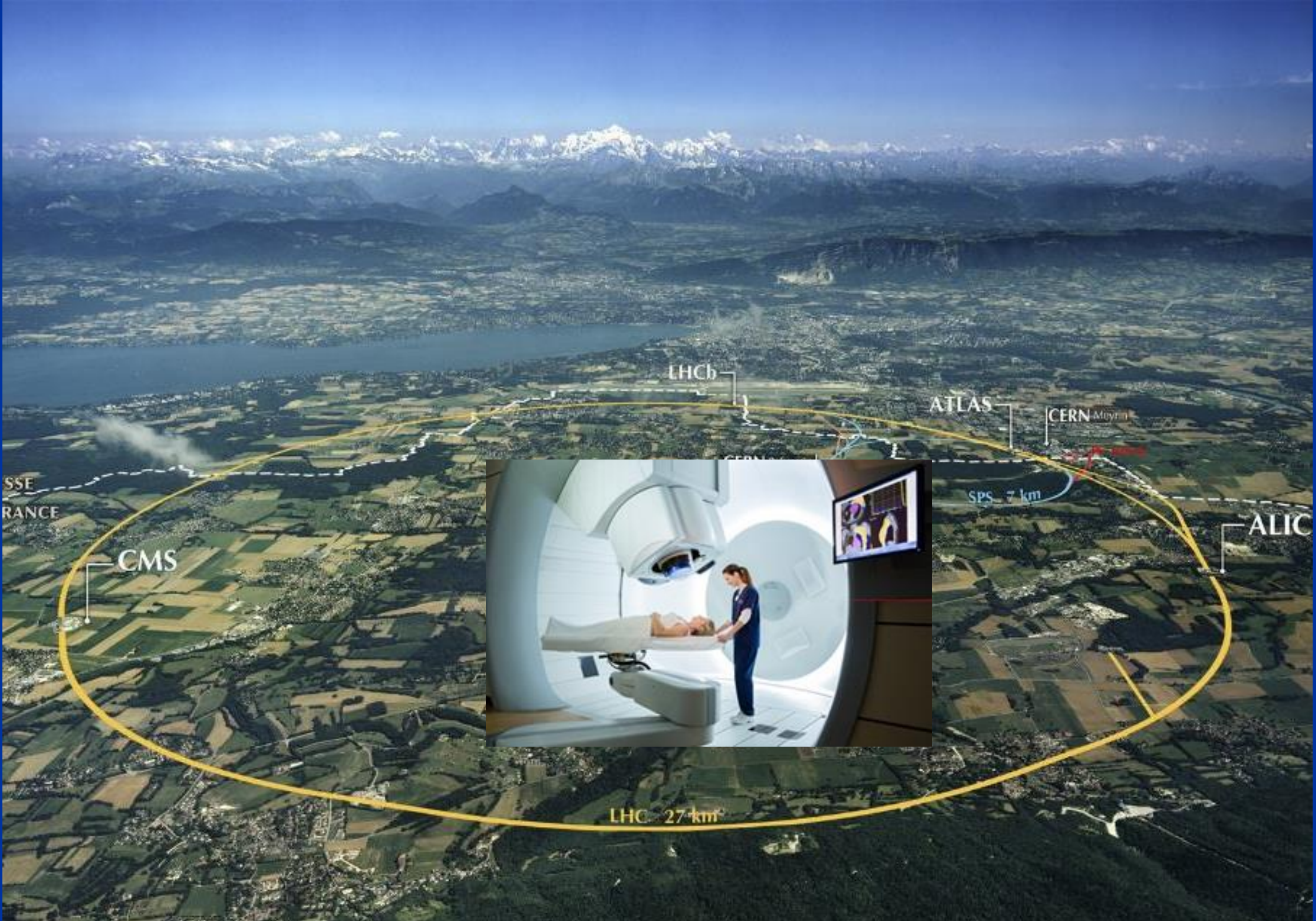
NIMMS: The Next Ion Medical Machine Study @ CERN



CERN Baltic Conference

30th June 2021

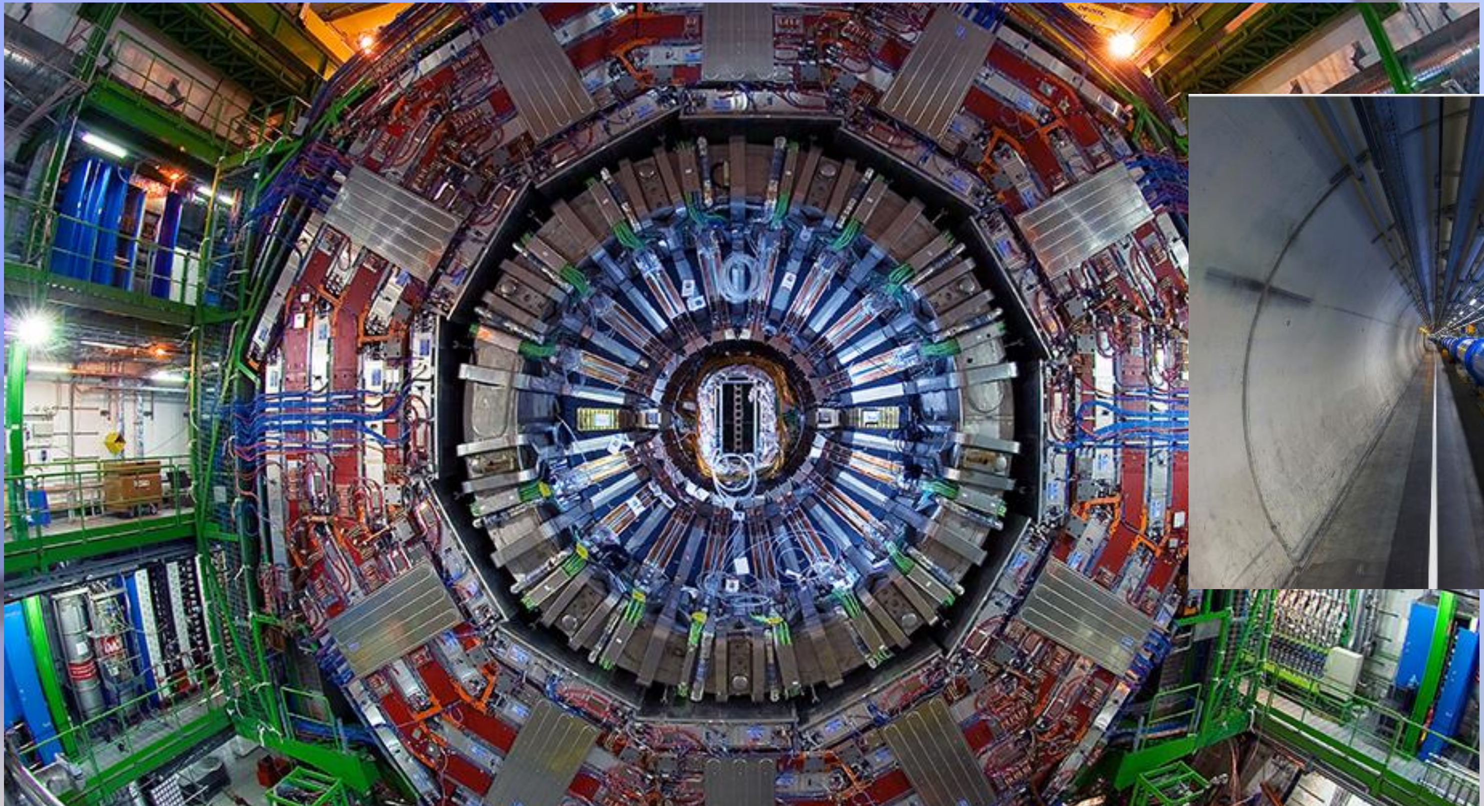
Elena BENEDETTO

for the NIMMS Collaboration

South East European International Institute for Sustainable Technologies

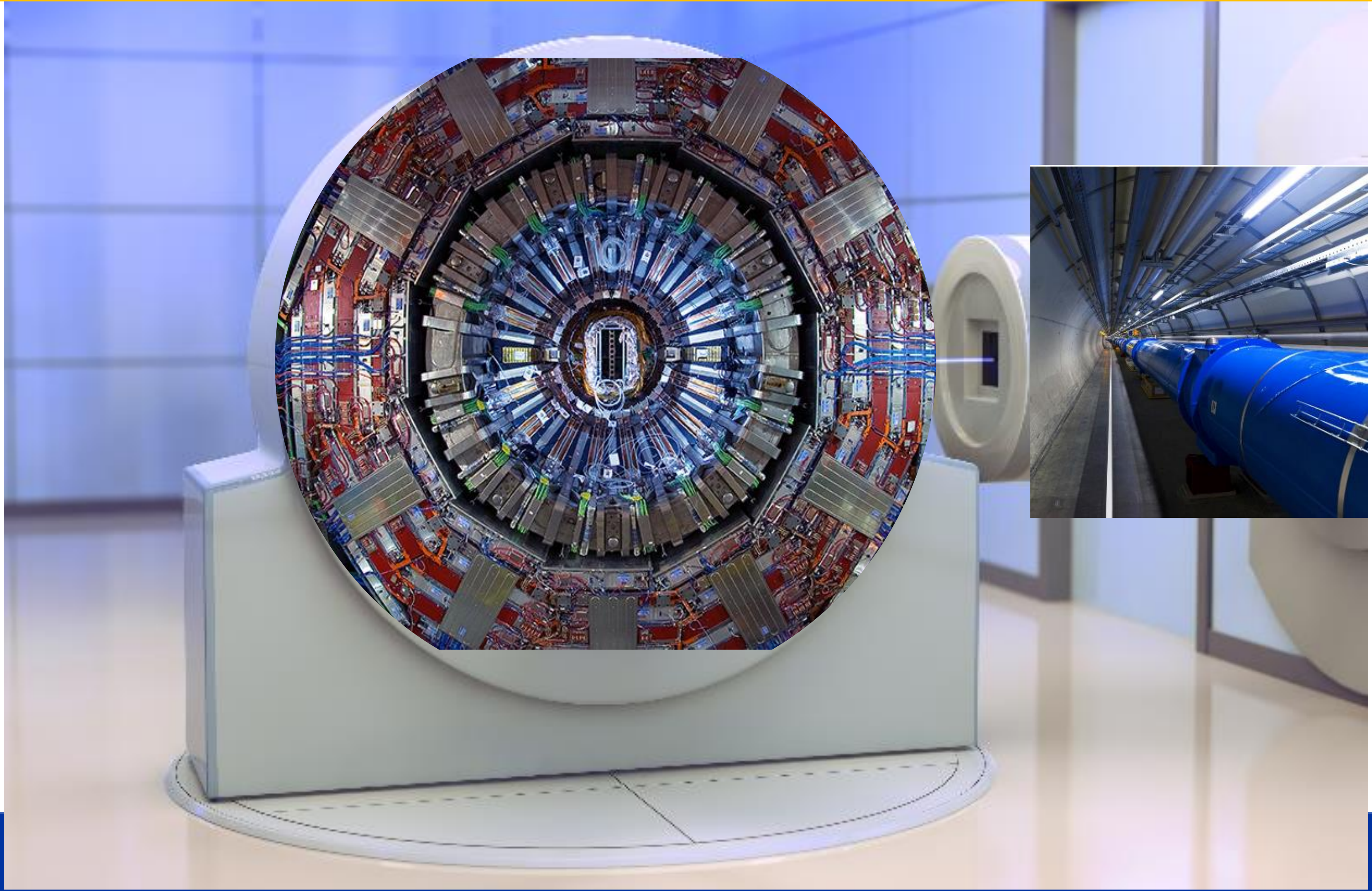
CERN

Bring the entire CERN…



…in a hospital room

…in a hospital room



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

- Promote the development within a wide collaboration;
- In contact with final users, to privilege “market pull” vs.“technology push”;
- Combining competences and expertise from many different CERN and non-CERN groups and teams:

*SEEIIST, TERA Foundation, GSI, INFN, **Riga Technical University**, CIEMAT, Cockcroft Institute, Imperial College, CNAO, MedAustron, U. Melbourne, …*

Credit: most of the material (and slides!) about NIMMS come from M.Vretenar’s KT-seminar 19/10/2020: https://cds.cern.ch/record/2742439?ln=en

Curing cancer with ions

Cancer a leading cause of death:
10 millions in 2020.

Radiotherapy

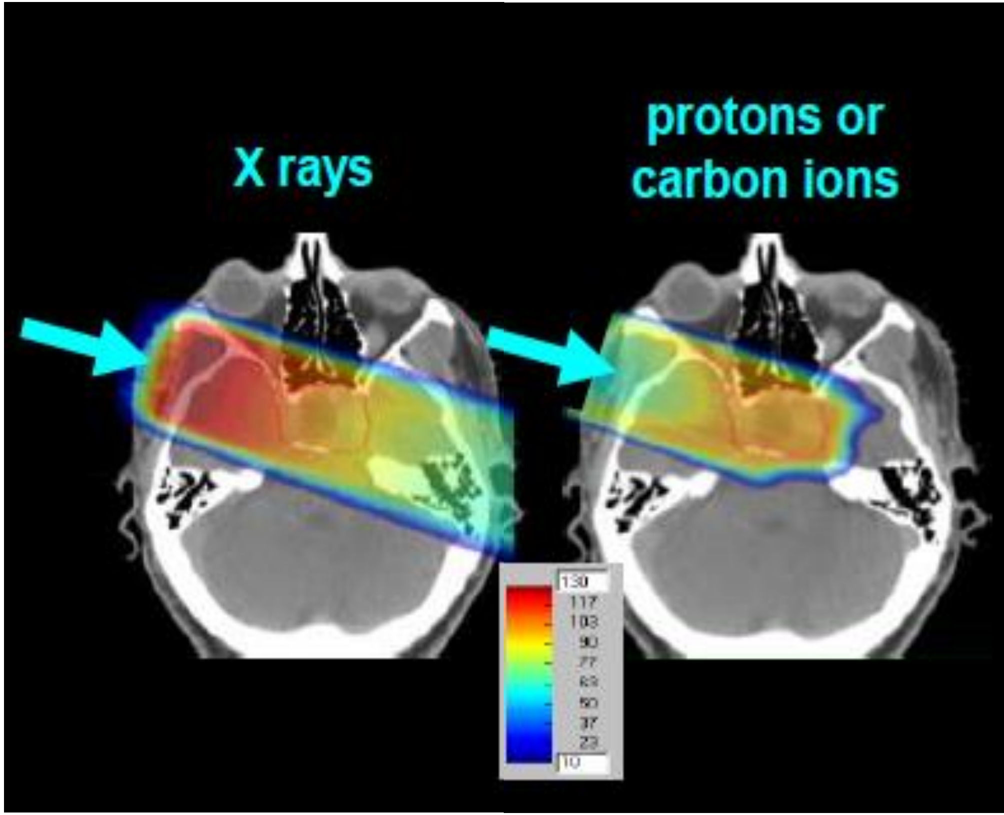
- for 50% patients
- alone or in combination with surgery, chemio, (immunotherapy)

X-rays go through tissues:

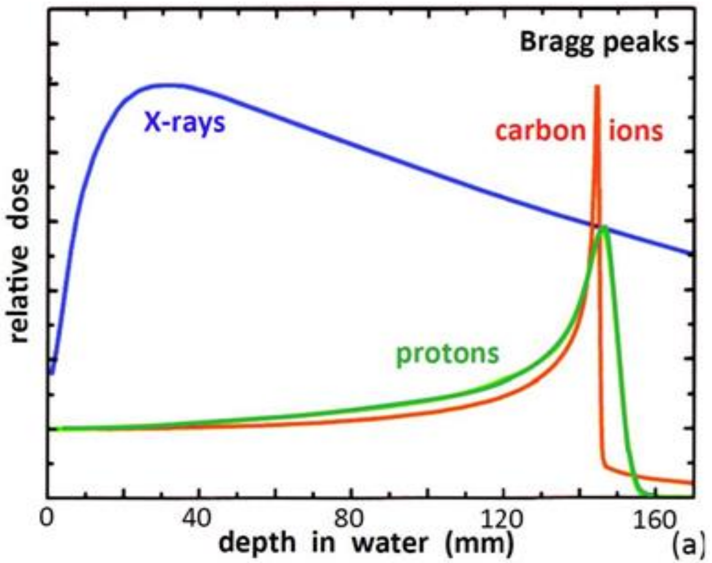
- healthy cells repair
- cancer cells die

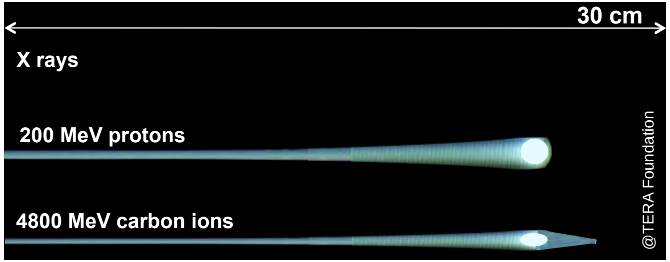
Charged particles stop @target:

…the Bragg peak!



The Bragg Peak: particles stop, X-rays go through!





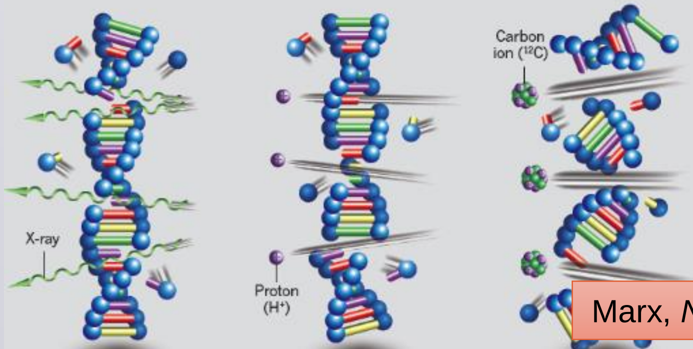
Energy is deposited at a given depth, which depends on the beam initial energy:

- Protons: 60 - 250 MeV ($B\rho$ = 2.42 Tm)
- Carbon: 100 – 430 MeV/u ($B\rho$ = 6.6 Tm)

~2.7x

Why Carbon ions?

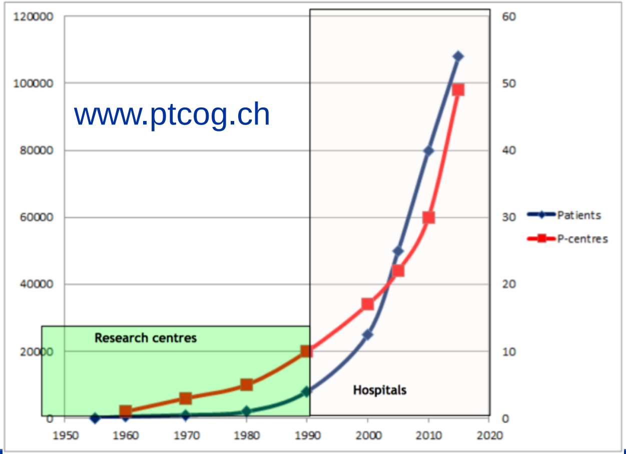
- ✓ double-strand breaks (not reparable)
- ✓ 2-3x more damage (RBE)
- ✓ also in "radioresistant" tumours



Marx, *Nature*, 2014

Medical accelerators are not new!

- 1954: 1st patient treated at Berkeley
- 1993: Loma Linda, first hospital facility
- 1994: NIRS-HIMAC built in Japan
- 1996-2000: PIMMS at CERN “Proton Ion Medical Machine Study” with TERA and MedAustron
- 2006: Industrial accelerators on the market (mostly p cyclotrons)
- 2009: Heidelberg; 2011: CNAO; 2016: MedAustron



BUT Hadron therapy remains a niche

22,000 patients/year (2018) vs.25,000,000 patients/year with conventional RT

Size (& cost) matters!

Carbon ~ Proton Bρ x 2.7

Superconducting magnets to make it smaller, cheaper, & more energy efficient

Varian X-ray linac

IBA proton gantry

HIT carbon gantry (600 tons)

Specifications from the scientific community

Accelerator

- ❑ Lower cost, compared to present (~120 M€);
- ❑ Higher beam intensities than present (10^{10} ppp);
- ❑ Reduced footprint, to about 1’000 m^2;
- ❑ Lower running costs.

Delivery

- ❑ Fast dose delivery (possibly with 3D feedback);
- ❑ Equipped with a rotating gantry;
- ❑ Using multiple ions (Carbon, Helium and others)
- ❑ With range calibration and diagnostics online.

(Archamps Workshop, June 2018)

NIMMS Origins and Goals

Started from an impulse by U. Amaldi in 2016-17
Structured after the **Archamps Workshop** in 2018
International collaborations started in 2018
CERN project
Support from EU-funded projects:

- **HITRI*plus*** - Integrating Activity for Ion Therapy
- **I.FAST** – General innovation programme for accelerator R&D

In line with CERN mission, build on CERN expertise to develop a **portfolio of technologies** that can be used in a next generation facility, more than developing a unique design (NIMMS as a «toolbox»)

SEEIIST as strategic partner and reference user

- The **SEEIIST** (South East Europe International Institute for Sustainable Technologies) is 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 is supported by the EU 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 devided, in the line of "science for peace".
- Promoted by H. Schopper, former Director General of CERN, and S. Damjanovic, ex-Minister of Science of Montenegro.

SEE ST
South East European International Institute for Sustainable Technologies

M.Vretenar's KT-seminar

NIMMS workpackages

	Workpackage	Objectives
1	Superconducting magnets	Comparison of magnet technologies (CCT, costheta) and cables (NbTi, HTS). Design of prototype magnets (gantry and synchrotron) for the selected option.
2	High-frequency hadron linacs	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	Advanced design and comparison of gantry options (optics and mechanical structure).
4	Synchrotron design	Design of Superconducting synchrotron and of a backup normal conducting version with advanced features: multi-turn injection for 10^{10} particles per pulse, fast and slow extraction, multiple ion operation, new upgraded linac injector.
5	AI/ML	Predictive maintenance, accelerator design adn dose delivery

***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.*

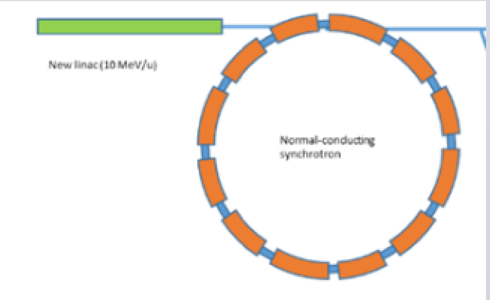
Under construction, the newly added one!

M.Vretenar's KT-seminar

Three alternative accelerator designs

Improved synchrotron (warm)

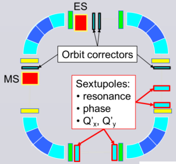
Equipped with several innovative features: multi-turn injection for higher beam intensity, new injector at higher gradient and energy, multiple extraction schemes, multi-ion.

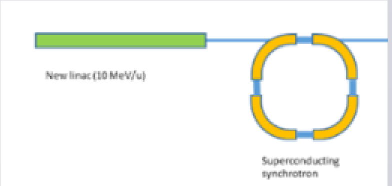


Improved synchrotron (superconducting)

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

Circumference ~ 27 m

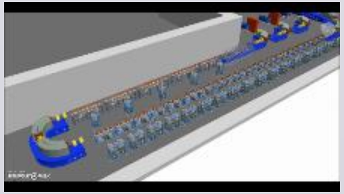


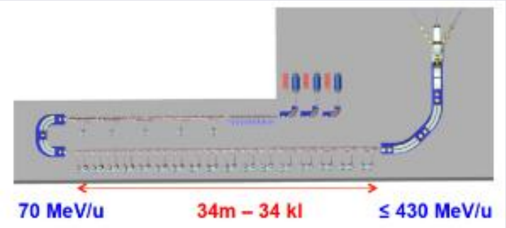


Linear accelerator

Linear sequence of accelerating cells, high pulse frequency.

Length ~ 53 m



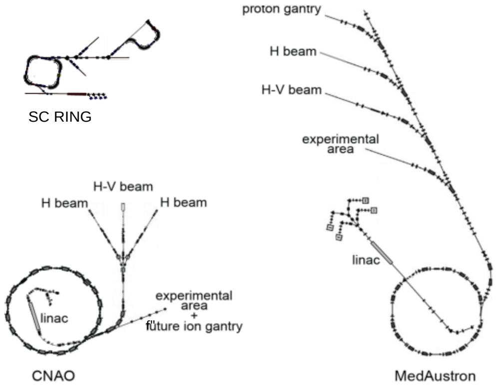


E.Benedetto, U. Amaldi, V. Bencini, M. Dosanjh, Y. Foka, D. Kaprinis, M. Khalvati, A. Lombardi, M. Sapinski, M. Vretenar, X.Zhang. CERN-NIMMS-Note-1, https://cds.cern.ch/record/2748083?ln=en

M.Vretenar's KT-seminar

Superconducting synchrotron

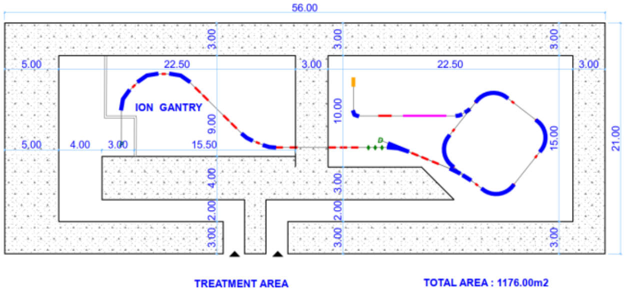
Needs: 3 – 4 T magnets ramped at 1 T/s



A superconducting C-ring at the same scale of CNAO and MedAustron

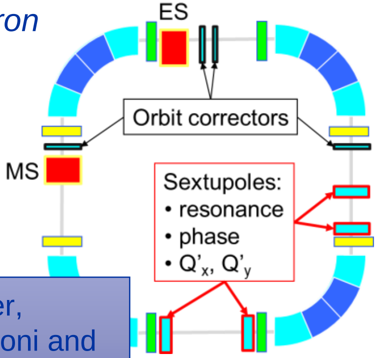
Advantages:

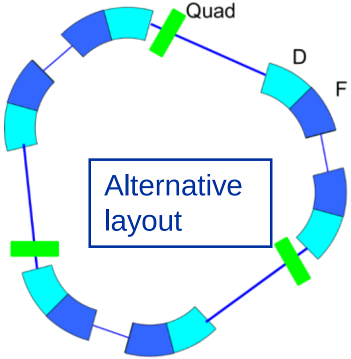
- Smaller dimensions
- Lower construction and operation cost
- Reduced power consumption



A compact single-room ion therapy facility in about 1,000 m² (comparable w. proton system)

TERA synchrotron Design:
CCT magnets 3.5T
Aperture 60 mm
Total circumference 27 m





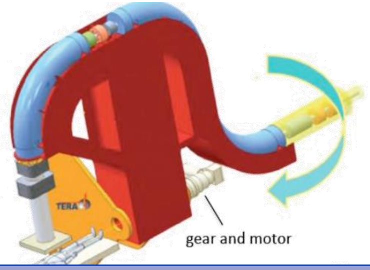
E. Benedetto, N.AlHarbi, L.Brouwer, D.Tommasini, S.Prestemon, P.Riboni and U.Amaldi, https://arxiv.org/abs/2105.04205

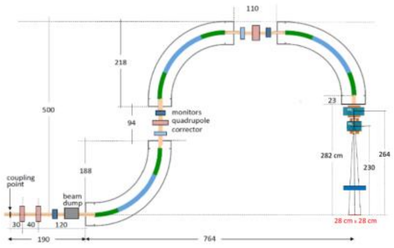
CERN
HITRIplus
Heavy Ion Therapy Research Integration
Partially supported by HITRI*plus* EU-founded project and CERN DOCT program

Superconducting rotating gantry

Compact gantry with 4T AG-CCT magnets of 90^0 (TERA design, 2018):

- external radius <5m
- rotating by 200^0 and attached to the wall
- magnets are extremely challenging





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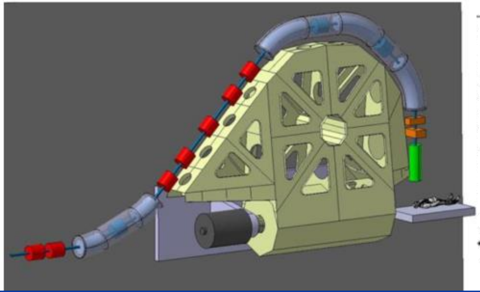
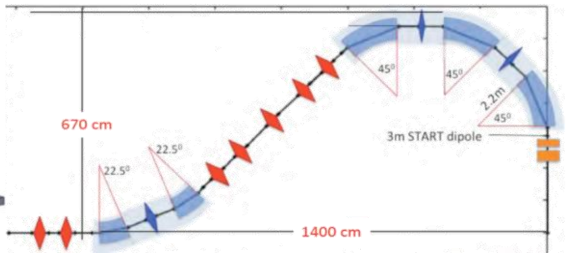




Design with 3T, 45^0 cosine-theta magnets

- similar mechanical structure concept
- more conservative, less R&D
- time to construction 10 years

U,Amaldi, N. Alharbi, E Benedetto[1], P.L. Riboni and M. Vaziri, TERA Foundation,D. Aguglia, V. Ferrentino. G. Le Godec, M. Karppinen, D. Perini, E. Ravaioli and D. Tommasini, CERN, CERN-NIMMS-Note-002: https://cds.cern.ch/record/2766876?ln=en

SC magnets for synchrotrons and gantries

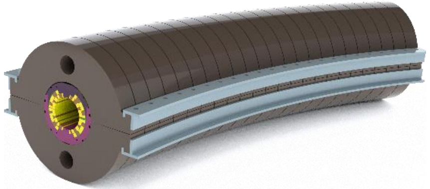
High Energy Physics is promoting a wide international effort in the development of conductors, designs and technologies for SC magnets.

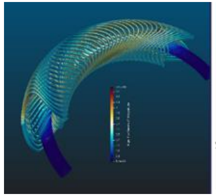
NIMMS aims at profiting of this R&D effort for compact synchrotron and gantry magnets.

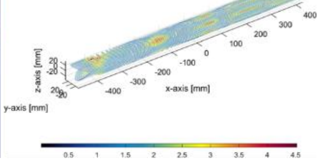
Some of the challenges are common, other are specific for medical accelerator magnets: ramping field, curved shape, quadrupole integration, use of cryocoolers.

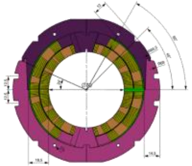
A few ideas

Solution for curved and straight CCT coils combining dipole and quadrupole in the same winding - Courtesy G. Kirby and J. van Nugteren, CERN









Curved cos-theta dipole with H-split yoke with assembly clamps - Courtesy Mikko Karppinen, CERN

Magnet Parameters for HITRI+ and IFAST

Bρ (Tm)	6.6	6.6
B_0 dipole (T)	3.0	4-5
Coil apert. (mm)	70-90	60 (90)
Curvature radius (m)	2.2	2.2 , ∞
Ramp Rate (T/s)	1	0.15-1
Field Quality (10^{-4})	1-2	10-20
Deflecting angle	90°	0 - 45°
Alternating-Gradient	yes (triplet)	N/A
Quad gradient (T/m)	40	40
B_{quad} peak (T)	1.54- 1.98	1.2
B_{peak} coil (T)	4.6 - 5	5.6-7
Operating current (kA)	< 6	< 5
Type of Superconductor	NbTi (Nb_3Sn)	NbTi (curved), HTS (straight)
Operating temperature (K)	5 (8)	5 (20)

Partially supported by

HITRI*plus* – Integrating Activity for Ion Therapy

- **WP8 on Magnet Design:** overview and assessment of various conductors (LTS, HTS, various types of cables) and magnet layouts (costheta, CCT, racetracks – spit coils or flare ends – etc…). Design construction and test of 1 demontrator 500 mm long (either LTS or HTS)

I.FAST – General innovation programme for accelerator R&D

- **WP8 on Innovative Superconducting Magnets:** General consensus to go toward CCT, different conductors. Development of a HTS cable suitable for low losses - large size - fast cycling - synchrotrons (led by GSI)

Both WPs coordinated by L. Rossi (I

M.Vretenar's KT-seminar

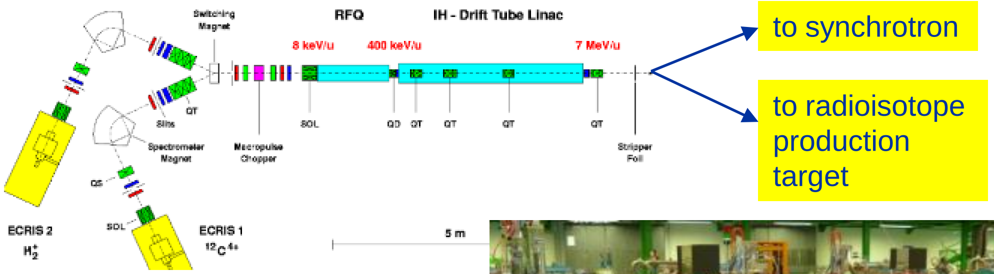
Participants: CEA, CERN, CIEMAT, INFN, PSI, UU, Wigner, SEEIIST, GSI + BNG, Sigmaphi, Elytt (industrial)

Synchrotron injector Linac

M. Vretenar, CERN
P. Foka, GSI
A. Marmaras, U. Thessaloniki
G. Bisoffi, INFN/CERN

The SEEIIST facility will have a **new injector linear accelerator** (linac) designed for higher energy (10 MeV/u), with lower cost, higher efficiency and higher intensity.

With a minor additional investment, the linac could have 2 modes of operation: for injection in the synchrotron, and for sending the beam to a target for production of medical radioisotopes.



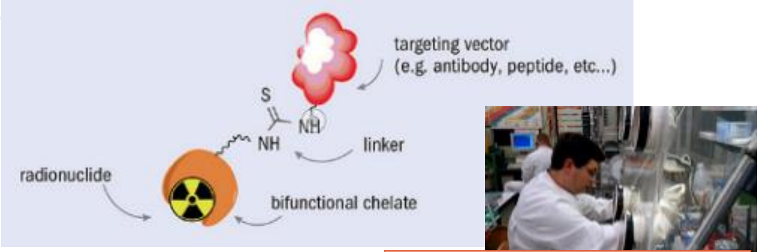
An example: **Targeted Alpha Therapy**

Alpha-emitting therapeutic isotopes: charged atomic nuclei emitting α particles (2 protons+2 neutrons), produced by bombardment of nuclei with an α beam.

Attached to antibodies and injected to the patient: accumulate in cancer tissues and selectively deliver their dose.

Advanced experimentation going on in several medical centres, very promising for solid or diffused cancers (leukaemia). Potential to become a powerful and selective tool for personalised cancer treatment.

If the radioisotope is also a gamma or beta emitter, can be coupled to diagnostics tools to optimise the dose



M.Vretenar's KT-seminar

Summary

NIMMS started 20y after "PIMMS" (which gave birth to CNAO and MedAustron), to enable a next generation of medical facilities.

A toolbox of CERN core technologies and competencies, with impact on society - medicine: **Superconducting magnets**, **Mechanics**, **Linac**, **Beam dynamics** and **AI/ML**

Users are existing medical facilities and potential new centers, such as SEEIIST, in the South-East Europe

Rich program open to collaborating partners!