POSSIBILITIES TO INCREASE THE NUCLOTRON'S INTENSITY

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Abstract

The superconducting heavy ion synchrotron Nuclotron is under operation in JINR – Dubna since 1993. The ways to increase the intensities of the accelerated ion beams are discussed in this paper.

As the polarized beams are of special interest the stripping injection of polarized protons and deuterons has been considered above all both analytically and by computer simulations.

Building a booster has been debated for many years and now a superconducting booster with Dubna-type magnets has been proposed. We have simulated different schemes for injection into the booster: multiturn injection, RF stacking, charge exchange injection and stacking by means of electron cooling. A comparison between the results of the simulations is given as well.

1 INTRODUCTION

The superconducting heavy ion synchrotron Nuclotron uses an Alvarez type linac capable to accelerate ions with $0.28 < Z/A < 0.5$ up to 5 MeV/u and protons up to 20 MeV as an injector - [1].

The available ion sources are: duoplasmatron for producing protons, deuterons and α - particles; a laser ion source for producing heavy ions; a EBIS ion source for producing high charge state ions and a cryogenic polarized deuteron source 'Polaris'. EBIS delivers 25 μs pulses with 4.10^8 Ar_{40}^{18+}, 1.10^8 Kr_{84}^{35+}, 1.10^6 Xe_{131}^{59+} etc. ions. EBIS has the highest charge-state performance. The laser ion source with 10J CO_2 laser produces 5-10 μs pulses with 5.10^{10} Li_7^{3+}, $1.5.10^{10}$ C_{12}^{6+}, $1.0.10^9$ Mg_{24}^{12+} etc. ions. Both ion sources generate short pulses and are well suited for single turn injection into Nuclotron. Hence the single turn injection is the appropriate injection method and it is used in Nuclotron since 1992.

The acceleration of polarized particles is one of the major items in the Nuclotron research program. The first test runs of polarized deuteron injection and acceleration in Nuclotron have been already carried out.

It is important to increase the intensity of the polarized beams. As the emittance of the injected beam is comparable with Nuclotron acceptance no multiturn injection can be applied. In this paper we have studied the possibility to use the charge exchange injection to store polarized deuterons in Nuclotron.

A more fundamental way to increase the intensity of Nuclotron beams is building of a circular injector, the so-called booster.

The first proposal - [2] was for a warm booster with circumference equal to one fifth of those in the Nuclotron and which would accelerate ions with Z/A=0.5 up to 200 MeV/u .

The new variant of the booster - [3] is based on superconducting magnets of Dubna type.It has circumference equal to one third of Nuclotron circumference and would accelerate ions with Z/A=0.5 up to 250 MeV/u. This will be a rapid cycling synchrotron with a frequency 1 Hz.

Several methods of injection into the booster have been studied in this paper, namely: stacking in the horizontal phase space, RF stacking, stripping injection and injection by means of electron cooling of the injected ions. A comparison between all these methods is given as well.

2 CHARGE EXCHANGE INJECTION OF DEUTERONS INTO NUCLOTRON

A natural development of the JINR LHE spin physics programme will be the acceleration of polarized beams of deuterons in Nuclotron. The scheme of acceleration covers : a cryogenic source of polarized deuterons Polaris, a 5 MeV/u linac, charge exchange $D^-\uparrow \rightarrow D^+\uparrow$ injection into Nuclotron and acceleration in it up to 6 GeV/u. In this paper we have studied the possibility to apply the method of stripping injection to the storage of polarized deuterons in Nuclotron. To study the process of charge exchange injection into Nuclotron we have applied both analytical description given in – [4] and computer simulations carried out by means of a special computer code. The results of the simulation are given below on Fig. 1 which shows the process of deuteron storage.

An intensity gain of about 40 could be achieved for a 100 turn stripping injection.

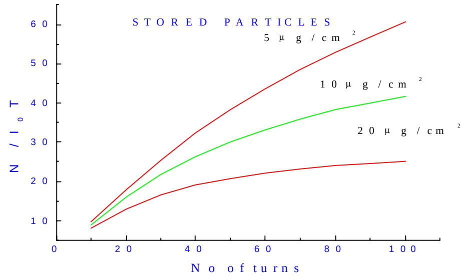

Figure 1. Storage of deuterons in Nuclotron by means of stripping injection.

3 INJECTION INTO NUCLOTRON’s BOOSTER

3.1. Multiturn Injection

The superconducting variant of the Nuclotron booster, which is now under consideration, has large acceptances: $A_x = 400\pi$ mm.mrad, $A_z = 225\pi$ mm.mrad. Nevertheless due to the large emittance of the injected beams $\varepsilon_x = 50\pi$ mm.mrad, $\varepsilon_z = 32\pi$ mm.mrad the ratio acceptance to emittance is rather small $A_x/\varepsilon_x = 8$, $A_z/\varepsilon_z = 7$. This is the main limitation factor for the multiturn injection into the booster.

We have studied betatron stacking in the horizontal phase plane.

Different kinds of orbit bump falls – linear, exponential, cosine etc. have been studied. If the bump fall is exponential the number of accumulated particles increases faster while the losses during the last periods are big due to the small orbit step. On the contrary the cosine bump fall has bigger losses during the first periods. The stacking efficiency slightly depends on the bump fall law.

The stacking efficiency depends on large number of parameters: the distance injected beam center-septum edge, the slope of the injected beam, the number of injected turns, the number of betatron oscillations per turn Q, the injector emittance and momentum spread etc. The efficiency versus the initial radial position of the injected beam and the efficiency versus the injected beam slope curves have resonant character. The dependence of the injection efficiency on the betatron tune Q has a typical symmetric shape .

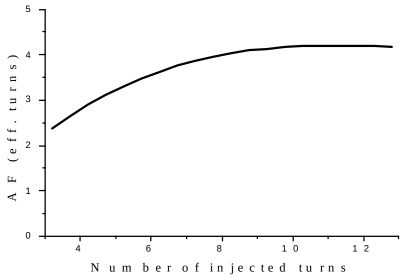

Figure 2. Accumulation factor for mutiturn injection versus the number of injected turns.

3.2 RF Stacking

The injection into the Nuclotron’s booster by means of RF stacking consists in following. The beam is injected by means of a kicker magnet. After the injection of the first portion of particles is completed the stacking RF cavity is switched on and the particles are accelerated (or usually decelerated) to an outer (inner) orbit. When the top of the stack is reached the RF voltage is switched off and the particles are released from the RF buckets. In the repetitive stacking mode of operation (stacking at the top) the new portion is moved again to the same position i.e. to the top of the stack. According to the Liouville’s theorem the particles already accumulated in the stack will be displaced toward lower (higher) energies. Due to the very small value of the momentum compaction factor the portions of particles with different energies largely overlap in the physical and transverse phase spaces. The stacking takes place in the longitudinal phase space while the density in the six - dimensional μ - phase space is conserved in agreement with the Liouville’s theorem. A beam slice with large intensity is built up. In the non-repetitive stacking mode (stacking at the bottom) each successive portion of particles is moved to a slightly different energy than the previous one. The energy difference is equal to the final bucket area A_b divided by 2π. So the new particles will be add to the bottom of the stack.

According to [4] the following relation must be satisfied at any point along the ring:

$$E_{inj} - E_{top} \le 2E\beta^{2}\left(\frac{a-\sqrt{\varepsilon\beta(s)}}{D(s)}\right) \qquad (1)$$

where $\beta(s)$ is the Twiss amplitude function and D(s) is the dispersion. At the injection point:

$$E_{inj} - E_{bot} = E\beta^{2}\left(\frac{2\sqrt{\varepsilon\beta_{inj}}+\Delta}{D_{inj}}\right) \qquad (2)$$

Δ being the distance between the stack bottom and injected beam edges. The number of RF cycles is:

$$n_{rf} = \varepsilon_{rf}\frac{E_{bot}-E_{top}}{\Delta E} \qquad (3)$$

where ΔE is the phase displacement of the stack during single crossing by the buckets and ε_{rf} is the stacking efficiency defined as the ratio of the ideal stack width to the width of the real stack. It follows from (2 - 4) that:

$$n_{rf} = \varepsilon_{rf}\frac{E\beta^{2}}{\Delta E}\left(\frac{2(a-\sqrt{\varepsilon\beta^{*}})}{D^{*}} - \frac{2\sqrt{\varepsilon\beta_{inj}}+\Delta}{D_{inj}}\right) \qquad (4)$$

For the Nuclotron booster a combination of single turn injection and RF stacking is a good choice. An estimation based on the formula (4) shows that the stored intensity in the booster could be increased by a factor of eight.

The stacking cycle consists in the following steps. After the first portion of particles is injected the stacking voltage is switched on adiabaticaly while $\phi_s = 0$ and the particles are captured in a stationary bucket with more than 90% efficiency. After that the stacking voltage and the equilibrium phase are changed also adiabaticaly so that the particles are decelerating towards the stack’s top while the bucket area is kept constant. After reaching the stack top the stacking voltage is switched off abruptly and the particles are deposited in the stack. The time development of the stacking voltage and phase are shown on Fig. 3.

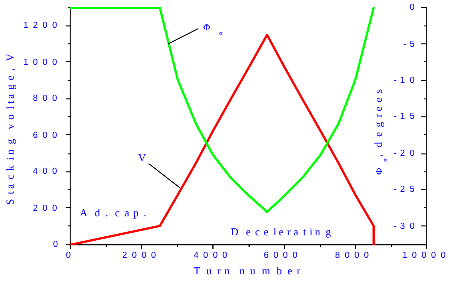

Figure 3. Time development of the stacking voltage and phase.

3.3. Charge Exchange Injection

Proposed by G. I. Dimov in Novosibirsk in 1969 nowadays the charge exchange or stripping injection is a preferred injection method for proton machines due to its relative simplicity and a very high intensity of the stored beams. Recently this injection method has been successfully applied for light ion storage in CELSIUS.

Heavy ions which change their charge from 1.3 to 1.7 times in stripping foil crossings could be injected into the booster with the help of a four magnets closed orbit bump.

A consistent analytical description of the charge exchange injection of heavy ions was developed in - [5] on the base of a kinetic treatment. Light ions with Z up to 14 could be successfully stored in the booster.

Fig. 5 shows the process of ion storage into the booster. It is seen that only light ions could be successfully stored in the booster due to the relatively low energy of the injector.

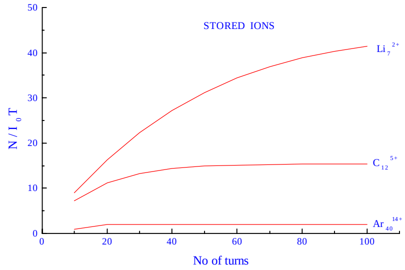

Figure 5. Ion storage during charge exchange injection of heavy ions into Nuclotron booster.

3.4. Injection by Means of Electron Cooling

An effective way of particle storage recently applied in TSR, SIS and CELSIUS is the use of electron cooling of the ion beam. This approach has several varieties. One may cool the phase space area filled by multiturn injection or the particle stack created by RF storage method. In CELSIUS particles stored by means of ion stripping are cooled. In all three methods the cooling shrinks the phase space area occupied by particles thus releasing space necessary for injection of new portion of particles.

In electron cooling the cooling time is proportional to $\beta^4\gamma^5$, β and γ being the relativistic factors, i.e. the method is well suited for injection energies.

On the other hand the cooling time in transverse direction is proportional to $\varepsilon^{3/2}$, ε being the emittance and the cooling time in longitudinal direction is proportional to $(\Delta p/p)^3$. Hence it is more effective to use single turn than multiturn injection and cool the beam afterwards.

We will propose here the following injection scheme. At the injection point the dispersion is nonzero while the electron cooler is disposed in a dispersion free area. The particles are put on an off-momentum orbit by means of a fast kicker. Then ions are cooled but the mean velocity of the electrons is set a bit smaller than the mean ion velocity ($\Delta v/v \sim -0.5\%$). Due to the dispersion in the injection point the ions are pushed toward the machine center. After that a new portion of particles is injected.

The cooling time in transverse direction is given by - [6]:

$$\tau_\perp = 2 \cdot 10^7 \frac{\beta^4 \gamma^5 \theta_\perp^3}{\eta\, j_e} \cdot \frac{A}{Z^2} \qquad (5)$$

where: $\theta_\perp$ is the maximum transverse angle, η is the ratio of the cooler length and accelerator circumference, j_e is the density of the electron beam in [A/cm^2].The cooling time in longitudinal direction is:

$$\tau_\parallel = 2 \cdot 10^7 \frac{\beta^4 \gamma^5 (\Delta p / p)^3}{\eta\, j_e} \cdot \frac{A}{Z^2} \qquad (6)$$

For the case of Nuclotron booster we will assume that the length of the electron cooler is 3 m and that the electron density is $n_e = 3.10^{13}$ m^{-3}. From (5, 6) one can receive that:

$$\tau_{\perp cool} = \frac{0.18}{Z} \qquad \tau_{\parallel cool} = \frac{0.96}{Z}$$

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