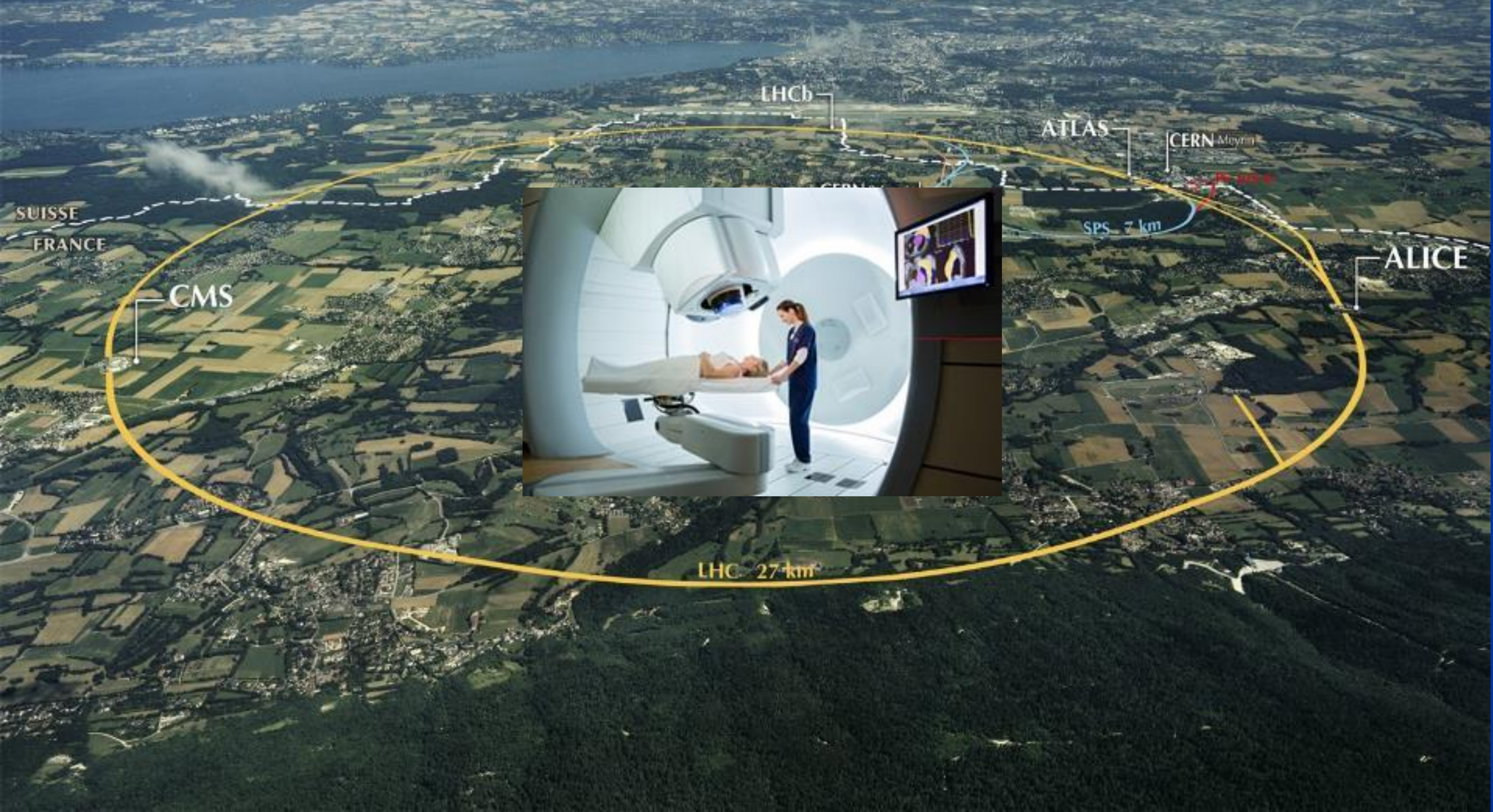
Next-generation facilities for cancer research and therapy with particle beams



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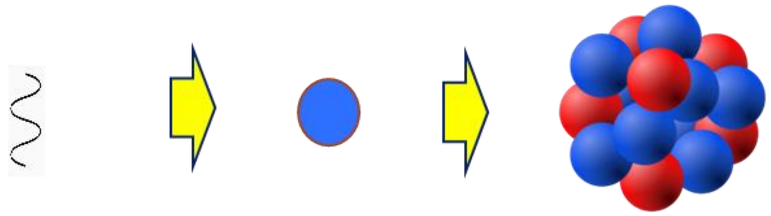
CERN, ATS/DO
Accelerator and Technology Projects and Studies

Perspectives for cancer research and therapy with ions

6 April 2022

Ion therapy: from photons to protons to ions



Photon (X-ray)
no mass

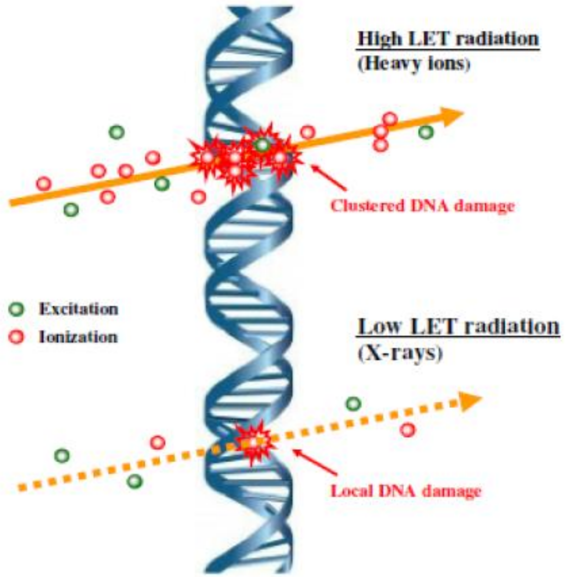
Proton
mass: 1 m_0

Carbon ion
mass: 12 m_0

Ions are heavier, and deliver more energy to the tissues: generate dense ionisations that damage DNA beyond repair. A different and more effective biological action than X-rays or protons.

Advantages of heavier ions (compared to protons or X-rays)

- Generate non-reparable double-strand DNA breakings that are effective on hypoxic radioresistant tumours.
- Energy deposition more precise, with lower straggling and scattering
- Opportunities from combination with immunotherapy to treat diffused cancers and metastasis.



- Only carbon ions licensed for treatment, after the pioneering developments at HIMAC (Japan) from the 90's
- First patient treatments with carbon ions only in 1994: ion therapy is still in its infancy !

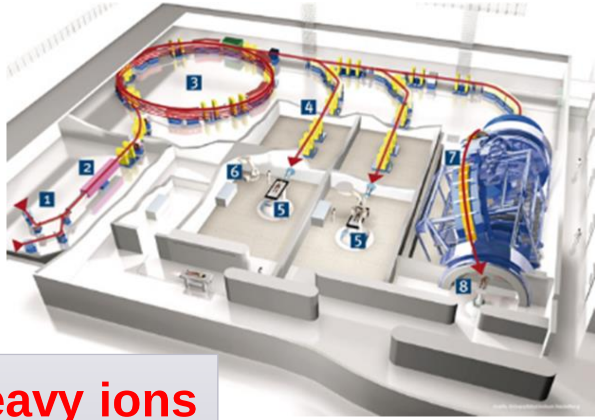
What accelerator for what particle

Ions deliver more energy to the tissues but need more energy to enter the body → higher energy accelerator, factor 2.8 in diameter with respect to protons

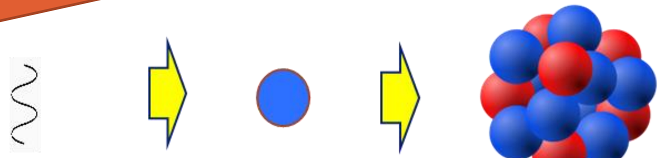
Linac, X-rays
~50 m^2
~5 M€

courtesy IBA

Cyclotron, protons
~500 m^2
~40 M€



Synchrotron, heavy ions
~5,000 m^2
~200 M€



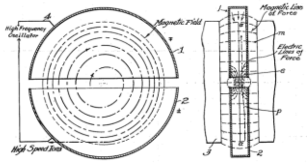
Photon (X-ray)
no mass

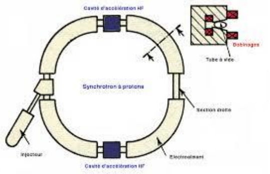
Proton
mass: 1 m_0

Carbon ion
mass: 12 m_0

A synchrotron is a “hollow cyclotron”: Because higher energies need larger particle orbits, in the synchrotron a time-varying magnetic field covers only the external part.

Wikimedia commons





New technologies for ion therapy accelerators

Ions deliver more energy to the tissues but need more energy to enter the body → because the diameter of the accelerator increases with energy, accelerator dimensions increase by a factor 2.8 from protons to carbon

The main limitation to the diffusion of ion therapy is the cost and size of the accelerator

Only 4 ion therapy facilities operating in Europe (+ 6 in Japan, 3 in China, 1 planned in US)

- CNAO and MedAustron based on a design started at CERN in 1996. 1st patient at CNAO in 2011.
- HIT and MIT based on a design started at GSI (Germany) in 1998 . 1st patient at HIT in 2009.

The ion gantry of the Heidelberg Ion Therapy facility: 600 tons

Particle accelerator technology has made a huge progress in the last 20 years, towards more compact and performant accelerator designs.

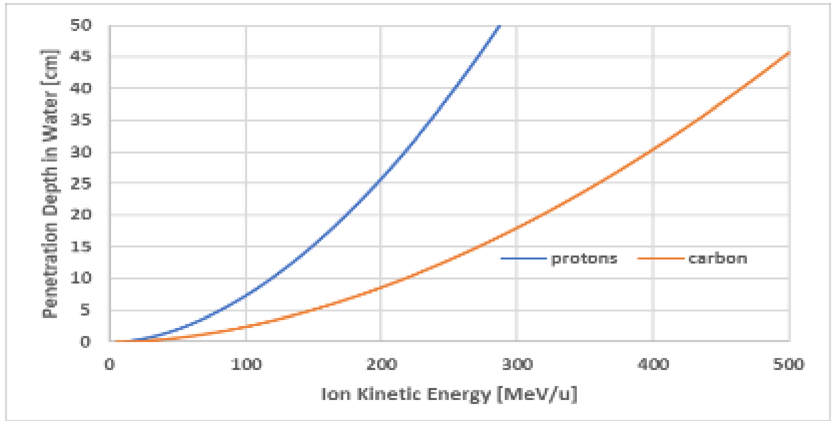
We can today explore new accelerator designs profiting of the latest advances in accelerator technologies.

A strategy for CERN

- **Proton** therapy is now commercial, and CERN, as an international organisation, cannot interfere with a mature commercial market.
- **Heavy ion** therapy is still in an early phase despite its advantages. Its diffusion is limited mainly by:
  - ✓ **Size and cost of the accelerator**;
  - ✓ **Lack of experimental data**.
- New demands from the medical community and new opportunities from recent research can be integrated in a newly designed ion therapy facility.

Strong impact on the medical field from 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.

For carbon ions, accelerator and gantry are almost 3 times larger than for protons. The HIT gantry has a mass of 600 tons for a dipole bending radius of 3.65 m.



The Next Ion Medical Machine Study (NIMMS)

Establishment of NIMMS, the
Next Ion Medical Machine Study at CERN (2018):

- Building on the experience of the PIMMS (proton-ion medical machine study) of 1996/2000;
- Federating a large number of partners to develop designs and technologies for next-generation ion therapy;
- **Partners** can use the NIMMS technologies to assemble their own optimized facility.

nimms

Basic requirements of the next generation cancer therapy accelerator:

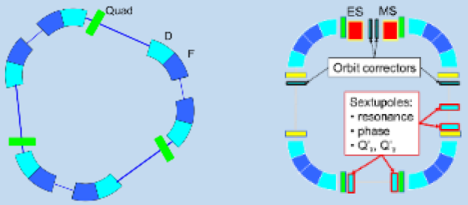
- ❑ Operation with multiple ions: protons, helium, carbon, oxygen, etc. for therapy and research.
- ❑ Lower cost and dimensions, compared to present;
- ❑ Faster dose delivery with higher beam intensity and new delivery schemes (FLASH)
- ❑ A gantry device to precisely deliver the dose to the tumour.

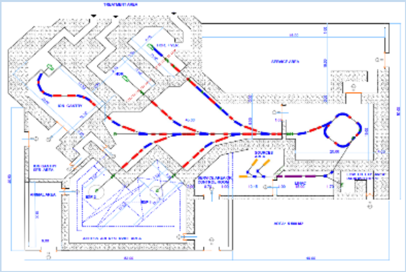
International partners collaborating with NIMMS:

- ❑ SEEIIST (South East European International Institute for Sustainable Technologies)
- ❑ TERA Foundation (Italy)
- ❑ GSI (Germany)
- ❑ INFN (Italy)
- ❑ CIEMAT (Spain)
- ❑ Cockcroft Institute (UK)
- ❑ University of Manchester (UK)
- ❑ CNAO (Italy)
- ❑ Imperial College (UK)
- ❑ MedAustron (Austria)
- ❑ U. Melbourne (Australia)
- ❑ ESS-Bilbao (Spain)
- ❑ Riga Technical University (Latvia)
- ❑ Sarajevo University (Bosnia &H.)

Main research lines for future ion therapy

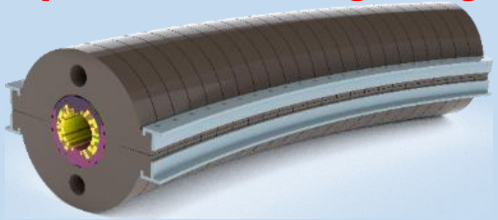
1. Small synchrotron accelerators (rings)

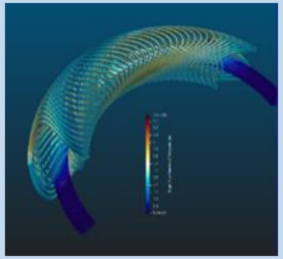




Reduced dimensions with improved performance (injection, extraction)

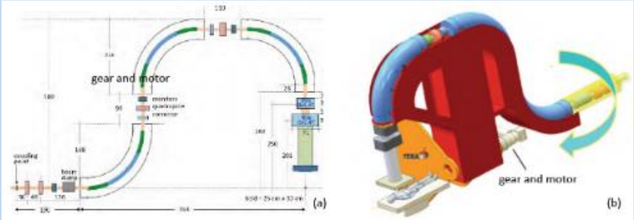
2. Superconducting magnets for small accelerators

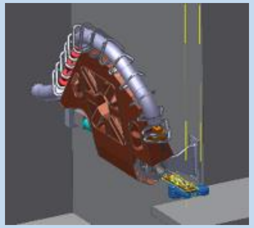


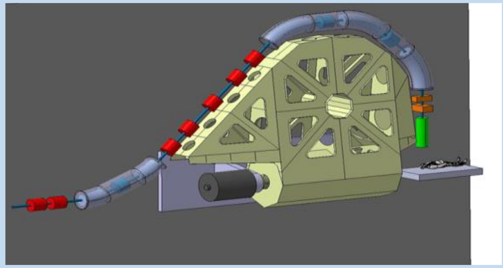


High magnetic fields to bend particles on small orbits

3. Superconducting rotating gantries for ions







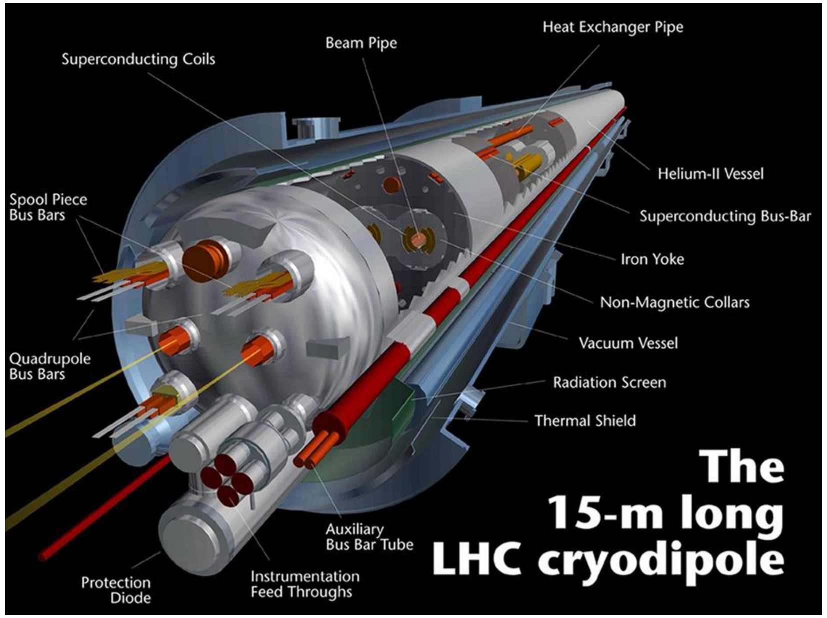
Precise beam delivery on multiple angles

Superconducting magnets for synchrotrons and gantries

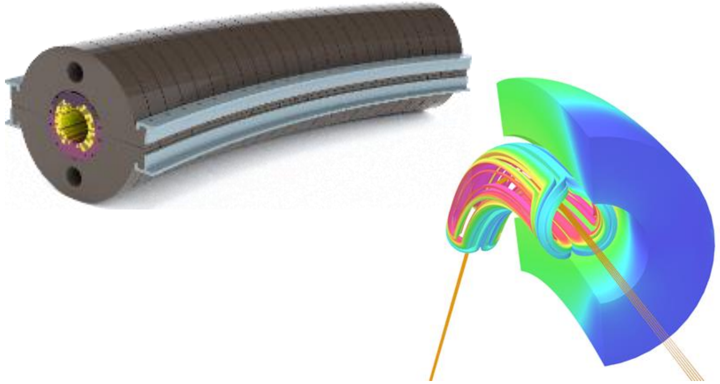
The main avenue to reducing the dimensions of a magnetic system is **superconductivity**.
Here the interest is not (only) in reducing power loss of conductors, but in increasing the magnetic field inside the large magnets that drive the particle beam.

The higher the magnetic field, the smaller the radius of the accelerator!

Medical accelerator magnets have specific challenges: ramping field, curved shape, beam focusing, …



LBNL, USA



CERN (courtesy M. Karppinen)

A new generation of compact superconducting magnets for ion therapy synchrotrons and gantries: 45^0 curvature in 1.3 m, 4 T field

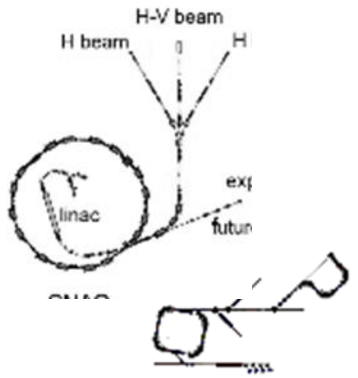
From the huge magnets of the Large Hadron Collider to small sophisticated magnets for therapy synchrotrons

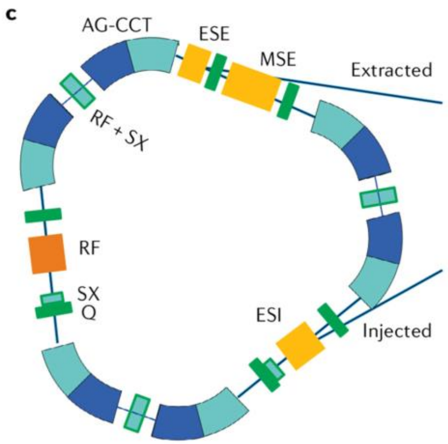
Being developed by a wide collaboration within two EU-funded projects: HITRI+ *(hitriplus.eu)*, I.FAST *(ifast-project.eu).*

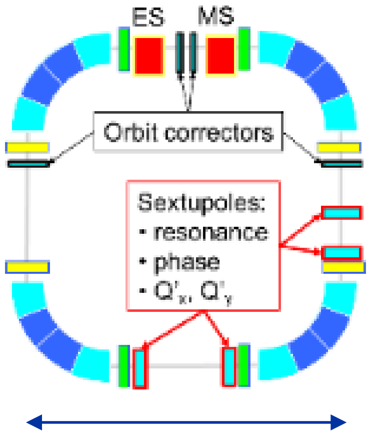
First demonstrator magnets in 3 years

The compact superconducting synchrotron

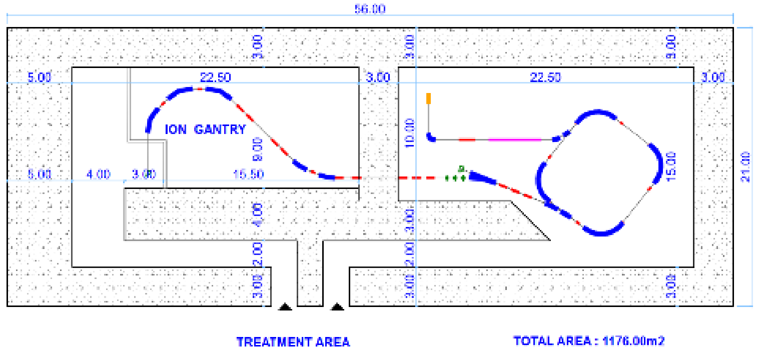
Considerable gain in dimensions thanks to superconductivity

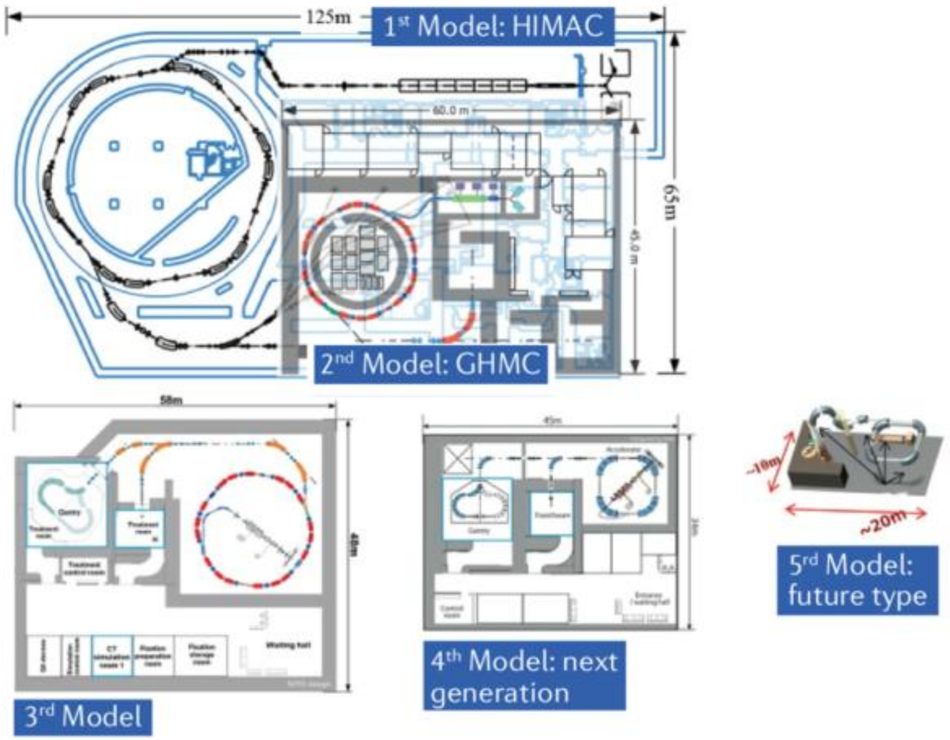






Alternative synchrotron layouts





Additional features

- High intensity (2 x 10^{10} C ions per pulse
- Slow and FLASH extraction
- Multiple ion operation

Goal: a compact single-room ion therapy facility in about 1,000 m²

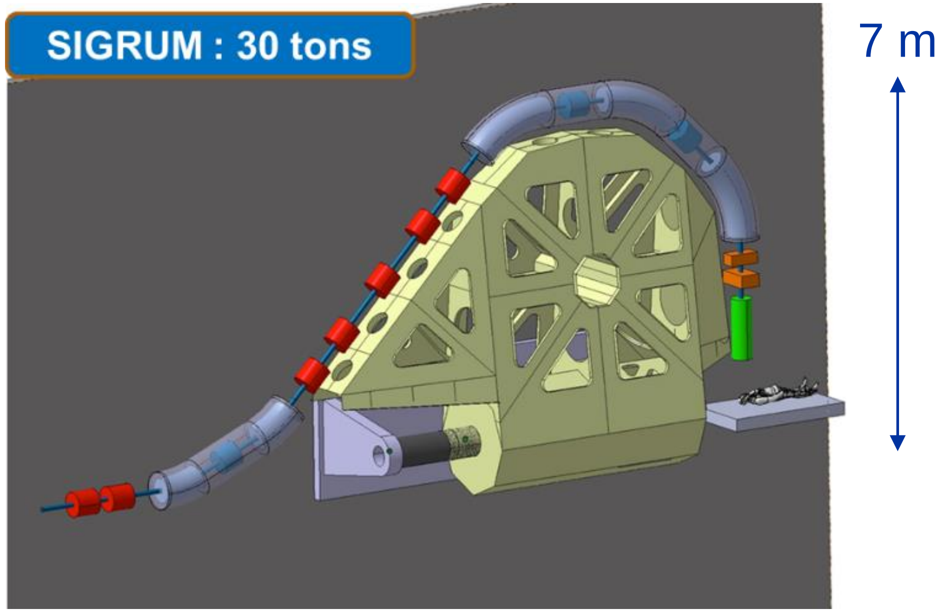
Japan: the roadmap of the National Institutes for Quantum and Radiological Science and Technology (NIRS-QST, Chiba) for reducing the footprint of heavy ion centres. Form the large HIMAC (1994) to 3rd and next generation (courtesy of K. Noda, NIRS-QST).

E. Benedetto et al., Comparison of accelerator designs for an ion therapy and research facility, CERN-ACC-NOTE-2020-0068, http://cds.cern.ch/record/2748083?ln=en

An innovative superconducting ion gantry

Development of a rotating Superconducting Gantry for Carbon ions (SIGRUM), Supported by 2 collaborations:

- CERN-INFN-CNAO-MedAustron: magnets, dose delivery, range verification, scanning system.
- HITRIplus EU project (CNAO, RTU, SEEIIST, CERN: optics and mechanics design.



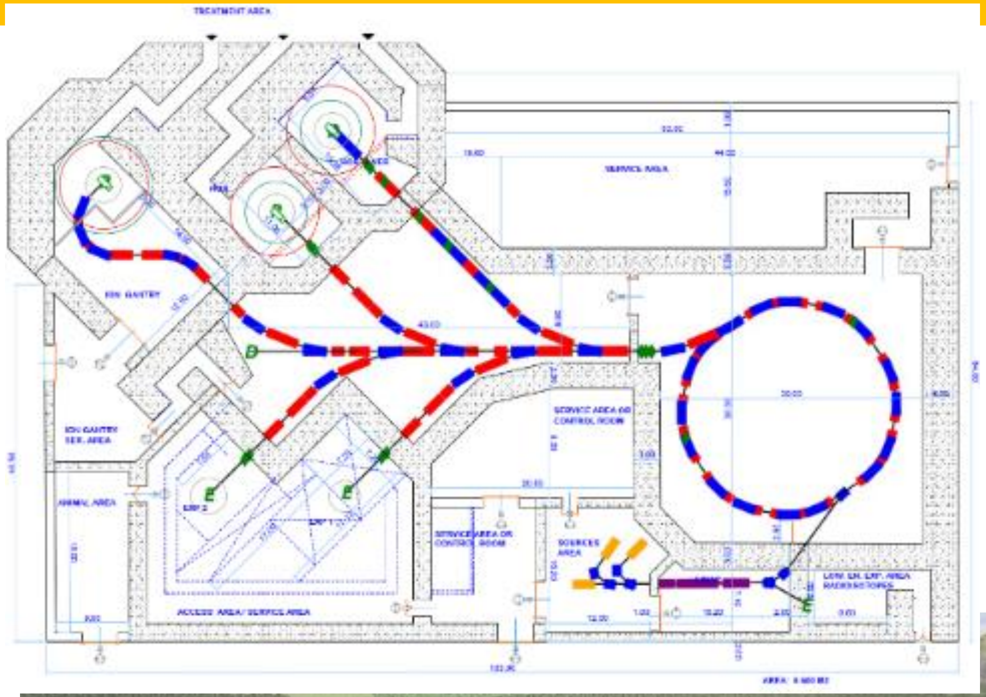
The SEEIIST initiative

- **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 (11 member countries).

- SEEIIST is supported by the European Commission, to develop the facility design in collaboration with CERN and other partners.

- 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, in the line of "science for peace".

SEE ST
South East European
International Institute
for Sustainable Technologies



Accelerator

Baseline: conventional normal-conducting synchrotron
Advanced option: superconducting synchrotron

The unique SEEIIST ion therapy and research facility

Intensive design work in 2019/20 in collaboration between CERN and SEEIIST, with the contribution of NIMMS partners and of the main European ion therapy centres

A. Innovative SEEIIST features:

1. Optimised for 50% research and 50% patient treatment (~400 patients/year);
2. Providing 20 times higher beam intensity for carbon ions than present facilities;
3. Equipped with flexible extraction for operation in FLASH mode;
4. Equipped with dual mode linear injector capable of producing radioisotopes for cancer imaging and therapy.

C. Conservative SEEIIST feature:

The synchrotron adopts the well-established PIMMS design (known and available components, flexible layout for research);

D. Specific SEEIIST features:

1. Environmental strategy: minimise energy consumption, strategy for energy generation;
2. Conceived as a multiple-hub facility, to federate partners in different countries.

B. Advanced SEEIIST features (common to other advanced facilities):

1. Operation with multiple ions: protons, Helium, Carbon, Oxygen, Argon;
2. Multiple energy extraction for faster treatment;
3. Equipped with a compact superconducting gantry of novel design.

The proposed SEEIIST facility

Roof of accelerator building is removed to show accelerator components

Thank you for your attention

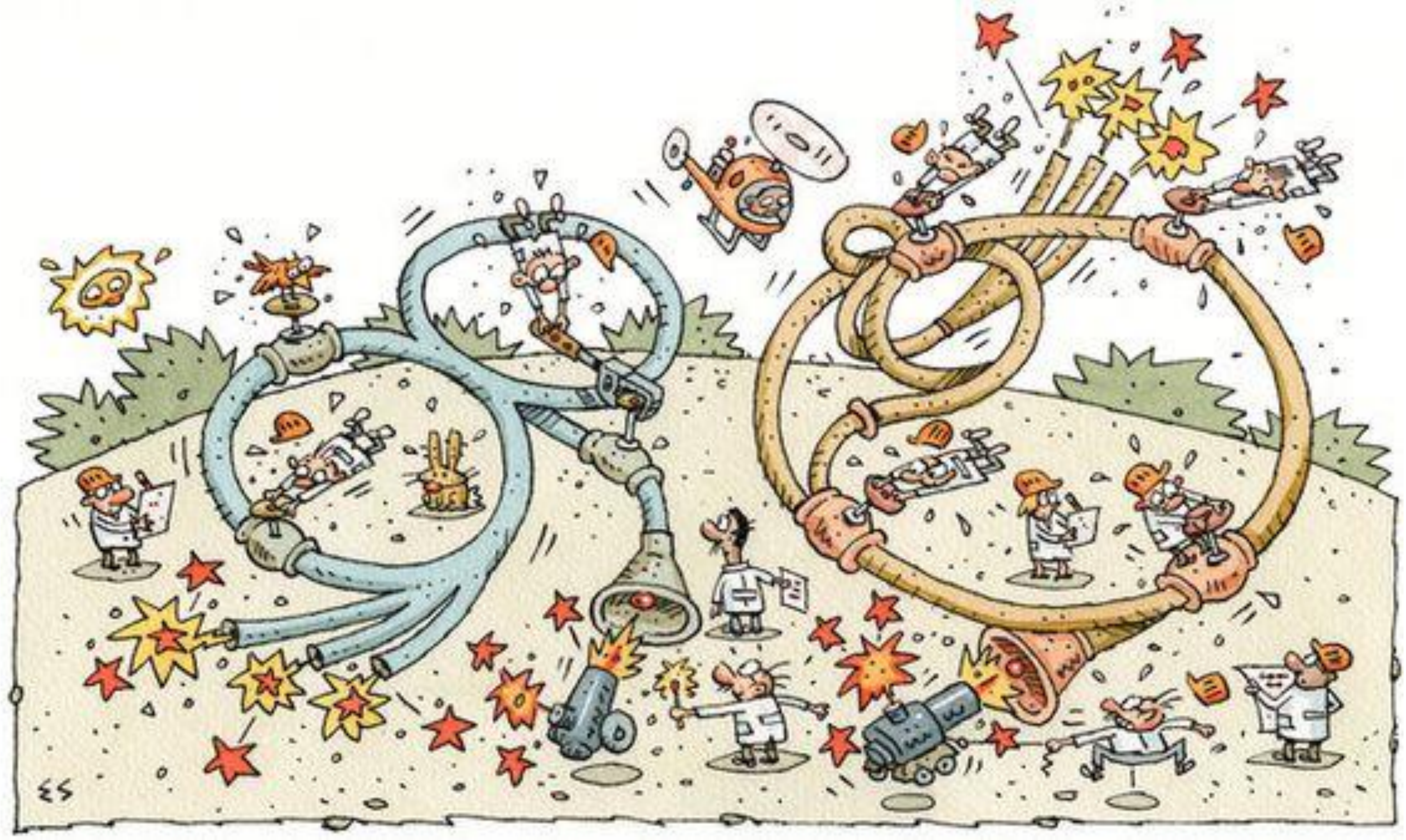


Image credit: Elwood H. Smith, The New York Times