The CERN Next Ion Medical Machine Study: towards a new generation of accelerators for cancer therapy

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for the NIMMS Collaboration

ATS&KT Seminar

19 October 2020

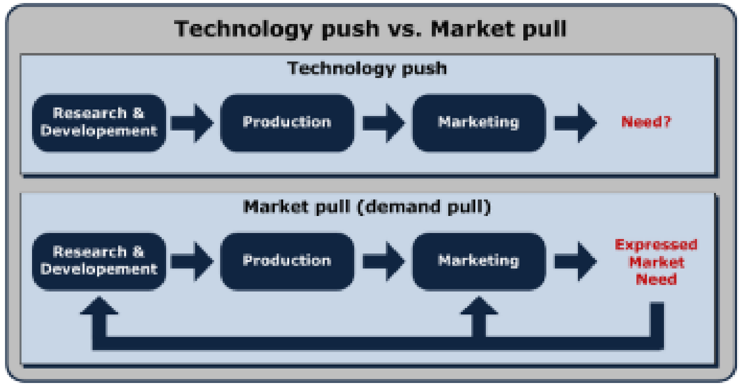
CERN Knowledge Transfer for Medical Applications

- Huge portfolio of CERN technologies with potential impact on society, some with related commercial interest;
- But: CERN technologies as such (optimized for particle physics) have little or no direct interest;
- **An additional R&D step is needed,** to adapt CERN technologies to what is required by society and by the market.

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

Challenges:

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



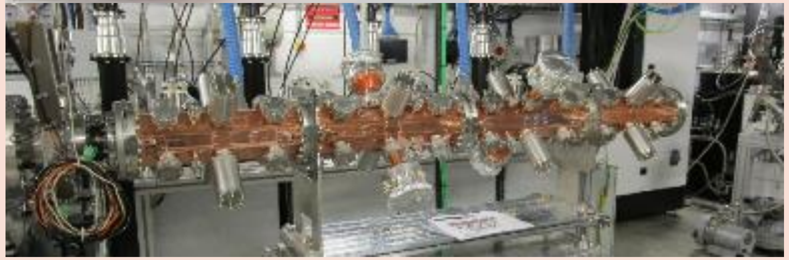
Wider Goal: highlight the social benefit of technologies developed for HEP

EXAMPLE: Linac4

Developed for particle physics, no societal or commercial interest as such

The CERN high-frequency RFQ

Developed using Linac4 technology, for medical and societal applications (2 years, 1.5 MCHF shared between CERN and industrial partner)



From PIMMS to NIMMS

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. This experience goes in 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, and 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.

June 2017 CERN Council Strategy document on KT for Medical Applications:

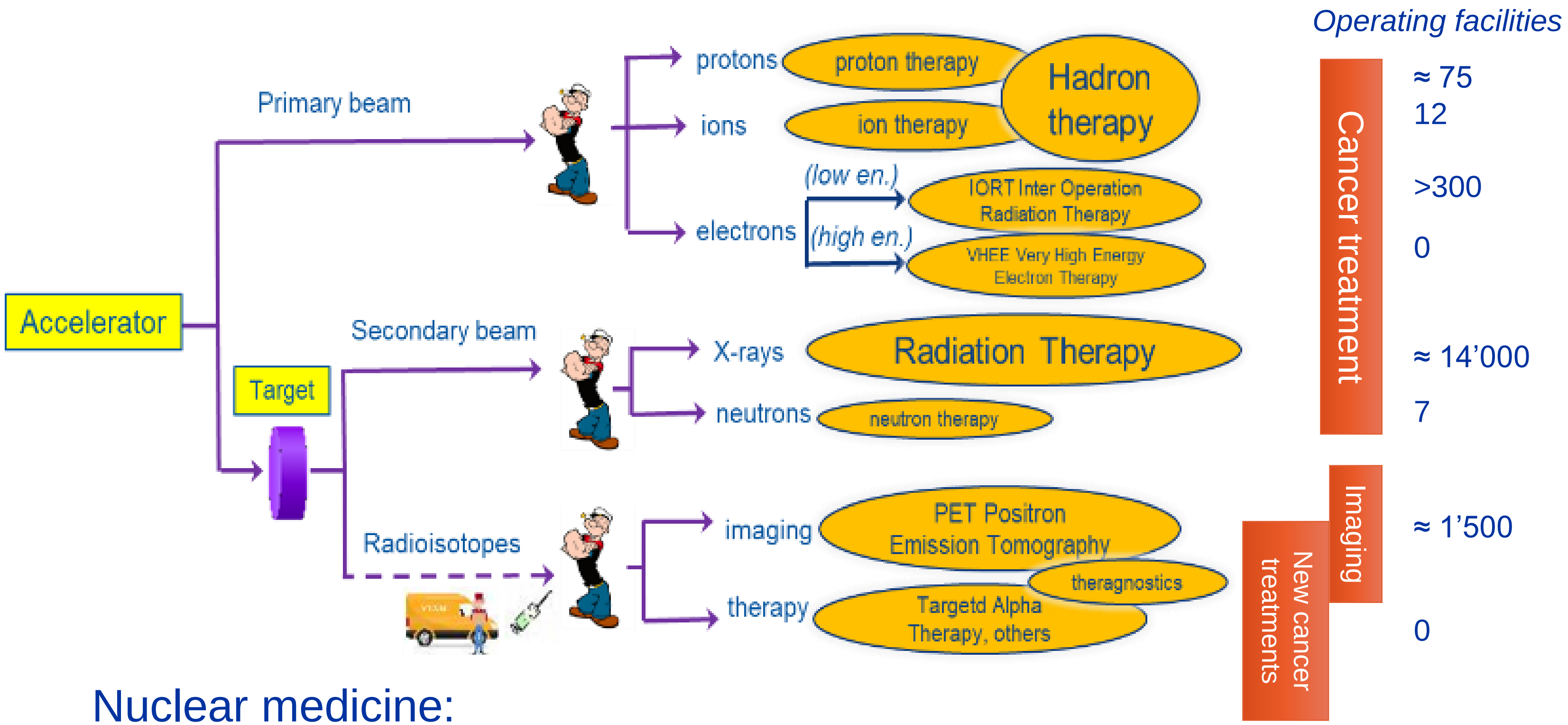
A collaborative design study coordinated by CERN would contribute to the development of a new generation of compact and cost-effective light-ion medical accelerators. A new initiative of this type would leverage existing and upcoming CERN technologies and the Laboratory's expertise in the fields of radiofrequency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

NIMMS = Next Ion Medical Machine Study

To be developed at CERN in collaboration with the existing ion therapy centres and with similar programmes in the Member States.

Particle accelerators: a formidable tool for medicine

- Particle beams (primary and secondary) precisely deliver large amounts of energy to small volumes, penetrate in depth (different from lasers) and interact with cells, molecules, and atoms (electrons and nuclei).
- Particles beams can activate the nuclei generating radiation that can destroy cancerous cells or can be detected from outside
- Accelerators are the way to realise the old dream of a **bloodless surgery and imaging**: penetrate into the human body to treat diseases and to observe internal organs without using surgical tools.



Operating facilities

Accelerator

Primary beam

protons – proton therapy – Hadron therapy – ≈ 75

ions – ion therapy – Hadron therapy – 12

electrons (low en.) – IORT Inter Operation Radiation Therapy – >300

electrons (high en.) – VHEE Very High Energy Electron Therapy – 0

Cancer treatment

Target

Secondary beam

X-rays – Radiation Therapy – ≈ 14’000

neutrons – neutron therapy – 7

Radioisotopes

imaging – PET Positron Emission Tomography – Imaging – ≈ 1’500

theragnostics

therapy – Targetd Alpha Therapy, others – New cancer treatments – 0

Nuclear medicine:

application of radioactive substances in the diagnosis and treatment of disease

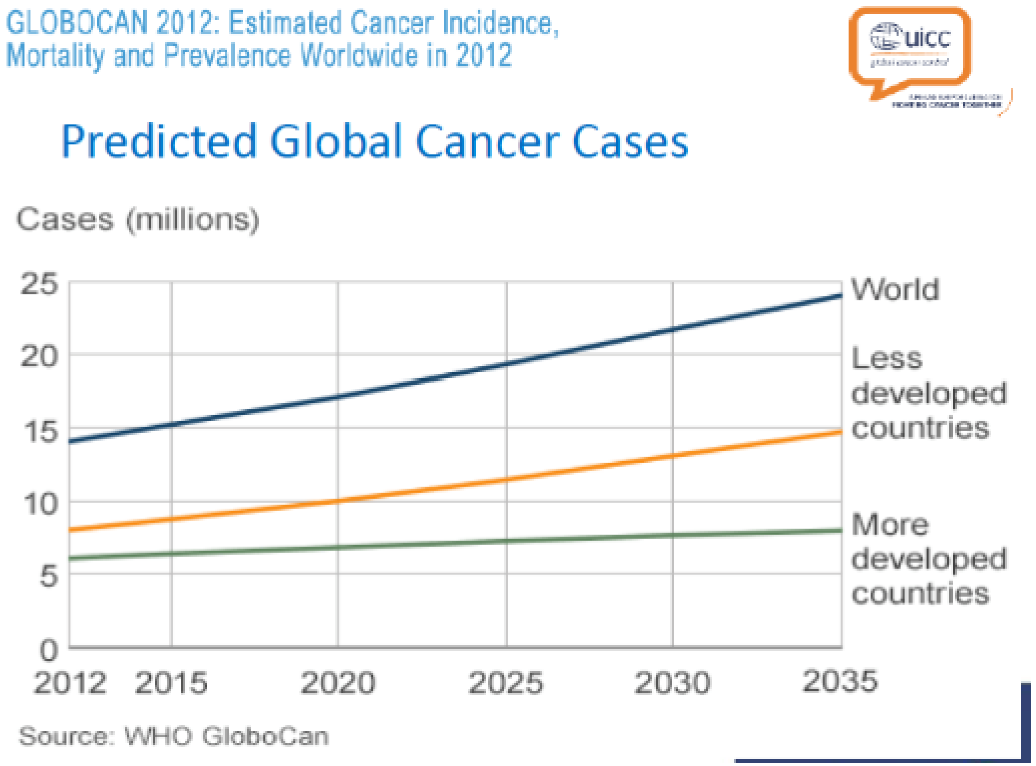
Radiation therapy:

therapy using ionizing radiation, generally as part of cancer treatment to control or kill malignant cells

≈ 16’000 particle accelerators operating for medicine worldwide, in cancer therapy and imaging

Fighting against Cancer

Cancer is the second leading cause of death globally, and was responsible for 8.8 million deaths in 2015. Globally, nearly 1 in 6 deaths is due to cancer (WHO).



Source: WHO GloboCan

Increase of cancer cases due to:

- Increasing age of population
- Aggressive environmental and living conditions in developing countries.

The standard protocol for treatment of most cancers is based on:

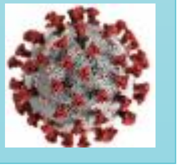
1. Surgery
2. **Radiotherapy** (mainly X-rays)
3. Chemiotherapy
4. (Immunotherapy)

New trend: personalised medicine based on combination of different high-technology treatments.

Cancer and Covid

193,000 deaths reported in Europe for Covid19 (at 7.10.20).

About **1,900,000** deaths of cancer every year in Europe.



→ **Factor 10** !

EU Mission on Cancer

Cancer research has been declared as one of the 5 specific mission areas of the next EU research and innovation framework programme, Horizon Europe (2021-27): conquering cancer, mission possible

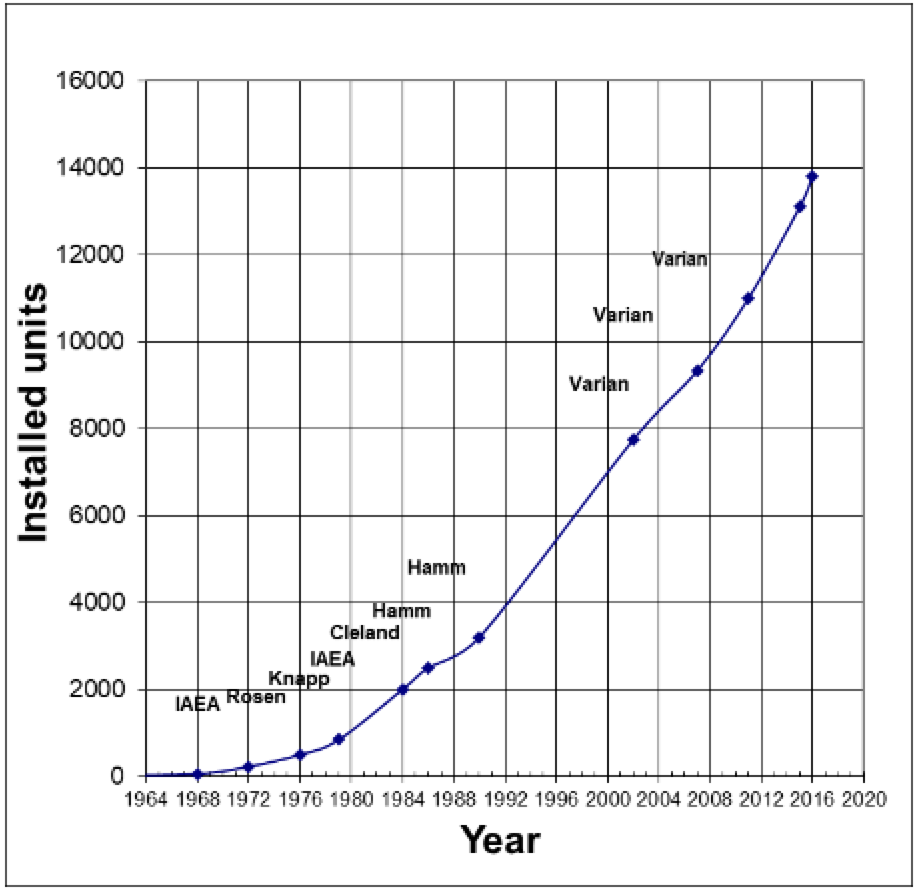
X-ray radiation therapy

New cancer patients per year:

Increasing from 12.5M in 2008 to 27M in 2030.

Over 60% treated with Radiation Therapy.

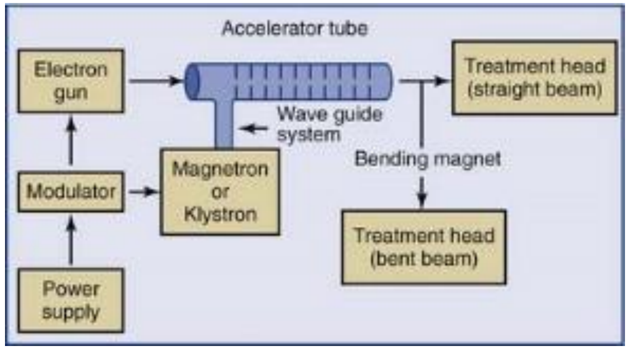
Courtesy of R. Hamm



The most successful particle accelerator in the world.

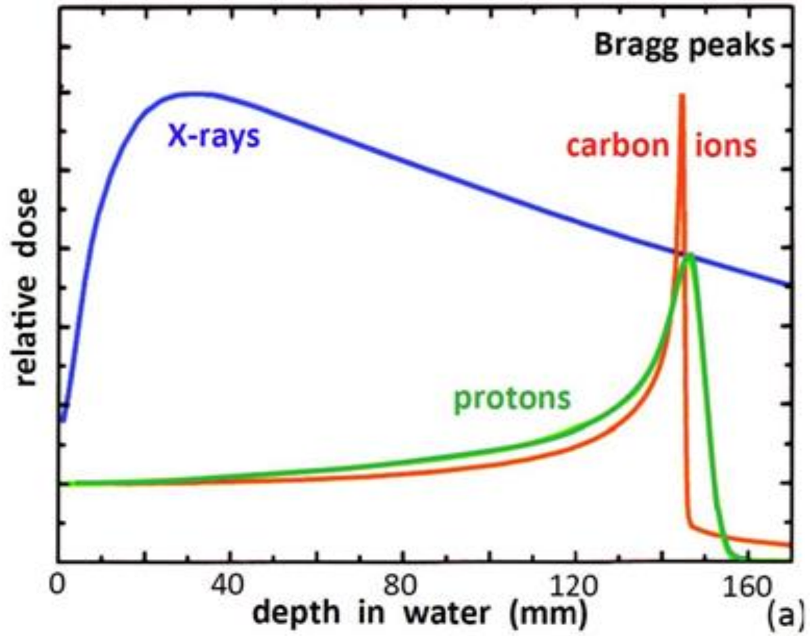
More than 15,000 operating units worldwide, at a cost of about 1-5 M€/unit.

Constant improvement (collimation, 3D conformal treatment, intensity modulation, combined imaging and therapy)



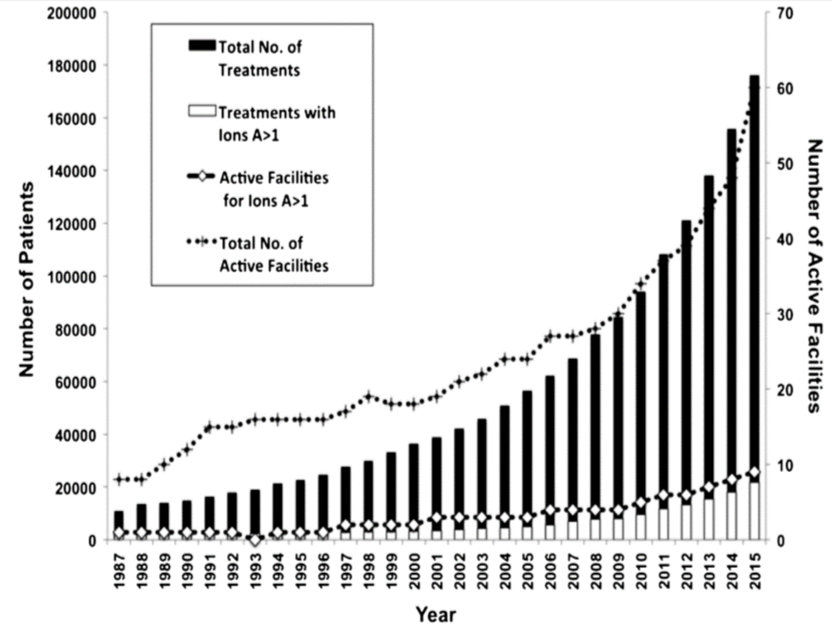
Hadron therapy (protons or ions)

The beauty of the Bragg peak

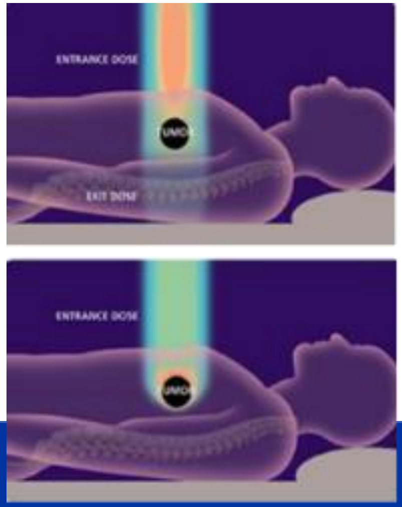


Different from X-rays or electrons, protons (and ions) deposit their energy at a given depth inside the tissues, **minimising dose to the organs close to the tumour,** sparing nearby organs.

Required energy for full-body penetration: 230 MeV protons, 450 MeV/u C-ions.



- First experimental treatment: 1954, Berkeley.
- First hospital-based proton treatment facility: 1993, Loma Linda, US.
- First treatment facility with carbon ions: 1994, HIMAC, Japan.
- Treatments in Europe at physics facilities from end of ‘90s.
- First dedicated European facility for protons and carbon ions: 2009, Heidelberg.
- From 2006, commercial proton therapy cyclotrons appear on the market (but Siemens gets out of proton/carbon synchrotrons market in 2011).
- Nowadays 3 competing vendors for cyclotrons, one for synchrotrons (all protons).

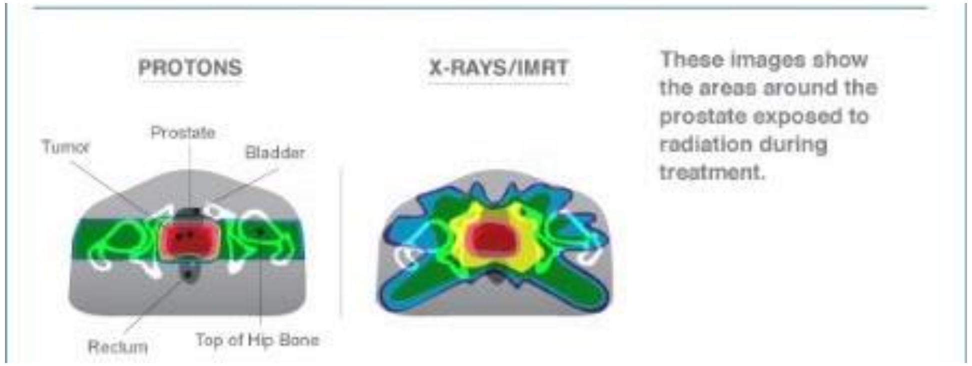


Hadron therapy remains a niche in cancer therapy: 22,000 patients/year (2018) treated with particle beams against 25,000,000 patients/year with conventional RT.

Particle therapy: a growing niche but not a panacea

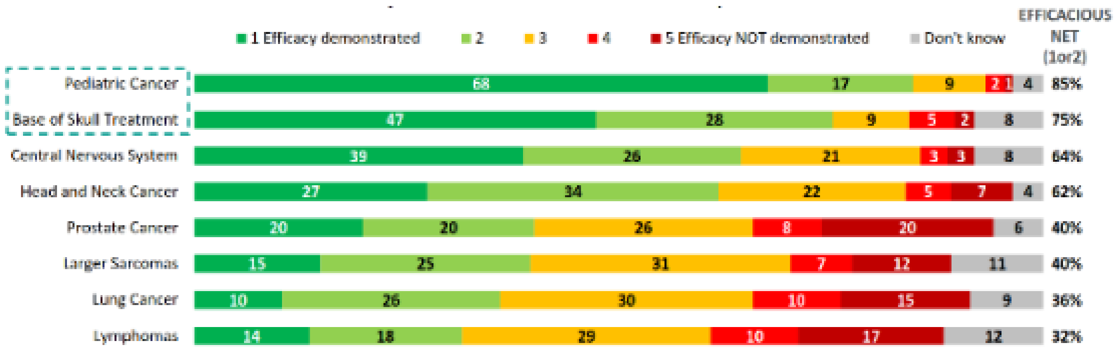
Factors limiting growth

- **X-ray Radiation Therapy is improving**: thanks to a wide market and a strong industry basis, RT is becoming increasingly precise and effective. FLASH therapy could give it another boost.
- **Cost**: a commercial single-room proton therapy system has a price from 30 M€, to be compared with 2-3 M€ of a X-ray radiotherapy system. An ion therapy centre has a cost of 150-200 M€.
- **Lack of clinical data**: the effect of protons and ions is not as known as that of X-rays, optimisation of treatment is still ongoing. Biological tests are needed to compare the loss of energy (Bragg peak) to the effect on the cells – not necessarily linear.
- **Quality of life appreciation**: protons and ions are superior in sparing the surrounding tissues, improving quality of life after treatment. But while survival rates are easy to measure and compare, quality of life is only recently becoming a “measurable” parameter.
- **Centralisation of medicine**: the high cost of particle treatment calls for large centralised units that have difficulties in attracting patients from other hospitals.



These images show the areas around the prostate exposed to radiation during treatment.

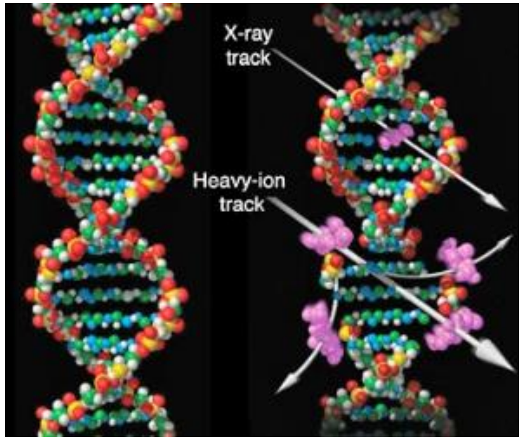
Proton therapy is mainly recommended for:
- Some specific tumours close to critical organs
- Pediatric tumours (less risk of recurrency)



Source: IBA, state of proton therapy market entering 2017

Therapy with heavier ions (Carbon and others)

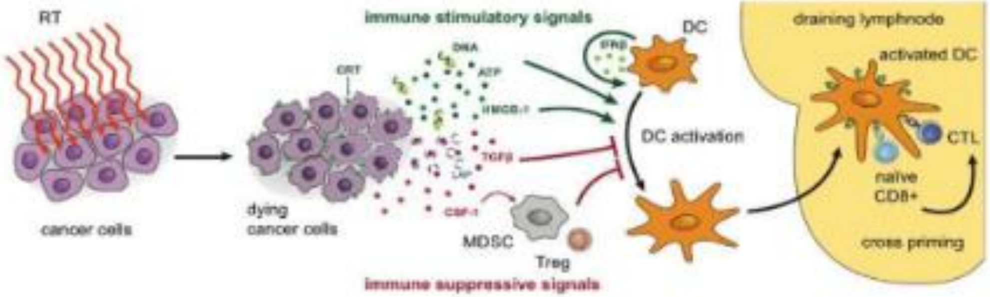
Ions (e.g. Carbon) are different from X-rays or protons!



Heavy ions are **more effective than protons or X-rays** in attacking cancer:

1. The higher energy deposition (and ionisation) per length generates a large number of double-strand DNA breakings that are not reparable by the cell itself.
2. The different damage mechanism makes them effective on hypoxic radioresistant tumours (while protons or X-rays act via generation of Reactive Oxygen Species) – 1 to 3% of all RT cases.
3. Are more precise, with lower straggling and scattering.
4. Recent studies show that ion therapy combined with immunotherapy may be successful in treating diffused cancers and metastasis.

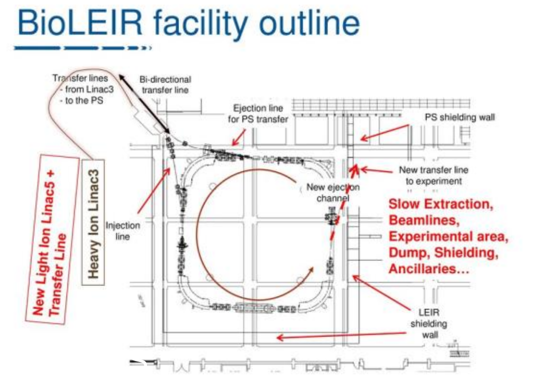
So far, 2/3 of cases at the mixed facilities like CNAO are treated with carbon.



The development of ion therapy needs to be supported by tests with **other ions (He, O, etc.)** and by a strong experimental effort covering:

- Pre-clinical radiobiology;
- Medical physics;
- Animal studies;
- Clinical trials on patients.

programme of the former BioLEIR study


BioLEIR facility outline

A strategy for CERN

- **Proton** therapy is now commercial, 4 companies offer turnkey treatment facilities (3 SC cyclotrons, one conventional synchrotron), and in competition with conventional radiation therapy (X-rays).
- **Heavy ion** therapy (mainly **carbon**) is still in an early phase (13 facilities worldwide, 4 in Europe) in spite of its several advantages but its diffusion is limited mainly by:
  - ✓ **Size and cost of the accelerator**;
  - ✓ **Lack of 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.

Specifications from the scientific community

(Archamps Workshop, June 2018)

Workshop

Ideas and technologies for a next-generation facility for medical research and therapy with ions

MAIN TOPICS:
- EXISTING FACILITIES
- CURRENT INITIATIVES
- NEW TECHNOLOGIES
- DESIGN PARAMETERS
- TECHNICAL OPTIONS

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;**

❑With **range calibration and diagnostics** online.

NIMMS Origins and Goals

Next Ion Medical Machine Study

- Started from an impulse by U. Amaldi in 2016-17
- Structured after the Archamps Workshop in 2018
- International collaborations started in 2018
- CERN funding approved by KT-MA in 2019 until 2022
- Submitted two proposals for H2020 EU support in 2020

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»)

Approved in June 2019 with a budget of 250’000 CHF/yr for 2020 and 2021 from the CERN KT Medical Applications, as “seed money” to launch collaborations and joint initiatives.

This presentation will report on the first 1.5 years of NIMMS

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 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, Minister of Science of Montenegro, and H. Schopper, former Director General of CERN.
- Strong support by the EC and by Switzerland.

Basic concepts for a
SOUTH-EAST EUROPE
INTERNATIONAL INSTITUTE FOR
SUSTAINABLE TECHNOLOGIES
(SEEIIST)

January 15, 2018

The NIMMS Collaboration

Large number of international partners collaborating with NIMMS (a collaboration MoU is planned):

SEEIIST	E. Benedetto, M. Sapinski, S. Damjanovic, P. Grübling
TERA Foundation	U. Amaldi, P. Riboni, N. Alharbi
GSI	P. Foka
INFN	G. Bisoffi, L. Rossi
CIEMAT	J. Navarro, C. Oliver, D. Perez
Cockcroft Institute	H. Owen
CNAO	S. Rossi, M. Pullia
Imperial College	K. Long, R. Taylor
MedAustron	P. Urschütz
U. Melbourne	S. Sheehy, X. Zhang

Interest in joining the collaboration expressed by other partners:

- Indian Institutions
- Baltic Institutions

- CERN contributors, who have in different ways contributed to the study:

M. Vretenar, A. Lombardi, V. Bencini, D. Gibellieri, A. Grudiev, H. Pommerenke, S. Ramberger, M. Khalvati, E. Oponowicz, D. Tommasini, D. Perini, M. Karpinen, etc.

- Input from medical community via the ENLIGHT Network (managed by M. Dosanjh with M. Ristova and P. Georgieva)

- Input from ion therapy scientific community via M. Durante (GSI) and his International Biophysics Collaboration.

NIMMS Workpackages – inside the toolbox

	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 2 gantry options (optics and mechanical structure): - Rotational - Toroidal
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.

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

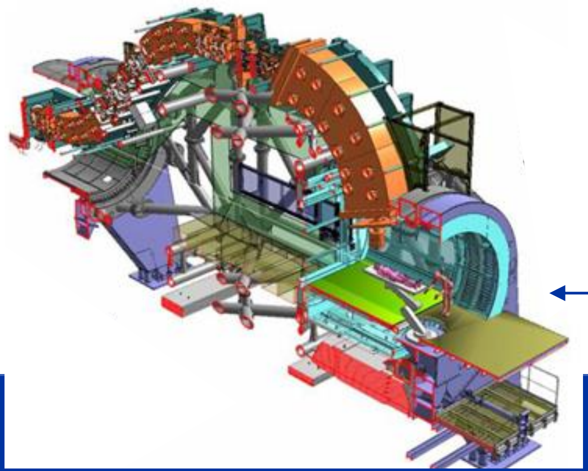
The __“full-linac”__, a different approach for fast 3D scanning of tumours

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.

Main challenge for ion acceleration is the magnetic rigidity (Bρ) at treatment energy:

2.27 Tm for protons (220 MeV)
6.63 Tm for carbon ions (430 MeV/u)
→ **factor 2.9**



Gantry=rotating beam line sending the beam to precise positions on the patient

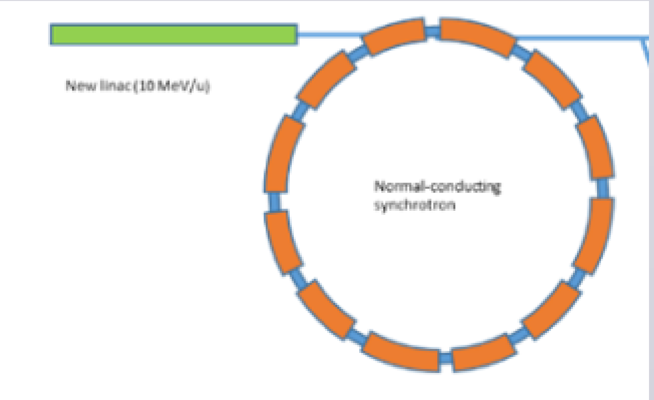
← HIT carbon ion gantry (RT magnets):
L=25 m, F = 13 m, 600 tons

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.

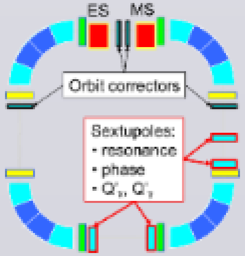
Circumference ~ 75 m

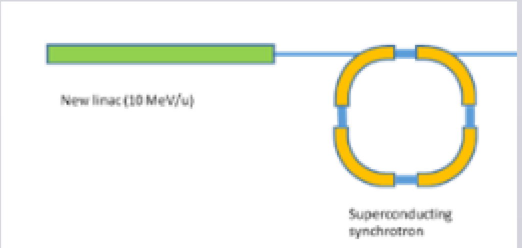


Improved synchrotron (superconducting)

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

Circumference ~ 27 m

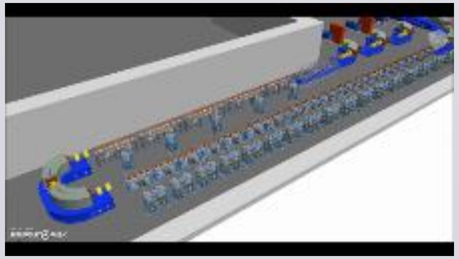


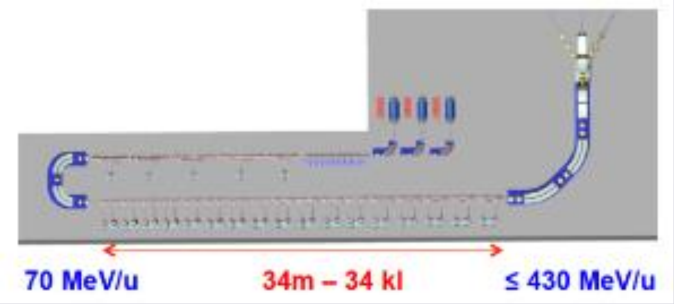


Linear accelerator

Linear sequence of accelerating cells, high pulse frequency.

Length ~ 53 m



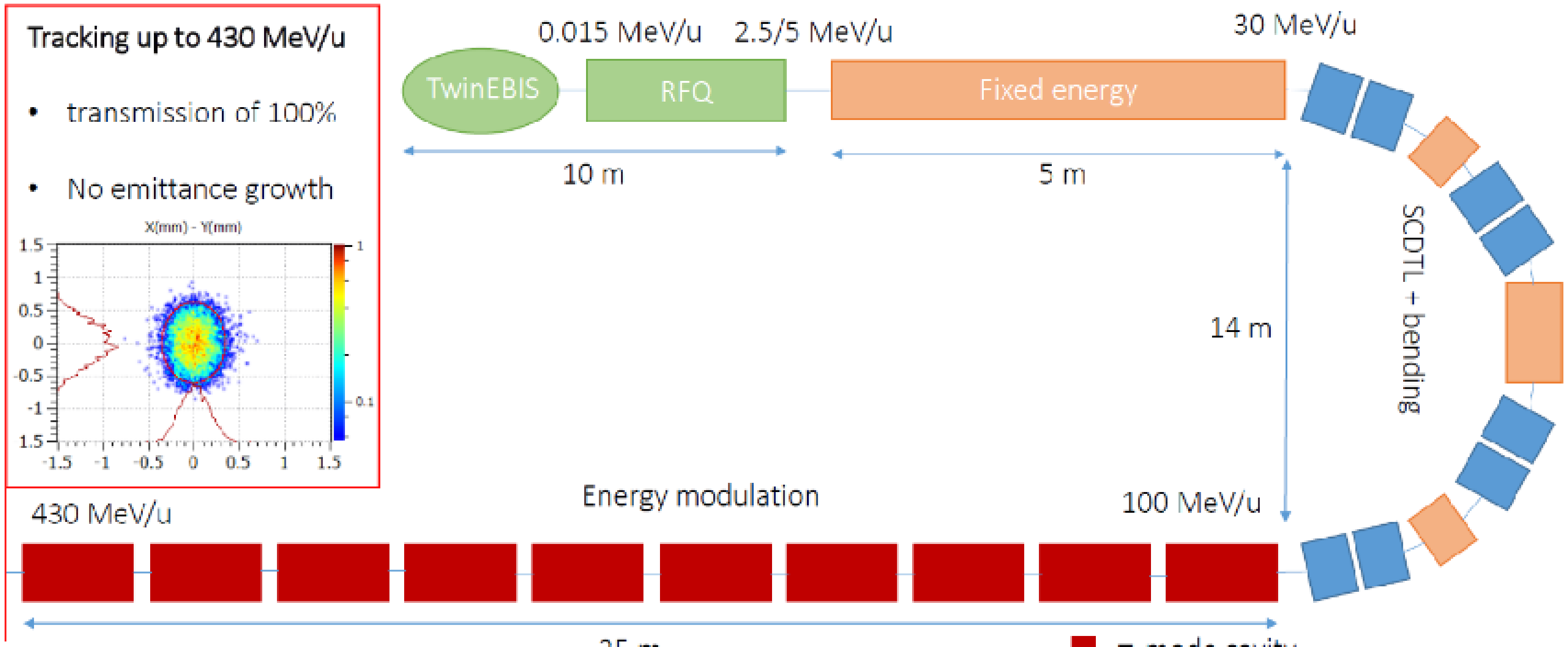


Other options considered as less interesting because of cost and/or required R&D: **RC synchrotron**, **FFAG**, **SC cyclotron**, **PWFA**

Accelerator option #1: the linac

A. Lombardi, V. Bencini, D. Gibellieri, F. Wenander, BE/ABP
A. Grudiev, H. Pommerenke, S. Ramberger, M. Khalvati, BE/RF
J. Navarro, C. Oliver, D. Perez, CIEMAT

High repetition frequency (360 Hz) with pulse-to-pulse energy modulation allow fast and accurate dose delivery to the tumour



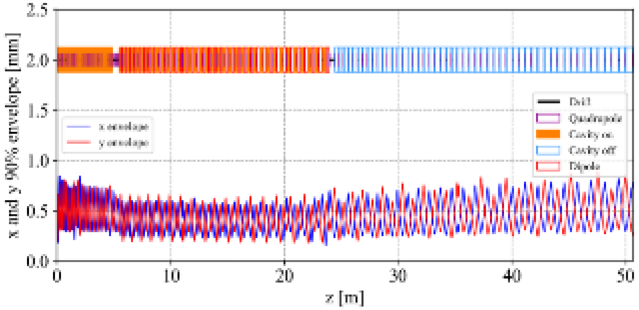
Tracking up to 430 MeV/u

- transmission of 100%
- No emittance growth

🟥 π-mode cavity
🟦 Dipole
🟧 2π-mode cavity
🟩 Injector

Parameter	Value
Frequency	750 MHz/3 GHz
Species	$^{12}C^{6+}$
Final energy	100-430 MeV/u
Repetition rate	200 (400) Hz
Pulse length	5 µs

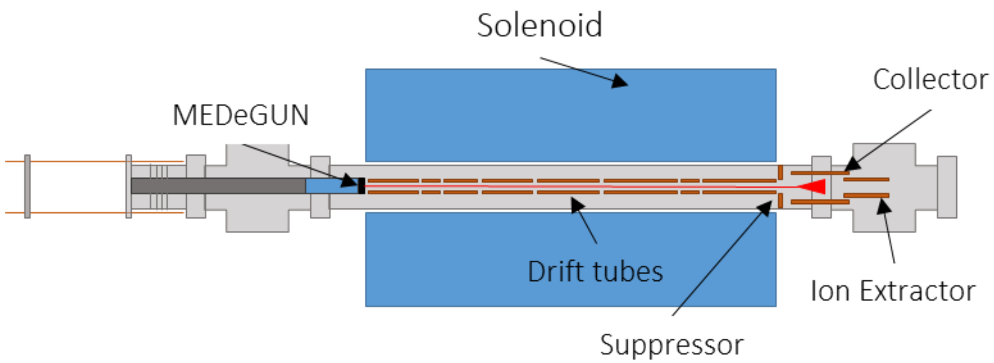
Acceleration of fully stripped Carbon with 750MHz/3GHz structures



- ➢ Starts from a TERA basic design (CABOTO)
- ➢ Innovative «folded» version to save space
- ➢ Particle tracking completed
- ➢ Prototype EBIS source under commissioning
- ➢ RFQ designed
- ➢ **Agreement with CIEMAT** for construction of pre-injector in collaboration with Spanish industry

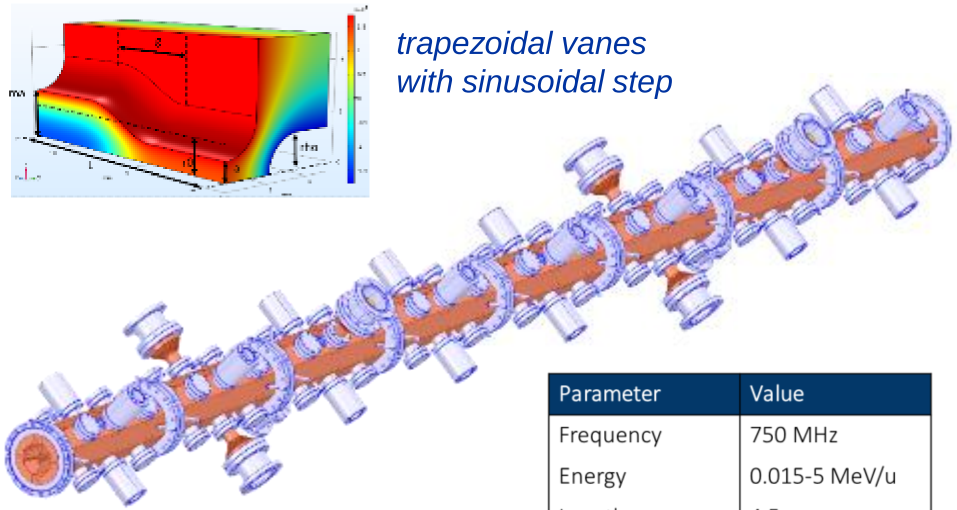
Linac key components: source, RFQ, acc. structures

2019 Commissioning of MEDeGUN



- Stable reproducible operation above nominal current
- Energy decreased to the lower theoretical limit
- Minimized losses (<1.5 mA)
- Calculation of expected ion current

Radio Frequency Quadrupole designed

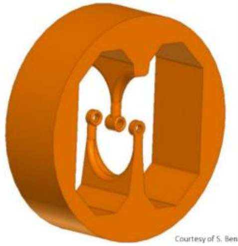


trapezoidal vanes
with sinusoidal step

Parameter	Value
Frequency	750 MHz
Energy	0.015-5 MeV/u
Length	4.5 m

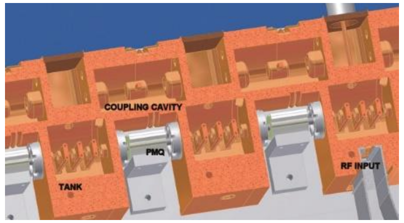
Comparison of alternatives for the fixed energy section 5-10 MeV/u

Interdigital-H



Courtesy S. Benedetti

Side-Coupled DTL



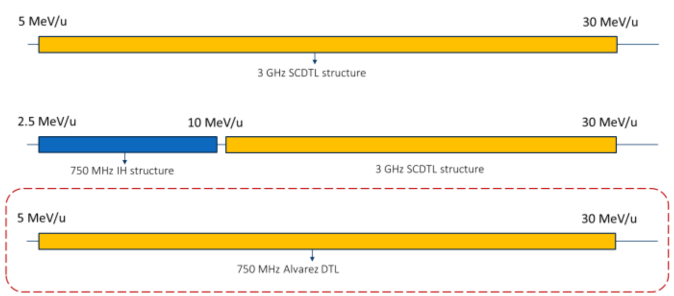
Courtesy L. Picardi

QuasiAlvarez

Courtesy M. Khalvati

	SCDTL	IH	QA
Total length [m]	3.84	4.31	4.27
Loss peak power [kW]	2310	345	1077
$\varepsilon_{x\text{-}x'}$ [π mm mrad]	0.0279	0.0265	0.0275
$\varepsilon_{y\text{-}y'}$ [π mm mrad]	0.0269	0.0287	0.0269
$\varepsilon_{\phi\text{-}w}$ [π deg MeV]	0.5559	0.4552	0.4321

Alternatives



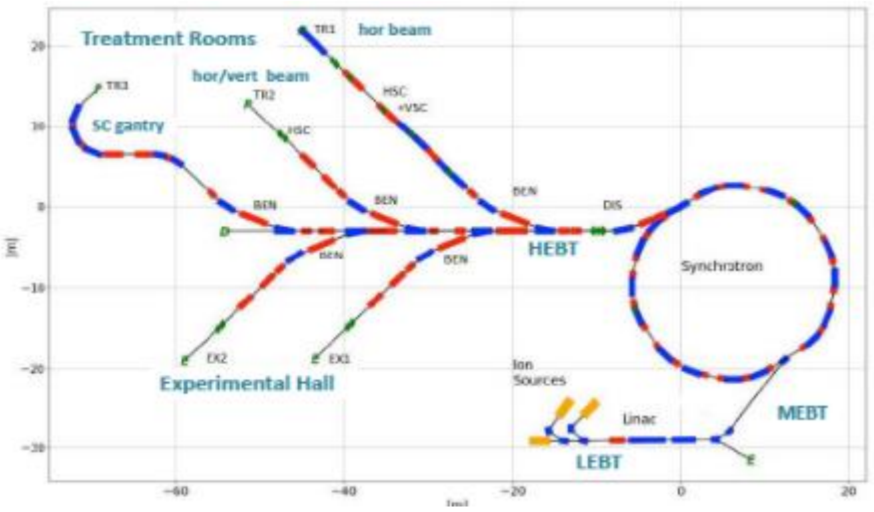
Accelerator option #2: the advanced RT synchrotron

E. Benedetto, M. Sapinski, TERA/SEEIIST
U. Amaldi, TERA
A. Avdic, A. Ibrahimovic, U. Sarajevo
X. Zhang, U. Melbourne
M. Vretenar, CERN

Starting point: the PIMMS design

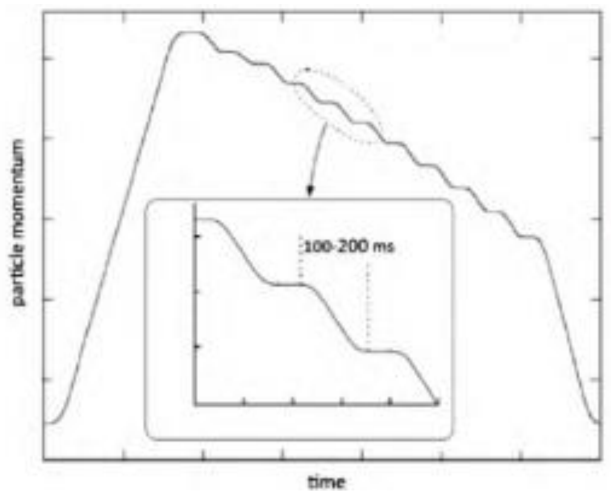
Improvements:

- Higher beam intensity for faster treatment ($2x10^{10}$, 20 times higher)
- Multiple energy extraction (multiple flat-tops)
- Additional fast extraction for FLASH operation
- Redesigned linac at higher frequency, for lower cost and parallel isotope production
- Multiple particles: p, He, C, O
- Optimised layout of beam transport, for both research and therapy

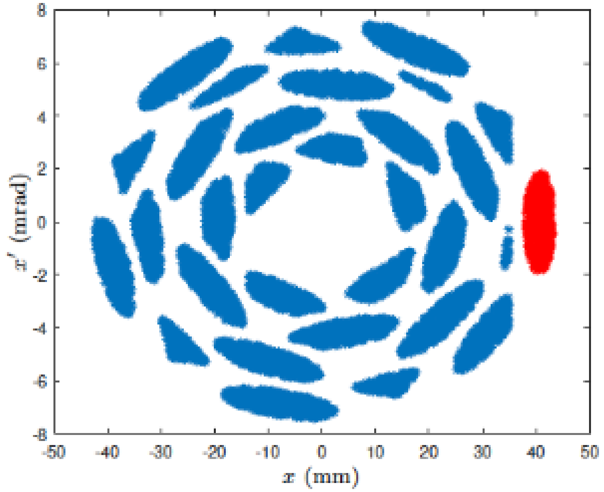


Injection/Acceleration	Unit					
Particle after stripping		p	$^{4}He^{2+}$	$^{12}C^{6+}$	$^{16}O^{8+}$	$^{36}Ar^{16+}$
Energy	MeV/u	7				
Magnetic rigidity at injection	Tm	0.38	0.76	0.76	0.76	0.86
Extraction energy range (**)	MeV/u	60 – 250 (1000)	60 – 250 (430)	100 - 430	100 - 430	200 – 350
Magnetic rigidity at highest energy (for therapy)	Tm	2.42	4.85	6.62	6.62	6.62
Maximum nominal field	T	1.5				
Maximum number of particles per cycle		$2.6 \cdot 10^{11}$	$8.2 \cdot 10^{10}$	$2 \cdot 10^{10}$	$1.4 \cdot 10^{10}$	$5 \cdot 10^{9}$
Ramp-up rate	Tm/s	<10				
Ramp-down time of magnets	s	1				
Spill ripple, intensity ratio I_{max}/I_{mean} (average on 1 ms)		< 1.5				
Slow extraction spill duration with multi-energy	s	0.1 – 60				
Fast extraction	s	$< 0.3\ 10^{-6}$				

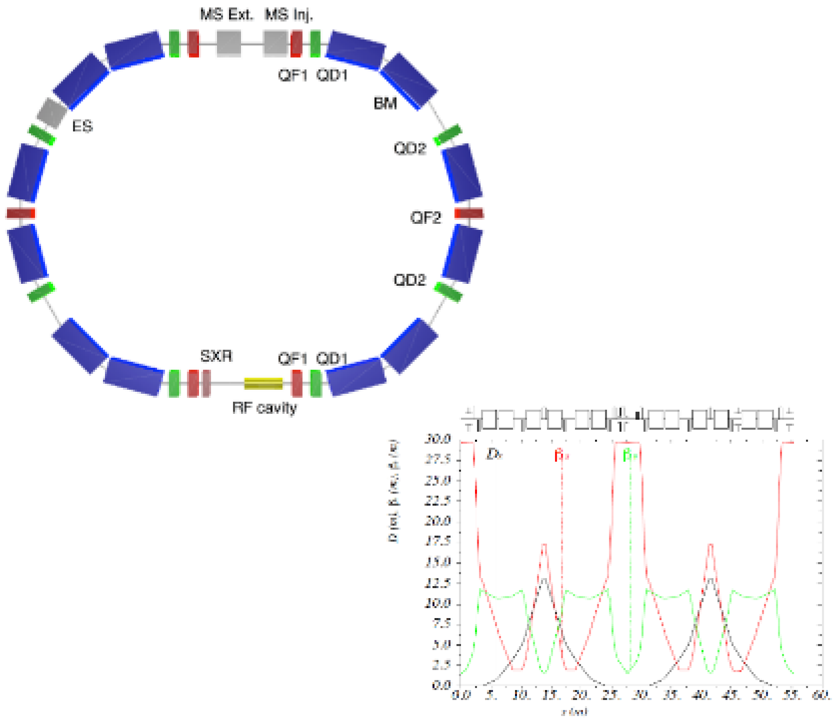
Advanced synchrotron design, key elements



Multiple flat-top operation
(from HIMAC, Japan)



Optimisation of multi-turn injection: phase space after 30 turns
(A. Avdic, U. Sarajevo)



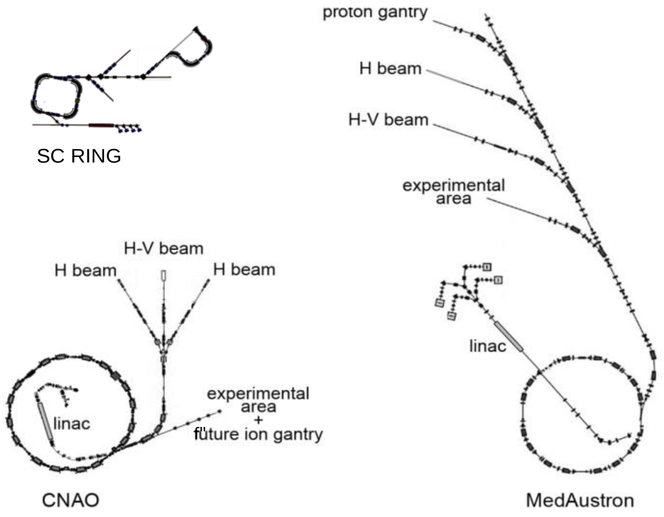
Alternative lattice based on Double Bend Achromat cells, with dispersion-free drift sections and only 12 dipoles and 14 quadrupoles (16 dipoles and 24 quadrupoles in PIMMS)
(X. Zhang, U. Melbourne)

Sources — LEBT — 350 MHz RFQ — 350 MHz IH/CH DTL

Sources — LEBT — 750 MHz RFQ — 750 MHz QuasiAlvarez

Two alternative concepts for a new 7 MeV injector linac at higher frequency (q/m = 1/3)

Accelerator option #3: superconducting synchrotron



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

Advantages:

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

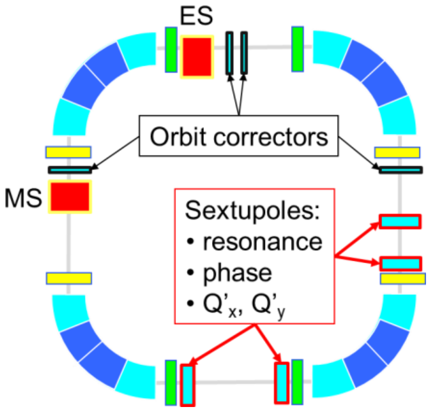
Need: 3 – 4 T magnets ramped at 1 T/s

Circumference	27 m
Injection energy	7 MeV/u
Extraction energy	100 → 430 MeV/u
Straight section 1	3 m
Straight section 2	3.6 m
AG-CCT Max. bending field	3.5 T
AG-CCT Bending radius	1.89 m
AG-CCT Magnetic bending angle	90°

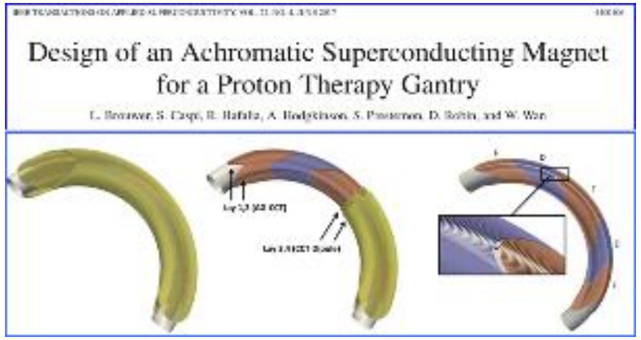
Magnet options to be explored:

- Conventional Nb-Ti
- Canted Cosine Theta
- High Temperature Superc.

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



Sextupoles:
- resonance
- phase
- Q'_x, Q'_y



Design of an Achromatic Superconducting Magnet for a Proton Therapy Gantry

Canted Cosine Theta magnets

Proposed by TERA, based on the LBNL experience in the design and prototyping of a proton gantry magnet

Layered construction, can include quadrupole layers

SC magnets for synchrotrons and gantries

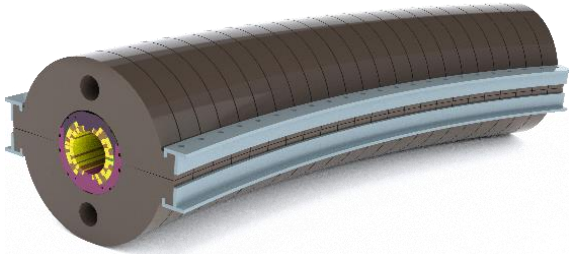
High Energy Physics is promoting a wide international effort in the development of conductors, designs and technologies for SC magnets.

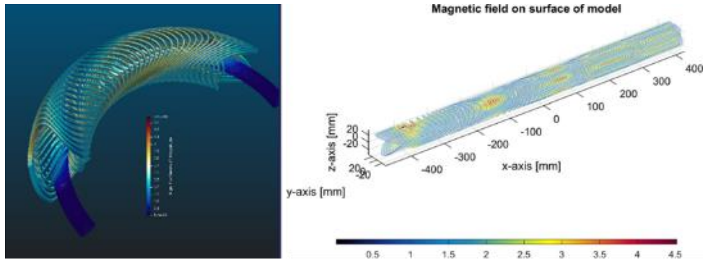
NIMMS aims at profiting of this R&D effort for compact synchrotron and gantry magnets.

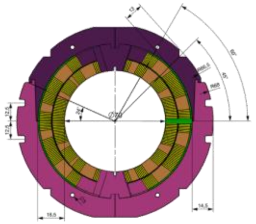
Some of the challenges are common, other are specific for medical accelerator magnets: ramping field, curved shape, quadrupole integration, use of cryocoolers.

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

Parameter	Synchrotron magnet	Prototype Magnet
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$_3$Sn)	NbTi (curved), HTS (straight)
Operating temperature (K)	5 (8)	5 (20)

2 proposals submitted to H2020 calls with Workpackages dedicated to SC magnets for medical accelerators – covering 2021/25

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

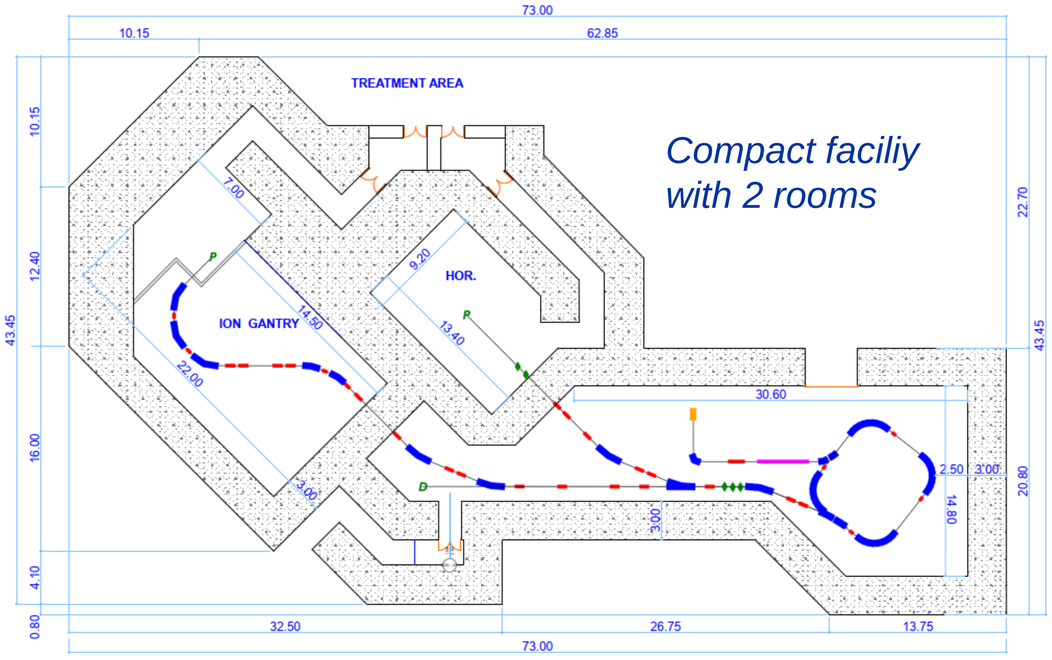
- **WP8 on Innovative Superconducting Magnets:** General consensus to go toward CCT, different conductors. Development of a HTS cable suitable for low losses - large size - fast cycling - synchrotrons (led by GSI)

Both WPs coordinated by L. Rossi (INFN, former CERN)

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

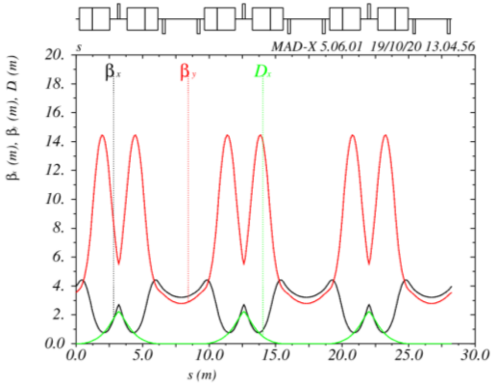
The compact SC synchrotron

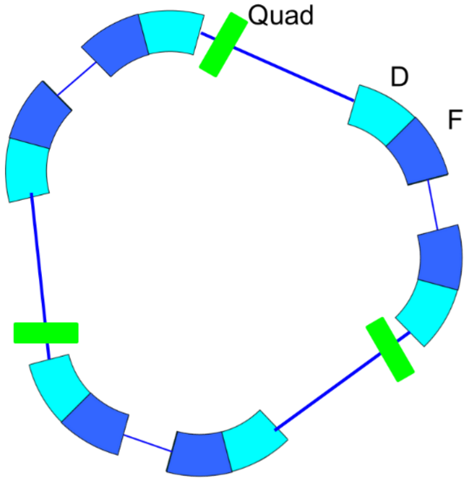
E. Benedetto, M. Sapinski, TERA/SEEIIST
P. Foka, GSI
D. Kaprinis, Kaprinis Architects
M. Vretenar, CERN

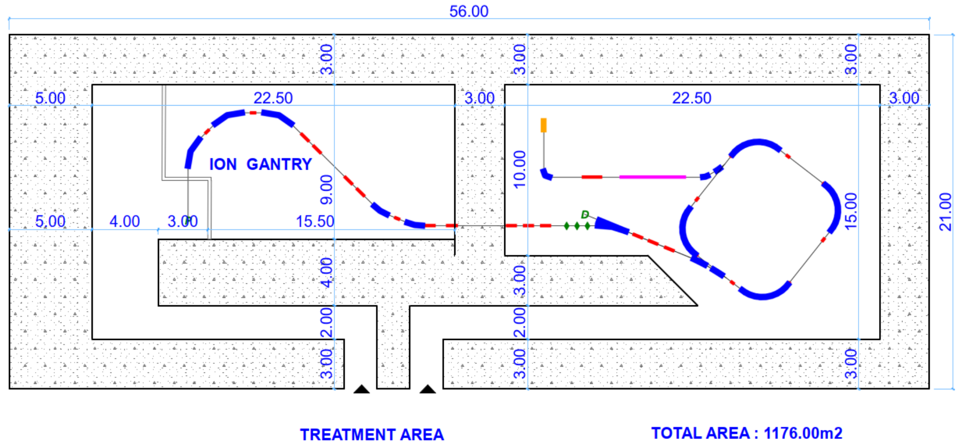


Compact faciliy with 2 rooms

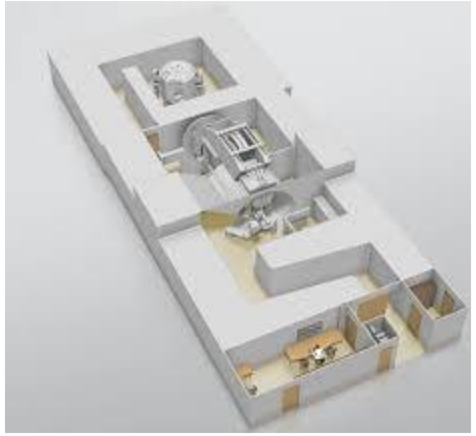
Alternative lattice with 60^0 magnets





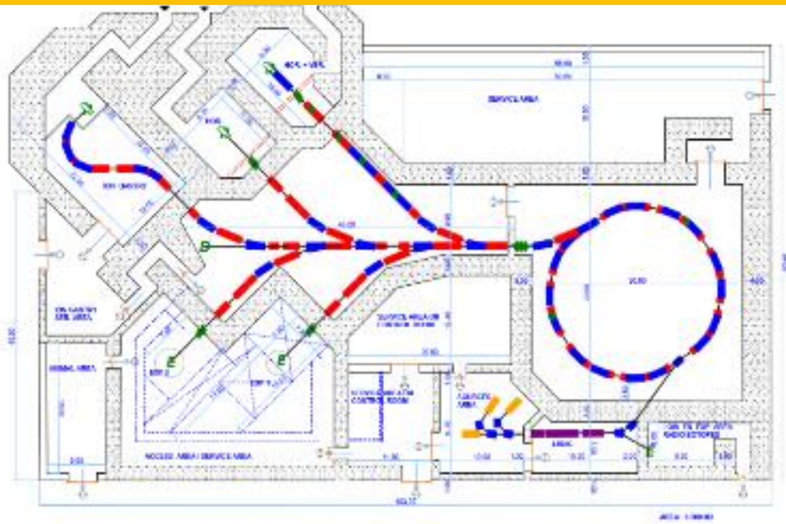


A compact single-room ion therapy facility in about 1,000 m^2

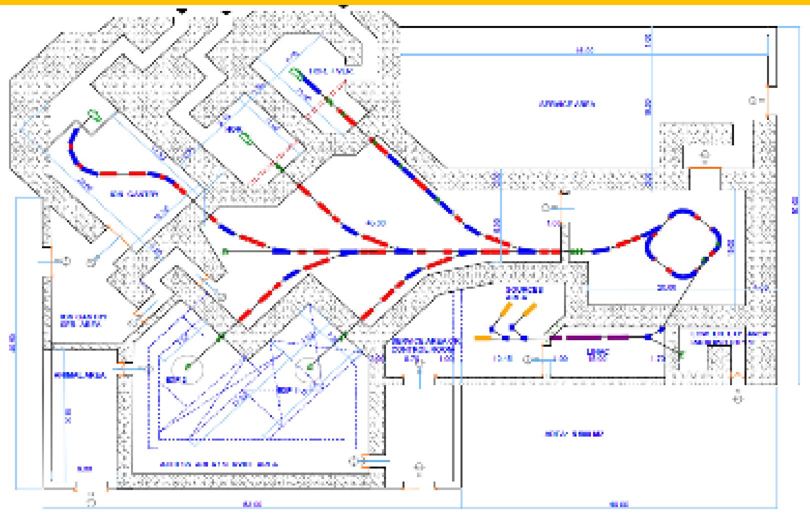


Comparable in size with proton therapy systems – here the single-room proton facility ProteusOne, from IBA)

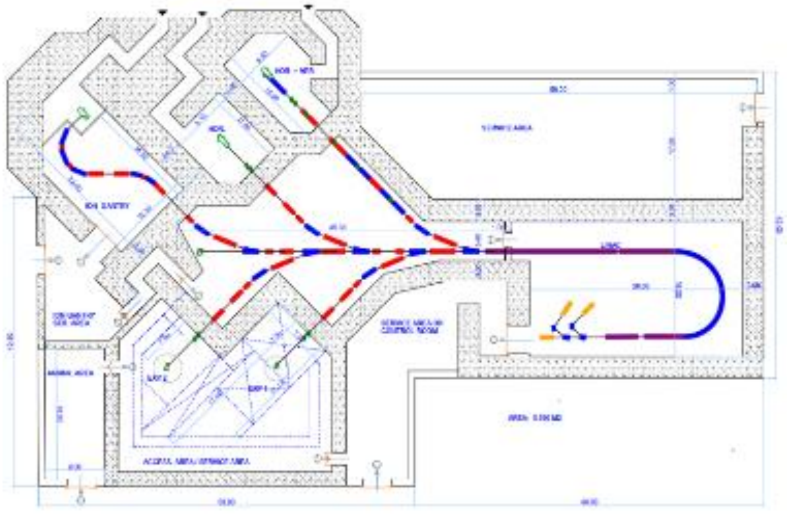
Comparing the three options for SEEIIST



RT synchrotron:
accelerator 1,200 m^2, facility 6,500 m^2
estimated cost (acc. only): 42 M€



SC synchrotron:
accelerator 600 m^2, facility 5,500 m^2
estimated cost (acc. only): 31 M€



Full linac:
accelerator 600 m^2, facility 5,500 m^2
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

Linac option discarded by SEEIIST because requires R&D, is not evolutive, and needs specific medical licensing.

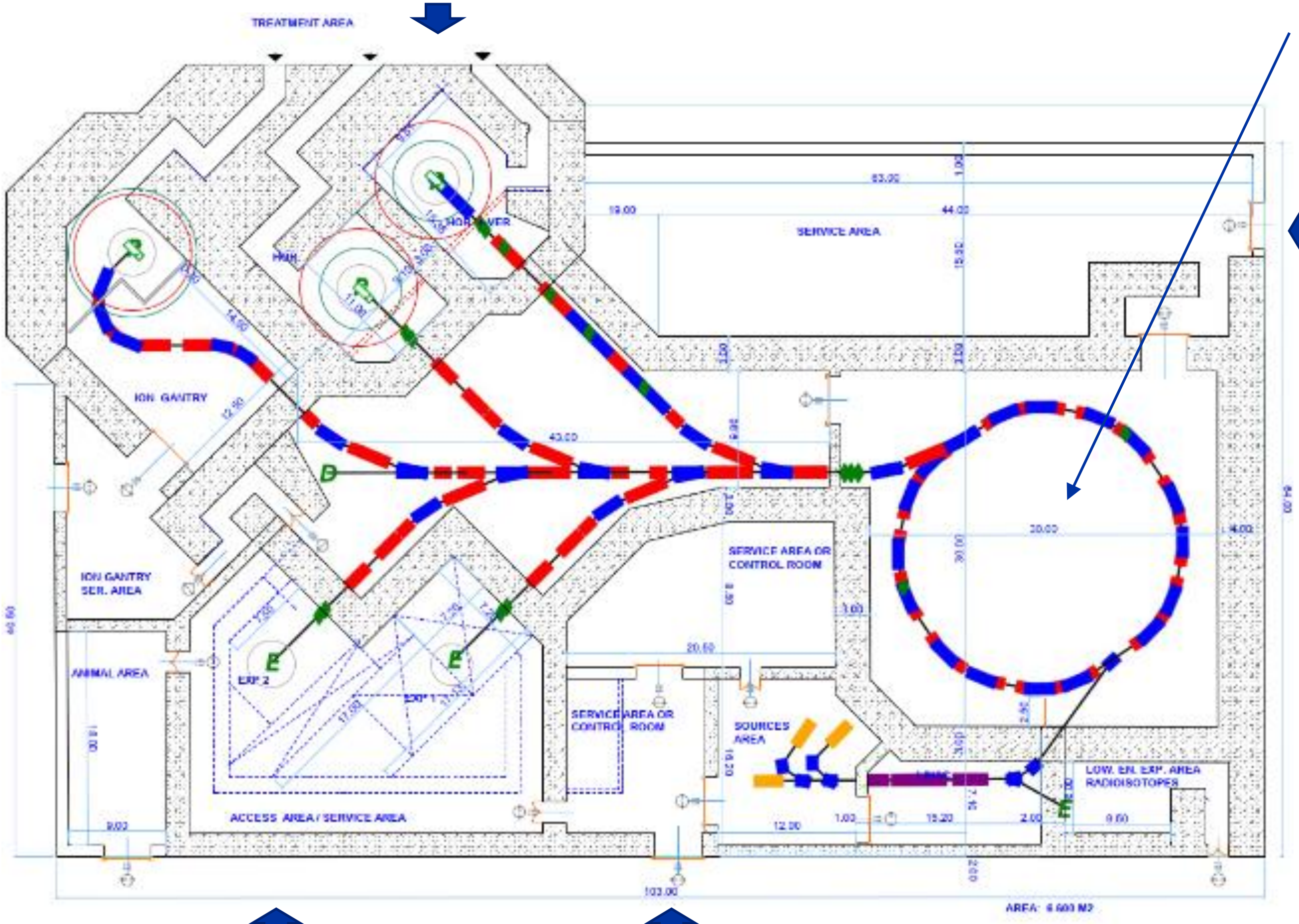
This study recommends to SEEIIST the adoption as baseline configuration of a warm-magnet synchrotron with novel features. Development of superconducting magnets and adequate superconducting synchrotron designs should continue as an advanced alternative option. The superconducting alternative with its 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.

Layout of the complete SEEIIST-type facility

All team, with P. Foka,
GSI and D. Kaprinis,
Kaprinis Architects

Research and Therapy Facility
(50% daily beam time for research, 50% for therapy)

Total 6,600 m^2



Access for therapy

The synchrotron can be replaced by an SC version if R&D successful

Equipment room and access to synchrotron

Target for isotope production

Access for animal testing

Reconfigurable experimental room

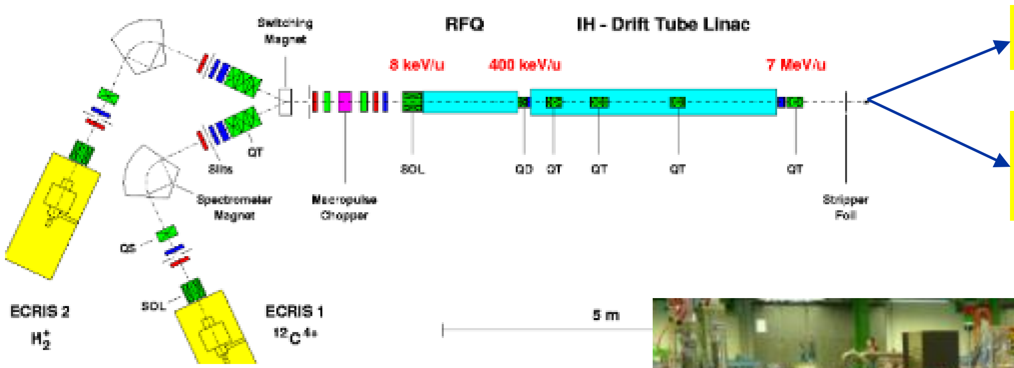
Access to experimental room and linac

Linac for production of medical radioisotopes

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.



to synchrotron

to radioisotope production target

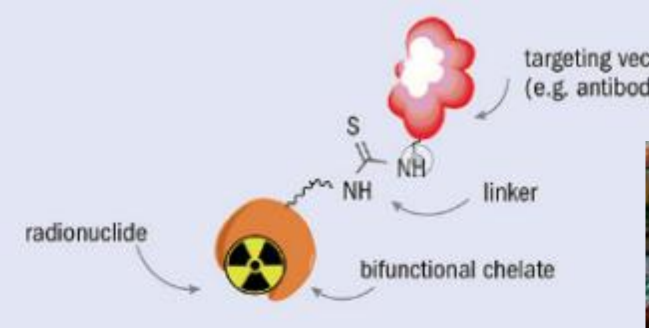
An example: **Targeted Alpha Therapy**

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 (theragnostics)



The gantry collaboration

CERN, CNAO, MedAustron, INFN
Coordinated by M. Cirilli, CERN
and S. Rossi, CNAO

CNAO

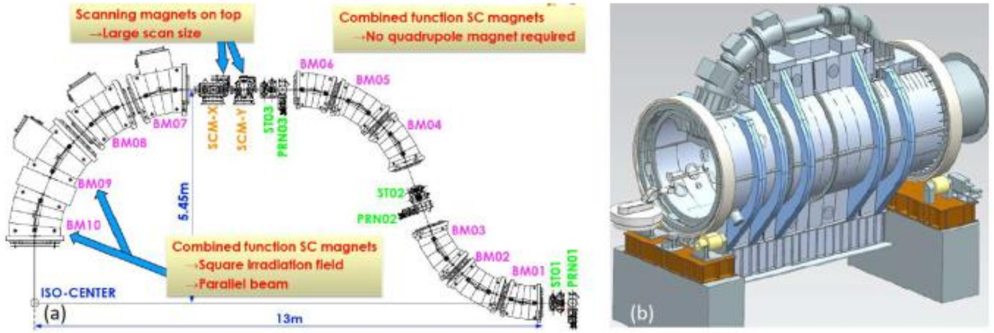
CNAO (Pavia, Italy) and MedAustron (W. Neustadt, Austria) have 3 treatment rooms but no gantry (too large and expensive).

CNAO plans to install a gantry within the next 10 years, MedAustron has a similar plan for the longer term.

They have both asked CERN to collaborate in the design of a superconducting gantry that would satisfy their requirements.

The same design could be adopted by SEEIIST.

MedAustron



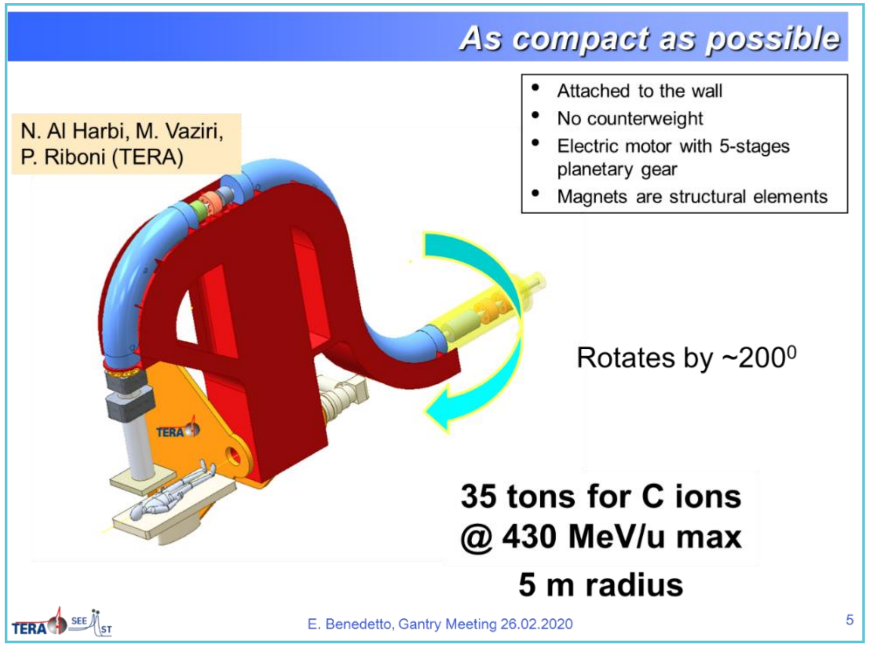
Term of comparison is the SC gantry built by Toshiba for HIMAC (Japan):
15 m long, 6 m radius, 300 tons

Two alternative designs are being considered.
A specially appointed Review Committee will select in early 2021the priority design for the collaboration

Gantry option 1

U. Amaldi, N. Al Harbi, P. Riboni (TERA)
L. Gentini, M. Karppinen, D. Perini, D. Tommasini (CERN)
E. Benedetto (TERA/SEEIIST)
M. Pullia (CNAO)

Basic idea from TERA: 5T 90^0 CCT magnets, light structure attached to a wall, rotating by only 180^0



As compact as possible

- Attached to the wall
- No counterweight
- Electric motor with 5-stages planetary gear
- Magnets are structural elements

N. Al Harbi, M. Vaziri, P. Riboni (TERA)

Rotates by ~200^0

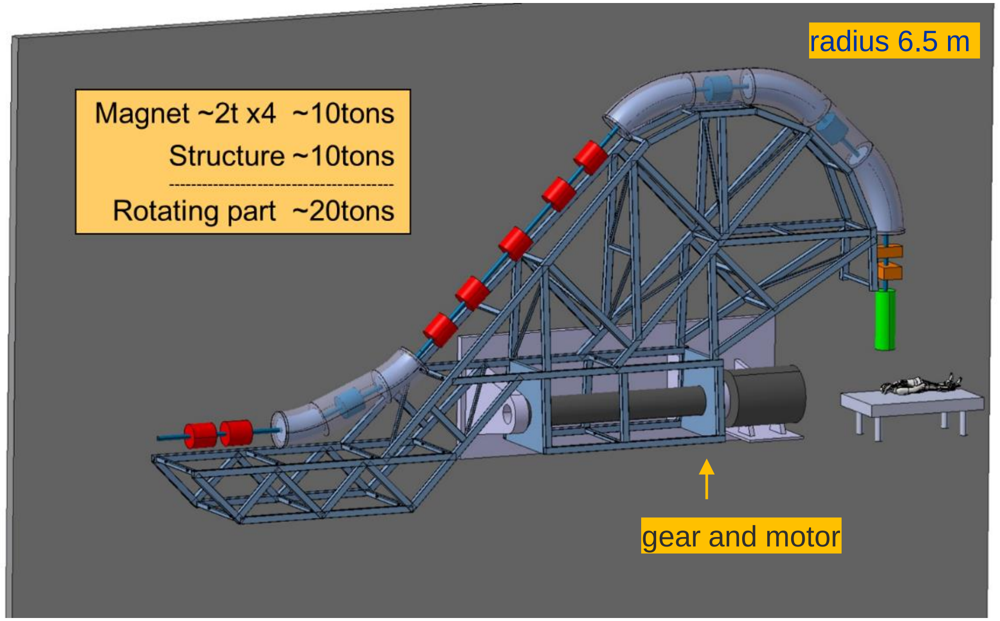
35 tons for C ions @ 430 MeV/u max

5 m radius

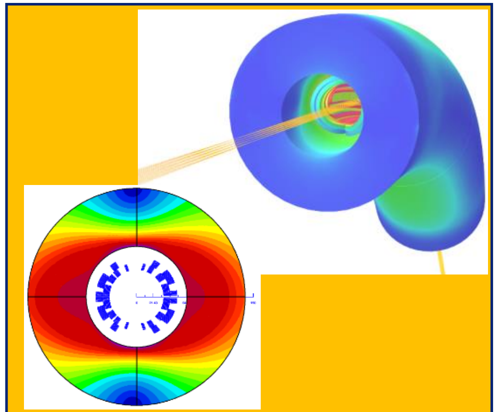
E. Benedetto, Gantry Meeting 26.02.2020

5

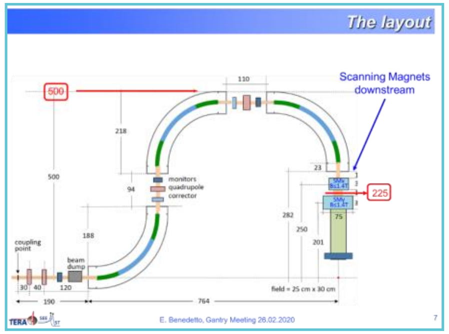
A CERN team is developing a more conservative version, compatible with the CNAO schedule, based on 3T cos-theta magnets at maximum 45^0



Magnet ~2t x4 ~10tons
Structure ~10tons
Rotating part ~20tons



- ➢ Ongoing development of analysis tools and magnet design for curved cos-theta magnets
- ➢ Application for KT-MA support of small demonstrator magnet



The layout

E. Benedetto, Gantry Meeting 26.02.2020

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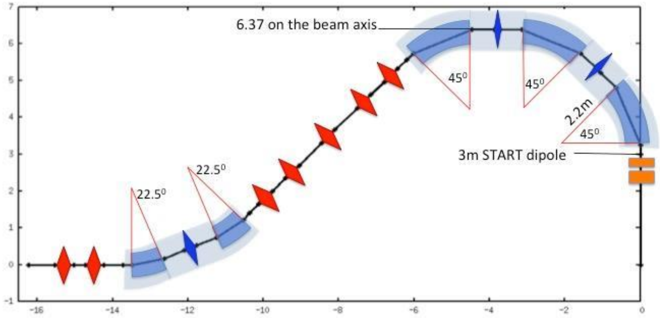
Small aperture (40mm)
Scanning magnets downstream



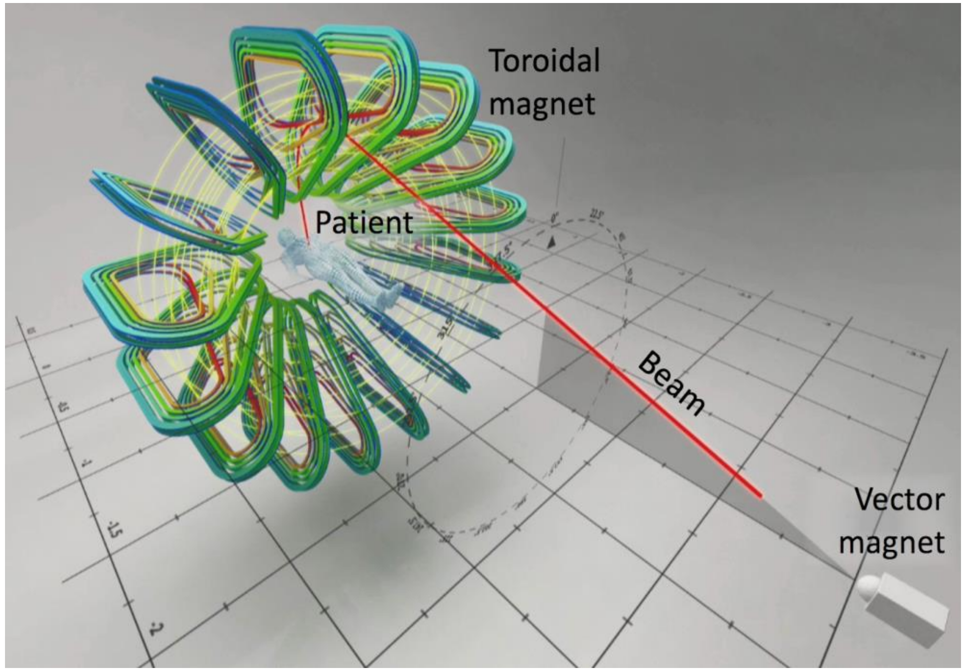
Optics completed:

- ➢ Bending sections inside 2 cryostats: 45^0 , 135^0 with SC quads between dipoles (achromaticity)
- ➢ Warm quadrupoles between cryostats

Source Axis Distance 2.5 m – challenge for the scanning magnets

Gantry option 2: GaToRoid

L. Bottura, E. Felcini, J. van Nugteren,
G. de Rijk, G. Kirby, B. Dutoit, CERN



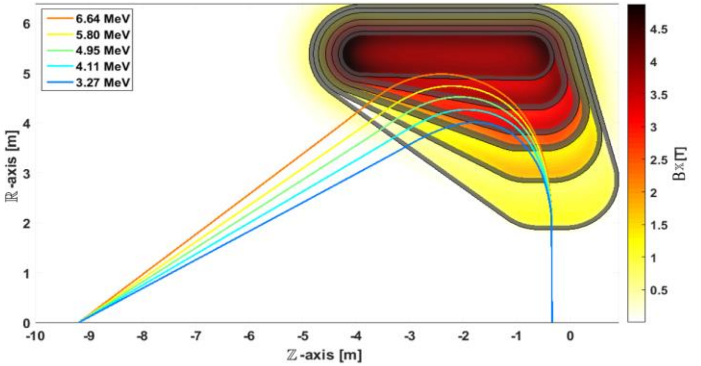
CERN development (L. Bottura, 2017)
Novel concept of a fixed toroidal gantry to deliver the dose from a number of discrete directions covering the full 360^0 range

Studied in 2 versions, for protons and for ions

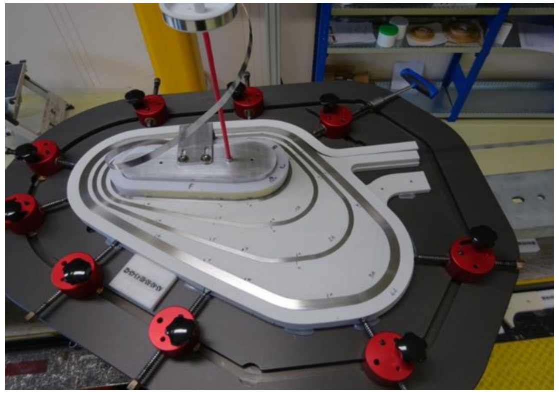
Reference parameters for ion version	
Internal diameter	3.7 m
External diameter	12.8 m
Number of treatment directions	20
Length (w/o vector magnet)	10 m
Peak field on coils	6 T
Torus mass	270 t

The requirements for the ion version are currently being revised to come to a more competitive set of parameters

Ongoing:
- Linear beam optics study
- Analysis and design of vector magnet
- Construction of a proton demonstrator coil

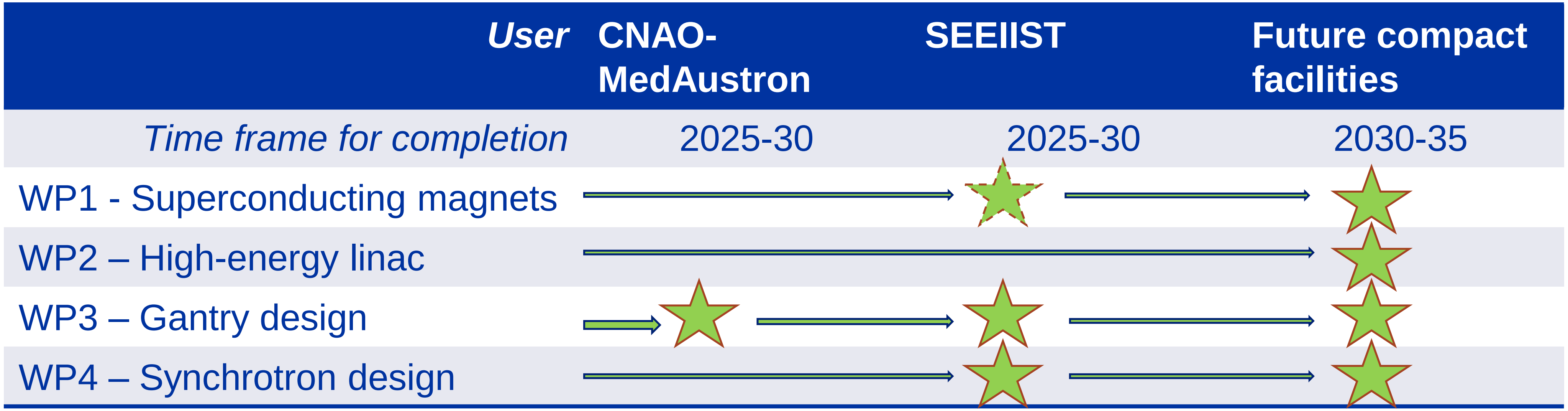


Single particles with different energies converge at the isocentre



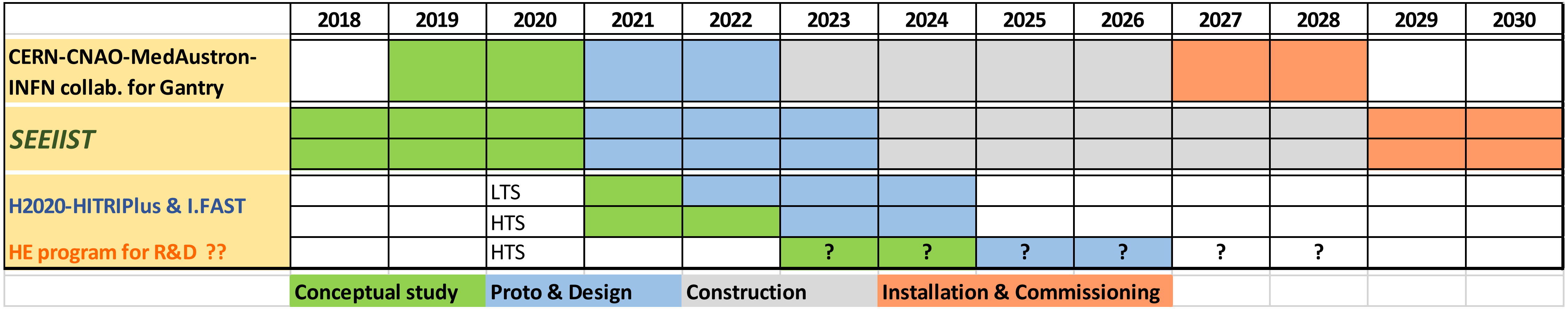
Demonstrator of a coil for the proton version: first winding test in stainless steel tape on 3D-printed spacers

NIMMS Future Goals and Timeline



User	CNAO-MedAustron	SEEIIST	Future compact facilities
Time frame for completion	2025-30	2025-30	2030-35
WP1 - Superconducting magnets	→	★ →	★
WP2 – High-energy linac	→	→	★
WP3 – Gantry design	→ ★ →	★ →	★
WP4 – Synchrotron design	→	★ →	★

Superconducting magnet plan – courtesy L. Rossi



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CERN-CNAO-MedAustron-INFN collab. for Gantry		🟩	🟩	🟦	🟦	▨	▨	▨	▨	🟧	🟧		
SEEIIST	🟩	🟩	🟩	🟦	🟦	🟦	▨	▨	▨	▨	▨	🟧	🟧
	🟩	🟩	🟩	🟦	🟦	🟦	▨	▨	▨	▨	▨	🟧	🟧
H2020-HITRIPlus & I.FAST			LTS	🟩	🟦	🟦	🟦						
			HTS	🟩	🟩	🟦	🟦						
HE program for R&D ??			HTS			🟩 ?	🟩 ?	🟦 ?	🟦 ?	?	?		
	🟩 Conceptual study		🟦 Proto & Design		▨ Construction		🟧 Installation & Commissioning						

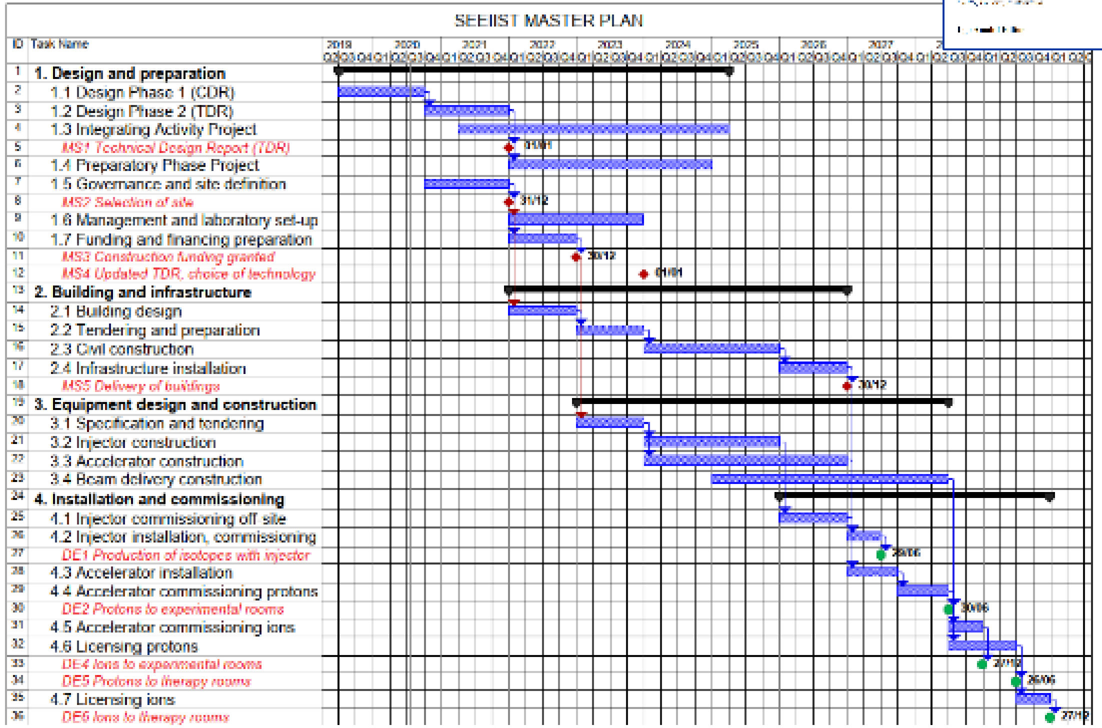
SEEIIST plans and schedule

SEEIIST has just submitted its application to enter into the ESFRI Roadmap of future Research Infrastructure of European relevance.

Based on 200 pages of technical documents prepared with an important contribution from NIMMS

An Accelerator-based Research Infrastructure for Cancer Therapy and Biomedical Research with Ion Beams

Masterplan for construction in 9 years



NIMMS Impact on Ion Therapy Accelerator Research

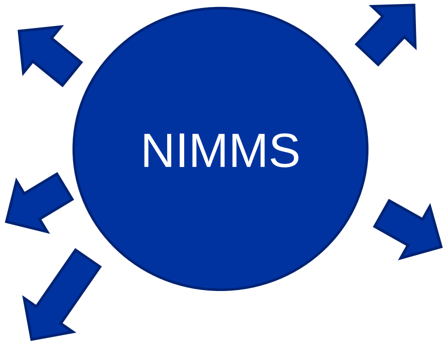
Service Contract for SEEIIST support, 0.5 M€ to CERN (total budget 1.3 M€ for support to SEEIIST)
2019/2021
- development RT synchrotron design
- design Quasi-Alvarez option for bent linac
- design SC gantry optics
- design transfer lines for therapy and experiment
- facility integration
- comparison of 3 accelerator designs

SEEIIST, TERA, CERN, GSI, SAE

with SEEIIST

HITRI+, submitted to H2020, 1.2 M€ for accelerator studies (total budget 5 M€ for all ion therapy, support to SEEIIST)
2021-2024
- synchrotron injection and extraction
- synchrotron beam optics and operational modes
- SC synchrotron lattice
- injector linac design
- gantry integration
- engineering design of SC magnets
- small SC magnet demonstrator

SEEIIST, CERN, CNAO, MedA, INFN, CEA, CIEMAT, PSI, UU, Wigner



Gantry collaboration for new SC gantry design
2019/…
- Design and prototyping of a novel SC ion gantry

CERN, CNAO, MedA, INFN, TERA

Bent-linac pre-injector collaboration
2021/…
- Engineering design and construction by Spanish industry

CERN, CIEMAT

Synchrotron design collaboration
2020/…
U. Melbourne, Cockcroft I.

Starting from a CERN investment of 500 k€ for 2019/21, NIMMS has launched collaborations that have collected funding for ~4 M€ (factor 8 leverage factor)

IFAST, submitted to H2020, 1.41 M€ for accelerator studies (total budget 10 M€ for accelerator Research & Innovation)
2021-2025
- Improvement of slow extraction spill quality (with FAIR)
- Engineering design of curvet CCT magnet
- Engineering design of HTS CCT magnet
- Construction of curved CCT magnet demonstrator
- Construction of HTS magnet demonstrator
- Development of ReBCO HTS nuclotron cable (with FAIR)

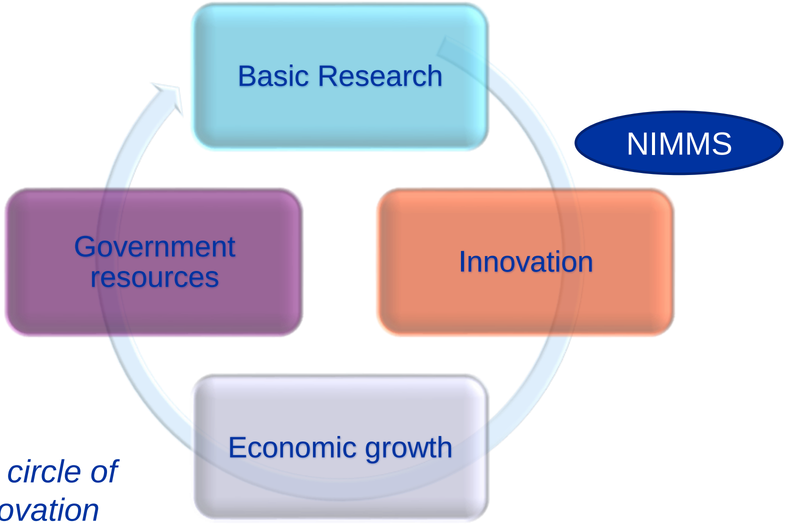
GSI, BI, BT, CERN, HIT, CERN, CEA, INFN, CIEMAT, Wigner, UU, PSI, Scanditronix, Elytt, SigmaPhi

Some conclusions - NIMMS and accelerator applications

The next years will be critical for the future of particle physics and of basic research in general.

We need to show the impact on society of our technologies by investing on applications of accelerators and in general of particle physics.

There is a wealth of applications of accelerators waiting to be developed not only in medicine, but also in environment, energy, security, industry,…


Basic Research

NIMMS

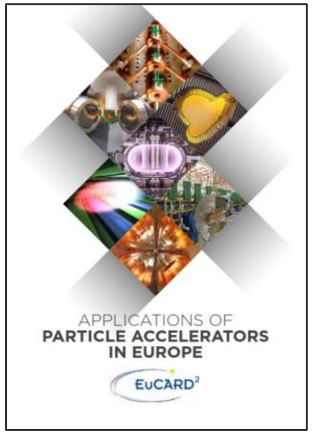
Government resources

Innovation

Economic growth

The virtuous circle of scientific innovation


The right way to communicate future projects:
In the «Code of the Universe» exhibition on CERN and FCC 10 out of the 38 panels quote applications, to medicine (3) and more general (7).


APPLICATIONS OF
PARTICLE ACCELERATORS
IN EUROPE
EuCARD²

2017 EuCARD2 Report on Accelerator Applications:
http://apae.ific.uv.es/apae/wp-content/uploads/2015/04/EuCARD_Applications-of-Accelerators-2017.pdf

Our community needs to address seriously this issue. For medicine, is the limited "seed-funding" KT-MA scheme the right tool to address it at CERN?

We need wide programs like NIMMS, to federate initiatives, provide coherence, ensure connection with final users, launch new initiatives, offer coordination, support and (some) funding.

Recognition as a strategic direction for our community.

the MedAUSTRON hall

Thank you for your attention

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