ELECTRON COOLING FOR THE THERAPY ACCELERATOR COMPLEX

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Abstract

Institute of Nuclear Physics (BINP, Novosibirsk) is engaged in R&D of the new therapy accelerator system based on the electron cooling. The electron cooling is used for the ion beam accumulation in process of repeated multi turn injection into the main ring from the fast cycling booster synchrotron. After acceleration of the carbon ions up to 200-400 MeV/u the electron cooling is used for shrinking the beam emittance to minimal value and for further extraction and distribution of small fractions of the ion beam according to the irradiation program. The extraction systems base on the electron cooling is discussed in the report. The computer simulation results are in a good agreement with the experimental data of the electron cooling of the carbon ion beam with energy 400 MeV/u obtained resently during the CSRe commissioning (May 2009).

INTRODUCTION

Heavy ion beam therapy is one of the most advanced and effective cancer treatments. It is more accurate, caused less damage to healthy tissue and has a higher cure rate in comparison with conventional kinds of radiotherapy with x-ray. Traditional therapy systems with carbon ion beam consist of following parts: ion source, linear accelerator up to 30 MeV/u, synchrotron for ions acceleration up to the energy of 100-400 MeV/u and irradiation channels including (in most radiotherapy centers) the gantry system intended for irradiation a tumor from different directions [1]. The application of the achievements of the ion beam cooling science to this therapy system can fundamentally improve the characteristic of beams used for therapy. If we discuss just adding the electron cooling to existing system [2] it looks like additional cost about 2 M$ to the existing equipment with total price about 70-100 M$. But new system based on the electron cooling from the very beginning (from stage of design) opens many unique possibilities unachievable for conventional systems namely:

1. Accumulation primary ion beams by means of repeating injection that relieves requirements on injection system.
2. Possibility to accumulate secondary positrons emitting nuclei that can be used for precise diagnostic of the radiation dose distribution in and around a tumor with the help of standard PET apparatus.
3. After acceleration with further cooling the ion beam has very small emitance that allow the extraction system to be less powerful and has failure-free operation
4. Possibility of the precise beam extraction by a recombination.

These advantages make it possible to construct therapy system more reliable and cheaper. According to a contract with Chinese company BINP works on development of the project for carbon therapy. But after the economic crisis begun the project got strong problems with financing. Initial construction of prototype of elements and calculation of the cooling process showed high level perspectives. This year experiments with cooling 400 MeV/u carbon ions at CSRe demonstrate very interesting results.

PRIMARY BEAM ACCUMULATION

Injector comprises the ion sources, tandem accelerator, the fast-cycling booster synchrotron and low energy beam transport lines. A multi-turn injection from the tandem accelerator into the booster synchrotron is performed in a horizontal plane. The booster synchrotron accelerates protons up the maximum energy of 250 MeV and the carbon ions $^{12}C^{+4}$ up to 430 MeV/u. The booster circumference is of 27 m, repetition rate is 10 Hz. The maximal energy of booster synchrotron is 30 MeV/u which is optimal for accumulation the carbon ions in the main synchrotron with period 0.1 sec. After injection into the main synchrotron, the ion beam is stored, cooled and accelerated up to the energy required for therapy then extracted into the high energy beam transport system. The ion beam is stored during 10 booster cycles with electron cooling.

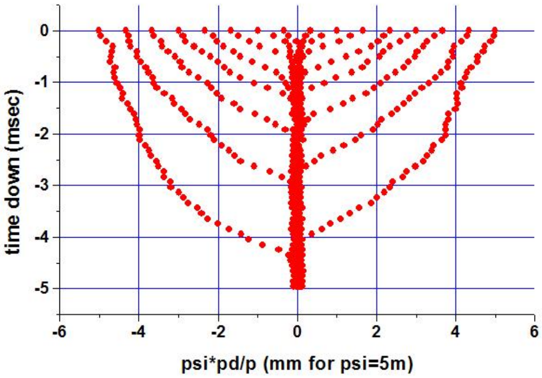

Figure 1: The computer simulation of initially injected beam cooling (momentum): electron current 0.5 A, electron energy 16 kV, time range arrow is shown from up to down in milliseconds.

Radioactive Isotopes Accumulation

The electron cooling can be used for an accumulation of radioactive nuclei which could be useful for cancer therapy. For example, treatment by the use of ^{11}C with life time about 20 min looks very effective for the dose diagnostic as far as all dose measurements after irradiation could be performed with normal Positron Emission Tomography. This is similarly to the process of proton treatment [3,4] where radioactive nuclei arise in considerable amount (about 1000-2000 1/cm) that also can be used for diagnostic. The cross section of the ^{11}C ions production has a maximum value 100 mb at proton energy near 30-40 MeV. The first estimations of production yield for ^{11}C nuclei on the special external hydrogen target gives hope to reach efficiency about 0.01 for transformation buster intensity ^{12}C to ^{11}C. This technology opens the possibility to combine the results of standard PET diagnostic which detects cancer tumor after taking isotopes medicine with the irradiation zone visualization after irradiation with the short life time isotopes. The points of stopping ^{11}C ions with known energy and initial space distribution gives precise information about the stopping ions power of the real muscular tissue.

EXTRACTION OF ION BEAM FROM MAIN SYNCHROTRON

Pellet Extraction

The presence of electron cooling in the synchrotron provides a small size and energy spread of the cooled beam thus enabling the realization of the original beam extraction scheme by small precisely dosed portions, the so-called pellet extraction. Electron cooling allows concentrating a portion of the ion beam in a given place of the phase space and then getting the ion beam low density in the neighboring regions for decreasing the "tails" of the distribution and losses at the extraction septum [5]. The operation scheme is the following. Upon the ion beam acceleration up to the required energy, RF voltage is off and the beam is de-bunched. In the period of 50-200 ms (depending on the extraction energy) the beam is cooled down to the relevant equilibrium state. Then the beam is prepared for its extraction, for example, by scanning the electron beam energy with respect to the mean energy of the ion beam we produce the flat distribution of ions with $\Delta p / p = \pm 2 \div 2.5 \cdot 10^{-3}$. Then it is necessary to separate a portion of particles with energy deviation from the main beam. The portion intensity should be controlled in the range of N = $10^6 \div 10^7$ particles. The neighbouring ions are concentrated under the friction force action. The intensity of obtained portion is controlled by the time of storage and de-tuning of the electron beam energy from the distribution edge. By placing the kicker at the azimuth of the ion orbit where the dispersion is sufficient to separate the main beam from the portion the single turn extraction of the portion is realized. It is clear that ions concentrate in a portion but close to the storage portion region there are many ions nearing the ion cooling region, which will be bombarded the septum knife. In order to improve the extraction efficiency, it is necessary to clean the septum knife region. One of simplest solutions is to use the betatron core for accelerating the ion beam and "separating" the main beam from the region where the beam is prepared for its extraction. The magnet field in the core slowly increases so that the energy of the ion beam also increases on every turn moving the beam aside the septum. In this case, the maximum electron cooling force should be sufficient for the confinement and cooling the ions in the extraction region (Fig.1). It is seen that the main beam is moving away from the storage region and the left side portion is concentrated in the extraction area. Such an ion energy swiping accelerates noticeably the beam preparation for its extraction and cleans the "knife" region from the lost particles.

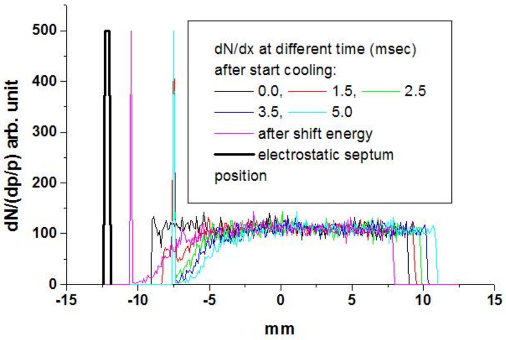

Figure 2: The 5 msec cycle of carbon ions extraction with electron cooling.

Upon completion of the extracted portion storage and cooling, the betatron core exchanges polarity rapidly enough and the stored portion is rapidly moving to the kicker and the main beam distribution tail returns again in the cooling region for storing a new portion. In the scheme of using swiping, the extraction efficiency is much higher for the system repetition frequency up to 500 Hz. In the region of 1-2 kHz, the losses are still high 20-30 % for the septum knife with thickness 0.5 mm.

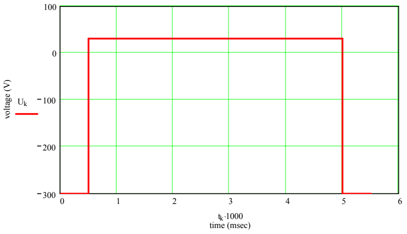

Figure 3: The voltage on betatron core versus time at cycle.

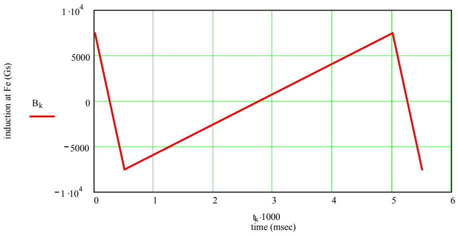

Figure 4: Magnet field at betatron core versus time.

For the beam extraction the fast kicker, electrostatic septum and permanent septum of the Lambertson type are used. Since the dispersion function at the kicker azimuth and electrostatic septum has the maximum value of 4.3 m, the main beam orbit and portions are separated by $\Delta X \approx$ 10 mm. After kick, the portion reaches the electrostatic septum aperture and acquiring an additional deflection along radius reaching the aperture of the Lambertson-type septum magnet, by which it is extracted vertically at the angle $\varphi_y = 13.5°$ with respect to the equilibrium orbit. The beam deflection angle corresponds to the ΔX =10 mm beam drop to the electrostatic septum aperture and, correspondingly, the electrostatic septum drops the beam into the septum magnet at the value of ΔX = 14 mm. The kicker kicks the beam by purely electric field and has the pulse duration of 80 ns with the fronts about 10 ns by order of magnitude. The presence of the cut in the inner plate causes the stray field and field non-uniformity inside the kicker aperture. With the separation of orbits by 10 mm, the main beam perturbation is $\Delta\varphi \leq 5 \cdot 10^{-6}$.

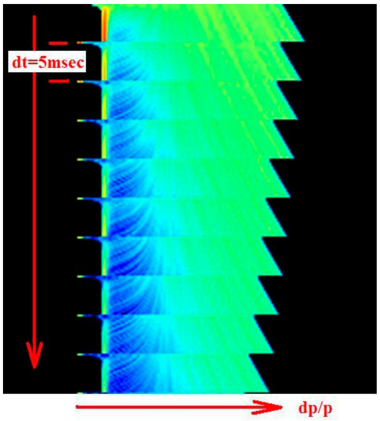

Figure 5: The computer simulation of 10 cycles of extraction with period 5 msec (full time 50 msec.), initial momentum spread $\Delta p/p = \pm 0.001$.

Figure 5 shows the 10 cycles of extraction when main beam during each 200 Hz cycles linearly moved to right and just before extraction jumped to the left (the time of the magnetic field polarity exchange). Slow moving to the left is connected with action of the cooling force which shifts the main beam to extraction zone.

Slow Extraction by Recombination

The project of the storage ring for the cancer therapy proposed by BINP team proposes using recombination reaction C^{+6}+e->C^{+5} for the extraction of the ion beam. The charge states C^{+6} and C^{+5} have difference 20% in momentum, so it is possible to organize the strong shift between primary and extracted beam by the proper choice of the dispersion with very low ion density in the gap between these two orbits. So, the flow of the particles on the septum elements can be low according the extraction scheme. It leads to small leakage of the particles during extraction and liberalizes the requirement to the power supply of the storage ring because the ripple of the magnetic field doesn't produce the interference of the primary and extraction beam in the space. The ion beam after cooling on high energy 100-400 MeV/u very small (see Fig.6) and beam after recombination too very small. For example, fig. 6 show photo of nuclear emulsion after exposition at hydrogen beam on distance 10 m from the electron cooler NAP-M.

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Рис. 4. Фотография ядерной фотоэмульсии, экспонированной пучком быстрых атомов водорода ($v/c = 0{,}35$), возникающих при рекомбинации протонного и электронного пучков на участке охлаждения

Фотоэмульсия расположена на расстоянии 10 м от участка взаимодействия. Метки нанесены через 1 мм. Размер изображения соответствует диаметру протонного пучка 0,5 мм и угловой расходимости $3 \cdot 10^{-5}$ рад

Figure 6: The first photo of hydrogen atoms beam after recombination at NAP-M cooler [6].

The recombination coefficient is proportional to electron density. This enables to operate by the dose of the extraction beam. The electron gun as an electron tube can modulate the electron current in the megahertz frequency range. This frequency is certainly enough for any regime of the tumor scanning. The presence of the diagnostic of the extraction dose enables to have a feedback for the stabilization dose in the tumor. Moreover the recombination extraction is more safety because it is very difficult to have breakdown extraction of all stored ion beam during very short time. Protection system can quickly switch off the electron current and stop the extraction. The main disadvantage of the recombination extraction is relatively small rate of the extraction namely 10^7/s at the number of the ions in the storage ring 10^{10} and the electron density 10^8 1/cm^3 in the cooling section. But this value is enough for the treatment of the small cancer tumor. For example, the tumor with diameter 30 mm should be irradiated ions those have the rest kinetic energy near 50 MeV/u. For accumulation doze of 5 Gy with ion flux 10^7/s required exposition time is near 1 min.

FIRST EXPERIMENTS ON CSRE WITH 400 MEV/U

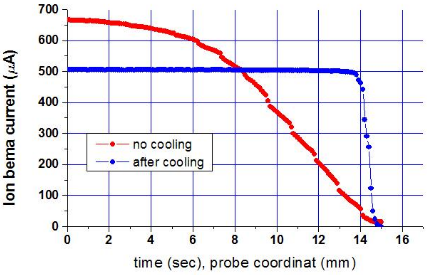

Figure 7: The scraping the ion beam at CSRe.

The first experiments at **CSRe** with cooling of carbon beam showed perspectives of this type of extraction. Fig.7 shows results of the carbon ion beam current measurement during moving the mechanical scraper inside vacuum chamber (with velocity 1 mm/sec) before cooling and after the electron cooling. As we can see, the ion beam size is near 15 mm in the case of absence of the cooling but after cooling it becomes less than 1 mm. It is more interesting that we can see many seconds of the ion beam life time when the scraper is located in less then 2 mm from the centre of the ion beam orbit. There is direct situation what was used for kick extraction simulation shown in fig.2 (just before stored portion of the beam was kicked out). The kicker voltage amplitude is required to excite the beam oscillations with amplitude about 2 mm. This corresponds to the angle about 2×10^{-4} at the point with a beta function value of 10 m. For producing so small kick we are going to use low power transistor generator instead of powerful gas-filled triode generator.

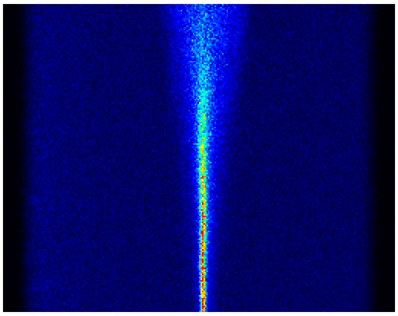

Figure 8: Schotky signal of carbon beam during cooling at CSRe with energy 400 MeV/u.

The cooling process of the ions with initial momentum spread $\delta p_{r.m.s.}/p = 2\times10^{-4}$ is shown in fig.8. Initial momentum spread is cooled down to equilibrium spread 1×10^{-5} with the exponential cooling time 20 sec. The electron beam diameter was about 50 mm and density of 1 A electron beam very low at these experiments. The alignment of ion and electron beams was far from optimum (was $\theta_{eff} \approx 5\times10^{-4}$) and the calculation of the cooling time with the same code as for fig.1 gives about 20 sec. In the case of using the electron beam with diameter of 1 cm and careful alignment with accuracy $\theta_{eff} \approx 1\times10^{-4}$ cooling rate should increase at factor $g \approx 1/a_e^2 \times 1/\theta_{eff}^3 \approx 3000$ that decreases the cooling time down to 5 msec.

ELECTRON COOLER DESIGN

Electron cooler consists of the following subsystems: the support and the vacuum system, the magnetic system comprising the focusing solenoids, toroids and correction magnets, the system of electrostatics including 300 kV accelerating tubes and electrodes, the high voltage power supply system, diagnostics, the gas vessel (SF6) system and the oil cooling system for collector and high voltage terminal. The electron cooler after acceleration should fast increased the high voltage and cooled ion on top energy. The electron beam from electron gun (14) move at gun solenoid (13), toroid solenoid (15), the cooling straight section (11) with ion beam and after turn at toroid (9) to collector solenoid (6) damped at collector (5). The high voltage system at pressed vessel (1) connected pressed high voltage lines (4) with the electron gun and collector (5). All the solenoids are mounted on the frame made of the magnetic soft steel. The frame closes the magnetic flux and serves as the magnetic shield.

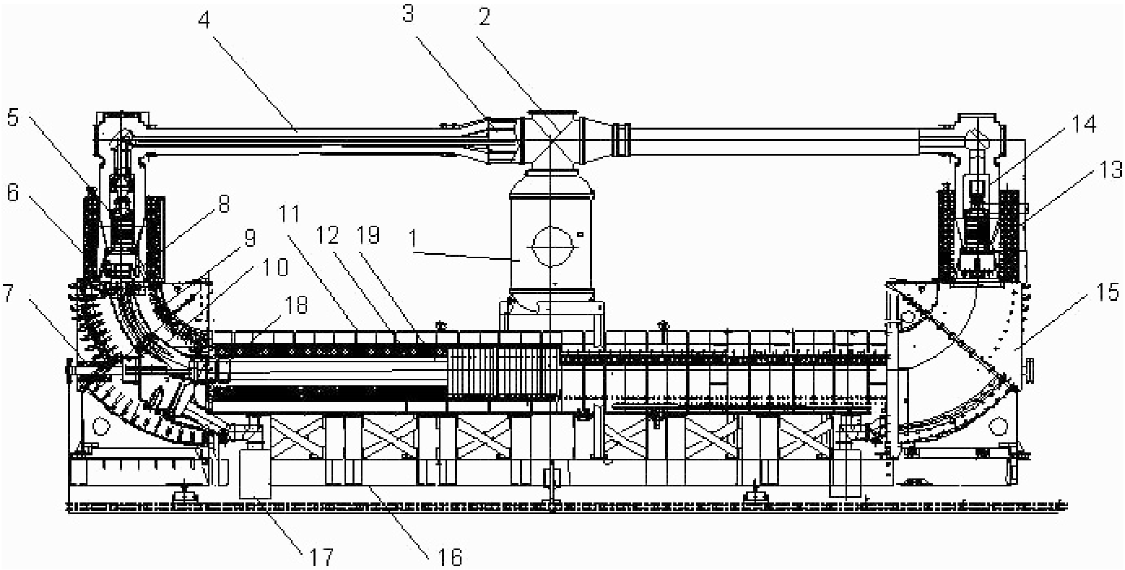

Figure 9: Design plot of the electron cooler for the therapy accelerator complex. The main parameters of cooler: electron beam energy up to 250 keV, total length 8 m, cooling length 4.8 m, magnetic field at cooling section 0.1-0.15 T,magnetic field straightness $\Delta H_{\perp}/H < 10^{-4}$, Pressure at vacuum chamber10^{-8}·10^{-9} Pa, SF6 gas pressure at the high voltage vessel 2-3 bar, the electric power consumption near 350 kWt, total weight 30 t, water consumption (5 bar) 1 m^3/minut, occupied area 10*10*5 m^3.

In the ion beam input/output places the dipole corrections are located (7) that compensates the ion beam displacements caused by the vertical component of the magnetic field in the toroidal section (9). The vacuum chamber is pumped off with two ion pumps placed near (17). An addition pumping is provided by the titanium pump placed near the accelerating tube of the decelerating column (8). The residual pressure is·10^{-8}-10^{-9} Pa.

CONCLUSION

The carbon ion beam system is based on a few approved key innovations historically came from BINP (Novosibirsk) such as: electron cooling, using negative ions for stripping injection, storage rings. Electron cooling helps to make operation of the system easier by decreasing the beam emittance which results in stable ions energy and easy extraction. Example of CSRm operation shows that electron cooler can stable operates many months without switching off

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