

# LATTICE STUDY FOR THE CARBON ION SYNCHROTRON FOR CANCER THERAPY WITH ELECTRON COOLING

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## Abstract

In this paper the preliminary design of magnet lattice of the Carbon Ion Therapy Facility with electron cooling is described. The influence of misalignments of magnetic elements on ring parameters and the layout of the orbit correction are estimated. The different methods of ion extractions from the synchrotron are considered including the pellet extraction, recombination extraction and the extraction on the sextupole resonance.

## INTRODUCTION

A project of the p-C facility for cancer therapy, which is now under development at BINP [1-3] will provide 250 MeV protons as well as 430 MeV/u carbon ions for patient treatment. An electron cooling, that is a distinctive feature of the new project, allows obtaining “cold” ion beams with extremely low transverse size and energy spread. The electron cooling application increases the beam intensity, reduces magnet aperture and power consumption and, finally, facility cost. Among other features of the new project are precise control of the beam energy and three unique beam extraction schemes.

Using of the electron cooling allows arranging of the pellet-type extraction with the low-aperture pulsed high-repetition kicker. In this method we plan to split the ion beam at 1000 pellets with a controlled intensity in each pellet.

Recombination of ions traveling through the cooling section is another option of the slow extraction scheme. An extremely low relative velocity of the ions and the electrons increases the recombination cross-section. Available control of the electrons intensity and transverse size allows fine adjustment of the  $^{12}\text{C}^{5+}$  ion beam intensity and emittance.

As the third possible extraction method we plan to apply a slow resonant extraction with the usage of existing magnetic elements of the ion synchrotron.

## ION SYNCHROTRON

For therapy purpose the synchrotron provides  $^{12}\text{C}^{+6}$  ions with the average intensity of  $10^{10}$  particles/s in the energy range from 140 MeV/u to 430 MeV/u. The synchrotron has a racetrack reflection-symmetry lattice with zero dispersion in straight sections. In one section the electron cooler is located with 6 quadrupole magnets, which provide flat and equal betatron functions of ~15 m in the region of the e-ion interaction. In the opposite straight section the injection and extraction equipment is located. The lattice functions of the synchrotron are shown in Fig.1. Table 1 lists main parameters of the ion synchrotron.

Table 1: Main parameters of the synchrotron

Ion	$^{12}\text{C}^{+6}$
Injection energy, MeV/u	30
Extraction energy, MeV/u	140 – 430
Circumference, m	82.9
Betatron tunes, h/v	2.76 / 2.82
Max $\beta_{x,\text{max}} / \beta_{y,\text{max}}$ , m	35 / 18
Max dispersion function $\eta_{\text{max}}$ , m	4.3
Natural chromaticity x / y	-5 / -4
Cooled emittance, nm-rad	20 – 150
Cooled energy spread, $dT_k/T_k$	$1 \cdot 10^{-4}$

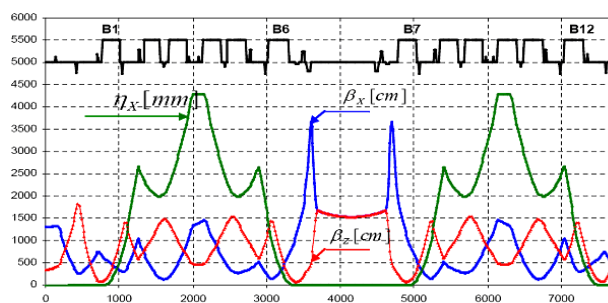


Figure 1: Synchrotron optical functions

The synchrotron has the following transverse acceptances  $A_x = 8 \text{ cm}\cdot\text{mrad}$  и  $A_y = 2 \text{ cm}\cdot\text{mrad}$  with the energy aperture of 0.7 %. The transverse emittance of the cooled ions with the intensity of  $N = 10^{10}$  as a function of beam energy is depicted in Fig.2.

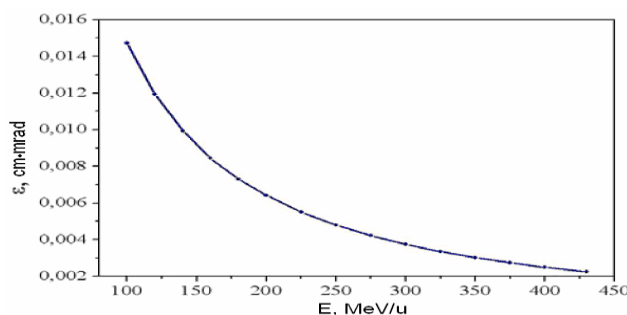


Figure 2: Beam emittance vs. energy

### COD CORRECTION

Extracted beam parameters require the following tolerance on the COD

- At the injection the COD amplitude should be inside  $\pm 10$  mm horizontally and  $\pm 7.5$  mm vertically
- At the extraction a global COD correction should provide the beam deviation less than  $\pm 5$  mm
- The local (at the azimuth of the septum and sextupoles) displacement at extraction is  $\leq 1.0$  mm

These requirements allow reaching an accuracy of the extracted pellet intensity at the level of 2%.

The tolerance on the magnets alignment is  $\sigma_{x,y} = 0.1$  mm; the roll angle is  $\sigma_{\theta} = 0.1$ ; the relative deviation of the magnets integrated field is  $\sim 0.5 \cdot 10^{-3}$ ; and the BPM read out error is 0.05 mm.

There are 20 BPMs and  $16h \times 12v$  steering magnets for the COD correction. Table 2 lists the results of the COD correction computer simulation. Fig.3 shows the maximum COD for  $Q_x = 2.67$ ,  $Q_y = 2.78$  before and after the global correction procedure.

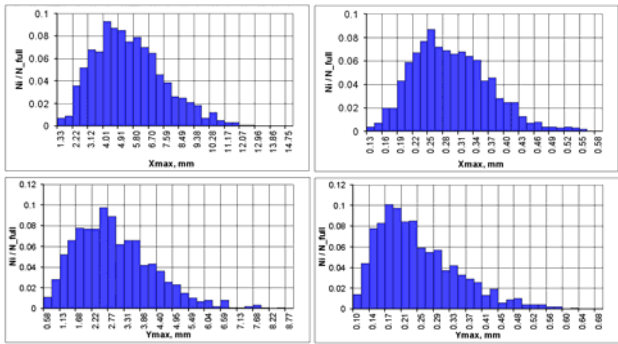


Figure 3: COD amplitude before (left) and after correction (right)

Table 2: COD correction simulation

Parameter	Before correction		After correction	
	H	V	H	V
Max COD, mm	14.75	8.77	0.579	0.677
Corrector bend angle (rms), mrad	-	-	0.238	0.093
Corrector bend angle (max), mrad	-	-	1.043	0.566
COD error	At the azimuth of extraction			
$\sigma_{\Delta X}$ , mm	3.34	1.18	0.035	0.037
$\sigma'_{\Delta X}$ , mrad	-	-	0.023	0.021

### PELLET EXTRACTION

The method is based on the possibility of the electron cooling to match the ion beam in the particular point of the phase space for further extraction. As in the other regions of the phase space the ions density decreases, the

particle loss at the septum edge reduces also. After the ion bunches acceleration, the RF cavity voltage is switched off; the beam is debunched and cooled down to the size shown in Fig.2. By scanning of the electrons energy relative to the average ion energy, the flat momentum distribution of the ions in the range of  $\Delta p/p = \pm 2 \cdot 2.5 \cdot 10^{-3}$  is achieved. At the next step the electron energy is fixed close to the edge of the ion energy distribution and under the friction force some fraction of the ions are collected around the equilibrium energy. The ion fraction (pellet) intensity can be adjusted in the range of  $N = 10^6 \div 10^7$  by controlling the collecting time and the energy deviation between ion and electron beams. The pellet can be separated from the main beam horizontally at the azimuth with the high value of the dispersion function and, if the kicker is placed at this azimuth, be extracted to the irradiation beam line. Fig.4 shows the process of the pellet formation in time. For this plot the following parameters were applied: the ions energy is 400 MeV/u, the ions momentum spread  $\pm 2 \cdot 10^{-3}$  and the dispersion function is 5 m; parameters of the cooling electron beam are:  $T_k = 200$  keV,  $I_e = 1$  A.

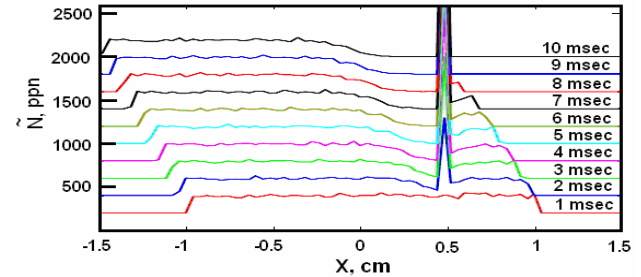


Figure 4: Pellet forming

Schematic view of the pellet extraction system and the ions trajectories are shown in Fig.5. The system consists of the fast kicker (K), electrostatic septum (SE) and the Lambertson type septum (SM). At the azimuth of these magnets beam bumps are arranged by the correctors. At the point of the extraction with high value of the dispersion function the pellet and the main ion beam are separated horizontally by  $\sim 1$  cm.

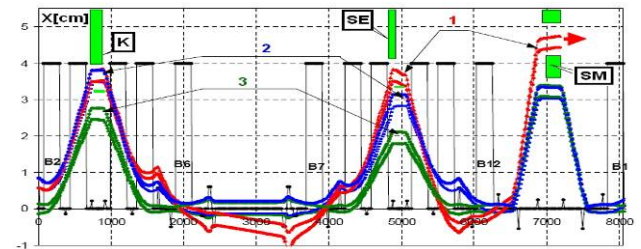


Figure 5: Pellet extraction scheme. The following trajectories are shown: for the particle with  $dE/E = 0.25\%$  after the kicker bump (1), the same but without the kicker bump (2) and the main beam trajectory (3).

### SLOW RECOMBINATION EXTRACTION

This approach uses a recombination of ions  $^{12}\text{C}^{+6} \rightarrow ^{12}\text{C}^{+5}$  in the cooling section. An intensity of the  $^{12}\text{C}^{+5}$  ions at the cooler exit can be controlled by the electron density.

The recombination coefficient has the form ( $\text{cm}^3\text{sec}^{-1}$ ):

$$\alpha_{rec} = 3.02 \times 10^{-13} \frac{Z_i^2}{\sqrt{T_e}} \left[ \ln \left( \frac{11.32 Z_i}{\sqrt{T_e}} \right) + 0.14 \left( \frac{T_e}{Z_i^2} \right)^{1/3} \right],$$

where  $T_e$  is the electrons temperature and  $Z_i$  is the ion charge. Recombinated ions are extracted from the vacuum chamber by the septum magnet (SM). A horizontal bump arranged downstream the cooler separates the trajectories of  $^{12}\text{C}^{+5}$  and  $^{12}\text{C}^{+6}$  by  $\Delta X \approx 8$  mm. Then the beam of  $^{12}\text{C}^{+5}$  traverses thin charge-exchange foil and  $^{12}\text{C}^{+6}$  enters the septum aperture placed after the synchrotron arc (Fig.6).

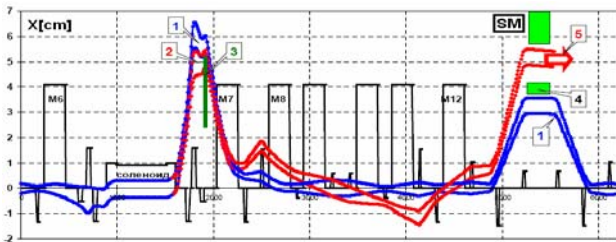


Figure 6: Recombination extraction. The plot shows: the main  $^{12}\text{C}^{+6}$  beam(1), the beam of  $^{12}\text{C}^{+5}$  (2), the foil (3), the septum magnet (4) and the trajectory of the extracted beam (5).

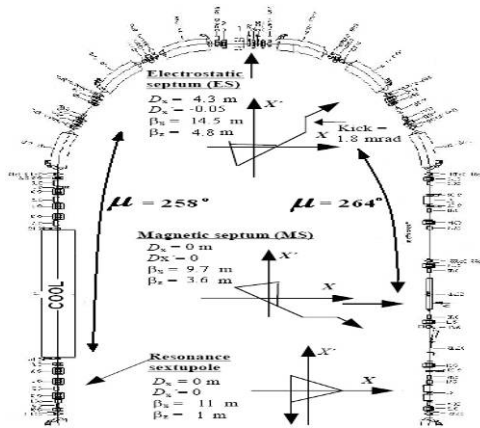


Figure 7: The resonance extraction scheme

### SLOW RESONANCE EXTRACTION

The following elements are used to arrange the particles extraction at the third-order resonance  $Q_x=8/3$ : the

sextupole magnet located upstream the cooler in the dispersion-free section, electrostatic septum and the magnet septum (see scheme in Fig.7).

The betatron phase advances between the sextupole and the electrostatic septum ( $258^\circ$ ) and between the electrostatic and magnet septums ( $264^\circ$ ) were optimized to provide high extraction efficiency. At the position of the resonant sextupole the betatron functions are arranged in such a way to minimize the betatron coupling:  $\beta_x < \beta_y$ . Low value of  $\beta_y$  allows reducing of the magnet septum aperture.

The results of a computer simulation of the ions extraction at the third-order resonance are shown in Fig.8. The extraction efficiency is close to 100%.

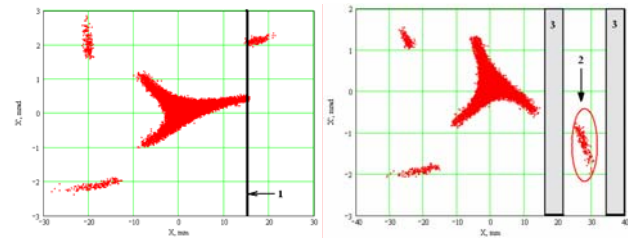


Figure 8: The resonance extraction simulation. The left plot is at the SE azimuth while the right one is at the SM azimuth.

### CONCLUSION

In the paper we have discussed the main characteristics of the carbon ions extraction from the medical purpose synchrotron. Electron cooling provides new advantageous features to the extraction process. In the near future we plan to study all proposed extraction schemes by realistic tracking with the nonlinear elements and errors.

### REFERENCES

- [1] E.B. Levichev et al., "Carbon Ion Accelerator Facility for Cancer Therapy", Proceedings of RuPAC 2006, Novosibirsk, Russia, pp.363-365.
- [2] V. Parkhomchuk et al., COOL05, Galena, AIP Conf.Proc. 821:365-369, 2006.
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