Electron Cooling for Cold Beam Synchrotron for Cancer Therapy

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Electron Cooling for Cold Beam Synchrotron for Cancer Therapy

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Abstract. A wide usage of carbon ions for cancer therapy is limited mostly due to technical difficulties, resulting in higher cost. This cost problem can be solved by our CBS (Cold Beam Synchrotron) proposal. In this paper a conceptual design of the facility for the carbon beam cancer therapy using a high precise active beam scanning system of synchronizing with respiration. The main feature of the CBS facility is an application of electron cooling device. The use of cold ion beam allows to decrease the aperture of synchrotron and components of high energy beam transport lines, significantly. The precise ion beam energy variation and two unique schemes of beam extraction ("pellet" extraction and extraction on recombination) enclose the list of possibilities appearing with EC applying.

Keywords: Electron Cooling; Ion Cancer Therapy.

INTRODUCTION

A carbon ion beam is a superior tool to x-rays or a proton beam in both physical and biological doses in a cancer treatment. Carbon ions compared with protons, have a better relative biological effect (RBE), an effective Linear Energy Transfer (LET) to a cancer tumor are more effective to treat radiation resistant and deep-seated tumors, a mitotic independence of the breakdown of a DNA double strands and so forth. Carbon ions have the property of lower scattering along their trajectory. It has been shown that a superior QOL (Quality Of Life) therapy is made possible by the carbon beam. A major focus of the hadron therapy community is transformation of particle therapy into a practical and affordable treatment option. A wide use of carbon ions cancer therapy is limited mostly due to technical difficulties, resulting in higher cost. This cost problem can be solved by our CBS (Cold Beam Synchrotron) proposal [1]. The main feature of the CBS facility is an application of electron cooling device.

The electron cooling technology applied to the heavy ion medical accelerator will open a world of high performance yet with considerably lower cost. Novel extraction techniques, a new approach to a high intensity beam and a new scanning method of low emittance beam is possible. It also enables high energy economic beam lines less power consumption. The highlight of the cold beam accelerator is a two axis rotating carbon gantry.

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COLD BEAM SYNCHROTRON

The general specifications for the CBS facility are based on the following premises for the clinical requirements;

Clinical spec: 2 fixed port (horizontal and 45 degree), 1 gantry;

Type of particles: Carbon, proton (option);

Ion energy: 100-400 MeV/u, a variable beam energy from spill to spill;

Average dose rate: 5 Gy/min;

Field size: 15 cm x 15 cm;

Dose uniformity: ± 4% of the prescribed dose over treatment field;

Delivered dose accuracy: 2%;

Irradiation method: revised spot scanning system with synchronization of respiration.

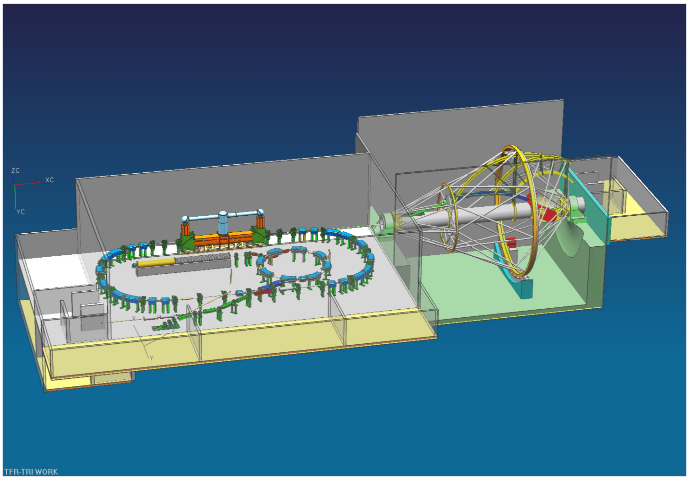

FIGURE 1. The layout of carbon beam facility for cancer treatment.

The accelerator part of CBS complex consists of linac (C^{+4}, 6 MeV/u), fast cycling booster (C^{+4}, 30 MeV/u), main synchrotron with electron cooling and HEBT (High Energy Beam Transport). In Fig. 1 the layout of CBS with the low aperture gantry is shown. In Tab. 1, the basic parameters of the main ring are listed.

TABLE 1. Basic Parameters of Main Synchrotron.

Parameter	**Units**	**Value**
Type of Particle		$^{12}C^{+6}$
Injection Energy	MeV/u	30
Extraction Energy	MeV/u	100 - 400
Magnet Rigidity	Tm	6.4
Circumference	m	80.6
Betatron Tunes (hor/vert)		3.42/ 2.43
Magnet Gap	mm	36

ELECTRON COOLING APPLICATION

Storage & Cooling of Intense Carbon Beam

The electron cooling process will be used both on the injection energy and on the final energy. In Fig.2. the evolution of the normalized transverse emittance and longitudinal momentum spread at injection are presented. The simulation was made for follow parameters: the beta-function in cooling section is 12.5 m, the ion energy is E_i = 30 MeV/u, the electron beam radius is 1.2 cm, the electron current is I_e = 0.6 A, the length of ion bunch is 0.33 from the synchrotron perimeter. As it is seen, the ion beam emittance and momentum spread are effectively decreased during less than 100 ms. The limiting factor for cooling is tune shift induced by the ion beam space charge.

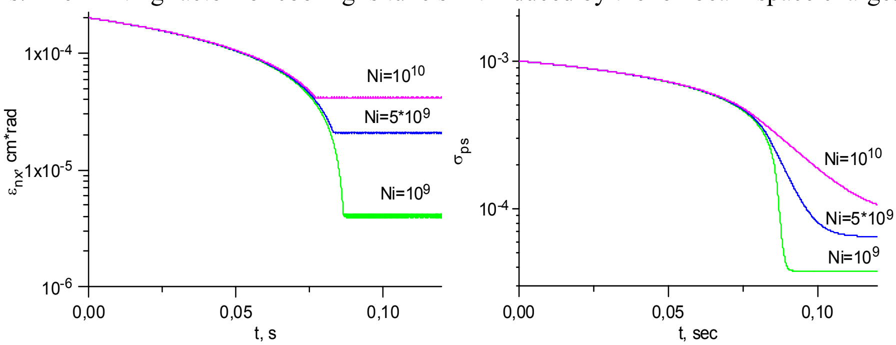

FIGURE 2. Time evolution of normalized transverse emittance (left) and longitudinal momentum spread (right), for different beam intensity, E_i = 30 MeV/u.

The main task for the cooler is the cooling of ion beam at the top energy (100 – 400 MeV/u). In Fig. 3 the evolution of normalized transverse emittance and longitudinal momentum spread for E_i = 400 MeV/u are presented. The simulation was made for follow parameters: the electron beam radius is 0.3 cm, the electron current is I_e = 0.6 A, the length of ion bunch is equal to the synchrotron perimeter. As it is seen, the ion beam emittance and momentum spread are effectively decreased during about 200 ms.

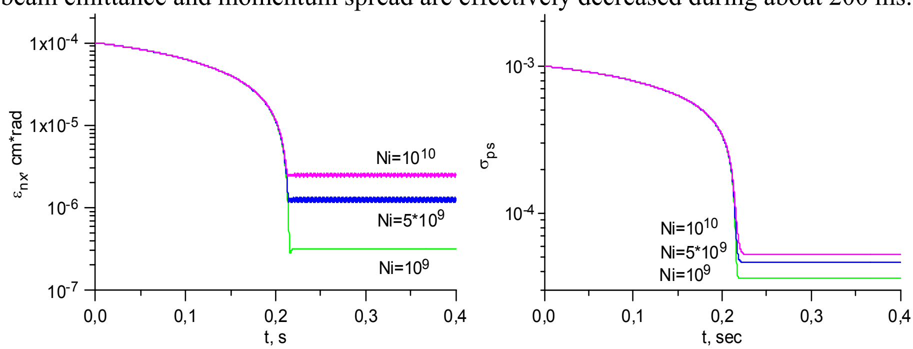

FIGURE 3. Time evolution of normalized transverse emittance (left) and longitudinal momentum spread (right), from top to bottom $N_i = 10^{10}$, $5{\cdot}10^9$, 10^9 accordingly, E_i = 400 MeV/u.

Precise Ion Beam Energy Scanning

For the active 3D scanning, the changing of the extracted beam energy with high accuracy is necessary. The possibility of the accelerating or decelerating the beam by means of the friction force of the electron beam has been demonstrated in the set of experiments. The electron cooling device allows operation with energy of the extracted beam by varying the electron beam energy simultaneously with the synchrotron magnet field. Dependence of the accelerating rate on the stored ion beam intensity at different ion energy is shown in Fig. 4.

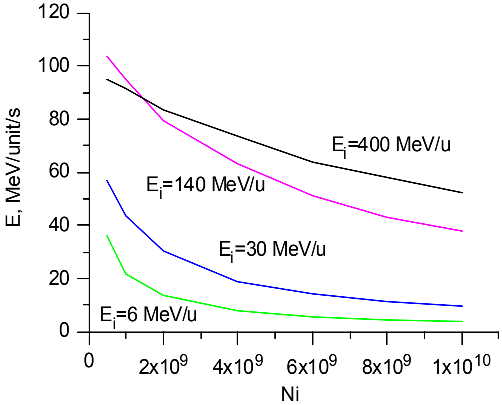

FIGURE 4. Dependence of the accelerating rate on the stored ion beam intensity. The parameters of electron beam are the following: I_e=0.4 A, a_e=1.5 cm (E_i=6 MeV/u), I_e=0.6 A, a_e=1.2 cm (E_i=30 MeV/u), I_e=0.8 A, a_e=0.5 cm (E_i=140 MeV/u), I_e=1.0 A, a_e=0.3 cm (E_i=400 MeV/u).

Extraction

Two different schemes of the extraction are possible to use. At condition of electron cooled ion beam, it is possible to used kicker extraction with very high repeating rate of extraction. The total ion beam can be divided up to 10 000 portions with controllable intensity of portion, by such method named as "pellet" extraction.

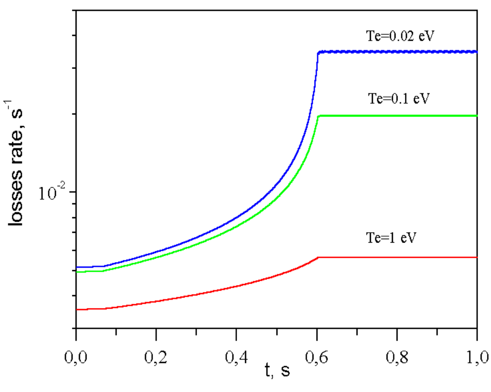

FIGURE 5. Recombination losses rate for different electron beam temperature.

Ion charge exchange by the electron beam recombination is utilized for a slow extraction scheme. The very small relative velocity between ions and electrons leads to the certain probability for a recombination process. Operating with the electron beam intensity and transverse profile gives the possibility for precise varying of the intensity and emittance of $^{12}C^{5+}$ beam extracted from the electron cooler.

In Fig.5. the recombination rates for different values of electron beam temperature are presented. The simulation was made for follow parameters: N_i=10^{10}, I_e=3 A, E=400 MeV/u.

ELECTRON COOLER DESIGN

As base for out project we take the design of the cooler EC-300 for CSRe storage ring, IMEP, China, designed and produced by BINP [2]. The main parameters of electron cooler are presented in Tab. 2. The sketch of the electron cooler design is shown in Fig 6.

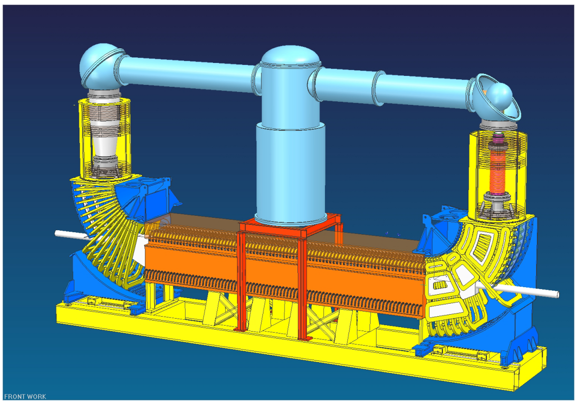

FIGURE 6. The layout of the electron cooler device for CBS.

TABLE 2. Electron Cooler Parameters.

Parameter	Units	Value
Electron Energy	keV	Up to 250
Total Length	m	10.2
Cooling Length	m	7
Magnet Field	kG	1.5
Quality of the magnetic field		Better 10^{-4}

REFERENCES

1. V.V.Parkhomchuk et al., Proc. of PAC 05.
2. V.V.Parkhomchuk et al., “Commission of electron cooler EC-300” in Proc of this Workshop.