Maurizio Vretenar CERN

LECTURES 1 & 2

RTU April 2022

An Introduction to Particle Accelerators

Spiralling in the particle accelerator world

Increasing complexity

Ion sources

Beam optics

Vacuum

Magnets

Accelerator types

Applications

Targets and materials

Radio-Frequency systems

Engineering

The first week of lectures

Planning of the
Course "**Accelerator Technologies**" (HEP700)
In-person @ CERN

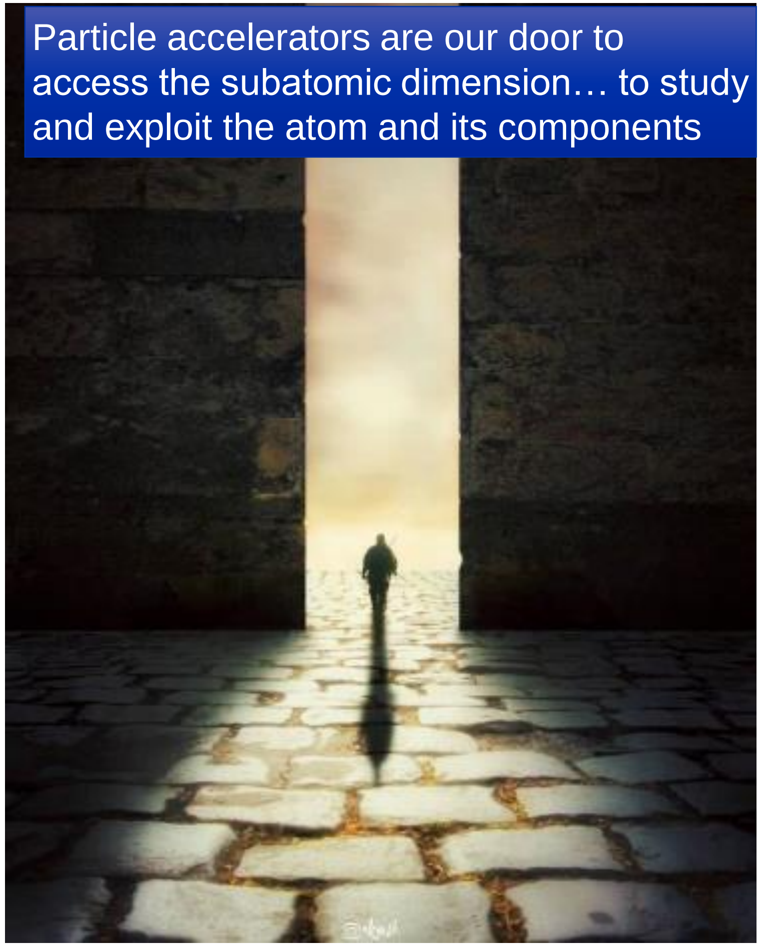
Date and time	Subject	Lecturer	Remarks
11 April 10.00-12.00 30/7-010	**Introduction to accelerators, overview of accelerator types – part 1/2** **History of accelerators – part 1/2**	Dr. Maurizio VRETENAR (CERN)	2 x 45 min + breaks and questions
11 April 14.00-16.00	Special relativity, electromagnetism, classical and quantum mechanics: What to remember for particle accelerators": Part 1/3	Dr. Elias METRAL (CERN)	2 x 45 min + breaks and questions
12 April 10.00-12.00 30/7-010	**Introduction to accelerators, overview of accelerator types – part 2/2** **History of accelerators – part 2/2**	Dr. Maurizio VRETENAR (CERN)	2 x 45 min + breaks and questions
12 April 14.00-16.00 30/7-010	Special relativity, electromagnetism, classical and quantum mechanics: What to remember for particle accelerators": Part 2/3	Dr. Elias METRAL (CERN)	2 x 45 min + breaks and questions
13 April 10.00-12.00 30/7-010	**Linear accelerators – part 1, 2** **(+ buffer time)**	Dr. Maurizio VRETENAR (CERN)	2 x 45 min + breaks and questions
13 April 14.00-16.00 30/7-010	Special relativity, electromagnetism, classical and quantum mechanics: What to remember for particle accelerators": Part 3/3	Dr. Elias METRAL (CERN)	2 x 45 min + breaks and questions
14 April 14.00-16.00 30/7-010	**Linear accelerators – part 3, 4**	Dr. Maurizio VRETENAR (CERN)	2 x 45 min + breaks and questions

Content of this module (lecture 1 and 2)

1. The accelerator as a scientific instrument, basic principles
2. History of accelerators 1 (linacs and cyclotrons)
3. Building blocks 1 – linacs
4. History of accelerators 2 – the synchrotron
5. Building blocks 2 – synchrotrons
6. History of accelerators 3 – colliders
7. Building blocks 3 – colliders and storage rings
8. The present – particle accelerators in the XXIst century

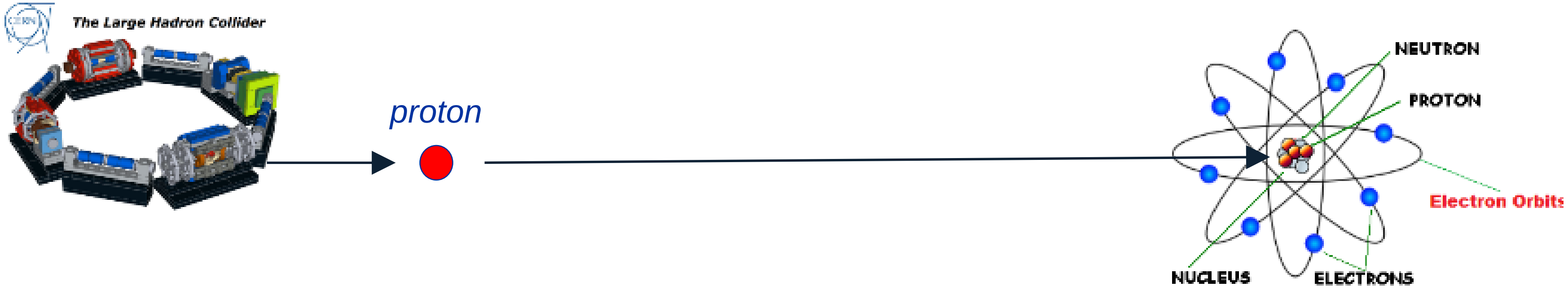
Particle Accelerators can concentrate energy

A particle accelerator is an instrument capable of concentrating large amounts of energy at subatomic dimensions



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

When we extract particles from an atom 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 some **energy to the electrons**.
2. Deliver some **energy to the nucleus** (if the particle has sufficient energy to penetrate the atom.

How large is the energy of a particle beam?

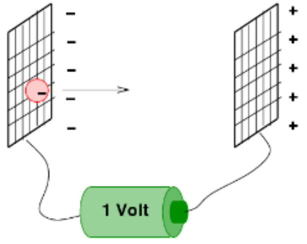
Comparing the energy of a single proton out of the CERN Large Hadron Collider, the largest particle accelerator ever built.

The energy is small, but the energy density is enormous!

	Proton out of LHC	**150g Yoghurt**	**TGV train**
	•		
Energy	1.1 10^{-6} J	5 10^{5} J	3.6 10^{8} J
Energy density	5.3 10^{38} J/m^3	3.3 10^{9} J/m^3	1.5 10^{5} J/m^3
Type of energy	Kinetic Subatomic scale	Chemical Macroscopic scale	Kinetic Macroscopic scale
Energy full LHC beam	3.6 10^{8} J		

TGV train:
400 tons, 200 m,
150 km/h

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



Where does the energy go?

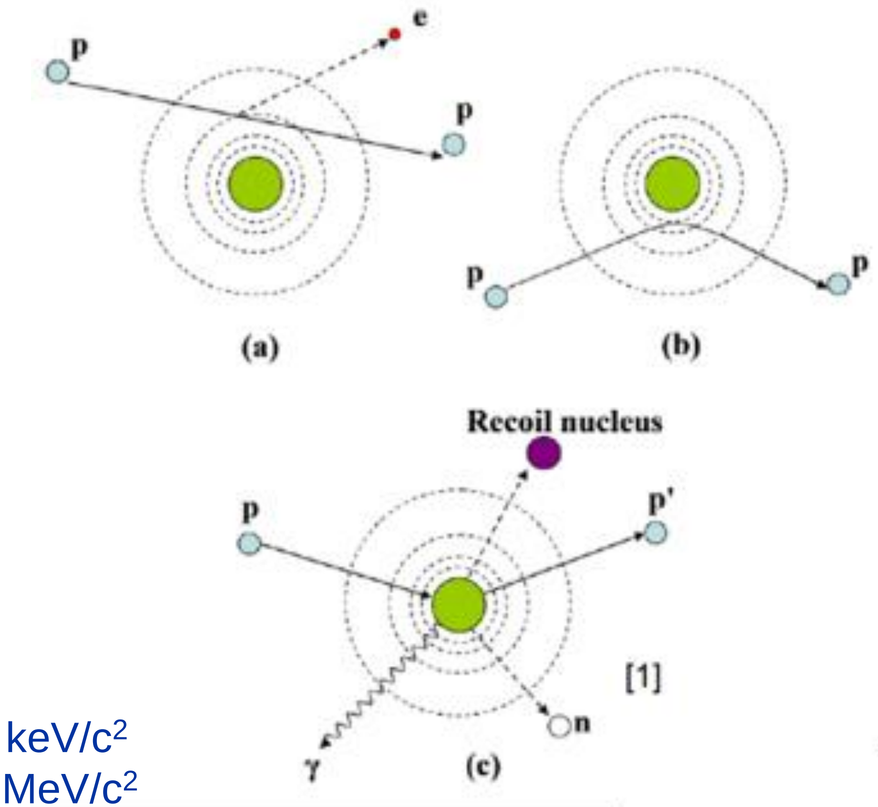
The accelerated particle can:

a) kick an electron out of the atom (ionization) or to a higher orbital (excitation) – in the latter case, the electron can come back generating an **X-ray** (photon).

b) be deflected by the nucleus and give energy to the atom - increase of temperature, **breaking of molecular bonds**.

c) be absorbed by the nucleus bringing it to an excited state that can **generate radiation** or secondary particles.

Scattering of an accelerated beam of particles



We can of course accelerate only charged particles:
Protons, Electrons, Ions (=ionised atoms)

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

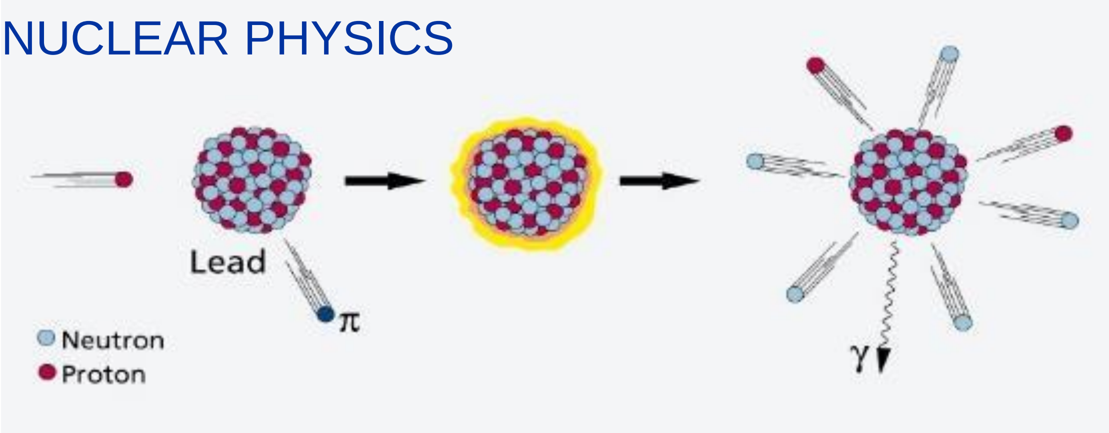
Unit charge 1 e = 1.6 × 10^{-19} Coulombs
Electron mass 1 m_e = 9.1 × 10^{-31} kg = 511 keV/c^2
Proton mass 1 m_p = 1.67 × 10^{-27} kg = 938 MeV/c^2

Accelerators can modify the nuclei and create new particles

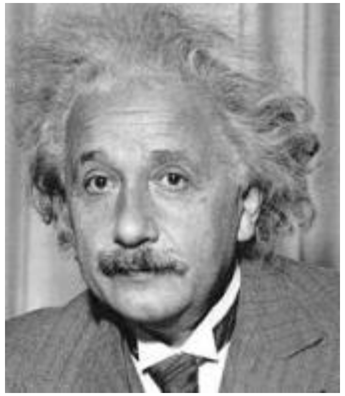
If the energy is sufficiently high, the particles in the beam transfer energy to the nucleus and its components (and are then scattered, reflected or absorbed).

The dream of the ancient alchemists coming true!

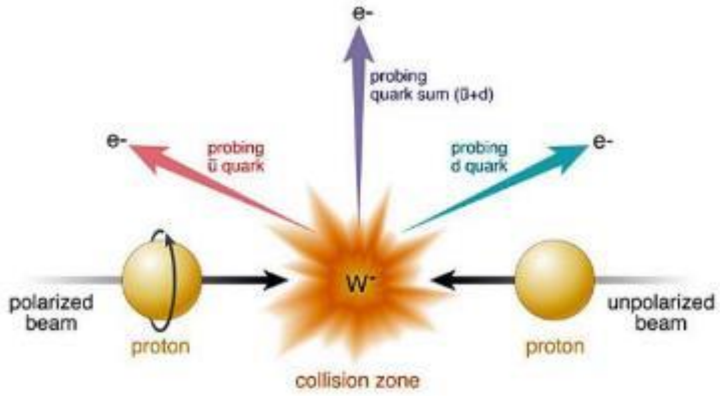
NUCLEAR PHYSICS



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

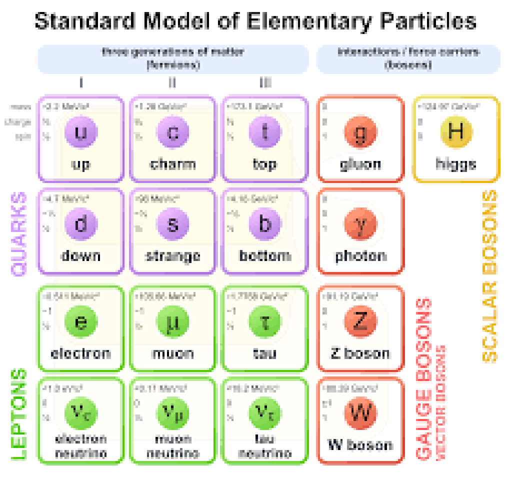


PARTICLE PHYSICS



$E = m c^2$

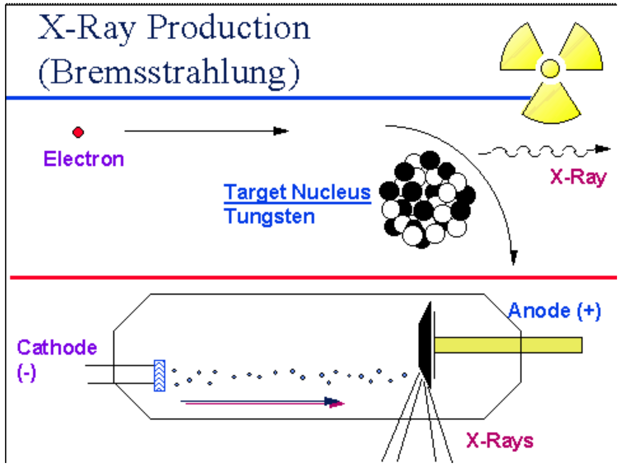
In the collisions can be generated new particles.

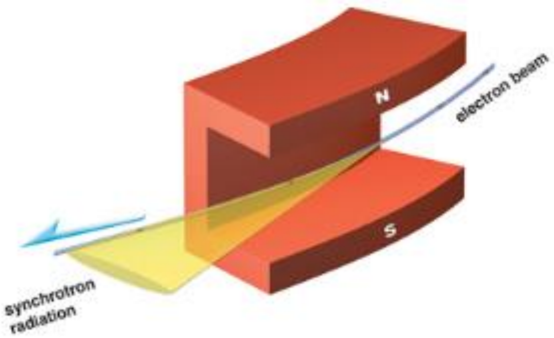


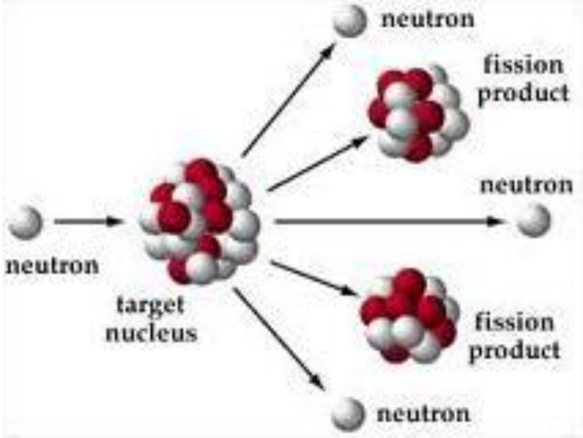
Accelerators can produce intense secondary beams

Accelerated electrons produce X-ray beams by interaction with a metal target (bremsstrahlung) or by synchrotron radiation in accelerator magnets)

Accelerated protons produce neutron beams by spallation reactions in a heavy metal target



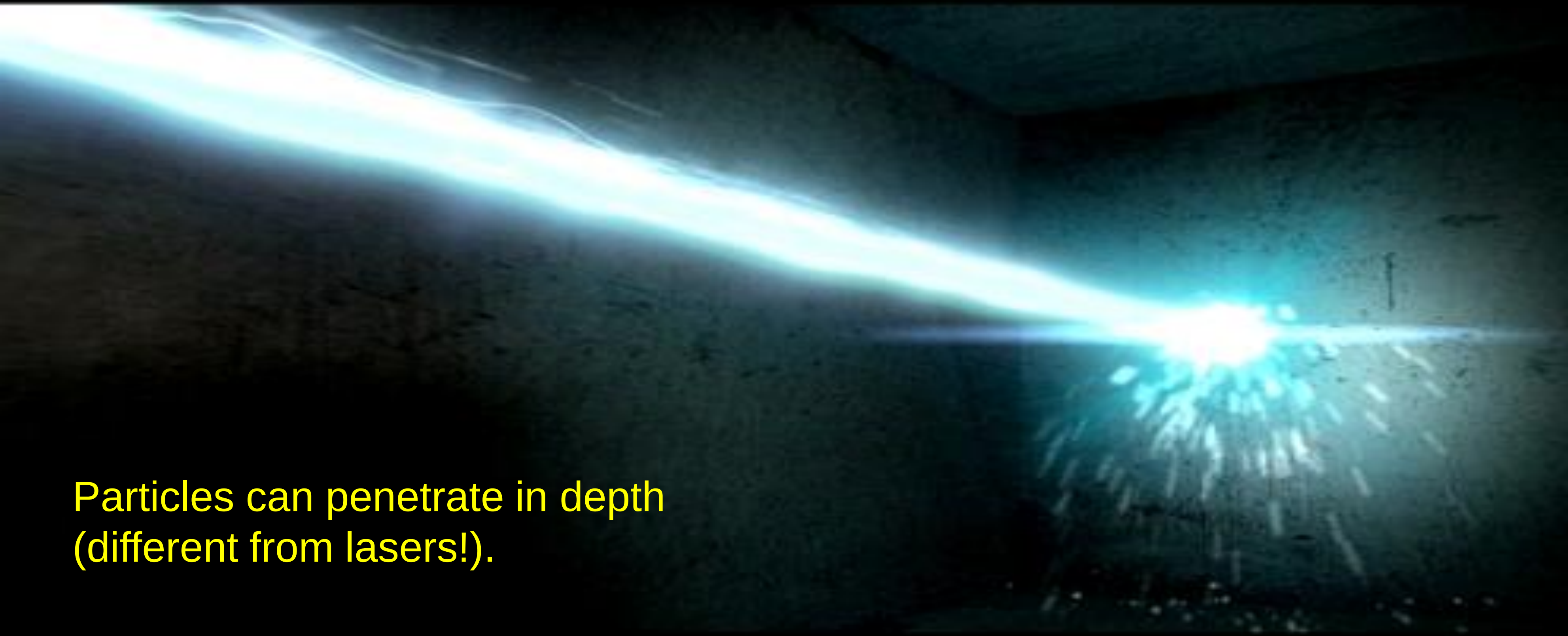




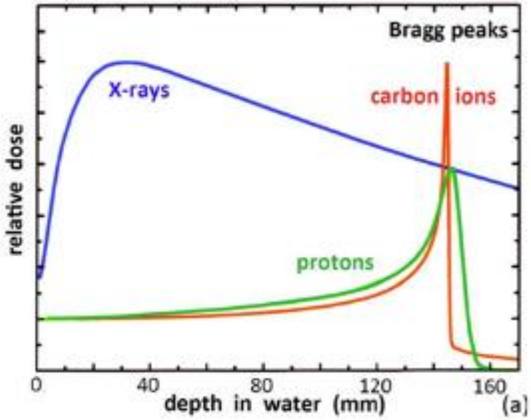
- X-rays generated by accelerators are commonly used in **medicine**
- Both X-rays and neutrons generated from accelerators are used for **advanced imaging** in many fields: life sciences, condensed matter, energy, material science, cultural heritage, life sciences, pharmaceuticals,…
- Additional applications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

Accelerators can precisely deliver energy

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



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



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

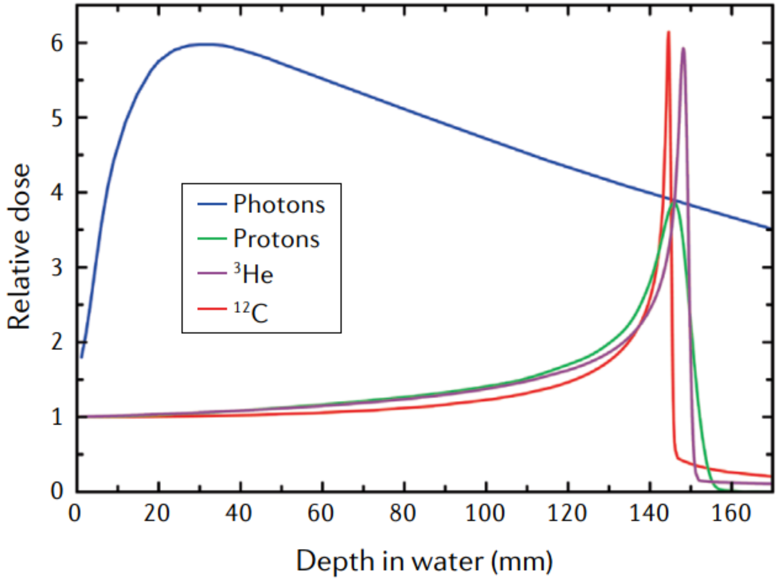
Particle beams are used in medical and industrial applications,
e.g. to cure cancer, delivering their energy at a well-defined depth inside the body (Bragg peak)

Bethe-Bloch equation

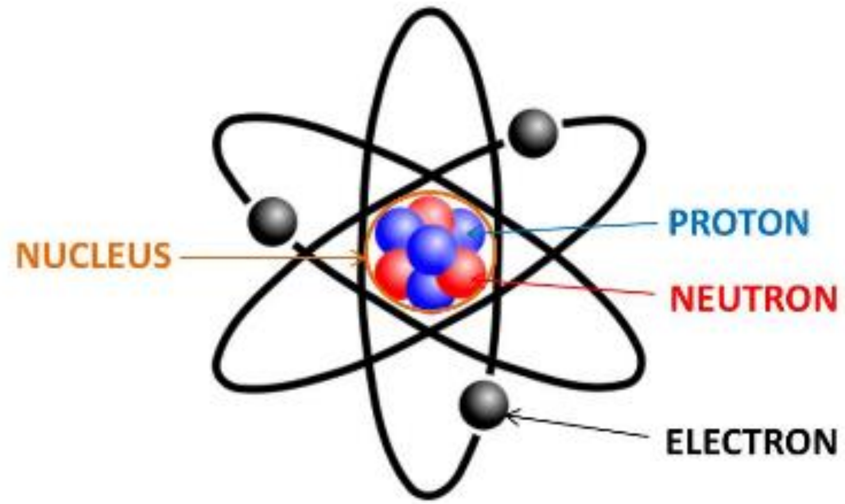
$$S = \frac{4\pi N_A e^4}{mc^2}\frac{Z_p^2}{\beta^2}\frac{Z_T}{A_T}\left[\ln\left(\frac{2mc^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{C(\beta)}{Z_T} + Z_p L_1(\beta) + Z_p^2 L_2(\beta) + L_3(\beta)\right]$$

S = stopping power (energy loss per unit mass and length)

e electronic charge
N_A Avogadro number
m mass of the electron
c speed of light
Z_p effective charge of the projectile
Β, γ relative velocity and Lorentz factor of projectile
Z_T atomic number of target material
A_T mass number of target material
I mean excitation energy
C shell correction, L_1 Barkas correction, L_2 Bloch term,
L_3 Mott and density corrections.



Combined effect on particles: the Lorentz force



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We extract the particles from the atoms and then:

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

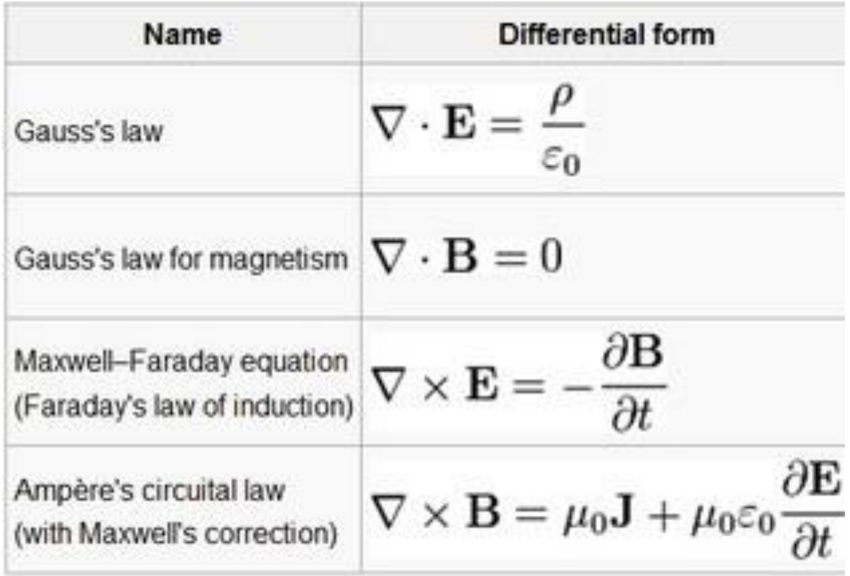
Newton-Lorentz force:

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

2nd term always perpendicular to motion => no acceleration

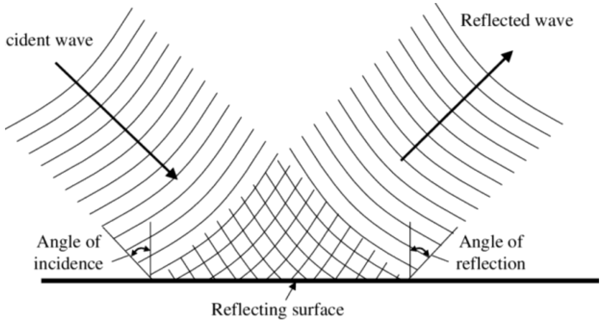
Can be accelerated only particles that have an electric charge: electrons, protons, ions (= charged nuclei)

Maxwell’s equations and the electromagnetic field



Name	Differential form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$

- ❑ Time varying electric and magnetic fields are closely related
- ❑ In particular, sinusoidal fields are described by wave equation.
- ❑ Electromagnetic «waves» propagate, and are reflected by metallic walls.



Electromagnetic Waves

Maxwell’s equations applied to empty space give the “wave equation”.

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} \qquad \frac{\partial^2 B}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B}{\partial t^2}$$

Solutions are electromagnetic sinusoidal waves

$$E = E_{\max} \cos(kx - \omega t);\, B = B_{\max} \cos(kx - \omega t)$$

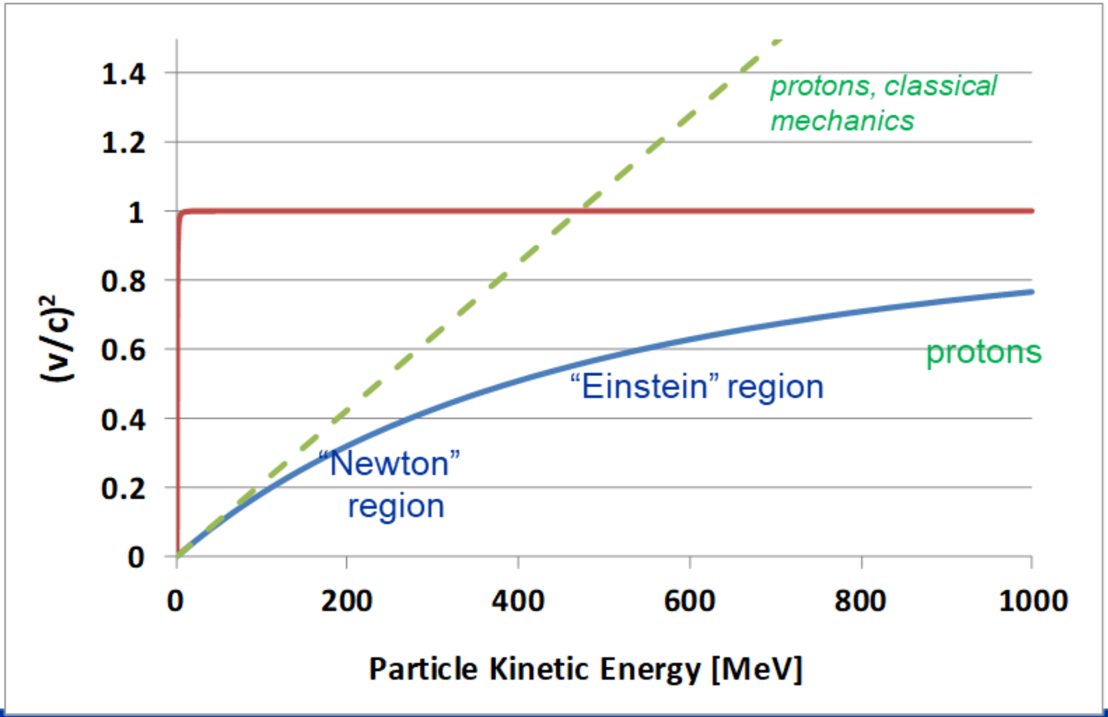
Speed of the electromagnetic wave in empty space is the speed of light

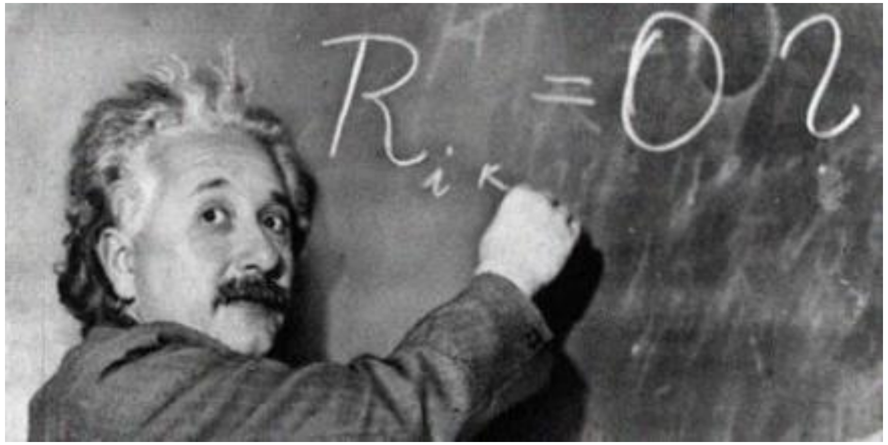
$$v = \frac{\omega}{k} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \equiv c = 2.99792 \times 10^8 \text{ m/s}$$

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

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

Useful relativistic relations

We are observers at rest, looking at particles travelling near the speed of light.
The particle properties that we observe are defined by the "Lorentz transformations"

$$\gamma \equiv \frac{1}{\sqrt{1-(v/c)^2}} \qquad \beta \equiv \frac{v}{c} = \sqrt{1-\frac{1}{\gamma^2}}$$

$$m = \gamma m_0 \qquad \vec{p} = \gamma m_0 \vec{v} = \frac{m_0 \vec{v}}{\sqrt{1-(v/c)^2}} \qquad \left(\frac{v}{c}\right)^2 = \frac{p^2}{(m_0 c)^2 + p^2}$$

$$E = mc^2 \qquad E_0 = m_0 c^2 \qquad \frac{E}{E_0} = \frac{m_0 \gamma c^2}{m_0 c^2} = \gamma$$

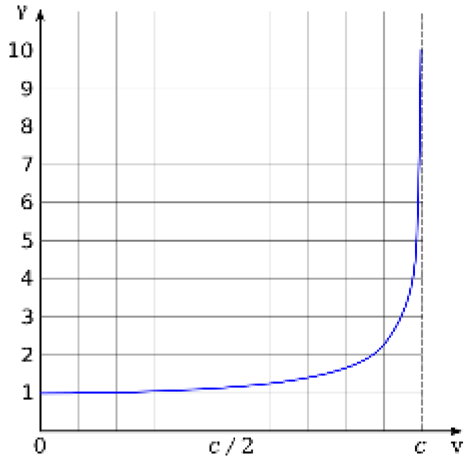
$$T = E - E_0 = m_0 \gamma c^2 - m_0 c^2 = m_0 c^2 (\gamma - 1)$$

β "relativistic velocity" is the fraction of the speed of light reached by a particle: $v = \beta c$

γ "Lorentz factor" measures the change of time and length for a moving particle. Ratio between relativistic mass and rest mass: $\gamma = m / m_0$

p (relativistic) momentum

Total energy $E = mc^2$ is the sum of rest energy E_0 and kinetic energy T : $E = E0 + T$



Lorentz factor γ as a function of velocity. Its initial value is 1 (when v = 0); and as velocity approaches the speed of light (v → c) γ increases without bound (γ → ∞).

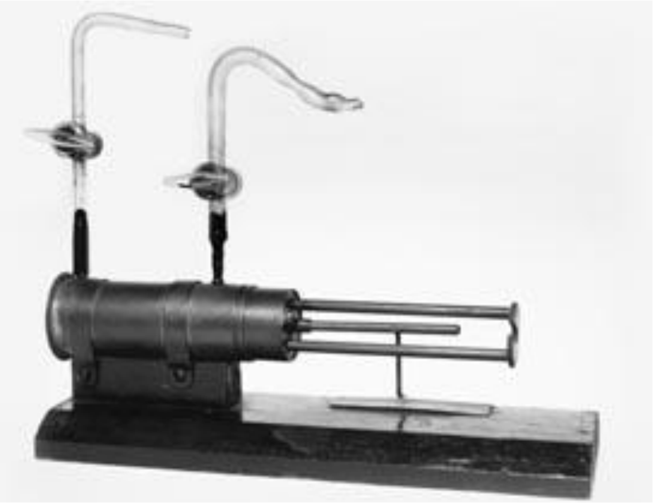
History of particle accelerators 1 – linacs and cyclotrons

From Rutherford to the Particle Accelerator

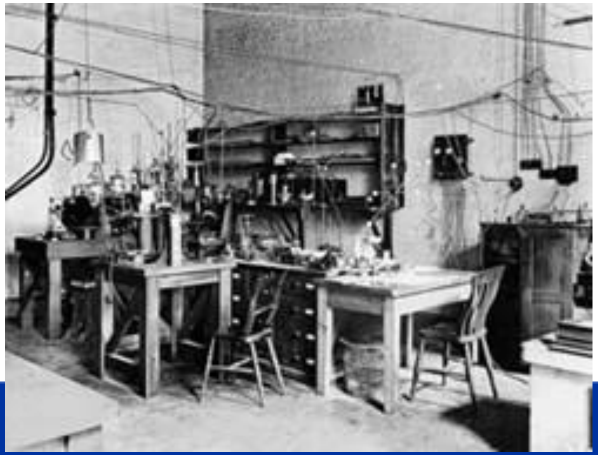
1919: Ernest Rutherford's historical experiment: some nitrogen nuclei are disintegrated by α-particles coming from radioactive decay of Ra and Th → **start of a new era for science**! But only few light atoms can be modified using particles from radioactive decays .

Men can transform the matter, the dream of the ancient alchemists!

1927: Rutherford in a famous speech at the Royal Society asks for "accelerators" capable to disintegrate heavy nuclei. Theory predicts the threshold for penetration of the nucleus at ~500 keV → from 1929, various labs start developing "**particle accelerators**" for >500 keV.



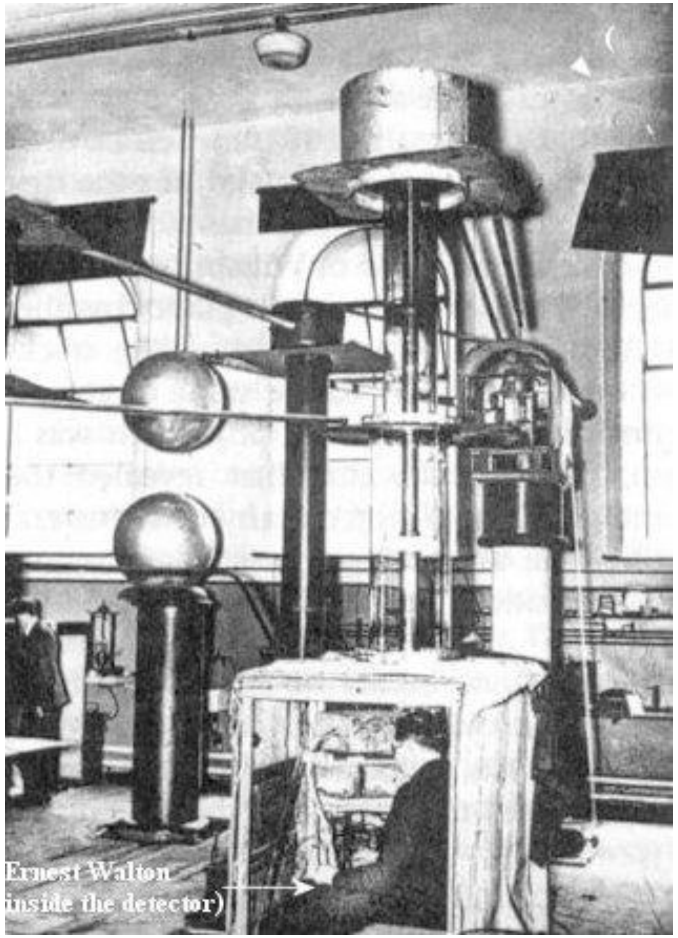
Reproduction of the Rutherford chamber: Bombardment of nitrogen atoms with alpha particles, producing oxygen and hydrogen nuclei.



Early Accelerators

1927 to 1932, development of electrostatic accelerators:

1. Cockcroft and Walton (Cavendish Lab, Cambridge) → extend to higher voltages the “voltage multiplier” used for X-ray production.
2. Van de Graaf (Princeton) → develops the belt-charged static generator.
3. Others explore pulsed techniques, capacitor discharges, transformers, etc.



And the winners of the accelerator race are… Cockcroft and Walton, who in 1932 obtain disintegration of lithium by 400 keV protons. But:

- higher energies are necessary to disintegrate heavier nuclei in quantities;
- DC technologies are limited by breakdown to few MeV.

→ A new technology is needed...

An alternative road: radio waves!

1864: Maxwell's equations.

1873, Maxwell: Theoretical basis of wave propagation.

1888, Hertz: Experimental generation/reception of e.m. waves.

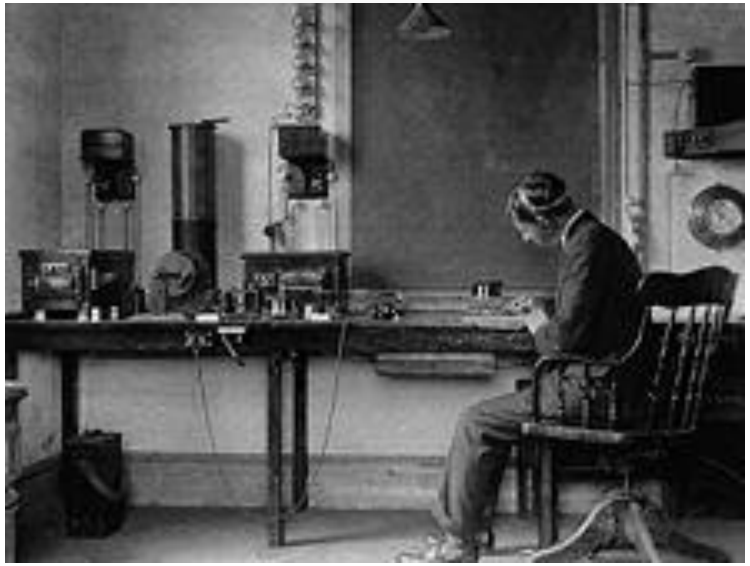
1891, N. Tesla, G. Marconi and others: wireless telegraph.

1905-14: early vacuum tubes (De Forest, triode in 1907).

1914-18: large quantities of tubes produced because of war effort, cost goes down.

1919-20: first attempts to broadcast with vacuum tubes using AM modulation, in the kHz range.

1920-25: start of regular radio broadcasting in most countries (1920: Argentina, US; 1923: Germany).



Marrying radio technology and accelerators

Who was the first to have the idea of using modern radio technology to build (linear) particle accelerators?

Remember:

1. the radio was around since 1920, and the technology became largely used in the 20's
2. since 1927 the scientific community was looking for ideas to build high-energy particle accelerators…

A 26 year old PhD student…

The first Radio-Frequency linac: Rolf Wideröe’s thesis

Rolf Wideröe: a Norwegian student of electrical engineering at Karlsruhe and Aachen.
The X-ray transformer that he had chosen for his PhD Thesis at Aachen University did not work, and he was forced to choose quickly another subject. Inspired by a 1924 paper by 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 RF 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!

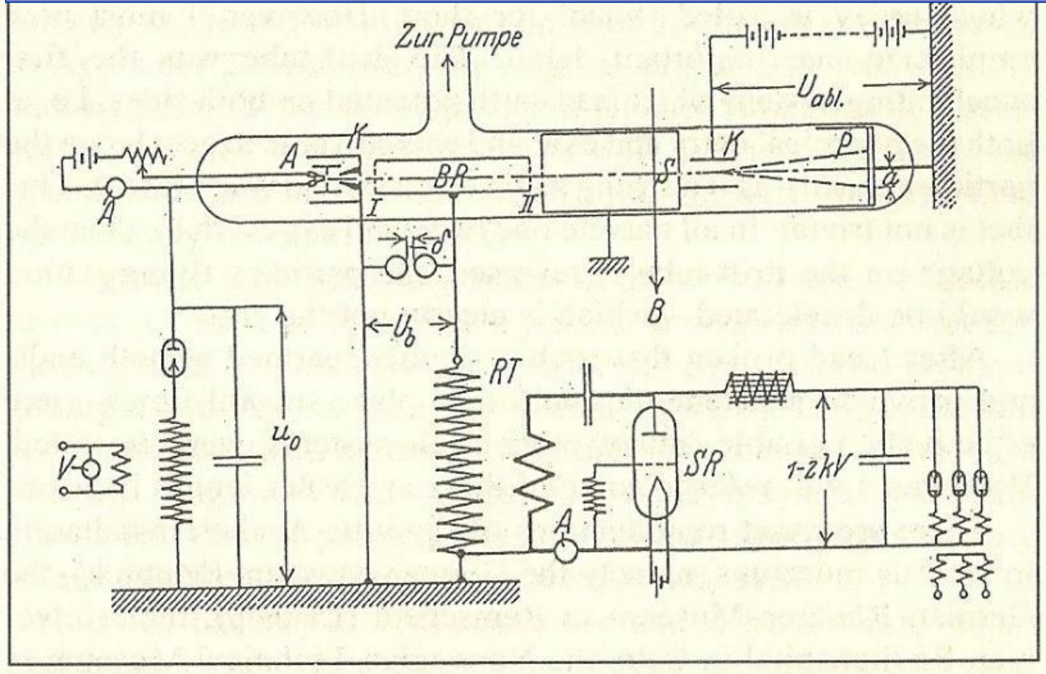
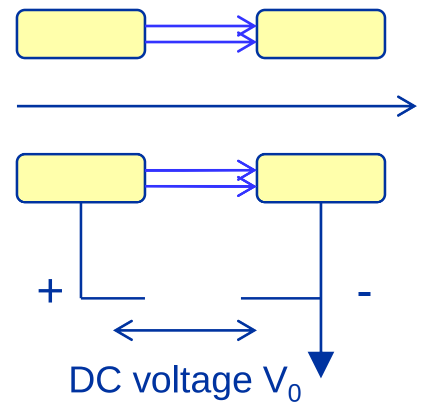
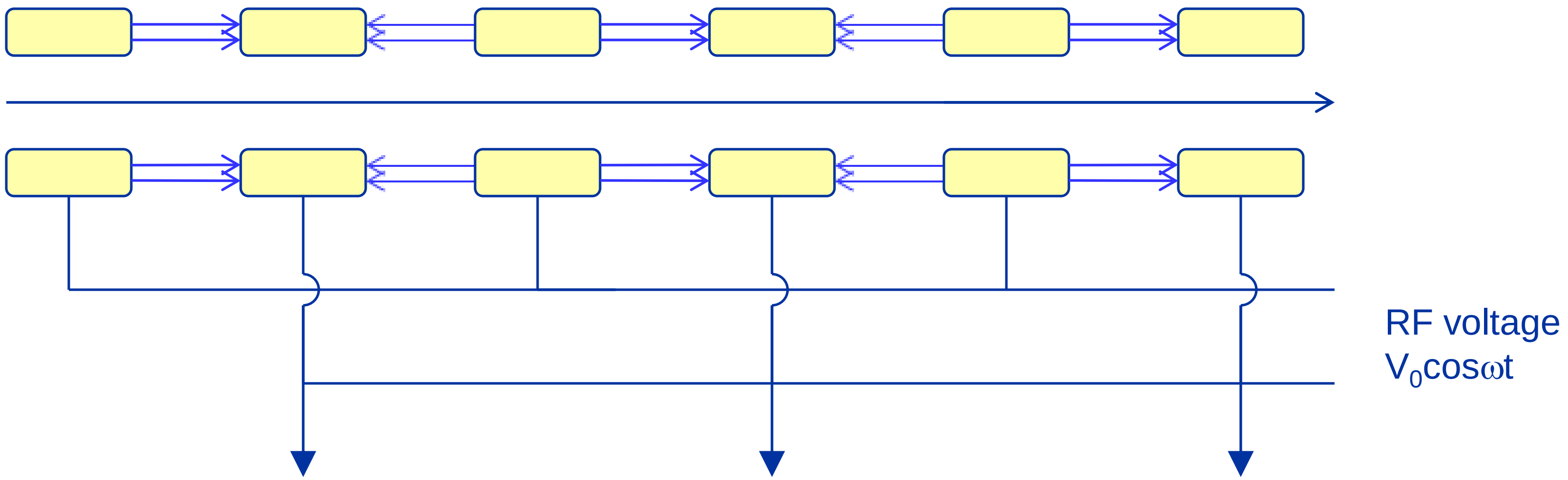


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

The invention of the linear accelerator



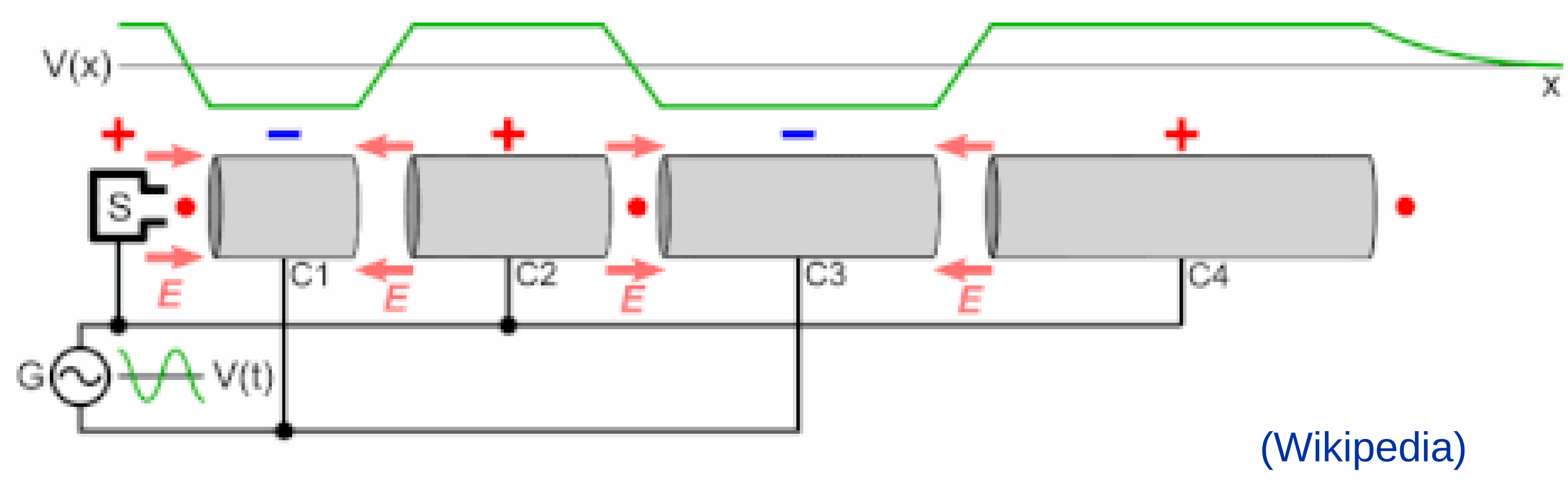
ELECTROSTATIC
acceleration
The voltage can be
applied only to one gap



RADIOFREQUENCY
acceleration
The voltage adds up
over several gaps

Higher energies in a Wideröe linac

The Wideröe structure can be used to reach higher energies, if the tubes are made longer and longer as the energy and velocity of the particle increase



(Wikipedia)

$T / 2 = d / v_{particles}$

$f_{RF} = v_p / 2d$

$\mathbf{d = v_p / 2f_{RF}}$

This is a “linear accelerator” (linac). Linacs are used as injectors to larger accelerators and as stand-alone when large beam intensities are required

After the start, a stop…

Limitation of the Wideröe device:
for protons, needs high frequencies
($d=\beta\lambda/2$, → taking d~10 cm, W=500 keV → f~50 MHz, λ~6 m)

☞ But a) higher frequency were not possible with the tubes of the time;
b) losses from a conventional circuit would have been too large!

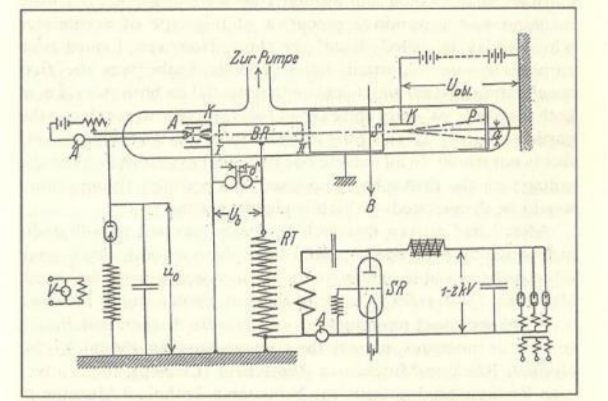


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

→ after the PhD, Rolf Wideröe works for AEG to build HV circuit breakers and his thesis, published in the "Archiv für Elektrotechnik", remains unnoticed.

... But the topic was hot!

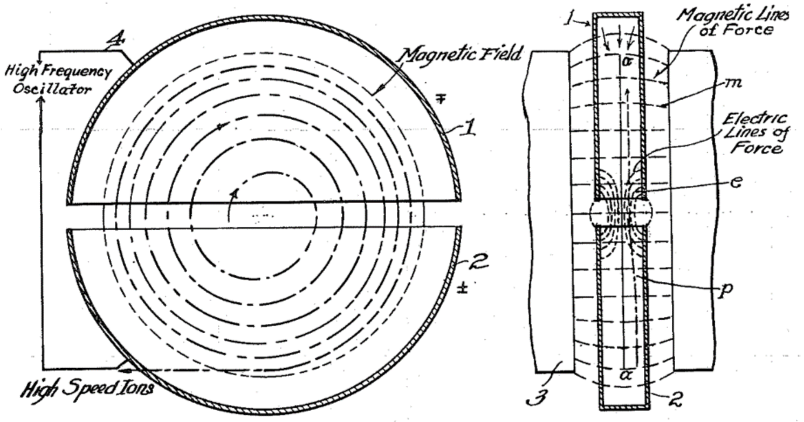
Ideas travel: from Aachen to Berkeley…

In the 1920's, Ernest O. Lawrence (born 1901), young professor of physics at Berkeley, wants to join the "energy race", and is looking for a new idea...

In 1929, during a conference, he goes to the university library and finds Wideröe's thesis in the 1928 "Archiv für Elektrotechnik" (but he did not speak German...).

Immediately, he realised the potential of the idea of Radio-Frequency acceleration, and starts working with his PhD students on 2 parallel activities:

1. A Wideröe "linear accelerator" (linac) with several drift tubes, to accelerate heavy ions (Sloan and Lawrence).
2. A "cyclic" accelerator, bending the particles on a circular path around Wideröe's drift tube (Livingston and Lawrence) → the **cyclotron**.



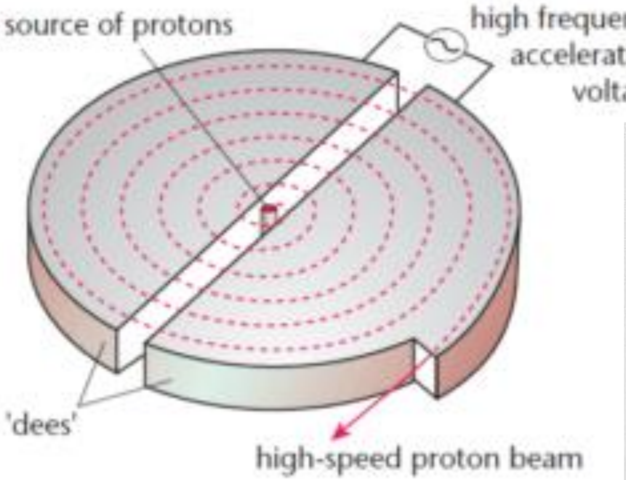
A compact low-energy accelerator: the cyclotron

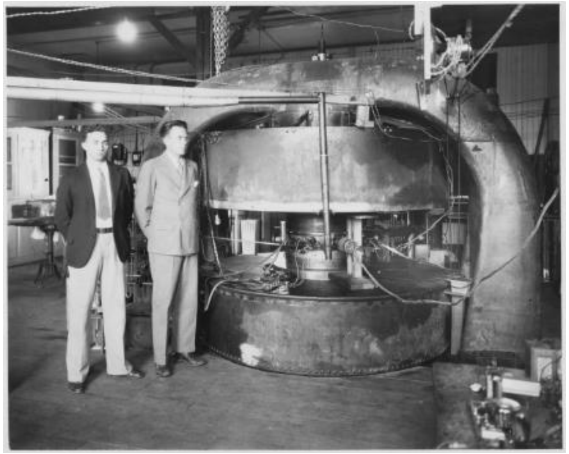
Immediately after R. Wideroe's invention of the linear accelerator, Ernest O. Lawrence at Berkeley proposes to perform radio-frequency acceleration in a circular system, inserted in a big magnet.

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 !



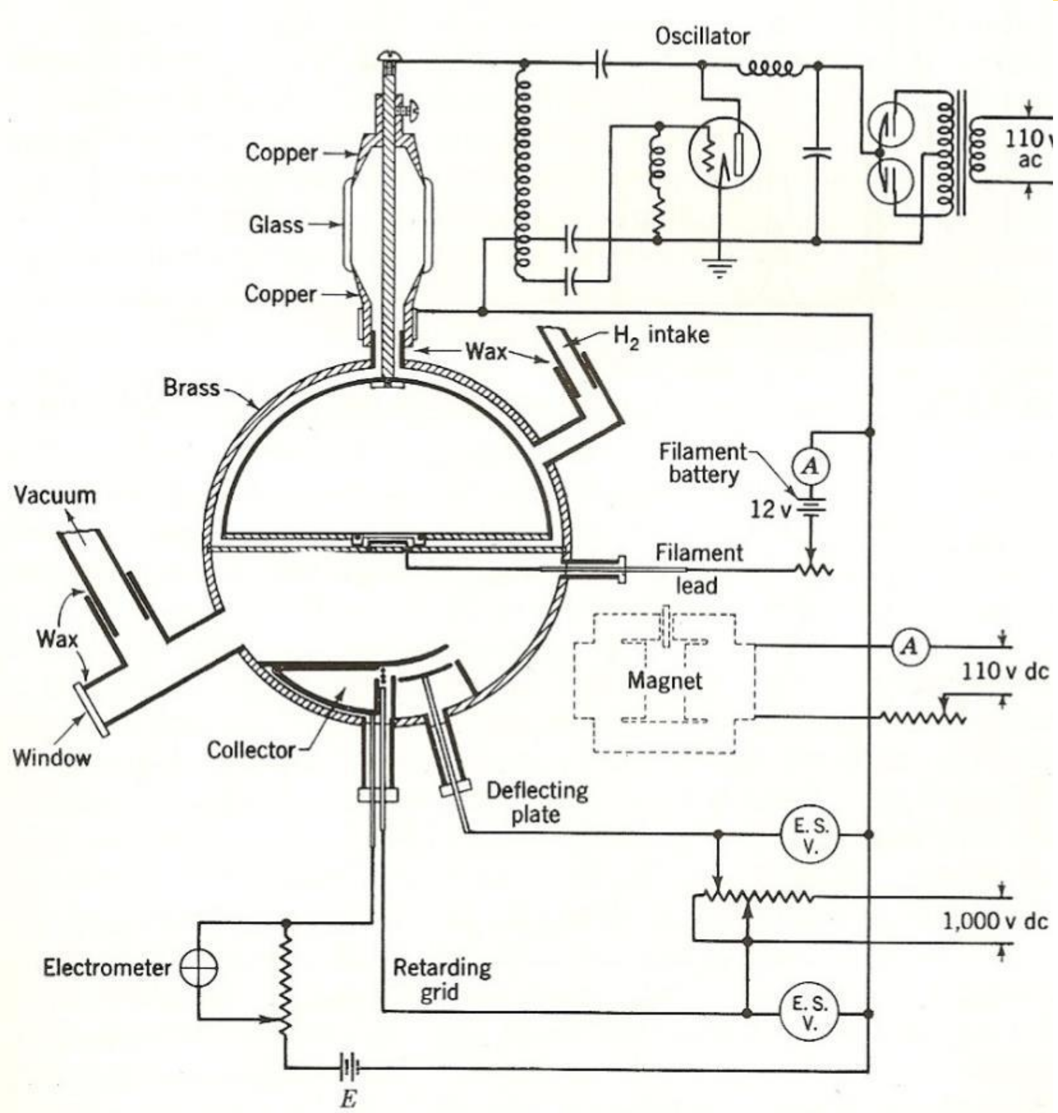


$$\frac{mv^2}{r}=evB \qquad f=\frac{1}{\tau}=\frac{2\pi r}{v}=\frac{2\pi r\, m}{eBr}=\frac{2\pi m}{eB}$$

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.

The first cyclotron



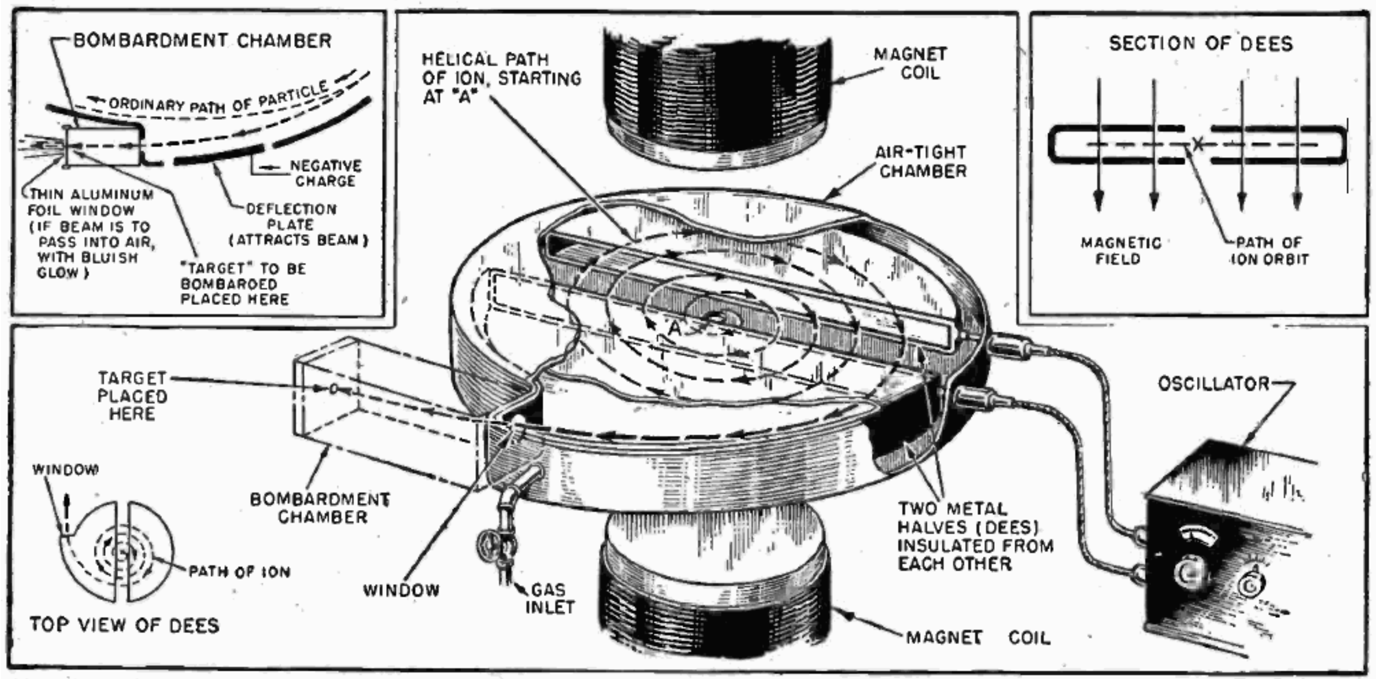
Scheme of the first Berkeley cyclotron, from S. Livingston’s PhD Thesis.

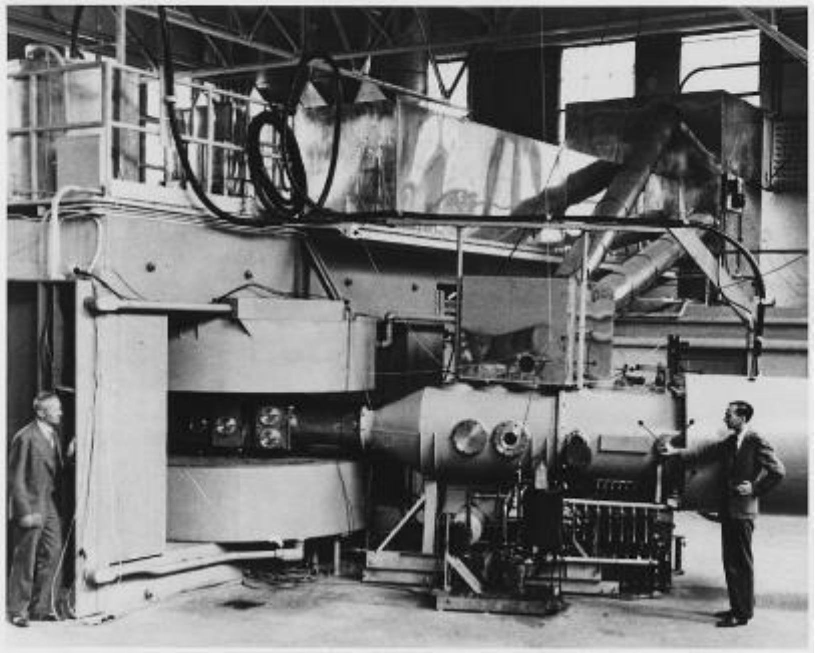
Cyclotrons give a boost to nuclear physics

1931: the Berkeley cyclotron reaches 1.2 MeV with protons. First atom disintegrations in 1932.

1934: 5 MeV reached on a new larger machine accelerating protons and deuterons (used for the production of neutrons, discovered in 1932).

Many institutes worldwide start the construction of cyclotrons. This technology made artificial production of heavy elements possible and paved the way for the discoveries in nuclear physics that provided the background for the US (and URSS) nuclear programmes.





Examples of modern cyclotrons

The range of BEST cyclotrons, from 15 to 70 MeV output energy

A compact cyclotron for production of PET radioisotopes (GE Healthcare)

Very compact, can accelerate large particle intensities, but their construction and operation are simple only when the particle energy is low (non relativistic).

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
Some special cyclotrons (synchrocyclotrons) can go higher (~ 500 MeV) but with high complexity and cost
→ invention of the **synchrotron.**

Limitation to Widerøe linacs: frequency

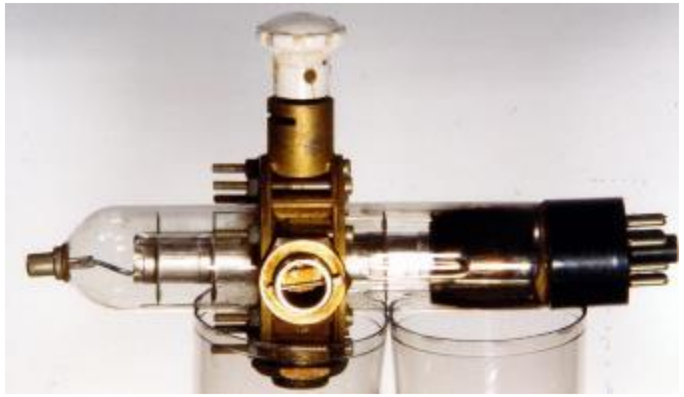
As velocity increases, to keep a reasonable distance between gaps the RF excitation frequency must increase: $f_{RF} = v_p / 2d$
When the RF excitation frequency becomes so high that the dimensions of the accelerator are comparable to the RF wavelength, the gaps start to generate electromagnetic waves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

Higher frequencies – the WWII technology leap

Early RF systems (LC-based) were limited by leakage of RF power at high freq.

→ W. Hansen (b. 1909) at Berkeley starts to work on "cavity resonators" for higher frequency and after moving to Stanford starts developing a new source of RF power, the klystron. But the progress is slow.

After the start of WWII, the war effort recruited the best UK and US scientists. In 1940 is established the Radiation Laboratory at MIT, which will develop the modern radar technology.

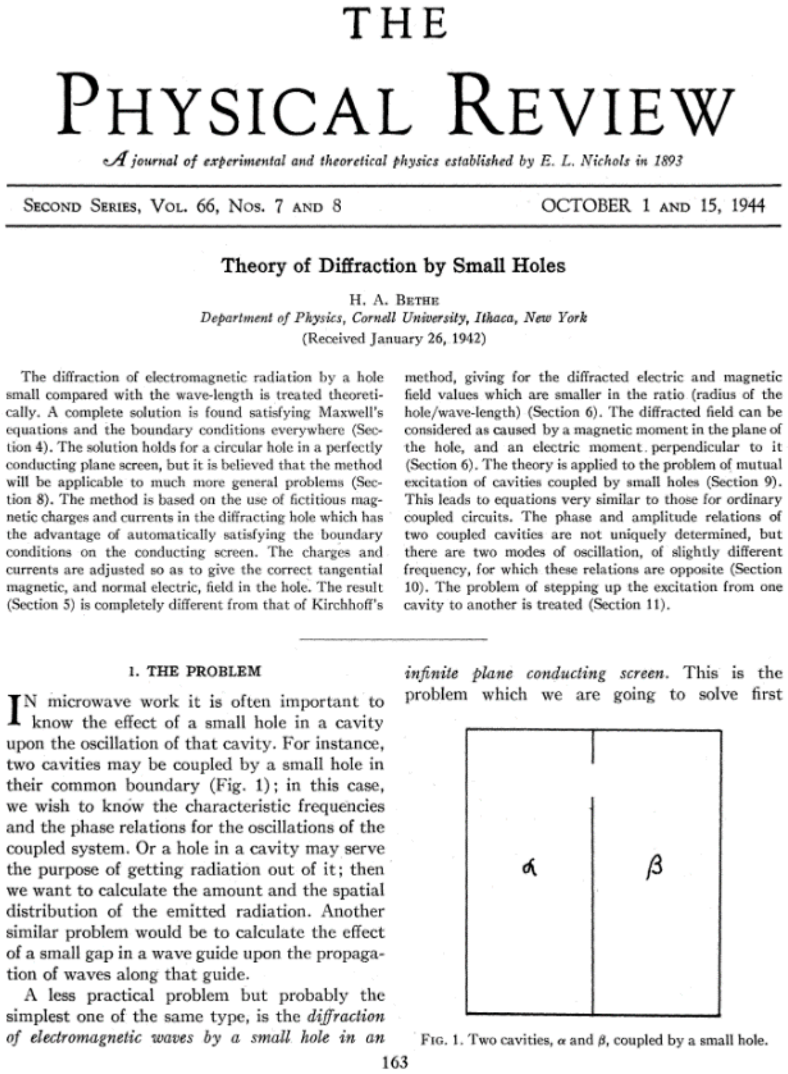


A WW2 3 Ghz klystron

The great boost to Radio Frequency technology that made modern particle accelerator possible came from the **radar development of WW II**.
All the US radar research was made public after the war and helped developing Radio-Frequency technologies for a new generation of accelerators.

Note that early radars were based on the magnetron, developed at Birmingham in 1930-40 (3-30 GHz). UK radar technology was shared with US from 1940.

Scientists at war… an interesting example



THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 66, NOS. 7 AND 8 OCTOBER 1 AND 15, 1944

Theory of Diffraction by Small Holes

H. A. BETHE
Department of Physics, Cornell University, Ithaca, New York
(Received January 26, 1942)

The diffraction of electromagnetic radiation by a hole small compared with the wave-length is treated theoretically. A complete solution is found satisfying Maxwell's equations and the boundary conditions everywhere (Section 4). The solution holds for a circular hole in a perfectly conducting plane screen, but it is believed that the method will be applicable to much more general problems (Section 8). The method is based on the use of fictitious magnetic charges and currents in the diffracting hole which has the advantage of automatically satisfying the boundary conditions on the conducting screen. The charges and currents are adjusted so as to give the correct tangential magnetic, and normal electric, field in the hole. The result (Section 5) is completely different from that of Kirchhoff's method, giving for the diffracted electric and magnetic field values which are smaller in the ratio (radius of the hole/wave-length) (Section 6). The diffracted field can be considered as caused by a magnetic moment in the plane of the hole, and an electric moment perpendicular to it (Section 6). The theory is applied to the problem of mutual excitation of cavities coupled by small holes (Section 9). This leads to equations very similar to those for ordinary coupled circuits. The phase and amplitude relations of two coupled cavities are not uniquely determined, but there are two modes of oscillation, of slightly different frequency, for which these relations are opposite (Section 10). The problem of stepping up the excitation from one cavity to another is treated (Section 11).

1. THE PROBLEM

IN microwave work it is often important to know the effect of a small hole in a cavity upon the oscillation of that cavity. For instance, two cavities may be coupled by a small hole in their common boundary (Fig. 1); in this case, we wish to know the characteristic frequencies and the phase relations for the oscillations of the coupled system. Or a hole in a cavity may serve the purpose of getting radiation out of it; then we want to calculate the amount and the spatial distribution of the emitted radiation. Another similar problem would be to calculate the effect of a small gap in a wave guide upon the propagation of waves along that guide.

A less practical problem but probably the simplest one of the same type, is the *diffraction of electromagnetic waves by a small hole in an infinite plane conducting screen*. This is the problem which we are going to solve first

FIG. 1. Two cavities, α and β, coupled by a small hole.

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Hans Bethe and the coupling cavity-waveguide

Theoretical physicist (nuclear physics, interaction particles/matter, ...)

Escaped to UK and then USA in 1933.

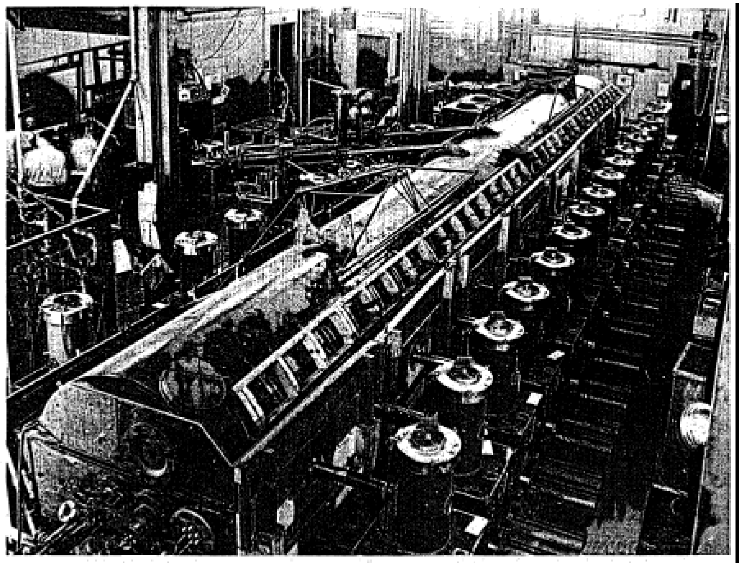
In 1941/42 was asked to contribute to the MIT work on radar, and given the problem of calculating the coupling from a hole between 2 cavity resonators.

The result was this paper, still the basis for understanding coupling problems in RF.

From 1942 Bethe left the RF field for the Manhattan Project, becoming one of the fathers of the atom bomb.

After the war, the big jump: linac technologies

Luis Alvarez and the Drift Tube Linac



The war effort gave the competences and the components to go to higher 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 "drift 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.

Another jump: higher frequencies and higher power

William Hansen (right) and colleagues with a section of the first electron linear accelerator that operated at Stanford University in 1947. It was 3.6 meters long and could accelerate electrons to 6 MeV.

The Stanford Linear Accelerator

Development of the first electron linac (Ginzton, Hansen, Kennedy, 1948) at Stanford University.

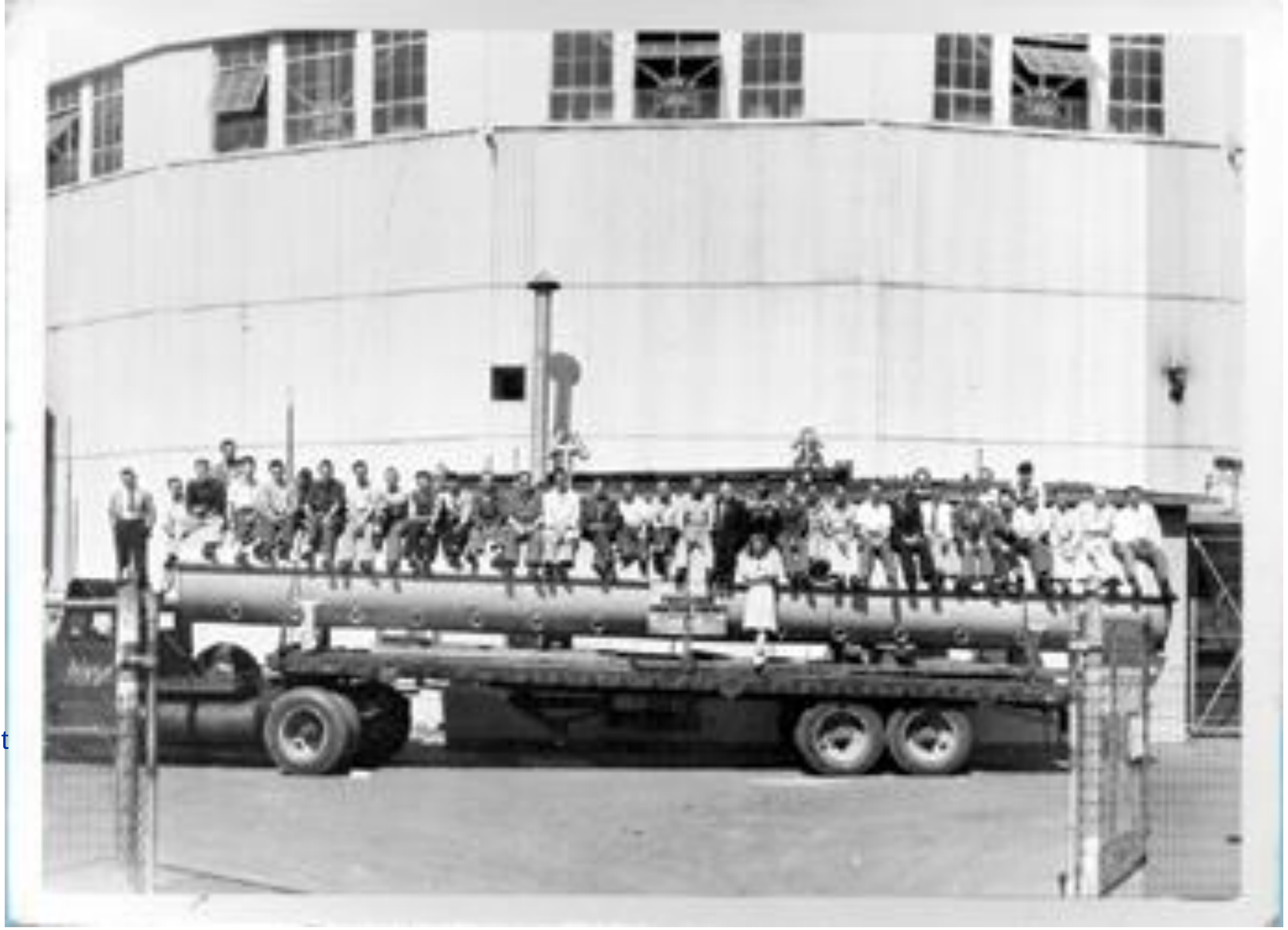
Travelling-wave structures, iris loaded.

Important decision to separate the vacuum of the accelerator from the vacuum of the klystron through the use of "windows".

3 GHz chosen as the highest frequency for which power sources were available (magnetron, 1 MW).

The Stanford team develops in 1946-49 a high-power klystron (8 MW) for its new linac.

A visual comparison between high and low frequencies…



The previous photograph was advertising the advantages of the 3 GHz frequency… compared to a famous photo of Alvarez’s 1st tank at 202 MHz!

Berkeley Laboratory group seated on top of the vacuum tank of their 40-foot 32-MeV proton linear accelerator on the back of a flatbed truck, probably in 1947.

Going to higher energies with linacs? Not so easy

- The focusing problem: in the first linacs, most of the particles were lost during acceleration → Alvarez used in his linac grids placed at the end of the drift tube hole, to avoid the RF defocusing: no defocusing, but losses on the grid → solution only after the invention of alternating-gradient focusing (1952) and the use of small quadrupole magnets (from 1954-55).

- The technology problem: initial proton and ion linacs had a separate vacuum and RF envelope (a light sheet copper structure inside a big vacuum-tight cylinder). In the 70's appeared the first linacs made of copper-clad stainless steel tanks with common RF and vacuum envelope. Copper-clad is not reliable, and at the beginning of the 80's copper plating of steel (first mild, then stainless) made possible reliable structures with common envelopes.

- The beam intensity problem: although alternating-gradient focusing allowed for beam transmissions coming close to 100%, several applications considered in the cold-war 70's called for top beam intensity from linacs (fusion material irradiation, military tritium production, star wars,…) → development of sophisticated beam simulation codes and of the Radio Frequency Quadrupole (removes the intensity bottleneck at low energy!).

Linacs becoming gigantic: an unfortunate attempt

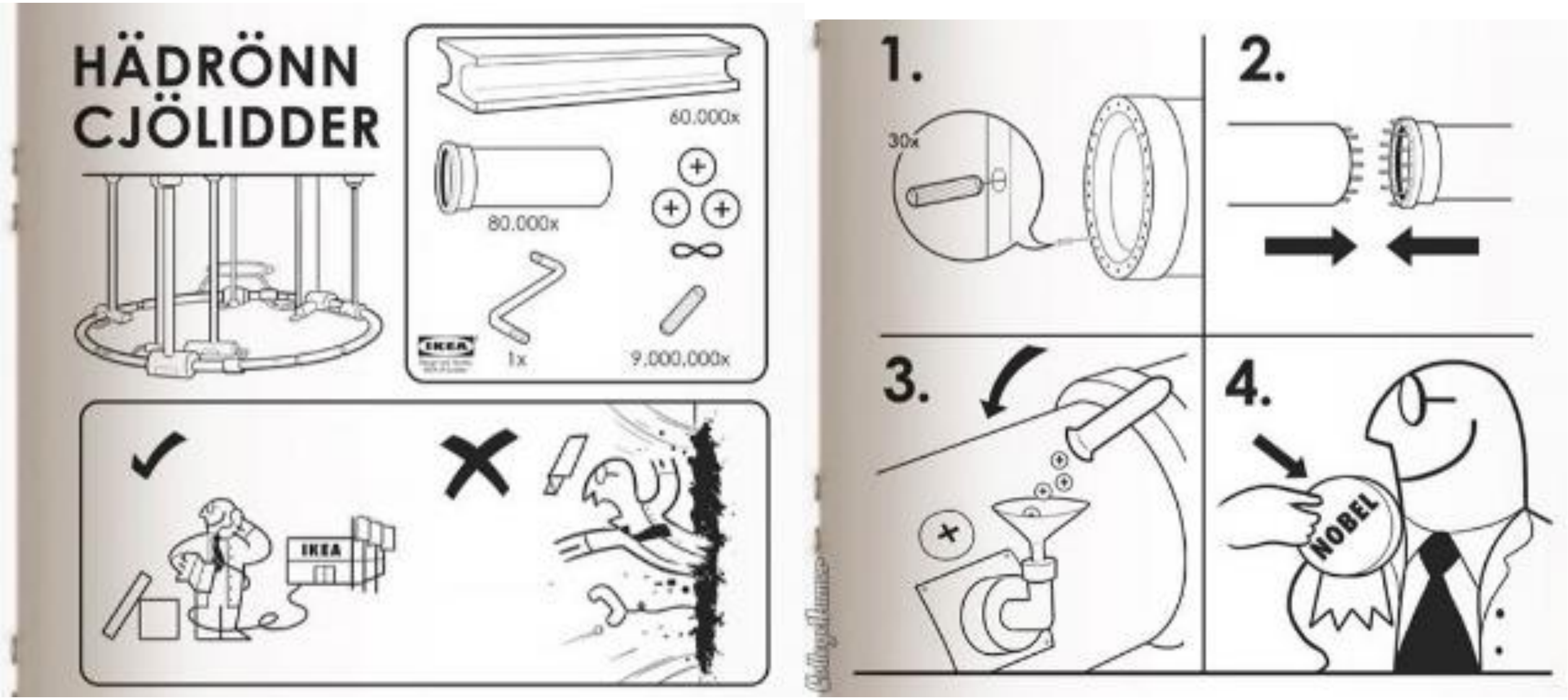
The Material Testing Accelerator (MTA) built in the early 50's by Alvarez and his team at the site that would later become the Lawrence Livermore Laboratory.

50 MeV deuteron accelerator, 400 m long, 18 m diameter, drift tubes weighing 40 tons.

Intended to produce large quantities of uranium for the US programme to produce 30'000 nuclear weapons, by producing spallation neutrons to transform natural into fissile uranium.

Never worked because of sparking problems…

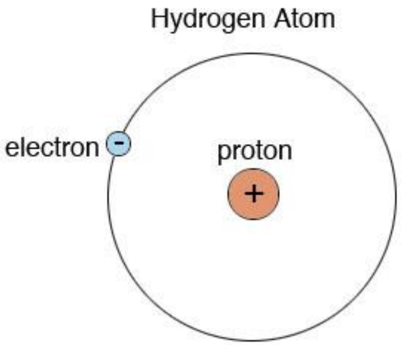
Building blocks 1 - linacs

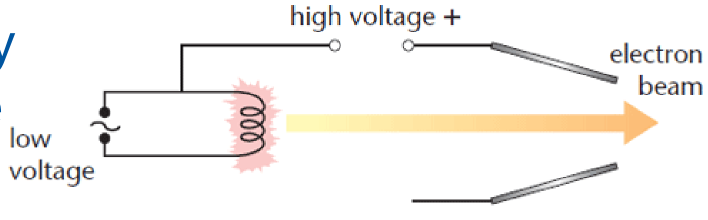


A modern accelerator: ion sources

Protons are obtained heating an hydrogen gas into a plasma and then extracting the protons with a high voltage

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





An electron gun

Scheme of the ion source delivering protons to all CERN accelerators

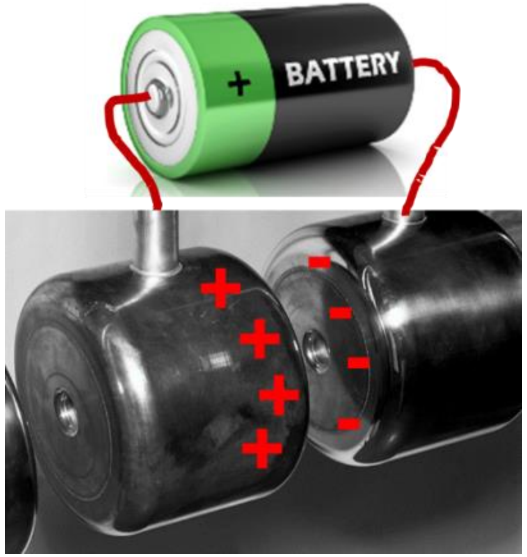
In both cases, after production we need to give a first small acceleration (< 100 keV) with an electrostatic section

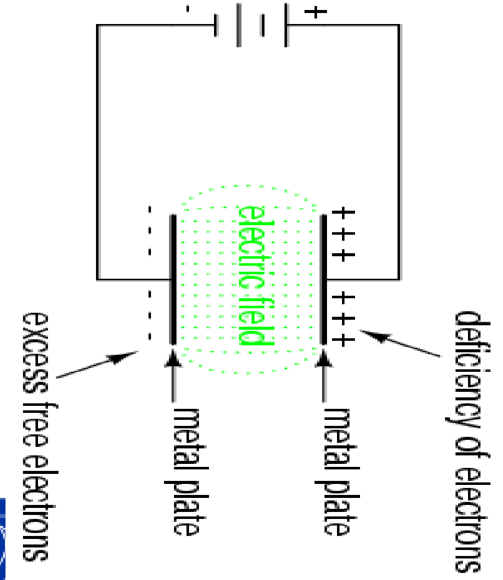
The origin of all CERN protons

A 5 kg bottle of hydrogen contains 3’000’000’000’000’000’000 billions of protons!

And the LHC needs only 1’200’000 billions of protons per day.

The initial acceleration stage

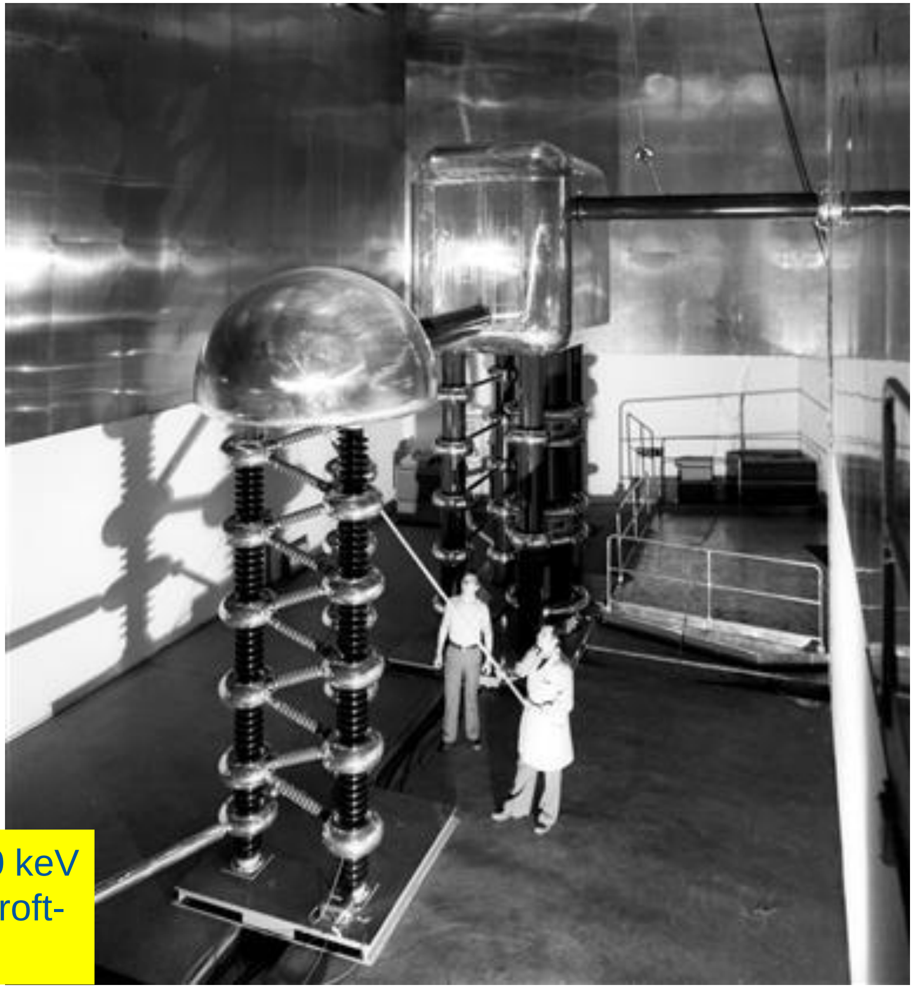




Electrostatic: use a DC voltage between 2 tubes

Corresponds to a capacitor

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



The old (1975-92) CERN 750 keV pre-accelerator, fed by a Cokroft-Walton generator.

The old CERN Cockroft-Walton 750 keV pre-injector

instrumentation cabinet

high-voltage electrode (750 kV)

high-voltage generator

Ion source (inside a voltage shield)

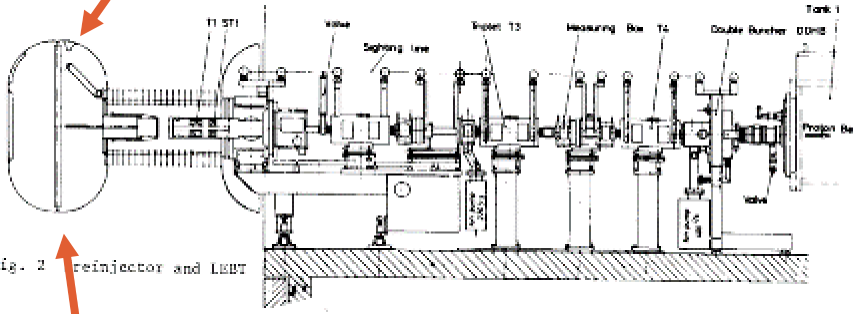
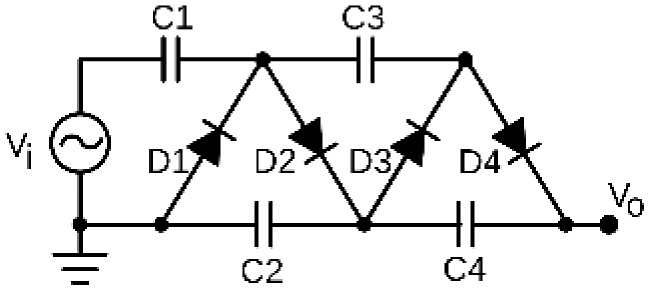
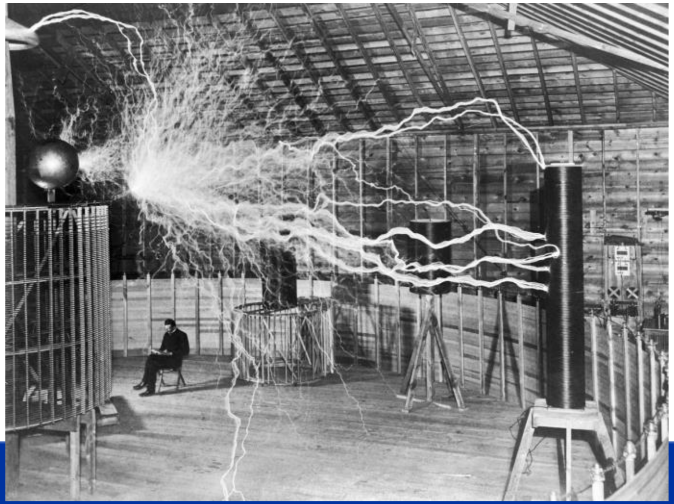


Fig. 2 reinjector and LEBT

Accelerating column (between 750 kV and ground)



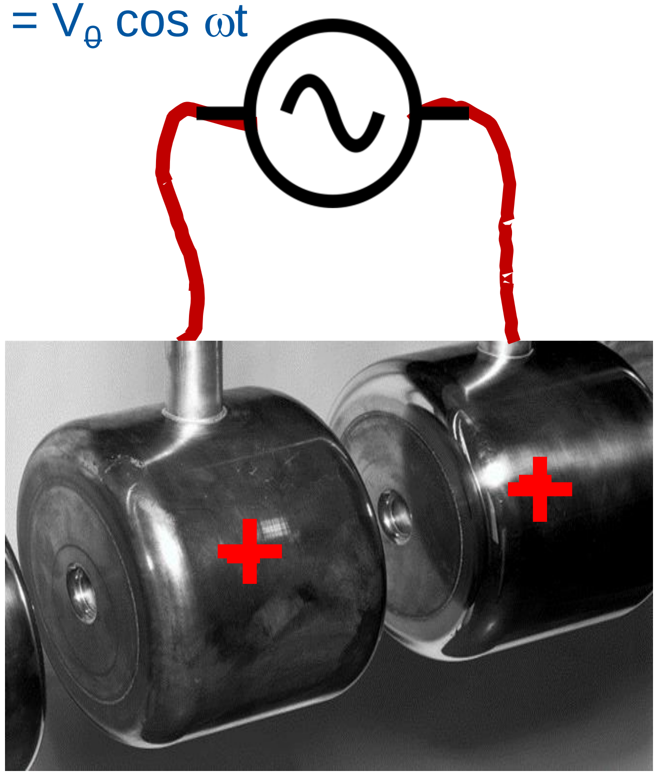


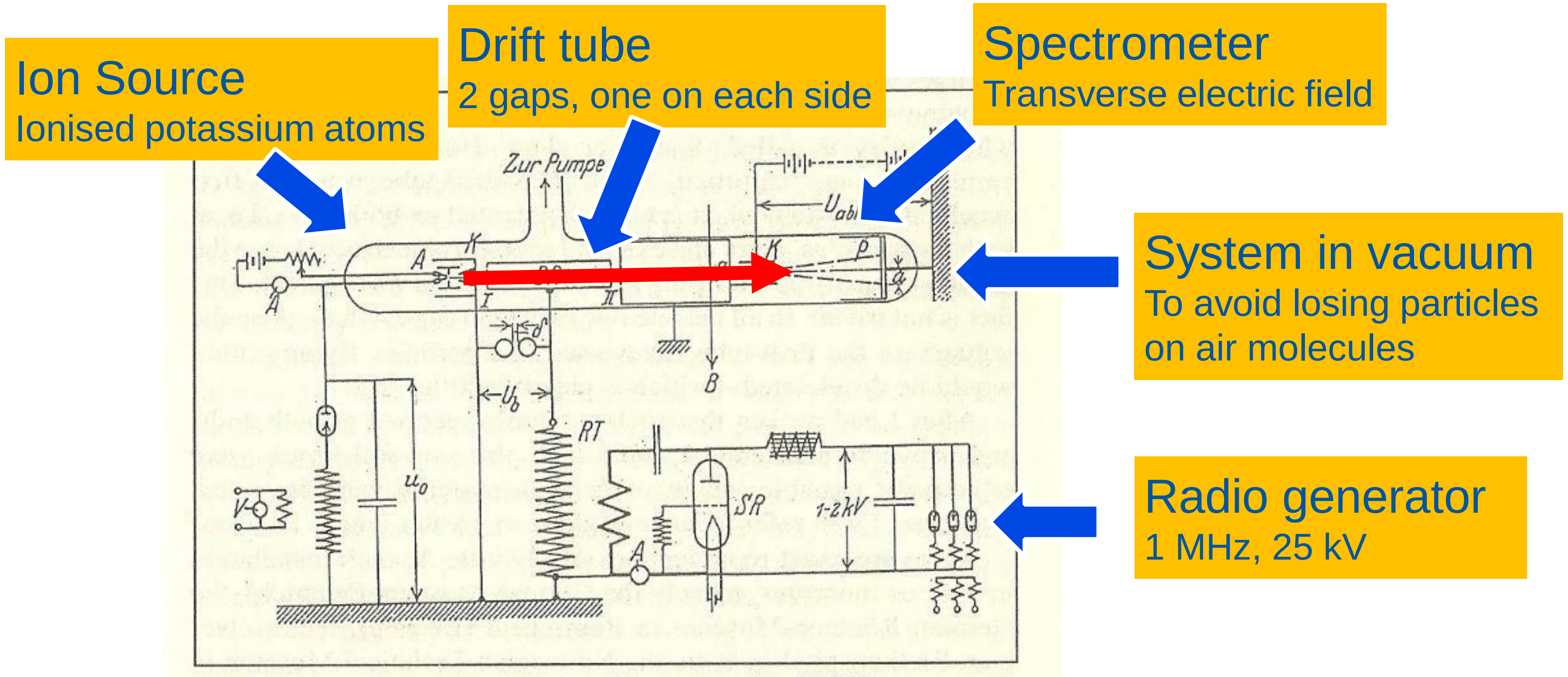
Limitation: Electric discharge (arc) between HV surfaces

And then? Use Wideröe’s idea: Radio-Frequency (RF) fields

Innovation by cross-fertilization: use the radio transmission technology that was rapidly developing in the 20’s and connect a radio transmitter to a system of tubes to obtain incremental acceleration.

$V = V_0 \cos \omega t$





Ion Source
Ionised potassium atoms

Drift tube
2 gaps, one on each side

Spectrometer
Transverse electric field

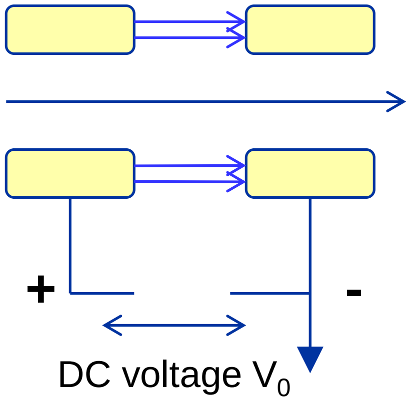
System in vacuum
To avoid losing particles on air molecules

Radio generator
1 MHz, 25 kV

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

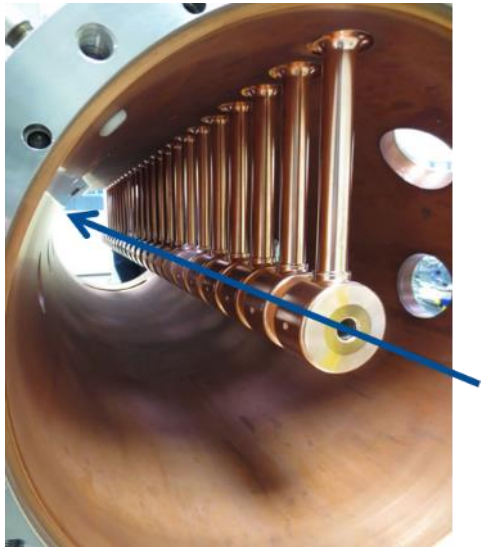
Demonstrated acceleration of potassium ions 1+ at 50 keV with 25kV of RF at 1 MHz

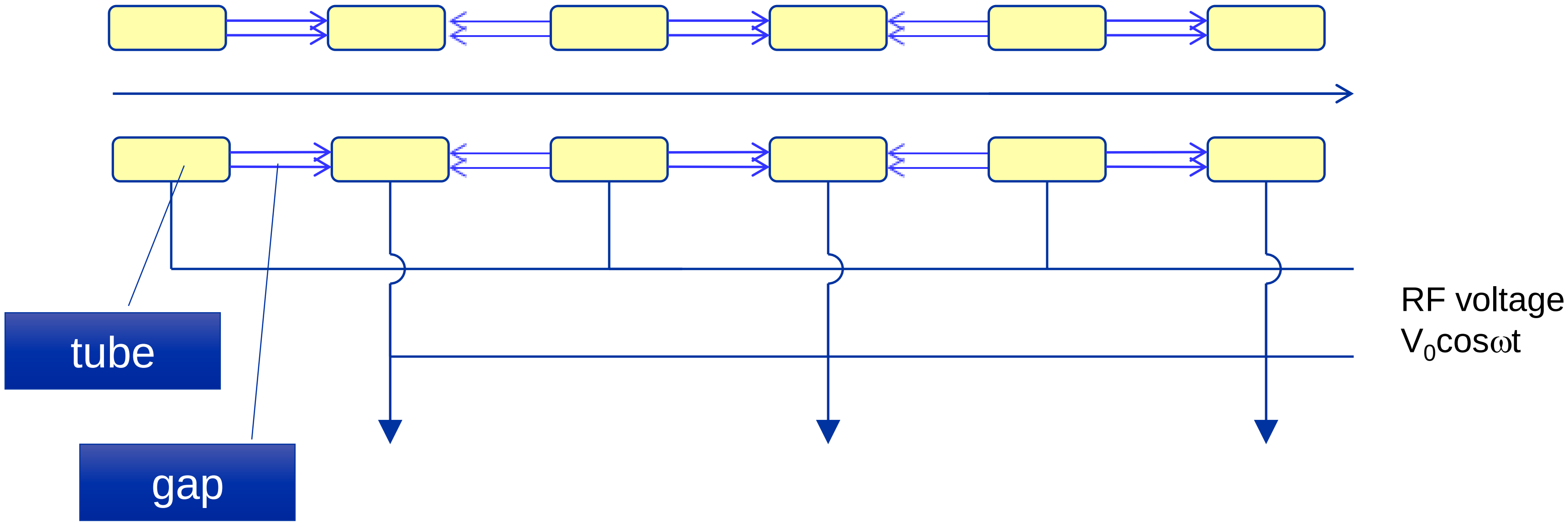
The principle of radio-frequency acceleration



ELECTROSTATIC acceleration
The voltage can be applied only to one gap

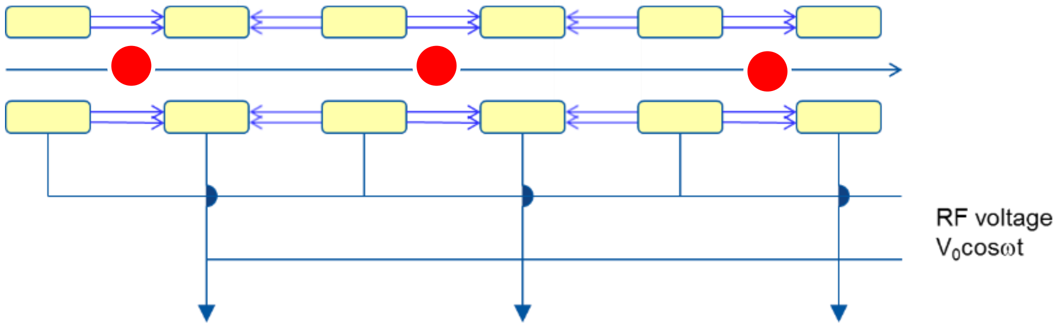
RADIOFREQUENCY acceleration
The voltage adds up over several gaps





Two important consequences of using variable RF electric fields

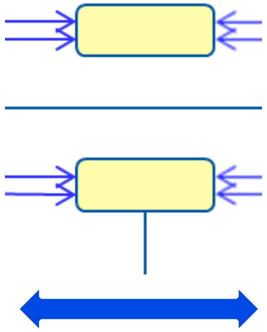
1. The beam of particles cannot be continuous. Particles must be grouped in “bunches” at the period of the radio-frequency



2. The length of the tubes must be proportional to the velocity of the particle

Consequence:

The tubes must become longer and longer as the energy and velocity of the particle increase



L = cell length

Time to travel L = period / 2

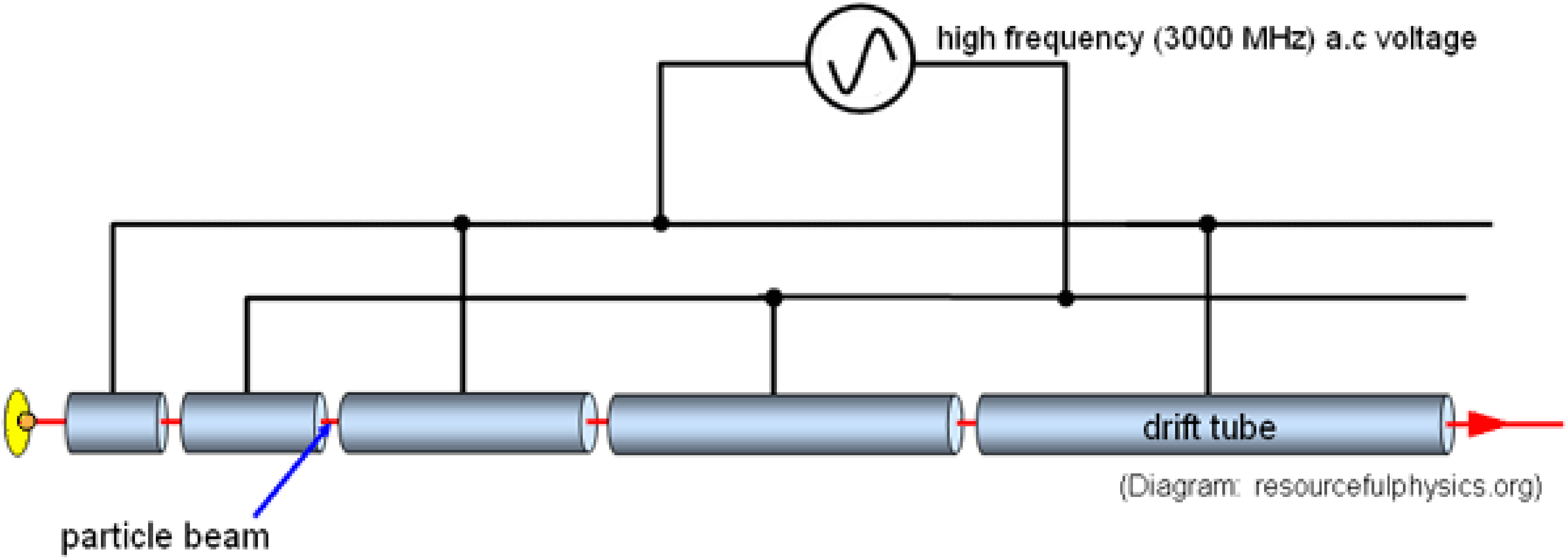
$L / v = T / 2 = 1 / 2f$

$L = v / 2f$

v = velocity of the particle

f = frequency of our generator

We have built a linear particle accelerator!

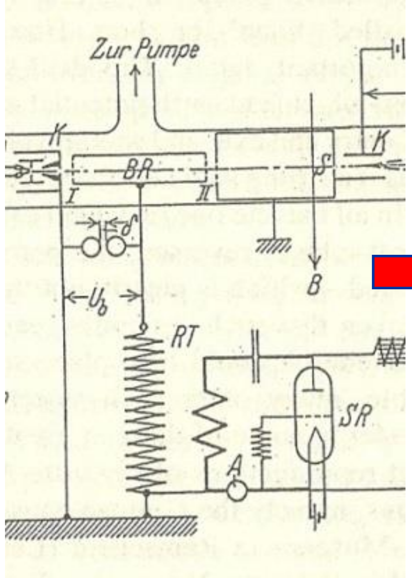


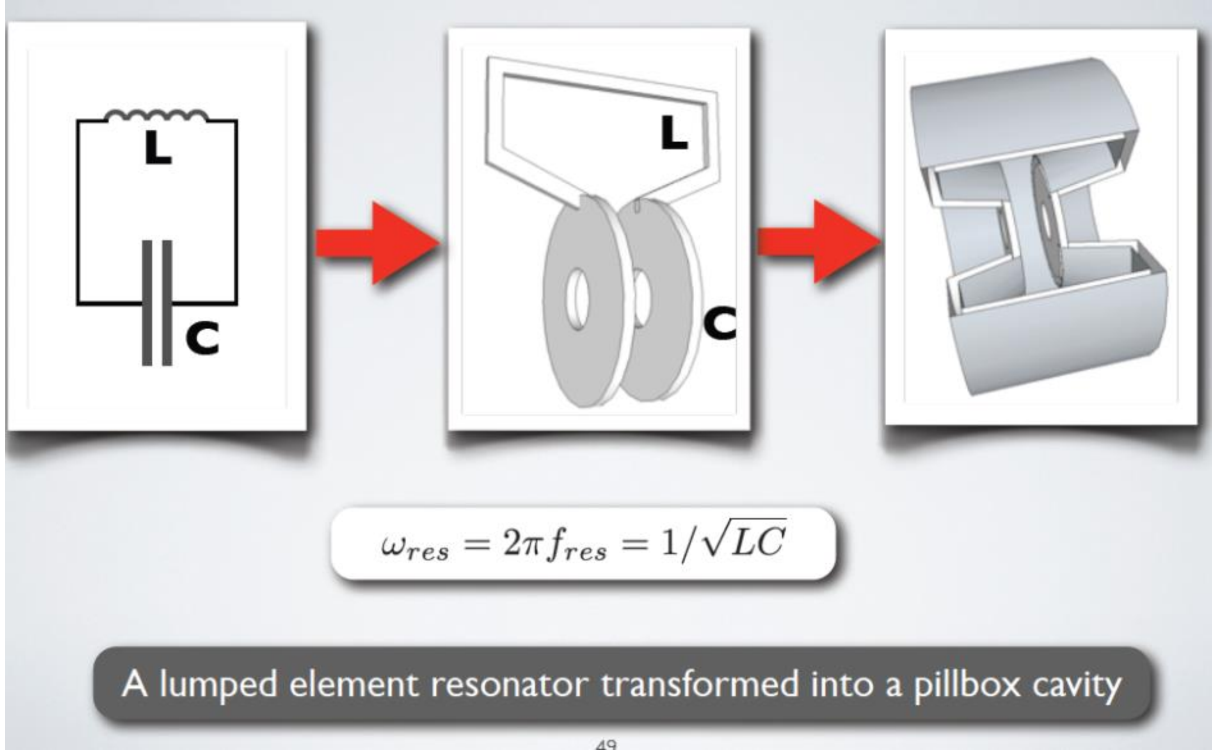
(Diagram: resourcefulphysics.org)

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

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

In modern accelerators, we use high frequencies and cavity resonators around our gaps





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

A lumped element resonator transformed into a pillbox cavity

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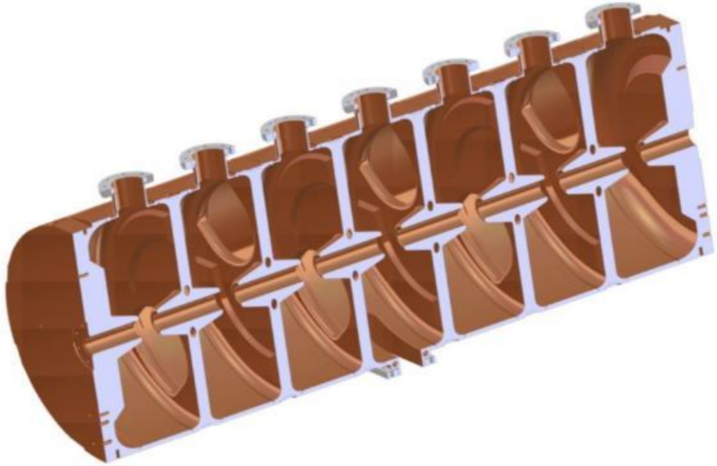
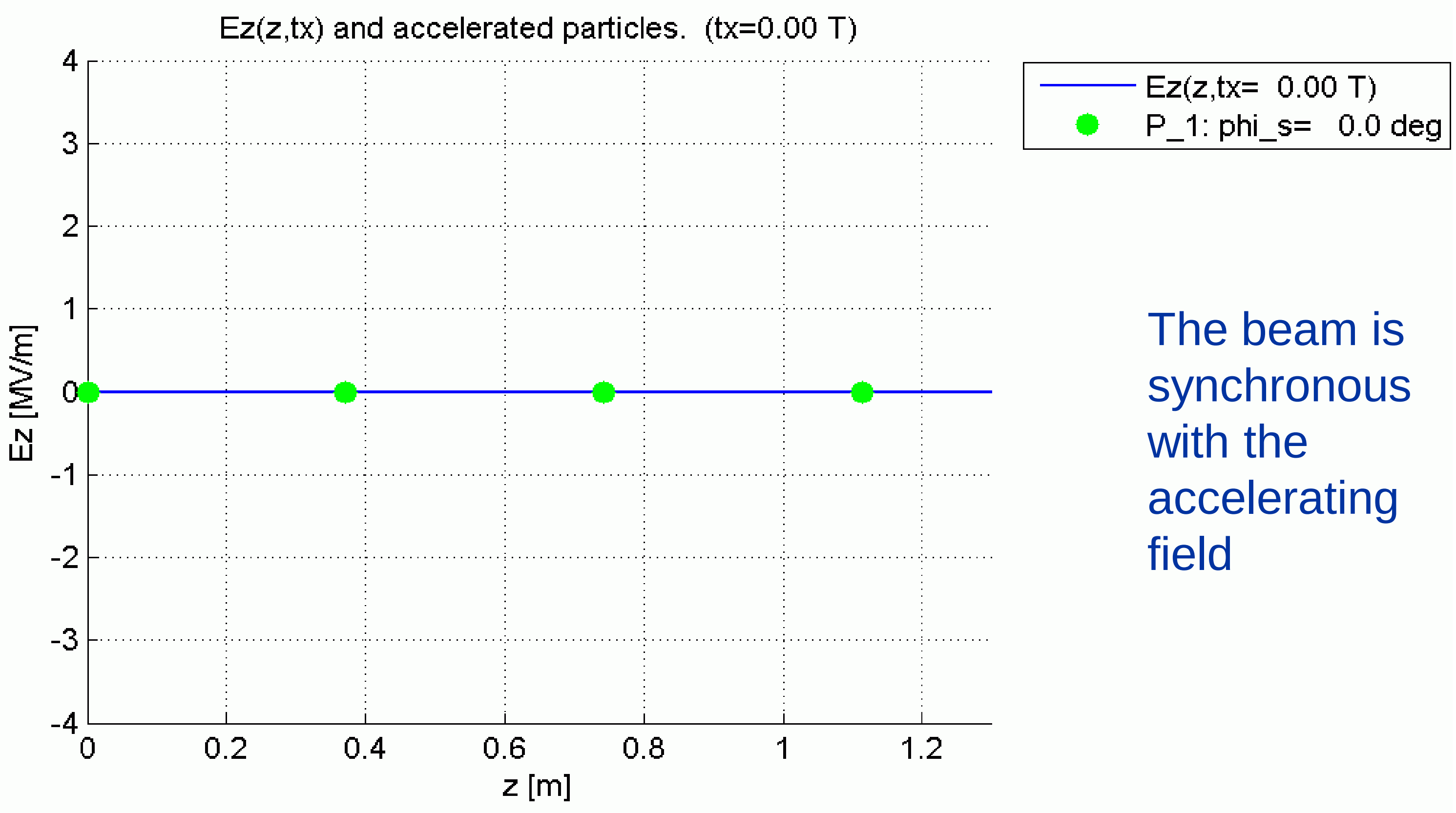
Single-gap cavity 88 MHz

Multi-cell cavity 3 GHz

Synchronism in the PIMS cavity of Linac4





The beam is synchronous with the accelerating field

7-gap cavity (6 tubes and 2 half-tubes)

The new Linac4 (looking from the ion source)

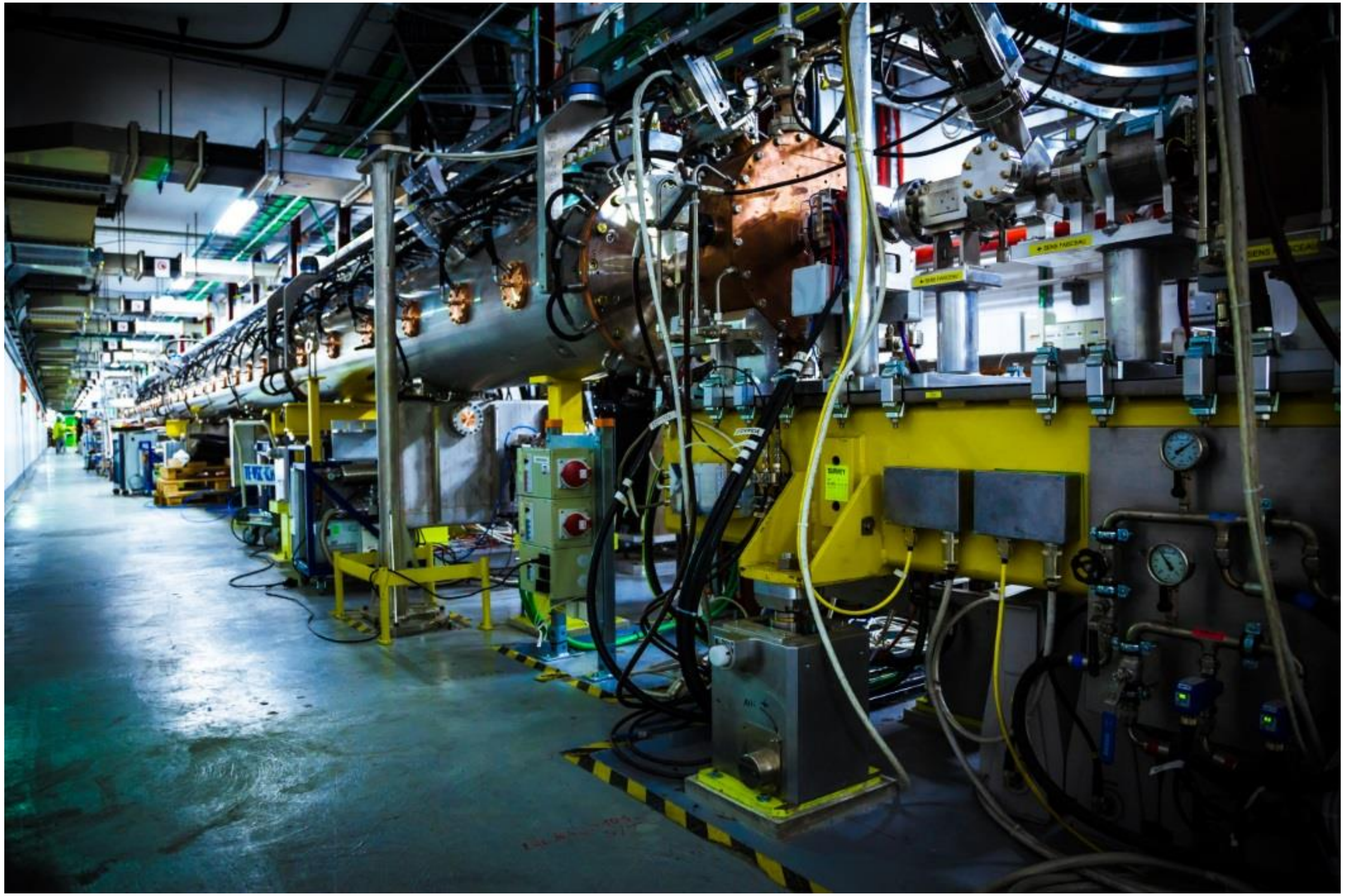
100-m long linear accelerator

160 MeV proton energy

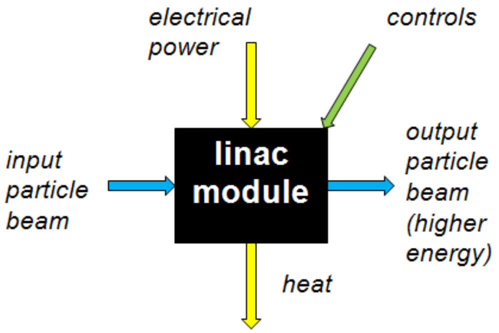
Built 2008-2016

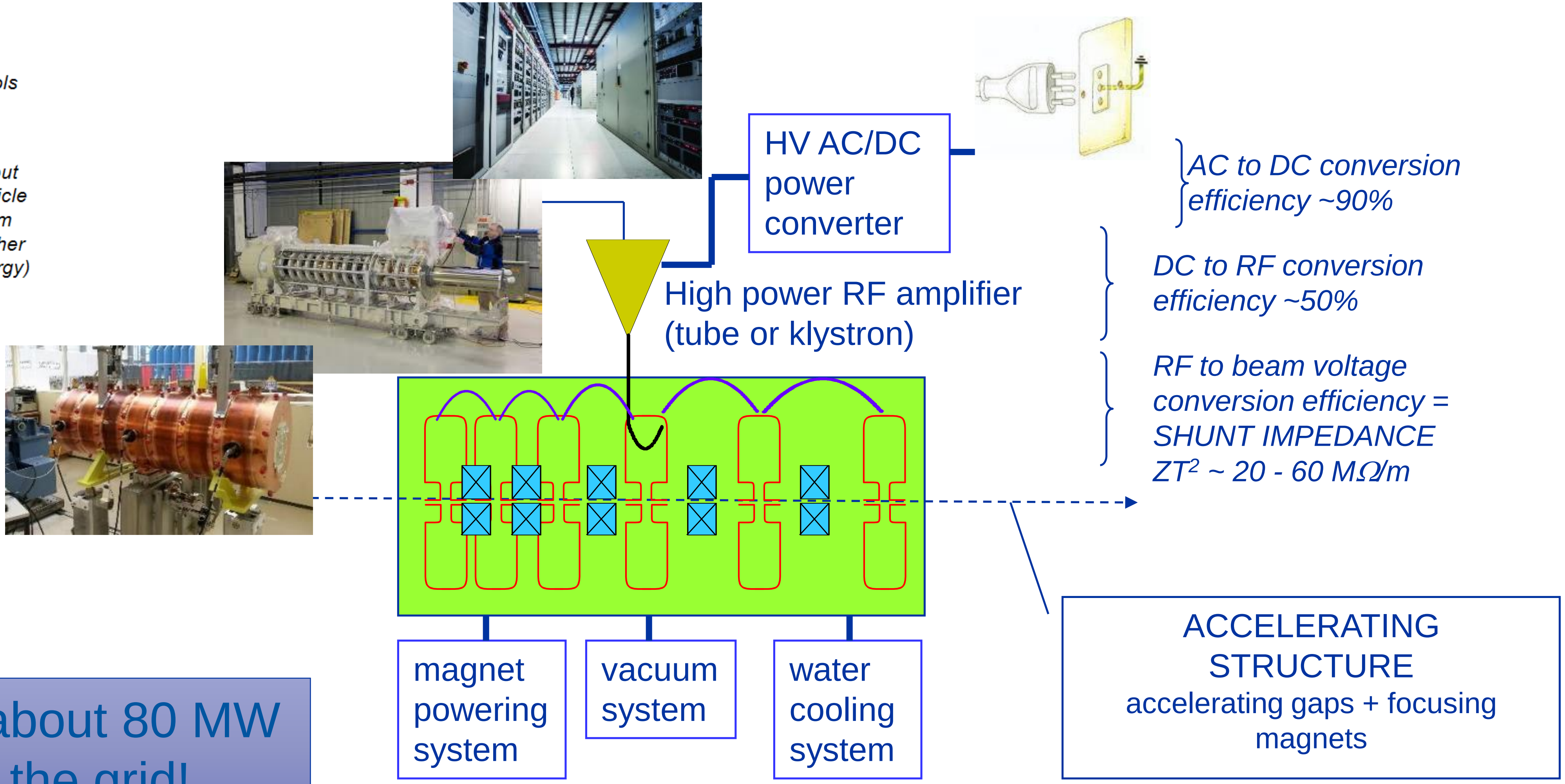
Will be connected to the LHC injector chain in 2020.

Will allow increasing by a factor of 2 the amount of protons in the LHC



Energy flow: from the power grid to the beam




HV AC/DC power converter

High power RF amplifier (tube or klystron)

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

magnet powering system

vacuum system

water cooling system

ACCELERATING STRUCTURE

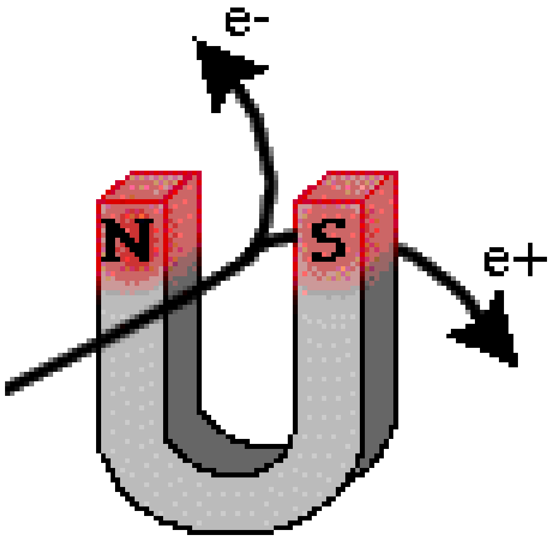
accelerating gaps + focusing magnets

The LHC needs about 80 MW of electricity from the grid!

Can we use a linac to go to very high energy?

A quick calculation:
With tubes we can make about 2 MeV per meter. At higher fields we have electric arcing between the tubes.
A linear LHC (7 GeV) would be long 3'500 km !

We need to go back to the cyclotron principle and think of how to adapt it to relativistic particles.

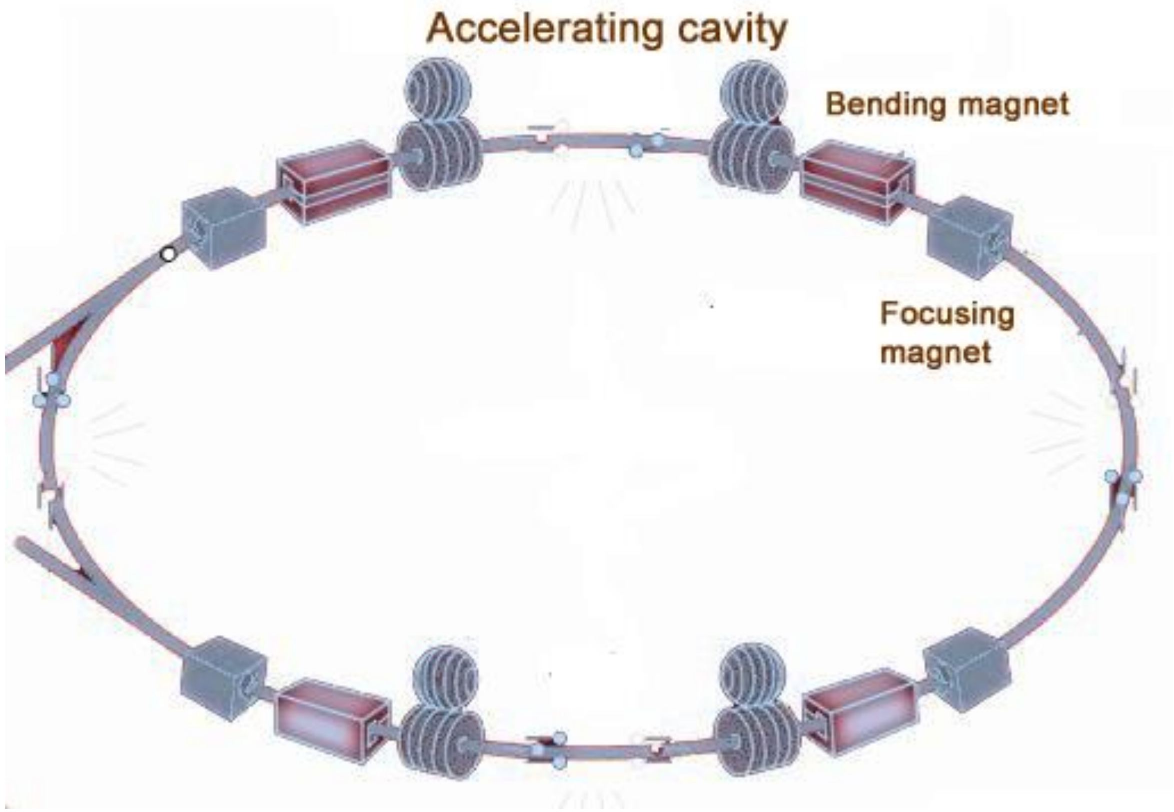


History of particle accelerators 2 – the synchrotron

The invention of the synchrotron

Initial idea: Sir Marcus Oliphant, UK scientist, when working at Oak Ridge for the US Manhattan project in 1943:

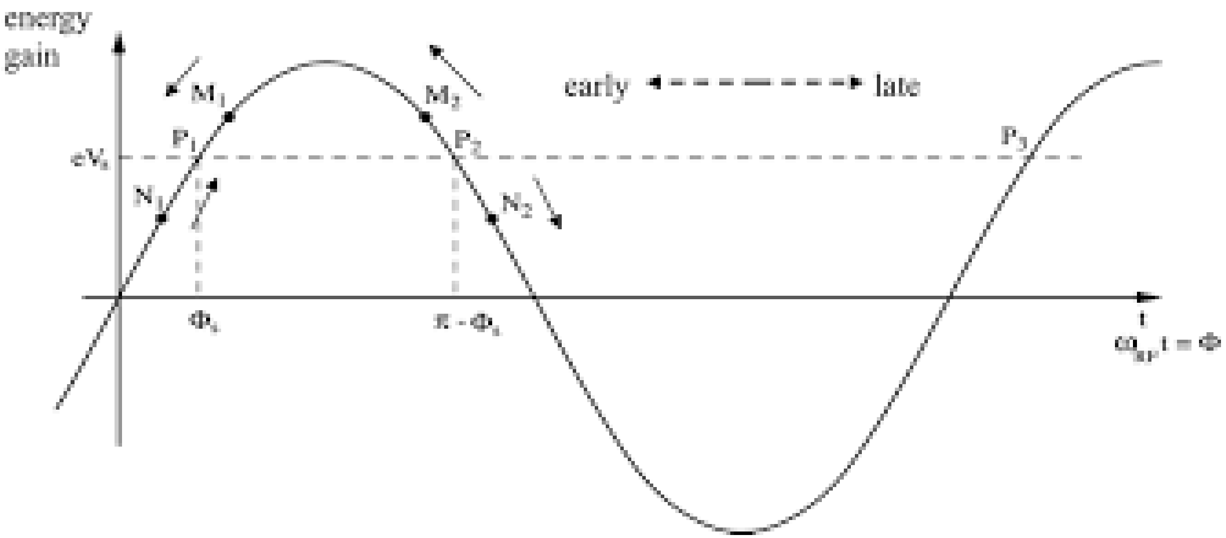
Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field ... which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes.

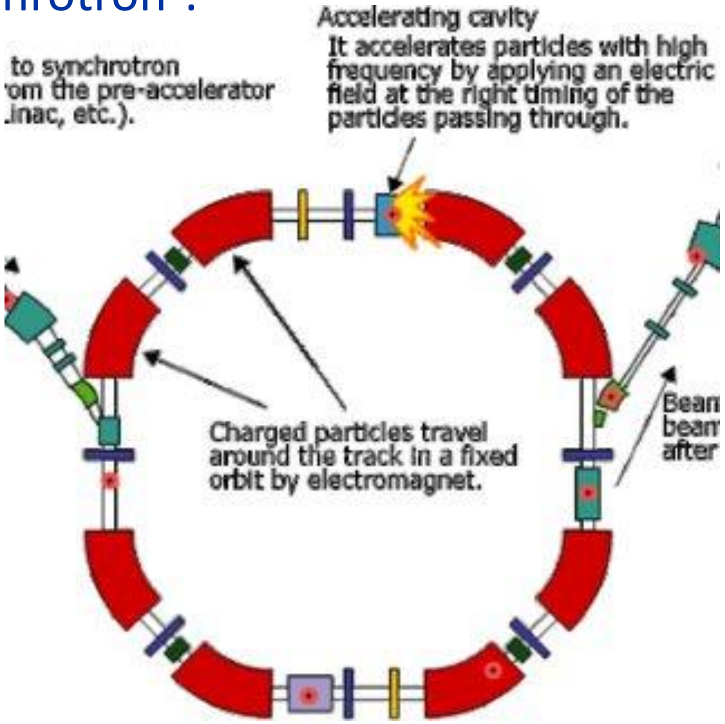


Phase stability

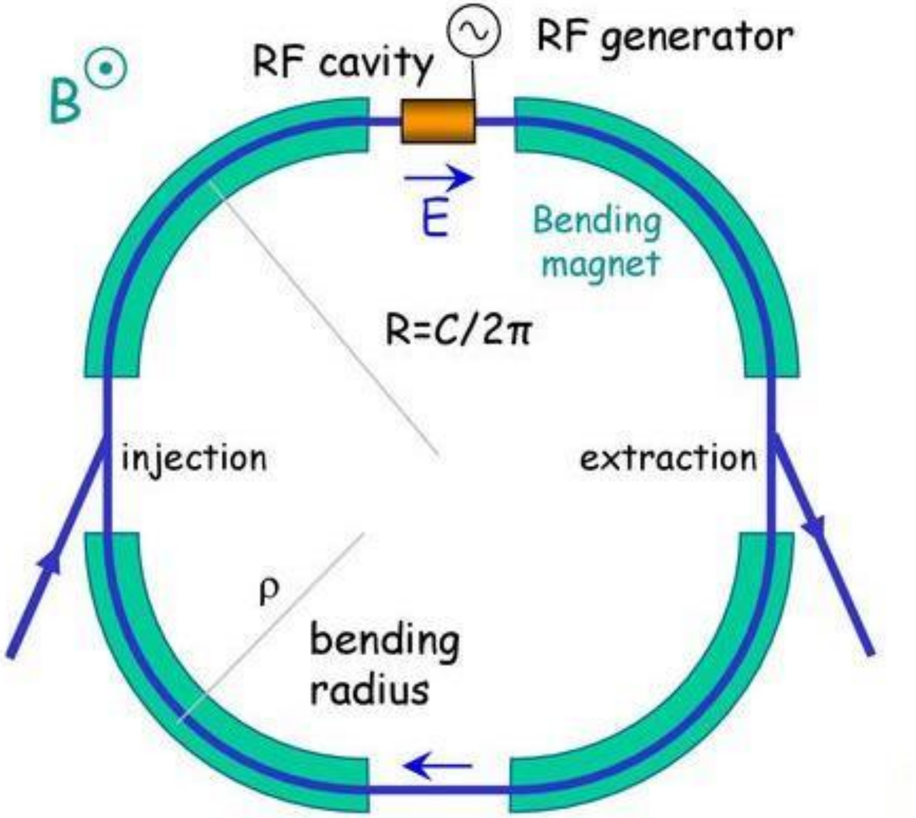
Oliphant's idea was greeted with skepticism. Among the objections, the problem to keep the beam "bunched" enough to allow its acceleration during the short accelerating periods of the RF cavity.

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".





Basic relations for a synchrotron



1. Constant orbit during acceleration

2. B must increase with time (proportionally to the momentum!) to keep the particles on the closed orbit:

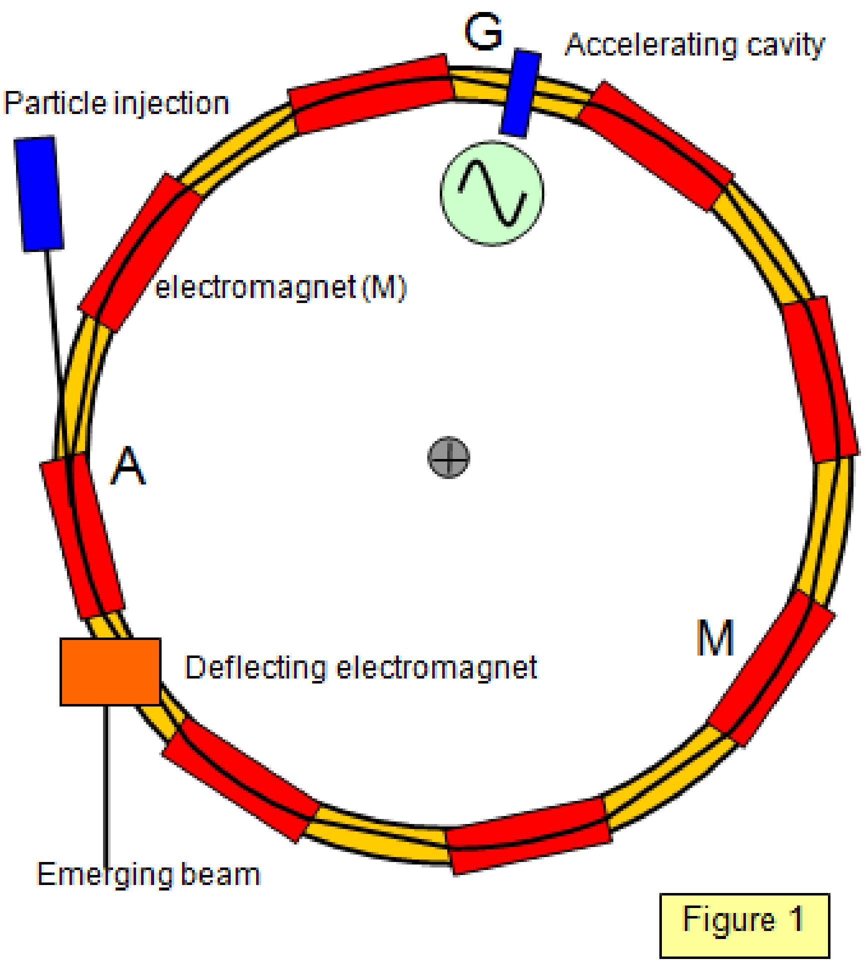
$$\Rightarrow \quad R = p / eB$$

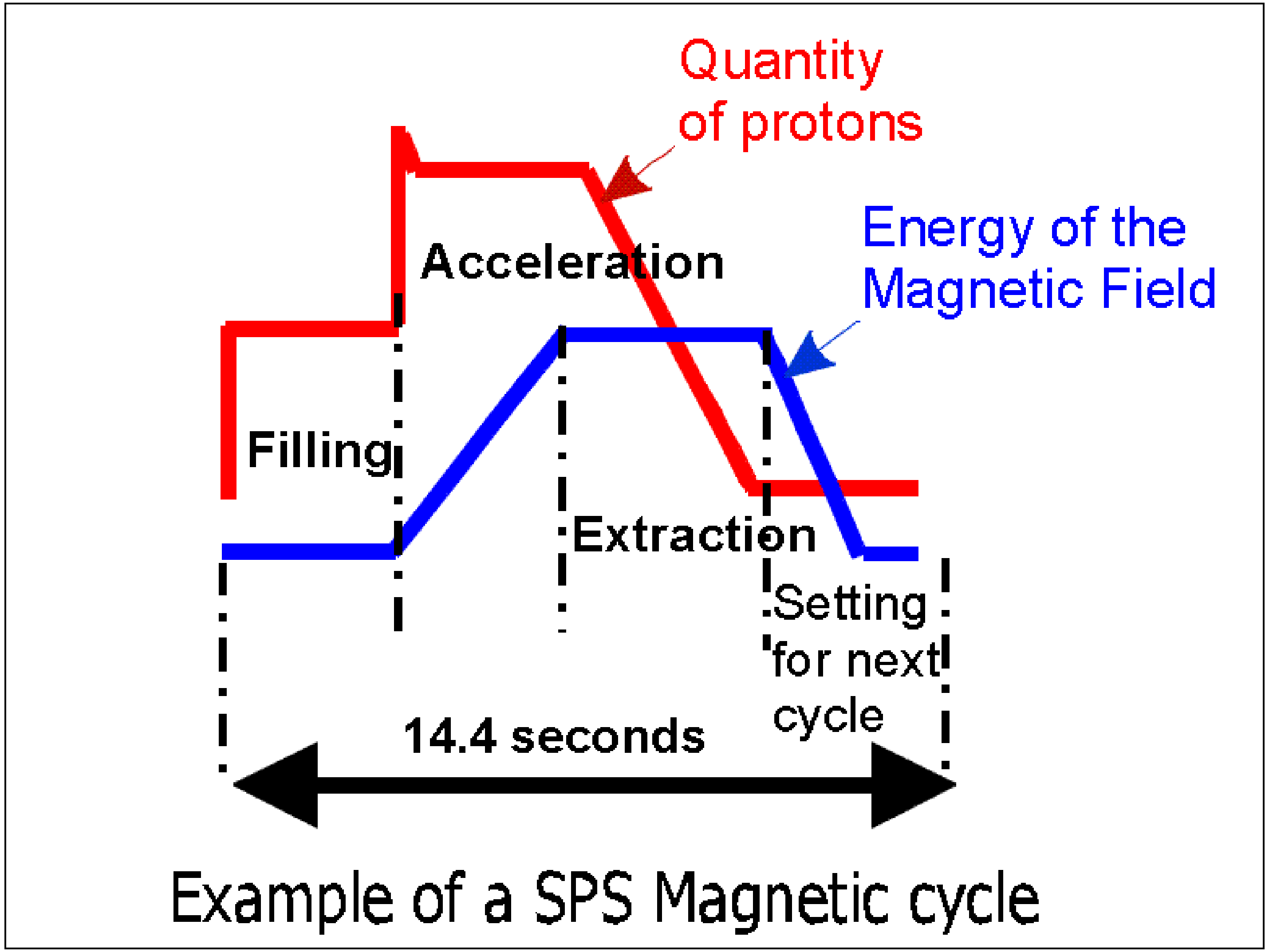
3. The RF frequency must increase with time (proportionally to the velocity!) to keep the particles on the stable phase:

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

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

Magnetic cycle

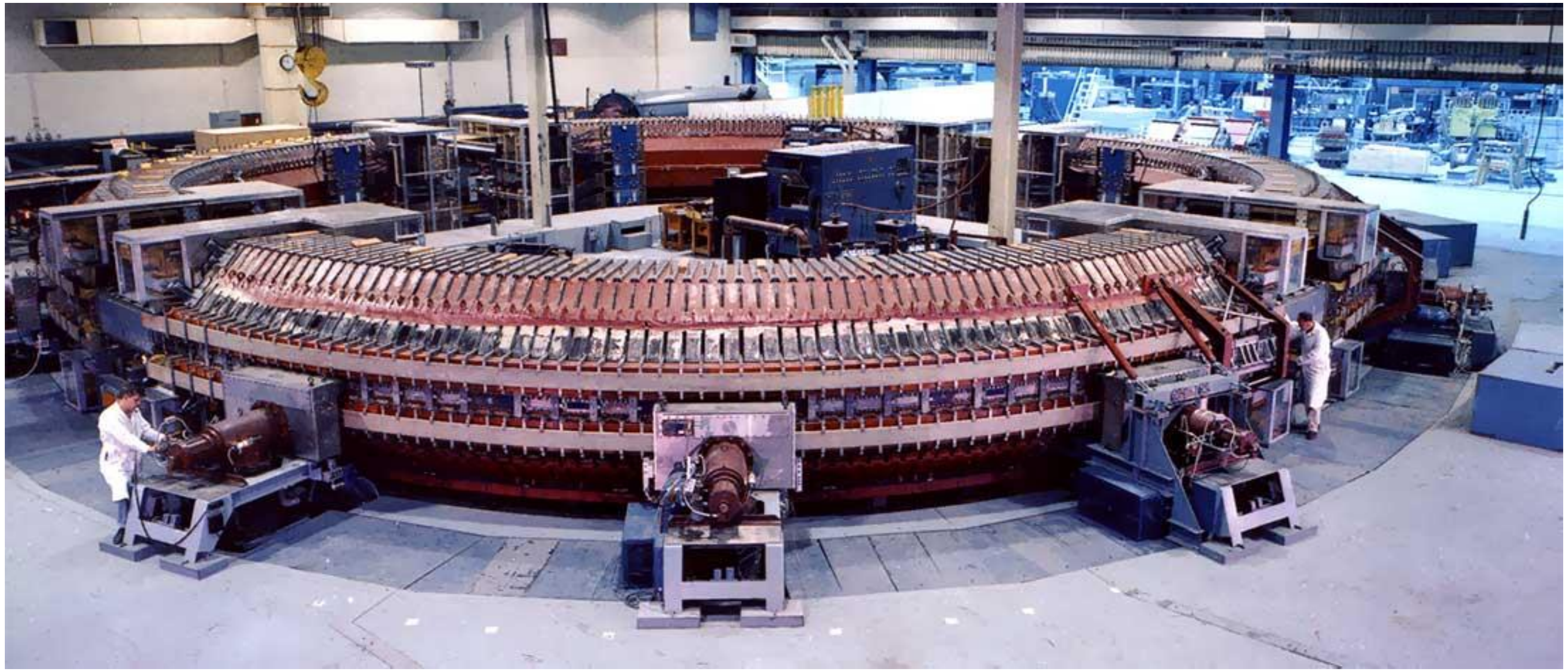




Example of a SPS Magnetic cycle

After the invention, slow progress…

Huge problems to be solved in the first generation of proton synchrotrons, aiming at the GeV energy (1 GeV Birmingham 1953, 3 GeV Cosmotron Brookhaven 1954, 6 GeV Bevatron Berkeley 1954)



The Cosmotron, 1954-1966)

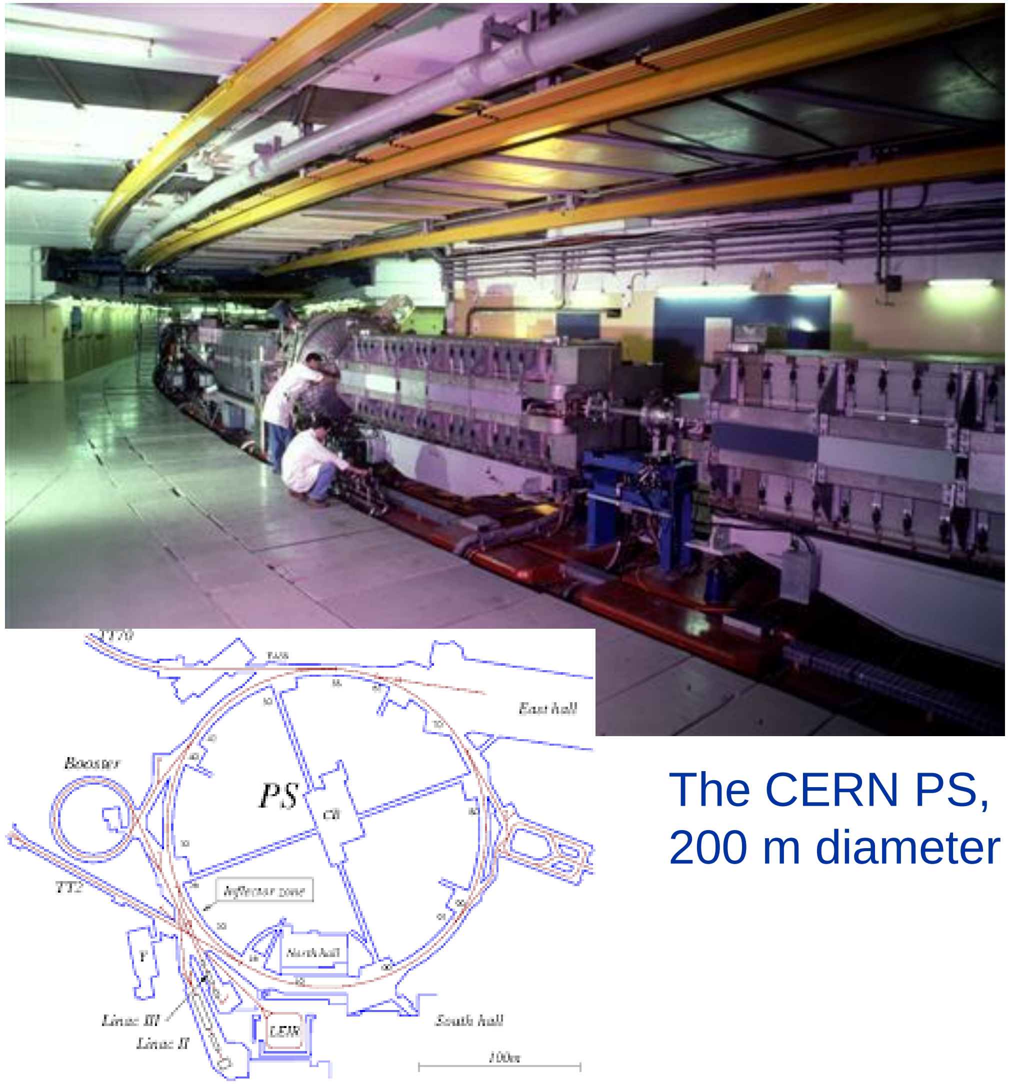
- Large frequency swing required for the RF system (fast variable inductors);
- High pulsed power to be fed to the magnets;
- Large magnet apertures (1.22x0.22m in the Cosmotron!). required at very high cost, to keep a beam with only weak focusing provided by shaping of the magnet poles;
- Fast magnets for injection (from a linac) and extraction of the beam.

The last missing element: strong focusing

E. Courant checks the effect of “turning” some of the Cosmotron magnets… and discovers the strong focusing effect of alternating gradients! This results in a famous paper by Courant, Livingston and Snyder published in 1952. The same idea had been independently patented in 1950 by N. Christofilos.

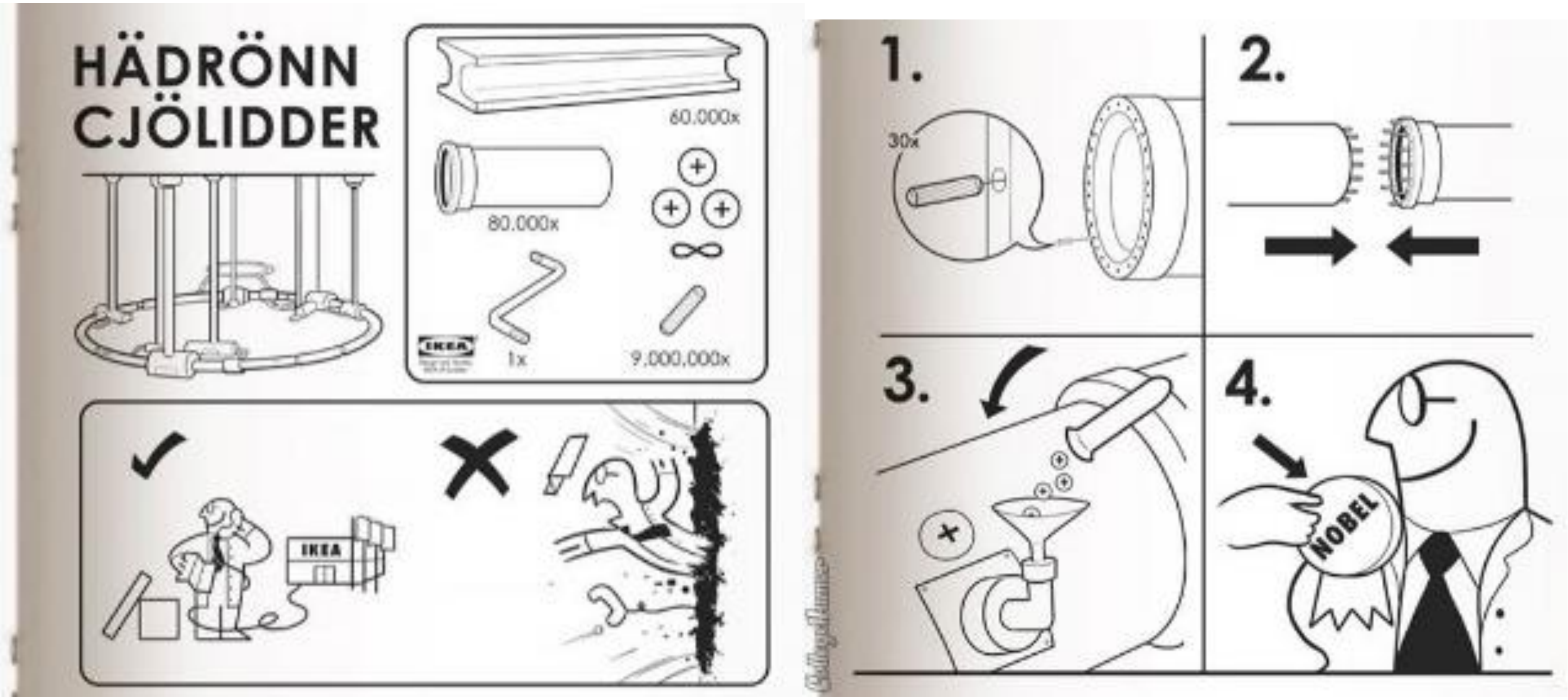
In 1953 a delegation from CERN arrived in Brookhaven (O. Dahl, F. Goward and R. Wideröe) and immediately abandoned the idea of a 10 GeV weak focusing PS for the newly established CERN laboratory, in favour of a 25 GeV strong focusing PS for the same price. Brookhaven had already made similar plans for their AGS. But more problems were feared with strong focusing, and all other labs remained on weak focusing.

In 1959 the CERN PS was completed, and the first beam was accelerated to full energy on 24.11 – after W. Schnell introduced a circuit to change phase at transition, placed in a Nescafe tin.

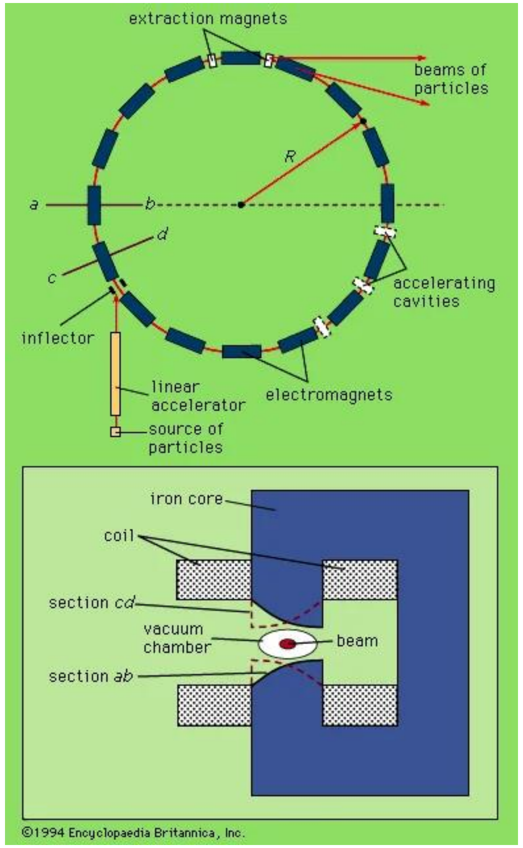


The CERN PS, 200 m diameter

Building blocks 2 - synchrotrons



Alternating gradient strong focusing in a nutshell



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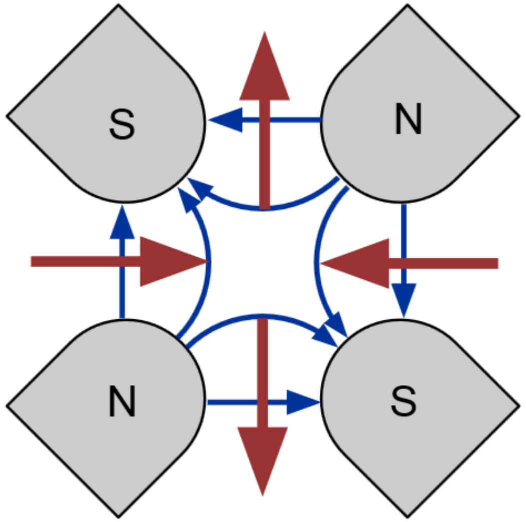


Figure 2.9: Blue magnetic field and red force directions for a focusing quadrupole

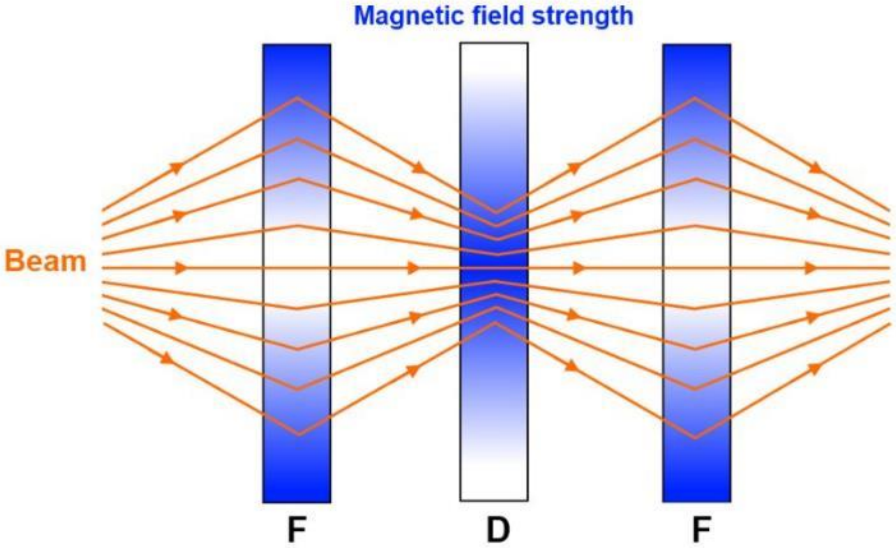
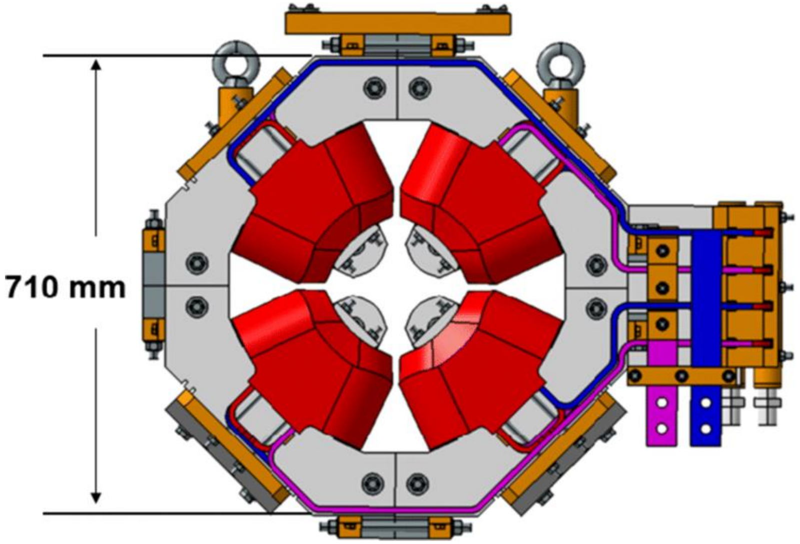


Figure 2.10: Strong focusing with alternating quadrupoles.

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 “contain” 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!

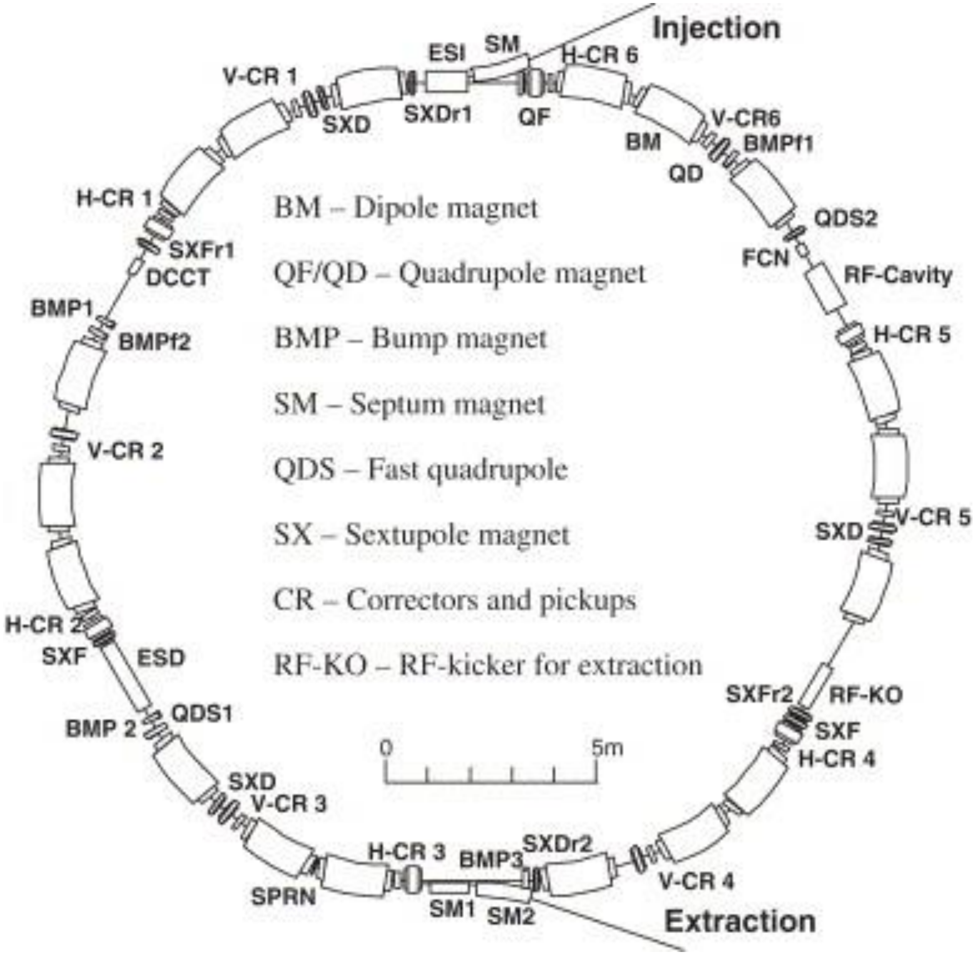
Some examples of quadrupole magnets



A quadrupole magnet installed in the CERN SPS

Electromagnets are used because changing the current and the field in the magnet allows changing the frequency and period of the transverse beam oscillations (“betatron oscillations”), thus protecting the beam from dangerous resonances due to errors and misalignments.

A complete synchrotron

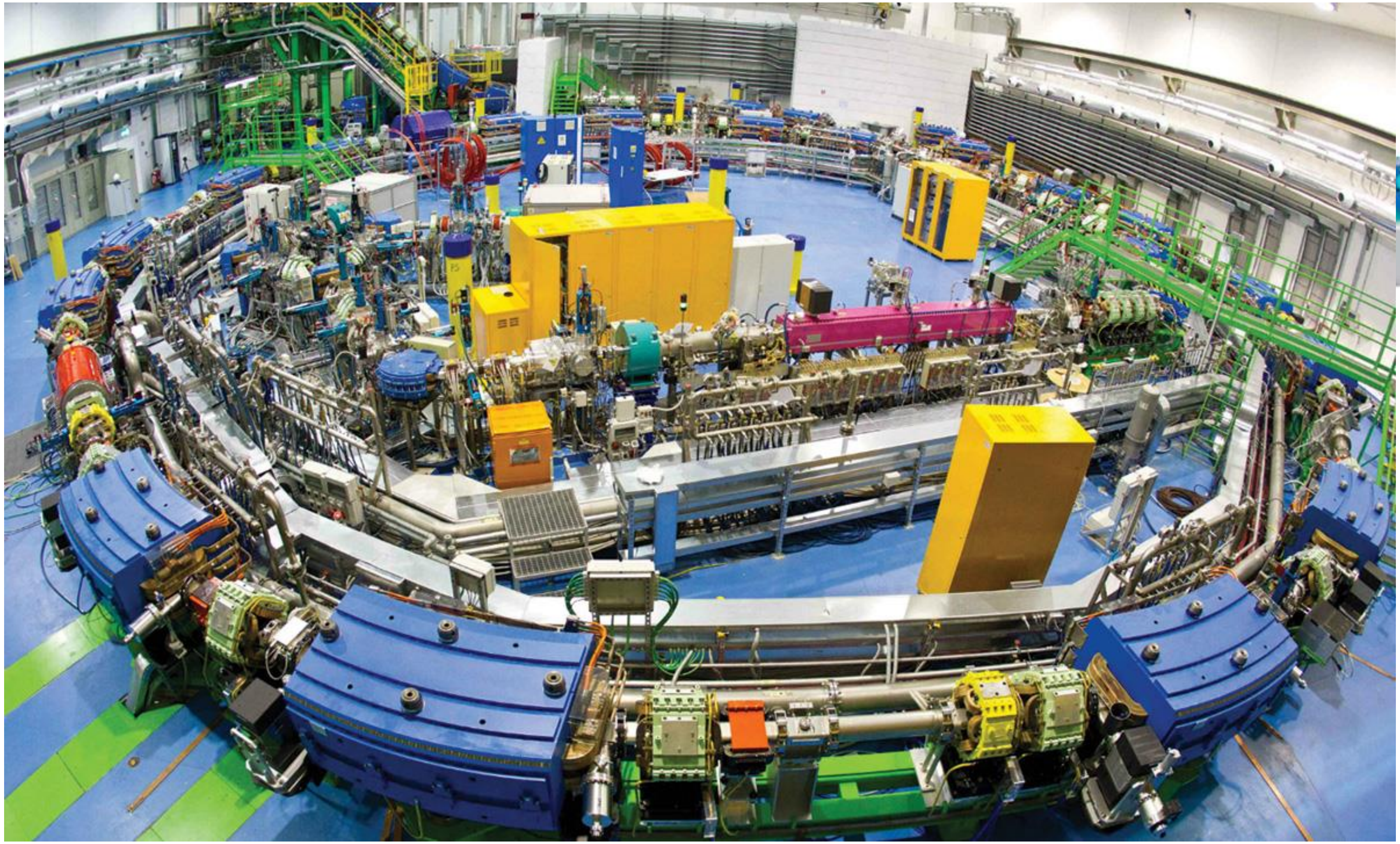


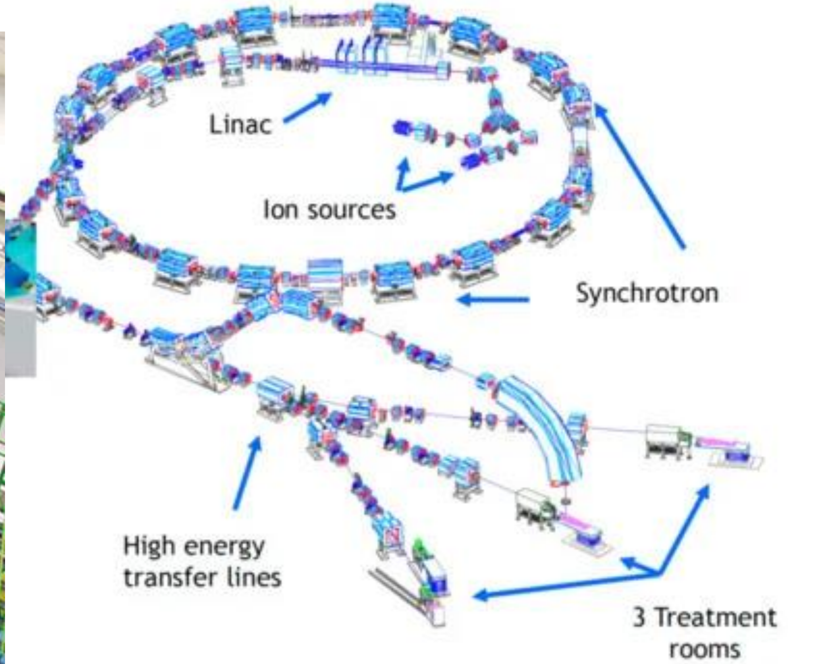
The HIMAC carbon ion therapy synchrotron (Japan)

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
- 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

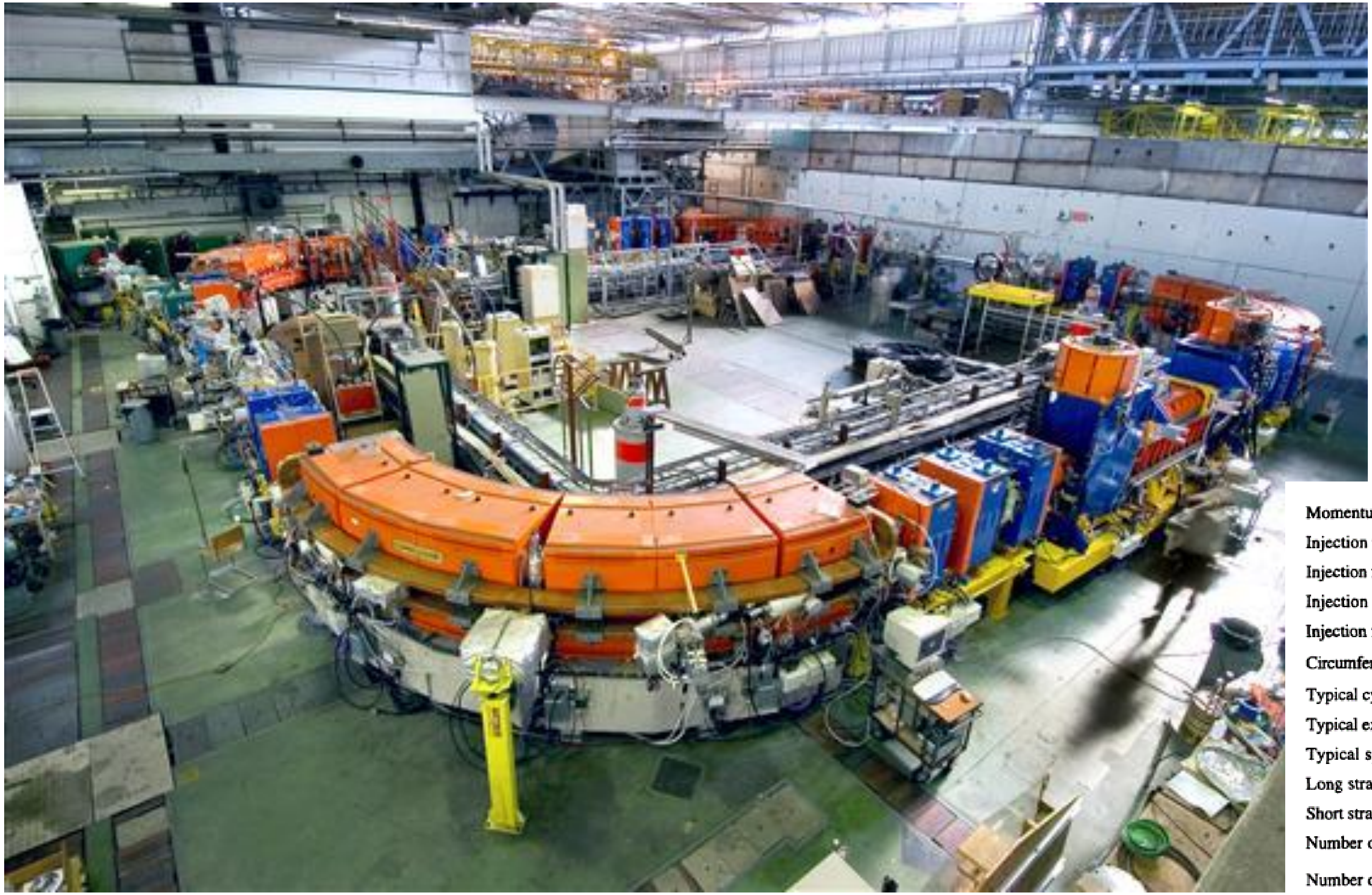
The CNAO synchrotron for carbon ion therapy





Accelerated Particles	H^+	C^{6+}
Mean Ring Diameter	24.5 m	
Typical Repetition Rate	0.5 Hz	
Injection Energy	7 MeV/u	
Injection Scheme	multi-turn	
Revolution Frequency at Injection	0.48 MHz	0.47 MHz
Ejection Energy	60-250 MeV/u	120-400 MeV/u
Ejection Scheme	Resonant - Betatron Core	
Output Emittance [π mm mrad (normalized, 4-rms)]	2.1	3.0
Estimated Particle Losses	30 %, from ion source to patient	

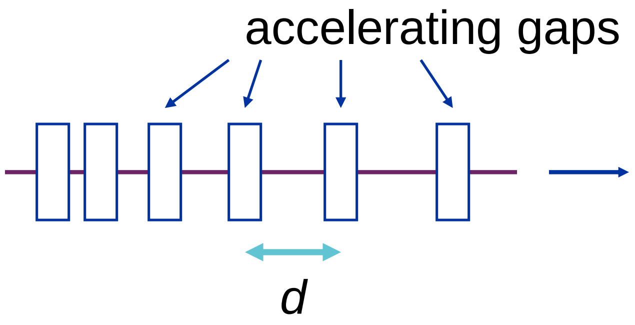
The smallest CERN synchrotron: LEIR

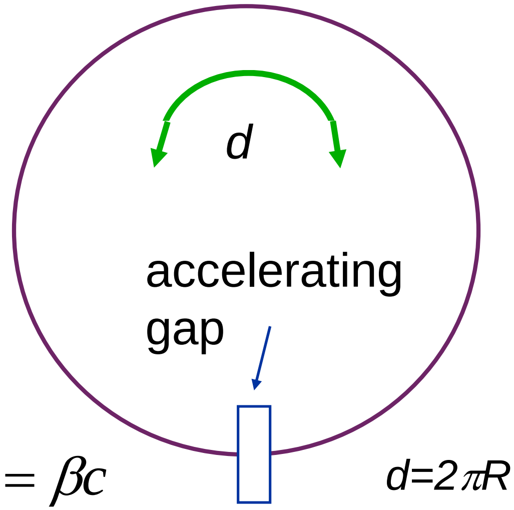


Momentum (kinetic energy) range	0.1-2 GeV/c (5.3 MeV-1.3 GeV)
Injection momentum (kinetic energy) for antiprotons	0.609 GeV/c (180 MeV)
Injection frequency for antiprotons	2 078.18 kHz
Injection momentum (kinetic energy) for protons	0.310 GeV/c (50 MeV)
Injection frequency for protons	1 197.84 kHz
Circumference	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)

Linear and circular accelerators

What is the ideal transition energy between a linac and a synchrotron?





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

$$d=\frac{\beta c}{2f}=\frac{\beta\lambda}{2}$$

$$2d\,f=\beta c$$

d=2π*R*=*constant*

Linear accelerator:

Particles accelerated by a sequence of gaps (all at the same RF phase).

Distance between gaps increases proportionally to the particle velocity, to keep synchronicity.

Used in the range where β increases. "Newton" machine

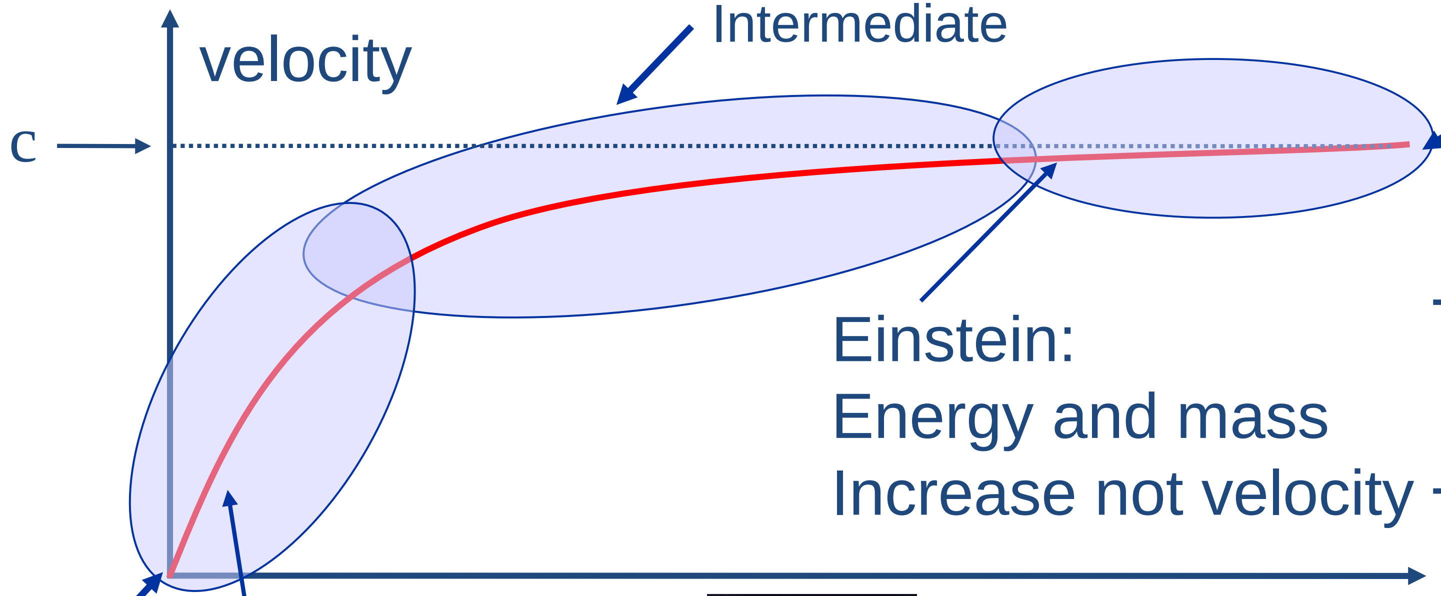
Circular accelerator:

Particles accelerated by one (or more) gaps at given positions in the ring.

Distance between gaps is fixed. Synchronicity only for β~const, or varying (in a limited range!) the RF frequency.

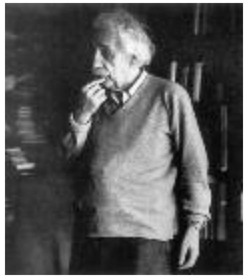
Used in the range where β is nearly constant. "Einstein" machine

Newton and Einstein regions



Einstein:
Energy and mass
Increase not velocity

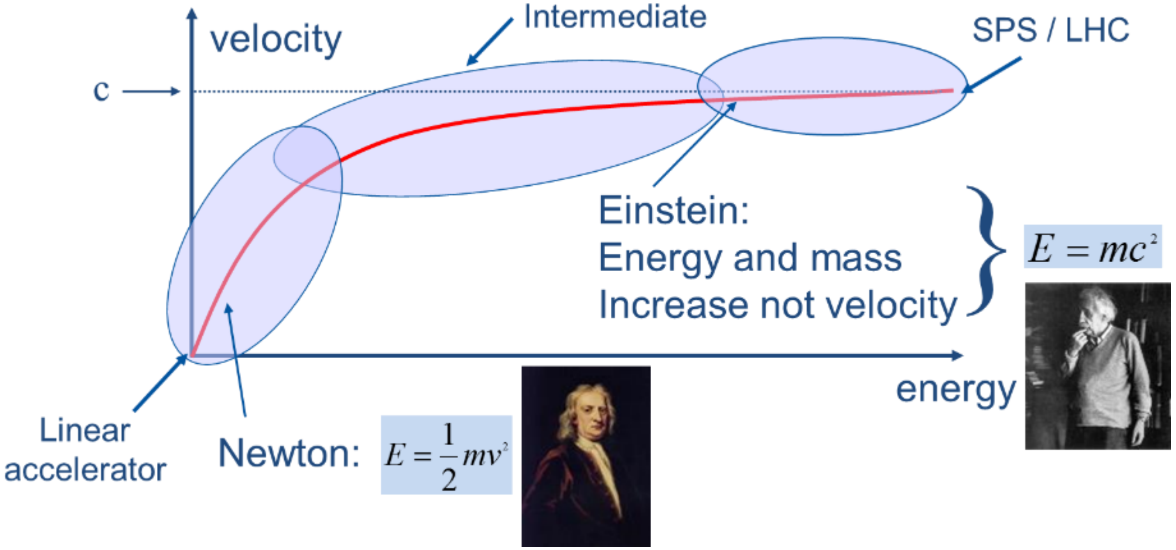
$$E = mc^2$$



Linear
accelerator

Newton: $E = \frac{1}{2}mv^2$

The intermediate region



In the intermediate region we can use long linear accelerators or small synchrotrons.

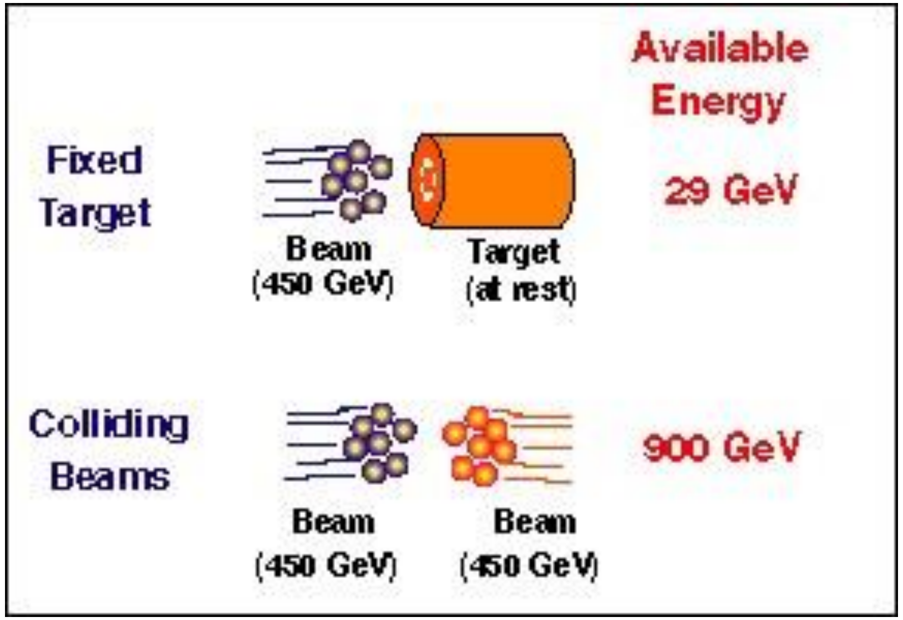
Linear accelerators are more expensive but can accelerate a larger number of particles.

Synchrotrons can accept a small variation of velocity by changing the frequency of their RF accelerating system (within some limits).

The CERN accelerator system was designed for high energy and the the old linac (Linac2) goes up to only 50 MeV (beta 0.31). The new Linac4 goes up to 160 MeV (beta 0.53).

History of particle accelerators 3 – colliders

Colliding particle beams



What counts for physics is the centre of mass energy developed in the collision.

Because of relativity, the energy available at centre of mass in fixed target collisions is much lower than the energy of the particle beam.

Instead, for heads-on collisions of two beams traveling in opposite directions, the available energy is exactly twice the energy of the particle beams.

Accelerators capable of colliding beams are much more efficient than accelerators sending their beam to a fixed target !

Fixed Target Accelerators vs. Colliders

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

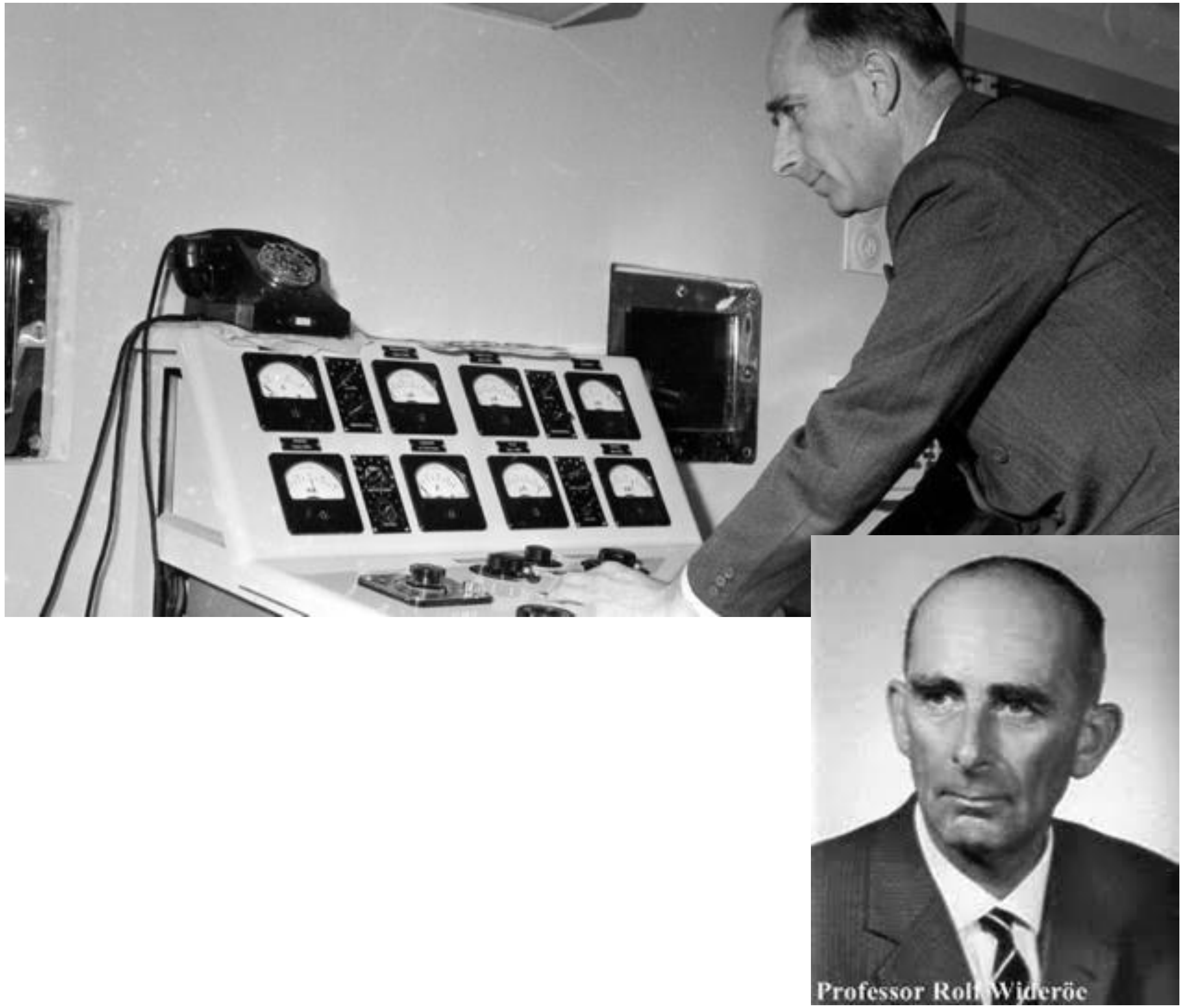
The long road to modern colliders

Who was the first to propose using particle colliders?

Again, **Rolf Wideröe** !

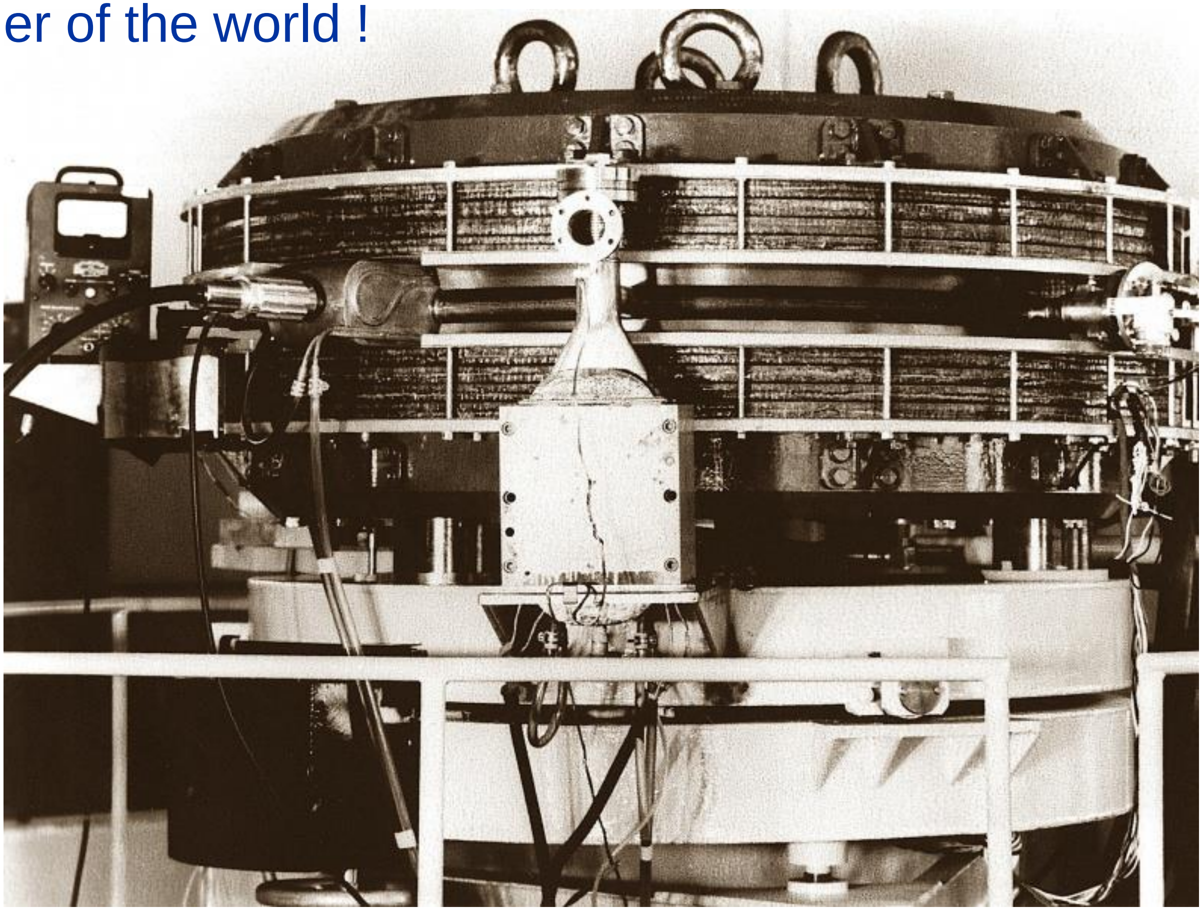
After inventing RF acceleration, he went to building betatron accelerators for electrons.

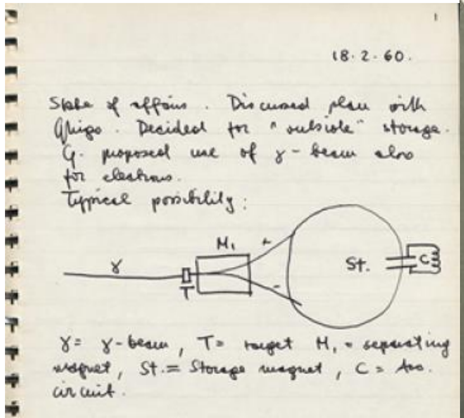
During the war years spent in Germany Widerøe patented his idea to use colliding beams to maximise the energy available (against the advice of his assistant Bruno Touschek, who found the idea too trivial to publish).



AdA – the first collider

Bruno Touschek in 1961 together with a team of Italian scientists and engineers was the first to use the collider principle in AdA (Anello di Accumulazione), a small e+e– storage ring in Frascati - the first collider of the world !



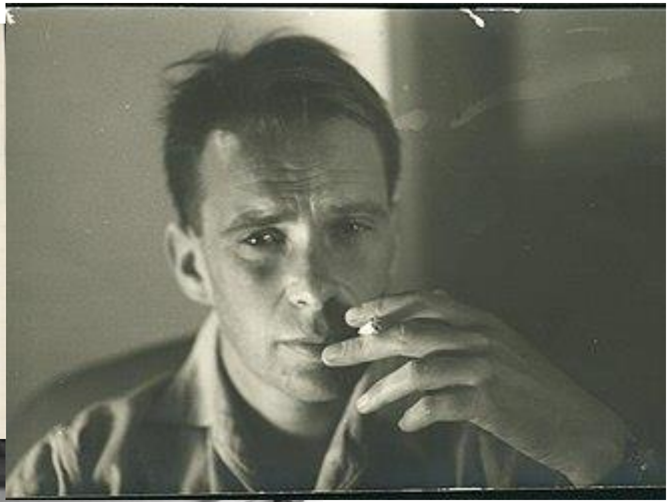


1

18.2.60.

State of affairs. Discussed plan with Ghigo. Decided for "outside" storage. G. proposed use of γ-beam also for electrons.
Typical possibility:

γ = γ-beam, T = target H₁ = separating magnet, St. = Storage magnet, C = r.f. circuit.



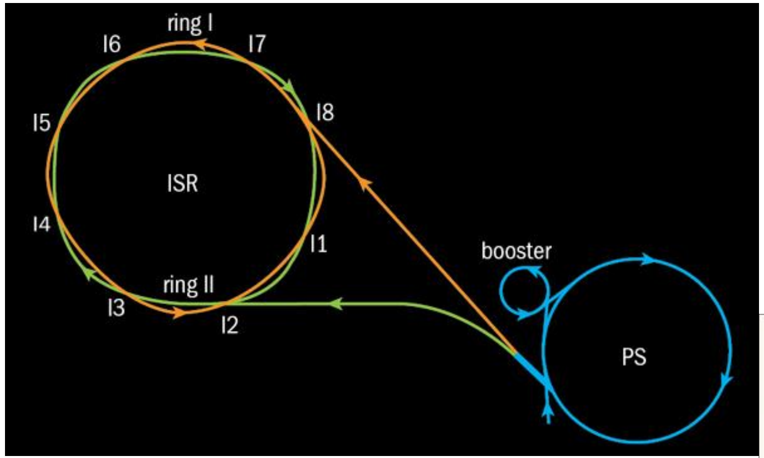
More colliders: electrons and hadrons

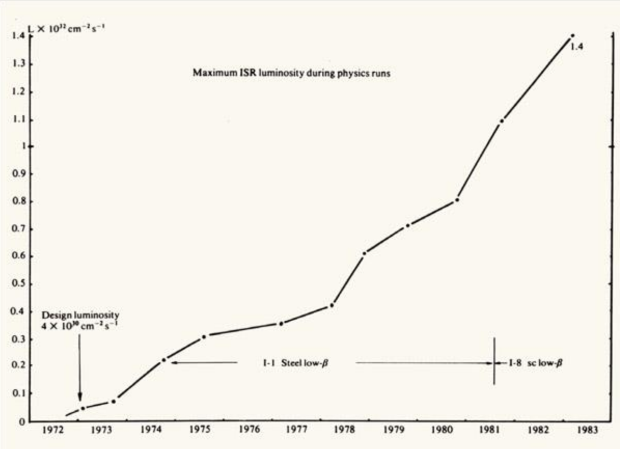
In parallel to the INFN AdA project, two other colliders were built:

- At Stanford, by a Stanford-Princeton team (W.C.Barber, B. Gittelman, G. O’Neill, B. Richter)
- At Novosibirsk (URSS), the VEP-1 electron-electron collider (Gersh Budker).

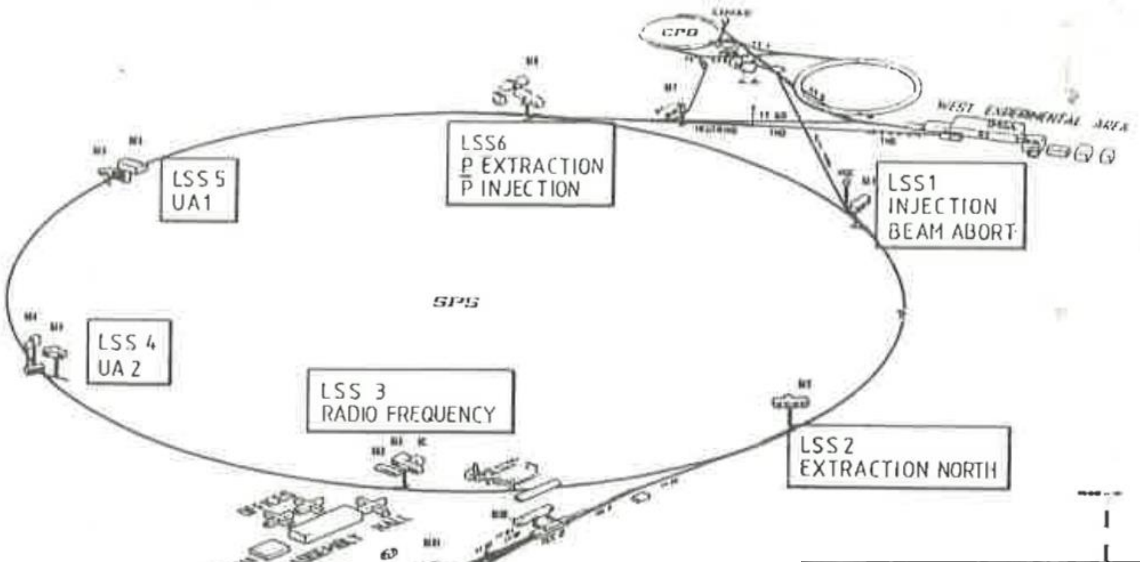
The first observations of particle reactions in the colliding beams were reported almost simultaneously by the three teams in mid-1964 - early 1965.

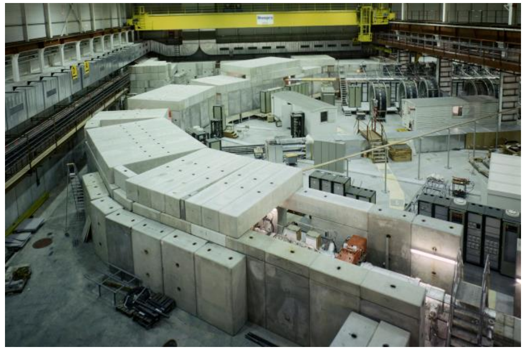
In 1966, work began on the proton-proton Intersecting Storage Rings at CERN, and in 1971, this collider was operational. The ISR was a pair of storage rings that accumulated and collided protons injected by the CERN Proton Synchrotron. This was the first hadron collider.

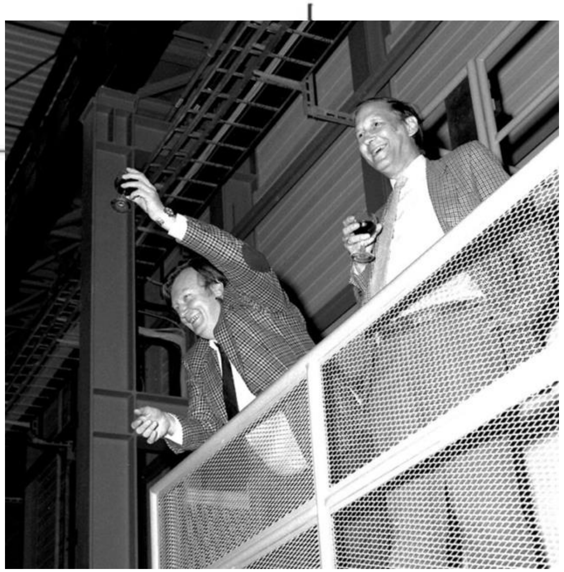




SppbarS collider

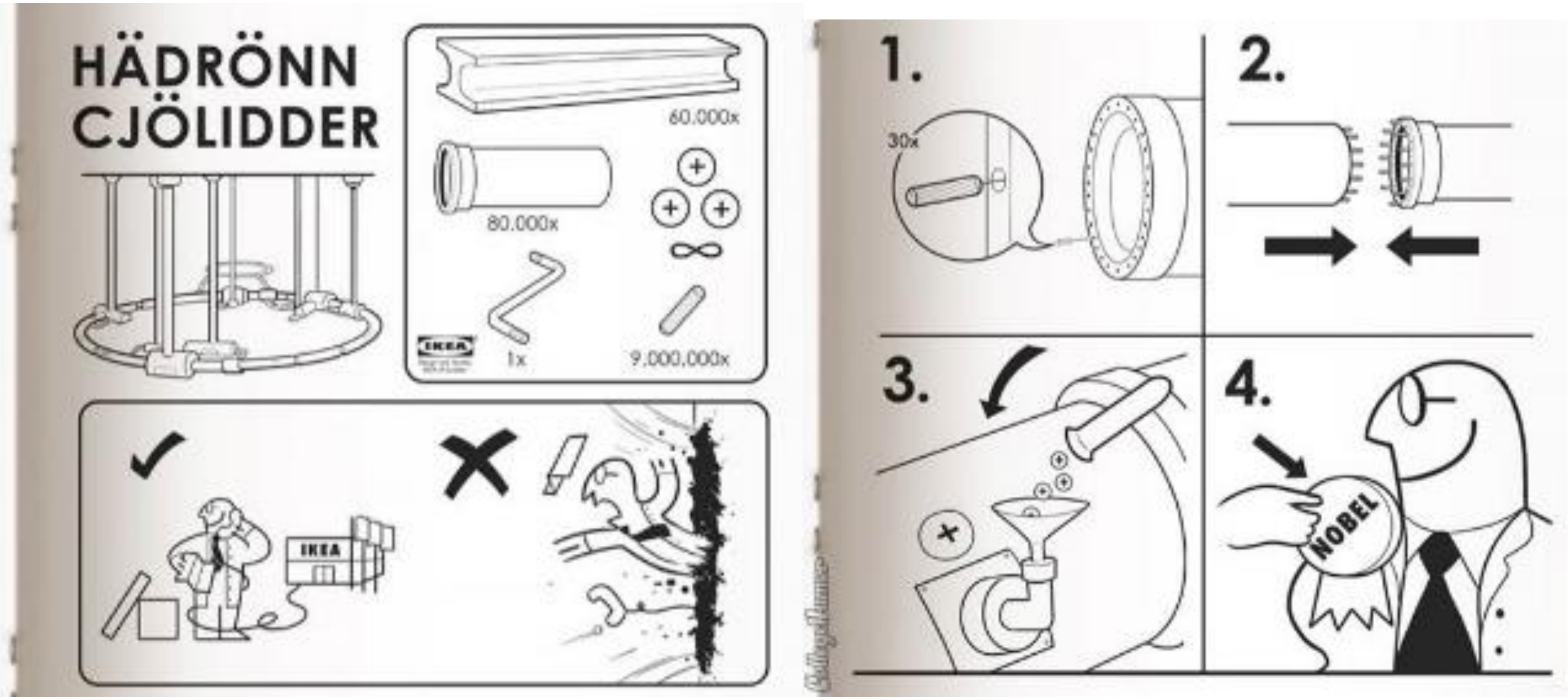






- 1976: C. Rubbia proposes to modify the CERN accelerator complex to transform the SPS into a collider, injecting antiprotons and colliding them with protons.
- 1978: project is approved, start preparation of the antiproton production, accumulation, and cooling (stochastic cooling by S. Van der Meer).
- 1981: start operation.
- 1983: discovery of the W and Z bosons.
- 1984: Rubbia and van der Meer receive the Nobel prize.

Building blocks 3 – colliders and storage rings



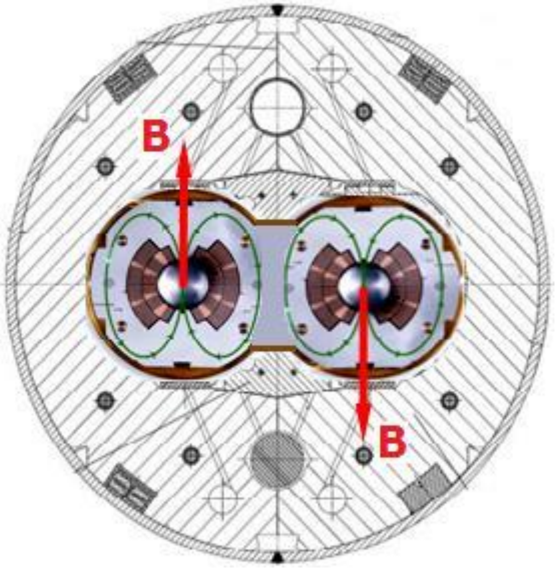
Technical challenges for particle colliders

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

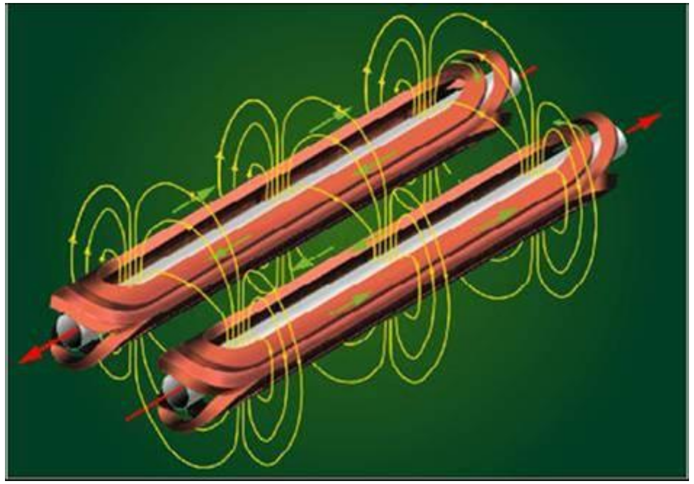
1. The particles have same mass but opposite sign and circulate in the same vacuum chamber and magnetic field (ex.: electron-positron and proton-antiproton colliders).
2. The particles are the same and they circulate in separate vacuum chambers and opposite magnetic fields (Ex.: the LHC).

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

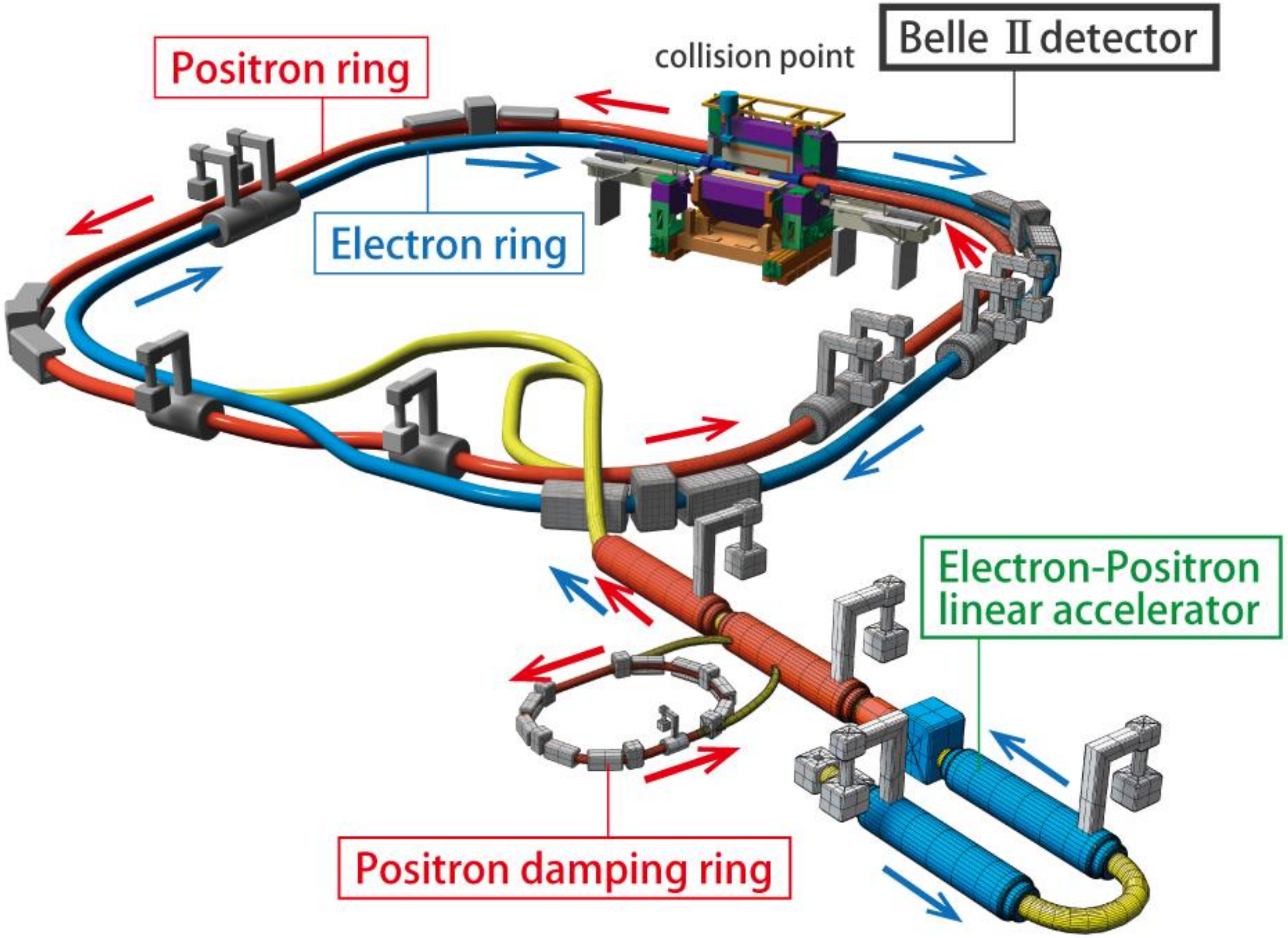
Problem with 2) is the need to use twin-bore dipole magnets or separate magnets



2-in-1 magnet configuration of LHC

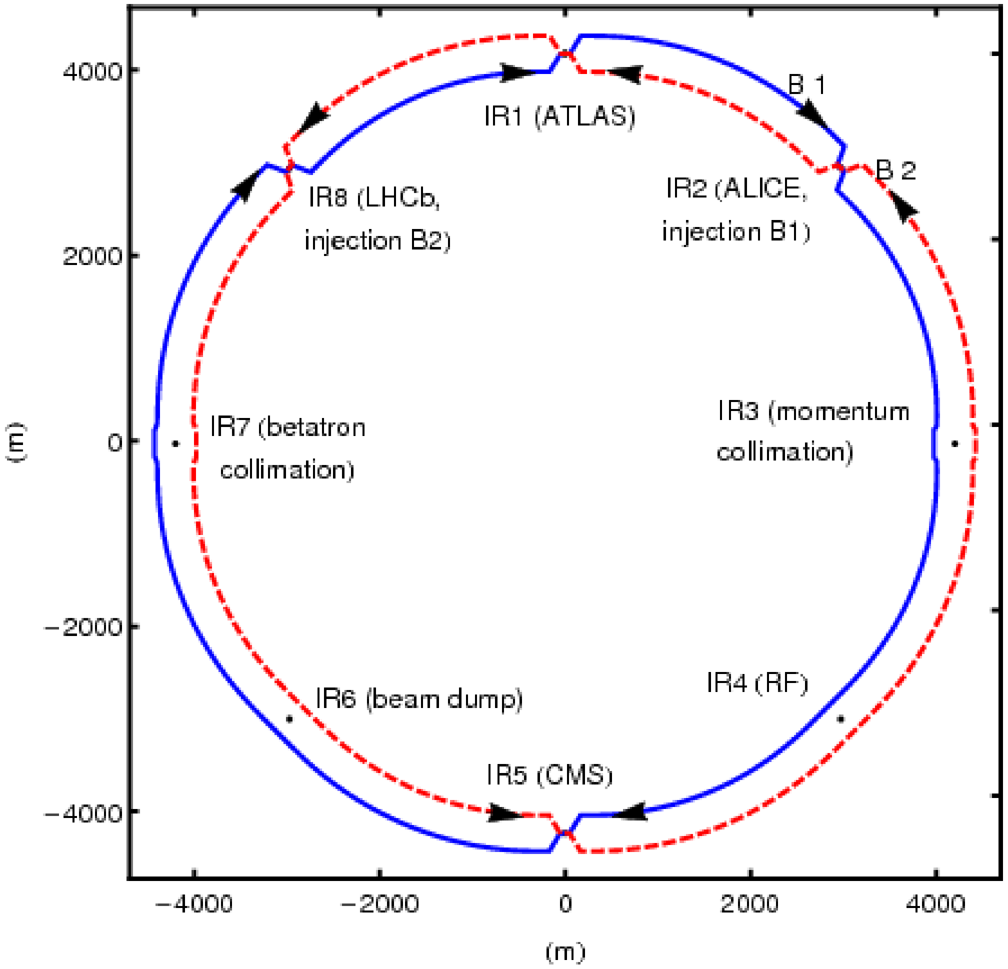


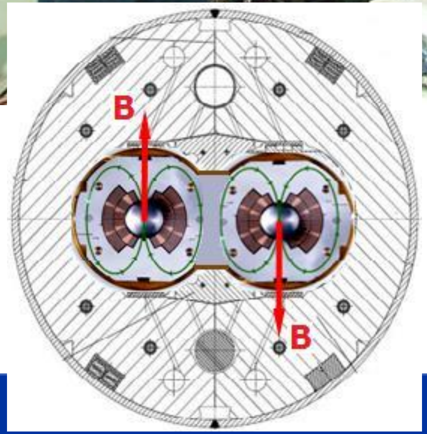
Electron – positron colliders



The KEK-B collider (Japan)

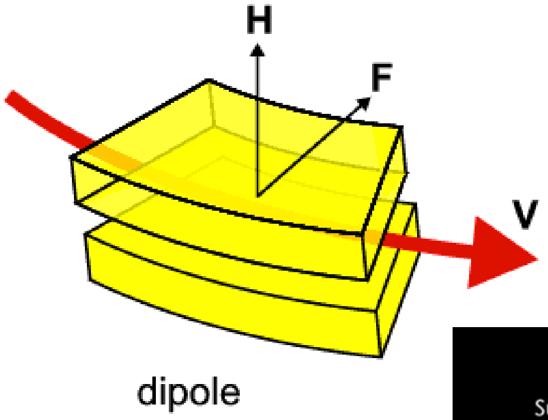
The Large Hadron Collider



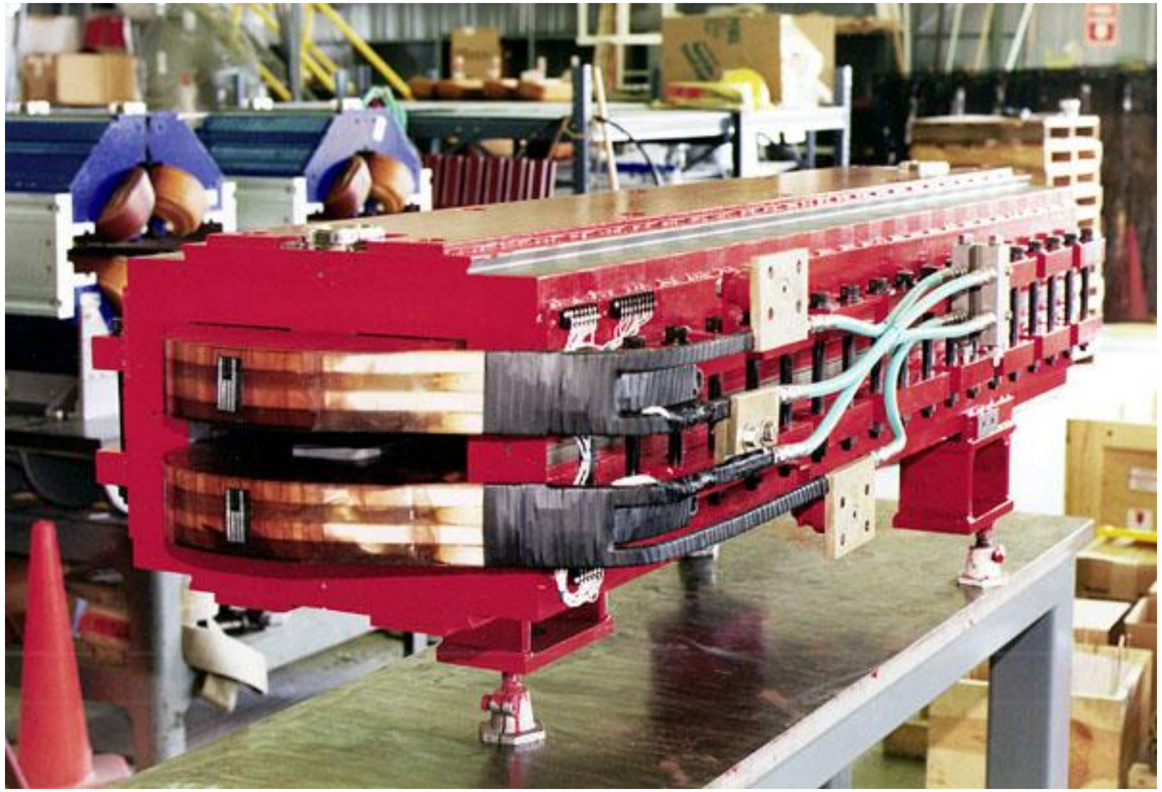


The 1232 LHC magnets contain two pipes, one for each of the counterrotating beams.

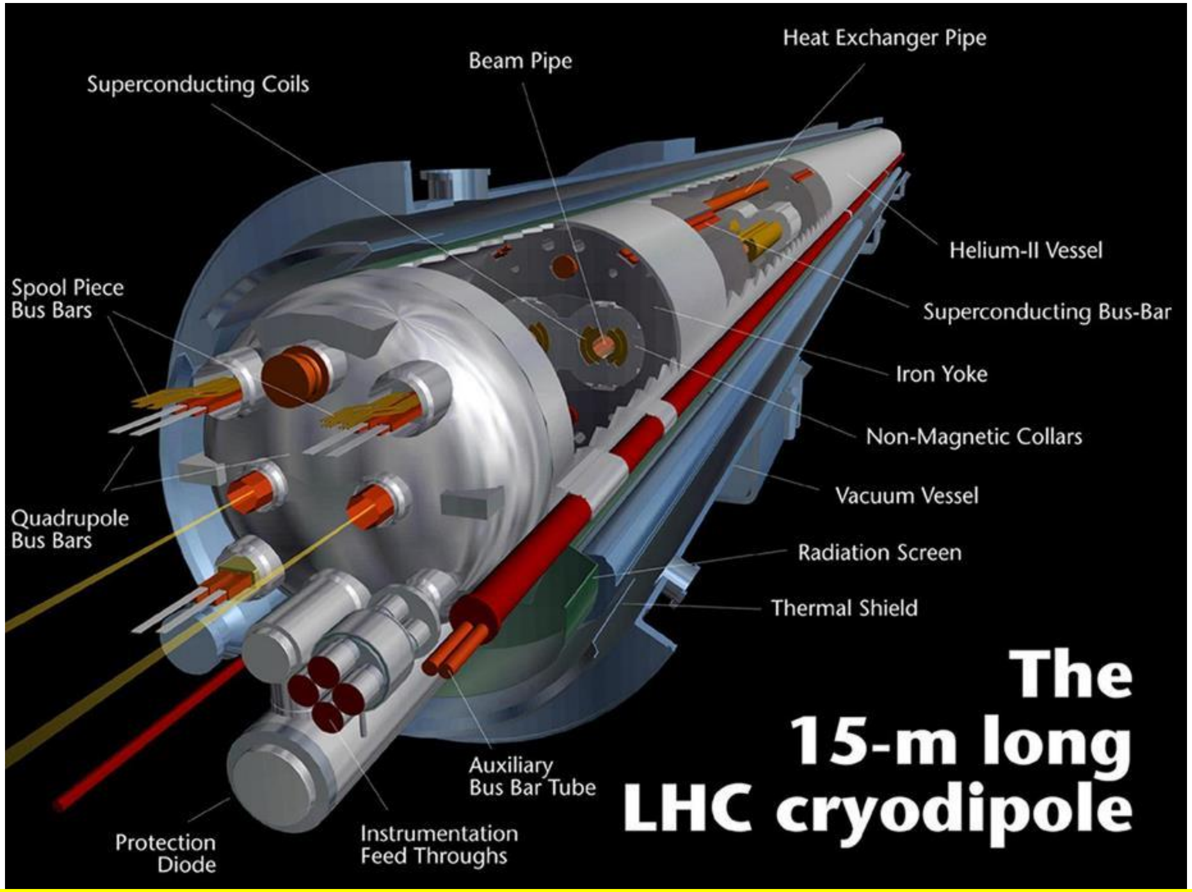
The magnets



Normal conducting



Superconducting

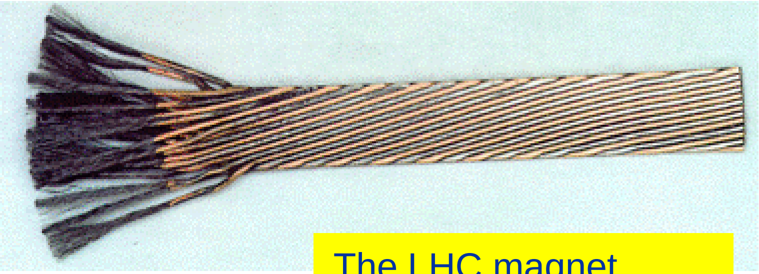


15 metres length, maintained at -269 degrees by a flow of liquid helium. Magnetic field 8 T, 5 times more than conventional magnets and 10’000 times a small house magnet

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.

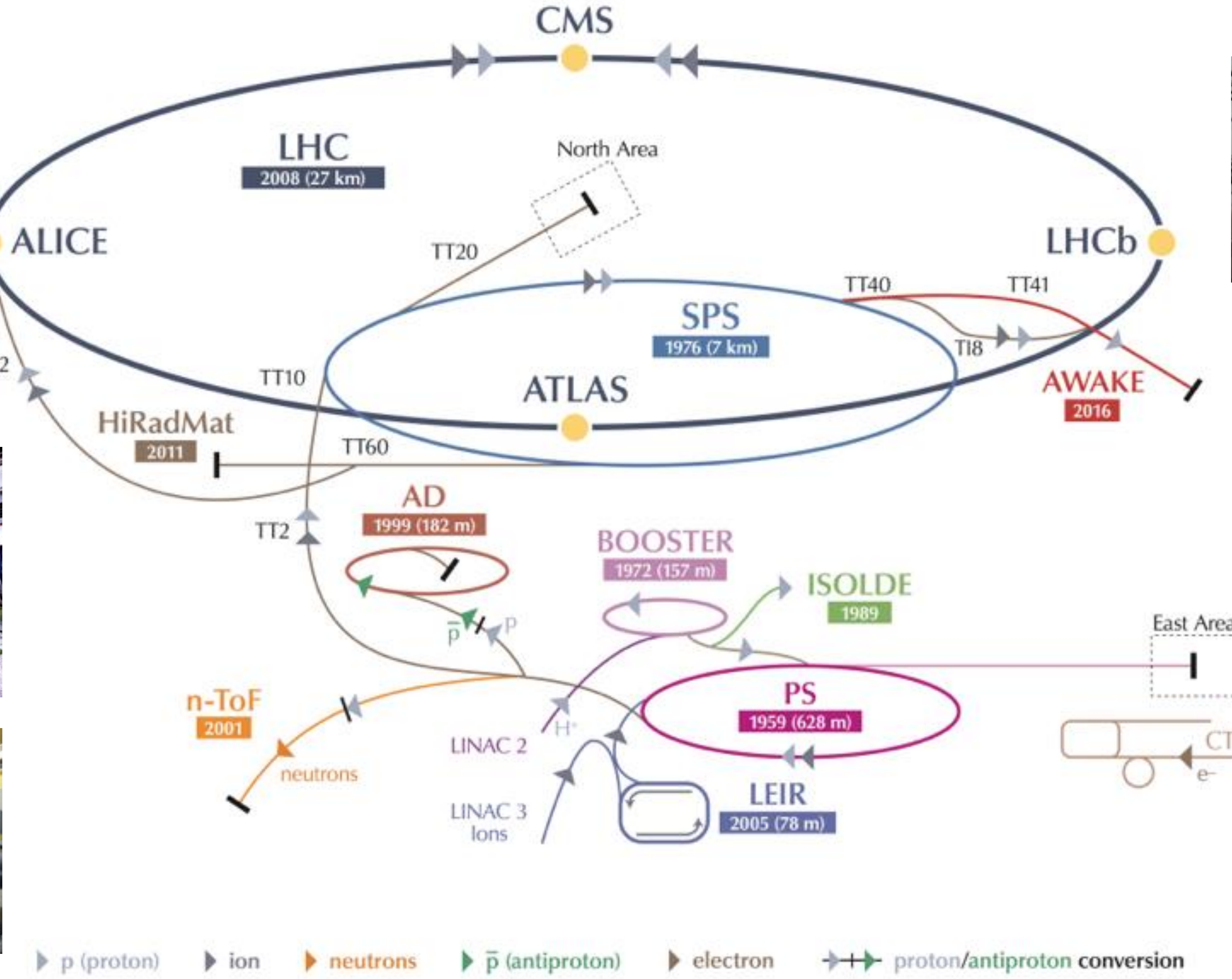

The LHC magnet superconducting cable


Clean room assembly of superconducting RF cavities


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

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

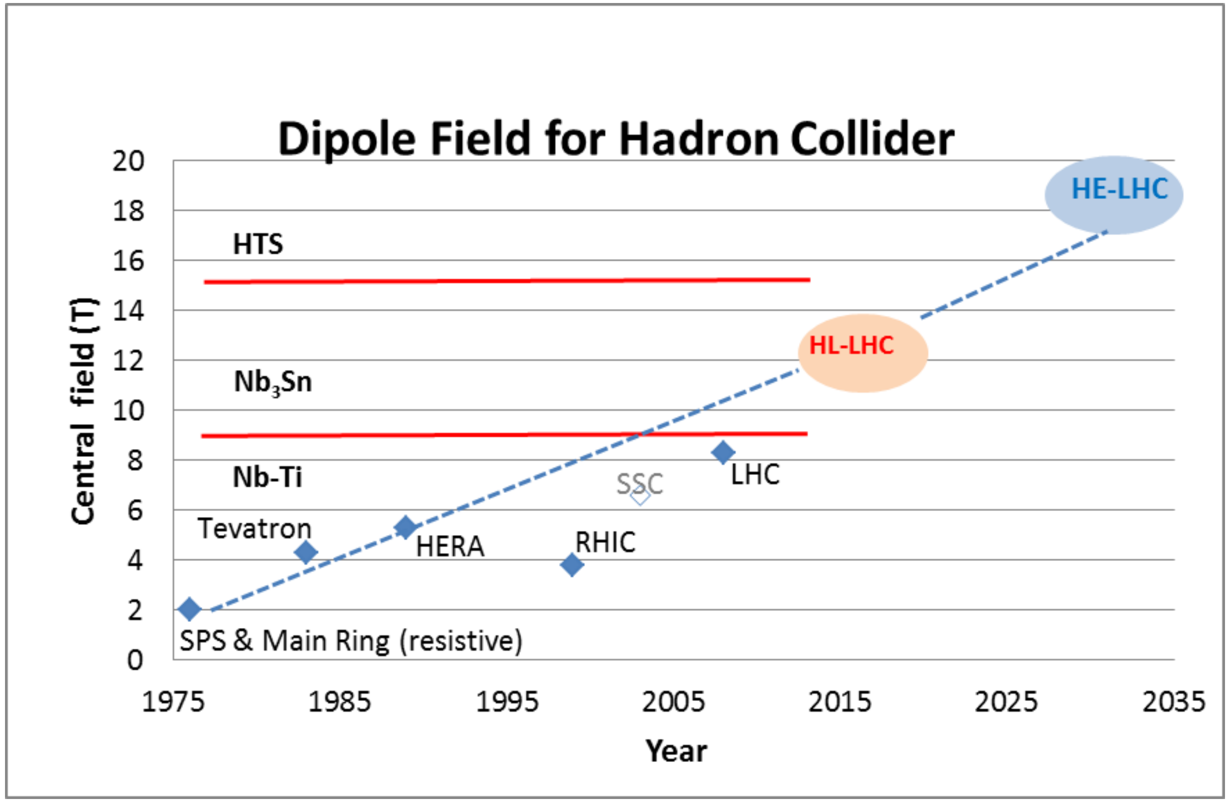
The CERN chain of accelerators



Linear Accelerator (50 MeV)
plus a chain of synchrotrons of increasing energy and radius:

Booster	1.4 GeV
PS	25 GeV
SPS	450 GeV
LHC	7 TeV

The magnetic field limitation



The final limitation to the size and to the energy of a synchrotron comes from the magnetic field that can be achieved.

Technological limit:
about 2 T normal conducting magnets
8 T Nb-Ti superconducting magnets
12 T future Nb3Sn superconducting magnets

$$B\rho = \frac{p}{e} \approx \frac{E}{ce} \text{ so } E[\mathrm{GeV}] \approx 0.3\, B[\mathrm{T}]\, \rho[\mathrm{m}] \text{ per unit charge}$$

Dealing with Energy

The energy in one LHC beam at high energy is about 320 Million Joules

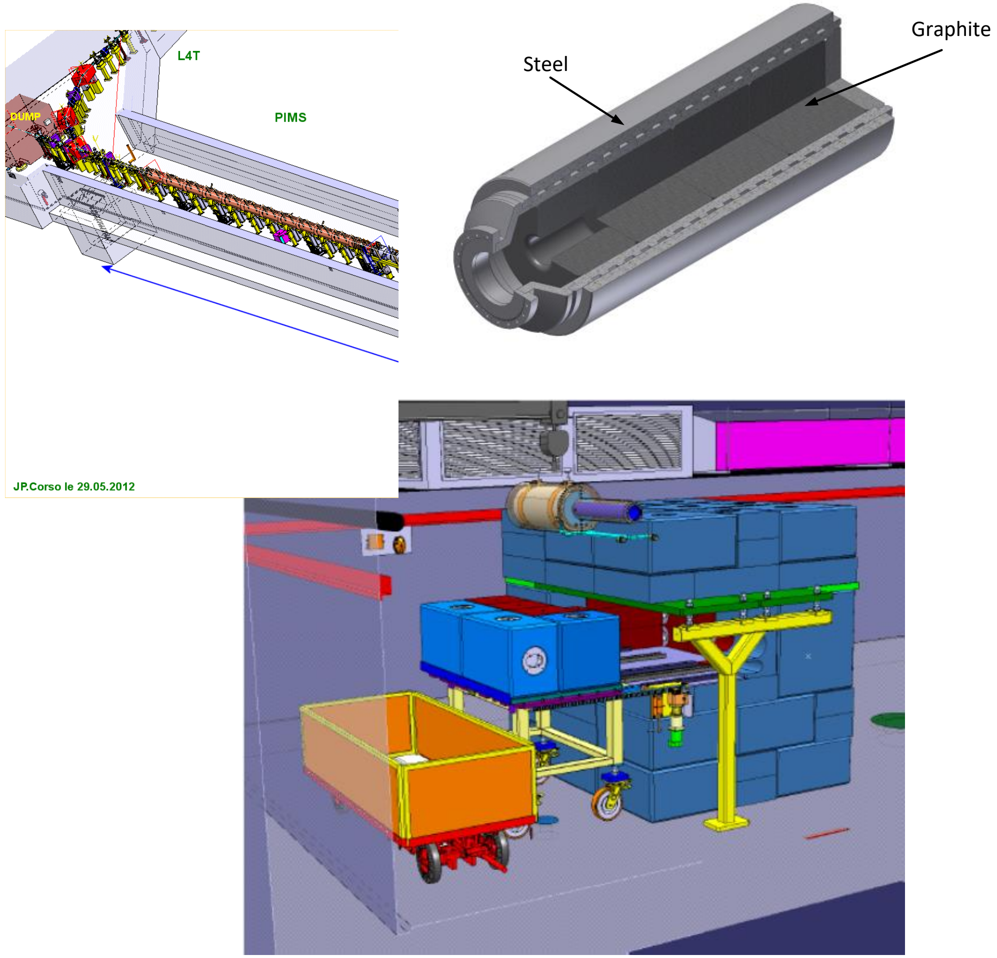
- This corresponds to the energy of a TGV engine going at 150 km/h

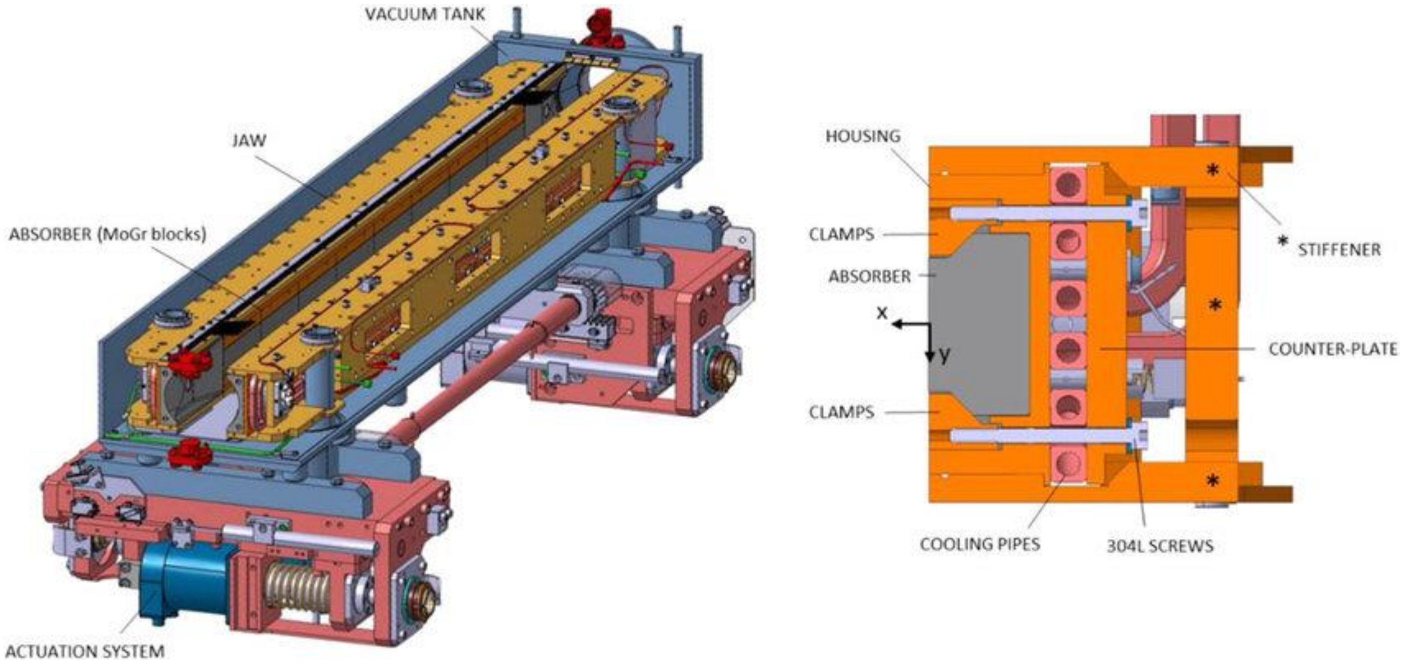
...... but then concentrated in the size of a needle

Beam collimators and dumps

Even a tiny fraction of the LHC beam lost in a magnet can cause a dangerous quench

Linac4 Main Dump





HL-LHC collimators

Luminosity, the Collider Figure of Merit

$$LUMINOSITY = \frac{N_{event/\sec}}{s_r} = \frac{N_1 N_2 f_{rev} n_b}{4ps_x s_y} F$$

Intensity per bunch

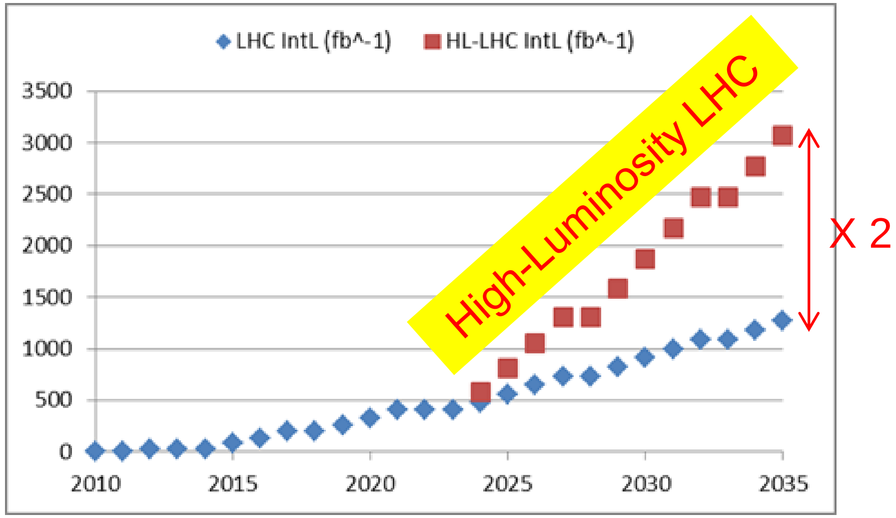
Number of bunches

Geometrical Correction factors

Beam dimensions

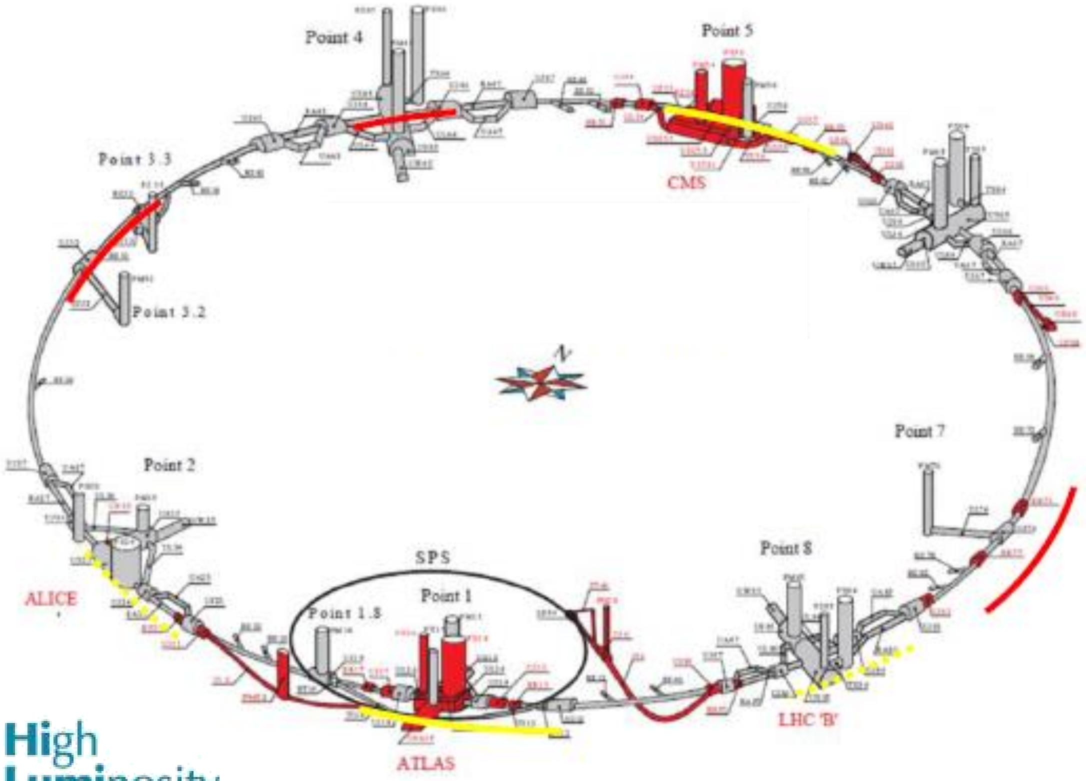
- More or less fixed:
  - Revolution period
  - Number of bunches

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



The High-Luminosity LHC Project

Is the major ongoing accelerator project at CERN – to be completed in 2026



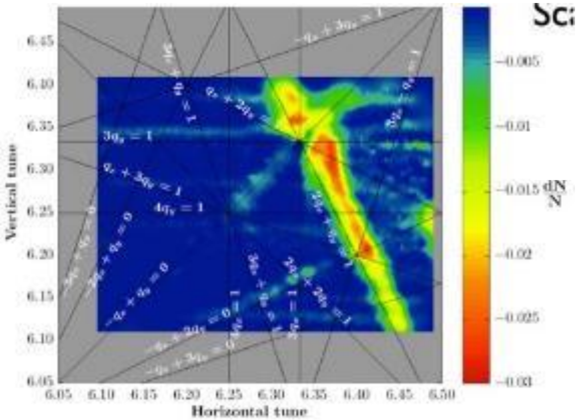
- New IR-quads (inner triplets)
- New 11T short dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major interventions on more than 1.2 km of the LHC

The LHC injectors for higher luminosity

- LINAC4 – PS Booster:
  - New LINAC 4 with H^- injection
  - Higher injection energy
  - New Finemet® RF cavity system
  - Increase of extraction energy

- PS:
  - Injection energy increase from 1.4 GeV to 2 GeV
  - New Finemet® RF Longitudinal feedback system
  - New RF beam manipulation scheme to increase beam brightness

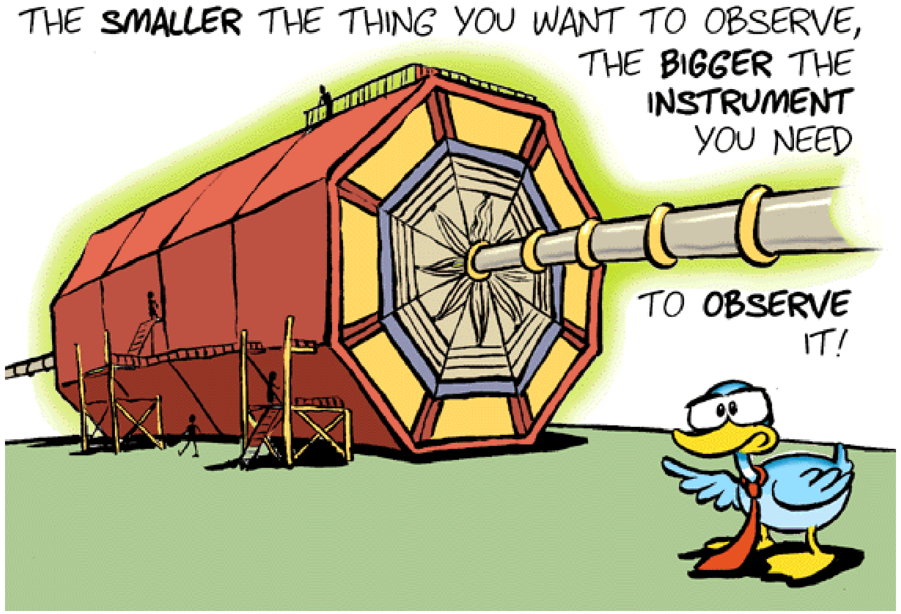


Courtesy of A. Huschauer

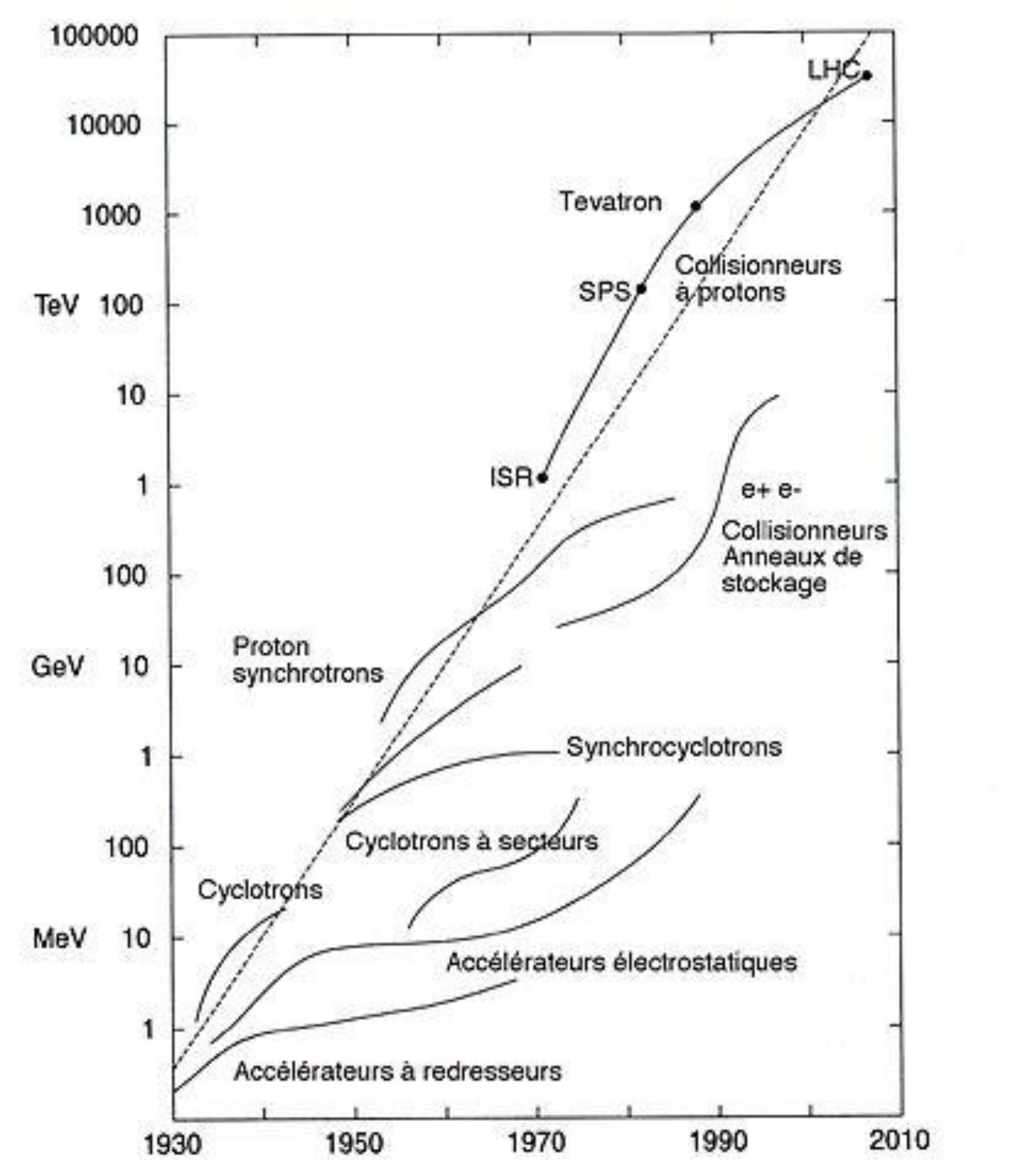
- SPS
  - Machine Impedance reduction (instabilities)
  - New 200 MHZ RF system
  - Vacuum chamber coating against e-cloud

These are only the main modifications and this list is not exhaustive

The present – particle accelerators in the XXIst century

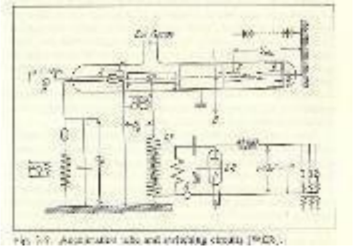


Progress in accelerator technology: Livingston plot



Exponential growth of particle accelerator top energy with time thanks to a series of enabling technologies

Innovation in the particle accelerator field



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

XXI century

?

Cyclotron: cyclic acceleration with magnets (Lawrence)

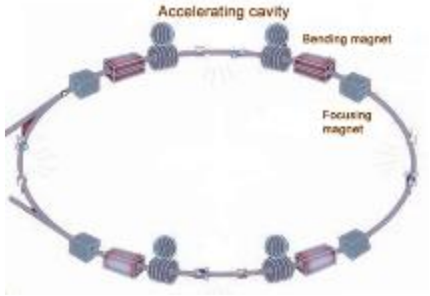
Strong focusing (Courant, Livingston, Snyder, Christofilos)

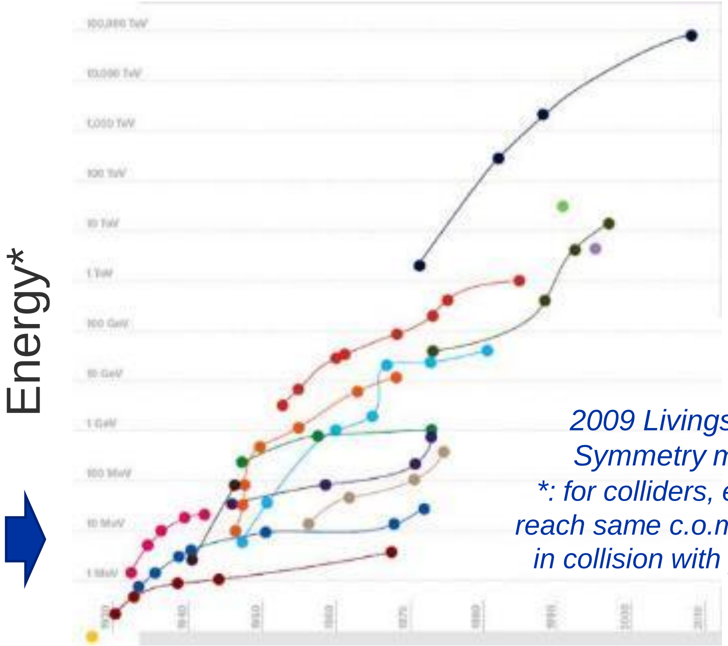
Superconducting magnets and acc. cavities

2008: the Large Hadron Collider

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

Succession of enabling technologies (technology leaps)





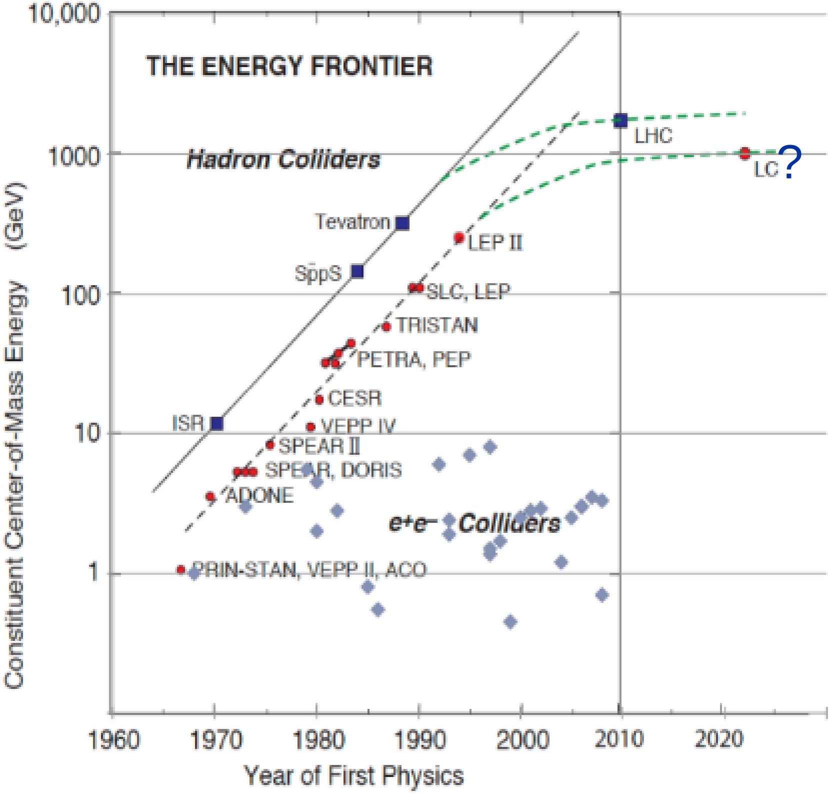
- ● First accelerator
- ● ● Cyclotrons
- ● Cockcroft-Walton electrostatic accel.
- ● Van de Graaff electrostatic accelerators
- ● Betatrons
- ● Synchrocyclotrons
- ● ● Linear accelerators
- ● Electron synchrotrons
- ● Proton synchrotrons
- ● ● ● Storage ring colliders
- ● Linear colliders

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

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

Particle Accelerators in 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!

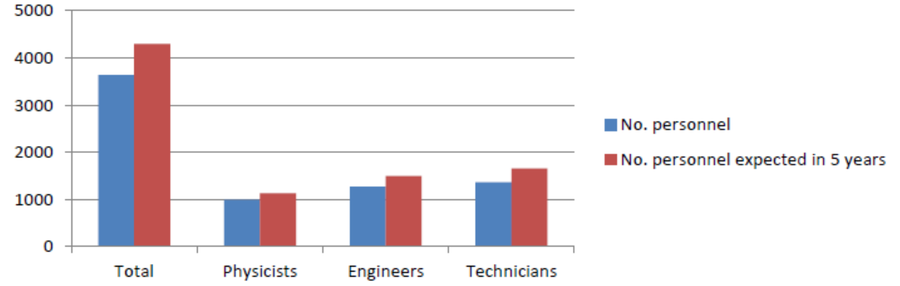


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

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.
- **Advanced medicine** and **new materials** are key technology drivers of the XXIst century.

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%

What is the role of accelerators in this transition?

Accelerators in transition – for physics and for society

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

Fundamental science

Limitations related to size, cost, energy.

innovation

New ideas and technologies

Applied science (photon and neutron sources)

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

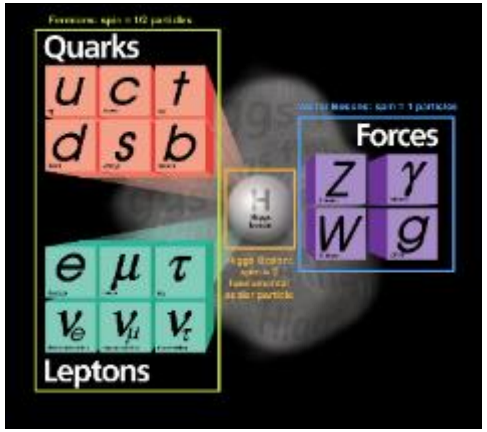
The electron linac for cancer radiotherapy, the most widespread accelerator in the world (> 12000 units)

Reaching the limits of sustainability ?

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

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

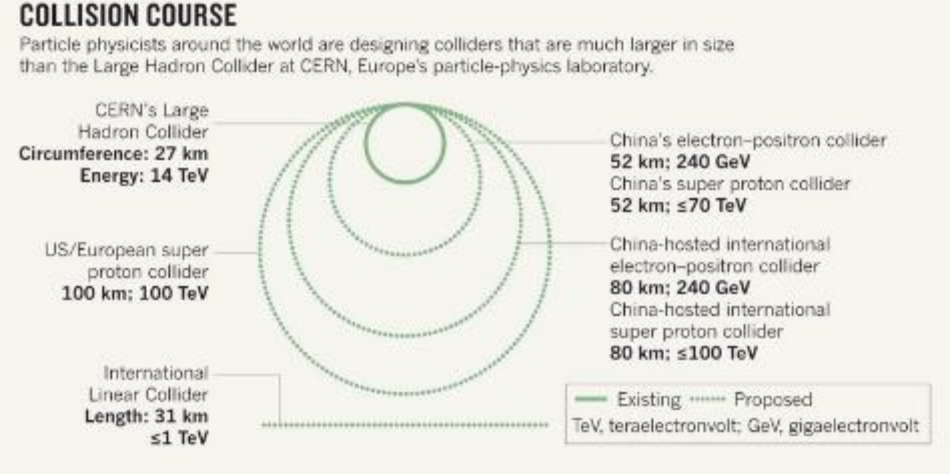
Difficulty to justify new large projects



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

Difficulty to implement new large projects

«Nature», July 2014



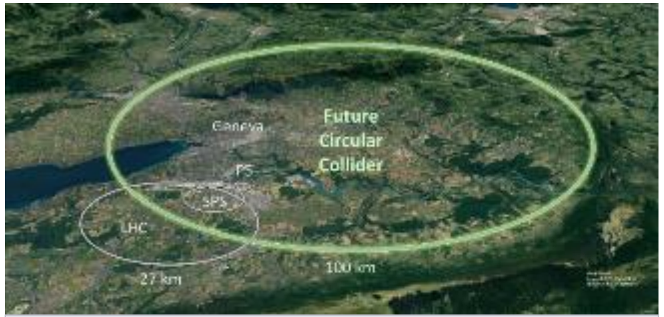
From the 19 December 2018 report of the Science Council of Japan on the construction of an International Linear Collider in Japan:

"In view of the finite resources available to humanity, the research style that presupposes an ever-growing scale-up of gigantic experimental facilities would eventually reach the limit of sustainability. The future way of "big science" is a theme to be deliberated by the whole academic community."

The big challenges for accelerator science

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

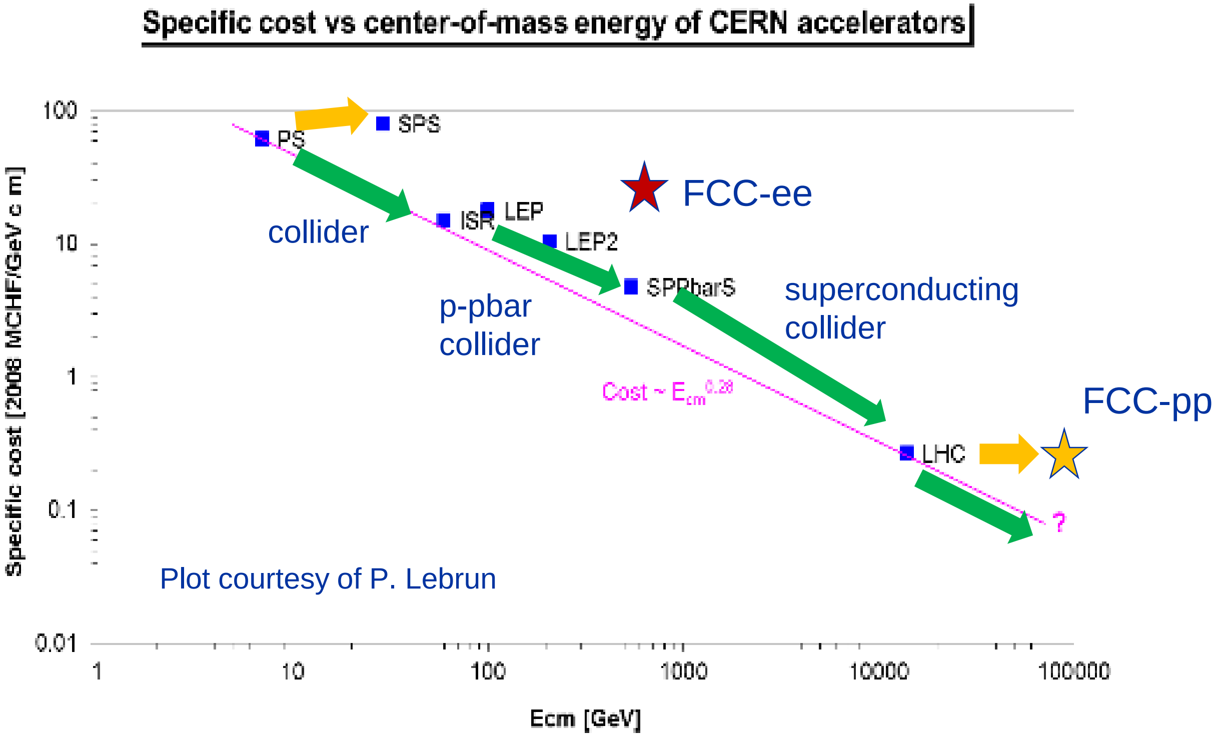
We need new ideas (innovation!) and a collaborative and creative environment for these ideas to grow



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

How does this translate into technical challenges?

Frontier accelerators – economic sustainability


Specific cost vs center-of-mass energy of CERN accelerators

Plot courtesy of P. Lebrun

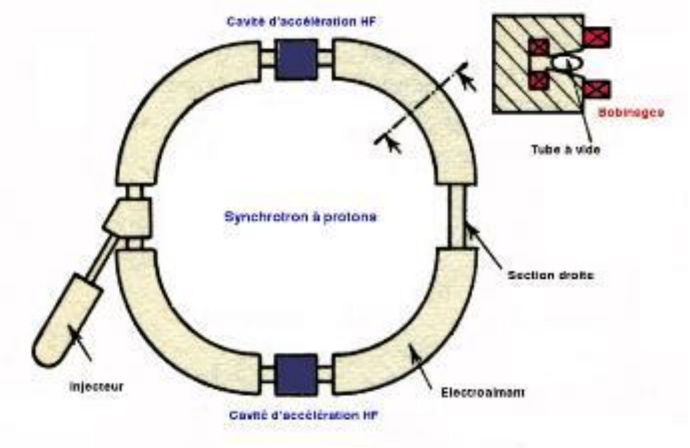
Moving along this line was made possible by new technologies (colliders – antiproton production and storage – superconductivity)

scaling of present technology

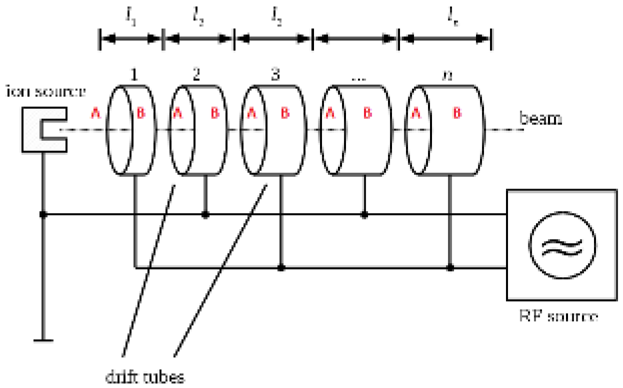
reduction in cost with new technologies?

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 ways to smaller accelerators

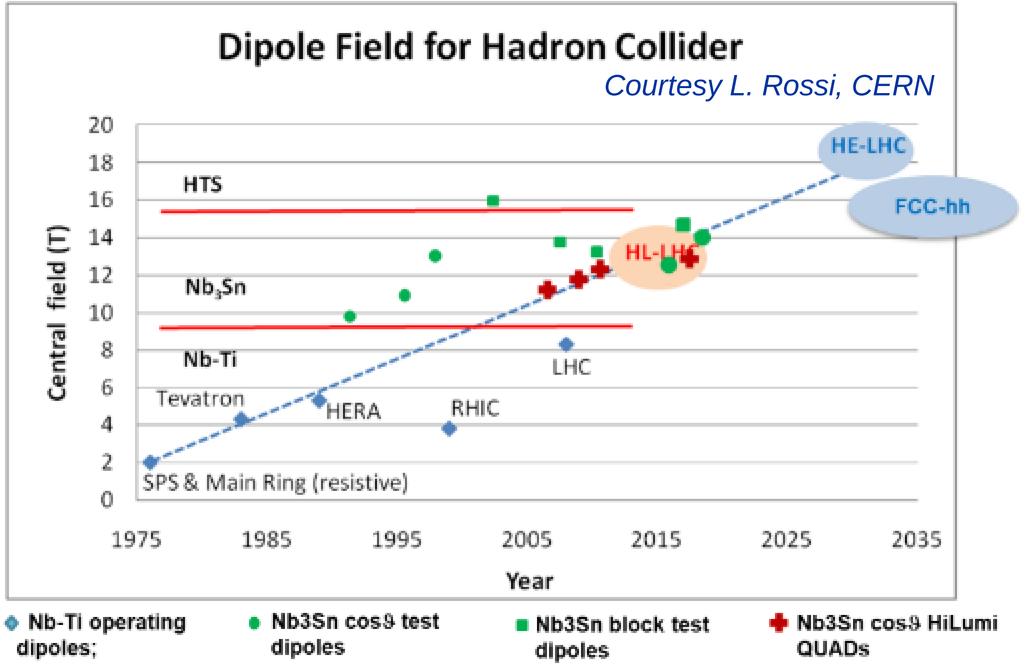


Synchrotrons: $p/q=B\rho$
Need to maximise ***magnetic field***
Superconductivity is mandatory, the limitations is the critical current density Jc for SC magnets



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



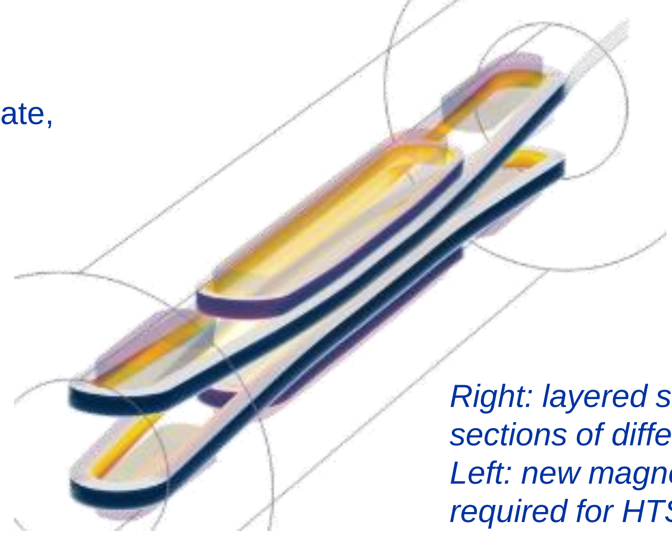
Courtesy L. Rossi, CERN

Three technologies under consideration

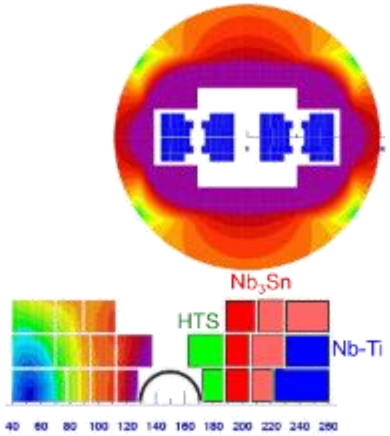
1. **NbTi** (Niobium Titanium as in the LHC): mature but limited to about 9T field.
2. **Nb$_3$Sn** (Niobium Tin) technology has seen a great boost in the past decade (factor 3 in J_C w/r to ITER) but is not yet used in an accelerator – The HL-LHC upgrade will be the first one.
3. **HTS** (High-Temperature Superconductor) technology still in the experimental phase (Production quantities, homogeneity and cost need to evolve!) but can be a disruptive technology for future high-field magnets.

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

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



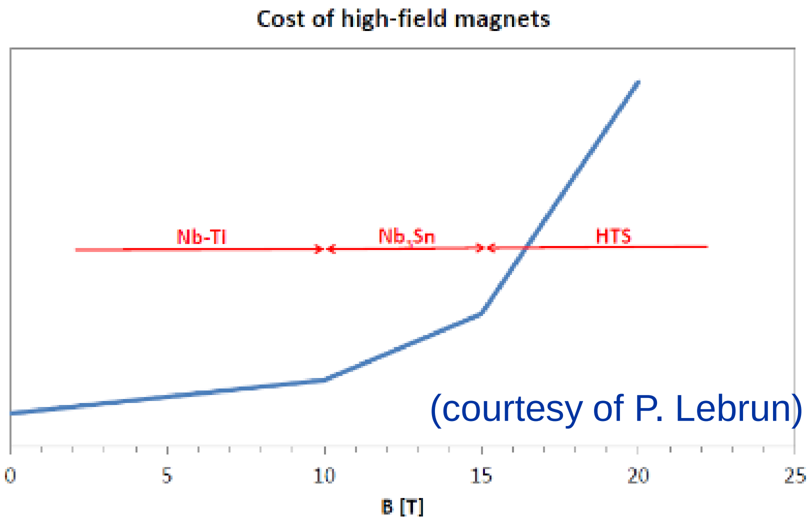
A 20 T HE-LHC dipole
L. Rossi & E. Todesco, (CERN)



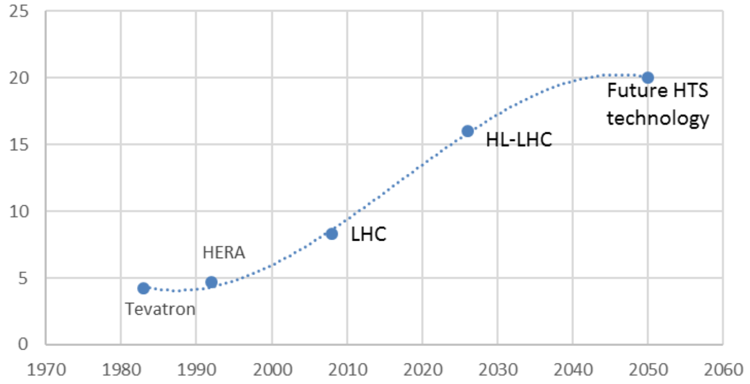
Cost optimized, graded winding

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

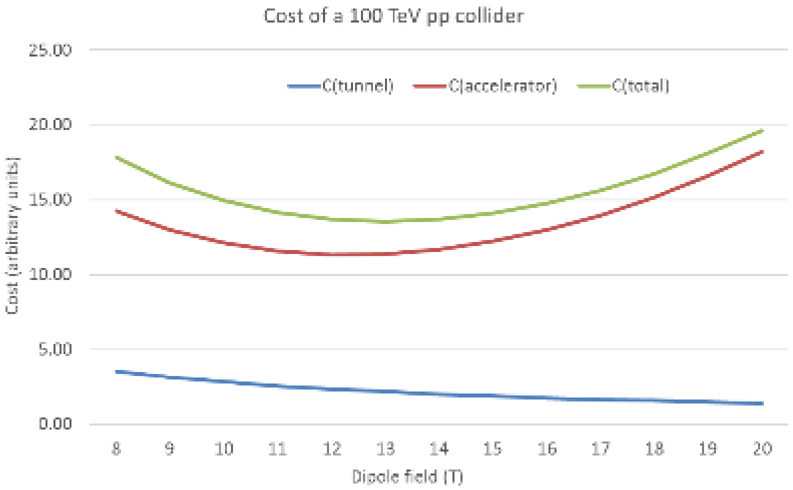
HTS magnets – reducing cost is the main challenge



(courtesy of P. Lebrun)



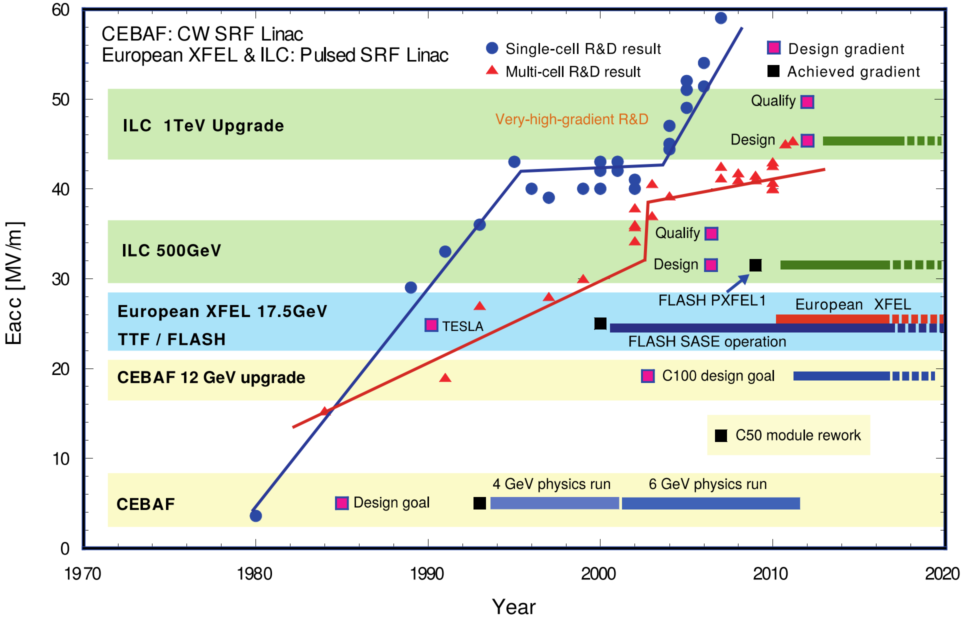
HTS allows reducing the size of the accelerator but not (yet) the cost.
HTS is presently about 5 times the cost of Nb3Sn, but other communities (e.g. fusion) could contribute to reducing the price in the next years.

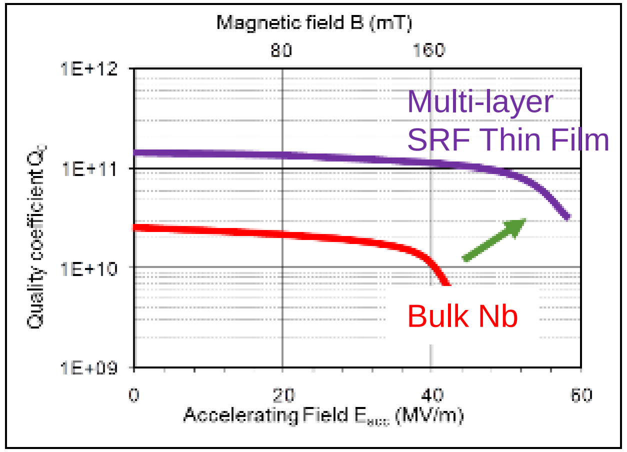


100 CHF (=100$) of YBCO HTS tape built by Bruker HTS for CERN

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

The electric field frontier – superconducting cavities



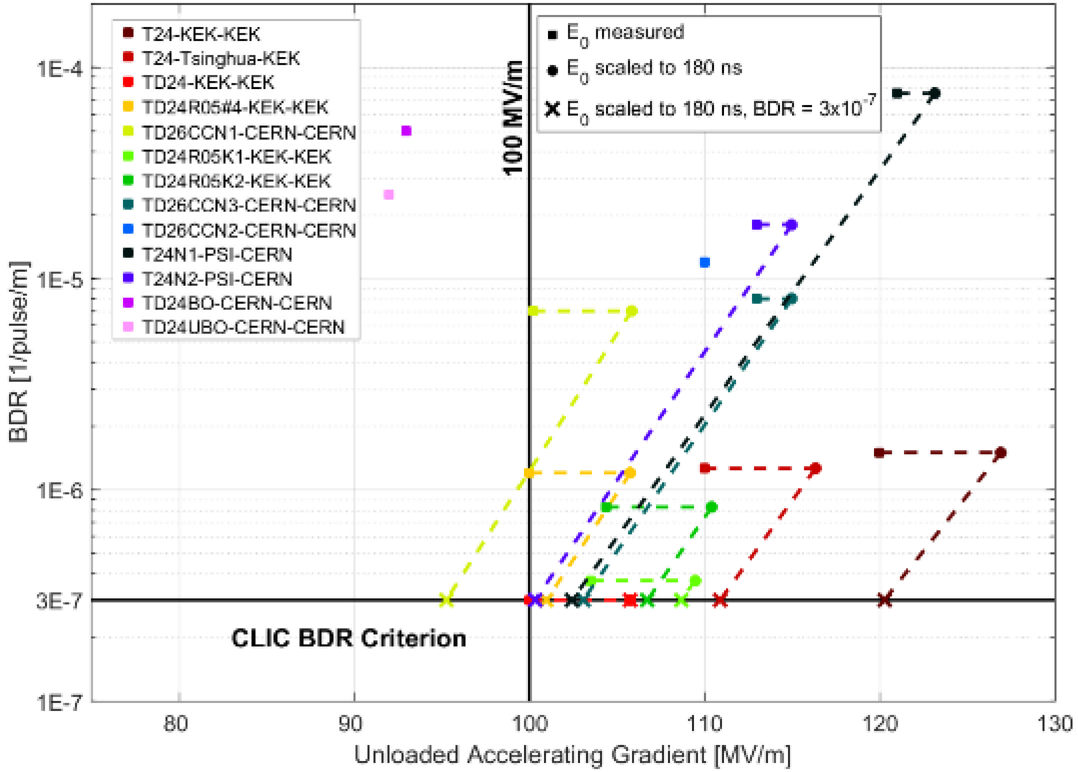


TRENDS:

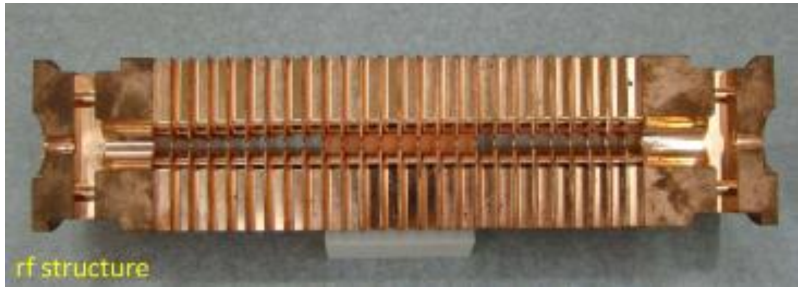
- Nitrogen infusion process (FNAL) and other doping techniques: high Q operation, gradients ~45 MV/m
- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency)
- Coating of Cu cavites with Nb by HiPIMS (High Power Impulse Magnetron Sputtering,

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.

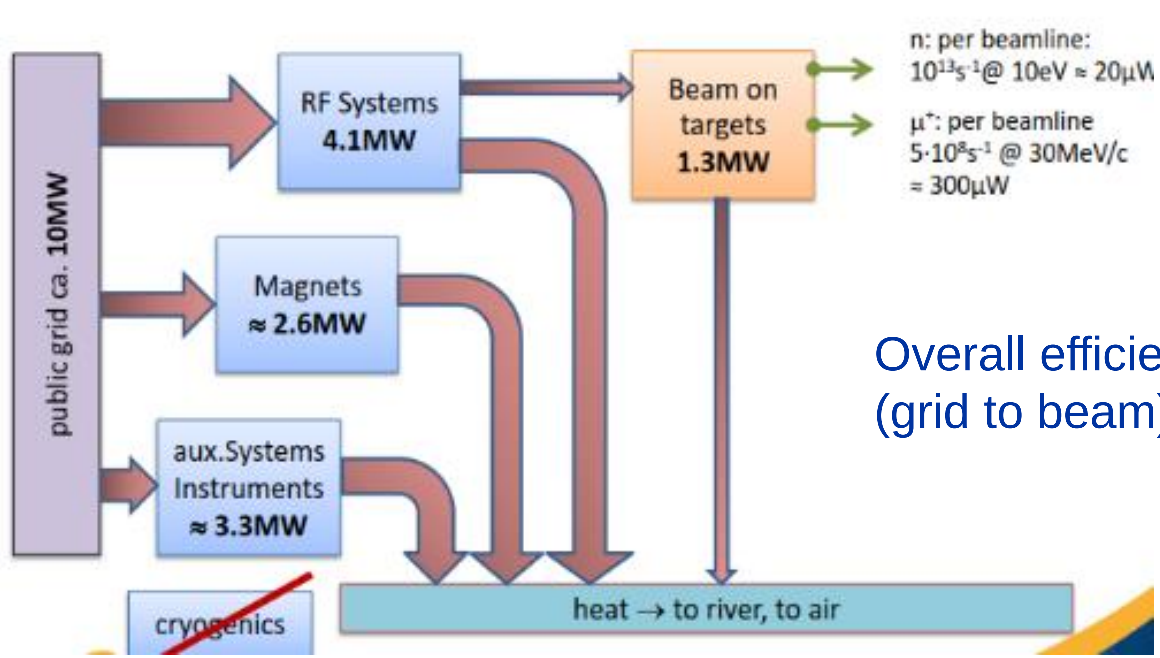
Efficient energy management – a must for future projects

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

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?



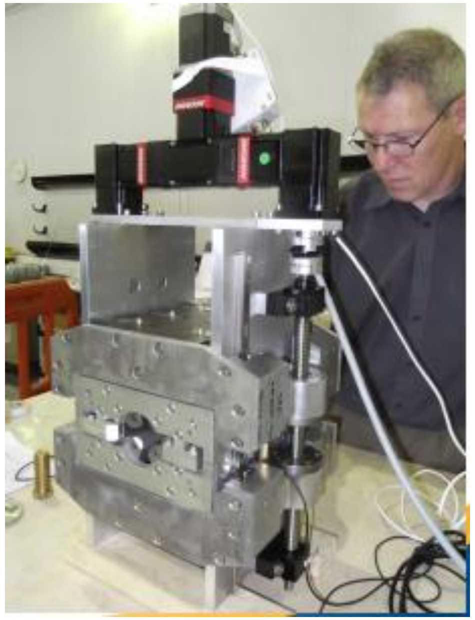
Overall efficiency (grid to beam): 13%

Example: power flow in the PSI cyclotron facility

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

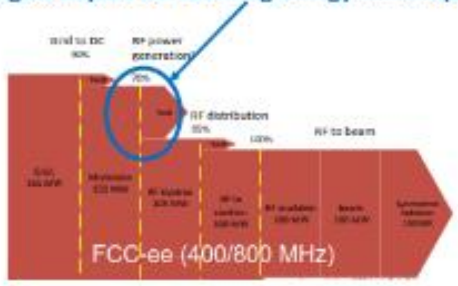
Some initiatives to improve power efficiency

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



Tunable high-gradient permanent magnet quadrupoles

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

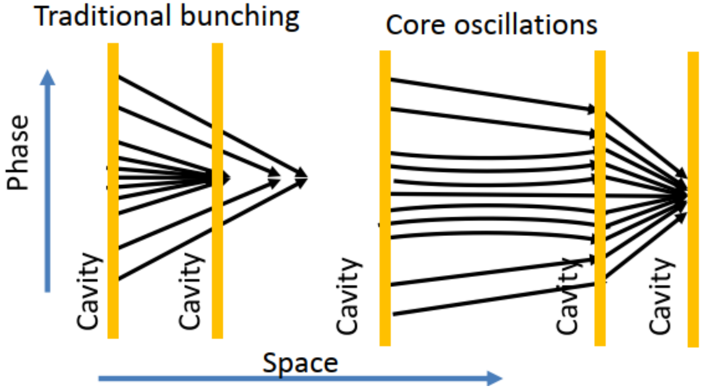


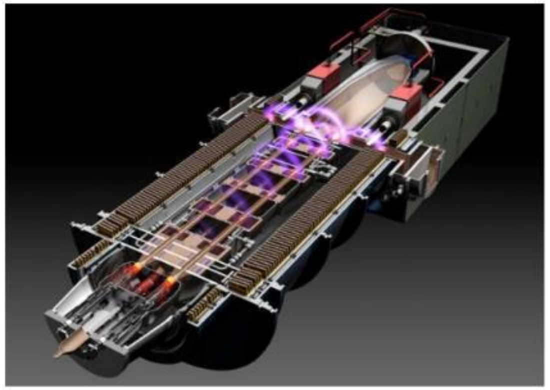
Increase of 5% efficiency for RF generation
➔10 MW less electricity consumed
➔gain 50 GWh/year (2M€/year)

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

Photo: CLIC Xbox 12 GHz facility for cavities conditioning

Development of high-efficiency RF power sources





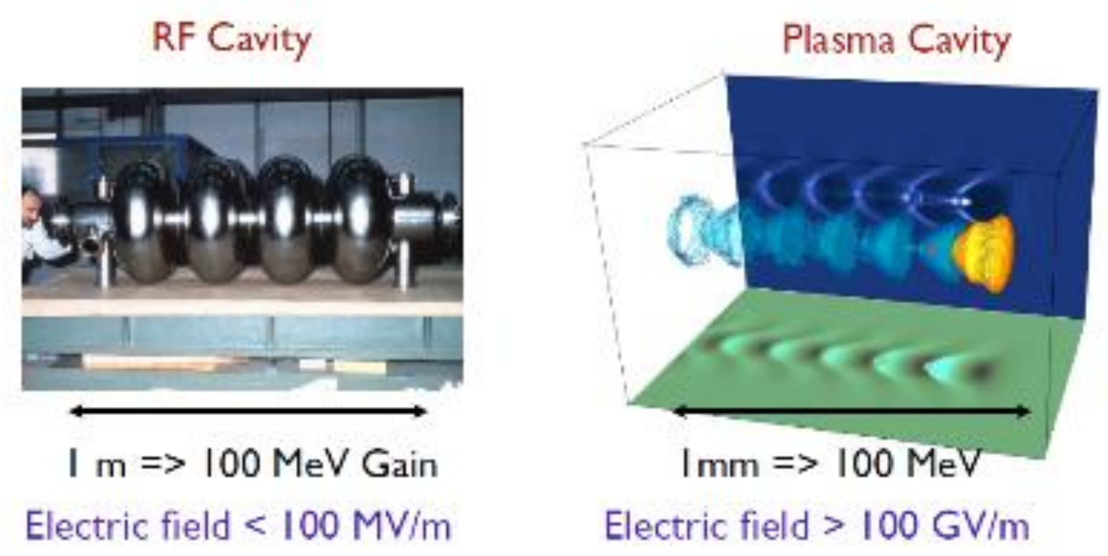
New acceleration techniques using lasers and plasmas

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

Several tens of kilometers for future linear colliders

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

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



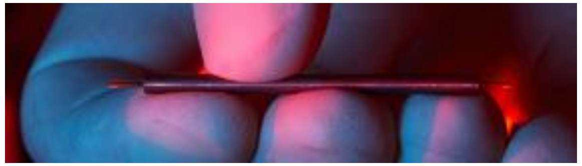
V. Malka *et al.*, Science **298**, 1596 (2002)

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

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

(1) Micro/Nano-Accelerators

Send THz Laser into Dielectric Waveguide (Micro-Accelerator)

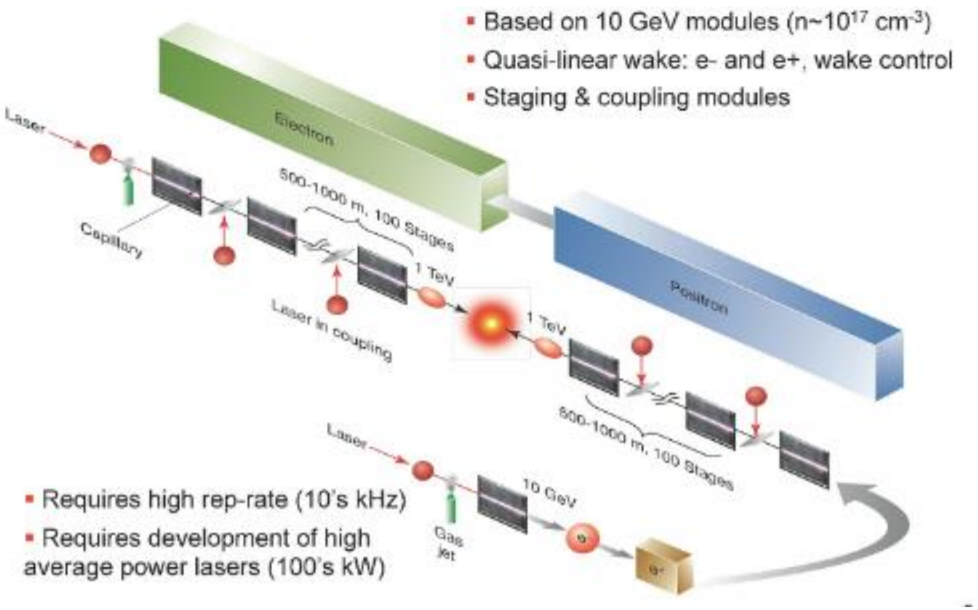


The «accelerator on a chip»

(2) Plasma Accelerators

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

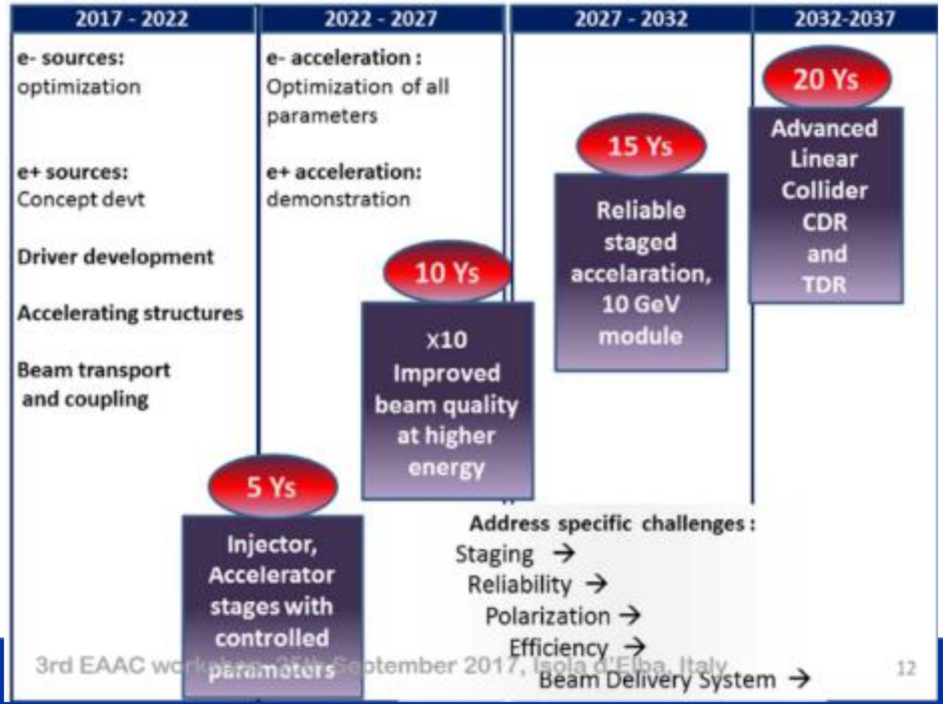
Towards a plasma-based linear collider?


- Based on 10 GeV modules (n~10^{17} cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules
- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

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

Main challenges

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


2017 - 2022

e- sources: optimization

e+ sources: Concept devt

Driver development

Accelerating structures

Beam transport and coupling

2022 - 2027

e- acceleration : Optimization of all parameters

e+ acceleration: demonstration

2027 - 2032

2032-2037

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 →

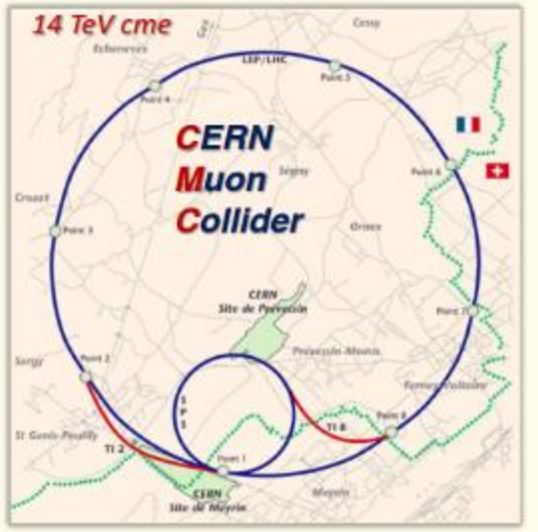
Polarization →

Efficiency →

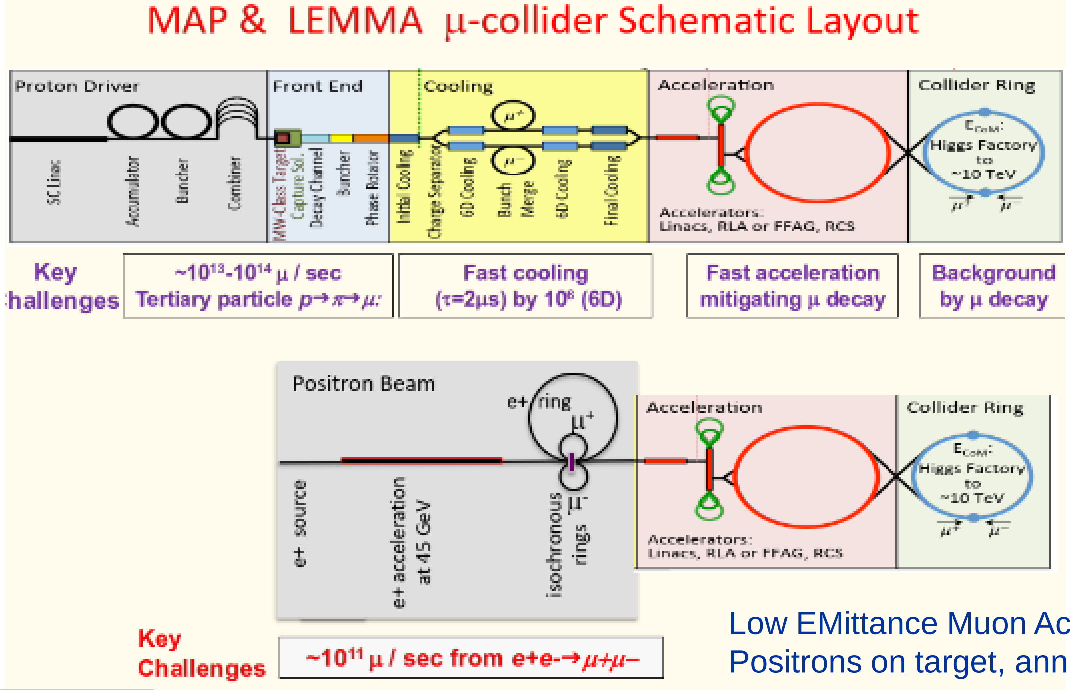
Beam Delivery System →

3rd EAAC workshop, 25th September 2017, Isola d'Elba, Italy 12

Other options for high energy: muon collider



MOPMF072, IPAC18, V. Shiltzev, **D. Neuffer**



MAP & LEMMA μ-collider Schematic Layout

Key challenges:

- ~10^{13}-10^{14} μ / sec Tertiary particle $p \to \pi \to \mu$:
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key Challenges: ~10^{11} μ / sec from $e+e- \to \mu+\mu-$

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

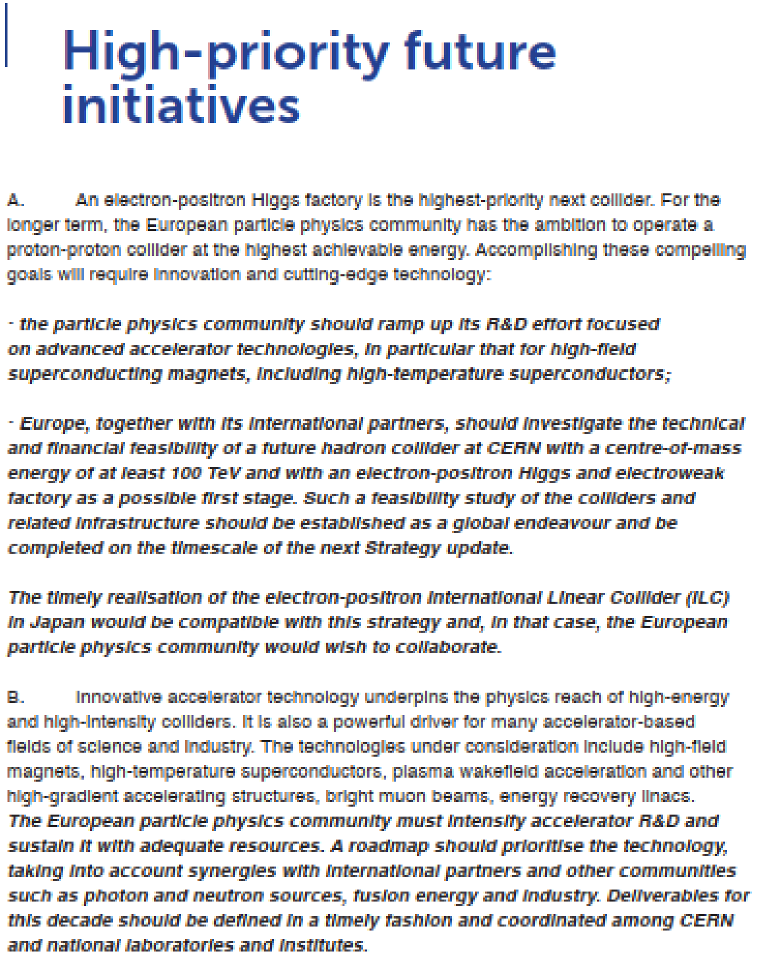
Directions of the new European Strategy for Particle Physics

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

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



High-priority future initiatives

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

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

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

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

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

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

In particular:

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

End of Lectures 1 & 2

Elwood
Smith