CRYSTAL: A STORAGE RING FOR CRYSTALLINE ION BEAMS

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1 INTRODUCTION

This is brief summary of the Design Report concerning the low-energy heavy-ion storage ring proposed for the experimental demonstration of Crystalline Beams and other applications.

The design of the project has been in a first stage optimized for the study of Crystalline Beams; but provisions have also been made for carrying out experiments of different nature with applications to nuclear, atomic and molecular physics. The Tandem-ALPI heavy-ion facilities of the Laboratori Nazionali di Legnaro is assumed as the injector for the storage ring.

2 THE STORAGE RING

The overall size of the storage ring [1] was determined by some general considerations such as the largest specific kinetic energy of the ions which have to be stored, the matching with the heavy ion injector and, most important, the requirements for Crystalline Beams. The maximum specific energy has been fixed at *50 MeV/u* for *Gold* ions *(51+)*, corresponding to a magnetic rigidity of *3.8 Tm*. The storage ring has a total length of *70 m*. The maximum magnetic rigidity was chosen in connection with the use of the storage ring for other purposes, namely nuclear, atomic and molecular physics. The value of *3.8 Tm* places the CRYSTAL Storage Ring in a complementary position with respect to the similar existing facilities.

At the design level particular emphasis has been given to the special characteristics of the proposed facility, mainly its high precision. This is connected to the fact that much colder beams can be prepared and that the proposed ring has much better stability of magnets ($\Delta B/B < 10^{-5}$), alignment, ring vacuum, electron and laser cooler, etc.

The shape and symmetry of the ring was determined by a compromise between an ideal machine for crystallization purposes, where the beam is preserved from external perturbations, and the need for several straight sections where to accomodate injection, extraction, acceleration, cooling and diagnostic devices.

It has been proven that minimization of the intrabeam scattering blow up is related to minimization of the first derivatives of the horizontal and vertical β–functions and of the dispersion function (η') along the machine. The simulations performed with the computer code MAD [2] show that high periodicity of the lattice and short drift sections are preferable. As a matter of fact, the electron cooler device needs a rather long drift space and this determines the length of all drift sections.

In addition, the demand for a single particle phase advance $\sigma_0 < 90^0$, in order to avoid envelope instability [3], imposes already a minimum periodicity to the ring; the eightfold symmetry is the minimum geometry satisfying this requirement.

Furthermore, the need for many straight sections, combined with the high periodicity required to obtain Crystalline Beams and to avoid crossing systematic betatron resonances, also imposes such a geometry (*Fig. 1*).

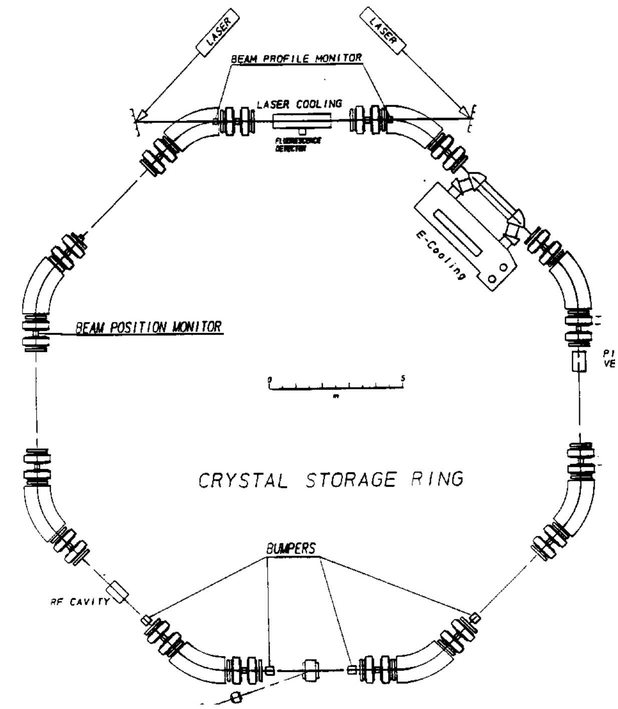

Figure 1 - Layout of the CRYSTAL Storage Ring

Several sets of values can satisfy the machine requirements and one can change between different working points and use the most suitable for the actual experiment. Although the storage ring can be used for different applications. As an example, in the follow only two typical working points will be considered: the "Crystalline" and "Standard" modes. The latter is most suitable for applications different than crystalline beams.

The magnetic lattice consists of eight *45°* bending magnets, *32* quadrupoles (and *32* sextupoles). The dipoles are sector magnets with zero entrance and exit angles; their length along the reference orbit is *2 m*. Only one type of quadrupole is used; their length is *0.25 m* and are assembled in four families for the standard operation mode. To operate the machine for Crystalline Beams only two families of quadrupoles are required. The bending magnets have a vertical aperture of *80 mm*, corresponding to a vertical acceptance of *50 π mm mrad*; while the quadrupoles have a bore radius of *65 mm*. Two families of sextupoles have been considered to correct horizontal and vertical chromaticities. The sextupoles have the same bore radius as the quadrupoles and their length is *0.20 m*.

The drift space between the quadrupole-sextupole and quadrupoles is *0.1 m* and *0.4 m*, respectively; while the length of the straight sections is *3.4 m*. These latter will house the injection and extraction system, cooling devices, RF cavity, diagnostic devices and correcting magnets. The transition energy $\gamma_{tr} = 1.76$ and $\gamma_{tr} = 6.56$ are large values which always keeps the machine operating well below it.

A summary of the lattice parameters for Crystalline and Standard Mode operation is given in *Table 1.*

Heavy ions will be injected into the CRYSTAL Storage Ring using the existing facilities at LNL: the XTU Tandem with the ALPI superconducting post-accelerator. The most efficient way of injecting into a storage ring is the pulsed mode, where the XTU Tandem-ALPI provides short beam pulses of heavy ions with peak current, giving good quality beams with small transverse emittance ($\varepsilon < 1\pi$ *mm mrad*) and momentum spread ($\Delta p/p = 10^{-4}$). With this scheme, it is possible to obtain beams with a wide range of mass numbers and sufficiently large charge states produced by stripping targets at proper location.

If required, it will also be possible to inject into the CSR directly from the Tandem, bypassing ALPI, or from a different kind of source.

Very efficient phase-space cooling has been designed for the CRYSTAL Storage Ring. Two techniques of cooling will be employed: electron cooling and longitudinal/transverse laser cooling. The electron cooling facility include also the possibility to operates with an ultra-cold electron beam generated by a photocathode.

In many cases the lifetime of a beam is limited by reactions with residual gas. The most important effects are the loss, and the capture, of electrons by scattering on residual gas. Single and multiple Coulomb scattering are also limiting the ion beam lifetime.

Table 1 - Lattice Parameters of the CRYSTAL Storage Ring.

Description	Crys. Mode	Stan. Mode
Max. Magnetic Rigidity [Tm]	3.8	3.8
Circumference [m]	68.8	68.8
Lattice Periodicity	8	4
Bending Radius [m]	2.55	2.55
Max. Dipole Field [T]	1.5	1.5
Dipole Vertical Gap [cm]	8	8
Quadrupole Gradient [T/m]	0.72	3.5
Quadrupole Bore Radius [cm]	6.5	6.5
Phhase Advance per Period:		
Horizontal	83^0	126^0
Vertical	53^0	80^0
Dispersion max. [m]	3.6	2.06
Gamma Transition	1.76	6.56
Betatron Tunes:		
Q_h	1.85	2.81
Q_v	1.185	1.77
Natural Chromaticity:		
ζ_h	-0.72	-3.36
ζ_v	0.21	-5.4
Momentum Compaction	0.32	0.023

In order to avoid considerable beam losses, the storage ring is designed for operation in the 10^{-12} *Torr* region.

3 STORAGE RING PERFORMANCES

The design of the project has been in a first stage optimized for the study of Crystalline Beams; but provisions have also been made for carrying out experiments of different nature with applications to nuclear, atomic and molecular physics.

3.1 Crystalline Beams

The accumulation of an ordered structure is the result of an equilibrium between the interparticle Coulomb force and the external focusing system. The effect of different lattices on the rate of intrabeam scattering (IBS) of a previously cooled ion beam was deeply investigated.

The working point for Crystalline Beams is characterized by smooth β–functions in order to decrease as much as possible the intrabeam scattering. Furthermore, crystallization requires low phase advance per super-period and hence low tunes.

Numerical calculations was performed by simulating a realistic storage ring and the ground s tate of Crystalline Beams were achieved [4]. Electron and laser cooling techniques are applied to cool down the ion beams to reach Crystalline states. In spite of the viscous heating by the shear induced in the bending fields, simulations indicates that even high density Crystalline Beams do exist in a storage ring [5]. A serious limitation of transverse beam temperature, which prevent the formation of Crystalline structures, is the main result of two phenomena appearing in the transport of very intense beam of particles: the envelope instability and the intrabeam scattering. Both phenomena have been numerically investigated. The simulations show that the heating of the beam due to envelope instability is even stronger than the heating due to the intrabeam scattering. By an independent analysis of both phenomena the required conditions to avoid envelope instability have been found. The effect of intrabeam scattering cannot be avoided, but only compensated by the cooling and reduced by the smoothness of the lattice.

3.2 Other Applications

Besides the study of Crystalline Beams the CRYSTAL Storage Ring can be used also for other important applications in nuclear, atomic and molecular physics.

The Storage Ring is suitable for storing considerable intense ion beams (up to 10^8 - 10^{10} particles) as well as working as a synchrotron, where particles are accelerated up to a *few hundreds MeV/u* with intensities in the range of 10^9 - 10^{11} *particles/s* at the repetition rate of *1 Hz* (extension up to a frequency of *50 Hz* is also envisaged).

The maximum dipole field has been adjusted to *1.5 T* not exceed the maximum ramp rate of *40 T/s* with a repetition rate of *50 Hz.* For this large field variation the magnets are laminated with a thickness of *0.35 mm* to minimize the iron eddy current. The intensity values showen in *Table 2* correspond to a space-charge betatron tune shift depression $\Delta Q_L = 0.5$, repetition rate of *1 Hz*, and the acceleration harmonic number *h* has been calculated corresponding to the RF frequency of *5 MHz* at injection. Similarly, the RF peak voltage has been calculated assuming full bucket at injection and a smooth increase toward the end of the accelaration cycle of the RF bucket area by a factor of *2*.

Typically the rms betatron emitttance at injection is approximately *1* π *mm mrad* where as the momentum spread is around 10^{-4} for all ion species. The beam is bunched at the frequency of *5 MHz* and the beam bunches have a total area in the range *2* to *20 meV/u-s*.

The development of a second generation cooler ring with better lattice will give large possibilities to investigate deeper in fundamental physics.

4 CONCLUSIONS

The feature of the CSR, which makes it quite different from other projects, is that it has now, at the design stage, the opportunity to optimize a storage ring for Crystalline Beams. In that sense the CSR will be indeed the storage ring dedicated to these studies whereas the research on Crystalline Beams will occur only in a later period and will be not obviously optimized with the other storage ring. For the rest of the research program, with applications of different nature, CSR will complement in range and performance the other existing facilities.

The construction of the storage ring, which we have called CRYSTAL from its major and more fundamental application, is foreseen to take a period of *five* years and has a total cost of *28 billions* of Italian Lire (quotation May 1995).

5 REFERENCES

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