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ELECTRON COOLING APPLICATION FOR HADRON THERAPY

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Abstract

The project of synchrotron for hadron therapy with electron cooling is developing in the Budker Institute of Nuclear Physics. The main goal of the project is design of the effective and low cost hadron therapy facility. The electron cooling is applied for an ion beam accumulation, cooling and preparation for slow extraction. The high quality cooled ion beam with an extreme small emittance and energy spread allows significantly decrease the synchrotron and beam transfer lines apertures. Moreover, the electron cooling can be applied for accumulation of short-lived radioactive isotopes that can be used for online visualization of treatment.

INTRODUCTION

Cancer is now the origin of death in one out of every four lives. Overcoming this scourge is a common goal for all of humanity. The common treatment for cancer includes surgery, chemotherapy and radiation therapy. The radiation therapy is one of the effective methods for cancer treatment and is prescribed to more than 50% of all patients. It is based on delivering high doses of ionizing radiation to localized tumours in the body. The goal is to destroy all the tumour cells with acceptable damage effects to the surrounding normal tissue, which is unavoidably irradiated.

Photons are used for most patients treated with a conventional radiotherapy. They deposit most of energy upstream of the tumour in healthy tissue. Special irradiation system from many directions and intensity modulation are used to increase the ratio of tumour to healthy tissue dose. The conventional therapy by photons is relatively inexpensive and wide world use.

Beams of protons and ions offer important advantages over conventional radiotherapy. The protons and ions power does not decrease exponentially with penetration in the body. Instead, they deposit more energy as they slow down, culminating in a Bragg peak. The depth at which the peak occurs can be operated by the value of particles energy are given by the accelerator. The proton and ion beams have little lateral scattering and can be precisely controlled. Therefore, the beam energy can be delivered accurately to the treatment volume without seriously damage of surrounding tissues or adjacent critical organs.

The hadron beam therapy has been shown to be effective in such cases as relatively large tumours of the esophagus and lung, liver, prostate and rectum, tumours of the head and neck, and eye.

For physical as well as for biological reasons, the light ions yield better clinical results than protons. Light ions, such as carbon, have a higher RBE than protons and provided treatment that is more effective for certain, deep-seated tumours that are often radio-resistant.

The clinical success of carbon therapy at the NIRS, Chiba, Japan and GSI, Darmstadt, Germany has led to the establishment of 10 more carbon ion therapy centres in Japan, Germany, Italy, Austria and China [1-3]. Several other centres are planned or are under construction in Europe and Asia. However, the high capital and operating costs limit the wide application of ion therapy. The development of robust, effective, and low costs ion therapy system is a paramount task to increase the availability of treatment to the patients.

ELECTRON COOLING APPLICATION

The idea of electron cooling was proposed and developed at BINP [4]. The electron and ion beams are converged inside the cooling section and during the particles co-moving the heat energy transfers from ions to electrons. Thus, the electron cooling reduces the spread in the longitudinal and transverse ion velocities, which means a decrease in the momentum spread and transverse emittance of the ion beam. Now, the low energy electron cooling is a routine and effective technique wide used in the high energy and nuclear physics. In particular, electron coolers are installed at the leading centres were methods of ion therapy was developed and continues to develop [5, 6]. However, at developing of standard design for ion therapy facility the electron cooling technology was not in demand. Usually, this is argued that the electron cooling is expensive and very complex equipment, redundant for therapy facility. The main goal of present article is the demonstration that electron cooling application helps design robust and not expensive medical accelerator.

The accumulated at BINP experience allows transferring the electron cooling technology to the application field. The ion therapy is the most favourable application. The ion beam energy range required for the cancer therapy is fully overlapped by the standard design of the BINP electron cooler (Fig. 1). This base design demonstrates the effective and robust long time operation at GSI (Darmstadt), IMP (Lanzhou) and LEIR (CERN) with success [7,8].

The cooled high intensity ion beam with extreme small energy spread and transverse emittance is a superior therapeutic instrument allowing irradiate tumour with high accuracy. Certainly, the size of beam spot on the tumour is determined primary by multiple scattering and fluctuations of ionization losses during the path in depth of tissues. Nevertheless, the electron cooling eliminates the beam spot broadening due to the inherent beam emittance and energy spread.

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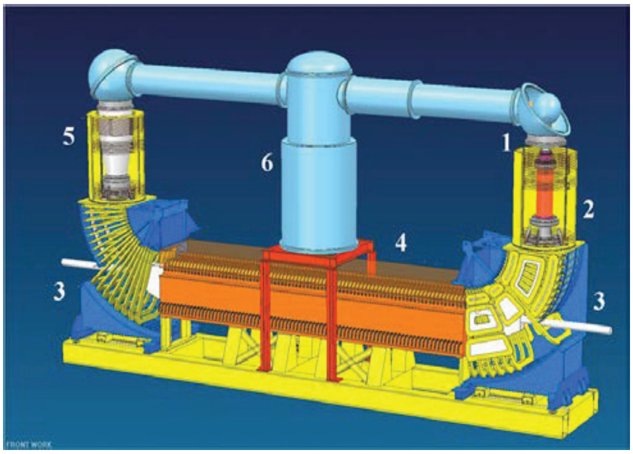

Figure 1: Layout of EC-300. 1 -electron gun, 2 - acceleration tube, 3 - ion beam vacuum chamber, 4 - cooling section, 5 - collector, 6 - high voltage generator.

The electron cooling allows accumulating the beam with high intensity that is important for increasing of the patient throughput. The suppression of beam losses due to space charge and IBS decreases influence of the radiation to the accelerator components and provides more safety of the treatment.

However, the insertion of electron cooler into the ion medical synchrotron with traditional design does not allows to fully revealing all possibilities. The most effective way is design the ion accelerator built around the key element - electron cooler.

The optimal structure for synchrotron with electron cooling has a racetrack mirror-symmetry lattice with achromatic arcs and long straight sections. One straight section is occupied by electron cooler. The set of quadrupole magnets should provide flat and equal betatron functions of high enough value, to achieve the optimal cooling decrements. In the opposite straight section the RF resonator, injection and extraction elements are installed.

In addition, the lattice shall include equipment for a transverse coupling compensation, caused by the cooling solenoid. The longitudinal magnetic field in the main cooling solenoid is constant for all range of the ion beam energies. Thereby at injection energy, the coupling influence is significant. The effective and compact solution is based on the application of sqew quadrupoles that ramping in synchronization with the beam energy.

Clear that the circumference of the synchrotron with electron cooling will be larger than for machine with traditional design. This circumstance contradicts the current trend towards the compaction of medical accelerators. Nevertheless, the resulting increasing in the synchrotron dimensions is insignificant especially in comparison with the area occupied by the total facility.

The small emittance of ion beam gives the possibility to decrease the apertures of synchrotron and HEBT elements significantly. It leads to decrease the weight, power consumption and cost of the synchrotron and the beam transfer lines. To be fair, it should be noted that the energy consumption of the electron cooler partially hides the positive effect. The most suitable would be the application of superconducting technologies in the implementation of the electron cooler magnetic system.

The advantages of small beam size are most evident at the design of a superconducting rotating ion gantry and beam scanning system. Application of the helium free magnets with maximum field about 4 T and small aperture about 15 mm allows design the compact rotating ion gantry with low weight. The small aperture of bend magnets leads to decrease the stored energy. The cooled beam using reduces the thermal load of the magnet assembly caused by particle losses.

The decrease of scanning magnets aperture gives possibility to increase the scanning rate. This seems important to reduce the total time of treatment and can be effective at irradiating of movable organs.

The minimum beam emittance at cooling is depends on the beam intensity and energy. At injection energy the beam emittance limited by the space charge phenomena, at extraction energy by IBS. For minimizing of synchrotron apertures, the injection energy of carbon beam with the intensity 10^{10} particles per pulse should be increased up to 20 MeV/u. For these purposes, the fast cycling booster in combination with the low energy injector (for example electrostatic tandem) can be applied. High repetition rate of booster allows accumulating and cooling the high intensity beam at the main synchrotron. The total cost of booster and injector is comparable with cost of the traditional ion linear accelerator with energy 6-7 MeV/u. This scheme is flexible and can be used for the production of different types of ions.

The two-stage acceleration scheme with electron cooling allows easy production and accumulation of the short-lived PET isotopes (as C^{11}, N^{13}, and O^{15}). The short-lived radioactive isotopes are produced in result of interaction of ion beam from booster with nuclei of gaseous target. The radioactive isotopes beam is injected into the main synchrotron for accumulation, cooling, and acceleration. The irradiation of tumour by short-lived radioisotopes in the treatment room equipped by PET tomography gives the possibility to build the online therapy. The possibility to observe the irradiation process in time is very promising for solving problem of movable tumours. As the rate production of PET isotopes is not so high, the treatment time for whole tumour will be increased. Therefore, the optimal scenario is the tumour marking by the radioactive labels in amount enough for online tracking and then irradiation the target volume by carbon beam.

Also for irradiation of movable tumours, the operative beam energy changing by the cooling friction force can be used.

EXTRACTION

In the synchrotron with electron cooling, few extraction schemes can be arranged. First is the traditional resonance extraction. The electron cooling leads to significant decrease of beam losses at extraction.

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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 and fast control of the transverse profile and current of electron beam allows fine adjustment of the $^{12}C^{5+}$ ion beam intensity and spot size. This type of extraction provides high level of the patient safety from over irradiation during treatment (see Fig. 2).

The small emittance and narrow momentum spread enables realize original scheme of extraction by small portions with the low-aperture pulsed high repetition kicker application. This scheme was proposed and applied in the COSY facility [9].

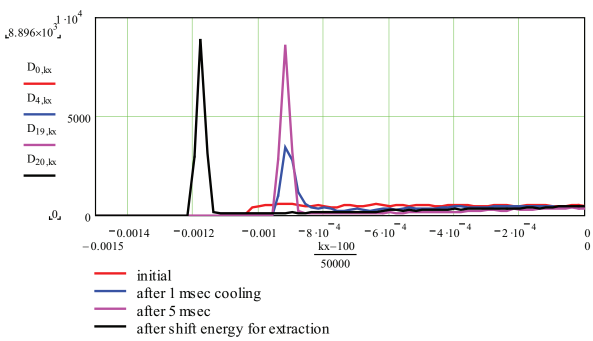

Figure 2: Computer simulation of portion extraction.

The circulating cooled ion beam can be split by cooling force with the well-controlled intensity in the portion.

The beam is shifted close to the septum by the local distortion of orbit. The flat momentum distribution of ions is prepared by the fast scanning of electron beam energy ($\pm 1.5 \cdot 10^{-3}$). After that, the electron beam energy is shifted to the edge of distribution. The neighbour ions cooled to the new energy and forming the portion of required intensity. Due to nonlinearity of friction force, the most part of beam is not affected. After that, the beam as whole fast shifted by the betatron core. The formed portion of beam comes into the kicker aperture, kicked out over septum and extracted. The circulated beam is slowly shifted back as whole by the betatron core reverse. The system is ready to start the forming of new portion. The proposed repetition rate of portion extraction 200 Hz is in good agreement with simulations [10].

EXPERIMENTS WITH COOLING

For demonstration of the electron cooling in action the results of recent experiments in CSRe (IMP, Lanzhou, China) and LEIR, CERN are presented [8, 10, 11].

At Fig. 3, the standard operation cycle of CSRe including the accumulation with cooling at injection energy and next acceleration of carbon beam is shown.

At Fig. 4, the evolution of ion beam profile in LEIR cycle is presented. The cycle starts from two injections with cooling, and then Pb^{54} ion beam is accelerated from 5 MeV/u to 71 MeV/u.

At Fig. 5, the Schottky signal of carbon beam with energy 400 MeV/u during cooling at CSRe is presented.

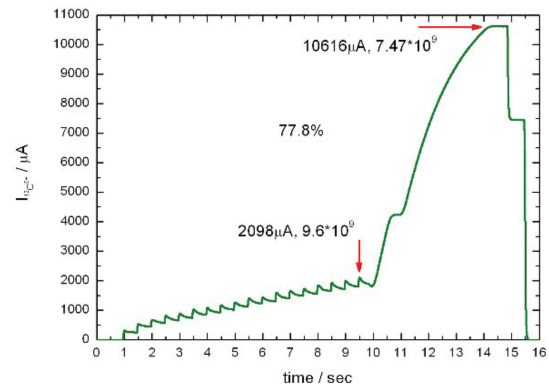

Figure 3: Beam current at single cycle: accumulation at CSRe with electron cooling $9.6 \cdot 10^9$ carbon ions beam on energy 7 MeV/u, then acceleration up to 600 MeV/u.

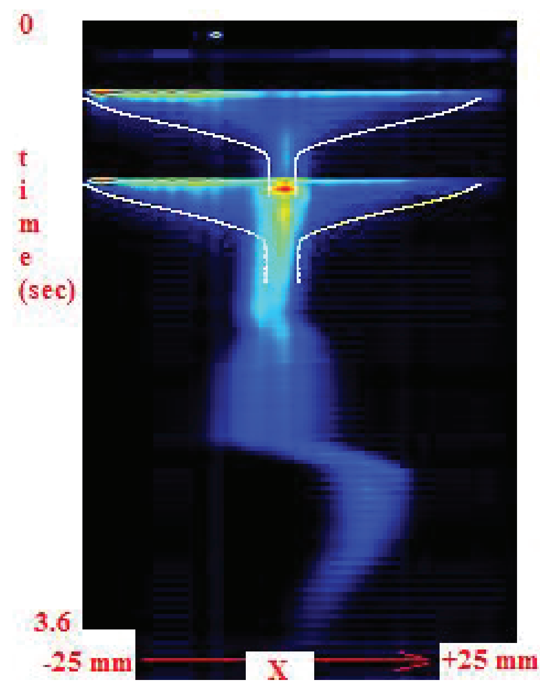

Figure 4: Pb^{54} ion beam profile at LEIR (CERN) cycle.

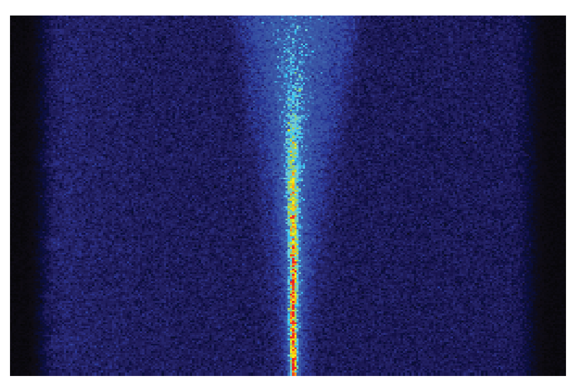

Figure 5: Cooling of carbon beam with energy 400 MeV/u at CSRe (IMP, Lanzhou).

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BINP PROJECT

Base on the described above conception the carbon ion medical accelerator is developed in BINP [12, 13]. The accelerator includes the tandem accelerator, the rapid cycling booster, and the main synchrotron with electron cooling. The synchrotron provides $^{12}C^{6}$ ions beam with the average intensity of 10^{10} particles per pulse in the energy range from 140 MeV/u to 430 MeV/u.

The comparison of main parameters of accelerator with PIMMS [14] is presented in Table 1. The main parameters of electron cooler for medical synchrotron are listed in Table 2.

Table 1: Main Parameters of Accelerator

Parameter	BINP	PIMMS
Injector	Tandem & rapid cycling booster	Linac
Injection energy	30 MeV/u	7 Mev/u
Intensity	10^{10} per cycle	10^{9} per cycle
Circumference	83 m	75 m
Electron cooling	EC-300	-
Synchrotron bend magnet gap	36 mm	72 mm
Synchrotron quad. bore diameter	70 mm	170 mm
HEBT bend magnet gap	20 mm	62 mm
HEBT quad. bore diameter	38 mm	80 mm
Extraction	Resonance, recombination, portion extraction	Resonance
Ion gantry	SC rotating	-

Table 2: Main Parameters of Electron Cooler

Parameter	Value
Electron beam energy	Up to 300 KeV
Total length	7.5 m
Cooling length	4.8 m
Magnetic field	0.1 – 0.15 T
Field quality	10^{-4}

CONCLUSION

BINP develops the hadron therapy facility based on the synchrotron with electron cooling. The robust design allows to decrease both capital and operation costs of the facility. The electron cooling allows significantly decrease the apertures of synchrotron, HEBT, gantry, and scanning system. Application of the short lived radioactive isotopes, and the energy scanning can help to solve the movable tumours problem. The electron cooling allows application different types of extraction for both raster and spot scanning simultaneously.

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