RADIATION THERAPY FACILITY BASED ON CARBON ION COOLER SYNCHROTRON

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Abstract

The irradiation of carbon ion beam cancer is very effective and successful treatment as was demonstrated at NIRS (Chibo) and other laboratories [1]. The scattering ion on the way to irradiation point so huge that initial small momentum spread and emitances cooled ion beam looks luxuries that really not necessary. At this article discussed way cooling can made this facility cheaper and more reliable. At this year started project this facility for the company IREN P.R. China. At report made short introduction acceleration aspects of this project development at BINP (Novosibirsk).

INTRODUCTION

The first public discussion idea using electron cooling for carbon ion beam cancer therapy facility had place on ECOOL05 workshop [2]. The carbon ions for irradiation should have energy at range 140-430 MeV/u for deep located cancer tumour [3]. If used scanning technique for distribution the ions pellets with radius 1 mm across 3D sphere radius 1 cm the $2*10^8$ of ions should be split on the more then 1000 portions with $2*10^5$ ions at each pellet. For repetition rate of the pellets 100 1/s this procedure irradiation tumour need as minimum 10 sec. So precise manipulation with ion beam can be made after strong collimation final beam or with preliminary cooled ion beam. The collimation produced additional problems with activation the material of the ion beam channel and need increasing initial ion beam intensity. The electron cooling shrink the ion beam after acceleration (when rule of the space charge became small) at very narrow cylinder with radius less 1 mm and momentum spread less 10^{-4} that made this manipulation procedure with the beam more easy technically and decreased the useless losses ion beam at many order magnitude. The fig.1 show photo of nuclear emulsion foil after exposition under proton beam cooled at the first cooler EPOHA (BINP). After recombination at cooler H^o atoms pass about 10 m.

Fig.1 Photo nuclear emulsion irradiated the 65 MeV atoms hydrogen generated at NAP-M electron cooler.

The second aim of using the electron cooler is help at accumulation the ion beam at injection. The first shoot of the multi turns injection the ion beam occupy usually the main part of the storage ring available acceptance. The electron cooling concentrated the ion beam at small dense core and make main part of the ring acceptance free for repeated new injection. This procedure became standard at the slow cycle synchrotron for increasing the ion beam intensity. Fig.2 show example of this cycle operation at China storage ring CSRm equipped new generation of the electron cooler designed and fabricated at BINP [4]. This carbon ion beam accumulated and cooled on the injection energy 7 MeV/u and then accelerated up to 1 GeV/u.

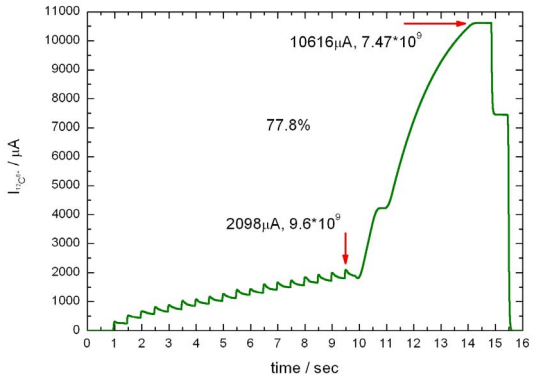

Fig.2 The ion beam current versus time at CSRm cycle with acceleration from 7 MeV/u to 1000 MeV/u.

At the first 10 s of the cycle the ion beam accumulated and intensity increase by multi turn injection repeated with half second period. Then start acceleration and the ion current increased by increasing the revolution frequency at the storage ring CSRm. The parameters of CSRm close to parameters need for our project the therapy system.

ACCELERATION COMPONENTS

The acceleration complex consist from the injection tandem based on the ELV electrostatic accelerator with 1.25 MV high voltage terminal. Then beam came to the booster ring and accelerated up to 30 MeV/u. The carbon beam with repetition rate 10 Hz injected and accumulation with an electron cooling at the main ring. After accumulation 10 injections the ion beam accelerated to required energy 140-430 MeV/u and extracted at the irradiation rooms.

INJECTOR

The tandem electrostatic accelerator with 1.25 MV at the high voltage terminal is used as the accelerator

complex pre-injector. For generation of the negative carbon ions C^- and hydrogen negative ions H^- two identical pulse sources of the sputtering type are used. The 20 keV beams of negative ions are transported along the low energy channel into the tandem accelerator. The negative ions accelerated in the first accelerating tube and stripped charge (C^{-1} at C^{+3}) while passing the vapor-magnesium target and accelerated again in the second accelerating tube. Then the carbon ions with energy of 0.417 MeV/u or 2.52 MeV protons are injected via the transport channel into the booster accelerator.

Table 1 Basic parameters of the tandem accelerator

Particles	Carbon ions C^{+3}	Protons p
Energy	0.417 MeV/u	2.5 MeV
Pulse intensity	$3.8\cdot10^9$ (30 μA)	$3\cdot10^{10}$ (150 μA)
Repetition frequency	10 Hz	10 Hz
Pulse duration	Up to 2 ms	up to 2 ms
Emittance	5 π mm mrad	2 π mm mrad
Energy spread	10^{-4}	10^{-4}

As the main source of the negative carbon ions we propose the sputter source. The source of such a type is being successfully operated in the accelerator mass spectrometer developed by BINP for the Accelerator Mass Spectrometer. This design was tested and with some modifications will used as prototype ion source.

BOOSTER

A fast-cycle 10 Hz synchrotron is used as an intermediate step of acceleration between the injector and the main ring. The presence of this step enables us to reduce substantially the space charge effects thereby to improve the cooling efficiency during storage of the intense ion beam in the main synchrotron. Maximum energy of the carbon ions $^{12}C^{+4}$ is 30 MeV/u and intensity is up to $2\cdot10^9$ particles per cycle.

Table 2 Characteristics of the booster synchrotron

	C-mode	p-mode
Type of particles	$^{12}C^{+4}$	P
Injection energy	0.417 MeV/u	2.5 MeV
Extraction energy	30 MeV/u	245 MeV
Injector	Electrostatic tandem	
Cycle intensity	$2\cdot10^9$	$5\cdot10^{10}$
Injection scheme	Multi-turn	
Extraction scheme	Single turn	
Magnet PS	Resonance scheme (10Hz)	

MAIN SYNHROTRON

Synchrotron is a high energy accelerator producing the carbon ion $^{12}C^{+6}$ beams with an energy ranging from 140 to 430 MeV/u for the cancer therapy [5]. For the active three-dimensional scanning it is necessary to vary the extracted beam energy with high accuracy. The intrinsic specificity of the complex is the use of electron cooling system providing extremely small transverse emittance and energy spread of the ion beam. The electron cooling device enables the control of the extracted beam energy by varying the energy of electron beam simultaneously with the synchrotron magnetic field. A feasibility of the beam accelerating or its decelerating has been demonstrated in a number of experiments. In the time-share mode, the synchrotron can serve three different treatment rooms. The switching time is less than 100 ms in case of using the beam of the same energy in all the treatment ports.

Table 3 Synchrotron basic parameters

Type of particles	$^{12}C^{+6}$	
Energy of injection, MeV/u	30	
Energy of extraction, MeV/u	140÷430	
Magnetic rigidity, T·m	6.7	
Circumference, m	82.944	
Revolution frequency, MHz	0.89	2.63
Injection field, T	0.39	
Maximum field, T	1.63	
Betatron frequency, hor./vert.	2.76/2.82	

COOLER

The cooler should have fast changing the high voltage potential for using at the synchrotron cycle from injection energy 16 kV and up to 234 kV for top ion beam energy. Fast manipulation of the rectifier energy with good precision required special design of the high voltage rectifier. As prototype for design used 300 kV cooler fabricated for CSRe [4]. Fig.3 shows the calculation results for cooling the beam of carbon ions of various intensities during injection into the synchrotron at energy of 30 MeV/u. The injected beam emittance (1σ) is ~0.8 cm·mrad, initial spread is $2\cdot10^{-3}$, and the beam is bunched, the bunch length is about 1/3 of the synchrotron circumference. The electron cooling parameters are the following: the cooling section length is 480 cm, the longitudinal magnetic field is 1.5 kG, the electron beam radius is 12 mm, the beam current is 0.4 A. The transverse emittance and energy spread are effectively damped in 300 ms. The injection type is a one-turn injection with a shift relative to the RF equilibrium phase, the injection repetition rate is 10 Hz, the booster circumference is 0.33 of the synchrotron circumference.

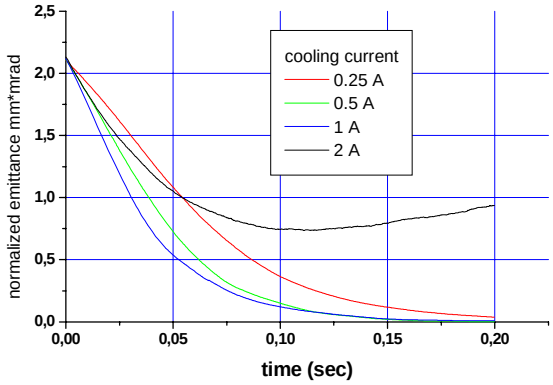

Fig. 3 Evolution of normalized transverse emittance during cooling for the C beam of intensities at the energy of 30 MeV/u with different cooled electron beam current.

PELLET EXTRACTION

The scheme operation the pellet extraxtion is the following. Upon the ion beam acceleration up to the required energy, RF amplitude is off and the beam is de-bunched. Then ion beam cooled and 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 electron cooler energy adjusted for cooling small part of ion beam as demonstrated fig.5.

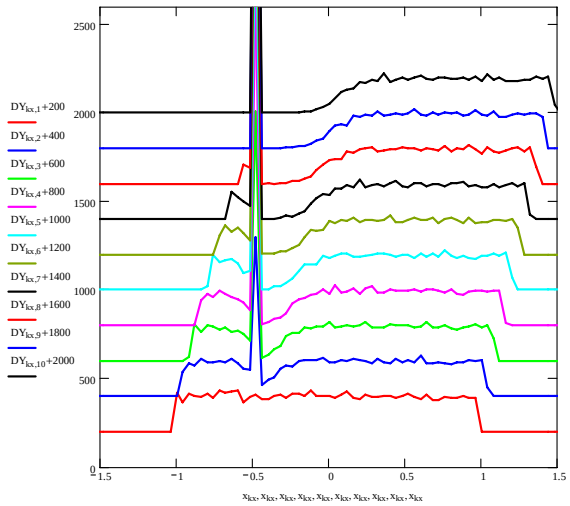

Fig.4. Combined action of the electron cooling (200 kV, 1 A) and betatron core accelerating the 30 V/turn.

In order to improve the extraction efficiency, it is necessary to clean the septum knife region from the "tail" ions. The clearest way is the use of the betatron core accelerating the ion beam and "separating" the main beam from the region where the beam is prepared for its extraction. The core moderate voltage at each turn increases energy of the ion beam moving it aside the septum. In this case, the maximum electron cooling strength should be sufficient for the confinement and cooling the ions in the extraction region. 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. For the beam extraction the fast kicker, electrostatic septum and permanent magnet septum of the Lambertson type are used.

CONCLUSION

The carbon ion beam system based on few approved key innovations historically comes from BINP (Novosibirsk): electron cooling, using negative ions for stripping injection, storage rings. Using booster system decreased preinjection electrostatic system energy to 1.2 mV and open proton beam mode operation at parallel with Carbon beam with relatively high energy 250 MeV. Electron cooling help made operation of system more easy by low emittance and as results more stable energy and easy extraction. Example of CSRm operation show that electron cooler can operated few months without switch off and problems with reliability mainly came from the electronics main ring and the injectors systems. This systems should designed with large safety reserve far from maximal parameters

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