note

Luminosity for *PAX* project

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Introduction

PAX project has a goal of colliding experiments with polarized antiprotons and protons. The scheme of accelerator devices should be possible to reach the luminosity in the colliding experiment about 10^{31} $cm^{-2}s^{-1}$. There are a few problems should be resolved for the achievement of this goal: injection scheme for antiprotons and protons, cooling process, parameters of interaction point, space charge limits, etc.

The present accelerator scheme for *PAX* project includes APR, CSR and HESR rings (Fig.1). Initially was proposed to use CSR for protons and HESR for antiprotons due to problems with injection of protons form SIS18 and acceleration its at HESR without distortion of antiprotons at CSR. Shatunov et.al proposed a good idea to accelerate together protons at HESR and antiprotons at CSR. The possible injection scheme in this case is discussed below.

One of the main questions is the using of bunched or coasting beams. The acceleration/ deceleration and injection one can realize more easily for the bunched beam which prevent also the additional particle losses. The coasting beam helps to resolve the problems of space charge limit and intrabeam scattering. In general case the using of coasting beams in colliding experiments decreases the luminosity. One of ways to increase the luminosity for coasting beams is the decreasing of beta-functions in the interaction point. The achievement of the maximum luminosity in both cases is discussed in this article.

Injection scheme

Some limitations for the injection scheme

A) Antiprotons from RESR should be decelerated at other ring and then injected to APR.
B) Antiprotons can not be injected directly from APR into HESR due to different range of the rigidity in these rings.
C) Antiproton / proton beams at CSR and HESR can not be accelerated / decelerated independently due to exiting of the common optics element at collision point.
D) Protons from SIS18 should be accelerated at HESR up to the final experimental energy

Possible injection scheme

1) non polarized antiprotons (n-pbar) from RESR are injected into CSR and decelerated down to the injection energy of APR
2) n-pbar are injected into APR and polarization process is started (20-35 hours)
3) when the polarization process at APR is finished then polarized antiprotons (p-pbar) are returned into CSR
4) p-pbar are accelerated at CSR up to intermediate energy 1.2 GeV and injected to HESR when PANDA line is used for circulated antiprotons
5) new portion of n-pbar are injected to CSR from RESR and decelerated down to the injection energy of APR
6) n-pbar at CSR are decelerated down to the injection energy of APR independently of p-pbar at HESR
7) n-pbar from CSR are injected into APR and new polarization process is started
8) p-pbar from HESR are returned into CSR
9) protons from SIS18 are injected into HESR at the intermediate energy 3.5 GeV

10) p-pbar at CSR and protons at HESR are accelerated together up to final energy 3.62 and 15 GeV correspondingly and then the colliding experiment can be started.
11) when the polarization process at APR is finished then p-pbar at CSR are decelerated down to injection energy from APR.
12) new portion of p-pbar from APR is added to p-pbar at CSR and so on since (4)

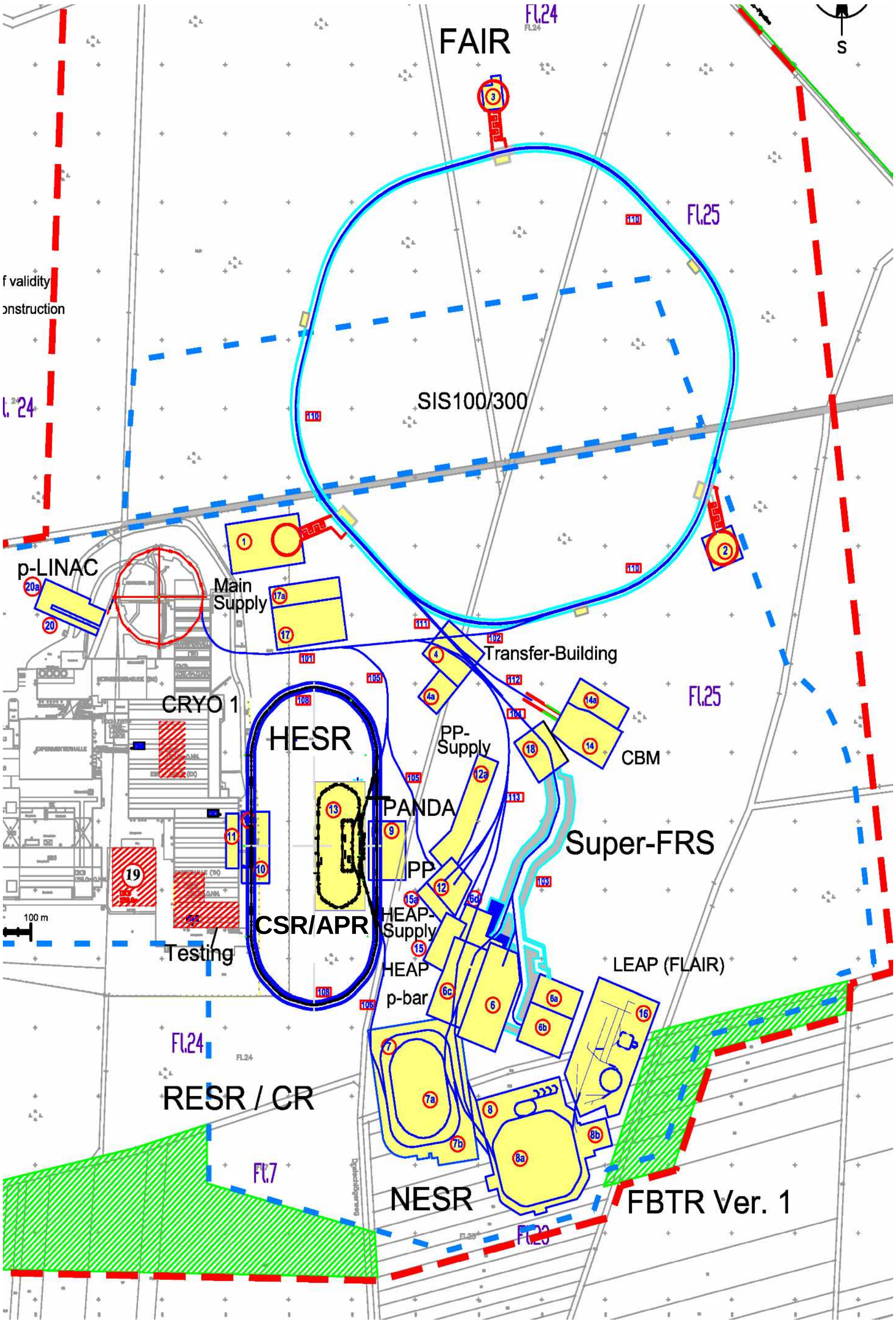

Fig.1. FAIR layout. CSR is placed inside HESR, APR is placed inside CSR.

This scheme can be used as for bunched as for coasting beams. During the colliding experiment antiprotons can circulate as at CSR as at HESR. But from the simple reason seems more better if the antiproton beam which has less intensity than proton one will be circulated at storage ring with smaller circumference and smaller energy.

Injection scheme seems reasonable from the technical point but it has some disadvantages. p-par should be every time dropped from CSR to HESR and back before each injection cycle from

RESR to CSR. It leads to additional particle losses and depolarization. If antiprotons can be directly injected from RESR to APR (limitation A) we can avoid these disadvantages.

If antiprotons can be directly injected from HESR to APR (limitation B) we can inject n-pbar from RESR to HESR, decelerate at HESR and then inject to APR. In this case we need to use PANDA line also to prevent of the distortion of circulated p-pbar at CSR during deceleration of new portion of n-pbar at HESR.

Luminosity at colliding mode

The simulation of equilibrium transverse emittances and momentum spread was done with BETACOOL program. Parameters of simulation are presented in the Table 1. Gray cells indicate the main difference between bunched and coasting mode of colliding beams.

In the case when colliding bunch beams have different parameters the program uses simplest analytical formula for the luminosity calculation:

$$L = \frac{n_b N_1 N_2}{2\pi\sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}T_{rev}}, \quad (1)$$

where N_1, is the particle number per bunch, $\sigma_{x,1}$, $\sigma_{y,1}$ - rms horizontal and vertical bunch sizes in the collision point of the beam, which parameters are simulated. Index 2 is related to the colliding bunch. n_b is the bunch number in simulated beam, T_{rev} – revolution period. This formula corresponds to Gaussian distribution of the ions and does not take into account hour-glass effect. Usually to avoid the hour-glass effect the bunch length is equal or smaller than transverse beta-functions in the colliding point.

In the case of coasting beams the luminosity is also defined by the interaction length d and the ring circumference of the colliding beam C_2:

$$L = \frac{N_1 N_2}{2\pi\sqrt{\left(\sigma_{x1}^2 + \sigma_{x2}^2\right)\left(\sigma_{y1}^2 + \sigma_{y2}^2\right)}T_{rev}} \cdot \frac{d}{C_2} \quad (2)$$

where N_1 and N_2 are total particle number in the colliding beams. The intrabeam scattering in the case of the coasting beam is much smaller and electron cooling devices can decrease the transverse emittances in comparison with bunched beams.

Space charge limits

Space charge of the colliding beams changes the betatron frequency at electron cooling and leads to the crossing of structure resonances. As usual the tune shift can not exceed value about 0.1. Space charge from the colliding beam is defined as beam-beam parameter which is for bunched beam:

$$\xi_{x,y} = \frac{N_2 Z_1 Z_2 r_p}{4\pi A_1} \frac{(1+\beta_1\beta_2)}{\gamma_1\beta_1} \cdot \frac{\beta^*_{x2,y2}}{\sigma_{x2,y2}(\sigma_{x2,y2} + \sigma_{y2,x2})}, \quad (3)$$

where N_2 – particle number per bunch, β^* – beta function at colliding point, Z and A– particle charge and mass, r_p – proton radius, γ and β - relativistic factors, σ – rms beam size at colliding point, index 1 corresponds to the simulated beam, index 2 – colliding beam, indexes x and y correspond to horizontal and vertical components. For coasting beam:

$$\xi_{x,y} = \frac{N_2 Z_1 Z_2 r_p}{4\pi A_1} \frac{(1+\beta_1\beta_2)}{\gamma_1\beta_1} \cdot \frac{\beta^*_{x2,y2}}{\sigma_{x2,y2}(\sigma_{x2,y2} + \sigma_{y2,x2})} \cdot \frac{d}{C_2}, \quad (4)$$

where N_2 – total particle in the colliding beam, d - interaction length, C_2 - ring circumference of the colliding beam.

Tune shift due to space charge of the simulated beam is

$$\Delta Q_{x,y} = \frac{Z^2 r_p N}{2\pi A \beta^2 \gamma^3 \varepsilon_{x,y} \left(1 + \sqrt{\frac{\varepsilon_{y,x}}{\varepsilon_{x,y}}}\right) B_f}, \quad (5)$$

where $\varepsilon_{x,y}$ – horizontal and vertical emittances, $B_f = L_b / L_s$ – bunching factor ($B_f = 1$ for coasting beam), L_b – bunch length, L_s – longitudinal separatrix length.

Table 1. Parameters of colliding mode

Initial parameters	**bunched**		**coasting**	
	CSR	**HESR**	**CSR**	**HESR**
Particles	antiproton	proton	antiproton	proton
Circumference [m]	183	574	183	574
Momentum [GeV/c]	3,65	15	3,65	15
Relativistic factor, γ	4,04	16,1	4,04	16,1
RF Harmonic number	10	100	---	---
RF Voltage [kV]	200	200	---	---
Length of interaction point [cm]	---	---	50	50
Number of bunches	10	30	---	---
Total number of particles	5×10^{11}	$2{,}4\times10^{12}$	5×10^{11}	1×10^{13}
Beta function at IP [m]	0,3	1	0,1	0,1
Cross section at IP [mbarn]	40	40	40	40
Transverse emittance [mm mrad]	1	0,13	1	0,13
Momentum spread, $\Delta P/P$	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Electron cooler				
Cooler length [m]	10	30	10	30
Magnetic field [kG]	2	5	2	5
Beam radius [cm]	0,5	0,5	0,5	0,5
Beam current [A]	1	1	1	1
Horizontal beta function [m]	14	100	14	100
Vertical beta function [m]	14	100	14	100
Cooling time [sec]	~300	~1000	~250	~1500
Particle losses				
Interaction Point [sec^{-1}]	$8{,}5\times10^{-8}$	$7{,}2\times10^{-8}$	$8{,}8\times10^{-8}$	$4{,}5\times10^{-8}$
Electron Cooler [sec^{-1}]	---	2×10^{-7}	---	$1{,}2\times10^{-7}$
Rest Gas (10^{-10} Torr) [sec^{-1}]	$8{,}4\times10^{-8}$	$7{,}2\times10^{-7}$	$8{,}5\times10^{-8}$	$7{,}2\times10^{-7}$
Total life time [hours]	~1500	~300	~1500	~300
Equilibrium parameters				
Transverse emittance [mm mrad]	0,5	0,08	0,05	0,05
Momentum spread, $\Delta P/P$	$2{,}7\times10^{-4}$	3×10^{-4}	1×10^{-4}	2×10^{-4}
Bunch length [cm]	28	31	---	---
Beam-beam parameter, ξ	0,01	0,0025	0,006	2×10^{-4}
Tune shift, ΔQ	0,05	0,02	0,02	0,006
Peak luminosity [cm^{-2} sec^{-1}]	**5×10^{30}**		**$1{,}2\times10^{31}$**	

Conclusion

The achievement of the necessary luminosity on the level of 10^{31} $cm^{-2}s^{-1}$ can be limited by space charge effects and the cooling force of the electron cooling device. The increasing of the antiproton number at CSR needs longer time for the injection cycles from APR to CSR (one cycle of the polarization process during 20 – 35 hours produces about 10^{11} antiprotons) and needs stronger cooling force to avoid hour-glass effect at interaction point. The increasing of the proton number at HESR is limited by space charge effects and cooling force also.

The using of coasting beams resolves the problems with the space charge and the strength of the cooling force. The main question is the small beta-functions at the interaction points. A special design of HESR lattice structure should be done for *PAX* project.