The Crystal Storage Ring Project at Legnaro

G. Bisoffi, 1) A.Burov 7), R. Calabrese 2), G. Ciullo 1), T. Clauser 3), A. Dainelli 1), N.S.Dikansky 7), G.Di Massa 8), M.Greiser 9), V. Guidi 2), S. Gustafsson 1), R.Hasse 10), I. Hofmann 10), A. Labrador 1) ,G.Lamanna 1), P. Lenisa 2), E. Mariotti 4), F.Masoli 2), M.R.Masullo 8), L.Moi 4), M.F. Moisio 1), D.V.Pestrikov 7), F. Petrucci 2), A. Pisent 1), V.Rotayev 7), A.G. Ruggiero 6), M. Rutigliano 3), A.Semyakin 7), A.Sharapa 7), V. Stagno 3), J.Struckmeier 10), B.Tiveron 1), V.Vaccaro 8), V. Variale 3), B. Yang 1)*, and L. Tecchio 5)*

1) Laboratori Nazionali di Legnaro-INFN, Legnaro, Italy
2) University of Ferrara and INFN, Ferrara, Italy
3) University of Bari and INFN, Italy
4) University of Siena and INFN, Italy
5) University of Torino and INFN, Torino, Italy
6) Brookhaven National Laboratory, Upton, NY, USA
7) Budker Institute of Nuclear Physics, Novosibirsk, Russian Federation
8) University of Napoli and INFN, Italy
9) MPI für Kernphysik, Heidelberg, Germany
10) GSI, Darmstadt, Germany
* Proel Tecnologie, Firenze, Italy

Abstract

We present a study on a storage ring dedicated to ion beam crystallization. Lattice has been designed in order to reduce the phenomena acting against the cooling such as intra-beam scattering and envelope instabilies. Computer simulations show different kinds of crystaline structures and some new features related to shear effect.

1. INTRODUCTION

The improvement of e-cooling technique and the use of new cooling techniques such as laser cooling might allow to achieve crystalline structures for an ion beam circulating in a storage ring.

During the last decade some theoretical models have been developed [1] and computer simulations have been carried out [1] showing different kinds of crystalline structures.

Experimental evidences of these structures were obtained when cooling down ions in ion traps [2]. An electron beam adiabatically accelerated reaching a liquid-like state with a plasma parameter greater then one [3], and NAP-M experiments in which correlation was found among the protons of the beam [4], look promising for the achievement of crystalline structures in storage ring..

1. GENERAL LAYOUT

Low IBS requires a smooth variation of lattice functions [5] along the ring structure. The best candidate is a betatron-like ring but has been already demonstrated [6] that it is not possible to get and store a crystalline structure in it due to negative mass instability. Hence the shape and the symmetry of the machine which is proposed hereafter gives rise to a "smooth" machine taking into account the need of straight section for experiments, diagnostic and cooling .

The lattice parameters of Crystal Storage Ring (CSR) is howed in Figure 1, lattice parameters in Table 1 and cell parameters in Table 2.

High periodicity has been chosen to have a working point far away from the systematic resonances up to the fifth order and from the first parametric resonance. It is also important because it allows phase advances lower than $\pi/2$ (in both planes), threshold above which for envelope instability would appear.

Table 1
Lattice Parameter of Crystal Storage Ring

Description	Crystalline Mode
Ring Length [m]	68.8
Lattice Periodicity	8
Magnetic Rigidity [Tm]	4.2
Bending Radius [m]	2.55
Phase Advance per Period:	
Horizontal	83^0
Vertical	53^0
Transition γ	1.76
Betatron Tunes:	
Q_x	1.85
Q_y	1.185
Natural Chromaticity:	
ζ_x	-0.72
ζ_y	+0.21
β_x, max [m]	6.74
β_y, max [m]	10.4
Dispersion max [m]	3.6
Momentum Compaction	0.32

2. SIMULATIONS OF CRYSTALLINE STRUCTURES AND SHEAR EFFECT

The Computer codes Parmt [7] and Slice [8] have been used in order to simulate the process of crystallization starting from hot beams. While Parmt simulates the transport of a cell of ions through a beam optic system under space charge conditions, in Slice, developed in LNL laboratory, the trajectories of the particles in a beam cell are determined using a straightforward ray tracing metod calculating the space charge effect before each step of trajectory calculation.

Table2
Cell Parameters of the Crystal Storage Ring

Description	Crystalline Mode
Period Length [m]	8.6
Dipoles:	
Dipole Length [m]	2.0
Bending Angle	45^0
Bending Radius [m]	2.55
Vertical Gap [cm]	6
Drifts:	
Drift length [m]	4
Drift length [m]	0.4
Quadrupoles	
QF length [m]	0.25
strength [m^{-2}]	0.4
QD length [m]	0.25
strength [m^{-2}]	-0.6
Bore Radius [cm]	6.5

Preliminary tests show a very good agreement between the two programs which produce the same structures with the same cooling factor.

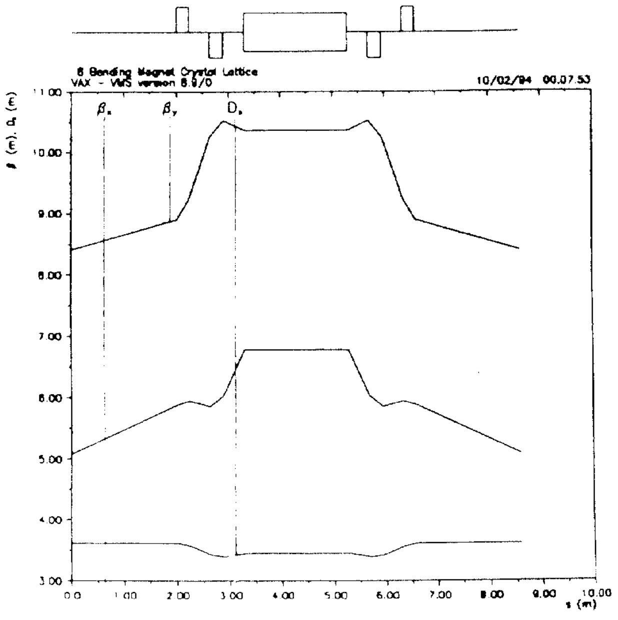

Figure 1. Lattice functions of Crystal Storage Ring

The cooling process was taken into account reducing the divergence of each ion by given factor F once per turn. Figure 2 shows a string obtained with $^{197}Au^{51+}$. The number of ions is N=2.7 10^5. The cooling factor used is Fxx'=Fyy'=Fzz'=1.003 corresponding to cooling a time of T=1 ms. The same structure has been obtained with $^9Be^{1+}$ with a cooling factor $F_x=F_y=F_z=1.0004$ corresponding to T=5 ms. The interparticle distance are D=0.260 mm in both cases.

If the beam intensity is increased other kinds of structures, shown in Figure 2 could be achieved. In order to save computer time the cooling factor used to obtain the more complicated structures is F=1.05.

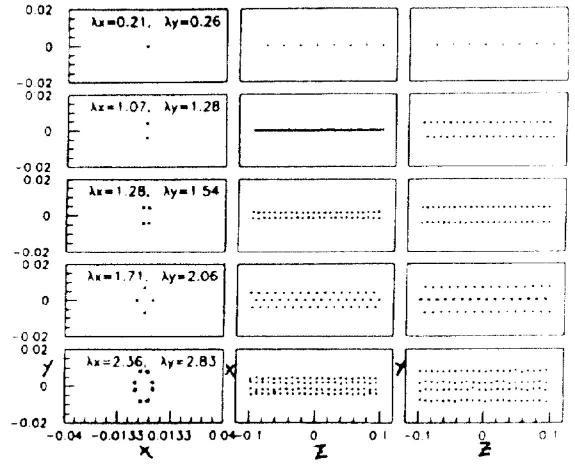

Figure 2. Crystalline Structures for different structure parameters $\lambda_{x,y}$

An important item is the demonstration that the shear forces introduced by dipoles [9] do not destroy the crystal beam. In Figure 3 is shown a shell structure projected onto the mantel at different position of storage ring period: in x direction beam breathing appears whereas in longitudinal direction ions complete one oscillation due to shear after one period length.

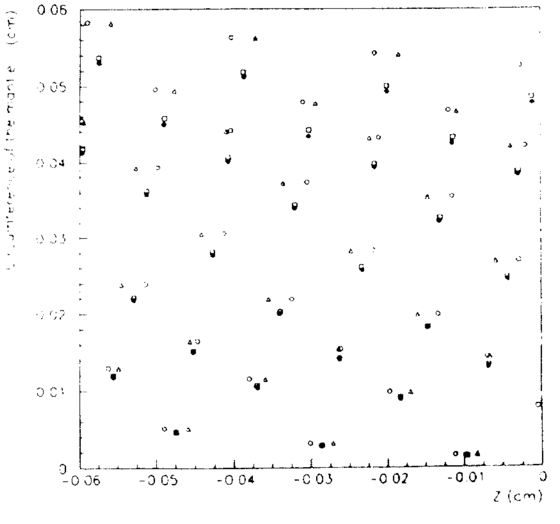

Figure 3. Shell structure projected onto the mantel at different position of storage ring period: • -middle of the drift space, ▵-entrance of the dipole, ○- exit of the dipole, □ -middle of the next drift space

This implies that shear forces are counteracted by other forces. In fact a crystallized beam in a storage ring arranges itself in such a way as to get a longitudinal velocity gradient, shown in Figure 4, in order to maintain the same average revolution frequency for all the ions.

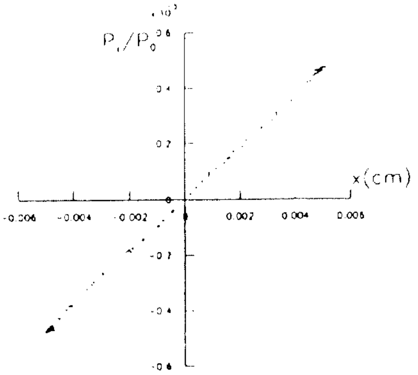

Figure 4. Longitudinal velocity gradient.

According to reference [9], a crystalline steady state can be described in the ion rest frame by the following averaged equations:

$$z' = \frac{p_z}{M\omega_0} - x = 0; \qquad p'_z = \frac{Fe}{\omega_0} - \frac{\gamma_c}{\omega_0} p_z = 0 \qquad (1)$$

where z is the longitudinal coordinates, γ_c is the longitudinal cooling factor and F_e is an elastic force felt by an ion in the beam due to shear forces. We get from the first of the equations (1) that a gradient is created inside the beam so that the angular velocity remains constant. The second equation is related to the oscillation due to shear forces and the cooling force.

3.1 Envelope Instability

We investigated the growth rate of the envelope instability, which also cause emittance growth in a non-linear system [10], simulating the CSR lattice with different working points. The beam is cooled down in 500 turns without letting it reach a crystalline structure and it is then allowed to blow-up. The higher the tune, above $\pi/2$, the larger the blow up.

The final real and phase space projections are shown in Figure 5. The instability structures are apparent in x phase plane for cases b) and c). Same perturbations can also be recognized in y phase plane but not so dramatic. The calculated cooling time is some milliseconds for a) ($\sigma_{0x}=113^0$, $\sigma_{0y}=97^0$), 4.5 μs for b) ($\sigma_{0x}=93^0$, $\sigma_{0y}=76^0$), 0.9 μs for c) ($\sigma_{0x}=83^0$, $\sigma_{0y}=53^0$),. This means that equivalent cooling factor would be needed to overcome this instability. It is therefore essential to operate CSR below $\pi/2$ in both planes, as shown in table 1.

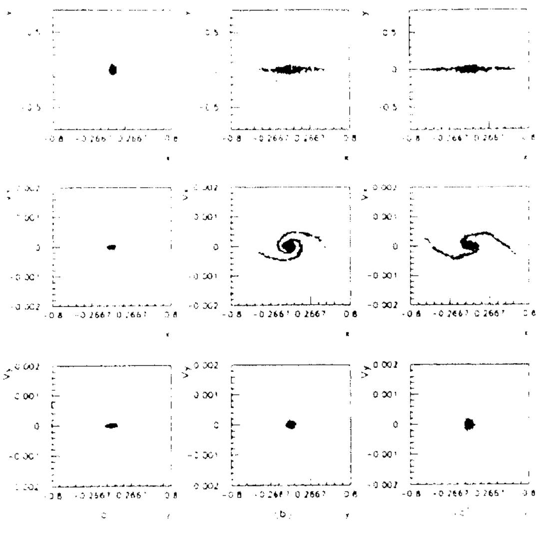

Figure 5. Final real and phase space projections.

4. CONCLUSIONS

The simulations carried out demonstrate that different crystalline structures are allowed in the Crystal Storage Ring if efficient cooling is provided. Shear forces are counteracted by a longitudinal velocity gradient created inside the ion beam, so that only stable oscillations exist.

Envelope instability are avoided choosing the phase advances properly.

5. REFERENCES

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