THE CRYRING LATTICE

J. Jeansson, A. Simonsson
Research Institute of Physics*
S-104 05 Stockholm, Sweden

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Manne Siegbahn Institute of Physics

Abstract

The CRYRING lattice has been optimized to meet the requirements from the different modes of operation. Advantages and disadvantages of the final design are examined. Effects of the electron cooler magnets on the ion beam, intrabeam scattering, and space charge are discussed.

Introduction

CRYRING will be a synchrotron/storage ring for highly charged heavy ions. The ions are produced in a CRYEBIS (CRYogenic Electron Beam Ion Source) source and accelerated in an RFQ (Radio Frequency Quadrupole) to 0.3 MeV/u before injection in the ring. The energy spread will be about 1%. The RFQ accepts ions with charge to mass ratio, $q/A \geq 0.25$. Since the length of a CRYEBIS pulse is longer than the ring circumference it is necessary to use multiturn injection. Once in the ring the ion beam can be accelerated/decelerated, electron cooled, stored, and extracted. The maximum energy will be 6-24 MeV/u depending on q/A.

Design Considerations

Several constraints placed on the CRYRING lattice which have influenced the final design are listed below.

- The circumference of the ring should not be larger than about 50 m.

- It is desirable to have injection, acceleration, electron cooling, extraction, experiments, and the Schottky detector in different straight sections. This means six straight sections and an intrinsic six-fold symmetry.

- The acceptance of the ring has to be large to swallow an entire pulse from the CRYEBIS source. The final emittances in the ring after multiturn injection are estimated to be $\epsilon_x = 200\,\pi$ mm mrad, and $\epsilon_y = 100\,\pi$ mm mrad[1]. This means large magnet aperture and/or small β-functions.

- A future experiment will be to merge the stored beam with an external beam. Therefore it is necessary to have magnet-free straight sections.

- The straight sections should be long enough to house the electron cooler; 3.5 m is adequate.

- Since slow third order resonant extraction is planned the working point has to lie close to a third order resonance.

- The space charge limit will be reached during injection into CRYRING ($\Delta Q_{s.c.} = 0.25$), which means that a working point must be found where one can accept a large Q-spread during the injection and acceleration phase.

- Dispersion should be small in the injection straight section.

- Chromaticity correction is not necessary in synchrotron mode or in storage mode with a working electron cooler. However, in order to store a beam *without* electron cooling or a beam with different charge states, chromaticity correction is necessary. For this purpose there should exist at least two positions in every superperiod suitable for a focusing and a defocusing sextupole. At the first position β_x has to be larger than β_y, and at the second position the opposite should be true. The dispersion has to be non-zero at both positions. In the interest of keeping the necessary sextupole strengths as low as possible the natural chromaticity should be minimized.

The Lattice

A lattice consisting of six identical superperiods, each made up of two rectangular bending magnets, a quadrupole triplet (FDF), and a 3.5 m long straight section was found to be optimal for our purposes. It should be noted that the bending magnets contributes to the vertical focusing.

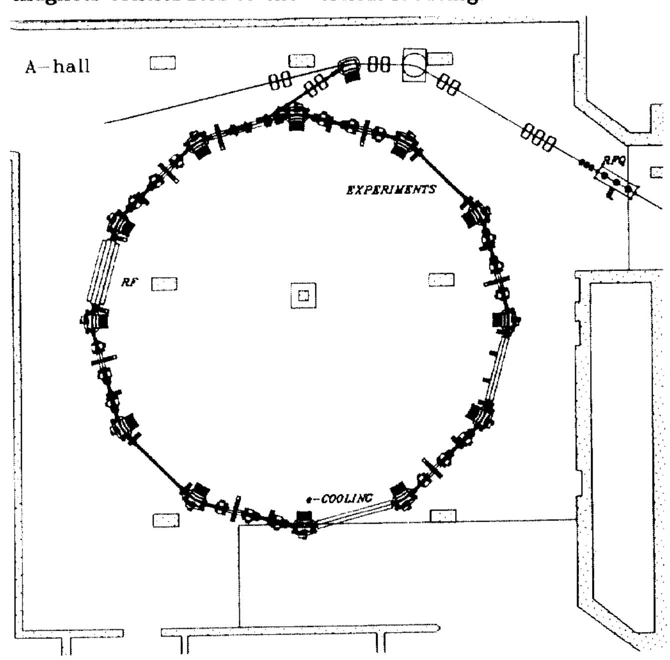

Fig 1. The CRYRING Lattice.

The dipoles have a gap of 8 cm, and a bending radius of 1.2 m. The maximum field will be 1.2 T. All quadrupoles have a length of 0.3 m and an aperture of 12.5 cm. In each superperiod two sextupoles have been placed close to the quads. Focusing sextupoles are adjacent to focusing quadrupoles and vice versa. With a total circumference of 51.6 m there is no more space for the ring to grow.

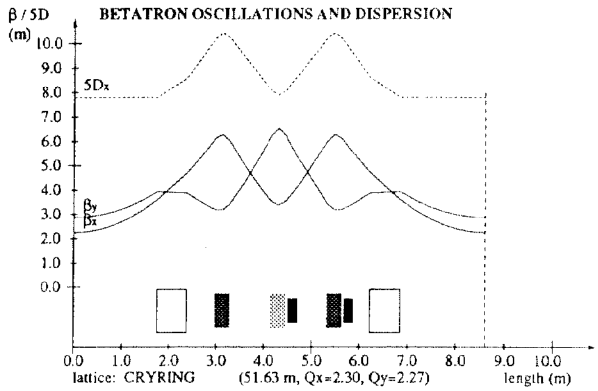

Fig 2. β-functions and Dispersion.

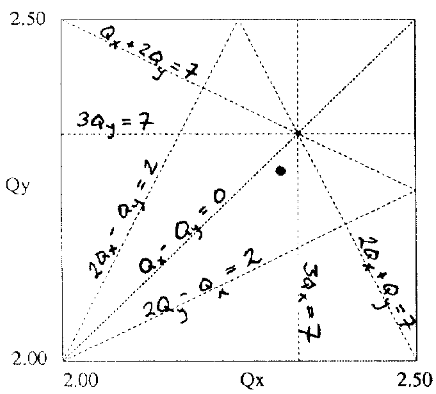

Fig 3. The Q-diagram with resonances up to third order.

All lattice parameters have been calculated with the MAD program[2]. Note that CRYRING will always operate below transition energy.

Table 1. Lattice Parameters.

β_{xmax}	6.3 m	
β_{ymax}	6.5 m	
D_{xmax}	2.1 m	
Q_x	2.3	
Q_y	2.27	
Q'_x	-1.3	hor. natural chrom.
Q'_y	-3.2	vert. natural chrom.
$\frac{\Delta p}{p}$	$5 \cdot 10^{-3}$	mom. spread at inj.
γ_{tr}	2.2	

The advantages with this lattice are:

+ It is a simple lattice with only two families of quadrupoles.

+ Six superperiods is beneficial to the stability of the machine since the number of systematic resonances are few.

+ The smooth β-functions results in a relatively low intrabeam scattering.

+ It is a very flexible lattice. Other solutions with other working points and/or three superperiods can be found.

The main disadvantage is the large dispersion in the straight sections. Despite this it seems that the efficiency of the multiturn injection will be satisfactory[1].

Two other working points with smaller dispersion have been studied to some extent. One is $Q_x = 3.3$, $Q_y = 1.8$, which still utilizes six superperiods. The other is a three superperiod solution, which requires three quadrupole families. In this case $Q_x = Q_y = 2.75$.

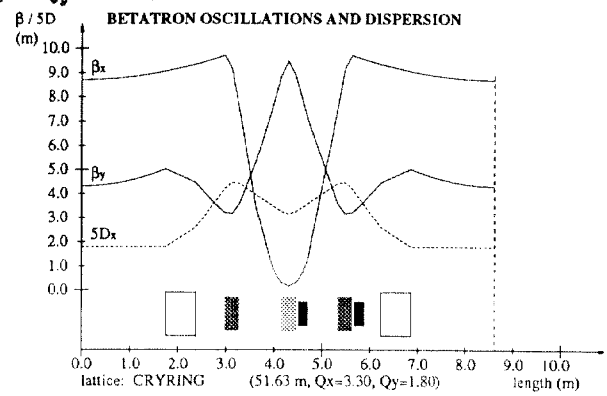

Fig 4. A working point with lower dispersion.

Effects from the Electron Cooler Magnets

Calculations have shown that the effects of the electron cooler toroids and solenoid on the ion beam are of such magnitude that they have to be compensated.

The toroidal field which guides the electron beam into the ion beam causes a distortion of the horizontal closed orbit. A toroid field of 0.3 T at $B\rho = 1.4$ Tm causes a maximum distortion of 90 mm, which means that the beam hits the vacuum chamber. Therefore it is planned to place two correction dipoles on each side of the electron cooler and backleg windings on the two adjacent bending magnets to correct the closed orbit distortion.

The solenoidal field will drive the resonance $Q_x - Q_y = 0$. A 1m long solenoid with a field of 0.3 T at $B\rho = 1.4$ Tm gives a resonance bandwidth[3] $\Delta e = 0.12$. Since this is quite large the resonance should be compensated. For this purpose correction solenoid(s) will be installed. Skew quadrupoles are not possible to use in this case.

Intensity Limitations

Space Charge

The number of ions it is possible to keep in the ring is limited by the space charge[4] (Uncooled beam).

$$N \leq \frac{\pi(\varepsilon_y + \sqrt{\varepsilon_x \varepsilon_y})\ \beta^2\gamma^3\ B_f\ \delta Q\ A}{F\ r_0\ q^2}$$

Typical values at injection:

$\varepsilon_x = 200\pi\ \mu$m·rad, $\varepsilon_y = 100\pi\ \mu$m·rad
$\beta^2\gamma^3 = 6.45 \cdot 10^{-4}$ (300 keV/u)
$B_f = 0.3$ (bunching factor)
$\delta Q = 0.25$ (maximum incoherent Q-shift)
$r_0 = 1.54 \cdot 10^{-18}$ m (classical proton radius)
$F = 1$ (form factor, important when γ is large)

If the A/q^2-dependence is isolated the formula becomes:

$$N \leq 24 \cdot 10^9 \cdot \frac{A}{q^2} = \quad (q/A = 0.25) \quad \frac{390 \cdot 10^9}{A}$$

Keil-Schnell Limit

The Keil-Schnell criterion[5] for CRYRING at injection energy is

$$N \leq \frac{460 \cdot 10^9}{A} \quad (q/A = 0.25)$$

But even above the Keil-Schnell limit the growth rate will be low, because the longitudinal coupling impedance is very close to the negative complex axis and the beam is perfectly stable on that axis. It is the space charge component which dominates the impedance (-18j kΩ).

Thus the Keil-Schnell limit should not be a problem without cooling and when the beam is cooled intrabeam scattering will be a bigger problem (IBS $\sim q^4$, KS $\sim q^2$). Maybe Keil-Schnell will be important for low charged ions at high energy.

Intrabeam Scattering

Intrabeam scattering (IBS) will be the factor that limits the beam quality when the beam is cooled, since it is especially severe for slow, highly charged ions.

$$\text{growth rate} \sim \frac{q^4 N}{A^2 \beta^3 \gamma^4}$$

It is thus essential for us to find a lattice with low IBS.

In a simple theory, where the lattice is assumed to be weak-focussing, IBS only transfers energy between the horizontal, vertical and longitudinal planes when the beam energy is below transition[6].

Another possibility is to make a lattice-independent theory, a formula which for all machines gives the correct order of magnitude for the growth rates[7].

We have used a more elaborate theory[8] to compare the IBS between different lattices. We have found that the IBS is lower if the lattice functions are smooth, and a strong focus gives very large emittance growth. It is also desirable to have low dispersion.

In the figure below the IBS in different positions in CRYRING is plotted for two different working points, 2.3, 2.27 and 3.3, 1.8. On the horizontal axis is position in the ring, and on the vertical the growth rate, $1/\tau_x + 1/\tau_y + 1/\tau_l$. The figure is rather independent of emittances and dp/p.

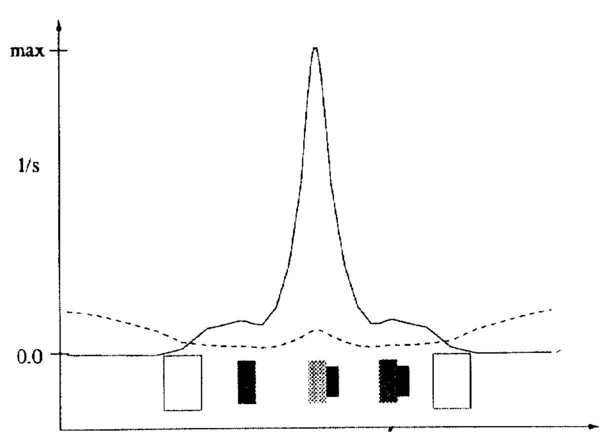

Fig 5. Relative growth rates due to IBS for a cooled beam for two different working points. Dashed line: Q_x=2.3, solid line: Q_x=3.3.

The table below shows three typical beams in CRYRING with electron cooling when the cooling times are ≈ 1 s. 10^6 Ar^{16+}_{40} ions. Q_x=2.3, the corresponding emittances for the Q_x=3.3 lattice are 2-3 times larger and the momentum spread 20-30% larger.

Table 2.

E MeV/u	ε_x π μm·rad	ε_y π μm·rad	dp/p 10^{-4}
0.3	0.4	0.4	3
6	0.08	0.07	1
16	0.03	0.02	0.8

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