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Superconducting racetrack booster for the ion complex of MEIC

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Abstract. The current design of the Medium-energy Electron-Ion Collider (MEIC) project at Jefferson lab features a single 8 GeV/c figure-8 booster based on super-ferric magnets. Reducing the circumference of the booster by switching to a racetrack design may improve its performance by limiting the space charge effect and lower its cost. We consider problems of preserving proton and deuteron polarizations in a superconducting racetrack booster. We show that using magnets based on hollow high-current NbTi composite superconducting cable similar to those designed at JINR for the Nuclotron guarantees preservation of the ion polarization in a racetrack booster up to 8 GeV/c. The booster operation cycle would be a few seconds that would improve the operating efficiency of the MEIC ion complex.

1. Introduction

A figure-8 booster in the ion complex of MEIC completely solves the problem of polarization preservation during acceleration of any ion species including protons and deuterons [1]. A racetrack booster has a smaller circumference, which may reduce its cost and relax the limitation related to space charge. For the same length of the booster straights, reduction of the field integral of the arc magnets equals about 70 T \cdot m at the ion momentum of 8 GeV/c, i.e., when using magnet with a maximum field of 3 T, the total arc length is reduced by 23 m, which is about 12% of the total booster circumference. Let us consider the question of preservation of the proton and deuteron polarizations in a racetrack booster.

2. Spin resonances in a racetrack booster

As an example, let us choose a racetrack design most similar to the existing figure-8 booster design, i.e. keep the optical beam characteristics in the straight and in one FODO cell period of the booster arc. Superperiodicity of the booster lattice is N=2 and the radial and vertical betatron tunes equal $\nu_x = 5.95$ and $\nu_y = 4.84$, respectively.

In a racetrack booster, the stable polarization points along the vertical axis and the spin tune is proportional to the beam energy $\nu = \gamma G$ (G is the anomalous magnetic moment) that unavoidably leads to crossing of spin resonances during acceleration and, as a consequence, to resonant depolarization of the beam. Table 1 gives the numbers of linear resonances along with conditions for their occurrence in the booster.

| | Number of resonances | | | | |
|-----------|----------------------|----------------------|----------------------|---------------------------------|--|
| Particles | integer | intrinsic | coupling | non-super-periodic | |
| | $\nu = k$ | $\nu = kN \pm \nu_y$ | $\nu = kN \pm \nu_x$ | $\nu = k \pm \nu_y (k \neq mN)$ | |
| protons | 16 | 16 | 32 | 16 | |
| deuterons | 0 | 0 | 0 | 1 | |

| Table 1. Number | of linear reson | nances in a rad | cetrack booster. |
|-----------------|-----------------|-----------------|------------------|
|-----------------|-----------------|-----------------|------------------|

Our calculations show that proton resonance strengths lie within the ranges of $10^{-4} \div 10^{-3}$ for integer resonances, $10^{-4} \div 10^{-3}$ for intrinsic resonances, and $10^{-7} \div 10^{-5}$ for coupling and non-super-periodic resonances. The strength of a single deuteron resonance is $w \sim 10^{-5}$. The calculations assumed that normalized emittances of the betatron motion are 5π mm mrad.

3. Crossing of spin resonances

Polarization after crossing of a resonance with a strength w is determined by the rate of crossing ε' . A fast crossing $\varepsilon' \gg w^2$ keeps the spin aligned with the field. A slow resonance crossing $\varepsilon' \ll w^2$ flips the spin direction along the field. In an intermediate situation $\varepsilon' \sim w^2$, the spin orientation significantly deviates from the field direction. In the considered example, the crossing rate can be expressed through the field ramp rate dB/dt as:

$$\varepsilon' \approx 4.5 \times 10^{-7} \frac{dB[T]}{dt[s]}$$
 for protons, $\varepsilon' \approx 1.8 \times 10^{-8} \frac{dB[T]}{dt[s]}$ for deuterons.

There are various techniques for crossing of spin resonances: resonance strength compensation, intentional enhancement of the spin resonance strength using specially introduced magnetic fields (a partial Siberian snake), betatron tune jump, spin tune jump [2, 3, 4, 5]. It is worth noting that the aforementioned techniques allow one only to reduce the depolarization for each resonance crossing. Thus, crossing of a large number of dangerous resonances may eventually lead to a significant polarization loss. References [6, 7] proposed and experimentally tested a transparent crossing technique, which, in principle, allows one to eliminate polarization loss during a crossing. The limiting factors for the transparent and fast resonance crossings are effects of the spin and betatron tune spreads in the beam. For slow resonance crossings, preservation of the polarization is a complex task that requires consideration of the synchrotron energy oscillations of the beam particles and higher-order resonances.

4. Acceleration of polarized protons in a racetrack booster

Polarized protons are successfully accelerated up to about 25 GeV in the AGS. The AGS uses warm magnets with a sufficiently high field ramp rate that provides fast crossing of essentially all resonances. To preserve the polarization, the AGS uses a weak partial snake for integer resonances and betatron tune jumps for intrinsic resonances. Polarization losses at the end of the acceleration cycle in the AGS also depend on the beam emittances and constitute 10-30%. A racetrack booster can be built with warm magnets using the AGS experience.

Application of superconducting magnets opens new opportunities when working with polarized beams. Due to a lower field ramp rate in superconducting magnets (dipoles, quadrupoles), one cannot apply the techniques used at the AGS. However, in a superconducting racetrack booster, it is possible to use a solenoidal snake, which completely eliminates resonant beam depolarization.

To preserve proton polarization up to 8 GeV/c, the required maximum longitudinal field integral of the snake is 30 T·m. Placement of the snake solenoids in a straight of the booster is shown in figure 1. For the snake length of 2×4.6 m, the maximum solenoid field is 3.3 T.



Figure 1. Placement of the snake in a booster's straight. SOL are solenoids, VB are arc dipoles.

The solenoids mainly introduce coupling of the betatron oscillations and shift the betatron tunes. For example, when matching the snake solenoids to the optics of the straight, it is sufficient to correct only the betatron tune shifts and leave the betatron oscillations coupled, similarly to what was proposed for the solenoidal snake in Nuclotron [8]. The tune shift can be compensated by adjusting the gradients of the two focusing and defocusing quadrupole families in the booster straight's triplets by small values δK_F and δK_D . Figures 2 and 3 show graphs of the β -functions for the cases of the booster without a snake and the booster with a snake with compensation of the betatron tune shifts introduced by the snake. A comparison of the graphs yields that the change in the β -functions in the booster with the snake is quite acceptable.



Figure 2. β -functions in one super-period of the booster without a snake.



Figure 3. β -functions in one super-period of the booster with a snake.

5. Acceleration of polarized deuterons in a racetrack booster

As for protons, deuteron polarization can be preserved in the booster using a snake. However, use of a snake is not efficient for deuterons, since it requires a maximum longitudinal field integral of $\sim 100 \text{ T} \cdot \text{m}$ and $\sim 30 \text{ m}$ of free space in a booster straight.

Due to small anomalous magnetic moment of the deuteron, its resonance grid is very sparse. In our example, there are no integer and intrinsic resonances at all. Also, the strength of the single non-super-periodic linear resonance related to lattice imperfections is quite small $w \sim 10^{-5}$. In this case, even when using superconducting magnets, it is possible to employ conventional acceleration of vertically polarized deuterons as for protons in the AGS.

Use of magnets with a field ramp rate of ~ 1 T/s guarantees fast crossing of the indicated resonance as well as of all higher-order spin resonances. Polarized deuterons were successfully accelerated in the Nuclotron, which uses superconducting magnets with a high field ramp rate [9].

6. Superconducting magnets for a racetrack booster

Superconducting pulsed solenoid and dipole with a field ramp rate of $dB/dt \approx 2 \div 4$ T/s can be manufactured using hollow high-current forced-helium-flow-cooled NbTi composite

superconducting cable similar to that designed and manufactured at JINR for the Nuclotron [10]. The maximum magnetic field of the Nuclotron dipoles is limited to 2 T. Dipoles with fields of up to $3 \div 4.5$ T and a field ramp rate of 1 T/s were proposed in references [11, 12]. A design work is presently being done on a solenoid for a proton snake for the Nuclotron. Use of Nuclotron-type magnets guarantees preservation of deuteron polarization in a racetrack booster.

When using conventional super-ferric magnets with a field ramp rate of ~ 1 T/min, preservation of polarization in the booster becomes a complex task, since the linear resonance is crossed at intermediate rate. In this case, one has to use fast quadrupoles to arrange a betatron tune jump. Higher-order resonances must be analyzed. One also has to carefully optimize the booster lattice and account for more subtle effects, such as those related to synchrotron energy oscillations, which lead to splitting of a resonance into a series of synchrotron side-band resonances. One should also take care of the orbital motion stability at the moments of betatron tune jumps.

Conclusion

In summary, one can draw the following conclusions:

- a racetrack booster built of superconducting magnets allows for acceleration of polarized protons and deuterons,
- acceleration of polarized protons requires a solenoidal Siberian snake,
- for acceleration of polarized deuterons, it is sufficient to use conventional spin resonance crossing techniques,
- fast-cycling Nuclotron-type magnets guarantee preservation of deuteron polarization in a racetrack booster up to 8 GeV/c and shorten the acceleration time to a few seconds.

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