ORDERED ION BEAM IN STORAGE RINGS

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Abstract

The using of crystalline ion beams can increase of the luminosity in the collider and in experiments with targets for investigation of rare radioactive isotopes. The ordered state of circulating ion beams was observed experimentally at several storage rings. New criteria of the beam orderliness are derived and verified with BETACOOL code with using molecular dynamics (MD) technique. The sudden reduction of momentum spread observed on a few rings is described with this code. The simulation shows a good agreement with the experimental results. The code has then been used to calculate characteristics of the ordered state of ion beams for ion rings which will have experimental programs for the study of crystalline beams. A new strategy of the cooling process is proposed which permits to increase the linear density of the ordered ion beam.

ESR EXPERIMENTS

Since the sudden reduction of momentum spread of circulating proton beam was observed on NAP-M [1] the ordered state of ion beams was achived on several storage rings also. The most extensive experemental program was perfomed on the ESR [2]. The momentum spread reduction was observed for wide range of the ion species.

On ESR the momentum spread of an uranium beam at 400 MeV/u cooled by 0.25 A electron beam drops around 1000 stored ions from a value of $\Delta p/p = 5\cdot 10^{-6}$ to $\Delta p/p = 5\cdot 10^{-7}$ corresponding to a change of the longitudinal temperature by two orders of magnitude (Fig.1) [3]. The scraper measurement allows deriving the momentum spread and the beam radius as a function of the number of stored ions. For the horizontal degree of freedom a radius reduction from 0.2 mm to less than 0.01 mm is obvious. Despite the limited resolution even for the vertical beam radius a reduction is suggested by the data points at the transition point of the longitudinal momentum spread and the horizontal radius.

The behavior of the ion beam parameter evolution can be explained using 3D diagrams of the beam parameter growth rates due to intrabeam scattering which were calculated using generalized Piwinski model (Fig.2a,b) [4]. The model presumes large enough number of particles and Gaussian distribution of the particles in all degrees of freedom. Horizontal and vertical emittances were chosen to be equal.

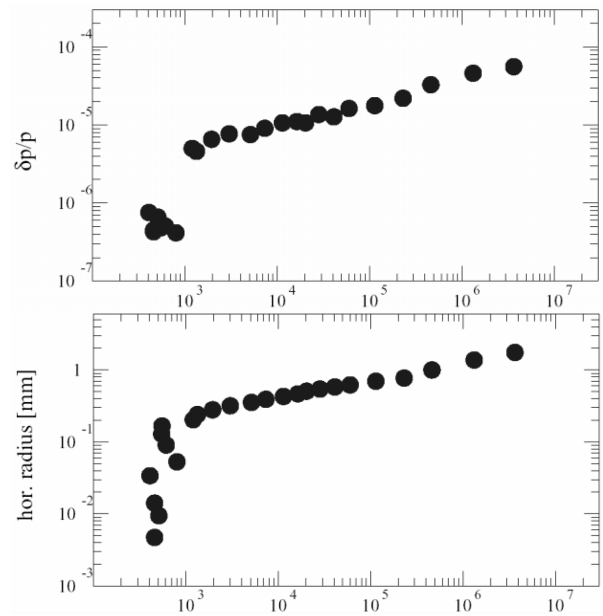

Fig.1. Beam behavior in the ESR experiment showing the anomalous temperature reduction at low intensity. Momentum spread and beam size are given as functions of number of stored ions. $^{238}U^{92+}$ 400 MeV/u

Crystallisation conditions [5] should be satisfied for 3D crystalline beams. In the case of 1D ordered beam other criterions were formulated [6]. The main criterion defines the situation when particles can not cross each other in the longitudinal direction:

$$\Gamma_2 = \frac{1}{4\pi\varepsilon_0}\frac{Z^2e^2}{T_{\parallel}\sigma_{\perp}} > \pi \ ,$$

where Ze - charge of particles, $T_{\parallel}$ - longitudinal temperature, $\sigma_{\perp}$ - transverse size of the ion beam. The condition $\Gamma_2 = \pi$ describes the following relation between beam emittance and momentum spread: $\varepsilon \sim (\Delta p/p)^{-4}$. In the twice-logarithmic scale this dependence is presented in the Fig.2c as a black solid line, where the comparison of the theoretical dependence of IBS on beam parameters at high particle number with the results of numerical simulation using MD method is presented [7]. In ESR experiments the magnitudes of beam emittances and momentum spread before the momentum reduction are defined by equilibrium between IBS growth and cooling rates (series of square points on Fig.2c). The experimental points lie on the line, which approximately corresponds to equal values of longitudinal and transverse growth rates. The particle number decreases with time and when Γ_2 parameter exceeds π the cooling forces suppress the IBS ones and the beam comes to the ordered state (last experimental point on Fig.2c).

The results of calculation using MD technique (Fig.2c) are in good qualitative agreement with 3D diagram (Fig.2a,b). Calculations were performed at the same particle number - $5 \cdot 10^5$ which is in three order larger than in ESR experiments. Cooling rates were also chosen in three order lager in comparison with real electron cooling systems. At the first stage of the beam cooling all the lines have the same angular inclination determined by ratio between cooling rates in transverse and longitudinal degrees of freedom. In the case of uniform cooling $\varepsilon \sim (\Delta p/p)^2$ one can see this dependence in the initial part of the beam phase trajectory independently on initial point. It means that at large initial phase space of the beam IBS process does not effect on the cooling process.

Before the ordered state MD calculations are in good agreement with position of the maximum of IBS growth rates predicted by Piwinski model. No another additional heating were used in these simulations. In the ordered state the IBS growth rates calculated using MD method are substantially less than predicted by Piwinski model. At the cooling rate $4 \cdot 10^4$ Hz and higher the beam emittance and momentum spread decrease to very small values.

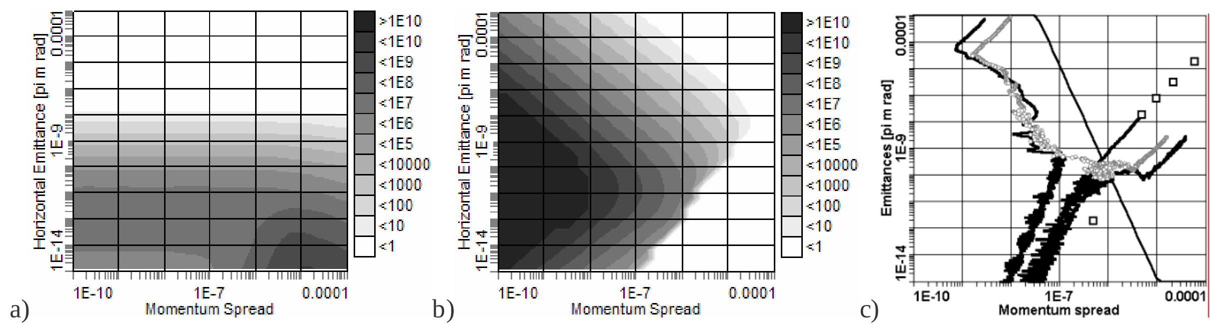

Fig.2. The theoretical dependence IBS growth rates on beam emittance and momentum spread for ESR: a) – horizontal component of IBS growth rates, b) – longitudinal one. Results of MD calculations (c): evolution of ion beam parameters during the cooling, solid black line corresponds to cooling rate $4 \cdot 10^4$ Hz, grey circles – 10^4 Hz, straight line is criterion $\Gamma_2=\pi$ ($N = 5 \cdot 10^5$). Square points – ESR experiment (Fig.1).

SIMULATION FOR TARN-II

The 3D phase diagrams of IBS heating rates in accordance with Martitni model for TARN-II ring [8] have the same behavior to the ESR ring (Fig.2a,b). To study the intrabeam scattering in ordered state the 3D phase diagram of heating rates was numerically simulated with using of Molecular Dynamics technique. Initial distribution is generated with the same distance between particles in longitudinal direction. Transverse emittances and momentum are generated with Gaussian distribution. It means that particles initially have only kinetic energy in longitudinal plane. Growth rates are calculated after few hundred turns when the relaxation between kinetic and potential energies in longitudinal plane is occurred. Black straight line (Fig.3) corresponds to criterion $\Gamma_2=\pi$, gray one is equilibrium between longitudinal and transverse temperatures. The cross point between criterion Γ_2 and the temperature equilibrium is the last point before the sudden reduction of momentum spread which was experimentally observed on a few storage rings.

The result of simulation (Fig.3) has a few differences from theoretical model of IBS heating (Fig.2a,b). Transverse components have very low heating rates for the range of momentum spread which are placed below the temperature equilibrium. Another big difference is the shape of longitudinal component of IBS heating rate. It was divided in two parts. First of them is defined by the heating from optic structure. Second part looks like island and its height is linearly dependence on particle number and well described by theory of IBS. The maximum of IBS island is placed near the crossing point between criterion $\Gamma_2=\pi$ and the temperature equilibrium.

The longitudinal component of IBS heating has the break-up where heating rates have very small value in comparison with the theoretical prediction. If the initial parameters of ion beams can be chosen near the break-up then the ordered state for a large number of particle $N = 10^5$ can be achieved for real cooling system with electron beam current $I_{ecool} = 5$ A (Fig.3c).

To achieve the ordered ion beams with a large number of particles and with a realistic cooling force a special strategy of the cooling process should be elaborated.

When the ion beam stays in equilibrium between IBS and cooling we may apply additional heating in the transverse direction. For example, heating by an RF-kicker can be used. Initially, the momentum spread will continue to decrease and emittances will increase. When the beam parameters have to satisfy the condition $T_\perp >> T_\parallel$ we can switch off the additional heating and the ion beam will continue to cool down to the ordered state. The same idea can be proposed for other storage ring. The experimental verification of the new strategy for the achievement of an ordered ion beam with large density can open new possibilities in the accelerator physics.

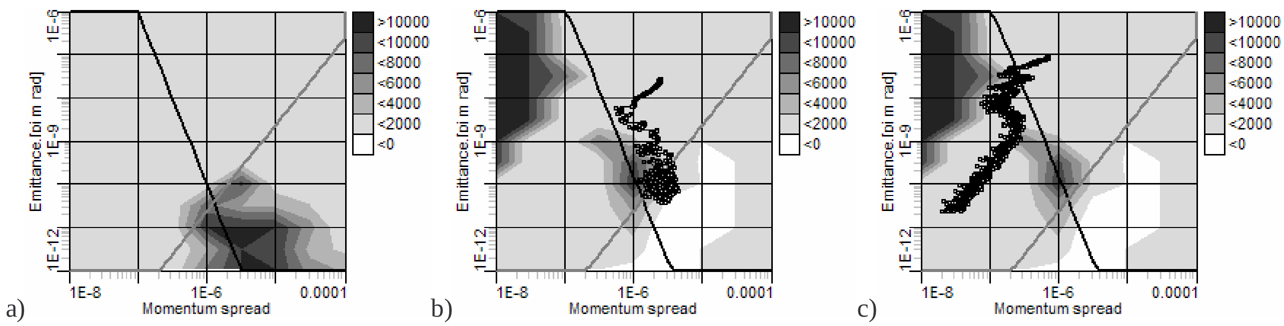

Fig.3. MD simulation: a)- horizontal component of IBS growth rates, b), c) - longitudinal component of IBS and evolution of beam parameters during cooling process. $I_{ecool} = 5$ A, $^{132}Sn^{50}+$ 220 MeV/u, $N = 10^5$.

CONCLUSION

The numerical simulation shows a large difference of the behavior of IBS heating in the ordered state in comparison with the analytical model. To increase the particle number in the ordered state a new strategy of cooling process is proposed. An additional heating in the transverse direction should be applied during cooling process. For real cooling systems the ordered state can be achieved with number of particle up to 10^5. IBS heating mechanisms in the ordered state is not explained completely and need further investigations.

ACKNOWLEDGEMENTS

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REFERENCES

[1] G.I.Budker, N.S.Dikansky, V.I.Kudelainen et al., Proc. 4th All-Union Conf. on Charged-Particle Accelerators [in Russian], Vol. 2 (Nauka, Moscow, 1975) 309; Part.Accel. 7 (1976) 197; At.Energ. 40 (1976) 49. E.Dementev, N.Dykansky, A Medvedko at al., Prep. CERN/PS/AA 79-41, Geneva (1979).

[2] M.Steck, K.Beckert, H.Eickhoff et al. Anomalous temperature reduction of electron-cooled heavy ion beams in the storage ring ESR. Phys.Rev.Lett., v.77 p.3803 (1996).

[3] M Steck, K Beckert, P Beller, B Franzke and F Nolden. New evidence for one-dimensional ordering in fast heavy ion beams. J. Phys. B: At. Mol. Opt. Phys. **36** p.991–1002 (2003).

[4] M. Martini. Intrabeam scattering in the ACOOL-AA machines. CERN PS/84-9 AA, Geneva (1984).

[5] J.Wei, A.Draeseke, M.Sessler, X.Li. Diverse topics in crystalline beams. Proceedings of the 31st Workshop of the INFN Eloisatron Project. Erice, Italy, November 12-21 (1995) p.229.

[6] T.Katayama, I.Meshkov, A.Sidorin, A.Smirnov, E.Syresin. Ordered State of Ion Beams. Preprint RIKEN-AF-AC-40 (2002).

[7] T.Katayama, I.Meshkov, A.Sidorin, A.Smirnov, E.Syresin, H.Tsitsui, D.Mohl. Simulation Study of Ordered Ion Beams. Prepirnt RIKEN-AF-AC-42 (2003).

[8] T.Katayama. TARN II project. Proceeding of IUCF workshop on nuclear physics with stored cooled beams. Spencer, IN, USA (1984).