PROGRESS IN THE NUCLOTRON BOOSTER DESIGN*

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Abstract

New results of the Nuclotron booster conceptual design, a 250 MeV/Amu rapid cycling superconducting synchrotron at a 1 Hz repetition rate and a circumference of 84 m, are presented. The paper describes different options of heavy ion accumulation in the booster for upgrading Nuclotron beam intensities. They are a traditional multiturn and "skew" injection, accumulation of exchange, acceleration of ions with filled K and L shells protons, deuterons and heavy ions up to carbon by charge, their stripping at the booster exit and transfer into the main ring. Numerical estimations of the injection efficiency are given. The application of electron cooling at the superconducting accelerator is considered.

1 INTRODUCTION

The set of Nuclotron heavy ion sources: a duoplasmatron (for protons, deuterons and α-particle), a source of polarized deuterons, a laser source (for nuclei up to silicon and an electron beam ion source (EBIS, for the heaviest ions) allows one to get ion beams over a wide range of masses. The existing injector (the Alvarez type linac), accelerates ions up to 5 MeV/u and protons up to 20 MeV/u at 1 Hz repetition rate, with a charge-to-mass ratio $0.33 \le q/A \le 0.5$ and $0.28 \le q/A \le 0.5$ after a coming upgrade.

The problem of heavy ion beam high intensity can be solved by means of including the rapid cycling superconducting booster [1] in the accelerator facility scheme. The general parameters of this accelerator are presented in the Table 1.

Table 1: General booster parameters

Maximum energy	250 MeV/u
Injection energy	5 MeV/u
Repetition rate	1 Hz
Circumference	84 m
Acceptance horizontal	400π mm mrad
vertical	225π mm mrad
Finite emittance horizontal	50π mm mrad
vertical	32π mm mrad
Vacuum	10^{-10} Torr

The maximum energy is defined by the possibility of the beam injection into the main ring, the booster circumference is equal to 1/3 of the Nuclotron one. The repetition rate and acceptance are limited by characteristics of the superconducting magnets.

The layout of the booster, Nuclotron, linac and beam transfer lines in the Synchrophasotron building is shown in Fig.1.

The booster magnetic lattice is presented in detail in [1]. In this paper we consider two operation modes of the booster: heavy ion accumulation and cooling. The progress in the tests of the lattice superconducting magnet prototypes is presented as well.

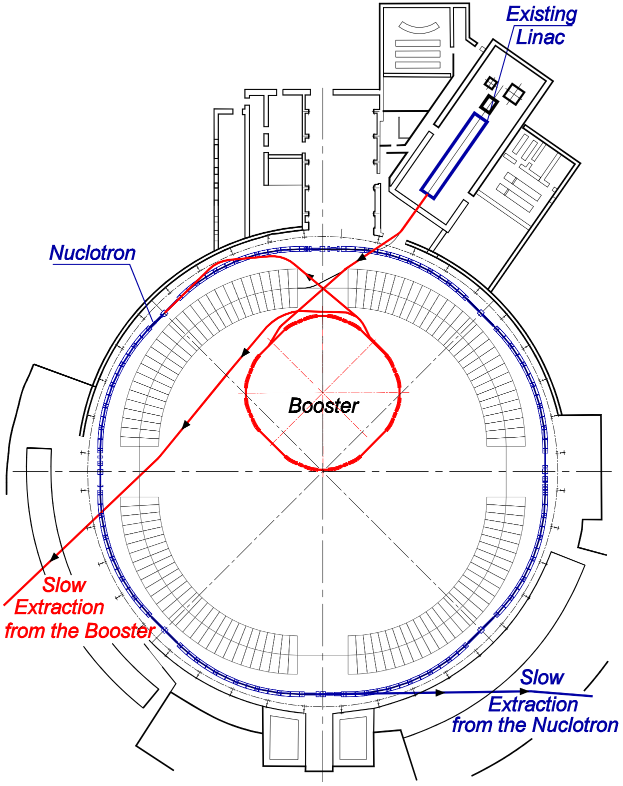

Figure 1: Layout of the Nuclotron accelerator facility.

2 HEAVY ION ACCUMULATION

The low phase density of the beams, getting in the heavy ion sources makes the problem of accumulation most actual.

The time duration of the beam current pulse of the laser and electron beam ion sources is equal about 25 µs. It is sufficiently for one turn injection ($\tau = 8$ µs) of the nucleus

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beams into the Nuclotron and eight turn “skew” injection into the booster (the booster transverse acceptance-emittance ratio equal 8). The multiturn injection scheme includes four bump magnets for displacement of a local closed orbit distortion for the injection time and septum-magnet. The numerical estimations show the intensity gain factor to be about 2. Here and further it is compared with one turn injection of the nuclei into the Nuclotron (for 1/3 booster-Nuclotron circumference ratio).

Including of a superconducting solenoid in the magnetic lattice for the perturbation of the difference betatron resonance Q_x - Q_z = 0 (so-called “skew” injection) increases this factor up to 3.

Higher intensities can be reached by the injection of ions with filled electron shells and stripping (or not) at the entrance of the Nuclotron. A charge-to-mass ratio range $0.28 \leq q/A \leq 0.5$ will permit one to inject nuclei up to $_{238}U^{92+}$ and ions with filled L shells starting with $_{12}C^{4+}$ and K and L shells beginning with $_{56}Fe^{16+}$ into the booster. Effect of the maximum intensity increase is more than 10 for heaviest ions. Maximum energy for ions with q/A = 0.28 after acceleration in the Nuclotron without stripping is limited by 3 GeV/u.

In the booster we shall try to realise the charge exchange injection for heavy ions from carbon to silicon [2]. The Monte Carlo simulation of these conditions has given the following results (see Fig.2). Using the “skew” injection , the intensity gain factor increases up to 8.

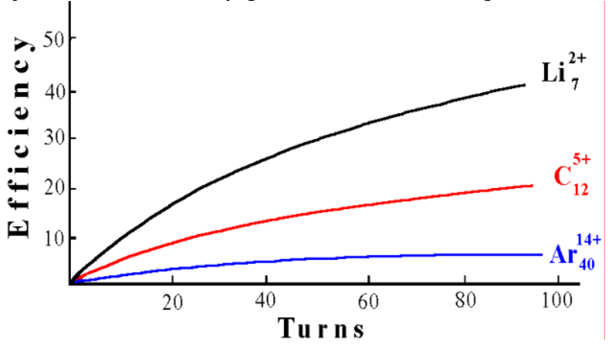

Figure 2: Efficiency of the charge exchange injection for carbon stripper of thickness of 10 μg/cm^2.

It is an attractive way to use the charge exchange method to store protons and deuterons (especially polarized deuterons). The time duration pulse of the duaplasmatron and source of polarized deuterons are about 500 μs. It allows to inject these ions during 180 turns. The accumulation process was simulated with the special Monte Carlo program as well. The intensity gain during 200-turn stripping ↑D^- injection for different thickness of a carbon stripper with the booster acceptance restriction is shown in Fig. 3. The intensity gain factor is about 50.

The acceleration harmonic numbers of the Nuclotron and booster are equal 1 and 5 respectively. It will allow to inject 5 beam pulses from the booster into the Nuclotron for the operation mode with the small Nuclotron repetition rate (ultraslow extraction or operation with internal target).

This procedure increases the intensity by a factor of five for any injection option.

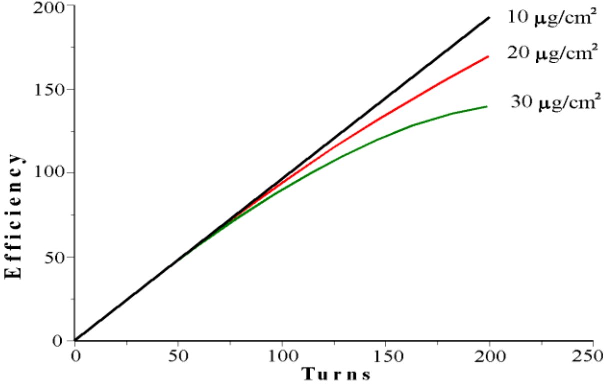

Figure 3. Efficiency of the charge exchange injection of the polarized deuterons.

The intensity gain factors for different injection modes are given in the Table 2.

Table 2: Intensity gain factors in comparison with one turn injection of the nuclei into the Nuclotron

Multiturn injection with closed orbit displacement	2
“Skew” injection	4
Injection of ions with filled electron shells	10
Charge exchange injection of $_{12}C^{4+}$	8
Polarized deuteron charge exchange injection	50
Five time injection from the booster into the Nuclotron	5

3 ELECTRON COOLING

Electron cooling just after the injection of heavy ions into the booster can be used to reduce the transverse emittance and momentum spread of the stored in the booster beam up to values of the Nuclotron lattice acceptance. After accumulation and cooling the 5 MeV/u beams are transferred into the Nuclotron without acceleration in the booster. This operation simplifies the problem of booster-Nuclotron beam transfer line and especially injection into the Nuclotron. In principle, this mode can be applied for all injection conditions. Electron cooling can help us to solve the problem of RF stacking and adiabatic capture as well.

The electron beam power must be as large as possible because of quite a large emittance of the heavy ion beam and limited cooling time.

The minimum required cooling time is determined by the Nuclotron repetition rate and has to be of the order of few seconds. The electron cooling system parameters (Table 3) are chosen to provide maximum cooling rate. The cooling section length is limited by the available space in the straight section of the booster. It is necessary to install here an additional solenoid or ‘skew” quadrupole for compensation of the coupling due to the main solenoid field. Two pairs of dipole magnets have to be installed for compensation of the closed orbit distortion caused by the solenoid edge fields. Maximum value of the electron beam current is limited by space charge effects. At current of 0.4 A (which corresponds to the electron density of the order of $1\cdot10^8$ cm^{-3}) the beam perveance reaches of 3 $\mu A/V^{3/2}$. The last value can be obtained in the gun with positive potential on the control electrode [3]. The use of the superconductive solenoids simplifies an achievement of high accuracy of the magnetic field in the cooling section and permits to provide easy the variation of the electron beam radius in the cooling section to optimise the cooling process.

Table 3: The main parameters of booster cooling system

Effective length of the cooling straight section	4 m
β-function horizontal vertical	4 m 8 m
Electron beam current	0.2 - 0.4 A
Magnetic field at the cathode	0.2 - 0.8 T
Magnetic field in the cooling section	0.1 - 0.2 T
Cathode radius	2 cm
Beam radius in the cooling section	2 – 4 cm
Electron temperature transverse longitudinal	200 MeV 0.5 MeV

The estimation of the cooling efficiency was made using BETACOOL computer program [5]. Fig. 4 shows the initial Courant Snider invariant of the deuteron, which can be decreased to the required finite value (Table 1) after the cooling during a fixed period of time at maximum electron beam current. Initial momentum deviation of the ion corresponds to momentum spread of $5\cdot10^{-3}$. Electron beam radius is equal 2 cm, magnetic field in the cooling section – 0.2 T.

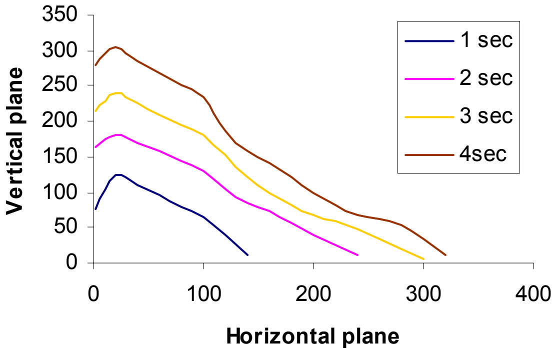

Figure 4. The initial values of the deuteron Courant Snider invariant in π·mm·mrad, which is cooled down to Nuclotron acceptance during a fixed time.

The calculation is performed taking into account the electron cooling, interaction with residual gas atoms and intrabeam scattering (deuteron number is 10^{10}). To stabilise the momentum spread value at a reasonable level an additional longitudinal heating of the ion beam was applied. The estimations show that an injected deuteron beam filled the total booster acceptance can be cooled down to the required value for transfer to Nuclotron during 3–5 s. For heavy ions the cooling rate is scaled as an ion charge number.

4 LATTICE SUPERCONDUCTING MAGNETS

The booster lattice magnets are based on the Nuclotron technologies. The Nuclotron magnets include a cold (4.5K) window frame iron yoke and a superconducting winding made from a hollow NbTi composite superconducting cable cooled with forced by two-phase helium flow at T = 4.5 K [5].

The design concept of the booster magnets was published in [6]. Since that time R&D work has been performed to improve the dipole magnet parameters: to reduce AC power losses using the 80 K iron yoke and to reduce magnetic field distortions. The main results of this work are presented at this Conference [7].

5 CONCLUSION

The 250 MeV/u rapid cycling superconducting synchrotron aimed to reach the beam intensities limited by the space charge forces. Advanced technologies of the superconducting magnet production makes it possible to minimise the cooling and electrical power and save materials (superconductor, cooper, stainless steel, etc). We are planning to prepare detailed technical design of the booster by the end of 2002.

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