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A COMPACT SYNCHROTRON FOR CANCER THERAPY WITH HELIUM IONS*

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Abstract

In the frame of the Next Ion Medical Machine Study (NIMMS) activities based at CERN, a compact synchrotron for radiotherapy with high-intensity helium beams is designed. Interest in helium ions is growing in the major ion therapy centers, since compared to protons they provide superior dose distributions, thanks to their sharper lateral penumbra, and higher linear energy transfer. Their properties lie in-between protons and carbon ions, without the fragmentation problems of the latter. Moreover, their lower magnetic rigidity allows helium-ion accelerators to be more compact than the large carbon-ion machines. The synchrotron design presented in this paper is based on normal-conducting dipole magnets at 1.65 Tesla and has a circumference of 35 meters. Optimized for helium ions, it can also accelerate protons, for treatment and particle radiography, and other heavier species to smaller penetration depths. The design choices for the different systems are described taking into consideration the mechanical integration in a compact layout and operational flexibility. The technology readiness level is evaluated and R&D options to achieve higher performances and reduce energy consumption are identified.

INTRODUCTION

Helium therapy is gaining traction in the field of cancer therapy with particle beams and is considered to be the natural evolution of proton therapy because of its superior dose distribution (sharper lateral penumbra and distal fall-off) and higher linear energy transfer [1–3].

Today only the large multi-ion facilities, four in Europe (CNAO, MedAustron, Heidelberg and Marburg), can provide helium ions for trials and definition of protocols; however, their accelerators dimensioned to accelerate carbon and other ions up to 400 MeV/u are large and expensive, and are not optimized in terms of energy consumption.

Within the NIMMS (Next Ion Medical Machine Study) initiative, CERN is hosting and supporting a small international study group to design a facility based on a compact synchrotron, optimized for accelerating helium ions up to 220 MeV/u energy [4–6], called HeLICS (Helium Light Ions Compact Synchrotron). Two major initiatives, one in the Baltic region [7], led by the CERN Baltic Group, and one more recent in Switzerland [8], led by the Tera-Care Foundation, base their project on the outcome of the NIMMS preliminary technical design study, which will be completed in the next few months. A possible facility layout, for a centre based on a helium-ion synchrotron that combines therapy and research, is presented in [9]. It features two treatment rooms (one of them equipped with a gantry) and an experimental one, together with an area at low energy to produce radioisotopes for theragnostics.

THE HELIUM SYNCHROTRON

The synchrotron layout is shown in Fig. 1 and its parameters are in Table 1.

The medical synchrotron is fed by an injector linac that accelerates helium ions up to 5 MeV/u and provides protons at 10 MeV. The linac, which is described in [10], has three tanks: the first to bring the beam at 5 MeV/u, and two additional that can be powered to further accelerate the beams: helium ions up to 7.1 MeV/u, for the production of At-211 and other isotopes, and protons up to 10 MeV to mitigate space-charge at synchrotron injection.

The intensity for both helium and protons corresponds to 2 Gy delivered to a 1 liter tumour [11]. Accelerating such a relatively high intensity in one synchrotron cycle, i.e. 10-20 times higher than what the European medical facilities can do, allows beam delivery in FLASH modality. Time in conventional irradiation is also saved by applying

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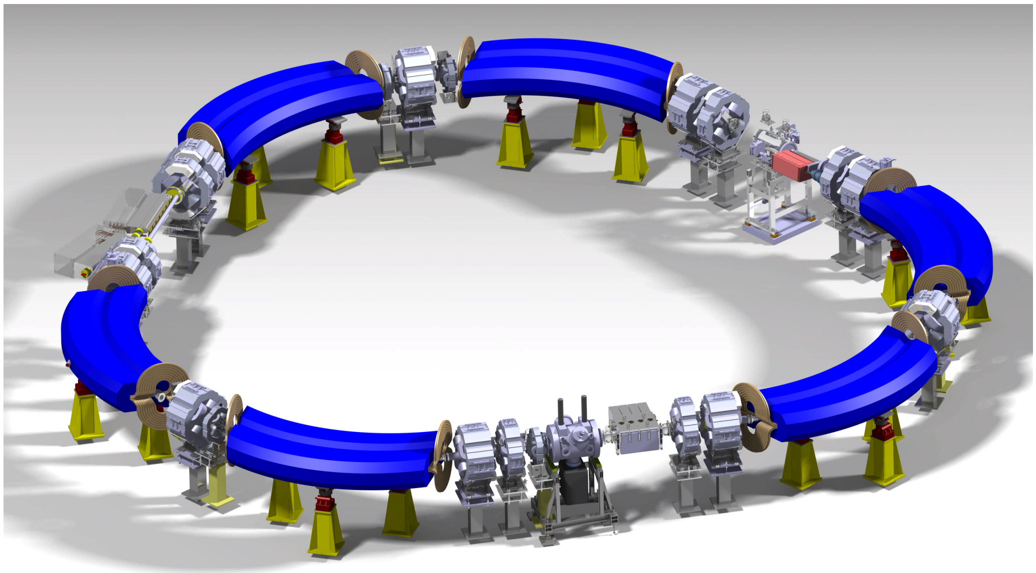

Figure 1: Layout of the HeLICS synchrotron.

Table 1: Synchrotron Parameters for Helium (and Protons)

Parameters	Value
Intensity /ions (protons)	8.2 (26) x 10^{10}
Injection energy (MeV/u)	5 (10)
Extraction energy (MeV/u)	220 (>330)
Circumference (m)	35
Max. beam rigidity (Tm)	4.5
H. emittance rms normalized (μm)	3
V. emittance rms normalized (μm)	0.8
Max. momentum spread $(\Delta p/p)_{\max}$	10^{-3}
H. tune at extraction	2.34 or 2.67
V. tune at extraction	1.15
Ramp time to top energy (ms)	650
Delivery mode	MEE and FLASH
Energy switching time (ms)	200

Multi-Energy Extraction (MEE), as used at HIMAC [12] and HITACHI proton synchrotrons [13], but not yet exploited in the multi-ion European centres. The latter employ different cycles for the different energies, requiring about 2 seconds to switch energy level, versus the 200 ms switching time possible with MEE. In HeLICS, the control system and the hardware low-level will be designed to comply with MEE.

As a drawback of the high intensity, the horizontal beam emittance is 3 µm rms normalized, significantly higher than in the European carbon ion synchrotrons, due to the Multi-Turn (MT) injection. The vertical emittance is designed to be 0.8 µm rms normalized, which is comparable to the values for the PIMMS study and CNAO [14]. Space-charge tune spread does not exceed 0.15 in vertical.

Table 2 shows the parameters for the MT injection. A simple linear bumper function has been assumed. The injector linac [10] has been dimensioned for a novel ECR source [15] that can achieve He^{2+} currents of 5 mA, which is important for production of radioisotopes. A conservative value of 2 mA is assumed for the He^{2+} source, within an emittance of 0.25 µm. A higher current will ease the MT injection and allow smaller horizontal beams, down to 2 µm. In this case space-charge limitations need to be carefully evaluated.

Table 2: Multi-turn Injection Parameters

Parameter	Value
Source intensity He^{2+}[mA]	2
Linac transmission	100%
Linac emittance rms, normalized [μm]	0.25
Horizontal tune	2.43
Injection offset x_i [mm]	0.5
Injection angle x_i' [mrad]	0.5
No. of inj. turns	18
Injection efficiency	0.62
Horizontal emittance [μm]	3.0
MT bumper function	linear

COMPACT LAYOUT

A triangular shape was chosen as baseline, with three long straight sections at zero dispersion. Because of the extremely compact layout and large horizontal emittance, from the very beginning mechanical integration was taken into account and studied in parallel with the optics, and iterations are presently ongoing to ensure the consistency of the design.

After a baseline optics was defined [16], all hardware elements and in particular magnet families and extraction septa, which dictate the length of the straight sections, have been dimensioned and positioned in the layout. For the multi-turn injection, the magnetic septum precedes the electrostatic one and is placed in straight section SS2. They are accompanied by fast bumpers decaying in approximately 100 µs. The electrostatic extraction septum shares the same section SS1 as

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the RF cavity, while the magnetic septum is positioned in the layout according to the required phase advance for the slow-extraction, that is in SS3.

Slow-extraction studies have allowed assessing the extraction septa specifications [17]. A new improved optics with reduced horizontal beam size and larger vertical one has recently been implemented, to fulfil aperture requirements at low energy [18] and detailed injection and extraction studies are ongoing with the new optics.

The main synchrotron magnets (MB) are 60^o with curvature radius 2.7 m, operating at 1.65 T. They have 30^o edges and, in addition, they carry a small combined function gradient of -0.5 T/m at maximum field, achieved by shaping the pole faces. The defocusing in the horizontal plane, due to the gradient and to the edges, allows keeping the vertical beta-function small after the strong focusing quadrupole (MQB) in between the main magnets used to suppress the dispersion. Two additional magnet families (MQF and MQD) in the long straight sections assure the regularity of the optics and the tunability of the machine. Table 3 summarizes the main magnet parameters [19].

Table 3: Main Magnets Parameters

Parameters	**MB**	**MQB**	**MQF**	**MQD**
No. of magnets	6	3	3	3
B_0 (T)	1.65	-	-	-
B_1 (T/m)	-0.50	12.26	12.26	-12.15
Edge angle	30^0	-	-	-
Field at pole tip	1.65	0.80	0.80	0.80
Mag. length (mm)	2866	400	400	235
Aperture (mm)	200×70	130	130	130
Current (A)	2470	338	338	-335
J density (A/mm^2)	7.8	5.4	5.4	-5.3
Power (kW)	106	10	10	7
Width (mm)	1050	760	760	760
Length (mm)	2900	489	489	324
Weight (kg)	8043	1050	1050	596

Previous studies of magnets with strong curvature showed that field harmonics and polynomial expansion on the mid-plane are different in curved geometry [20] and that integrated quantities along the magnet are not enough for compact rings [21]. A better model is being implemented, to improve tracking tools and provide magnet specifications accounting for higher order effects, with the goal of reducing tunability and possibly number of components [22].

For compactness, most of the elements have combined functions. Sextupoles also carry coils for orbit correction, as designed for SESAME [23]. Three of them, for chromaticity correction, are located in the short straight section, next to the MQB between the two dipoles [18], and an additional one for slow extraction will be introduced in the long straight section. Nine Beam Position Monitors are located inside the MQDs and the MQBs. The tune measurement system, based on Direct Diode Detection, allows measuring bunched and unbunched beams. The RF-KO exciter for the slow extraction will also be used to drive the oscillations for tune measurement. A screen close to the septum is used to check position and profile of the injected beam, and a DC transformer plus a wall current monitor are implemented in the layout.

The RF system is composed of four FINEMET cells, providing a peak voltage of 2 kV in a compact device 682 mm long [24]. It allows acceleration over a wide range of frequencies and can operate in double harmonic mode, to increase bunch length and reduce space-charge effects at injection. The time necessary to reach the flattop energy is 650 ms.

ENERGY EFFICIENCY

The synchrotron design is based on existing technology and in particular on warm magnets that reach 1.65 T and have a relatively high current density, required for compactness. As a preliminary step to optimising energy efficiency, consumption of the main magnets of HeLICS has been estimated and compared with CNAO's carbon ion therapy synchrotron (Table 4), which values have been computed in [25], based on one year of operational data. The average current used in the CNAO study was extrapolated to estimate HeLICS performance, since it covers the same treatment range for protons and ions as CNAO.

Table 4: Dipole Power Consumption in CNAO and HeLICS

Parameter	**CNAO**	**HeLICS**	**HeLICS MEE**
C^{6+} / He^{2+} (kW)	34.3	35.7	32.1
Proton (kW)	3.1	5.9	5.3
Peak Power (kW)	617	707	–

The present HeLICS magnet design results in a power demand comparable to CNAO, due to the high current density and magnetic saturation at the upper end of the treatment range, with the advantages of a more compact layout. Ongoing research is investigating the use of high-temperature superconducting (HTS) dipoles, aiming to retain compactness while reducing energy consumption. For the septa, the other large energy consumer, pulsed devices will be used and a novel solution will be studied and prototyped to reduce energy consumption by more than 50%.

CONCLUSIONS

Helium ion therapy, with its superior dose delivery accuracy compared to protons, could significantly improve cancer treatment outcomes, reduce adverse side effects, and significantly improve the quality of life of patients. The HeLICS synchrotron as a new compact, cost-effective and environmentally sustainable accelerator is designed to make this new treatment modality widely accessible.

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