CARBON ION ACCELERATOR FACILITY FOR CANCER THERAPY

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Abstract

A carbon ion or proton beams are a superior tool to x-rays in both physical and biological doses in treating a cancer. The carbon beam has an advantage in treating radiation resistant and deep-seated tumors. The main limitation of wide application is a high cost of facility. This problem can be solved by our carbon ion accelerator facility proposal on the base of Cold Beam Synchrotron. The main feature of the facility is an application of electron cooling device. The ion beam is cooled down and the beam emittance and an energy spread are decreased. The final high quality cold ion beam with small transverse emittance and momentum spread allows to decrease significantly the aperture of the synchrotron and components of high energy beam transfer lines.

INTRODUCTION

The carbon ion accelerator facility for cancer treatment is designed in BINP [1, 2]. The accelerator facility consists of an injection complex, the main synchrotron with electron cooling, the high energy beam transport lines, three fixed treatment ports (horizontal, vertical and combined) and superconducting gantry. Preliminary layout of CBS facility is presented in Figs.1, 2. For radiation shielding and operation costs optimization accelerators are placed in the underground hall without housed crane. The equipment loads from the technical floor through few hatches by temporal cranes.

The injection complex placed inside the main synchrotron includes a pre-injector and fast cycling booster synchrotron [3]. The 10 Hz booster provides possibility of pre-injector different types application (from tandem accelerator up to linac). The magnet rigidity of booster corresponds to proton energy 250 MeV. So, the independent proton treatment can be additionally served simultaneously with general carbon beam operation.

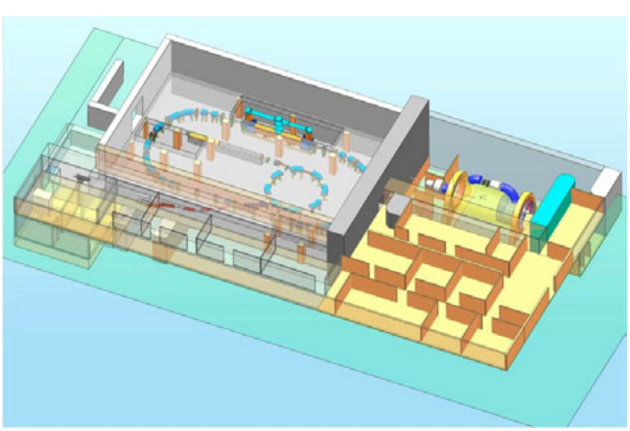

Figure 1: Preliminary layout of CBS.

The main synchrotron provides carbon ion beam with energy up to 430 MeV/u. The ion beams have very small transverse emittance and narrow energy spread owing to using the electron cooling device. Cold beam application allows significantly decrease aperture of main ring, high energy transport lines and gantry elements. At the same time, electron cooling enables to storage high intensity ion beam. So, the cost of facility, power consumption and treatment cost should be reduced. The precise ion beam energy variation and two unique schemes of beam extraction are possible under applying electron cooling.

One of the specific features in treatment is the use of a computer controlled high precision active beam scanning system synchronized with respiration and other organs motion. Through time-sharing CBS facility can simultaneously serve up to five separate treatment rooms. All the systems are totally integrated and handled through a distributed control system. This provides easy use and set-up, which in turn enables superior patient throughput (annual throughput in base design is about 2,500 patients).

The technical specifications of the CBS are based on the following premises for clinical requirements.

Table 1: Main CBS parameters

Clinical specification	3 fixed ports (horizontal, vertical and combined) and gantry port; proton port optionally;
Type of particles	C (carbon);
Particle energy	100-430 MeV/u;
Average dose rate	5 Gy/min;
Field size	20 cm x 20 cm for fixed ports;
Dose uniformity	± 4% of the prescribed dose over treatment field;
Delivered dose accuracy	±2%;
Irradiation method	Revised spot scanning system with synchronization of respiration;
Beam position accuracy in iso-center	± 0.5 mm;
Accuracy of patient positioning	Sphere with a radius of 0.5 mm;
Level and time for energy change	250 levels for energy; < 2.5 s;
Time for cut beam off	< 300 μs
Beam intensity	Average beam intensity $3{\cdot}10^9$ pps; Variable extraction time:1-10 s;
Beam spot size in iso-center	Size (2-10 mm (FWHM)) is changeable from cycle to cycle;

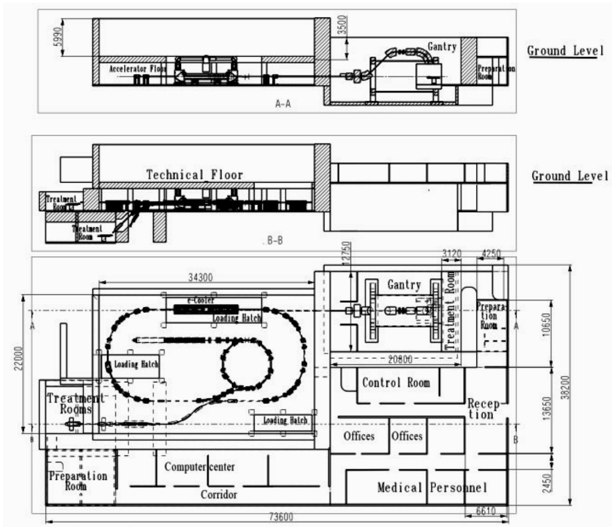

Figure 2: Preliminary layout of CBS.

MAIN SUBSYSTEMS

Injector

The injector system includes pre-injector and 10 Hz booster synchrotron. Booster application is premised on the follow CBS features.

The main synchrotron operation assumes the ion beam storage and cooling at injection energy during 1 s. The maximal intensity of stored beam is about 10^{10} ions. At low energy the equilibrium emittance of cooled high intensity beam is limited by space charge tune shift. So, the main synchrotron aperture reducing is sufficient only with increasing of injection energy.

The injection scheme with intermediate booster is flexible with respect to choice of pre-accelerator design and energy. Two ECR ion sources and linear accelerator with energy about 6 MeV/u is reliable and expensive. Reducing of pre-injector energy leads to complication of booster power supplies and RF system. Inexpensive tandem accelerator with terminal voltage 2 MV keeps acceptable booster design.

At least 60% of facility operation time, during the main synchrotron acceleration cycle and extraction, the injector system is unused. Beam line from the booster for independent passive proton treatment increase facility efficiency.

In further development the combination of booster with high average intensity and main synchrotron with electron cooling can be simply adapted for the production and accumulation of intense radioactive beams. The irradiation by beams of isotopes that decay by positron emission (C^{11} for example) provides treatment with online PET monitoring of delivered doze.

Main Synchrotron

The lattice consists of two symmetrical achromatic 180º arcs and two long drifts. One drift is reserved for electron cooling device. Other drift is instrumental for installation of RF cavity and injection/extraction elements. The arc includes four FODO cells with rectangular 30º dipole magnets. The dipoles with gap 36 mm and length 2.15 m have a maximal magnet field 1.62 T. For dispersion suppression in long drifts the scheme with missed magnet is realized. The instrumental drift is designed as regular FODO structure. The electron cooling drift consists of two quadrupole triplets with enlarged bore diameter. For circumference reducing the last triplet lens is combined with first arc lens. The main parameters of synchrotron are listed in Tab.2. The optical functions of main synchrotron are presented in Fig.3.

The longitudinal magnet field of the cooling section solenoid perturbs coupling of transverse betatron oscillations. The maximal value of coupling coefficient is $\Lambda = 0.15$ (that corresponds injection energy 30 MeV/u), and tune shift is $\Delta\nu_{x,y} = 0.03$. For compensation of coupling, three pairs of antysymmetrically excited sqew-quadrupoles are enough. The sqew-quadrupoles are installed between triplet lenses. So, the coupling is fully compensated out of the electron cooling drift.

Table 2: Parameters of Main Synchrotron

Particles	$^{12}C^{+6}$
Injection energy, MeV/u	30
Extraction energy, MeV/u	90-430
Magnet rigidity, T·m	6.65
Circumference, m	69.8
Revolution frequency, MHz	1.06 – 3.07
Tunes ν_x/ν_y	2.7/3.7
Chromaticity $\xi_x/\ \xi_y$	-4.6/-6.2
Max. β-function x/y, m	46.5/16.2
Max. dispersion, m	4.6
β-function in cooling section, m	15

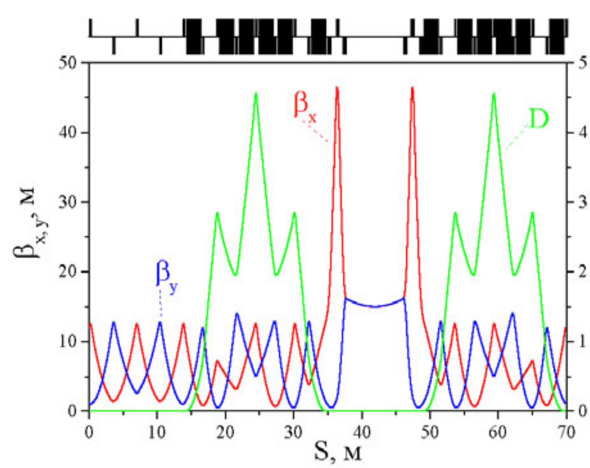

Figure 3: Optic functions of main synchrotron.

Electron Cooler

The electron cooling installation provides high intensity beam cooling and accumulation at injection, cooling or cold beam preparation at high energy, recombination extraction and local scanning of extracted beam energy. For the past few years BINP SB RAS designed, manufactured and successfully commissioned several electron coolers of new generation with hollow electron beam and electrostatic bending. It is EC-35 and EC-300 for HIRFL-CSR (IMP, Lanzhou, China) and EC-40 for LEIR, CERN [4-6]. The electron cooler for CBS bases on the same design (See Tab.3).

Table 3: Main Parameters of Electron Cooler

Electron beam energy, keV	up to 250
Cooling section length, m	4.6
Total length, m	7.8
Magnetic field value, T	up to 0.15

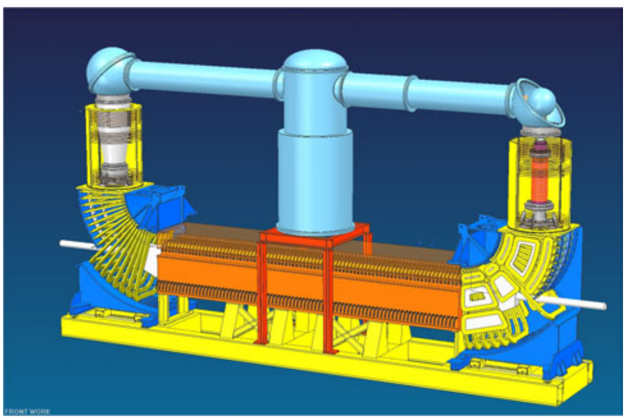

Figure 4: Layout of electron cooler.

For 10^{10} ions the transverse emittance of cooled down continuos beam is 1.2 cm·mrad at injection and 0.03 cm·mrad at 400 MeV/u. The cooling time is about 100 and 200 ms accordingly.

For the active scanning, the changing of extracted beam energy with high accuracy is necessary. The ion beam can be accelerated or decelerated by means of the friction force of electron beam. So, the electron cooler allows the local scanning of extracted beam energy by varying the electron beam energy. The predicted rate depends on the energy and intensity of ion beam and amounts from 20 MeV/u·s to 80 MeV/u·s.

Extraction

Two extraction schemes proposed for CBS facility. In the condition of cold ion beam the low aperture kicker with high repetition rate (up to 10 kHz) can be used for "pellet" extraction. By the local bump the reference orbit shifted into the kicker. By 1^{st} and 2^{nd} RF harmonics gymnastics the longitudinal phase space is divided on two buckets. Initially the whole beam is bunched in the first bucket. After that the small portion of beam ("pellet") can be adiabatically transferred into the second bucket and extracted. So, the whole beam can be divided up to 10 000 portions with controlled intensity of each "pellet".

The ion charge exchange by the electron beam recombination is utilized for other type of slow extraction. The small relative velocity between ions and electrons leads to the certain probability for recombination. Operating with the electron beam intensity and transverse profile gives the possibility for precisely varying of the intensity and emittance of extracted beam. The beam of $^{12}C^{+5}$ is separated in the first bend magnet after cooling section and extracted through septum placed downstream. Both schemes of extraction are combined and use the same septum.

HEBT & Gantry

The base design includes three fixed carbon treatment ports and the ion superconducting gantry. The total length of high energy transport lines (HEBT) for carbon beam distribution in the treatment ports is long enough. Reducing of the HEBT dipole magnets aperture to 20 mm leads to sufficient decreasing of power consumption.

Also, for gantry design it permits to reduce weight of rotating part and total weight. In the frameworks of CBS project BINP develops conceptual design as normal conductive "flexible" gantry as compact superconducting gantry. The isocentric superconducting gantry is based on the helium free bend magnets with magnet field up to 8.5 T. The gantry diameter is about 11 m and total weight is about 150 t [7].

Each treatment port is equipped by small aperture fast scanning system and monitoring. Reducing of aperture allows increasing the repetition rate of scanning system. This is important for successful treatment of moving organs in turn. The monitoring system is responsible for control and correction beam delivery for each voxel in order to ensure a safe treatment.

CONCLUSION

BINP SB RAS design the carbon and proton accelerator facility for cancer treatment of new generation. Application of electron cooling and compact superconducting ion gantry allows to reduce accelerator facility cost and operation expenses with increasing of efficiency. Conceptual design of CBS bases on BINP abundant experience in electron cooling technique development. Recent successful EC-300 commissioning and experiments with cooling of carbon beam in IMP, Lanzhou validate proposed conception once more [6]. The further facility optimization and detail design of components and subsystems is continued.

REFERENCES

[1] M. Kumada et al., PAC 05, Knoxville, 1108.
[2] V. Parkhomchuk et al., COOL05, Galena, AIP Conf.Proc. 821:365-369, 2006.
[3] E. Levichev et al., RUPAC06, Novosibirsk.
[4] V. Parkhomchuk, COOL05, AIP Conf.Proc. 821:249-258, 2006.
[5] V. Bocharov et al., NIM, A 532 (2004) p. 144-149.
[6] V. Parkhomchuk et al., RUPAC06, Novosibirsk.
[7] K. Zolotarev et al., Will be published.