# Antiproton — Ion Collider for FAIR Project

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# Antiproton – Ion Collider for FAIR Project

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**Abstract.** An antiproton-ion collider (AIC), with extensive using of electron cooling, is proposed to determine rms radii for protons and neutrons in unstable and short lived nuclei by means of antiproton absorption at medium energies. The experiment makes use of the electron-ion collider complex with appropriate modifications of the electron ring to store, cool and collide antiprotons of 30 MeV energy with 740 MeV/unit ions in the NESR. Antiprotons are collected, cooled, decelerated up to 30 MeV and transferred to the electron storage ring. The radioactive nuclei beams are transferred to the CR and cooled at 740A MeV and transported via the RESR to NESR, in which especially short lived nuclei are accumulated continuously to increase the luminosity. Luminosities of about $10^{23}$ cm$^{-2}$s$^{-1}$ may be reached with $10^6$ ions accumulated in the NESR in coasting mode of operation, used for Schottky spectroscopy of the fragments.

**Keywords:** FAIR, Electron cooling, Luminosity.

## INTRODUCTION

An antiproton-ion collider [1] is proposed to independently determine rms radii for protons and neutrons instable and short lived nuclei by means of antiproton absorption at medium energies [2]. The experiment makes use of the electron ion collider complex [3] with appropriate modifications of the electron ring to store, cool and collide antiprotons of 30 MeV energy with 740A MeV ions in the NESR (Fig.1). Antiprotons are collected, cooled and slowed to 30 MeV. Hereafter the antiprotons are transferred to the electron storage ring using a new transfer line. Radioactive nuclei are produced by projectile fragmentation and projectile fission of 1.5A GeV primary beams and separated in the Super FRS. The separated beams are transferred to the collector ring (CR) and cooled at 740A MeV and transported via the RESR to NESR, in which especially short lived nuclei are accumulated continuously to increase the luminosity. In Tabs. 1, 2 the parameters of NESR and antiproton ring are presented.

**TABLE 1.** Main Parameters of NESR.

| Parameter | Units | Value |
|---|---|---|
| Circumference | m | 222.11 |
| Reference nucleus | | $^{132}Sn^{50}$ |
| Maximum energy for reference nucleus | MeV/ unit | 740 |
| Momentum acceptance | | ±1.75% |
| Acceptance (hor/vert) | π mm mrad | 160/100 |
| Betatron tune (hor/vert) | | 3.4/3.2 |

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**TABLE 2.** Main Parameters of Antiproton Storage Ring.

| Parameter | Units | Value |
|---|---|---|
| Circumference | m | 45.215 |
| Energy | MeV | 20 – 125 |
| Revolution frequency | MHz | 0.68 – 3.1 |
| Betatron tunes (hor/vert) | | 3.8/2.8 |

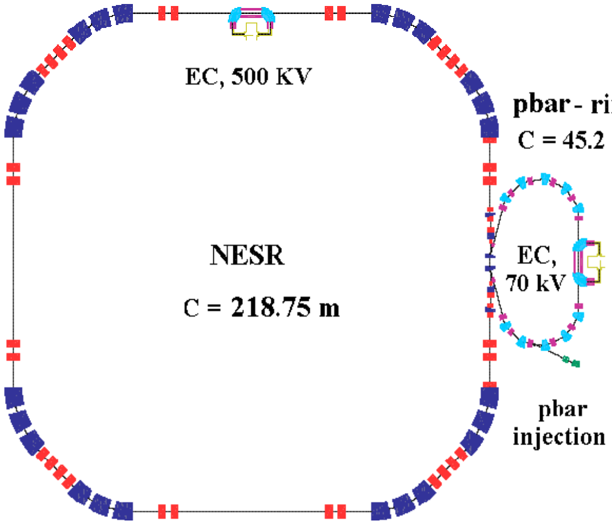


**FIGURE 1.** Schematic layout of the antiproton – ion collider.

## ELECTRON COOLING

Here, we estimate the electron cooling force using the following phenomenological expression which has been proposed in Ref. [4]

$$\Delta\vec{p} = \vec{F}\cdot\tau = -\frac{4e^4 n_e \vec{V}\tau}{m_e(\sqrt{V^2+V_{eff}^2})^3}\ln\left(1+\frac{\rho_{\max}}{\rho_L+\rho_{\min}}\right). \qquad (1)$$

For simulation of the time behavior of the normalized emittances $\varepsilon_{nx}, \varepsilon_{ny}$ and the momentum spread $\sigma p$ (1σ-values) we used the following equation system

$$\begin{aligned}
\frac{\partial\varepsilon_{nx}}{\partial t} &= \lambda_{IBS}^{x}(\varepsilon_{nx},\varepsilon_{ny},\sigma p)+\lambda_{heat}^{x}(\varepsilon_{nx},\varepsilon_{ny},\sigma p)-\lambda_{cool}^{x}(\varepsilon_{nx},\varepsilon_{ny},\sigma p),\\
\frac{\partial\varepsilon_{ny}}{\partial t} &= \lambda_{IBS}^{y}(\varepsilon_{nx},\varepsilon_{ny},\sigma p)+\lambda_{heat}^{y}(\varepsilon_{nx},\varepsilon_{ny},\sigma p)-\lambda_{cool}^{y}(\varepsilon_{nx},\varepsilon_{ny},\sigma p), \qquad (2)\\
\frac{\partial\sigma p}{\partial t} &= \lambda_{IBS}^{\sigma p}(\varepsilon_{nx},\varepsilon_{ny},\sigma p)+\lambda_{heat}^{\sigma p}(\varepsilon_{nx},\varepsilon_{ny},\sigma p)-\lambda_{cool}^{\sigma p}(\varepsilon_{nx},\varepsilon_{ny},\sigma p).
\end{aligned}$$

In our calculation we consider the cooling drag force $\lambda_{cool}$, the heating induced by the thermal motion of the electron $\lambda_{heat}$, the IBS process $\lambda_{IBS}$. The increments and decrements of the rms values of $\varepsilon_{nx}$, $\varepsilon_{ny}$, $\sigma p$ were calculated for a single turn. If the tune-shift becomes more than 0.1 then the cooling force is supposed to be zero. So, the space charge phenomena are simulated.

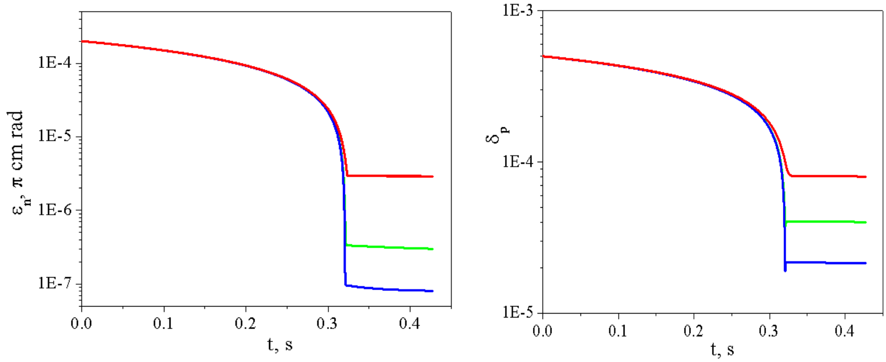


**FIGURE 2.** Time evolution of normalized transverse emittance (left) and momentum spread (right), for different antiproton beam intensity, from top to bottom $N_i = 10^{10}$, $10^9$, $10^8$ accordingly, $E_{\bar{p}}$ = 30 MeV.

In Fig. 2 the evolution of normalized transverse emittance and longitudinal momentum spread of antiproton beam are presented. The simulation was made for follow parameters: the beta-function in cooling section is 4.5/6.5 m (h/v), the antiproton energy is $E_{\bar{p}}$=30 MeV, the electron current is $I_e$=1 A. The initial antiproton beam normalized transverse emittance is 2 π mm mrad, momentum spread is $\pm 5\cdot 10^{-4}$. As it is seen, the ion beam emittance and momentum spread are effectively decreased during 330 ms. The further cooling is limited due to achieving of the beam tune shift value $\Delta\nu = 0.1$, if beam intensity more than $10^9$. At lower beam intensity the further cooling limited by IBS.

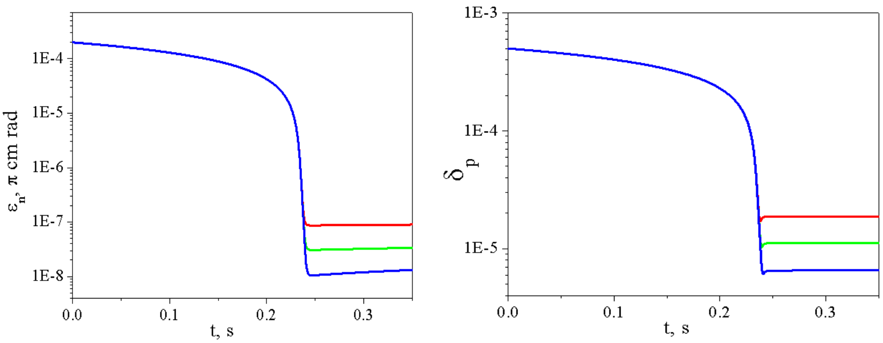


**FIGURE 3.** Time evolution of normalized transverse emittance (left) and momentum spread (right), for different ion beam intensity, from top to bottom $N_i = 10^7$, $10^6$, $10^5$ accordingly, $E_i$ = 740 MeV/u.

In Fig. 3 the evolution of normalized transverse emittance and longitudinal momentum spread of ion beam in the NESR are presented. The simulation was made for follow parameters: the beta-function in cooling section is 30 m, the $^{132}Sn^{50}$ ion energy is $E_i$ = 740 MeV/u, the electron current is $I_e$ = 1 A. The initial ion beam transverse emittance is 1.4 mm mrad, momentum spread is $\pm 5 \cdot 10^{-4}$. As it is seen, the ion beam emittance and momentum spread are effectively decreased during 250 ms. The further cooling is limited due to IBS.

The Fig. 4 shows the tune shift as function of time for different number of ions (left) and antiprotons (right). Simulations shows that the Laslett tune shift of ion beam is a far from threshold value. On the contrary, the transverse emittance of pbar beam is limited by space charge phenomena.

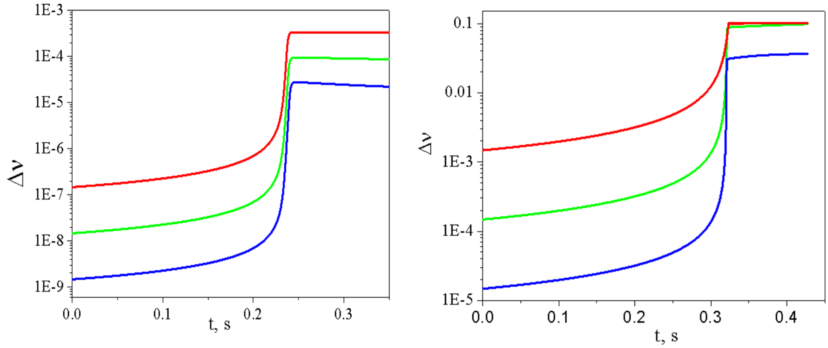


**FIGURE 4.** Time evolution of the tune – shift value for $^{132}Sn^{50}$ ion with energy $E_i$ = 740 MeV/u (left), from top to bottom $N_i$ = $10^7$, $10^6$, $10^5$, and for antiprotons with energy 30 MeV (right), from top to bottom $N_i$ = $10^{10}$, $10^9$, $10^8$ accordingly.

The motion of a particle passing the IP is perturbed by the fields of the counter – moving beam. Such perturbations result in resonant phenomena. Their strengths and relevant increases in the particle oscillations amplitude depend on the values of the particle oscillation tunes. It may result in the instability of both coherent and incoherent oscillations of colliding beams, limiting the value of the collider luminosity. For the case of pbar-RI collider, the beam-beam parameters for pbar and ion beams of the round cross-sections read

$$\xi_{\bar{p}} = Z_i \frac{N_i r_p L_{IP}\left(1+\beta_i \beta_{\bar{p}}\right)}{4\pi \Pi_i \gamma_{\bar{p}} \beta_{\bar{p}}^2 \varepsilon_i}, \quad \xi_i = \frac{Z_i}{A_i} \frac{N_{\bar{p}} r_p L_{IP}\left(1+\beta_i \beta_{\bar{p}}\right)}{4\pi \Pi_{\bar{p}} \gamma_i \beta_i^2 \varepsilon_{\bar{p}}}. \quad (3)$$

Beam-beam parameters are $\xi_{\bar{p}} = 4.3 \cdot 10^{-3}$, $\xi_i = 2.3 \cdot 10^{-4}$ for the follow parameters: $E_i$=740 MeV/u, $E_{\bar{p}} = 30$ MeV, $N_i$=$10^6$, $N_{\bar{p}} = 10^9$, $\varepsilon_i$=$2 \cdot 10^{-8}$ cm·rad, $\varepsilon_{\bar{p}}$ = $1.8 \cdot 10^{-6}$ cm·rad. So, clear those values of beam-beam parameters are safe.

The design of electron cooler device for NESR is presented in details in Ref.[5]. The design of electron cooler device for antiproton storage ring is based on electron cooler manufactured by BINP for LEIR storage ring [6]. List of main parameters is presented in Tab.3.

**TABLE 3.** Parameters of EC for Antiproton Storage Ring.

| Parameter | Units | Value |
|---|---|---|
| Maximum electron energy | keV | 70 |
| Maximum electron current | A | 2 |
| Electron beam diameter | mm | 5 – 20 |
| Magnet field in cooling section | T | 0.2 |
| Length of cooling section | m | 3.5 |

# LUMINOSITY

The luminosity for head-on collisions of two coasting beams, with interaction length $L_{IP}$, is given by

$$L_0 = \frac{n_i n_{\bar{p}}}{\pi} c\left(\beta_i + \beta_{\bar{p}}\right) \int_0^{\frac{L_{IP}}{2}} \frac{ds}{\sqrt{\sigma_{xi}^2(s) + \sigma_{x\bar{p}}^2(s)}\sqrt{\sigma_{yi}^2(s) + \sigma_{y\bar{p}}^2(s)}}, \qquad (4)$$

where suffixes $i$ and $\bar{p}$ mark the values related to ion and antiproton beams, $A$ is the atomic number of the ion, $n_i$ and $n_{\bar{p}}$ are the line density of particles, $c\beta_i$ and $c\beta_{\bar{p}}$ are the velocity of particles, $\sigma^2(s) = \varepsilon\beta_0\left(1 + \frac{s^2}{\beta_0^2}\right)$ is the beam size.

For modeling parameters: $E_i$=740 MeV/u, $E_{\bar{p}} = 30$ MeV, $N_i$=$10^6$, $N_{\bar{p}} = 10^9$, $\varepsilon_i$=$2\cdot10^{-8}$ cm·rad, $\varepsilon_{\bar{p}}$= $1.8\cdot10^{-6}$ cm·rad, $\beta_{\bar{p}} = 30\,cm, \beta_i = 40/25\,cm$ the estimated luminosity value is $L_0 = 9.5\cdot10^{22}\,cm^{-2}s^{-1}$. In Fig. 5 the luminosity dependence on antiproton beam energy is shown.

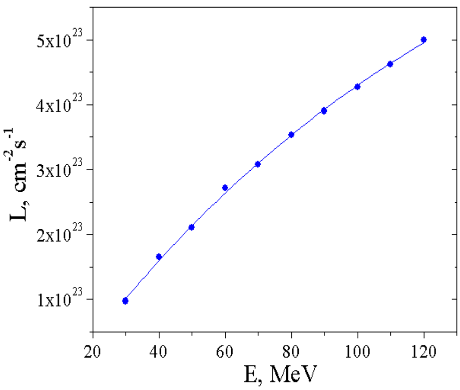


**FIGURE 5.** Luminosity versus antiproton beam energy.

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