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ORIGINAL PAPER

New accelerator designs: NIMMS

Maurizio Vretenar[1] · Elena Benedetto[2]

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Abstract

Purpose This article summarises the presentation given at the "Hadrontherapy: status and perspectives" event.

Methods Structure, methodology, and objectives of the Next Ion Medical Machine Study collaboration are introduced. Its four Work Packages are: small synchrotrons for particle therapy, curved superconducting magnets for synchrotrons and gantries, superconducting gantry design, and high-frequency ion linacs. Synchrotrons under study include a superconducting design for carbon ion therapy, and a normal-conducting design for ions up to helium. Superconducting magnet R&D is carried out in two European projects. Within the scope of these projects, five magnet demonstrators with different technologies are in different phases of design and production. Beam optics and mechanical design of a superconducting gantry for carbon ions is being developed. A high-frequency linac design has been completed, and tests are starting on a prototype high-frequency injector.

Results The designs of two facilities based on NIMMS technological developments are presented. A carbon ion research and therapy facility was designed for the SEEIIST project, based on a conventional synchrotron with high beam intensity. A smaller facility aimed at cancer therapy and research with light ions, in particular helium beams has also been designed. Both facilities can produce FLASH-type beams.

Conclusions The traditional design of carbon ion therapy facilities can be improved by adding new features as higher beam intensity and new beam extraction schemes. A cost-effective alternative to the traditional design is a compact facility for light ions, exploiting the potential for treatment with helium ions and allowing an experimental programme with different ion species.

Keywords Accelerator · Synchrotron · Superconducting · Gantry · Linac · Helium

1 The next ion medical machine study: origins, objectives, structure and collaborations

The Next Ion Medical Machine Study (NIMMS) is an international collaboration based at CERN, established in 2018 with the support of the CERN Knowledge Transfer for Medical Applications (KT-MA), with the goal of developing new technologies for the future generation of accelerators for cancer therapy with ions heavier than protons [1].

NIMMS has been structured to follow in the successful line of the old PIMMS (Proton-Ion Medical Machine Study) initiative of 1996–2000, which led to the construction of two ion therapy centres in Europe, CNAO and MedAustron [2]. From the PIMMS study, the new initiative borrowed a part of the acronym and the idea that CERN should contribute to the development of accelerator technologies for societal applications in the frame of wide collaborations, which contribute with ideas and resources and provide the vital connection with the final users of the technology. Times were mature for a renovated CERN engagement because after the demanding period of LHC construction and commissioning, some limited resources were again available for accelerator activities not linked to CERN's core scientific programme. The importance of showing the societal impact of technologies developed for particle physics became again clear at CERN, as an essential condition to build support for the future CERN projects.

To kick-off the NIMMS activity in consultation with the European ion therapy community, a Workshop on "Ideas and technologies for a next generation facility for medical

✉ Maurizio Vretenar
Maurizio.Vretenar@cern.ch

1 European Organization for Nuclear Research, Geneva 1211, Switzerland

2 TERA-CARE Foundation, Geneva, Switzerland

research and therapy with ions" was organised at the European Scientific Institute (Archamps, France) from 19 to 21 June 2018 [3]. This Workshop gave the opportunity to formulate user requirements and express guidelines for the future evolution of the European ion therapy infrastructure. The Workshop was also intended to connect with a new initiative promoted by the South East European Institute for Sustainable technologies (SEEIIST) [4]. This new international partnership was established in October 2017 by 8 countries and 2 observers in the South East European area. It aims at the construction in the region of a new scientific laboratory in the line of "science for peace", to build international cooperation and scientific capacity in a region that is developing with the view of joining the EU but is still divided after years of wars. In March 2018 the SEEIIST Steering Committee decided to support the construction of a Centre for Hadron Cancer Therapy and Biomedical Research with Protons and Heavy Ions, based on a preliminary conceptual design report [5].

Basic requirements for a future facility that emerged from the Workshop were: a) operation with multiple ions (protons, helium, carbon, oxygen, etc.); b) lower cost and dimensions, compared to present; c) faster dose delivery with higher beam intensity and new delivery schemes, including ultra-high dose irradiation in very short pulses ("FLASH") and using arrays of small beam spots ("mini-beams"); d) availability of a gantry device to deliver the dose to the tumour from different directions. Another strategic consideration was that cancer ion therapy is still in its early phase and much pre-clinical research is still needed, in radiobiology and medical physics with different ions and treatment modalities. The consequence is that priority should be given to a facility that could devote a large fraction of its operation time ($\approx$ 50%) to a wide research programme.

Several accelerator designs were considered for the new facility, as compact superconducting synchrotrons, conventional synchrotrons with higher performance, high-frequency linear accelerators, all equipped with superconducting gantries. None of these designs appeared however as standing out, since all present advantages and disadvantages, pointing to the fact that research is needed not only on the radiobiological side but also on accelerator designs and components that could satisfy the needs of future ion therapy facilities.

The Workshop contributed to the definition of the strategic direction for the NIMMS Study. Since it appeared that proton therapy is now commercial, with several companies on the market having their own R&D programmes, while ion therapy is still experimental and not yet on the commercial market, the latter provides an opportunity for CERN to have an impact in the medical field leveraging on its expertise in accelerator technologies without being in competition with European industry. Since several accelerator designs are proposed, NIMMS instead of concentrating on one specific option aims at developing a wide portfolio of technologies related to advanced ion therapy accelerators. This would leave to projects and initiatives participating in the collaboration the choice of the accelerator design and of the NIMMS technologies to be integrated. In this way, more than as a project NIMMS has been structured as a "toolbox". The activity was thus structured in four technological Work Packages:

1. *Small synchrotrons for particle therapy*. Small synchrotron design is a CERN core competence based on the recent experience with the LEAR/LEIR machines and with the new ELENA antiproton decelerator. CERN can contribute to improving performance with multi-turn injection and new extraction schemes including FLASH.
2. *Curved superconducting magnets*. Magnets is another field where CERN has a strong tradition and competence. An R&D effort is however needed in this domain since the superconducting (SC) magnets required for new therapy synchrotrons and gantries are different from usual CERN dipoles. Specific challenges for medical SC magnets are small curvature radius, fast ramping rate, and the need to integrate focusing quadrupoles in the cryostat or in the magnet itself.
3. *Superconducting gantries*. Rotating gantries are considered by the medical community as a must-have for future ion therapy. New designs based on SC magnets are needed, to provide the required accuracy in beam delivery keeping the size and weight of the system within reasonable limits.
4. *High-frequency ion linacs*. Linear accelerators (linacs), where CERN has a long tradition and experience, are a promising alternative direction to achieve compact-

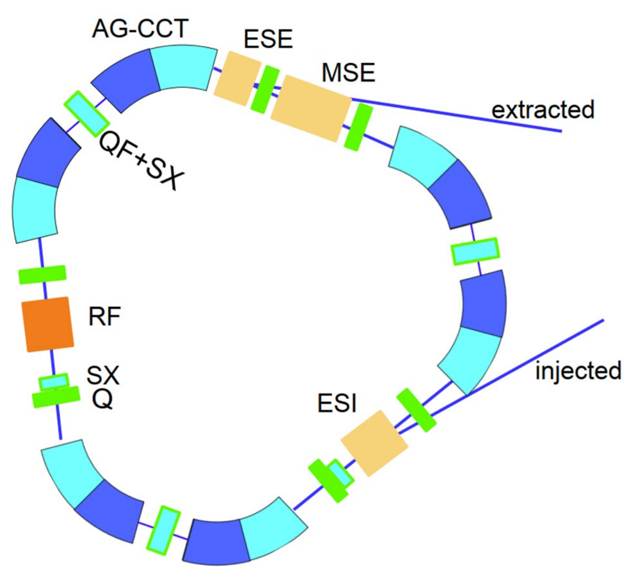

Fig. 1 Layout of the triangle-shaped synchrotron being developed by the NIMMS collaboration

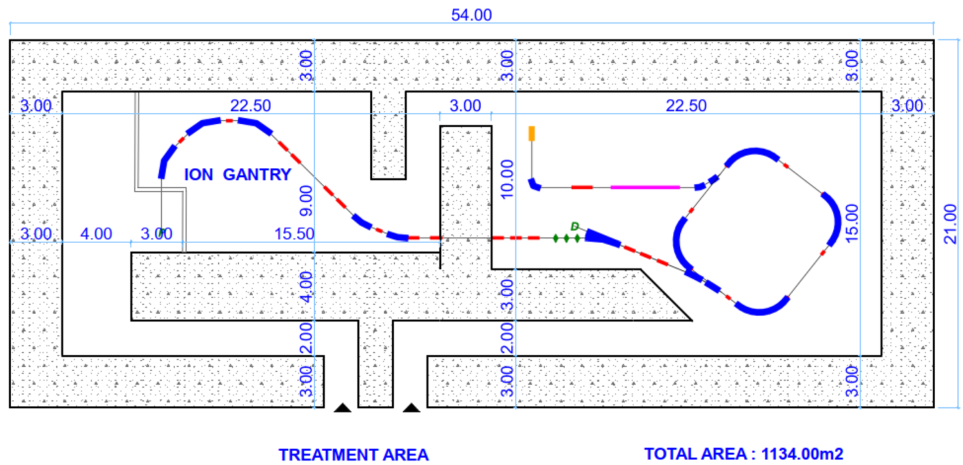

Fig. 2 Preliminary layout of a single-room carbon ion therapy facility based on a superconducting square synchrotron and a superconducting gantry. Surface 1134 sqm including shielding

ness and cost efficiency. Challenges are related to the ion source, to the design of the low and medium energy accelerating sections, and to the RF system.

To these Work Packages, NIMMS has associated a wide collaboration, including (October 2023) 19 international partners, out of which 7 have signed collaboration agreements for NIMMS-related activities. Three partners in particular contribute to the study with personnel resources based at CERN: SEEIIST, TERA Foundation (Italy), and the Riga Technical University (RTU, Latvia) in representation of the CERN Baltic group. To extend the reach of the NIMMS activities, CERN is also participating with some of the partners in two European projects that are developing NIMMS-related technologies. The Integrating Activity HITRIplus (Heavy Ion Therapy Research Integration) includes studies on synchrotron, linac, beam lines, gantry, and superconducting magnet design, and the Innovation Pilot I.FAST (Innovation Fostering in Accelerator Science and Technology) includes a Work Package dedicated to the development of curved superconducting magnets for medical applications.

1.1 The NIMMS work packages

1.1.1 Synchrotron design

The synchrotron design aims at a high-intensity carbon ion accelerator, delivering up to 1×10^{10} carbon ions per pulse, equipped with superconducting magnets. It should allow for both standard slow extraction and extraction with FLASH modalities. Two alternative layouts are being considered, a square one as initially developed by TERA, and a more compact triangular one shown in Fig. 1 [6].

The magnets considered in these schemes are of the Canted Cosine Theta (CCT) type, as those studied in the Superconducting magnets Work Package.

The goal of this study is the design of a single-room carbon therapy facility with a surface of about 1000 square

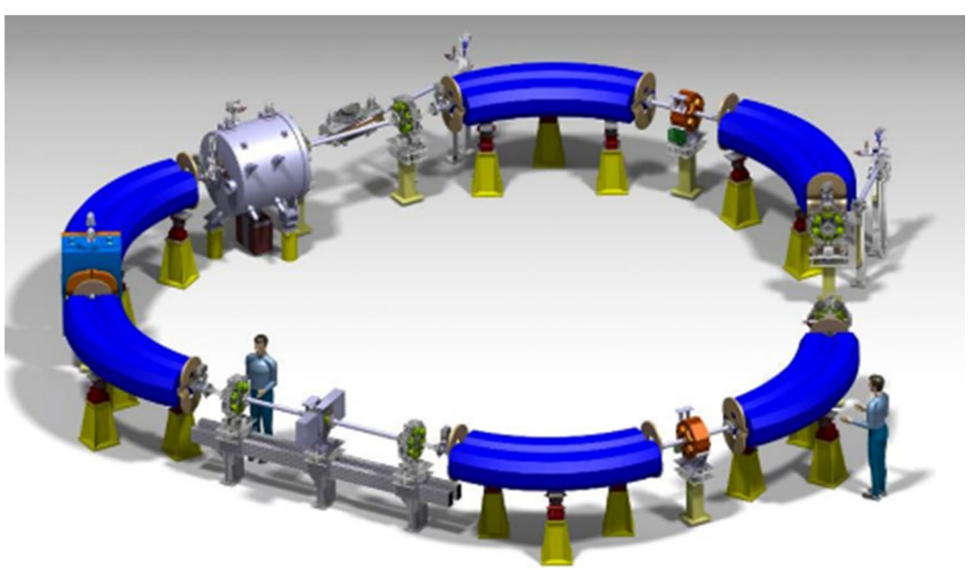

Fig. 3 Preliminary 3D integration of the compact helium synchrotron

Table 1 Superconducting demonstrator magnets in construction within NIMMS-related collaborations

Type	Target	Responsible	Collaboration	Parameters
Cos-theta for thermal studies	Gantry	CERN	EuroSIG	4 T, 0.4 T/s, 80 mm aperture, straight
Cos-theta, curved	Gantry	INFN	EuroSIG	4 T, 0.4 T/s, 80 mm aperture, curvature radius 1.65 m
CCT, curved	Ring, gantry	INFN	HITRIplus	4 T, 0.4 T/s, 80 mm aperture, curvature radius 1.65 m, 30^0
CCT, combined functions, LTS	Ring, gantry	INFN	I.FAST	4 T, 5 T/m quadrupole, 80 mm aperture, lenght 0.73 m, LTS, straight
CCT, combined functions, HTS	Ring, gantry	INFN	I.FAST	4 T, 5 T/m quadrupole, 80 mm aperture, lenght 0.73 m, HTS, straight

CCT Canted Cosine Theta, *MEDA* MedAustron, *LTS* Low Temperature Superconductor, *HTS* High Temperature Superconductor

meters, comparable to present proton single-room facilities. A compact design based on a "square" synchrotron design is presented in Fig. 2.

In parallel, CERN in collaboration with the TERA-CARE Foundation and with SEEIIST, has developed the design of a compact synchrotron optimised for acceleration of proton and helium beams [7, 8]. The synchrotron is based on a new room-temperature magnet design and can provide both slow and fast extraction for conventional and FLASH therapy. Production of mini-beams, and operation with multiple ions for imaging and treatment are also considered. Output helium energy is 220 MeV/u, corresponding to a penetration of 30 cm in water for a magnetic rigidity of 4.5 Tm. The helium source has to provide a $4He^{2+}$ current of at least 2 mA to deliver 8×10^{10} ions to the synchrotron via multi-turn injection, to irradiate a 1 liter tumour with 2 Gy with a margin of a factor 2 to account for inefficiencies in the extraction process. The helium beam out of the ion source is accelerated to the synchrotron injection energy of 5 MeV/u in a 352 MHz linac for charge to mass ratio q/m = 1/2. An additional linac tank designed for q/m = 1 brings the proton beam to its injection energy of 10 MeV. For the lattice, a triangular shape was chosen for the sake of compactness and to ease the magnets manufacturing, following a similar approach to the SC carbon synchrotron design. A conservative dipole field of 1.65 T was assumed for the magnets, leading to a bending radius of 2.7 m. The straight sections are about 5 m long, to accommodate the required hardware, which account for about 33 m total circumference length. A preliminary 3D view of the synchrotron showing the main components is presented in Fig. 3.

1.1.2 Superconducting magnets

As a preliminary step to address the specific challenges of superconducting magnets for compact synchrotrons and gantries, NIMMS has supported the establishment of three collaborations that will design and produce five demonstrator magnets (segments of an approximate length of 1 m), each focused on a different magnet technology or configuration. The 5 demonstrators are expected to be tested in the first half of 2025, making possible a comparison of performances and a final choice of the technology to be used in the prototype magnets for gantry and synchrotron. The five demonstrators are listed in Table 1. EuroSIG is a collaboration joining CERN, the Istituto Nazionale di Fisica Nucleare (INFN), the Centro Nazionale di Radioterapia Oncologica (CNAO), and the MedAustron therapy facility (MEDA). HITRIplus and I.FAST are projects supported by the European Commission in the frame of the Horizon 2020 Programme.

Figure 4 shows the preliminary design of the cos-theta magnet foreseen for the superconducting gantry, to be produced by the EuroSIG project. Figure 5 shows some initial designs for the CCT magnet demonstrators of I.FAST.

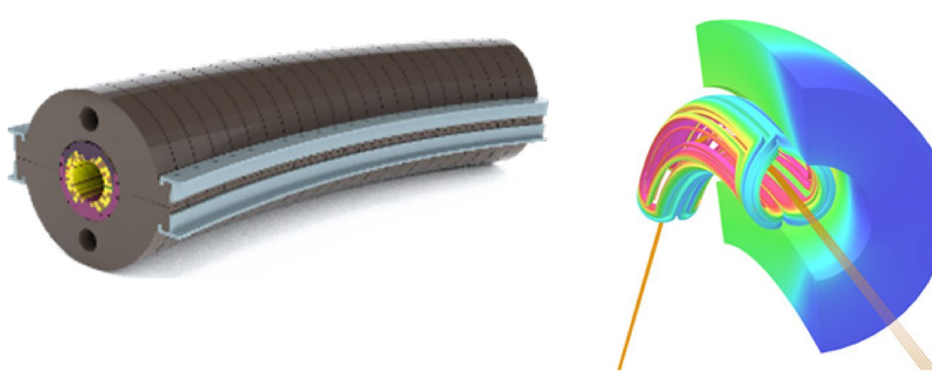

Fig. 4 Preliminary design of the cos theta magnet for gantries (courtesy M. Karppinen, CERN)

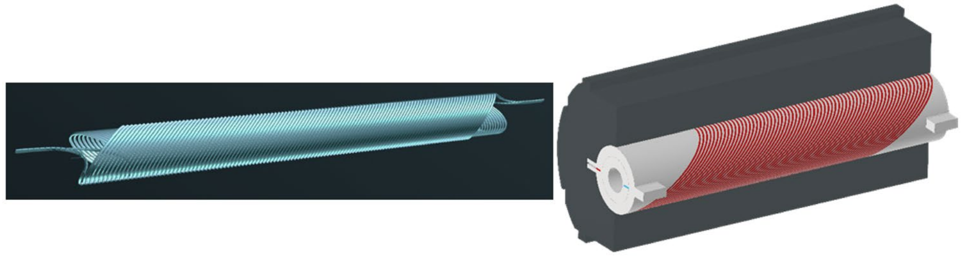

Fig. 5 Preliminary design of the CCT magnet demonstrators (courtesy E. De Matteis, INFN)

1.1.3 Superconducting gantries

The NIMMS activity on superconducting gantries consists in supporting a collaboration within the HITRIplus EU Project that aims at developing an optimised beam optics design for a gantry, based on the magnets described in the previous section, and at integrating all elements into a complete mechanical design. The collaboration includes CERN, CNAO, SEEIIST, and Riga Technical University [9].

The optics design selected after analysing several options is shown in Fig. 6. It is based on 45-degree dipole magnets all identical, providing a pure dipole field, with no need for combined function magnets with over imposed quadrupole gradient. Four warm quadrupoles and five superconducting quadrupoles provide the matching. Scanning magnets are placed after the last bending magnet [10].

In this design, the mechanical structure supporting the magnets will allow a full 360^0 rotation (Fig. 7). Because of its advantages from the treatment point of view, this configuration has been preferred out of four different options that were analysed in the HITRIplus project [11]. Starting from these general choices, a CERN-CNAO-INFN-MedAustron collaboration has now started the detailed design of a gantry aimed at operation in the CNAO carbon treatment facility.

1.1.4 High-frequency linac

An alternative option to reach the 430 MeV/u carbon ion energy required for treatment consists in using a compact high-frequency linac, similar to the one developed by ADAM-AVO for proton ion therapy [12], as originally proposed by the TERA Foundation [13]. Its main advantage with respect to a synchrotron is the capability of fast change of the energy from pulse to pulse by switching on and off groups of cavities in the high energy section.

The linac version analysed in NIMMS is based on a "folded" design that reduces the overall footprint of the accelerator with respect to a conventional straight configuration (Fig. 8). The main feature of this design is that the 180^0 bend is made of dipole magnets interleaved with RF accelerating cavities that keep the beam bunched during the turn providing at the same time an additional acceleration [14].

The foreseen ion source is a Twin-EBIS capable of producing a fully stripped carbon ion beam with small emittance at 360 Hz repetition frequency. The ion source is followed by an RFQ and by a fixed energy section, for which different configurations are possible, at 750 MHz (Quasi-Alvarez) or at 3 GHz frequency (Side-Coupled DTL). Particle tracking through the linac is shown in Fig. 9.

In the frame of this activity, a prototype RFQ for C^{6+} ions is in construction within a collaboration with CIEMAT (Spain). It will be installed in a dedicated test stand and fed with a He^{2+} ion beam (same charge to

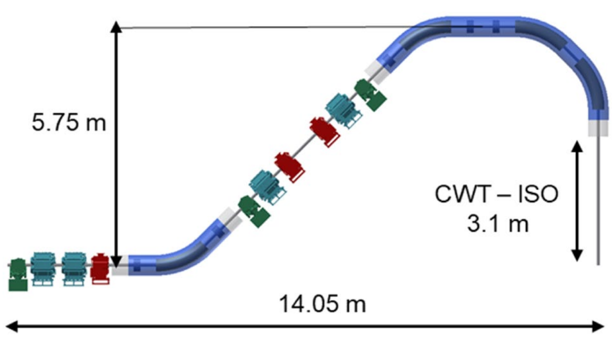

Fig. 6 Superconducting gantry beam optics (courtesy M. Pullia, CNAO)

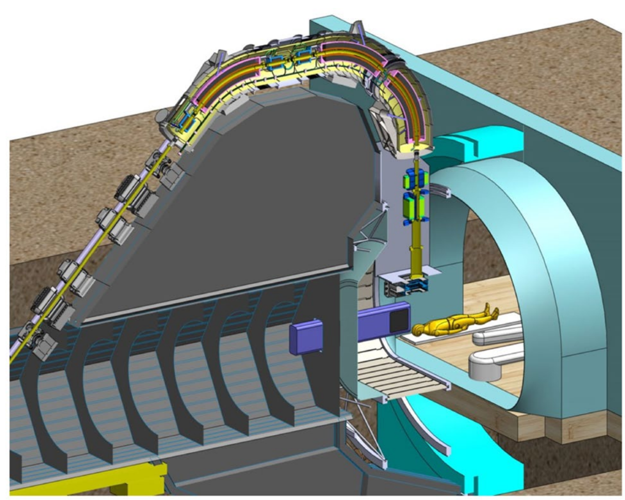

Fig. 7 3D gantry layout (courtesy L. Piacentini, RTU)

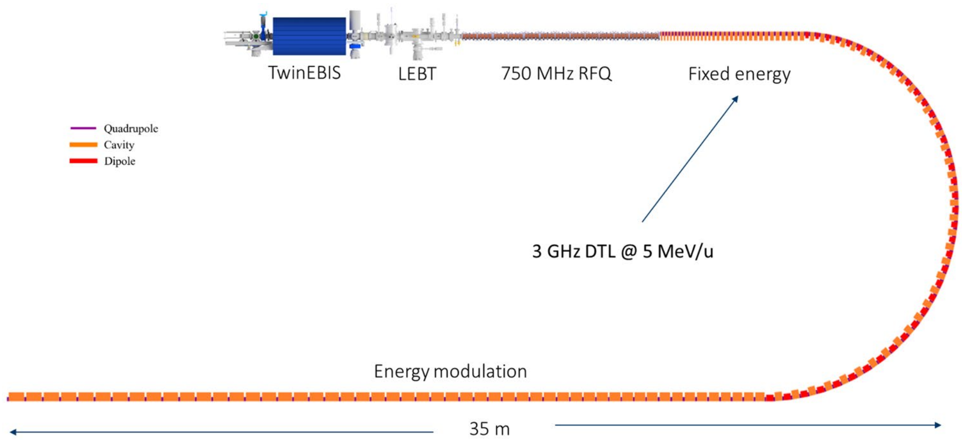

Fig. 8 Bent-linac configuration (courtesy A. Lombardi, CERN)

mass ratio as fully stripped carbon) produced by an ion source to be provided via a donation for future use at the University of Sarajevo.

1.2 Projects and initiatives supported by NIMMS

NIMMS is presently providing its portfolio of technologies to two major initiatives for the construction of new facilities for ion therapy.

1.3 The SEEIIST ion therapy and research facility

SEEIIST is the new combined ion therapy and research facility proposed for construction in South East Europe. To identify an ideal SEEIIST configuration, the NIMMS collaboration has compared three accelerator options, in terms of expected construction cost, footprint, performance and readiness for construction: a synchrotron with room-temperature magnets, a synchrotron with superconducting magnets, and a linac. A possible layout for the three configurations is shown in Fig. 10, following the general layout selected by SEEIIST: three treatment rooms (horizontal and vertical beam lines, and gantry), and a large experimental room with two beam lines [15].

The analysis of the three cases above indicated that while the accelerator area is 50% smaller for both superconducting synchrotron and linac as compared to the conventional synchrotron, when the overall facility surface is considered the reduction in size amounts to less than 20%. The estimated cost of SC-magnet synchrotron and linac were very similar, both about 20% lower than the conventional synchrotron. The two synchrotron designs have similar performance, while the linac has the advantage of the easier energy modulation that requires, however, a fast control of the extracted beam intensity. The development time is considered as slightly longer for the linac. Following this study, SEEIIST has adopted as baseline configuration for fast construction a warm-magnet synchrotron with improved performance with respect to the present European ion therapy facilities [16].

The detailed layout of the proposed facility is presented in Fig. 11, while Fig. 12 shows a general 3D view with roof removed to visualize the different components.

The proposed facility adopts the basic PIMMS lattice but complements it with a number of advanced

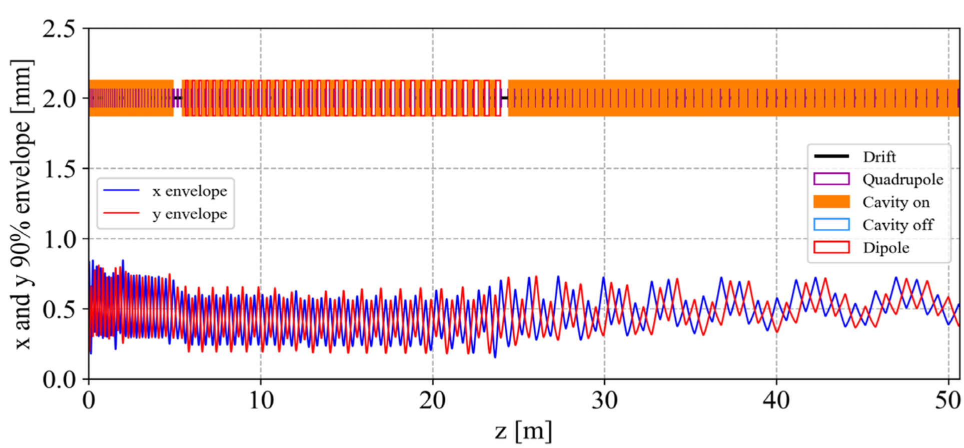

Fig. 9 Particle tracking through the bent linac: scheme of the three sections (top) and transverse envelopes for 90% of the beam (bottom) (courtesy A. Lombardi, CERN)

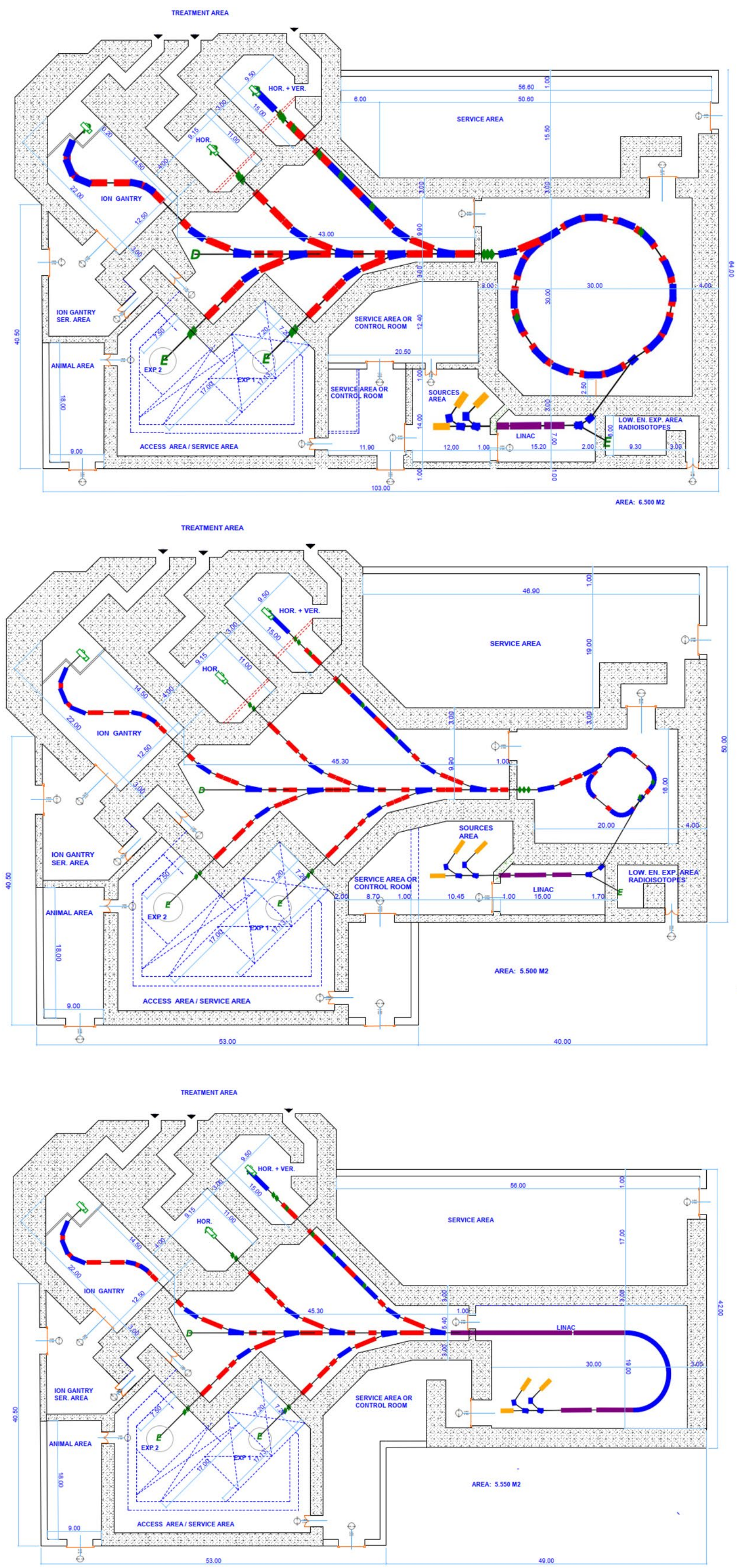

Fig. 10 The three SEEIIST configurations. From top, room-temperature synchrotron, superconducting synchrotron, and linac

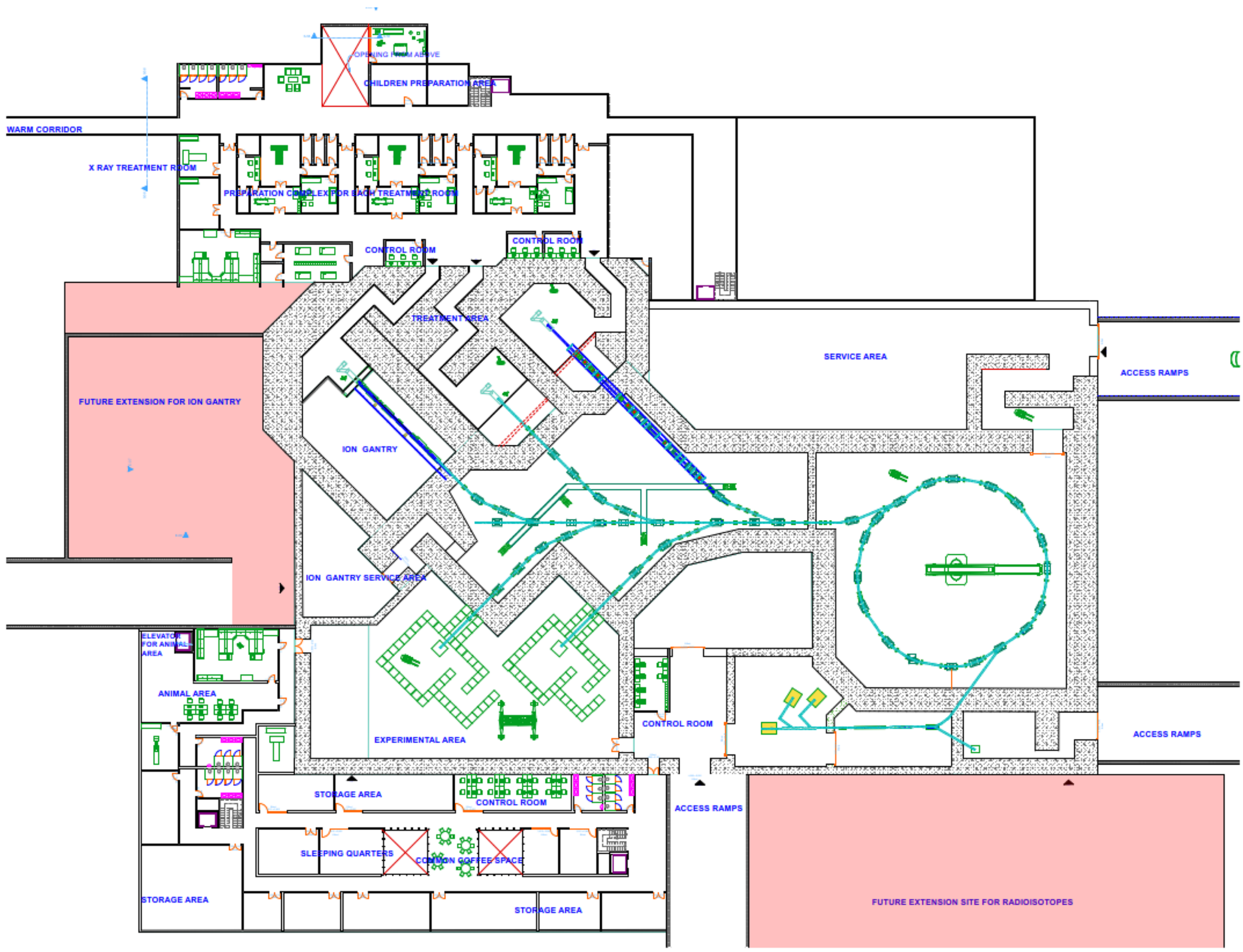

Fig. 11 The proposed SEEIIST configuration

state-of-the-art technological solutions that will make it a unique world-class facility. In particular it will allow storing and accelerating a record intensity of up to $2 \cdot 10^{10}$ C-ions per cycle, and equivalent intensities for all the other therapy ions, corresponding to a radiation dose of 2 Gy in a 1-L target.

1.4 The Advanced Particle Therapy Centre for the Baltic States

Recent years have seen an increased interest in the use of helium for radiation therapy of cancer, an ion that provides superior conformality with respect to protons or carbon thanks to its narrower Bragg peak compared to protons and to its reduced fragmentation tail with respect to carbon. The required treatment energy of 220 MeV/u (30 cm penetration) leads to a magnetic rigidity of 4.5 Tm, 70% that of carbon ions, with a proportional reduction in the accelerator and gantry dimensions. Additionally, helium ions produce a lower neutron dose than protons or carbon, reducing risks in paediatric patients, and might treat some radioresistant tumours at lower cost than carbon. An accelerator designed for therapy with helium can easily produce protons at and above treatment energies and be used for research with helium as well as with heavier ions.

More than 2,000 patients were treated with helium at Berkely in the 1970's before priority was given to carbon; the reintroduction of helium for standard treatment is now foreseen in a detailed roadmap prepared by the Heidelberg ion Therapy team [17]. A first patient has been treated with helium in September 2021. Clinical trials are now in preparation.

The basic design of a synchrotron optimised for helium therapy has been presented in Section 2 and Fig. 3. Integrated in a facility like the one shown in Fig. 13, it might provide unique opportunities for advanced particle therapy, by combining treatment with helium with pre-treatment proton radiography performed using a high energy proton beam,

Fig. 12 General 3D view of the proposed SEEIIST facility (with roof removed to show the accelerator)

and with, in addition to RF-KO based slow extraction, a dedicated system for extraction of pulses in the 100–200 ms range as required for FLASH treatment. As an additional feature, the linear accelerator to be used as an injector for the synchrotron can be easily dimensioned to accelerate proton and helium beams between synchrotron pulses. Sent to a dedicated target, they might produce large quantities of radioisotopes to be used for treatment and/or imaging, and for experimental activities. The linac would operate at a maximum duty cycle of 10%, accelerating protons up to 10 MeV, as required for production PET scanning isotopes, and helium ions up to 28 MeV total energy as required for production of ^{211}At for targeted alpha therapy [18].

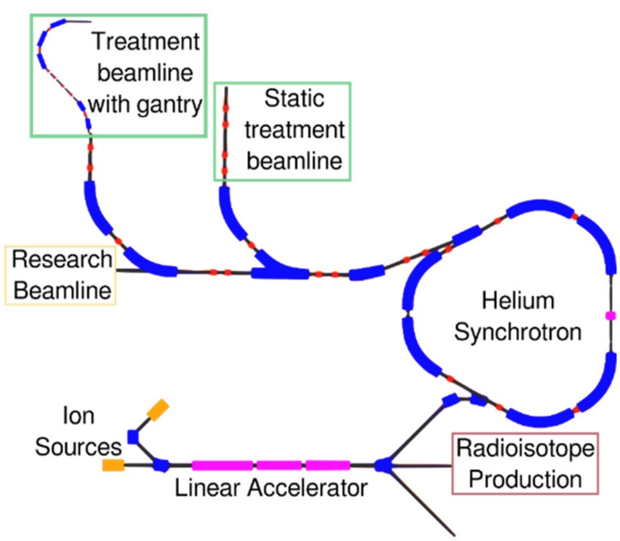

Fig. 13 Scheme of the helium-based facility

Recently the CERN Baltic Group, an association of Latvian, Estonian and Lithuanian research institutions involved in CERN activities, has launched an initiative to identify possible options to realise a research and therapy facility in the Baltic region, aimed at cancer treatment and more in general at research in the fields of particle therapy and nuclear medicine. After comparing different options, from commercial proton therapy to a SEEIIST-type carbon facility, the Group has recommended the synchrotron-based helium facility as an ideal option for the region, for treating patients and for developing a research community in an emerging domain at the boundary between medicine, biology, and physics. The concept of an "Advanced Particle Therapy Centre for the Baltic States" has been presented to the Health, Welfare and Family Committee of the Baltic Assembly, the main Baltic inter-parliamentary organisation, that has considered its medical and social impact on the region and expressed its support. In parallel, the initiative has been presented to the oncology communities of Estonia, Latvia, and Lithuania that have expressed their interest for a regional facility. Presently, five locations are being considered, two in Lithuania and Estonia, and one in Latvia.

A possible integration of the synchrotron-based helium facility, including production of protons and of radioisotopes, is presented in Fig. 14. The technical design on the facility is now progressing within the NIMMS study, with the goal of producing in 2025 a technical design report for a "green field" facility that could be built in any of the CERN member and associate member states. In parallel, the Baltic team under the coordination of Riga Technical University will produce a feasibility study addressing the clinical aspects, the research programme, the local implementation, and the business plan of the facility.

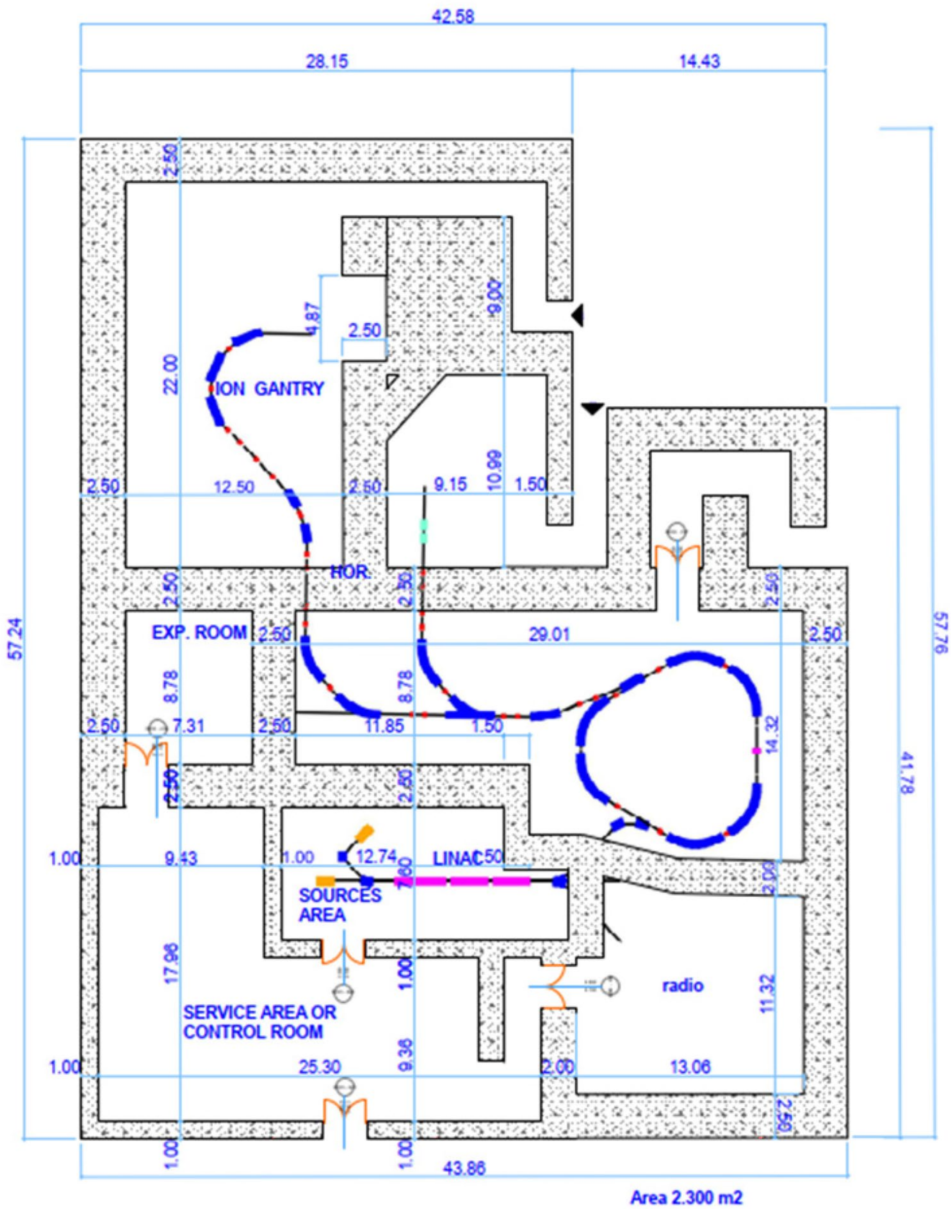

Fig. 14 Layout of the proposed facility for the Baltics

2 Conclusions

The traditional design of carbon ion therapy facilities can be considerably improved by adding new features as higher intensity, FLASH extraction, and a compact superconducting gantry. A cost-effective alternative to this traditional design is a compact facility for light ions, exploiting the potential for treatment with helium ions possibly coupled with FLASH and with proton radiography, allowing at the same time a wide experimental programme with different ion species.

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Declarations

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Consent to participate No Consent to Participate was required for this article.

Consent to publish No Consent to Publish was required for this article.

Conflict of interest The author has no competing interests.

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