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CERN

Machine Learning and Artificial Intelligence for the next generation of Ion Therapy Accelerators

The Next Ion Medical Machine Study

The **Next Ion Medical Machine Study (NIMMS)** is a new CERN-based initiative, aimed at leveraging on CERN technologies developed for HEP for a new generation of accelerators for cancer therapy with ion beams

Launched in 2019 with the support of the CERN Management within the Knowledge Transfer for Medical Applications, following the recommendations of the CERN Council Strategy document on KT for Medical Applications:

A collaborative design study coordinated by CERN would contribute to the development of a new generation of compact and cost-effective light-ion medical accelerators. A new initiative of this type would leverage existing and upcoming CERN technologies and the Laboratory's expertise in the fields of radiofrequency systems, advanced magnet design, superconducting materials, and beam optics.

Key motivation:

- **Proton** therapy now commercial, 4 companies offer turnkey treatment facilities (3 SC cyclotrons, one conventional synchrotron), and in competition with conventional radiation therapy (X-rays).
- **Ion** therapy (mainly **carbon**) still in an early phase (13 facilities worldwide, 4 in Europe) despite its advantages. Diffusion limited by:
  - ✓ **Size and cost of the accelerator**;
  - ✓ **Need of more research and experimental data**.

⇒ Opportunity for a strong impact on the medical field with an R&D programme based on critical accelerator technologies for a next generation ion therapy and research facility, smaller, possibly less expensive and more performant than the present reference design.

From PIMMS to NIMMS: a new collaborative project

1996/2000: CERN hosts **PIMMS** (Proton-Ion Medical Machine Study), a collaborative study (CERN, TERA Foundation, MedAUSTRON, Onkologie 2000) for the design of a cancer therapy synchrotron. The study has been the foundation for the construction of the CNAO and MedAustron particle therapy centres.
In parallel, **GSI** develops a similar technology and treats the first patients, contributing to the construction of the HIT and MIT therapy centres

Successful technology, but developing slowly because of:
- high treatment costs linked to **cost and size** of the facility
- slow acceptance by the medical community

20 years later, with the experience gained with LHC construction, it is time to explore new technologies to extend to a wider fraction of society the benefits of cancer therapy with particle beams.

The **NIMMS collaboration** includes some major international partners and is taking part in two recently approved EU projects

Partners: SEEIIST, TERA Foundation, GSI, INFN, CIEMAT, Cockcroft Institute, Manchester University, CNAO, Imperial College, MedAustron, U. Melbourne, Riga Technical University.

EU Projects: HITRIplus (Heavy Ion Therapy Research Integration, 2021-25) and IFAST (Innovation Fostering in Accelerator Science and Technology, 2021-25)

Strong CERN support under the new (2021) management, a new work plan for 2022-24 is in preparation

SEEIIST, key partner and reference user

- **SEEIIST** (South East Europe International Institute for Sustainable Technologies): a new international partnership aiming at the construction of a new Research Infrastructure for cancer research and therapy in South East Europe (8 member countries and 2 observers).
- SEEIIST has received a preliminary funding from the EC to develop the facility design, in collaboration with CERN.
- Goals are to develop a new advanced design and to build international cooperation and scientific capacity in a region that will join EU but is less develop and still divided after the wars, in the line of “science for peace”.
- Promoted by S. Damjanovic, formerMinister of Science of Montenegro, and H. Schopper, former Director General of CERN.
- Strong support by the EC and by Switzerland.

NIMMS Workpackages

NIMMS as a «technology toolbox»
more than a unique fully-fledged design

	Workpackage	Objectives
1	Superconducting magnets (D. Tommasini, TE/MSC)	Comparison of magnet technologies (CCT, costheta) and cables (NbTi, HTS). Design of prototype magnets (gantry and synchrotron).
2	High-frequency hadron linacs (A. Lombardi, BE/ABP)	End-to-end beam dynamics design, study of 180-degree bend, design of medium-beta accelerating structures (5-20 MeV/u), RF optimisation.
3	Gantries (M. Cirilli, IPT/KT)	Advanced design and comparison of 2 gantry options (optics and mechanical structure): Rotational (SIGRUM) and Toroidal (GaToroid).
4	Synchrotron design (E. Benedetto, SEEIIST)	Design of superconducting and normal conducting synchrotrons with advanced features: multi-turn injection for 10^{10} particles per pulse, fast and slow extraction, multiple ion operation, new upgraded linac injector.

***Superconductivity**, the main avenue to accelerator miniaturisation.*
Long-standing CERN expertise, needs high fields, pulsed operation, strong curvature

*The **"full-linac"**, a different approach for fast 3D scanning of tumours*

*The **gantry**, a strategic component merging traditional CERN competences: magnets, beam optics, mechanics.*

*Design of **synchrotrons**, key element of most ion therapy systems, is a core competence of CERN.*

There is space here for a 5th Work Package… could it be related to application of ML/AI to design and operation of the next generation of ion accelerators?

Ongoing initiative on transfering Linac4 experience to particle therapy linacs…
Can we extend it to other accelerator designs and beyond reliability studies?

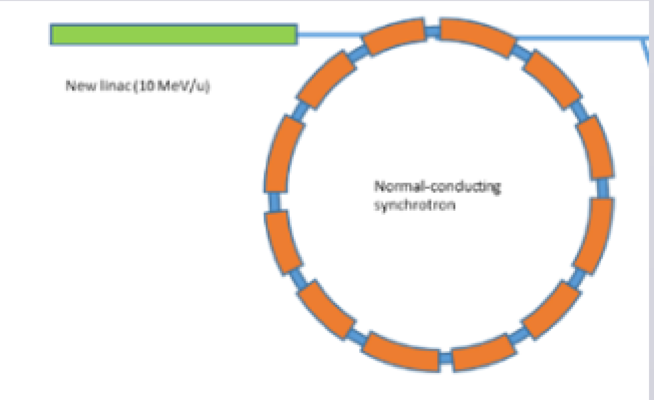
Several collaborators, in particular from SEEIIST, do not have experience in accelerators but have competences (and people ready to work!) in software, and interest in AI-related topics.
They have contacted us to find subjects to collaborate with CERN on subjects related to medical accelerators.

Three alternative accelerator designs

Improved synchrotron (warm)

Equipped with several innovative features: multi-turn injection for higher beam intensity, new injector at higher gradient and energy, multiple extraction schemes, multi-ion.

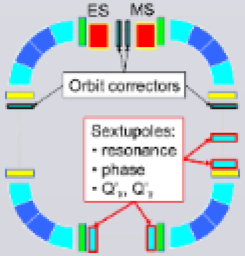
Circumference ~ 75 m

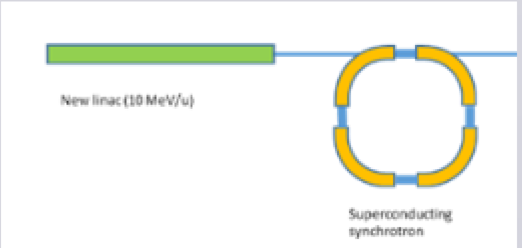


Improved synchrotron (superconducting)

Equipped with the same innovative features as warm, but additionally 90^0 superconducting magnets.

Circumference ~ 27 m

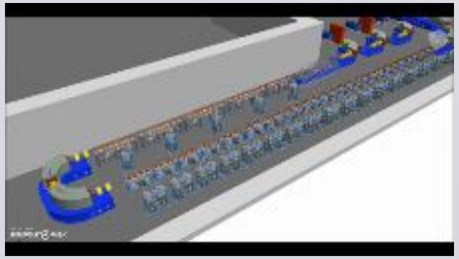


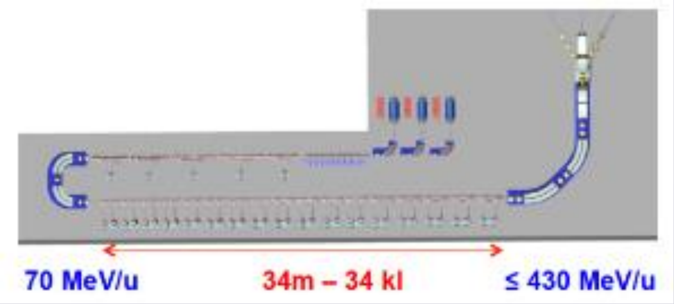


Linear accelerator

Linear sequence of accelerating cells, high pulse frequency.

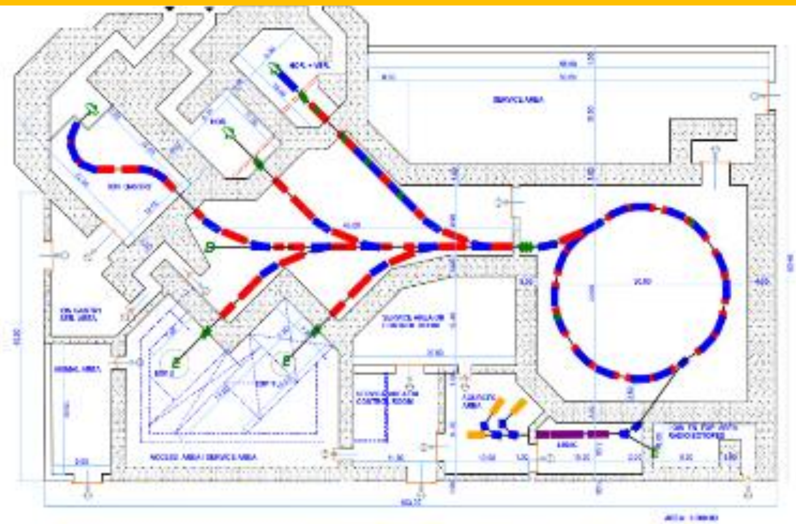
Length ~ 53 m



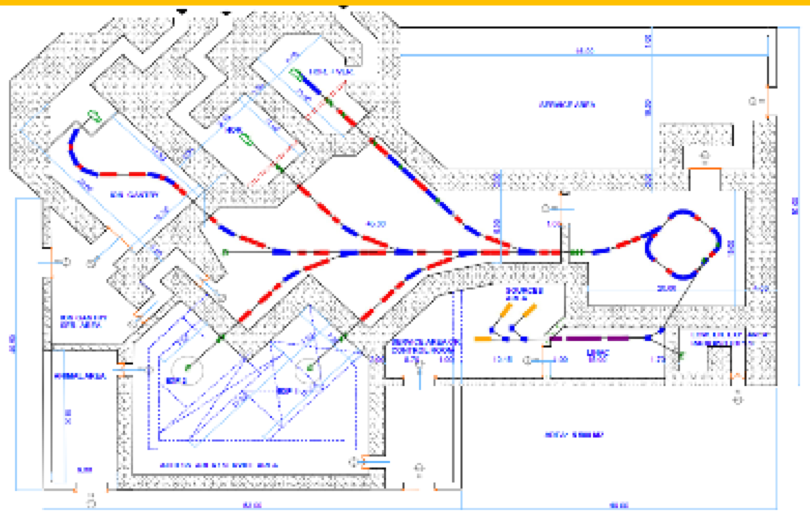


Other options considered as less interesting because of cost and/or required R&D: **RC synchrotron**, **FFAG**, **SC cyclotron**, **PWFA**

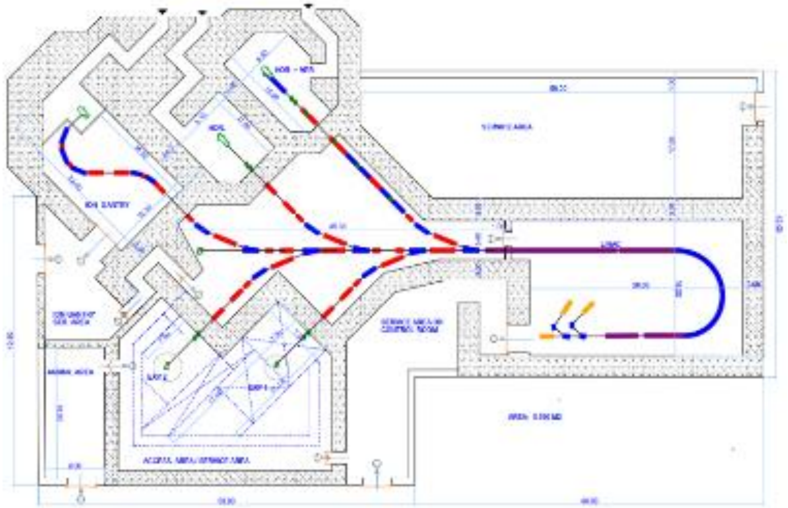
Comparing the three options for SEEIIST



RT synchrotron:
accelerator 1,200 m², facility 6,500 m²
estimated cost (acc. only): 42 M€



SC synchrotron:
accelerator 600 m², facility 5,500 m²
estimated cost (acc. only): 31 M€



Full linac:
accelerator 600 m², facility 5,500 m²
estimated cost (acc. only): 31 M€

SC synchrotron or linac allow 50% reduction in accelerator dimensions, 15% in overall facility dimensions, and 20% reduction in cost.

	Construction Cost	Operation cost	Footprint	Performance	Time to development	Risk of development	Treatment protocols	Gantry
Warm (new) synchrotron	Medium	Medium	Large	Good	Low	Low	Existing	Simple design
Superconducting synchrotron	Lower	Lower	Small	Good	Medium	Medium	Existing	Simple design
Linear accelerator	Lower	Lower	Small	Better	Long	Medium	To be developed	Complex design

This study recommends to SEEIST the adoption as baseline configuration of a warm-magnet synchrotron with novel features. Development of superconducting magnets and adequate superconducting synchrotron designs should continue as an advanced alternative option. The superconducting alternative with its potentially lower cost and smaller dimensions might become the baseline in case preparation for construction of SEEIIST would take more time than foreseen and in case of success of the superconducting magnet development. Additionally, the superconducting option might more easily become a standard commercial design for a next generation of ion therapy facilities beyond SEEIIST.

Why are we interested in ML/AI

Several collaborators, in particular from SEEIIST, do not have experience in accelerators but have competences (and people ready to work!) in software, and strong interest in AI-related topics.
They have contacted us to find subjects to collaborate with CERN on topics related to medical accelerators.

Technically, two elements are of paramount importance in medical accelerators, much more than for scientific accelerators:

1. **Accelerator Reliability**
2. **Beam stability**

Reliability can be improved by: a) appropriate design (redundancy, architecture); b) preventive maintenance; c) fast automatised procedures (beam recovery after failure, switch to degraded performance,…)

All this is based on knowing the architecture, the history, and the data from other similar facilities to take decisions → Machine Learning

Beam stability depends on hardware stability and beam physics. Can be improved by: a) selection of appropriate hardware; b) fast feedback systems; c) slow feed-forward systems based on previous history and data analysis → Artificial Intelligence

Please note that this is my personal view of the problem, I am an hardware person and I am lost with all what is software!

Possible subjects

- We would like to extend the work that is already going on with linacs to ion therapy synchrotrons – or more in general to "small synchrotrons".
- We can profit of the large amount of operational data accumulated by the CNAO facility in Pavia and draw some lessons for the design and operation of the SEEIIST "advanced" synchrotron. The CERN PSB and PS can be other useful sources of data.
- Another important information would be a comparison of our normal conducting and superconducting synchrotron designs in terms of reliability and beam stability: there are reasons to believe that superconducting might be better (less components, simpler and more stable power supplies), but can we prove this "feeling"?

Our interests can be summarised in 3 topics:

1. Design optimisation for reliability of ion therapy synchrotrons
2. Predictive maintenance and operation plans for ion therapy synchrotrons
3. Procedures for dose delivery stabilisation.

The discussion is open!

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