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ACCELERATORS FOR MEDICINE AND OTHER APPLICATIONS

A Project for Synchrotron with Electron Cooling for Cancer Therapy

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Abstract—A project for a new generation of proton and ion accelerator facilities for cancer therapy has been developed at the Budker Institute of Nuclear Physics (BINP), Siberian Branch, Russian Academy of Sciences (SB RAS). This facility includes an electrostatic injector, a booster with a 10-Hz repetition rate, and a main synchrotron with electron cooling and beam transport lines for delivering the beam to treatment rooms. The application of electron cooling makes it possible to increase the beam intensity and reduce the apertures of both the synchrotron and the high-energy transport lines, as well as save construction costs and energy consumption as required by the accelerator complex. This paper describes the main features of the synchrotron and the requirements for its main systems and their parameters.

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INTRODUCTION

The main element of the proton–ion accelerator complex for cancer therapy [1–3] is a synchrotron with electron cooling. The synchrotron generates a carbon ion beam up to an intensity of 10^{10} ions per acceleration cycle with a 1-Hz repetition rate in the 140–430 MeV/n energy range (Fig. 1). The booster synchrotron serves as an injector providing the 30 MeV/n energy of injection. The ion beam is accumulated by repeated injection and cooled. Upon

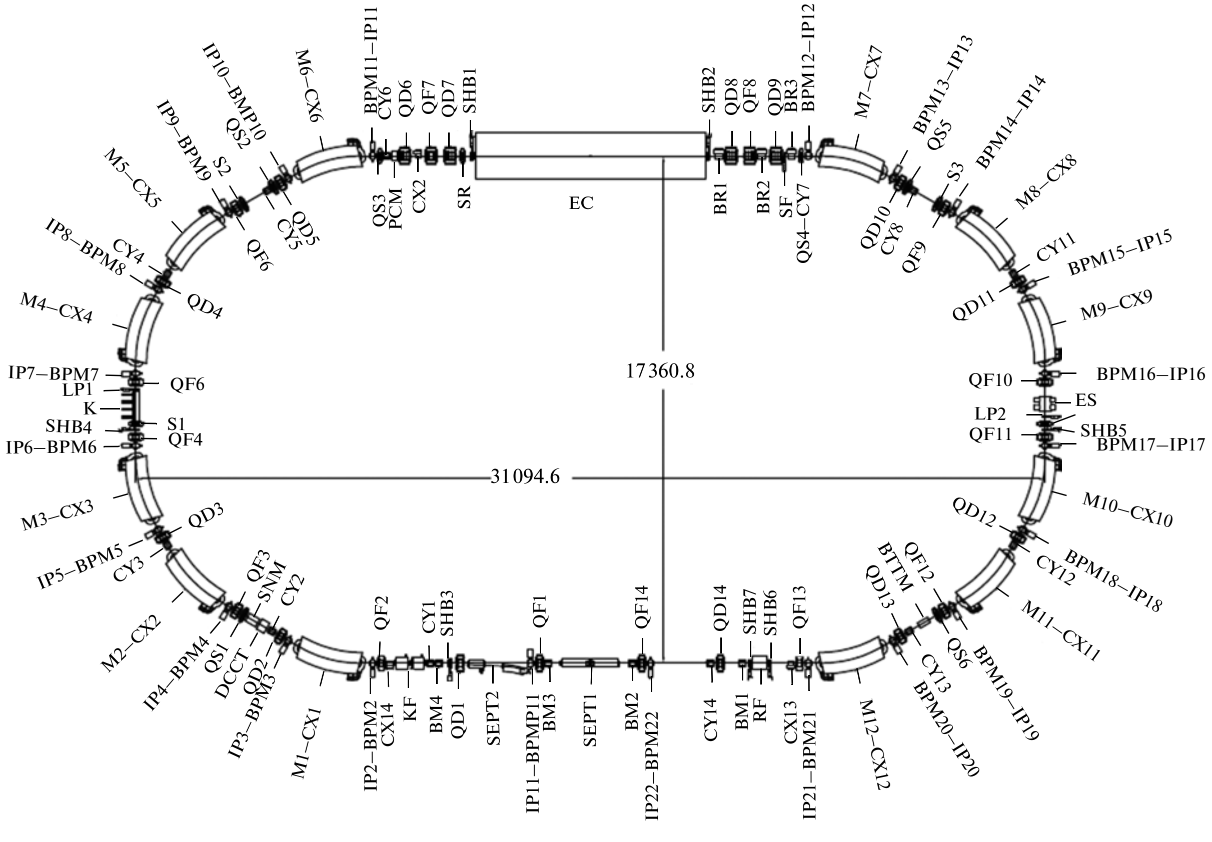

Fig. 1. General layout of the synchrotron: (M) dipole magnets, (QF, QD) quadrupole lenses, (CX, CY) dipole correctors, (BR, BM) bump magnets, (QS) skew quadrupole magnets, (S) sextupole magnets, (SEPT) septum magnets, (ES) electrostatic septum, (KF) kicker, (EC) electron cooler, (BPM) pickups, (RF—HF) resonator, (IP) ion pumps.

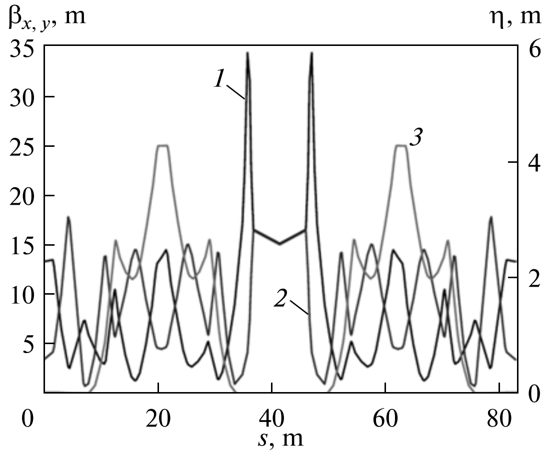

Fig. 2. Optic functions of the synchrotron: (*1*) horizontal βx–function, (*2*) vertical βy–function, and (*3*) dispersion function.

achieving the required intensity, the beam is accelerated to the desired energy and extracted into a high-energy beam transport line. By cooling the beam using extraction energy, an extremely small transverse emittance and an extremely small energy spread of the therapeutic beam are achieved. The structure of the synchrotron allows the beam to be extracted by three different methods: in portion ("pellet") beam extraction as a series of intensity-modulated pellets, resonance extraction, and recombination-based extraction. In addition, electron cooling allows the extracted beam energy to be smoothly modulated. A combination of these options allows us to deliver high-precision doses of radiation to tumors.

1. OPTICAL STRUCTURE

The synchrotron has a reflection-symmetry structure where the axis of symmetry passes the centers of rectilinear sections with a zero variance function. One section accommodates an electron cooler along with six lenses that provide equal and quite large (nearly 15 m) β functions (Fig. 2) at the electron beam interaction point. The opposite section is intended for locating the beam injection–extraction systems, while the adjacent gap is intended for inserting a wideband resonator to ensure the capture of the beam into the first harmonic. The horizontal and vertical acceptances of the synchrotron are $A_X = 8$ cm mrad and $A_Y = 2$ cm mrad with an energy aperture of 0.7%. The main parameters of the synchrotron are given in Table 1.

Table 1. Main parameters of the synchrotron

Type of particles	C^{6+}
Injection energy, MeV/u	30
Extraction energy, MeV/u	140–430
Magnetic rigidity, T m	6.7
Perimeter, m;	82.94
Revolution frequency, inj/ext, MHz	0.89/2.82
Maximum field, T	1.63
Betatron frequency, hor/vert	2.76/2.82
Max.$\beta x_{\max}/\beta y_{\max}$- function, m	35/18
$\eta_{\max}$, m	4.3
Orbit compaction factor, α	0.13
Emittance of the cooled beam, nm rad	20–150
Energy spread of the cooled beam	1×10^{-4}

The parameters of the extracted beam impose the following constraints on the amplitudes of the closed orbit distortions: at injection they are within ±10 mm horizontally and ±7.5 mm vertically; upon extraction, the local deflection (at the azimuths of the septum and sextupoles) is below ±1 mm and it is below ±5 mm in all other regions.

2. MAGNET SYSTEM

The magnet system of the synchrotron consists of 12 30°-dipole magnets ($R = 4.11$ m, $H = 1.65$ T, the gap is 36 mm), 14 quadrupole magnets of 70 mm in D ($L = 24$ cm, $G = 16$ T/m), and 14 quadrupole magnets of 100 mm in D ($L = 40$ cm, $G = 16$ T/m). Quadrupole lenses with an enlarged aperture are used in the cooling section and near the septa. In addition, we use 6 SQ-quadrupoles, 5 sextupoles, 16 horizontal and 12 vertical dipole correctors, and 7 bump magnets for a local orbit distortion upon injection and extraction.

3. INJECTION AND EXTRACTION FROM THE SYNCHROTRON

A single-turn injection with a shift relative to the RF equilibrium phase is applied (Fig. 4). A ferrite kicker ($L = 62$ cm, $H = 430$ G) is used, as is a 15.8° permanent septum magnet ($H = 5.7$ kG and the effective thickness of the knife is $h = 24$ mm).

The in-portion beam extraction as a series of pellets with a controllable intensity was made basic for spot scanning. After the acceleration and RF switch-off, the beam is debunched and cooled down. By scanning the electron beam energy relative to the mean energy, a flat distribution of the ions per pulse is created $\Delta p/p = \pm 2.5 \times 10^{-3}$. Further the electron beam energy is stabilized by the edge of the ion distribution per pulse. The nearby ions are bunched under the effect of friction forces, while the intensity of a portion is regulated by the time of the accumulation and the value of the detuning of the electron beam energy. By placing the kicker along with a dispersion that is sufficient for separating the main beam and the portion, a single-turn extraction of the portion is achievable. Local bumps are created at the places where the kicker ($L = 1.2$ m, $E = 9$ kV/cm), the electrostatic septum ($L = 40$ cm, $E = 37$ kV/cm), and the 13.5°-permanent sep-

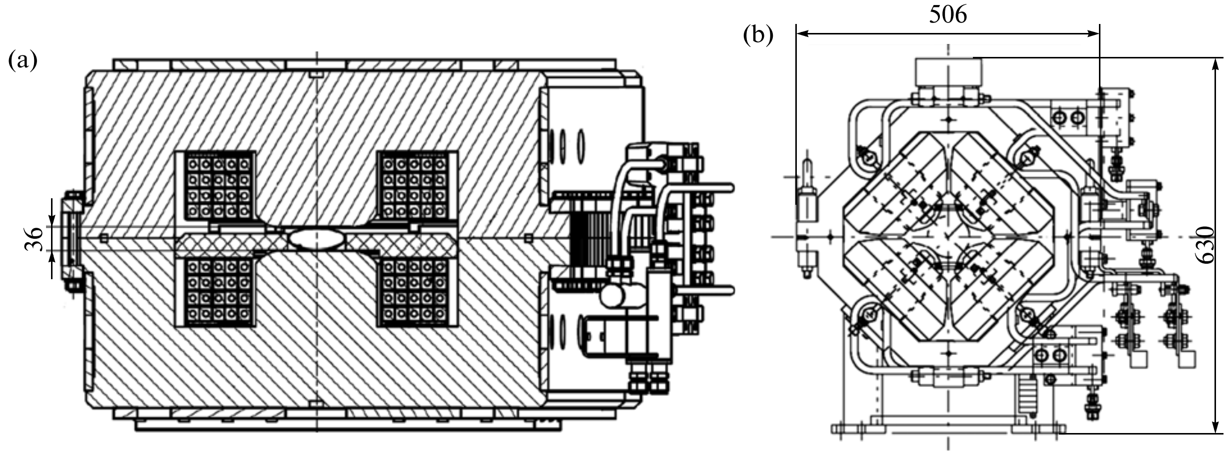

Fig. 3. Design of (a) a dipole magnet and (b) a quadrupole lens 70 mm in D.

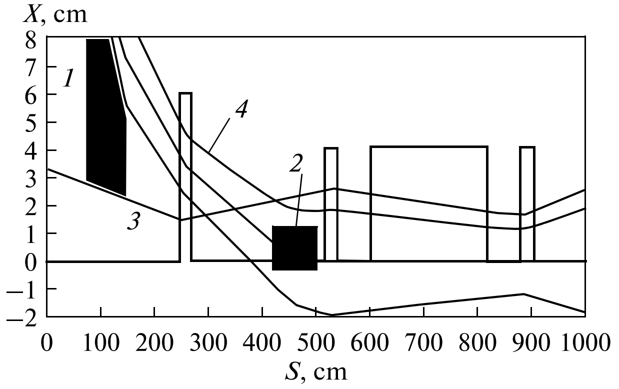

Fig. 4. System of injection into the synchrotron: (*1*) septum magnet, (*2*) ferrite kicker, (*3*) synchrotron acceptance limit, and (*4*) injected beam.

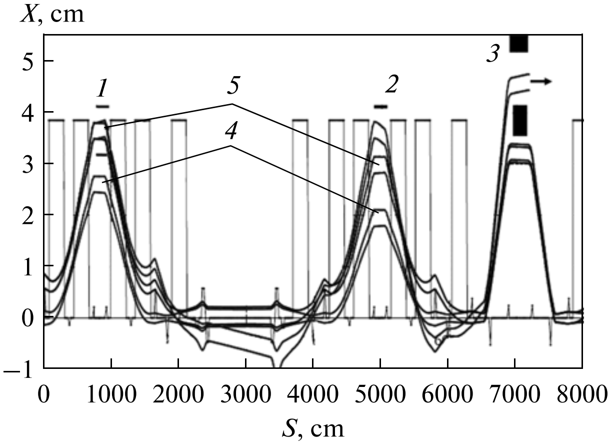

Fig. 5. Pellet extraction: (*1*) kicker, (*2*) electrostatic septum, (*3*) septum magnet, (*4*) the main beam, and (*5*) trajectory of particles with $dE/E = 0.0025$ (the kicker is off).

tum magnet ($H = 8.5$ kG, $h = 5$ mm) are located, and these bumps displace the orbit of the main beam towards the acceptance boundary (Fig. 5). At the azimuth of the kicker and the electrostatic septum, the orbits of the main beam and the portion are separated by 10 mm.

The recombination of carbon ions $C^{6+} \rightarrow C^{5+}$ during their passage through the cooling section is applied under another slow extraction scheme (Fig. 6). A small relative velocity between ions and electrons leads to a significant probability for such a recombination. By altering the electron-beam density, we can control the intensity of the beam being extracted. Like under other extraction schemes, the orbit of the main beam is brought to the knife of the septum magnet. A local bump is created at the exit from the cooling section, and the bump separates the orbits of the C^{6+} and C^{5+} beams by 8 m at its center, where a thin charge-exchange foil is inserted. After the stripping, both the angle and the coordinates of the ions are such that, after passing the semi-ring, they are over the septum-magnet knife.

The extraction based on the third order resonance is traditional for such facilities (Fig. 7). It should be noted that cooling significantly improves the quality and stability of the extracted beam current, which improves the control of the irradiation procedure.

Table 2. Main parameters of the electron cooler

Electron-beam energy, keV	up to 250
Beam current, A	1
Length of the cooling section, m	4.8
Magnetic field, T	0.1–0.15
Magnetic-field quality	10^{-4}
Electron-beam radius, cm	0.3–1.5

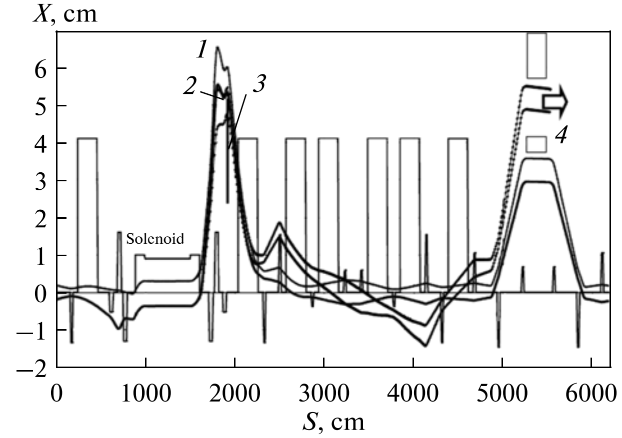

Fig.6. Recombination-based extraction: (*1*) the main beam of C^{6+}, (*2*) the beam of C^{5+}, (*3*) charge-exchange foil, and (*4*) septum magnet.

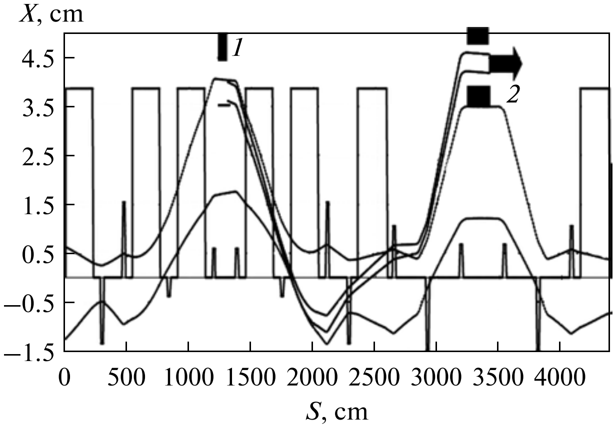

Fig.7. Resonance extraction scheme: (*1*) electrostatic septum and (*2*) septum magnet.

4. ELECTRON COOLING SYSTEM

The structure of the EC-300 electron cooler developed at the Budker Institute of Nuclear Physics (BINP) of the Siberian Branch, Russian Academy of Sciences (SB RAS), for the Institute of Modern Physics, Lanzhou, China, was accepted as a prototype [4]. The long-term and reliable exploitation of the EC-300 has proven the reliability of this design.

CONCLUSIONS

The use of the electron cooling method in medical accelerators for cancer therapy opens up new opportunities for improving the quality of a patient's treatment and reducing the costs required for the creation and exploitation of the accelerator complex. Works on designing and simulating the main elements of the complex are continuing at the BINP SB RAS.

REFERENCES

1. E. B. Levichev et al., "Carbon Ion Accelerator Facility for Cancer Therapy," in *Proceedings of RuPAC* (Novosibirsk, 2006), p. 363.
2. V. A. Vostrikov et al., "Electron Cooling for Cold Beam Synchrotron for Cancer Therapy," AIP Conf. Proc. **821**, 365 (2006).
3. M. Kumada et al., "The CBS - the Most Effective and High Performance Carbon Beam Source Dedicated for a New Generation Cancer Therapy," in *Proceedings of the Conference PAC05* (Knoxville, 2005), p. 1108.
4. V. V. Parkhomchuk et al., "Commission of Electron Cooler EC-300 for HIRFL-CSR," in *Proceedings of the Conference EPAC04* (Lucerne, 2004), p. 1419.