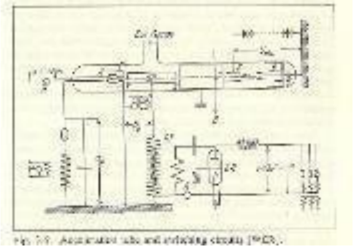
Maurizio Vretenar CERN

LECTURE 5: Challenges, Applications

August 2021

Introduction to Particle Accelerator Science and Technology

100 years of innovations in particle accelerators



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

XXI century

?

Cyclotron: cyclic acceleration with magnets (Lawrence)

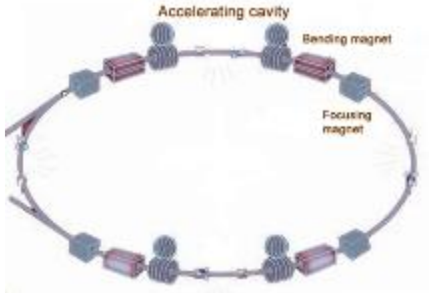
Strong focusing (Courant, Livingston, Snyder, Christofilos)

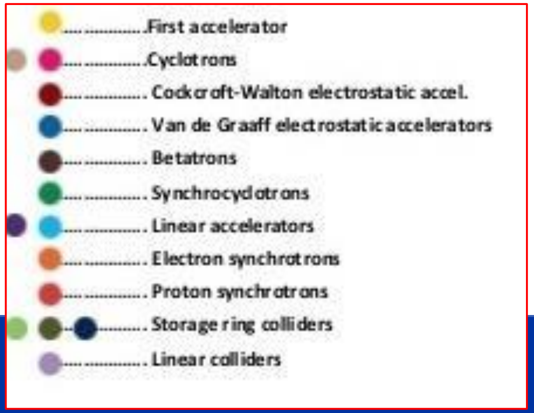
Superconducting magnets and acc. cavities

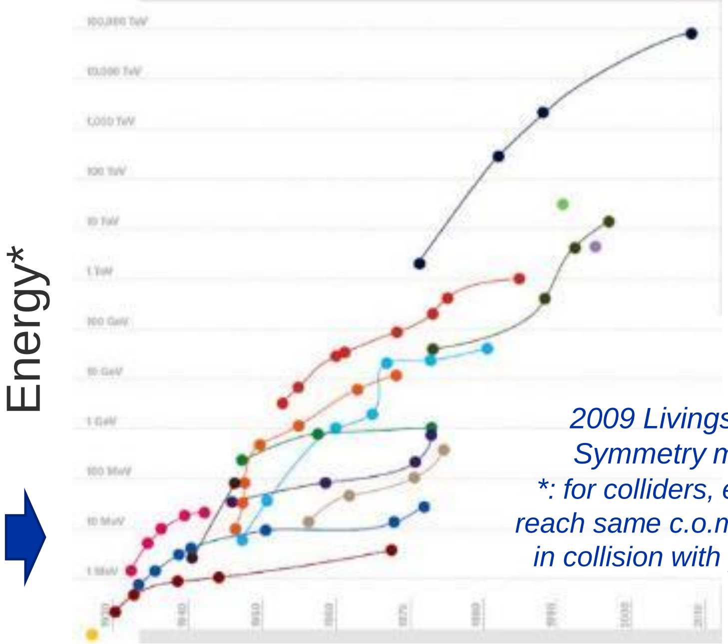
2008: the Large Hadron Collider

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

Succession of enabling technologies (technology leaps)





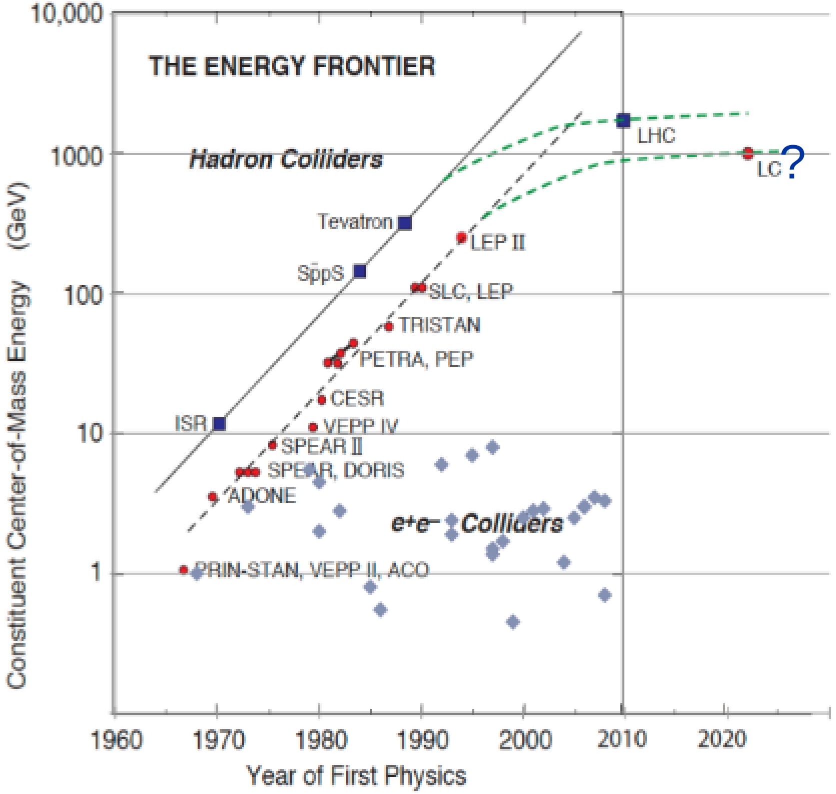


2009 Livingston plot, Symmetry magazine
**: for colliders, energy to reach same c.o.m. energy in collision with proton at rest*

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

Particle Accelerators in 2021

Apparently, we have reached the end of exponential energy growth



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

But the field has never been so flourishing…

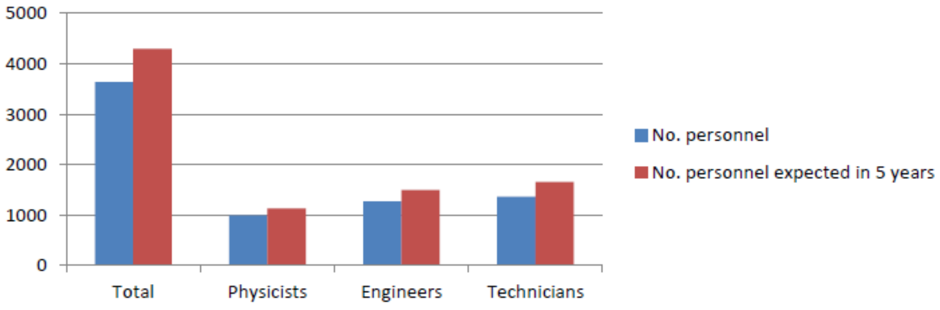


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

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

CONSTRUCTION PROJECTS AND UPGRADES OF PARTICLE ACCELERATORS

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

2’200 papers submitted at IPAC20

Multiple challenges for accelerator science

- 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 transition XX-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** appear as key technology drivers of the XXIst century.

What is the role of accelerators in this transition?

There are more than 35’000 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%

Accelerators in transition – not only particle physics!

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 centralized 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.

New ideas and technologies

Applied science (photon and neutron sources)

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

Big challenges for accelerator science

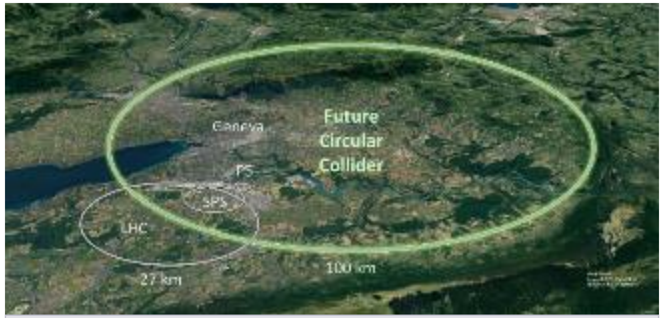
Making accelerator-based particle physics research more sustainable is going to be one of the main challenges to the accelerator community in this XXIst century.

At the same time, we need to work to bring accelerator technology outside of our traditional laboratories, to be used for applied science (materials, biology, etc.), medicine and industry.

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

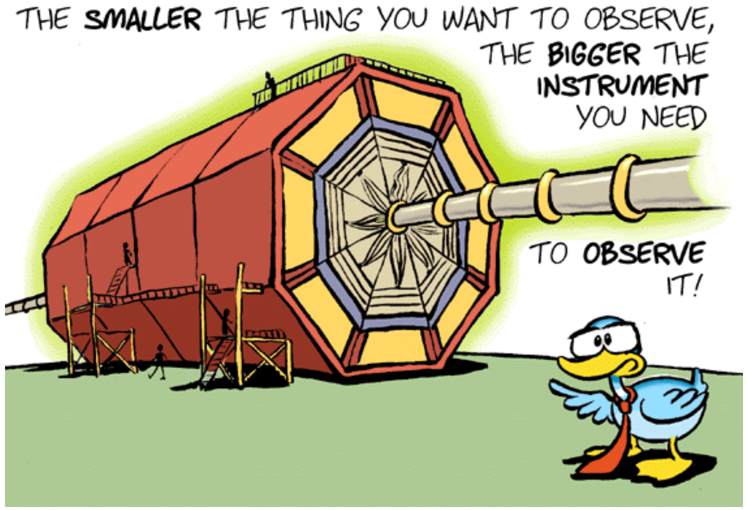
After the LHC, the next generation of accelerators for basic science will reach unprecedented dimensions and costs.

Developing their technology requires new ideas to be developed in a larger environment than basic science

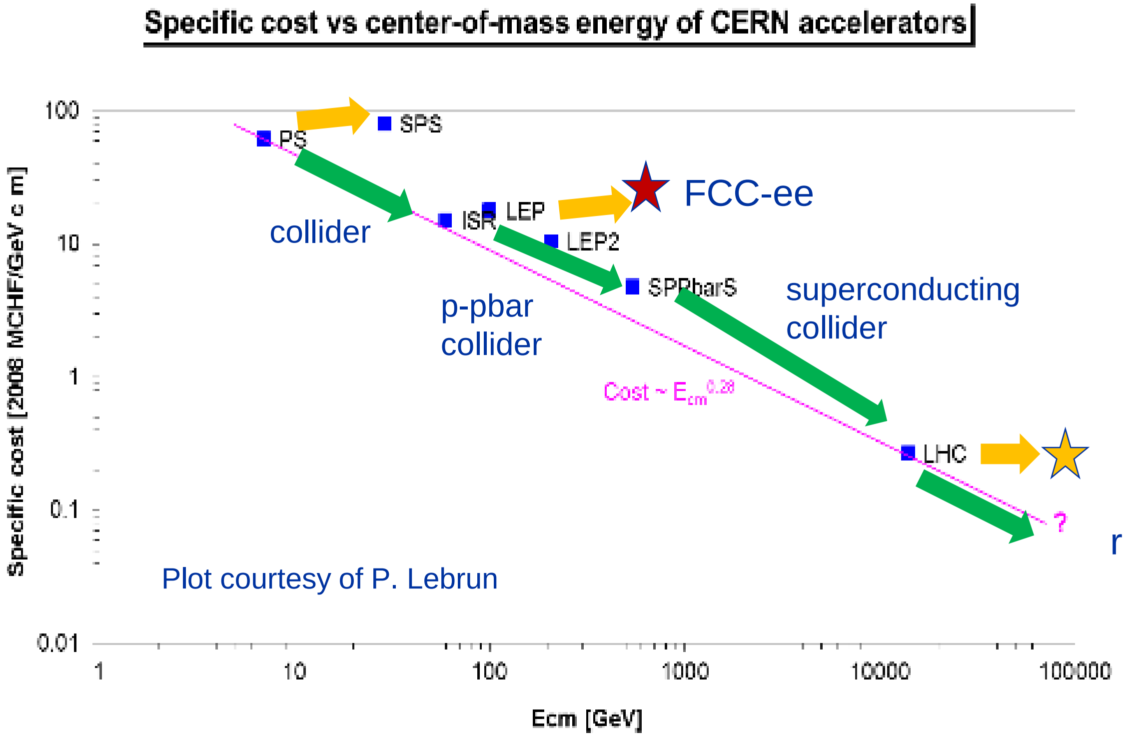


From the LHC (27 km) to the Future Circular Collider (100 km) ?

Multiple dimensions of accelerator R&D



Frontier accelerators – economic sustainability



FCC-ee

collider

p-pbar collider

superconducting collider

Plot courtesy of P. Lebrun

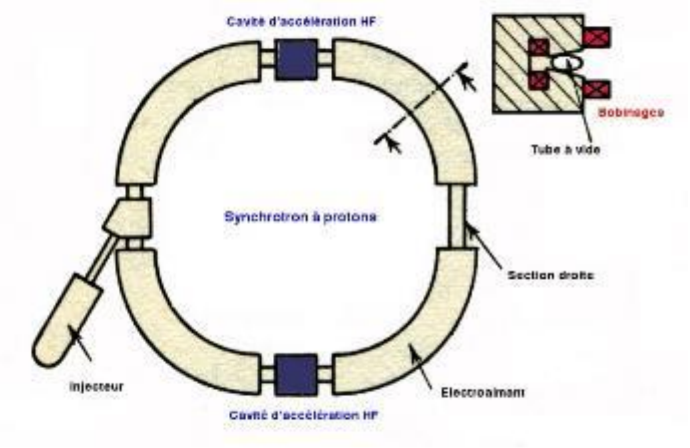
Moving along this line was made possible by new technologies (colliders – antiproton production and storage – superconductivity)

scaling of present technology

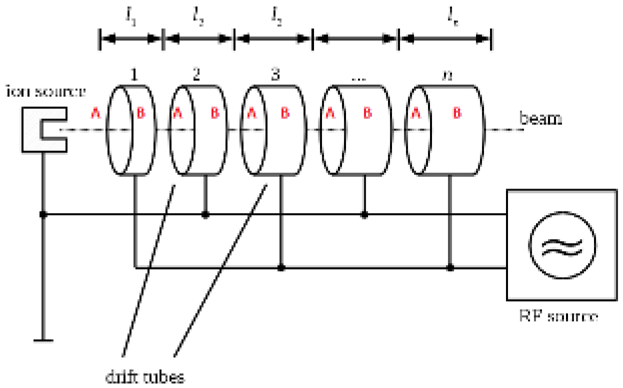
reduction in cost with new technologies?

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: how to make smaller accelerators?

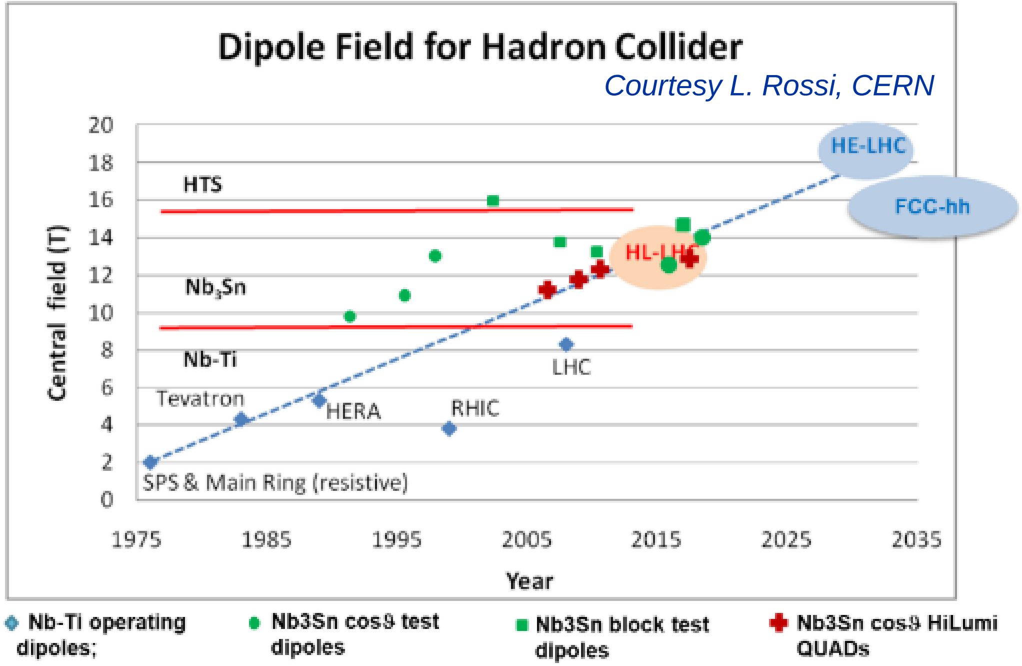


Synchrotrons: $p/q=B\rho$
Need to maximise ***magnetic field***
Superconductivity is mandatory, the limitations is the critical current density Jc for SC magnets



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

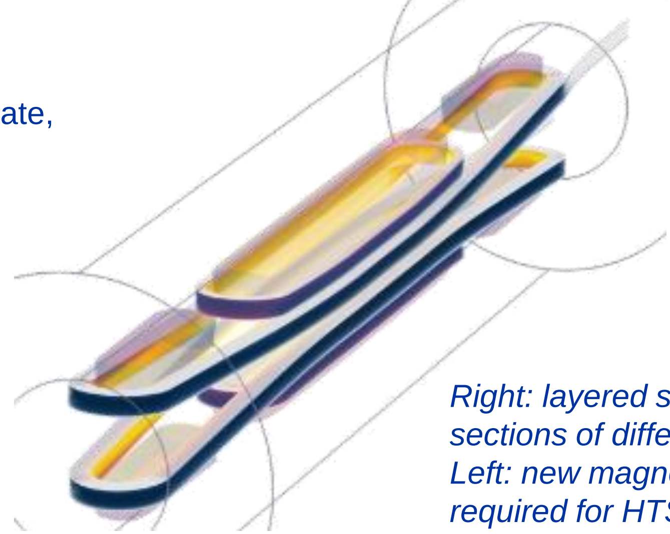


Three technologies under consideration

1. **NbTi** (Niobium Titanium as in the LHC): mature but limited to about 9T field.
2. **Nb$_3$Sn** (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.

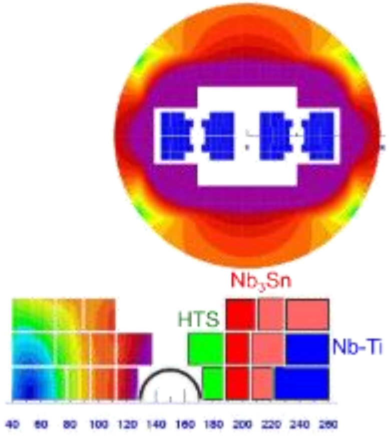
R&D towards a 20 T HTS dipole magnet, develop 10 kA cable.
REBCO (rare earth barium copper oxyde) deposition on stainless substrate, tape arranged in Roebel cables.
values of 900-1200 A/mm2 at 4.2 K , 18-20 T have been obtained

Fig. 1. A 12 mm tape produced by BHTS via ABAD and PLD method.



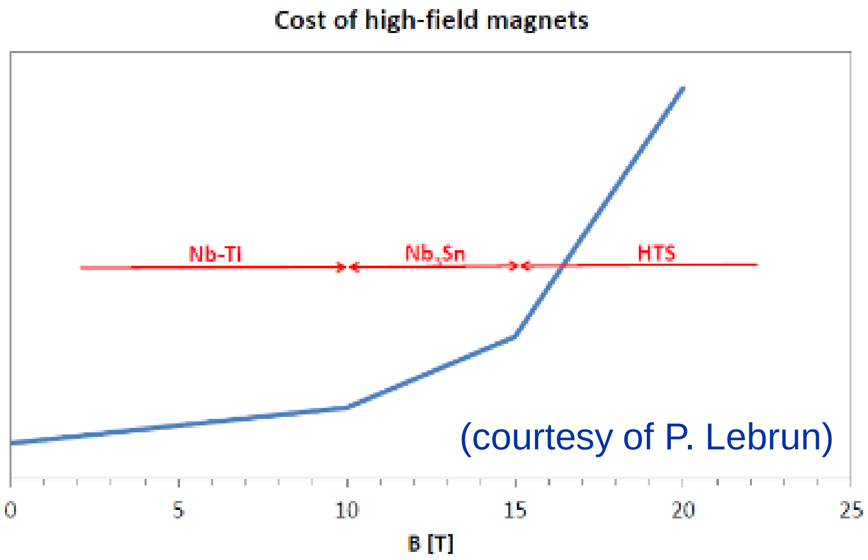
Right: layered structures with sections of different conductors
Left: new magnet designs are required for HTS

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

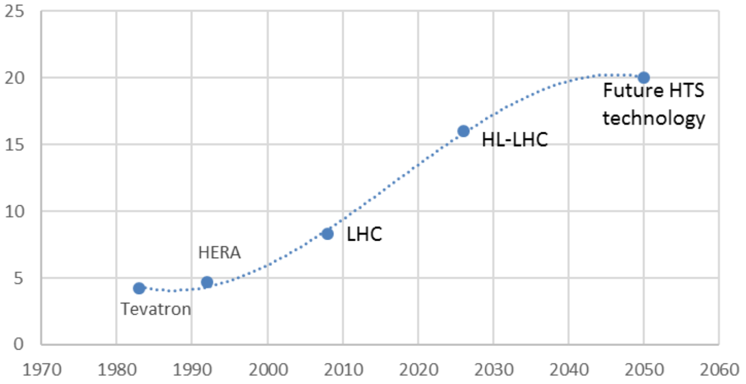


Cost optimized, graded winding

HTS magnets – reducing cost is the main challenge

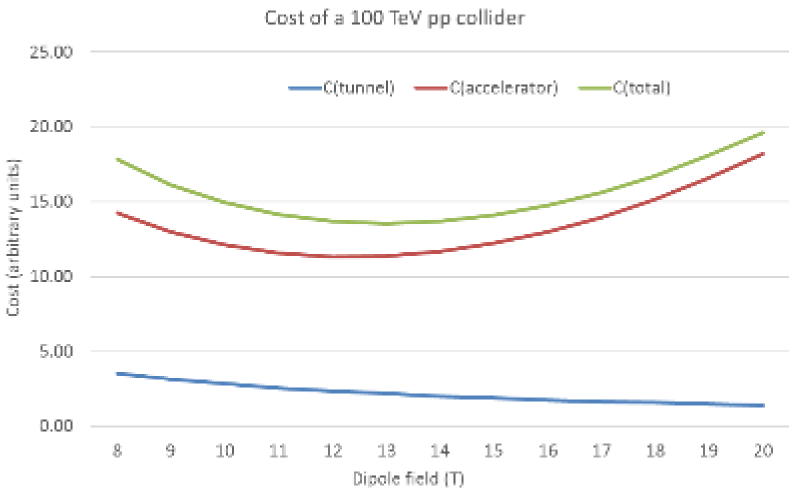


(courtesy of P. Lebrun)



Maximum B field as function of time

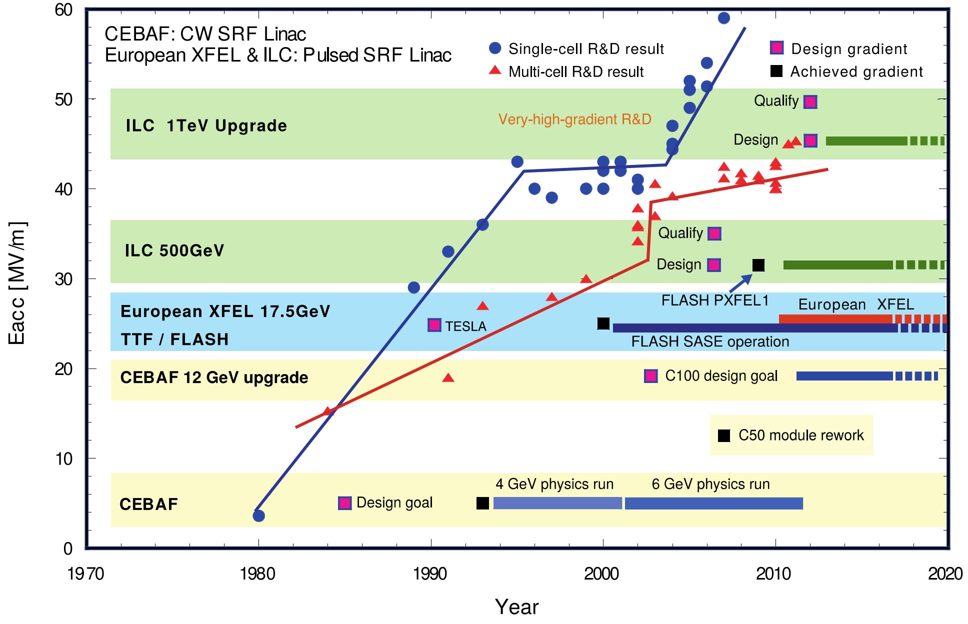
HTS allows reducing the size of the accelerator but not (yet) the cost. Presently about 5 times the cost of Nb3Sn, but other communities (e.g. fusion) could contribute to reducing the price in the next years.

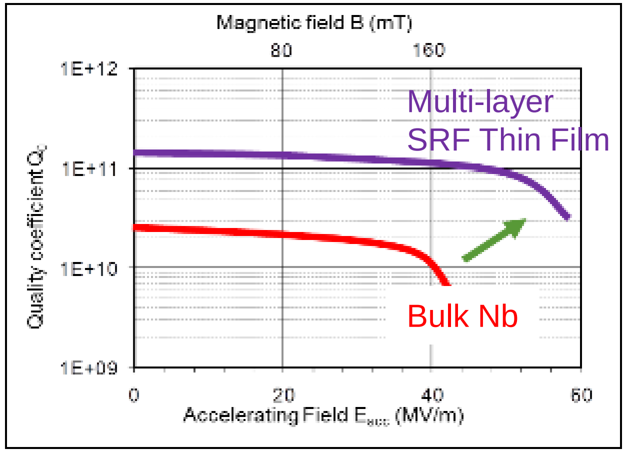


100 CHF (=100$) of YBCO HTS tape built by Bruker HTS for CERN

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

The electric field frontier – superconducting cavities



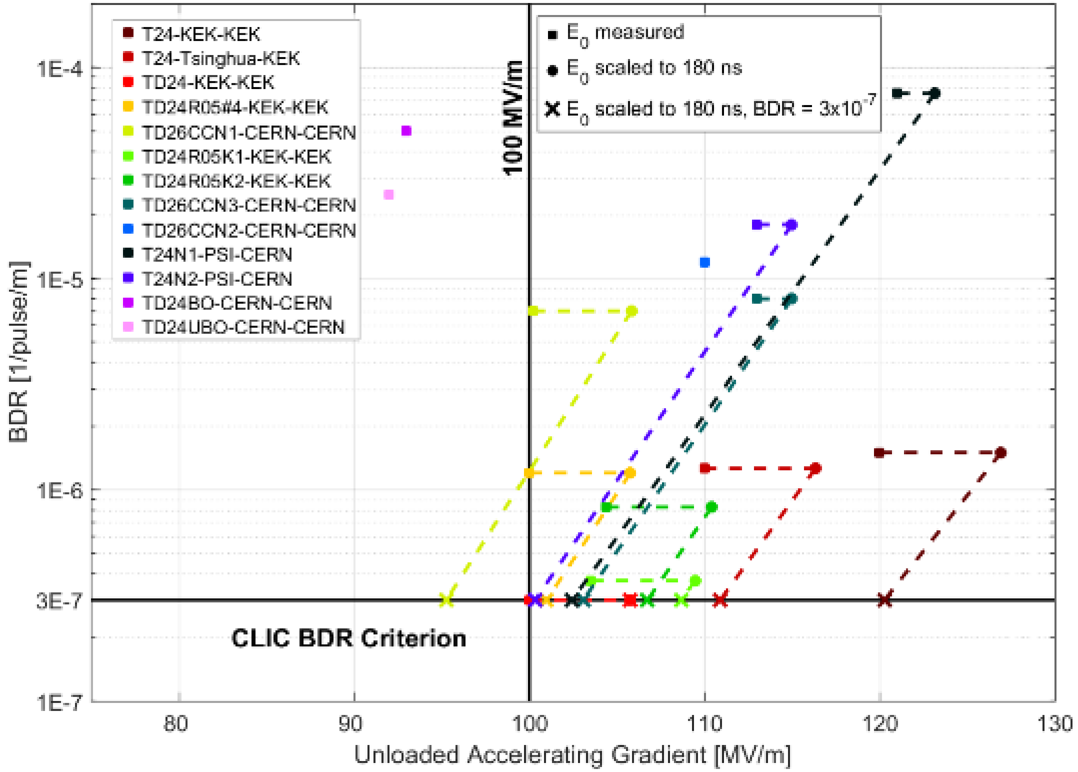


TRENDS:

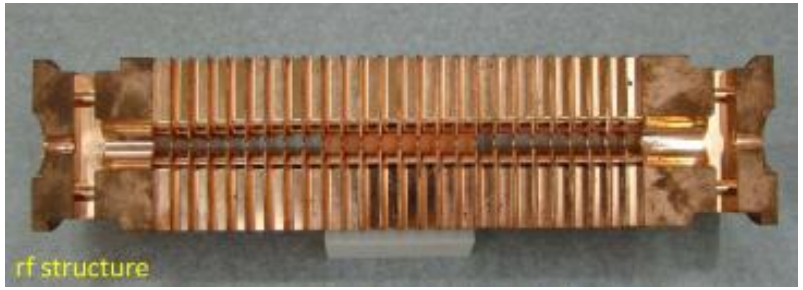
- Nitrogen infusion process (FNAL) and other doping techniques: high Q operation, gradients ~45 MV/m
- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency)
- Coating of Cu cavites with Nb by HiPIMS (High Power Impulse Magnetron Sputtering,

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

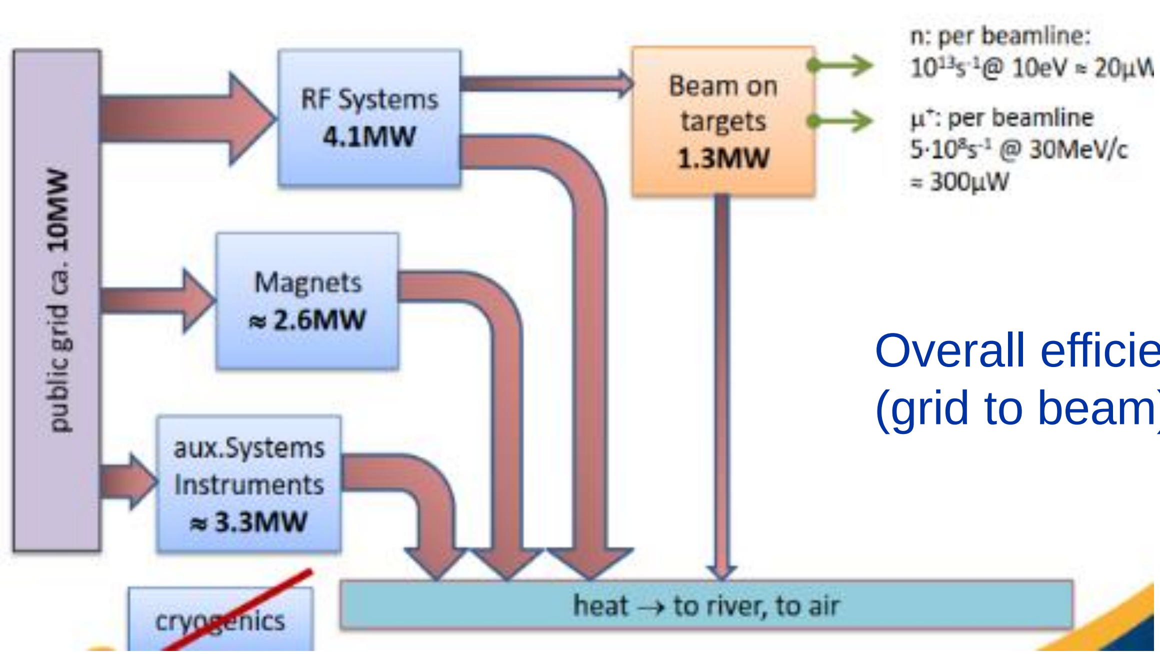
Efficient energy management – a must for future projects

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

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 pp	250?	150?

Future large projects require huge amounts of electrical power.
Example: the ILC needs about 1/3 of a Fukushima-type nuclear reactor.
Going green? to supply CLIC500 or ILC would be needed 200 large windmills (80m diameter, 2.5 MW, 50% efficiency) covering a 100 km distance.



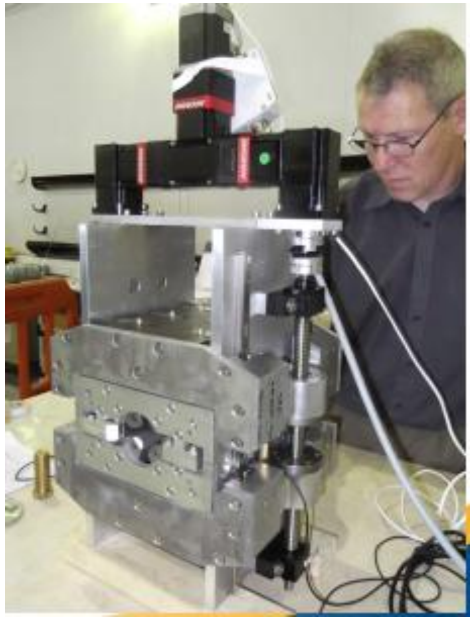
Overall efficiency
(grid to beam): 13%

Example: power flow in the PSI cyclotron facility

«From the energy point of view, particle accelerators are large water heaters, which occasionally produce some particles…»

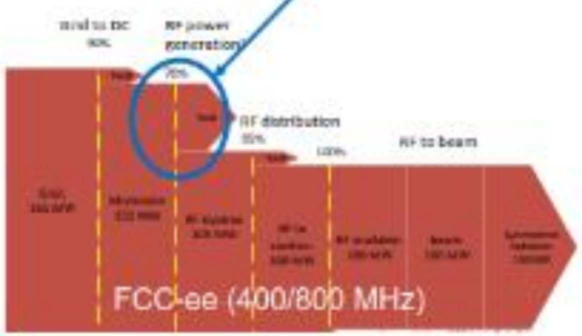
Some initiatives to improve power efficiency

Energy recovery from cooling, more efficient RF systems, energy storage, virtual power plant, low-power transport channels.



Tunable high-gradient permanent magnet quadrupoles

Largest impact for reducing energy consumption of accelerators by RF power generation



Increase of 5% efficiency for RF generation
→10 MW less electricity consumed
→gain 50 GWh/year (2M€/year)

Increase of 5% efficiency of 12 GHz klystrons
→10% less electricity consumed
→gain 100 GWh (4 M€)

Photo: CLIC Xbox 12 GHz facility for cavities conditioning

Development of high-efficiency RF power sources

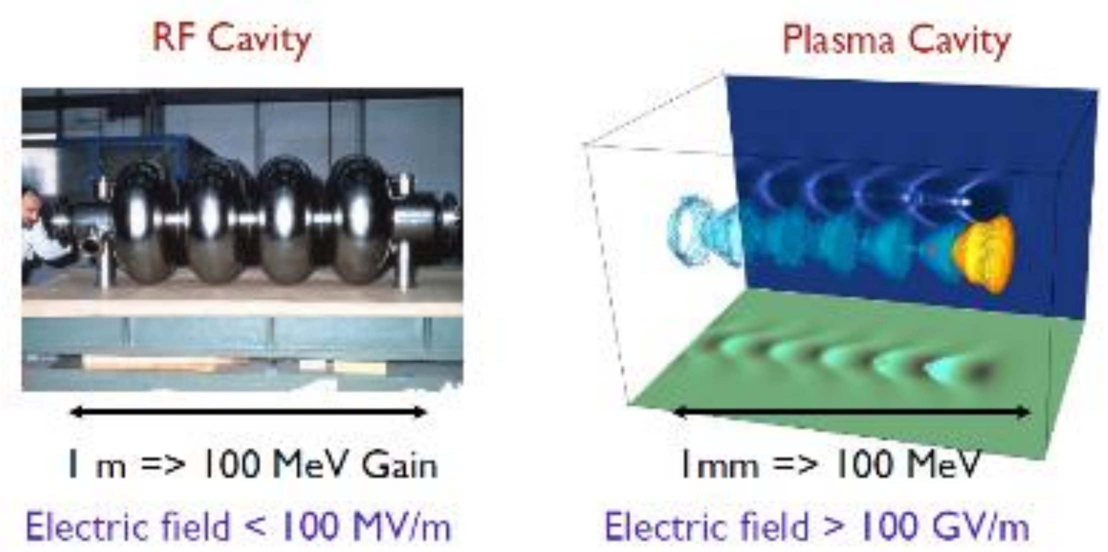
New acceleration techniques using lasers and plasmas

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



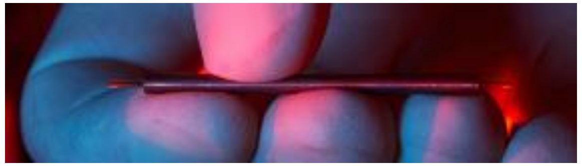
V. Malka et al., Science **298**, 1596 (2002)

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)

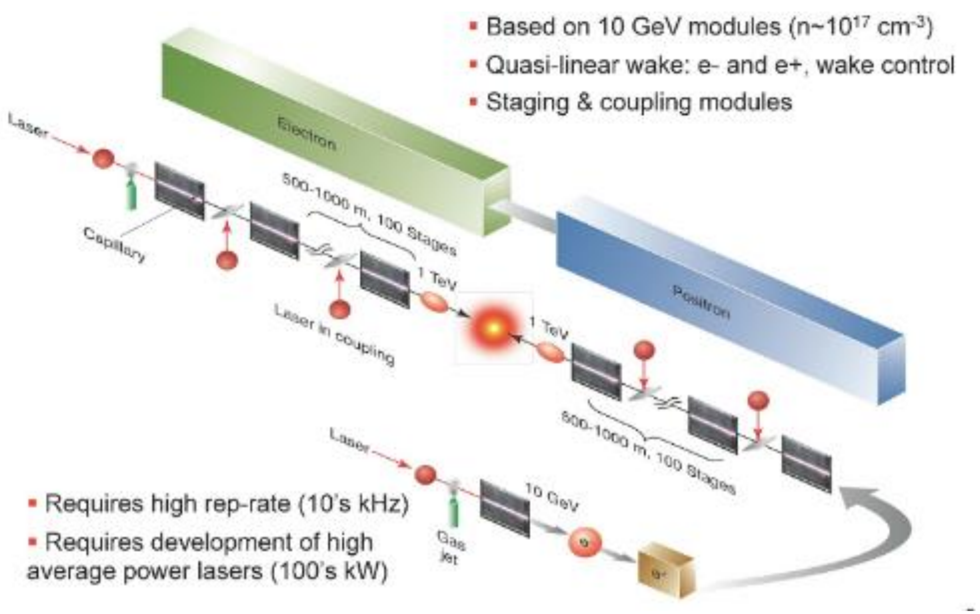


The «accelerator on a chip»

(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?



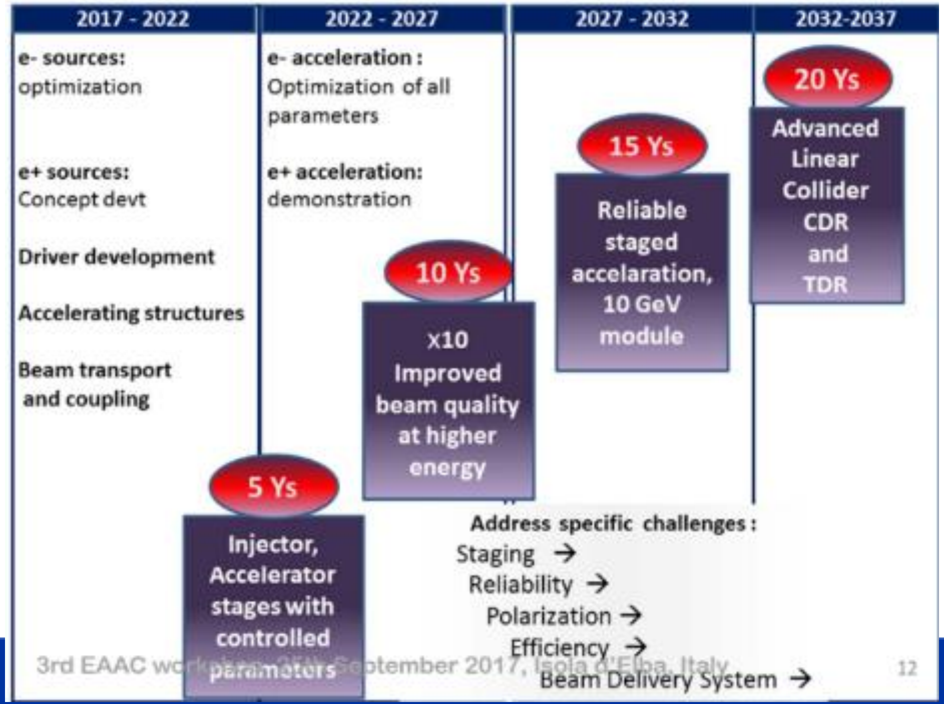
- Based on 10 GeV modules (n~10^{17} cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules

- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

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**



2017 - 2022	2022 - 2027	2027 - 2032	2032-2037
e- sources: optimization **e+ sources:** Concept devt **Driver development** **Accelerating structures** **Beam transport and coupling**	**e- acceleration :** Optimization of all parameters **e+ acceleration:** demonstration		

5 Ys Injector, Accelerator stages with controlled parameters

10 Ys x10 Improved beam quality at higher energy

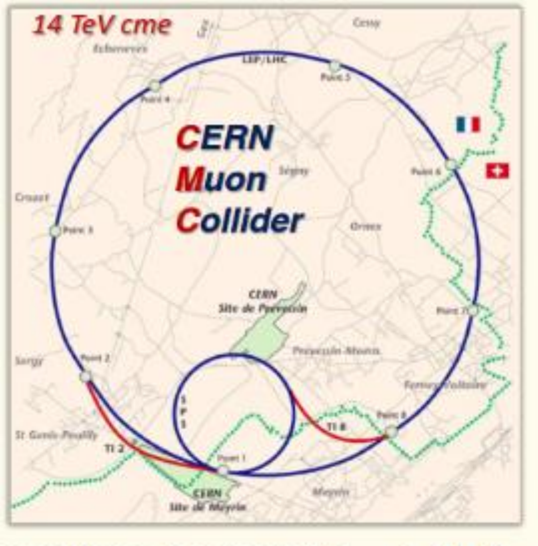
15 Ys Reliable staged accelaration, 10 GeV module

20 Ys Advanced Linear Collider CDR and TDR

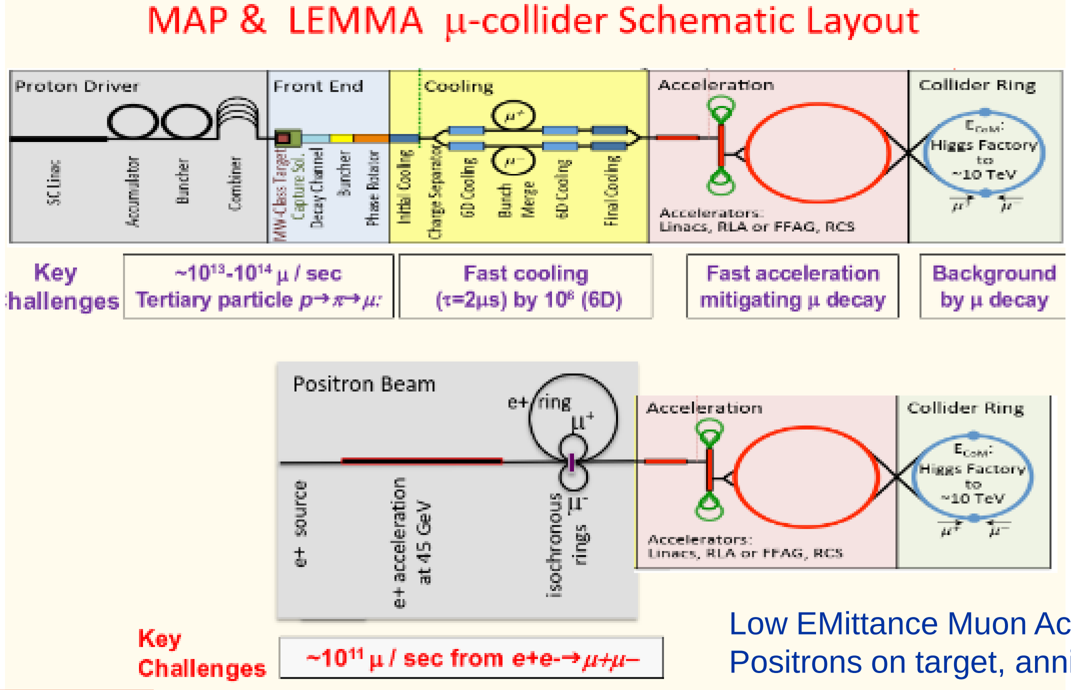
Address specific challenges :
Staging →
Reliability →
Polarization →
Efficiency →
Beam Delivery System →

3rd EAAC wo ptember 2017, Isola d'Elba, Italy 12

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.

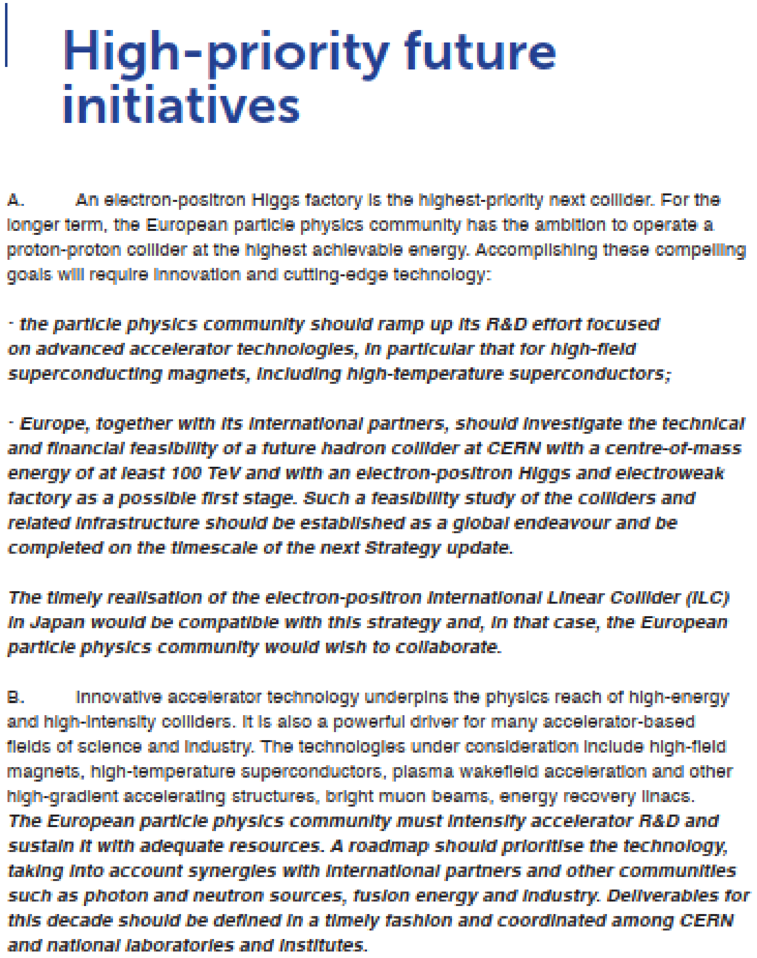
- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in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

Directions of the new European Strategy for Particle Physics

2020 Update of the European Strategy for Particle Physics (May 2020):



High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

Development of **innovative accelerator technology** as driver for **science and industry**.

In particular:

1. high-field magnets and high temperature superconductors
2. Plasma wakefield and other high-gradient acceleration
3. Muon beams
4. Energy recovery linacs

Accelerator for society

The Economist, October 2013

Accelerators for medicine and industry

>30000 accelerators in use world-wide:

- **44% for radiotherapy**
- **41% for ion implantation**
- **9% for industrial applications**
- **4% low energy research**
- **1% medical isotope production**
- **<1% research**

Treating cancer

Making better semi-conductors

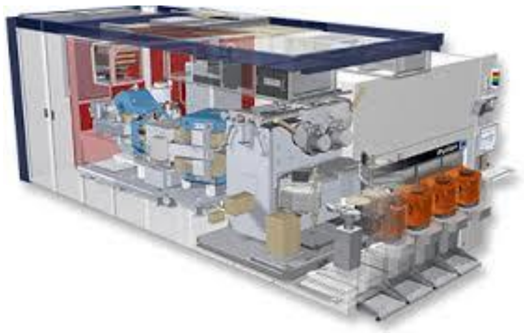
"Curing" materials:
sterilisation; carbon dating;
treating flue gases or water; etc

Microanalysis of materials, mass
spectroscopy, PIXE, etc

PET and SPECT medical imaging

Radiotherapy electron linac

Proton cyclotron for radioisotope production

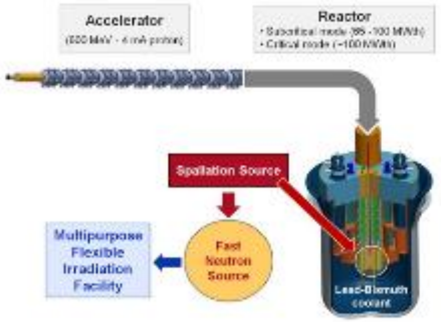


Commercial system for ion implantation

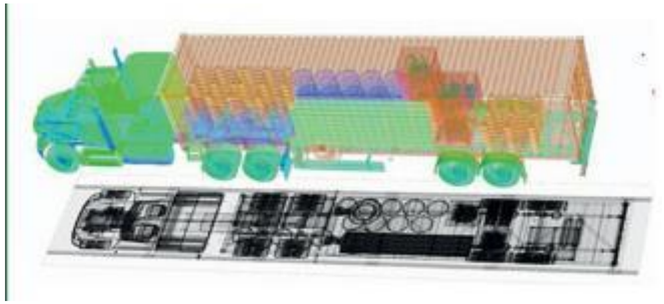
Accelerators for medicine is the subject of the next lecture

Particle accelerators for industry, energy and security

ENERGY production of neutrons for advanced nuclear power (Accelerator Driven Systems, energy amplifier)



SECURITY Production of X-rays to scan containers, of neutrons to search for nuclear material



INDUSTRY

	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
Ions		surface analysis, ion implantation, nanomaterials

Radiation or Reason?
The diffusion of sterilisation with accelerators is limited by very restrictive regulations and very cautious consumer habits. Treatment with «radiation» has no effect on the final consumer and avoids using dangerous chemicals to sterilise food.

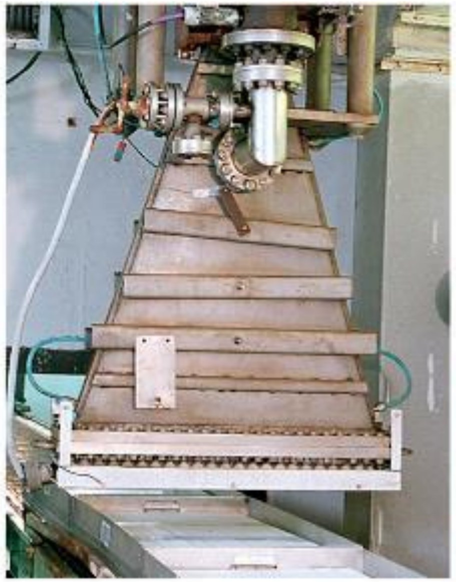


Fig. 4.12: E beam technology for sterilising medical products.

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

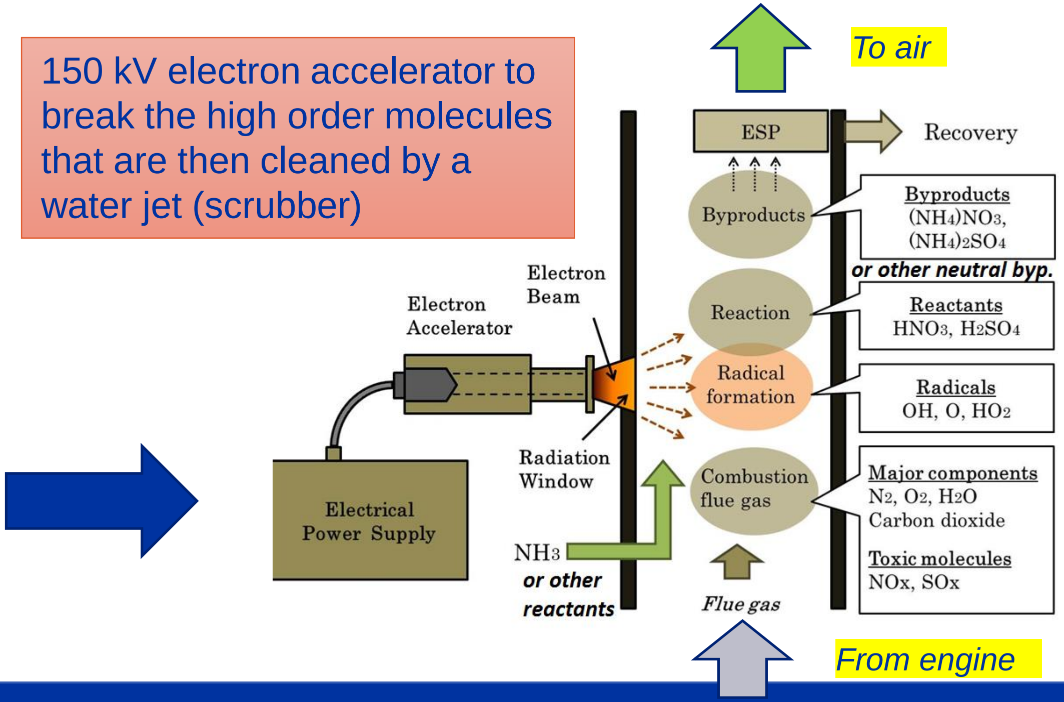
Environmental applications of accelerators

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.

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

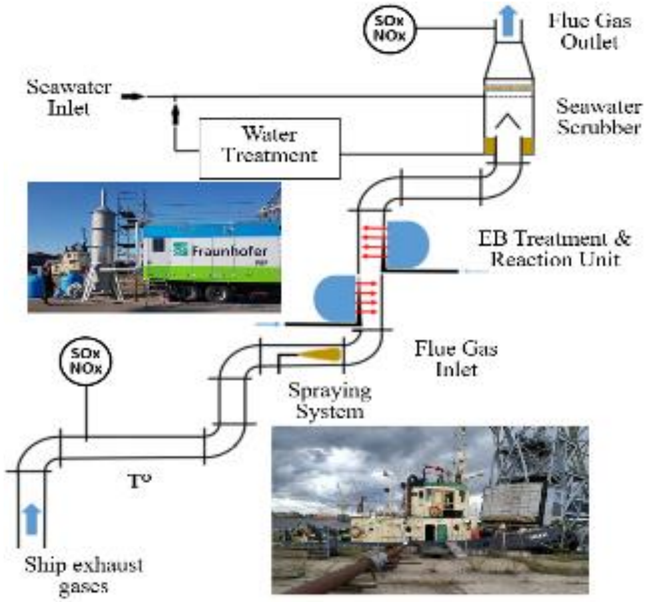
A project based on a patent from INCT Warsaw promoted by a collaboration of research institutions (including CERN), accelerator industry, shipyards, maritime companies, maritime associations (Germany, UK, Switzerland, Poland, Latvia, Italy).



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

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.

Accelerators for art

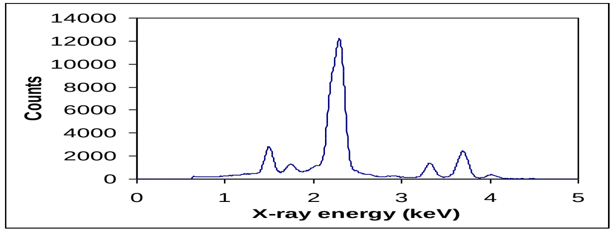
Ion Beam Analysis (e.g. PIXE, Proton Induced X-ray Emission)

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

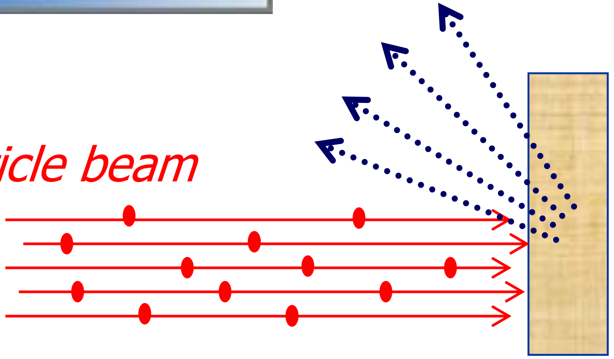
The atoms are excited and emit different types of radiation (X-rays, gammas, etc.)

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).

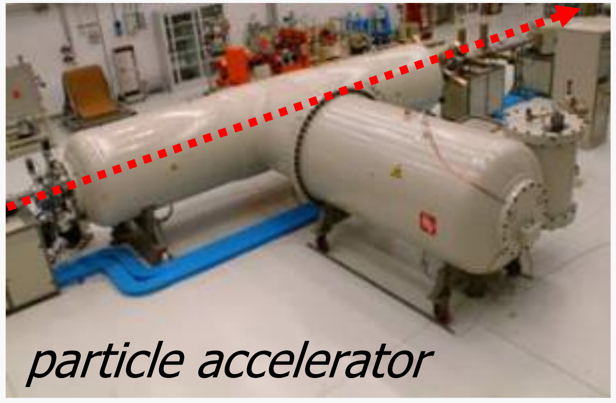
Radiation detection and spectral analysis



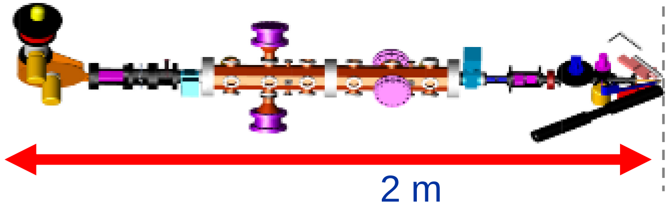
Emission of radiation of characteristic energies (X-rays, γ, particles…)



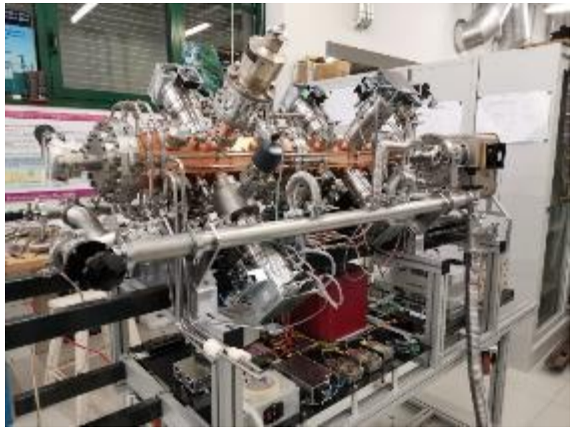
particle beam



particle accelerator



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

Towards the miniature accelerator?

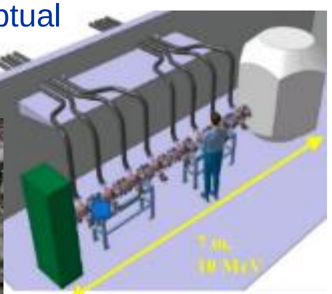
Important trend towards miniaturization of accelerators, for use in medicine and industry

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

The mini-RFQ

750 MHz
92 mm diameter
2.5 MeV/m

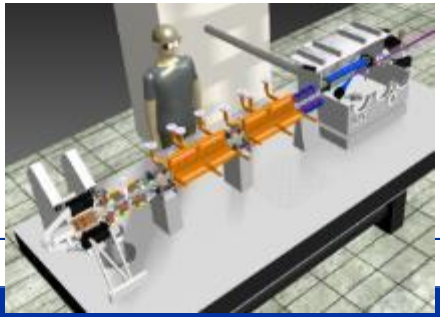
Proton therapy injector (in operation)
Artwork PIXE analysis (in construction, transportable)
Isotope production (design)
Neutron radiography (conceptual stage)



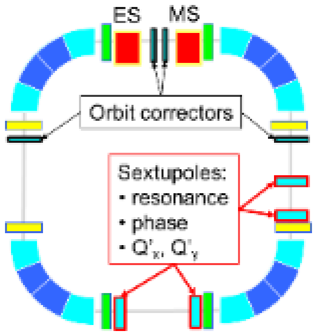
X-band structures

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)

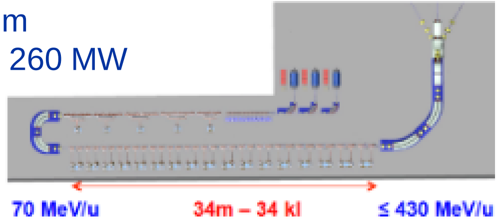


Compact accelerators for ion therapy



Superconducting C-ion synchrotron
Bmax 3.5 T
27m circumference

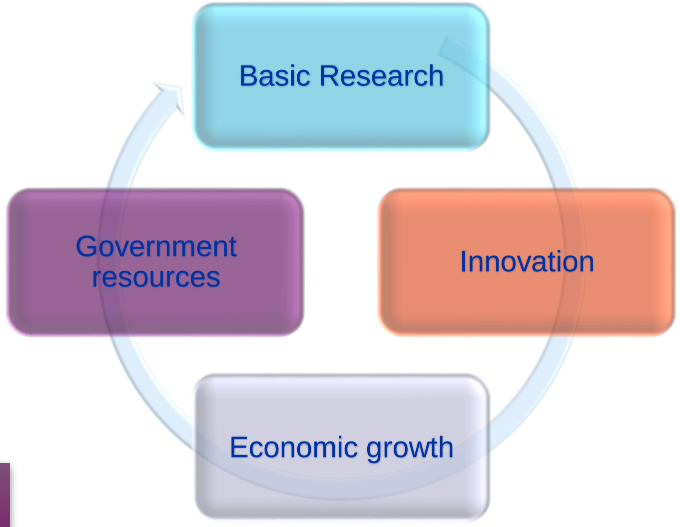
Folded C-ion linac,
Tot. length 53 m
Tot. RF power 260 MW



Some conclusions - at the roots of innovation

Particle accelerators are facing a critical moment in their evolution.

In this early XXI century, extrapolating present technologies to reach new physics may soon bring accelerators towards the limits of sustainability.
New ideas and technologies are needed to further advance basic science.
In parallel, increasing demands are coming from accelerators for applied science, medicine and industry, while new advanced societal applications of accelerators are appearing.


Basic Research

Government resources

Innovation

Economic growth

The virtuous circle of scientific innovation

> *We crucially need innovation in particle accelerators and in their applications to society, to address key societal challenges and to demonstrate the return to society from basic science.*

The 4 industrial revolutions

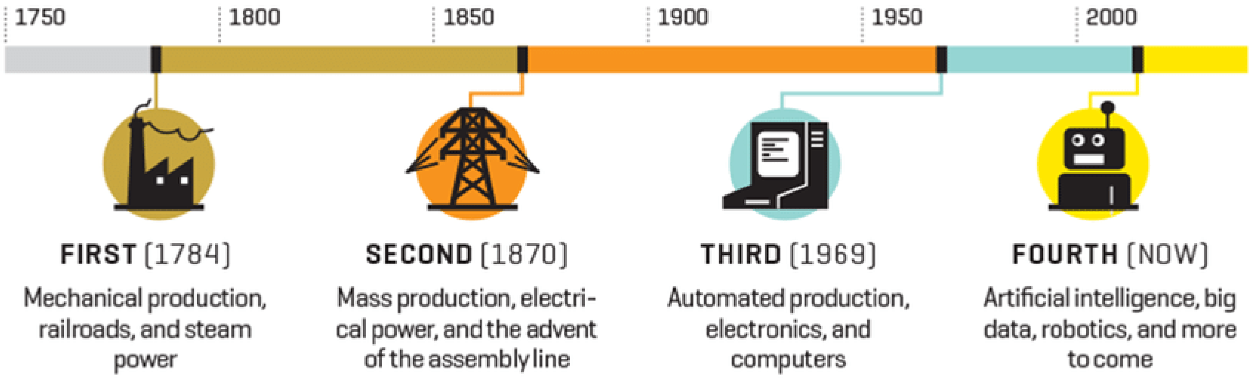
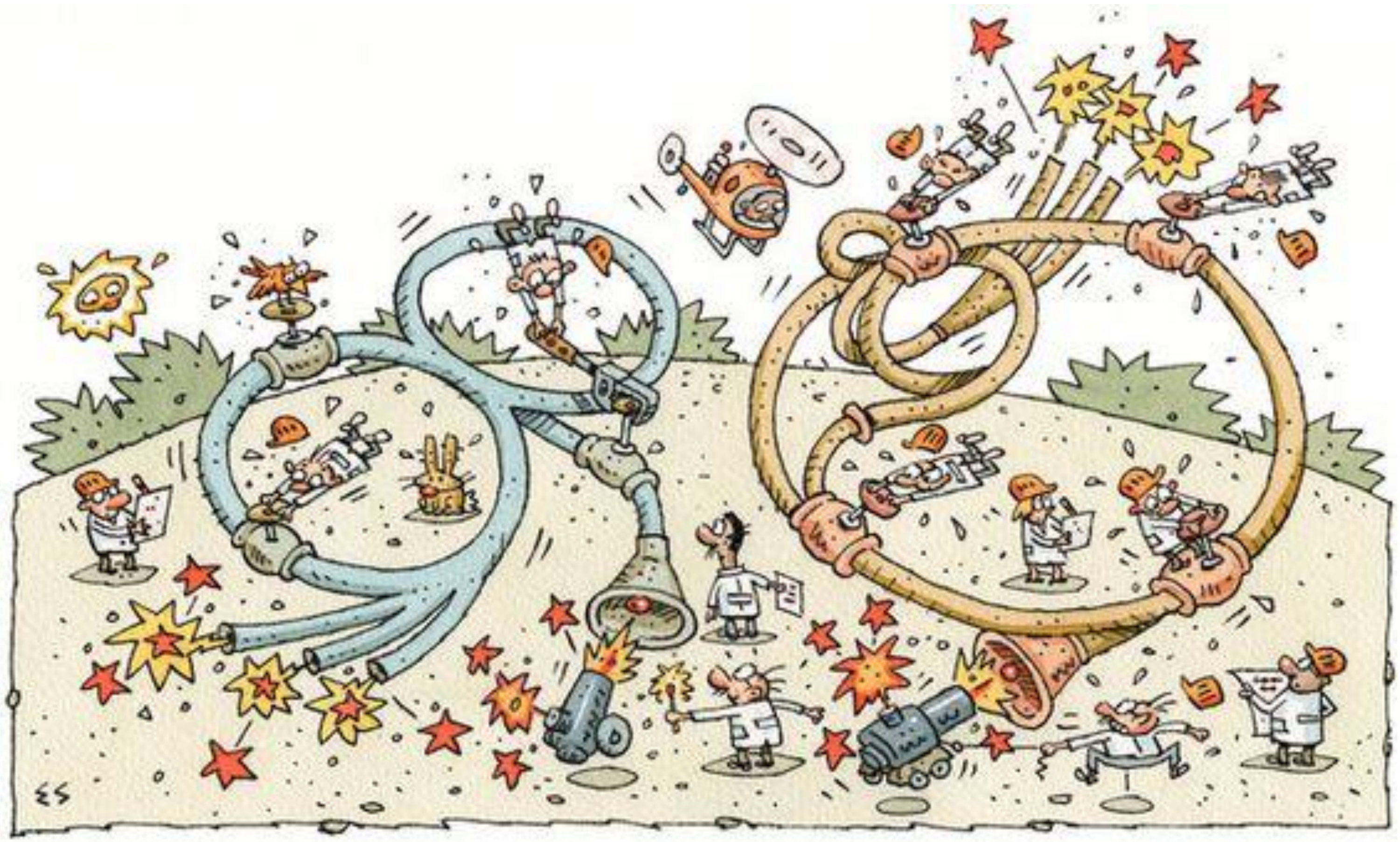


Image credit: B. Horvath, S. Mundi, 2018

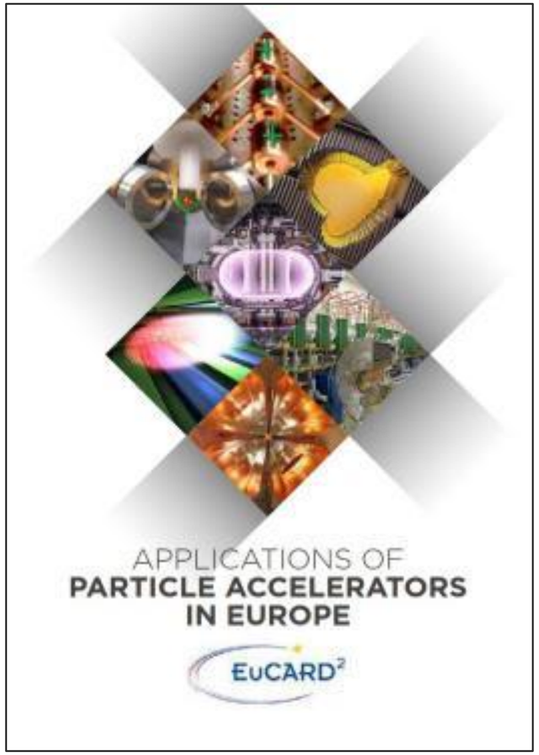
Particle accelerators can become fundamental actors of the 4th industrial revolution allowing industry and medicine to exploit technologies based on the usage of subatomic particles



End of Lecture 5

Thank you for your attention!

Further reading on applications of accelerators


APPLICATIONS OF
PARTICLE ACCELERATORS
IN EUROPE

EuCARD²

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