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Simulation of beam dynamics for ***PAX*** project using BETACOOL code

Simulations were done for the experiments on CSR and HESR for the proton-antiproton colliding experiments. During simulation RMS-Dynamics algorithm of BETACOOL code was used. The physical model of this algorithm is based on the following general assumptions:

1) the ion beam has Gaussian distribution over all degrees of freedom, and it is not changed during the process;
2) algorithm is considered as a solution of the equations for RMS values of the beam phase space volumes of three degrees of freedom (no any test particles);
3) maxima of all the distribution functions coincide with equilibrium orbit, all instability factors (linear and nonlinear resonances, space charge effects, beam-beam tune shift, etc.) does not take into account during simulation.

The following effects are used during simulation:

1) Electron cooling (EC)
2) Intrabeam scattering (IBS)
3) Interaction in collision point (IP)
4) Scattering on residual gas (RG)
4) Particle losses (PL)

EC effect uses Parkhomchuk model of the friction force. The IBS growth rates are calculated with Martini model using ring lattice functions imported from output file of the MAD program. IP effect is used for the simulation of luminosity and beam-beam parameters. The following PL effects were used during simulation: electron capture in EC for proton beam, losses due to interaction events at IP with cross section 40 mbarn, scattering on residual gas (electron capture, single scattering, nuclear reaction).

The most critical parameters in colliding mode are the following: the luminosity is limited by minimum value 10^{30} cm^{-2}sec^{-1}, bunch length have to be less than 30 cm what is equal to beta function at IP (to avoid hourglass effect). Parameters of RF system are responsible to keep the bunch length 30 cm in the equilibrium state. The simulation for the colliding mode was done for highest energy (15 GeV/c HESR and 3,65 GeV/c CSR) of storage rings (Table 1).

Initial emittances of proton/antiproton beams in colliding mode were chosen to satisfy the condition that the ion beam size is less than electron one in the cooler section (Table 1). After achievement of equilibrium proton/antiproton beams have approximately the same radius and bunch length in collision point. Cooling rates in the equilibrium state is equal to the value of IBS growth rates.

HESR electron cooler has the same design parameters as for experiments with internal hydrogen target. CSR electron cooler needs mode strong cooling force for cool down of short proton bunch. Cooling section length is 10 m what is in 3 times larger than was proposed for CSR cooler.

Table 1. Parameters of colliding mode

Initial parameters	**CSR**	**HESR**
Particles	proton	antiproton
Momentum [GeV/c]	3,65	15
Relativistic factor, γ	4,04	16,1
RF Harmonic number	10	90
RF Voltage [kV]	200	200
Number of particles per bunch	10^{11}	10^{10}
Number of bunches	10	30
Beta function at IP [m]	0,3	1
Cross section at IP [mbarn]	40	40
Transverse emittance [mm mrad]	1	0,13
Momentum spread, $\Delta P/P$	10^{-3}	10^{-3}
Beam-beam parameter	3×10^{-3}	6×10^{-3}
Electron cooler		
Cooler length [m]	10	30
Magnetic field [kG]	2	5
Beam radius [cm]	0,5	0,5
Beam current [A]	3	1
Horizontal beta function [m]	14	100
Vertical beta function [m]	14	100
Equilibrium parameters		
Transverse emittance [mm mrad]	0,42	0,032
Momentum spread, $\Delta P/P$	$2,5\times10^{-4}$	$1,9\times10^{-4}$
Bunch length [cm]	27	22
Transverse cooling/heating rates [sec^{-1}]	0,059	0,012
Longitudinal cooling/heating rate [sec^{-1}]	0,102	0,014
Cooling time [sec]	~100	~1500
Peak luminosity [$cm^{-2}\ sec^{-1}$]	$1,6\times10^{30}$	$1,6\times10^{30}$
Particle losses		
Interaction Point [sec^{-1}]	$6,5\times10^{-8}$	$2,2\times10^{-7}$
Electron Cooler [sec^{-1}]	$6,1\times10^{-6}$	$(1,2\times10^{-7})$*
Rest Gas (10^{-10} Torr) [sec^{-1}]	$6,8\times10^{-8}$	$1,3\times10^{-7}$
Total life time [hours]	~45	~800

)* calculated for protons, absent for antiproton

COOLING PROCESS

The behavior of RMS parameters during cooling process is presented on Fig.1. Left pictures correspond to CSR and right ones to HESR. Initial values are listed in Table 1. After cooling process all parameters achieved constant value and does not change for a long time. Particle loss rates are in a few order less in comparison with cooling time and don't take into account during these simulations.

An unexpected behavior of emittance and respectively of luminosity can be explained with 3D diagram of space phase (Fig.2). These diagrams presented dependence of growth rates on the momentum spread and horizontal emittance. The vertical emittance is assumed to be equal to the horizontal one.

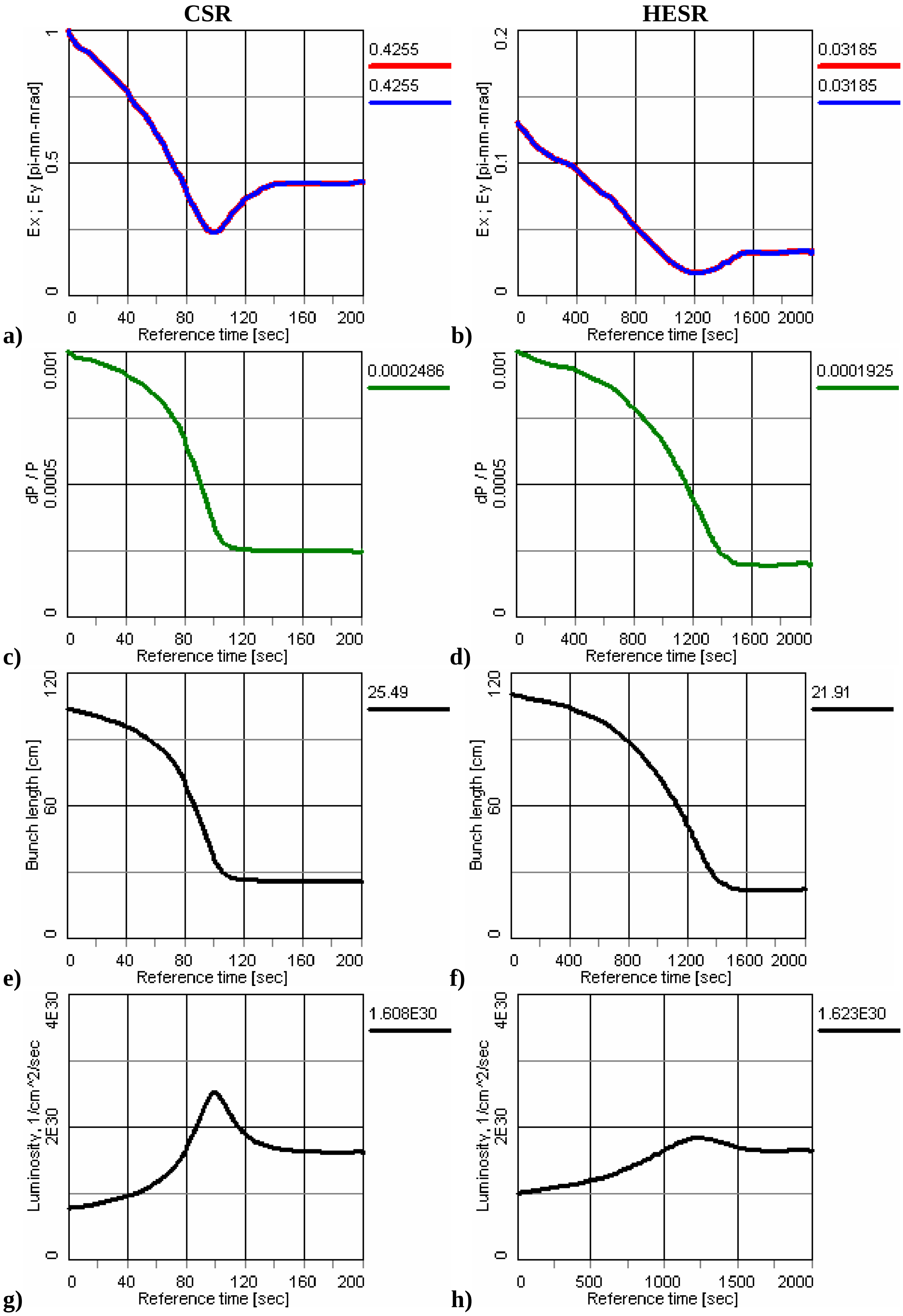

Fig.1. RMS beam dynamics. **a,c,e,g** – CSR, **b,d,f,h** - HESR

IBS growth rates (Fig.2a,b) are calculated in accordance with Martini model. Color areas indicate different values of growth rates. White area for longitudinal component means that in this region of beam parameters the momentum spread is decreased and emittances is increased. The temperature relaxation exists for large momentum spread and small emittance. Beam parameters due to IBS come to the equilibrium temperature between all degree of freedom.

Cooling rates for EC (Fig.2c,d) are calculated in accordance with Parkhomchuk formula of cooling force. This model usually underestimates cooling force in comparison with experimental results on storage rings where electron cooler under operation. Transverse and longitudinal components of cooling rates have approximately the same behavior.

Summary of cooling and heating rates are presented on Fig.2e,f. Boundaries between color and white areas shows the equilibrium between IBS and EC for transverse and longitudinal components. Equilibrium point can be found if one overlaps these pictures each other (Fig.2g). Position of this point does not depend on initial coordinate. For very complicate pictures more then one equilibrium points can be found. In this case the equilibrium parameters can be depend on initial values.

Fig.2h shows the dependence of the transverse emittance on the momentum spread during cooling process for RMS dynamics on Fig.1b,d. Initially the electron cooling force achieves the equilibrium with transverse component of IBS. During this process the emittance and momentum spread are decreased. Then cooling process continues and beam parameters change in accordance with the equilibrium boundary of transverse component. Momentum spread continues to decrease but transverse emittance begins to increase.

When the cooling force also reach the equilibrium with longitudinal component of IBS then beam parameters achieve the equilibrium point, which does not depend on initial parameters. RMS dynamics is rather difference and the cooling time can be change very large. It means that initial parameters of ion beam don’t influence on the equilibrium point but its have a large influence on the cooling time.

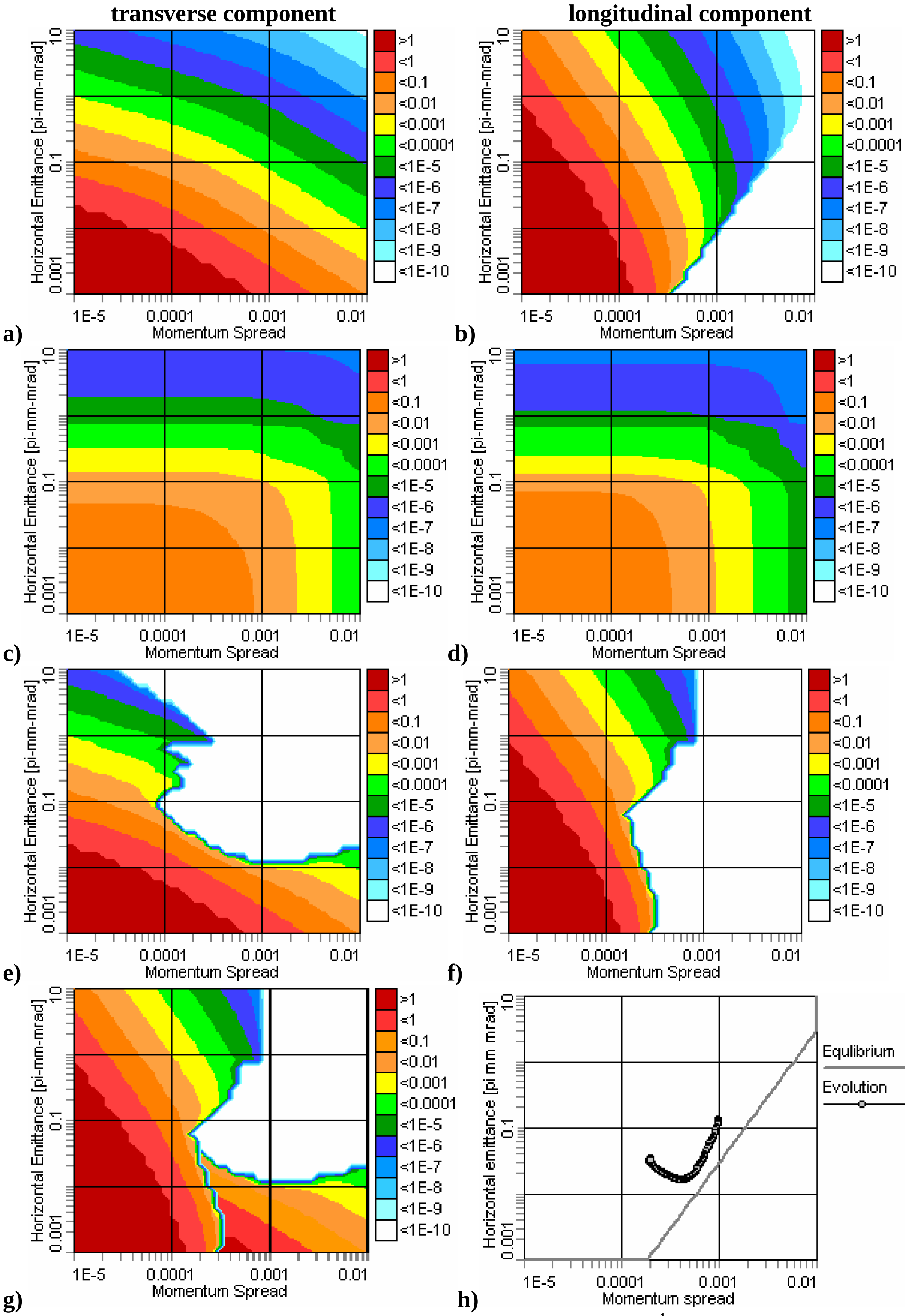

Fig.2. 3D phase space diagram of growth rates [sec^{-1}]. HESR

a, b – transverse and longitudinal components of IBS growth rates, **c, d** – cooling rates of EC, **e, f** – summary of cooling and heating rates, **g**– overlapping pictures **e** and **f**, **h** – RMS dynamics in accordance to Fig.1.

TIME TABLE OF *PAX* EXPERIMENT

Time table of ***PAX*** experiment has the aim to achieve the maximum luminosity in colliding experiments. Some effects are fast enough and don't influence on the integral luminosity: injection, acceleration, bunching, cooling time. The following effects define the time table of experiment:

1) Production rate of antiprotons
2) Polarisation time of antiproton at APR
3) Space charge limit of particles at injection energy
4) Beam lifetime at all storage rings

The proposed production rate of antiproton is estimated on the level 10^7 per seconds ($R = 3{,}6\times10^{10}\ h^{-1}$). The polarisation time at APR is defined by the lifetime of antiproton beam in the interaction with the hydrogen target. To achieve the maximum polarisation level about 40% the ring acceptance angle is $\psi_{acc} = 50$ mrad what is corresponds to beam lifetime $\tau_{APR} = 17$ h. Number of particle which can be injected to APR at each injection cycle is

$$N_{pbar} = 2 \times R \times \tau_{APR} = 1{,}2\times10^{12}$$

This value is a space charge limit for APR at the injection energy. After two lifetimes of the polarisation process the number of antiprotons decreases in one order $N_{pbar} = 10^{11}$.

Next step is an injection of antiprotons to CSR. After acceleration and bunching the antiprotn beam has 10 bunches with 10^{10} particle per bunch. Then antiprotons are injected to HESR. If some antiprotons is circulating at HESR before they should be decelarated to injection energy. After injection of new portion of antiprotons to HESR the acceleration up to experimental energy and cooling process can be started.

In the same time the proton beam with intensity $N_{pbar} = 10^{12}$ is injected to CSR which is also space sharge limit for injection energy. After acceleration and bunching of proton beam the electron cooler switch on.When cool down will be done for both beams the experiment with colliding beams can be started.

Proton lifetime at CSR is mainly defined by electron capture in cooler section (Table 1). But this effect is absent for antiproton at HESR and lifetime is defined by cross section at IP and residual gas pressure. Vacuum pressure at HESR shoud be less then 10^{-10} Torr.

Scheme of time table is presented on Fig.3. Blue line corresponds to antiprotns, red line to protons. After cooling proces (green ares) at CSR and HESR which described above the colliding experiment can be started (black fill areas). Electron coolers stay in operation during experiments in both storage rings CSR and HESR to suppress growth up from intrabeam scattering.

Beam lifetime at CSR is in one order less then in HESR. It means that CSR should be refilled with protons a few times while antiprotons is circulated in HESR. After first injection of antiprtons to HESR the colliding experiment can be started immidiately. But the peak luminosity will be achieved after 3 cycles of injection from APR.

Total cycle of PAX experiment is defined by lifetime of antiprotons at HESR. After each cycle the new portions of antiprotons replace particles which are circulated in ring before. In this scheme the average luminosity have not so large difference from peak luminosity. Between injection cycles APR and antiproton production devices can operate for other tasks during a few days while CSR and HESR operate for colliding experiments.

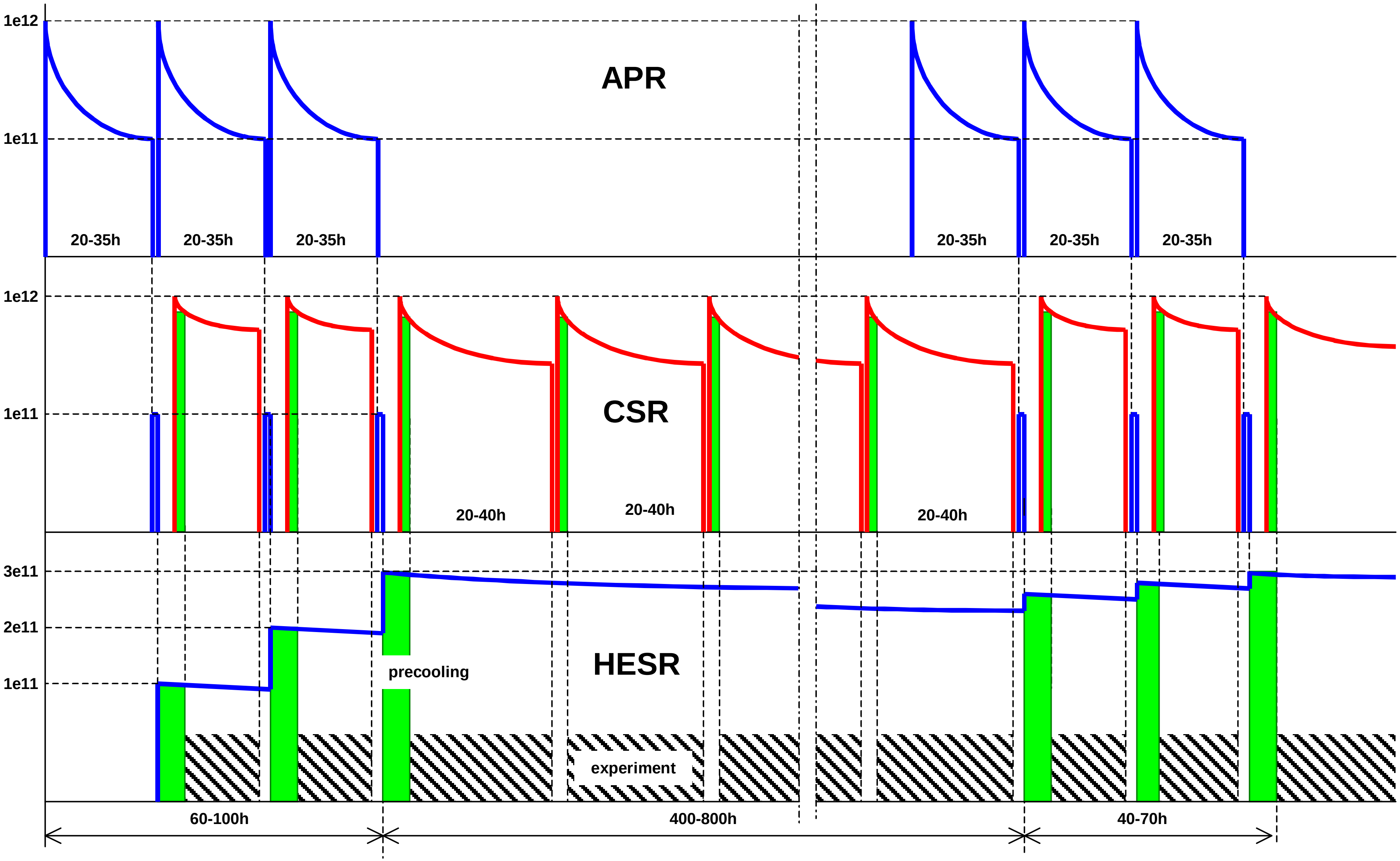

Fig.3. Scheme of time table for ***PAX*** experiment.

To increase the luminosity in a fews times one can proposed some changes of parameters of PAX experiment. One way is increasing of injection energy for CSR to avoid space charge limit and increasing also of particle number. But the lifetime of antiproton beam is linear proportional to the density of the proton beam. The increasing of peak luminosity leads to the decreasing of the antiproton lifetime.

Other way is increasing number of antiprotons what leads to more strong IBS growth rates and more longer cooling time. The time for the filling of HESR with antiprotons is linear proportional to the particle number due to the production rate of antiprotons. In this case the injection cycle will take about one week or may be more time.

Any increasing of particle number makes more stronger the space charge instabilities. The present simulation does not take into account any instabilities due to resonances, space charge effects, etc. The final conclusion for the proposed time table can be done after estimations all these effects.

Summary

The present simulation show that to achieve the nessasary luminosity 10^{30} $cm^{-2}sec^{-1}$ in the colliding mode the strong cooling force should be applied in both ring CSR and HESR. Parameters of proton / antiproton beams are defined by the equilibrium between electron cooling and intrabeam scattering with values of heating growth rates about 0.01-0.1 sec^{-1}. The main particle losses process at CSR is electron capture in cooler section. Particle losses at HESR are defined by the scattering on rest gas and experimental events at interaction point. The influence of space charge effects on the stability of proton / antiproton beams should be done for the final conclusion of this colliding scheme.

Reference

[1] http://lepta.jinr.ru/betacool.htm

[2] V.Parkhomchuk. New insights in the theory of electron cooling. NIM A 441 (2000) 9-17, p.9

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