INFN ACCELERATORI ERICE Accelerator School

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

Medical and other applications of Accelerators

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M. Vretenar, CERN, (60% of the slides form his talks!)
F. Bordry, CERN
A. Fauss-Golfe, CNRS Orsay, S. Sheehy, Univ. of Melbourne

Material

- **Maurizio Vretenar, CERN, Accelerators for Society – lecture 1 and lecture 2, at Scuola F. Bonaudi, Cogne, 30.6.2023**
- Maurizio Vretenar, CERN, Accelerators for Medicine, talk at doctoral School RTU/CERN May 2022
- Frédérick Bordry, CERN, APPLICATICNS of ACCELERATORS: an OVERVIEW, talk at 6th Summer School on INtelligent signal processing for FrontIEr Research and Industry, Madrid, 25th August 2021
- Suzie Sheehy, Univ. of Melbourne, Application of Accelerators, talk at Cern Inytoductpry Accelerator School, Geneva 2021.
- Angeles Paus-Golfe, CNRS Orsay, The brave new world of Accelerators Applications, talk at IPAC’19 (Melbourne).

Accelerators concentrate an enormous amount of energy in a very tiny volume

1 J = W s
$\sim 10^{-6}$ MW $3\ 10^{-4}$ h
= $3\ 10^{-10}$ MWh
= $3\ 10^{-8}$ €

Because of this they are very penetrating, having a short
λ = *p/h* (am@LHC)
not easy for laser…

	LHC Proton	LHC Bunch	Yoghurt	TGV train
				
Energy	$1.1\ 10^{-6}$ J	$1.3\ 10^{5}$ J	$5\ 10^{5}$ J	$1.4\ 10^{9}$ J
Energy density	$5.3\ 10^{38}$ J/m³	$5\ 10^{11}$ J/m³	$3.3\ 10^{9}$ J/m³	$6\ 10^{11}$ J/m³
Type of energy	Kinetic Subatomic scale	Kinetic Subatomic scale	Chemical Macroscopic	Kinetic Macroscopic

Accelerators and their use (beyond HEP&NP)

Accelerators and their Use

"A beam of particles is a very useful tool…"

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

Today: > 40'000 accelerators operational world-wide*

The **large majority** is used in **industry** and **medicine**

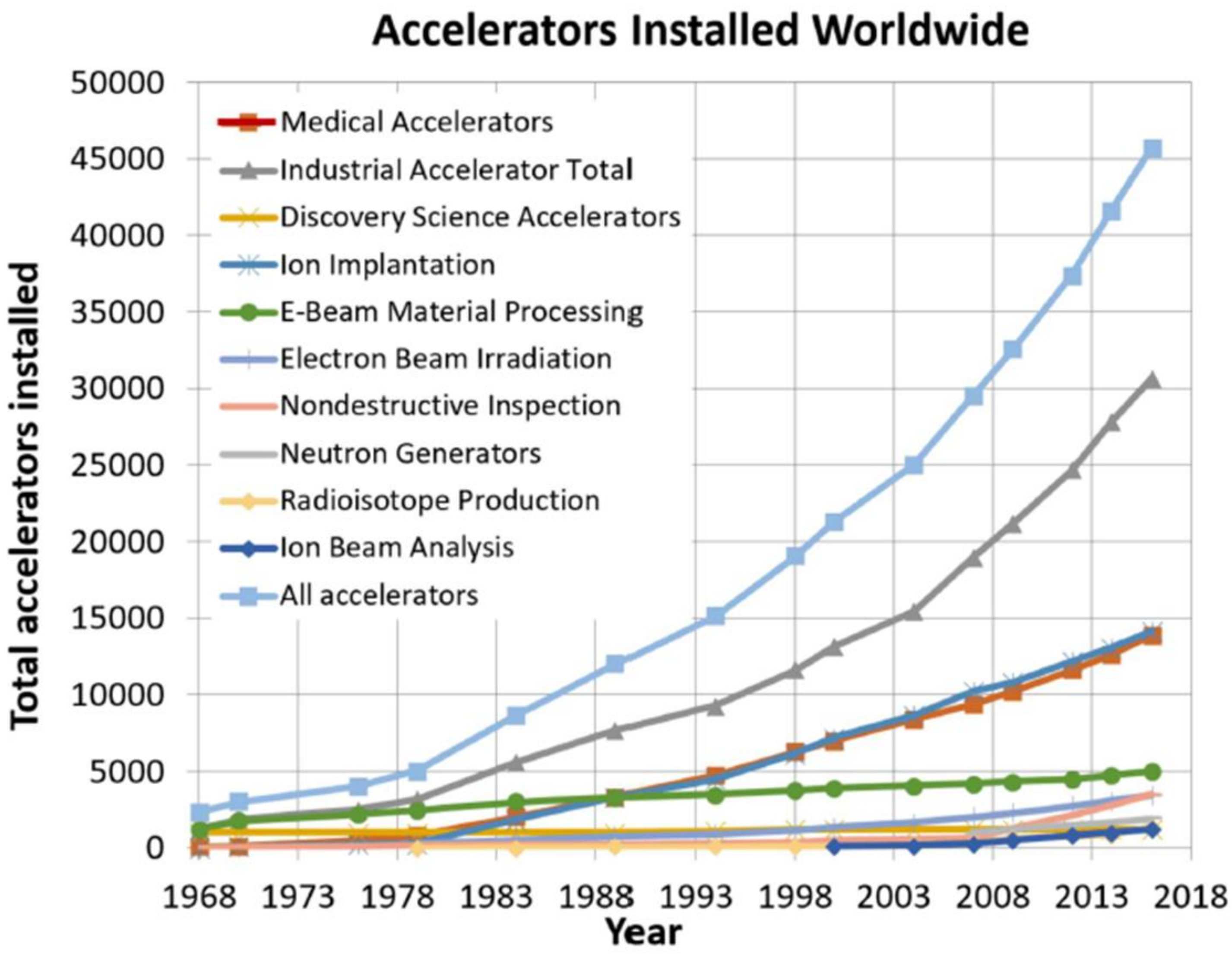
- Industrial applications: ~ 25'000*
- Medical applications: ~ 15'000*

** Source: World Scientific Reviews of Accelerator Science and Technology A.W. Chao*

Les than a fraction of a percent is used for **research** and discovery science

- Cyclotrons
- Linear accelerator
- Synchrotrons
- Synchrotron light sources (e^-)

* not including CRT (Cathode-Ray Tube) televisions…



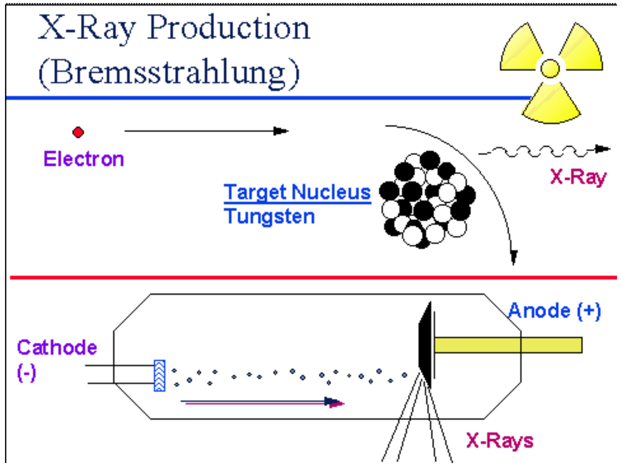
Research		**6%**
	Particle Physics	0,5%
	Nuclear Physics, solid state, materials	0,2 - 0,9%
	Biology	5%
Medical Applications		**35%**
	Diagnostics/treatment with X-ray or electrons	33%
	Radio-isotope production	2%
	Proton or ion treatment	0,1%
Industrial Applications		**<60%**
	Ion implantation (semiconductors)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

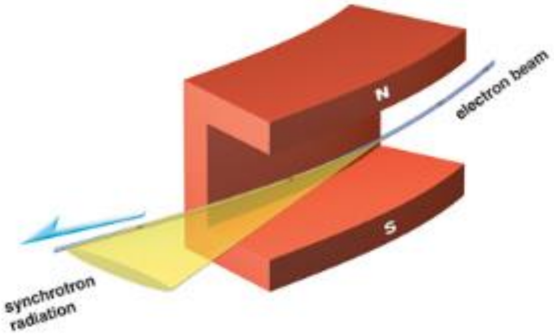
Annual Sales: 5 B$, ↑ by 4-5% per annum
Annual product sales, > 5 T$

Doyle, McDaniel, Hamm, *The Future of Industrial Accelerators and Applications, SAND2018-5903B*

Accelerators can produce intense secondary beams

Accelerated electrons produce X-ray beams by interaction with a metal target (bremsstrahlung) or by synchrotron radiation in accelerator magnets)





Accelerated protons produce neutron beams by spallation reactions in a heavy metal target

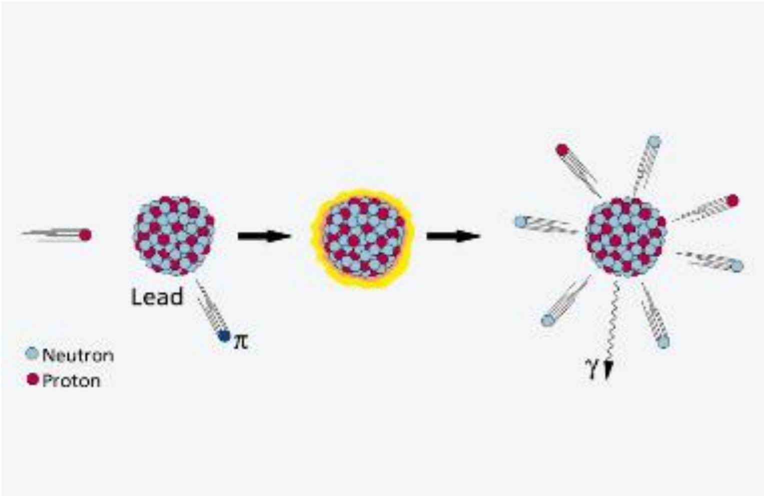
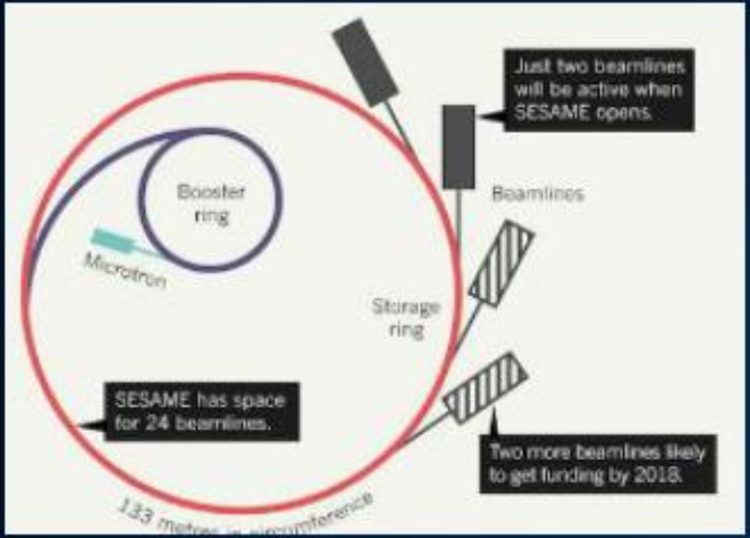


Image courtesy of PSI

- X-rays generated by accelerators are commonly used in **medicine**
- Both X-rays and neutrons generated from accelerators are used for **advanced imaging** in many fields: life sciences, condensed matter, energy, material science, cultural heritage, life sciences, pharmaceuticals,…
- Additional applications are appearing for other types of secondary beams.

Accelerators bringing nations together : SESAME

SESAME (Synchrotron light for Experimental Science and Applications in the Middle East)**in Allan (Jordan)**
Members: Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestinian Authority, Turkey

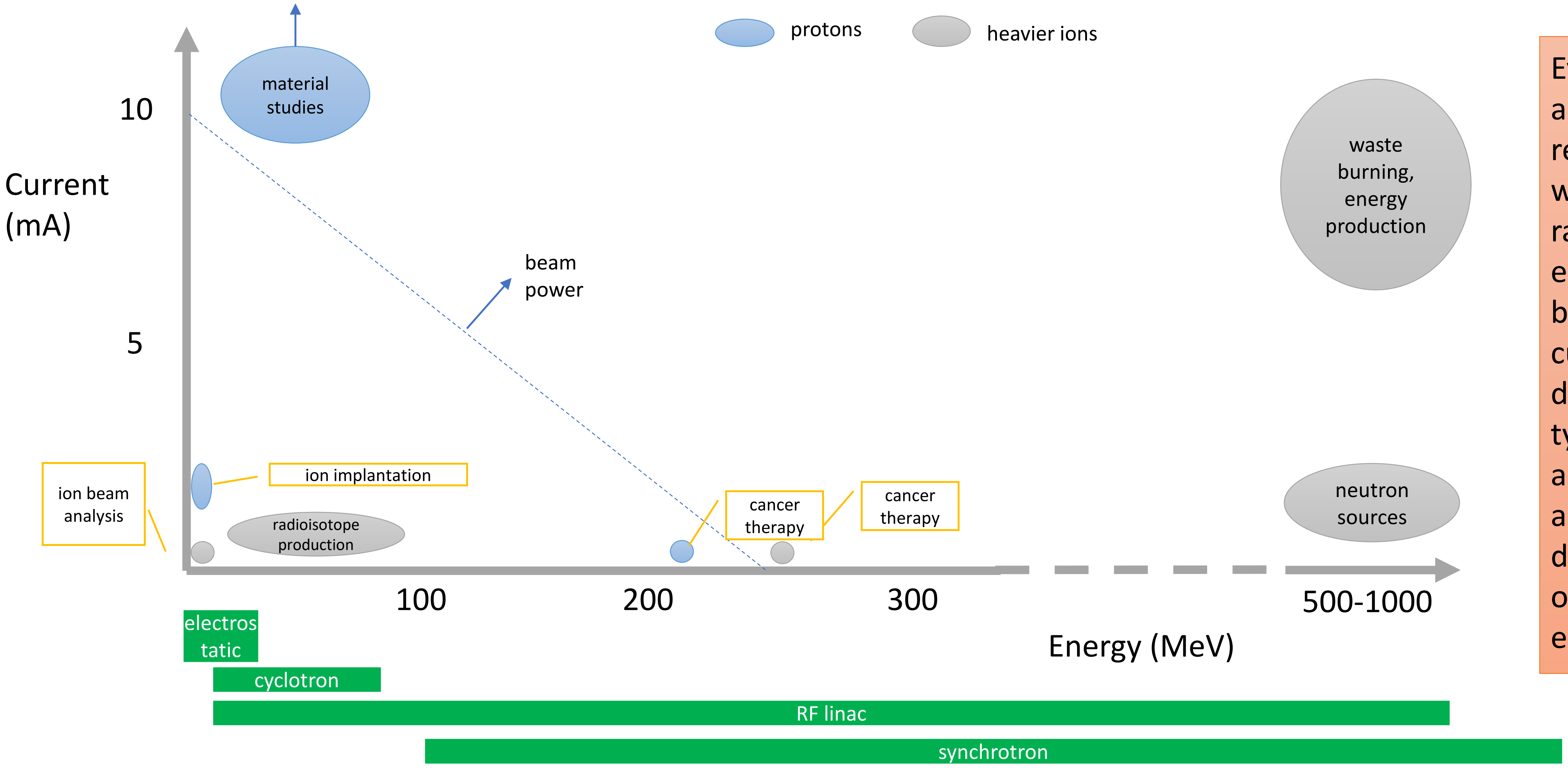


Inauguration 16th May 2017

CERN involved in design, production, tests of magnets and power supplies within CESSAMag project (5 M€ from EC)

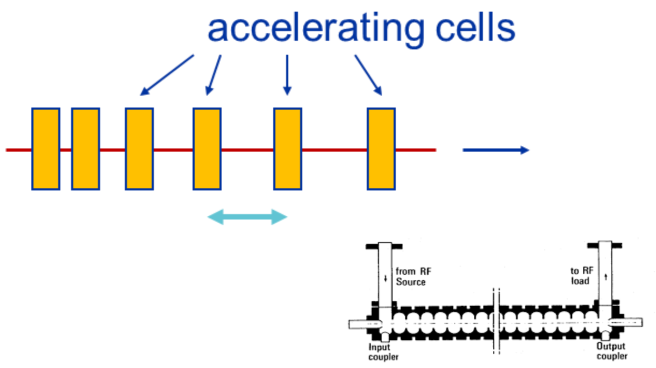
FP7 Contract 338602
In support of

The application map – protons and ions



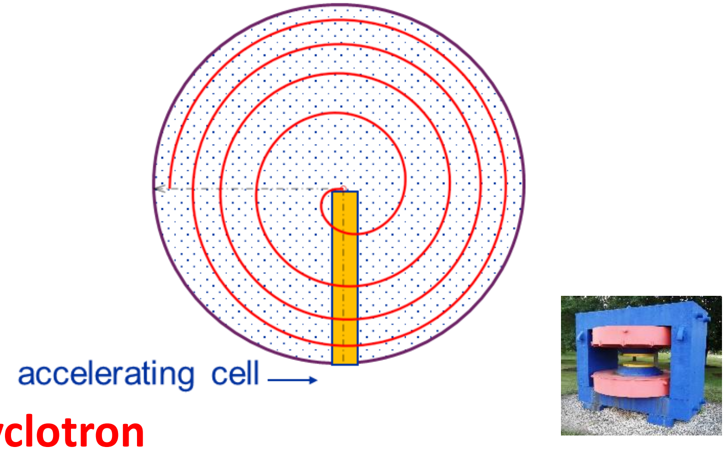
Every application requires a well defined range of energies and beam currents → a different type of accelerator and a different operational environment

Ion accelerators: linac, cyclotron, or synchrotron?



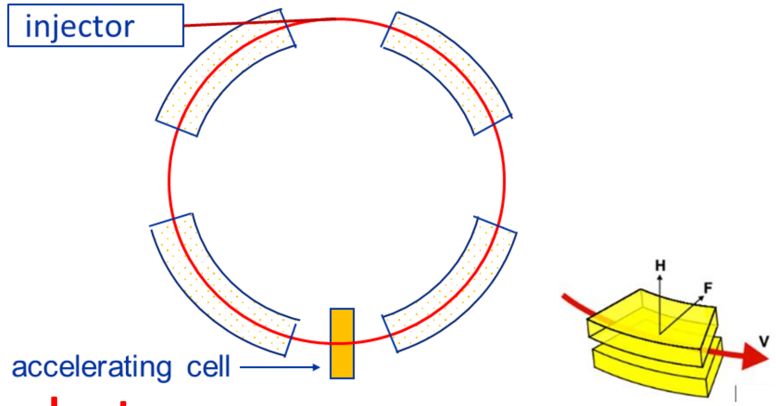
Linac

many cells, low efficiency, any beta, no magnet



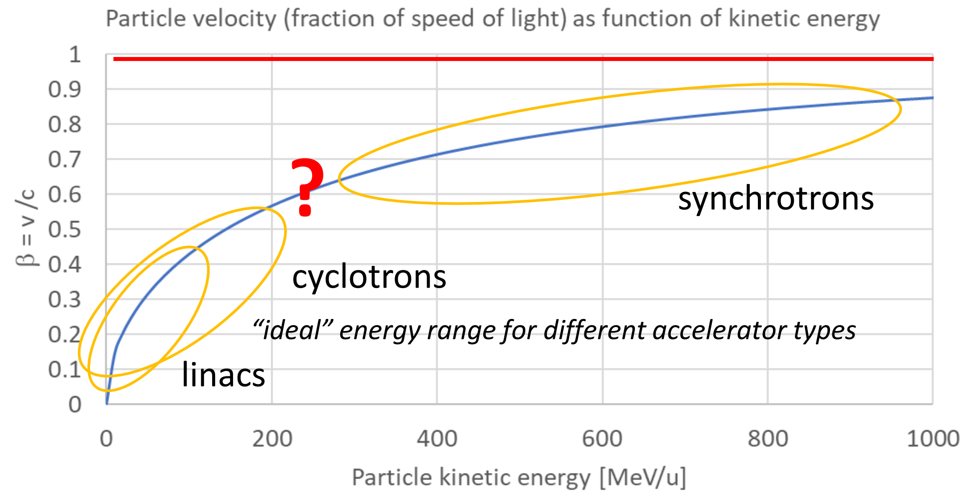
Cyclotron

one cell, high efficiency, low beta, large magnet



Synchrotron

one cell, high efficiency, high beta, small magnets



A particle accelerator is made of a sequence of accelerating cells, adapted to a particle velocity (beta=v/c)

$$\frac{v^2}{c^2} = 1 - \frac{1}{\sqrt{1 + T/m_0c^2}}$$

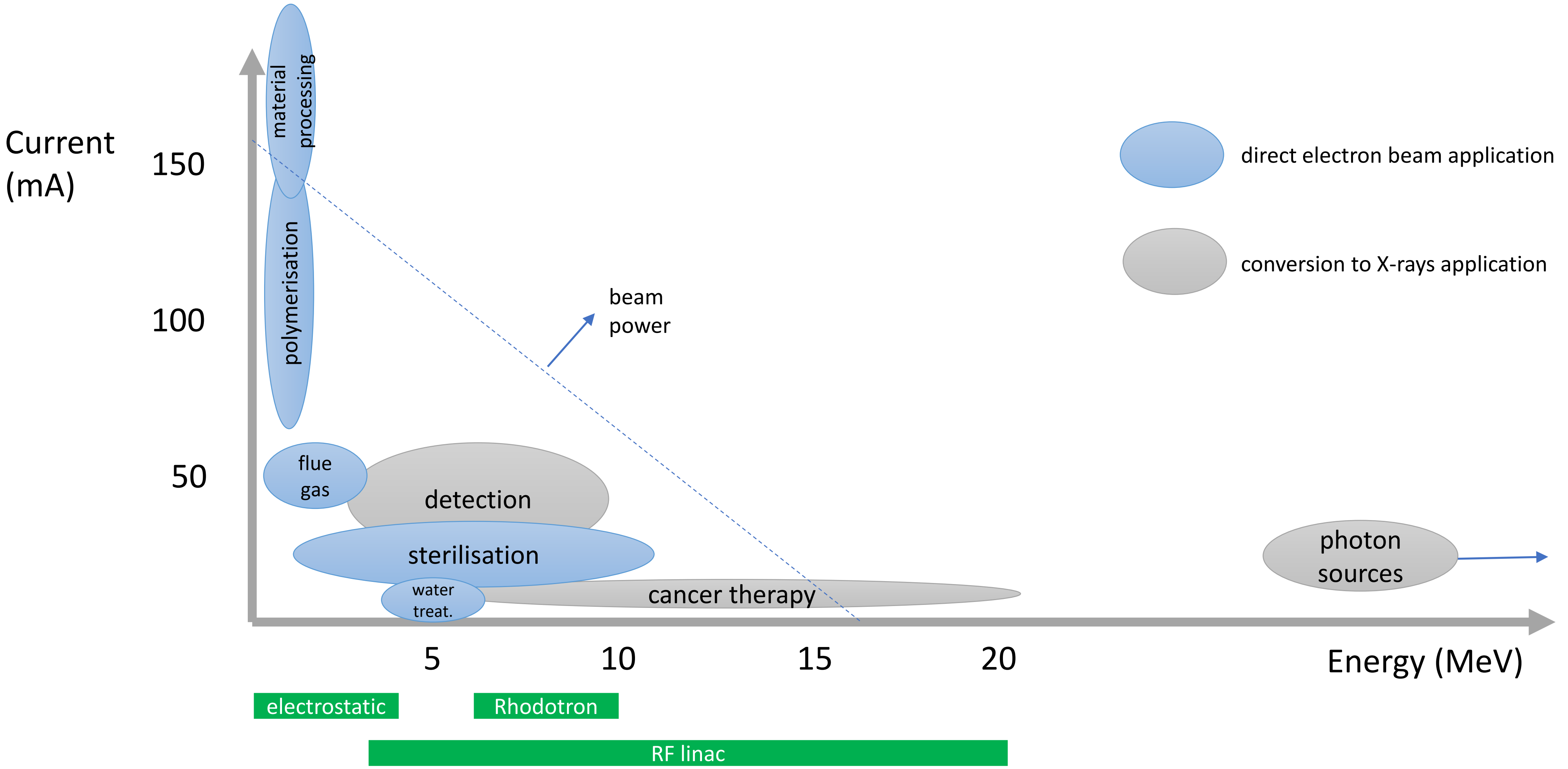
Linac, cyclotron: low β
Synchrotron: high β

To increase efficiency (accelerate many times through the same accelerating cell) magnets can be added to keep particles on a circular trajectory.

Bρ [Tm] = 3.33 p [GeV/c]

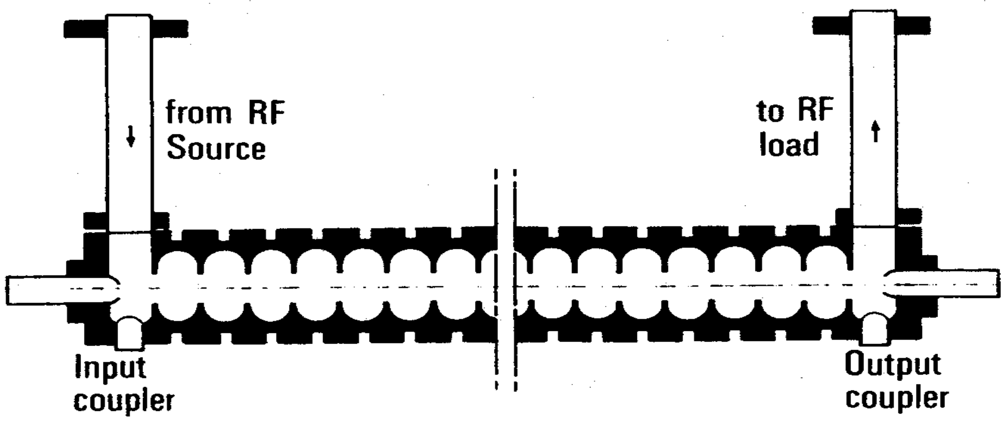
For a standard magnetic field (1-2 T), the accelerator diameter (2ρ) increases with the energy.

The application map - electrons

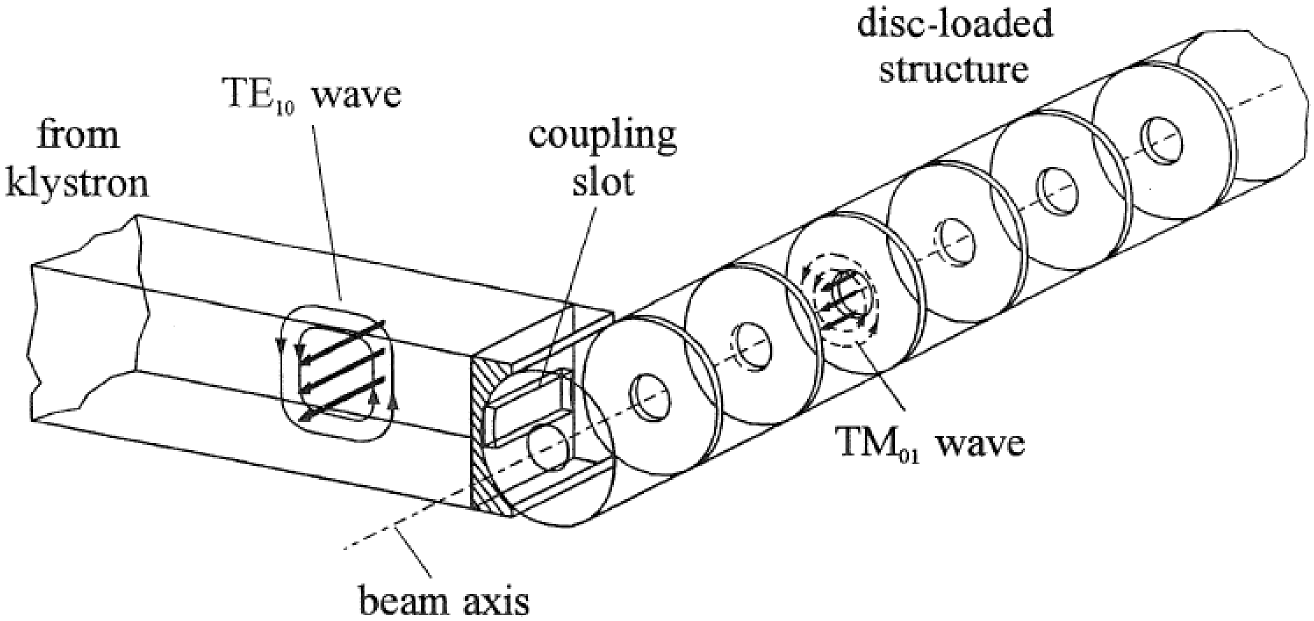


Electron accelerators: linacs

At the low energies of interest for applications, only linear accelerators are used for electrons.



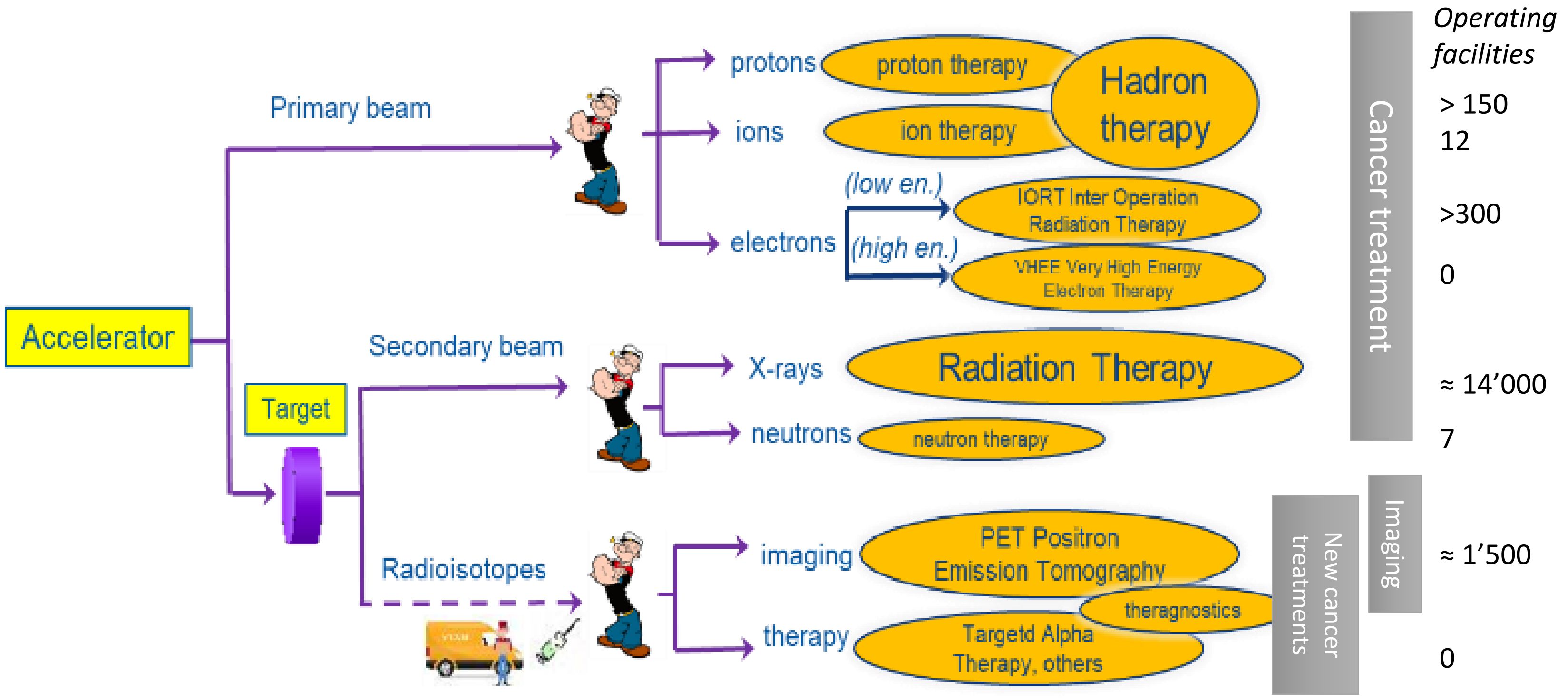
1. In an electron linac velocity is ~ constant.
2. the linac structure is made of a sequence of identical cells. The cells are grouped in cavities operating in travelling wave mode.



Pictures from K. Wille, The Physics of Particle Accelerators

Particle accelerators: a formidable tool for medicine

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.



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

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.**

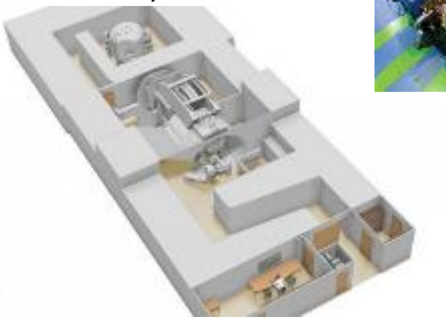
The role of the medical physicist is essential in planning the treatment and in guaranteeing the delivered dose.

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

Comparing accelerator designs

Ions deliver more energy to the tissues but need more energy to enter the body → factor 2.8 in accelerator diameter going from protons to carbon

courtesy IBA



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

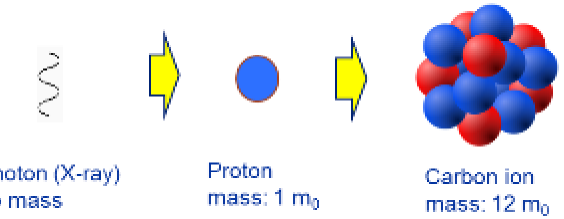
Cyclotron, protons
~500 m^2
~few 10 M€

Linac, X-rays
~50 m^2
~few M€

Commercially available

Specially designed and built

Space for translational R&D



Range: max. 300 mm (Bragg Peak)

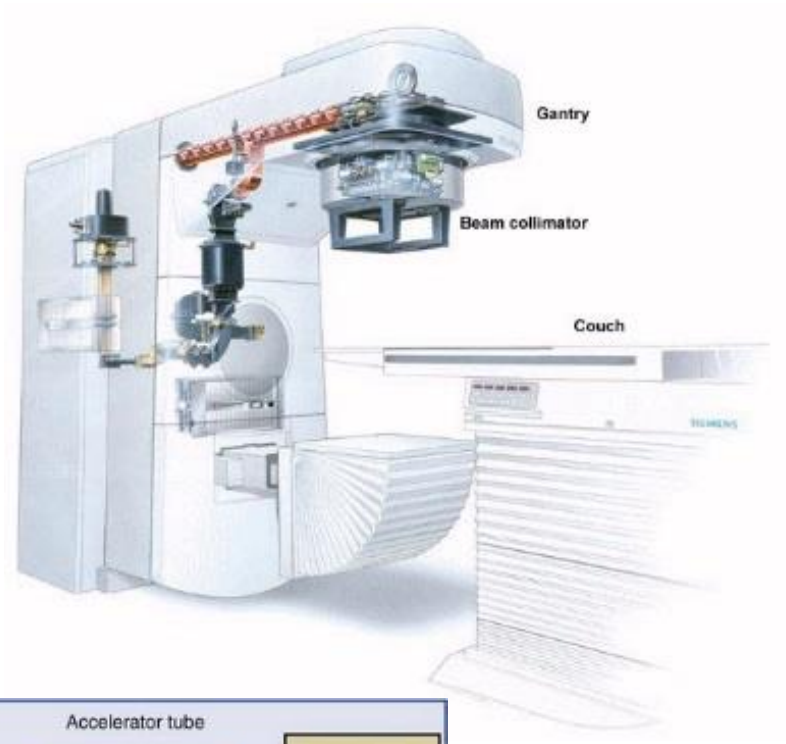
Protons: 220 MeV (max. Bρ = 2.4 Tm)

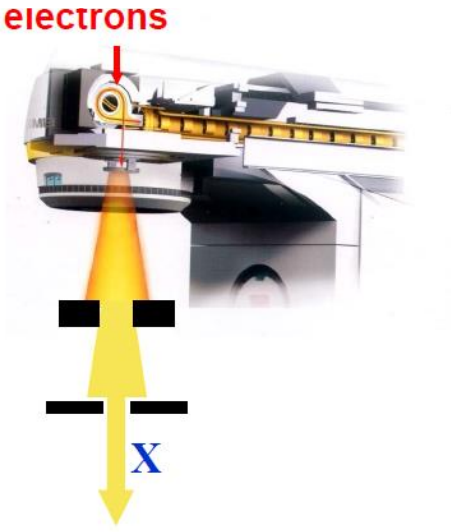
Helium: 220 MeV/u (max. Bρ = 4.5 Tm)

Carbon: 400 MeV/u (max. Bρ = 6.3 Tm)

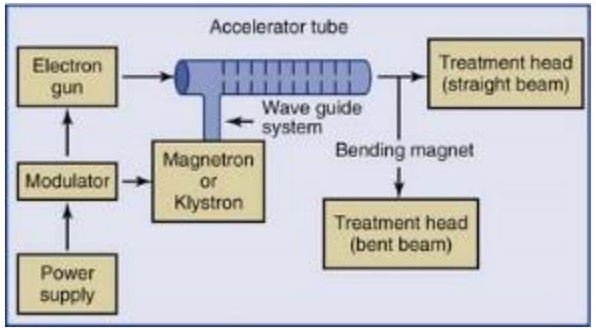
The most successful accelerator

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





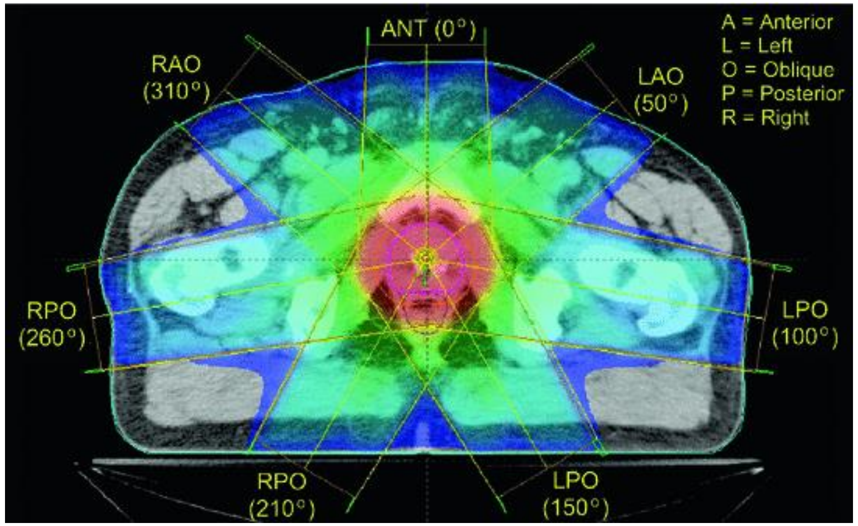
5 – 25 MeV e-beam
Tungsten target



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.



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).

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.

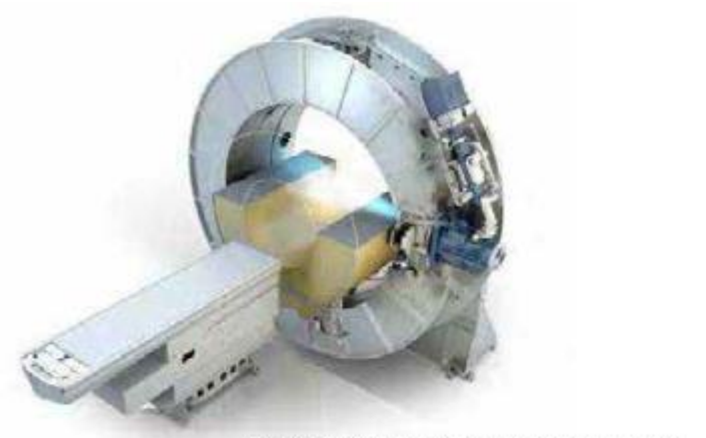


Fig. 3.4: The MR-linac, developed by Elekta, consists of a linear accelerator equipped with multi-leaf collimator technology for accurate radiotherapy dosage, combined with a high-field MR imaging system. The MR-linac is work in progress and is not available for sale or distribution (courtesy of Elekta).

The advantage of the Bragg peak

The Nobel Prize in Physics 1915

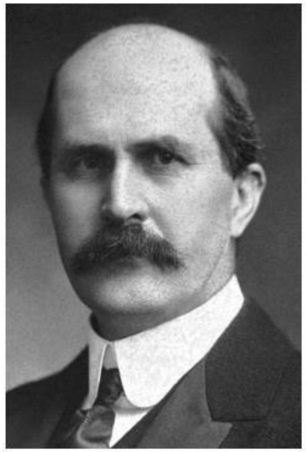


Photo from the Nobel Foundation archive.

Sir William Henry Bragg

Prize share: 1/2

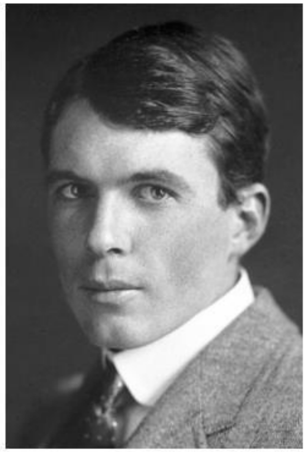


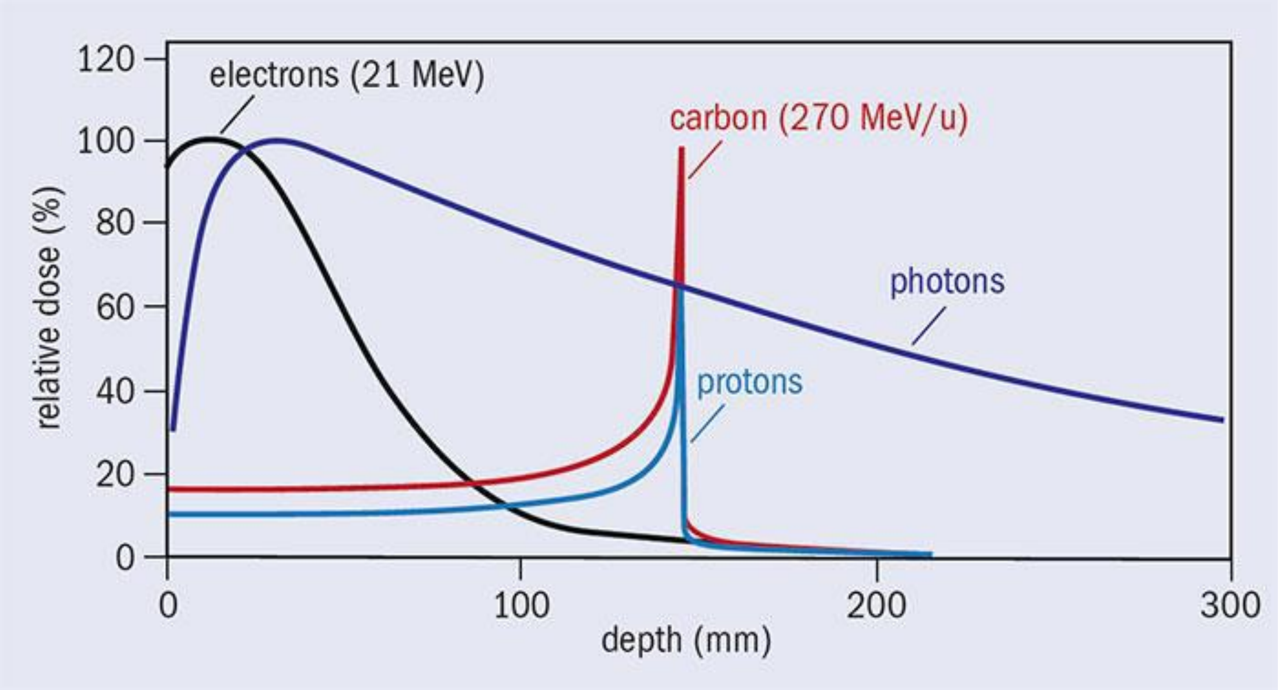
Photo from the Nobel Foundation archive.

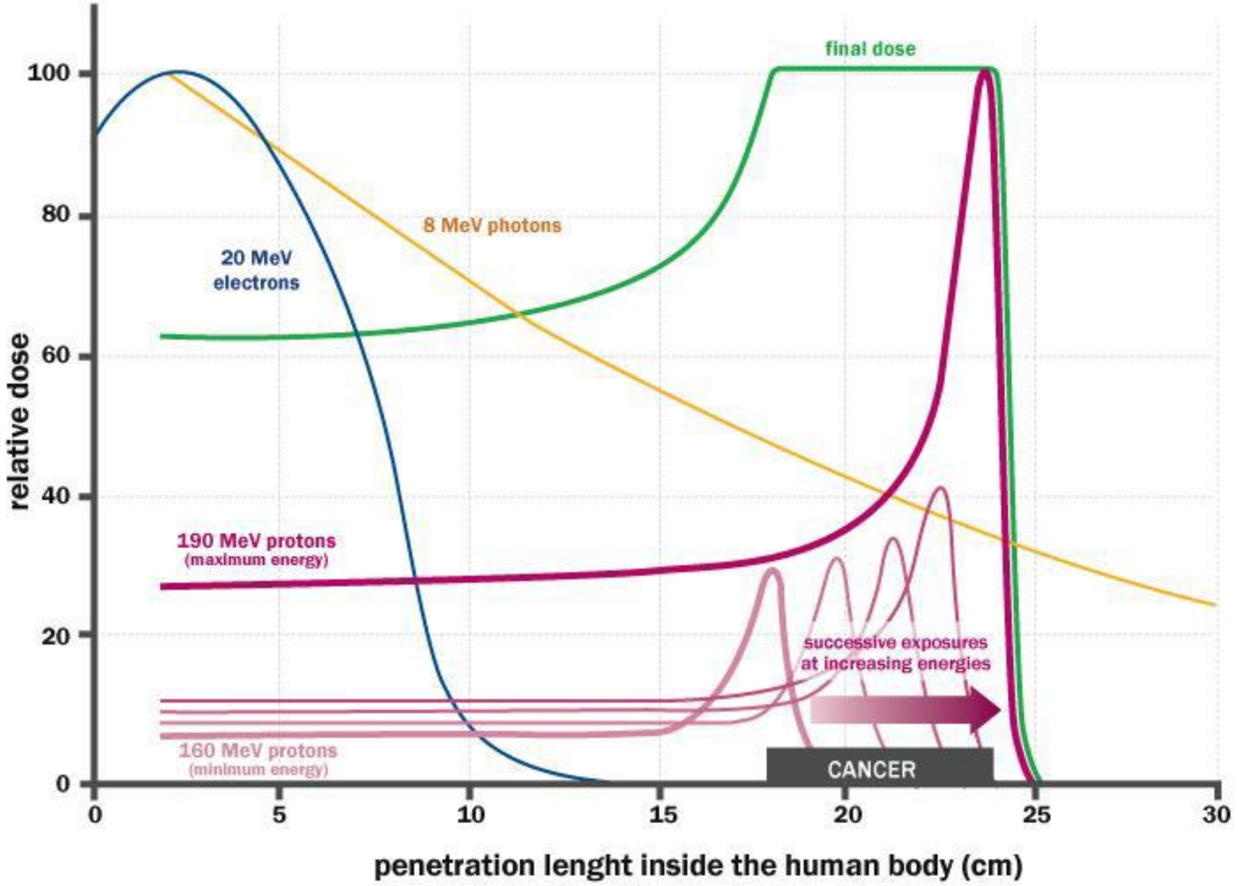
William Lawrence Bragg

Prize share: 1/2

The Nobel Prize in Physics 1915 was awarded jointly to Sir William Henry Bragg and William Lawrence Bragg "for their services in the analysis of crystal structure by means of X-rays."

Fpr Proton and other ions the peak of energy loss occurs jusdt before the particle is stopped.





Different from X-rays or electrons , protons and ions deposit their energuat a given depth inside tissue, minimmisinbg the dose tohealthy tissue/organs organs near surrounding the tumour

Required energies:

Protons: 60- 250 MeV

Carbons : 120- 440 MeV/u

Beam energy accuracy:_ 0.25 MeV/u

Protons and Carbons: ca. 10^{10} pe pulse.

Hadron-therapy Centres

2017: 60 Proton Centres
10 Carbon Ion Centres

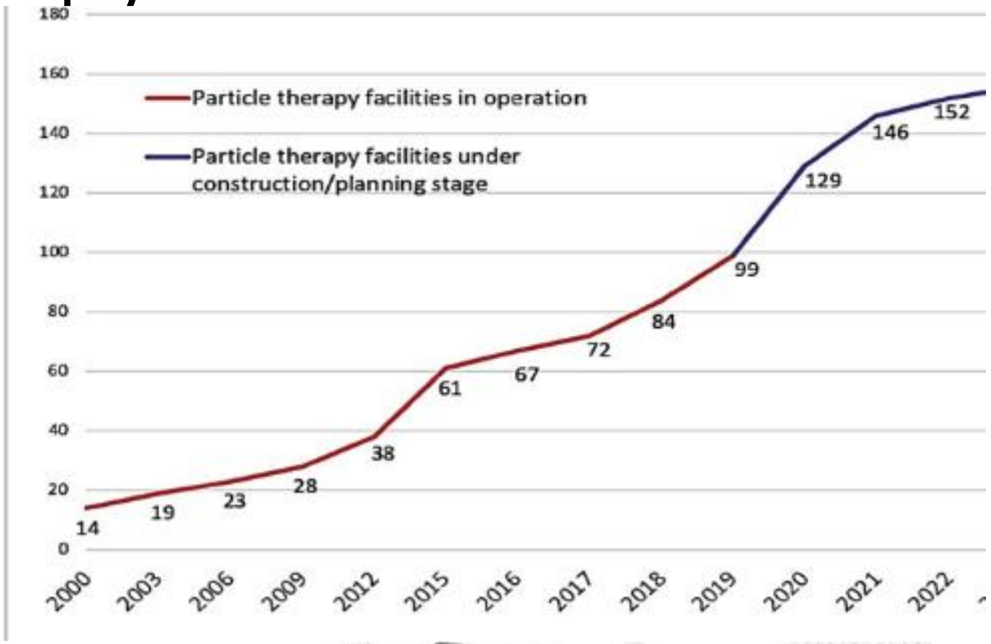
Durante M, Orecchia R, Loeffler JS, 2017

The rise of proton and ion therapy

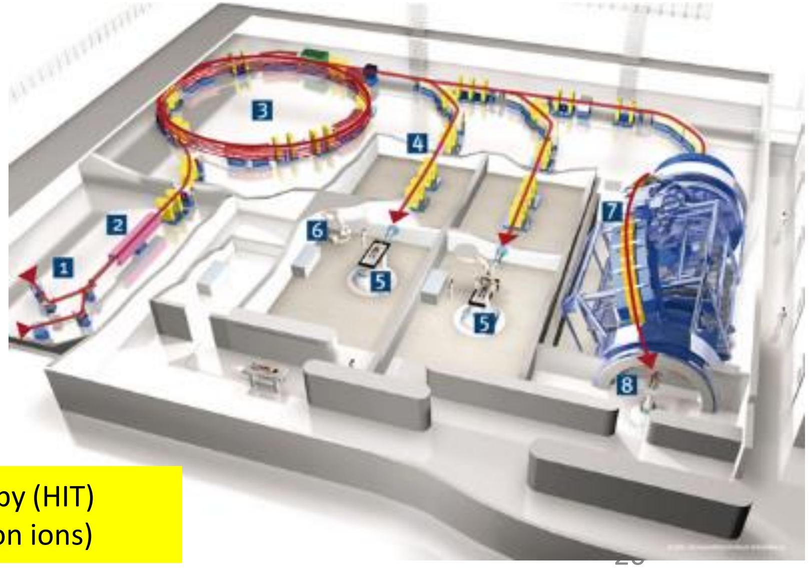
Hadrons = protons and heavier atomic nuclei (ions)

- Proposed 1946, first experimental treatment Berkeley 1954.
- First hospital-based proton treatment facility in 1993 (Loma Linda, US).
- First treatment facility with carbon ions in 1994 (HIMAC, Japan).
- Treatment in Europe at physics facilities from end of '90s.
- First dedicated European facility for proton-carbon ions in 2009 (HIT).
- From 2006, commercial proton therapy accelerators (mostly cyclotrons) come to market.
- In 2022, 6 competing vendors for protons, 1 for carbon ions. A total of 152 centres worldwide.

A success story, but … many ongoing discussions on effectiveness, costs and benefits.

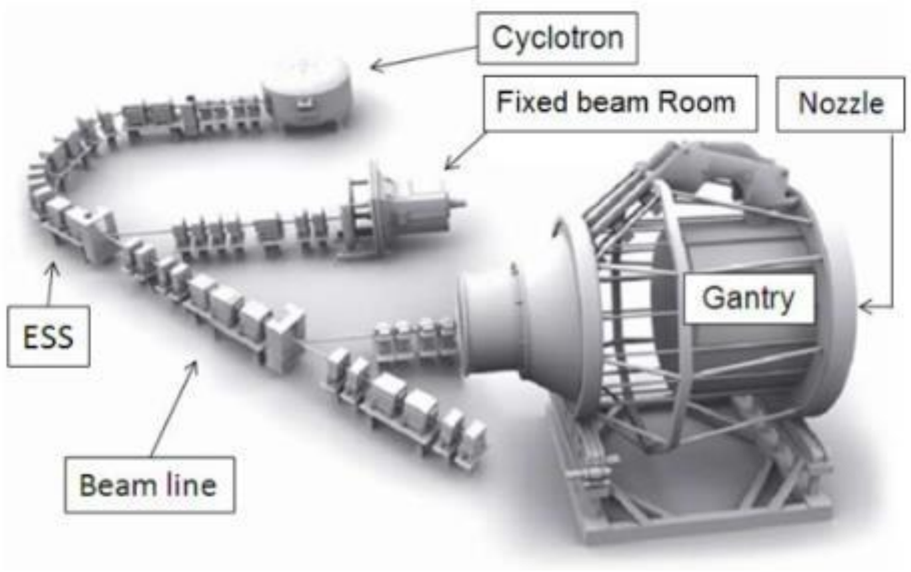


ptcog.com



The Heidelberg Ion Therapy (HIT) facility (protons and carbon ions)

Proton therapy accelerators: cyclotrons



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

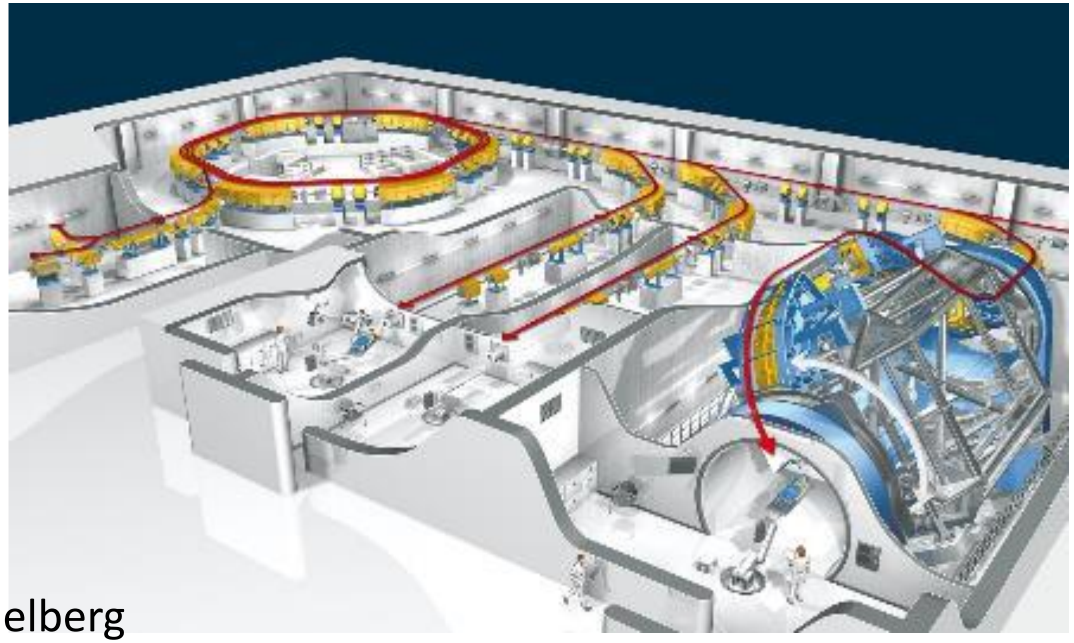
Critical issues with cyclotrons:

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. Beam loss indices activation requiring large shielding

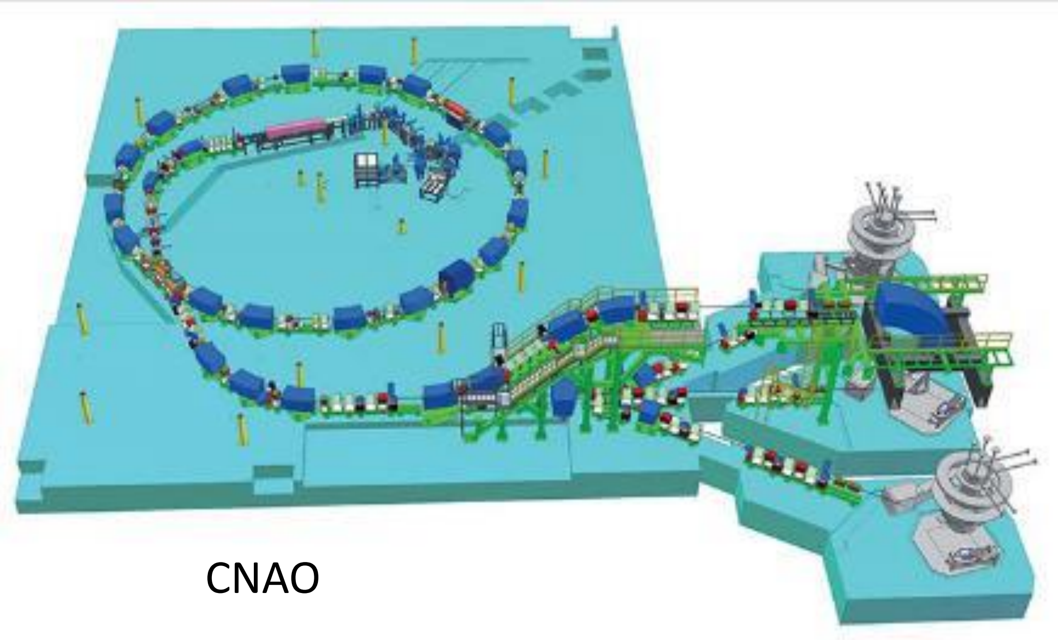
ProteusOne and ProteusPlus turn-key proton therapy solutions from IBA (Belgium)

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

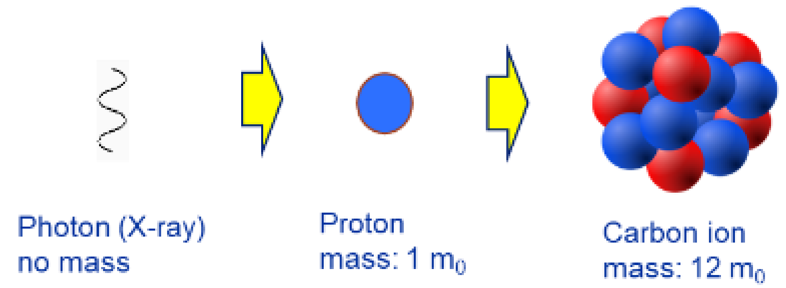


CNAO

Ion therapy: from photons to protons to ions

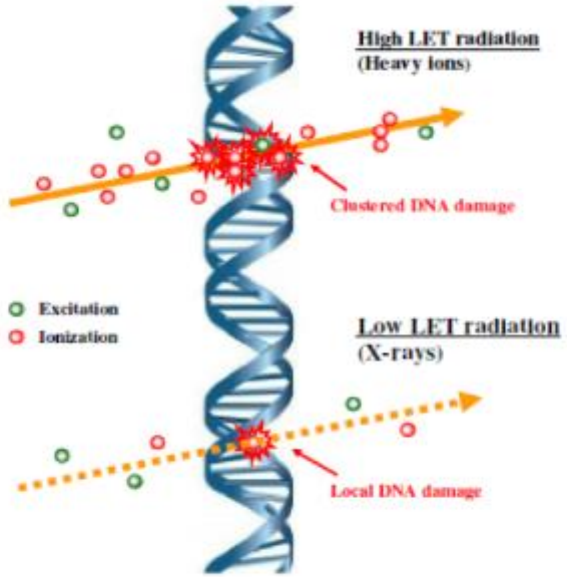
High LET radiation (ions) generates denser ionisations inducing clustered DNA lesions difficult for the cell to repair.

→ **RBE(carbon)=2.0-2.4**



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

- **Higher LET and RBE** generate non-reparable double-strand DNA breakings that are effective on **hypoxic radioresistant tumours**.
- Energy deposition is more precise, with lower straggling and scattering
- Emerging opportunities from combination with immunotherapy to treat diffused cancers and metastasis.



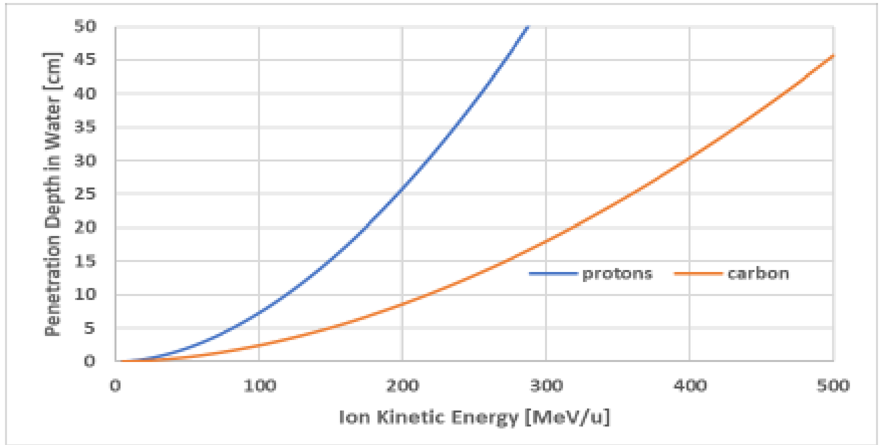
Helm A, Ebner DK, Tinganelli W, Simoniello P, Bisio A, Marchesano V, et al. Combining heavy-ion therapy with immunotherapy: an update on recent developments. Int J Part Ther. (2018) 5:84–93.
Durante M, Formenti S. Harnessing radiation to improve immunotherapy: better with particles? Br J Radiol. (2019) 192:20190224.

- 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 an early stage of its development !

Ion therapy: accelerator challenges

Particle accelerators for heavy ions are large and complex:

1. The high energy deposition means that to reach deep seated tumours ions must be accelerated to **higher energies** than protons: ion energy loss goes as (charge of the incident particle)^2. → around 440 MeV/u for carbon, compared to 240 MeV for protons.



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

Magnetic rigidity Bρ for carbon ions at full energy is **2.76 times higher** than protons.

→ For cyclotrons and synchrotrons, accelerator diameter scales with rigidity

2. The required energies fall into a **transition range between accelerator technologies**: cyclotrons and linacs are better at low energies, synchrotrons at high energies. In the intermediate region, there is not an **ideal accelerator** configuration → need to compare options, characterised by **complexity, cost, and R&D requirements**.

For a given magnet field, in an ion synchrotron or cyclotron 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.

New technologies for ion therapy accelerators

Ions deliver more energy to the tissues but need more energy to enter the body → the required diameter of the accelerator increases with energy, accelerator dimensions increase by a factor 2.8 going 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)

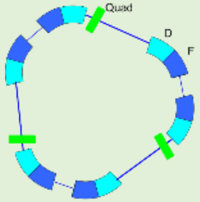
- CNAO and MedAustron based on a design started at CERN in 1996. 1st patient at CNAO in 2011.
- HIT and MIT based on a design started at GSI (Germany) in 1998 . 1st patient at HIT in 2009.

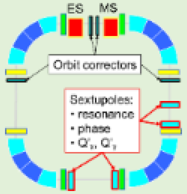
Four avenues to future ion therapy: the NIMMS Work Packages

Curved superconducting magnets for synchrotrons and gantries

Superconductivity to reach higher magnetic field and small dimensions

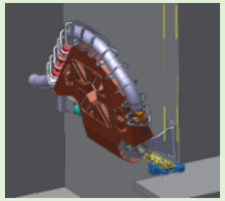
Small synchrotrons for particle therapy

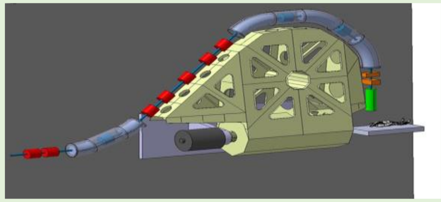




Reduced dimensions with improved performance (injection, extraction)

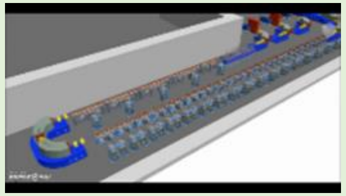
Superconducting gantries

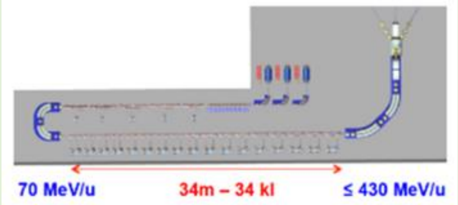




Precise beam delivery on multiple angles

High-frequency ion linacs





Compact bent layout

HITRIplus EU project

IFAST EU project

EU supporting initiatives

Superconducting magnets for synchrotrons and gantries

The main avenue to reducing the dimensions of a magnetic system is **superconductivity**.
But medical accelerator magnets have specific challenges: ramped field, curved shape, integrated focusing

4 projects launched for the construction of 5 **demonstrator magnets** (short length, pre-prototypes) supported by 3 collaborations:

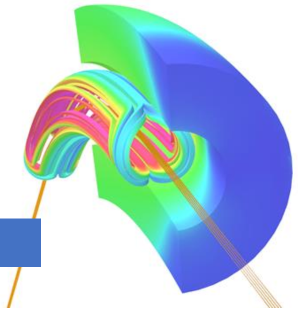
1. **Cos-theta** (2 demonstrators, thermal and curved) for **gantry**
   4 T, 0.4 T/s, 80 mm ø, r=1.65 m (430 MeV/u)
   collaboration INFN-CERN-CNAO-MedAustron

2. **Canted Cosine Theta (CCT)** curved demonstrator
   4 T, 0.4 T/s, 80 mm ø, r=1.65 m (430 MeV/u), 30^0
   EU Project HITRIplus (2021-25)

3. **Combined-functions CCT** straight demonstrator
   4 T + 5 T/m quadrupole, 80 mm ø, L=0.73 m

4. **Combined-functions HTS CCT** straight demonstrator
   4 T @ 10 K, ReBCO tapes, 80 mm ø, L=1 m
   EU Project I.FAST (2021-25)

Timeline: mid-2025 for experimental results!

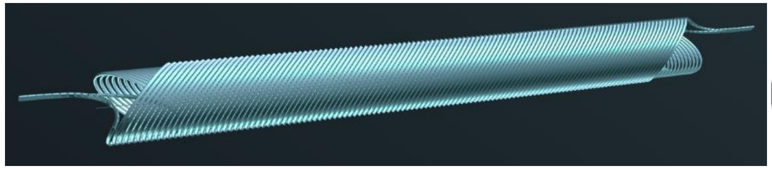
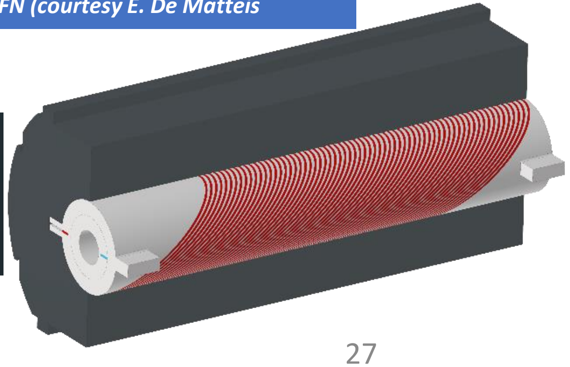
CERN (courtesy M. Karppinen)

Curved Canted Cosine Theta

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

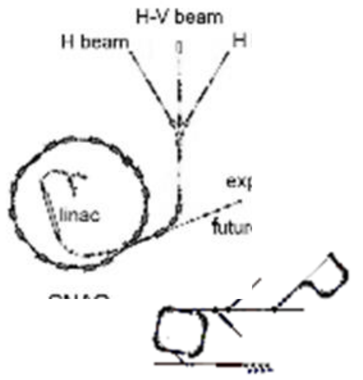
INFN (courtesy E. De Matteis)

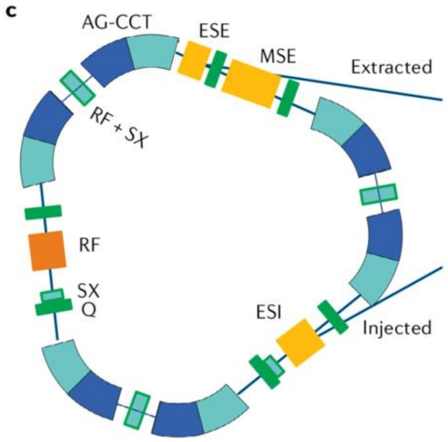
HTS=High Temperature Superconductor

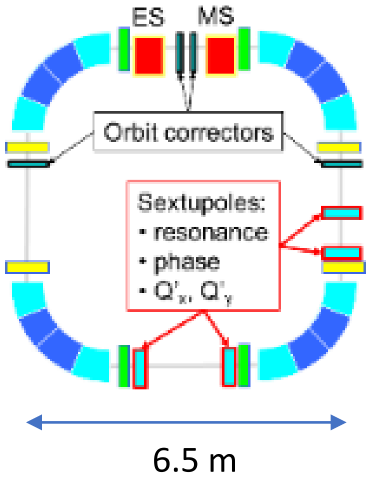



The compact superconducting synchrotron

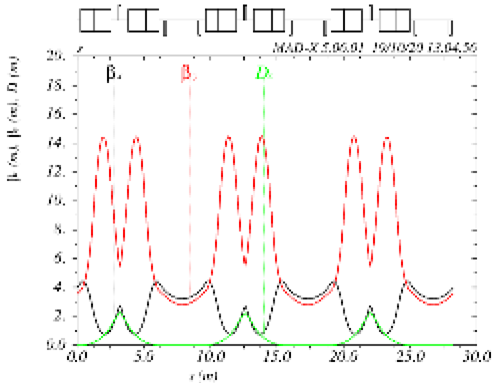
Considerable gain in dimensions thanks to superconductivity







Lattice with 60^0 magnets

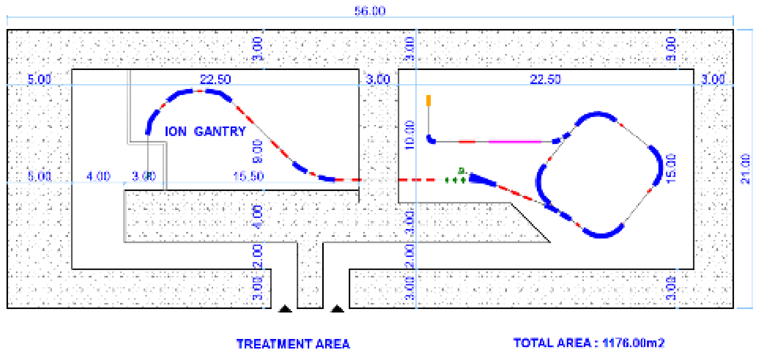


Additional features

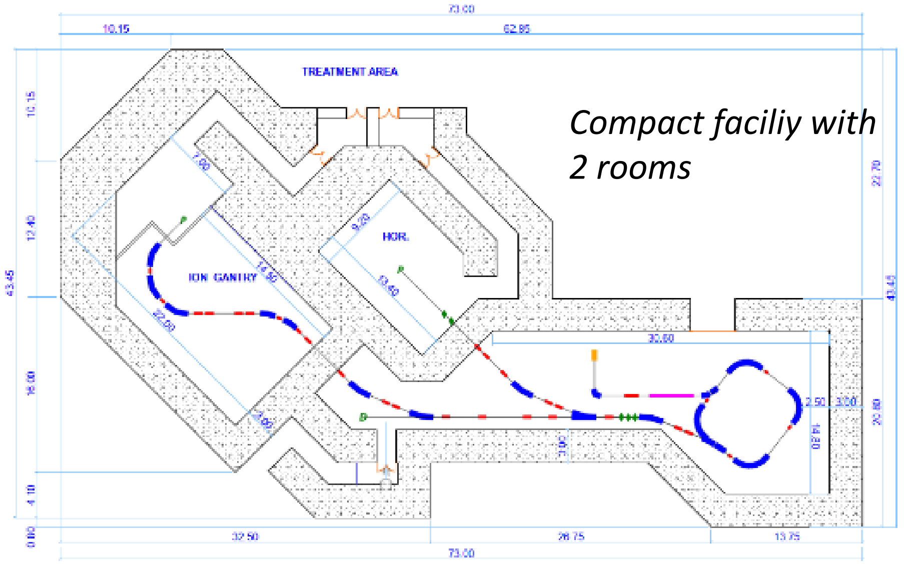
- High intensity (2 x 10^{10} C ions per pulse
- Slow and FLASH extraction
- Multiple ion operation

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

Alternative synchrotron layouts



Compact faciliy with 2 rooms



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

Superconducting magnets for synchrotrons and gantries

The main avenue to reducing the dimensions of a magnetic system is **superconductivity**.
But medical accelerator magnets have specific challenges: ramped field, curved shape, integrated focusing

4 projects launched for the construction of 5 **demonstrator magnets** (short length, pre-prototypes) supported by 3 collaborations:

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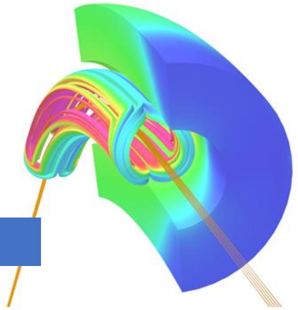

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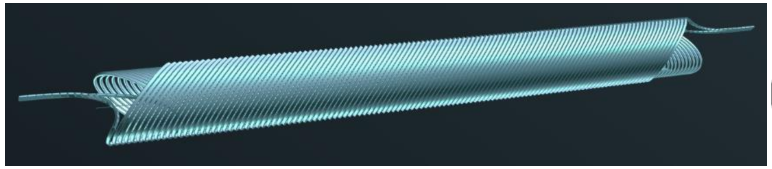
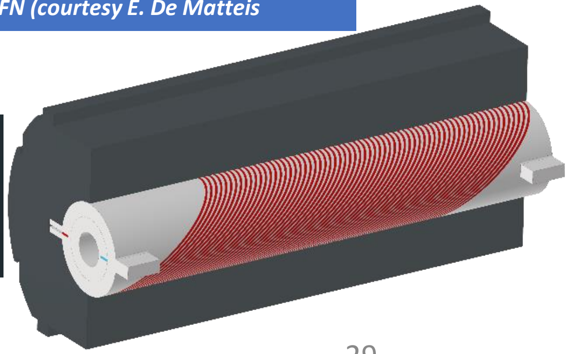
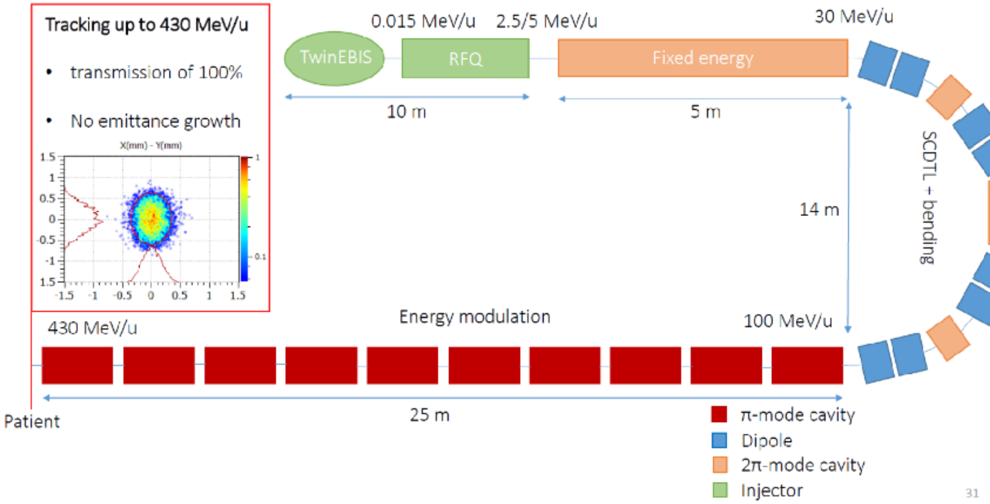




The carbon linac

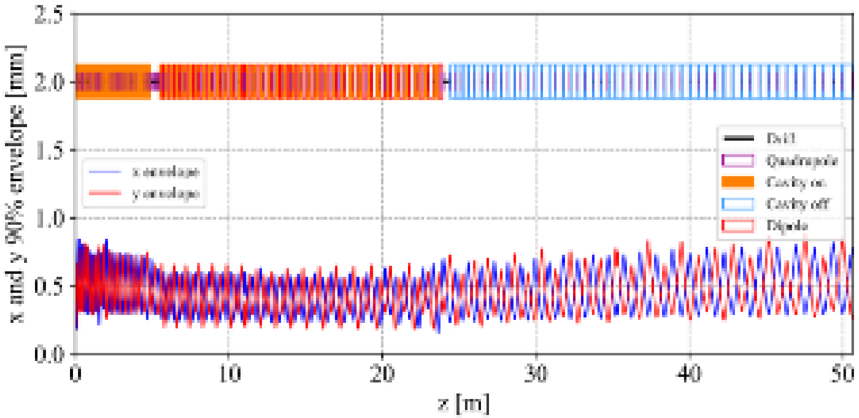
A. Lombardi (CERN)

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



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

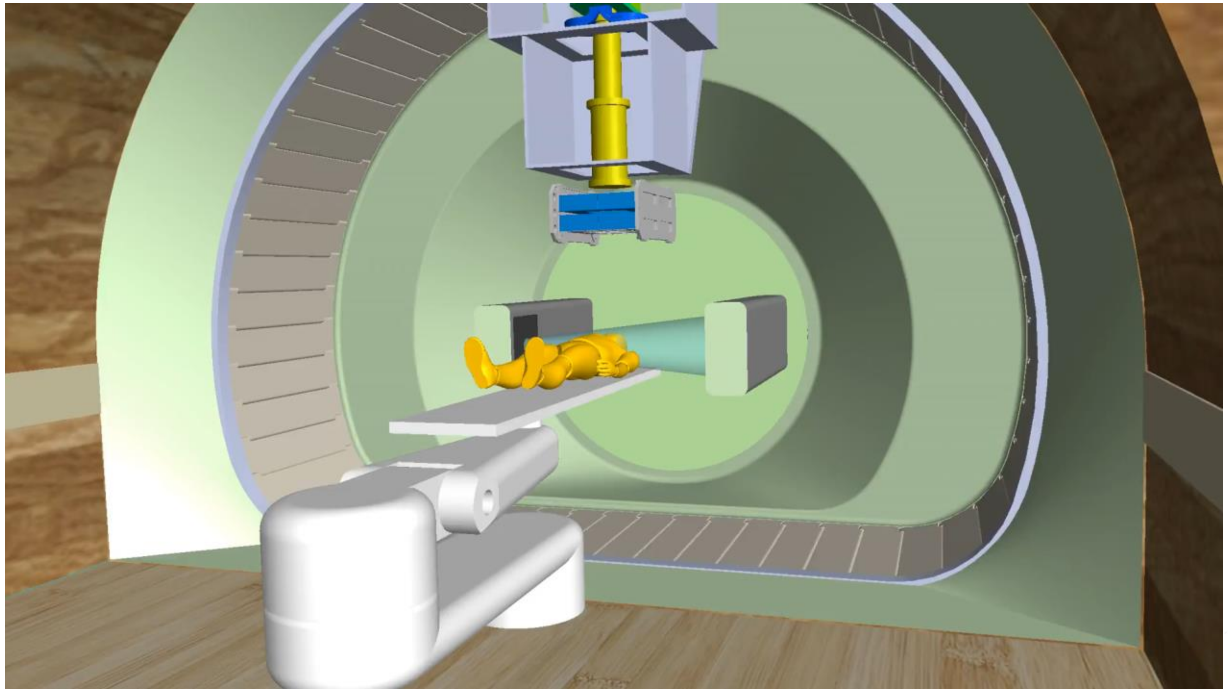


- Innovative «folded» version to save space
- Particle tracking completed
- Prototype EBIS source under commissioning
- RFQ designed, agreement with CIEMAT for construction in Spain
- Test stand being prepared at CERN for test of the injector using a He-source provided by a donor, in collaboration with Sarajevo Univ. and ITRE (Slovenia)

Gantries: superconducting ion gantry, gatoroid

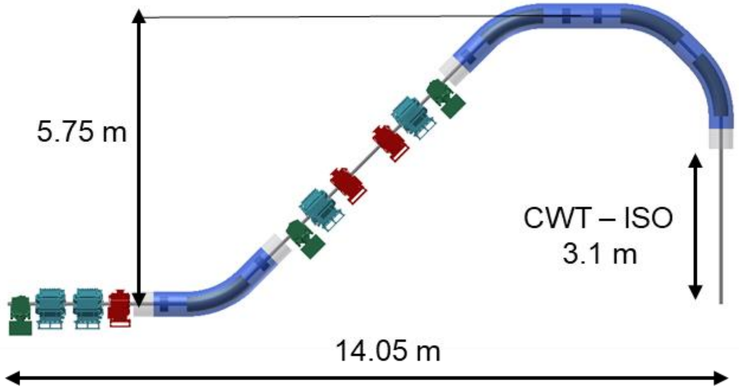
Development of a rotating SC gantry for Carbon ions:

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



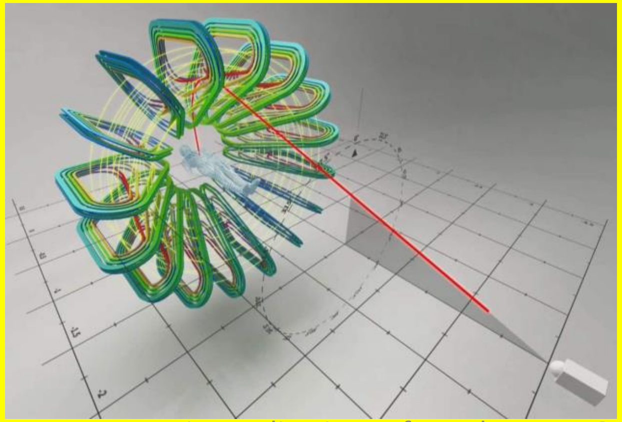
Courtesy L. Piacentini (CERN, RTU), E. Felcini, M. Pullia (CNAO)

4 magnets 45^0, 360^0 rotation



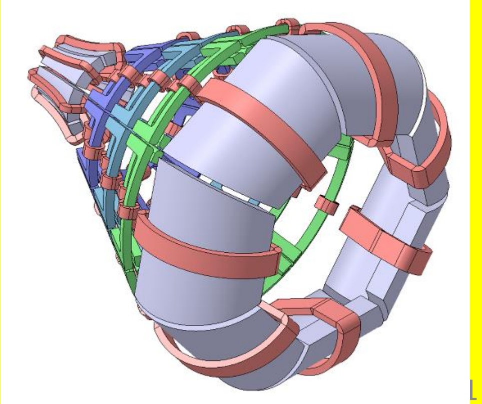
Development of a toroidal gantry (Gatoroid) at CERN.

- Explored proton and carbon versions, now concentrates on a non-superconducting version for electrons, to be tested with low-energy protons.



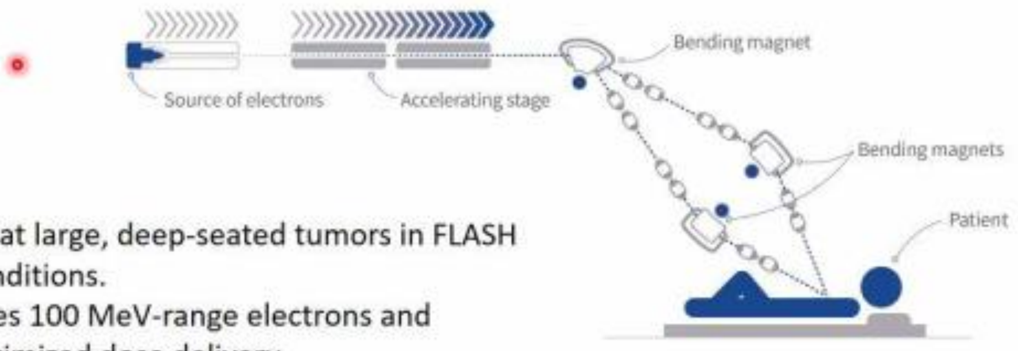
VHEE version of the Gatoroid gantry, based on normal conducting magnets.
Inherent FLASH capability with multidirectional treatment.
Being designed at CERN.

(image courtesy T. Lehtinen, L. Bottura)



FLASH with electrons – a new avenue to radiation therapy

CLIC technology for a FLASH facility being designed in collaboration with CHUV



Treat large, deep-seated tumors in FLASH conditions.
Uses 100 MeV-range electrons and optimized dose delivery.
Compact to fit on a typical hospital campus.

Construction of the prototype

Installation 2023

First patient 2024-25

Press Release — Lausanne and Geneva, September 15th 2020

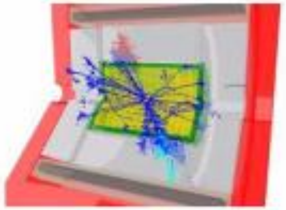
Lausanne University Hospital and CERN collaborate together on a pioneering new cancer radiotherapy facility

Lausanne University Hospital (CHUV) and CERN, in Switzerland, are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment. The facility will capitalise on CERN breakthrough accelerator technology applied to a technique called FLASH radiotherapy, which delivers high-energy electrons to treat tumours. The result is a cutting-edge form of cancer treatment, highly targeted and capable of reaching deep into the patient's body, with less side-effects. The first phase of the study comes to a conclusion this September.

In radiotherapy, the FLASH effect appears when a high dose of radiation is administered almost instantaneously – in milliseconds instead of minutes. In this case, the tumour tissue is damaged in the same manner as with conventional radiotherapy, whereas the healthy tissue appears to be less affected, meaning that less side effects are expected.

The remarkable connection between CLIC and FLASH

Both need:
- Very intense electron beams
  - CLIC – to provide luminosity for experiments
  - FLASH – to provide dose fast for biological FLASH effect
- Very precisely controlled electron beams
  - CLIC – to reduce the power consumption of the facility
  - FLASH – to provide reliable treatment in a clinical setting
- High accelerating gradient
  - CLIC – fit facility in the Geneva area and limit cost
  - FLASH – fit facility on a typical hospital campus and limit cost of treatment

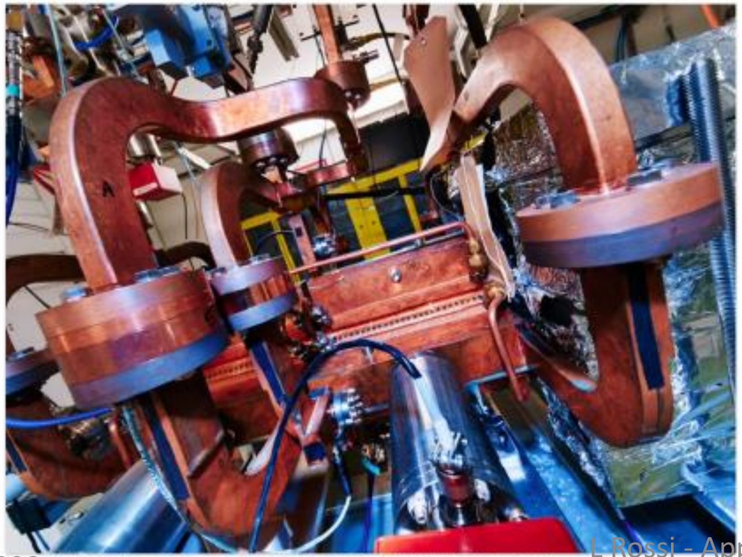


FLASH radiotherapy: CDR in 2020

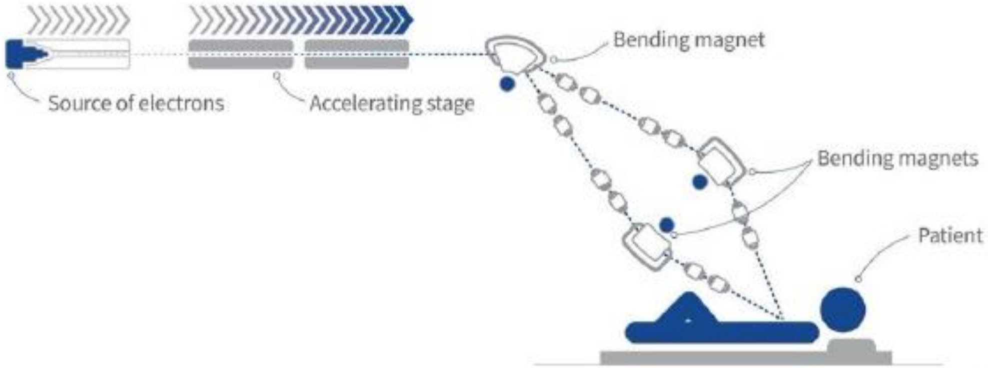
CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020



... of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)



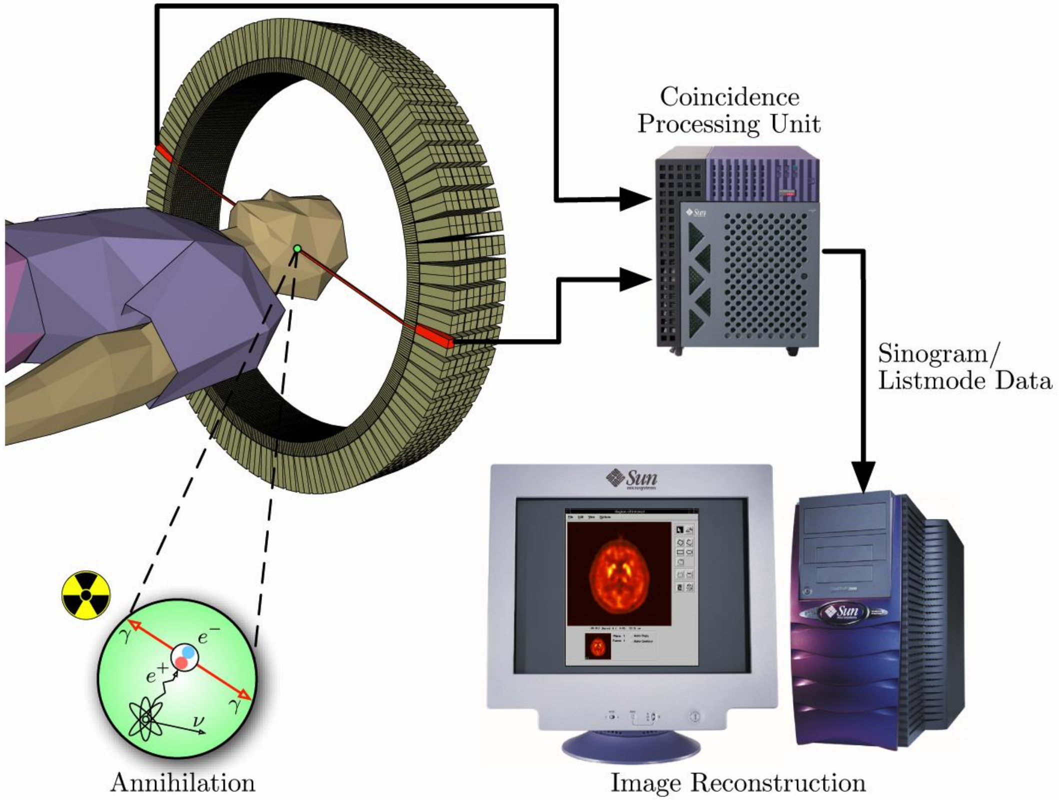
An intense beam of electrons is produced in a photoinjector, accelerated to around 100 MeV and then is expanded, shaped and guided to the patient.

The design of this facility is the result of an intense dialogue between groups at CHUV and CERN.

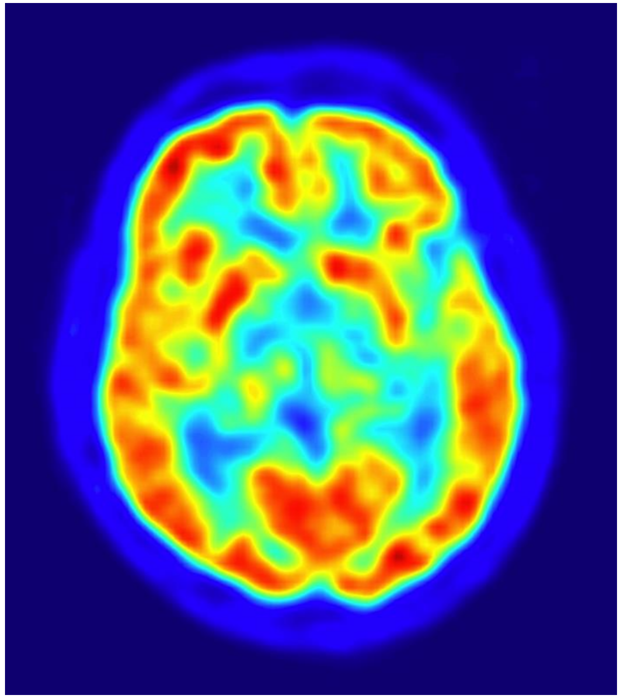
The solution comes from the conceptual design of a unique apparatus based on the CLIC (Compact Linear Collider) accelerator technology, which will accelerate electrons to treat tumours up to 15 to 20 cm in depth.

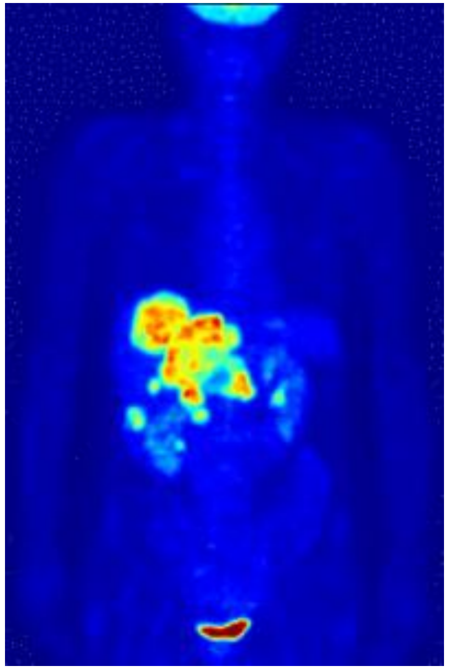
Radioisotope production

- Accelerators (compact cyclotrons or linacs) are used to produce radio-isotopes for medical imaging.
- 7-11MeV protons for short-lived isotopes for imaging
- 70-100MeV or higher for longer lived isotopes



- Positron emission tomography (PET) uses Fluorine-18, half life of ~110 min





- Fluorodeoxyglucose or FDG carries the F18 to areas of high metabolic activity
- 90% of PET scans are in clinical oncology

Radiopharmaceuticals

p, d, 3He, 4He
beams

Isotopes used for PET, SPECT and Brachytherapy etc…

TABLE 2.1. THE RADIOISOTOPES THAT HAVE BEEN USED AS TRACERS IN THE PHYSICAL AND BIOLOGICAL SCIENCES

Isotope	Isotope	Isotope
Actinium-225	**Fluorine-18**	**Oxygen-15**
Arsenic-73	**Gallium-67**	**Palladium-103**
Arsenic-74	**Germanium-68**	**Sodium-22**
Astatine-211	Indium-110	**Strontium-82**
Beryllium-7	**Indium-111**	Technetium-94m
Bismuth-213	Indium-114m	**Thallium-201**
Bromine-75	Iodine-120g	Tungsten-178
Bromine-76	Iodine-121	Vanadium-48
Bromine-77	**Iodine-123**	Xenon-122
Cadmium-109	**Iodine-124**	Xenon-127
Carbon-11	Iron-52	**Yttrium-86**
Chlorine-34m	Iron-55	Yttrium-88
Cobalt-55	**Krypton-81m**	Zinc-62
Cobalt-57	Lead-201	Zinc-63
Copper-61	Lead-203	Zirconium-89
Copper-64	Mercury-195m	
Copper-67	**Nitrogen-13**	

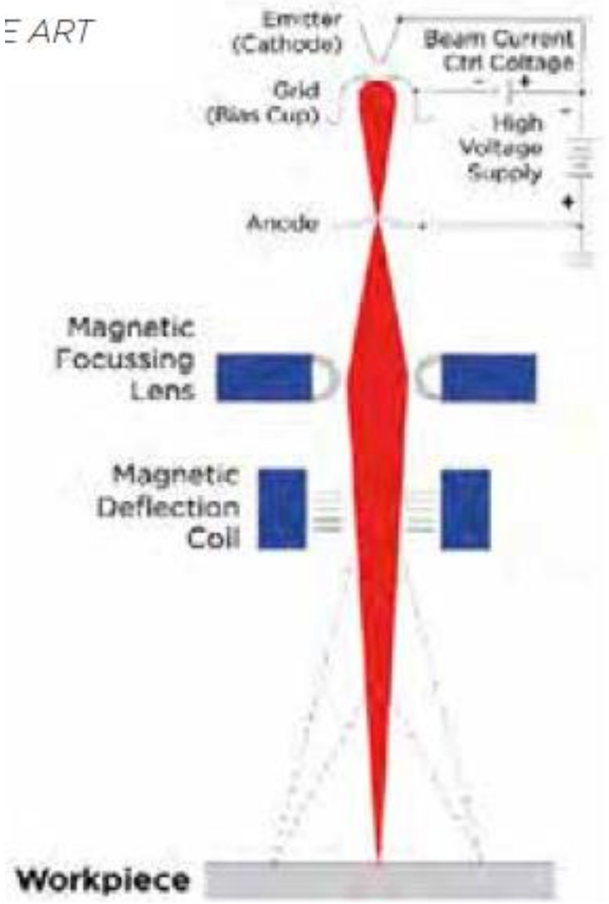
Very low energy electrons

	Energy	Applications
Very low energy electrons	<350 keV	detection, welding, 3D-sintering, sterilisation, seed and grain treatment
Low-energy electrons	<10 MeV	polymer modification, sterilisation, treatment of flue-gas, wastewater, sewage

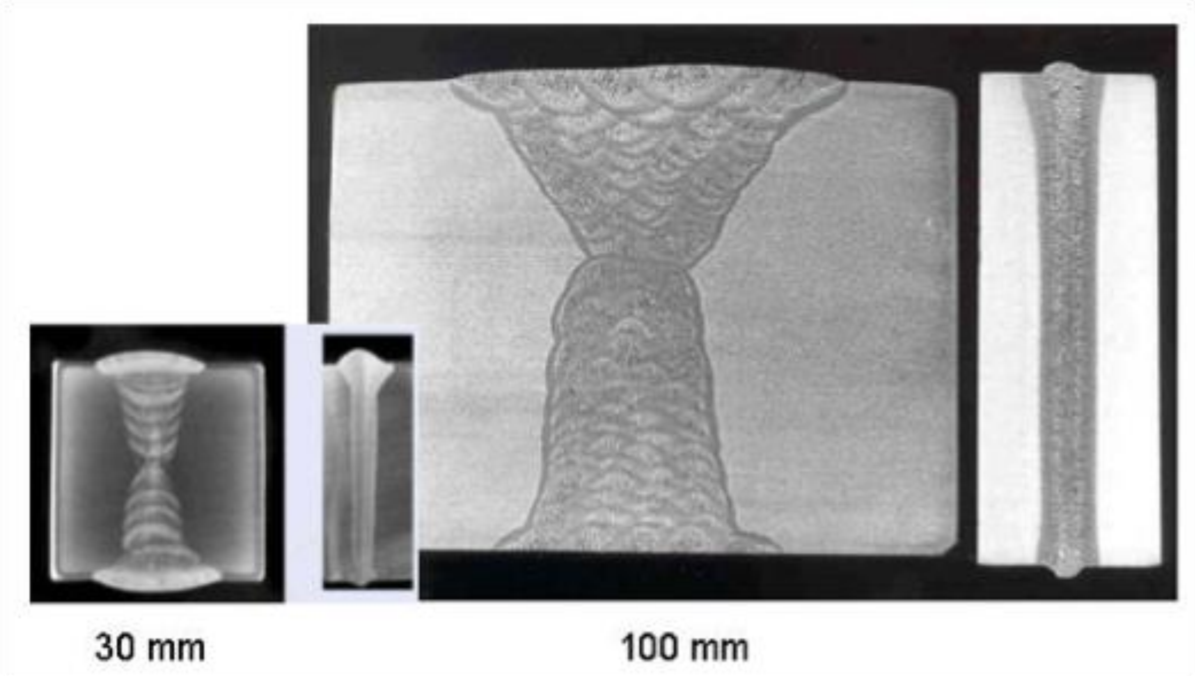
- Non-thermal: breaking molecular bonds, chemical modifications of organic materials, creation of radicals.
- Thermal: melting, evaporation, welding, joining, drilling, hardening, sintering,…

Fig. 4.7: An impressive example of an EB-welding application. In a huge vacuum chamber two 70-mm-thick aluminium plates, with a diameter of 6 metres, are joined with a 'single-shot'. It is the basic material used in forging and machining the main stage of Ariane-rocket tanks.

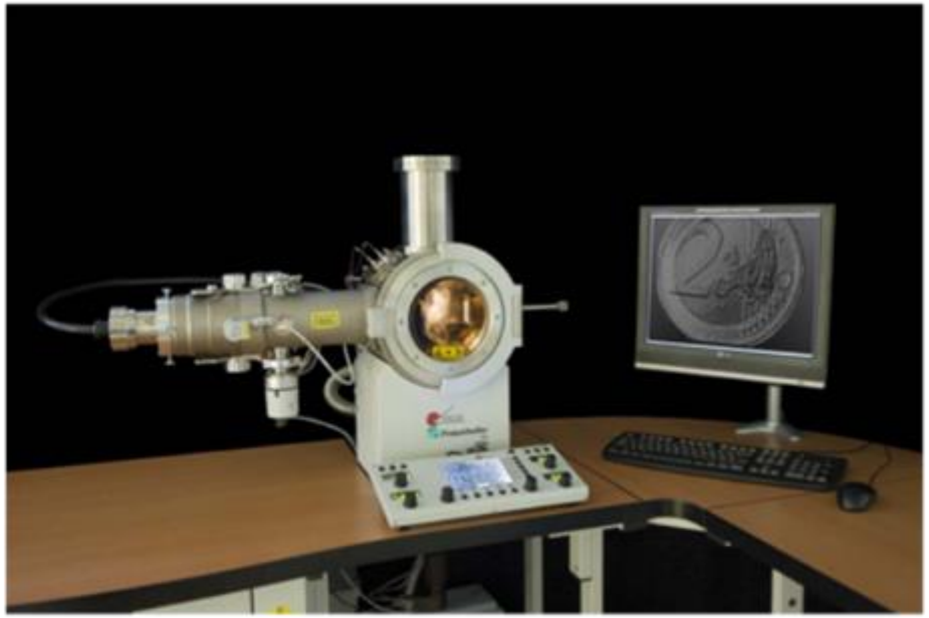
Fig. 4.8: A desk-top e-beam laboratory machine for welding and structuring with a magnified backscattered electron-image.



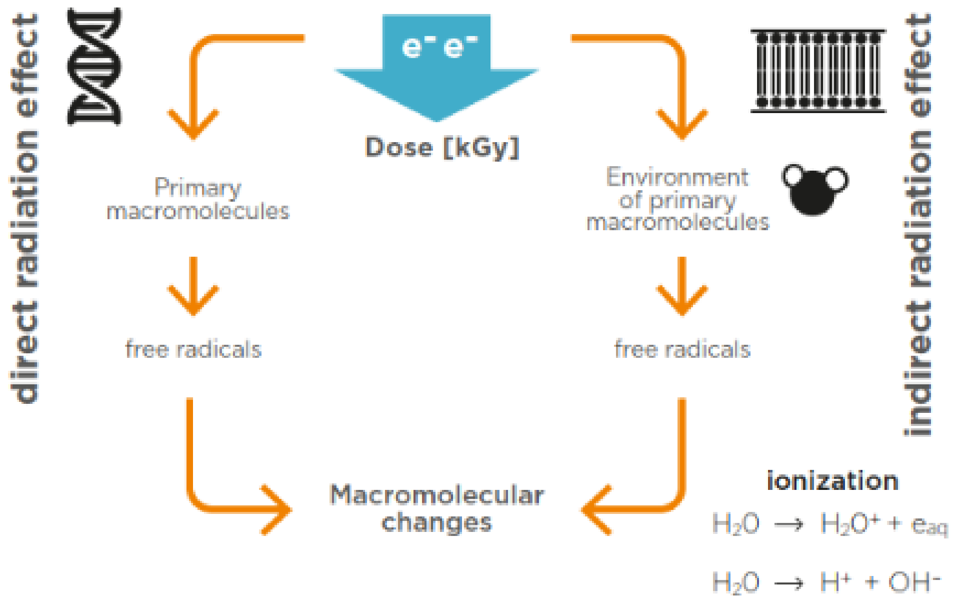
Electron beam welding



Cross-sections - Comparison of extensive TIG-welding with a lot of weld seams with the single-weld seam of EB-welding at the same material thickness

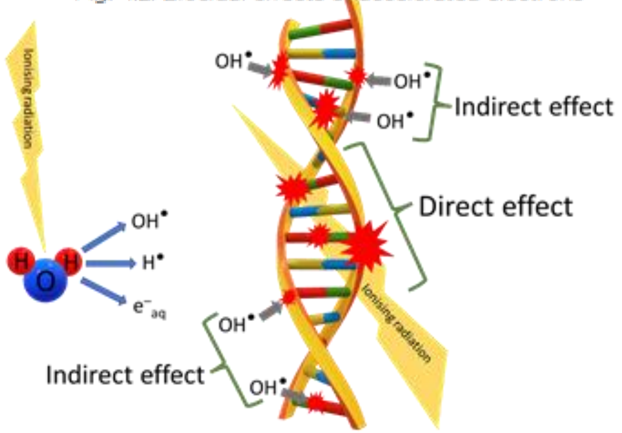


Sterilisation



- DNA Line-break (single, double)
- Change or damage of bases
- Denaturation
- Cross linking
- Absorption of proteins

Fig. 4.2: Biocidal effects of accelerated electrons



- Sterilisation processes caused by the breaking of molecular bonds associated with the water and DNA in microbial cells.
- Medical products (implants and instruments), food, and pharmaceutical packaging can be sterilised.
- Energy between 1 and 10 MeV, all surfaces must be accessible (small penetration depth).
- The world market-leader in the aseptic carton packaging of liquid foods has installed e-beam sterilisation machines in the majority of its production facilities.

Fig. 4.12: E-beam technology fo sterilising medical products

Fig. 4.13: Tetra Pak has a new generation of automated filling machines that uses e-beams to sterilise packaging.

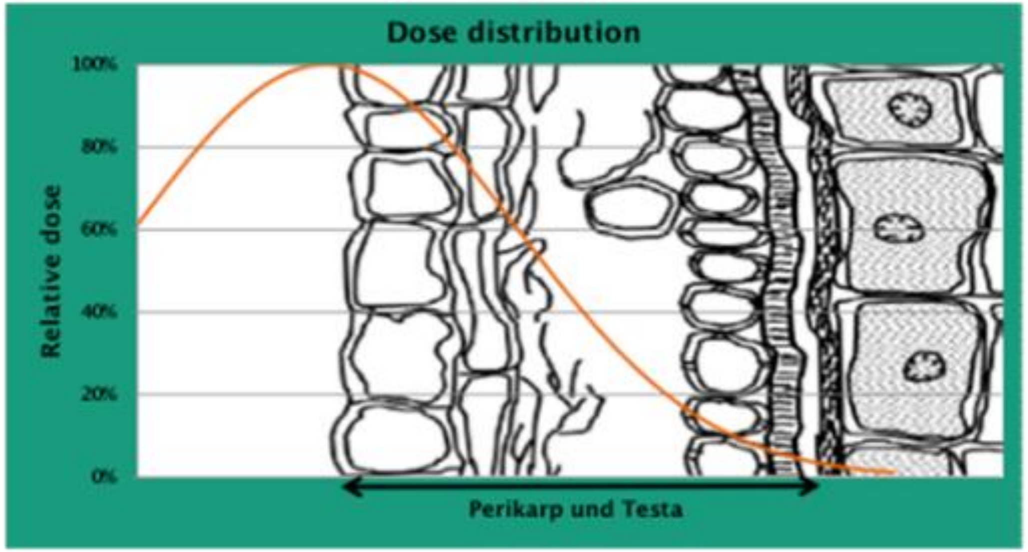
Food sterilisation and radiophobia

Seed and crop treatment – *20 to 30% of food harvested is lost to rotting and insect infestation*
Crop seeds must be free from pathogens (fungi, bacteria and viruses) that can endanger health and food security. Standard treatment: chemical seed dressing that can result in the contamination of soil and ground water with waste products, drifting of dressing agents across fields, killing of probiotic microorganisms.

Alternative: physical disinfection of seed using the **biocidal effect of accelerated electrons**. By precisely adjusting the energy of the e-beam, contamination on the seed surface can be treated without damaging the DNA of the seed grain.

Advantages:

- no change in taste, texture of colour;
- no toxic residue;
- less energy consumption than e.g. steaming;



E-beam treatment diffusion is limited by **low social acceptance** of any association between “radiation” and “food”, which results (in Europe) in stringent regulatory constraints.

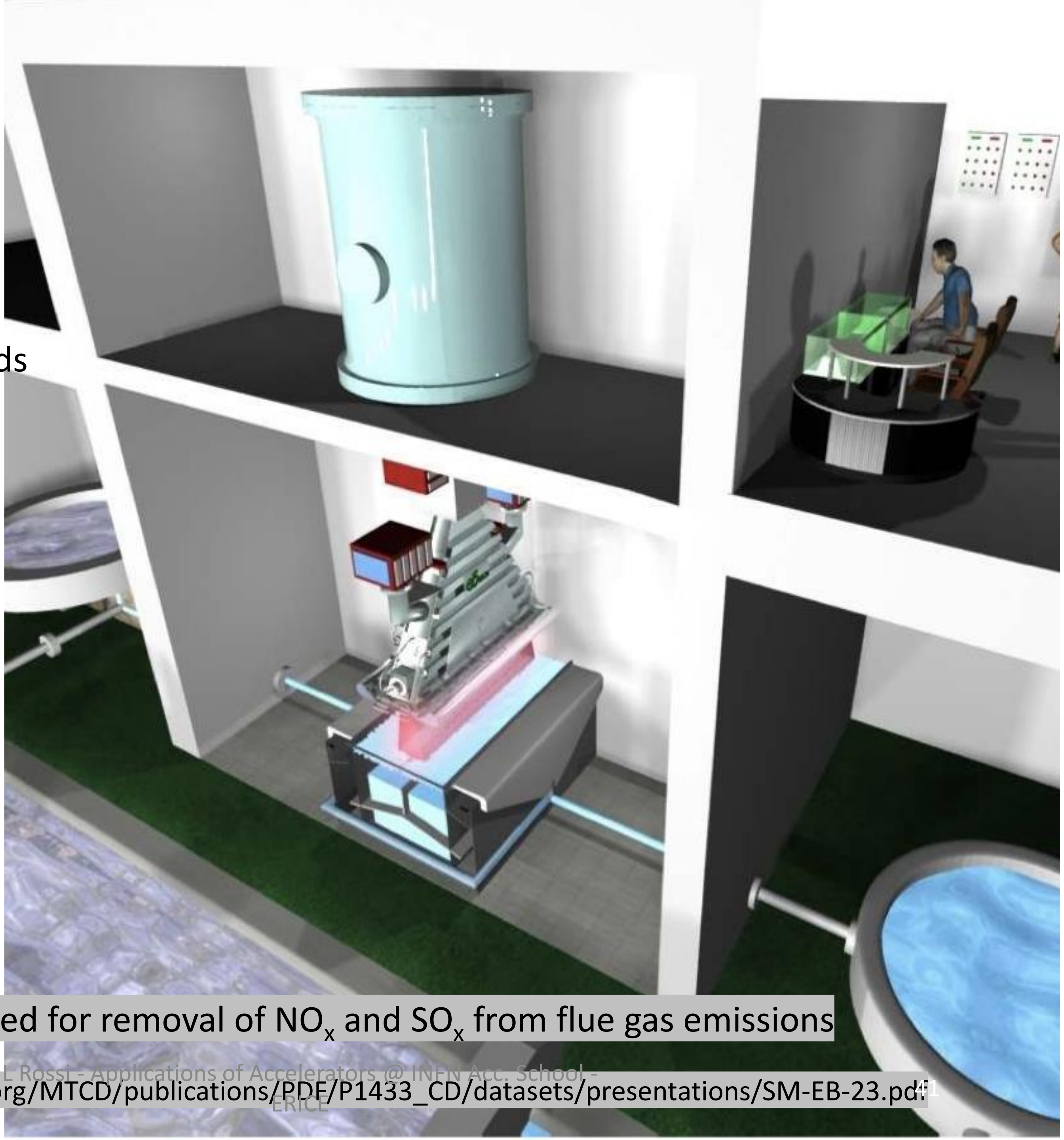
Crop treatment companies never use the word “radiation”…

Wastewater Irradiation

Remove organic compounds and disinfect wastewater.

Can be used to treat/reclaim:
- Textile Dyeing
- Pharmaceutical
- Petrochemical
- Municipal Wastewater
- Contaminated Underground Water

1 MeV, High Current, scanning system



Also used for removal of NO_x and SO_x from flue gas emissions

https://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/presentations/SM-EB-23.pdf

Environmental applications of accelerators - 1

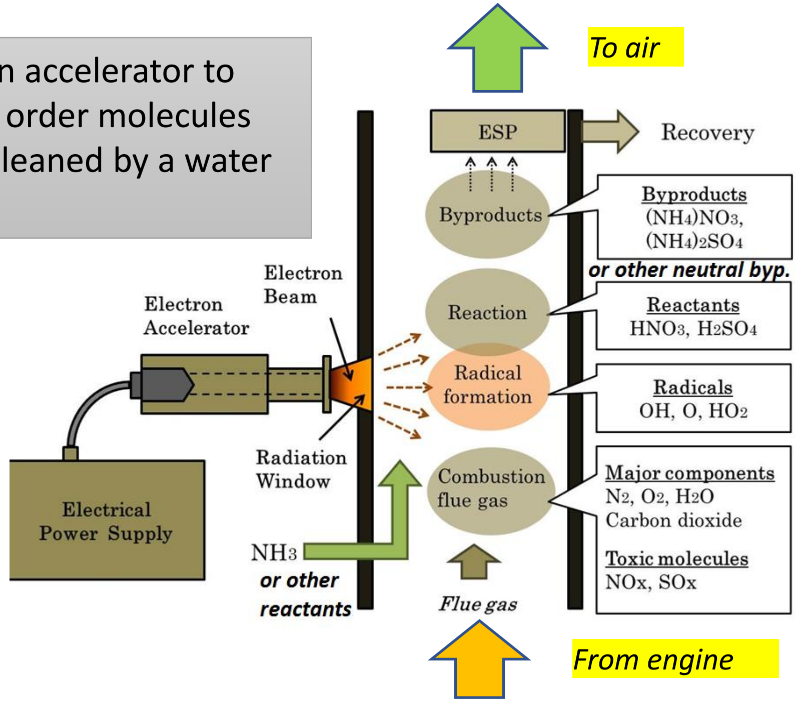
Low-energy electrons can break molecular bonds and be used for:
- Flue gas treatment (cleaning of SOx from smokes of fossil fuel power plants)
- Wastewater and sewage treatment
- Treatment of marine diesel exhaust gases (removal of SOx and NOx).

- **Maritime transport** is the largest contributor to air pollution: a cruise ship emits as much sulphur oxides as 1 million cars!
- Ships burn Heavy Fuel Oil, cheap but rich in Sulphur. Diesels (high efficiency) emit Nitrogen oxides and particulate matter.
- New legislation is going to drastically limit SOx and NOx emissions from shipping, with priority to critical coastal areas.
- So far, technical solutions exist to reduce SOx or NOx, but there is no economically viable solution for both.

150 kV electron accelerator to break the high order molecules that are then cleaned by a water jet (scrubber)

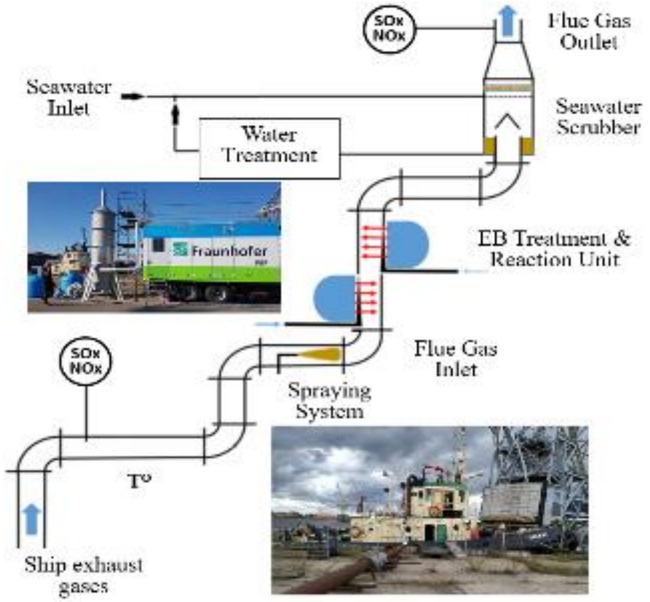
Hybrid Exhaust Gas Cleaning Retrofit Technology for International Shipping (HERTIS)

A project based on a patent from INCT Warsaw promoted by a collaboration of research institutions (including CERN), accelerator industry, shipyards, maritime companies, maritime associations (Germany, UK, Switzerland, Poland, Latvia, Italy).



Test of HERTIS at Riga Shipyard, July 2019

Mobile electron accelerator system from FAP Dresden commonly used to treat crops connected to the exhaust funnel of the Orkāns, an old Soviet-built tugboat. The fumes then passed through a small water scrubber before being released in the air.



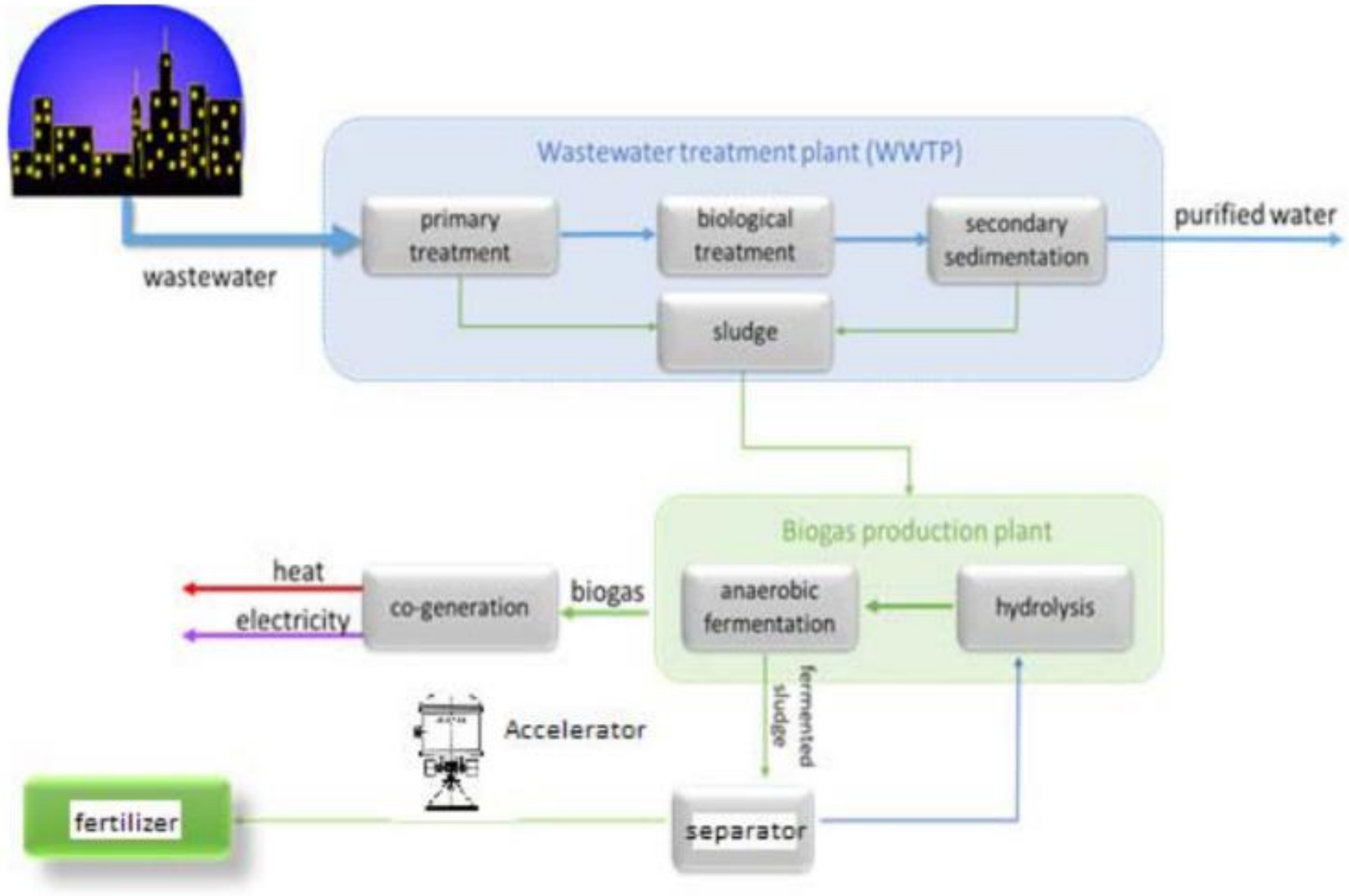
The tests confirmed the laboratory measurements and the overall effectiveness of the system.

Measured **NOx removal rate 45%** at full engine power with the available scrubber and accelerator. Estimated removal with optimised scrubber and homogeneous e-beam 98%.
SOx removal only measured in laboratory (no Sulphur allowed in port) with similar removal rates.

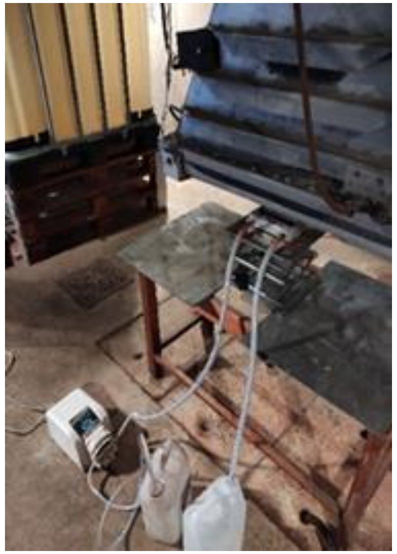
At the border between high- and low-tech…

Environmental applications of accelerators - 2

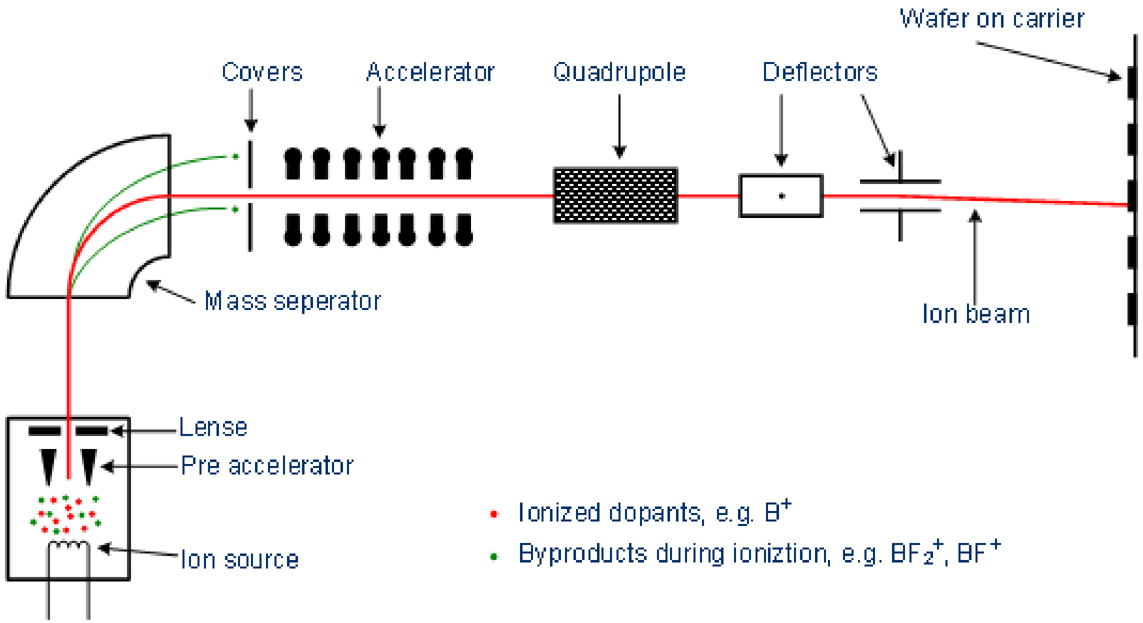
Design of an advanced electron accelerator plant for biohazards treatment

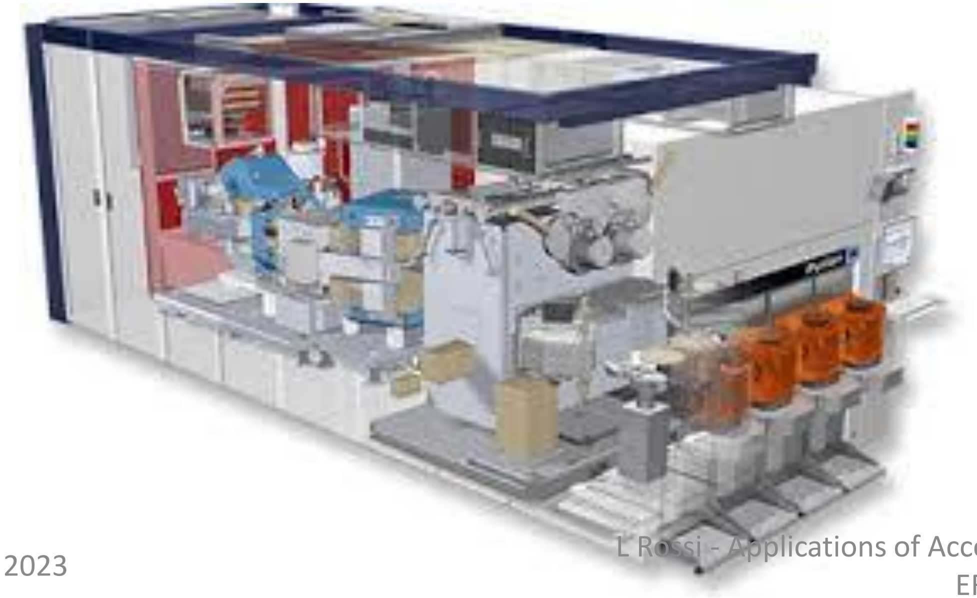


Sludge produced in municipal sewage treatment plants is highly contaminated with parasite eggs.
An expensive hygienization process is needed before agricultural utilization, with the consequence that in most cases the sludge is dumped.
Treatment with an electron accelerators provides a simple and inexpensive way to sanitize sludge and directly convert it into fertiliser, using the energy produced onsite.



Ion implantation

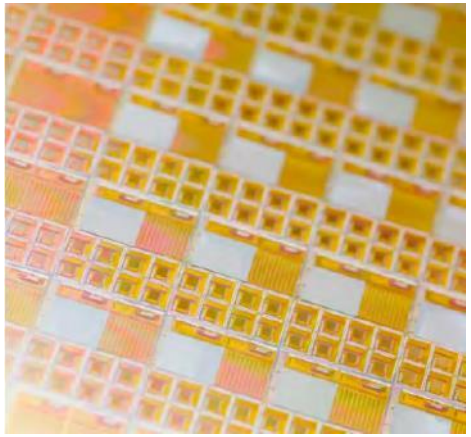


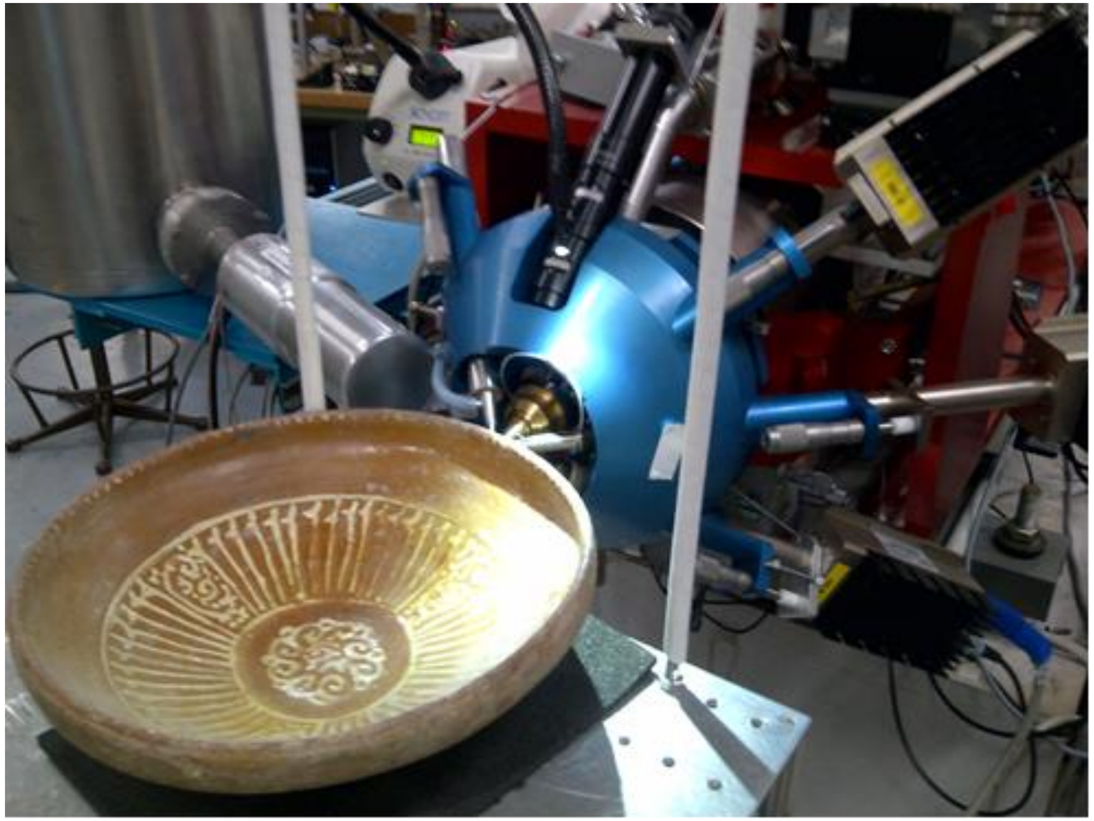


The **semiconductor industry** requires
ion implantation to introduce atoms into semiconducting materials to alter
their electronic properties (doping).
Huge industry and one of the most important uses of particle accelerators.

Developing into research for quantum computing (single ions with nanometre-scale spatial accuracy) and novel opto-electronic devices (nano-precipitates in silicon-dioxide layers for light-emitting devices).

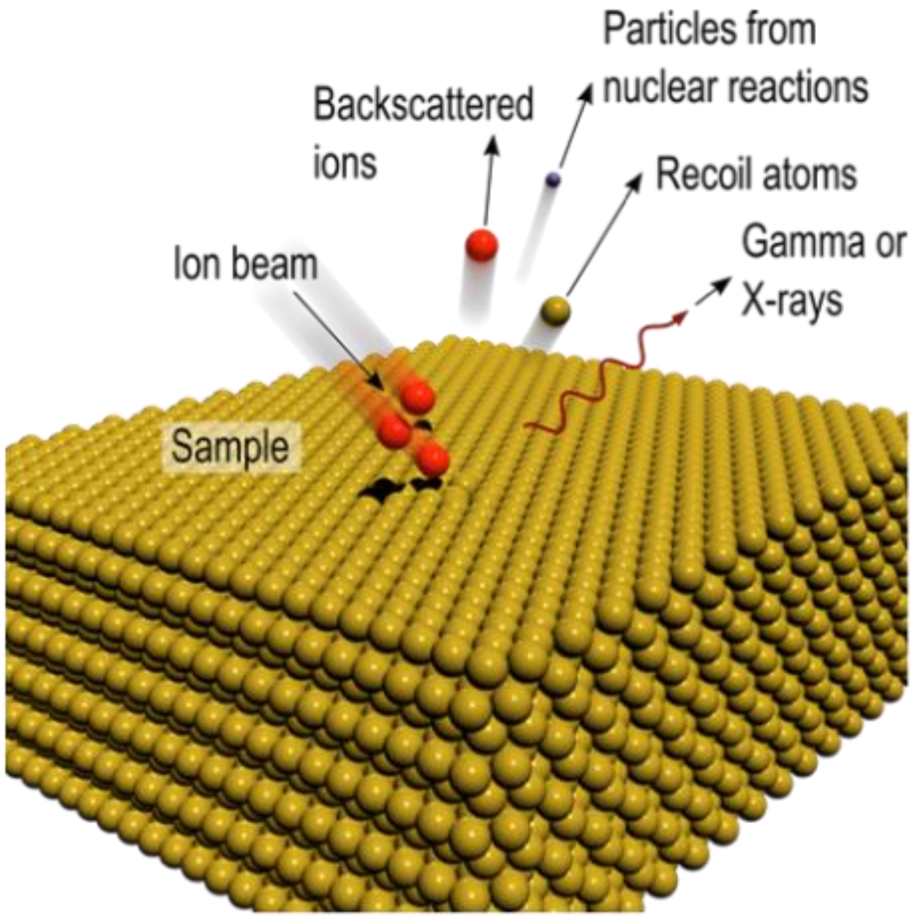
Commercial system for ion implantation





Surface analysis applications

Ion Beam Analysis



Analytical techniques that exploits the interactions of MeV protons or heavier ions with matter in order to determine the elemental composition and structure of the surface regions of solids (to depths of about 100 μm), from measured quantities such as the characteristic spectra of the resulting X-rays, gamma-rays or charged particles emitted.

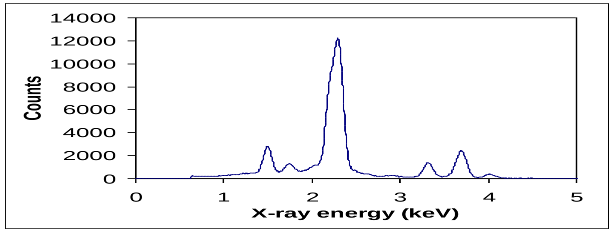
- Elastic or Rutherford backscattering (EBS or RBS), with a particle detector at a backscattering angle;
- Particle-induced X-ray emission (PIXE), with an X-ray detector;
- Particle-induced gamma-ray emission (PIGE), with a gamma detector;
- Elastic recoil detection analysis (ERDA) with a particle detector at a forward recoil/scattering angle.

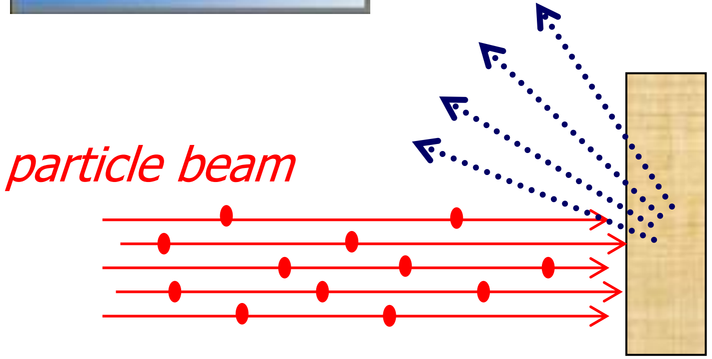
Accelerators for art

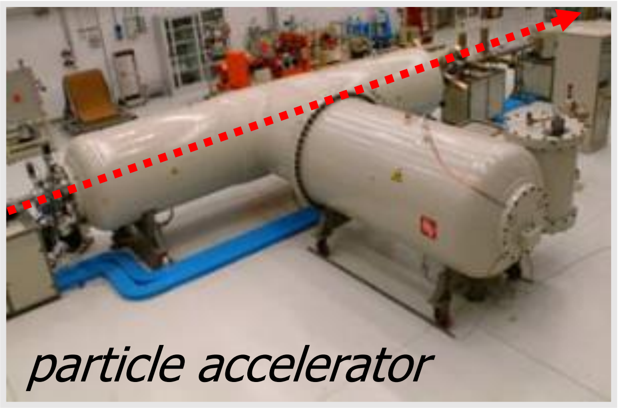
PIXE, Proton Induced X-ray Emission

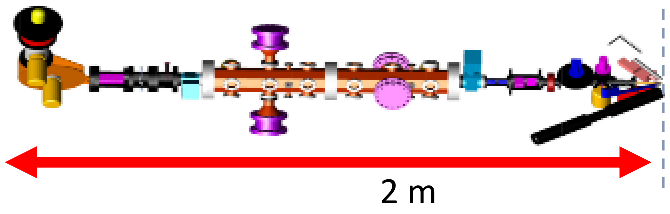
A beam of particles (protons) from an accelerator is sent on a sample (e.g. a painting)
The atoms are excited and emit different types of radiation (X-rays, gammas, etc.)
Different atomic elements emit X-rays at different energies – Spectral analysis from one or more detectors allows determination of the chemical composition (e.g. of the pigments).

Radiation detection and spectral analysis

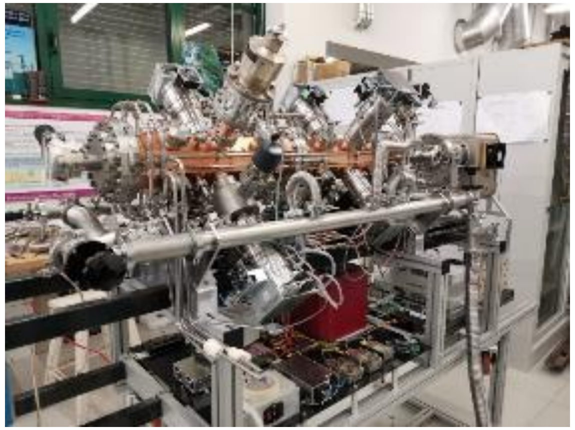






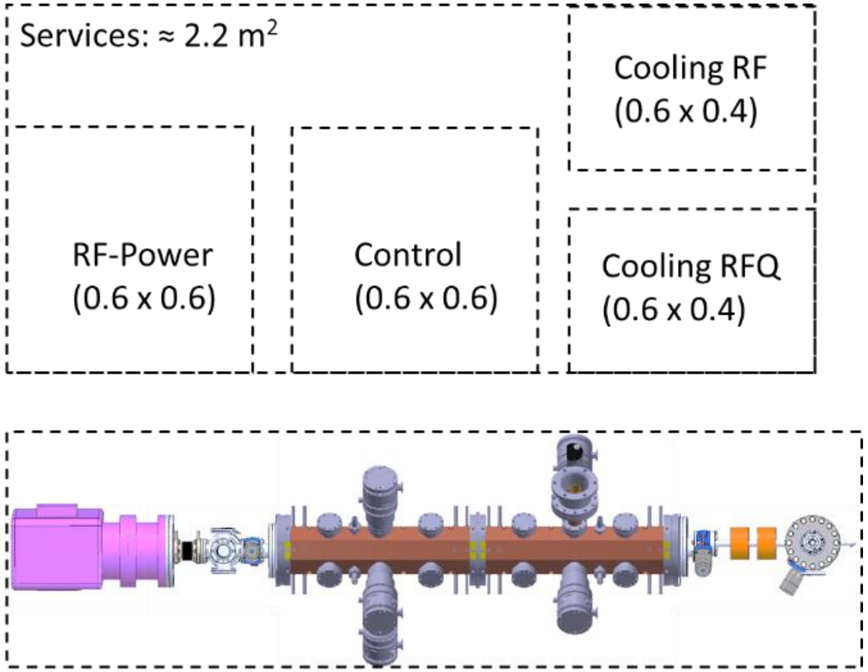


Ritratto Trivulzio by Antonello da Messina, 1476 – analysis at INFN-LABEC (Florence)



Portable PIXE system based on an RFQ linac built by CERN and LABEC

The MACHINA project

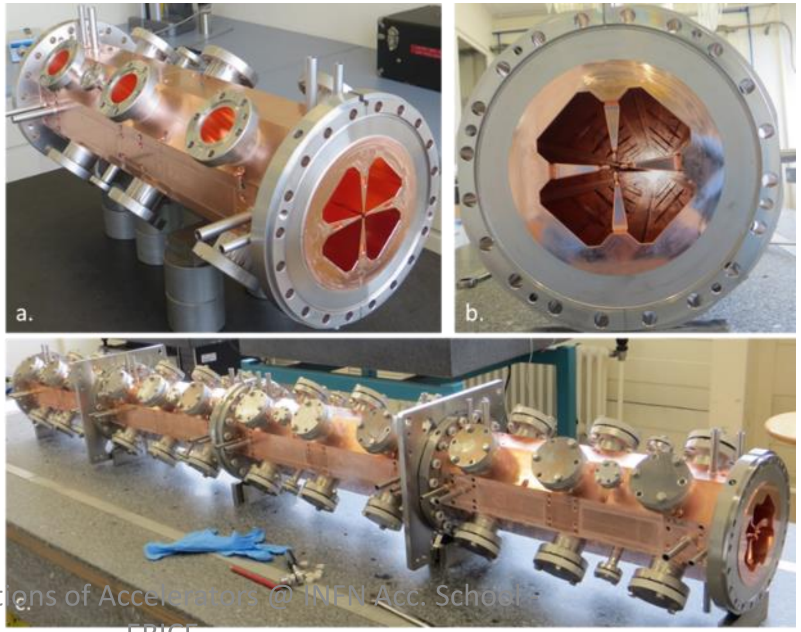


Accelerator: ≈ 2.35 x 0.6 = 1.4 m²

MACHINA (Movable Accelerator for Cultural Heritage In situ Analysis) project of CERN and INFN.

Construction of a transportable RFQ (PIXE-RFQ) optimized for the analysis of material with a 2 MeV proton beam.

Will be installed in the Opificio delle Pietre Dure in Florence (Italian central institution for artwork analysis)



RF Frequency (MHz)	749.48
Length (mm)	1072.938
Input Energy (MeV)	0.02
Output Energy (MeV)	2
Average Current (nA)	5
Peak Current (nA)	200
Repetion Rate (Hz)	200
Pulse Duration (ms)	0.125
Duty Cycle (%)	2.5
Vane Voltage (kV)	35
Min Aperture (mm)	0.7
Max Modulation	2
Ro (mm)	1.439
Rho (mm)	1.439
Rhol min (mm)	1.709
Transmission (%)	30
(for matched beam)	
Output Beam diameter (mm)	0.5
Acceptance (π mrad mm)	0.2
(Total norm.)	
Output Energy Spread (keV)	10
RF Peak Power (kW)	80
RF Average Power (kW)	2
RF Efficiency (%)	35
Coupler (#)	1
Plug Power (Total) (KVA)	5.7

Towards the miniature accelerator?

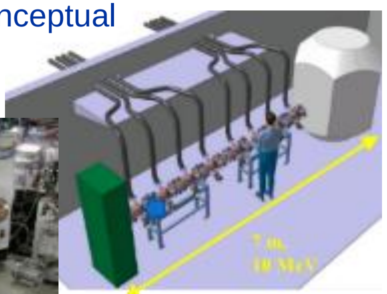
Important trend towards miniaturization of accelerators, for use in medicine and industry

Here are presented only three examples of recent developments at CERN:

The mini-RFQ

750 MHz
92 mm diameter
2.5 MeV/m

Proton therapy injector (in operation)
Artwork PIXE analysis (in construction, transportable)
Isotope production (design)
Neutron radiography (conceptual stage)

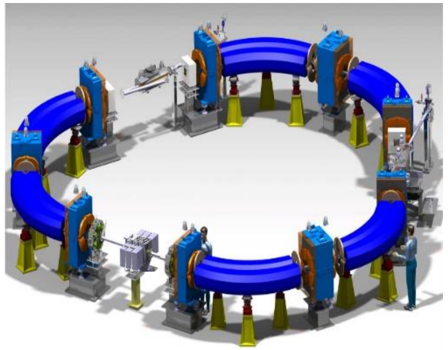


X-band structures

12 GHz
100 MeV/m

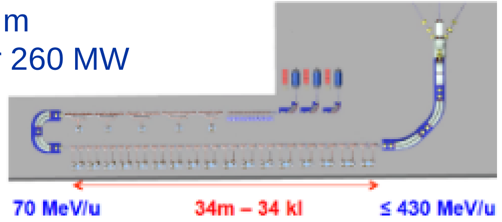
Developed for CLIC, in operation at CLIC test stand
- Compact XFEL (CompactLight Design Study)
- VHEE and FLASH therapy linac (design)
- SmartLight (table top inverse Compton scattering light source, design)

Compact accelerators for ion therapy



Superconducting C-ion synchrotron
Bmax 3.5 T
27m circumference

Folded C-ion linac,
Tot. length 53 m
Tot. RF power 260 MW



Accelerators for energy

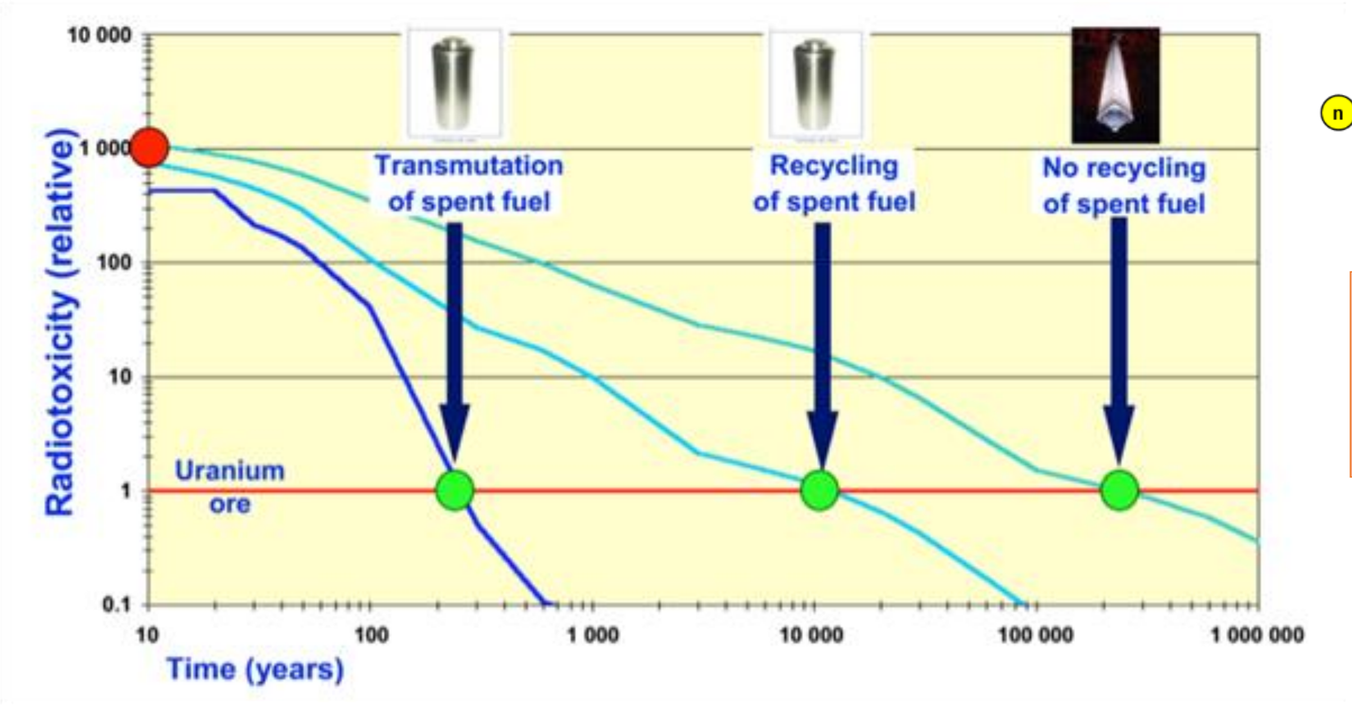
Accelerators addressing the issues of nuclear power

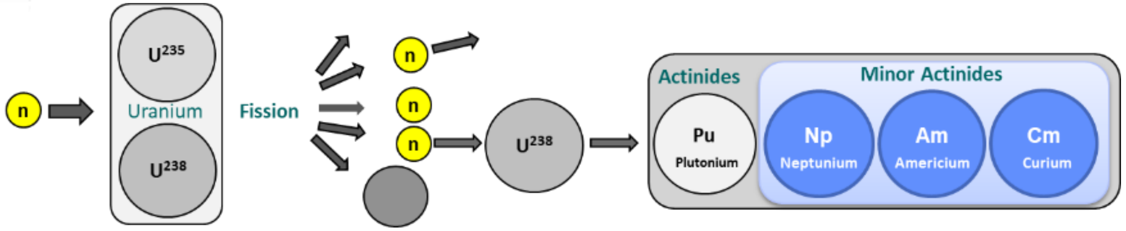
Main public concerns with nuclear power:

1. Risk of critical accidents
2. Long-term waste disposal
3. Risk of nuclear proliferation

The accelerator answer:

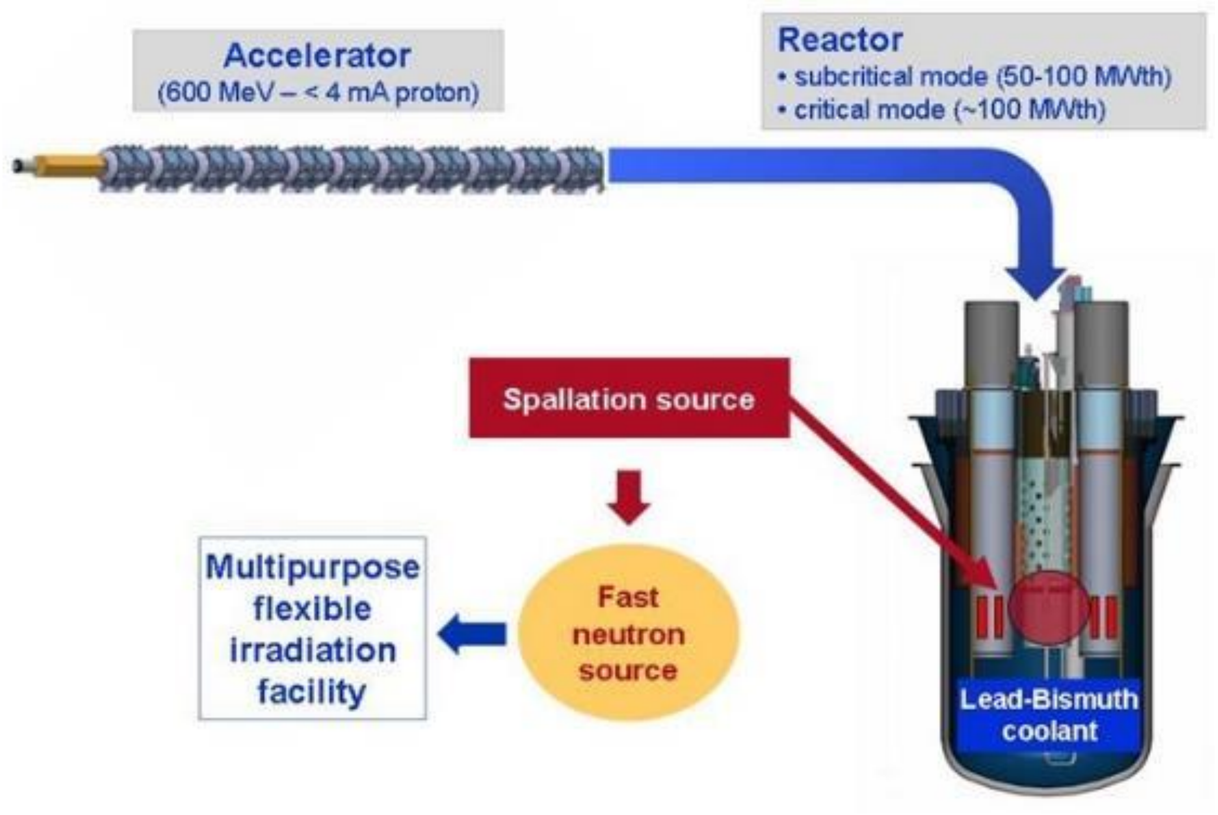
- Accelerator-driven sub-critical operation
- Waste treatment (transmutation) with accelerators
- Thorium-based reactors





Transmutation of Minor Actinides (heavier radioactive isotopes of neptunium, americium and curium) requires a fast-neutron system, possibly not reactor-based.

Accelerator Driven Systems

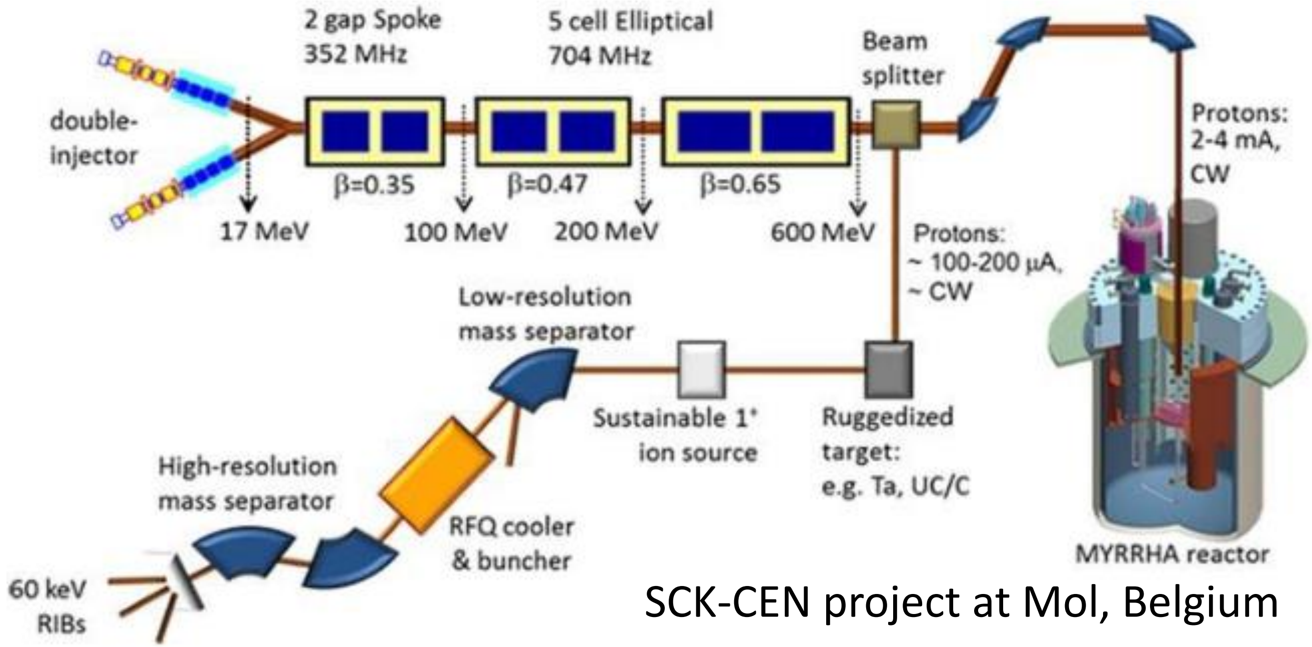


A linac coupled to a spallation source provides the missing neutrons to maintain the reaction in a subcritical reactor.

Could be used for energy production allowing alternative fuel cycles (thorium) and with no safety concerns (subcritical).

Pros	Cons
Safety: subcritical reaction, allows for immediate switch-off	High reliability (→cost) required for the accelerator, to protect structures from thermal shocks
Possibility to operate below criticality opens the way to new reactor concepts	Reduction in net plant power efficiency due to power consumption of accelerator
Simple reactor control by modulating accelerator current	Increased complexity (and cost)

The MYRRHA project



SCK-CEN project at Mol, Belgium

Multi-purpose hYbrid Research Reactor for High-tech Applications)

Development, construction & commissioning of a new large fast neutron research

❶ **ADS demonstrator**

❷ **Fast neutron irradiation facility**

❸ **Pilot plant for LFR technology**

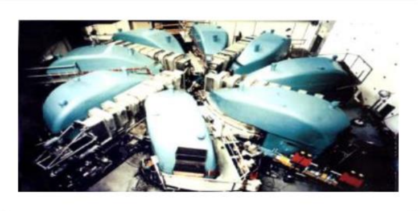
- subcritical reactor core,
- spallation target
- particle accelerator

Advantage: large quantities (<40% of core) of MAs loaded for transmutation.

A small number of dedicated ADS transmutation systems in Europe can burn the waste from a large number of fast reactors for electricity generation.

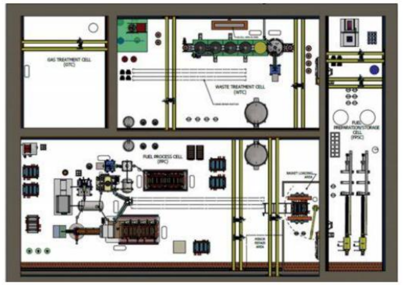
Transmutex initiative and goal

Goal: 100 MW Pilot Plant by 2032



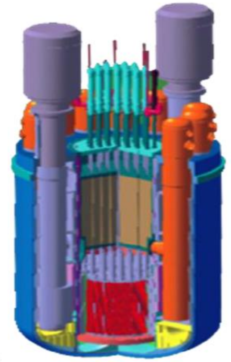
High-Power Cyclotron:
PSI - CH, INFN - Italy

Waste pyro-processing:
Argonne National Laboratory - USA



Spallation Target:
PSI – CH

Lead-Bismuth fast reactor
SVBR 100 from AKME - Russia



Neutron sources for material testing

3 fields of application:

1. Compact neutron radiography → cargo screening, concrete analysis
2. Advanced organic material analysis (spallation sources)
3. Test of nuclear materials (e.g. for fusion)

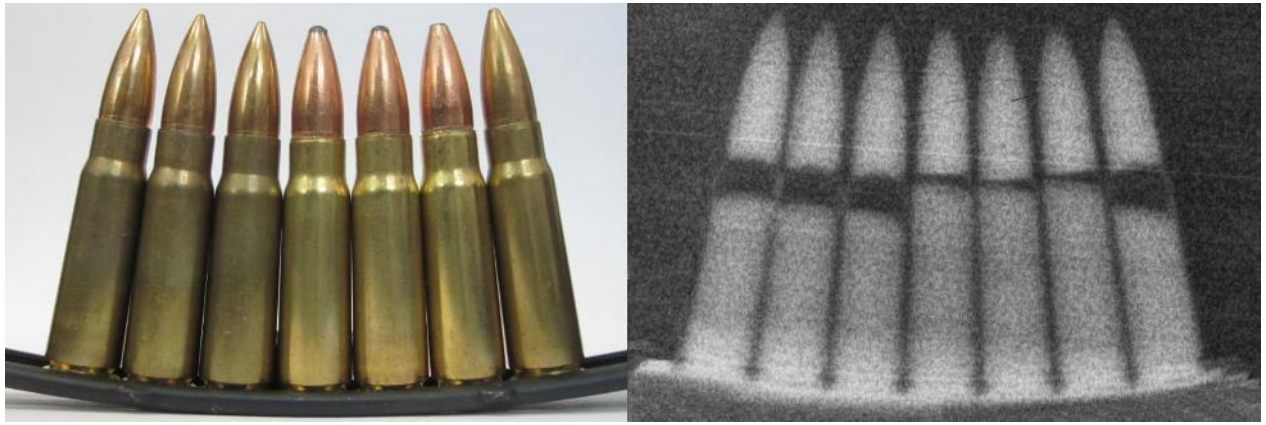
RIKEN (Japan):
Concept of a a truck-mounted device sending neutrons from a source (accelerator + target) aboard the truck to the detector attached to the arm.
The system can non-invasively inspect the structural soundness of bridges by detecting steel fractures and their water content (rust). Neutrons have much better penetration than X-rays that are blocked by the steel structure inside the concrete.

Neutron sources for security and inspection

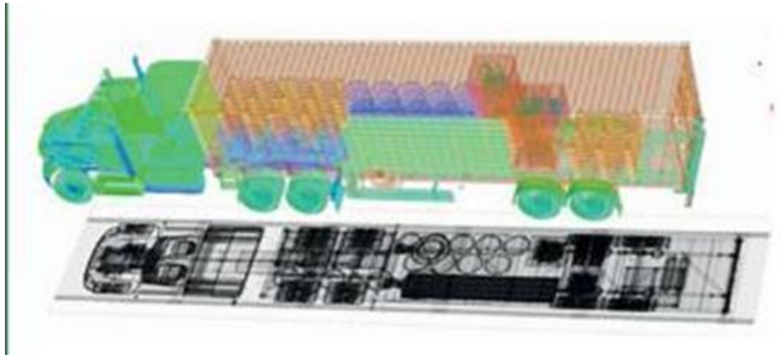
- Neutron radiography: detecting the neutrons transmitted through an object;
- Neutron-induced gamma spectroscopy: gamma-rays produced by neutron interactions with the cargo are detected.

Application to nuclear detection, e.g. of highly shielded nuclear materials. Neutron sources stimulate detectable fission in nuclear material.

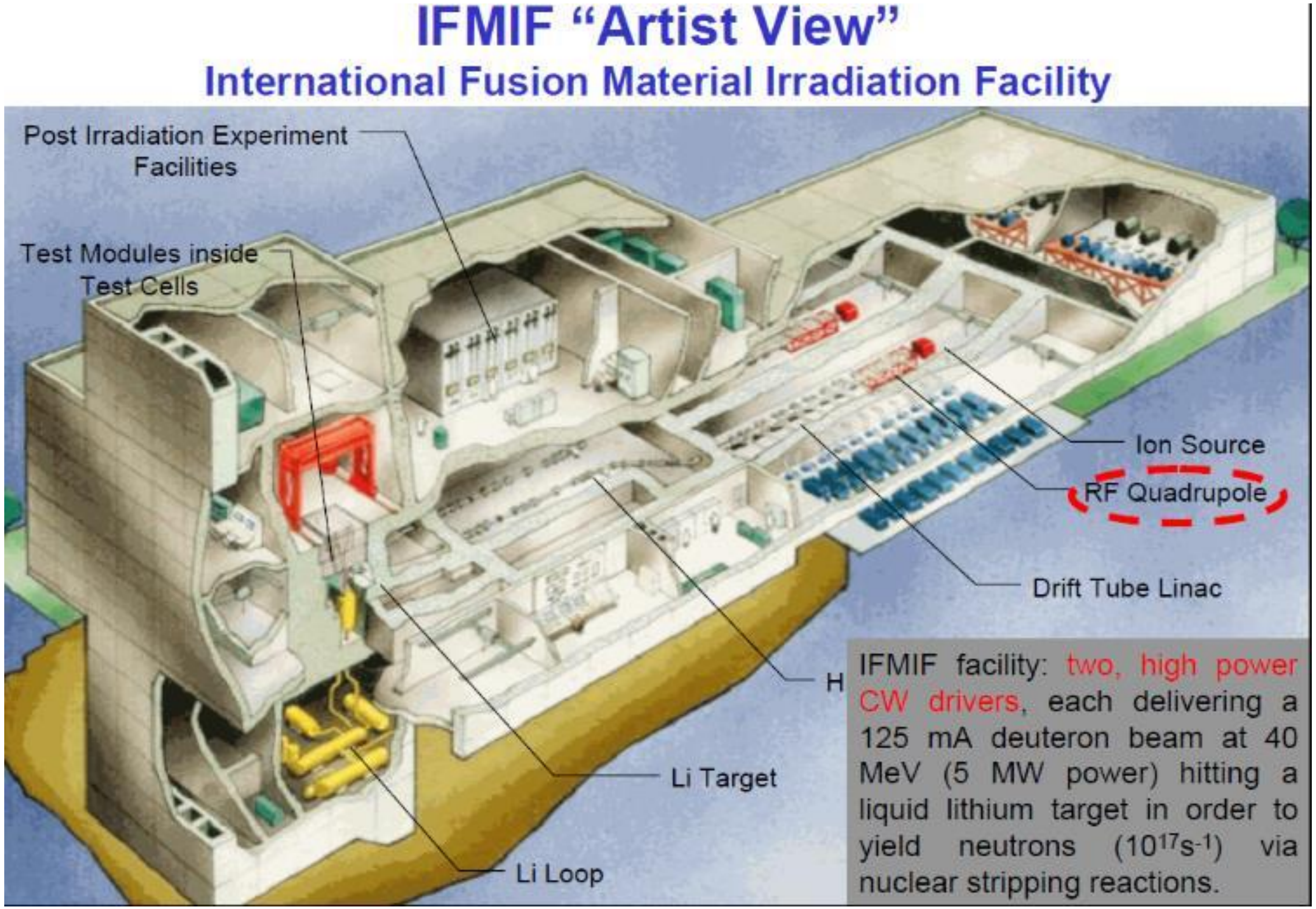
Accelerators: acceleration of protons or deuterium to targets made of deuterium or tritium.



Pictures courtesy of Starfire Industries, USA



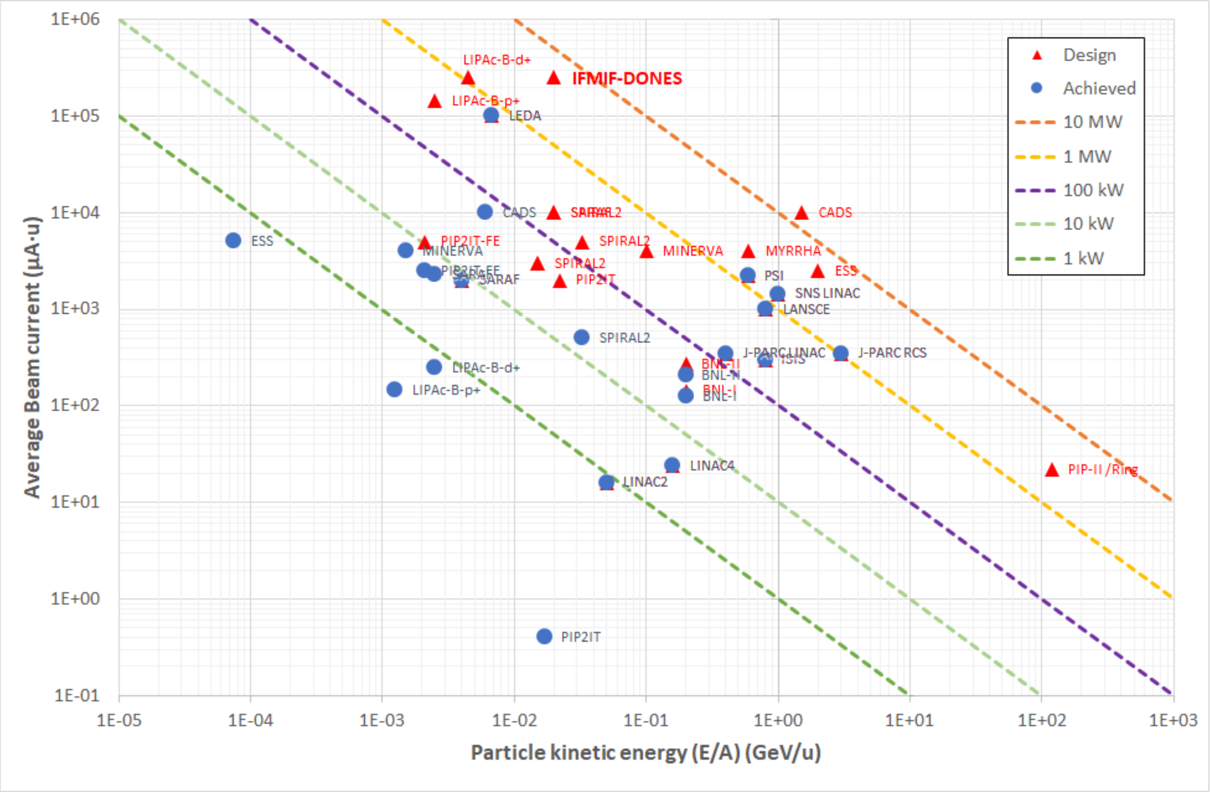
Accelerators for fusion material testing: IFMIF

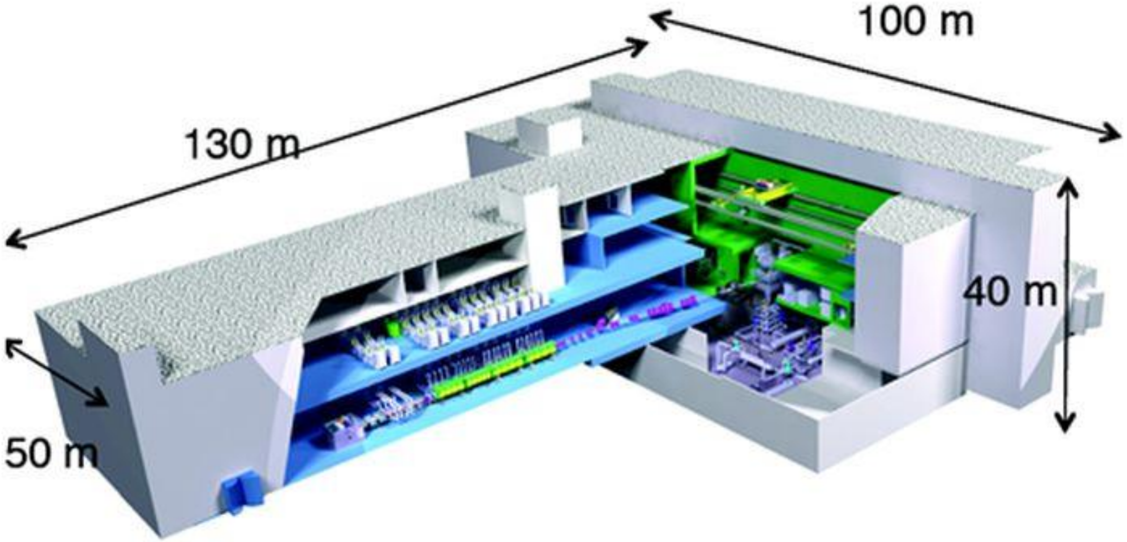


Test under strong neutron fluxes of materials to be used in ITER

IFMIF - DONES

In construction near Granada (Spain), will reach a beam power of 5 MW (125 mA, 40 MeV, D+)





Beam power

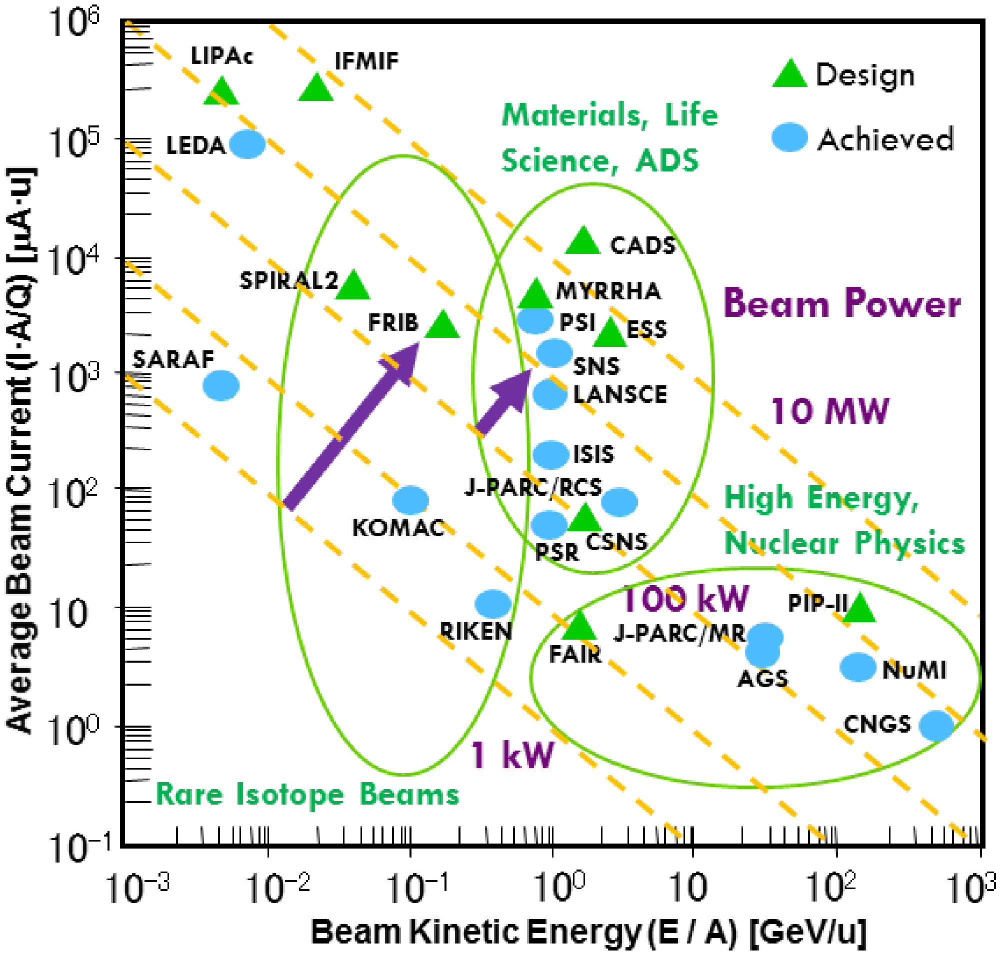


Figure of merit for accelerators at the intensity frontier is beam power P=W×I×duty cycle

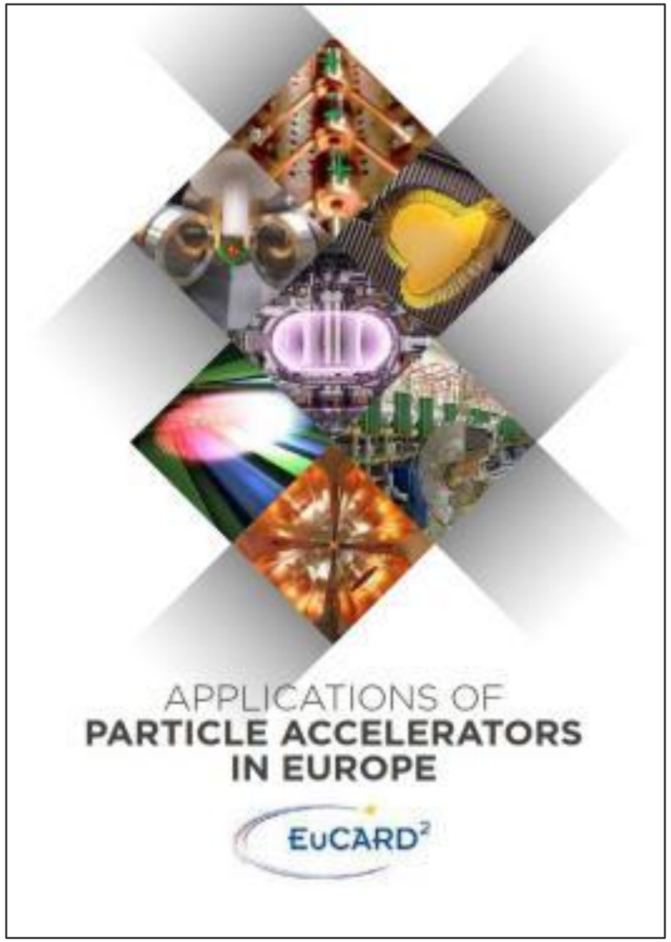
Production rate (cross-section) for most of the particles in high-intensity applications is independent on the energy (above a certain threshold) but proportional to beam power.

The new generation of accelerators under project or construction aims at moving the power from the 100 kW's range to the MW's range.

A MW-class machine presents a large number of challenges and requires the development of specific technologies.

Jie Wei, IPAC 2014

Some resources for further reading



2017 EuCARD2 Report on Accelerator Applications in Europe (112 pages):

http://apae.ific.uv.es/apae/wp-content/uploads/2015/04/EuCARD_Applications-of-Accelerators-2017.pdf

Other useful resources are:

The TIARA site on accelerators for society:
http://www.accelerators-for-society.org/

The US action on Accelerators for America's future:
http://www.acceleratorsamerica.org/report/index.html