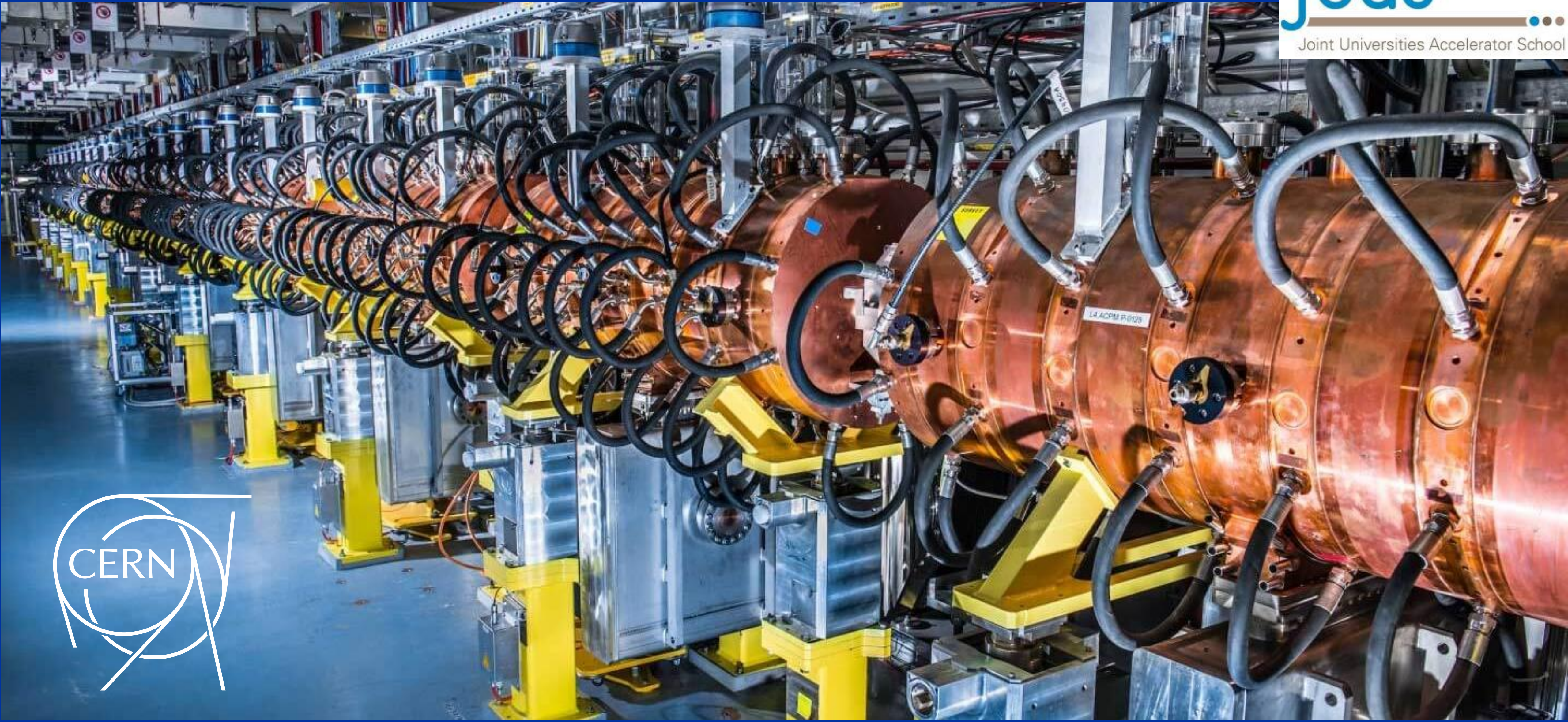
Maurizio Vretenar CERN ATS-DO (Project Office)

JUAS 2023

Joint Universities Accelerator School



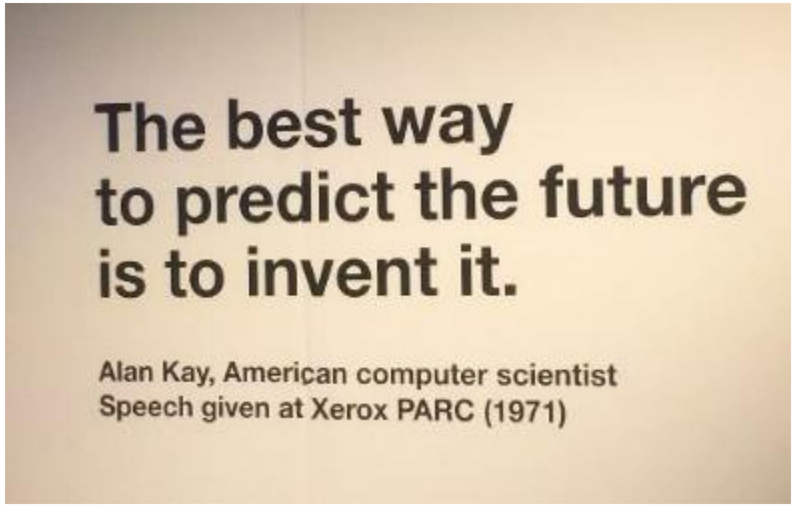
Particle Accelerators in the XXI Century

Outline and Motivations for this Seminar

This Seminar is intended as an “**appetizer**” to introduce you to the Science and Technology of Particle Accelerators

Goals:
- Give a general overview of accelerator technologies and applications, with no maths;
- Give some hints to guide your study and your future choices.

Outline:
- Accelerators as **instruments**
- Accelerator and **innovation**
- Key accelerator **challenges**
- Accelerators for **society**
- The **future**…

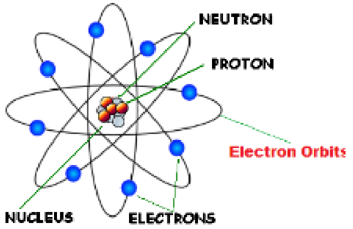


Accelerators: our access to the subatomic world

Particle accelerators are our door to access the subatomic dimension… to study and exploit the atom and its components

When we extract particles from an atom (protons, electrons, charged nuclei) and we accelerate them we concentrate **enormous amounts of energy in tiny volumes**

proton



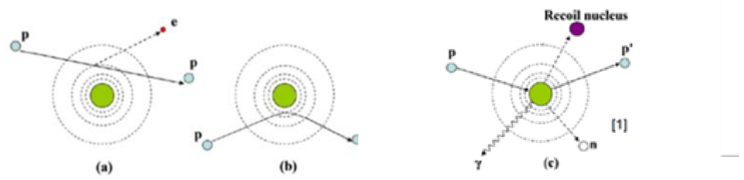
	Proton out of LHC	150g Yoghurt	TGV train
	• 7 TeV	 120 cal	
Energy	$1.1\ 10^{-6}$ J	$5\ 10^{2}$ J	$3.6\ 10^{8}$ J
Energy density	$5.3\ 10^{38}$ J/m^3	$3.3\ 10^{6}$ J/m^3	$1.5\ 10^{5}$ J/m^3
Type of energy	Kinetic Subatomic scale	Chemical Macroscopic scale	Kinetic Macroscopic scale

Energy in an LHC bunch ($1.15\ 10^{11}$ protons) is $1.3\ 10^{5}$ J, in the full beam (2808 bunches) $3.6\ 10^{8}$ J.

Energy density of an LHC bunch at interaction point (30 cm, 16x16 μm^2) ≈ ***$0.5\ 10^{12}$ J/m^3***

Where will this energy go? An accelerated subatomic particle sent towards an atom will:

1. Deliver some **energy to the electrons**.
2. Deliver some **energy to the nucleus** (after penetrating the Coulomb barrier).

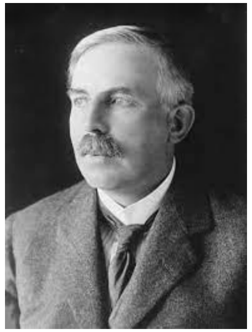


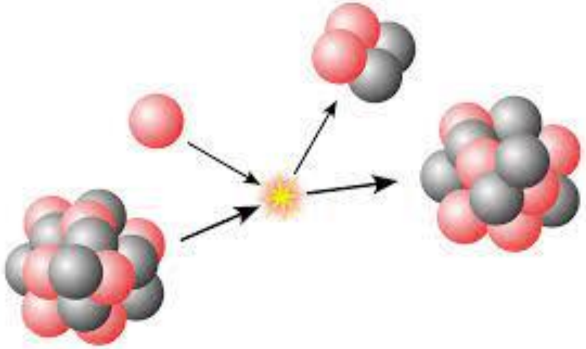
Accelerators can modify the nuclei and create new particles

If the energy is sufficiently high, the particles in the beam transfer energy to the nucleus and its components (and are then scattered, reflected or absorbed).

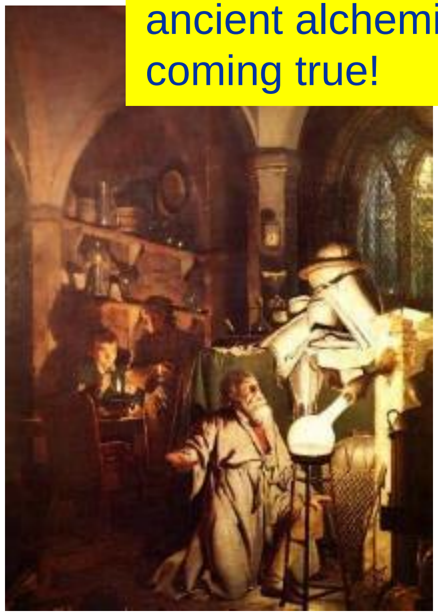
It's the dream of the ancient alchemists coming true!

NUCLEAR PHYSICS

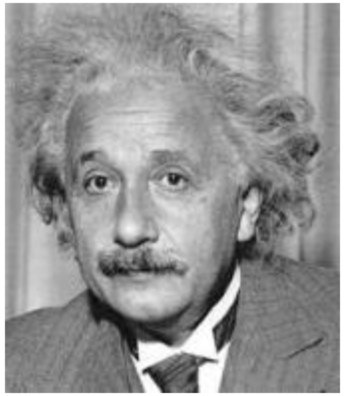




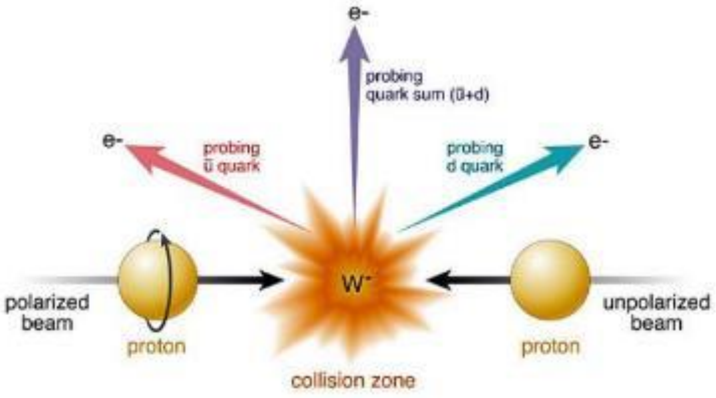
Collisions between particles and nuclei can break and modify the nucleus, to generate new elements and transform the matter!)



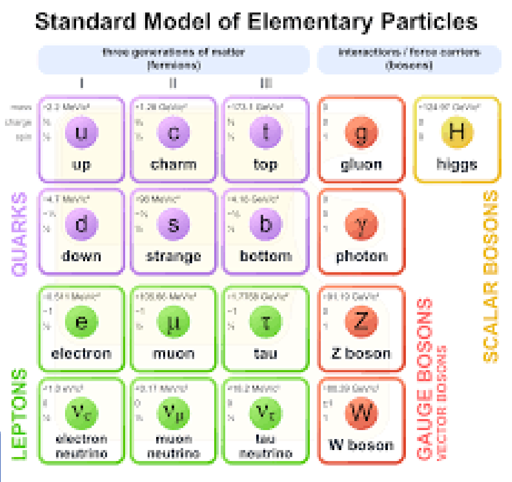
PARTICLE PHYSICS



$E = m c^2$



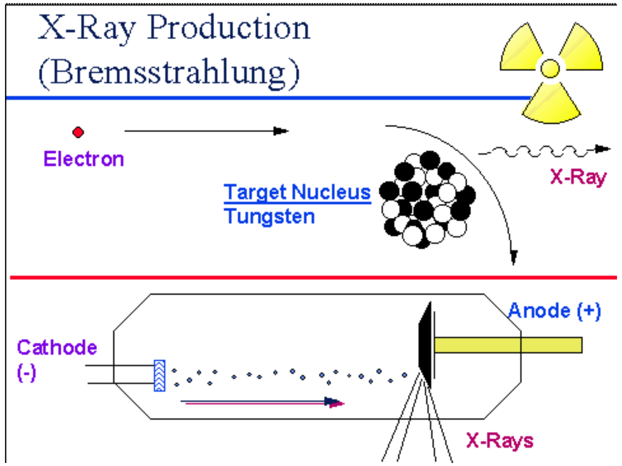
In high energy particle collisions new particles are generated, converting matter into energy

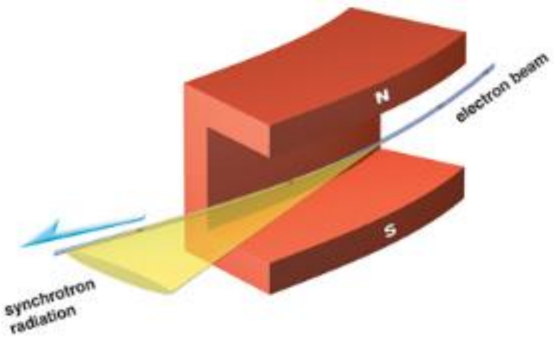


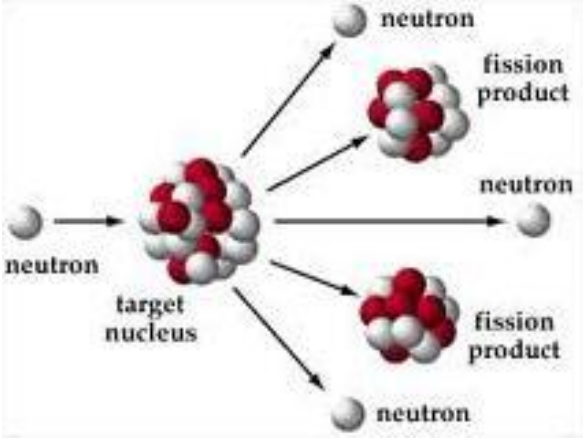
Accelerators can produce intense secondary beams

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





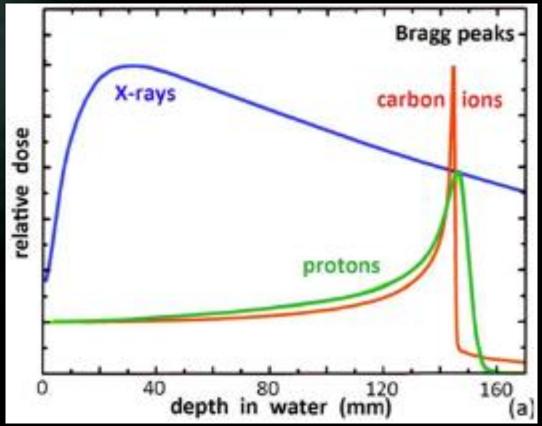


- X-rays generated by accelerators are commonly used in **medicine**
- Both X-rays and neutrons generated from accelerators are used for **advanced imaging** in many fields: life sciences, condensed matter, energy, material science, cultural heritage, life sciences, pharmaceuticals,…
- Additional applications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

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.



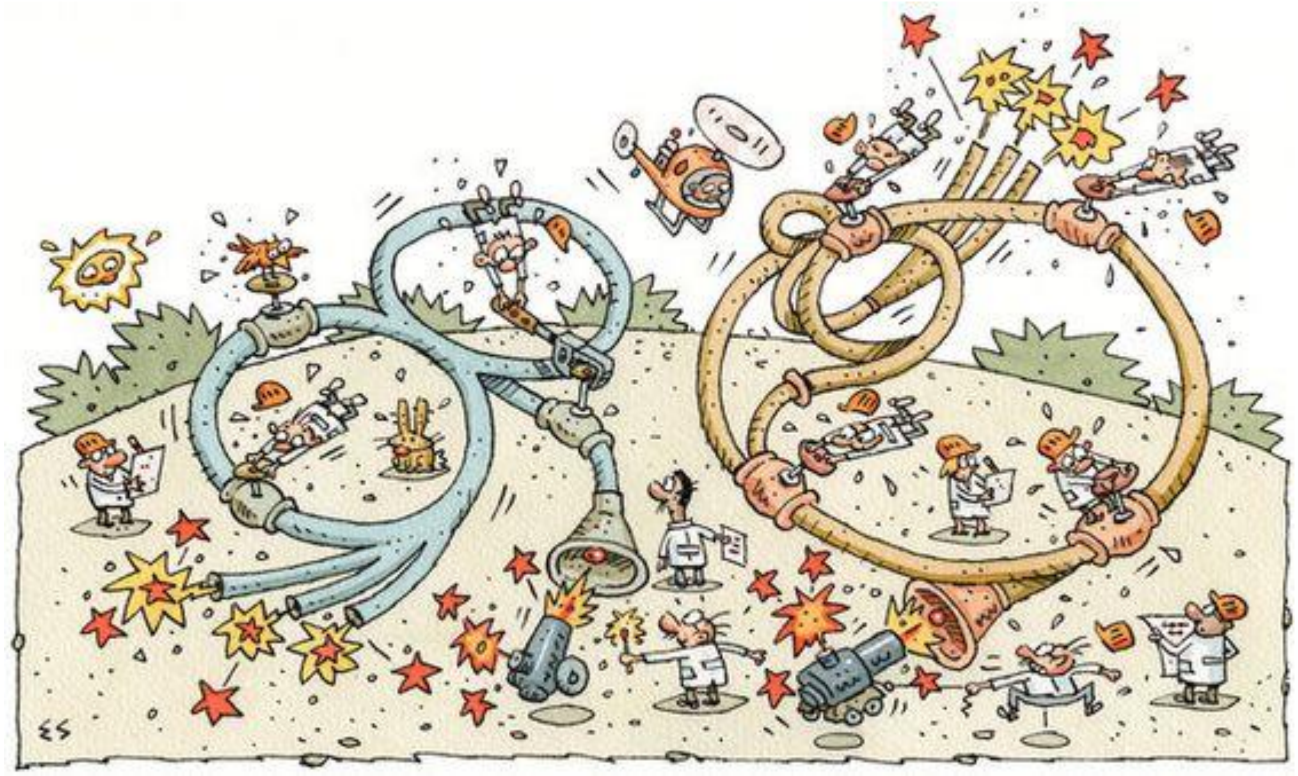
Particles can penetrate in depth (different from lasers!).

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)

Lasers and accelerators have comparable peak energy densities, but different interactions and penetration

Accelerators have a long history…

Question:
How old are particle accelerators?



Modern particle accelerators are 95 years old

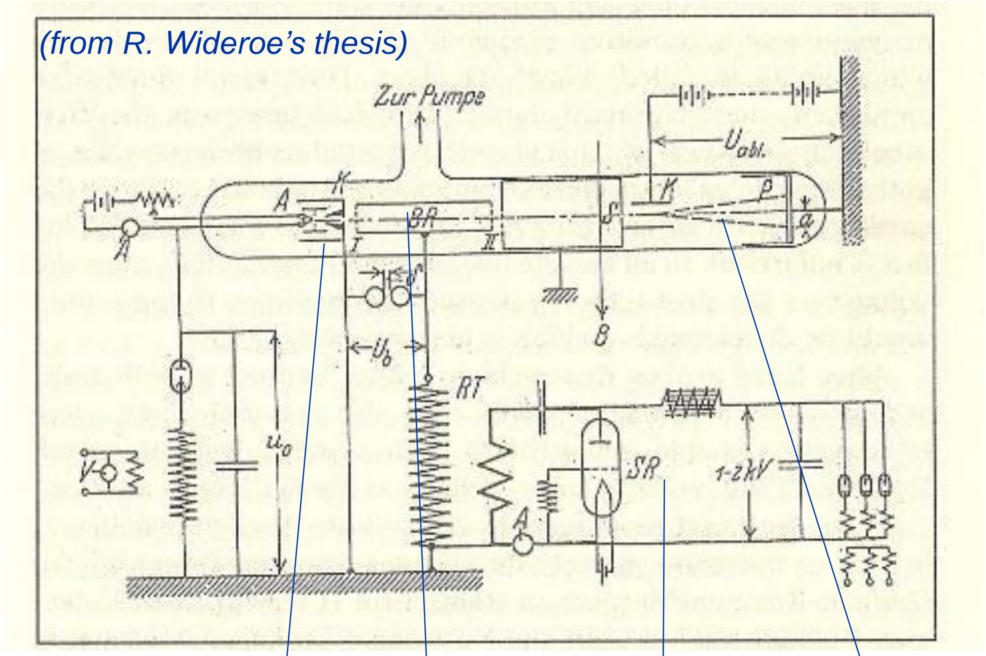
In 1928 a PhD Thesis introduced the basic concept of modern particle accelerators, using periodic acceleration provided by electric field at Radio-Frequency (RF).

This was a major step from the previous DC (constant voltage) acceleration, limited to few MeV

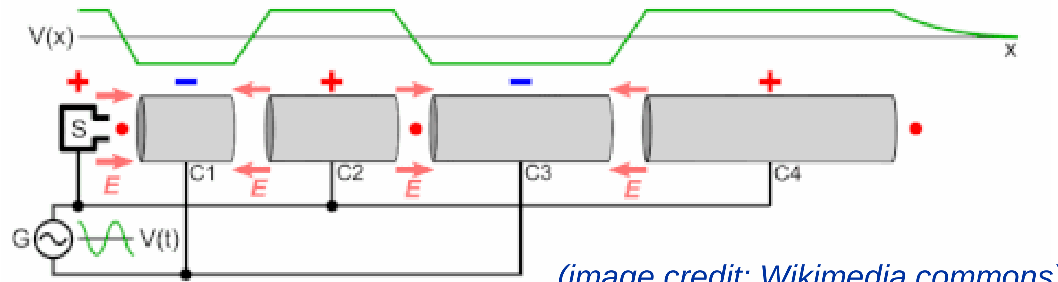
Rolf Wideröe's PhD thesis, 1928, University of Aachen – he was 26 years old!

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration in a 88 cm long glass tube) "at a cost of four to five hundred marks", less than 2'000 € today!

(from R. Wideroe's thesis)



1. use of Radio-Frequency technology (at the time limited to 1-2 MHz) → marrying radio technology and accelerators.
2. Use of a drift tube separating 2 accelerating gaps → invention of periodic acceleration.
3. complete accelerator: ion source, RF accelerator, detector, all in vacuum.



(image credit: Wikimedia commons)

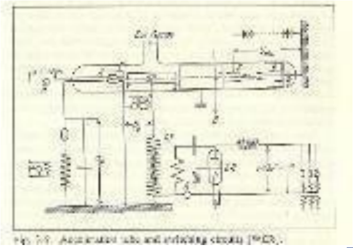
At the roots of innovation

What were the ingredients of Rolf Wideröe's innovation?

- **He was young and curious (*PhD student, fresh ideas and time available*)**
- **He was under pressure to complete his thesis *(«necessity is the mother of invention»)***
- **He was merging information and experience from different fields *(cross-fertilisation)***
- **He was going all the way down to practical realisation (*to «innovate»*).**

The Oslo Manual (OECD/Eurostat, 2005), defines innovation as "the implementation of a new or significantly improved product or process …"

Innovation in the particle accelerator field



1931………….1945/48….1952…………..1965/90's…….

XXI century

?

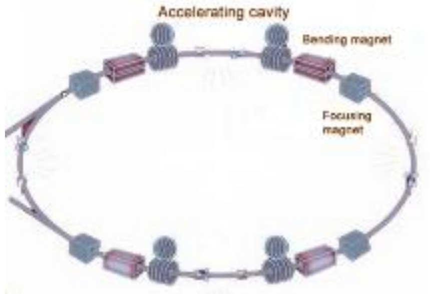
Cyclotron: cyclic acceleration with magnets (Lawrence)

Strong focusing (Courant, Livingston, Snyder, Christofilos)

Superconducting magnets and acc. cavities

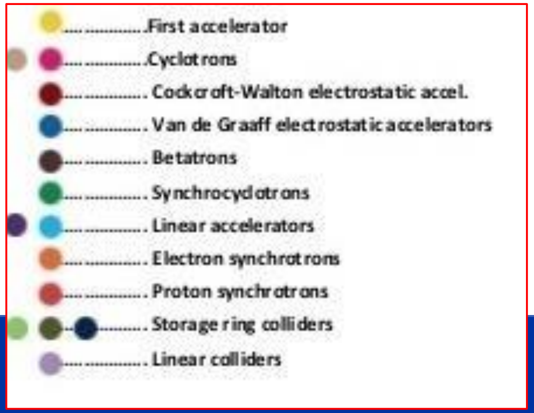
2008: the Large Hadron Collider

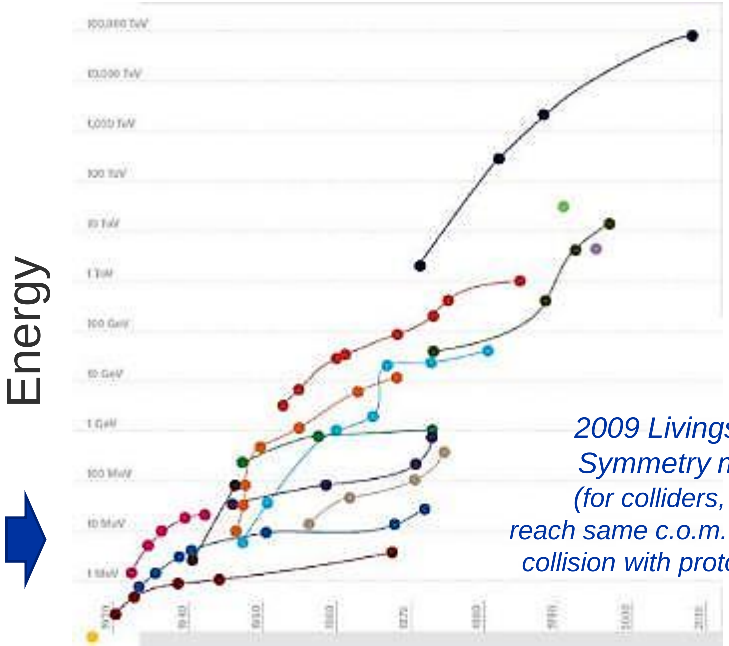
Application of WW2 radar technology to accelerators (Hansen, Alvarez)



Succession of enabling technologies (technology leaps)

S. Livingston, 1959:
Accelerator energy increases by a factor of 10 every 6 years
(Moore's law of accelerators)

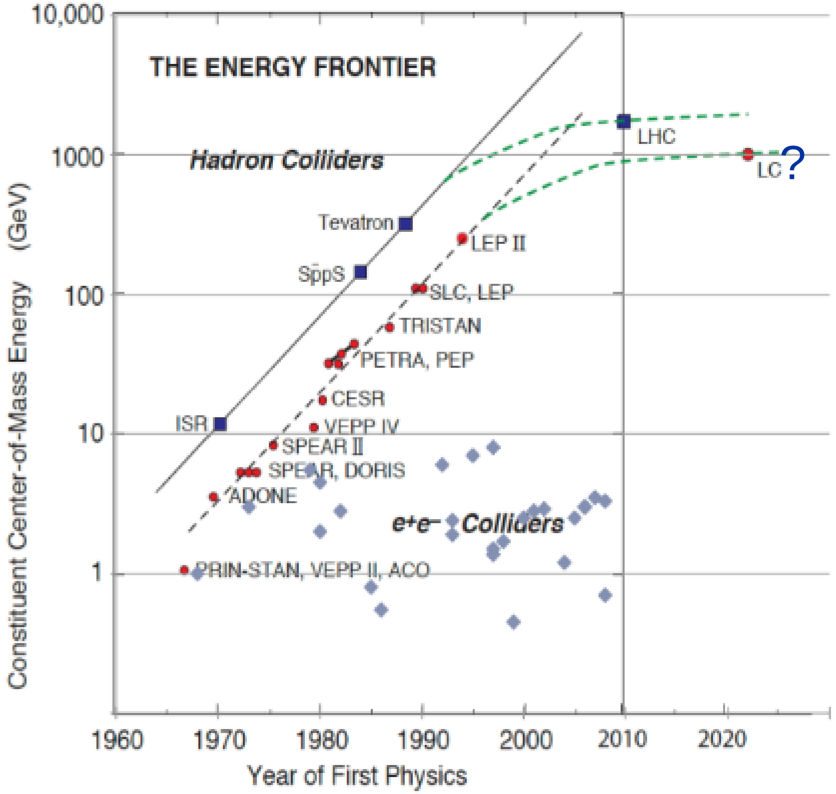




2009 Livingston plot, Symmetry magazine
(for colliders, energy to reach same c.o.m. energy in collision with proton at rest)

Particle Accelerators in 2023

We have reached the end of exponential growth…



Updated Livingstone-type chart (Wikipedia 2014, uploaded by J.Nash, Imperial College)

but the field has never been so flourishing!

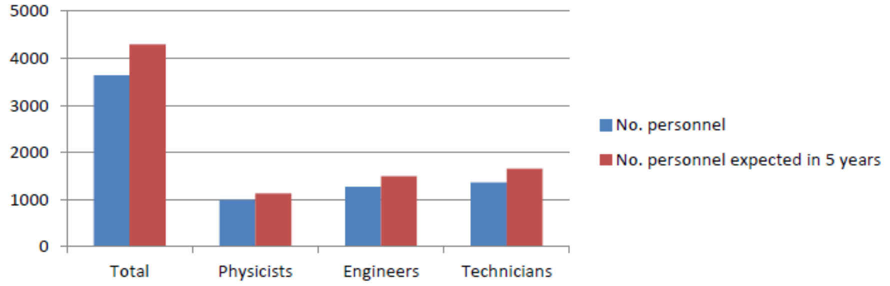


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

TIARA Need for Accelerator Scientists report, 2013: 3’700 people engaged in accelerator science in Europe, growing to **4’400** by 2018.

As many as **50** ongoing accelerator construction or upgrade projects listed in the 2017 IPAC Conference (13 America, 11 Asia, 26 Europe)

How many particle accelerators there are in the world, and where are they?

Multiple challenges for accelerator science

There are more than 35’000 particle accelerators in operation around the world:

- For all XXth century, **fundamental science** has been the driving force for the development of new accelerators, with its continuous quest for high energies required to discover new particles.
- In this early XXI century, we are moving to a new paradigm where together with particle physics **applied science** (photon and neutron science) and **healthcare** appear as driving forces for innovation.
- **Advanced medicine** and **new materials** are key technology drivers of the XXIst century.

What is the role of accelerators in this transition?

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%

Accelerators in transition – for physics and for society

1. Transition to new more affordable and sustainable technologies for basic science
2. Transition from basic science as main technology driver to a multiple system where basic and applied science, medicine and industry will together drive accelerator development.
3. Transition from a centralised configuration based on large laboratories to a distributed scheme (project clusters of small and large laboratories and industry)

Fundamental science

Limitations related to size, cost, energy.

innovation

New ideas and technologies

Applied science (photon and neutron sources)

Societal applications (medicine, industry, environment, etc.)

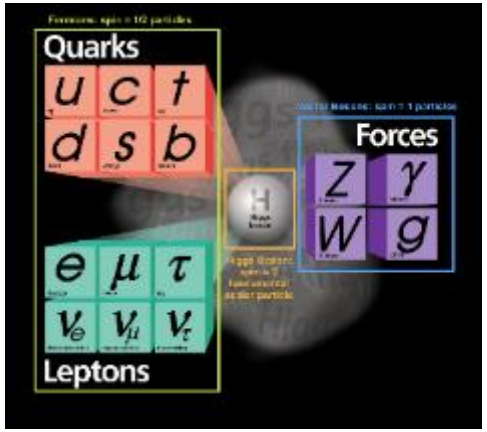
The electron linac for cancer radiotherapy, the most widespread accelerator in the world (> 12000 units)

Reaching the limits of sustainability ?

Particle physics has been from the very beginning the **technology driver** for the development of particle accelerators: the **quest for new particles** at increasingly higher energies has motivated the development, construction and financing of increasingly large accelerators. And now?

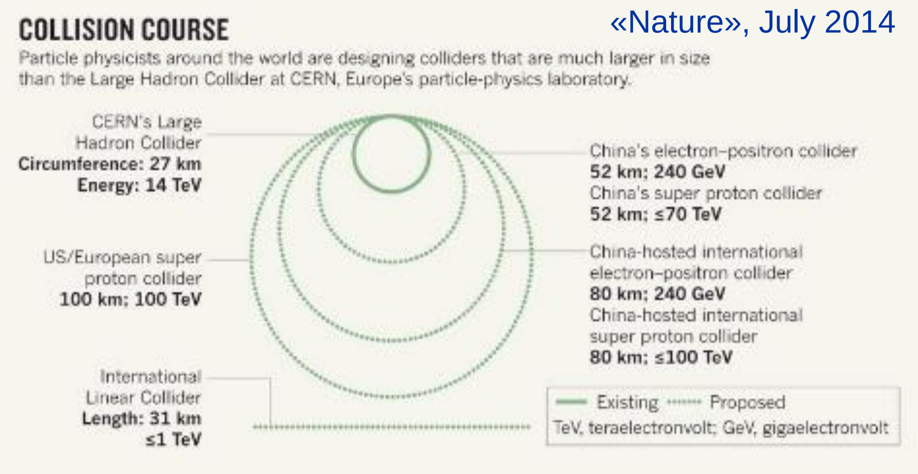
Physics:
After the discovery of the Higgs boson the Standard Model is complete – many questions remain open (origin of dark matter and energy, antimatter asymmetry, etc.) and their solutions may be related to new unknown particles, but so far no clear predictions exist to be verified by an accelerator.

➡ Difficulty to justify new large projects



Accelerators:
The **size, cost and energy consumption** of the accelerators required to go beyond the standard model rise questions on the long term sustainability of accelerator-based particle physics.

➡ Difficulty to implement new large projects



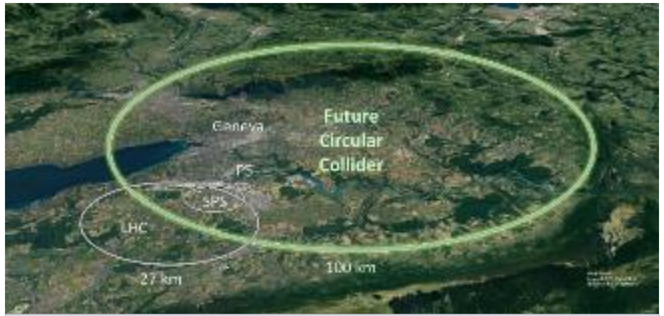
«Nature», July 2014

The recent (2022) international crisis has shown that **energy reduction** is a must for future project, and that governance models based on **science globalisation** will be increasingly difficult to implement.

The big challenges for accelerator science

Making accelerator-based particle physics research sustainable over the long-term, increasing at the same time the benefits of particle accelerators for society are the main challenges to the accelerator community in this XXIst century.

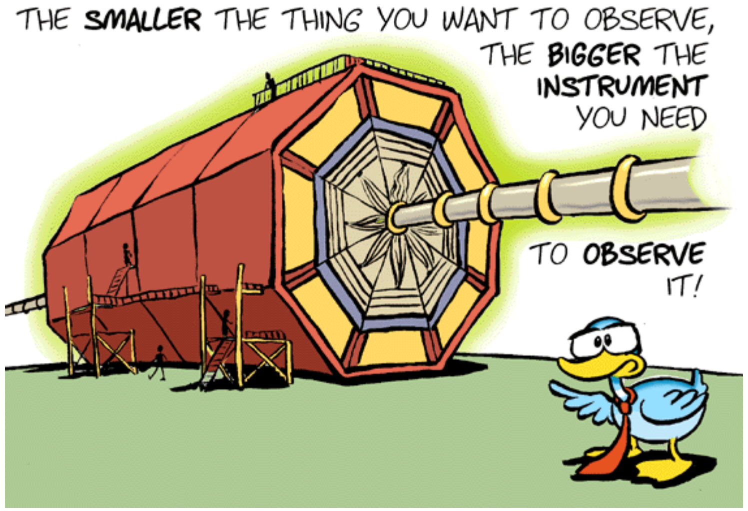
We need new ideas (innovation!) and a collaborative and creative environment for these ideas to grow



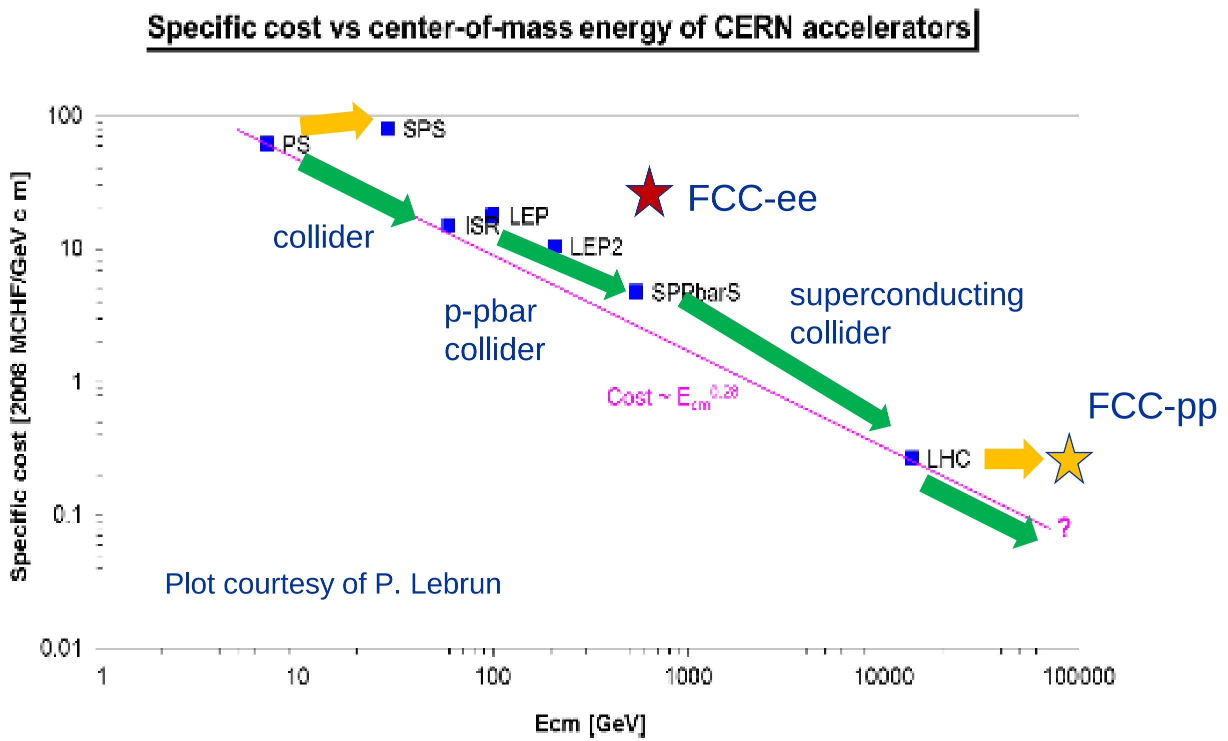
From the LHC (27 km) to the Future Circular Collider (100 km)

How does this translate into technical challenges?

Multiple dimensions of accelerator R&D



Frontier accelerators – economic sustainability



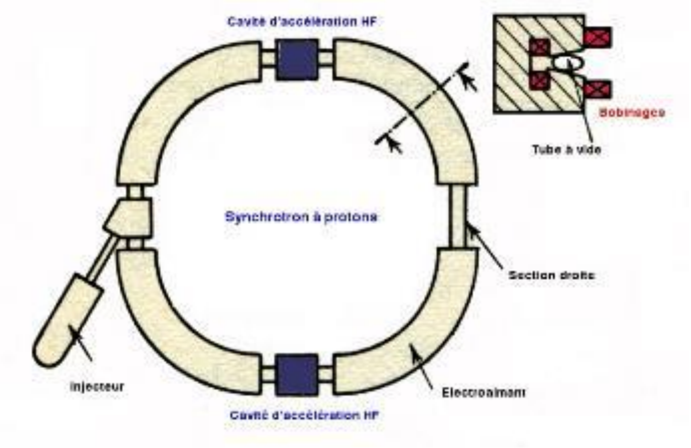
Moving along this line was made possible by new technologies (colliders – antiproton production and storage – superconductivity)

scaling of present technology

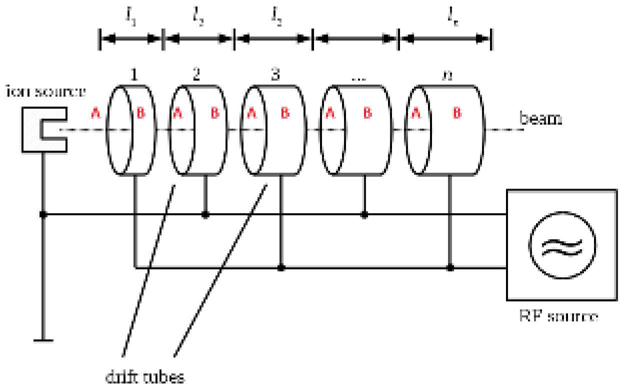
reduction in cost with new technologies?

Where is the limit of sustainability? It depends on the economical environment and on the priorities of a given society. To remain within the present limits we need an effort to produce innovative technologies.

Step 1: smaller accelerators

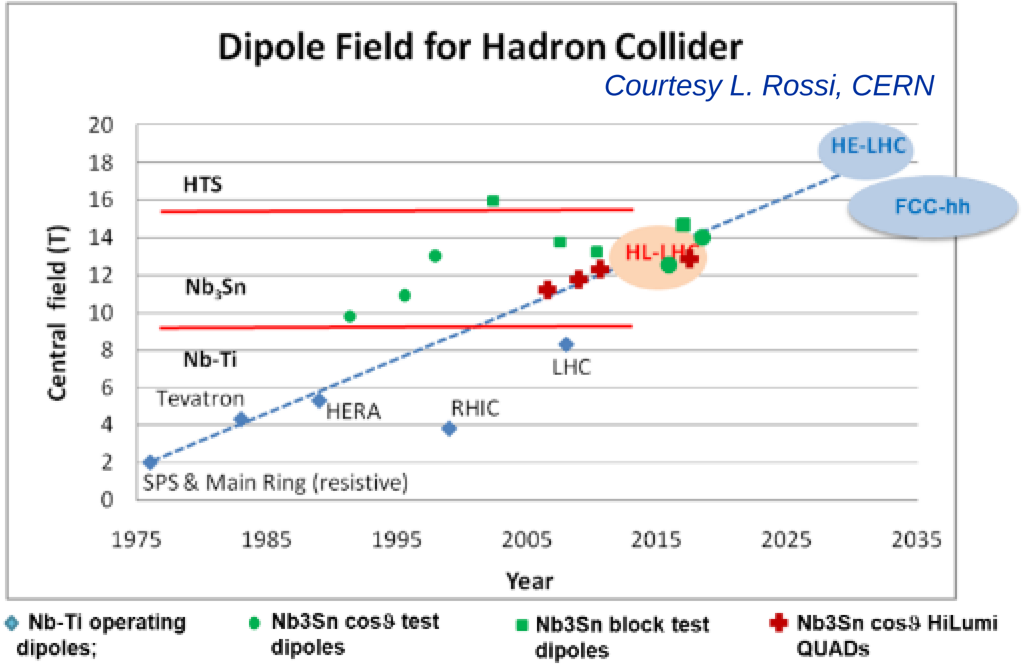


Synchrotrons: $p/q=B\rho$
Need to maximise ***magnetic field***
Superconductivity is mandatory, the limitations is the critical current density Jc for SC magnets



Linear accelerators: $W=E\ell$
Need to maximise ***electric field***
Limitations: arcing between electrodes, field emission, etc.
(and RF power, proportional to V^2 !)

The magnetic field frontier in superconducting magnets



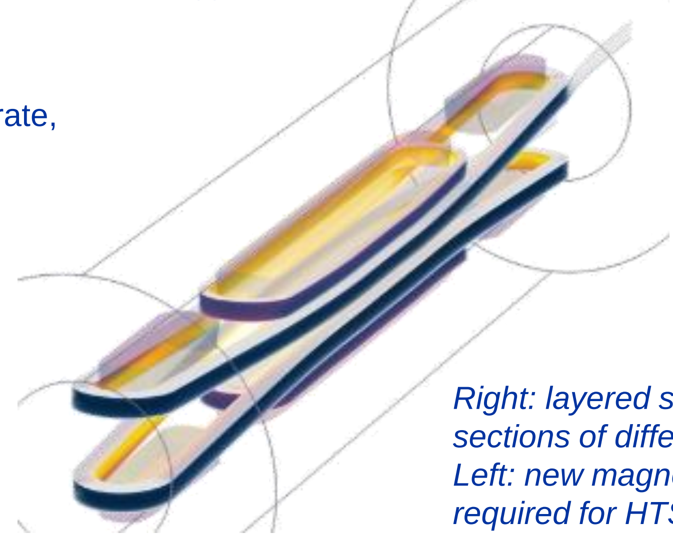
Three technologies under consideration

1. **NbTi** (Niobium Titanium as in the LHC): mature but limited to about 9T field.

2. **Nb_3Sn** (Niobium Tin) technology has seen a great boost in the past decade (factor 3 in J_C w/r to ITER) but is not yet used in an accelerator – The HL-LHC upgrade will be the first one.

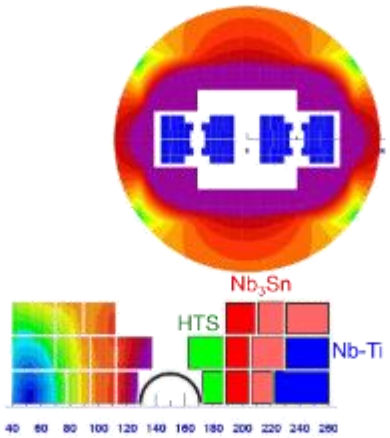
3. **HTS** (High-Temperature Superconductor) technology still in the experimental phase (Production quantities, homogeneity and cost need to evolve!) but can be a disruptive technology for future high-field magnets.

R&D towards a 20 T HTS dipole magnet, develop 10 kA cable.
REBCO (rare earth barium copper oxyde) deposition on stainless substrate, tape arranged in Roebel cables.
values of 900-1200 A/mm2 at 4.2 K , 18-20 T have been obtained



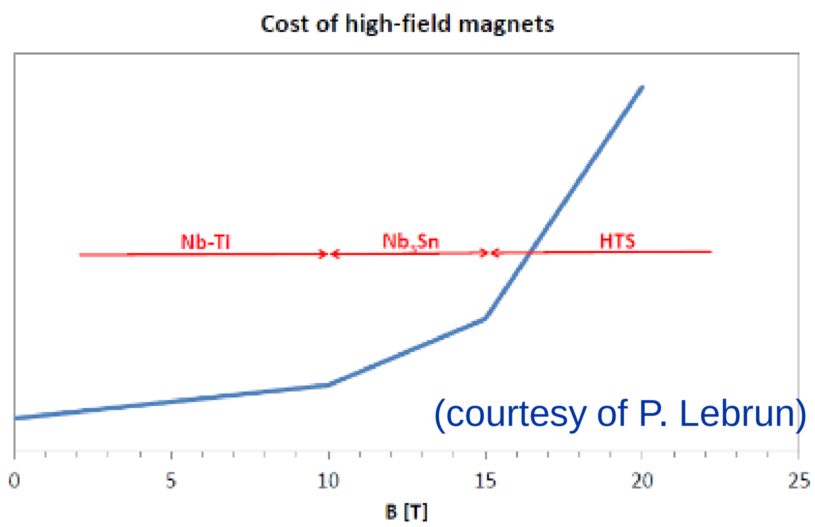
Right: layered structures with sections of different conductors
Left: new magnet designs are required for HTS

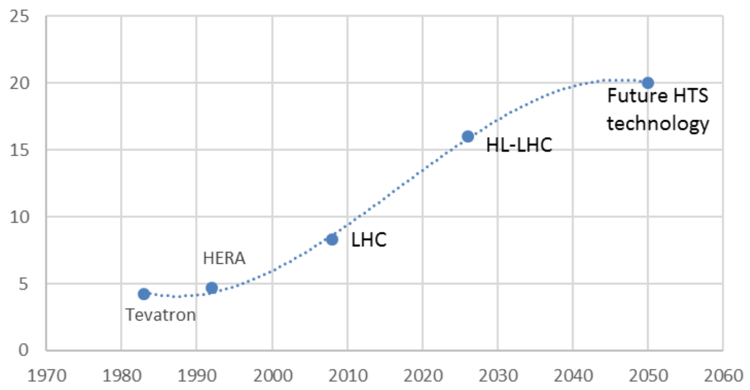
A 20 T HE-LHC dipole
L. Rossi & E. Todesco, (CERN)



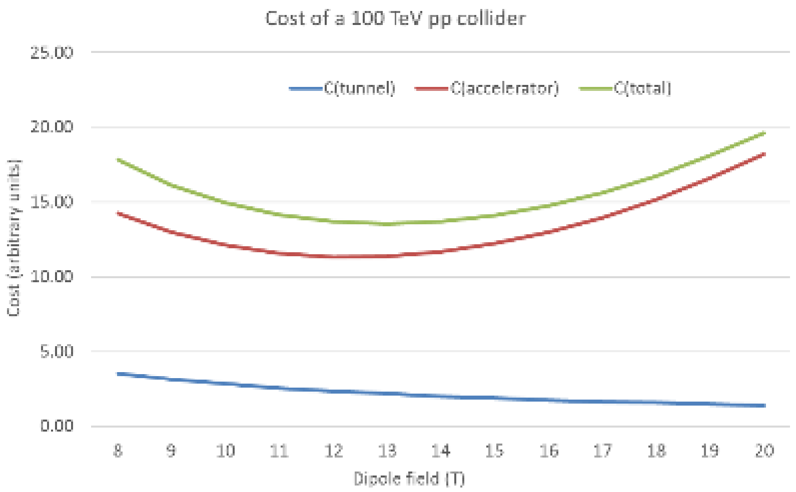
Cost optimized, graded winding

HTS magnets – reducing cost is the main challenge





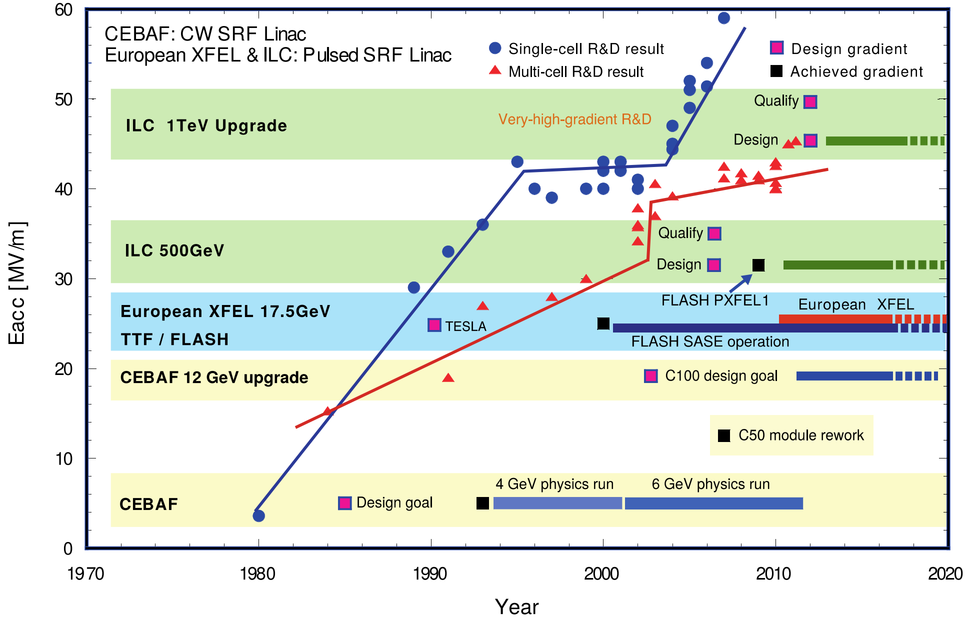
HTS allows reducing the size of the accelerator but not (yet) the cost.
HTS is presently about 5 times the cost of Nb3Sn, but other communities (e.g. fusion) could contribute to reducing the price in the next years.

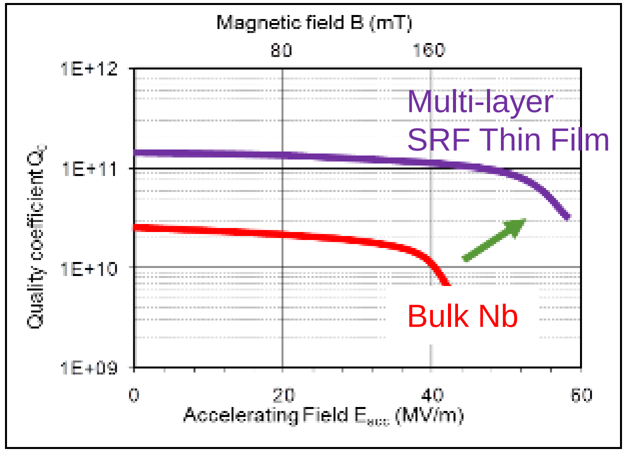


100 CHF (=100$) of YBCO HTS tape built by Bruker HTS for CERN

Is superconducting magnet technology approaching saturation ?
Large increase in cost for small performance improvements

The electric field frontier – superconducting cavities



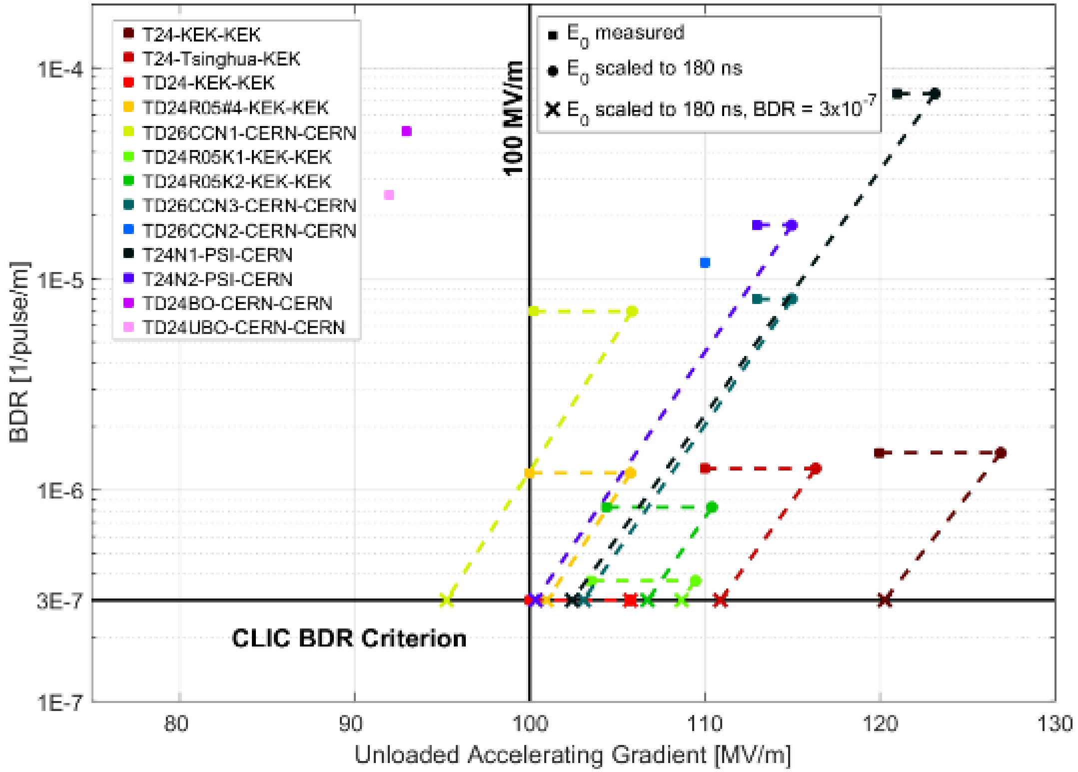


TRENDS:

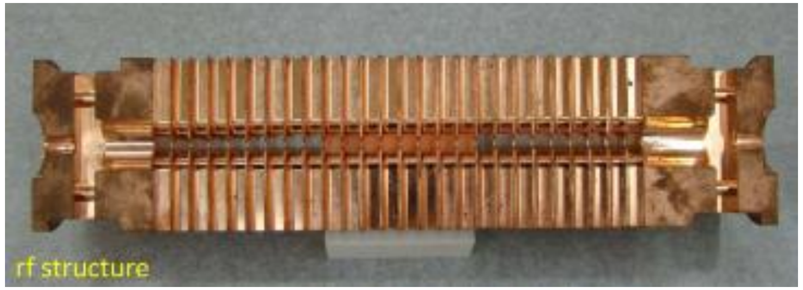
- Nitrogen infusion process (FNAL) and other doping techniques: high Q operation, gradients ~45 MV/m
- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency)
- Coating of Cu cavites with Nb by HiPIMS (High Power Impulse Magnetron Sputtering,

Long-term goal: 60 → 90 MV/m

The electric field frontier – normal conducting cavities



Most advanced results by the Compact Linear Collider (CLIC) study based at CERN (X-band, 12 GHz)
Large international collaboration to understand the physics of breakdown phenomena.



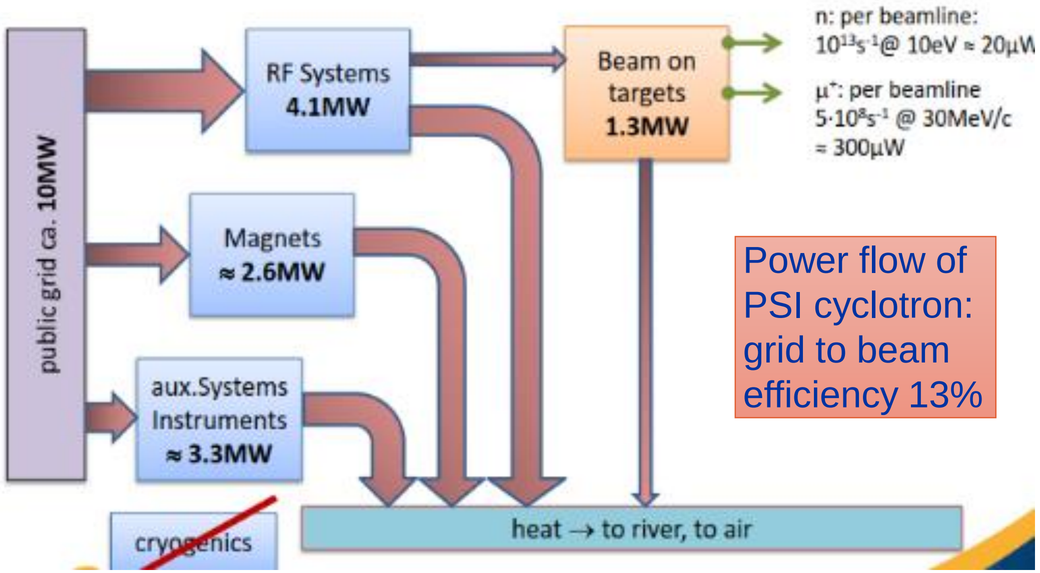
Pulsed systems, characterised by a BreakDown Rate (BDR), pulses lost because of vacuum arcing in the structure

100 MV/m gradient can be achieved (and exceeded)

… but power scales as the square of gradient! High gradient means smaller dimensions but higher power consumption.

The sustainability frontier – energy and efficiency

Total electricity consumption (GWh/y)	
PSI	125
ESRF	60
ISIS	70
KVI	4
INFN	25
ALBA-CELLS	20
GSI	60
CERN	1200
SOLEIL	37
ESS	317
MAX IV	66
DESY	150



Power flow of PSI cyclotron: grid to beam efficiency 13%

A particle accelerators is a device that converts electrical energy from the grid into high-quality kinetic energy at sub-atomic scale (*beam energy*).

After a series of transformations, most of the energy is lost into low-quality heat.

Efficiency can be increased using special devices (e.g. permanent magnets, high-efficiency RF sources, SC RF cavities, etc.) but there is an intrinsic efficiency limit related to the "high-quality" of the energy produced by the accelerator and to its use.

Recuperation of heat is possible, but very inefficient because of low temperatures and distance.

Most of the electricity used by a particle accelerator goes to heating water and air – intrinsic limitation due to the "quality" of the energy stored in the beam

Electrical power consumption (MW) for LHC and future projects (estimated)		
	normal	Stand-by
LHC	122	89
HL-LHC	141	101
ILC	230	
CLIC 500 GeV	235	167
CLIC 1.5 TeV	364	190
FCC hh	580	300?

Future large projects require huge amounts of electrical power

Example: the ILC needs about 1/3 of a Fukushima-type nuclear reactor, or in alternative 200 large windmills (80m diameter, 2.5 MW, 50% efficiency) covering a 100 km distance.

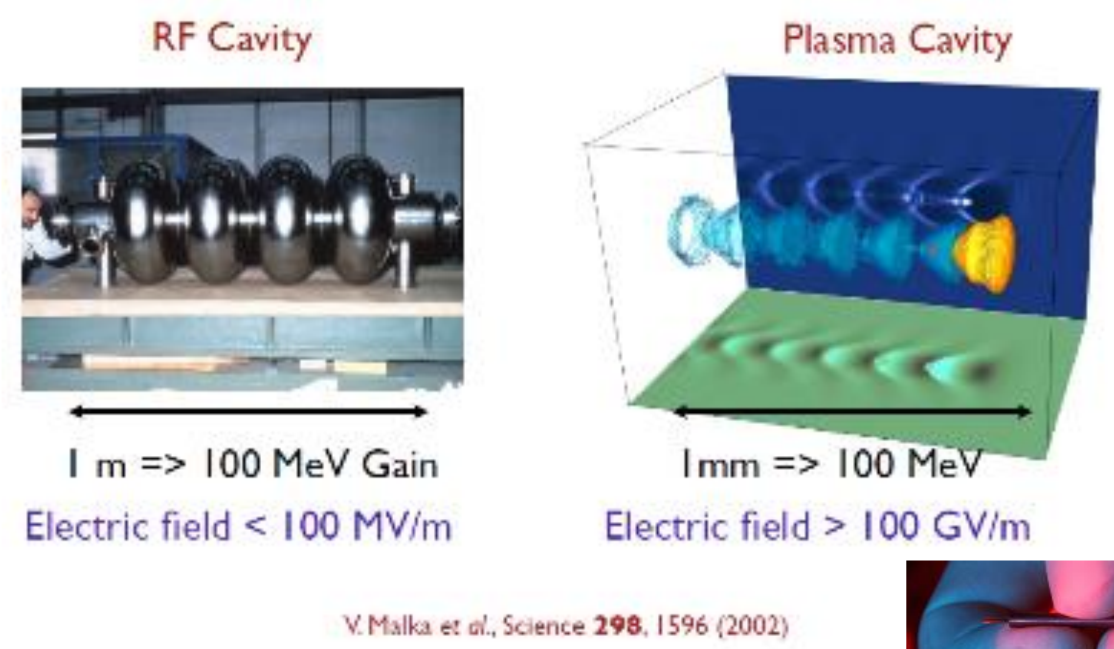
New acceleration techniques using lasers and plasmas

Accelerating field of today's RF cavities or microwave technology is **limited to <100 MV/m**

Several tens of kilometers for future linear colliders

Plasma can sustain up to **three orders of magnitude much higher gradient**

SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient

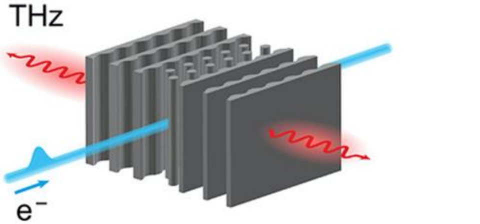


Lasers can produce huge transverse electric fields (TV/m !)

Can we convert the transverse fields into longitudinal and use them for acceleration?

(1) Micro/Nano-Accelerators

Send THz Laser into Dielectric Waveguide (Micro-Accelerator)

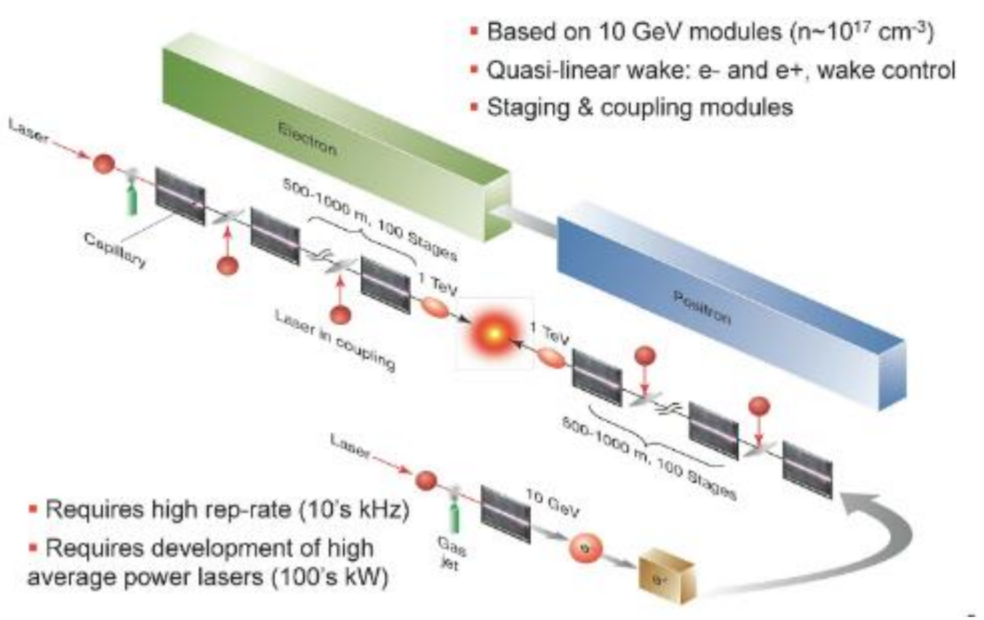


The «accelerator on a chip»

(2) Plasma Accelerators

Use a plasma to convert the transverse electrical field of the laser (or the space charge force of a beam driver) into a longitudinal electrical field, by creating plasma waves.

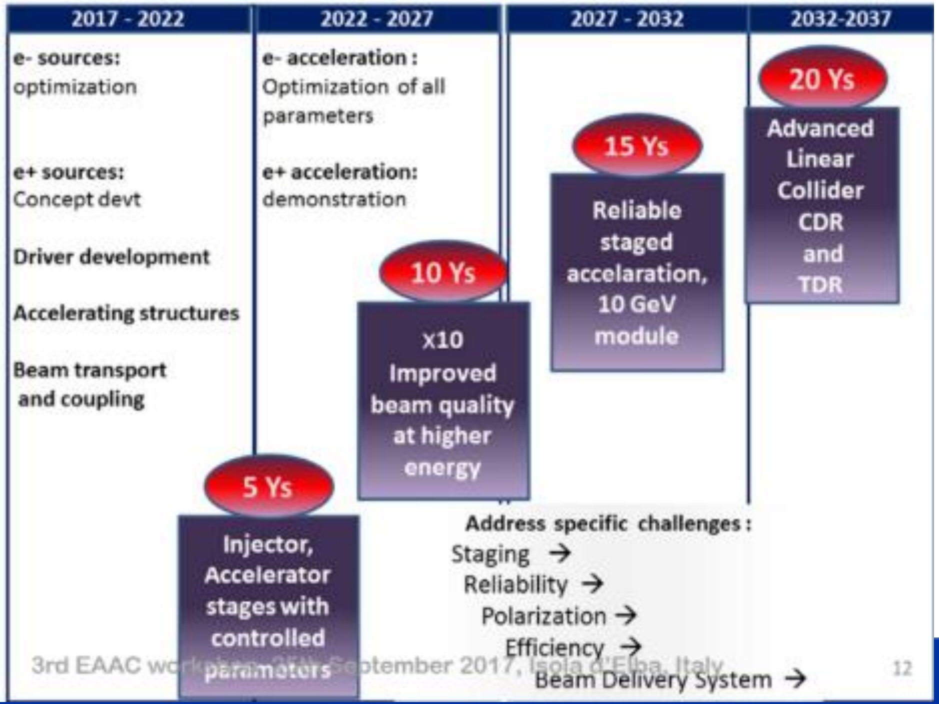
Towards a plasma-based linear collider?



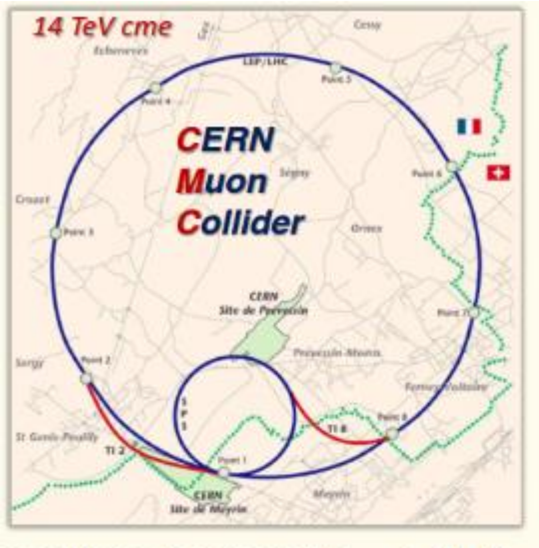
W.P. Leemans & E. Esarey, Physics Today, March 2009

Main challenges

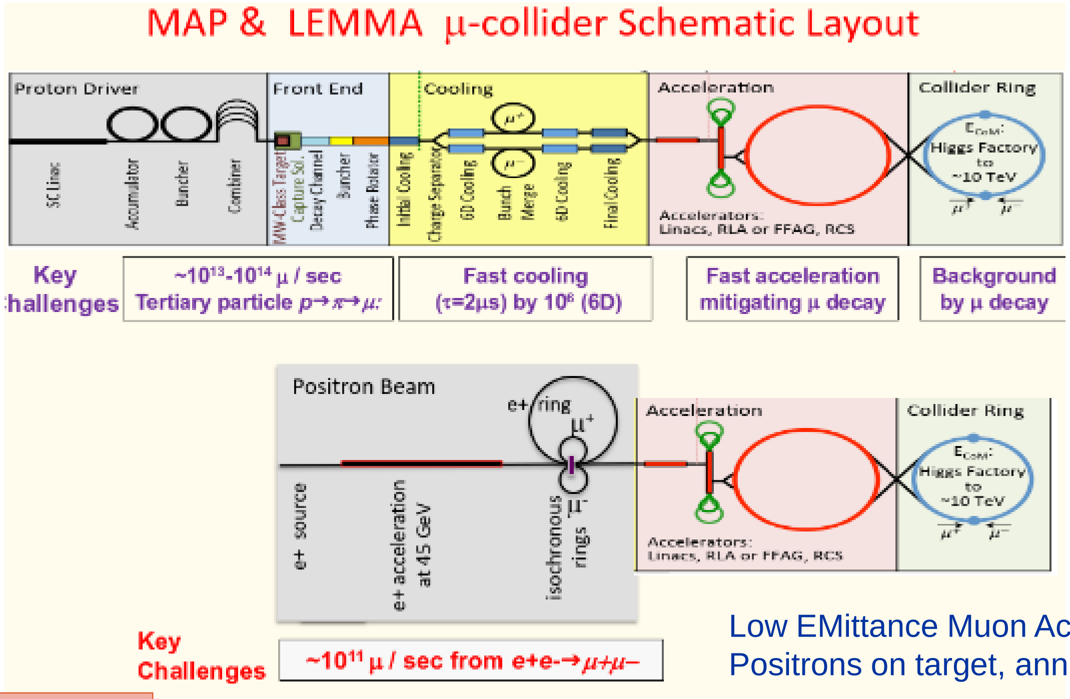
- Beam acceleration with small **energy spread**
- Preservation of small e-beam **emittance**
- Concepts for **positron acceleration** with high brightness
- **High efficiency** of acceleration for e^- and e^+
- **Staging** required to reach very high energies
- **Repetition rates** averaging 10s of kHz
- Beam **stability and reproducibility**



Other options for high energy: muon collider



MOPMF072, IPAC18, V. Shiltzev, D. Neuffer



Low EMittance Muon Accelerator
Positrons on target, annihilation

Colliding muons:
Muons are leptons, similar to electrons but heavier (207 times), produced by pion decay or electron/positron annihilation, have a lifetime of only 2.2 μs.

- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

Critical components:
- Muon production complex (proton or positron beam, MAP or LEMMA)
- Muon acceleration complex
- Neutrino radiation

Excellent in term of power/luminosity, potential for cost savings
Many critical technical challenges requiring R&D

Accelerator for society

The Economist, October 2013

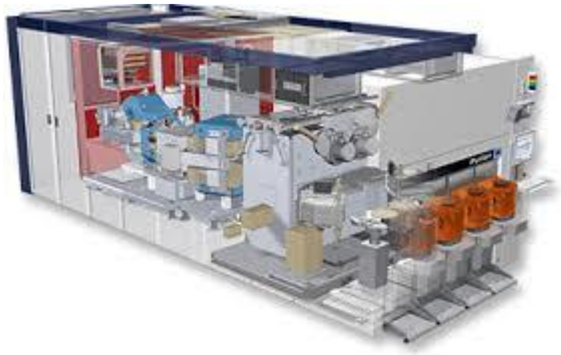
Accelerators for medicine and industry

>35000 accelerators in use world-wide:

- **44% for radiotherapy** ← Treating cancer
- **41% for ion implantation** ← Making better semi-conductors
- **9% for industrial applications** ← "Curing" materials: sterilisation; carbon dating; treating flue gases or water; etc
- **4% low energy research** ← Microanalysis of materials, mass spectroscopy, PIXE, etc
- **1% medical isotope production** ← PET and SPECT medical imaging
- **<1% research**

Radiotherapy electron linac

A tandem accelerator for material and artwork analysis



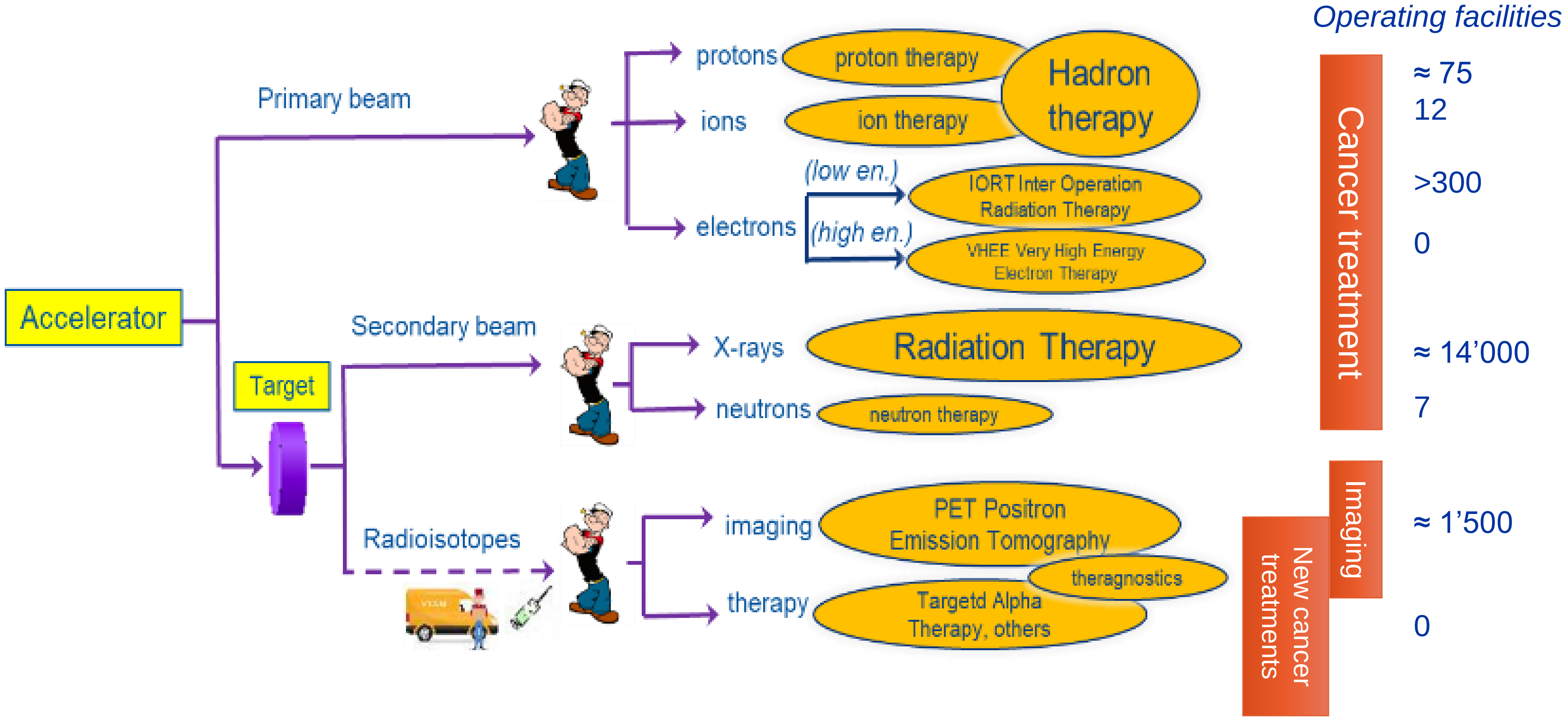
A commercial system for ion implantation

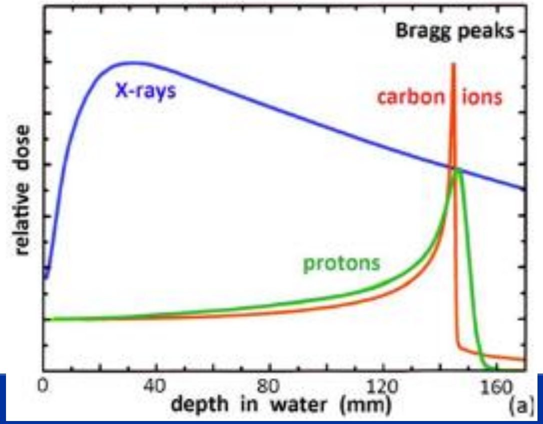
The IBA Rhodotron for production of intense electron beams

Proton cyclotron for radioisotope production

Particle accelerators: a formidable tool for medicine

- Particles beams can activate the nuclei generating radiation that can destroy cancerous cells or can be detected from outside.
- The energy deposited by a proton or ion beam has a well-defined peak (**Bragg peak**) inside the body: can destroy the cancer cells with minimum damage to other tissues.
- 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.

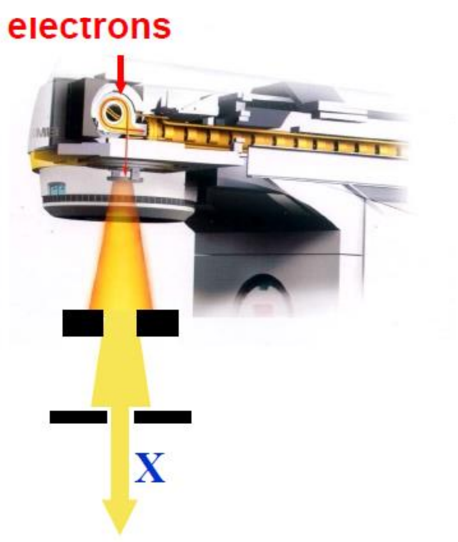




≈ 16’000 particle accelerators operating for medicine worldwide, in cancer therapy and imaging

Treating cancer with particle beams

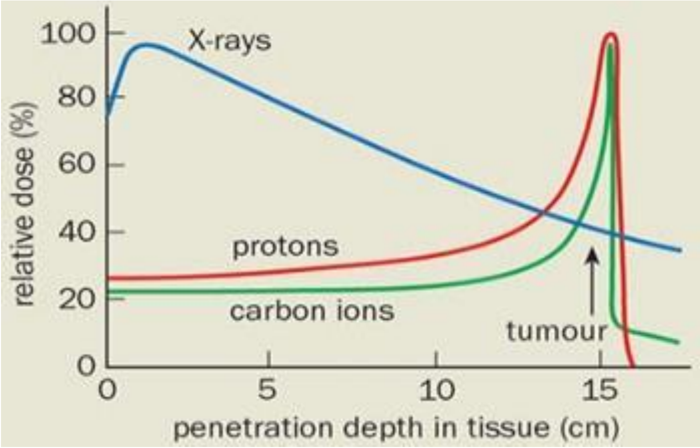
Electron Linac (linear accelerator) for X-ray radiation therapy of cancer



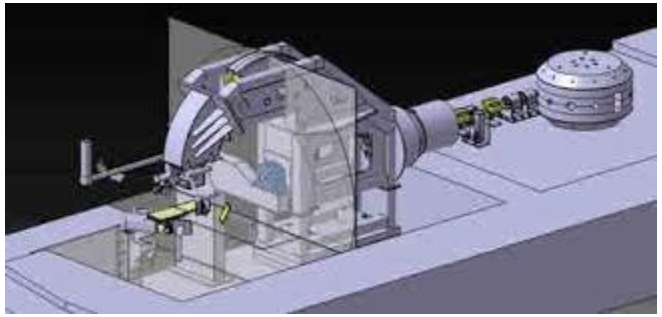
5 – 25 MeV e-beam
Tungsten target

>14,000 in operation worldwide!

Proton Cyclotrons and Ion (Carbon) synchrotrons for particle therapy of cancer



Different from X-rays, protons and ions deposit their energy at a given depth inside the tissues, **minimising the dose to the organs close to the tumour**. (“Bragg peak”)

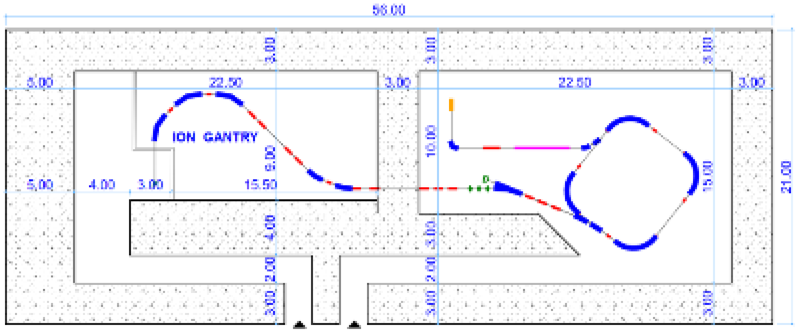


>100 centres for protons, 12 for carbon

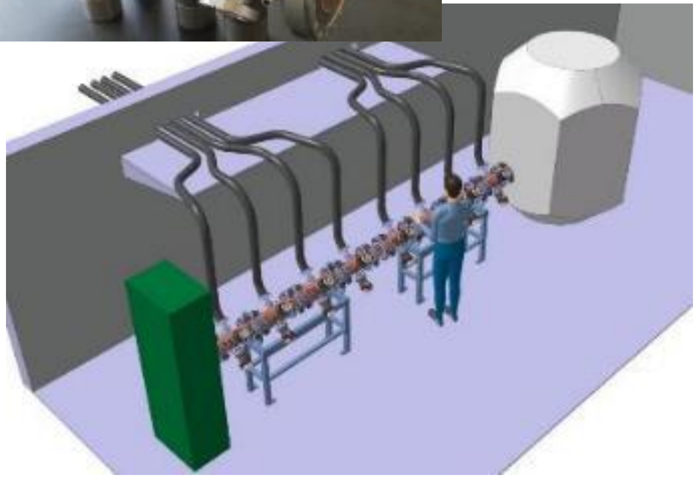
Compact accelerators for medicine

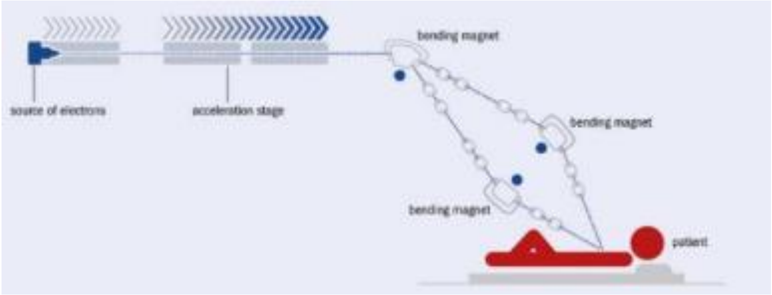
The trend is to move the accelerator inside the hospital, but how can we **miniaturise the accelerator** ?
The challenges are the same as for future particle physics facilities: high field SC magnets, high-gradient and high frequency accelerating structures.

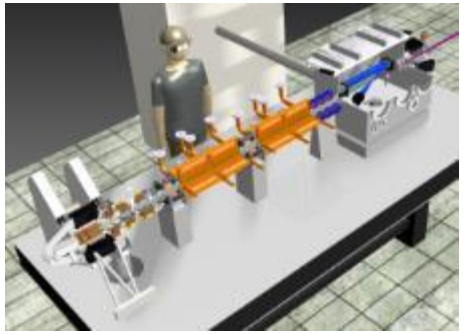
AMIT superconducting cyclotron for isotope production (CIEMAT, Spain)



Carbon ion cancer therapy facility in <1000 m^2 based on a superconducting synchrotron (CERN, SEEIIST)







CLIC 12 Ghz technology for FLASH therapy in hospitals (CERN, CHUV)

RFQ linac system for isotope production in hospitals (CERN)

Environmental applications of accelerators

Low-energy electrons can break molecular bonds and be used for:

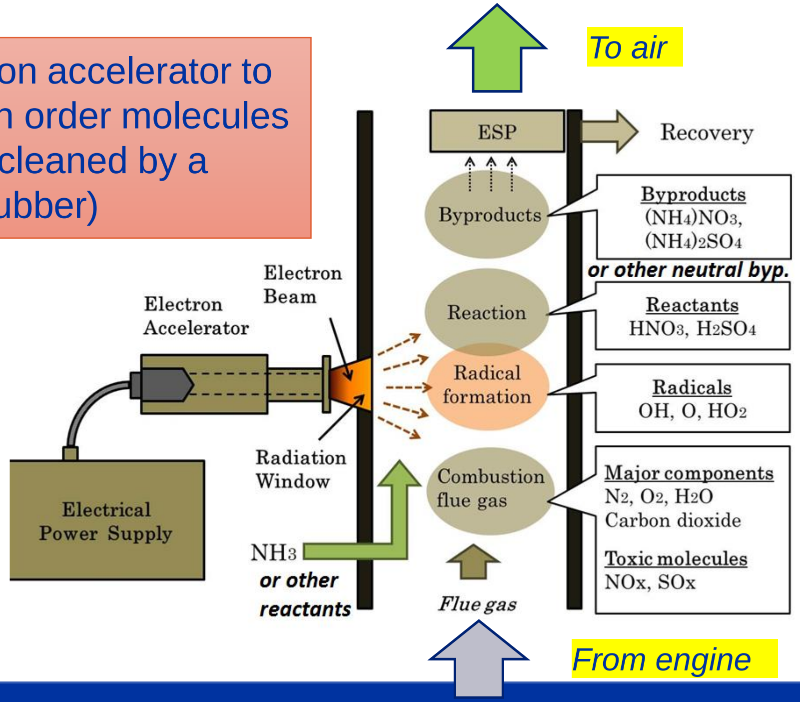
- Flue gas treatment (cleaning of SOx from smokes of fossil fuel power plants)
- Wastewater and sewage treatment
- Treatment of marine diesel exhaust gases (removal of SOx and NOx).

- **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).

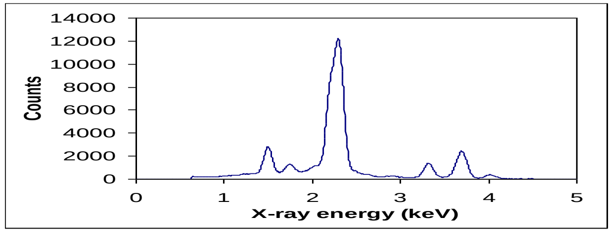


Accelerators for art

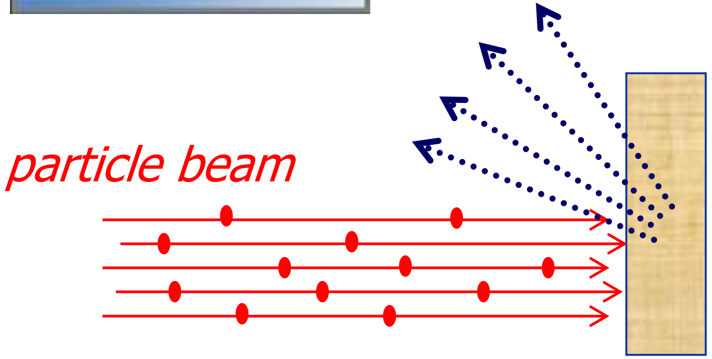
Ion Beam Analysis (e.g. PIXE, Proton Induced X-ray Emission)
A beam of particles (protons) from an accelerator is sent on a sample (e.g. a painting)
The atoms are excited and emit different types of radiation (X-rays, gammas, etc.)
Different atomic elements emit X-rays at different energies – Spectral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

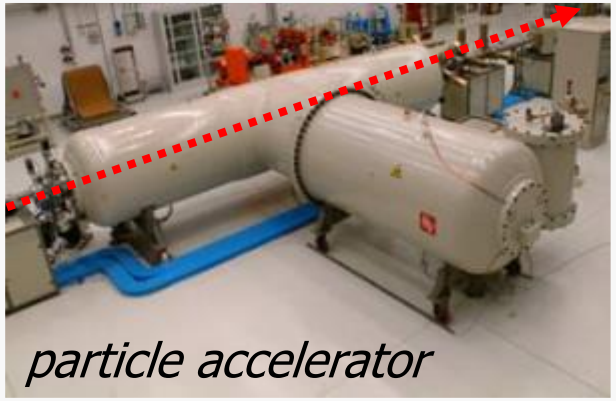
Ritratto Trivulzio by Antonello da Messina, 1476 – analysis at INFN-LABEC (Florence)

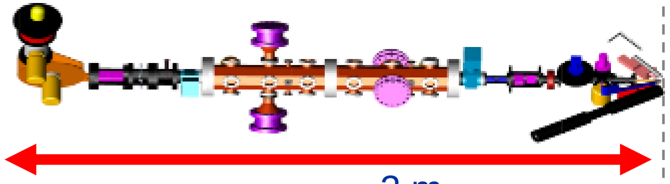
Radiation detection and spectral analysis

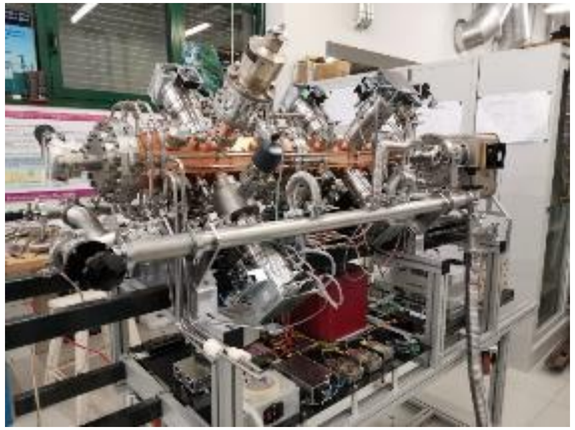


Emission of radiation of characteristic energies (X-rays, γ, particles…)









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

Some conclusions - at the roots of innovation

Particle accelerators are facing a critical moment in their evolution.

The expectations on accelerators from basic science, applied science, medicine and industry are increasing but some of our technologies are still the same as Wideröe's invention almost 100 years ago.

There is today a lot of space and encouragement for **innovative ideas**!

But, what are the ingredients of innovation? Remember the first slide on Wideröe's invention!

1. Merge inputs from different science and technology fields (look around you!)
2. Challenge the established traditions (but respect experience!)
3. Take risks (but foresee mitigations!)

The 4 industrial revolutions (4th still ongoing!)

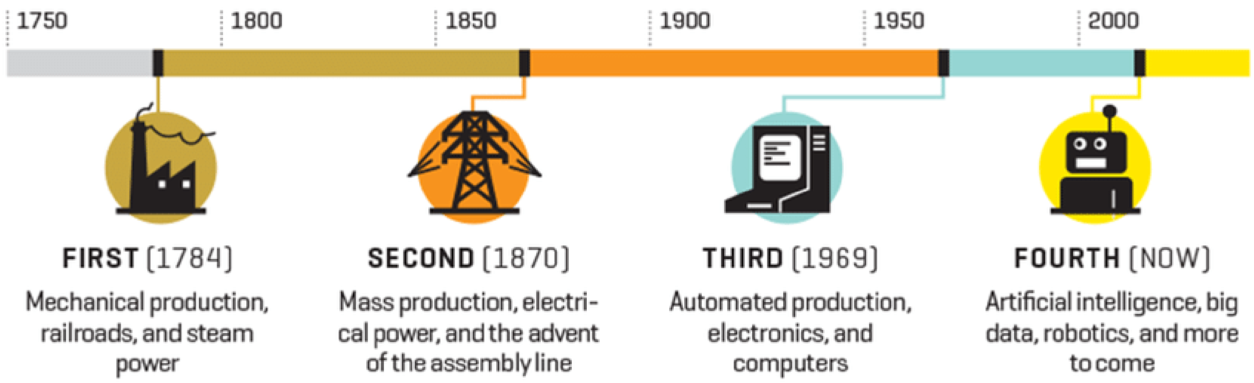


Image credit: B. Horvath, S. Mundi, 2018

Particle accelerators can become crucial actors of the 4th industrial revolution allowing industry and medicine to exploit technologies based on the usage of subatomic particles

The final words…

Particle accelerators are a vibrant and growing field, in full transition from basic science to applied science and to wider societal applications.

But to drive this transition and to push further the frontiers of accelerators we need fresh ideas, technology jumps, and (why not!), some change in paradigm.

The secret for the success are novel ideas by young people developed in a collaborative environment, jumping across borders between different scientific fields.

To achieve this we need multinational research programmes with wide support from governments and scientific communities, but above all…

Thank you for your attention!

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