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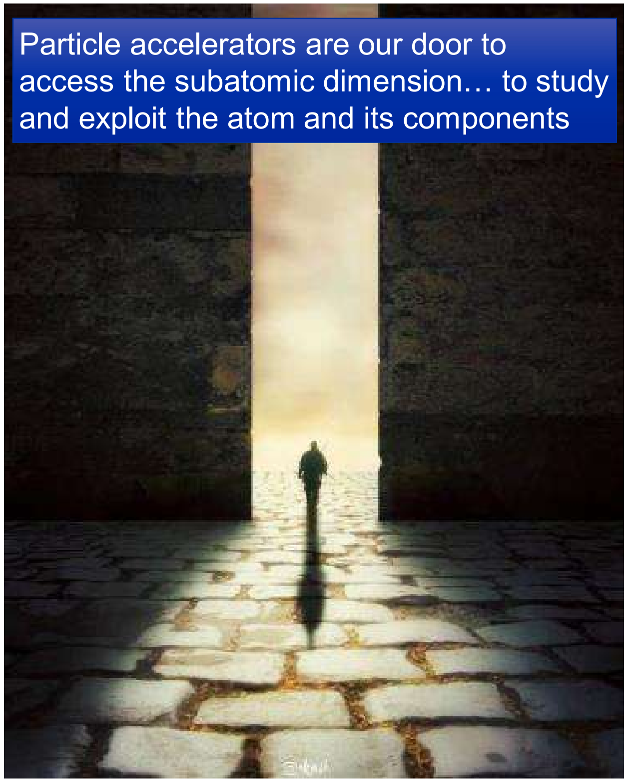
3rd Baltic School of High-Energy Physics and Accelerator Technologies

1: Introduction to Particle Accelerators: principles, technologies, challenges

Particle Accelerators can concentrate energy

A particle accelerator is an instrument capable of concentrating large amounts of energy at subatomic scale, to be used for applications in science, medicine, and industry



When we extract particles from an atom and we accelerate them, we concentrate **enormous amounts of energy in tiny volumes**

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

1. Deliver **energy to the atoms.**
2. Deliver **energy to the nucleus** (if it has enough energy to penetrate).

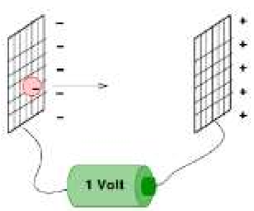
How large is the energy of a particle beam?

Comparing the energy of a proton out of the CERN Large Hadron Collider, the largest particle accelerator ever built.
The energy is small, but the energy density is enormous!

	LHC Proton	LHC Bunch	Yoghurt	TGV train
	•	⁘		
Energy	$1.1\ 10^{-6}$ J	$1.3\ 10^{5}$ J	$5\ 10^{5}$ J	$1.4\ 10^{9}$ J
Energy density	$5.3\ 10^{38}$ J/m^3	$5\ 10^{11}$ J/m^3	$3.3\ 10^{9}$ J/m^3	$7\ 10^{5}$ J/m^3
Type of energy	Kinetic Subatomic scale	Kinetic Subatomic scale	Chemical Macroscopic	Kinetic Macroscopic

LHC bunch: 7 TeV, 1.15 10^{11} protons, at interaction point (30 cm, 16x16 μm^2)
Yoghurt: 150 g, 120 calories
TGV train: 400 tons, 200 m, 300 km/h

Accelerator energies in eV (energy acquired by an electron in a potential of 1V)
1 eV = 1.6 x 10^{-19} Joules

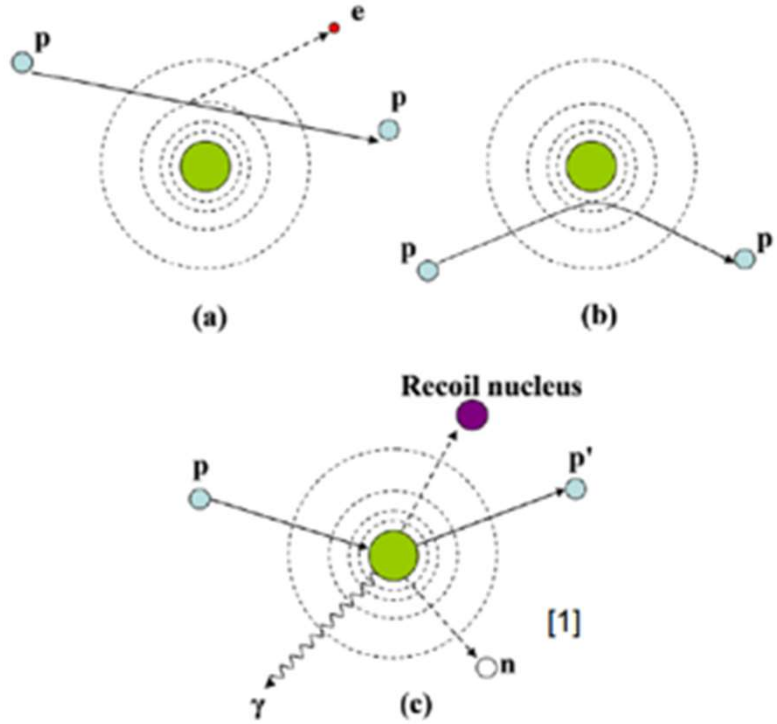


*1 Joule is really small: =1 W*s, cost ≈ 10^{-7} €*

Where does the energy go?

The 4 effects of a particle beam

Scattering of an accelerated beam of particles



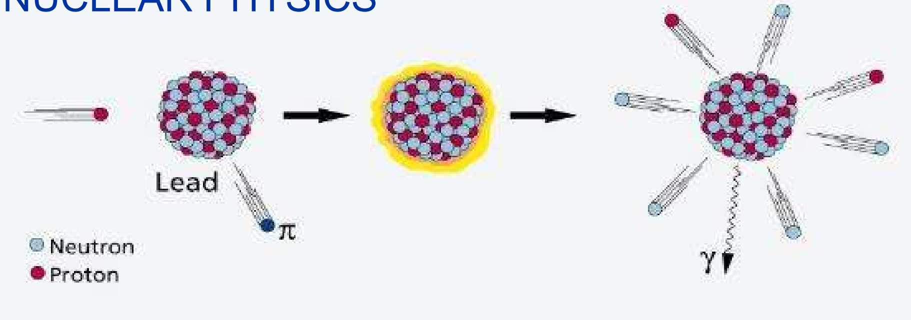
- An accelerated particle when sent on an atomic lattice (target) can:
  - kick electrons out of the atom **(ionization**) or to a higher orbital (**excitation**) – this can break molecular bonds or generate **X-rays** (photons) when the electrons come back to their stable orbit.
  - be deflected by the nucleus and give energy to the nucleus, increasing **temperature**, or breaking **molecular bonds**.
  - be absorbed by the nucleus bringing it to an **excited state** that can extract **secondary particles** (i.e. **generate radiation)**.
- An accelerated particle when **colliding** with another accelerated particle will produce an enormous concentration of energy that can generate new (unstable) particles.

Accelerators can modify the nuclei and create new particles

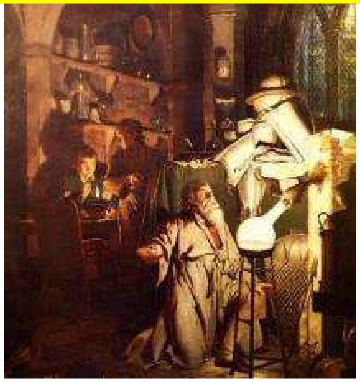
If the energy is sufficiently high, the particles in the beam transfer energy to the nucleus and its components (and are then scattered, reflected or absorbed).

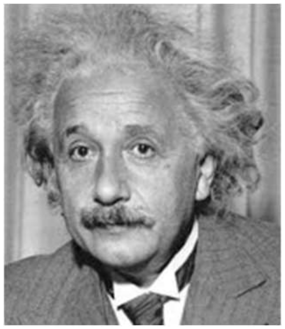
Transforming elements: the dream of ancient alchemists!

NUCLEAR PHYSICS



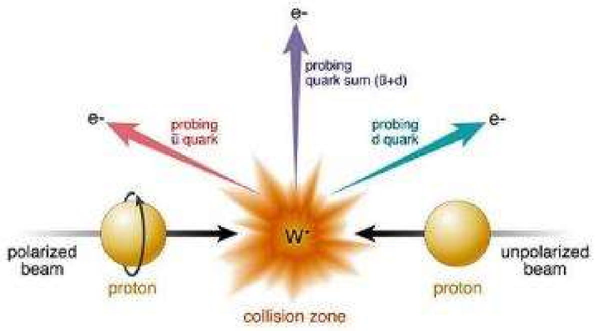
Particles in the beam can break and modify the nucleus (and then generate new elements and transform the matter!)





$E = m c^2$

PARTICLE PHYSICS

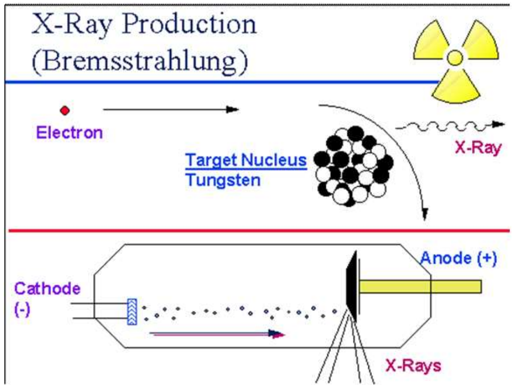


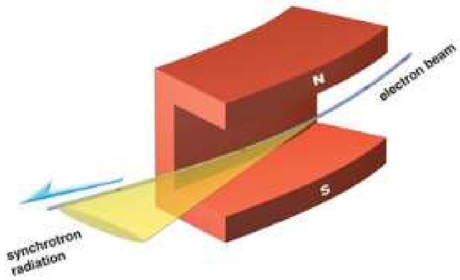
In the collisions can be generated new particles.

Creating matter (from energy): more than a dream, it's God's job!

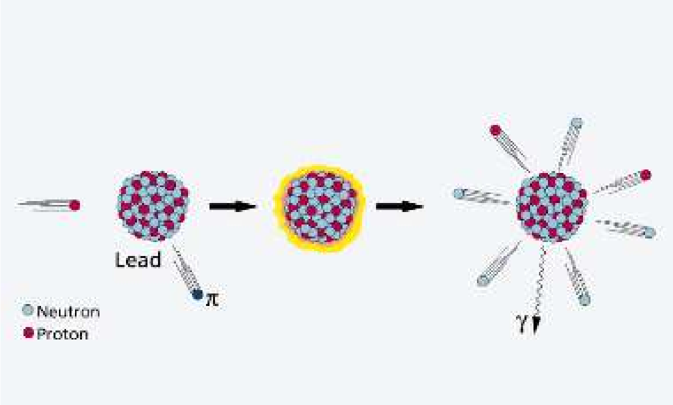
Accelerators can produce intense secondary beams

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



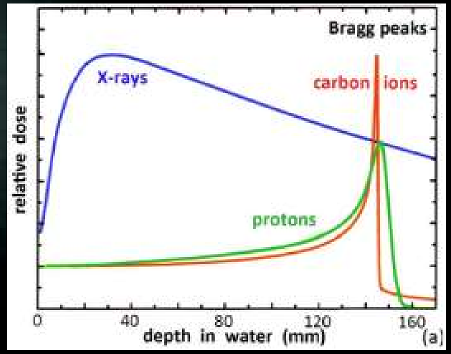
neutron spallation reaction, courtesy of PSI

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

Accelerators can precisely deliver energy

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

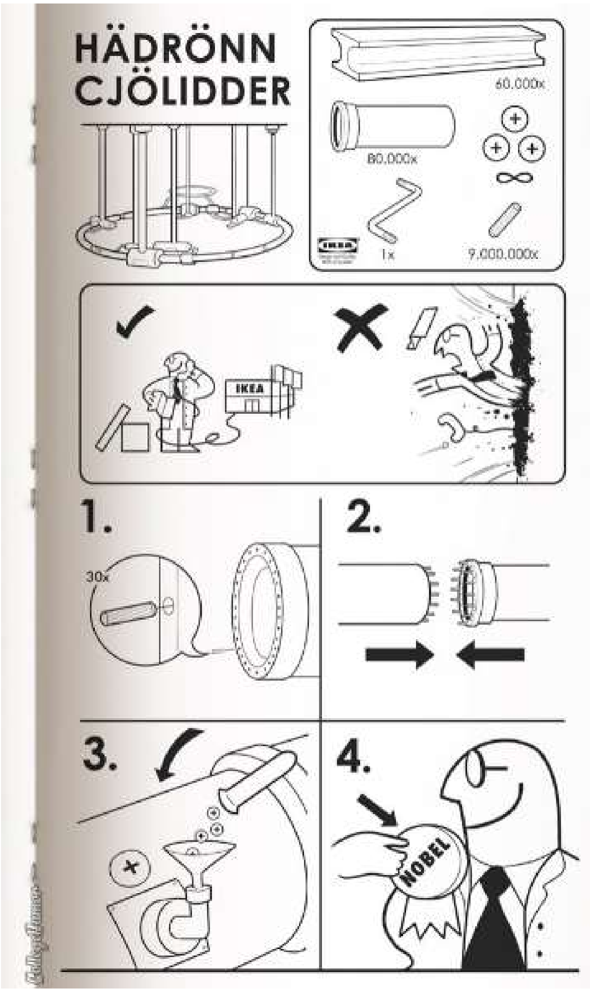
Thanks to the «Bragg peak» a particle beam can deliver energy to a precisely defined area.



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

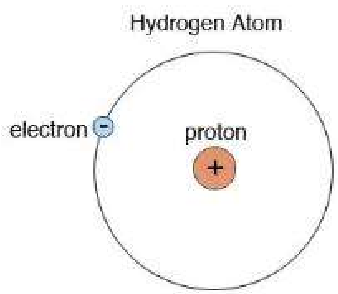
Because of these properties, particle beams are widely used in medicine and industry.

A simple review of particle accelerator principles and technologies

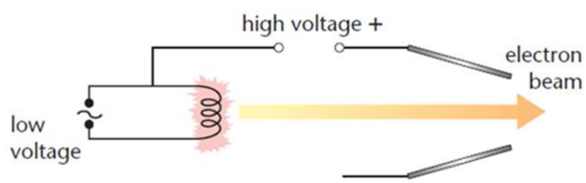


How do we get the particles?

Protons are obtained heating a hydrogen gas (plasma) and extracting the protons with a high voltage



Electrons are obtained by heating of a filament (exactly like an electric bulb)



An electron gun

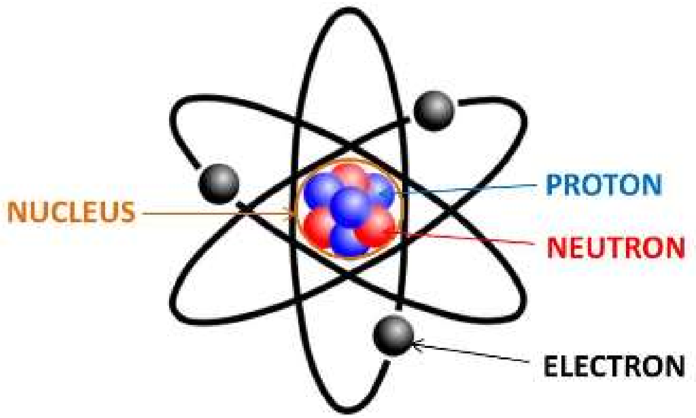
Ions are obtained in a similar way as protons

Scheme of the ion source delivering protons to CERN accelerators

All protons going to the LHC come out of this single bottle of industrial hydrogen (5 kg) that contains 3 10^{27} protons! The LHC needs only 1.2 10^{15} protons per day.

The ion source at the CNAO hadron therapy facility

Combined effect on particles: the Lorentz force



	Charge	Mass
Electrons	-1 e	1 m_e
Protons	+1 e	1 m_p
Ions	+1 / +82 e	1 – 238 m_p

Unit charge 1 e = 1.6×10^{-19} Coulombs
Electron mass 1 m_e = 9.1×10^{-31} kg = 511 keV/c^2
Proton mass 1 m_p = 1.67×10^{-27} kg = 938 MeV/c^2

We extract the particles from the atoms and then:

- give them energy using electric fields,
- guide them using magnetic fields

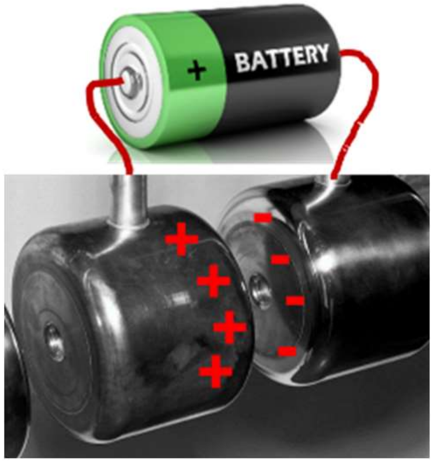
Newton-Lorentz force:

$$\vec{F} = \frac{d\vec{p}}{dt} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

2nd term always perpendicular to motion => no acceleration

Can be accelerated only particles that have an electric charge: electrons, protons, ions (= charged nuclei)

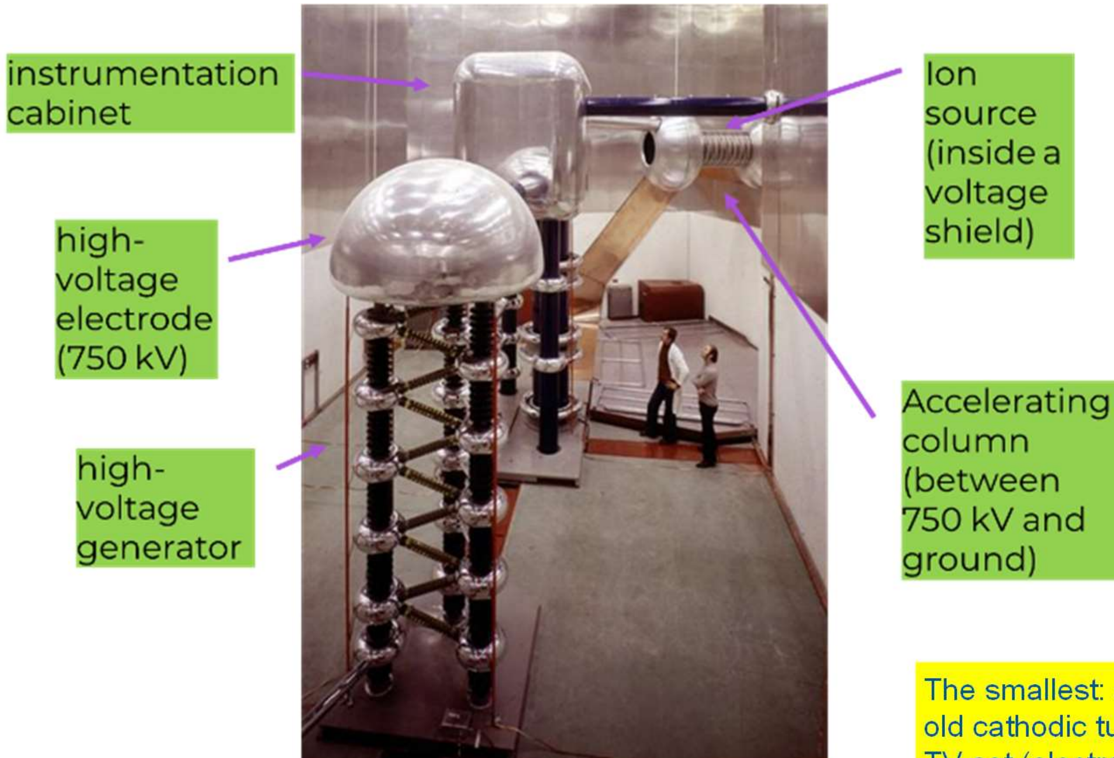
Low energy: electrostatic accelerators



Electrostatic: use a DC voltage between 2 tubes

(A simple capacitor !)

Limitations: few 100 kV are possible but difficult, few MeV possible but require huge installations



The largest: the old (1975-92) CERN 750 keV proton pre-accelerator

The smallest: an old cathodic tube TV set (electrons, max. 30 keV)

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!

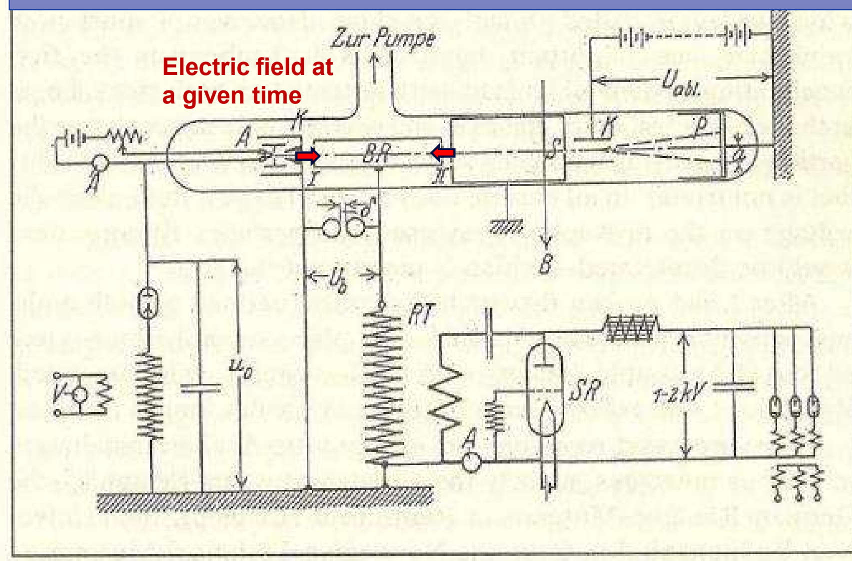
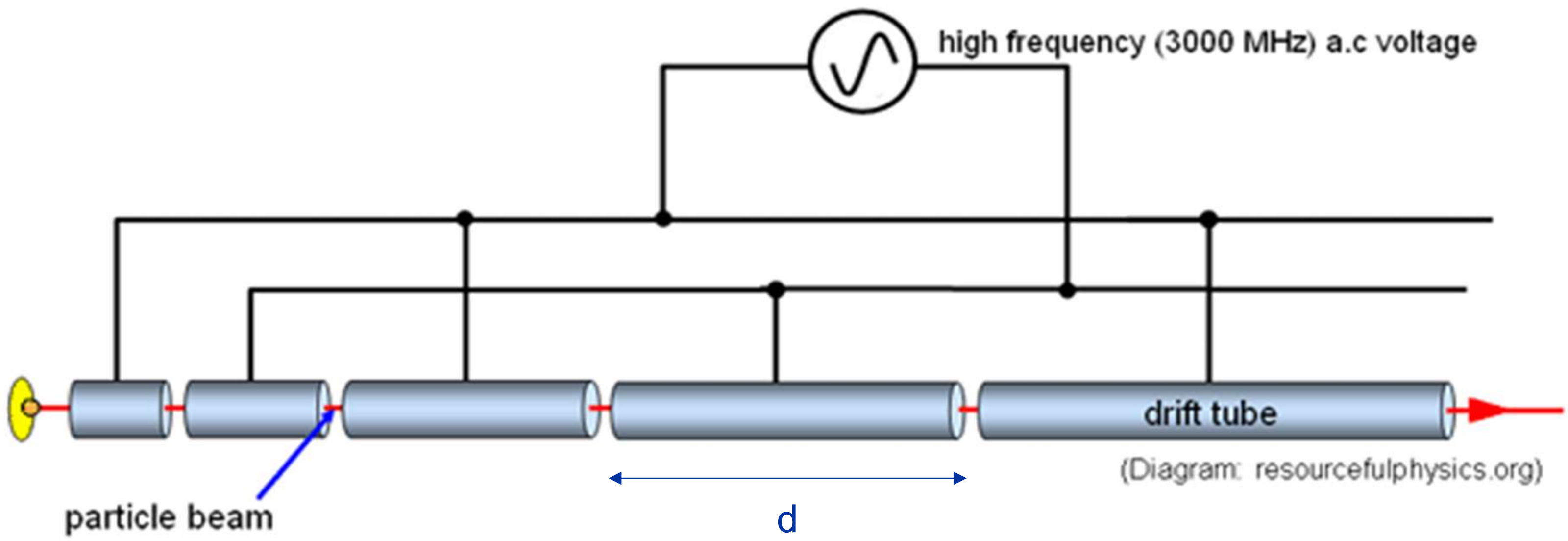


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

The linear particle accelerator



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 **$d = \beta\lambda / 2$**

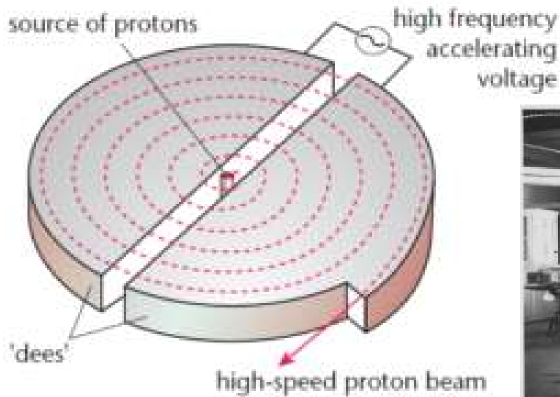
RF with cyclic acceleration: the cyclotron

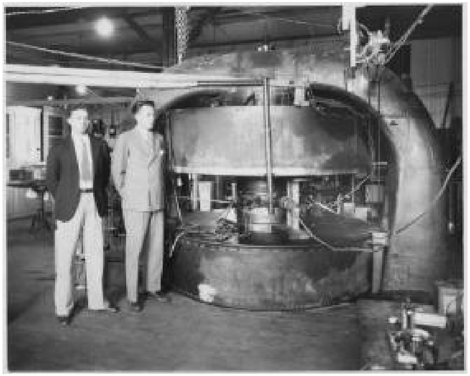
Immediately after R. Wideoroe's invention of the linear accelerator, Ernest O. Lawrence at Berkeley proposes to perform radio-frequency acceleration in a circular system, inserted in a big magnet.

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. In **classical mechanics**, the revolution frequency does not depend on the beam energy → RF frequency is constant !





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

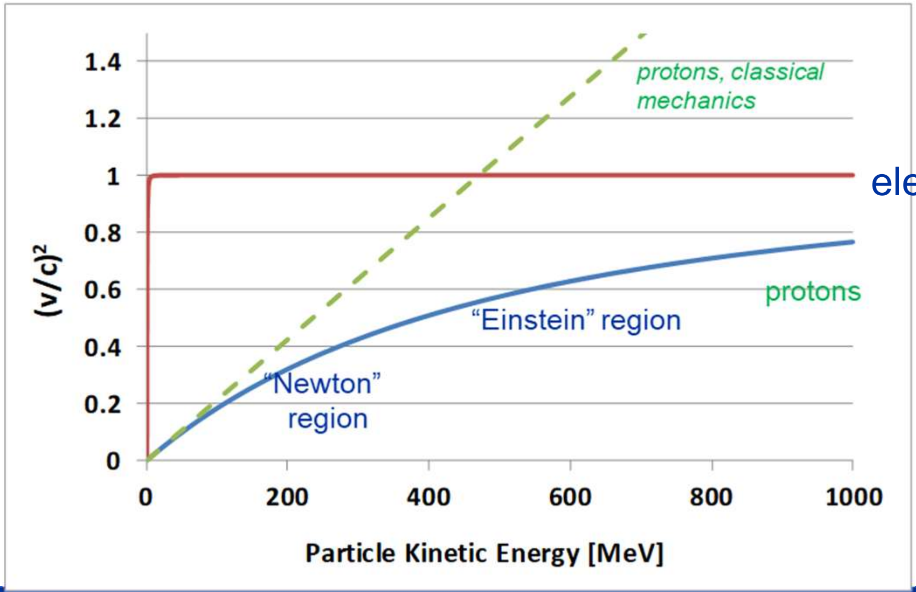
f revolution frequency

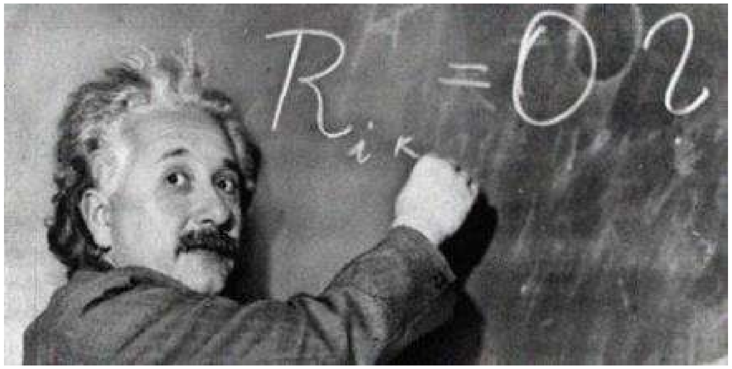
- Protons are produced by a "source" in the centre
- They are accelerated in the gap between 2 electrodes fed with RF
- The protons go in larger and larger spirals, and their velocity increases proportionally to the spiral radius, keeping revolution frequency constant.

Relativity

When we accelerate, we give energy to the particles that become faster and faster.
But a hard limitation is given by special relativity: we cannot exceed the speed of light.
Before reaching the speed of light, the energy goes to increasing the mass and not the velocity!

$\beta^2=(v/c)^2$ as function of kinetic energy T for protons





Relation kinetic energy / velocity:

Classic (Newton) relation

$$T = m_0 \frac{v^2}{2}, \quad \frac{v^2}{c^2} = \frac{2T}{m_0 c^2}$$

Relativistic (Einstein) relation

$$\frac{v^2}{c^2} = 1 - \frac{1}{\sqrt{1 + T/m_0 c^2}}$$

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

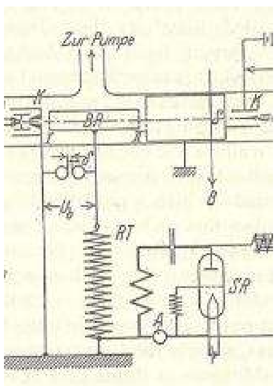
→ invention of the **synchrotron**

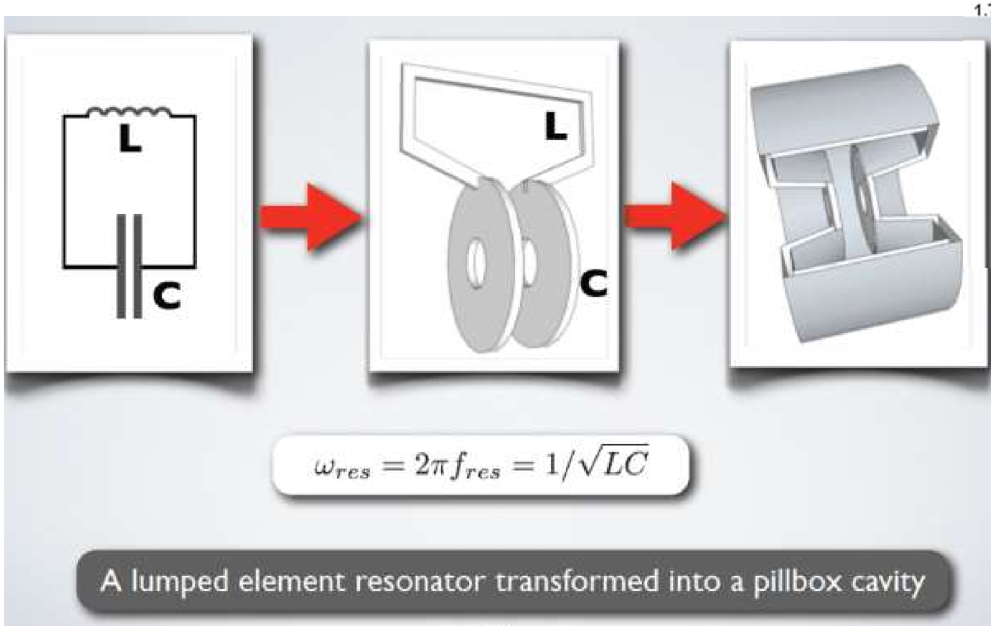
Limitation to Widerøe linacs: frequency

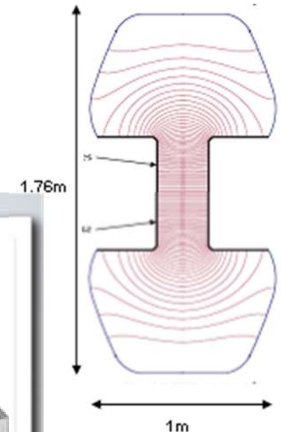
As velocity increases, to keep a reasonable distance between gaps the RF excitation frequency must increase: $f_{RF} = v_p / 2d$
When the RF excitation frequency becomes so high that the dimensions of the accelerator are comparable to the RF wavelength, the gaps start to generate electromagnetic waves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

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

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



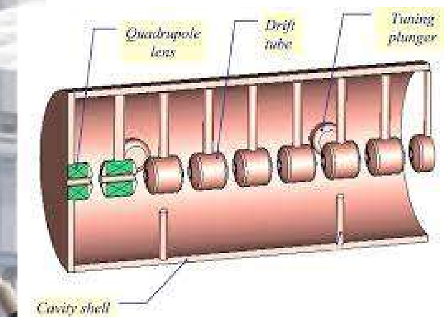




Single-gap cavity 88 MHz

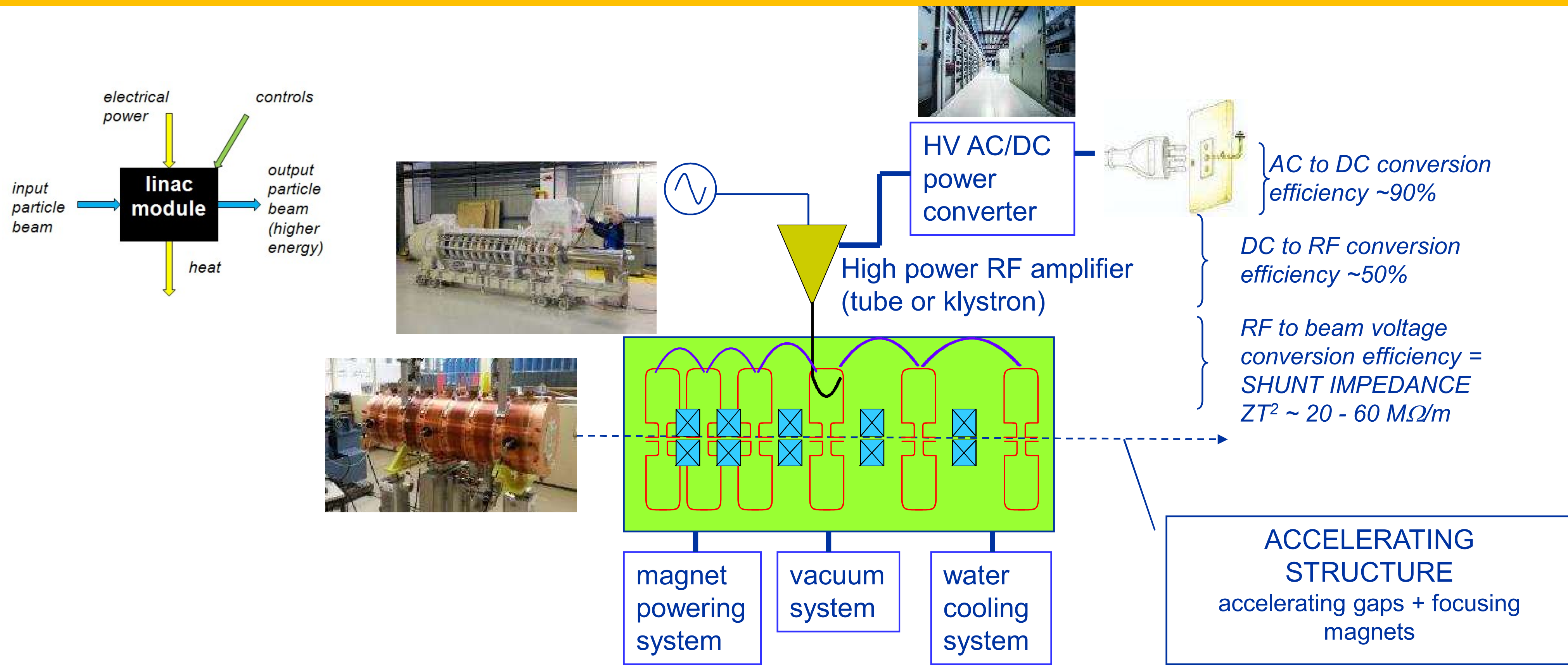
Multi-cell linac cavity (Linac4 120 MeV, 352 MHz)

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

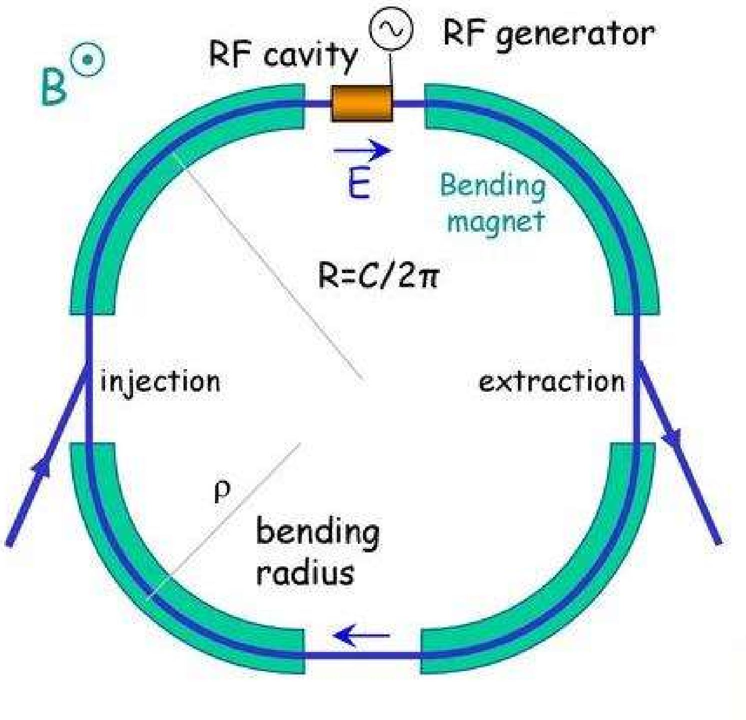


Drift tubes contain magnetic quadrupoles that are used to guide (focus) the particles in the beam

Energy flow: from the power grid to the beam



From cyclotron to 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:

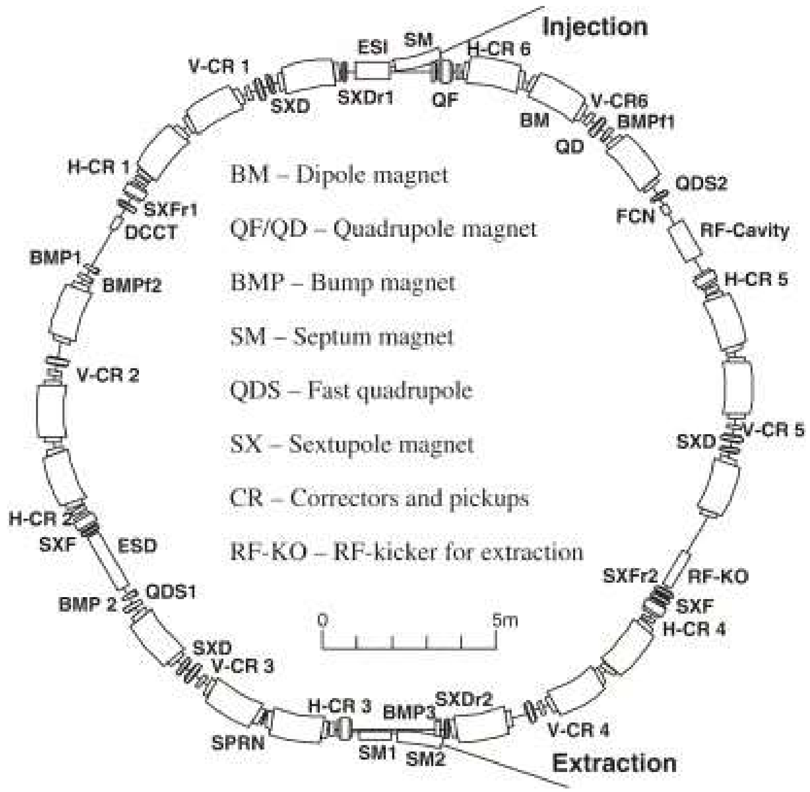
$$R = p / eB$$

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

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

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

A complete synchrotron

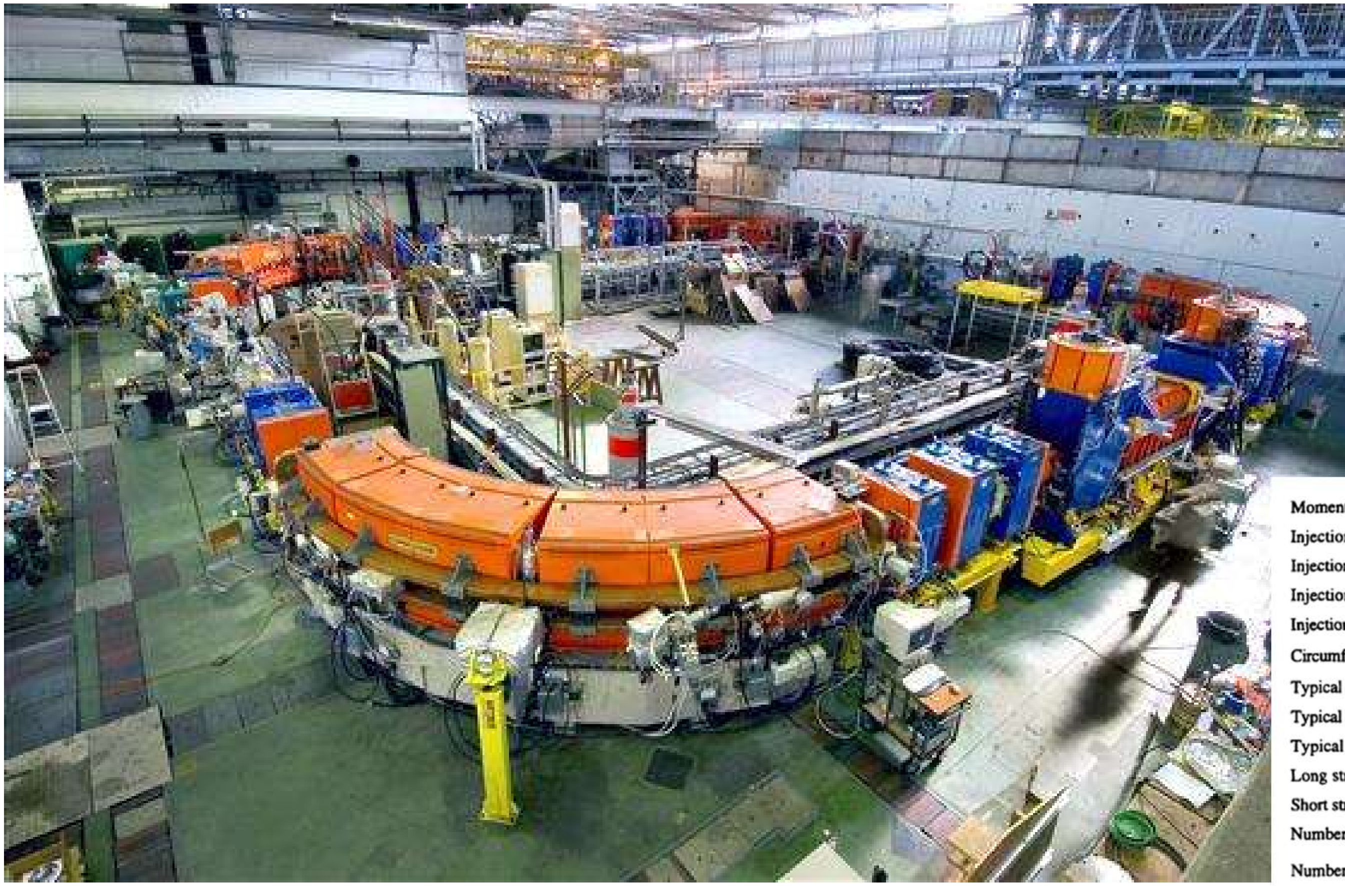


The HIMAC carbon ion therapy synchrotron (Japan)

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”:

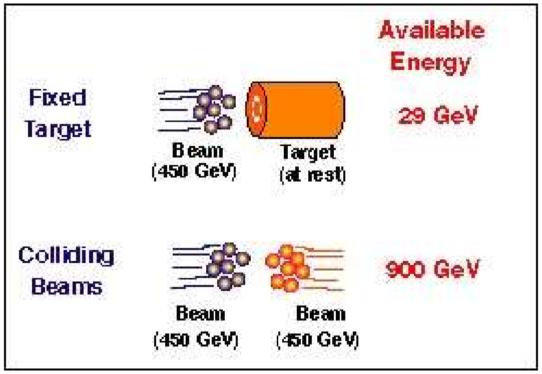
- Dipole magnets for bending (18 in this case for 20^0 each)
- Quadrupole magnets for focusing
- Septum magnets for injection and extraction
- Sextupoles for correcting perturbation in orbits
- Correctors and pickups
- RF caviti(es) for acceleration
- Beam diagnostics and measurement devices
- Bump magnets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

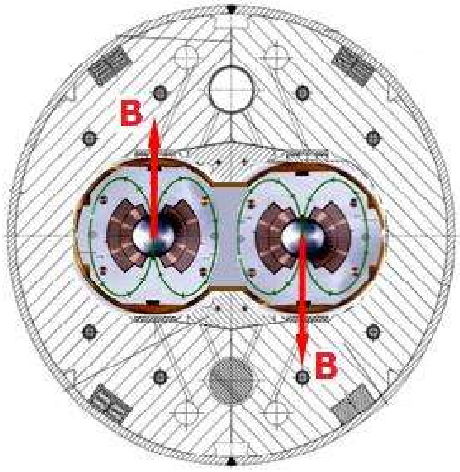
Technical challenges for particle colliders

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

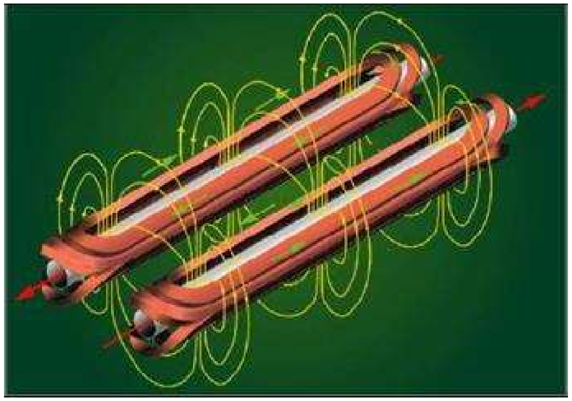
1. The particles have same mass but opposite sign and circulate in the same vacuum chamber and magnetic field (ex.: electron-positron and proton-antiproton colliders).
2. The particles are the same and they circulate in separate vacuum chambers and opposite magnetic fields (Ex.: the LHC).

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

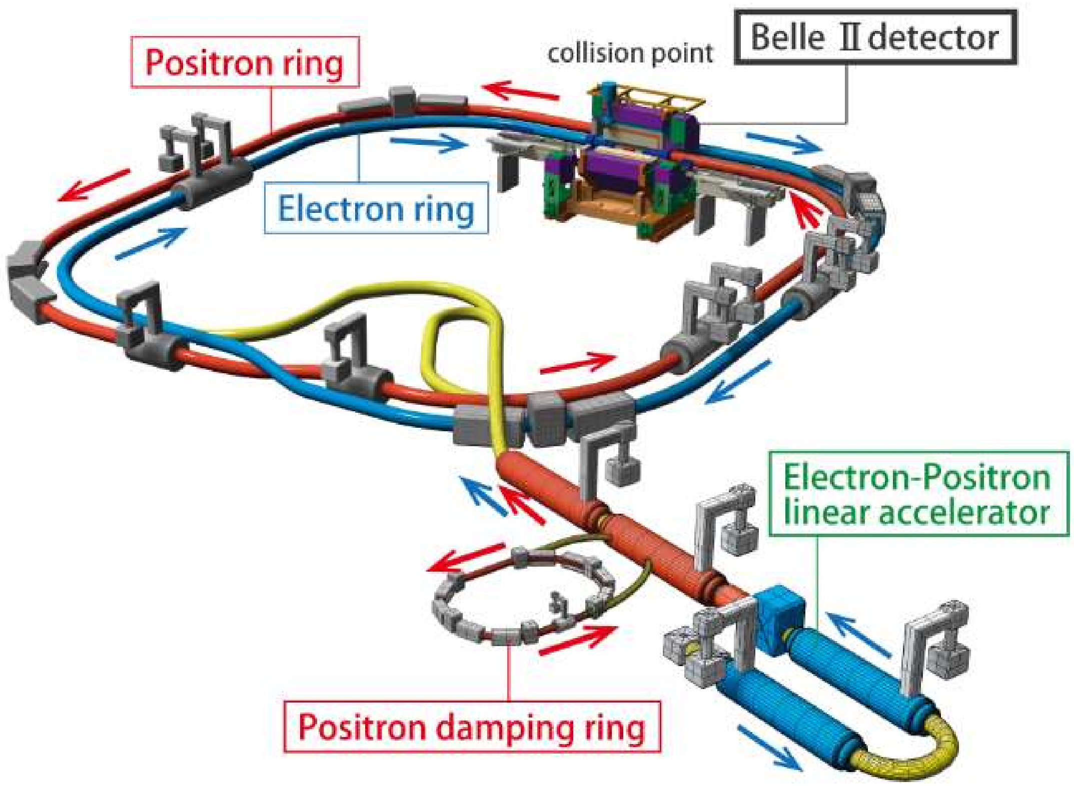
Problem with 2) is the need to use twin-bore dipole magnets or separate magnets



2-in-1 magnet configuration of LHC

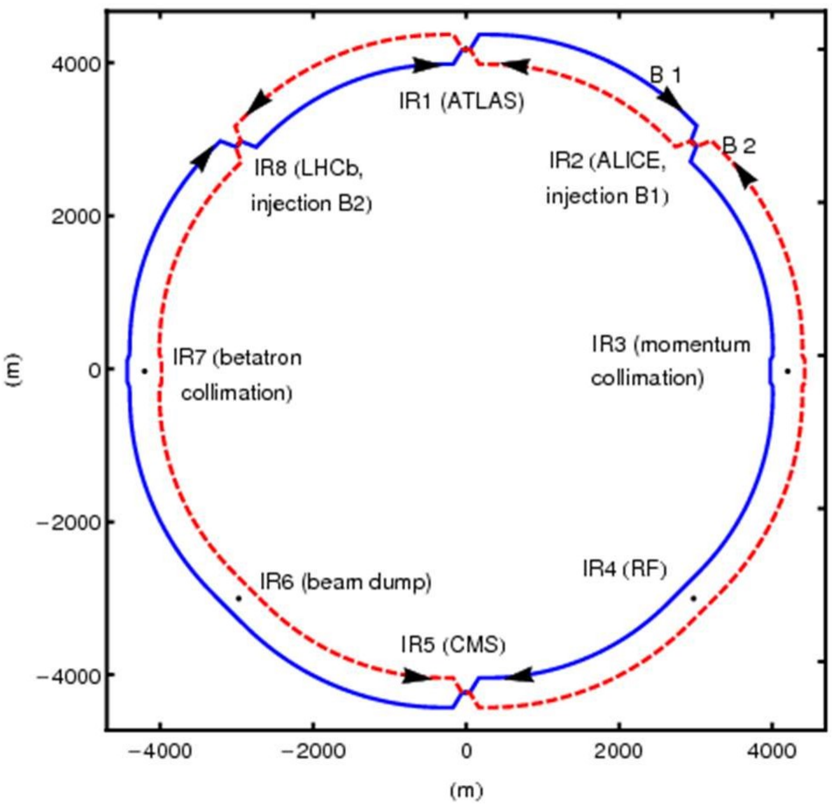


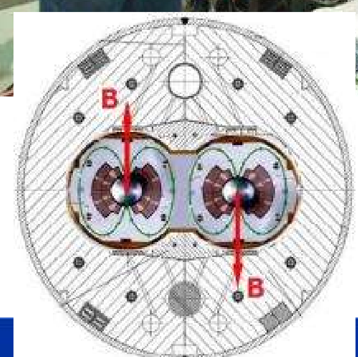
Electron – positron colliders



The KEK-B collider (Japan)

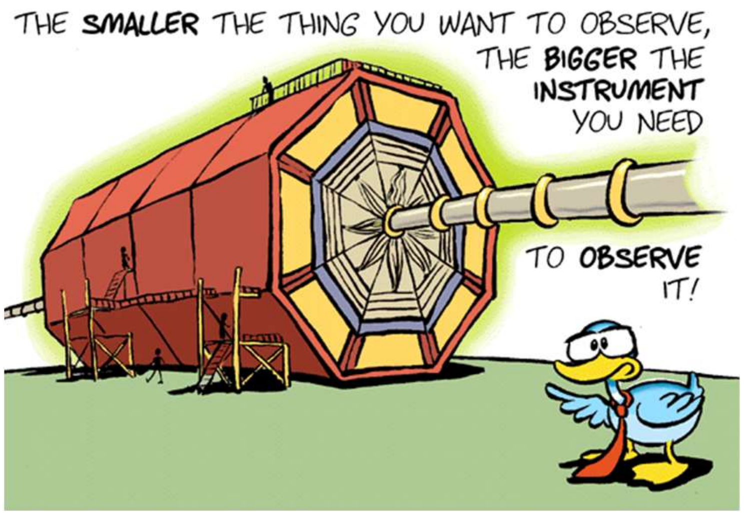
The Large Hadron Collider



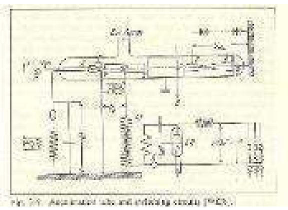


The 1232 LHC magnets contain two pipes, one for each of the counterrotating beams.

Challenges for particle accelerator science in the XXIst century



Innovation in the particle accelerator field



Widerõe linac

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

Cyclotron: cyclic acceleration with magnets (Lawrence)

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

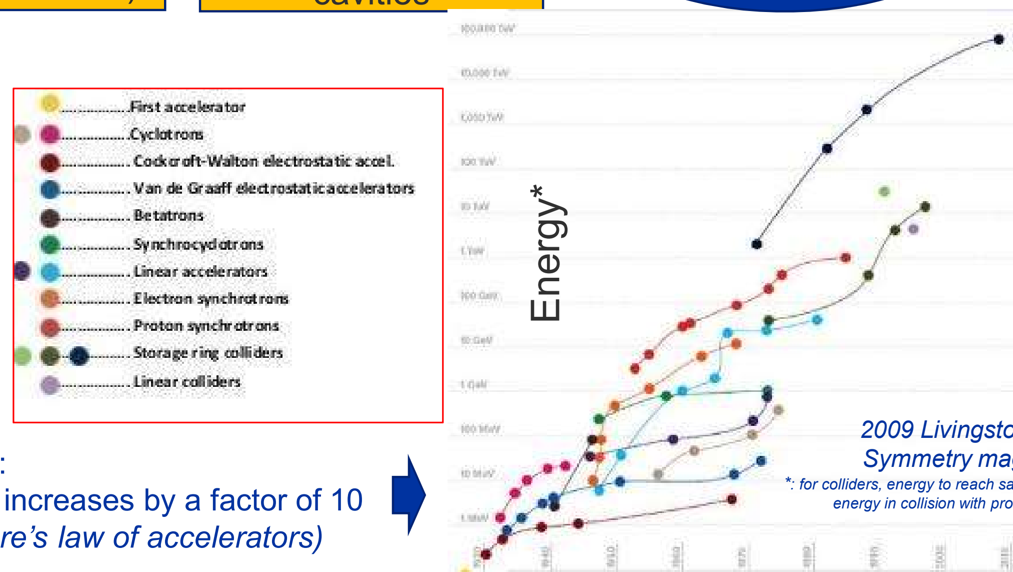
Strong focusing (Courant, Livingston, Snyder, Christofilos)

Superconducting magnets and acc. cavities

2008: the Large Hadron Collider

XXI century ?

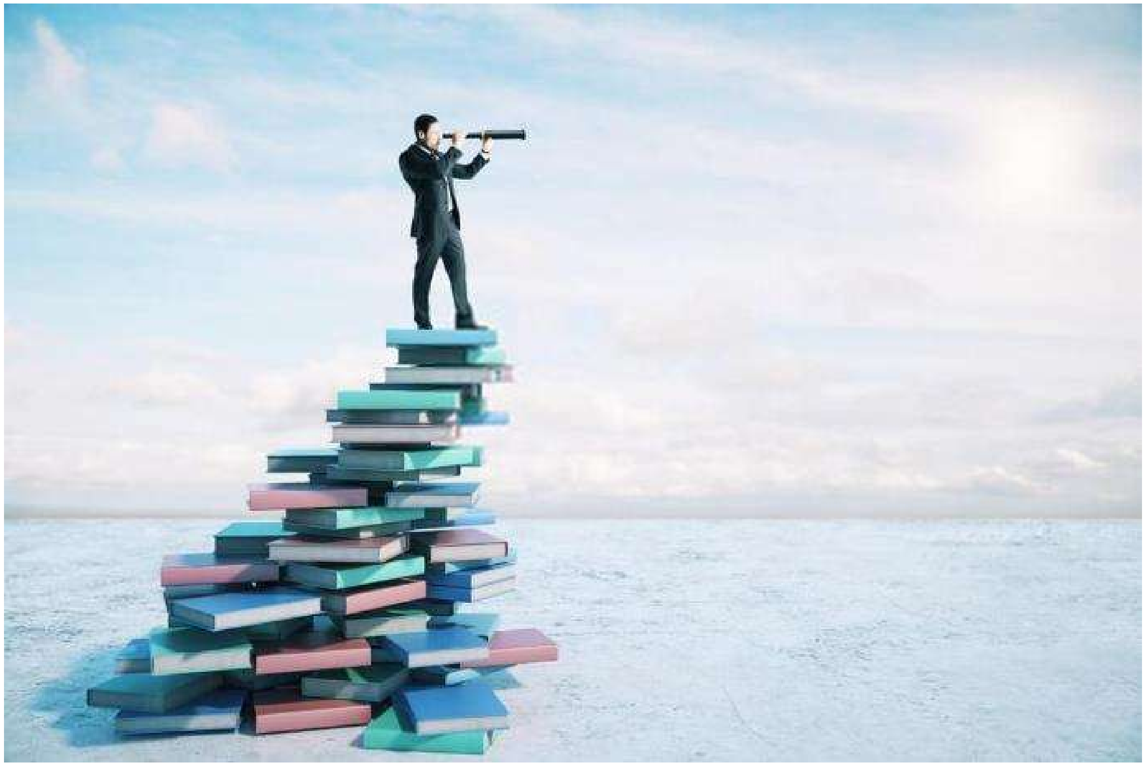
Succession of **enabling technologies** (technology leaps)



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

2009 Livingston plot, Symmetry magazine

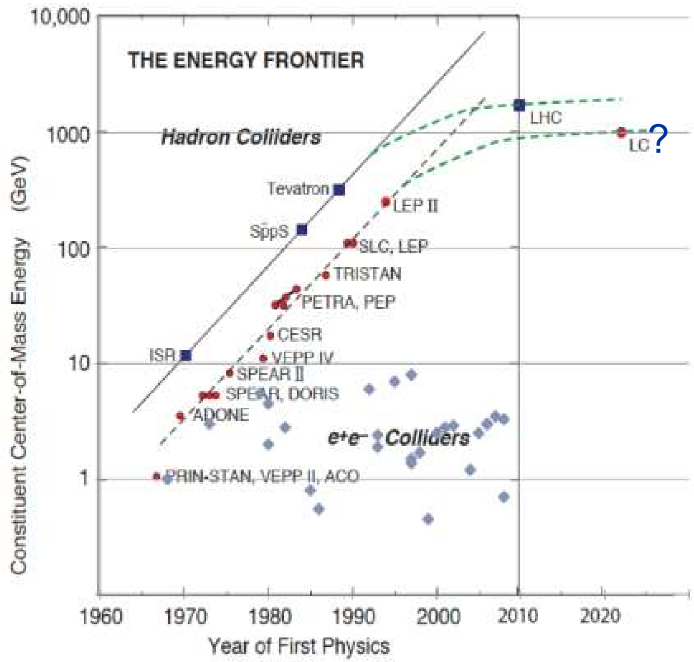
**: for colliders, energy to reach same c.o.m. energy in collision with proton at rest*



What next?

Particle Accelerators today

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!

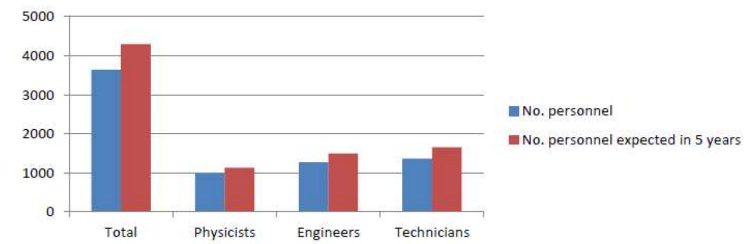


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

TIARA Need for Accelerator Scientists report, 2013: 3'700 people engaged in accelerator science in Europe, growing to more than **5'000** today.

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

Today's 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.

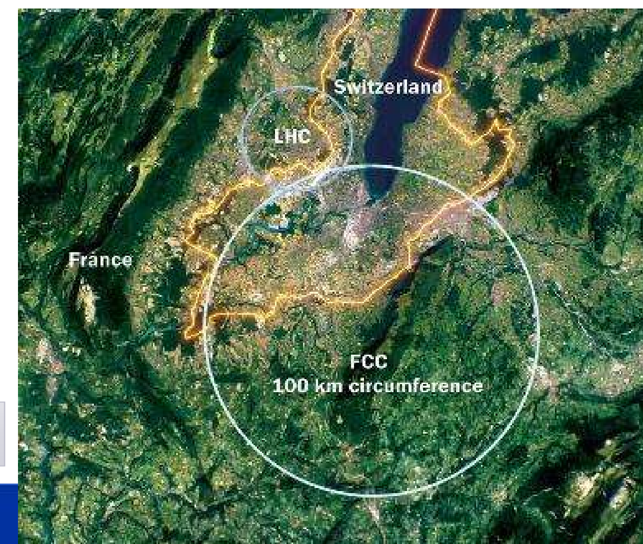
At the same time, we are working to bring accelerator technology outside of our traditional laboratories, to be used for applied science (materials, biology, etc.), medicine and industry.

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

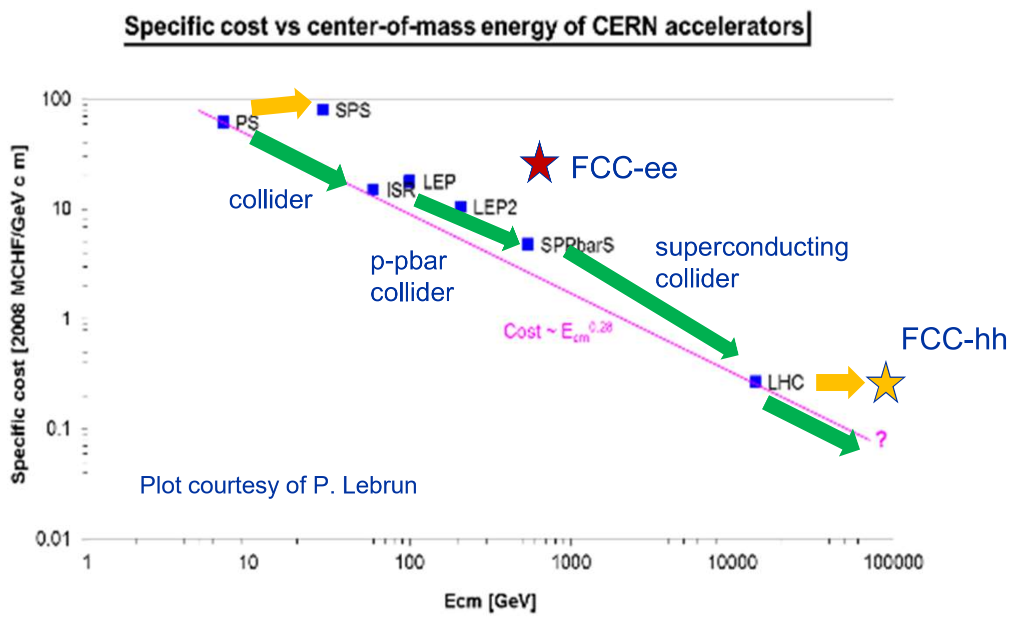
Developing their technology requires new ideas to be developed in a larger environment than basic science

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

From the LHC (27 km) to the Future Circular Collider (80 km)



Frontier accelerators – economic sustainability



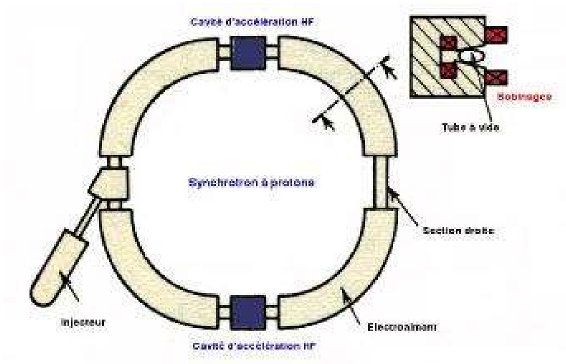
Moving along this line was made possible by new technologies (colliders – antiproton production and storage – superconductivity)

scaling of present technology

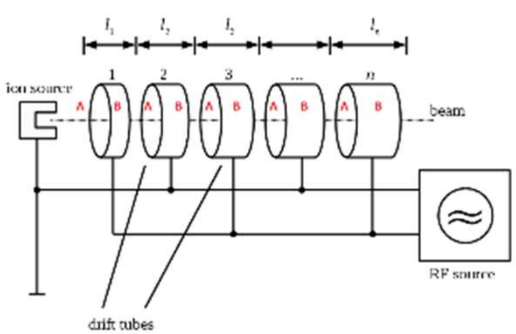
reduction in cost with new technologies?

Innovative technologies can allow reducing the impact and the cost of future large accelerator facilities.

Two directions to make smaller accelerators

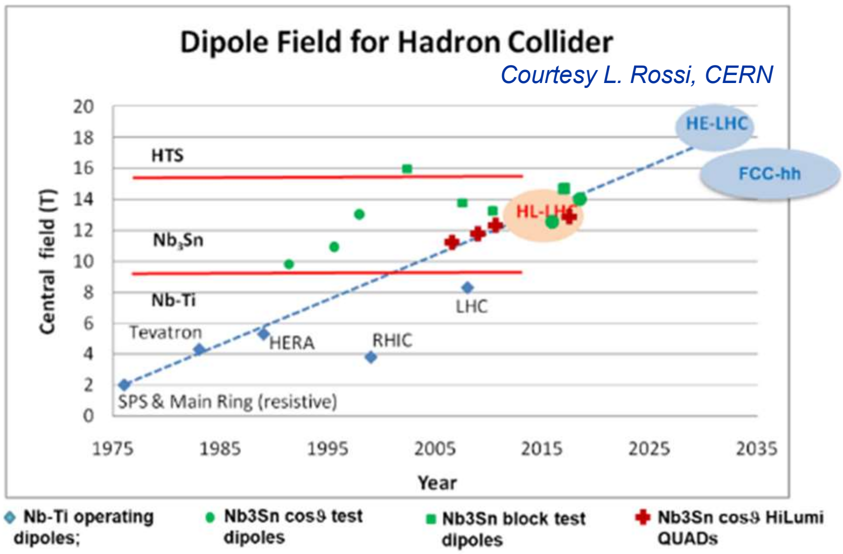


Synchrotrons: $p/q = B\rho$
Need to maximise ***magnetic field***
Superconductivity is mandatory, the limitations is the critical current density Jc for SC magnets



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



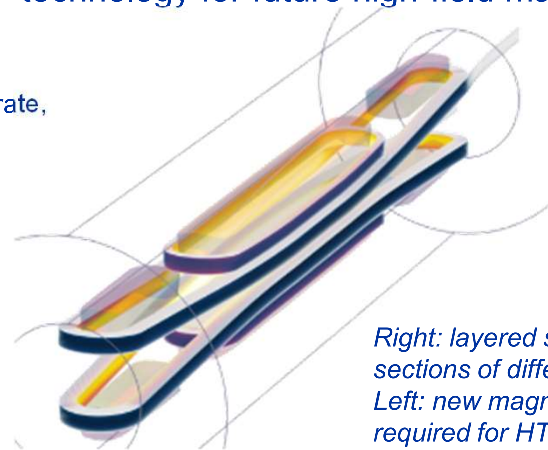
Three technologies under consideration

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.

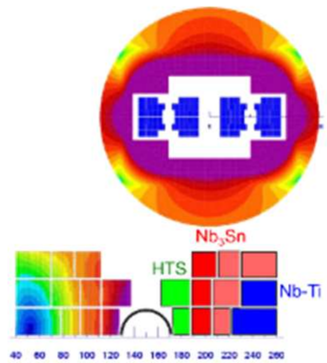
3. **HTS** (High-Temperature Superconductor) technology still in the experimental phase (Production quantities, homogeneity and cost need to evolve!) but can be an enabling technology for future high-field magnets.

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



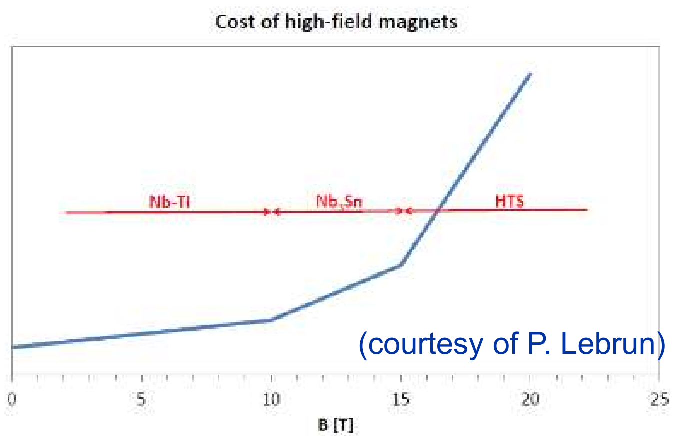
Right: layered structures with sections of different conductors
Left: new magnet designs are required for HTS

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

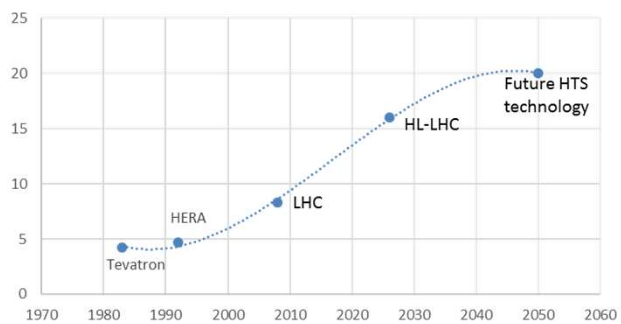


Cost optimized, graded winding

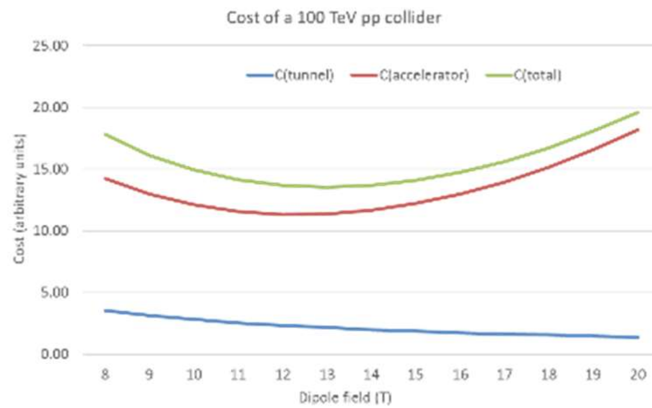
HTS magnets – reducing cost is the main challenge



(courtesy of P. Lebrun)



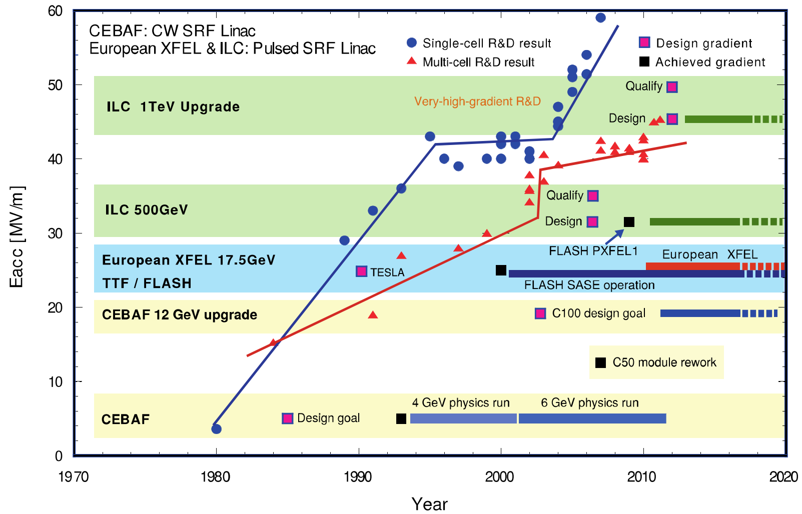
HTS allows reducing the size of the accelerator but not (yet) the cost.
HTS is presently about 5 times the cost of Nb3Sn, but other communities (e.g. fusion, medical MRI) could contribute to reducing the price in the next years.

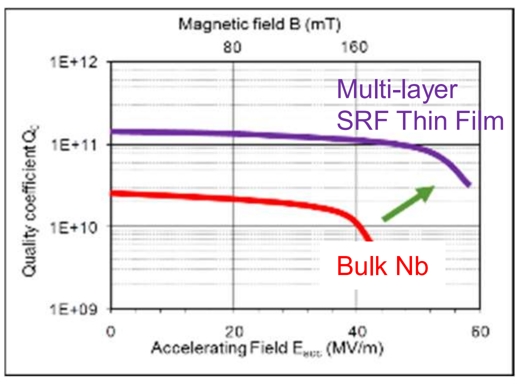


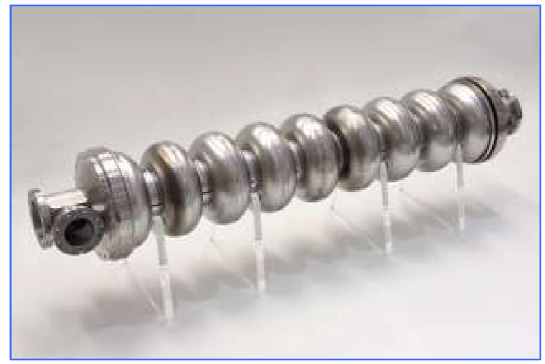
100 CHF (=100$) of YBCO HTS tape built by Bruker HTS for CERN

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

The electric field frontier – superconducting cavities





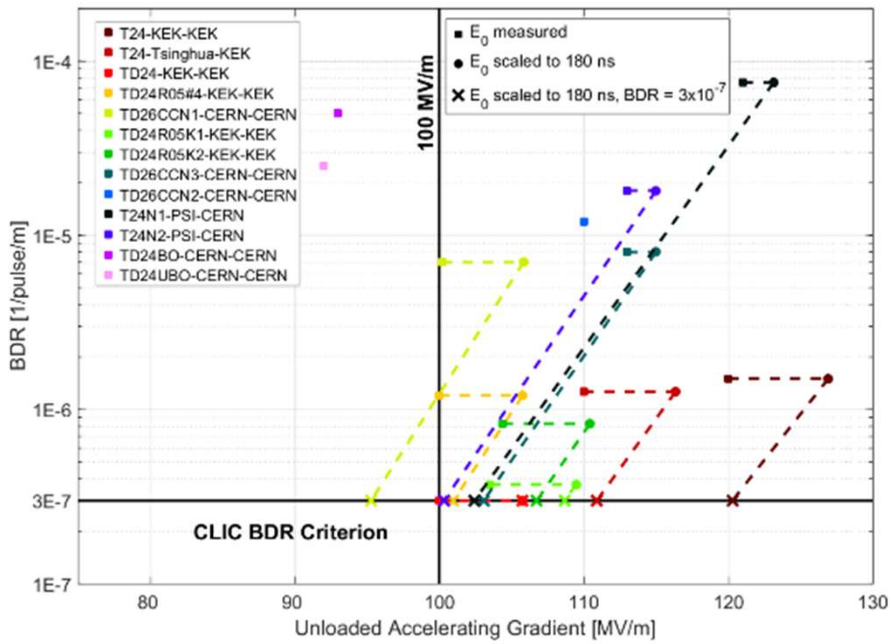


TRENDS:

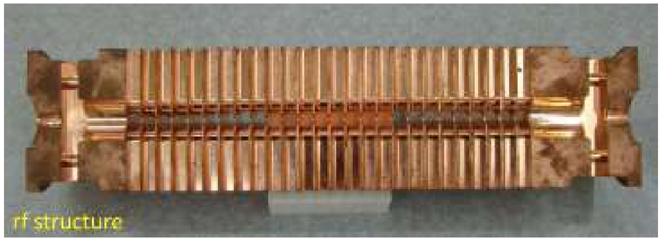
- Nitrogen infusion process (FNAL) and other doping techniques: high Q operation, gradients ~45 MV/m
- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency)
- Coating of Cu cavites with Nb by HiPIMS (High Power Impulse Magnetron Sputtering,

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

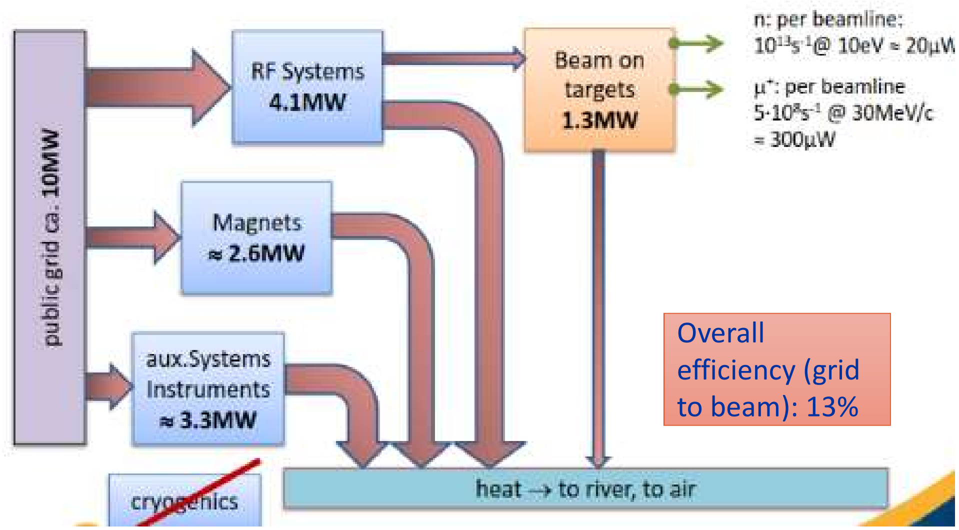
Future large projects require huge amounts of electrical power. Example: the ILC needs about 1/3 of a Fukushima-type nuclear reactor.
Going green? to supply CLIC500 or ILC would be needed 200 large windmills (80m diameter, 2.5 MW, 50% efficiency) covering a 100 km distance.

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?

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 (beam time structure) 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.



Example: power flow in the PSI cyclotron facility

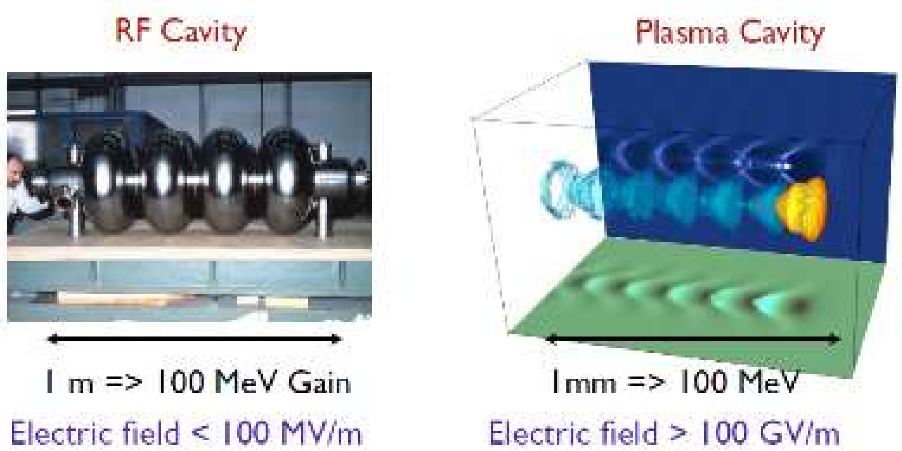
New acceleration techniques using lasers and plasmas

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 → 52 GV/m gradient



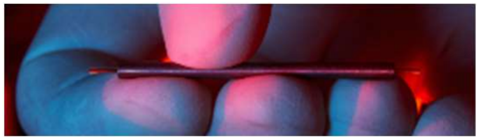
V. Malka et al., Science **298**, 1596 (2002)

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)

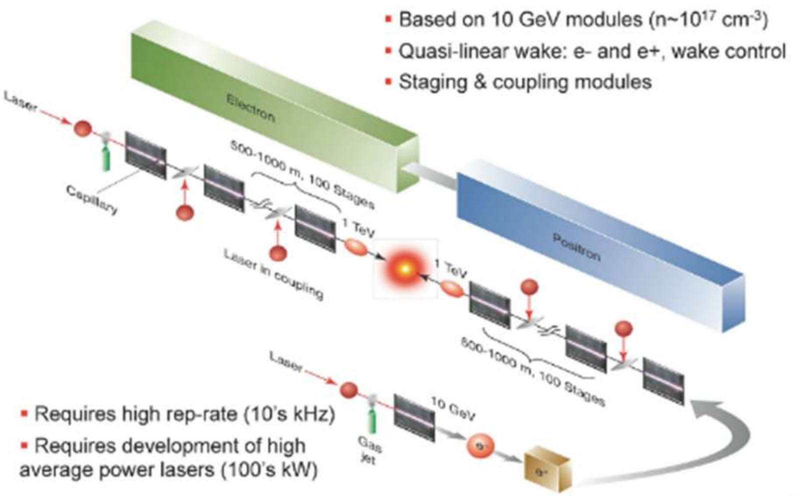


The «accelerator on a chip»

(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.

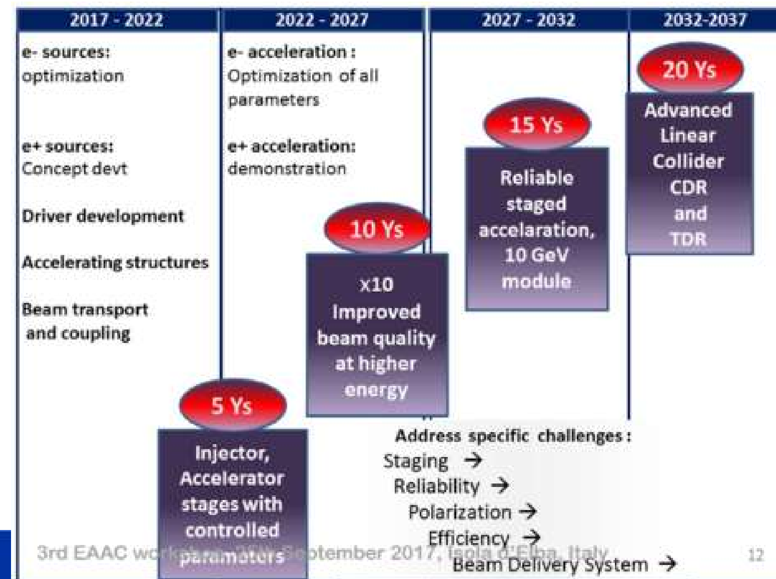
Towards a plasma-based linear collider?



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

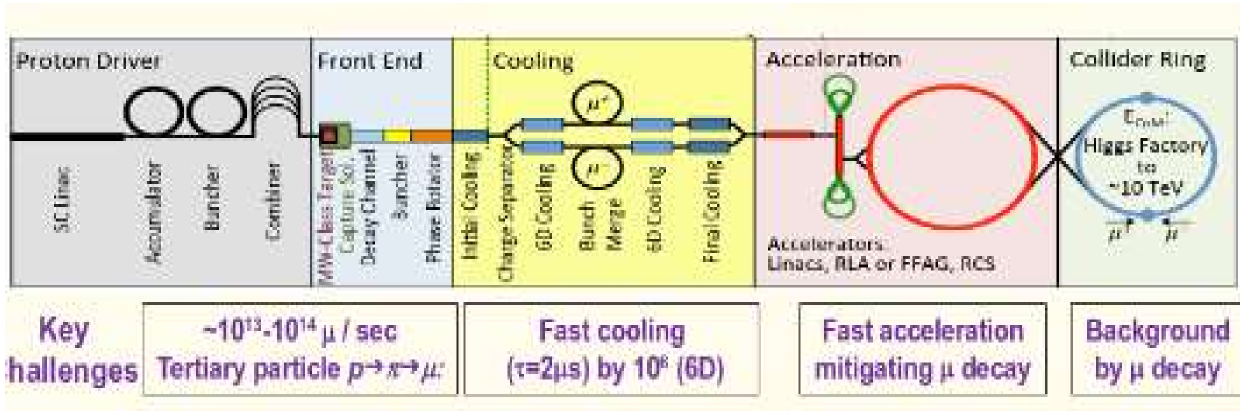
Main challenges

- 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



- 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

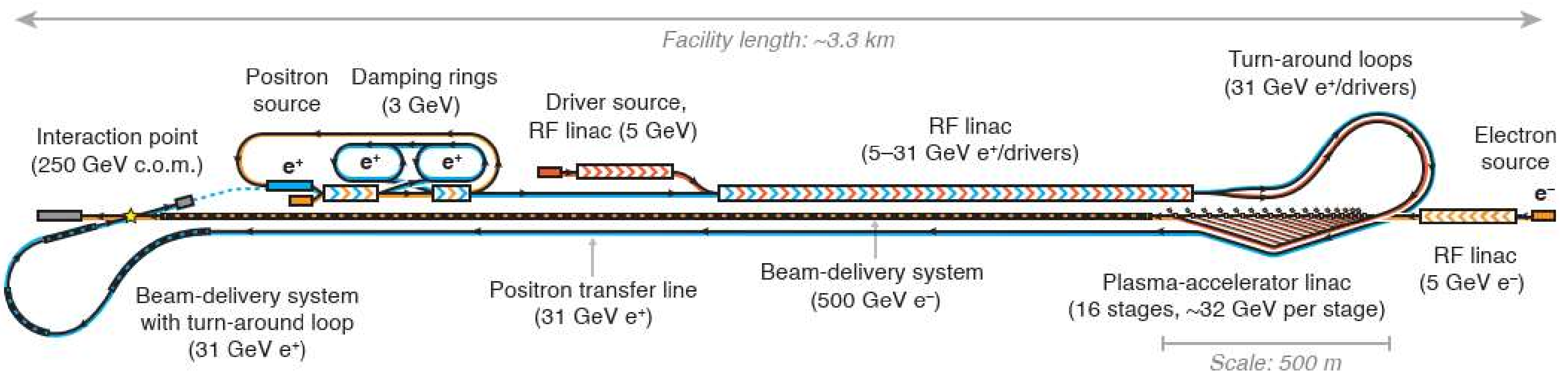
Colliding muons:
Muons are leptons, similar to electrons but heavier (207 times), produced by pion decay or electron/positron annihilation, have a lifetime of only 2.2 μs.

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

Many critical technical challenges requiring R&D !

New concepts for future colliders: the HALHF concept

HALHF: Hybrid Asymmetric Linear Higgs Factory

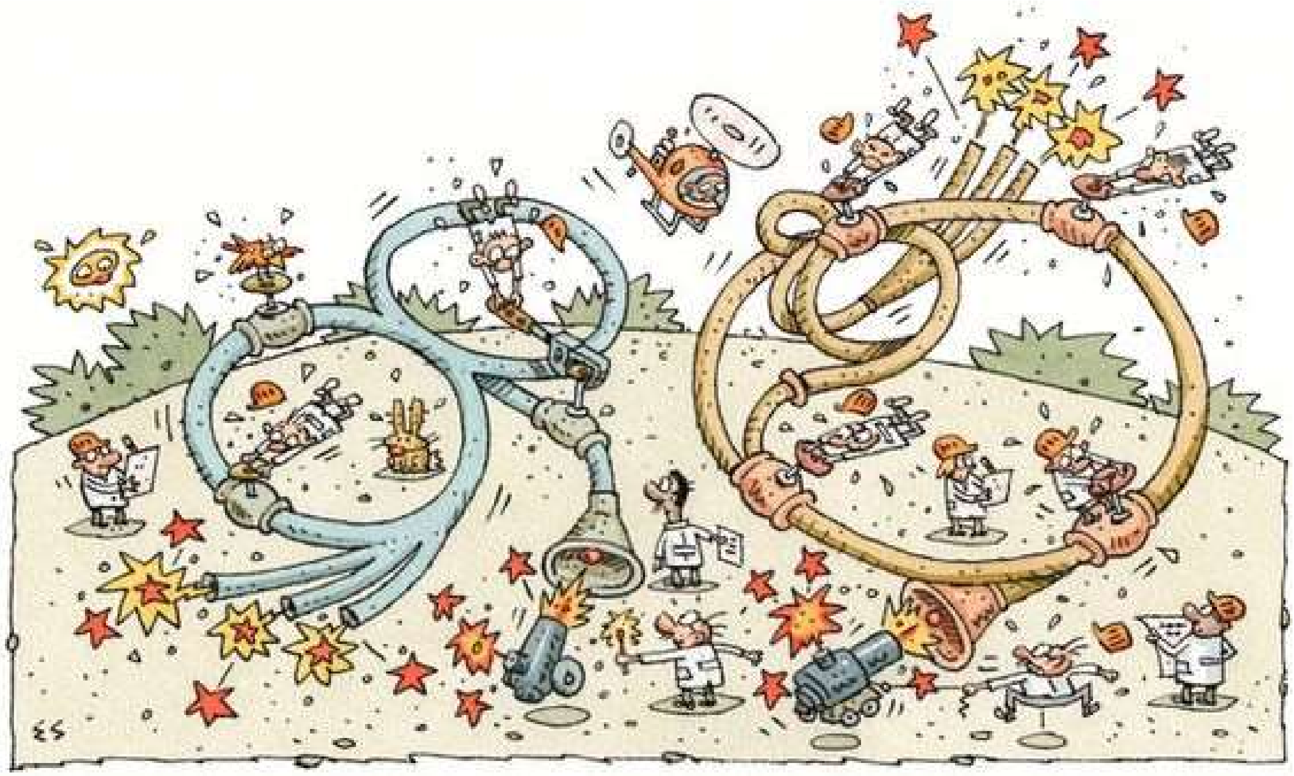


Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

>Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**

- Accelerate electrons in plasma and positrons using RF
- use electron bunches to drive the plasma wakefields
- Asymmetric linac energies for Higgs energy: electrons 500 GeV, positrons 31 GeV.
- Asymmetric charge to increase power efficiency.

Thank you for your attention !



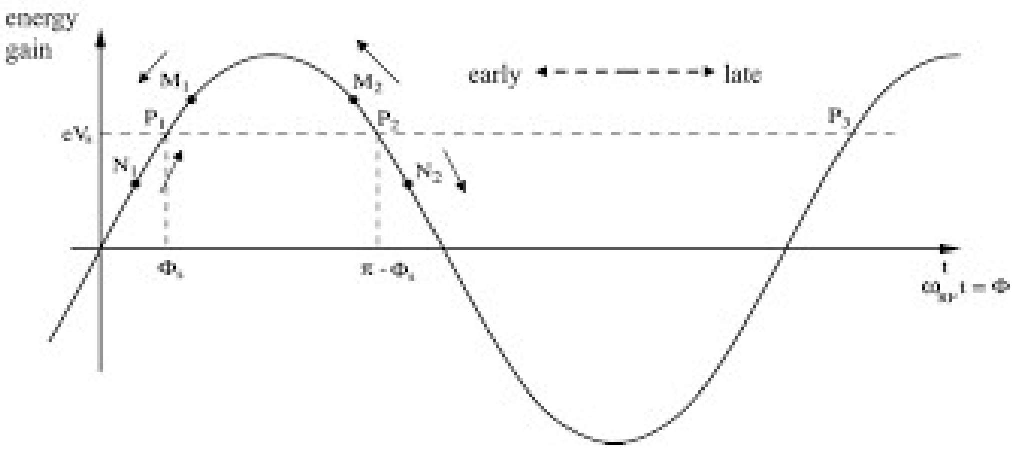
END OF
LECTURE 1

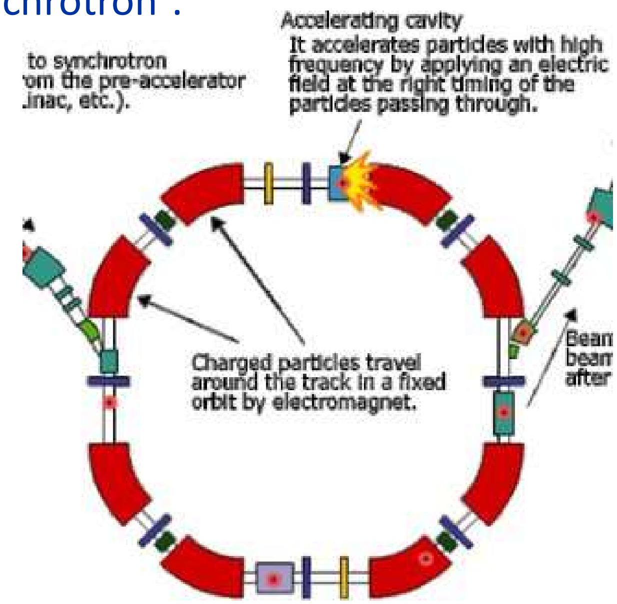
Elwood Smith, NYT

Phase stability

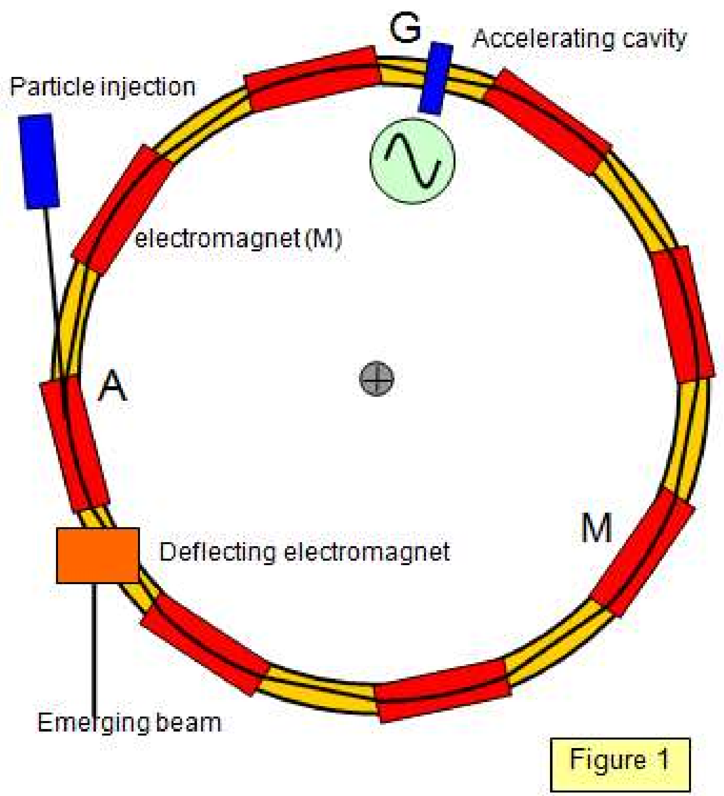
One of the main problems in the synchrotron was to keep the beam "bunched" enough to allow its acceleration during the short accelerating periods of the RF cavity.

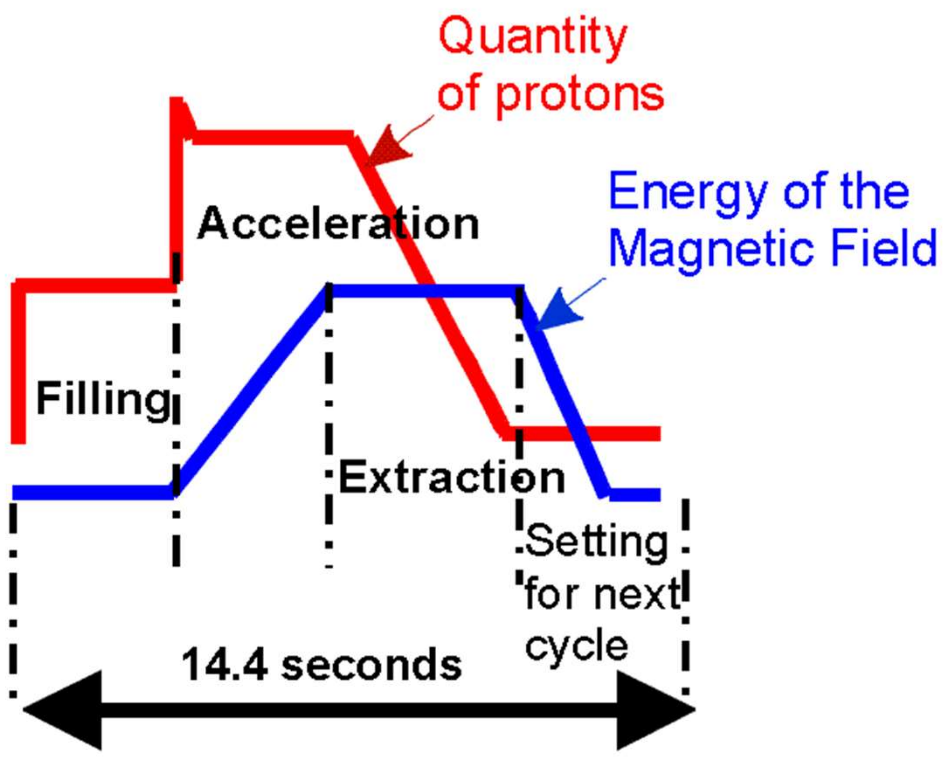
A solution to this problem came from the parallel invention of phase stability by V. Veksler (USSR, 1944) and E. McMillan (US, 1945) – McMillan is the first to use the term "synchrotron".





Magnetic cycle



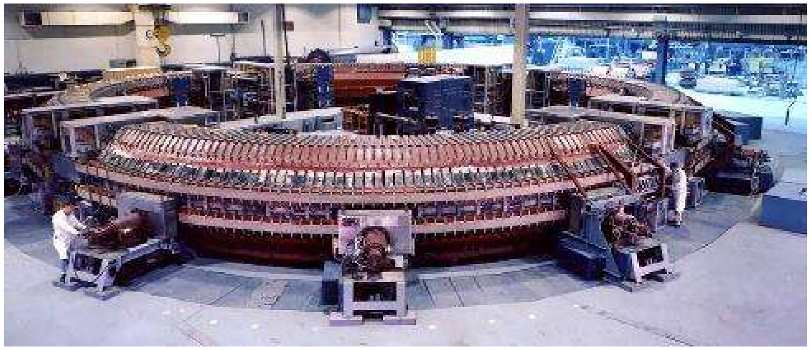


Example of a SPS Magnetic cycle

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

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

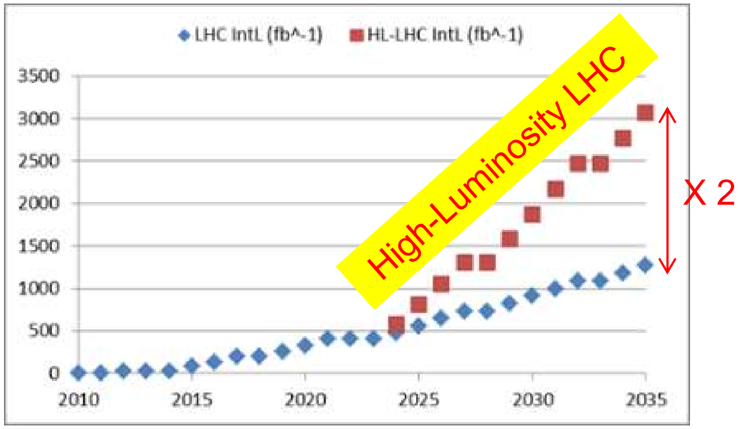
Number of bunches

Geometrical Correction factors

Beam dimensions

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

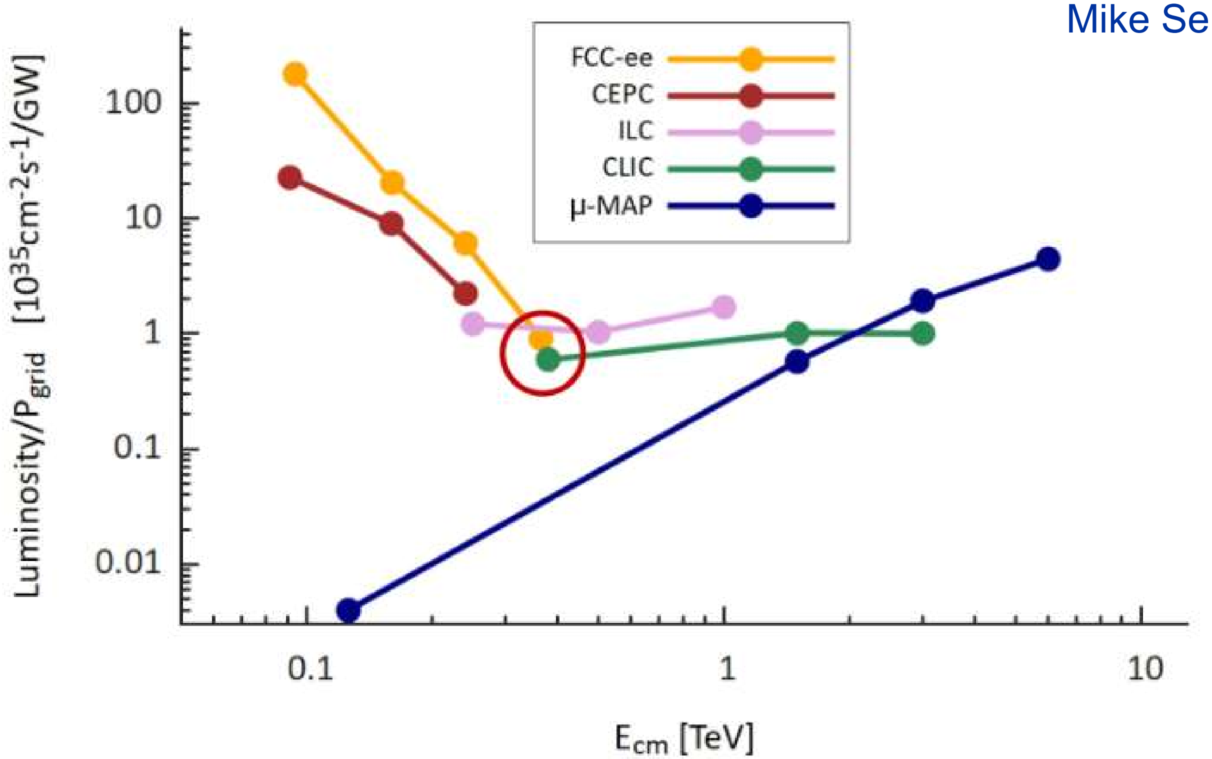
- Parameters to optimise:
  - Number of particles per bunch
  - Beam dimensions
  - Geometrical correction factors



Efficiency of proposed high-energy lepton accelerators

Mike Seidel, IPAC 22

energy specific
luminosity production:



Superconductivity and particle accelerators

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

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

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