LONG TERM BEAM DYNAMICS SIMULATION WITH THE BETACOOL CODE

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Abstract

General goal of the BETACOOL program is to simulate long term processes (in comparison with the ion revolution period) in the ion storage ring leading to variation of the ion distribution function in 6 dimensional phase space. The ion beam motion inside a storage ring is supposed to be stable and it is treated in linear approximation. Results of the numerical simulation of the beam dynamics for new project NICA (JINR, Russia) are presented.

APPLICATIONS OF BETACOOL CODE OVER THE WORLD

The idea of the BETACOOL code was appeared about 18 years ago for the simulation of the beam dynamics under action of the electron cooling. BETACOOL means that simulations take into account the beta function in the cooling section.

In the present time the BETACOOL code includes different models of a few physical process which are usually exist in the storage rings [1]: electron, stochastic and laser cooling, intrabeam scattering, scattering on atoms of the residual gas and different types of internal target, colliding regime and particle losses, etc.

The BETACOOL code was elaborated in the collaboration with different scientific centres in the world where was benchmarked on the existing experiments and used for the simulation of new accelerator projects:

- Benchmarking of IBS and electron cooling models: CELSIUS (TSL) [2], ESR (GSI), TechX (Colorado), RHIC (BNL) [3], Recycler (FNAL), COSY (FZJ) [4], S-LSR (Kyoto Univ.) [5];
- Luminosity preservation in colliders: MUSES (RIKEN) [6], RHIC-II (BNL) [7], PAX (FAIR) [8], NICA (JINR) [9];
- Simulations of experiments with internal target: PANDA@HESR (FAIR) [10], WASA@COSY (FZJ) [11], ESR (GSI) [12];
- Beam ordering (crystalline beams): S-LSR (Kyoto University) [13], NAP-M (BINP), COSY (FZJ) [14], ESR (GSI) [15];
- Simulations of cooling-stacking process: LEIR (CERN), HIRFL-CSR (Lanzhou), NICA Booster (JINR) [16];
- Low energy electron cooling: TSR [17] and USR (MPI) [18], ELENA (CERN);
- RF burrier bucket system: Recycler (FNAL) [19], ESR (GSI), NESR and HESR (FAIR) [20], NICA Collider (JINR).

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Basic algorithms and software structure are described in details in BETACOOL guide [21]. The possibilities of the BETACOOL application for optimization of a storage ring operational regimes are illustrated in this report on example of the heavy ion mode of the NICA collider operation mainly. The beam cooling (both – electron and stochastic) at the NICA collider has two relatively independent goals: beam stacking using barrier bucket technique and luminosity preservation during collisions.

PARTICLE ACCUMULATION WITH RF BARRIER BUCKET SYSTEM

RF barrier bucket system was proposed for the particle accumulation in the NICA collider in order to provide required beam intensity independently on intensity of the bunch at single injection [22]. In the ion energy range from 1 to about 3 GeV/u the beam stacking is planned to be realized using stationary burrier pulses with the electron cooling of the injected beam.

RF barriers divide a ring circumference on two parts: one of them corresponds to unstable synchrotron motion, in the second one the motion is stable. After injection into the unstable region the particles are cooled down with the electron cooling and accumulated between barriers in the part opposite to the injection region. At the next injection all the particles located in the injection region are killed by the injection kicker pulse. The NICA collider RF barrier bucket system is designed to provide the barriers of rectangular shape. Example of the stacking process simulation with BETACOOL is presented in the Fig.1.

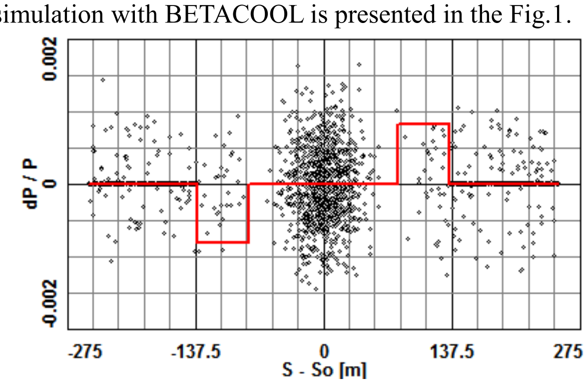

Figure 1: Longitudinal phase space after second injection for the ion energy 1.5 GeV/u: dots – model particles, red line – barrier bucket potential distribution in the momentum deviation units.

The stacking efficiency is determined by the ratio between the injection repetition period and the cooling time. The working cycle of the NICA injection chain is equal to about 5 seconds and it provides single bunch of about 10^9 Gold nuclei. Even accelerated bunch is injected into the first collider ring the odd – into the second ring. It

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means that for each collider ring the injection repletion period is about 10 seconds. Dynamics of the stacking process simulated with the BETACOOL is shown in the Fig. 2.

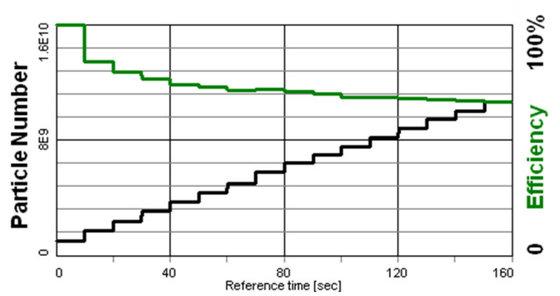

Figure 2: Particle accumulation with barrier bucket and electron cooling: black line – particle number, green – accumulation efficiency. Ion energy 2.5 GeV/u.

The accumulation efficiency decreases with increase of the the ion energy. It is equal to 92% for ion energy 1.5 GeV/u and 66% for 2.5 GeV/u. For the ion energy more than 2.5 GeV/u the electron cooling times are much longer than the injection repetition period (Table 1) and the stacking efficiency decreases very fast.

Table 1: Beam stacking in the NICA collider

Ion ring			
Ion energy, GeV/u	1.5	2.5	4.5
Particle number per injection cycle		10^9	
Initial emittance (h/v), π mm mrad		1.1/0.9	
Initial momentum spread		5×10^{-4}	
Barrier bucket voltage, kV		2	
Electron cooling			
Cooler length, m		6	
Electron current, A		1	
Electron beam radius, cm		1	
Magnetic field, kG		1	
Beta function at cooling section, m		16	
Longitudinal cooling time, sec	3	12	80
Accumulation efficiency, %	**92**	**66**	**34**

These results are in good agreement with independent simulations presented in [23].

The BETACOOL provides tools for optimization of the RF and electron cooler parameters in order to improve the situation. The beam losses during injection are related with the already circulating particles having very small momentum deviation in the unstable region. Such "frozen" particles are not affected practically by the cooling and they can move through the unstable region during a few hundreds of seconds. To push out them from the injection region one can slightly modify the barrier voltage shape introducing small accelerating (or decelerating) voltage in the unstable region keeping the integral over circumference equal to zero. The cooling efficiency can be also increased with the deviation of the electron energy.

For instance, the particle accumulation with electron energy shift ($\Delta P/P=10^{-4}$) and nonzero voltage at the injection region (+10 V) increases the stacking efficiency by about 10% at the ion energy 2.5 GeV/u (Fig.3).

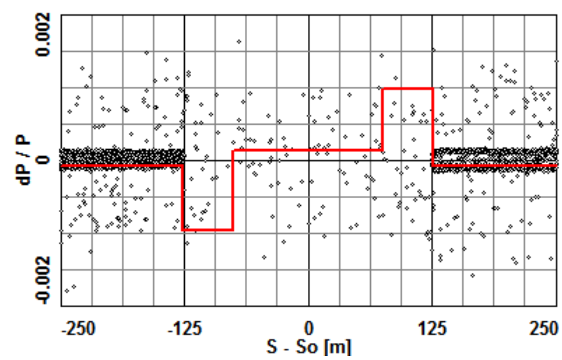

Figure 3: Longitudinal phase space after 160 sec with electron energy shift ($\Delta P/P=10^{-4}$) and nonzero voltage at the injection point (+10 V). Ion energy 2.5 GeV/u.

LUMINOSITY PRESERVATION WITH ELECTRON COOLING

The bunch parameters in the NICA collider are chosen near thermo dynamical equilibrium between all three degrees of freedom in the total energy range. At this condition the intrabeam scattering (IBS) heating times are equal to each other for transverse and longitudinal planes (Table 2). Role of the cooling during the collisions is to compensate the IBS heating and to stabilize the bunch parameters during long period of time. General problems at electron cooling application are the ion recombination with the cooling electrons and formation of specific shape of the ion distribution function. Electron cooling leads to formation of small dense core of the beam and long tails which are not cooled practically. One of the way to avoid both problems is to use so called "hollow" electron beam: the beam with very small electron density in the central part.

Table 2: Colliding regime

Bunch number		24	
Bunch length, m		0.6	
Beta function at colliding point, m		0.35	
Ion energy, GeV	1	3	4.5
Particle number per bunch, 10^8	2.7	24	22
Momentum spread, 10^{-3}	0.62	1.25	1.65
Emittances (hor/ver), π mm mrad	1.1/1	1.1/0.9	1.1/0.8
Luminosity, 10^{27} cm^{-2} sec^{-1}	0.01	1	1
Inrabeam scattering time, sec	**186**	**702**	**2540**

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The BETACOOL provides a possibility to simulate the cooling process at arbitrary shape of the electron distribution over the radial coordinate. In the simplest case the hole has to be chosen equal to the ion beam radius in the cooling section corresponding to required emittance. The electron density inside the hole is chosen to stabilize the ion momentum spread (Fig. 4).

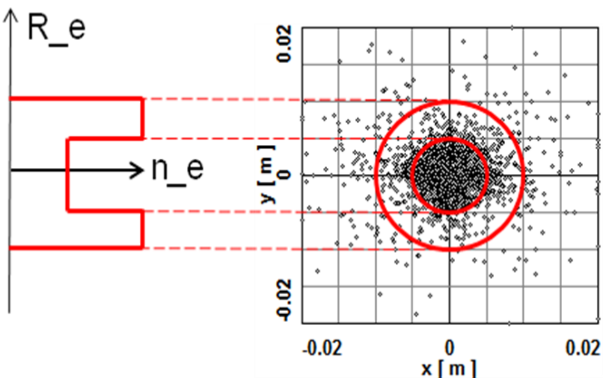

Figure 4: Hollow electron beam with the hole radius of 0.5 cm: black dot – particle distribution in real space, red lines – distribution of the electron beam density.

At optimum choice of the electron beam parameters the ion momentum spread and transverse emittances are practically stable during long period of time (Fig.5a). The slight increase of the luminosity (Fig.5b) is explained by the deviation of the transverse beam profiles from Gaussian shape. However the sharp central peak typical for electron cooling is not formed. The recombination rate is determined by the electron density inside the hole which is about in one order less than in the outer layer.

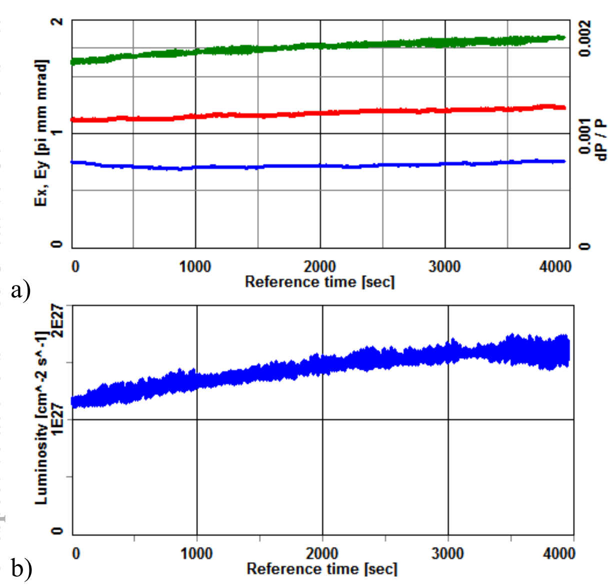

Figure 5: Evolution of beam parameters for ion energy 4.5 GeV/u and electron current 0.33 A: a) green line – momentum spread, blue and red – horizontal and vertical emittances, b) luminosity.

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