Particle Accelerators 1

Introduction

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1. Applications of Particle Accelerators

A very powerful tool for society

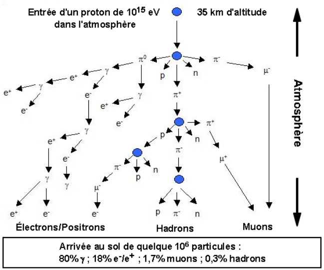
The accelerators: a great solution for great needs

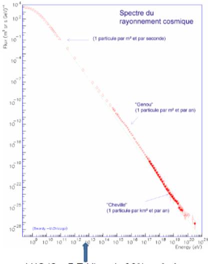
1927 E. Rutherford to the Royal Society:

> *... if it were possible in the laboratory to have a supply of electrons and atoms of matter in general, of which the individual energy of motion is greater even than that of the alfa particle, ... this would open up an extraordinary new field of investigation. ...*

Until this time, physicists could use:

- α particles (<10 MeV),
- β particles from radioactivity.
  - Low energy.
- Astroparticles.
  - Low flux + cascade.

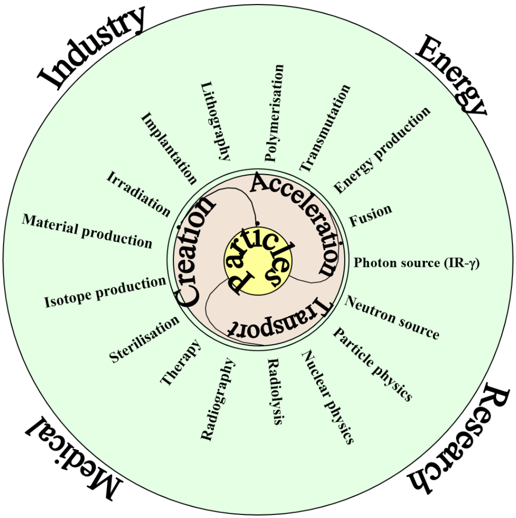




LHC (2 x 7 TeV) mais 10^{34} cm^{-2} s^{-1}

Need for an intense flux of energetic particles.

Accelerator applications



Particle accelerators in a few numbers

More than **400 B€** of end products are produced, sterilized, or examined using industrial accelerators annually worldwide.

More than **24 000** particle accelerators have been built globally over the past **60 years** to produce charged particle beams for use in industrial processes. This number does not include the more than **11 000** particle accelerators that have been produced exclusively for medical therapy with electrons, ions, neutrons, or X-rays.

More than **24 000** patients have been treated by hadron therapy in Europe.

More than **75 000** patients have been treated by hadron therapy in the world.

Around **200** accelerators are used for research worldwide, with an estimated yearly consolidated cost of **1 B€**.

The world's largest particle accelerator, the Large Hadron Collider (LHC), is installed in a tunnel **27 km** in circumference, buried 50-175 m below ground.

The temperature of the superconducting magnets in the LHC reaches **– 271 °C.** In contrast, the temperature at collision point is 1000 million times hotter than that of the Sun's core.

References
Numbers related to industrial accelerators
Robert W. Hamm and Marianne E. Hamm, Eds., "Introduction to the Beam Business" in Industrial Accelerators and their Applications (World Scientific, Singapore, 2012), ISBN-13 978-981-4307-04-8, pp.1–8.
Numbers related to LHC
CERN (European Organization for Nuclear Research) website
http://home.web.cern.ch

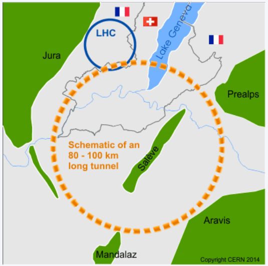
Particle Physics

- Study of particle physics model (standard, Higgs ...).
- Search of new physics.

⇒ Needs:

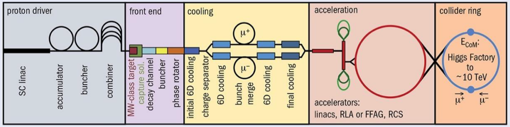
  - Very high energy (e.g. FCC-hh: up to $50\,\mathrm{TeV}$)
  - Very high luminosity (e.g. FCC-ee up to $1 \times 10^{36}\,\mathrm{cm^{-2}\,s^{-1}}$).

Future Circular Collider



Muon colliders

The development of muon-neutrino plants requires several years of R&D in particular for collection, cooling and fast acceleration of muons.

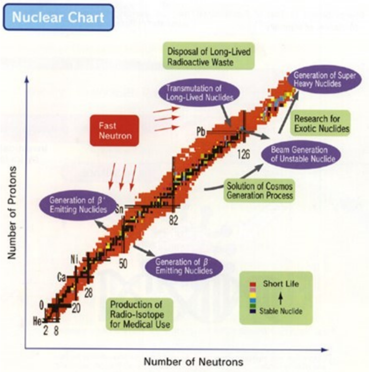


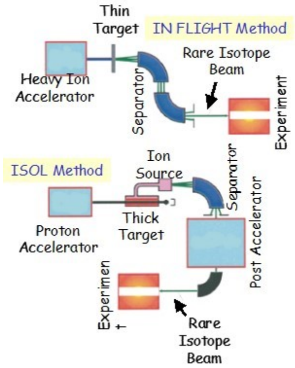
Nuclear physics

- Nuclear model validation/exploration (resonant interactions).

⇒ Neutrons of a few MeV, produced with protons.

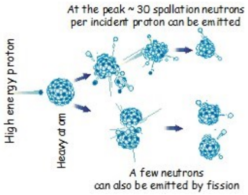
- Study of exotic nucleus.
- Use of electrons, protons, deuterons, heavy ions.



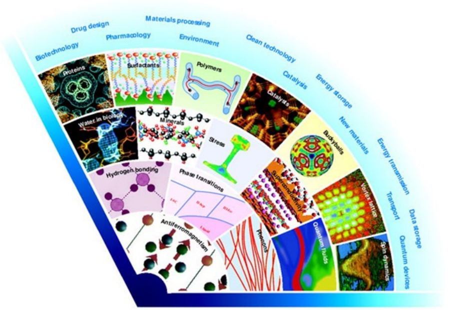


Matter Physics

- High neutron flux.
- Protons ($\approx$1 GeV) on heavy atoms: spallation.
- ISIS, LANSCE, SINQ, SNS, ESS.

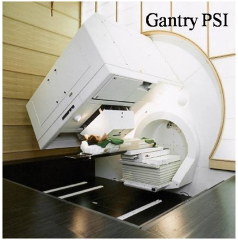


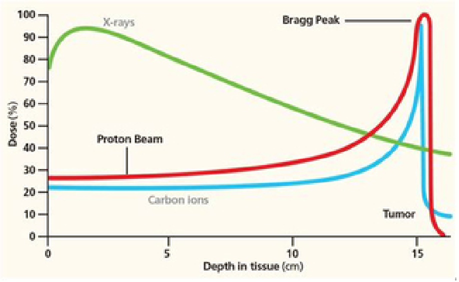
- High photons flux (X-rays).
- Electrons (2 GeV to 6 GeV): synchrotron radiation.
- ESRF, ALS, ELETRA, SOLEIL



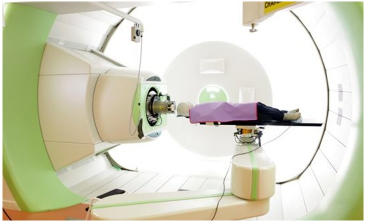
Therapy

- Tumour destruction with high flux particle "bombing".
- Gamma, electron, protons, ions, neutrons.
- Thousands of patients per year.

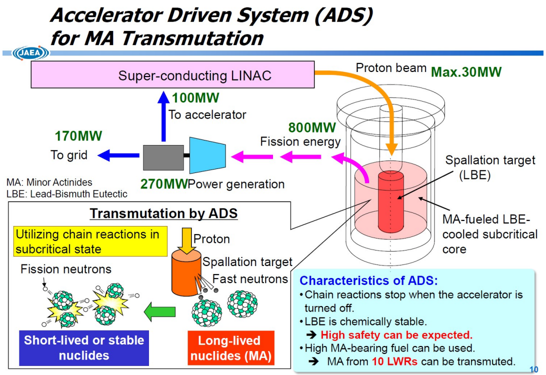




Protontherapy Center, Orsay



Transmutation of long-life nuclear waste

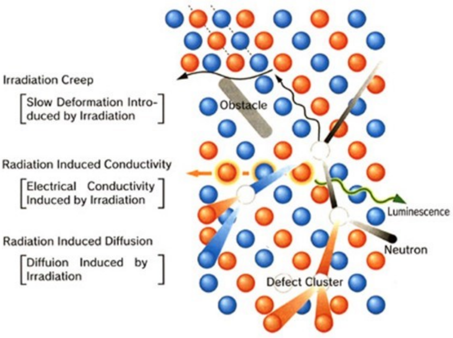


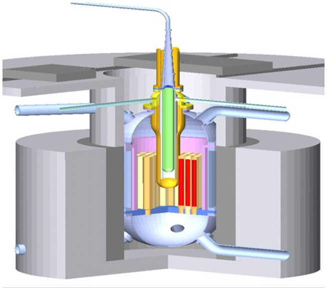
Public acceptance of nuclear energy requires solutions for nuclear wastes

- MA : Minor Actinides are extremely long-lived radioactive elements $> 10^6$ years.
- Sub-critical core : Assembly of MA fuel in which transmutation takes place through fission reactions provoked by spallation neutrons from the target. The reaction stops immediately when the accelerator is turned off.

Irradiation

- Material irradiation results in large disturbances in the atomic organisation (defects, clusters, ...).
- During and after irradiation, mechanical, electrical, optical properties are changed.
- This research is fundamental to promote new materials for transmutation plants, fusion, and other nuclear systems.



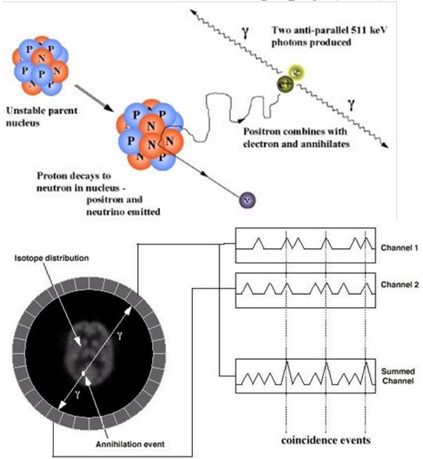


SPALLAX (CEA - DRN)
Technical Irradiation Tool
Based on spallation neutrons

Radio-isotope production

- Principle:
  - Radio-isotopes are produced by irradiation and injected in "system".
  - Radiation study informs on their position in the "system".
  - Radiation can also interact with the system.
- Possible applications:
  - Fluid flow diagnostics.
  - Medical diagnostics.
  - Chemical and biological reactions.
  - Therapy.
- Protons/deuterons $8\,\mathrm{MeV/A}$
- Heavy ions $80\,\mathrm{MeV/A}$

Positron Emission Tomography (PET)



Sterilization

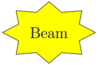
- Use domain:
  - Bacteria killing.
  - Medical material
  - Food (spices, potatoes)
  - Flowers
- X-ray, electrons, Cobalt60
- Advantages:
  - Fast.
  - The objects can be treated packed at factory exit.

Electron beam accelerator (10 MeV) by IBA

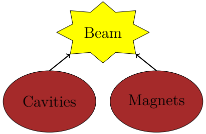
2. Basics on beams

Very short introduction to beam dynamics (lectures 2 and 3)

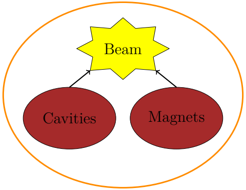
Main accelerator parts



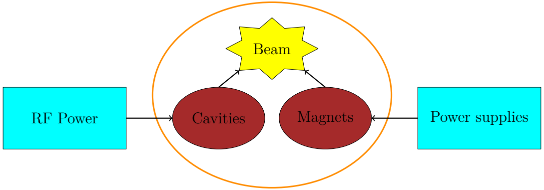
Main accelerator parts



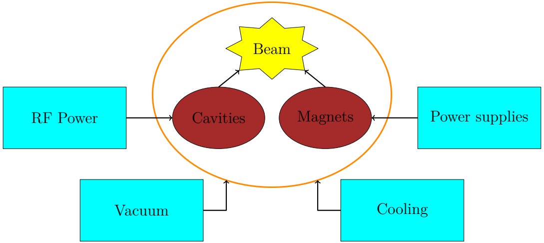
Main accelerator parts



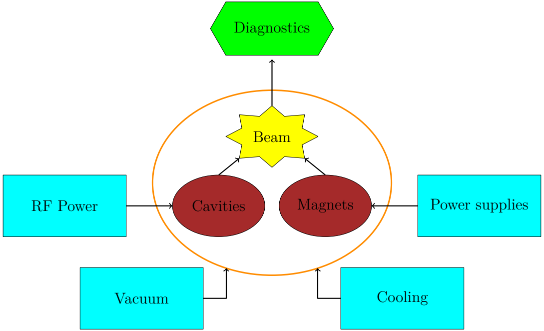
Main accelerator parts



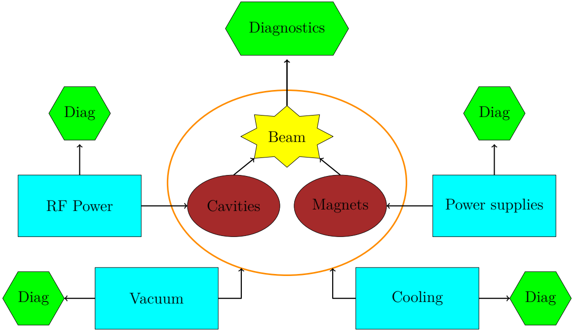
Main accelerator parts



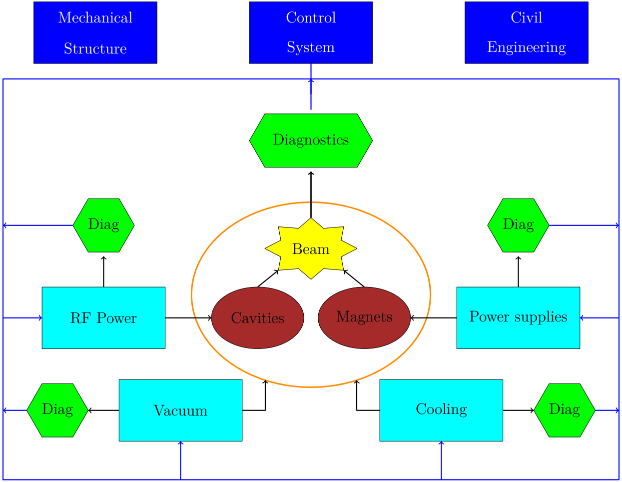
Main accelerator parts



Main accelerator parts



Main accelerator parts



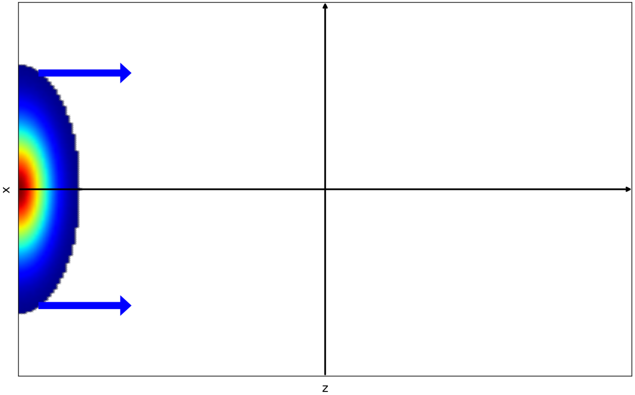
What is a beam?

Definition of a beam

A beam is a set of particles with average momentum along 1 direction (z) much higher than the momentum along two others directions (x, y).

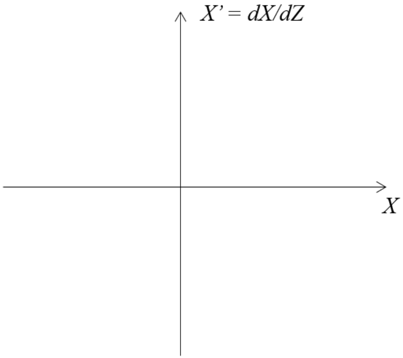
$$p_z^2 \gg p_x^2 + p_y^2$$

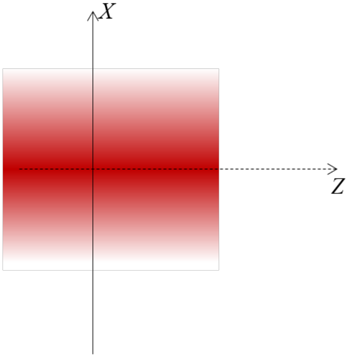
A beam in a drift (no external field)



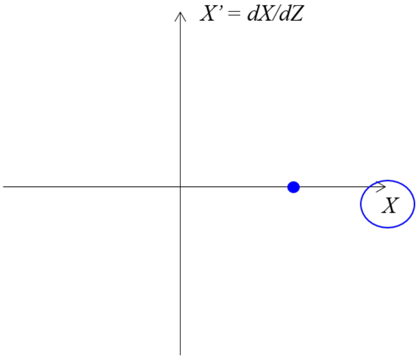
Q: Is that the expected beam behaviour in a drift?

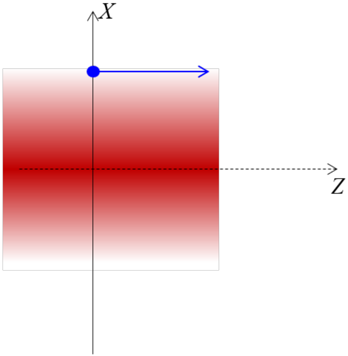
Phase space (x, x')



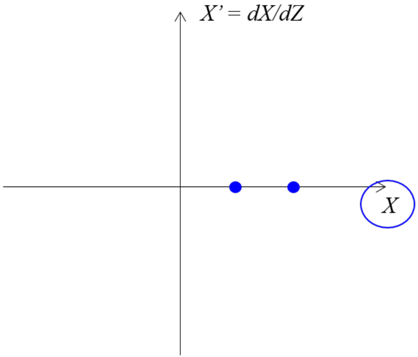


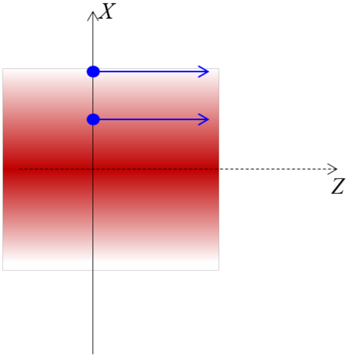
Phase space (x, x')



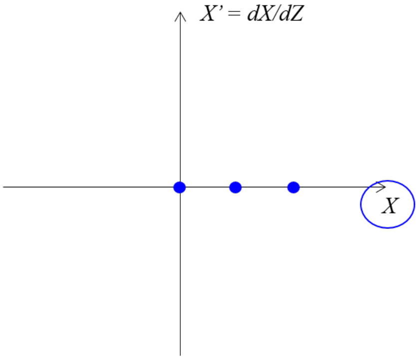


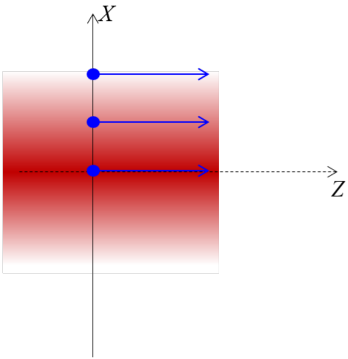
Phase space (x, x')





Phase space (x, x')





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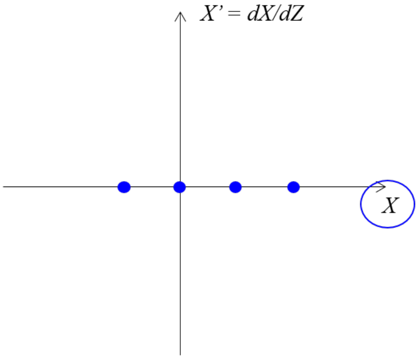

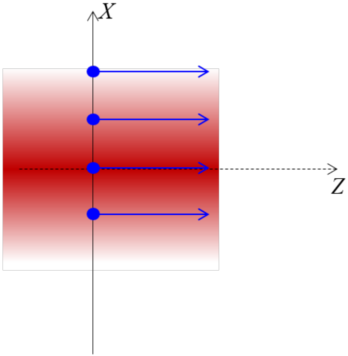

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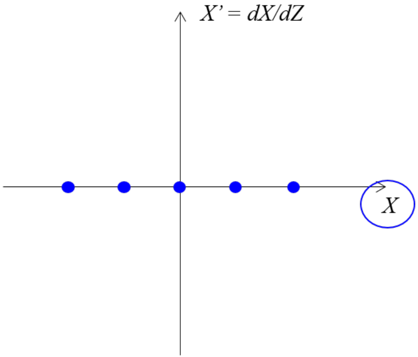

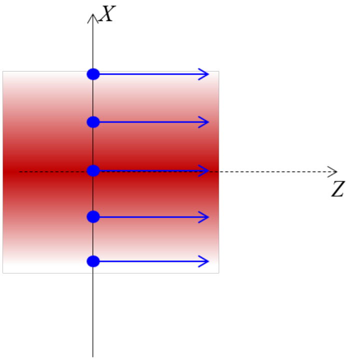

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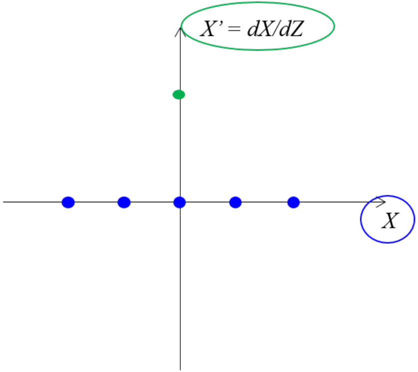

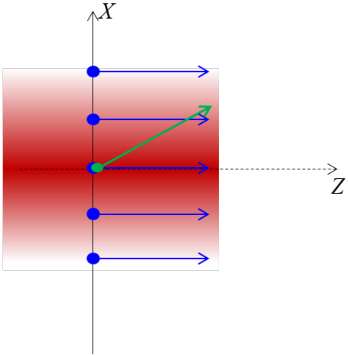

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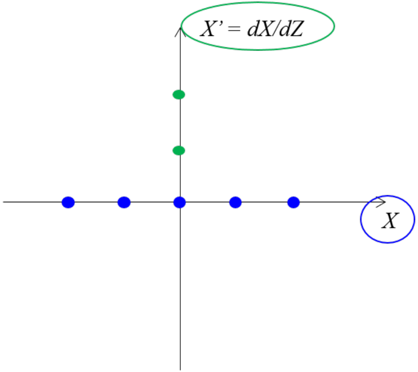

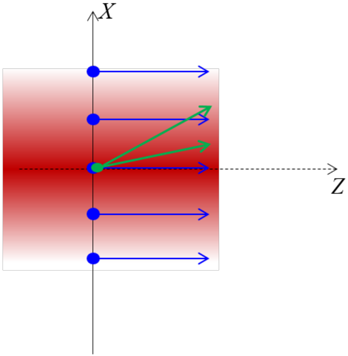

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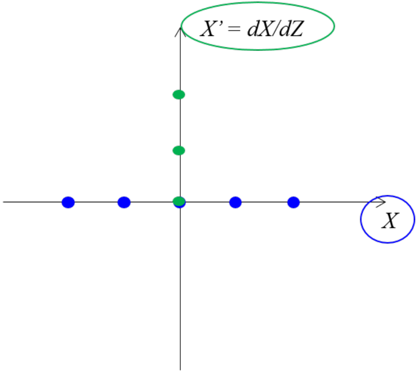

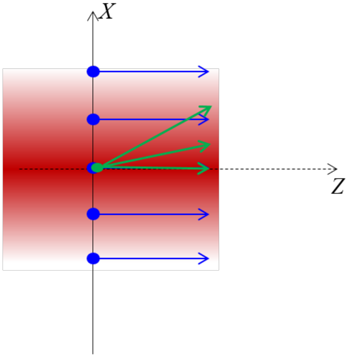

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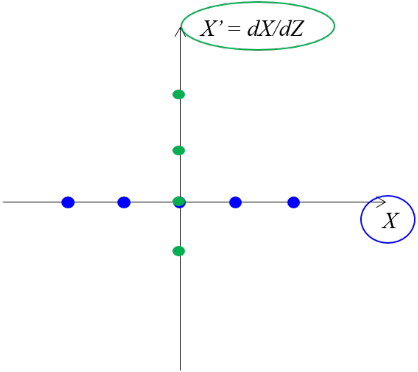

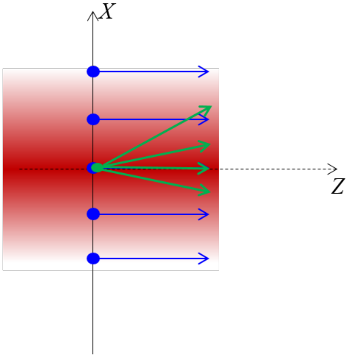

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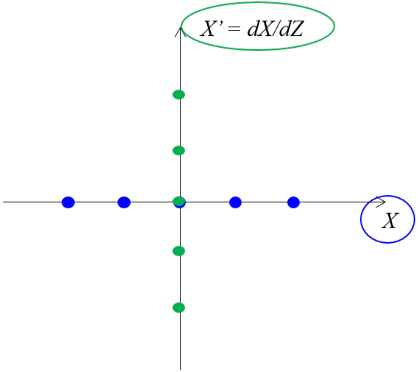
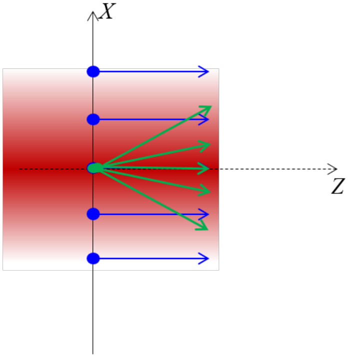
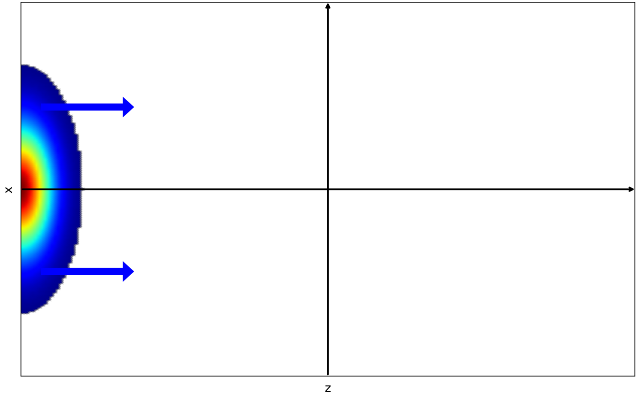


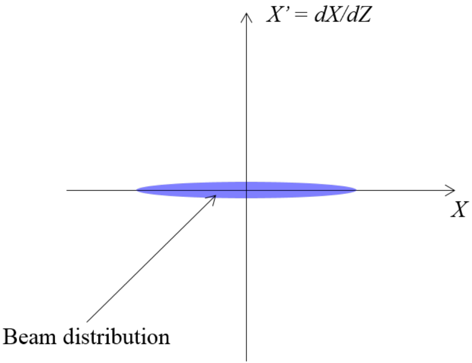


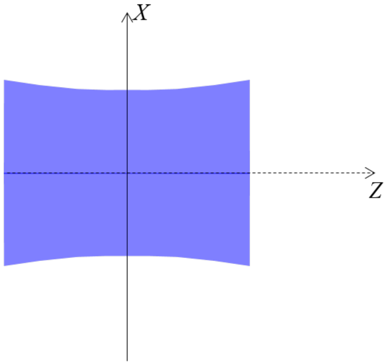
A beam in a drift (2)



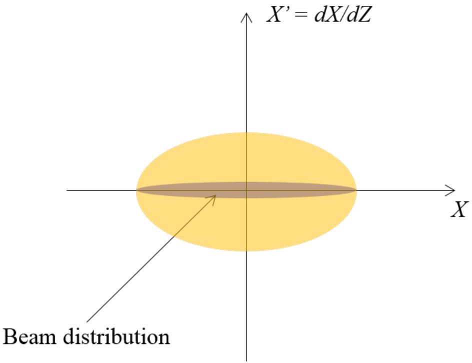
The beam size varies with position.

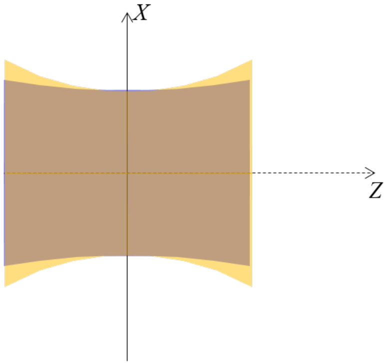
Natural divergence





Natural divergence





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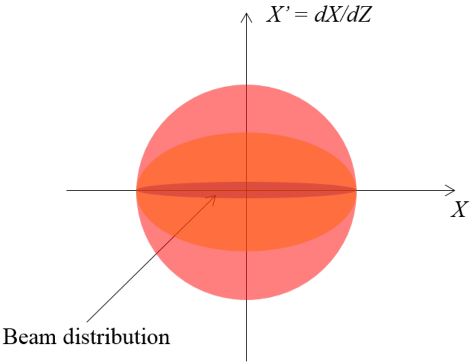
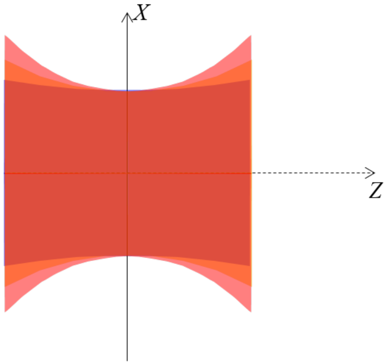
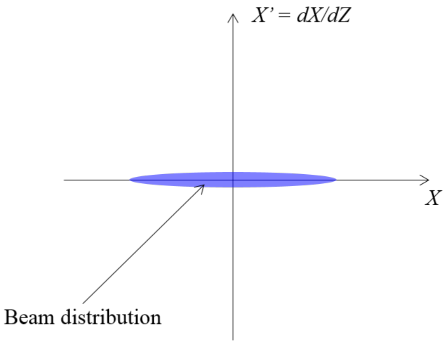
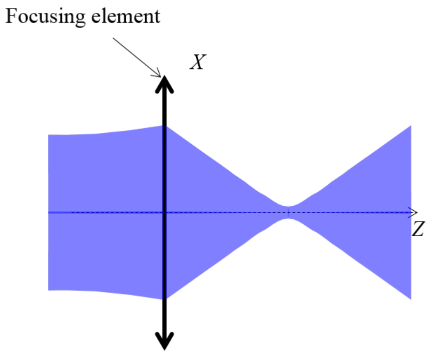




Focusing limit





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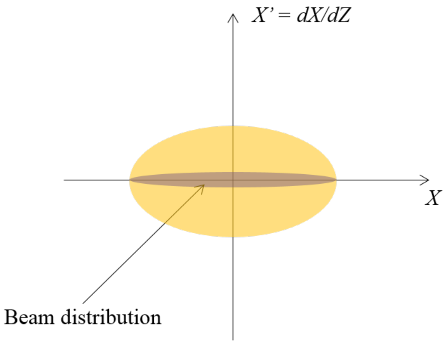

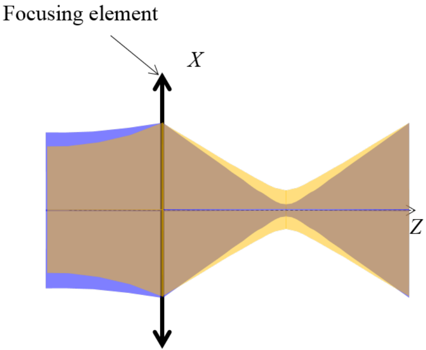

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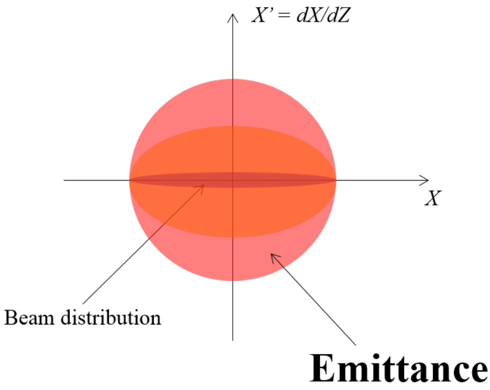
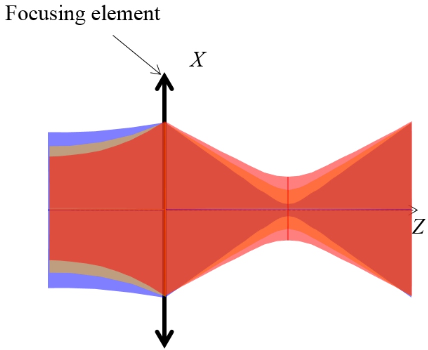
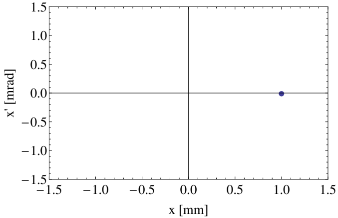


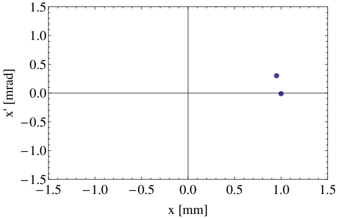


Particle motion in a ring

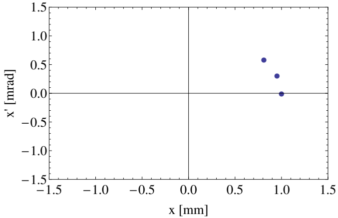
Initial position



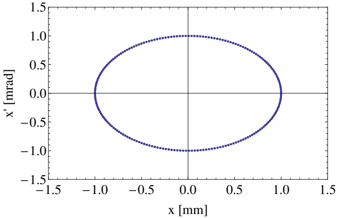
After 1 turn



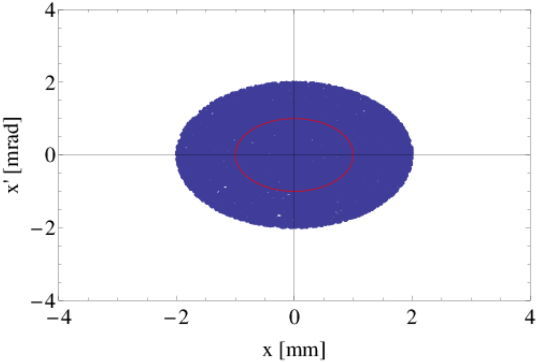
After 2 turns



After *n* turns

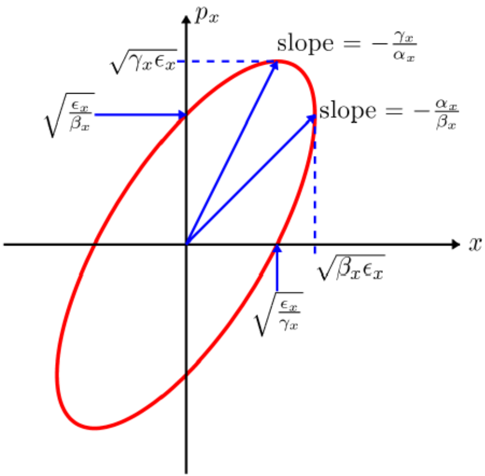


Emittance



The emittance is proportional to the beam ellipse area in the phase space.

Beam parameters

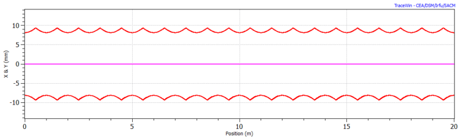


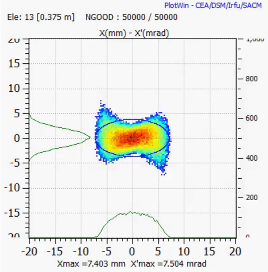
Emittance (2)

- Native property of the beam.
- Product of a size by a divergence at a waist.
- Limits the beam ability to be transported parallel and focused small.
- Is conserved in linear forces (motion invariant).
- Can only increase with non-linear forces (but under specific conditions).

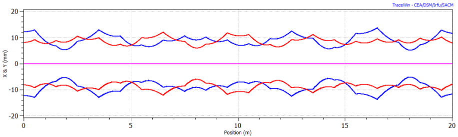
Matching ?

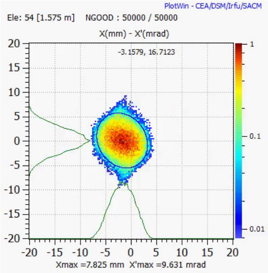
- Beam envelope as regular as possible (difference between smallest and biggest size).





Mismatching ?





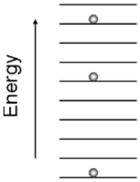
3. How to produce a beam

Electron and ion sources

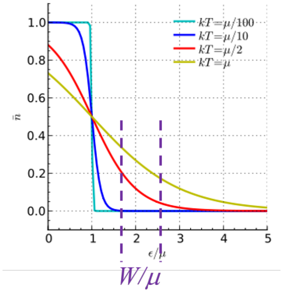
Electron sources

Electrons are attached to the matter :

- To atoms, with quantified binding energy E_i,
- To "structure" as free electrons following Fermi-Dirac distribution .



$$n(E) \approx \frac{1}{\exp\left(\frac{E-\mu}{kT}\right)+1}$$



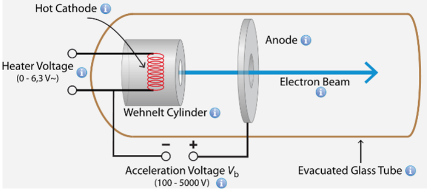
- Lower binding energies (E_0) or chemical potential (μ) are a few eV.
- W : work function $\approx$ a few eV.
- To pull electrons from matter, one has to provide energy!

Thermionic gun

$$W = 1\,\text{eV} \iff T = 11\,600\,\text{K} \quad (\text{kT}\approx\text{W})$$

$$J = A_G T^2 \exp\left(-\frac{W}{kT}\right)$$ Richardson law

- A cathode (peace of material) is heated allowing some electrons to excess the chemical potential energy and exit the material.
- An electric field accelerates the particles toward an anode (higher potential than the cathode).



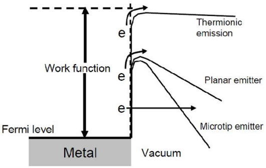
Field emission gun

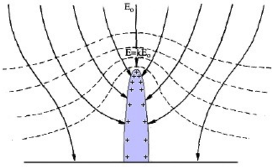
$$W = 1\,\text{eV} \iff E = 6831\,\text{MV/m}$$

$$J = K_1 \frac{E^2}{W} \exp\left(-K_2 \frac{W^{3/2}}{E}\right)$$

Fowler-Nordheim

- Electric field reduces the energy barrier to pull electrons.
- On a surface, electric field can be locally largely enhanced with peaks (peak effect).



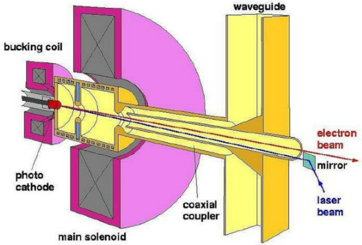


Laser electron gun (photoinjector)

$$W = 1\,\mathrm{eV} \Longleftrightarrow \lambda = 1.24\,\mu\mathrm{m}\ (\lambda \approx W)$$

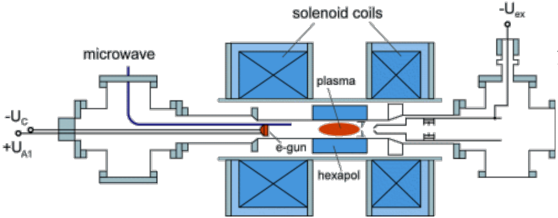
- A laser illuminates a cathode.
- Photons gives to electrons enough energy to exit the cathode.
- An electric field accelerates the particles toward an anode (higher potential than the cathode).

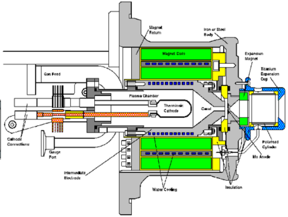
[Serafini, Joint Accelerator School, 2002]



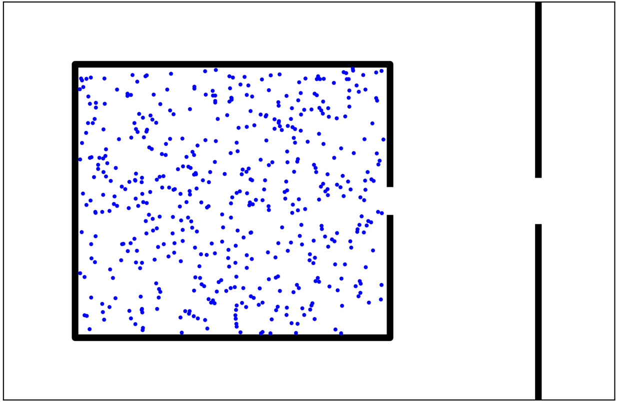
Ion sources

- An ion is an atom with pulled out electrons !
- However, this ion has to be "free" ($\Rightarrow$ gaseous atoms).
- Producing a gas:
  - Naturally (Hydrogen, Nitrogen, ...).
  - Heating mater to surface vaporisation (from solid or liquids, ...).
- Heating a gaz:
  - RF field (e^- production, acceleration, collision, ionization, ...).
  - Electron discharge.

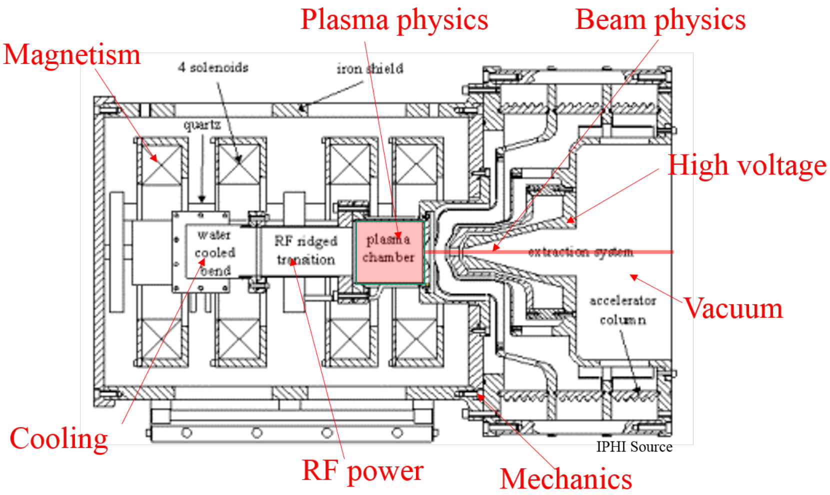




Principle of ion sources



One moment on an ECR source

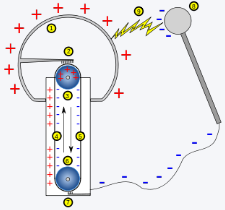


4. How to accelerate a beam

Use an electric field (see lecture 4)

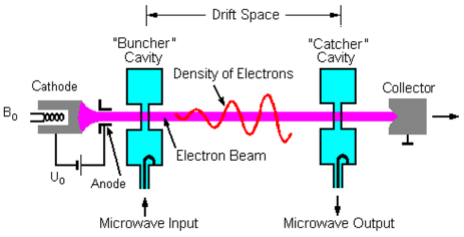
Producing electric field

Static electric field



Maximum energy limited to a few MV.

Oscillating electric field: the klystron



Can be added as much as needed.

Radio-frequency resonant acceleration

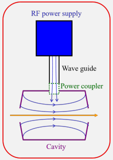
Motivation

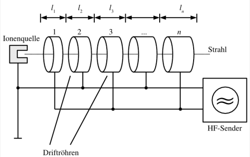
Adding a large number of successive accelerating gaps with resonant cavities instead of increasing the voltage difference.

- Proposed by Gustaf Ising in 1924.
- Realized by Widerøe in 1928.
- Mainly all the accelerators of today.

The resonant radio-frequency (RF) cavity

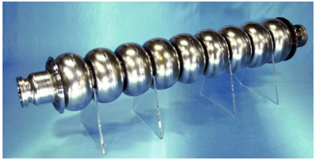
Confining a stable RF wave in an accelerator region and making the beam pass through.

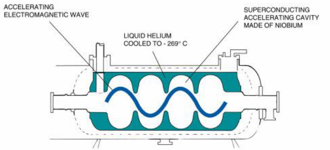




The superconducting cavities

- ☺ Very low losses due to the surface resistance (very high quality factor $Q_0 > 10^9$).
  - Stationary wave with a reduced need in peak power.
- ☺ Good efficiency.
- ☺ Standard operating frequency (1.3 GHz).
- ☺ Large iris size.
  - Easier tolerance manufacturing.
  - Low wakefield.
- ☺ Possibility of longs pulses.
  - Dynamic correction possible during the pulse.

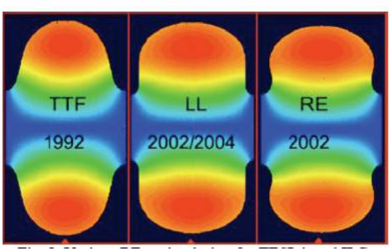




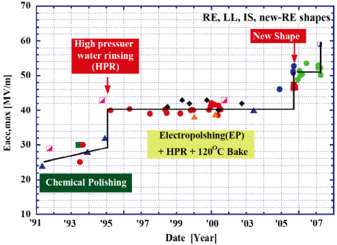
The superconducting cavities (2)

- ☹ The field E_{acc} is limited by the surface magnetic field B_{crit}. Otherwise the cavity quenches (superconductivity lost).
  - ⇒ Shape optimisation.
  - ⇒ Surface state as smooth as possible.
  - ⇒ Thin layers/new materials.
- Maximum: ≈ 60 MV/m for a cavity alone.
- Maximum: ≈ 35 MV/m for a multi-cavity structure.

Shape optimisation

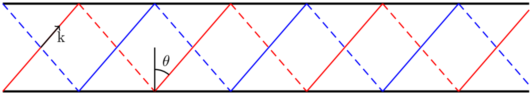


Surface state



Traveling wave cavities

- For ultra-relativistic beams ($\beta \approx 1$).
- In wave guides, the phase velocity v_ϕ is greater than c, and thus than the beam velocity.

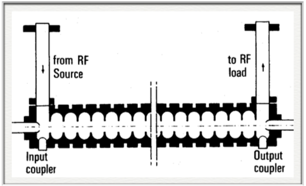


$$v_g = c \sin\theta < c$$
$$v_\varphi = \frac{\omega}{k_\parallel} = \frac{c}{\sin\theta} > c$$

$\Rightarrow$ We couple the wave with resonant structures.

$\Rightarrow$ $v_{\text{beam}} = v_\phi$.

- The particles see an accelerating phase when going through the whole structure.



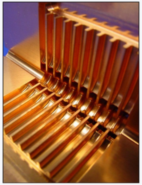
1947: structure 3 GHz

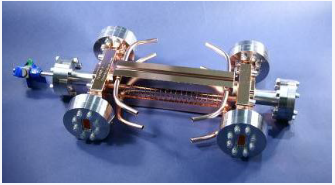
To high gradients with resistive structures

- ☺ E_{acc} limited by the breakdowns $> 100\,\mathrm{MV/m}$.
- ☹ Necessary to use high frequencies $> 10\,\mathrm{GHz}$ and very short pulses $< 1\,\mathrm{\mu s}$ to get high gradients. $\Rightarrow$ Traveling wave cavities ($t_{\mathrm{filling}} = \int \frac{dz}{v_g}$).
- ☹ Large Joule losses because of surface resistance.
  - $\Rightarrow$ Very large RF power required.
  - $\Rightarrow$ Reduced transverse sizes.
  - $\Rightarrow$ Harder manufacturing and strong wake fields.
  - $\Rightarrow$ Necessary to damp higher frequency modes.

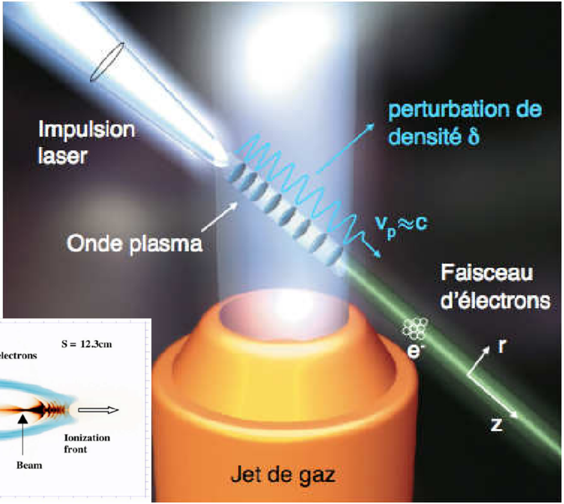
CLIC Structure

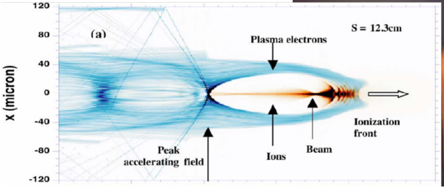
- $E_{acc} \approx 100\,\mathrm{MV/m}$
- $f = 11.424\,\mathrm{GHZ}$
- Length: $29\,\mathrm{cm}$
- Pulse of $230\,\mathrm{ns}$
- $P_{peak} = 55.5\,\mathrm{MW}$





Plasma acceleration: $> 1\,\mathrm{GV/m}$



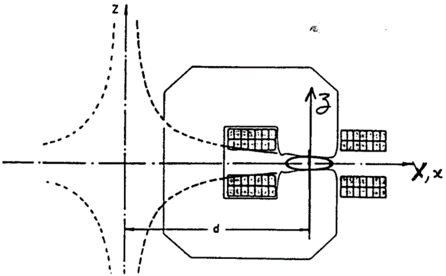


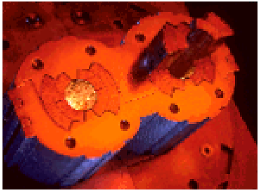
5. How to guide a beam

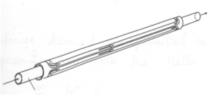
Use a magnetic field (and electric field for very low energy)

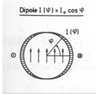
The magnetic dipole

Dipoles are magnets used to guide/deviate the beam





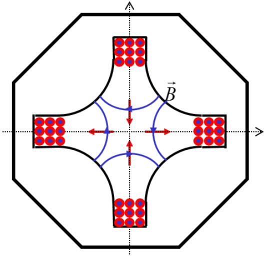


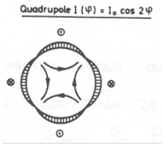


- Limitations:
  - Ferromagnetic technology: $1\,\mathrm{T}$ to $2\,\mathrm{T}$ (material saturation, copper coil heating).
  - SC technology: $20\,\mathrm{T}$ (by adding LTC and HTC wires, limited by Quench).

The magnetic quadrupole

Quadrupoles are used to focus the beam at any energy.



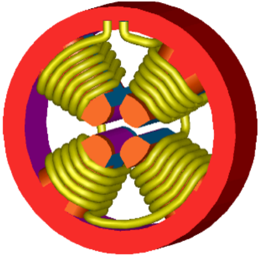


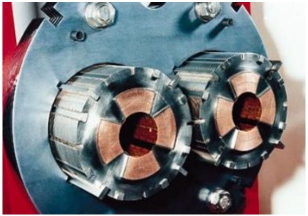
Magnetic field

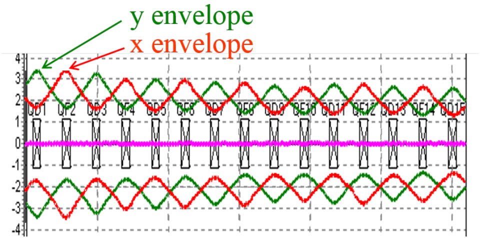
$$\begin{cases} B_x = G \cdot y \\ B_y = G \cdot x \end{cases}$$

Magnetic force

$$\begin{cases} F_x = -q \cdot v \cdot G \cdot x \\ F_y = q \cdot v \cdot G \cdot y \end{cases}$$

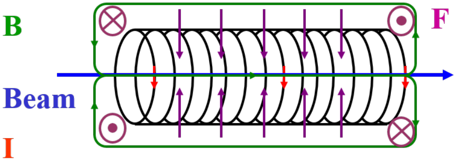


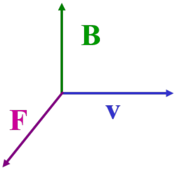




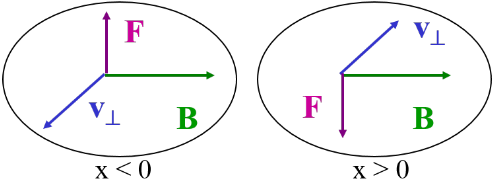
The solenoid

Solenoids can be used to focus the beam at low energy.





Input: $B = B_\perp$
$F \propto v \cdot B_\perp$
Beam transverse rotation
$v_\perp \propto v \cdot B \cdot r$

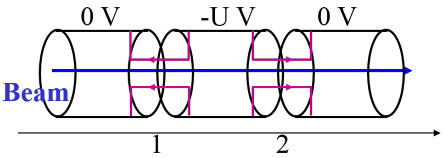


Middle: $B = B_\parallel$
$F \propto v_\perp \cdot B_\parallel \propto v \cdot B^2 \cdot r$

$\Rightarrow$Linear beam focusing

Electrostatic lens

Electrostatic lenses canal be used to focus the beam at very low energy.



$$m\frac{d^2x}{dt^2} = q \cdot E_x$$

$$\frac{d^2x}{ds^2} = \frac{q \cdot E_x}{m \cdot v^2} = \frac{dx'}{ds}$$

- When the particle enters the gap, it receives a defocusing transverse kick.
- When it travels through the gap, it is decelerated.
- When the particle goes out of the gap, it receives a focusing transverse kick.
- The focusing kick is stronger than the defocusing one:
  - the kick is inversely proportional to the square of the particle velocity,
  - the beam size is slightly bigger at the output of the gap (FODO effect).
- The mean effect is focusing. Be careful to the non linearity !

6. The accelerator family

The machine types

Machine types

Linear machines: Beam goes only once through each cavity

Circular machines: Beam goes many times through the same cavities

Machine types

Linear machines: Beam goes only once through each cavity

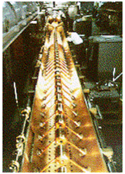
- Electrostatic accelerators
  - Acceleration through potential difference

Circular machines: Beam goes many times through the same cavities

Machine types

Linear machines: Beam goes only once through each cavity

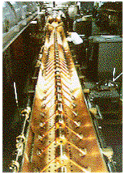
- Electrostatic accelerators
  - Acceleration through potential difference
- RF Linac
  - Acceleration by RF cavities



Circular machines: Beam goes many times through the same cavities

Machine types

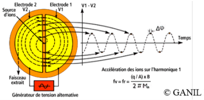
Linear machines: Beam goes only once through each cavity



- Electrostatic accelerators
  - Acceleration through potential difference
- RF Linac
  - Acceleration by RF cavities

Circular machines: Beam goes many times through the same cavities

- Cyclotrons
  - Constant magnetic field,
  - Growing trajectory radius.



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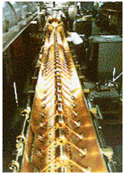
Machine types

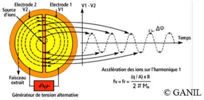
Linear machines: Beam goes only once through each cavity

- Electrostatic accelerators
  - Acceleration through potential difference
- RF Linac
  - Acceleration by RF cavities



Circular machines: Beam goes many times through the same cavities

- Cyclotrons
  - Constant magnetic field,
  - Growing trajectory radius.
- Synchrotrons
  - Growing magnetic field,
  - Constant trajectory radius.



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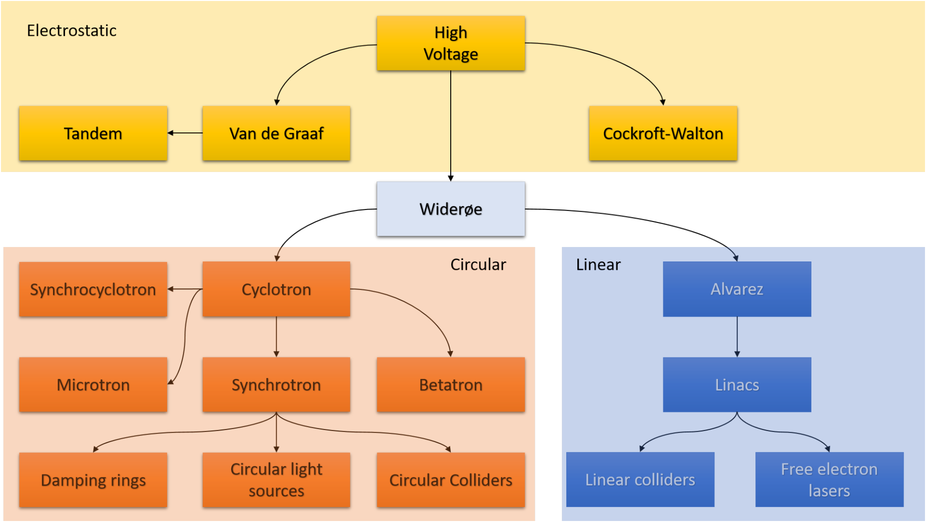
A very big family



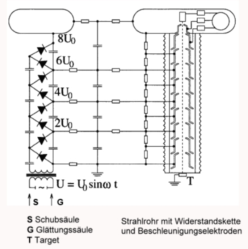
6. The accelerator family

Electrostatic accelerators

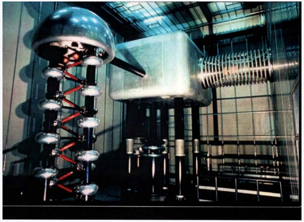
The Cockroft-Walton

- 1930: Increase of the accelerating voltage with Greinacher's cascade.
- 1932: Cockroft and Walton: first decay of Li by protons of 400 keV.
- System still used as a hadron injector although often replaced by an RFQ (Radiofrequency Quadrupole).

Principle



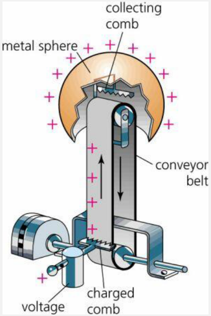
The 810 kV injector of the Mega-Watt cyclotron (PSI-Switzerland)



The electrostatic generator

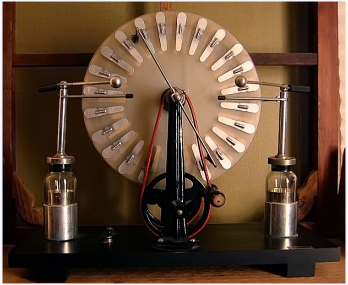
- 1929: Robert Van de Graaf works in Princeton on the principle of a tape transporting electric charges.
- 1931: 1.5 MV are reached with 2 machines.

Principle

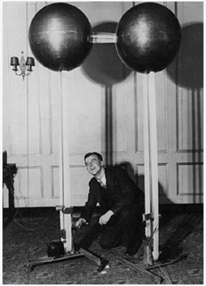


Examples

Whimshurst (1880)



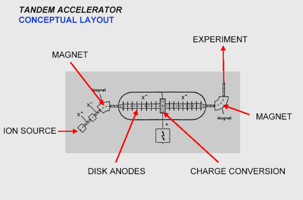
Van de Graaf



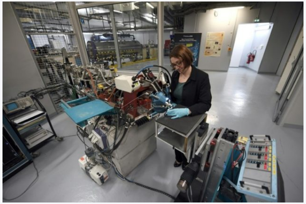
The tandem accelerator

- **Principle**: Accelerate negative ions, "strip" them to make them positive ions and then accelerate twice.
- Advantages and drawbacks:
  - ☺ 2 successive accelerations.
  - ☺ The ion source and target stay at ground voltage.
  - ☹ Smaller intensity (negative ions).

Principle



AGLAE: the Tandem of the Louvre



Limitations and advantages of electrostatic acceleration

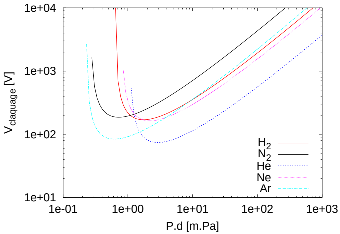
☺ All ions.

☺ Very low energy spread.

To avoid breakdowns:

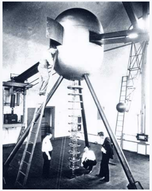
- Increase the gap size.
- Increase the insulation with gases with large electric rigidity and pressure.
- Operate with high vacuum.

Limitation Paschen's law:



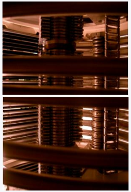
Installation bigger and bigger

1933: 1.2 MV



5 MV

Tandem Daresbury: 30 MV



6. The accelerator family

The linear accelerators (linacs)

The first linacs

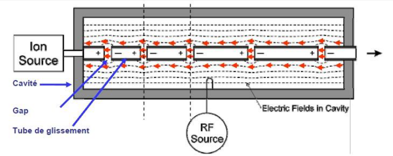
- Widerøe (1928 during his PhD! K^+ at $50\,$keV) and Sloan (1931 Hg $1.26\,$MeV): resonant acceleration.

Limitations at the time

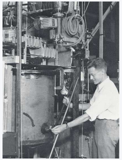
- No high frequency sources ($> 10\,$MHz).
- Electromagnetic power lost by radiation (antenna).

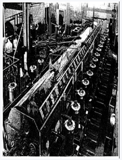
- 1947: Luis Alvarez puts the drift tubes (DTL) in a resonant cavity at $202.56\,$MHz (radio emitter of the US army). Become a standard frequency for the linacs.

Principle of the Drift Tube Linac



Linacs of Sloan and Alvarez

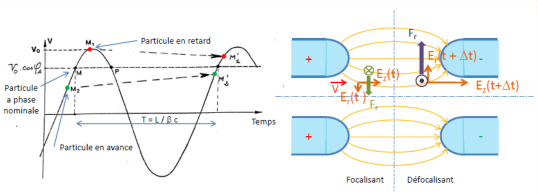




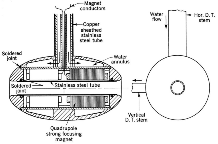
Stability issues of the drift tube

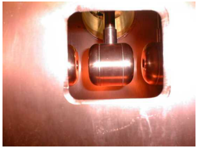
Transverse and longitudinal focusing incompatible

- The particles should be on the RF ascending phase.
- Longitudinal stability $\rightarrow$ Transverse defocusing.



$\Rightarrow$ Quadrupoles in each tube.



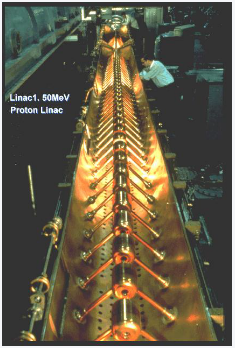


The Drift Tube Linac (DTL)

- Easy to inject and extract.
- Protons of $10\,\text{MeV}$ to $100\,\text{MeV}$ $(0.1 < \beta < 0.4)$.
- Fixed energy for each ion.

DTL examples

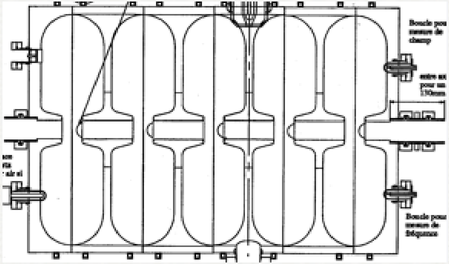
1957: Lawrence Radiation Lab.

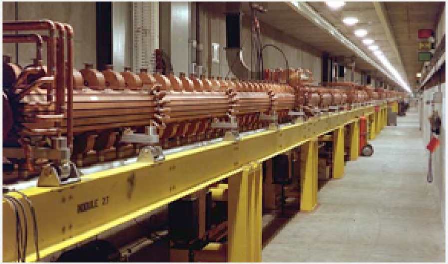


The Coupled Cavity Linac (CCL)

- Used to accelerate beams with high velocity ($\beta > 0.4$).
- The cells are coupled by slits or external cavities.
- Dephasing of π between 2 cavities (inversion of the field sign between 2 cavities).
- Transverse focusing performed by external quadrupoles.

CCL examples



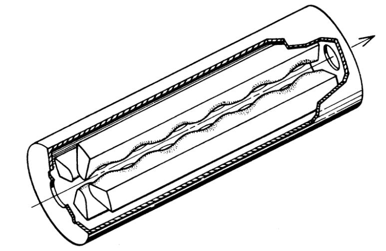


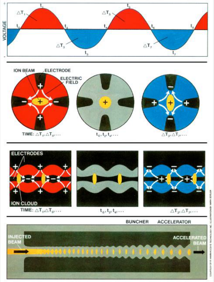
The Radio-Frequency Quadrupole (RFQ)

- RFQ: concept found in 1970 by Kapchiski and Teplyakov.
- Focus, bunch with high capture efficiency and accelerate an ion beam up to a few MeV ($\beta < 0.1$).
- Replace the Cockroft-Walton as an ion injector.

RFQ principle

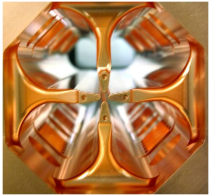
RFQ with its 4 vanes

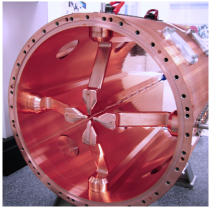




The RFQ: a very delicate manufacturing

- Very strict manufacturing tolerances (tenths of millimetres).
- Delicate warming to manage if continuous operation.
- Video: Spiral2 manufacturing



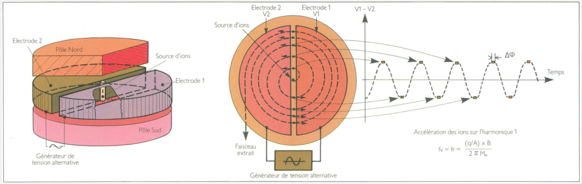


6. The accelerator family

The cyclotrons

The cyclotron

Cyclotron principle



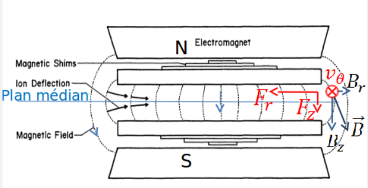
- Uniform B.
- Bending radius:

$$R = \frac{\sqrt{E_{\text{cin}}(E_{\text{cin}}+2E_0)}}{B_z q c}$$

- Pulsation: $\omega = \frac{qB_z}{\gamma m}$

$\Rightarrow$ Isochronous at low energy

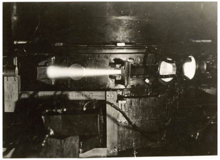
Vertical stability



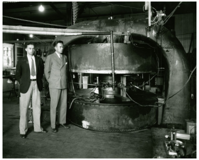
- Stability ensured by the field lines of B.
- $\nabla \times \mathbf{B} = 0$
- $\frac{\partial B_r}{\partial z} = \frac{\partial B_z}{\partial r}$

Bigger and bigger cyclotrons

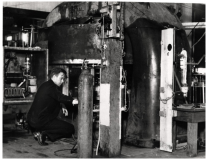
1931: 28 cm p^+ 1.2 MeV



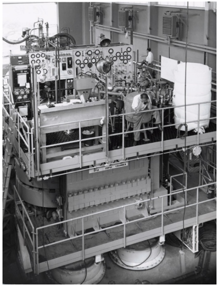
1932-1936: 69 cm D^+ 4.8 MeV



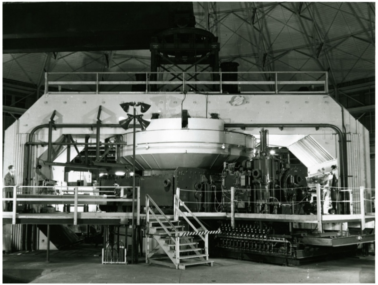
1937-1938: 94 cm D^+ 8 MeV



1939-1941: 152 cm D^+ 16 MeV



1942: 467 cm heavy ions >100 MeV



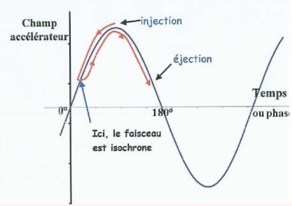
Cyclotron limitations

Synchronism issue

- Revolution frequency decreases with γ.

$$\omega = \frac{v_\theta}{r} = \frac{qB_z}{\gamma m_0}$$

- Dephasing between particles and RF continuously increase.
- p^+ up to $20\,\mathrm{MeV}$.



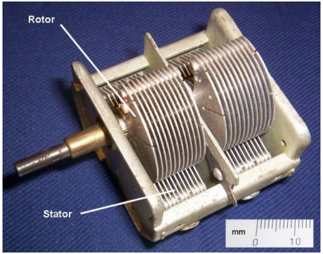
A few solutions

- Match the RF frequency to energy: synchrocyclotron (ions).
- Increase B with radius: isochronous sectors cyclotron (ions).
- Match B and f at the same time: synchrotron (ions + e^-).
- Create a circular electric field E: betatron (e^-).
- Switch by an RF peiod at each turn: microtron (e^-).
- Do not turn!: Linear accelerator.

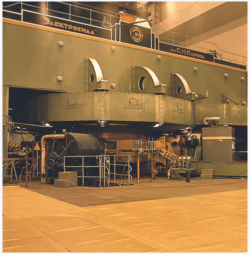
The synchrocyclotron

- 1945: Edwin McMillan (USA) and Vladimir Veksler (URSS).
- The RF frequency cycles thanks to a very big rotating capacitor (period $1\,$Hz to $100\,$Hz).
  - Very large number of turns $\Rightarrow$ less RF voltage.
  - Energy limitation comes from the dipole size (Leningrad: diam. $7\,$m $7000\,$t $1\,$GeV p^+)
  - But the beam is pulsed : reduce average intensity.
- Still a few machines under operation like the Centre of Protontherapy in Orsay until 2008.

Variable capacitor:



1949: Dubna $6\,$m $700\,$MeV p^+



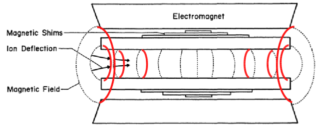
Sectors cyclotron

- Increase B_z with γ and thus r: $\omega = \frac{v_\theta}{r} = \frac{qB_z}{\gamma m_0}$

Vertical stability is lost!

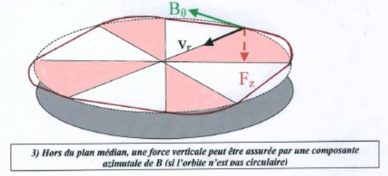
Field lines oriented to the inner side.

$$\frac{\partial B_r}{\partial z} = \frac{\partial B_z}{\partial r}$$

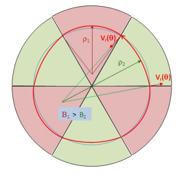


Solution: additional force $qv_r \times B_\theta$

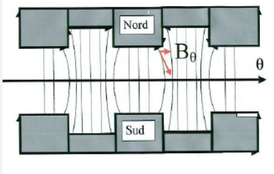
Modulation of B with θ



Modulation of v_r with θ



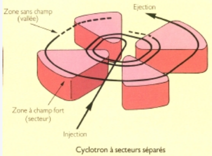
B_θ out of the medium plane



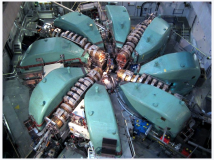
Hills and valleys

- The dipole faces are not perpendicular to the trajectory.
- 1938: L. H. Thomas focusing with the edges.
- 1954: Kerst (spiralled sectors)

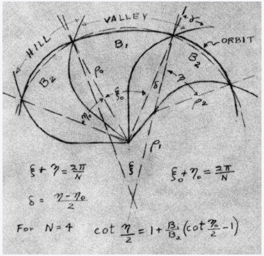
Sectors cyclotrons



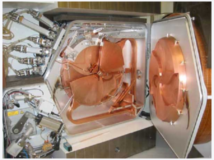
Sectors Cyclotron of PSI 590 MeV p^+



Kerst's manuscript



Spiralled cyclotrons



6. The accelerator family

The synchrotrons

The synchrotron

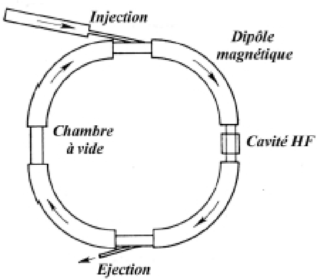
- Interest: reduce the size of the vacuum chamber.
- O-ring chamber with a constant trajectory radius.
- Idea proposed by M. Oliphant in 1943 and realized in 1953 for protons of 1.0 GeV in Birmingham University.
- The magnetic field and RF frequency must always match with the beam energy.

$$B(t) = \frac{\gamma(t) m_0 v(t)}{R}$$

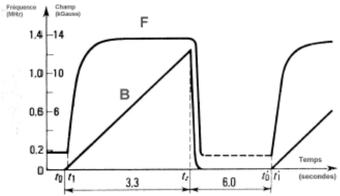
$$\omega_{RF} = h\frac{v(t)}{R}$$

h: harmonic number

Scheme

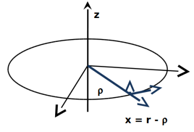


RF frequency and magnetic field cycle



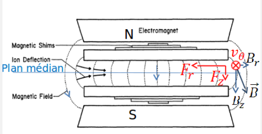
The weak focusing

Stability in the horizontal and vertical planes



- Let be the equilibrium trajectory: $\rho = \frac{mv}{qB_0}$
- Let be a small difference x of the trajectory radius ρ such as: $r = \rho + x = \rho\left(1 + \frac{x}{\rho}\right)$
- The motion is stable if $evB_z(r) \begin{cases} > \frac{mv^2}{r} & \text{when } r > \rho \\ < \frac{mv^2}{r} & \text{when } r < \rho \end{cases}$
- Let be $n = -\frac{\rho}{B_0}\frac{\partial B_z}{\partial r}$ the field gradient ($B_z(r) = B_z(\rho)\left(\frac{\rho}{r}\right)^n$).

$\Rightarrow \frac{mv^2}{r} \approx \frac{mv^2}{\rho}\left(1 - \frac{x}{\rho}\right)$ and $evB_z(r) \approx evB_0\left(1 - n\frac{x}{\rho}\right)$



- Horizontal stability only if $n < 1$.
- Vertical stability if field lines oriented to the outer side

$\Rightarrow 0 < n < 1$

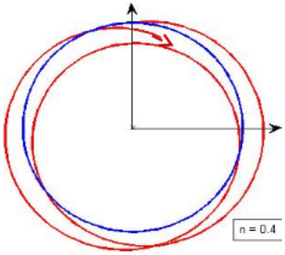
Limitations of the weak focusing

- The motion equations are:

$$\frac{d^2x}{dt^2} + \omega_0^2(1-n)x = 0 \qquad \frac{d^2z}{dt^2} + \omega_0^2 nz = 0 \qquad \omega_0 = \frac{qB_0}{m}$$

- The periods of the solutions are larger than the revolution frequency:
  $f_x = \sqrt{1-n}f_0 \qquad f_z = \sqrt{n}f_0$
- The trajectory variations are then big compared to the reference trajectory, the vacuum chamber and the dipole gaps are large.

Oscillations in the horizontal plane ($n = 0.4$)

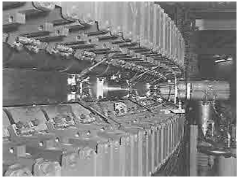


The first synchrotrons

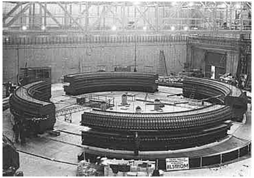
	Birmingham	Saclay Saturne I	Brookhaven Cosmotron	Berkeley Bevatron	Dubna Synchrophasotron
Mean radius [m]	4.5	11	10.7	18.2	30.5
Chamber section [cm^2]	50×21	60×10	91×22	122×30	150×40
Start date	1953	1958	1952	1954	1957

The synchrotrons in pictures

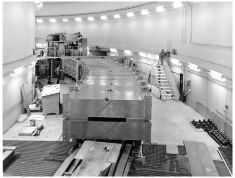
1952: Cosmotron in Brookhaven $3\,\text{GeV}$



1958: Saturne 1 in Saclay $3\,\text{GeV}$



1962: ZGS in Argonne $10\,\text{GeV}$ p^+

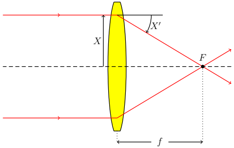


1957: Synchrophasotron in Dubna $12.5\,\text{GeV}$

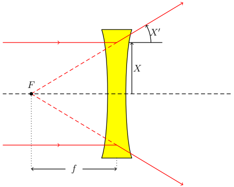
2002: After its dismantling

The strong focusing

- 1952 : E. Courant, H. Snyder, and S. Livingston propose the strong focusing or with alternating gradients.



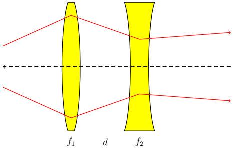
$f > 0$ focusing



$f < 0$ defocusing

$$\begin{pmatrix} X \\ X' \end{pmatrix}_1 = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} X \\ X' \end{pmatrix}_0$$

- Alternating focusing/defocusing elements is focusing in average.



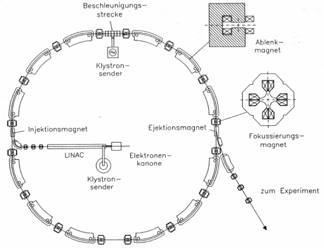
$$\begin{pmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{d}{f_1} & d \\ \frac{d - f_1 - f_2}{f_1 f_2} & 1 - \frac{d}{f_2} \end{pmatrix}$$

$f_1 = -f_2 = f$ et $d < |f| \Rightarrow \frac{d - f_1 - f_2}{f_1 f_2} = -\frac{d}{f^2}$ thus focusing

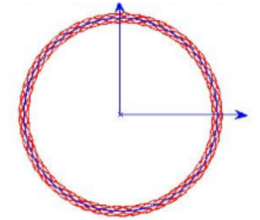
The synchrotron with strong focusing

- The constant dipole gradient is replaced by magnetic elements with dedicated purposes:
  - dipoles to bend the trajectory,
  - quadrupoles to focus the beam,
  - sextupoles and other multipoles to correct the aberrations.
- The ring is made of lattices.

A generic synchrotron



Betatron oscillations in the horizontal plane



Why colliding?

R. Widerøe:

"... I had thus come upon a simple method for improving the exploitation of particle energies available for nuclear reactions. As with cars (collisions), when a target particle (at rest) is bombarded, a considerable portion of the kinetic energy (of the incident particle) is used to hurl it (or the reaction products) away.
Only a relatively small portion of the accelerated particle's energy is used to actually to split or destroy the colliding particles. However, when the collision is frontal, most of the available kinetic energy can be exploited. For nuclear particles, relativistic mechanics must be applied, and ... be even greater."
"... It it were possible to store the particles in the rings for longer periods, and if these 'stored' particles were made to run in opposite directions, the result would be one opportunity for collision at each revolution."

Fixed target against Collider. Application to LHC

$$E_{\text{cm}} = \sqrt{(E_1 + E_2)^2 - (\mathbf{P_1} + \mathbf{P_2})^2 c^2}$$

Fixed target

$$E_{\text{cm}} = c\sqrt{2mE_1}$$

$$\left.\begin{aligned} E_1 &= 7\ \text{TeV} \\ E_2 &= m_p c^2 \end{aligned}\right\} \begin{aligned} E_{\text{cm}} &= \sqrt{2 \cdot 7 \cdot 0.001} \\ E_{\text{cm}} &= 0.118\ \text{TeV} \end{aligned}$$

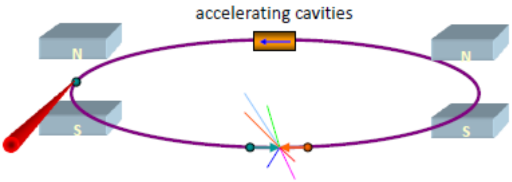
Collider

$$E_{\text{cm}} = 2E_1$$

$$\left.\begin{aligned} E_1 &= 7\ \text{TeV} \\ E_2 &= 7\ \text{TeV} \end{aligned}\right\} \begin{aligned} E_{\text{cm}} &= 2 \cdot 7 \\ E_{\text{cm}} &= 14\ \text{TeV} \end{aligned}$$

The circular colliders

Circular colliders



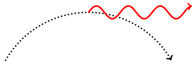
- ☺ Energy gain in several turns in a few cavities.
- ☺ Collisions at each turn (several interacting points are possible).
  - ⇒ Strong luminosity (number of collisions per time and surface unit).
- ☺ RF and particles used again.
  - ⇒ Energy efficient.
- ☹ Synchrotron radiation losses may be large $P \propto \frac{\gamma^4}{R}$
- ☹ Bending magnets
  - ⇒ Strong magnetic field (LHC : superconduncting dipoles)

Synchrotron radiation

- When free charged particles are curved, they lose kinetic energy by emitting an electromagnetic field (Maxwell's equations)

$$P_{\text{radiated/turn}} \propto \frac{\gamma^4}{R}$$

$$P^{\text{electrons}}_{\text{radiated/turn}}[\text{keV}] \approx 88.5 \frac{E^4[\text{GeV}^4]}{R[\text{m}]}$$



☺ Light source (SOLEIL, X-FeL)

☺ Strongly damps the emittance of electron beams.

☹ Limits the maximal current you can store in a synchrotron.

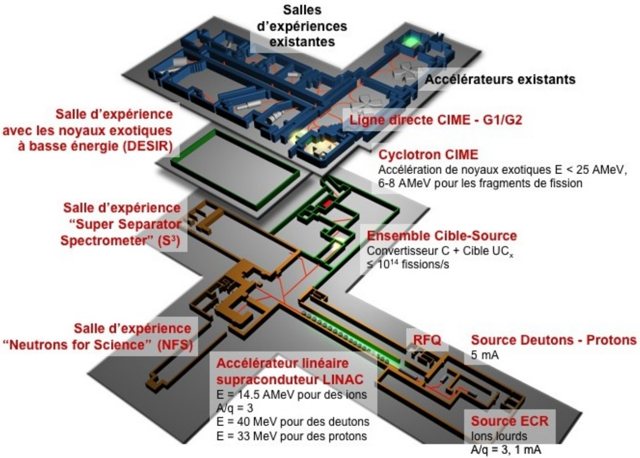
Case of electrons of 7 TeV in the LHC

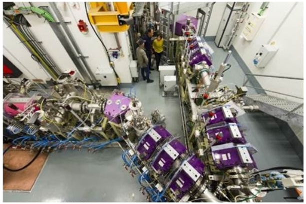
$$\left.\begin{array}{l} E = 7\,\text{TeV} \\ R \approx 5\,\text{km} \end{array}\right\} P_{\text{radiated/turn}} \approx 42\,000\,\text{TeV!!!}$$

7. Big accelerator projects

A few examples of existing and future installations

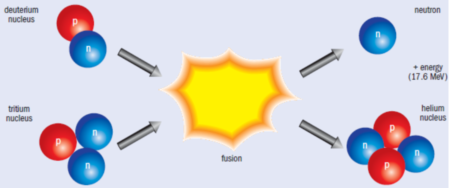
SPIRAL2 in GANIL: for nuclear physics

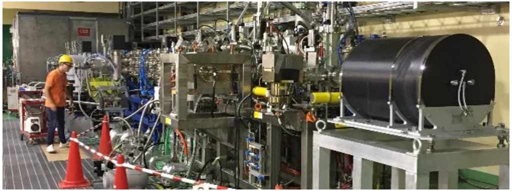


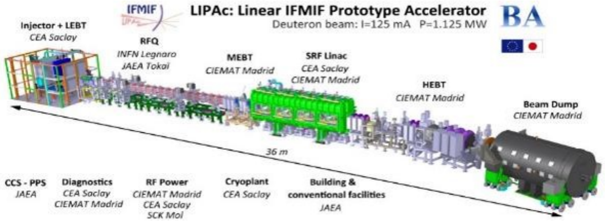


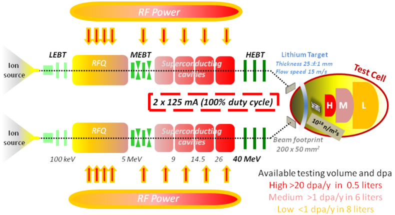
IFMIF/EVEDA: for the fusion

- IFMIF/ EVEDA: neutron facility of 14 MeV in Japan for material tests and fusion plants.





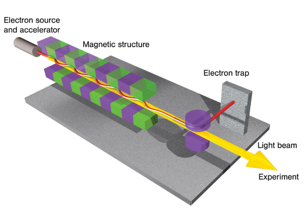


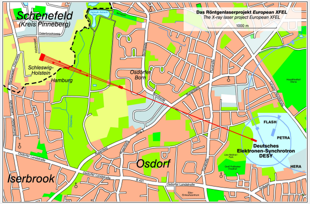


XFeL: a X-ray source (free electron laser)

X-FeL in a few figures

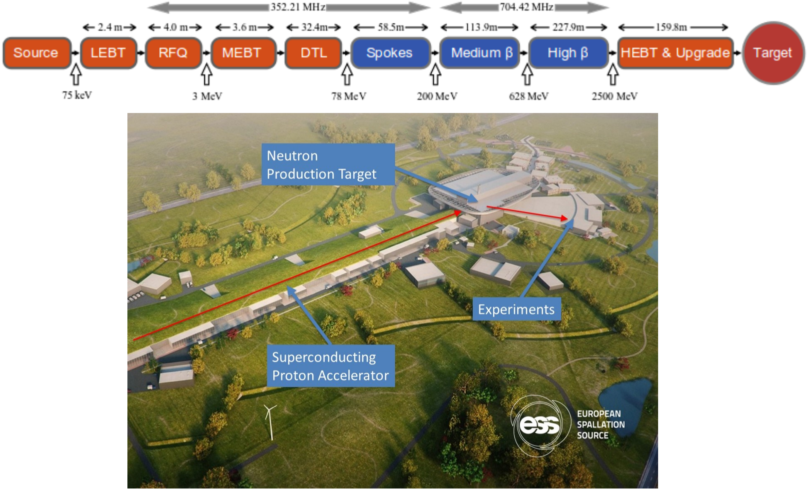
- First beam: 2017
- Length: 2 km
- Final energy: 17.5 GeV
- 101 modules
- $\lambda_\nu = 0.05$ nm to 6 nm



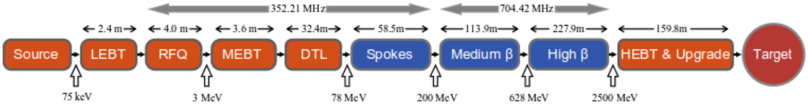


Cryomodule: length of 12 metres

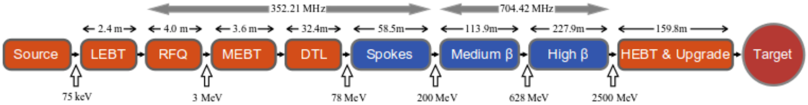
ESS: a spallation source to probe the matter



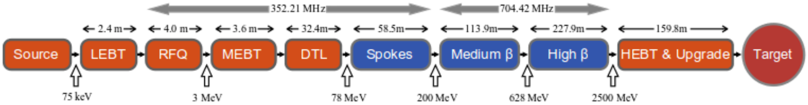
ESS: a spallation source to probe the matter



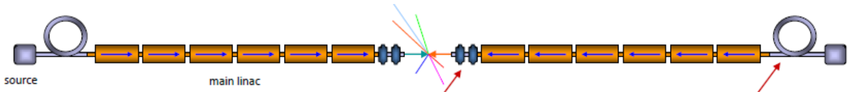
ESS: a spallation source to probe the matter



ESS: a spallation source to probe the matter



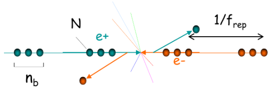
Linear colliders: ILC or CLIC



Collisionneurs linéaires

- Less synchrotron radiation losses (due to the trajectory bending).
- Energy gain in a single pass.
  $\Rightarrow$ Large accelerating gradient to minimize the machine size.
- Unique collision per particle.
  $\Rightarrow$ Very dense beam to get a large luminosity.

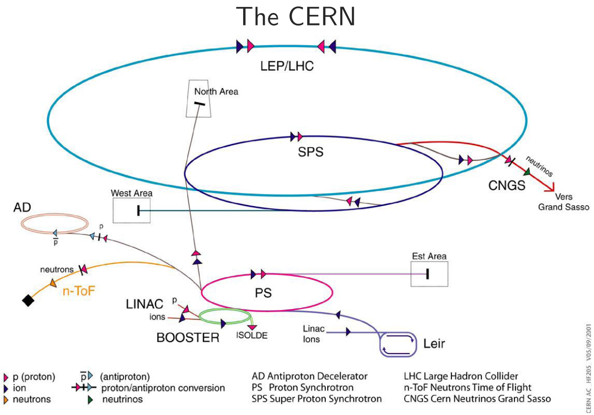
$$\mathcal{L} = \frac{f_{\text{rep}} n_b N^2}{4\pi\sigma_x^*\sigma_y^*}$$



$\Rightarrow$ Very small beam size (nanometre!), large repetition rate, alignment and machine stability critical..

$\Rightarrow$ Energy efficiency to optimize.

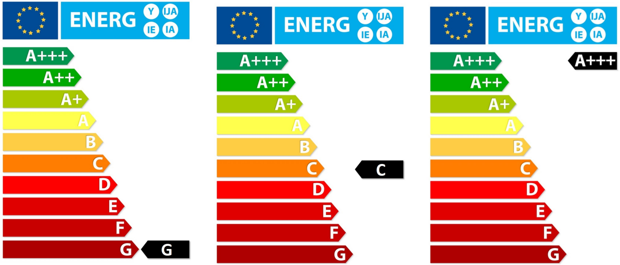
The post LHC

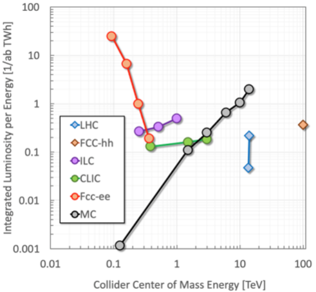


- The LHC: the most powerful machine today.
- Physics program until 2030-2040.
- Quid after 2040?
- Lepton colliders (CLIC, ILC, muon colliders ...)
- Hadron colliders: 20 years of design are necessary!
- That is today to prepare the machines of the future.

Energy efficiency

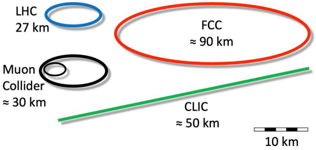
In 1940 | In 2022 | Tomorrow ?



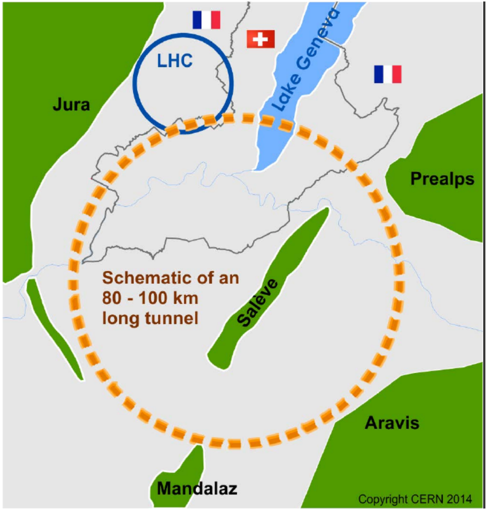


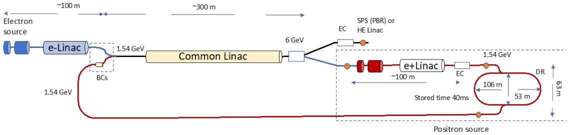
Limitations

- Beam power.
- Size.
- Cost (building and operating).



FCC-ee (Future Circular Collider for electrons)



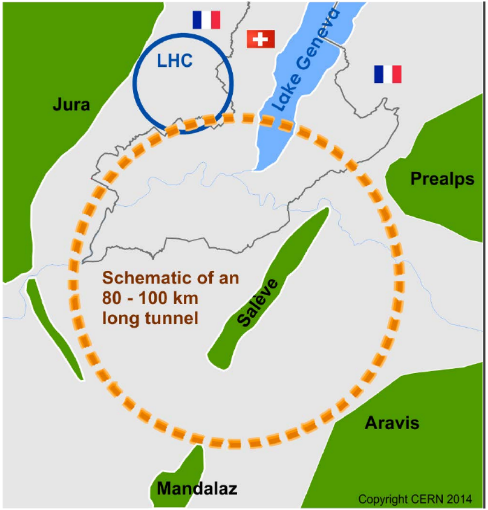


A radiating machine

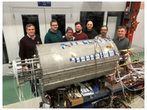
- $100\,\mathrm{km}$ (3 x LHC).
- $P_{\mathrm{radiated}}=50\,\mathrm{MW/beam}$!
- The radiated power limits the beam power. The beam current depends on the collision energy.
- $1280\,\mathrm{mA}$ at $45.6\,\mathrm{GeV}$

→ $5.0\,\mathrm{mA}$ at $182.5\,\mathrm{GeV}$

FCC-hh (Future Circular Collider pour hadrons)



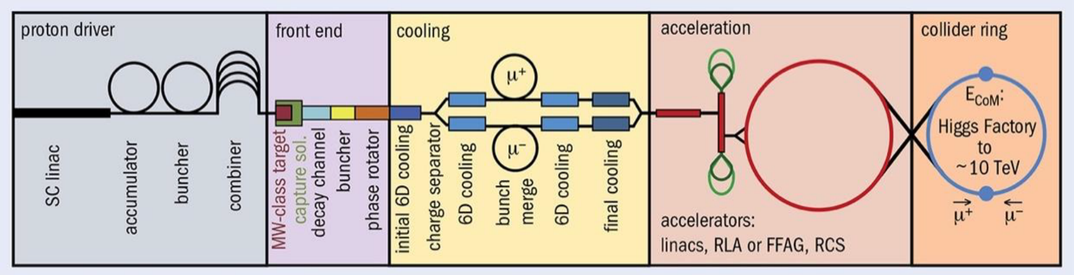
8.3 T → 12 T → 14.5 T



Numerous challenges

- 100 km (3 x LHC).
- $E_{c.m.}$=100 TeV! (7 x LHC).
- B_{dipole}=16 T! (2 x LHC).
- Stored energy: 8.2 GJ/beam (1/2 A380 in flight)! (20 x LHC).
- Radiated power: 26 W/m.
- Machine protection.
- Maybe after FCC-ee.

Muon colliders



- ☺ Leptons. All the collision energy is for physics (contrary to particles like protons).
- ☺ Particle 200 times heavier than electron. Synchrotron radiated power reduced by 1.6×10^9 at same collision energy.
- ☹ Unstable particle. Half-life time: $2.2\,\mu s$. You should accelerate very fast!
- ☹ You have to produce and cool very fast to get efficient collisions!

Thank you for your attention!
Any idea for the future?

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