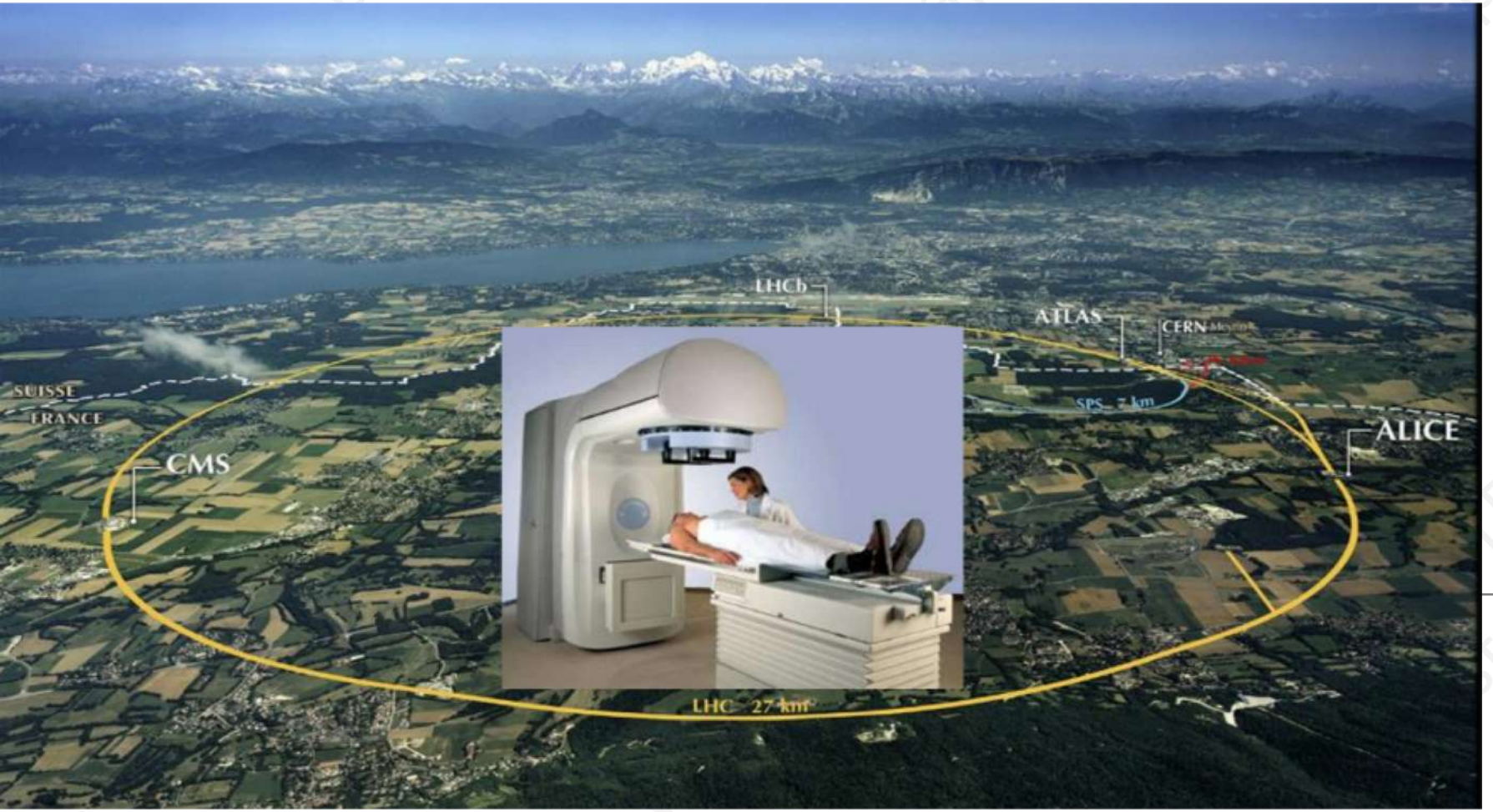
HITRI
Heavy Ion Therapy Research Integration




# ACCELERATORS FOR MEDICINE

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HEAVY ION THERAPY MASTERCLASS SCHOOL

MAY 2021

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# Accelerators for Society

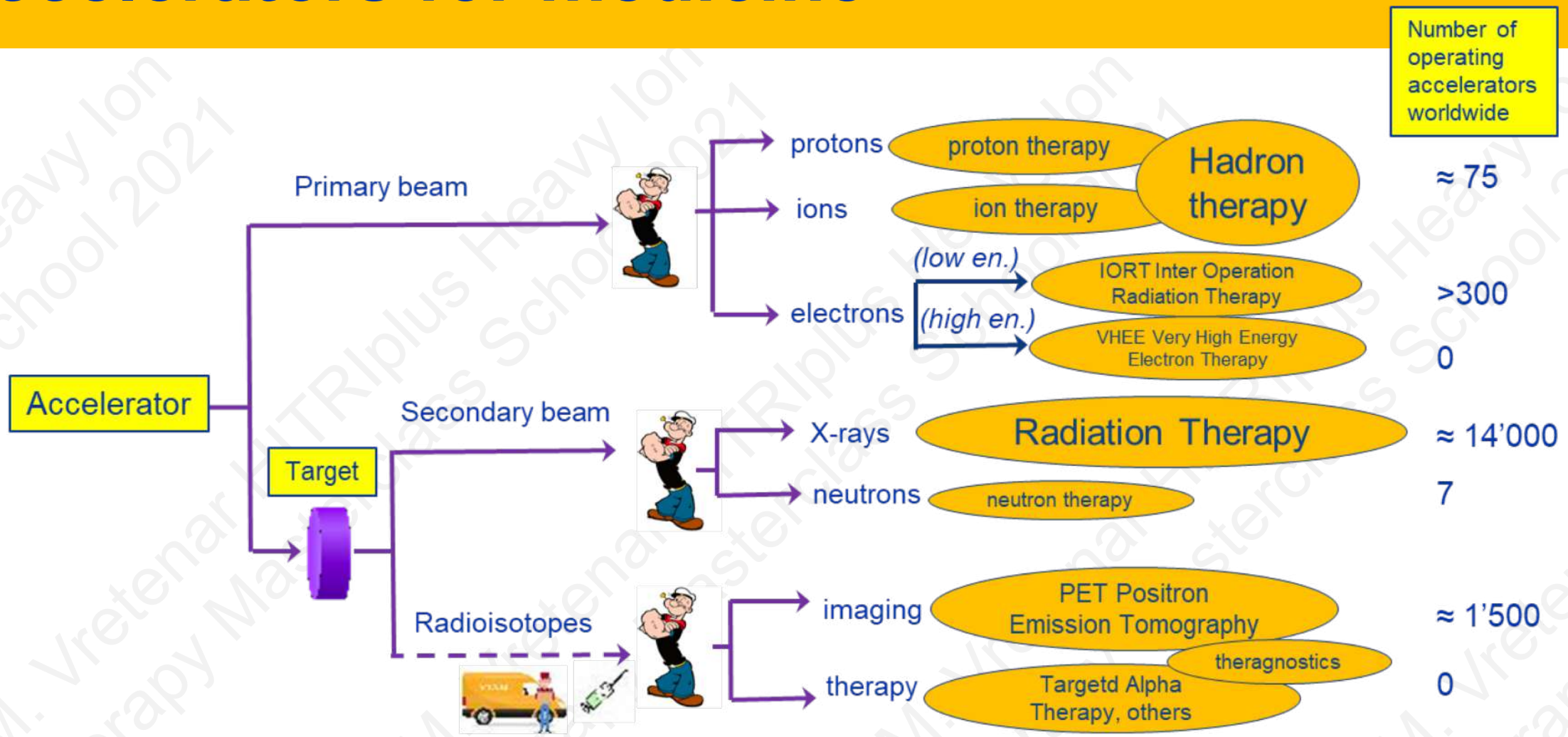
Over 30’000 particle accelerators are in operation world-wide.

Only ~1% are used for fundamental research.

Medicine is the largest application with more than 1/3 of all accelerators.

| | | |
|---|---|---|
| **Research** | | **6%** |
| | Particle Physics | 0,5% |
| | Nuclear Physics, solid state, materials | 0,2 - 0,9% |
| | Biology | 5% |
| **Medical Applications** | | **35%** |
| | Diagnostics/treatment with X-ray or electrons | 33% |
| | Radio-isotope production | 2% |
| | Proton or ion treatment | 0,1% |
| **Industrial Applications** | | **<60%** |
| | Ion implantation | 34% |
| | Cutting and welding with electron beams | 16% |
| | Polymerization | 7% |
| | Neutron testing | 3.5% |
| | Non destructive testing | 2,3% |

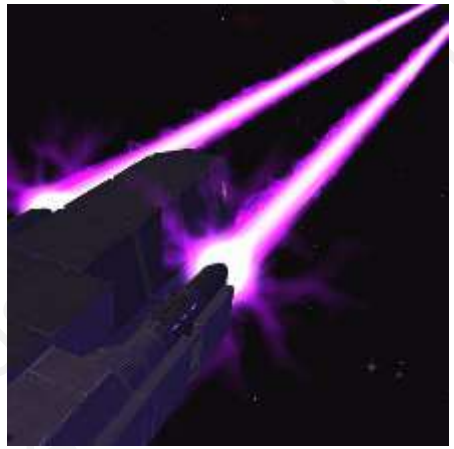
# Accelerators for medicine

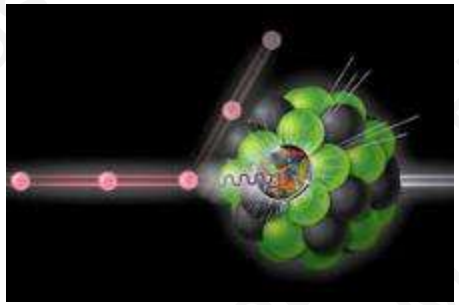



Total: ≈ 16'000 particle accelerators operating for medicine

# The potential of accelerators

- All these systems share the vision of a **bloodless surgery and imaging**: penetrate into the human body to treat diseases and to observe internal organs without using surgical tools.
- 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 be detected from outside.





Nuclear medicine:
*application of radioactive substances in the diagnosis and treatment of disease*

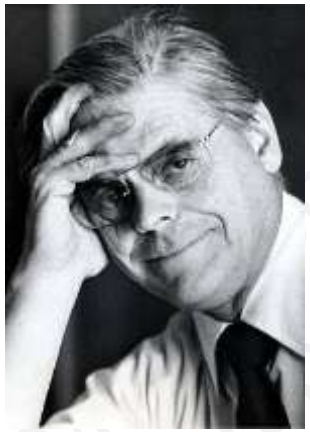
Radiation therapy:
*therapy using ionizing radiation, generally as part of cancer treatment to control or kill malignant cells*

*For a U.S. population of over 300 million people, there are some 16 million nuclear medicine procedures per year.*

# Medicine at the first accelerators

The idea of using accelerators for treating diseases is almost as old as accelerators!

- In 1929 Ernest O. Lawrence develops the cyclotron and in 1936, his new 37-inch cyclotron starts producing isotopes for medicine, in parallel to nuclear physics.
- Starting in 1937, Lawrence's brother John was the pioneer of injecting radioisotopes produced at the cyclotron to cure leukemia and other blood diseases.
- In 1938 starts direct irradiation of patients with neutrons from the new 60-inch cyclotron.



In 1946, Robert Wilson proposed to use protons to treat cancer, profiting of the Bragg peak to deliver a precise dose to the tumour.

First treatment of pituitary tumours took place at Berkeley in 1956.

First hospital-based proton treatment center at Loma Linda (US) in 1990.

Early ideas of curing cancer with particle accelerators

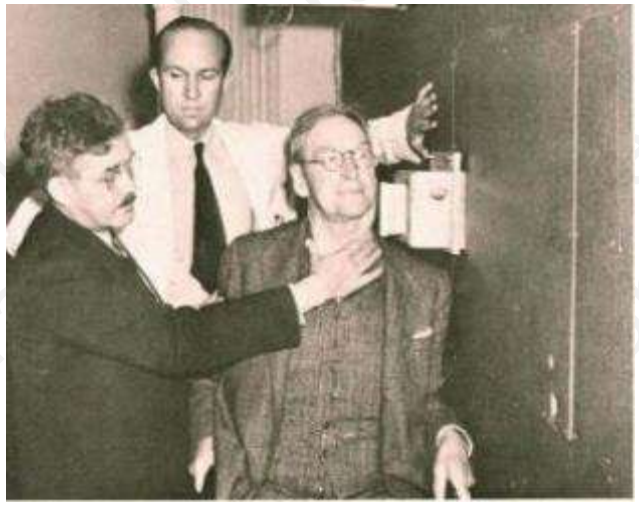
# Modern accelerators for cancer treatment and isotope production

There are today about 16’000 accelerators in hospitals or working for hospitals, complex devices that have specific requirements, somehow different from a scientific accelerator:

- The beam must be perfectly known, stable and reliable.
- The accelerator (as the radiopharmaceutical unit in case of production of isotopes) have to follow strict Quality Assurance procedures.

Example: factor 4 in the complexity and cost of the control system for a medical accelerator as compared to a scientific one.

The role of the medical physicist is essential in planning the treatment and in guaranteeing the delivered dose.

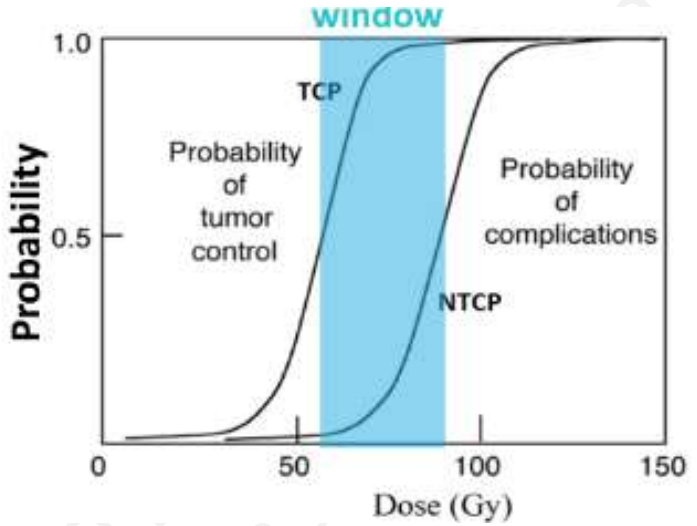


*From the early tests at Lawrence’s cyclotron to a modern treatment room at CNAO*

# Medical exposure – a critical issue

*TCP=Tumor control probability*
*NTCO=normal tissue complication probability*

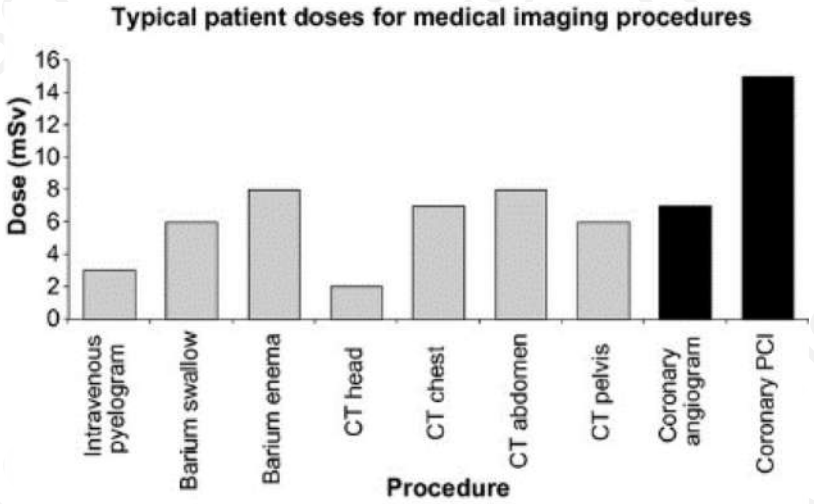
Radiation management and control is a key issue in nuclear medicine.
- important doses are delivered to patients (comparison risk-benefit)
- the dose to medical personnel is subject to strict legal limits.




## CERN limits

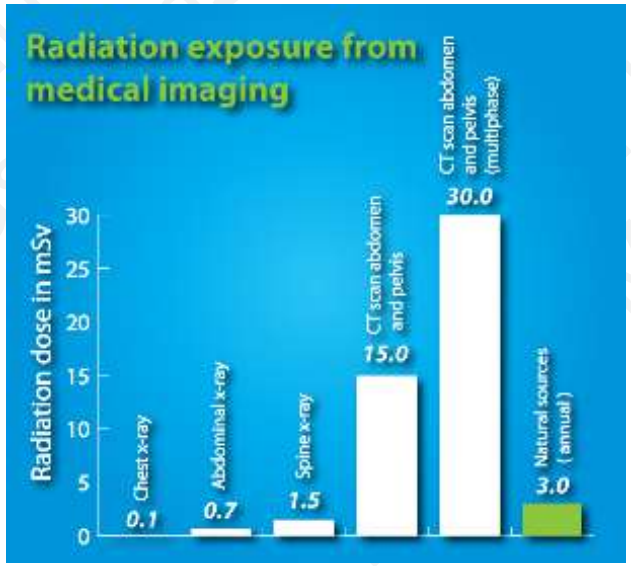
| Area | Dose limit [year] | Ambient dose equivalent rate | |
|---|---|---|---|
| | | Work place | Low occupancy |
| Non-designated | 1 mSv | 0.5 µSv/h | 2.5 µSv/h |
| Supervised | 6 mSv | 3 µSv/h | 15 µSv/h |
| Simple | 20 mSv | 10 µSv/h | 50 µSv/h |
| Limited Stay | 20 mSv | | 2 mSv/h |
| High Radiation | 20 mSv | | 100 mSv/h |
| Prohibited | 20 mSv | | > 100 mSv/h |

Radiation Area

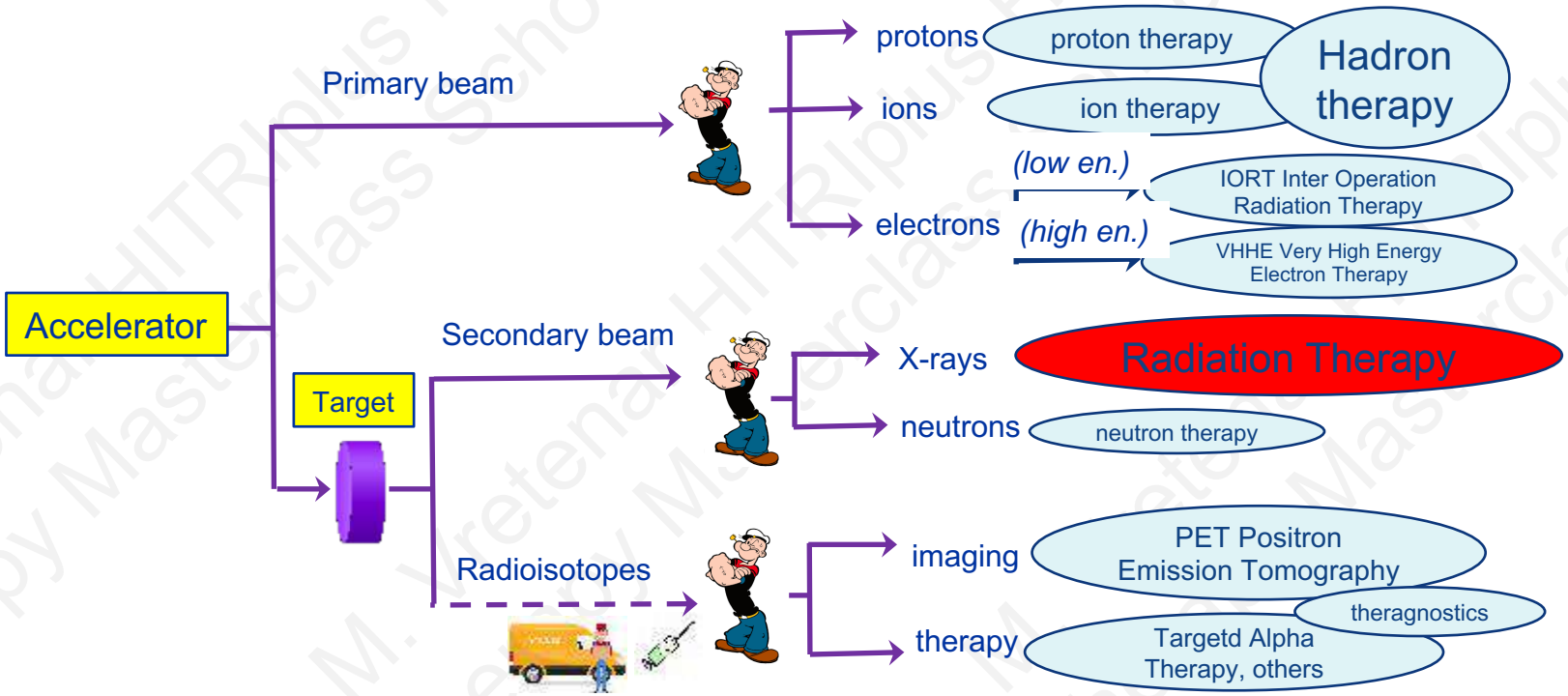



Up to 2000 mSv highly targeted dose in conventional radiotherapy !

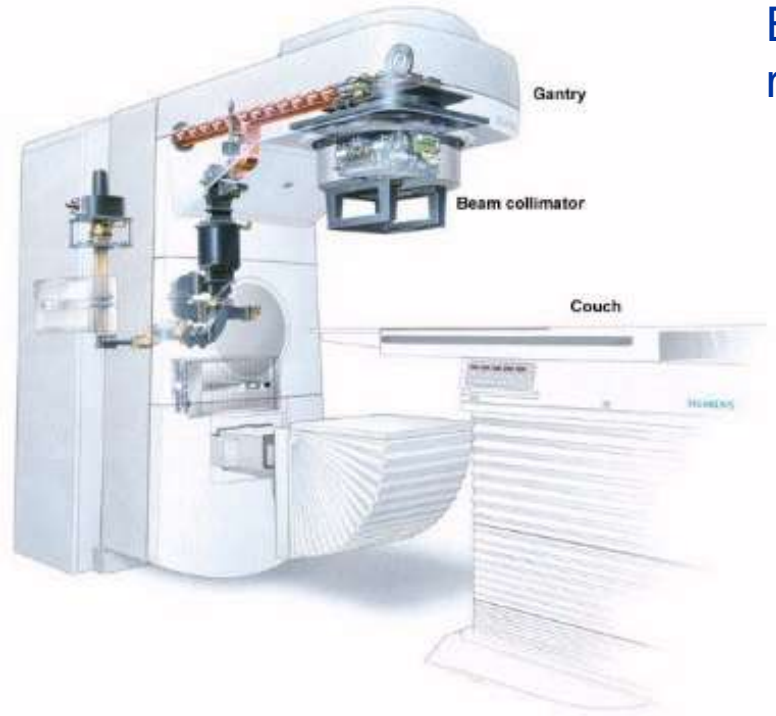
*Source: S. Liauw et al., Translational Medicine, 5, 173*

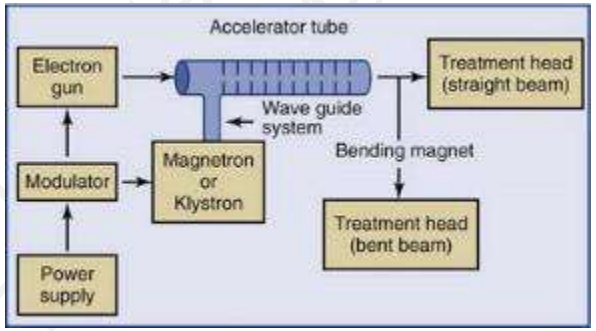


# 1. Radiation therapy

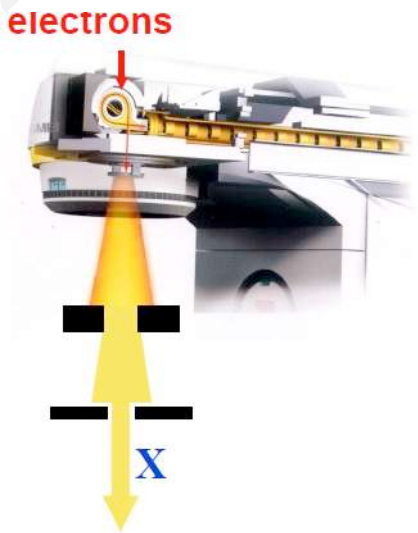


# The most successful accelerator




Electron Linac (linear accelerator) for radiotherapy (X-ray treatment of cancer)

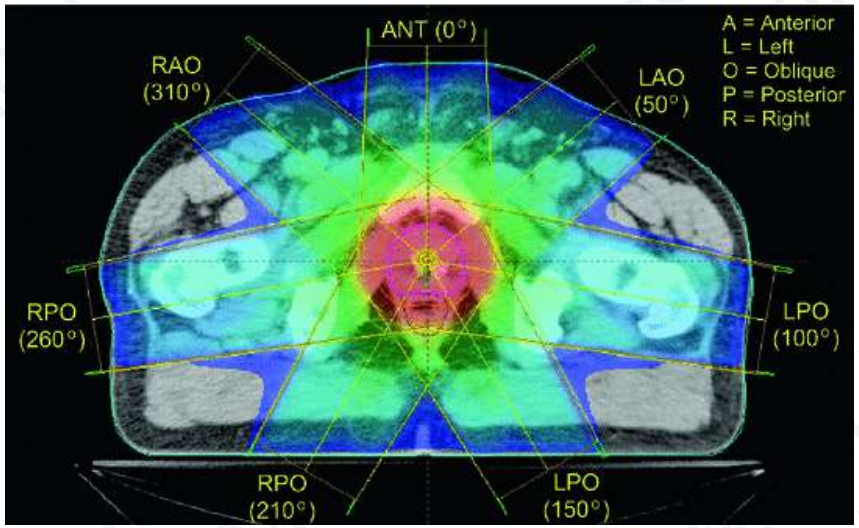



5 – 25 MeV e-beam
Tungsten target

**14,000 in operation worldwide!**

# Modern radiotherapy

X-rays are used to treat cancer since last century. The introduction of the electron linac has made a huge development possible, and new developments are now further extending the reach of this treatment.




**Combined imaging and therapy**

Modern imaging techniques (CT computed tomography, MRI magnetic resonance imaging, PET positron emission tomography) allow an excellent 3D (and 4D, including time) modelling of the region to be treated.
The next challenge is to combine imaging and treatment in the same device.

**Accurate delivery of X-rays to tumours**

To spare surrounding tissues and organs, computer-controlled treatment methods enable precise volumes of radiation dose to be delivered. The radiation is delivered from several directions and transversally defined by multi-leaf collimators (MLCs).

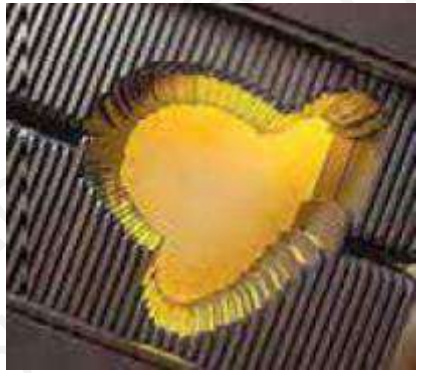
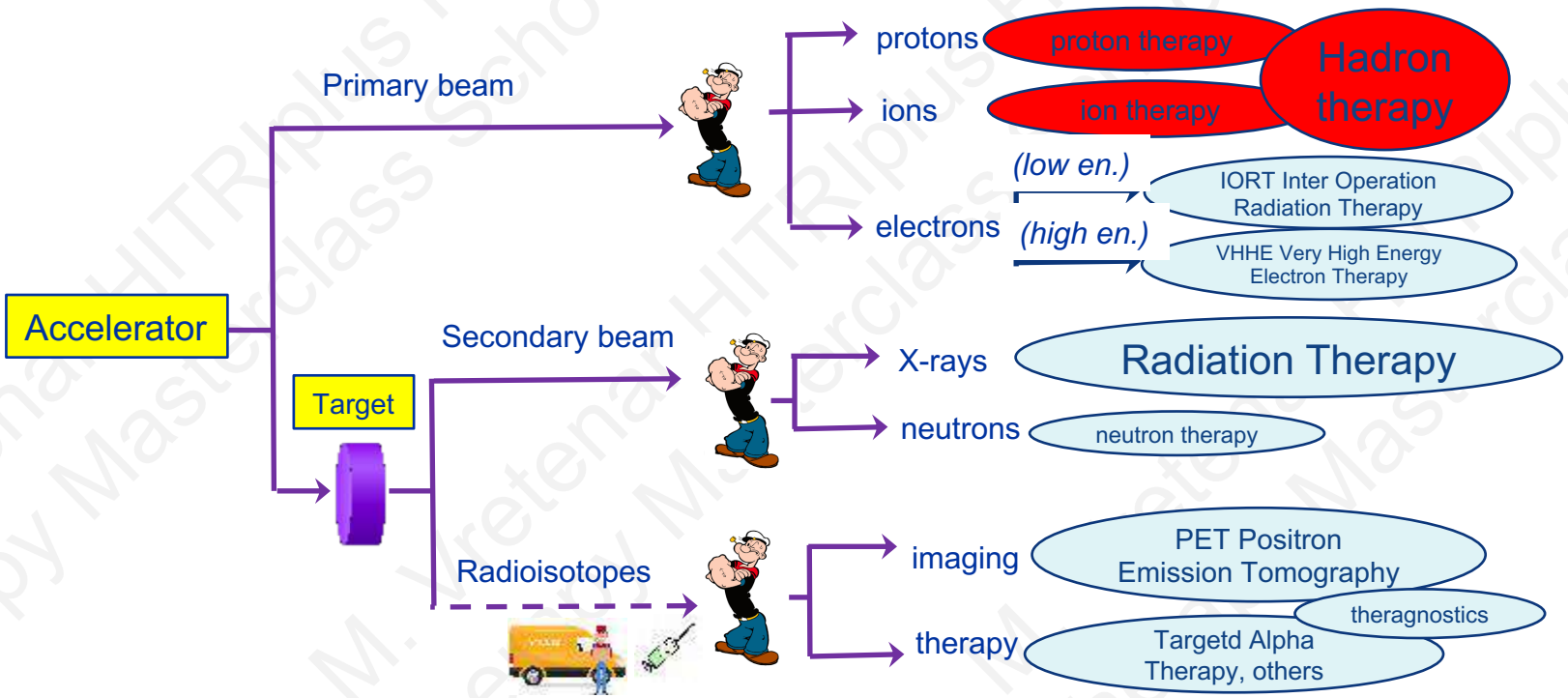


Fig. 3.4: The MR-linac, developed by Elekta, consists of a linear accelerator equipped with multi-leaf collimator technology for accurate radiotherapy dosage, combined with a high-field MR imaging system. The MR-linac is work in progress and is not available for sale or distribution (courtesy of Elekta).

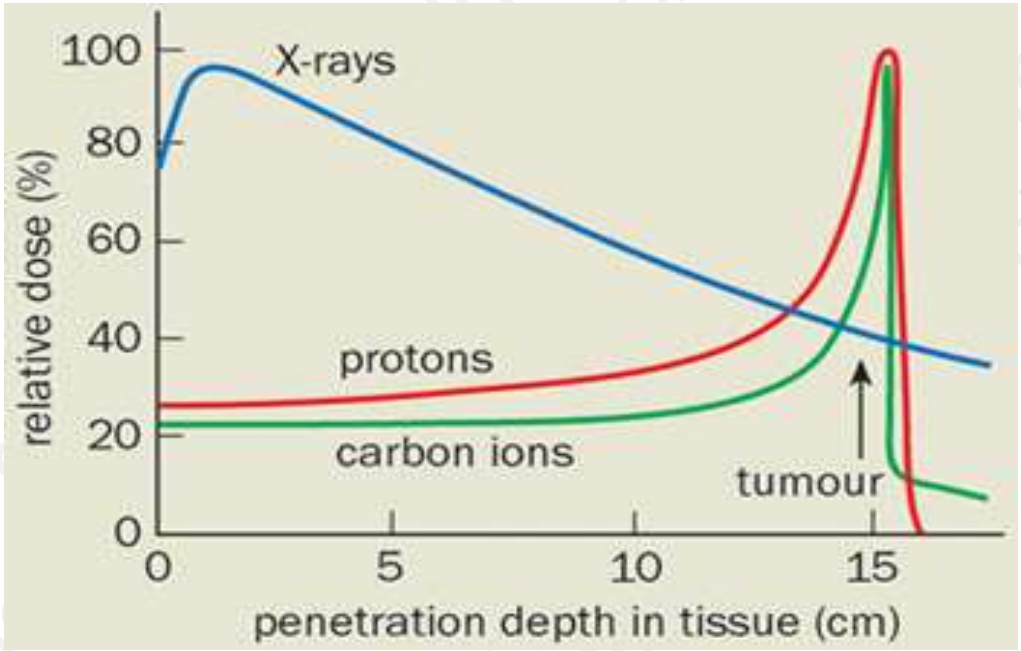
# 2 – Hadron therapy



# The Bragg peak

Bethe-Bloch equation of ionisation energy loss by charged particles

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I.(1-\beta^2)}\right) - \beta^2\right]$$



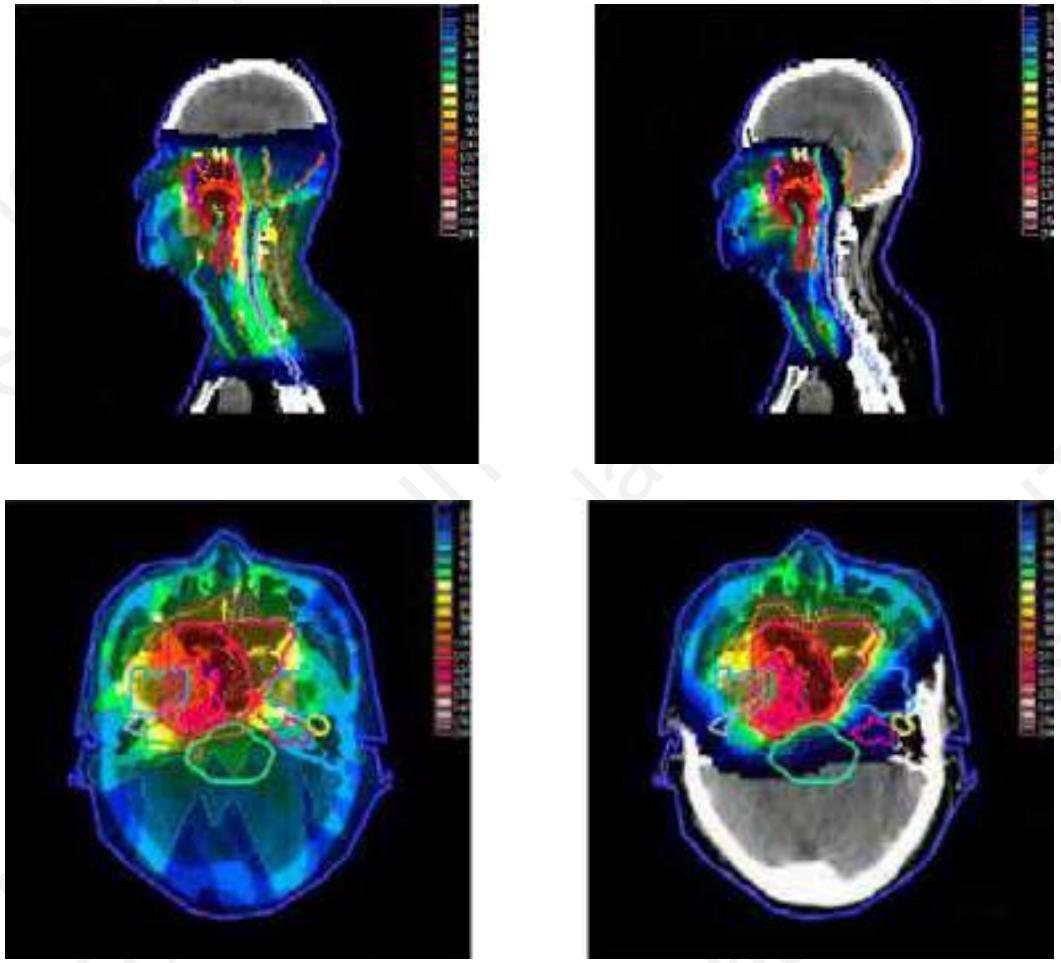

«Bragg» peak

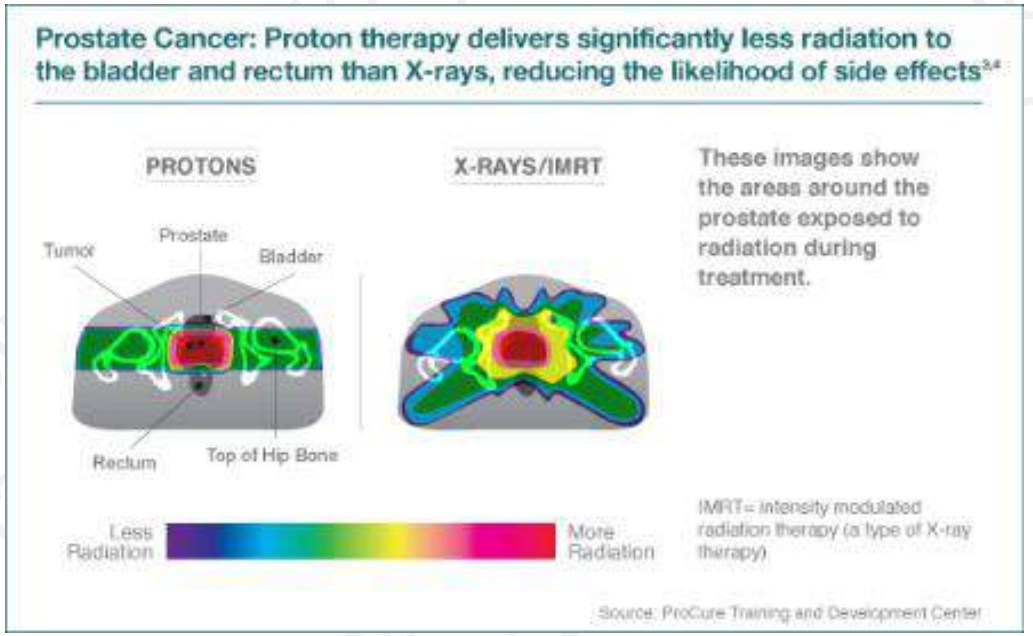
Different from X-rays or electrons, protons and ions deposit their energy at a given depth inside the tissues, **minimising the dose to the organs close to the tumour**.

Required energy (protons) about 230 MeV, corresponding to 33 cm in water.
Small currents: 10 nA for a typical dose of 1 Gy to 1 liter in 1 minute.

*accelerators-for-society.org*

# Comparing proton and X-ray therapy






The results of irradiating a nasopharyngeal carcinoma by X-ray therapy (left) and proton therapy (right), showing the potential reduction in dose outside the tumour volume that is possible with proton treatment. (Z. Taheri-Kadkhoda et al., Rad. Onc., 2008, 3:4 – from APAE Report, 2017).

# The rise of particle therapy



First experimental treatment in 1954 at Berkeley.

First hospital-based proton treatment facility in 1993 (Loma Linda, US).

First treatment facility with carbon ions in 1994 (HIMAC, Japan).

Treatments in Europe at physics facilities from end of '90s.

First dedicated European facility for proton-carbon ions in 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).

More centres are planned in the near future.

A success story, but …

many ongoing discussion on effectivness, cost and benefits.

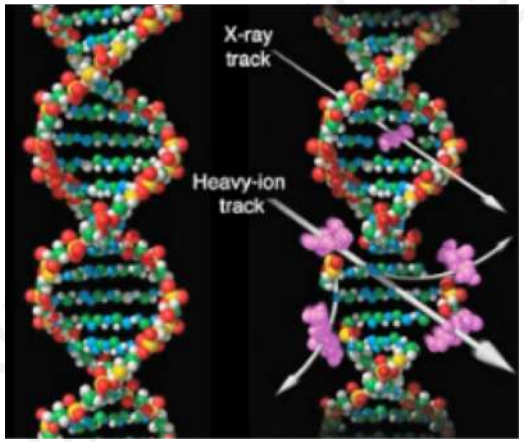
# Therapy with heavier ions (Carbon and others)

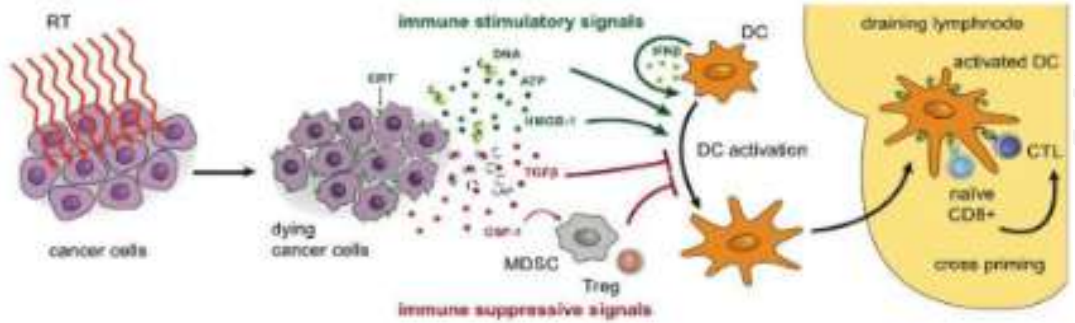
Ions (e.g. Carbon) are different from X-rays or protons!

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.



# Ion therapy is more challenging!

For practical and historical reasons, all ion accelerators operate with fully stripped **Carbon ions**.

Bethe energy loss goes as $z^2$, z=charge of the incident particle → the energy loss is higher for ions → we need a higher energy (per atomic mass unit) to fully penetrate inside the body → around **440 MeV/u**.

The accelerator is more complex than for protons: magnetic rigidity at full energy is **2.76 times** that of proton at full treatement energy.

$$B\rho[T.m] = 3.3356 \cdot pc[GeV]$$

For a given magnet field, in a medical ion synchrotron with respect to a proton one accelerator and gantries have to be almost 3 times larger.

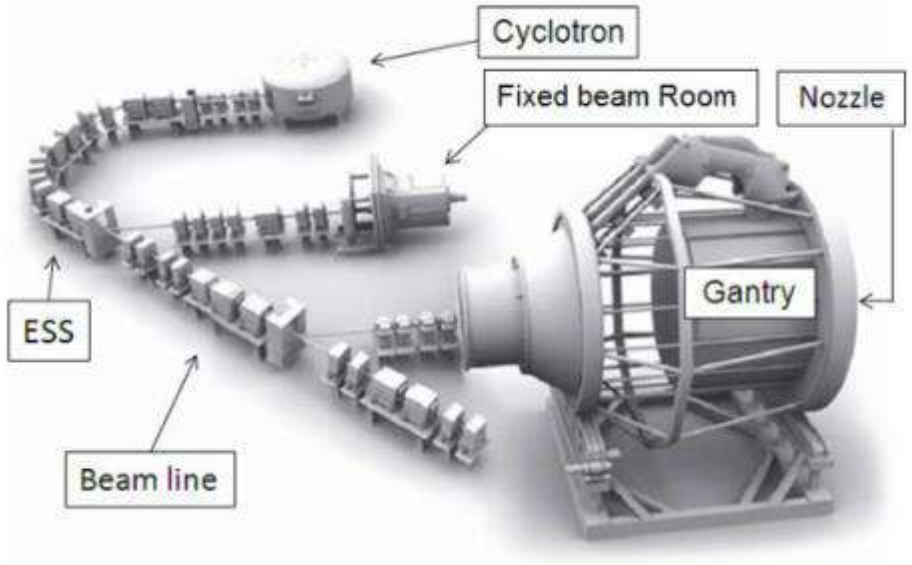
The HIT gantry has a mass of 600 tons for a dipole bending radius of 3.65 m.

| Particle | $H^+$ | | $C^{6+}$ | | |
|---|---|---|---|---|---|
| Ring 1 | inj | ext | inj | ext | |
| Ring 2 | | | | inj | ext |
| Energy [MeV/u] | 31 MeV | 250 | 7.9 | 68.8 | 440 |
| $B\rho$ [T·m] | 0.811 | 2.432 | 0.811 | 2.432 | 6.716 |

All existing ion therapy accelerators are large synchrotrons.

Cyclotrons cannot be easily used because of the dimensions and complexity (needs superconductivity) and because of the difficult ion extraction.

# Proton therapy accelerators: cyclotrons

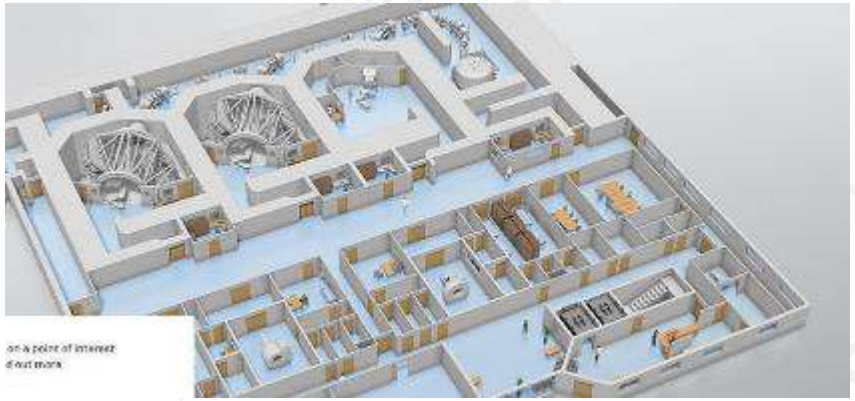



At present, the cyclotron is the best accelerator to provide proton therapy reliably and at low cost (4 vendors on the market).

Critical issues with cyclotrons:

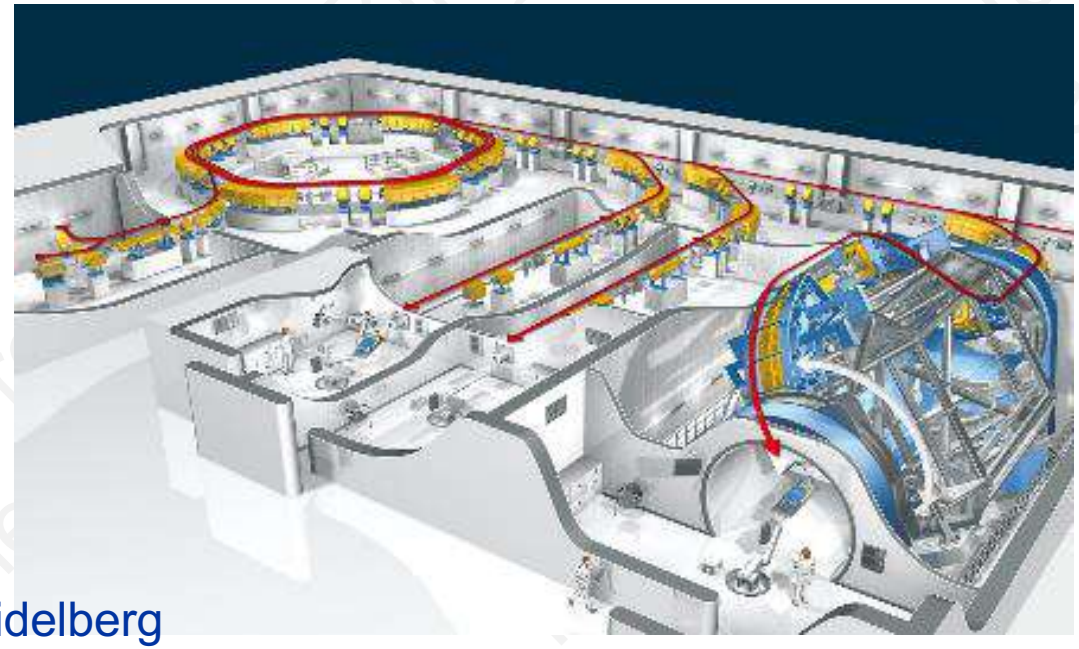
1. Energy modulation (required to adjust the depth and scan the tumour) is obtained with degraders (sliding plates) that are slow and remain activated.
2. Large shielding

*ProteusOne and ProteusPlus turn-key proton therapy solutions from IBA (Belgium)*

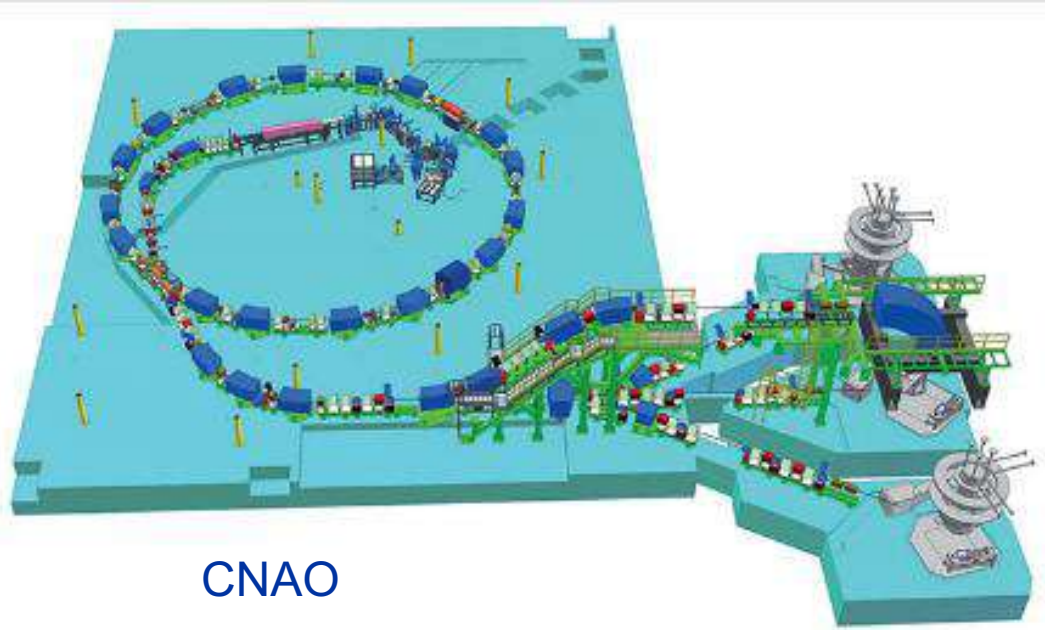


# Synchrotrons for proton and ion therapy

- The Loma Linda Medical Centre in US (only protons) and the ion therapy centres in Japan have paved the way for the use of synchrotrons for combined proton and ion (carbon) therapy).
- 2 pioneering initiatives in Europe (ion therapy at GSI and the Proton-Ion Medical Machine Study PIMMS at CERN) have established the basis for the construction of 4 proton-ion therapy centres: Heidelberg and Marburg Ion Therapy (HIT and MIT) based on the GSI design, Centro Nazionale di Terapia Oncologica (CNAO) and Med-AUSTRON based on the PIMMS design.



HIT Heidelberg

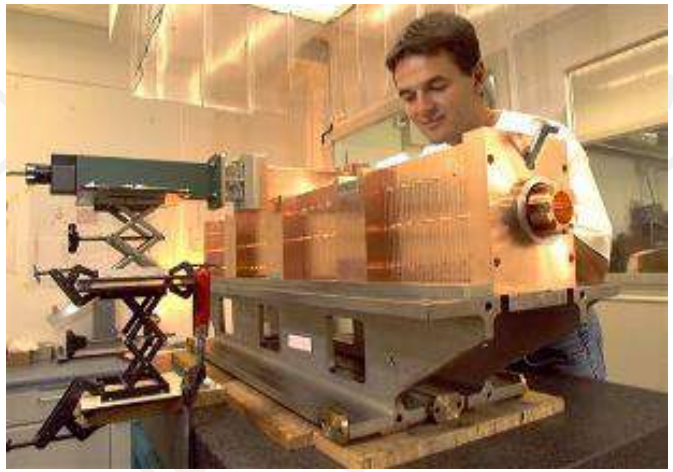


CNAO

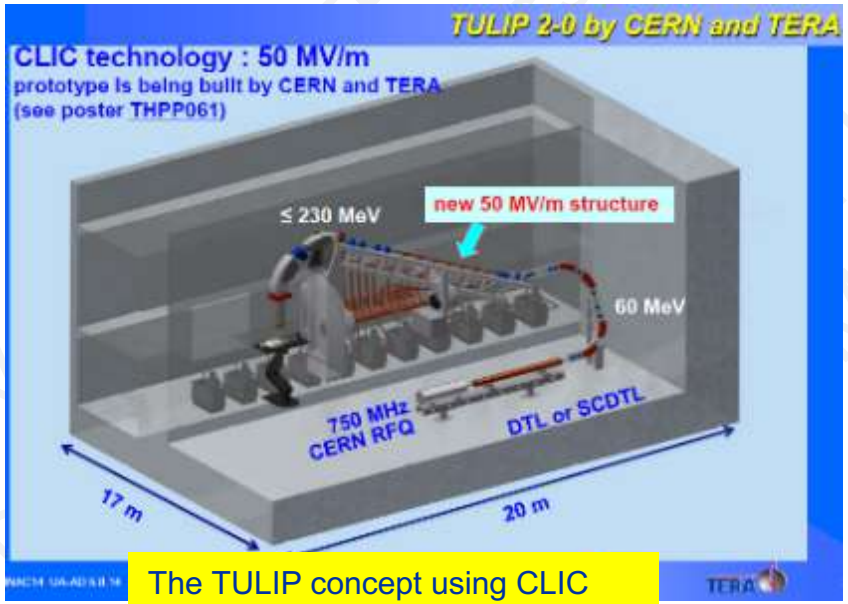
# Alternative solutions: the linear accelerator

Collaboration TERA Foundation / CERN for the development of a proton therapy linac operating at high frequency (3 GHz) and high gradient (30-50 MV/m) reaching 230 MeV in 25 meters. The development is now continued by the AVO company that is building a proton therapy linac to be installed in UK Hospitals.

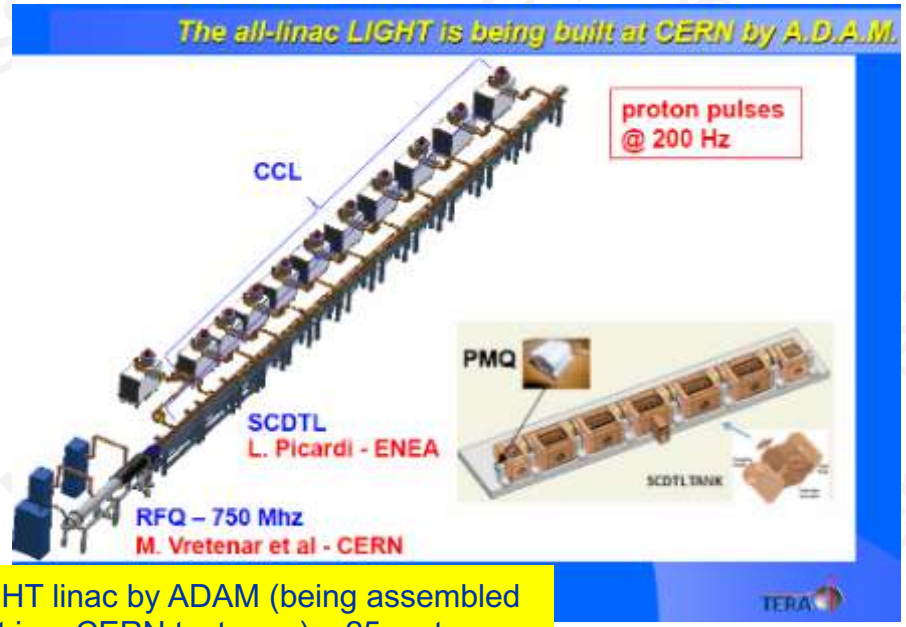
Advantages of a LINAC:
- High repetition frequency with pulse-to-pulse energy variability
- Small emittance, no beam loss.



The LIBO prototype structure and accelerating cells (CERN)

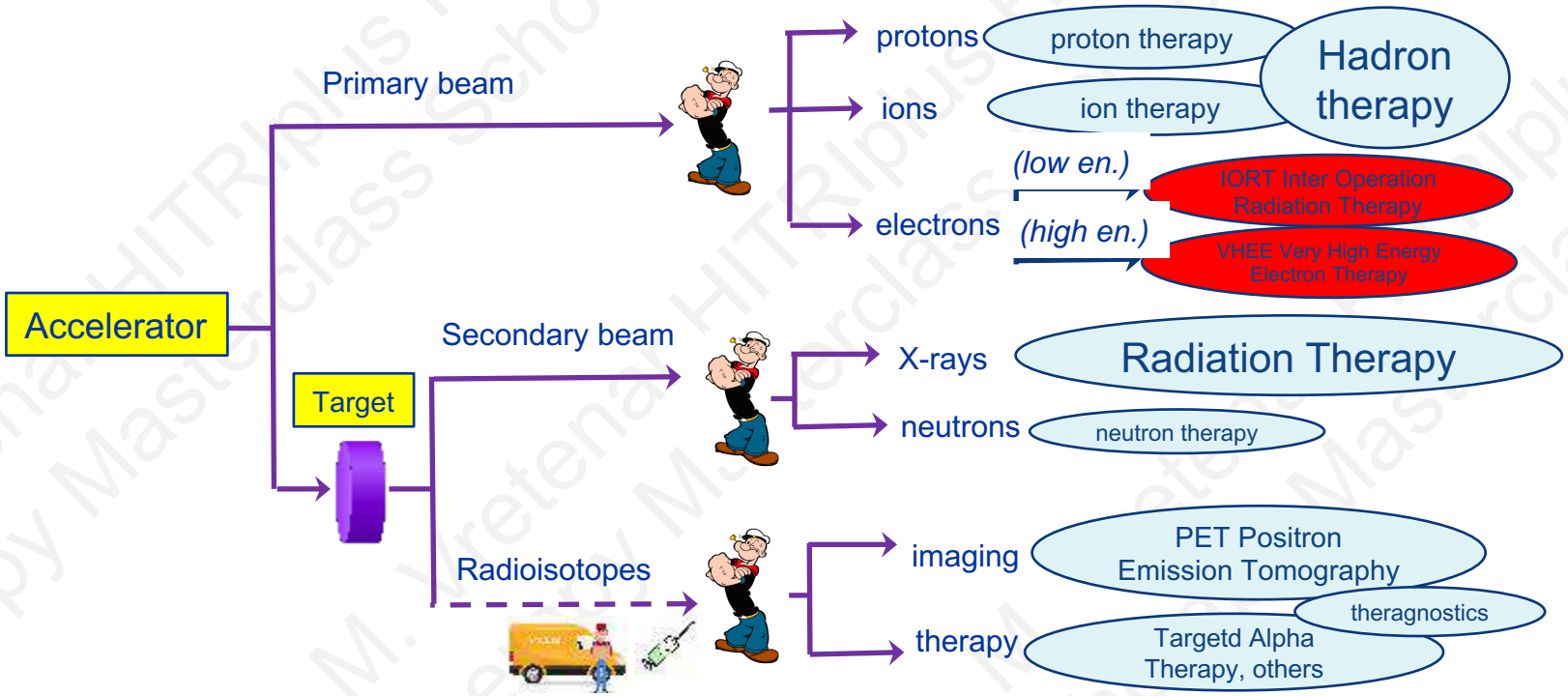



The TULIP concept using CLIC high-gradient cavities – 15 meters



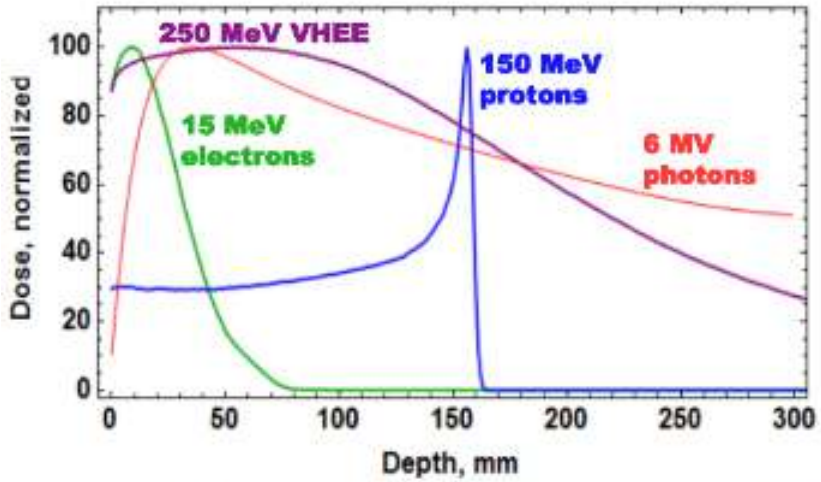

The LIGHT linac by ADAM (being assembled and built in a CERN test area) – 25 meters

# 3 – electrons

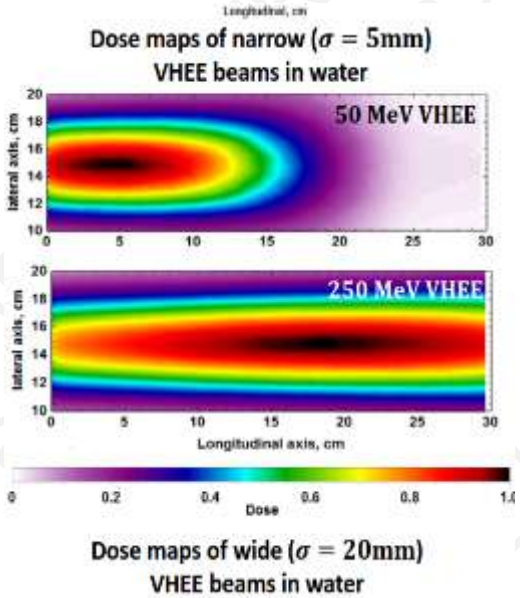

Accelerator
Primary beam
protons
ions
electrons
proton therapy
ion therapy
Hadron therapy
(low en.)
(high en.)
IORT Inter Operation Radiation Therapy
VHEE Very High Energy Electron Therapy
Target
Secondary beam
X-rays
neutrons
Radiation Therapy
neutron therapy
Radioisotopes
imaging
therapy
PET Positron Emission Tomography
theragnostics
Targetd Alpha Therapy, others

# Electrons: IORT and VHEE

**Inter Operational Radiation Therapy (IORT) – (5-20 MeV):**
Technique derived from radiation therapy, where a compact electron linac is not used to produce X-rays, but to send the electrons directly on the tissues. It delivers a concentrated dose of radiation therapy to a tumour bed during surgery. This technology may help kill microscopic diseases, reduce radiation treatment times, preserve more healthy tissue.



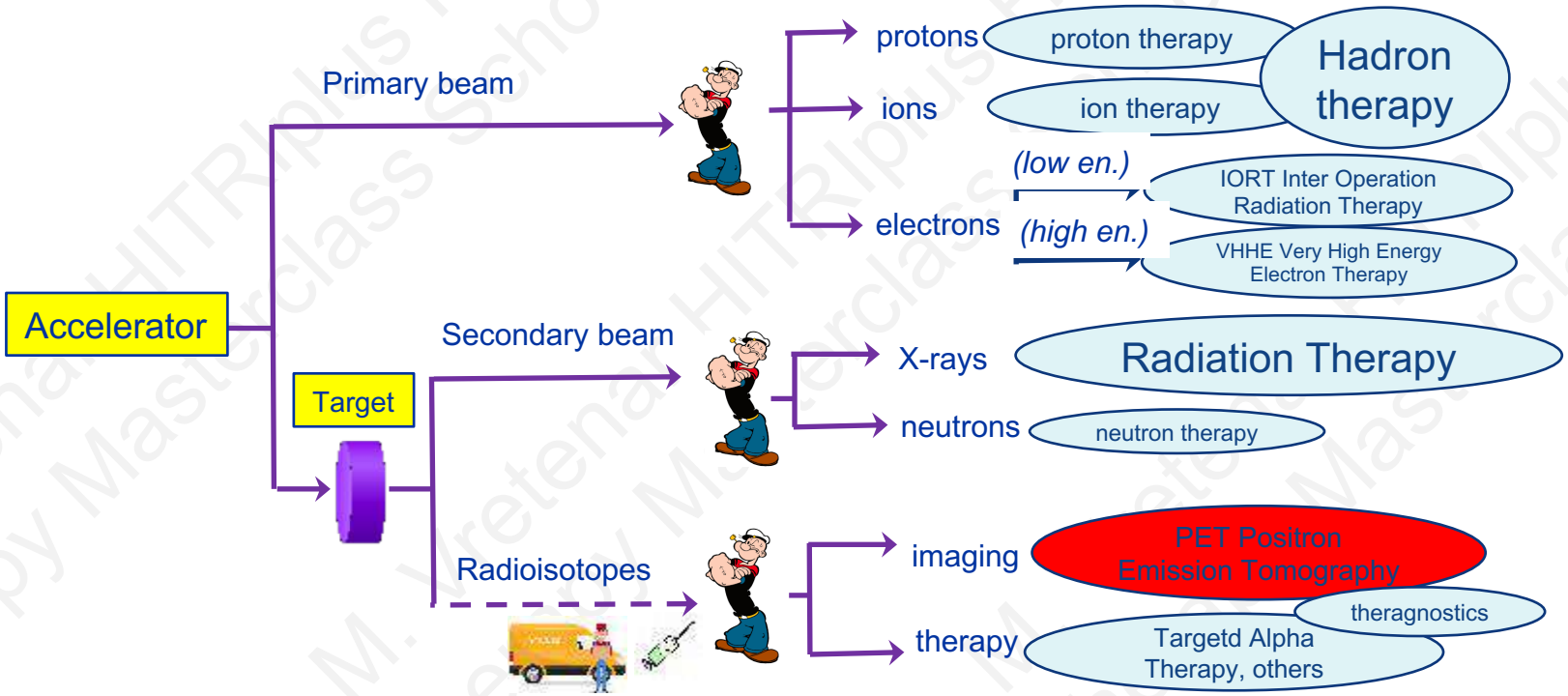
Dose profiles for various particle beams in water (beam widths r = 0.5 cm)



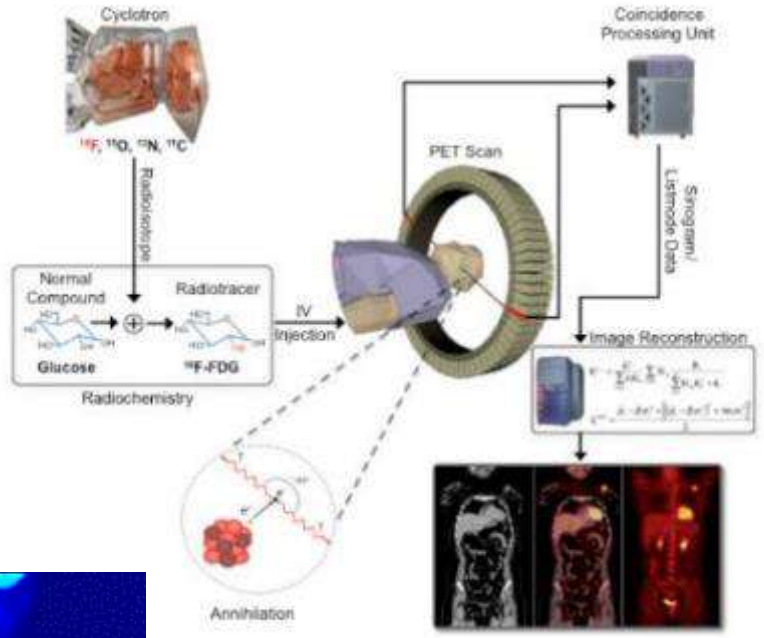
Dose maps of wide (σ = 20mm)
VHEE beams in water

**Very High Energy Electrons (50-250 MeV) for radiotherapy:**
Proposed as a lower-cost alternative to hadron therapy, treat deep seated tumours with high-energy electron beams. High dose deposition, less sensitive to errors, good sparing of healthy tissues.
Made possible by recent advances in high-gradient linac technology (CLIC, etc.).

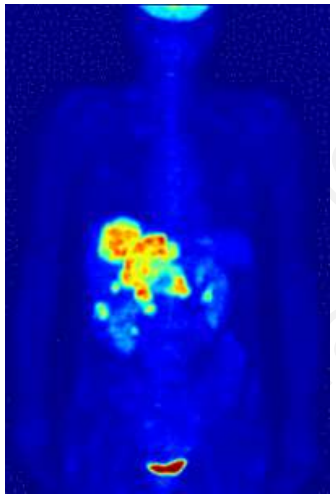
# 4- Radioisotopes - imaging



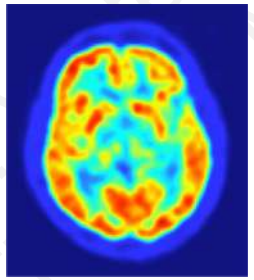
# Radioisotope-based tomographies




*(source: Huntsman Cancer Institute)*

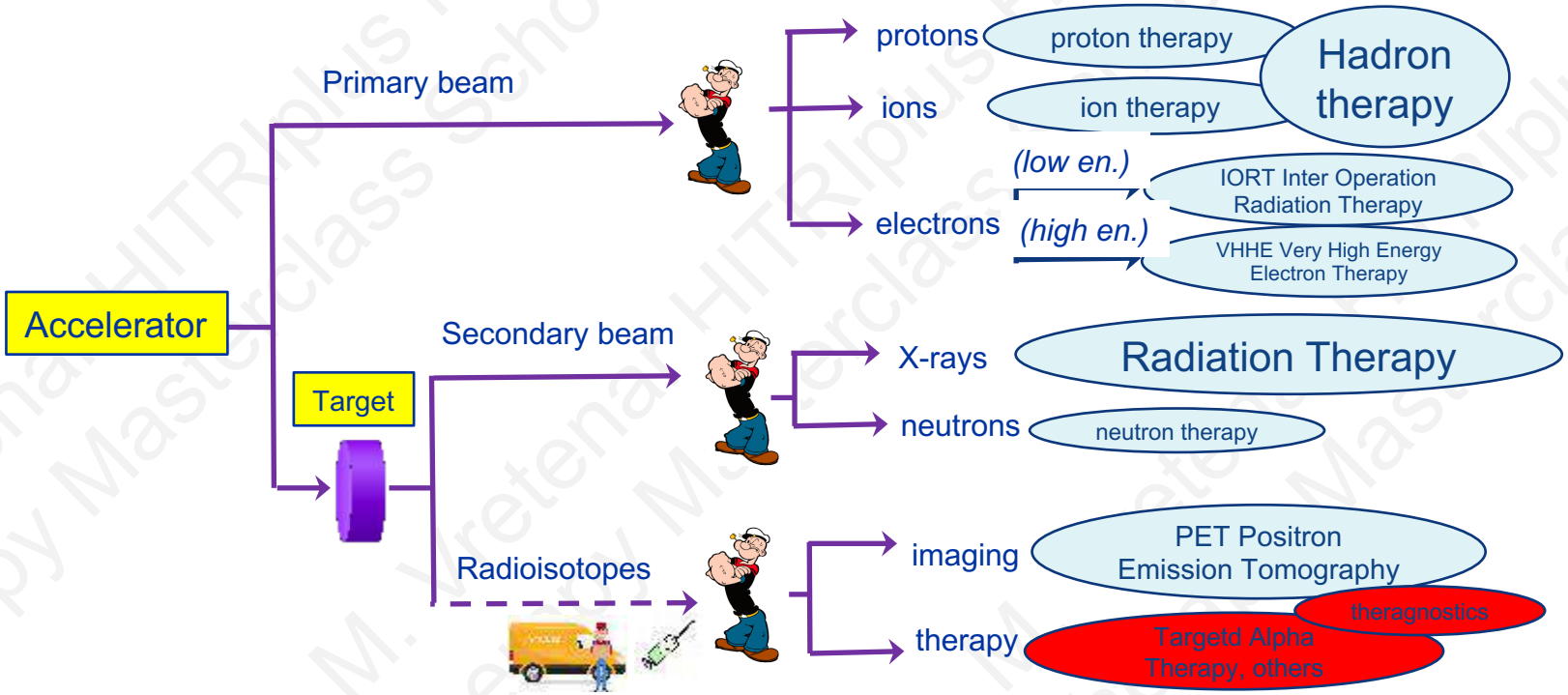


90% of PET scans are in clinical oncology



- A **radioisotope** (radiotracer) is produced by an accelerator (usually a cyclotron) and attached to a normal chemical compound, usually a glucose, in a radiopharmaceutical unit.
- The compound is injected to the patient and accumulates in tissues with high metabolic activity, as tumours – and metastasis.
- When the radioisotope decays, the emitted particles are detected by a scanner allowing a precise mapping of the emitting areas.
- In **SPECT** (single photon emission computed tomography) is used Technetium-99 (6 hours half-life) that emits a photon. 99-Te is generated in the hospital by Molybdenum-99 (66 hours half-life) produced at a nuclear plant.
- In the much more precise **PET** (Positron Emission Tomography) is used Fluorine-18 (1h50' half-life) attached to Fludeoxyglucose (FDG) molecules, which emits positrons that annihilates with electrons producing 2 gamma rays in opposite directions.

# 5 – Radioisotopes, treatment



# Targeted Alpha Therapy

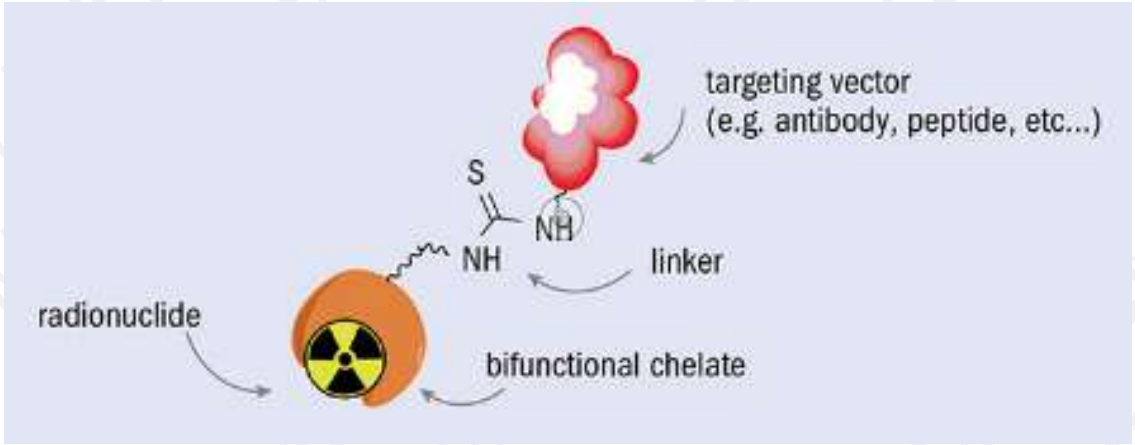
Alpha-emitting therapeutic isotopes as an example of therapeutic isotopes

Injected radiolabeled antibodies accumulate in cancer tissues and selectively deliver their dose. Particularly effective with alpha-emitting radionuclides (minimum dose on surrounding tissues).

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)



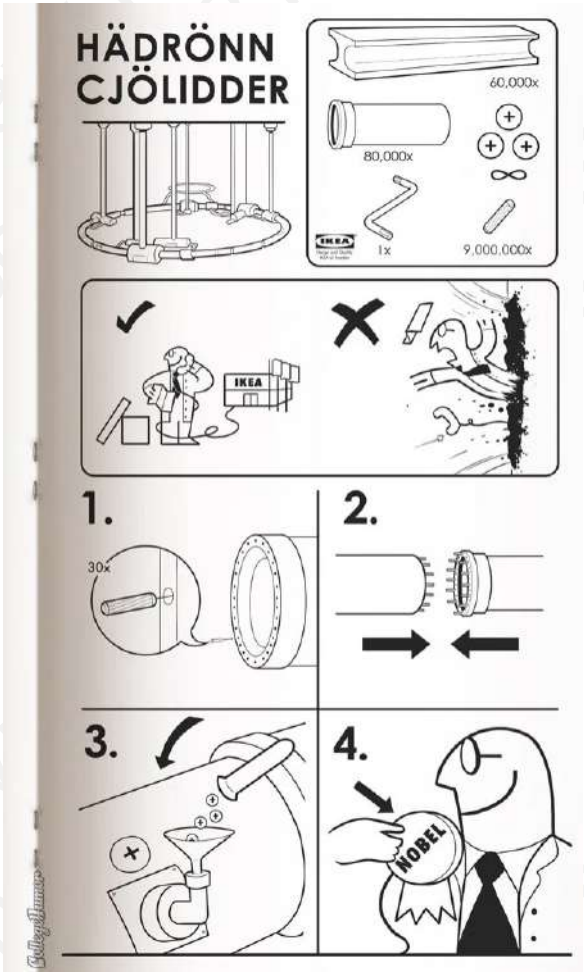

Alpha particles: very high RBE (up to 1'000) Penetration in tissues only 10's of μm

# Accelerators for Alpha Emitters - Astatine

- In the trial phase, only small quantities of α-emitting radionuclides are needed, provided by research cyclotrons.
- If this technique is successful, there will be a strong demand of α-emitters that the accelerator community will have to satisfy.
- One of the most promising α-emitters is Astatine-211, obtained by α bombardment of a natural Bismuth target (209Bi(α,2n) 211At nuclear reaction).
- At production needs α (q/m=1/2) accelerator; optimum energy 28 MeV (sufficient yield but below threshold for 210Po), current >10 mA.
- The use of α's in cyclotrons is limited by extraction losses; linacs have a strong potential.
- Synergy with low-energy section of carbon therapy linacs (q/m=1/2).

*Astatine, an amazing element:*
*The rarest element on earth (only 25 g at any given time)*
*The less stable element in the periodic table (<100)*
*Half life (210At): 7.2 hours*

# 6 – New ideas and initiatives



# Towards a next generation ion therapy facility

- **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**.

## Specifications from the scientific community

**(Archamps Workshop, June 2018)**

**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.


# The CERN Next Ion Medical Machine Study

**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

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 European Commission, 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, in the line of “science for peace”.
- Promoted by H. Schopper, former Director General of CERN, and S. Damjanovic, former Minister of Science of Montenegro.


SEE IIST
South East European International Institute for Sustainable Technologies

# NIMMS Workpackages – inside the toolbox

| | Workpackage | Objectives |
|---|---|---|
| 1 | Superconducting magnets | Comparison of magnet technologies (CCT, costheta) and cables (NbTi, HTS).<br>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):<br>- Rotational<br>- 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. |

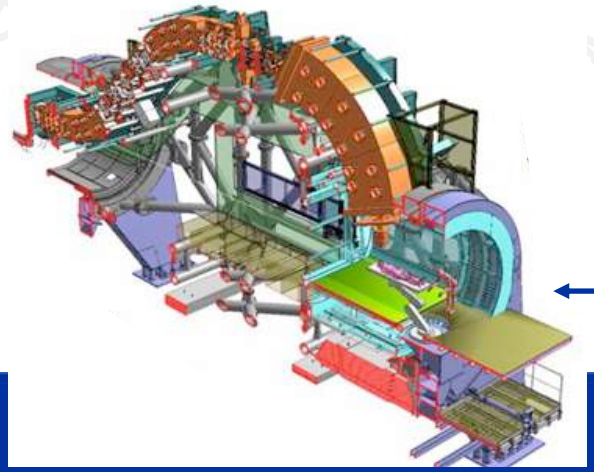
***Superconductivity**, the main avenue to accelerator miniaturisation.*
*Long-standing CERN expertise, needs high fields, pulsed operation, strong curvature*

*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 ($B\rho$) 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

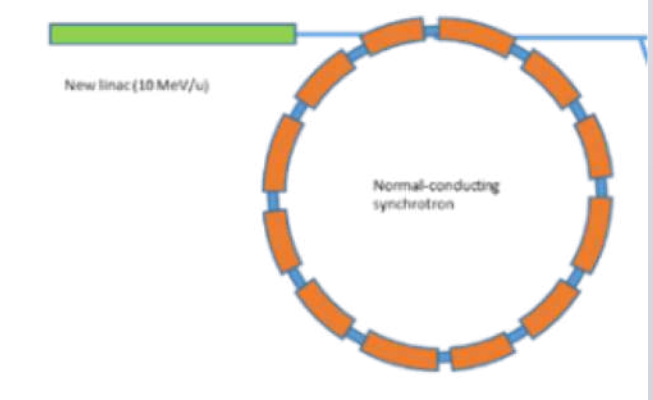
HIT carbon ion gantry (RT magnets):
L=25 m, F = 13 m, 600 tons

# 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.

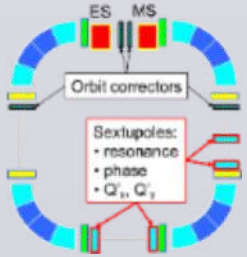
Circumference ~ 75 m

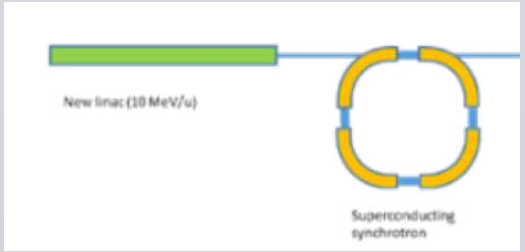



## Improved synchrotron (superconducting)

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

Circumference ~ 27 m

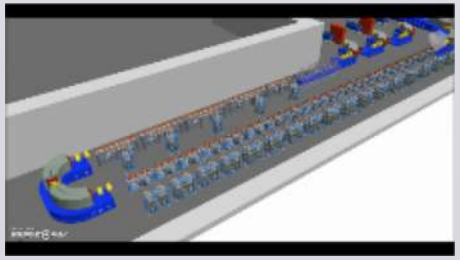


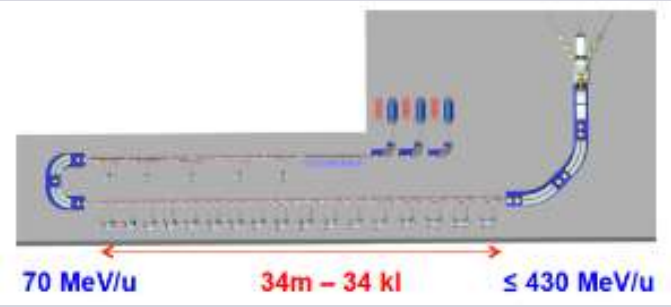




## Linear accelerator

Linear sequence of accelerating cells, high pulse frequency.

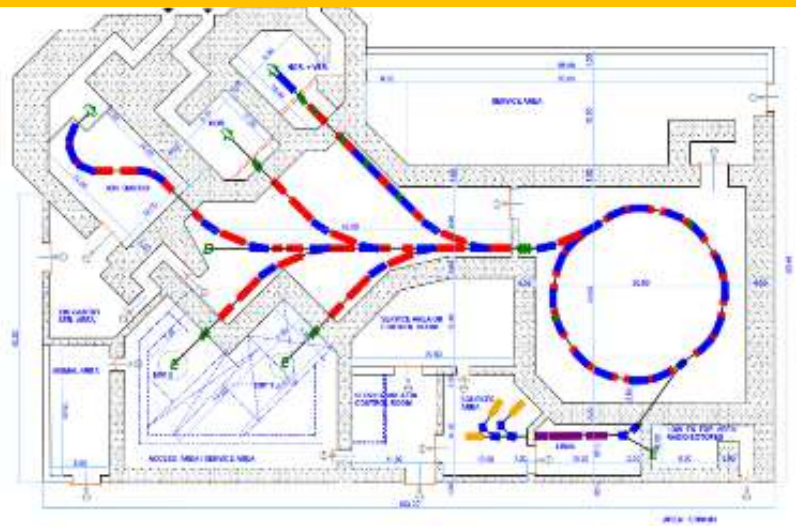
Length ~ 53 m



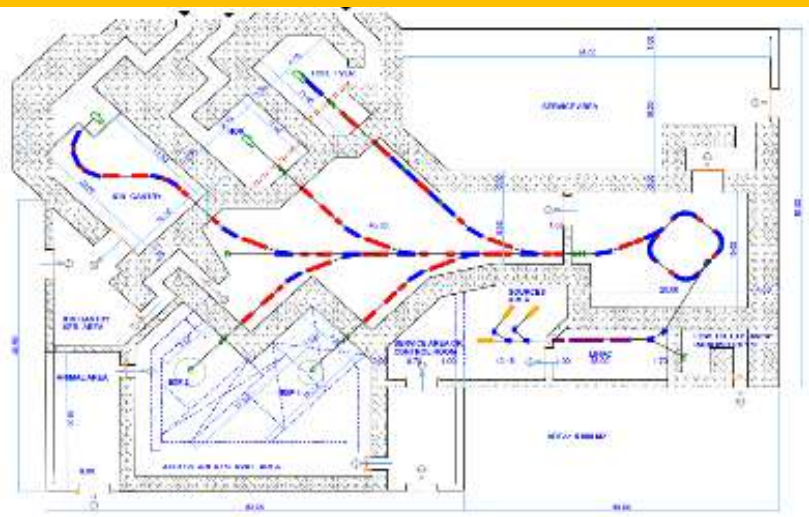



Other options considered as less interesting because of cost and/or required R&D: **RC synchrotron**, **FFAG**, **SC cyclotron**, **PWFA**

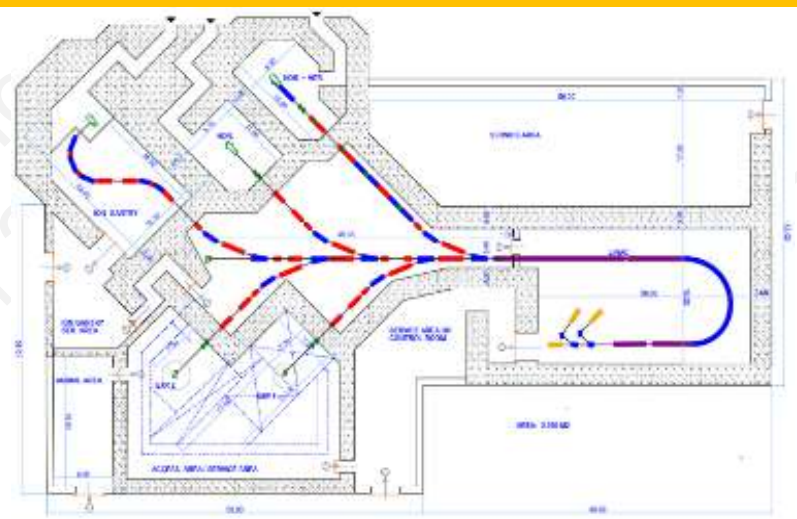
# Comparing three accelerator options for SEEIIST



RT synchrotron:
accelerator 1,200 m², facility 6,500 m²
Reference for cost calculation



SC synchrotron:
accelerator 600 m², facility 5,500 m²
estimated cost (acc. only): 20% lower



Full linac:
accelerator 600 m², facility 5,500 m²
estimated cost (acc. only): 20% lower

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

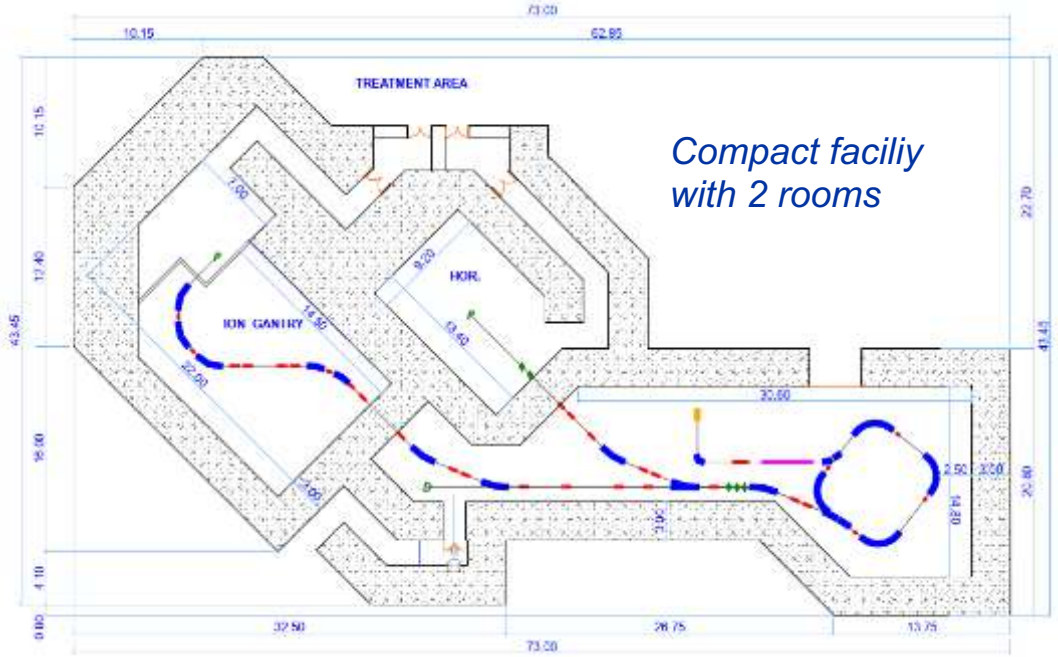
| | Construction Cost | Operation cost | Footprint | Performance | Time to development | Risk of development | Treatment protocols | Gantry |
|---|---|---|---|---|---|---|---|---|
| Warm (new) synchrotron | Medium | Medium | Large | Good | Low | Low | Existing | Simple design |
| Superconducting synchrotron | 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.

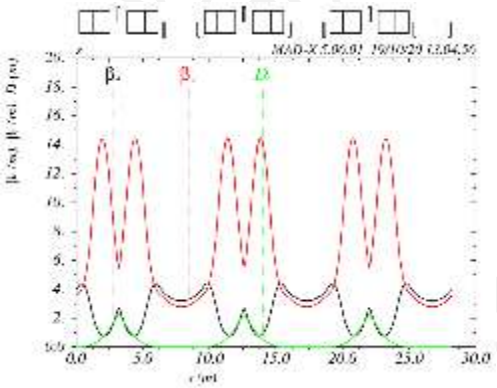
# The compact SC synchrotron

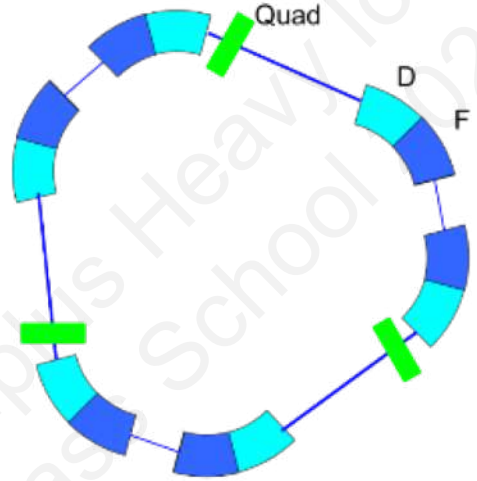
**E. Benedetto,** M. Sapinski, TERA/SEEIIST
P. Foka, GSI
D. Kaprinis, Kaprinis Architects
M. Vretenar, CERN

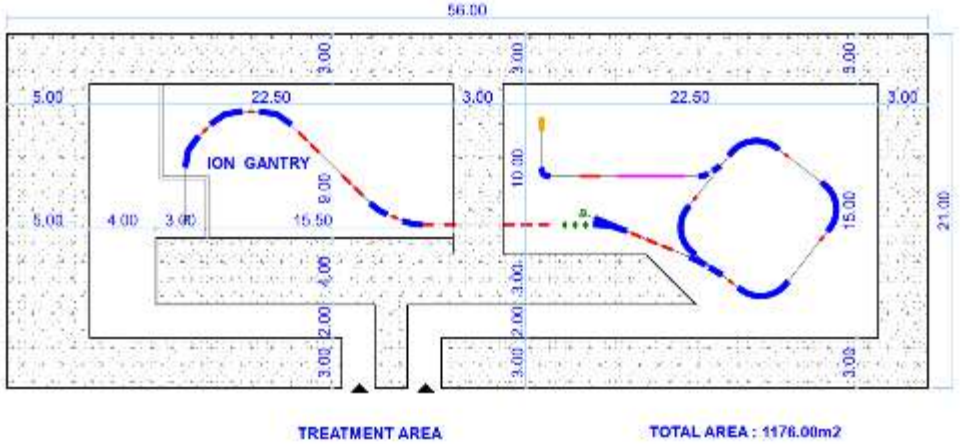



*Compact faciliy with 2 rooms*

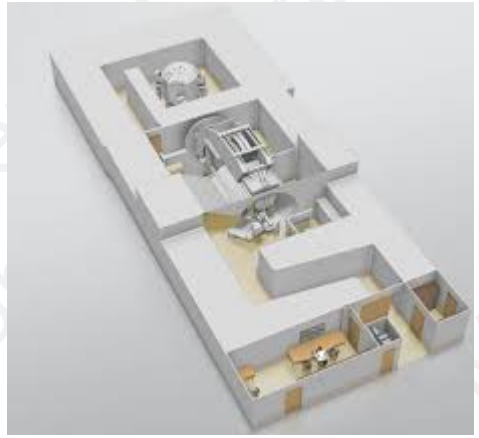
*Alternative lattice with 60⁰ magnets*






**A compact single-room ion therapy facility in about 1,000 m²**

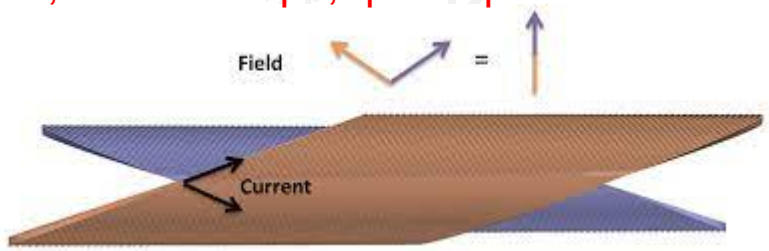


*Comparable in size with proton therapy systems – here the single-room proton facility ProteusOne, from IBA)*

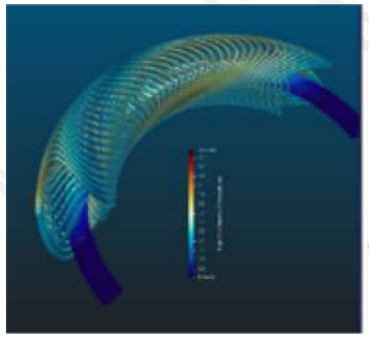
# Development of supercondcuting magnets for ion therapy

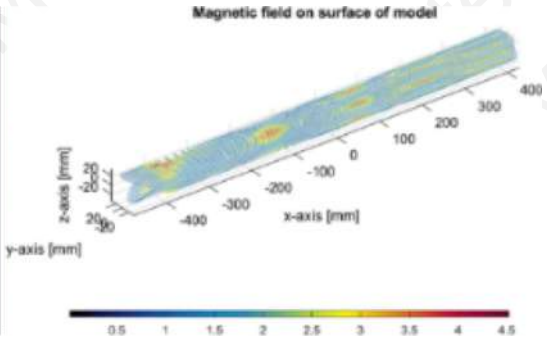
Wide international effort towards the development of a new generation of superconducting magnets for ion therapy.
Some of the challenges are common, other are specific for medical accelerator magnets: ramping field, curved shape, quadrupole integration, use of cryocoolers.

Canted Cosine Theta magnets
(drawing: E. Oponowicz)




*Solution for curved and straight CCT coils combining dipole and quadrupole in the same winding - Courtesy G. Kirby and J. van Nugteren, 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 ($Nb_3Sn$) | NbTi (curved), HTS (straight) |
| Operating temperature (K) | 5 (8) | 5 (20) |

**2 EU-supported projects addressing the design and prototyping of superconducting CCT (Canted Cosine Theta) magnets for ion therapy accelerators:**

**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)

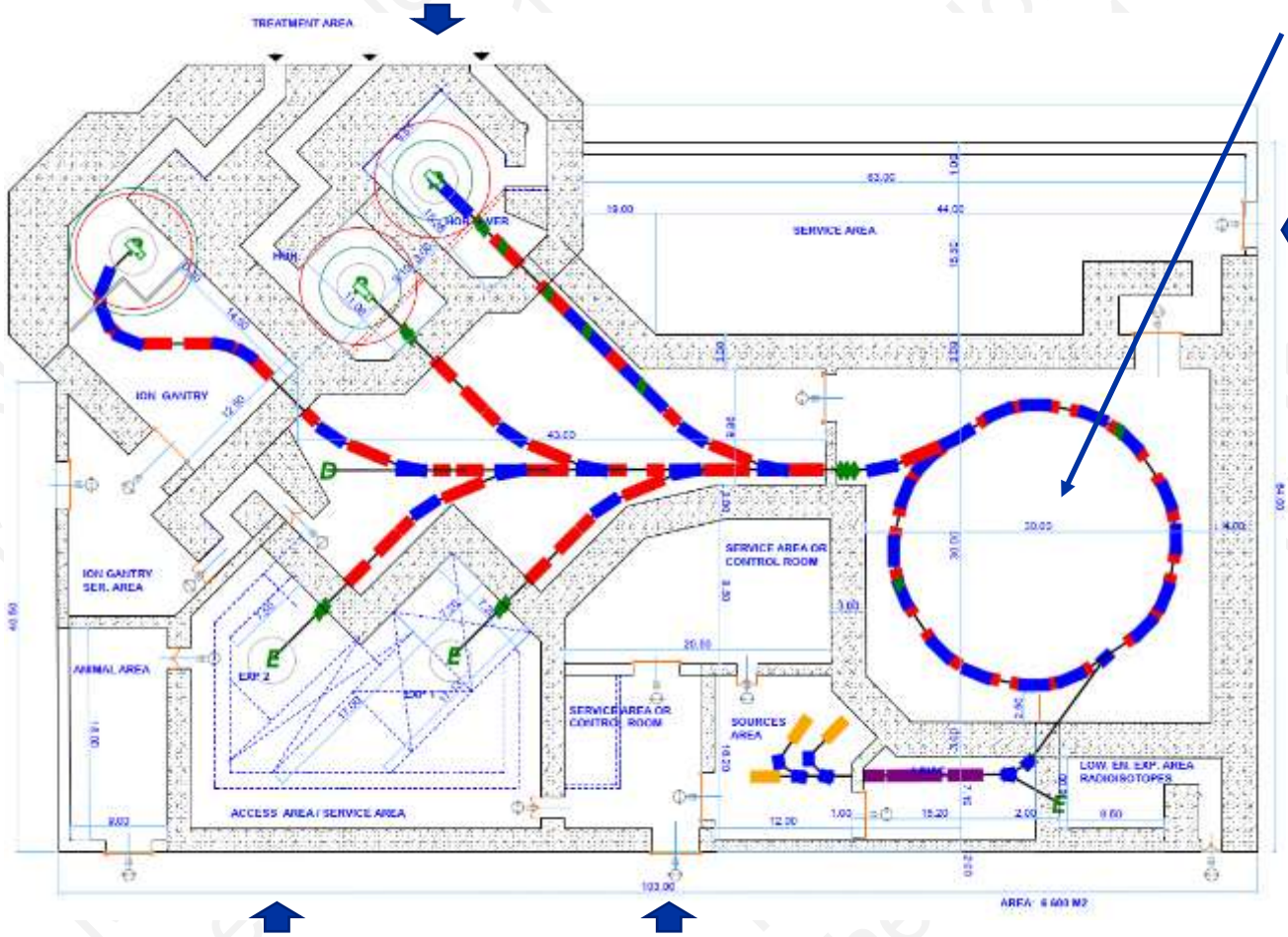
**Both WPs coordinated by L. Rossi (INFN, former CERN)**

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

# Layout of the complete SEEIIST-type facility

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

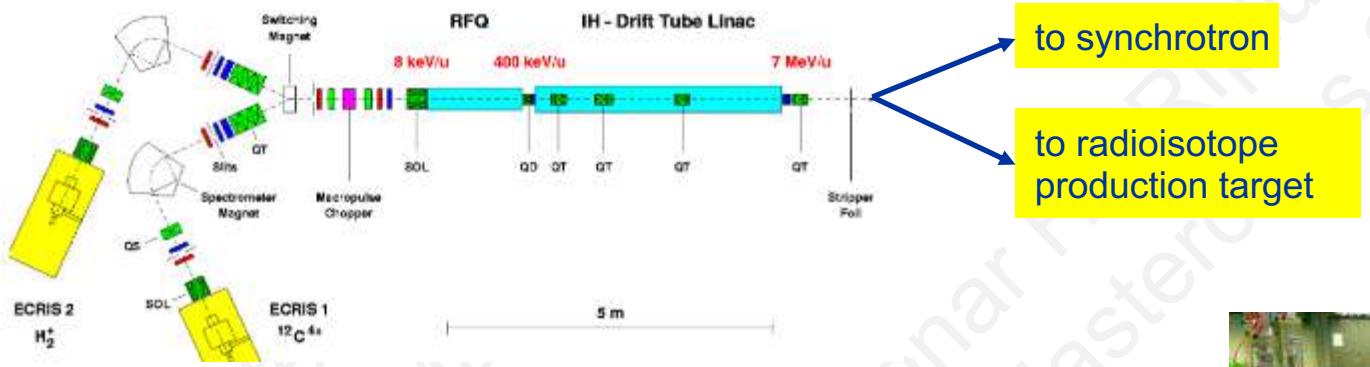
Total 6,600 m$^2$



# Linac for production of medical radioisotopes

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.

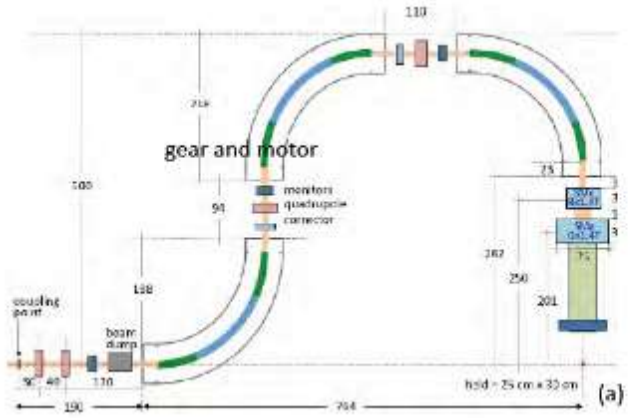
With a minor additional investment, the linac could have 2 modes of operation: for injection in the synchrotron, and for sending the beam to a target for production of medical radioisotopes.

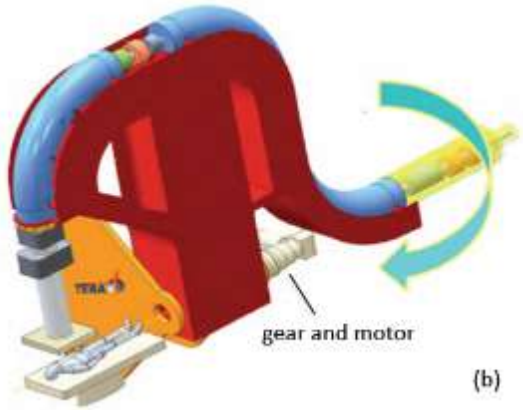



Three isotopes being considered:

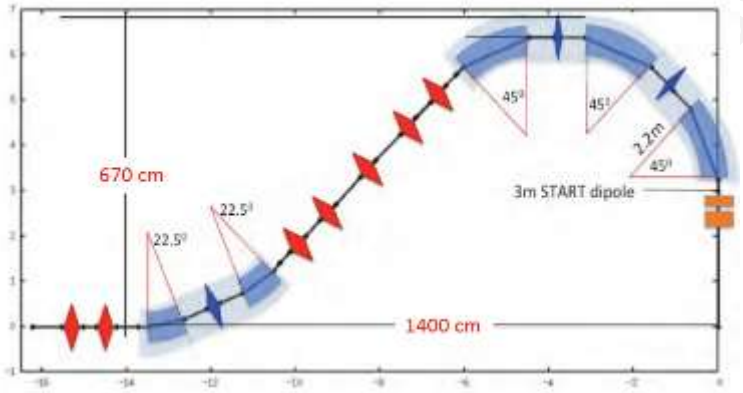
1. 211 At for Targeted Alpha Therapy, with alpha particles.
2. 117 mSn, for theranostic, arthery plaque and bone malignancies, with alpha particles.
3. 11 C for PET scanning, with protons.

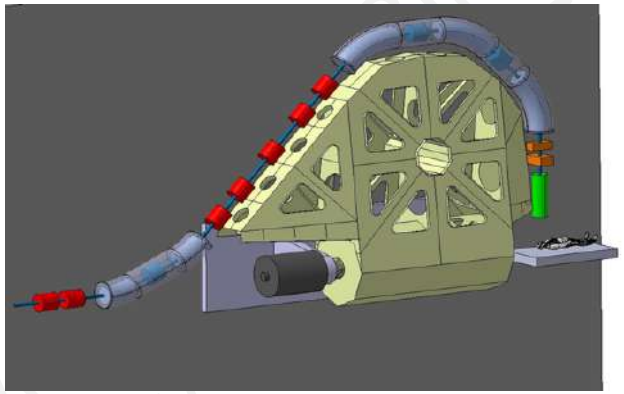
# A superconducting ion gantry



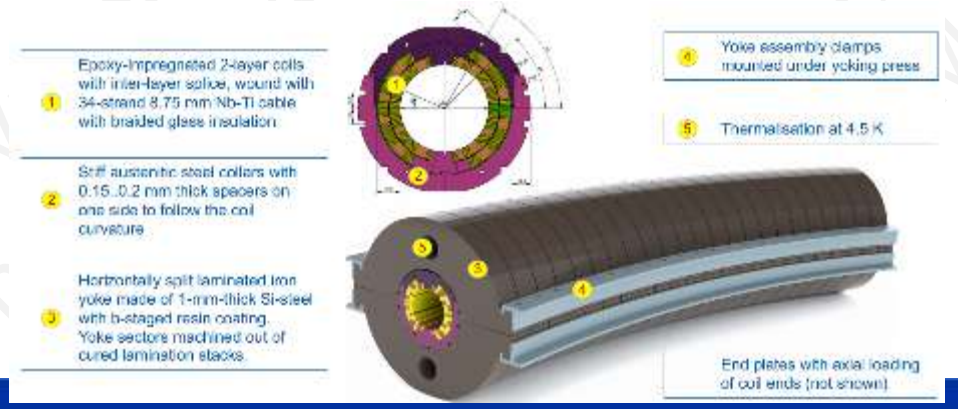




2018 design of a 4 T gantry equipped with Canted Cosine Theta (CCT) dipole magnets of $90^0$ with nested-quadrupoles. The cables are in NbTi and the magnets weight 4 tons.



2020 design of a 3 T gantry equipped with cos-theta dipole magnets.
Collaboration for prototyping being formed (CERN, INFN, INFN, MedAustron).
Time to construction: 10 years




From “SIGRUM, A Superconducting Ion Gantry with Riboni’s Unconventional Mechanics”
U. Amaldi, N. Alharbi, E. Benedetto, 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-2

# The SEEIIST facility

# Thank you for your attention!

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548