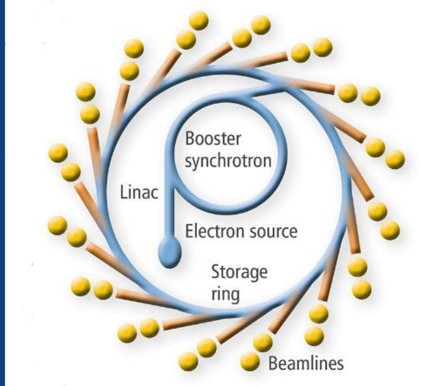
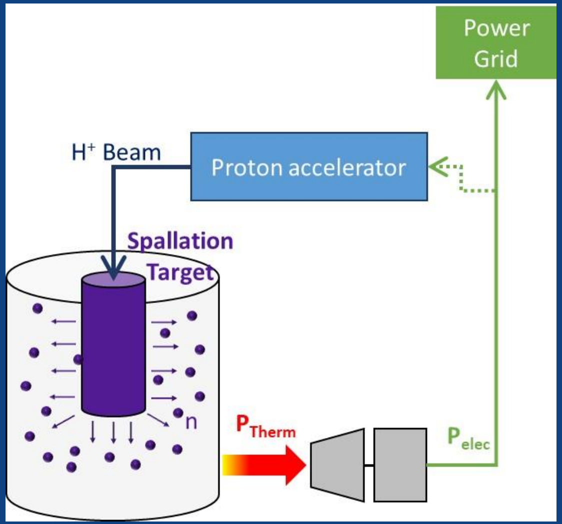
APPLICATICNS of ACCELERATORS: an OVERVIEW

Frédérick Bordry





6th Summer School on INtelligent signal processing for FrontIEr Research and Industry

Particle Accelerators: a tool to the subatomic world

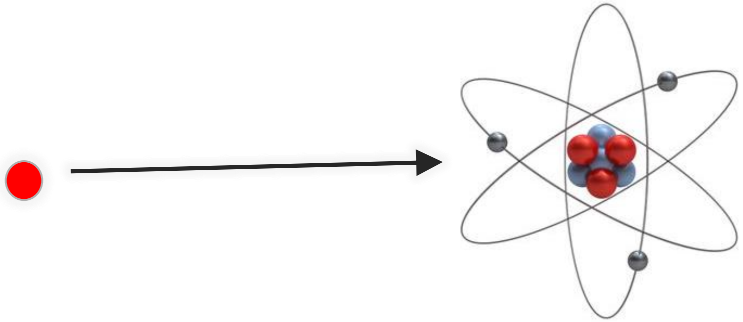
By extracting elements from an atom (protons, electrons, charged nuclei) and accelerating them, large amounts of energy can be concentrated in tiny volumes.

- to study the atom and its components,
- to break and modify the nucleus (and then synthetize new nuclei (new isotopes,…)

	Proton of LHC at 7 TeV	**TGV train**
		 *400 tons, 200 m, 150 km/h*
Energy	1.1 10^{-6} J	**3.6 10^{8} J**
Volume	2.5 10^{-45} m^3	1.8 10^{3} m^3
Energy density	**5.3 10^{38} J/m^3**	2.0 10^{5} J/m^3
Type of energy	Kinetic Subatomic scale	Kinetic Macroscopic scale
Energy full LHC beam	**3.6 10^{8} J**	

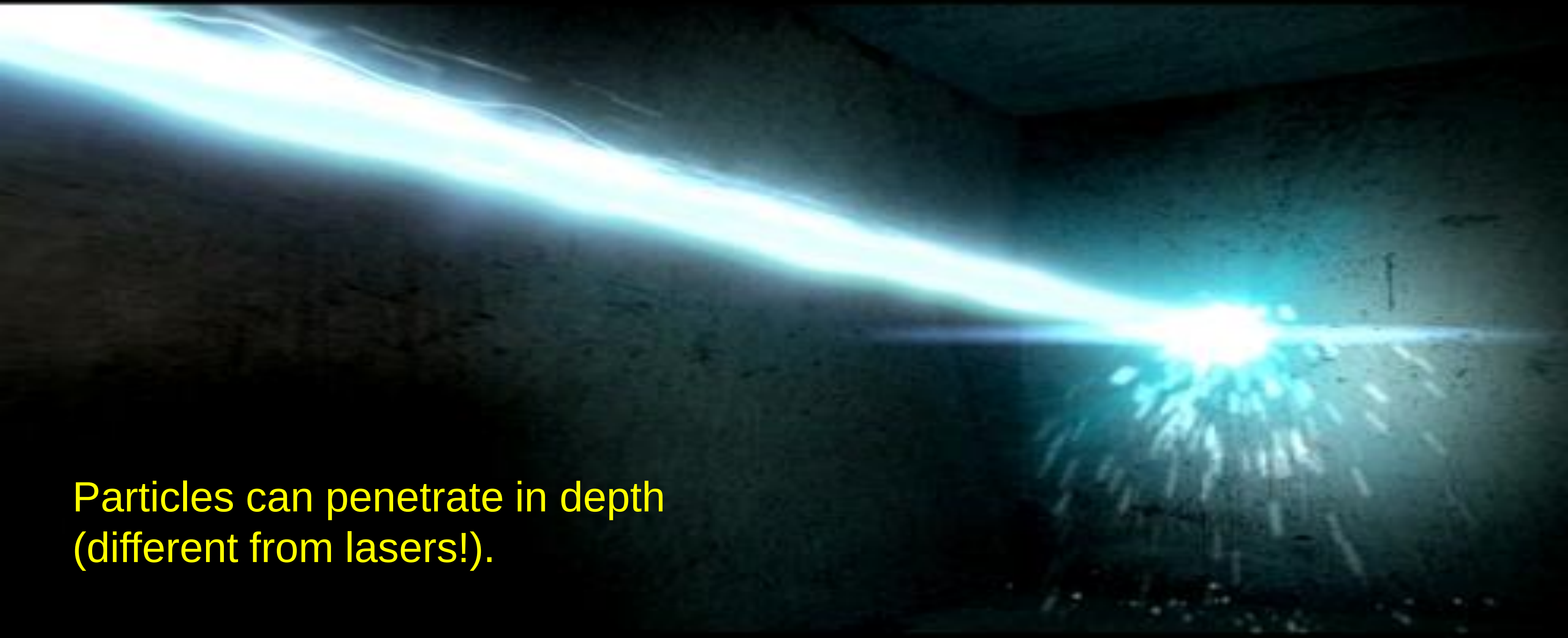
An accelerated subatomic particle sent towards an atom will:

1. Deliver some **energy to the electrons**.
2. Deliver some **energy to the nucleus** (if the particle has sufficient energy to penetrate the Coulomb barrier).

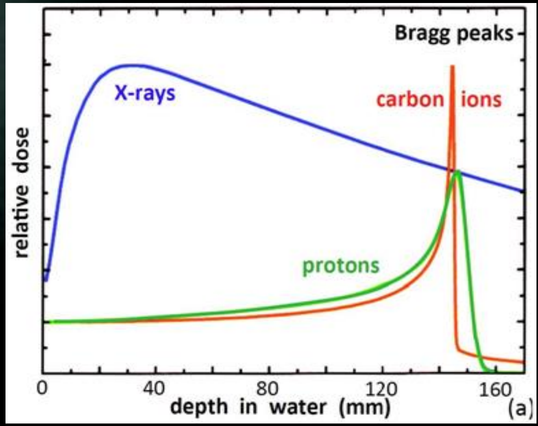


Accelerators can precisely deliver energy

A «beam» of accelerated particles is like a small "knife" penetrating into the matter



A particle beam can deliver energy to a very precisely defined area, interacting with the electrons and with the nucleus.



Particles can penetrate in depth (different from lasers!).

Particle beams are used in medical and industrial applications,
e.g. to cure cancer, delivering their energy at a well-defined depth inside the body (Bragg peak)

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

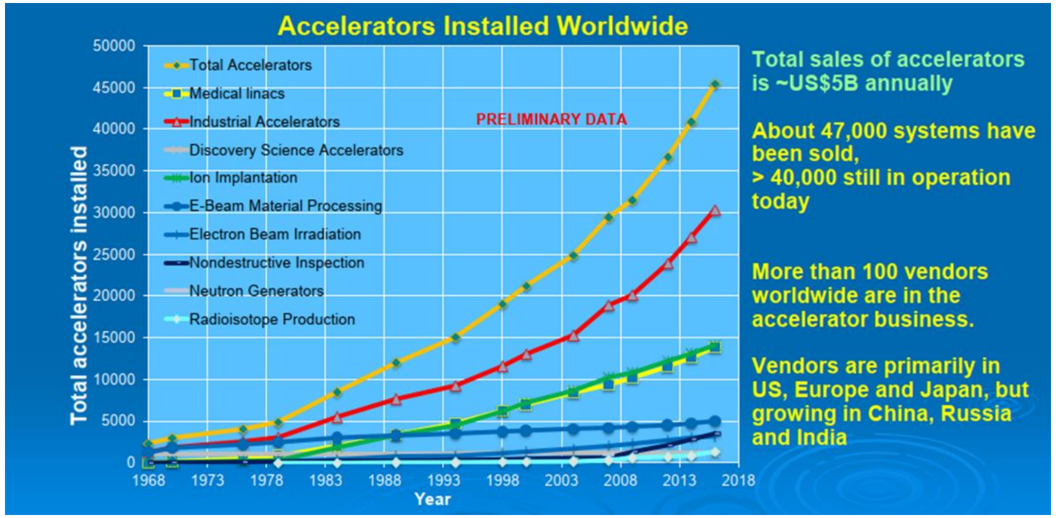
- Cyclotrons
- Linear accelerator
- Synchrotrons
- Synchrotron light sources (e^-)

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

Accelerators and their Use

More than 40’000 particle accelerators in the world

Research		**6%**
	Particle Physics	0,5%
	Nuclear Physics, solid state, materials	0,5%
	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%



Annual sales: > $5B

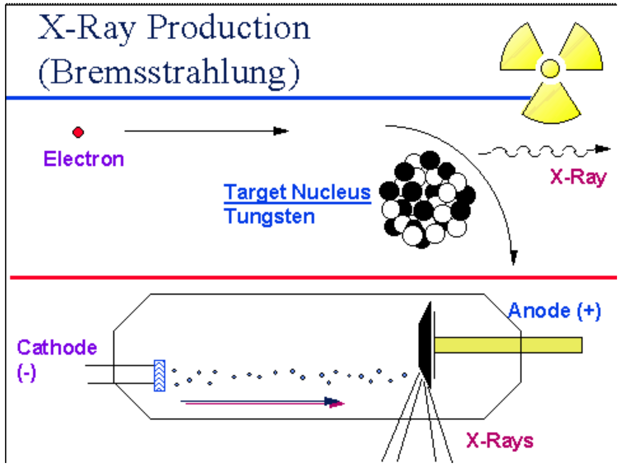
Annual product, etc., sales:

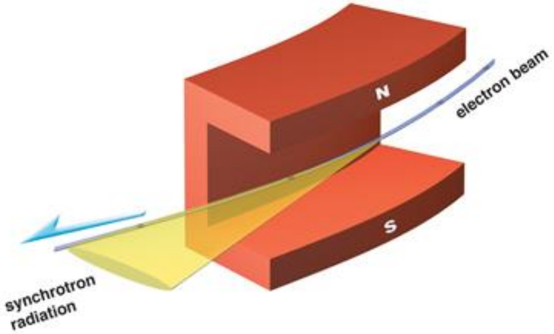
> $0.5T

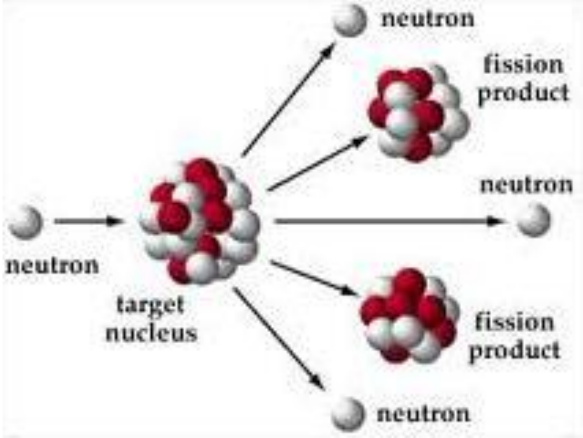
Accelerators can produce intense secondary beams

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



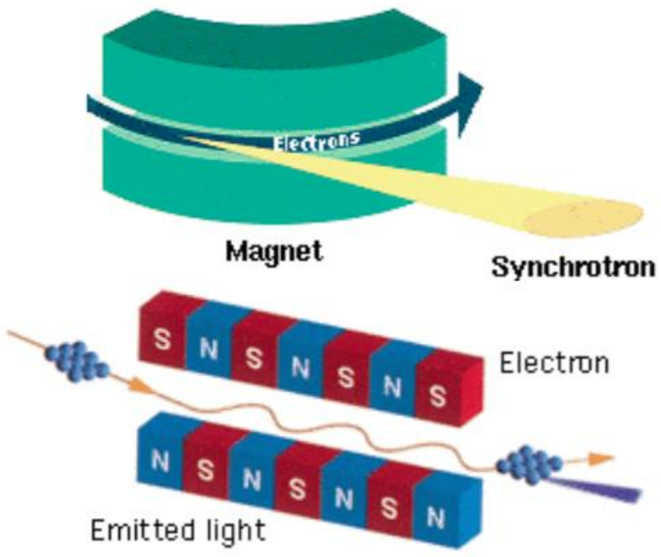


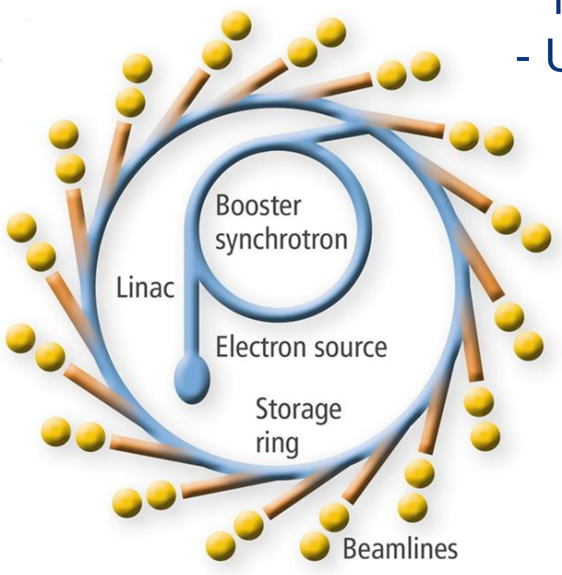


- X-rays generated by accelerators are commonly used in **medicine**
- Both X-rays and neutrons generated from accelerators are used for **advanced imaging** in many fields: life sciences, condensed matter, energy, material science, cultural heritage, life sciences, pharmaceuticals,…
- Additional applications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

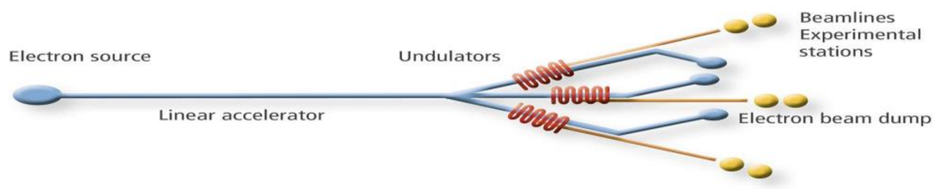
Accelerator-based light sources

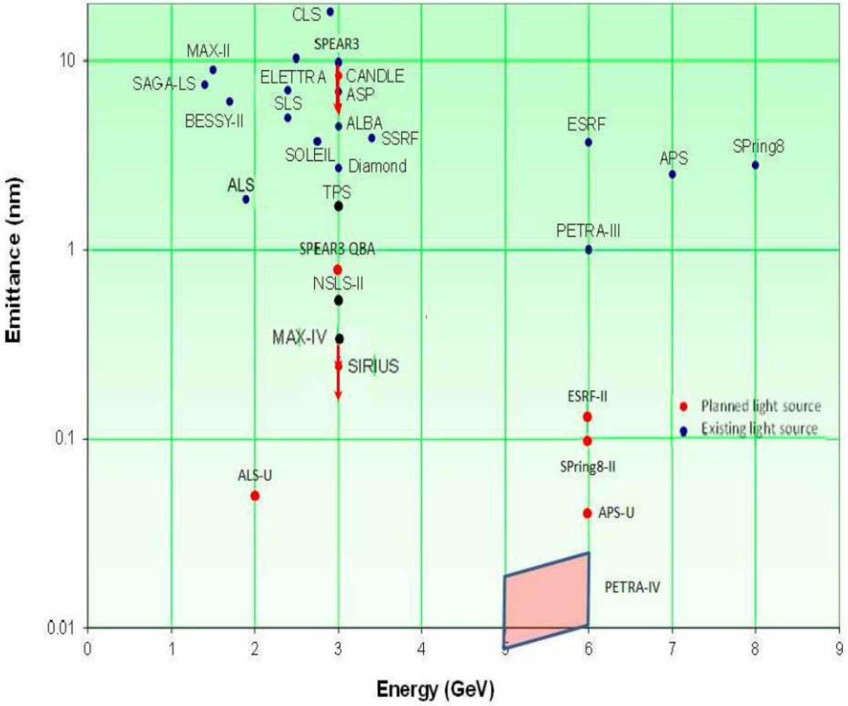
- The last two decades, enormous increase in the use of synchrony radiation, emitted from particle accelerators
- Can Produce very intense light (radiation) at a wide range of frequencies (visible or not)
- Useful in a wide range of scientific applications





The two main types of accelerator-based light source are synchrotrons (circular machines) and free-electron lasers (linear machines).



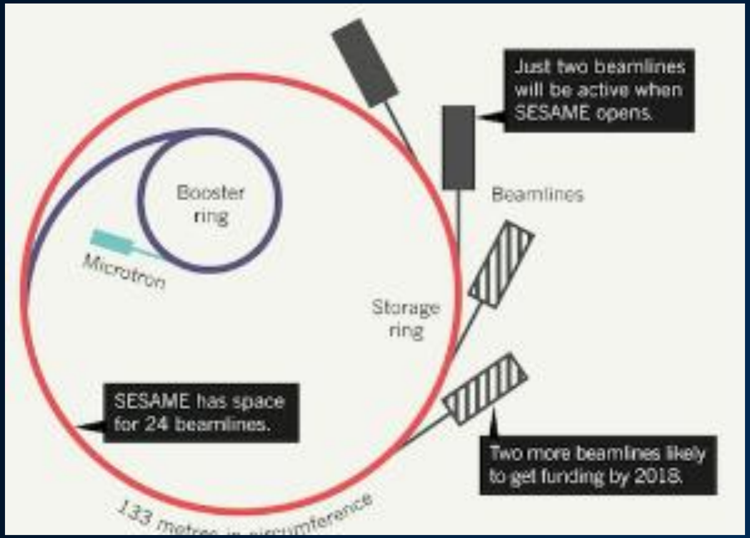


Horizontal beam emittances at existing and planned world light sources.

Figure courtesy of Argonne National Laboratory, managed and operated by UChicago Argonne, LLC, for the US Department of Energy under Contract No. DE-AC02-06CH11357.

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)

CERN FP7 Contract 338602 In support of SESAME

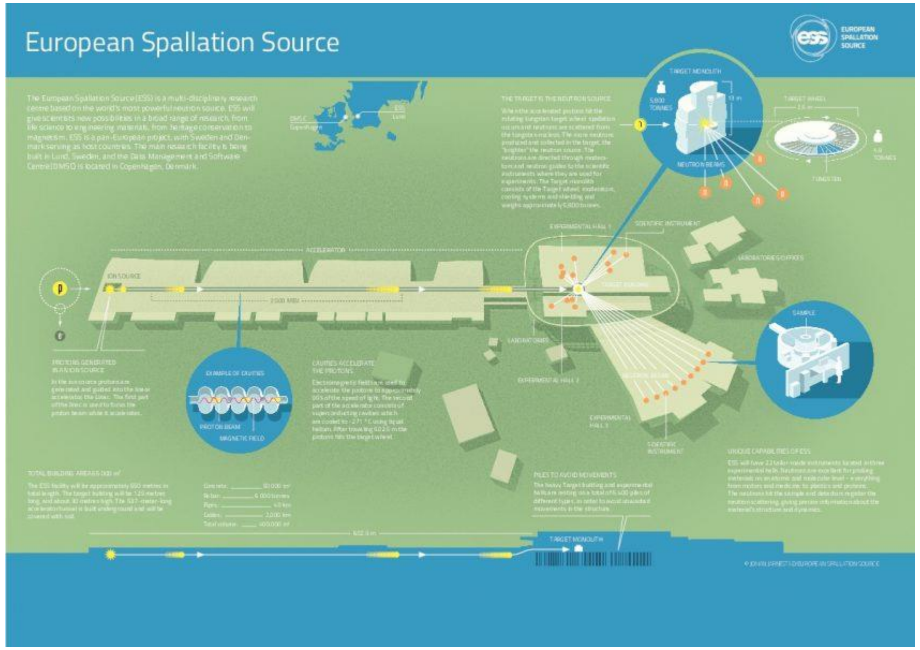
Spallation Neutron Source

SNS produces neutrons with an accelerator-based system that delivers short (microsecond) proton pulses to a steel target filled with liquid mercury through a process called spallation. Those neutrons are then directed toward state-of-the-art instruments that provide a variety of capabilities to researchers across a broad range of disciplines, such as physics, chemistry, biology, and materials science.

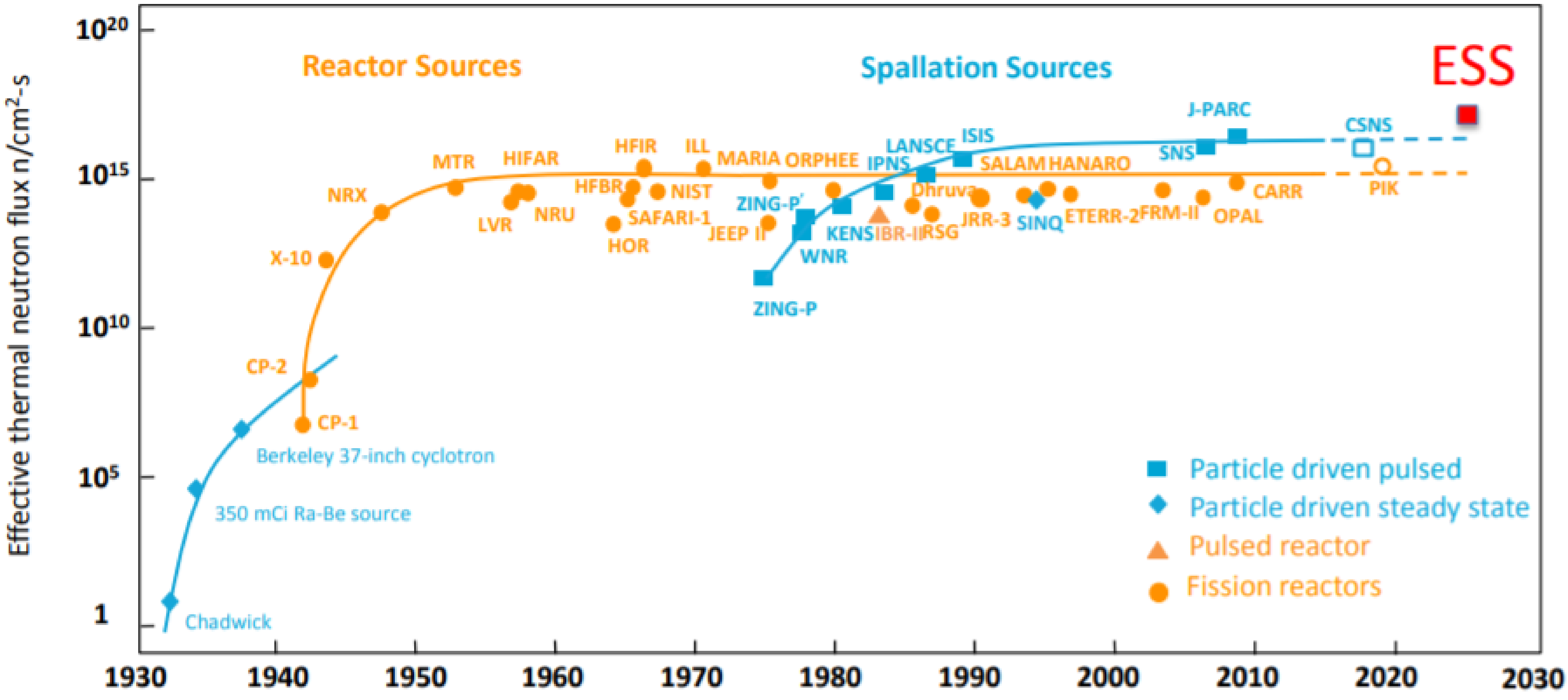
The linear accelerator accelerates the H- beam from 2.5 to 1000 MeV (1 GeV).
1.4 MW on target

European Spallation neutron Source

ESS will use nuclear spallation, a process in which neutrons are liberated from heavy elements by high energy protons. Unlike existing facilities, the ESS is neither a "short pulse" (micro-seconds) spallation source, nor a continuous source like the SINQ facility in Switzerland, but the first example of a "long pulse" source (milli-seconds): Repetition rate is 14 Hz, and the pulses of protons are 2.86 ms long.



The linear accelerator will accelerate a beam of protons from the exit of its ion source at 75 keV to 2 GeV
Rotating, helium-cooled tungsten target : 2 MW and up to 5 MW



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Accelerators and their Use

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Accelerators: Essential Tools in Industry

Ion Implantation

- Accelerators can precisely deposit ions modifying materials and electrical properties (boron, phosphorous)

Semi Conductors

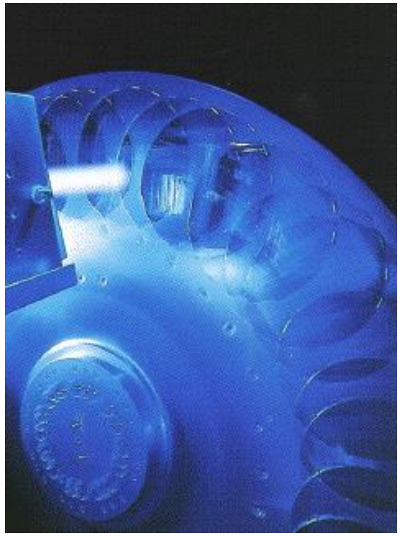
- CMOS transistor fabrication of essentially all IC's
- CCD & CMOS imagers for digital cameras
- Cleaving silicon for photovoltaic solar cells
- Typical IC may have 25 implant steps

Metals

- Harden cutting tools
- Reducing friction
- Biomaterials for implants

Ceramics and Glasses

- Harden surfaces
- Modify optics
- Color in Gem stones!



N2 ions reduce wear and corrosion in this artificial femur

Courtesy of Nigel Lockyer

Accelerators: Essential Tools in Industry

Electron beam printing

- Conventional printing requires use of enormous amounts of solvents that are created, evaporated, and must be disposed of … all with significant environmental impact
- EB printing can print 12 colors at 600 M/min with water based inks
- EB's also enables new packaging methods for food (foil-glue-foil)
- Your milk carton or potato bag may have been manufactured with this technology

Electron Beam Packaging

Accelerators for Industrial Processes

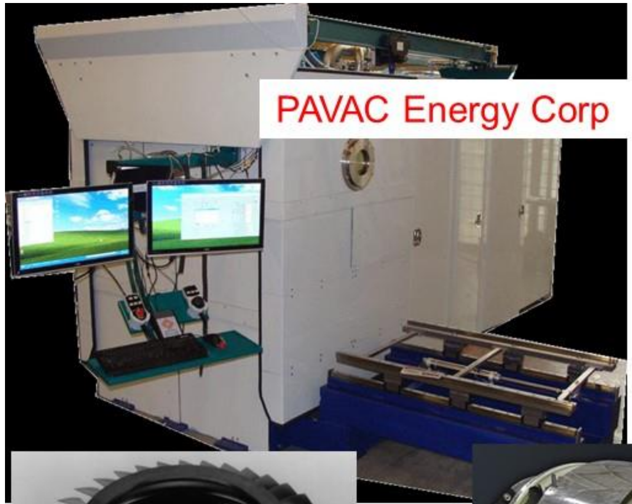
Fuel injectors

Turbo chargers

Weld gear boxes
Harden gears

Electron Beam Welding and Machining

- Deep welds, low weld shrinkage
- Dissimilar or refractory metals, etc
- Widely used in automotive and aerospace industry
- Drill 3000 holes/sec!



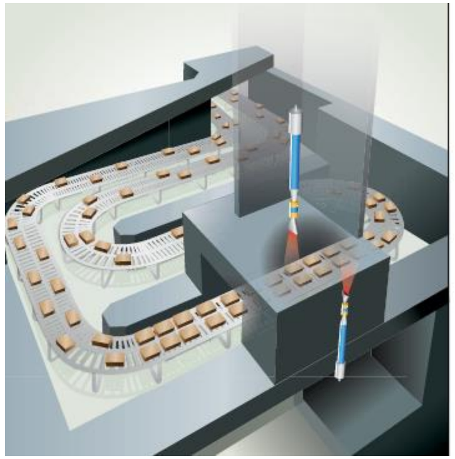
Accelerators: Food Preservation

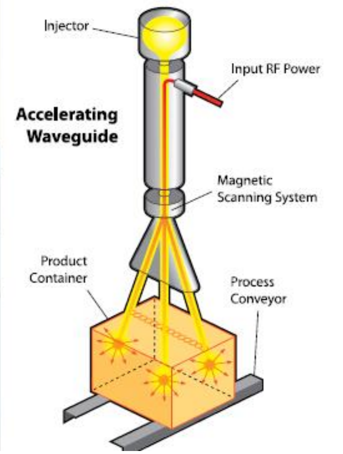
Low-energy beams of electrons can help beat food-borne illness

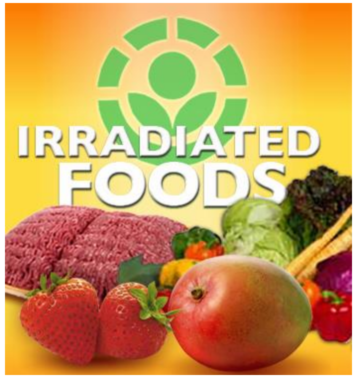
- ~60 people die from food-borne illness in the U.S. each week
- Food poisoning is estimated to cost the US $152 billion a year.

- Electron beams and/or X-rays can kill bacteria like E. coli, Salmonella, and Listeria.
- Currently in use for: Spices, fruit, lettuce, ground beef, milk, juice, military rations…

- Many more opportunities exist
- **Barriers = cost & public acceptance**







Radura symbol

Accelerators for security

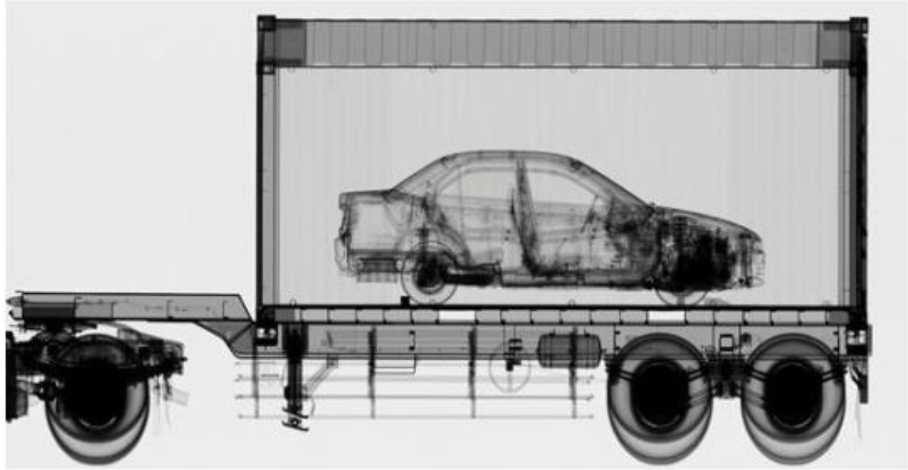


Image source: Varian medical systems

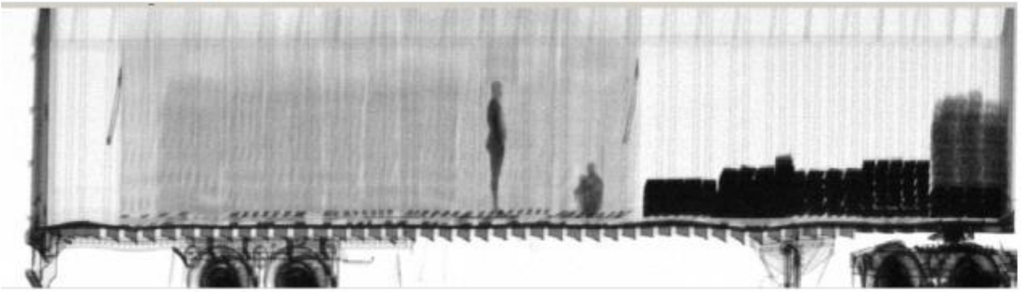


Image: dutch.euro

Accelerators are used for cargo containers scanning at ports and border crossings

Accelerator-based sources of X-Rays are far more penetrating than Co-60 sources

Container must be scanned in 30 seconds

Accelerators and their Use

More than 35’000 particle accelerators in the world

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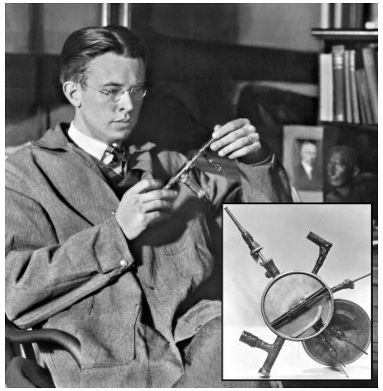
AMIT (Advanced Molecular Imaging Technologies) compact superconducting cyclotron for isotope production (CIEMAT, Spain)

Beam requirements: $E > 8.5\text{MeV}$ $I > 10\mu\text{A}$

Accelerators % Medicine



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

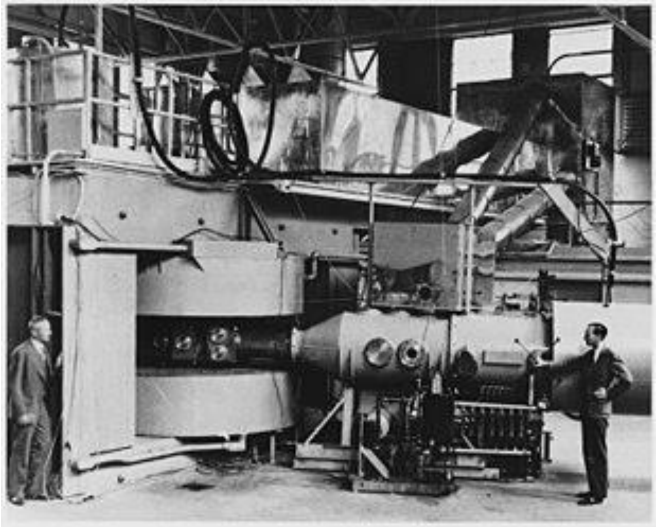
- 90 years ago in 1928 Rolf Wideröe invents the modern radio-frequency accelerator (for his PhD Thesis at Aachen).
- In 1929 Ernest O. Lawrence in Berkeley adds cyclic acceleration and develops the cyclotron, the first high-energy accelerator, producing 1.1 MeV protons in 1931.

- In 1936, the new Berkeley 37-inch *(94 cm)* cyclotron was producing isotopes for physics, biology and medicine – in parallel to the time devoted to discoveries in nuclear physics.
- Starting in 1937, Lawrence's brother John was the pioneer of injecting radioisotopes produced at the cyclotron to cure leukaemia and other blood diseases.

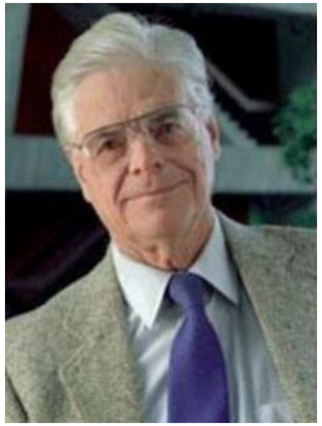
Particle beam treatments – from neutrons to protons

In 1938 starts **direct irradiation** of patients with **neutrons** from the new 60-inch (152 cm) cyclotron. First direct irradiation of a patient, 20 Nov. 1939 (from left: Dr. R. Stone, J. Lawrence, patient R. Penny) in a special treatment room on the new 60-inch cyclotron

Lawrence's priority was to promote his science and to build larger and larger cyclotrons. He considered medical applications as a formidable tool to show the public the potential of this new technology and to raise more funding for his projects.
During the 30's, more than 50% of beam time was devoted to producing isotopes for medicine and other applications, to the disappointment of the physicists that were using the cyclotron beams to lay the ground of modern nuclear physics.



a "truly colossal machine."



In 1946, Robert Wilson proposed to use protons to treat cancer, profiting of the Bragg peak to deliver a precise dose to the tumour *(Wilson had been working at Berkeley, then moved to Harvard and finally founded Fermilab).*

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

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

The Bragg peak

The Nobel Prize in Physics 1915

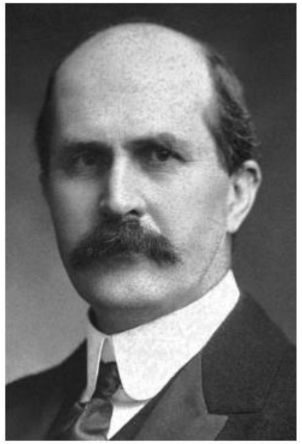


Photo from the Nobel Foundation archive.
Sir William Henry Bragg
Prize share: 1/2

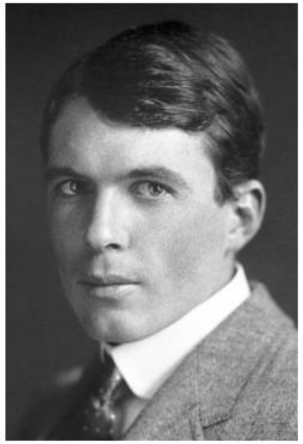


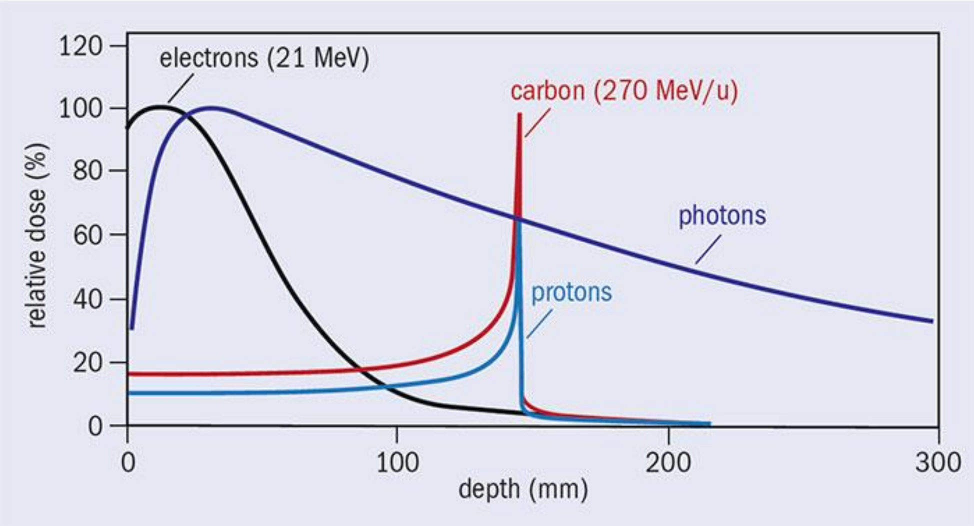
Photo from the Nobel Foundation archive.
William Lawrence Bragg
Prize share: 1/2

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."

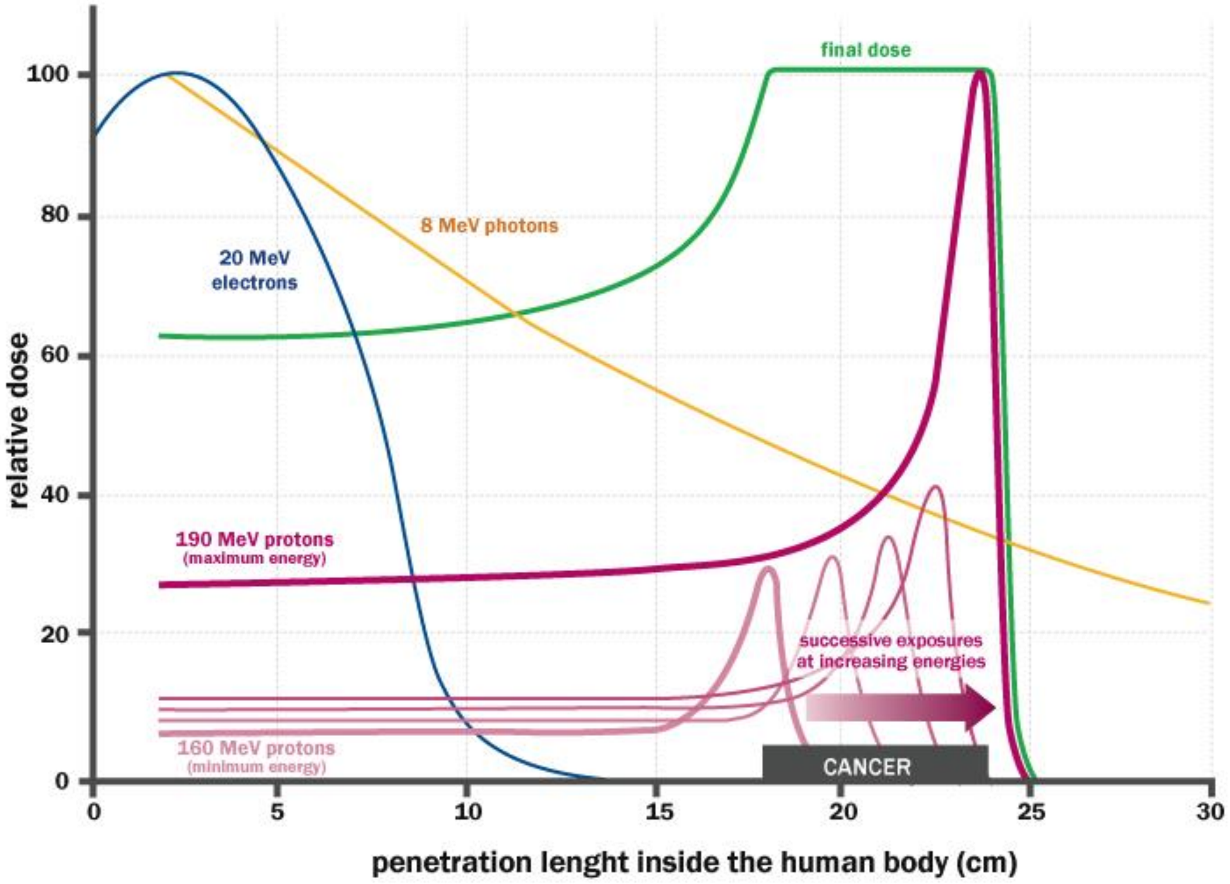
The Bragg peak is a pronounced peak on the Bragg curve which plots the energy loss of ionizing radiation during its travel through matter. For protons, α-rays, and other ion rays, the peak occurs immediately before the particles come to rest.

When a fast charged particle moves through matter, it ionizes atoms of the material and deposits a dose along its path. A peak occurs because the interaction cross section increases as the charged particle's energy decreases.

For protons and other ions the peak of energy loss occurs just before the particles reach a halt.



The 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 energies:
Protons: 60 – 250 MeV/u
Carbons: 120 – 430 MeV/u
Beam energy accuracy : 0.25 MeV/u
Protons and Carbons: ~ 10^{10} per pulse

Short history of Proton Beam Therapy

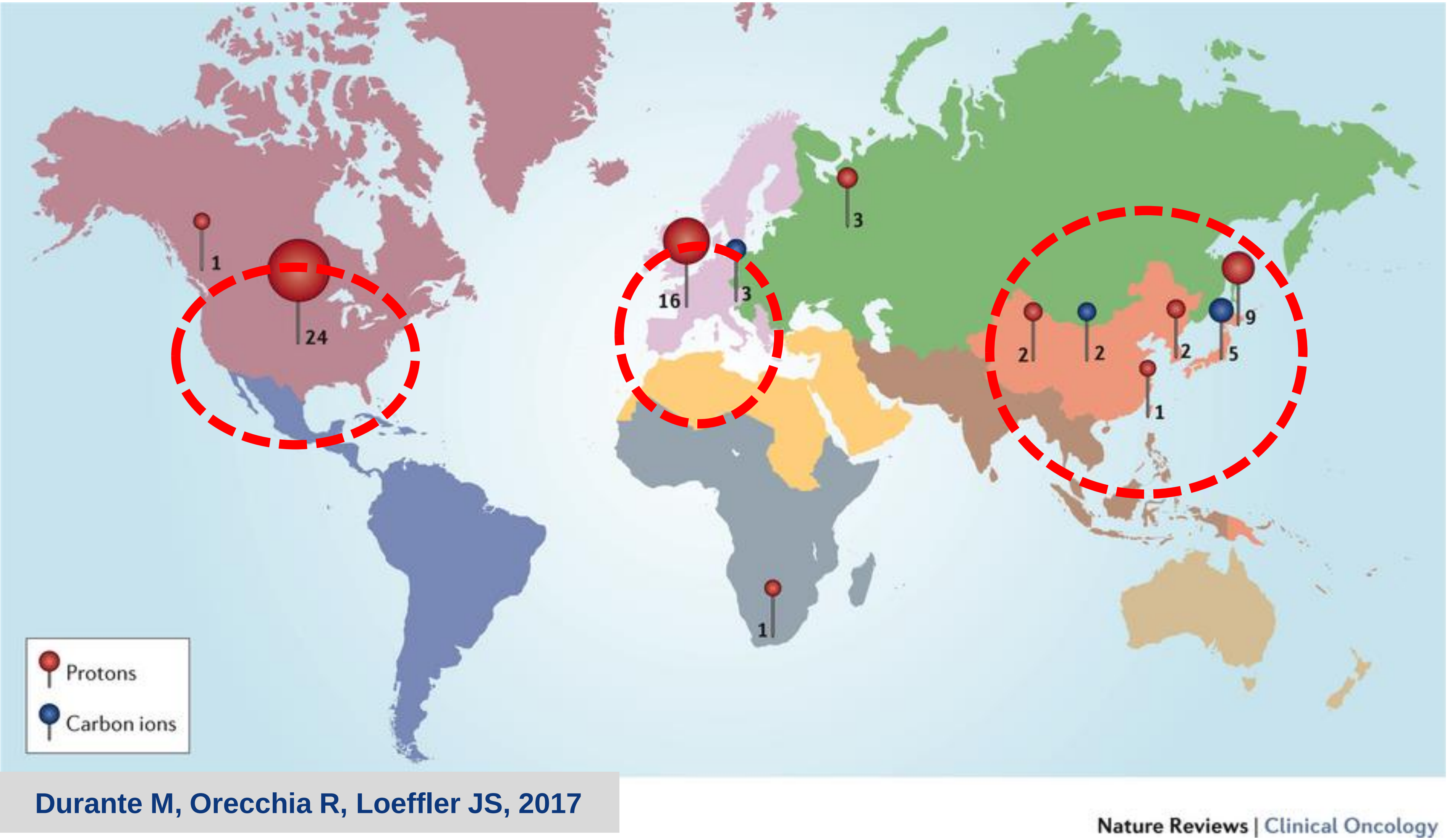
- 1946, Robert Wilson proposed to use protons to treat cancer, profiting of the Bragg peak
- 1954 first experimental treatment in Berkeley.
- 1956 treatment of pituitary tumours in Berkeley
- 1958 first use of protons as a neurosurgical tool in Sweden
- 1974 large-field fractionated proton treatments program begins at HCL, Cambridge, MA
- 1990 first hospital-based proton treatment facility (Loma Linda, US).
- 1994 first treatment facility with carbon ions in 1994 (HIMAC, Japan).

- **From end of ‘90s, treatments in Europe at physics facilities.**
- **2009 first dedicated European facility for proton-carbon ions (Heidelberg).**
- **From 2006, commercial proton therapy cyclotrons appear on the market (but Siemens gets out of proton/carbon synchrotrons market in 2011).**
- **Nowadays 4 competing vendors for cyclotrons, one for synchrotrons (all protons).**

A success story, but … increasing investment and operation cost, still large footprint,…

Hadron-therapy Centres

2017: 60 Proton Centres
10 Carbon Ion Centres



Durante M, Orecchia R, Loeffler JS, 2017

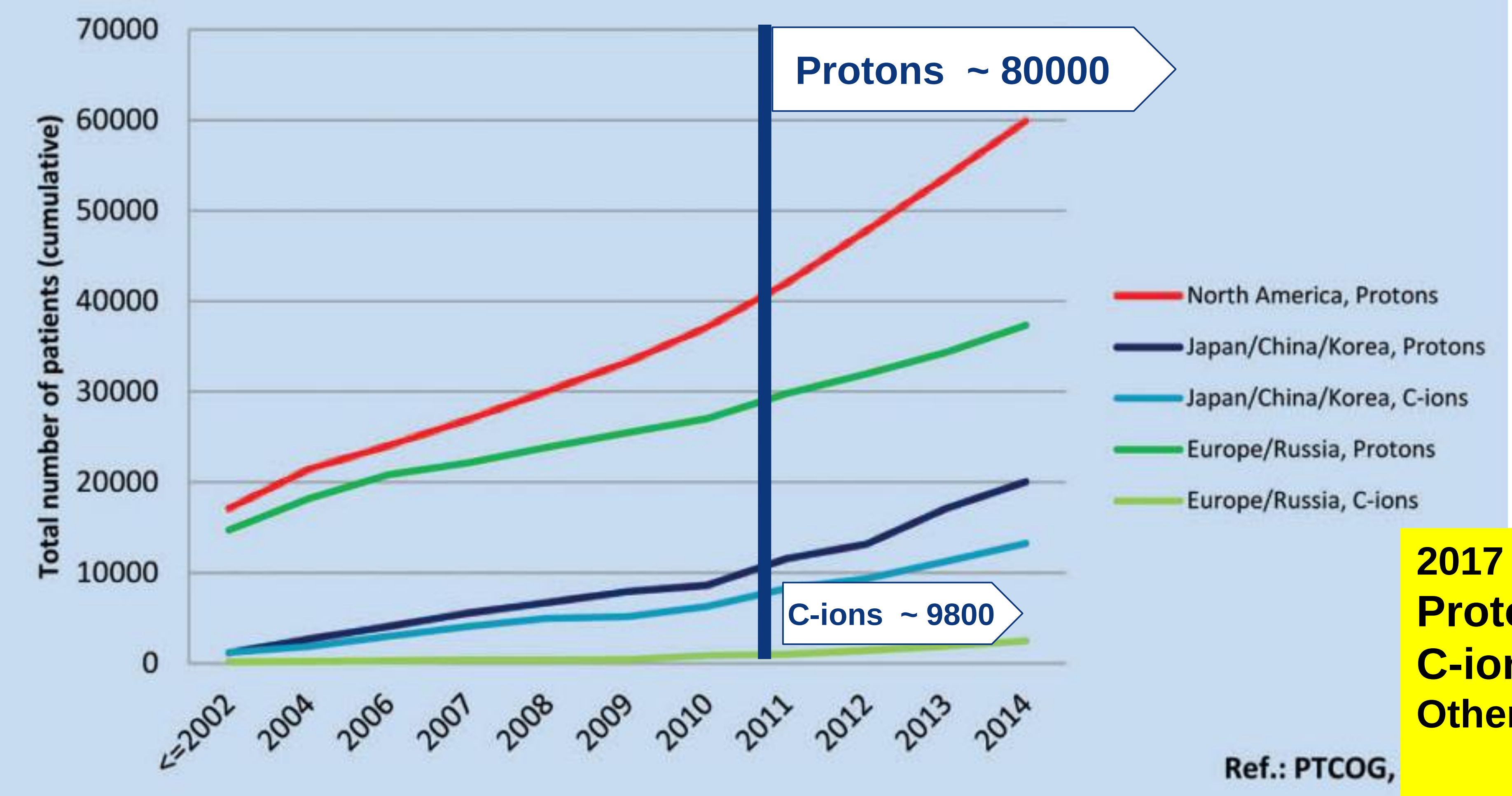
Particle Therapy in operation in Europe

In Europe, the interest in hadron therapy has been growing rapidly and the first dual ion (carbon and protons) clinical facility in Heidelberg, Germany started treating patients at the end of 2009. Three more such facilities are now in operation: CNAO in Pavia, MIT in Marburg, and MedAustron in Wiener Neustadt are treating patients.

Globally there is a huge momentum in particle therapy, especially treatment with protons (industrial offers).

By 2022 it is expected there will be almost 120 centres around the world, with over 30 of these in Europe.

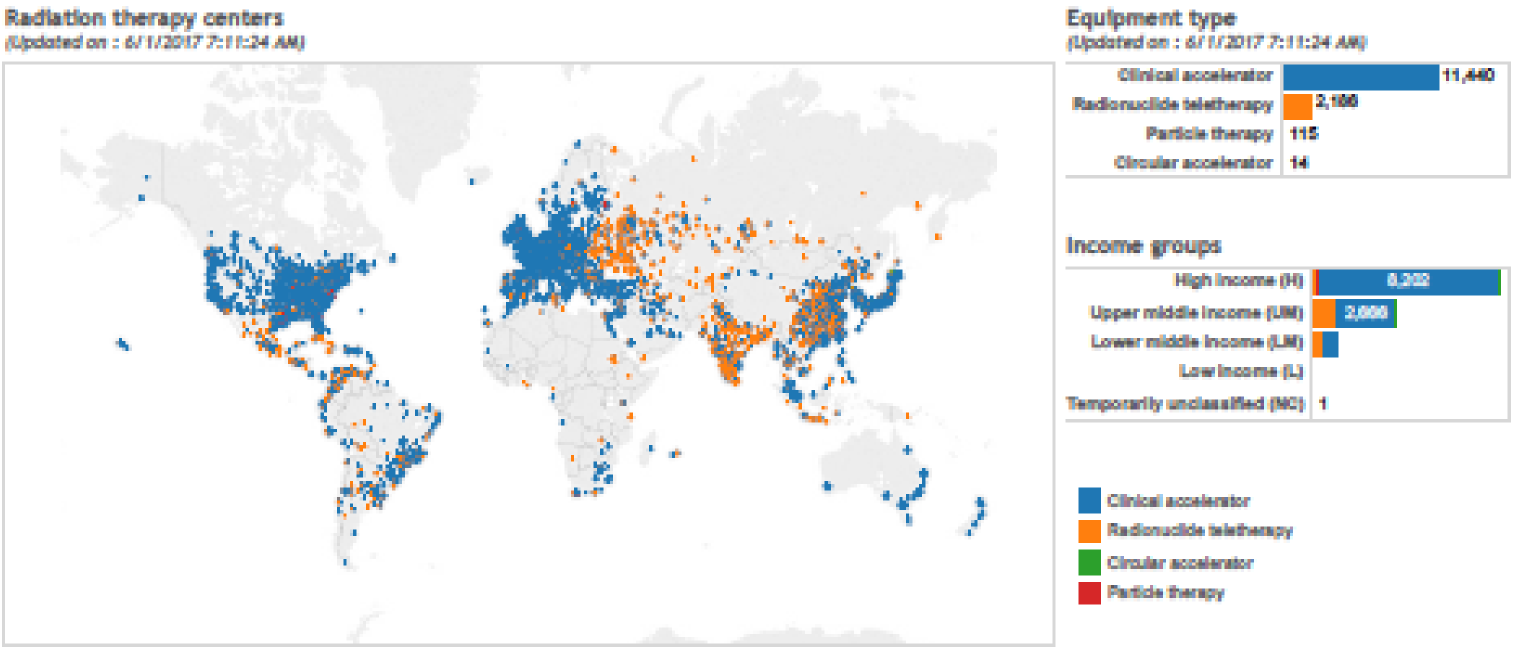
Number of treated patients with Protons and Carbon-ions



2017
Protons ~ 150'000 (+80%)
C-ions ~22'000 (+120%)
Other ions ~3'600

Total 175'600

Radiation therapy worldwide



Countries	RT centers	Equipment	Linac	Radionuclide Therapy	Circular Accelerator	Particle Therapy
139	7041	13755	11440	2186	14	115

(courtesy ENLIGHT Network)

~14'000 in operation worldwide!

Cobalt therapy

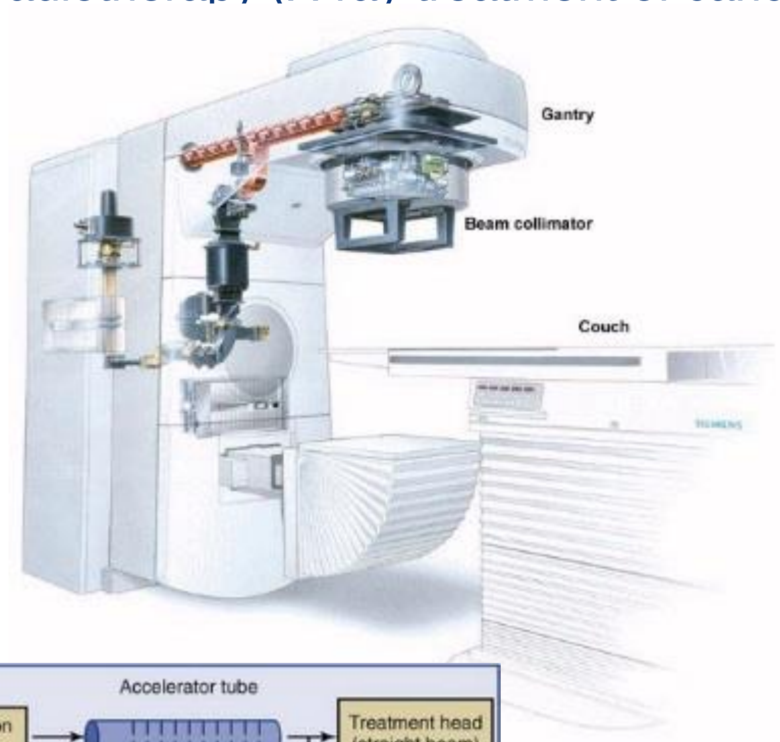
Radiation therapy nowadays relies mostly on linear accelerators, which in developed countries have replaced the cobalt therapy

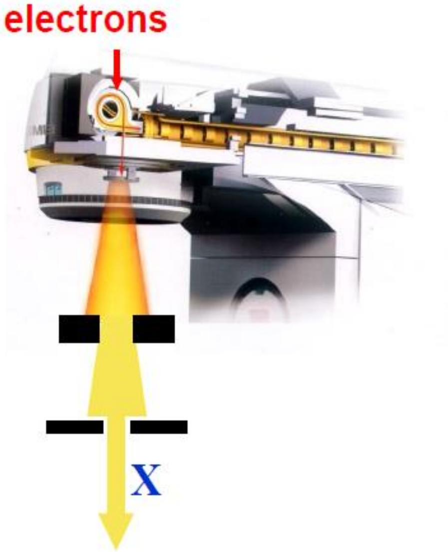
Unfortunately many countries with an expected increasing cancer rate are not covered.

The most successful accelerator

A great example of technology transfer from basic science to society

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





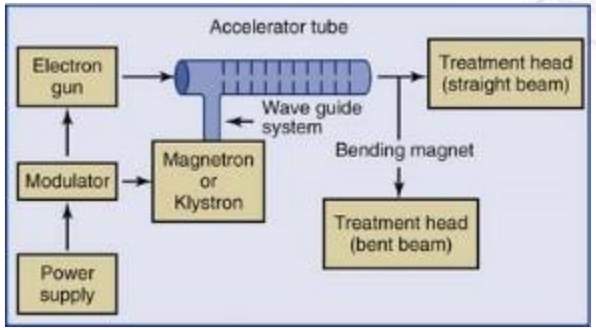
5 – 25 MeV e-beam
Tungsten target

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).

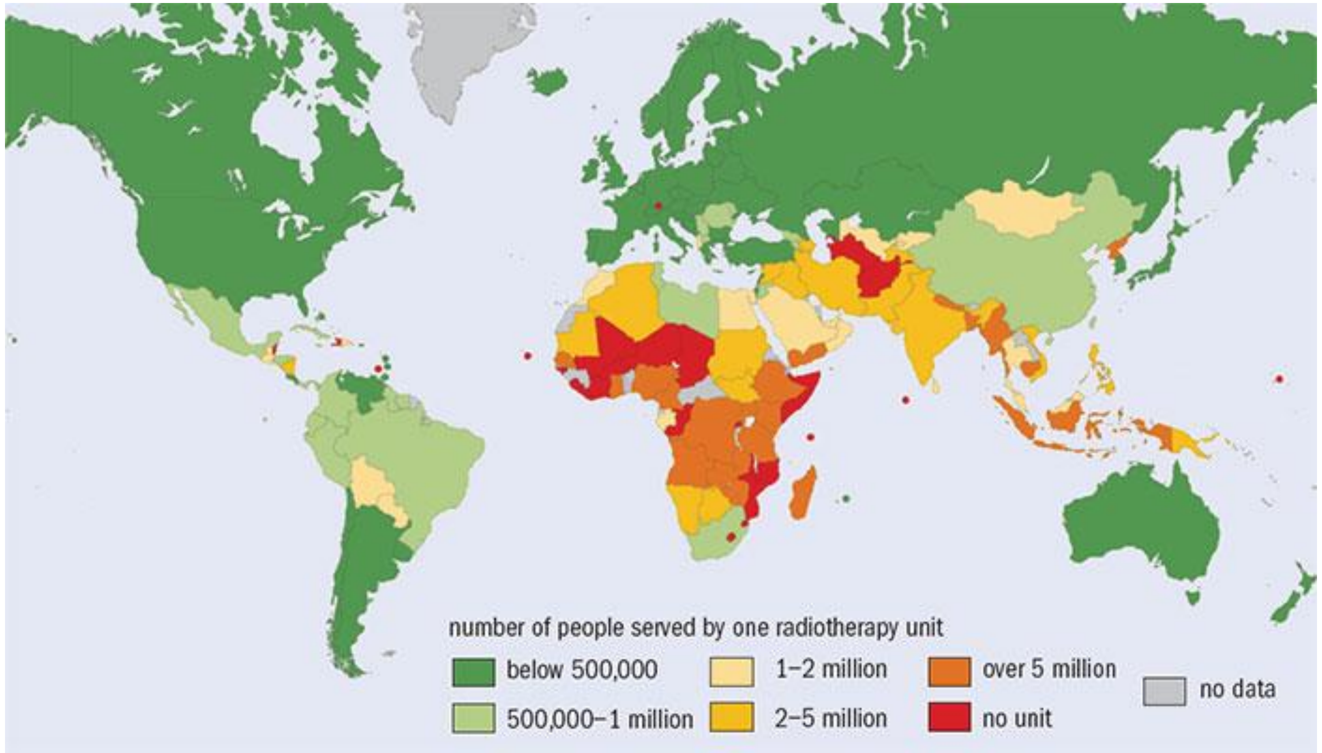
Combined imaging and therapy

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.



~14’000 in operation worldwide!

Medical linacs for challenging environments



Equipment is expensive, requires maintenance and a stable operating environment (electricity, humidity, dust, etc.)
=> this has reduced the access of low and middle income countries to radiation therapy.

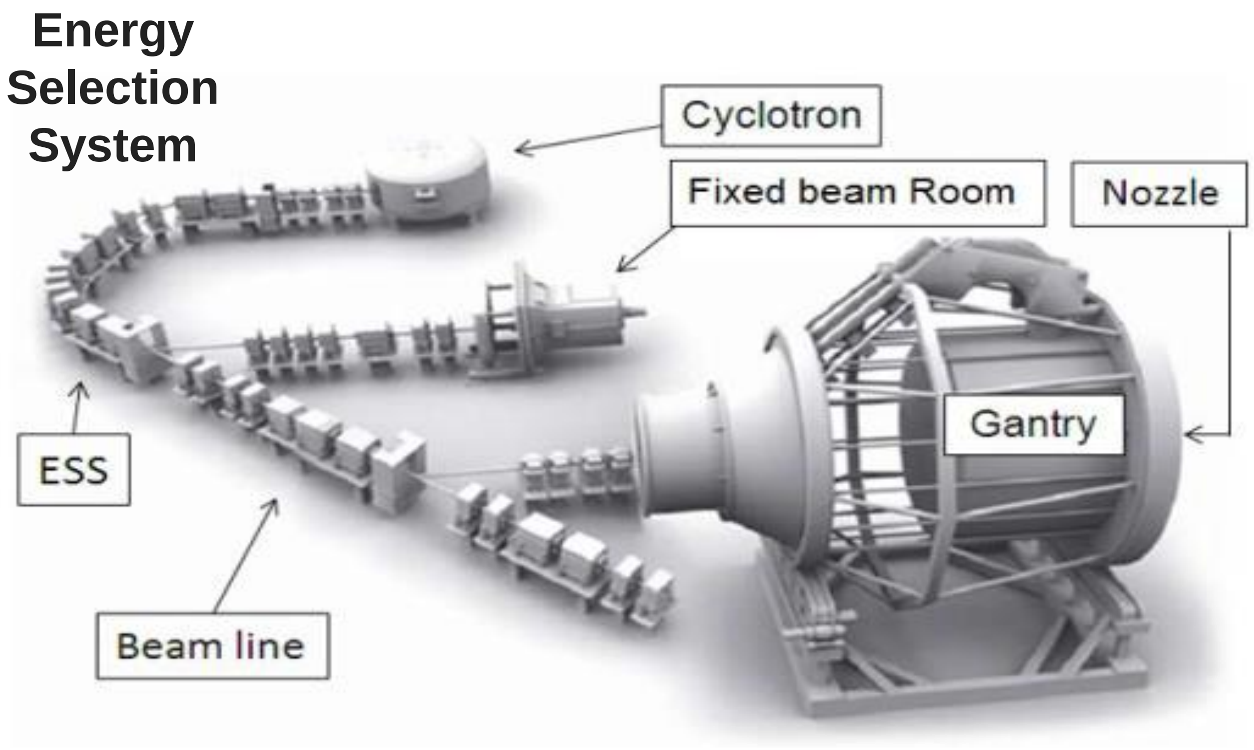
Develop a medical linear accelerator that provides **state-of-the-art conventional radiation therapy** in regions where power supply is unreliable, the climate harsh and/or communications poor.

Science & Technology Facilities Council

CERN

International Cancer Expert Corps
Partnering to transform global cancer care

Proton therapy accelerators: cyclotrons



At present, the cyclotron is the industrial accelerator to provide proton therapy reliably and at "**lower cost**" (4 vendors on the market).

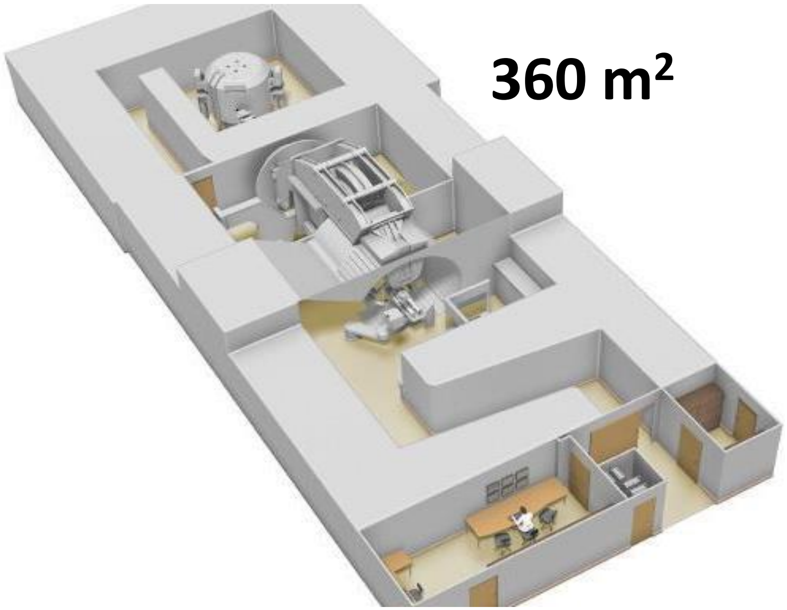
Proton Therapy Unit

- Quirónsalud Proton Therapy Center, located in Madrid, is a modern centre equipped with cutting edge medical technology to offer the highest quality and precision treatment.
- It will be a space for innovation and research and it will contribute to the **improvement of the results of cancer treatments** and the **quality of life of patients**.
- **IBA Proteus ONE** includes the latest generation Pencil Beam Scanning, isocenter volumetric imaging as well as the Philips Ambient Experience .This machine reduces the acceleration weight and energy consumption by a factor of four.
- **Largest user community of the world: 34 IBA-equipped proton therapy centres are in operation today around the world.**
- **Capacity of 800 patients/year**. (400 patients/year initially)
- First level of medical staff composed of experts of national and international prestige with great background in proton therapy in international centers in France, Netherlands or Switzerland.
- **First patient treatment in Spain with proton therapy in Spain: *December 26, 2019***

quirónsalud
La salud persona a persona

IBA Proteus ONE, Cyclotron

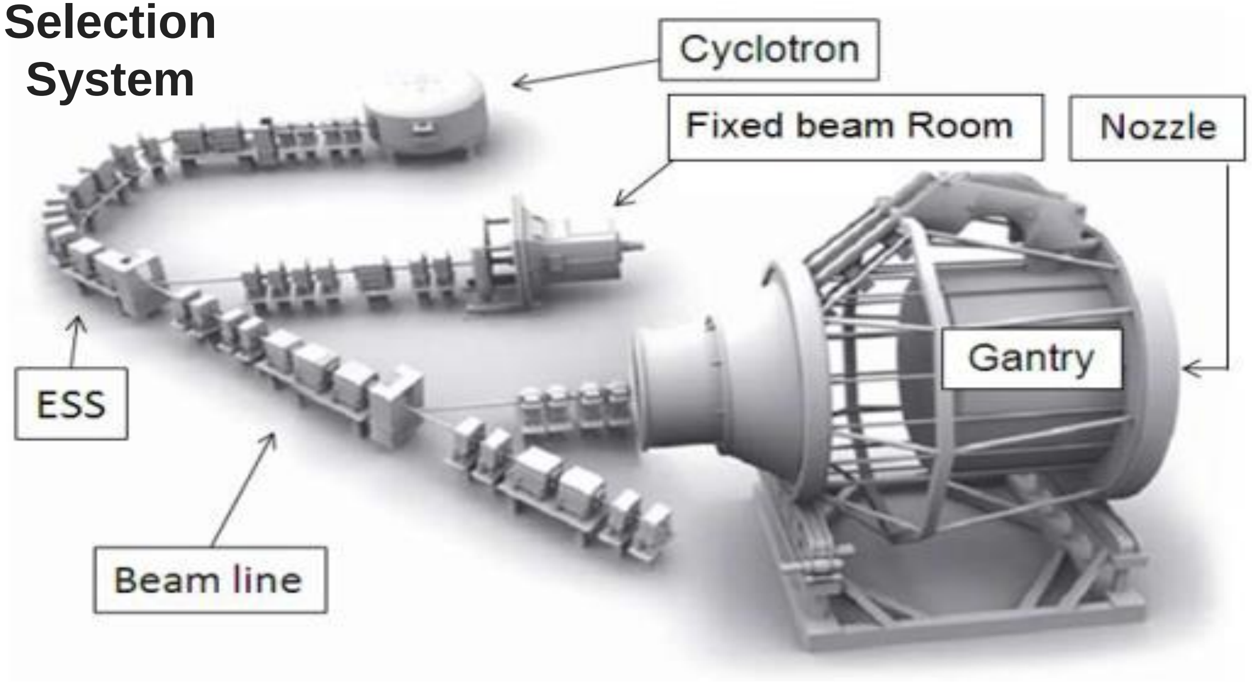
Hospital Universitario quirónsalud Madrid



- **Most compact design ever developed** → Easy to install, integrate, operate and finance.
- **Sub-millimetric precision**→ Compact gantry 360º with its 220º rotating structure combined with the 6 degrees of freedom of movement of Robotic Patient Positioner.
- **First flash radiotherapy technic** in the only compact image-guided IMPT solution. → high dose of radiation at an ultra-high dose rate.
- **Compact image guided solution** → Stereoscopic X-ray imaging and Cone Beam Computed Tomography CBCT at isocenter for patient position verification and anatomical modification assessment.
- **Latest Pencil Beam Scanning** → Minimum radiation exposure to healthy tissue.
- Possibility to upgrade the facility with PT modules.

Ion therapy accelerators: cyclotrons ?

Energy Selection System



At present, the cyclotron is the industrial accelerator to provide **proton therapy** reliably and at "**lower 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**
3. **Ion therapy: cyclotrons cannot be easily used because of the dimensions and complexity (needs superconductivity) and because of the complexity of ion extraction from cyclotrons.**

All existing ion medical accelerators are large synchrotrons.

Proton Therapy Unit

Clínica Universidad de Navarra

Cancer Center Universidad de Navarra

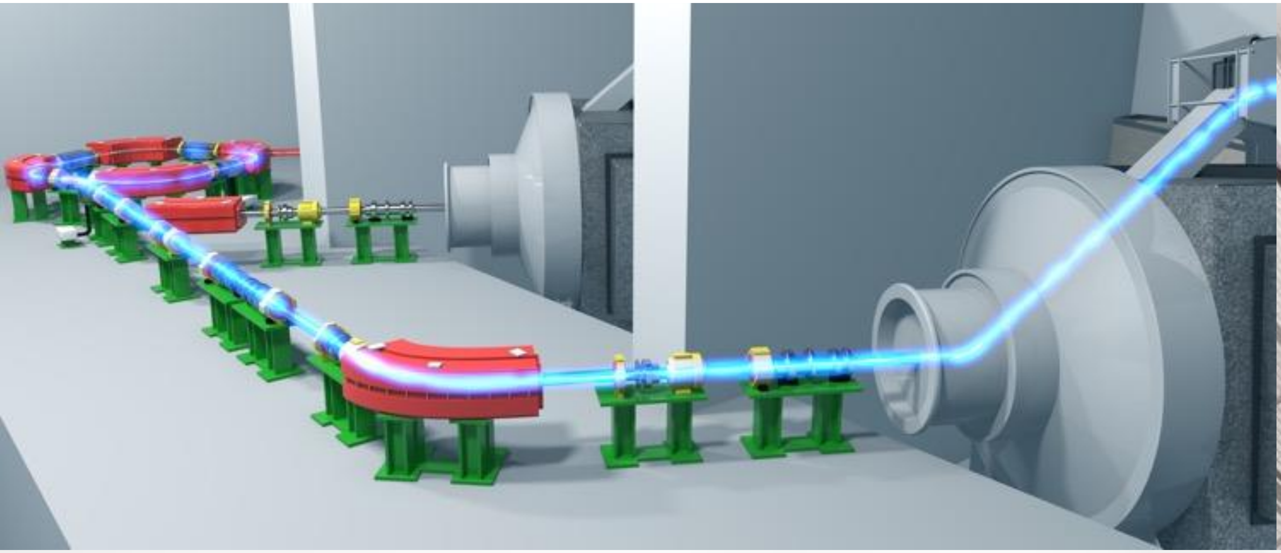
Caring · Researching Innovating · Teaching

- First In-Hospital Proton Therapy Unit at a Cancer Centre in Spain
- Being part of the Universidad de Navarra, it is a non-profit academic institution with two distinctive features in its DNA: research and knowledge transfer
- Integrating state-of-the-art technology: **the first Hitachi synchrotron in Europe**, present in American and Japanese hospitals internationally renowned for cancer treatment
- Integrated in a Hospital and the Cancer Centre Universidad de Navarra:
  - Access to the most advanced cancer therapies
  - Designing a personalised treatment with all available precision therapies
  - Clinical trials and competitively funded research projects (national and international bids)
  - Legacy of having led the implementation of the most advanced radiotherapy techniques
- A team of renowned professionals with proven care and research experience, trained at the world's most specialised facilities in proton therapy and synchrotron technology

Clínica Universidad de Navarra

Hitachi Synchrotron

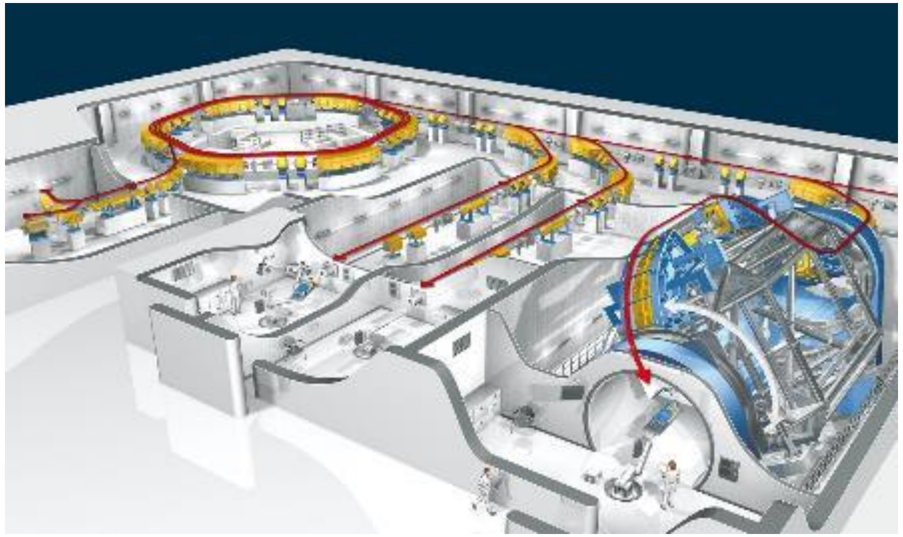
Cancer Center Universidad de Navarra
Caring · Researching Innovating · Teaching



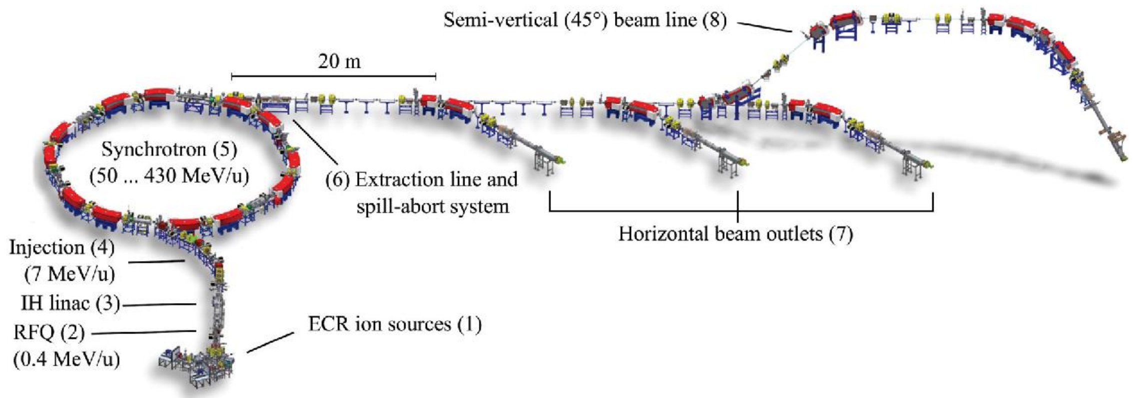
- 360º rotation → Irradiation from any angle
- 30 x 40 cm² Maximum field
- Cone Beam CT → Reduces uncertainty in patient preparation
- Pencil Beam Scanning → Greater dose accuracy and less damage to healthy tissue
- “Real-time tumour tracking” based on orthogonal fluoroscopy images → tumour motion
- No subsequent beam degradation process required
- “Multi energy extraction system” → reduces the patient's irradiation time
- Two-gantry expandable system

Ion therapy accelerators: synchrotrons

- **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.**



Heidelberg Ion Therapy Center



Marburg Ion-beam Therapy Centre

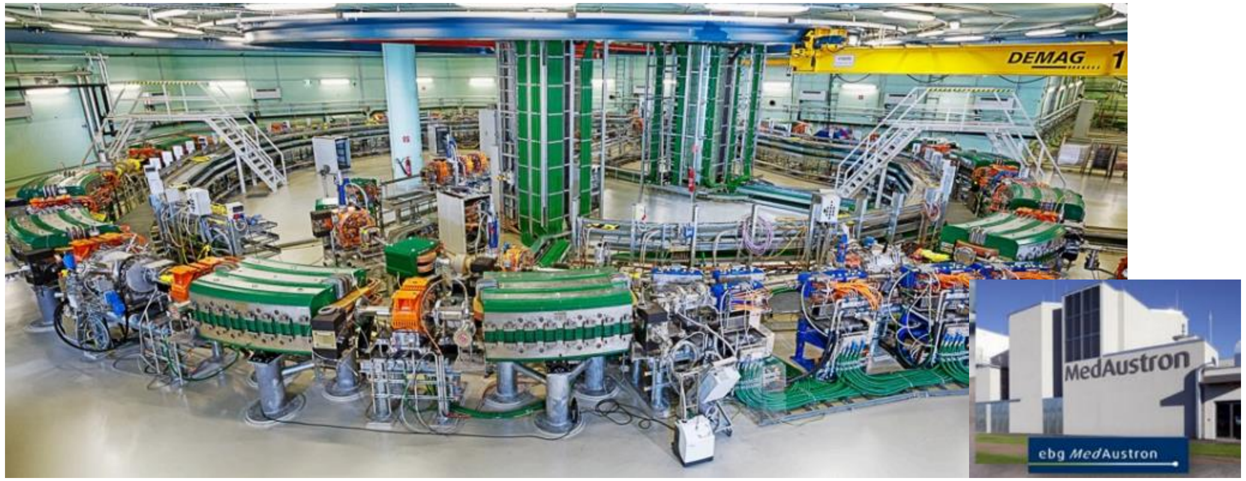
PIMMS

The **Proton Ion Medical Machine Study (PIMMS)** was hosted at CERN at the end of the 1990s and supported by MedAustron, Onkologie-2000 and the TERA Foundation

Outcome: **synchrotron design optimised for treating cancer with protons and carbon ions (a toolkit !)** 

Design further adapted by TERA and finally evolved into CNAO (Italy), with seminal contributions from INFN

MedAustron (Austria) was built starting from the CNAO design.



From PIMMS to NIMMS

NIMMS = Next Ion Medical Machine Study

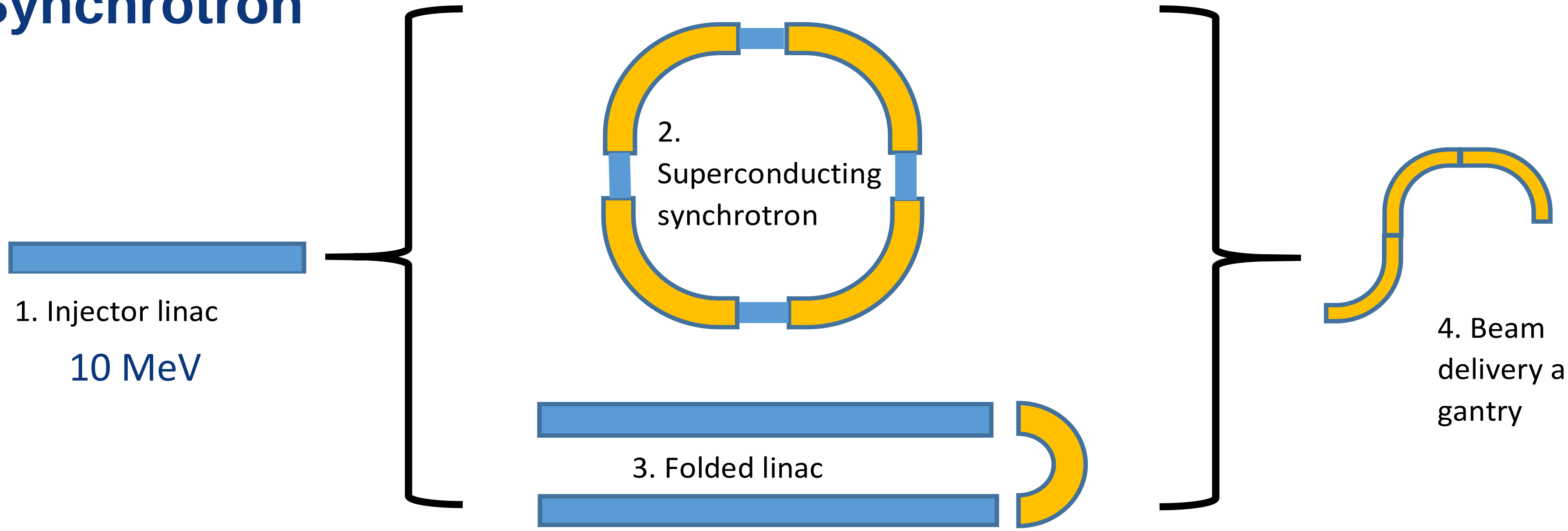
~20 years later (and after the LHC construction!):

next generation of ion therapy accelerators ?

A new **collaborative study** to develop the design and the key components for a new generation of medical accelerators:

- **more compact**
- **cost-effective**
- **light-ion (carbon, helium,…)**

Two possible designs for the future facility:
- **Superconducting Synchrotron**
- **Linear Accelerator**



Compare and analyse different options

Intermediate report

Jan 2019- Jun 2020

Jul 2020 – June 2022

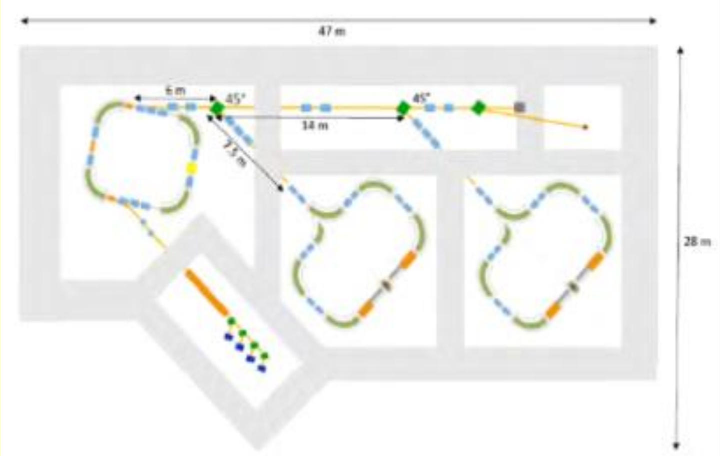
Technical design study and prototyping of the selected accelerator configuration

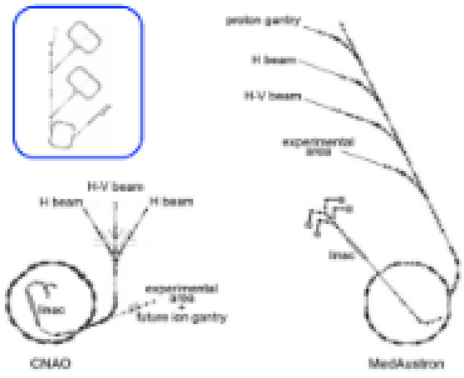
Design report

Options for next generation ion therapy

Superconducting synchrotron

CCT-type magnets,
Bmax 3.5T,
Ring 27m

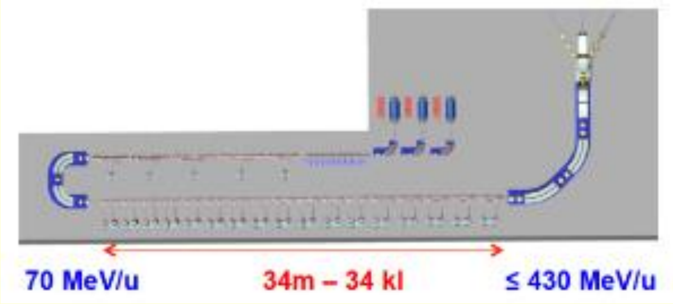


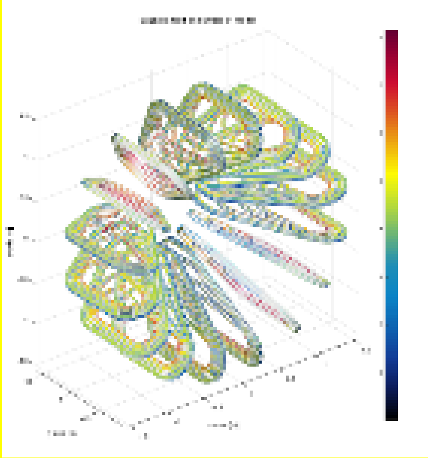


Size comparison:
Superconducting (top left)
vs. CNAO (bottom left)
and Medaustron (right)

Linear accelerator

Folded, 53m length,
high rep. frequency and intensity,
low emittance



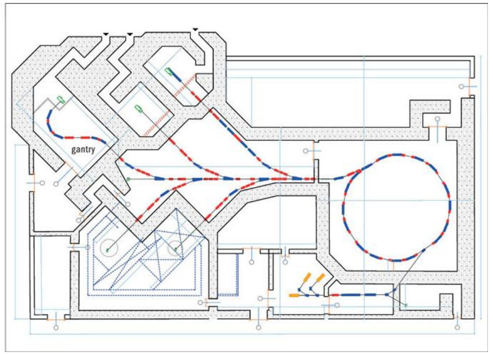


Superconducting gantry

Two options being analysed:
- Rotational CCT magnets (TERA)
- Toroidal (L. Bottura, CERN)

SEEIIST project

- CERN is collaborating with the **SEEIIST** (South East Europe International Institute for Sustainable Technologies), a new international partnership aiming at the construction of a particle therapy facility in South East Europe.
- SEEIIST has received a preliminary funding of 1 M€ from the EC, part of which will be used to finance 2 FTEs working on ion therapy accelerator design for the next 18 months under the supervision of CERN (18pm for beam optics, 6pm for diagnostics and extraction + 6pm for magnet design).
- EU **Design Study** proposal to the last call of H2020 Research Infrastructures, was submitted in November 2019, mobilising some 15-20 partners. 3 years duration 2020/23, 3 MEUR, co-funded. **Heavy Ion Therapy Research Infrastructure Design Study Proposal (HITRI)**
- The Design Study with: CERN, GSI, CEA, U. Liverpool, INFN, CNAO, Medaustron, HIT, IAP, Cosylab, U. Melbourne + SEEIIST and other partners in the region.
- Other partners interested in collaborating with CERN are from India, Latvia, Iran, Spain, Sweden, etc.
- A dedicated collaboration for the design of a superconducting gantry, possibly of the toroidal type, has been started with CNAO, INFN and MedAustron.



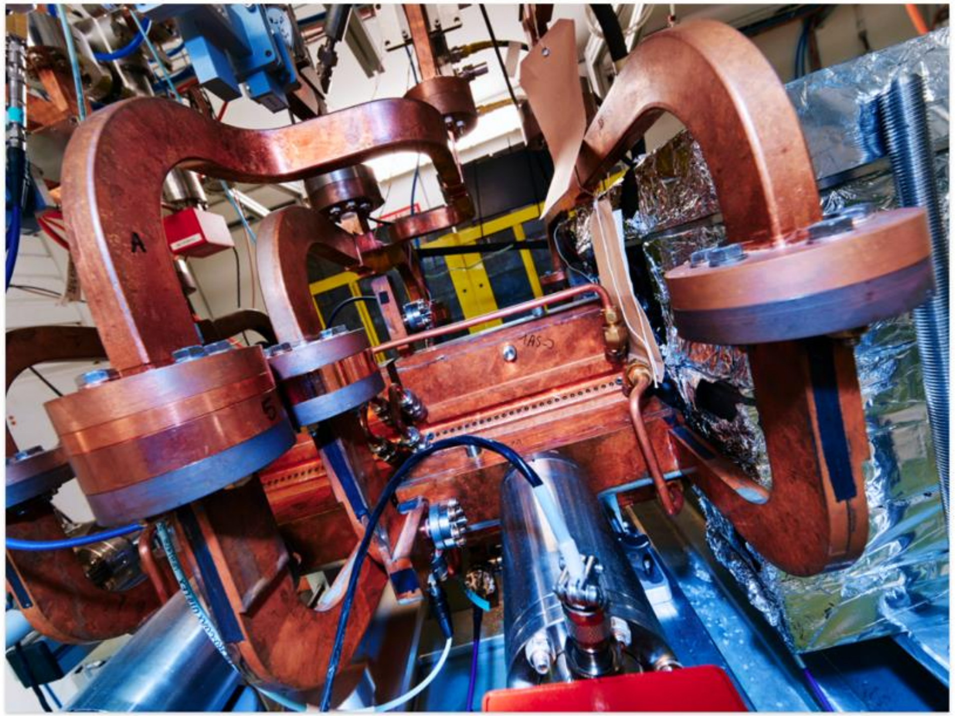
HITRI plus
Heavy Ion Therapy Research Integration

FLASH radiotherapy: CDR in 2020

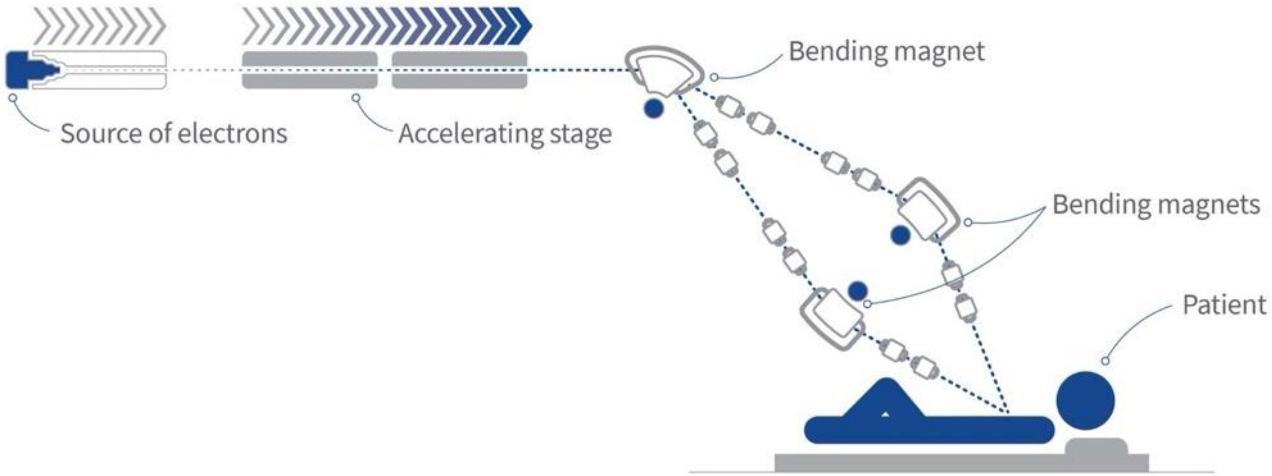
CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

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



Close-up 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.

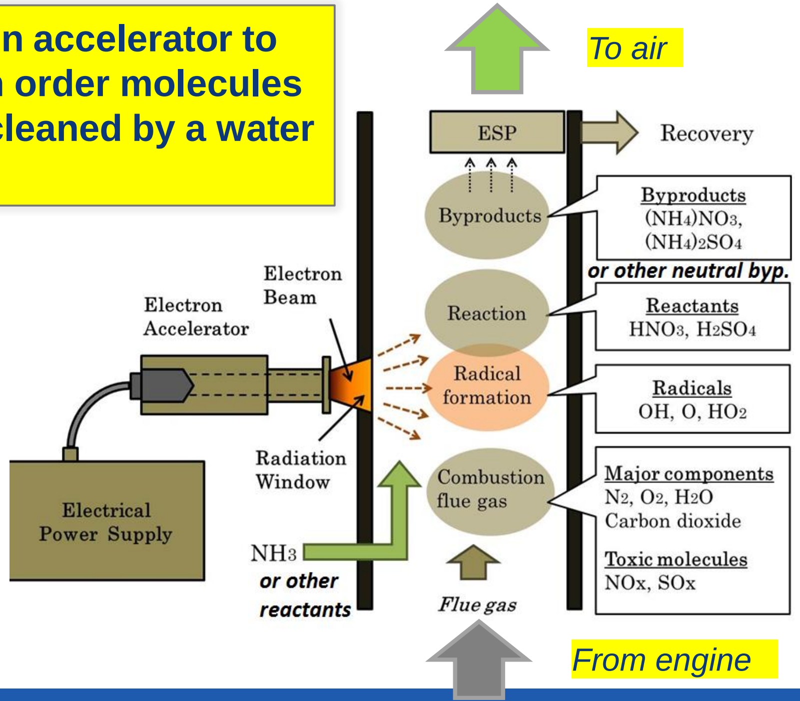
The solution comes from the conceptual design of a unique apparatus based on the CLIC (Compact Linear Collider) accelerator technology, which will accelerate electrons to treat tumours up to 15 to 20 cm in depth.

Environmental applications of accelerators

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)

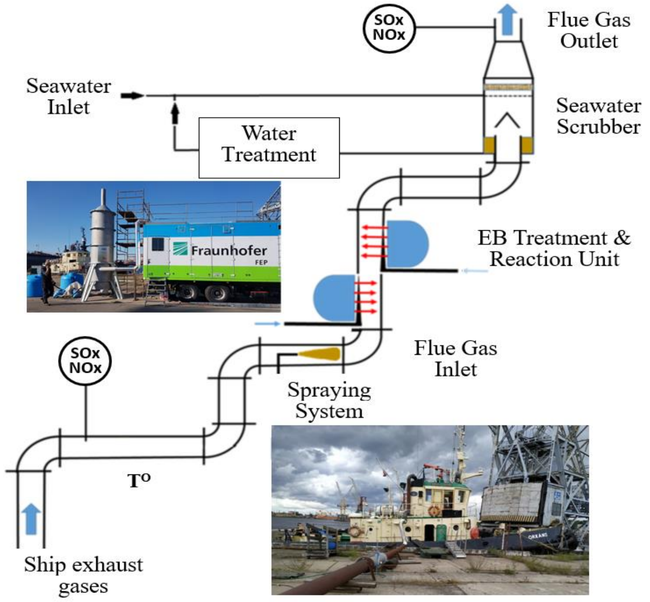


Hybrid Exhaust Gas Cleaning Retrofit Technology for International Shipping (HERTIS)

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

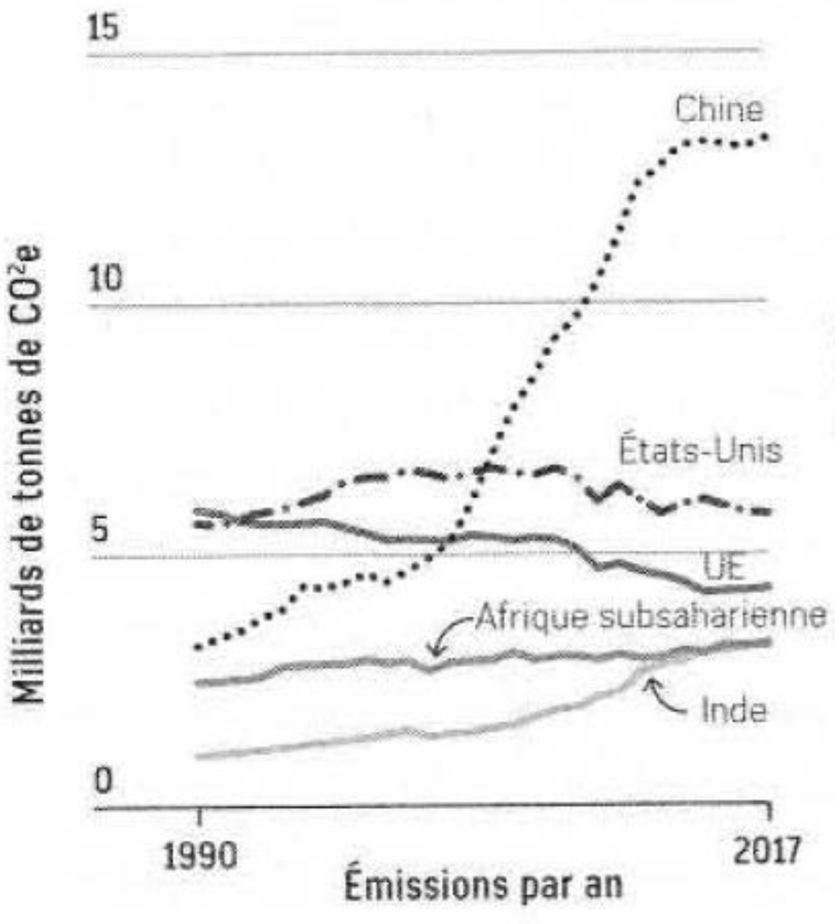
Mobile electron accelerator system from FAP Dresden commonly used to treat crops connected to the exhaust funnel of the Orkāns, an old Soviet-built tugboat. The fumes then passed through a small water scrubber before being released in the air.

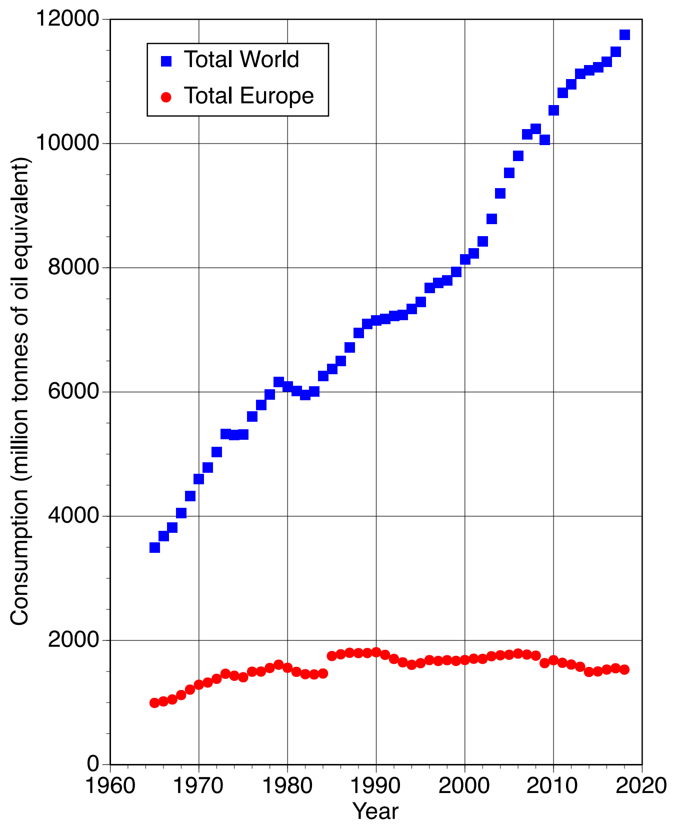


The tests confirmed the laboratory measurements and the overall effectiveness of the system.

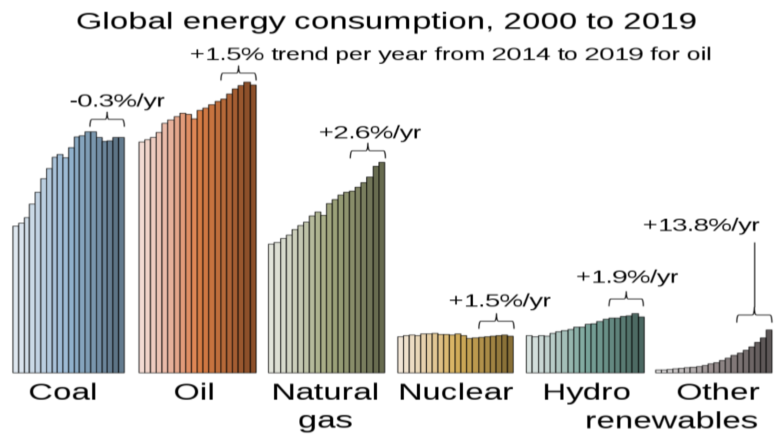
Measured **NOx removal rate 45%** at full engine power with the available scrubber and accelerator. Estimated removal with optimised scrubber and homogeneous e-beam 98%.
SOx removal only measured in laboratory (no Sulphur allowed in port) with similar removal rates.

Today, we collectively emit around 50 billion tonnes of CO_2e each year.





Europe is not representative of the whole world

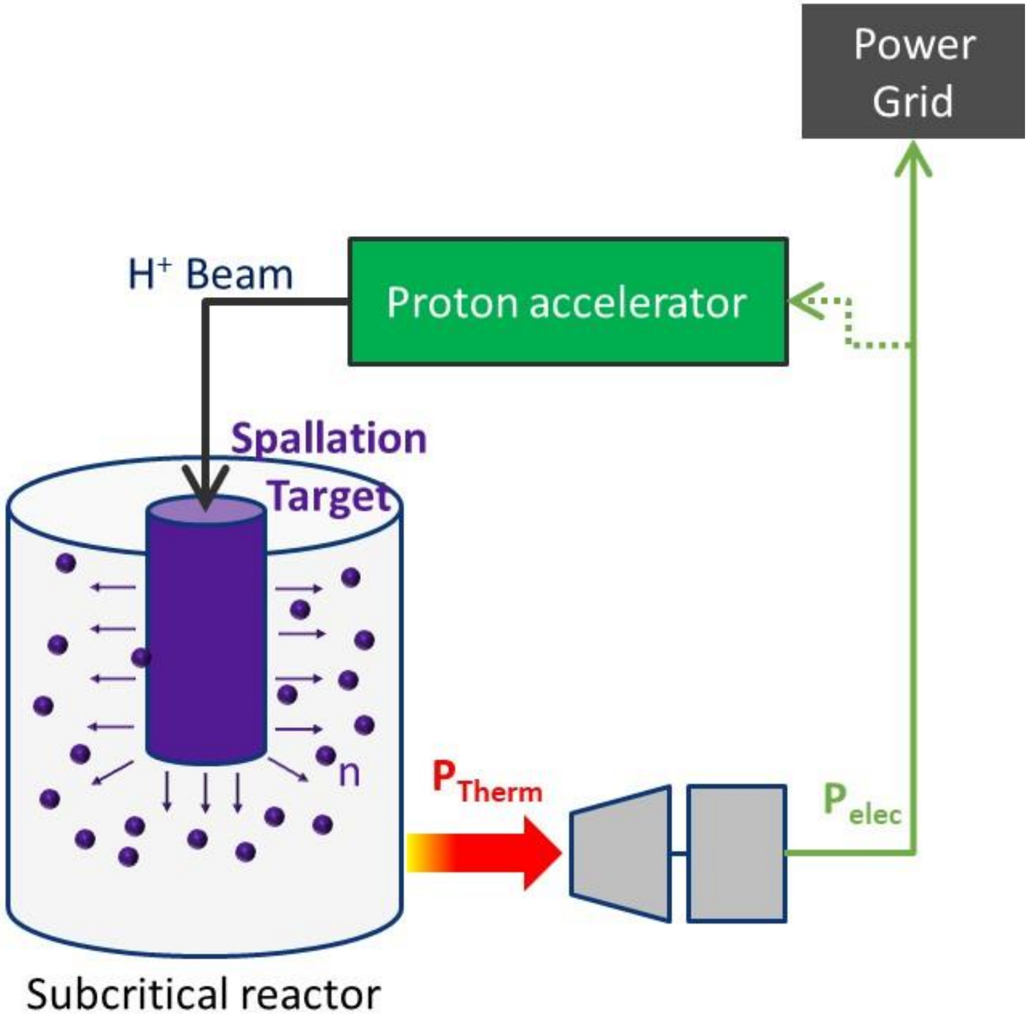


The world needs to provide access to energy to nearly a billion people who still lack it (China, India, Brazil, Pakistan, Africa, etc.)
And by 2050, meet the demand of two billion more people

Without a global strategy, there will be no solution to achieve 2050 carbon-neutral target

Options can only come from solid R&D, which implies strong and long-term political support

ADS (Accelerator Driven System) concept



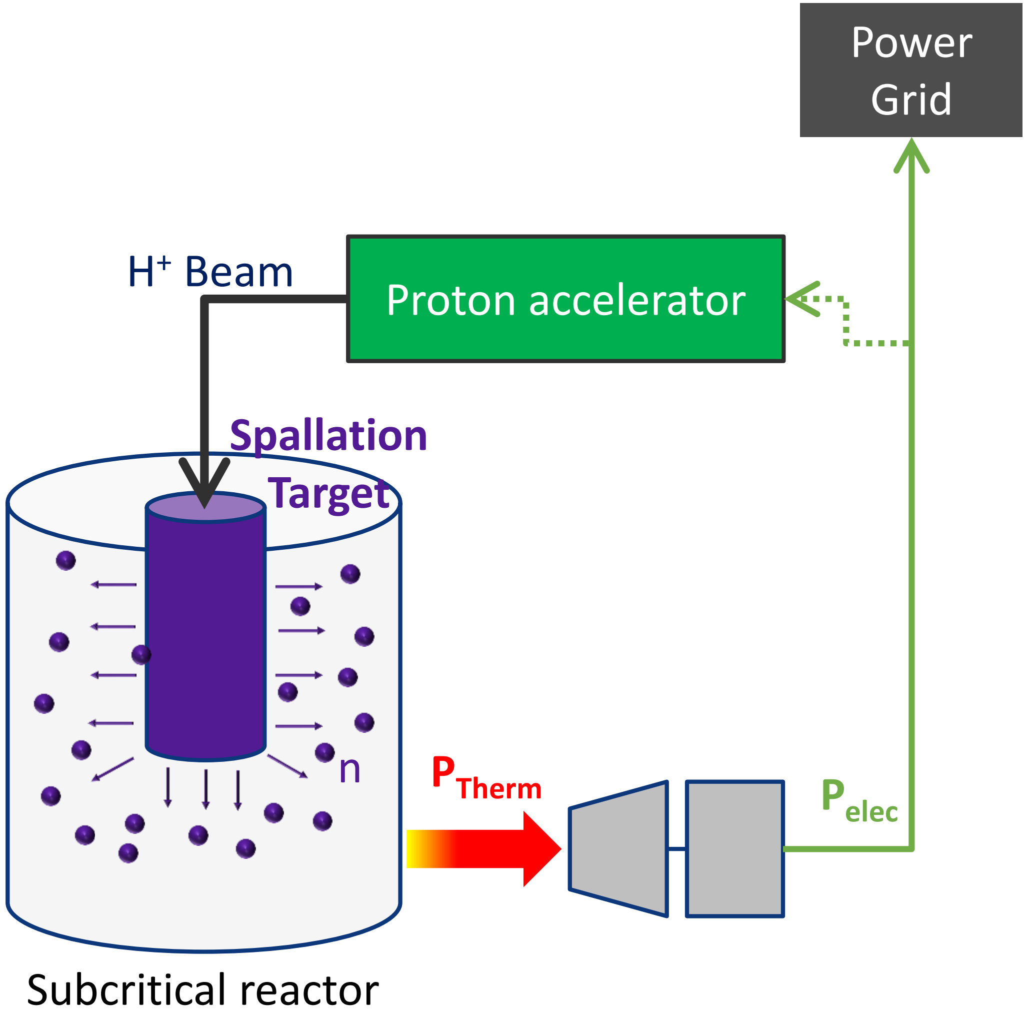
Principle :

Based on a sub-critical reactor

- Requires an external neutron source to maintain the chain reaction
- External source = Accelerator + Spallation Target
- Reactor driven by the source via the accelerator beam

Requires an High Power Proton Accelerator

ADS (Accelerator Driven System) concept



70s - Concept introduced in US (Brookhaven)
Initially for “Non-proliferation” Policy reasons
To incinerate or manage Pu stocks produced in reactors

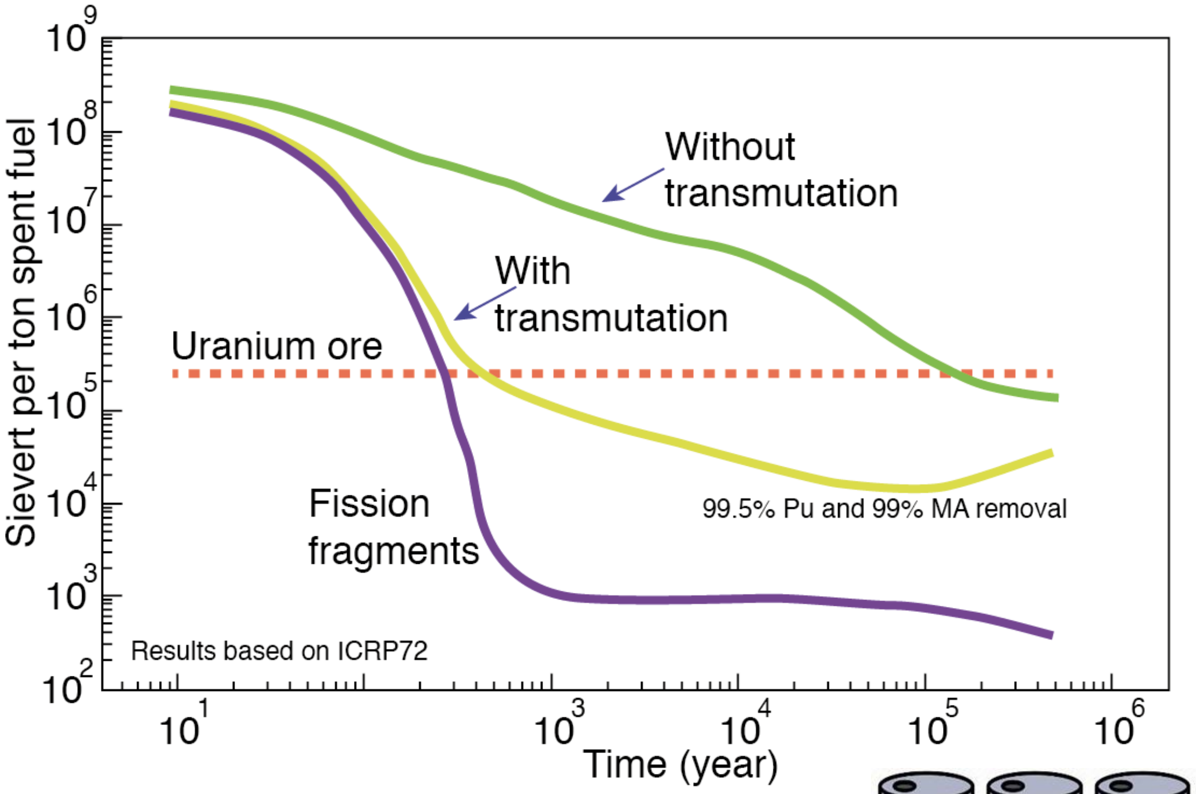
90s - concept of “energy amplifier” (CERN)
Produce electricity ($P_{reactor} > P_{beam}$); thorium cycle
Transmutation of Nuclear wastes

2000s : several projects are underway but with a lack of aggressive scheduling
- China : CiADS (China initiative Accelerator Driven System)
- Belgium/Europe : MYRRHA projet
- Japan: JAEA-ADS
- India: Low Energy High Intensity Proton Accelerator (LEHIPA), as front-end injector of the 1 GeV accelerator for the ADS programme

…..

Transmutex initiative

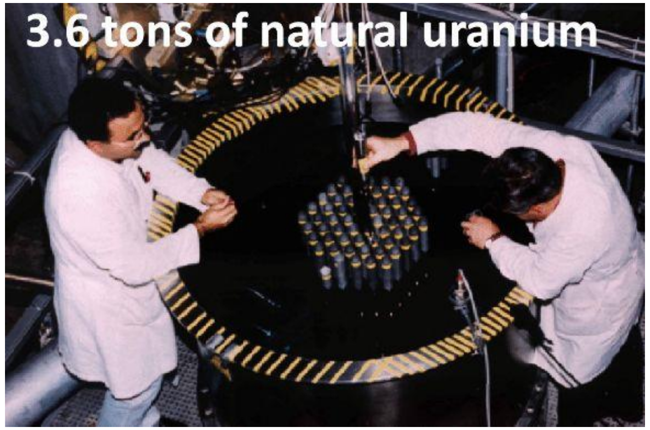
Two goals:
- **Nuclear wastes Incineration**
- **Energy production**



Instead of storing the long-lived waste, the transmutation strategy proposes to:

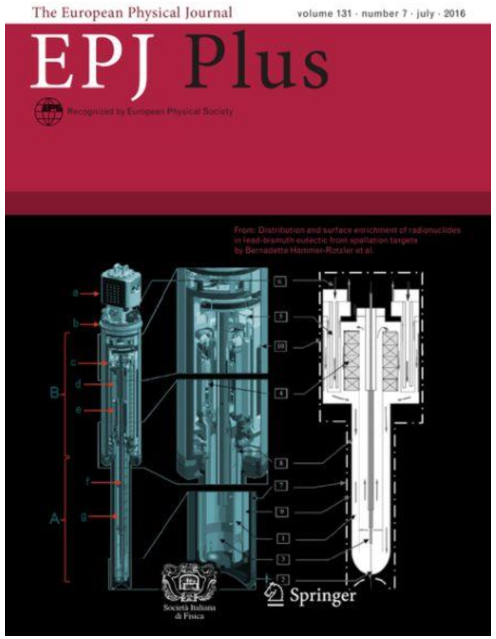
- reduce radiotoxicity and heat loads of long-lived nuclear wastes (especially Minor Actinides)
- to minimize the surface required for waste storage

Experimentally Validated at CERN and PSI



The First Energy Amplifier Test experiment **demonstrated an Energy Gain** from the coupling of an accelerator to a nuclear Fuel core.
CERN 1995
Link to description

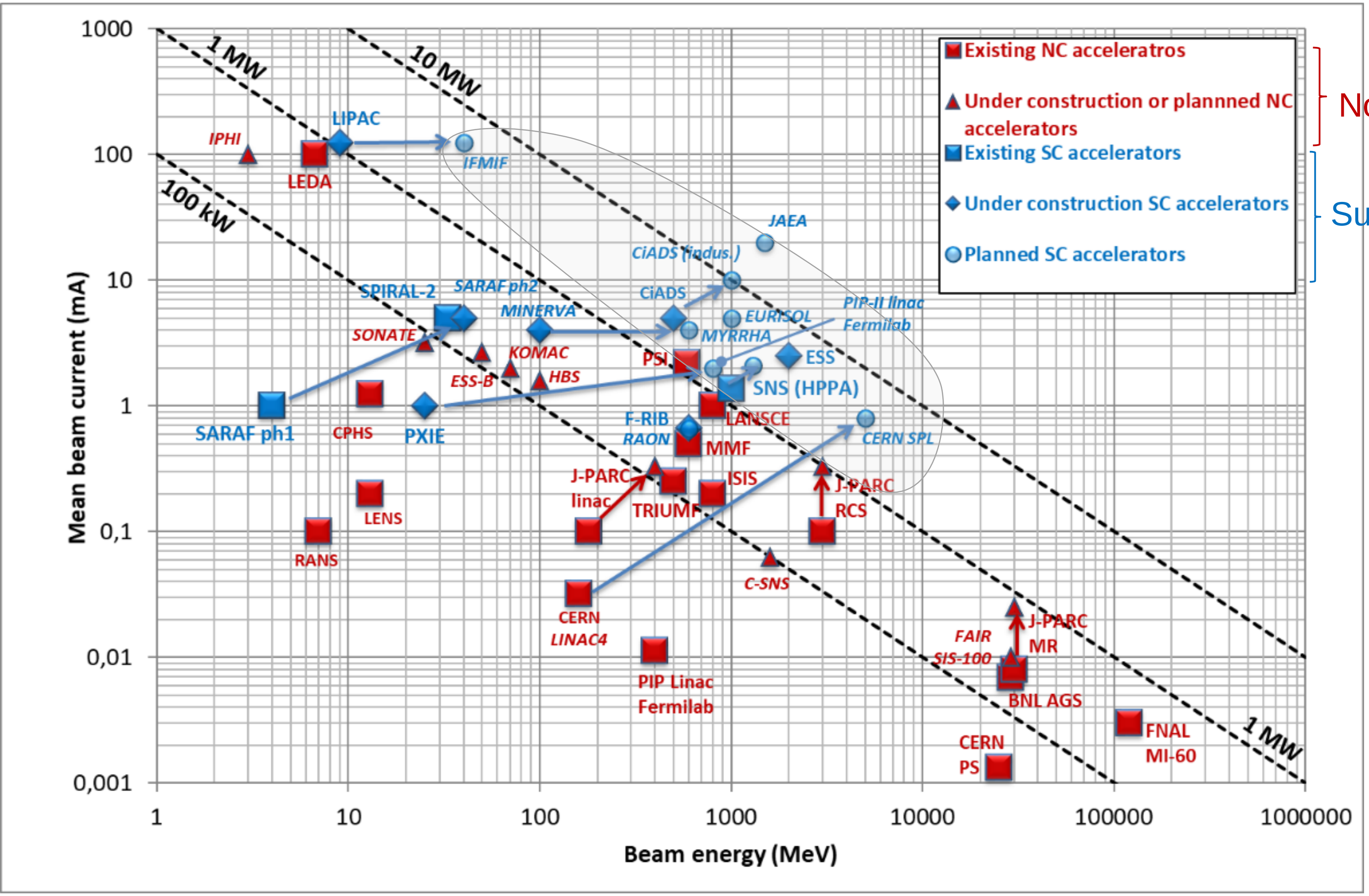
TARC experiment to confirm the "**Burn" rate of nuclear waste**, namely Tc^{99} and I^{129}. Simulation software was validated. CERN 1997
Link to description

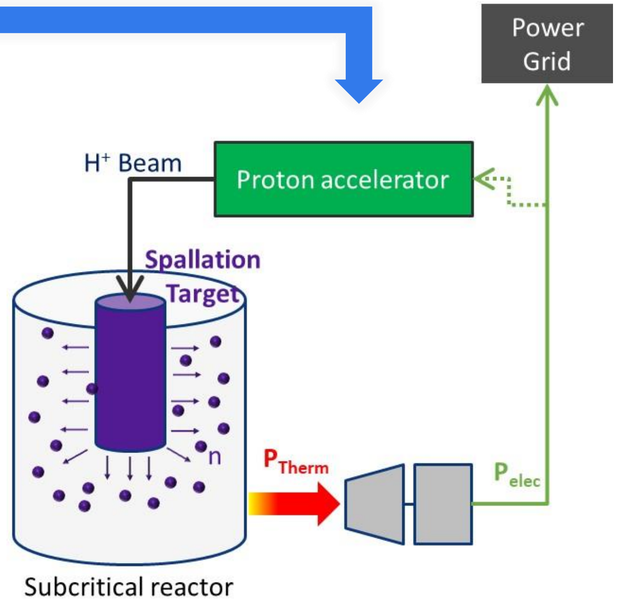


MEGAPIE experiment demonstrated **the stable long time operation of a metal target** as neutron source.
PSI 2006
Link to description

High power proton accelerators

Non-exhaustive list





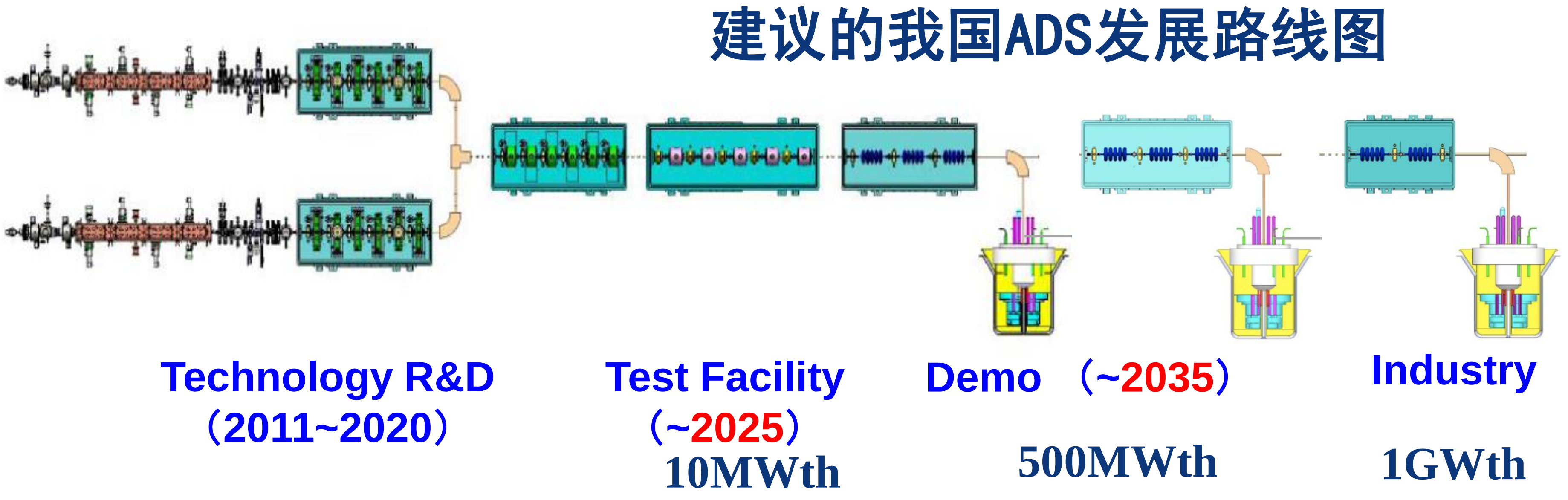
Currently 2 machines are operating above the MW level

- PSI (cyclotron, 600 MeV, ~2 mA)

- Spallation Neutron Source (linac)

Chinese ADANES (Accelerator Driven Advanced Energy System)

Huizhou, in the Guangdong province



“It is legitimate to hope for this system to provide a long-term, safe, and stable energy supply to meet the world’s energy needs in a green and sustainable way. The nuclear waste output shall be minimized and easy to manage, which can significantly reduce the burden of long-term settlement and greatly improve the impact on public health and on the environment. Meanwhile, this system should provide protection from nuclear proliferation, leading to a less significant risk of nuclear fuel thefts and terrorist attacks.”

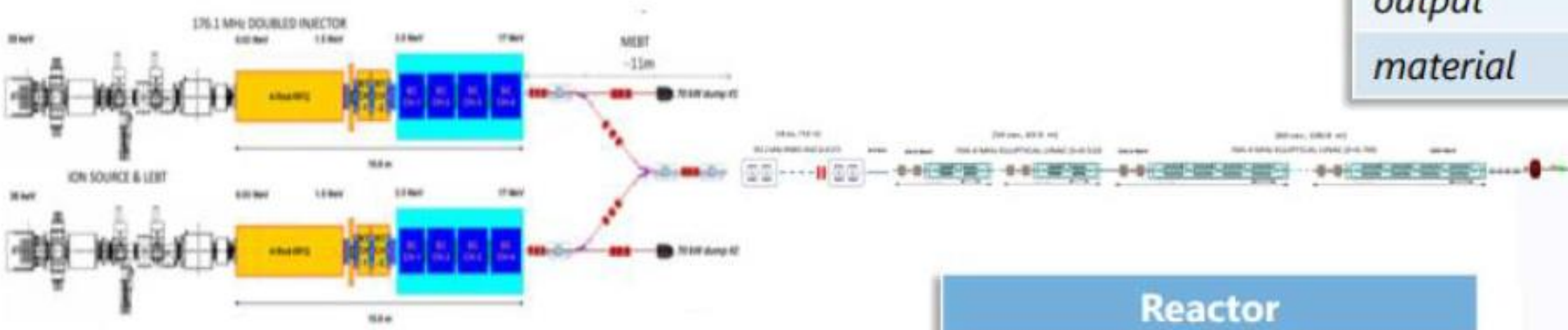
Report to the Chinese Academy of Sciences, *Concept of an Accelerator-Driven Advanced Nuclear Energy System*, 2017 (Link to chapter)

MYRRHA project

Multi-purpose hYbrid Research Reactor for High-tech Applications

First phase partially funded, by the Belgium government

Expected to be operational by **2033** (100 MeV)

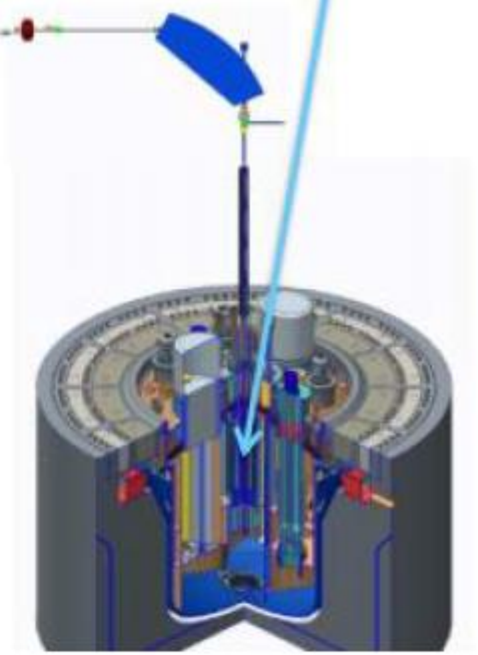


Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)

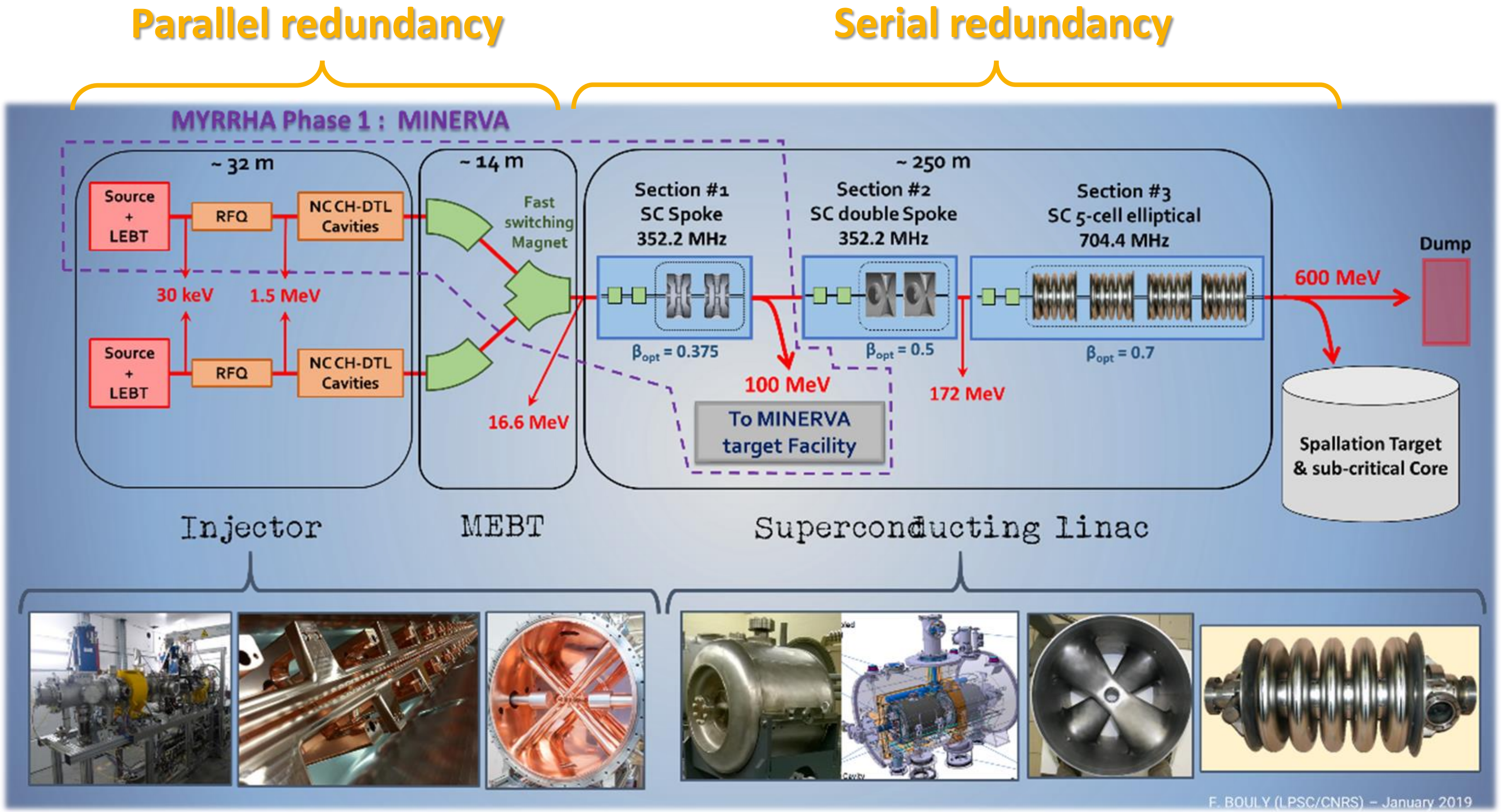
Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA

Reactor	
power	65 to 100 MW_{th}
k_{eff}	0,95
spectrum	fast
coolant	LBE

Lead-Bismuth Eutectic



Reliability Guidelines – MYRRHA



- Reliability guidelines for the ADS accelerator design:
  - **Robust design** i.e. robust optics, simplicity, low thermal stress, operation margins…
  - **Reparability** (on-line where possible) and efficient maintenance schemes
  - **Redundancy** (serial where possible, or parallel) to be able **to tolerate/mitigate failures**

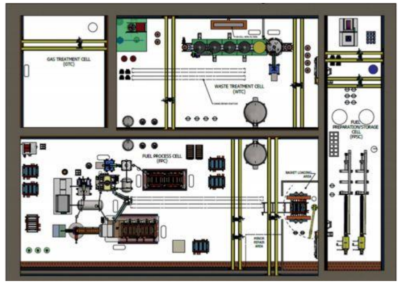
Transmutex initiative and goal

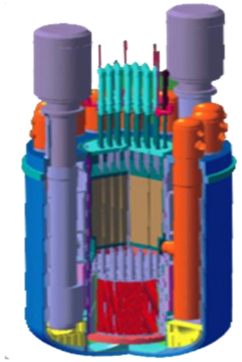
Goal: 100 MW Pilot Plant by 2032

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

Spallation Target:
PSI – CH

Waste pyro-processing:
Argonne National Laboratory - USA



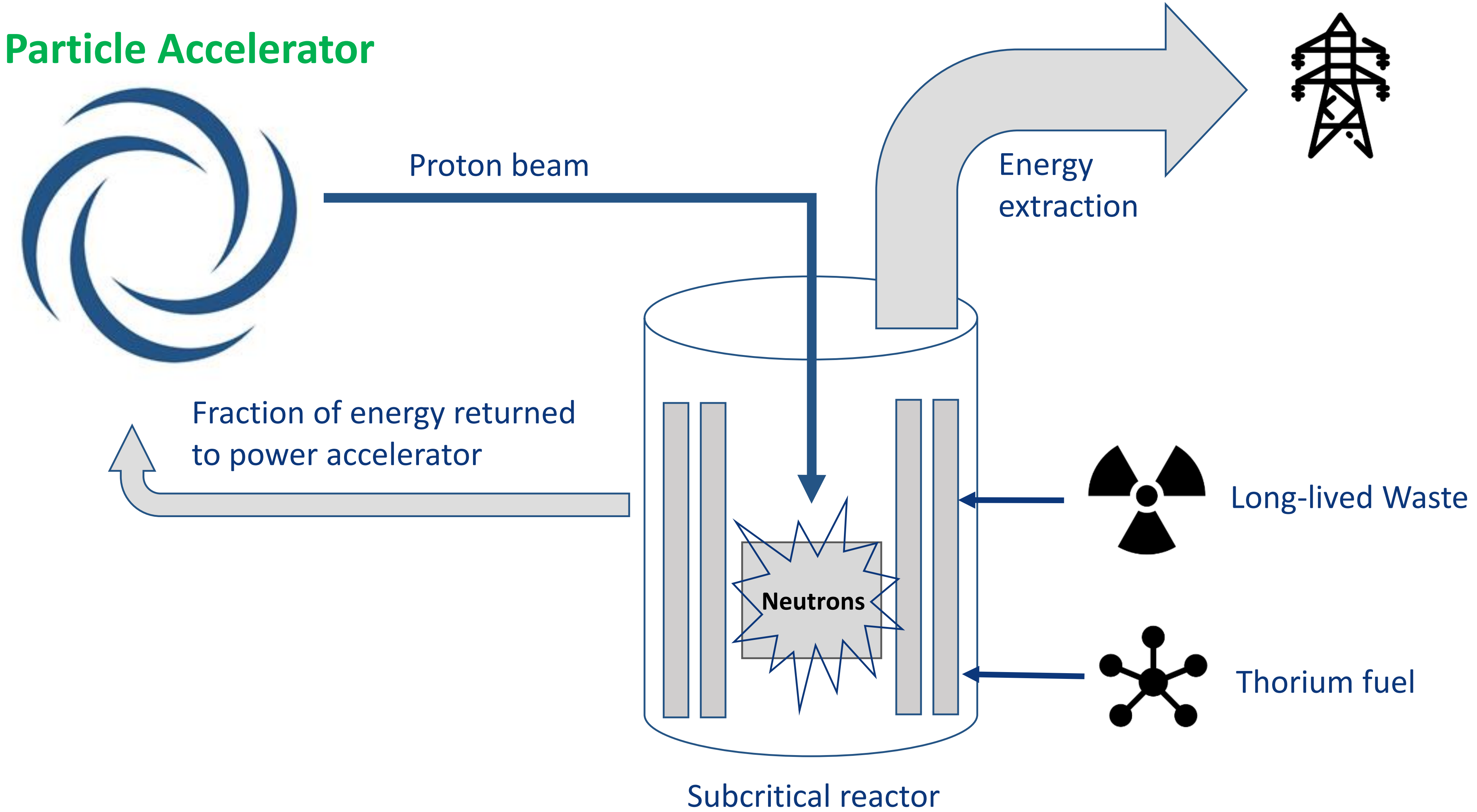


Lead-Bismuth fast reactor
SVBR 100 from AKME - Russia

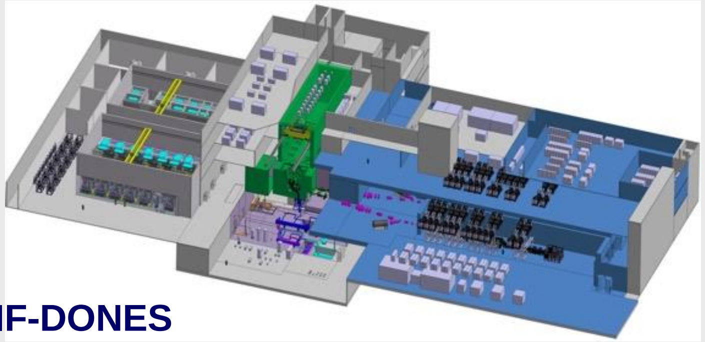
TRANSMUTEX: Roadmap and Budget

I	II	III	IV
			
Study	Engineering	Pilot Plant 100MW	Ongoing Deployment
2020 - 2021	2022 - 2027	2028 - 2032	2033 - 2037
$3 million	**~ $250 million**	**~ $1 Billion**	

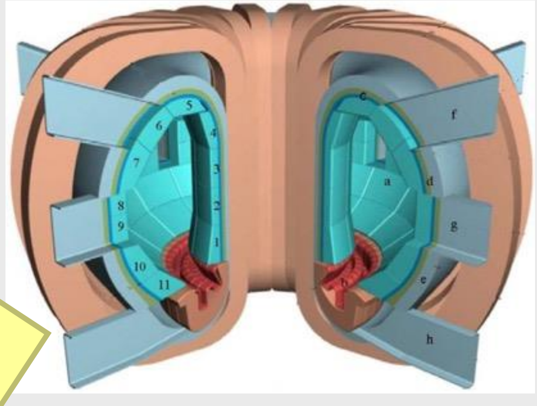
Energy Amplifier with up to 100x Gain (Q = 100)



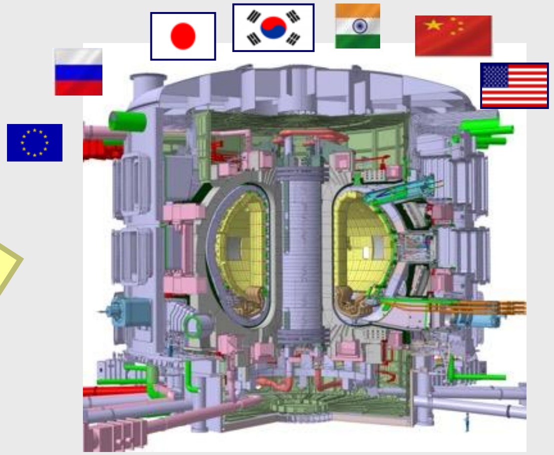
ROADMAP TOWARDS FUSION ENERGY



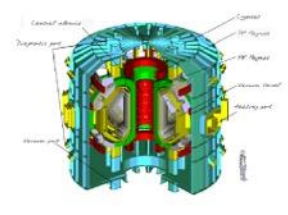
IFMIF-DONES
D+ beam, 40 MeV, 125 mA on a Li target

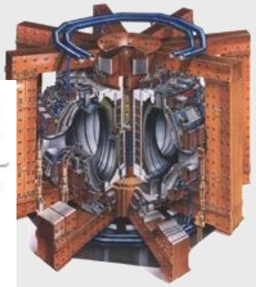


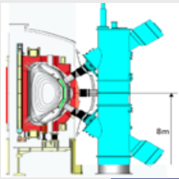
DEMO ≥ 500 MW_{el} :
1-2 hours



ITER – 500 MW_{th}
300– 500 secs



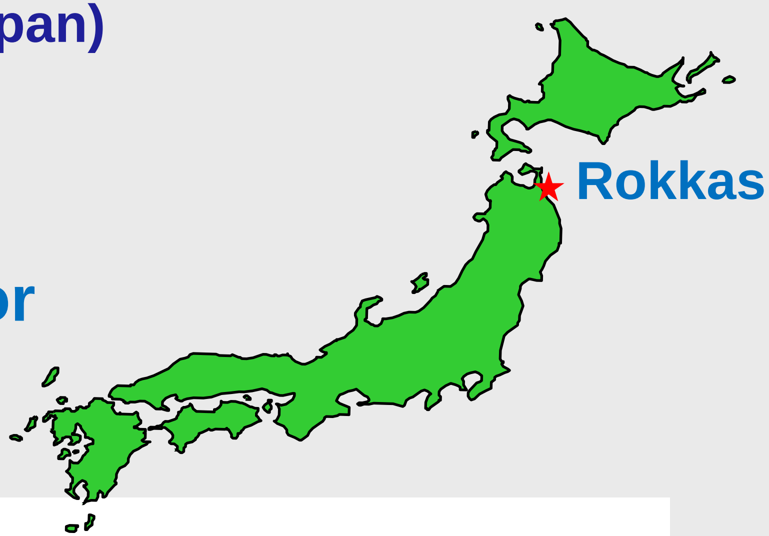




K-STAR JET JT-SU

Courtesy of José M. Pérez

Position on IFMIF-DONES gained through significant CIEMAT involvement in the preparatory R&D project (Japan)



LIPAc
Linear IFMIF Prototype Accelerator

Injector + LEBT
CEA Saclay

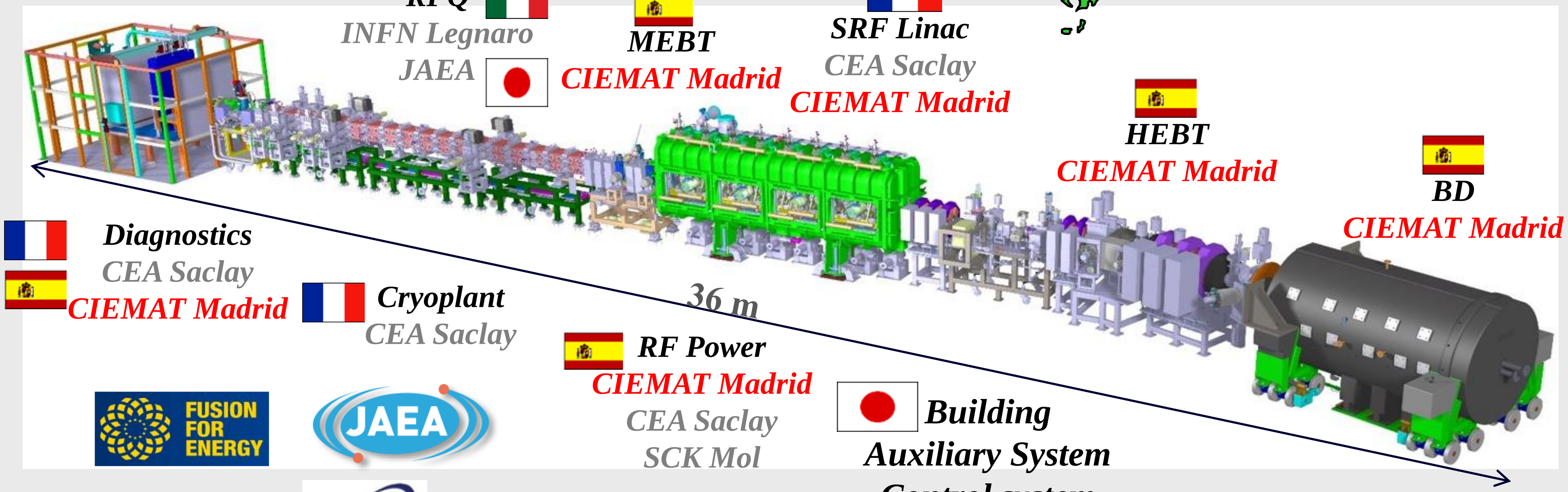
RFQ
INFN Legnaro
JAEA

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid



Diagnostics
CEA Saclay
CIEMAT Madrid

Cryoplant
CEA Saclay

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Building
Auxiliary System
Control system
Installation
QST

Next time someone asks you what accelerators are for :

"A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or…

… discover the secrets of the universe"

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

“There is no applied science if there is no science to apply”

Bernardo Houssay, Nobel Laureate in Medicine (1947).

“The greatest economic benefits of scientific research have always resulted from advances in fundamental knowledge rather than the search for specific applications.”

Margaret Thatcher

Muchas gracias por su atención.

CERN

Accelerating Science and Innovation

Accelerators for art

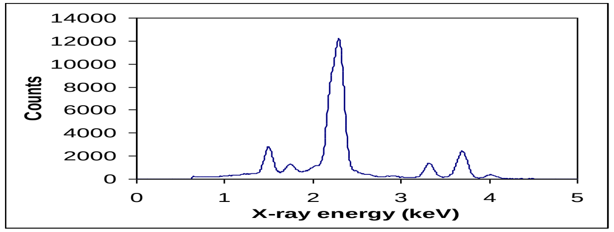
Ion Beam Analysis (e.g. PIXE, Proton Induced X-ray Emission)

A beam of particles (protons) from an accelerator is sent on a sample (e.g. a painting)

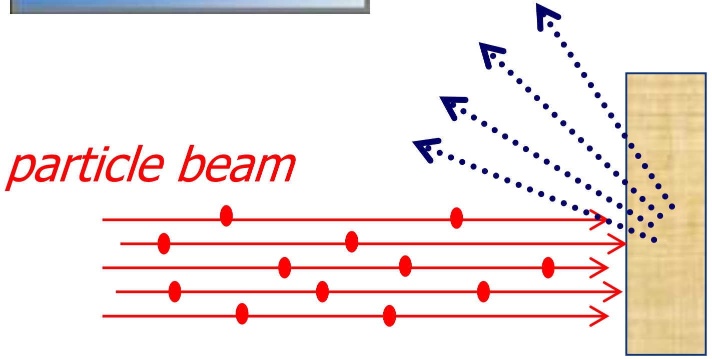
The atoms are excited and emit different types of radiation (X-rays, gammas, etc.)

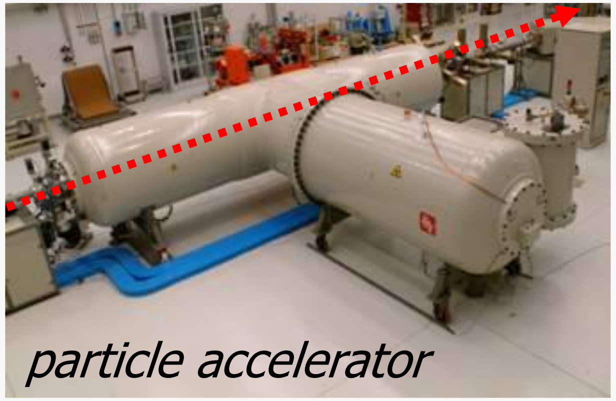
Different atomic elements emit X-rays at different energies – Spectral analysis from one or more detectors allows determination of the chemical composition (e.g. of the pigments).

Radiation detection and spectral analysis

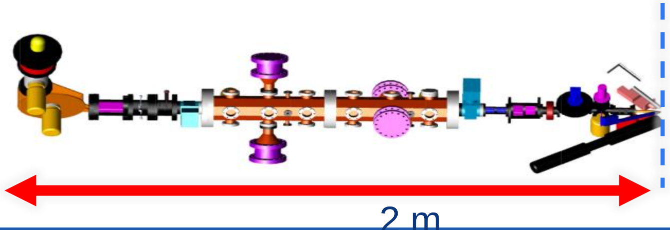


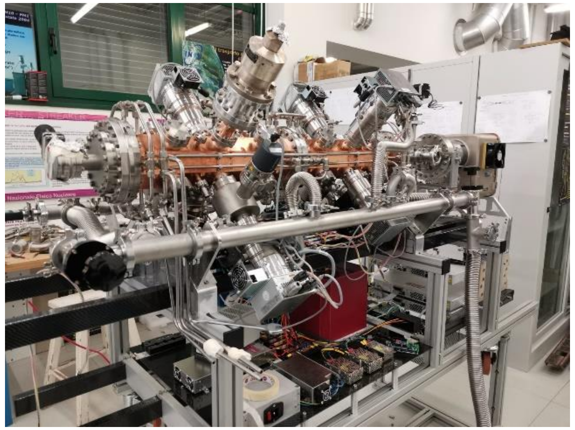
Emission of radiation of <u>characteristic energies</u> (X-rays, γ, particles…)





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





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

Finally, just one more application…

Detecting wine fraud

Use ion beam to test the bottle of "antique" wine – chemical composition of the bottle compared to a real one.

"In a recent and spectacular case, American collector William Koch sued a German wine dealer, claiming four bottles – allegedly belonging to former U.S. president Thomas Jefferson – purchased for 500,000 dollars, were fake. The case has yet to be settled."

- http://www.cosmosmagazine.com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Atomic boffins spot fake wines

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Bottles are zapped with beams of charged ions generated by a particle accelerator

Bottles are zapped with beams of charged ions generated by a particle accelerator

By Roger Highfield, Science Editor
7:25PM BST 03 Sep 2008

A rare wine merchant has joined forces with nuclear scientists to develop a 21st-century tool for unmasking counterfeit vintage wines.

Courtesy of Suzie Sheehy