ION STORAGE RING AT LOW ENERGY WITH HIGH INTENSITY AND ELECTRON COOLING

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Abstract

The report deals with a new conception of the storage ring for low energy with electron beam and internal target. The using of the electron cooling in the storage ring with the strong longitudinal field looks promising in order to obtain the luminosity value 10^{33} – 10^{34} $\text{cm}^{-2}\text{s}^{-1}$ that may be used in the physics nucleus experiments.

INTRODUCTION

The first problem in the storage of low energy ion beam is the space charge. Especially it is important at the electron cooling, when the minimal emittance value (or angular spread) is realized. The second problem is injection and extraction of the ion beam with low energy to the strong longitudinal magnetic field. It requires the special analyse of the ring optics. These problems were observed in the experiment on NAP-M device [1].

In order to avoid this problem the storage ring with the longitudinal magnetic field is proposed. This magnetic structure resembles the stellarator type device [2]. The transverse magnetic field in the bending magnets forms the proton orbit but the longitudinal field focuses the beam. The longitudinal magnetic field is larger than the transverse bending field. So, the motion of proton separates into two types formally. Because of the longitudinal field the proton has a fast Larmor oscillation. Moreover the proton beam has a slow drift rotation in the azimuthal direction in the bending magnets. At an electron cooling the size of proton Larmor circle decreases to minimal possible value. But even at strong cooling the transversal cross-section of proton beam remains circular or elliptical with a large size. The proton beam will look as if it consists of many small-size beams each but with big size of the whole beam. Actually, the proton beam at the same density may contain about 1000 beams.

The motion in dipole magnet can be used for separation of the proton and electron beams. The presence of the transversal field in dipole leads to the shift of magnetic force line from the magnetic axis. The proton beam will move in the orbit plane since the transversal (dipole) field will be compensated by centrifugal force but electrons being 1836 times lighter will go along the force line. In this variant there is no optic problem with extraction and injection of an ion beam to a cooling section. The ions are immersed to the longitudinal beam along its entire trajectory.

The target effects (ionization loss, fluctuation of ionization loss and small angle spreading) may be compensated with help of electron cooling process. In this case the good quality and the large life-time of the ion beam is been able to obtain. The estimation shows that the power of the cooling is enough for compensation all effects. The luminosity 10^{33} – 10^{34} $\text{cm}^{-2}\text{s}^{-1}$ may be discussed.

The strong longitudinal magnetic force enables to better control the compensation regime in the cooling section. It is required condition because the space charge at low energy is very high. The small value of the residual electric field of the space charge strong decreases the cooling force.

The injection can be carried out with neutral atoms. The negative ions from the ion source is accelerated in the cyclotron or low power DC electrostatic accelerator, is stripped to atomic state on the intermediate target and is stripped to ion on the main target in the storage ring.

ELECTRON COOLING AND TARGET PROCESSES

The electron cooling enables to solve the problem with degradation of the proton beam quality induced by the interaction with target. Figures 1 and 2 show the result of the Monte-Carlo simulation of the combined processes in the target and electron cooler. The initial proton beam is cooled down. The electron energy is 1 keV, the electron current is 1.5 A, the radius of electron beam is 0.4 cm. Figures 3 and 4 show the interaction of the proton beam with the target without cooling process. It is shown that the cooler enable practically “quasy-stationary” process without essential degradation of the beam quality. The absence of the cooler leads to the fast degradation of the proton beam at the small target density yet.

If the electron cooling may effective suppress the target effect then the luminosity of such device can be made

$$L = \frac{I_p}{q} n_t = 1.6 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$$

at the target density $n_a = 5 \cdot 10^{15}\ \text{cm}^{-2}$ and the proton current $I_p = 0.5\,\text{A}$. Certainly, this optimistic estimation of the ultimate luminosity requires demands the detailed R&D programs and the investigation of prototypes of many elements.

The space charge effect is very strong at the low energy for electron cooling process too. The potential sagging is

$$\Delta\varphi = \frac{30 \cdot I}{\beta} = 100\ \text{V}$$

at the electron current 0.2 A and the electron energy 1 keV that is unfit for the cooling process. So the neutralization needs for the elimination of space charge effects in the electron beam. The secondary ions decrease not only the effect of space charge field on the electron motion but also allow getting electron beams with higher intensity.

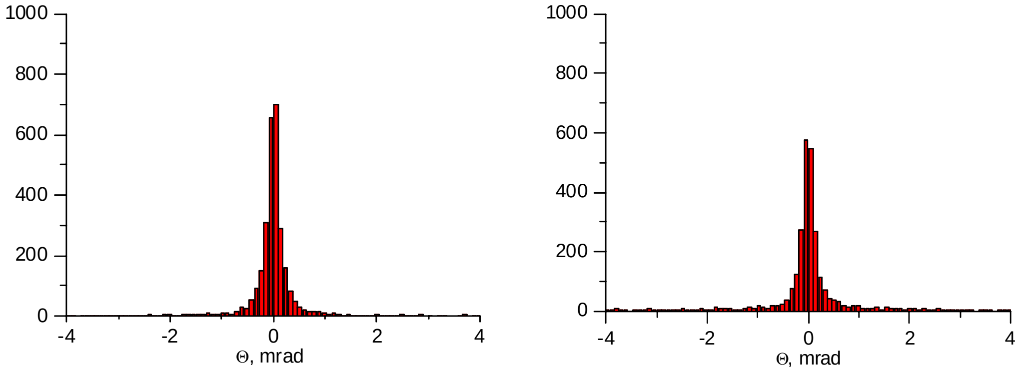

Figure 1: Angle spread of the proton beam under the cooling and target processes. Target thickness is $4.0{\cdot}10^{15}$ cm^{-2}. The left picture corresponds time Δt=147 μs and right picture corresponds time Δt=750 μs.

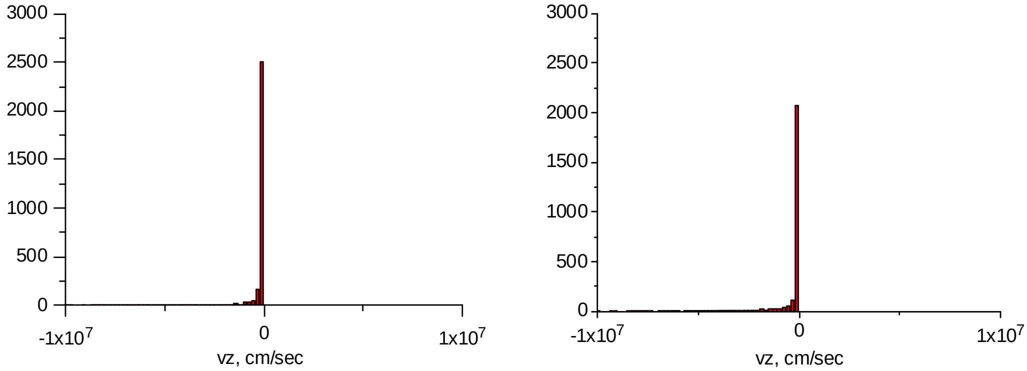

Figure 2: Longitudinal proton velocity (in beam reference system) evolution after target switch on. Target thickness is $4.0{\cdot}10^{15}$ cm^{-2}. The left picture corresponds time Δt=147 μs and right picture corresponds time Δt=750 μs.

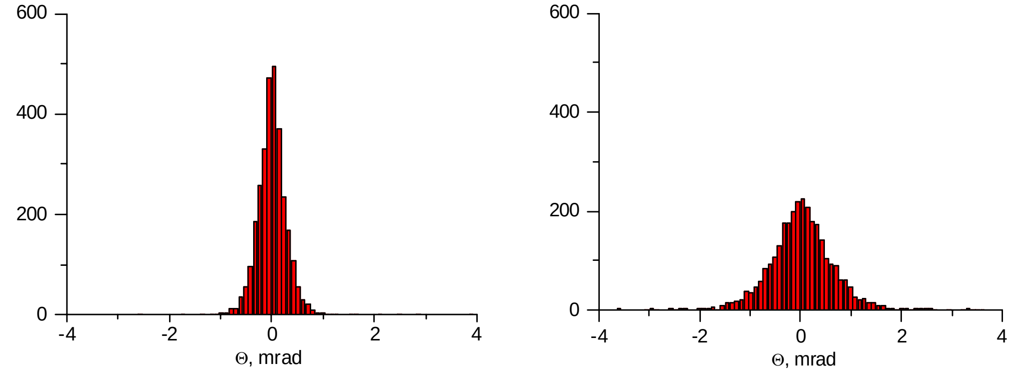

Figure 3: Angle spread of the proton beam under the target process only. Target thickness is $1.0{\cdot}10^{15}$ cm^{-2}. The initial proton beam is cooled down. The left picture corresponds time Δt=73 μs and right picture corresponds time Δt=370 μs.

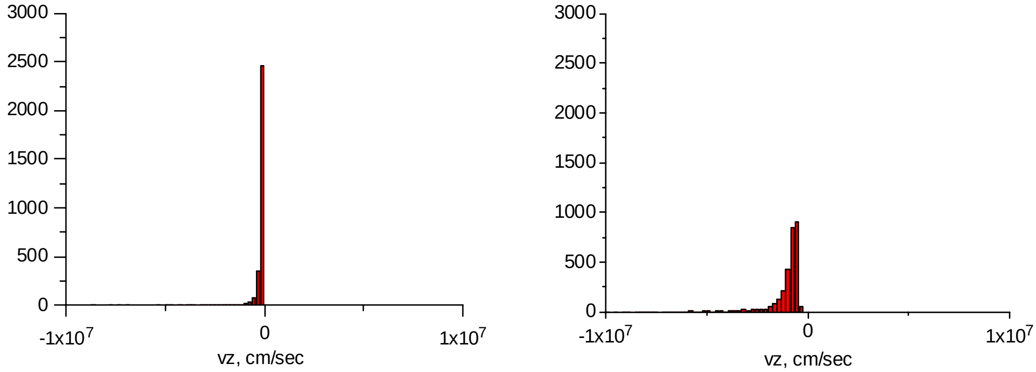

Figure 4: Longitudinal proton velocity (in beam reference system) evolution without electron cooling after target switch on. Target thickness is $1.0{\cdot}10^{15}$ cm^{-2}. The left picture corresponds time Δt=73 μs and right picture corresponds time Δt=370 μs.

Figure 5 shows the comparison of the cooling rate at the different levels of the neutralization parameter. If the non-neutralized electric field is even 0.2% from maximum value then there are significant problems in obtaining of the maximal parameters.

One of the limitations on getting stable compensated state is the appearance and progress of different beam-driven instabilities. The rough criterion of compensated state stability is a small value of oscillation phase advance of the electron drift motion during time of flight through the cooling region [3-5]

$$\omega_d \frac{l_{cool}}{\beta c} < 1 .$$

It gives the limit of maximal possible density of electron beam

$$n_e < \frac{B\beta}{2\pi e\, l_{cool}} \approx 4\times10^9\,\mathrm{cm}^{-3} .$$

Although this condition is not absolute its realization leads to short length of the electron beam and a large value of the magnetic field.

STORAGE RING STRUCTURE

Figure 5 shows the structure of the storage ring with the longitudinal magnetic field. The negative ions produced by the cyclotron or DC-accelerator are stripped to neutral state on the first target. These neutral atoms are injected to the strong magnetic field along the injection line (1). The target (3) serves for charge exchange from neutral atoms to ions. The protons move anticlockwise. The non stripped atoms go out the storage ring along line (2). The electron beam is produced in the electron gun located in the bending section (4). The electrons and protons move together in the cooling sections (5). So, there are three sections for the cooling process. The electron beam is absorbed to the collector located in another bending (6).

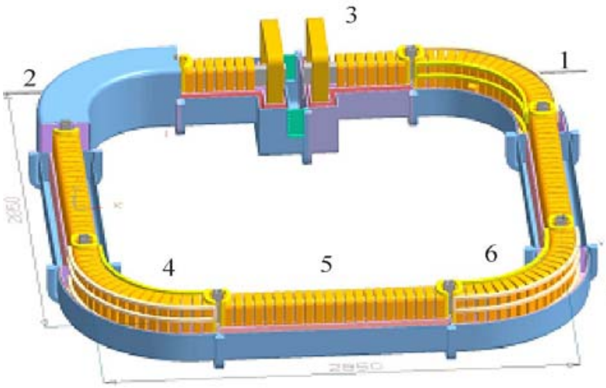

Figure 5: Sketch of the storage ring.

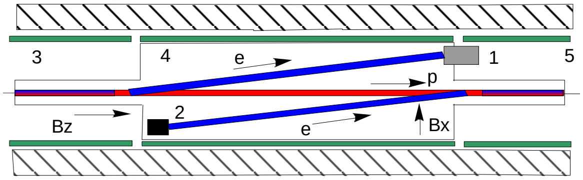

Figure 6: Separation scheme of the electron and proton beams in the dipole magnet. The electron gun is 2, the electron collector is 1, the bending section is 4, the straight sections are 3 and 5.

The motion in dipole magnet is used for separation of the proton and electron beams. The example of such a separation scheme is given in Figure 6. The transversal magnetic field in dipole shifts the magnetic force line from the magnetic axis.

The field index n=0.5 formed the closed orbit for the drift trajectory of the ion beam [6].

CONCLUSION

The supposed method looks promising in order to obtain the luminosity value $10^{33} - 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the nucleus experiments at low energy. Certainly, this optimistic estimation of the ultimate luminosity requires demands the detailed R&D programs and the investigation of prototypes of many elements.

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