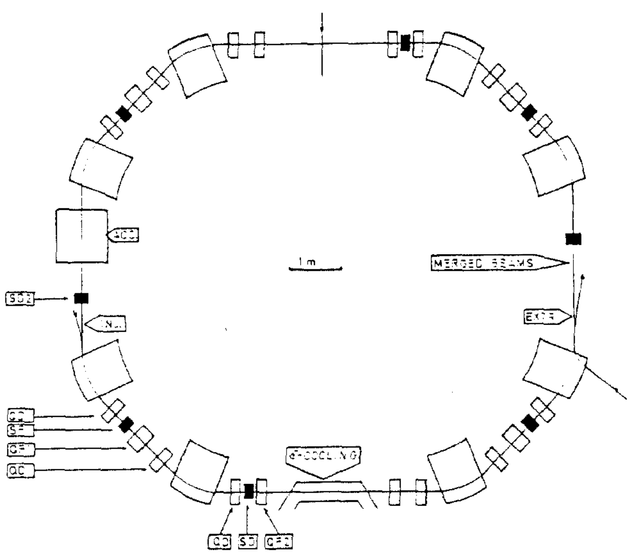

Figure 2. The lattice of CRYRING.

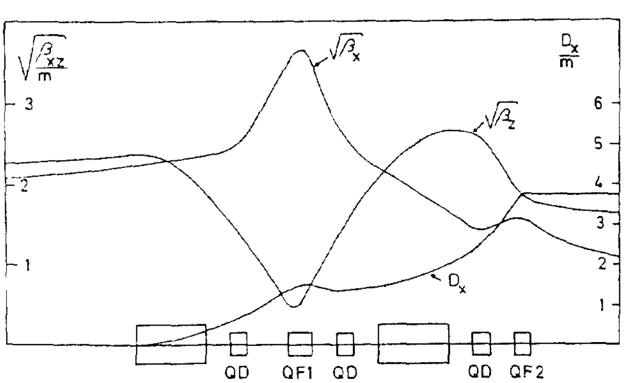

Figure 3. The lattice functions of one quadrant (the sextupoles are not shown).

Table 1

Main parameters of CRYRING

Circumference	30.51 m
$B\rho_{max}$	1.35 Tm
Dipoles, laminated, rectangular	
no field gradient	
bending radius	1.1 m
vertical gap	10.0 cm
Quadrupoles	
F (4 x 20 cm, 4 x 30 cm)	8
max gradient	5 T/m
D (20 cm)	12
max gradient	4 T/m
Sextupoles	
F (20 cm)	4
D (20 cm)	4

Table 2

Space charge limit for CRYRING

a) $E_x = E_z = 100\ \pi$ mm mrad (multi turn injection), T = 300 keV/u

b) $E_x = E_z = 0.1\ \pi$ mm mrad, T = 100 keV/u

Ion	N (a)	N (b)
Ar^{18+}	$3 \cdot 10^9 \cdot B_f$	$10^6 \cdot B_f$
Kr^{34+}	$2 \cdot 10^9 \cdot B_f$	$6 \cdot 10^5 \cdot B_f$
Xe^{44+}	$2 \cdot 10^9 \cdot B_f$	$6 \cdot 10^5 \cdot B_f$
Pb^{60+}	$1.5 \cdot 10^9 \cdot B_f$	$5 \cdot 10^5 \cdot B_f$

Table 3

Keil-Schnell limit for ions in CRYRING

a) T = 100 keV/u, $\delta p/p = 10^{-4}$

b) T = 300 keV/u, $\delta p/p = 10^{-2}$ (injection)

c) T = 5 MeV/u, $\delta p/p = 10^{-3}$

Ion	a	b	c
Ar^{18+}	$1.6 \cdot 10^5$	$4.9 \cdot 10^9$	$8.2 \cdot 10^8$
Kr^{34+}	$9.7 \cdot 10^4$	$2.9 \cdot 10^9$	$4.8 \cdot 10^8$
Xe^{44+}	$9.1 \cdot 10^4$	$2.7 \cdot 10^9$	$4.5 \cdot 10^8$
Pb^{60+}	$7.7 \cdot 10^4$	$2.3 \cdot 10^9$	$3.8 \cdot 10^8$

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