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BALTIC SCHOOL OF
HIGH ENERGY PHYSICS AND
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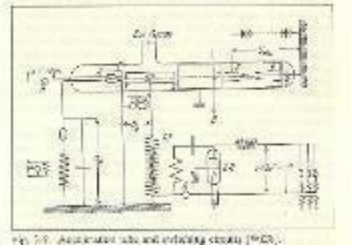
# Introduction to Particle Accelerators and their Applications – Part 2

# 1. Accelerator evolution through innovation

# Innovation in the particle accelerator field



Wideröe linac

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

XXI century

?

Cyclotron: cyclic acceleration with magnets (Lawrence)

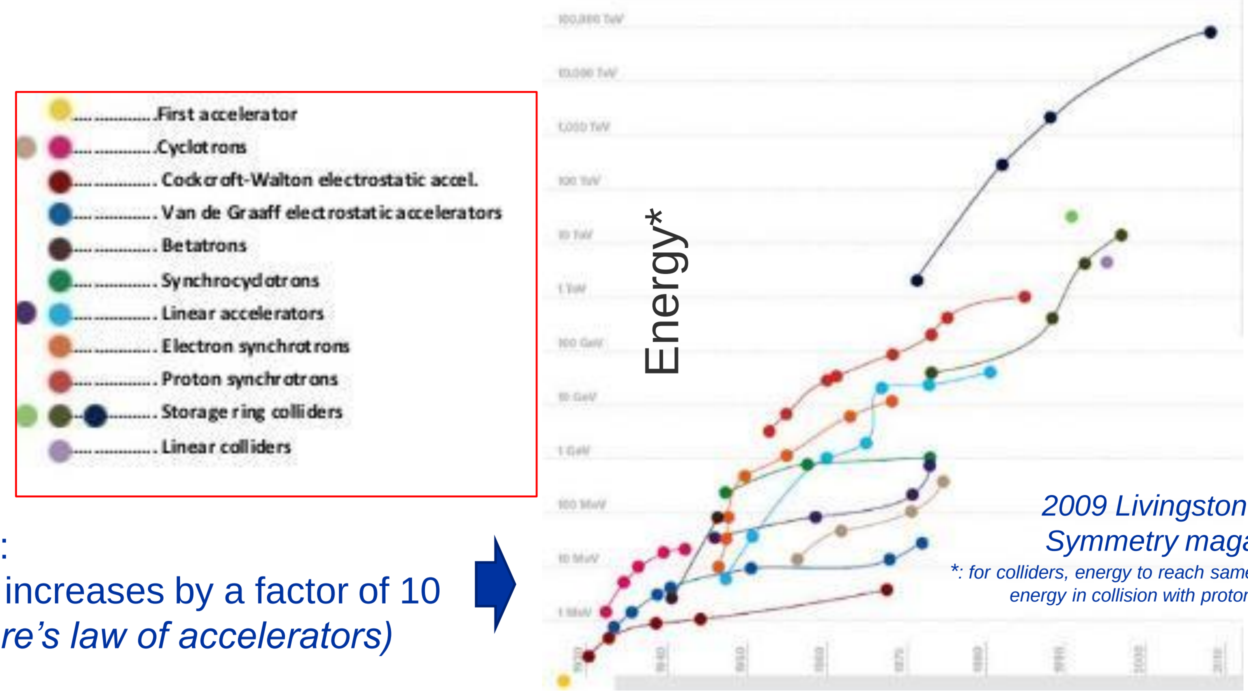
Strong focusing (Courant, Livingston, Snyder, Christofilos)

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*

# The first Radio-Frequency accelerator: Rolf Wideröe's thesis

Rolf Wideröe: a Norwegian student of electrical engineering at Karlsruhe and Aachen.
Inspired by a 1924 paper by G.Ising, a Swedish professor (acceleration of particles using "voltage pulses"), in 1928 he put together for his thesis a device to demonstrate the acceleration of particles by Radio Frequency fields:

1. use of a triode and of radio 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 synchronous RF accelerators.
3. complete accelerator: ion source, RF accelerator, detector, all in vacuum

*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!*

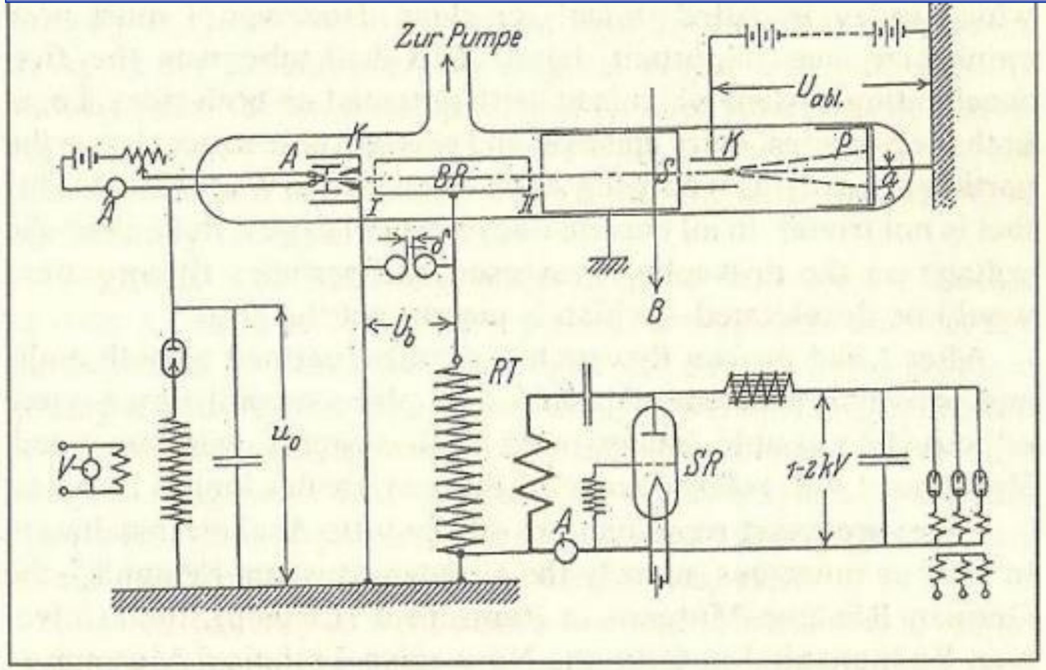
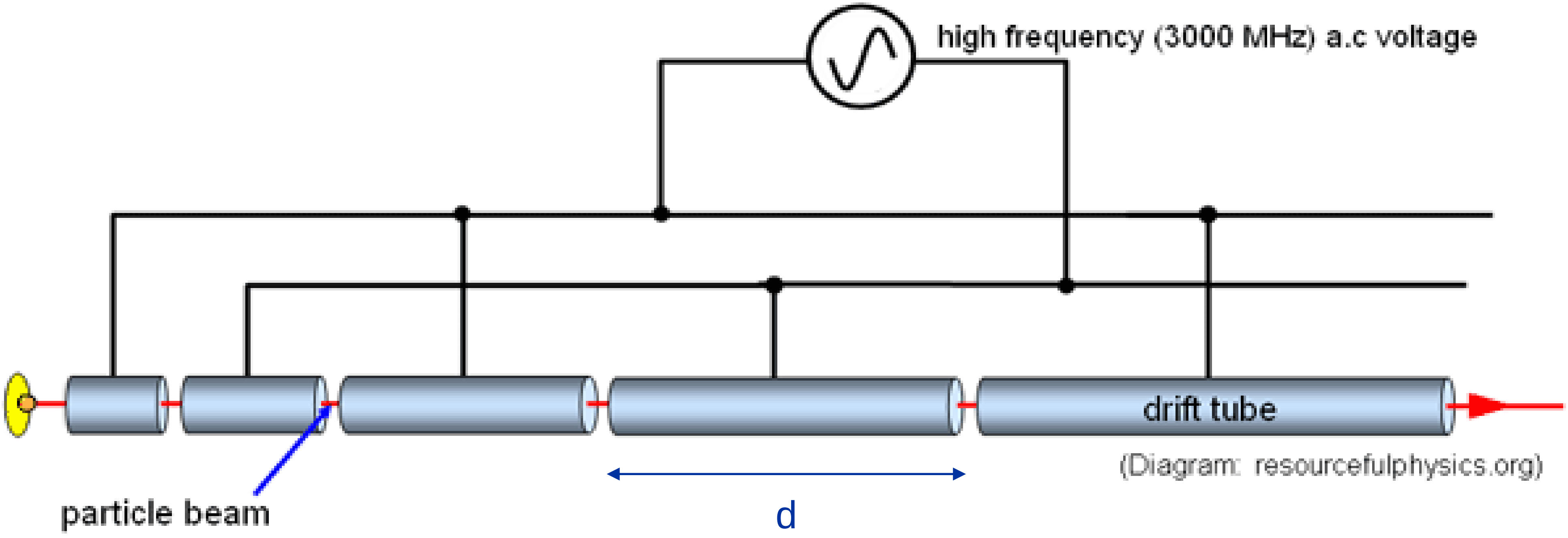


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

# The linear particle accelerator



(Diagram: resourcefulphysics.org)

Linear accelerators are used as injectors to larger accelerators and as stand-alone when large beam intensities are required

Synchronicity:
Time to travel from one accelerating «gap» to the next must be $t = T_{RF}/2$
But $t = d / \beta c$, with d = distance between gaps and b relativistic velocity factor

$d / \beta c = T_{RF}/2 = 1/2f_{RF}$ , or **$d = \beta\lambda / 2$**

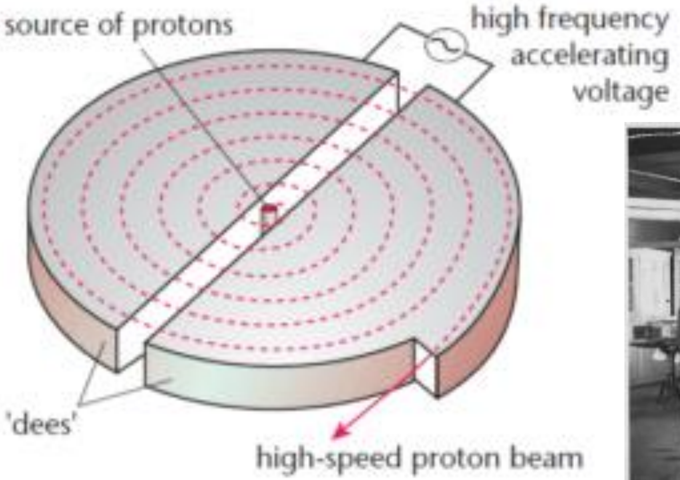
# RF with cyclic acceleration: the cyclotron

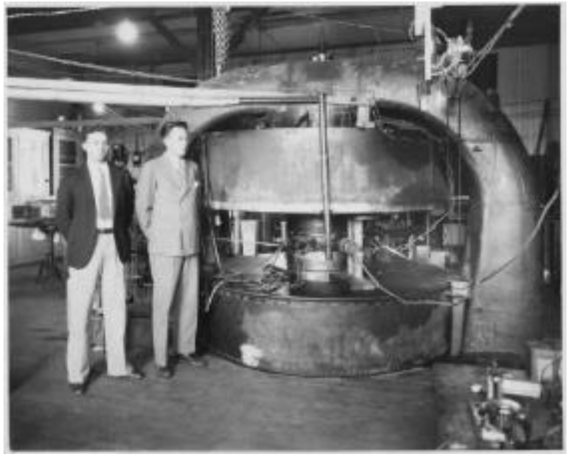
Immediately after R. Wideroe's invention of the linear accelerator, Ernest O. Lawrence at Berkeley proposes to perform radio-frequency acceleration in a circular system, inserted in a big magnet.

Basic principle: Use RF **electric field** to accelerate, **magnetic field** to keep particle in a circular orbit

The cyclotron is born!

1. Acceleration in the gap between two "D" → long path of the particles in the D, frequencies ~1 MHz can be effectively used (3.5 MHz, 1st Berkeley cyclotron).
2. Fortunate "coincidence": the revolution frequency does not depend on the beam energy → RF frequency is constant !





$$\frac{mv^2}{r} = evB \qquad f = \frac{1}{\tau} = \frac{2\pi r}{v} = \frac{2\pi r\, m}{eBr} = \frac{2\pi m}{eB}$$

*f* revolution frequency

- Protons are produced by a "source" in the centre
- They are accelerated in the gap between 2 electrodes fed with RF
- The protons go in larger and larger spirals, and their velocity increases proportionally to the spiral radius, keeping revolution frequency constant.

# Basic limitations of Wideröe linac and cyclotron

## Limitation to cyclotrons: relativity

$$\frac{mv^2}{r} = evB \qquad f = \frac{1}{\tau} = \frac{2\pi r}{v} = \frac{2\pi r\, m}{eBr} = \frac{2\pi m}{eB}$$

The cyclotron principle is valid only for **non-relativistic** particles:
When the mass start to increase accordingly to $m = \gamma m_0$, the revolution frequency increases and the particles are no longer in phase with the RF excitation frequency.

Some corrections (modulation of the excitation frequency or shaping of the magnet field) can be applied, but conventional cyclotrons are limited in energy to ~ 70 MeV. Synchrocyclotrons can go higher (~ 500 MeV) but with high complexity and cost

→ invention of the **synchrotron**

## Limitation to Widerøe linacs: frequency

As velocity increases, to keep a reasonable distance between gaps the RF excitation frequency must increase:
$f_{RF} = v_p / 2d$
When the RF excitation frequency becomes so high that the dimensions of the accelerator are comparable to the RF wavelength, the gaps start to generate electromagnetic waves and to radiate their energy

→ invention of the **RF accelerating cavity (resonator)**

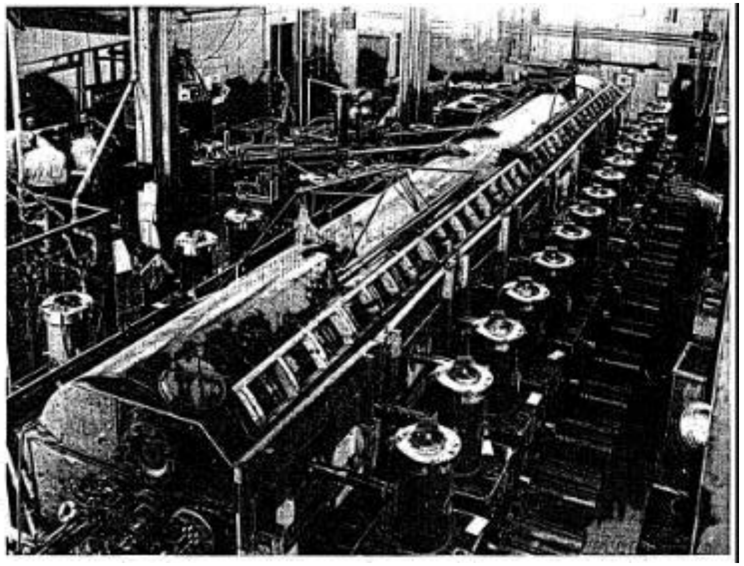
# After the war, high frequencies: linacs and cavities

## Luis Alvarez and the Drift Tube Linac

The war effort gave the competences and the components to go to frequencies in the MHz – GHz range and to try acceleration of a proton beam to the MeV range using a modified Wideröe principle.

The 1st Drift Tube Linac by L. Alvarez and his team at Berkeley, reaches 32 MeV in 1947.

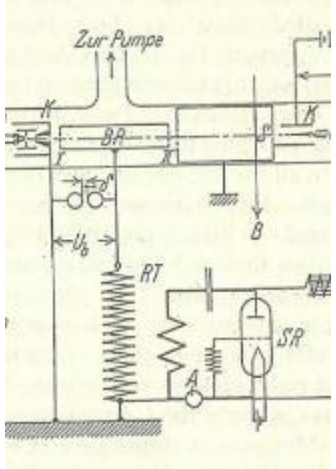
Alvarez, an experimental physicists, worked at MIT on radar during the war. In 1945 had the tools and the competences to build his own accelerator.

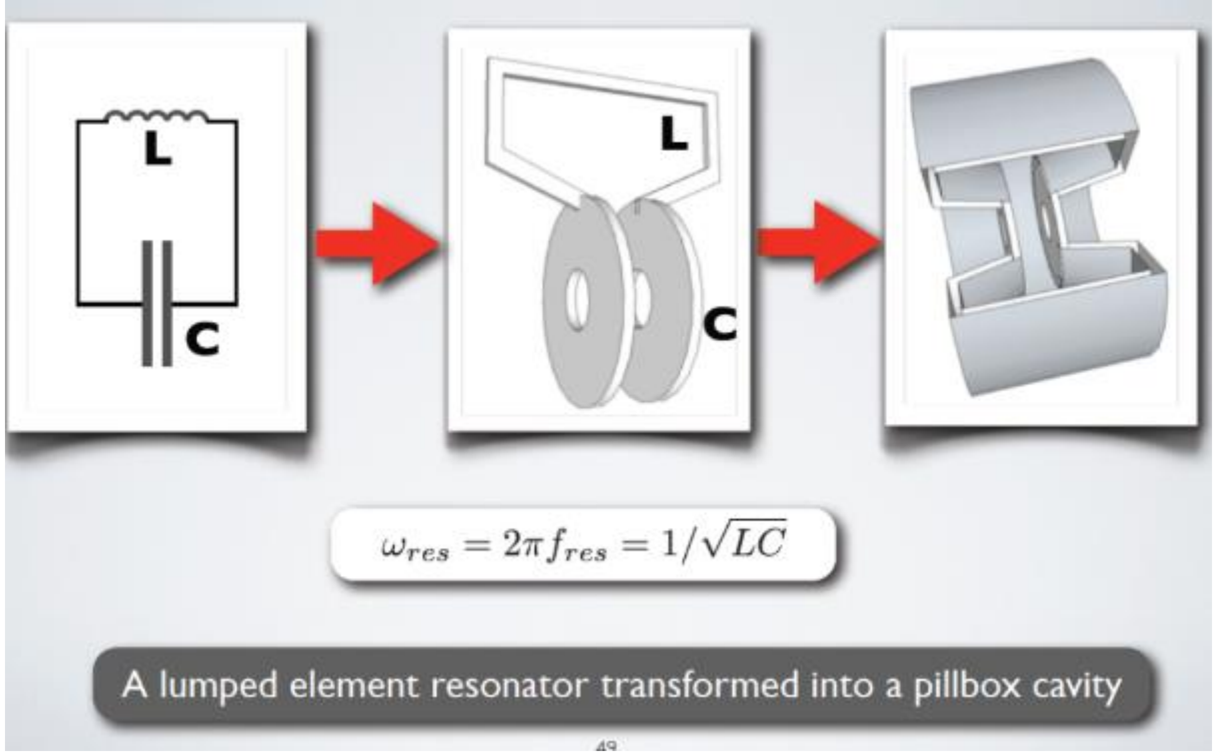


1. The “tubes” are inside a cavity resonator.
2. Frequency : Alvarez receives from the US Army a stock of 2’000 (!) surplus 202.56 MHz transmitters, built for a radar surveillance system. 26 were installed to power the DTL with a total of 2.2 MW. They were soon replaced because unreliable, but this frequency remained as a standard linac frequency.

# The Drift Tube Linac of Linac4, the new linear injector for the LHC

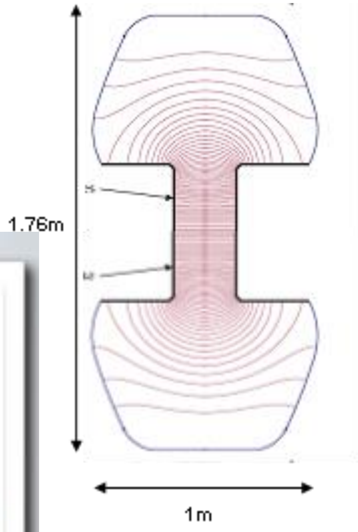
# Giving energy to the particles: from the resonant circuit to the accelerating cavity





$$\omega_{res} = 2\pi f_{res} = 1/\sqrt{LC}$$

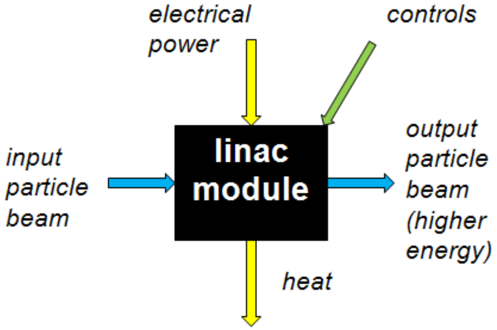
A lumped element resonator transformed into a pillbox cavity



Single-gap cavity 88 MHz

Multi-cell linac cavity (Linac4 120 MeV, 352 MHz)

# Energy flow: from the power grid to the beam


*electrical power*

*controls*

*input particle beam*

**linac module**

*output particle beam (higher energy)*

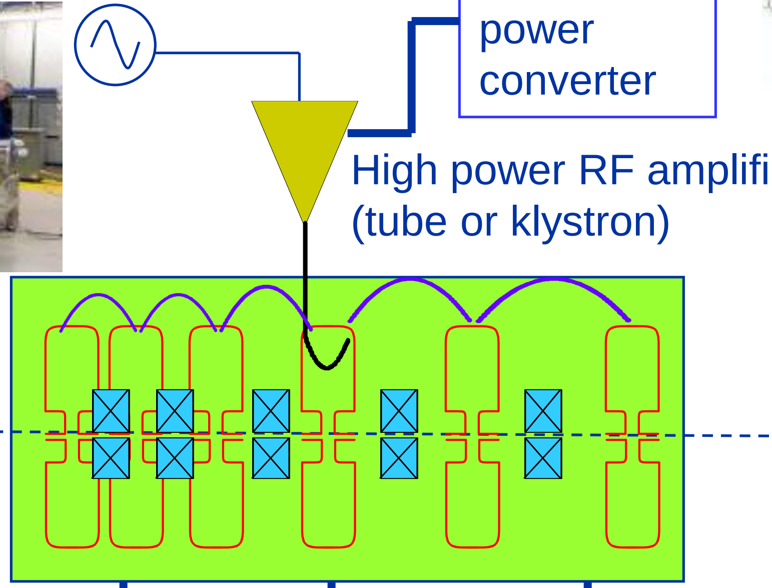
*heat*

HV AC/DC power converter

*AC to DC conversion efficiency ~90%*

*DC to RF conversion efficiency ~50%*

*RF to beam voltage conversion efficiency = SHUNT IMPEDANCE $ZT^2$ ~ 20 - 60 MΩ/m*



High power RF amplifier (tube or klystron)

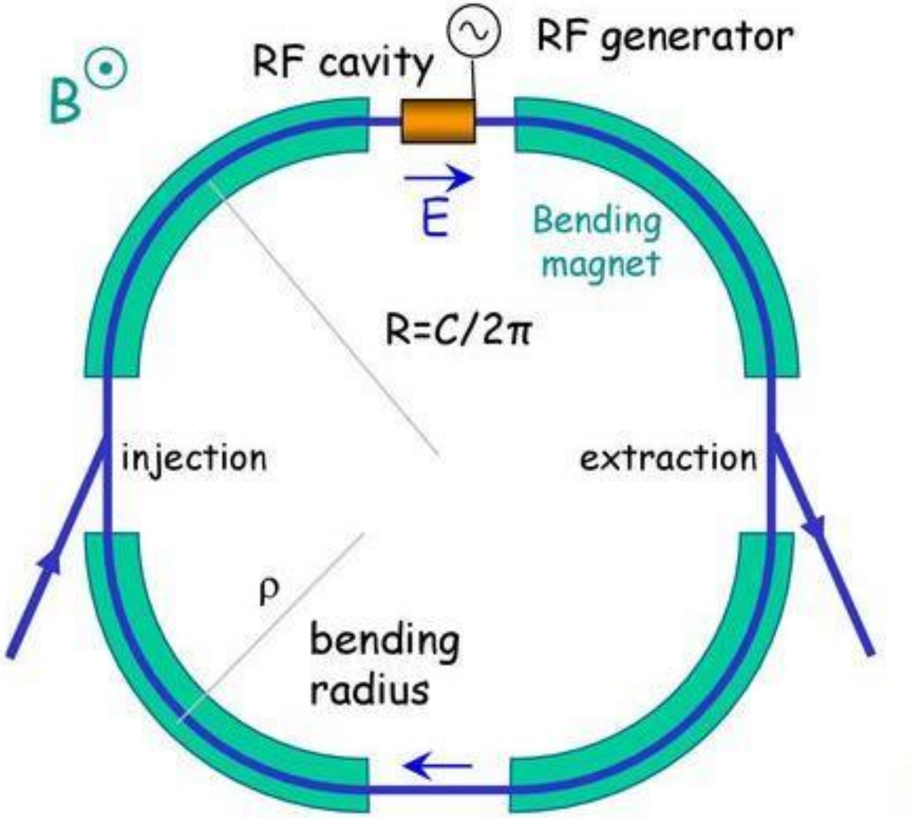
magnet powering system

vacuum system

water cooling system

ACCELERATING STRUCTURE
accelerating gaps + focusing magnets

# The synchrotron



$$E^2 = (pc)^2 + \left(m_0 c^2\right)^2$$

Almost independently invented by V. Veksler (USSR, 1944), E. McMillan (USA, 1944) and M. Oliphant (UK, 1945, for protons).

*Important step forward from the cyclotron: The orbit is fixed, the magnetic field increases during acceleration. But can work only in pulsed mode!*

1. Constant orbit during acceleration
2. B must increase during acceleration proportionally to the momentum, to keep the particles on the closed orbit:

$$R = p / eB$$

3. The accelerating RF frequency must increase with time proportionally to the velocity to keep the particles on the stable phase:

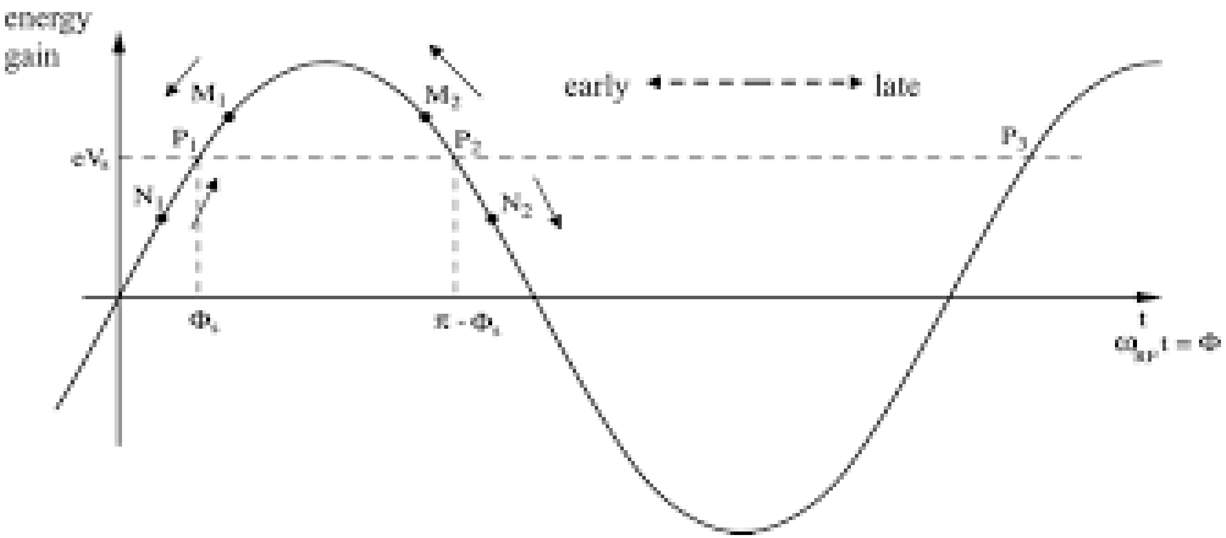
$$T_{rev} = 2\pi R / v$$

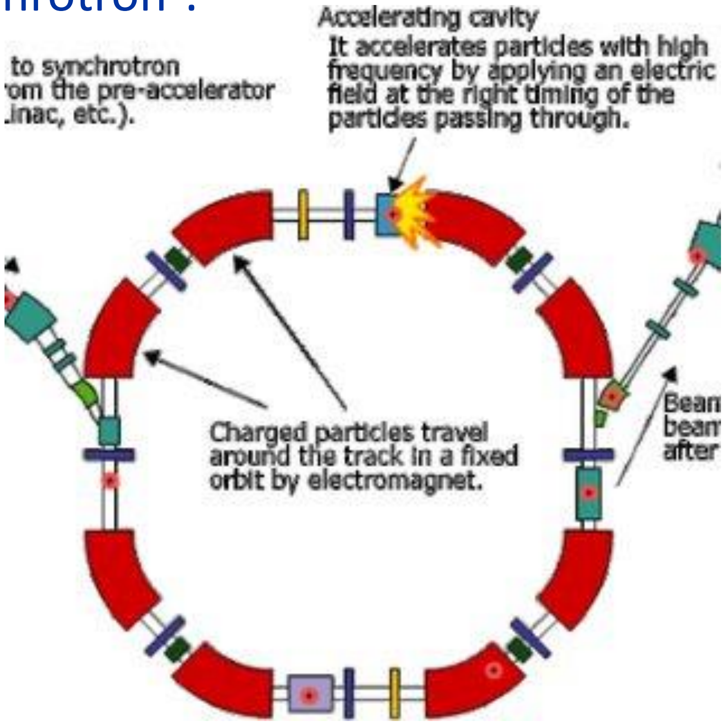
$$f = h/T_{rev} = v/2\pi R$$

# Phase stability

One of the main problems in the synchrotron was to keep the beam "bunched" enough to allow its acceleration during the short accelerating periods of the RF cavity.

A solution to this problem came from the parallel invention of phase stability by V. Veksler (USSR, 1944) and E. McMillan (US, 1945) – McMillan is the first to use the term "synchrotron".





# Magnetic cycle

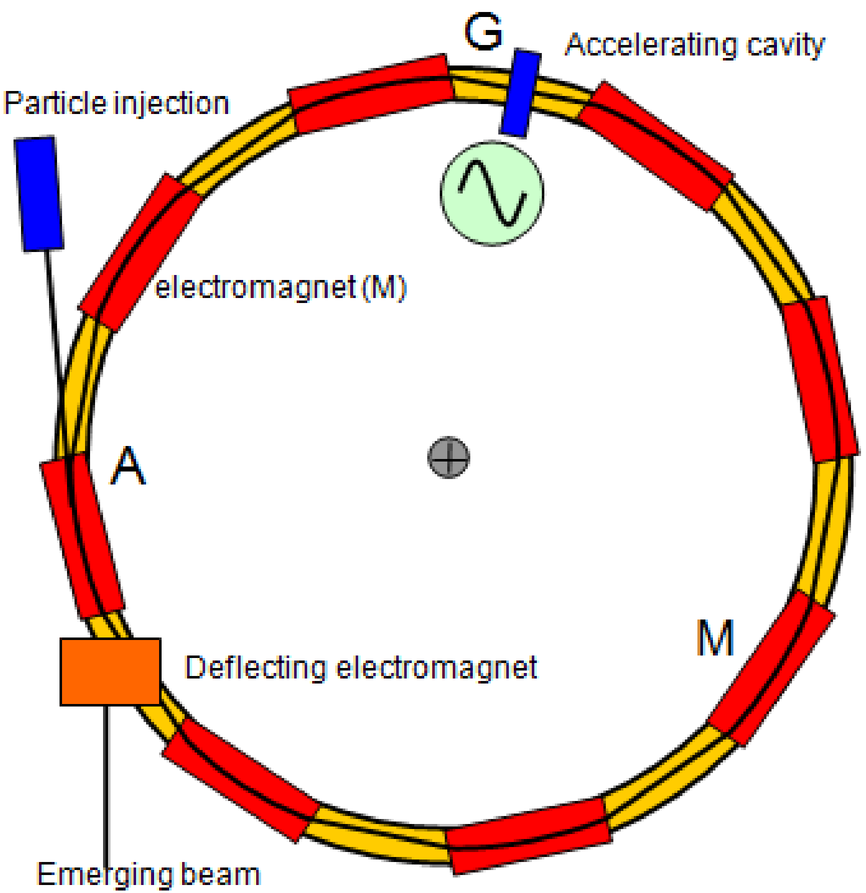
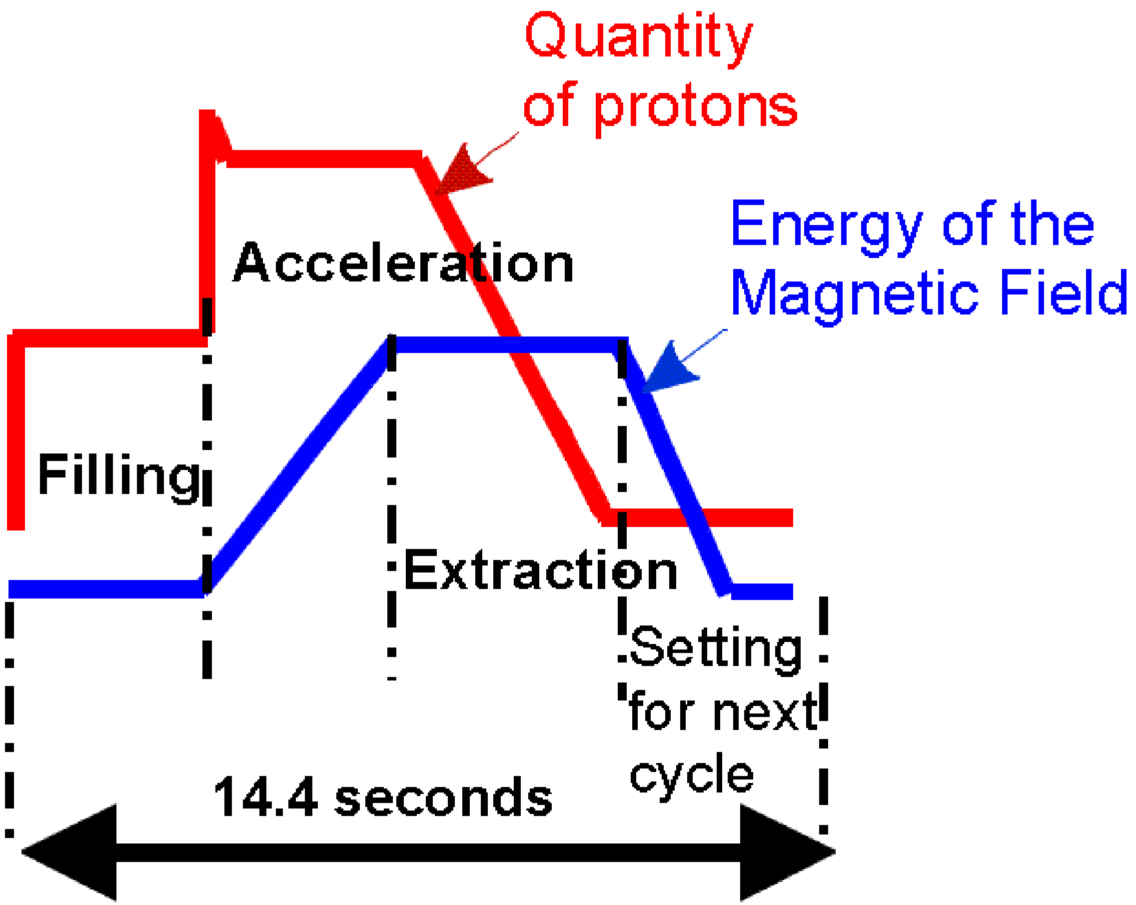


Figure 1



Example of a SPS Magnetic cycle

# The last missing element: strong focusing

Major problems with the first synchrotrons:

- Large magnet apertures (1.22x0.22m in the Cosmotron at BNL!) to control the beam using only some weak focusing provided by shaping of magnet poles;
- Large frequency changes required for the RF system during acceleration;
- High pulsed power to be fed to the magnets.

*The BNL Cosmotron, 3.3 GeV, 23 m diameter*

Discovery by E. Courant (BNL) of “strong focusing” obtained by “turning” some of the Cosmotron magnets. Published in 1952 by Courant, Livingston and Snyder - the same idea had been independently patented in 1950 by N. Christofilos.

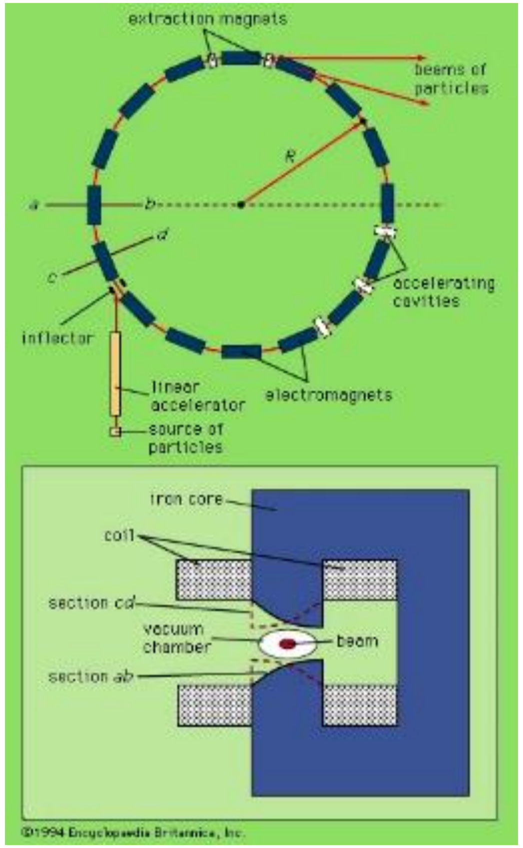
Strong focusing allows a smaller magnet aperture at much lower cost

In 1953 a delegation from CERN arrived at BNL and immediately adopted the new idea for their Proton Synchrotron (achieving 25 GeV instead of 10 GeV with the same dimensions!).

In 1959 the CERN PS was successfully commissioned, and is still in operation.

*The CERN PS, 25 GeV, 200 m diameter*

# Alternating gradient strong focusing in a nutshell



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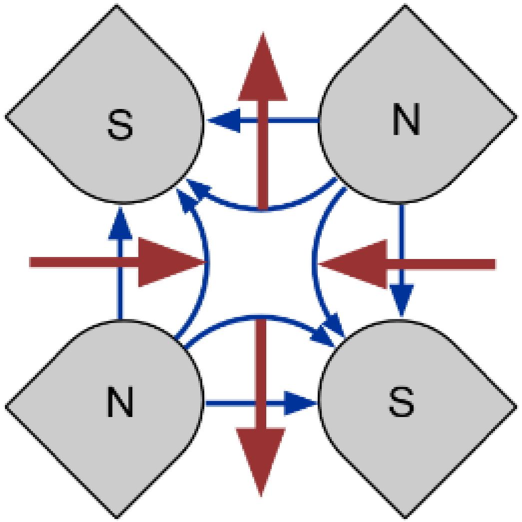


Figure 2.9: Blue magnetic field and red force directions for a focusing quadrupole

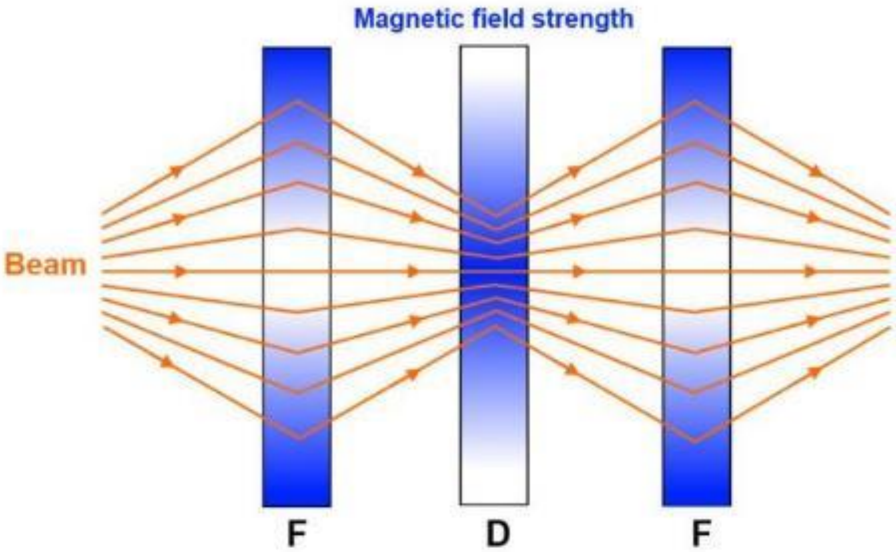
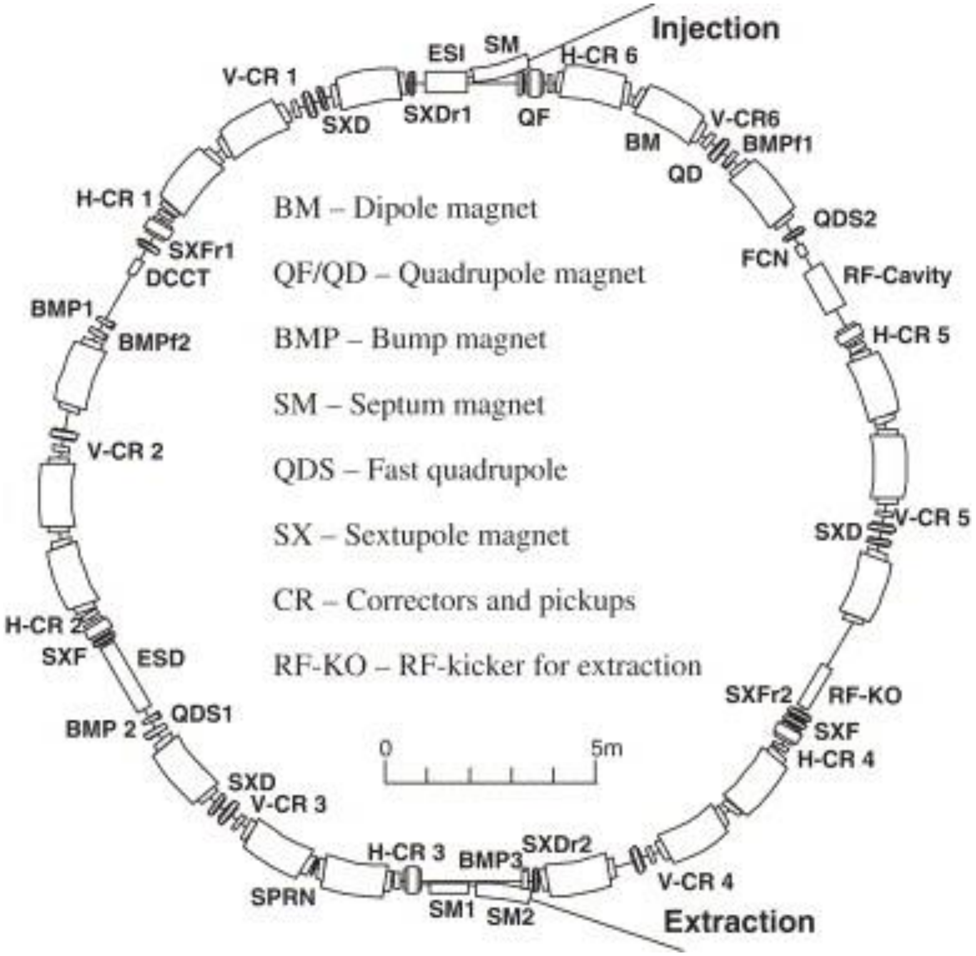


Figure 2.10: Strong focusing with alternating quadrupoles.

From the initial idea of alternate orientation of the focusing/defocusing magnet poles, to the introduction inside the ring of alternate focusing/defocusing quadrupole magnets that “control” the transverse dimensions of the beam.

The main advantage is in reducing the size of the magnet aperture, with a strong reduction in magnet cost!

# A complete synchrotron

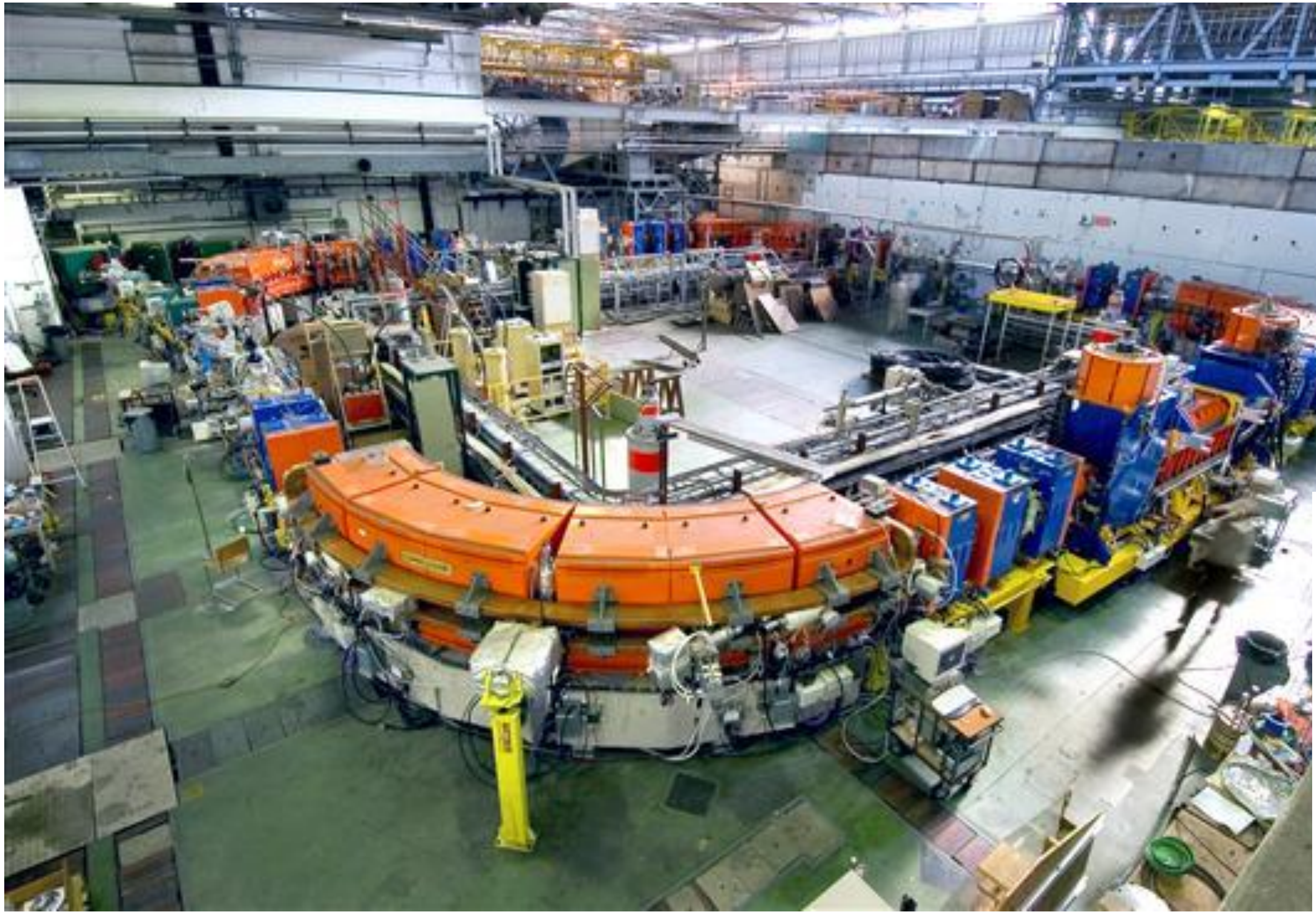


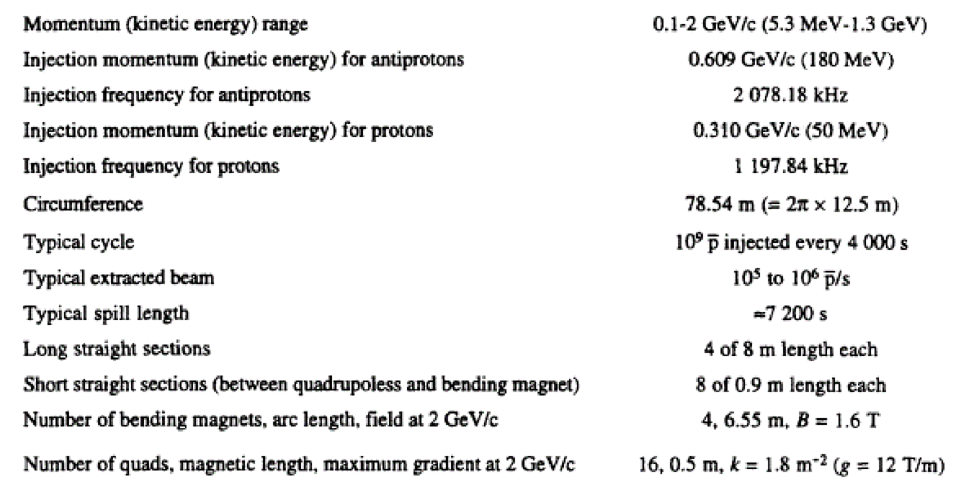
**The HIMAC carbon ion therapy synchrotron (Japan)**

The synchrotron is made of a long vacuum chamber where the beam circulates, which goes through a large number of different elements arranged in a “lattice”:

- Dipole magnets for bending (18 in this case for $20^0$ each)
- Quadrupole magnets for focusing
- Septum magnets for injection and extraction
- Sextupoles for correcting perturbation in orbits
- Correctors and pickups
- RF caviti(es) for acceleration
- Beam diagnostics and measurement devices
- Bump magnets for beam manipulations

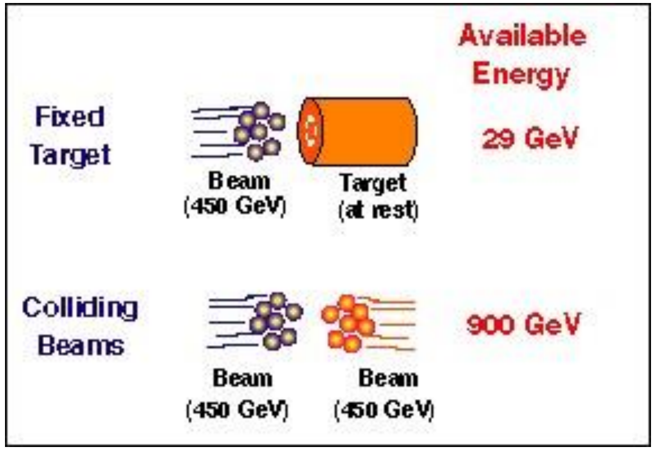
# The smallest CERN synchrotron: LEIR





| | |
|---|---|
| Momentum (kinetic energy) range | 0.1-2 GeV/c (5.3 MeV-1.3 GeV) |
| Injection momentum (kinetic energy) for antiprotons | 0.609 GeV/c (180 MeV) |
| Injection frequency for antiprotons | 2 078.18 kHz |
| Injection momentum (kinetic energy) for protons | 0.310 GeV/c (50 MeV) |
| Injection frequency for protons | 1 197.84 kHz |
| Circumference | 78.54 m ($= 2\pi \times 12.5$ m) |
| Typical cycle | $10^9$ $\bar{p}$ injected every 4 000 s |
| Typical extracted beam | $10^5$ to $10^6$ $\bar{p}$/s |
| Typical spill length | ≈7 200 s |
| Long straight sections | 4 of 8 m length each |
| Short straight sections (between quadrupoless and bending magnet) | 8 of 0.9 m length each |
| Number of bending magnets, arc length, field at 2 GeV/c | 4, 6.55 m, $B = 1.6$ T |
| Number of quads, magnetic length, maximum gradient at 2 GeV/c | 16, 0.5 m, $k = 1.8$ m$^{-2}$ ($g = 12$ T/m) |

# Colliding particle beams



Generation of new particles depends on the centre of mass energy developed in the collision.

Relativity: energy available at centre of mass in fixed target collisions is much lower than the energy of the particle beam.

Head-on collisions of two beams traveling in opposite directions: available energy is exactly twice the energy of a single beam.

**Fixed Target**

$$E \propto \sqrt{E_{beam}}$$

Much of the energy is lost in the target and only part is used to produce secondary particles

**Collider**

$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

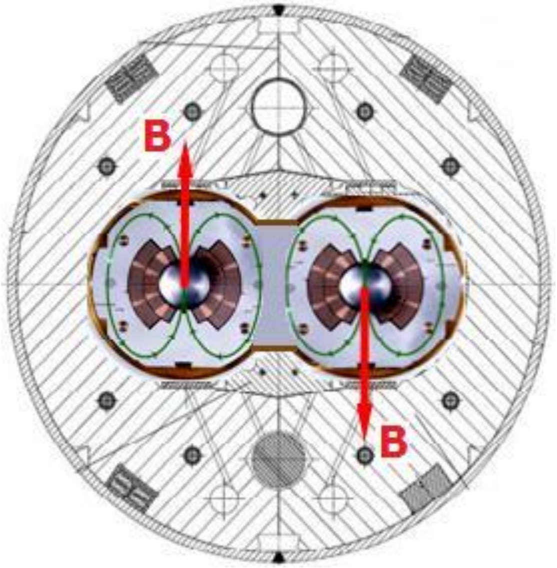
# Technical challenges for particle colliders

There are only 2 options to make a synchrotron with two circulating beam in opposite directions:

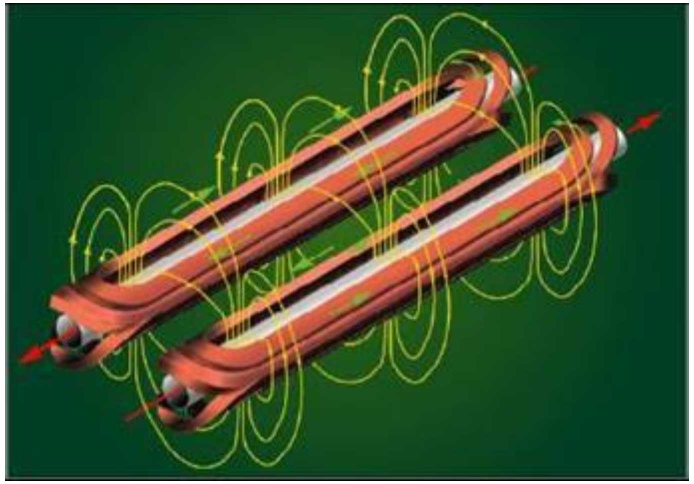
1. The particles have same mass but opposite sign and circulate in the same vacuum chamber and magnetic field (ex.: electron-positron and proton-antiproton colliders).
2. The particles are the same and they circulate in separate vacuum chambers and opposite magnetic fields (Ex.: the LHC).

Problem with 1) is the need to create intense beams of unstable particles (positrons, antiprotons).

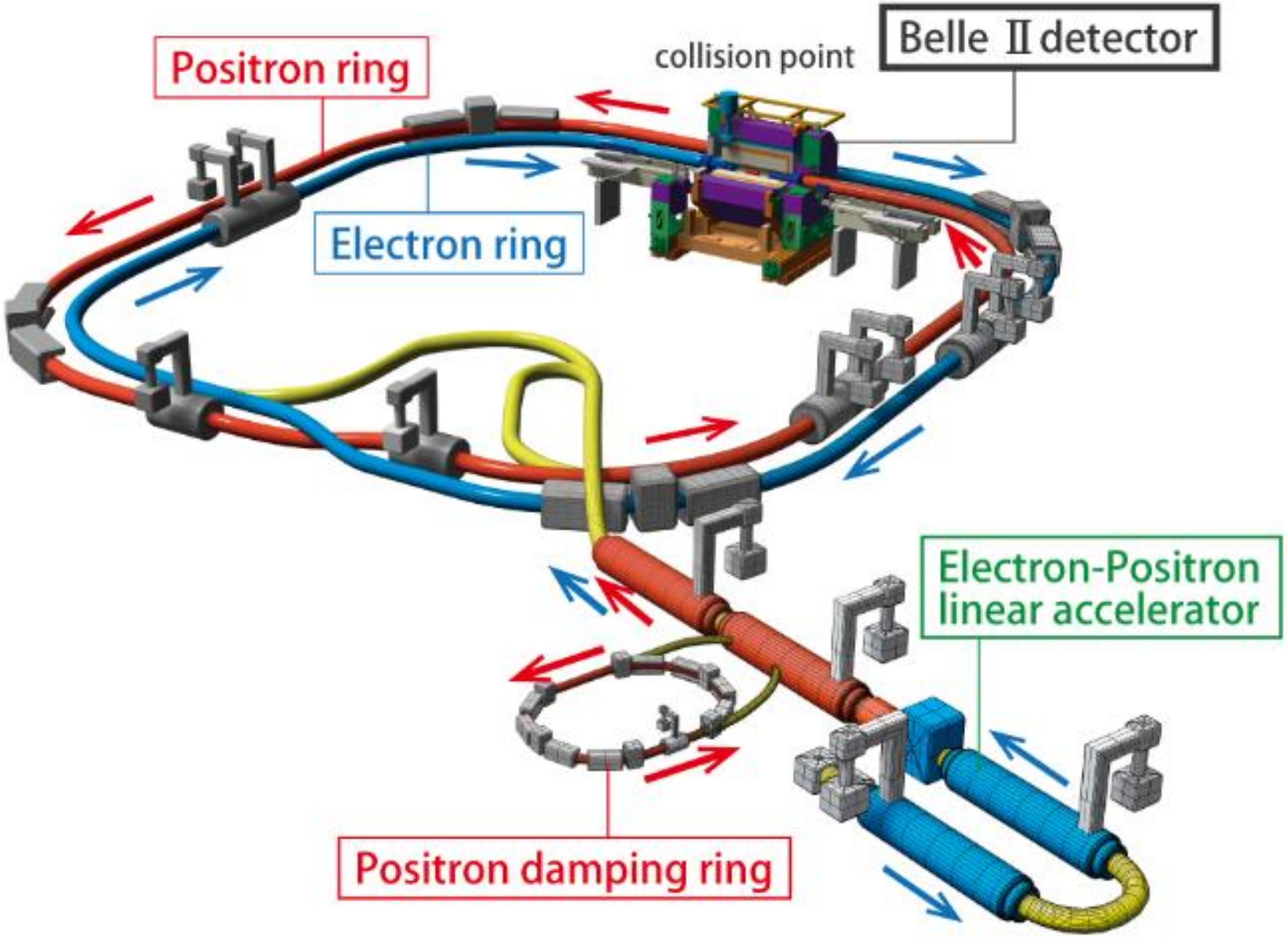
Problem with 2) is the need to use twin-bore dipole magnets or separate magnets



2-in-1 magnet configuration of LHC

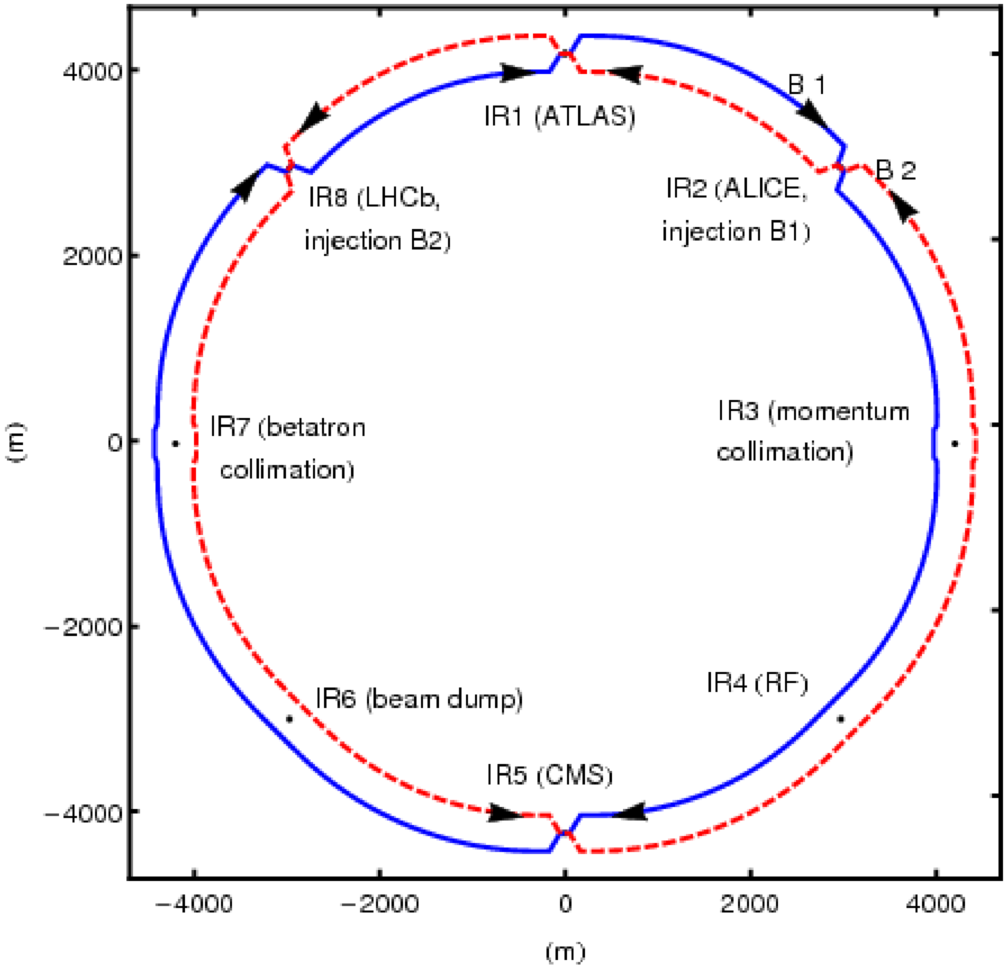


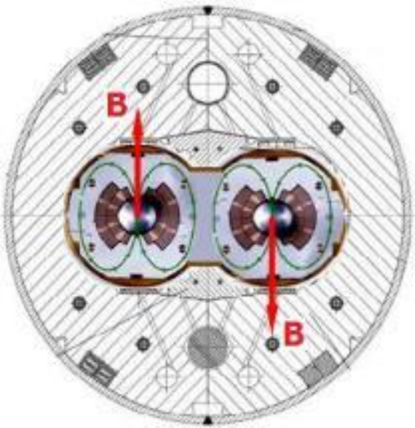
# Electron – positron colliders



The KEK-B collider (Japan)

# The Large Hadron Collider





The 1232 LHC magnets contain two pipes, one for each of the counterrotating beams.

# Luminosity, the Collider Figure of Merit

$$LUMINOSITY = \frac{N_{event/\sec}}{\sigma_r} = \frac{N_1 N_2 f_{rev} n_b}{4\pi\sigma_x\sigma_y} F$$

Intensity per bunch

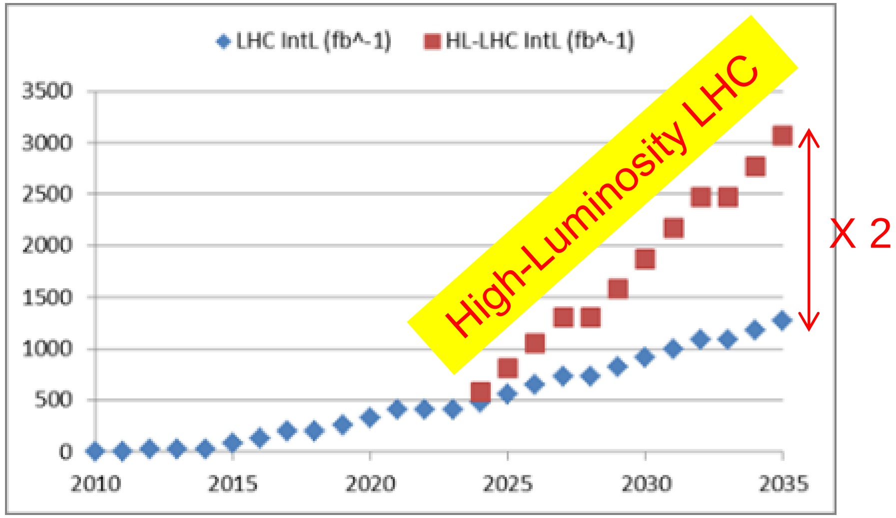
Number of bunches

Geometrical Correction factors

Beam dimensions

- More or less fixed:
  - Revolution period
  - Number of bunches

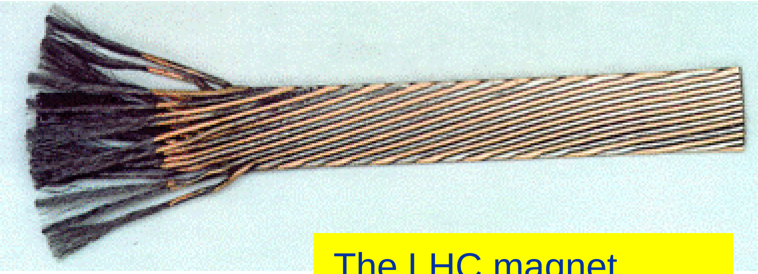
- Parameters to optimise:
  - Number of particles per bunch
  - Beam dimensions
  - Geometrical correction factors



# Superconductivity and particle accelerators

Some materials present a zero electrical resistance when cooled below a characteristic temperature.
Discovered in 1911, explained in 1958, started to be used for accelerators in the 1970's.
Allows to build magnets that can stand higher electric currents and higher fields (not limited by water cooling) and accelerating RF cavities that do not dissipate power and have higher electrical efficiency.

Materials used in accelerators are
Niobium-Titanium for magnets
Niobium for RF cavities.



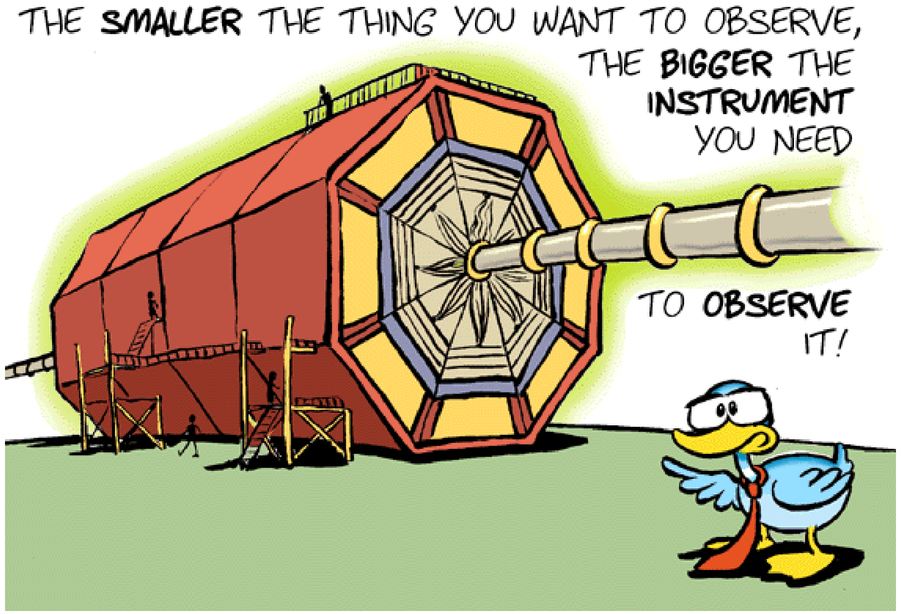
The LHC magnet superconducting cable

Clean room assembly of superconducting RF cavities

BUT: a superconducting accelerator requires a huge cooling system
That  keeps all elements at liquid helium temperature

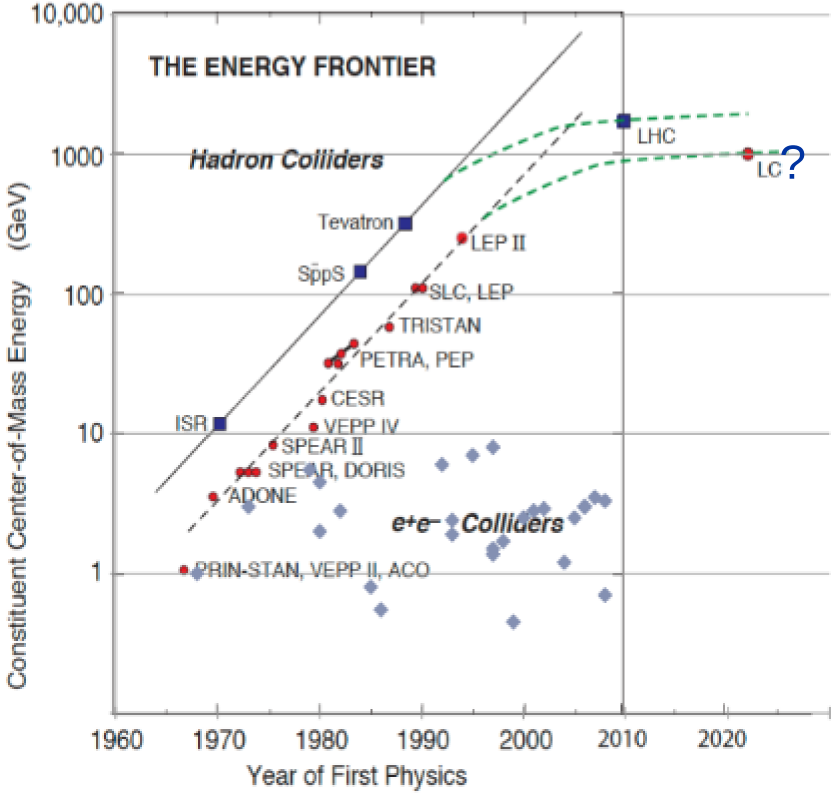
One of the 8 compressor units of the 4.5 K refrigerator for LHC

# 2. Challenges for particle accelerator science in the XXIst century



# Particle Accelerators in 2022

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!

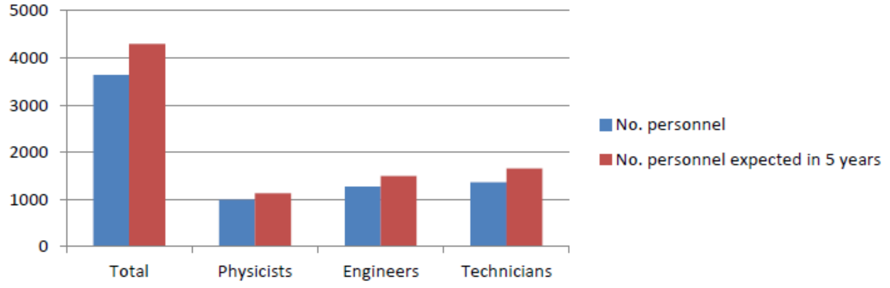


*Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.*

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?

# 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.

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

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

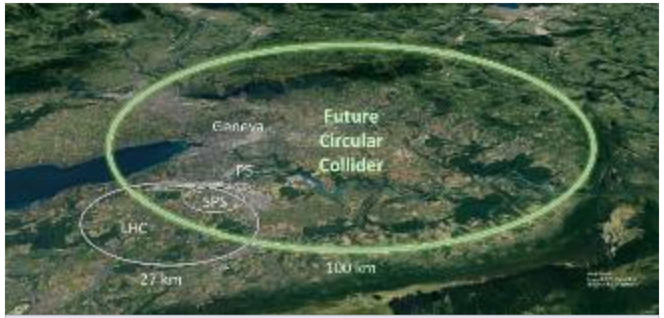
Making accelerator-based particle physics research more sustainable is one of the main challenges to the accelerator community in this XXIst century.

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.

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

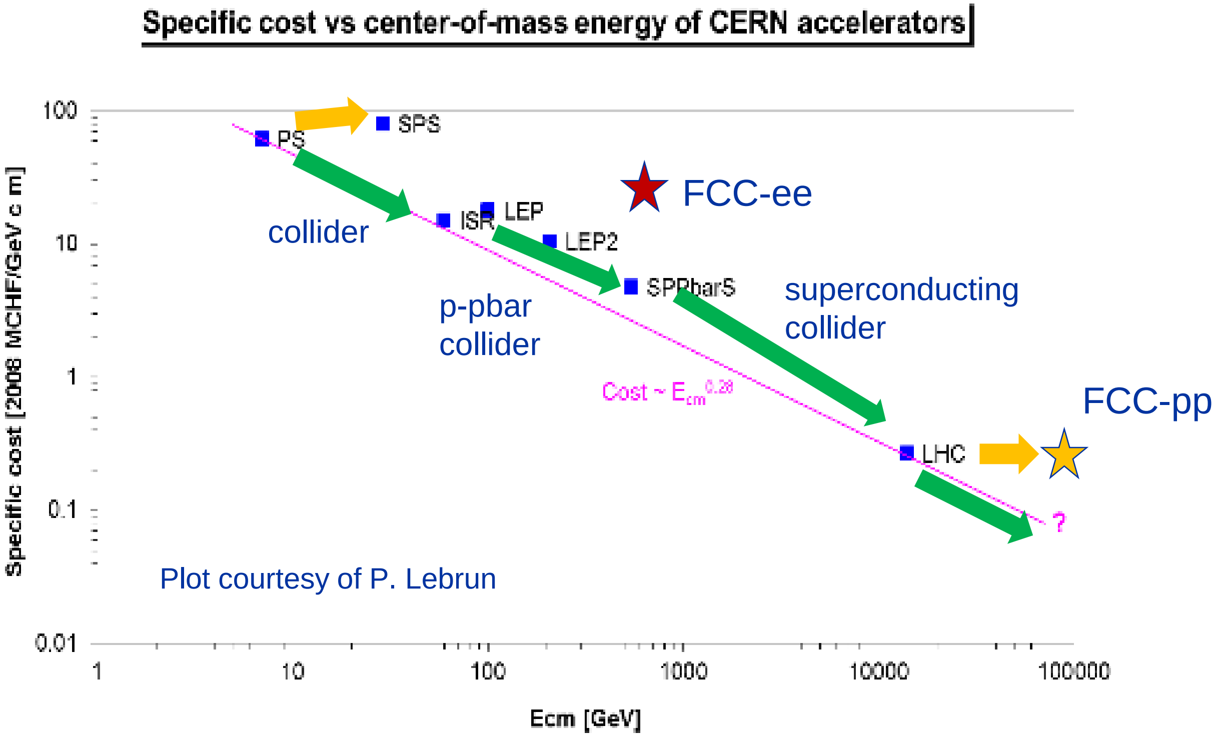
Developing their technology requires new ideas to be developed in a larger environment than basic science

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



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

# Frontier accelerators – economic sustainability



Plot courtesy of P. Lebrun

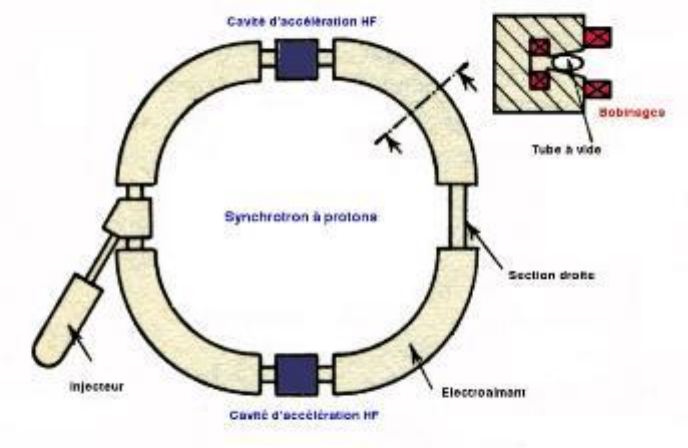
Moving along this line was made possible by new technologies (colliders – antiproton production and storage – superconductivity)

scaling of present technology

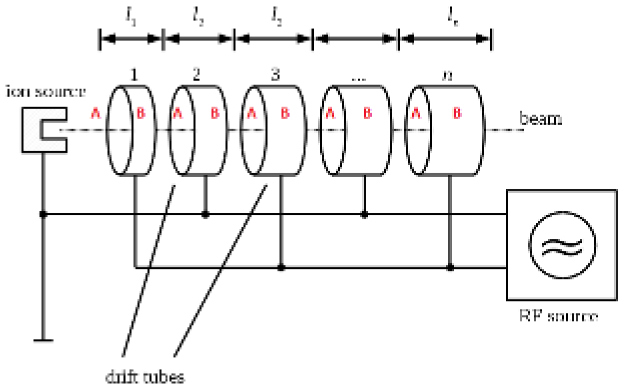
reduction in cost with new technologies?

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.

# Two directions to make smaller accelerators

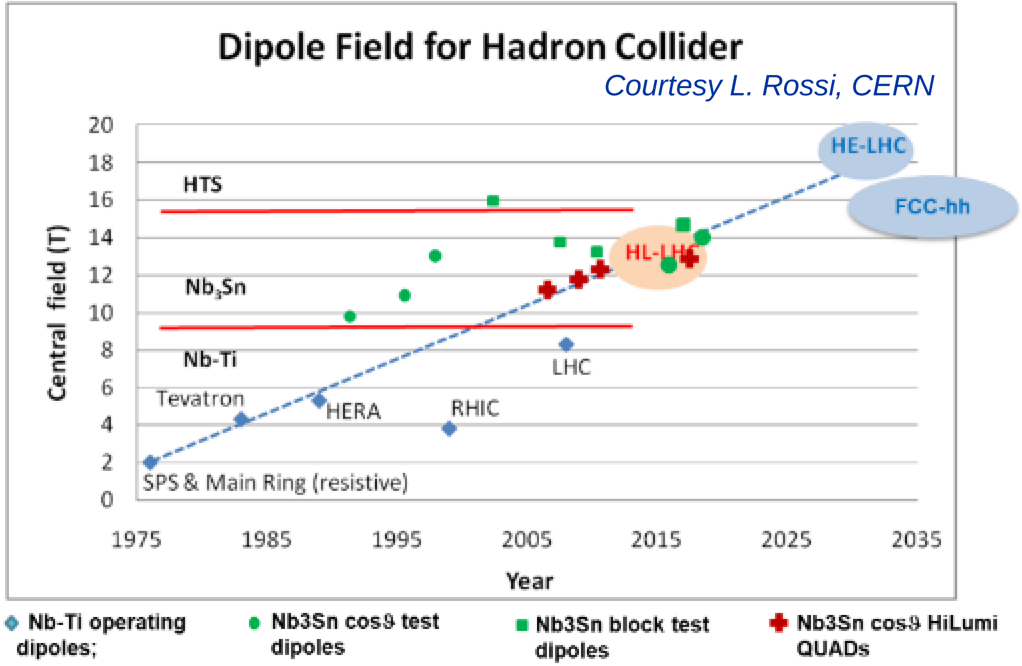


Synchrotrons: $p/q=B\rho$
*Need to maximise* ***magnetic field***
Superconductivity is mandatory, the limitations is the critical current density Jc for SC magnets



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

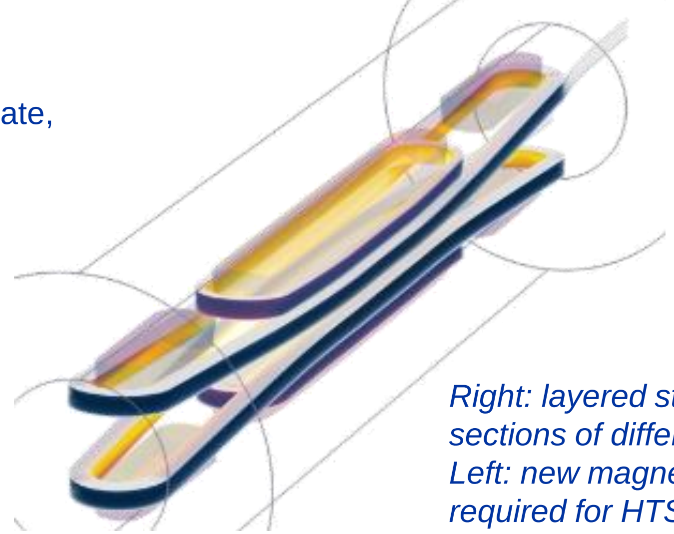
1. **NbTi** (Niobium Titanium as in the LHC): mature but limited to about 9T field.

2. **$Nb_3Sn$** (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.

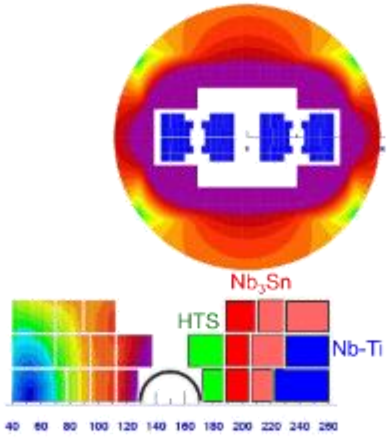
R&D towards a 20 T HTS dipole magnet, develop 10 kA cable.
REBCO (rare earth barium copper oxyde) deposition on stainless substrate, tape arranged in Roebel cables.
**values of 900-1200 A/mm2 at 4.2 K , 18-20 T have been obtained**

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



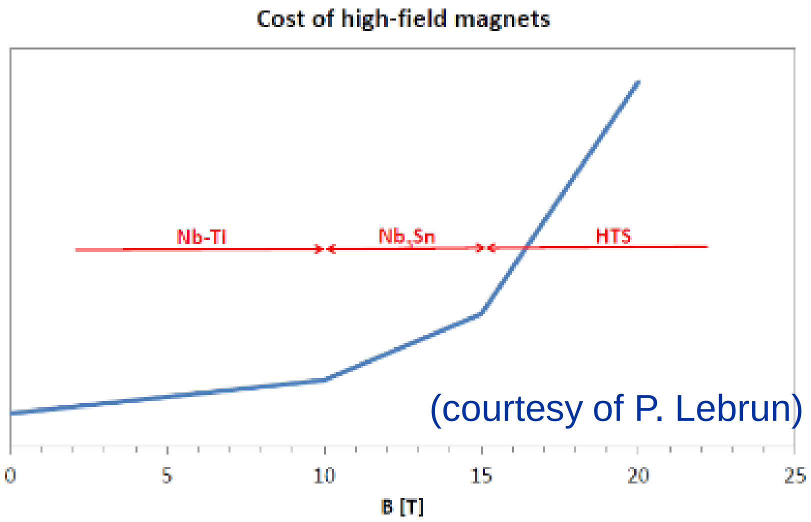
*Right: layered structures with sections of different conductors*
*Left: new magnet designs are required for HTS*

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

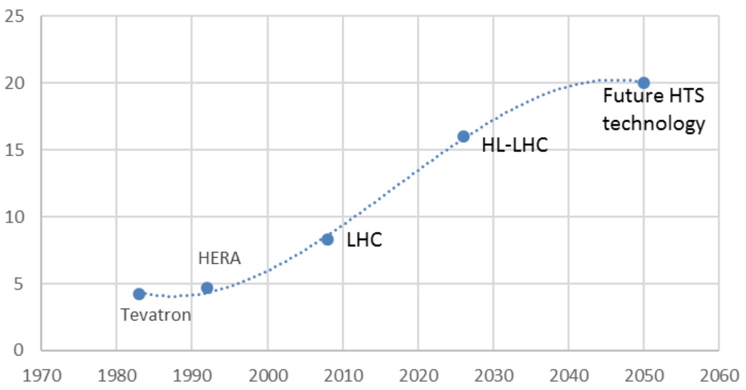


Cost optimized, graded winding

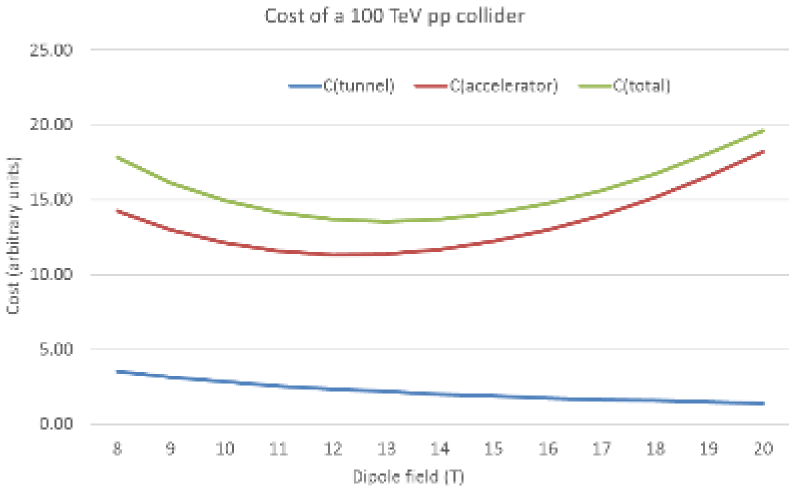
# HTS magnets – reducing cost is the main challenge



(courtesy of P. Lebrun)



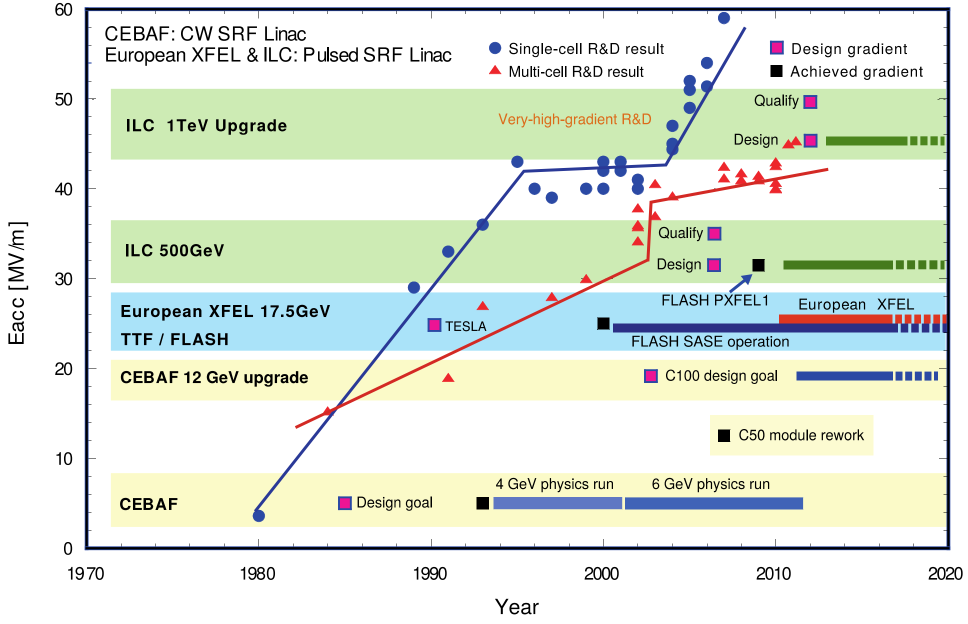
HTS allows reducing the size of the accelerator but not (yet) the cost.
HTS is presently about 5 times the cost of Nb3Sn, but other communities (e.g. fusion) could contribute to reducing the price in the next years.

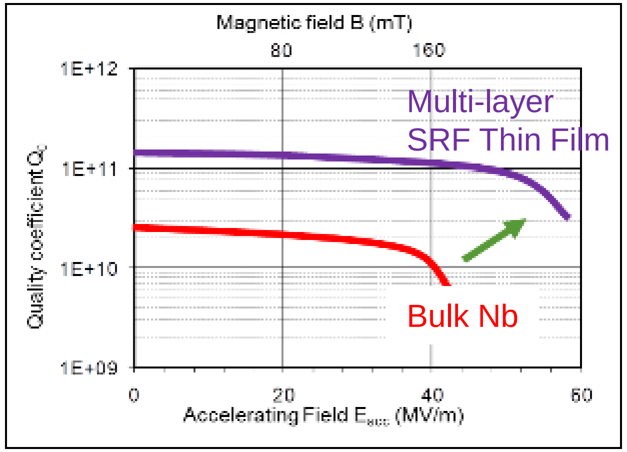


*100 CHF (=100$) of YBCO HTS tape built by Bruker HTS for CERN*

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

# The electric field frontier – superconducting cavities



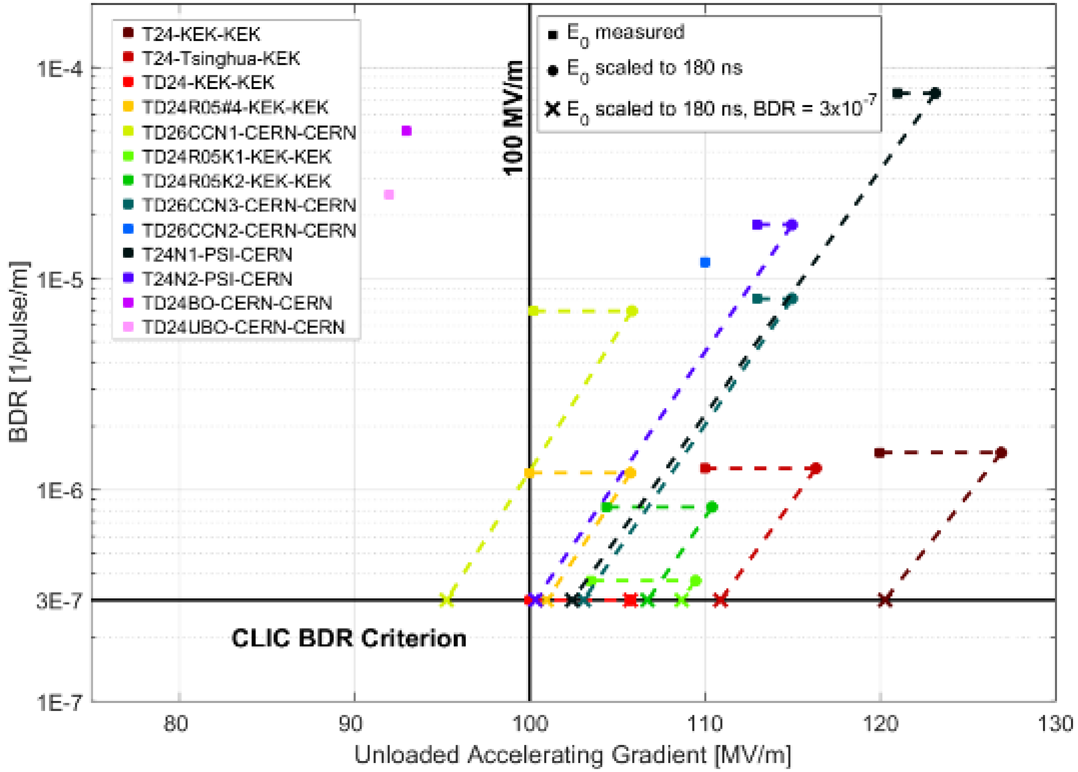


TRENDS:

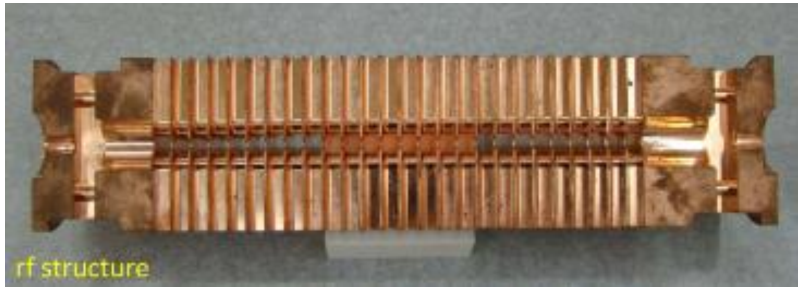
- Nitrogen infusion process (FNAL) and other doping techniques: high Q operation, gradients ~45 MV/m
- Coating of Nb with a thin layer of $Nb_3Sn$ (allows operation at larger $T$, improved cryogenic efficiency)
- Coating of Cu cavites with Nb by HiPIMS (High Power Impulse Magnetron Sputtering,

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.

# 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 hh | 580 | 300? |

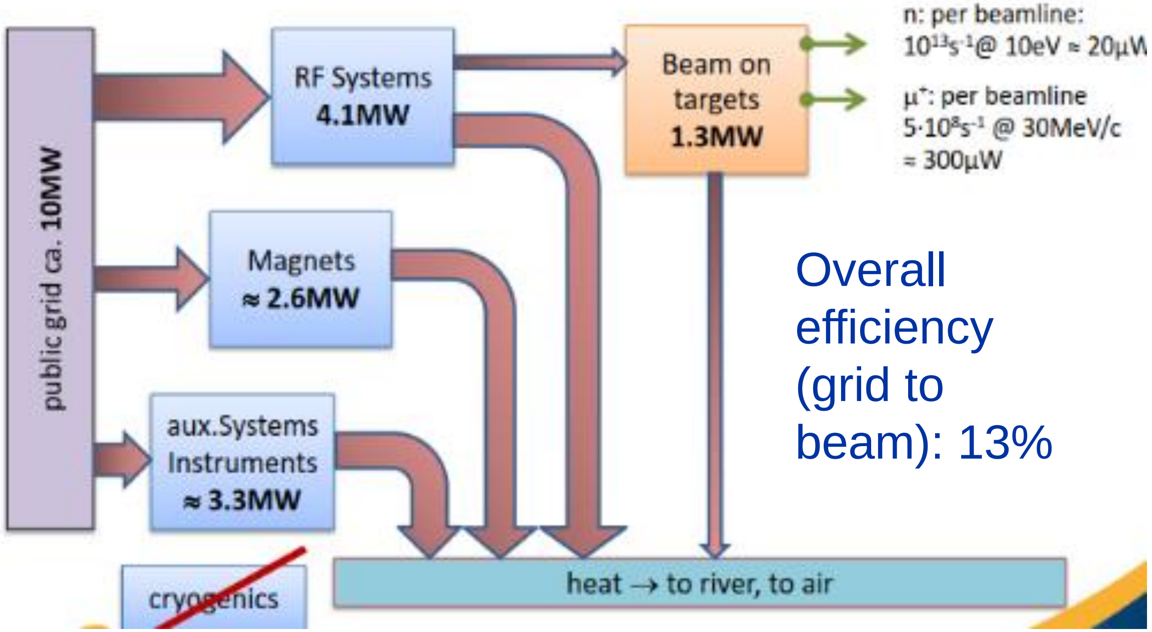
Future large projects require huge amounts of electrical power. Example: the ILC needs about 1/3 of a Fukushima-type nuclear reactor.

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.

Accelerators dissipate large amounts of power - this is related to the high «energy quality» of the particle beam energy.

Overall efficiency from <1% to some 20%, depending on the application (more than on the accelerator).

Large efforts ongoing in the accelerator community to develop components with better efficiency (e.g. superconductivity, permanent magnets, high-efficiency RF sources). 50% reachable for some high-power superconducting systems.



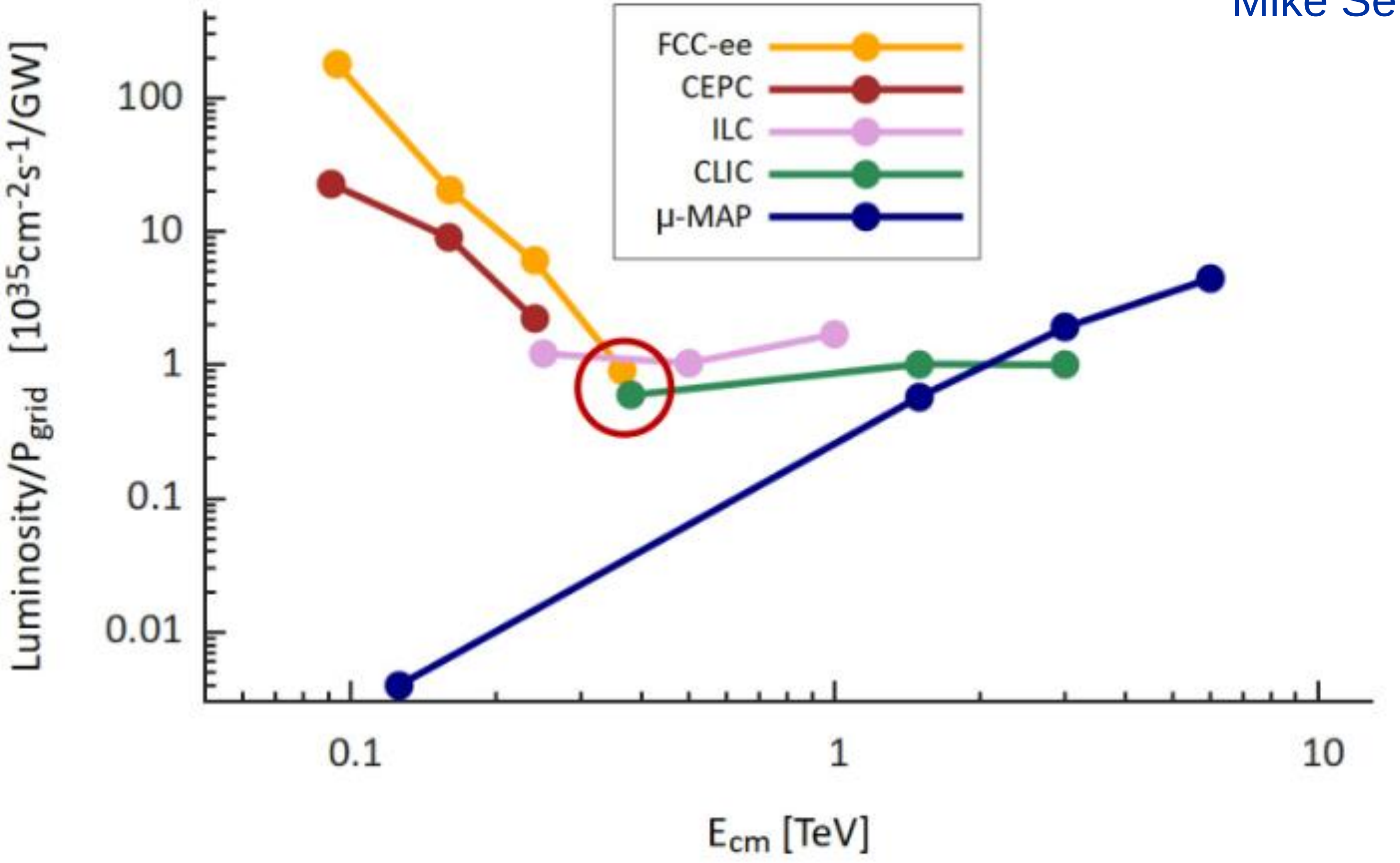
Overall efficiency (grid to beam): 13%

Example: power flow in the PSI cyclotron facility

# Efficiency of proposed high-energy lepton accelerators

Mike Seidel, IPAC 22

energy specific
luminosity production:



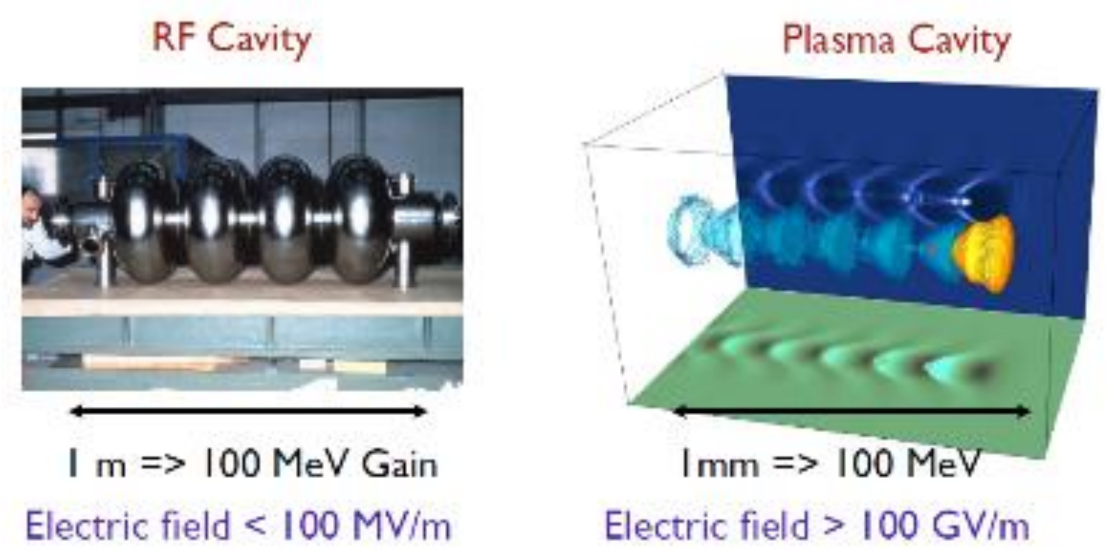
# New acceleration techniques using lasers and plasmas

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



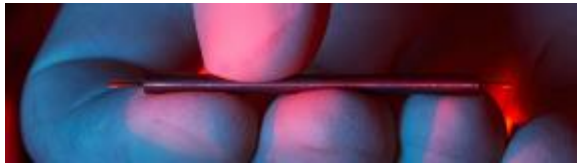
V. Malka et al., Science **298**, 1596 (2002)

**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)

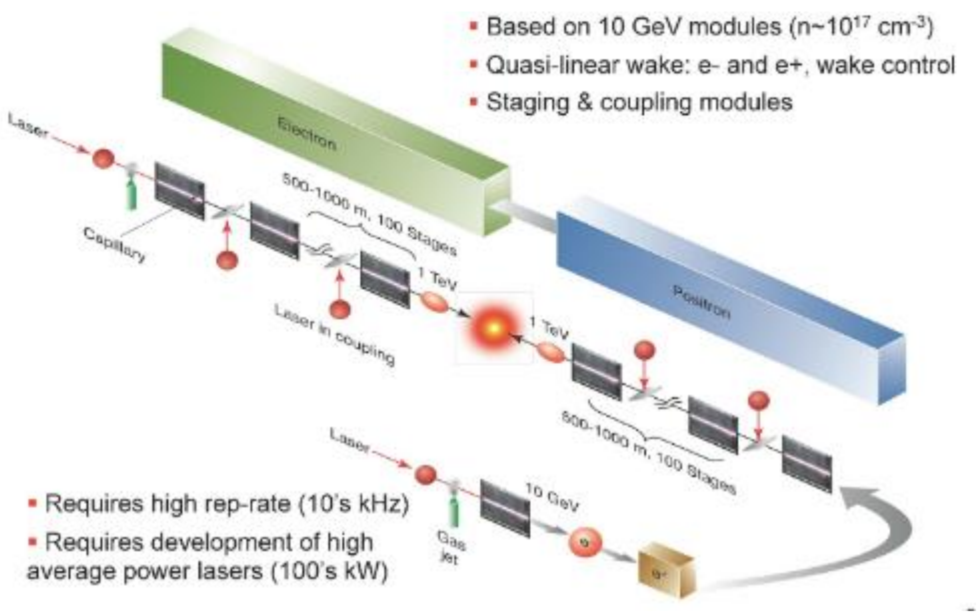


*The «accelerator on a chip»*

**(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?



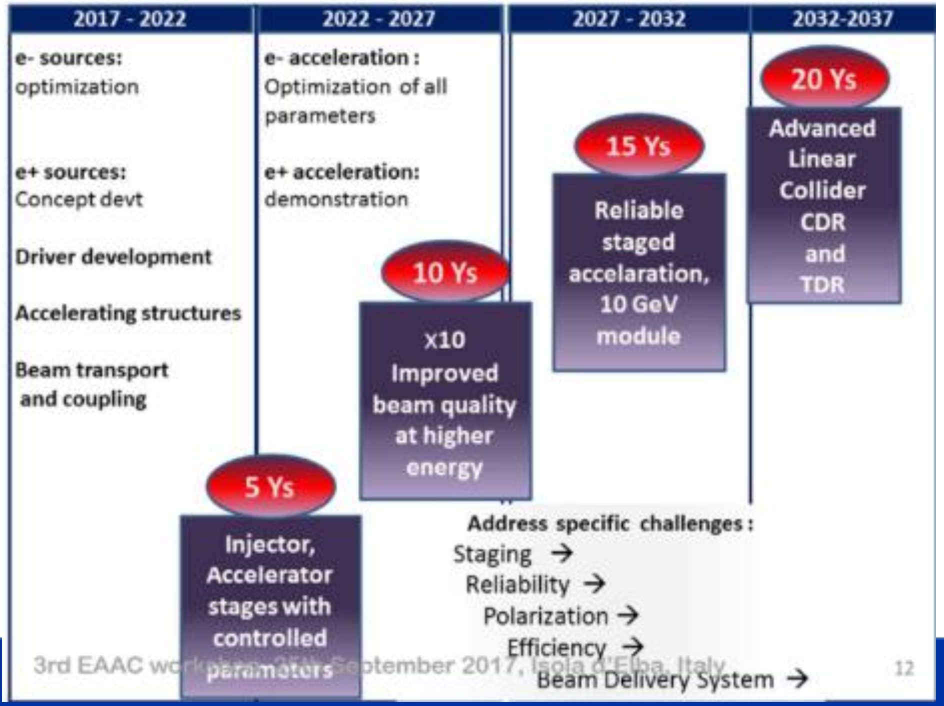
- Based on 10 GeV modules ($n \sim 10^{17}\ cm^{-3}$)
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules

- 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:**<br>optimization<br>**e+ sources:**<br>Concept devt<br>**Driver development**<br>**Accelerating structures**<br>**Beam transport and coupling** | **e- acceleration :**<br>Optimization of all parameters<br>**e+ acceleration:**<br>demonstration | | |

**5 Ys**
Injector, Accelerator stages with controlled parameters

**10 Ys**
x10 Improved beam quality at higher energy

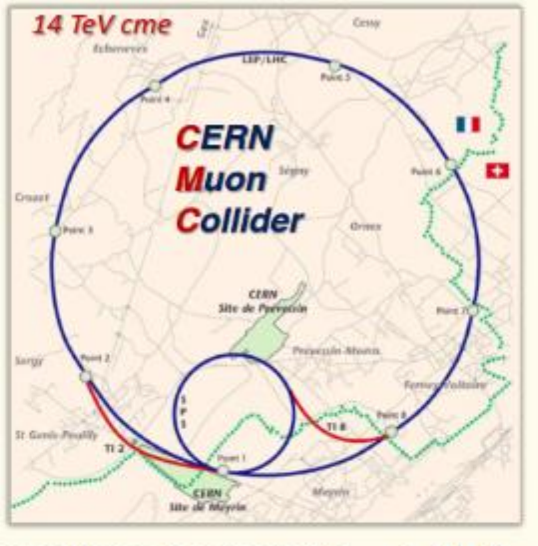
**15 Ys**
Reliable staged accelaration, 10 GeV module

**20 Ys**
Advanced Linear Collider CDR and TDR

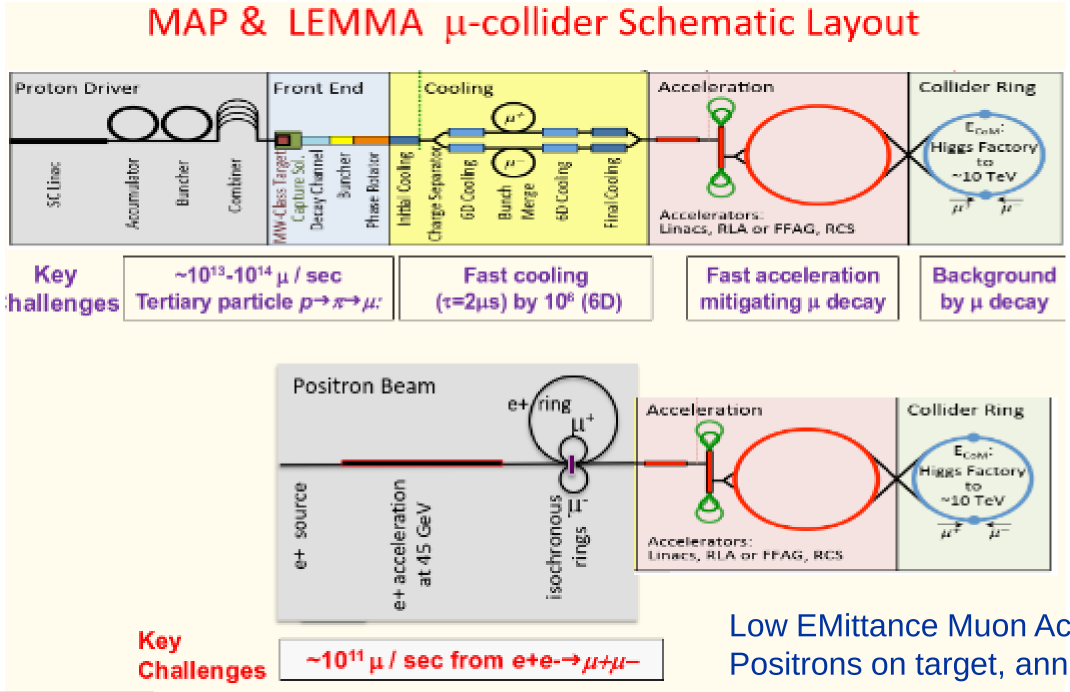
**Address specific challenges :**
Staging →
Reliability →
Polarization →
Efficiency →
Beam Delivery System →

3rd EAAC wo[illegible]eptember 2017, Isola d'Elba, Italy

# Other options for high energy: muon collider



MOPMF072, IPAC18, V. Shiltzev, D. Neuffer



Low EMittance Muon Accelerator
Positrons on target, annihilation

- 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

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.

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

# 3. Accelerators for society

The Economist, October 2013

# Accelerators for medicine and industry

**>35000 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

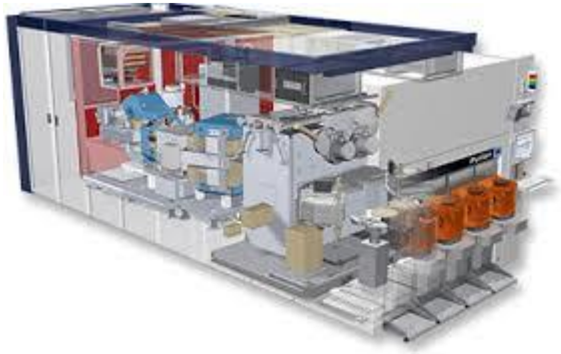
"Curing" materials:
sterilisation; carbon dating;
treating flue gases or water; etc

Microanalysis of materials, mass
spectroscopy, PIXE, etc

PET and SPECT medical imaging

*Radiotherapy electron linac*

*A tandem accelerator for material and artwork analysis*



*A commercial system for ion implantation*

*The IBA Rhodotron for production of intense electron beams*

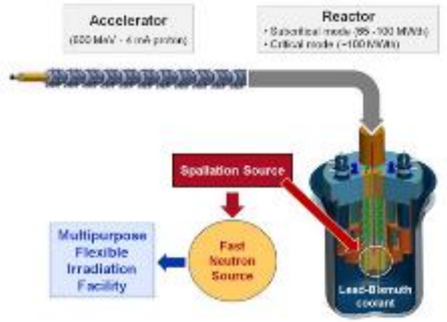
*Proton cyclotron for radioisotope production*

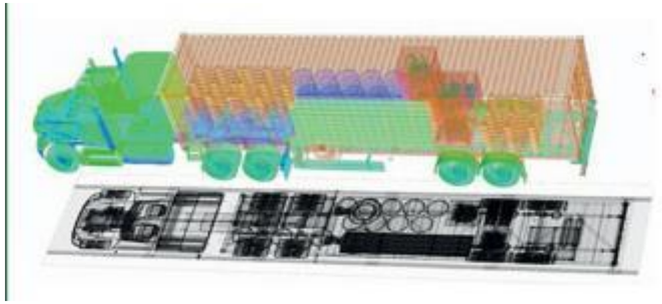
# Particle accelerators for industry, energy and security

**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.

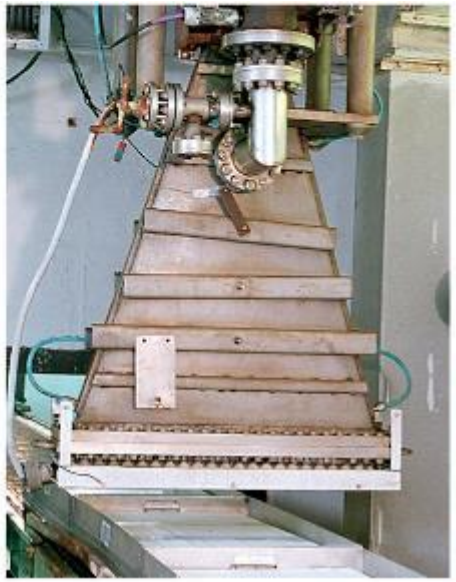


*Fig. 4.12: E-beam technology for sterilising medical products.*

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

# Environmental applications of accelerators

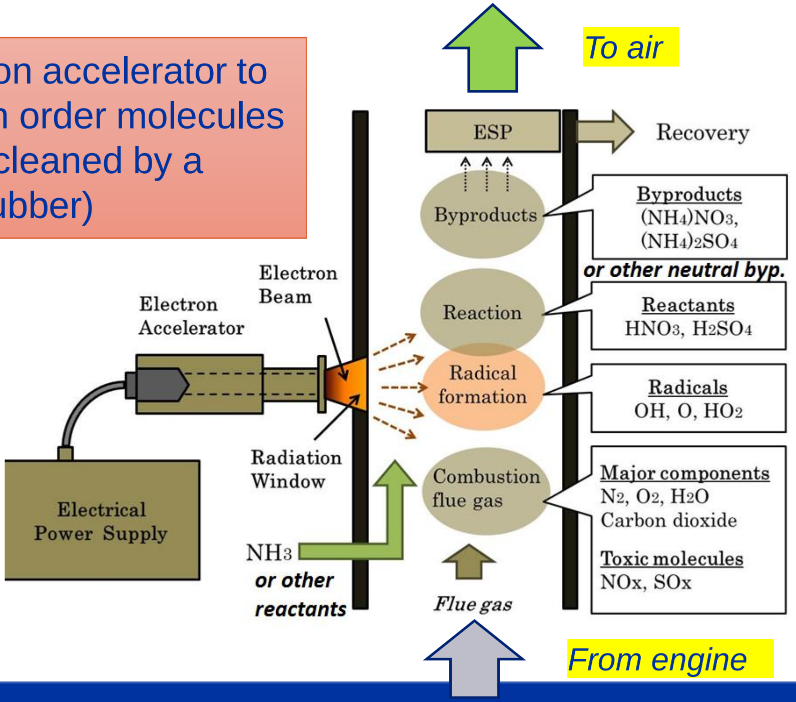
Low-energy electrons can break molecular bonds and be used for:
- Flue gas treatment (cleaning of SOx from smokes of fossil fuel power plants)
- Wastewater and sewage treatment
- Treatment of marine diesel exhaust gases (removal of SOx and NOx).

- **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)**

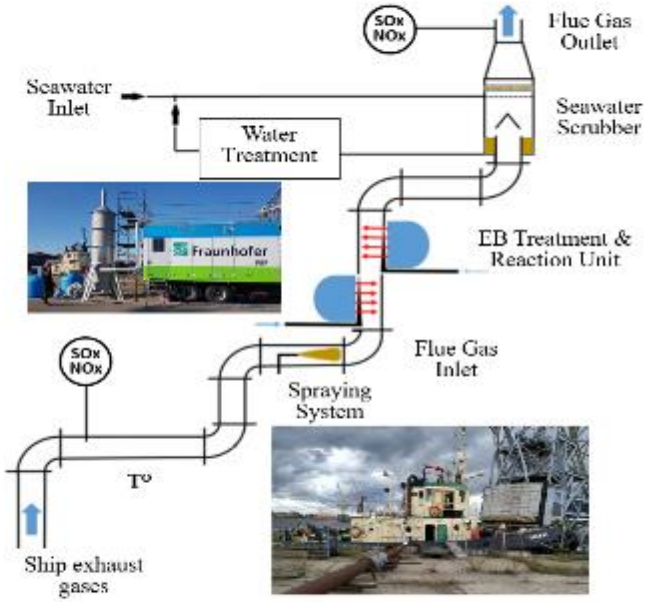
A project based on a patent from INCT Warsaw promoted by a collaboration of research institutions (including CERN), accelerator industry, shipyards, maritime companies, maritime associations (Germany, UK, Switzerland, Poland, Latvia, Italy).

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.

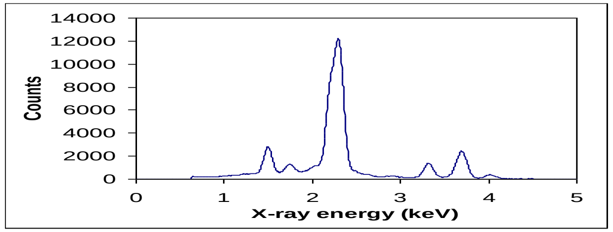
Measured **NOx removal rate 45%** at full engine power with the available scrubber and accelerator.
Estimated removal with optimised scrubber and homogeneous e-beam 98%.
SOx removal only measured in laboratory (no Sulphur allowed in port) with similar removal rates.

# Accelerators for art

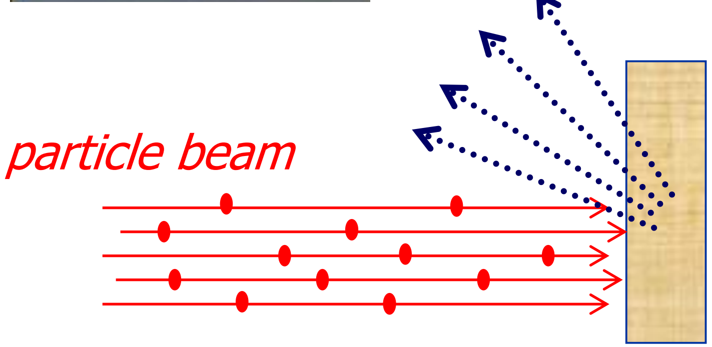
## Ion Beam Analysis (e.g. PIXE, Proton Induced X-ray Emission)

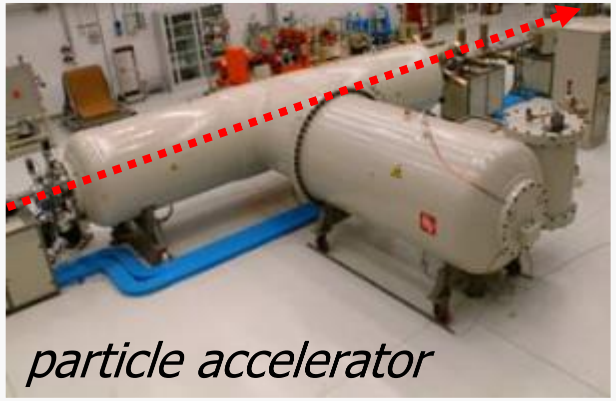
**A beam of particles (protons) from an accelerator is sent on a sample** (e.g. a painting)
The atoms are excited and emit different types of radiation (X-rays, gammas, etc.)
Different atomic elements emit X-rays at different energies – Spectral analysis from one or more detectors allows determination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

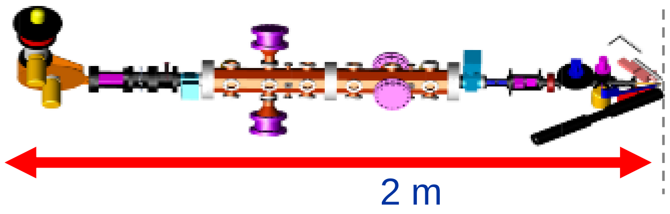
*Radiation detection and spectral analysis*



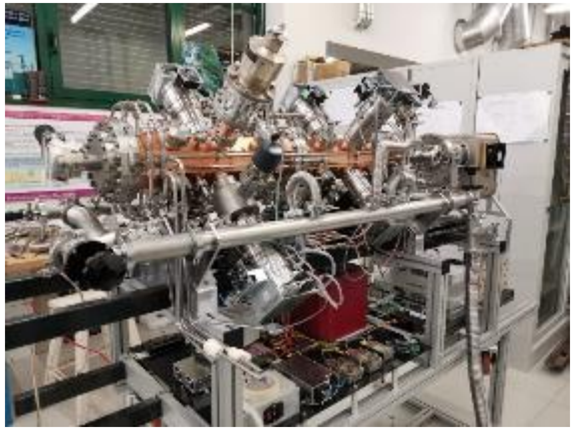
*Emission of radiation of <u>characteristic energies</u>* (X-rays, γ, particles…)







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

# 4. Miniature accelerators?

# Towards the miniature accelerator

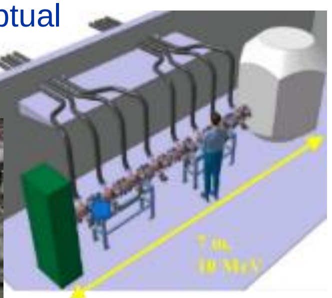
Important trend towards miniaturization of accelerators, for use in medicine and industry

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

## The mini-RFQ (Radio Frequency Quadrupole)

750 MHze
92 mm diameter
2.5 MeV/m

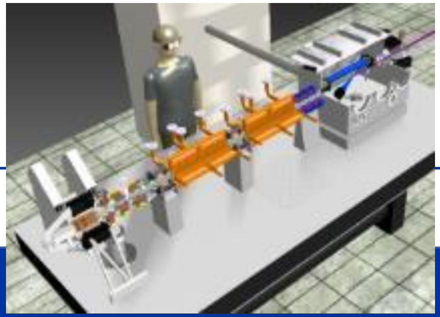
Proton therapy injector (in operation)
Artwork PIXE analysis (in construction, transportable)
Isotope production (design)
Neutron radiography (conceptual stage)



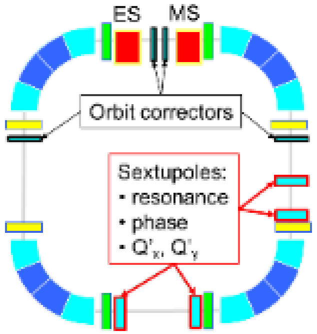
## X-band structures

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)

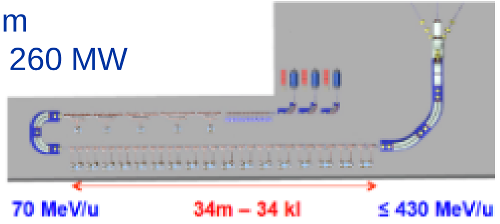


## Compact accelerators for ion therapy



Superconducting C-ion synchrotron
Bmax 3.5 T
27m circumference

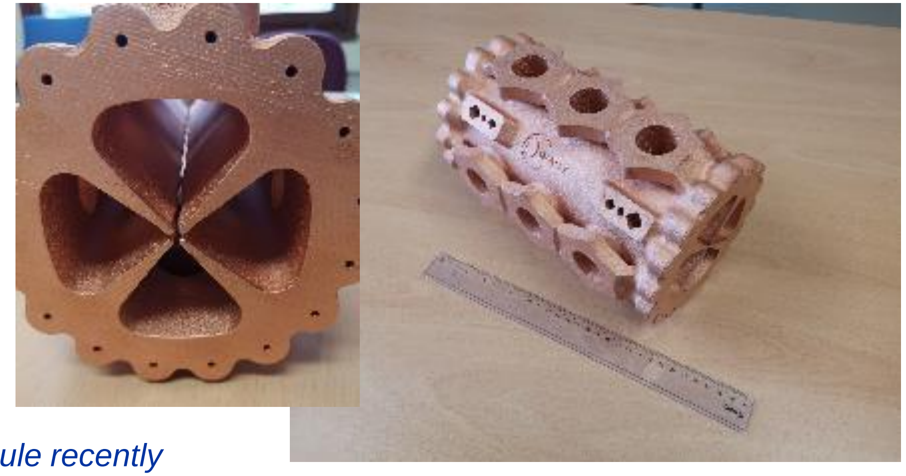
Folded C-ion linac,
Tot. length 53 m
Tot. RF power 260 MW



# Miniature technologies today

| Category | Particle | Configuration | Energy/Footprint (achieved, acc. only) | Ancillaries | Main limitations |
|---|---|---|---|---|---|
| **Incremental** technologies (RF) | protons | mini-RFQ | ~ 2 MeV/m$^2$ | RF system | RF power density, beam acceptance |
| | protons | mini-cyclotron | ~ 5 MeV/m$^2$ | RF, power supply | Shielding, magnet weight |
| | electrons | X-band RF | ~ 20 MeV/m$^2$ | RF system | Breakdown rate |
| **Disruptive** technologies (laser/based) | p, ions | laser accelerator | ~ 10 MeV/m$^2$ | Laser | Energy dispersion, beam emittance, efficiency |
| | electrons | dielectric laser (DLA) | ~ GeV/m$^2$ | Laser | Beam optics, thermal loading, radiation damage, efficiency |

- Some margin for improvement in conventional RF technologies
- Long R&D needed for disruptive laser technologies
- Thermal limitations due to power density: the small accelerator will never be able to generate large beam powers.



*The Additive Manufactured Mini-RFQ (750 MHz) prototype module recently developed by I.FAST WP10.2 (RTU, CERN, CNRS, TalTech, CEA, INFN)*

# The demand for compact accelerators: applications

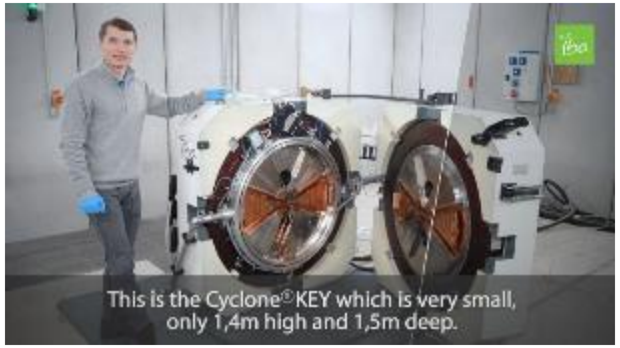
| | | Minimum energy | Market | Challenges | Opportunities |
|---|---|---|---|---|---|
| Medicine | Radioisotope production | 7 MeV (PET) | Mature (several competing vendors) | Reduce cost/dose, production in hospitals | New isotopes under study or clinical trials (theragnostics, alpha therapy, etc.) |
| | Cancer treatment | 250 MeV (protons),<br>100 MeV (electrons)<br>430 MeV/u (carbon) | Expanding (6 vendors for protons) | Reduce cost, size. Integrate diagnostics. | FLASH treatment for electrons and protons |
| Industry | Ion Beam Analysis | 2 MeV (protons) | Limited by cost | Reduce cost, size | Artwork analysis, film analysis in industry, etc. |
| | Neutron radiography | 4 MeV (deuterons, protons) | Presently small | Activation, portability | Industrial imaging |
| | X-ray analysis | > 4 MeV electrons | Mature, expanding | Portability | Security |
| | Beam treatment | < 1 MeV electrons | Presently limited | Beam power, public perception | Environment (sludge, microplastics, flue gas) |
| *plus many more ideas on alternative and original usages of particle beams…* | | | | | |

- while many companies sell accelerator components, only few company in the market sell a «beam», i.e. are fully responsible for the beam quality.
- Small ("miniature") accelerators can be excellent entry points for new companies entering the field.

# Some examples, protons and ions

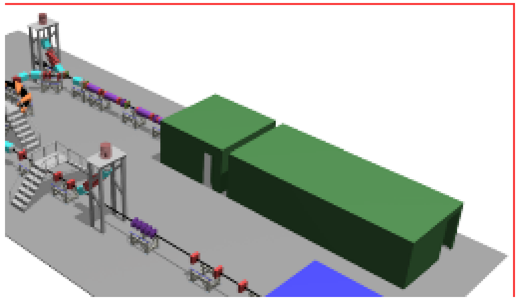
*The CERN-INFN high-frequency RFQ-based system for artwork analysis: 2 MeV in 1.4 m2, less than 250 kg, 3 electronic racks*

*T. Antaya with steel pole and yoke pieces for the Ionetix, a 12.5 MeV cyclotron called the Isotron. (Courtesy of Ionetix)*



*Cyclone KEY from IBA, 9.2 MeV (courtesy IBA)*

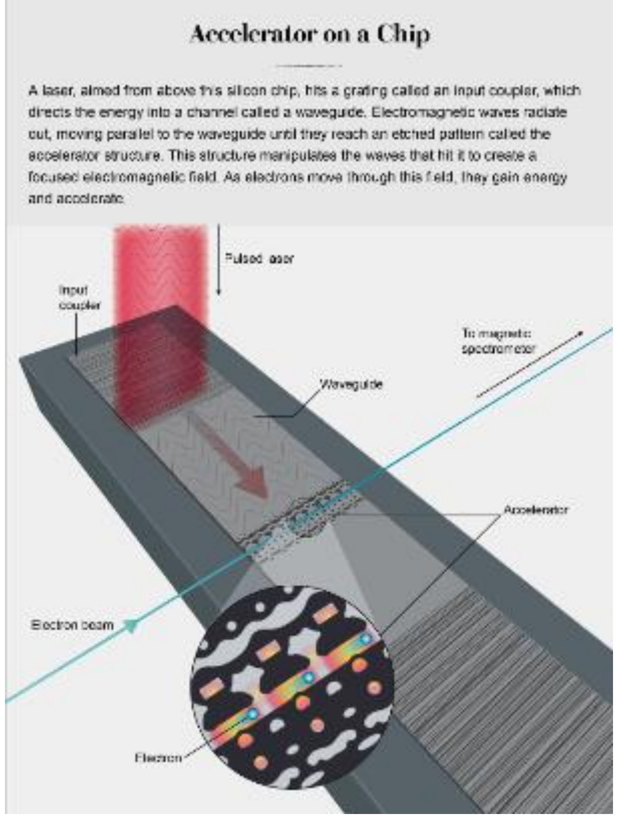
*The AMIT superconducting cyclotron of CIEMAT (Spain), 8.5 MeV, 10 uA, in construction*



*Design of the 10 MeV laser linac section of LhARA (Laser-hybrid Accelerator for Radiobiological Applications) a collaboration coordinated by Imperial College, UK*

# Some examples, electrons

Disruptive

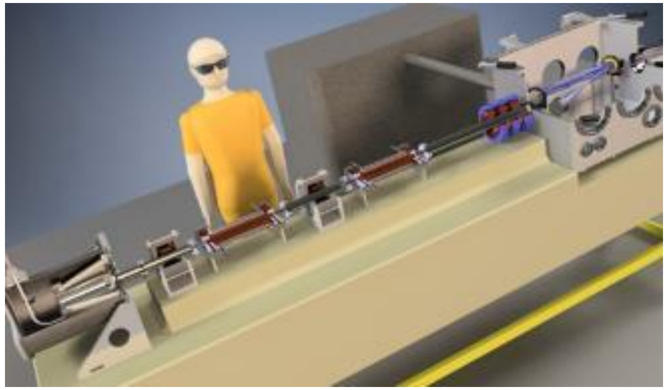


### Accelerator on a Chip

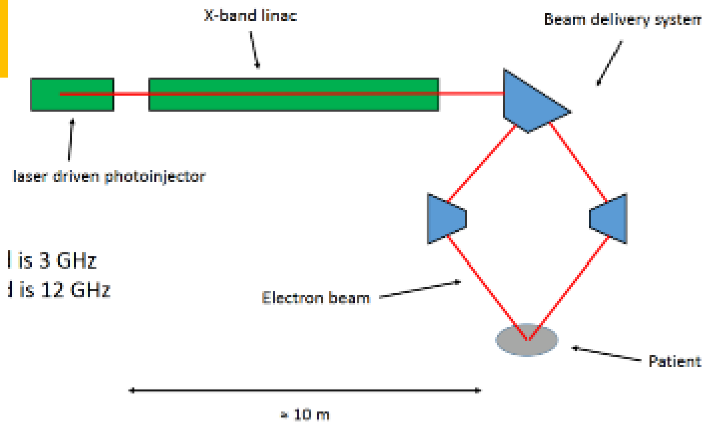
A laser, aimed from above this silicon chip, hits a grating called an input coupler, which directs the energy into a channel called a waveguide. Electromagnetic waves radiate out, moving parallel to the waveguide until they reach an etched pattern called the accelerator structure. This structure manipulates the waves that hit it to create a focused electromagnetic field. As electrons move through this field, they gain energy and accelerate.

*Credit: M. Thomas Baum, Buckyball Design, from “On-Chip Integrated Laser-Driven Particle Accelerator,” by Neil V. Sapra et al., in Science, Vol. 367; January 3, 2020*

Incremental

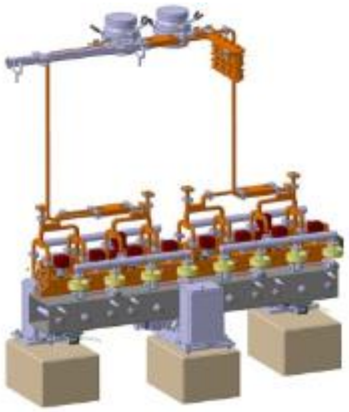


*Smart*Light, a Compact Inverse Compton Scattering Xray Source in construction at TU Eindhoven (NL), 60 MeV electrons, high brilliance @ 100 keV X-rays*



*DEFT (Deep Electron FLASH Therapy) facility being built by a collaboration CERN/CHUV, to produce 100 MeV electrons for FLASH cancer therapy.*

- Maximum energy of beam > 100 MeV – Depth of tumor
- Treatment time < 500 ms – FLASH effect
- Largest field > 10 cm – Clinical scope
- Current average over treatment > 100 µA – Field size over time capability



*The CLIC accelerating module*

# 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?

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!)*

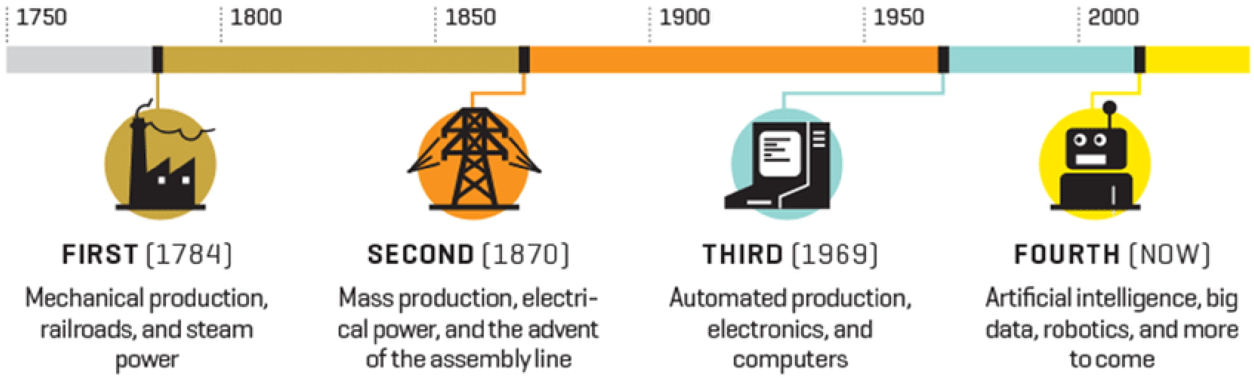
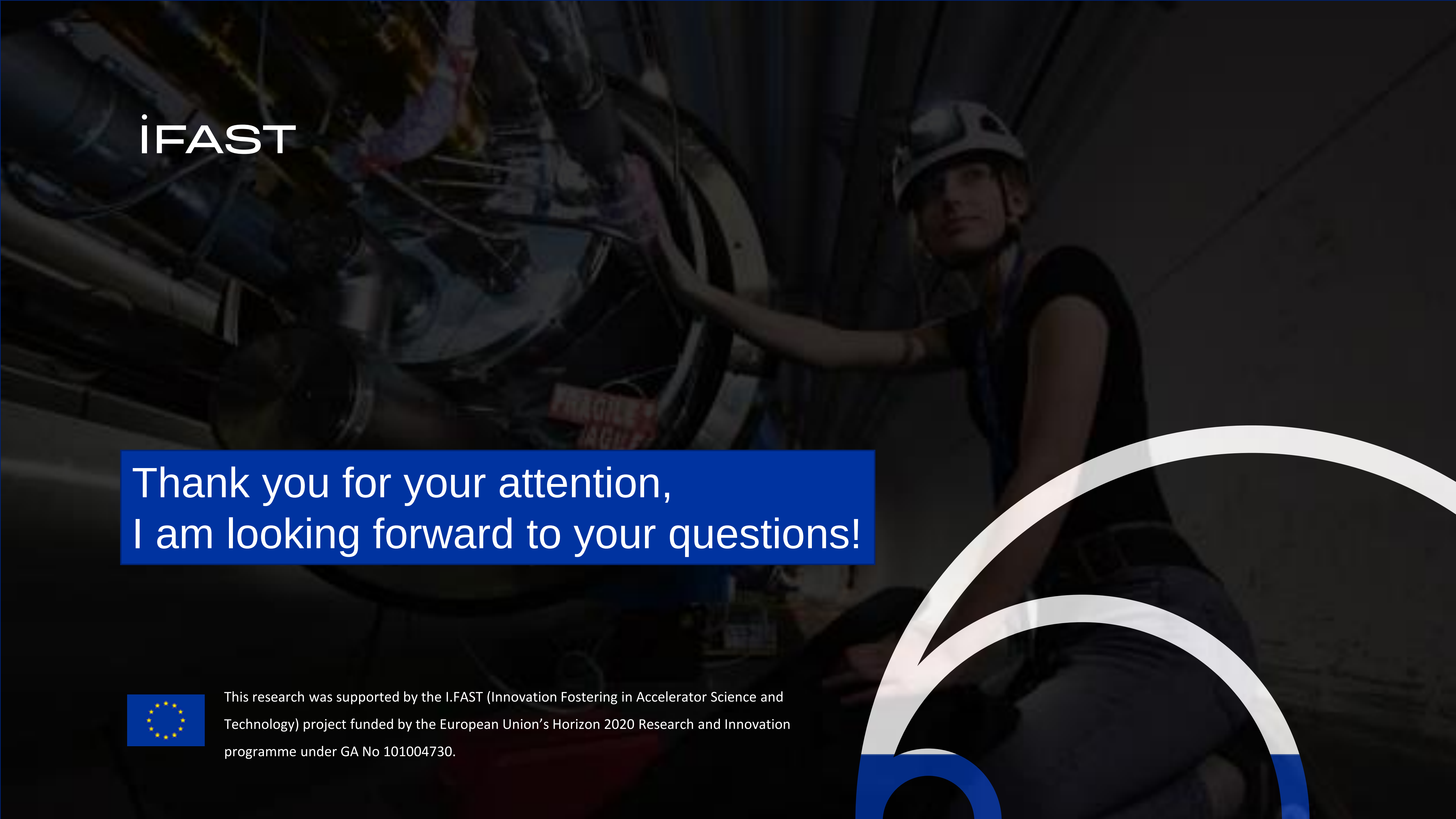


*Image credit: B. Horvath, S. Mundi, 2018*

**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



# Thank you for your attention,
# I am looking forward to your questions!

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