Greek Teachers Programme 2022

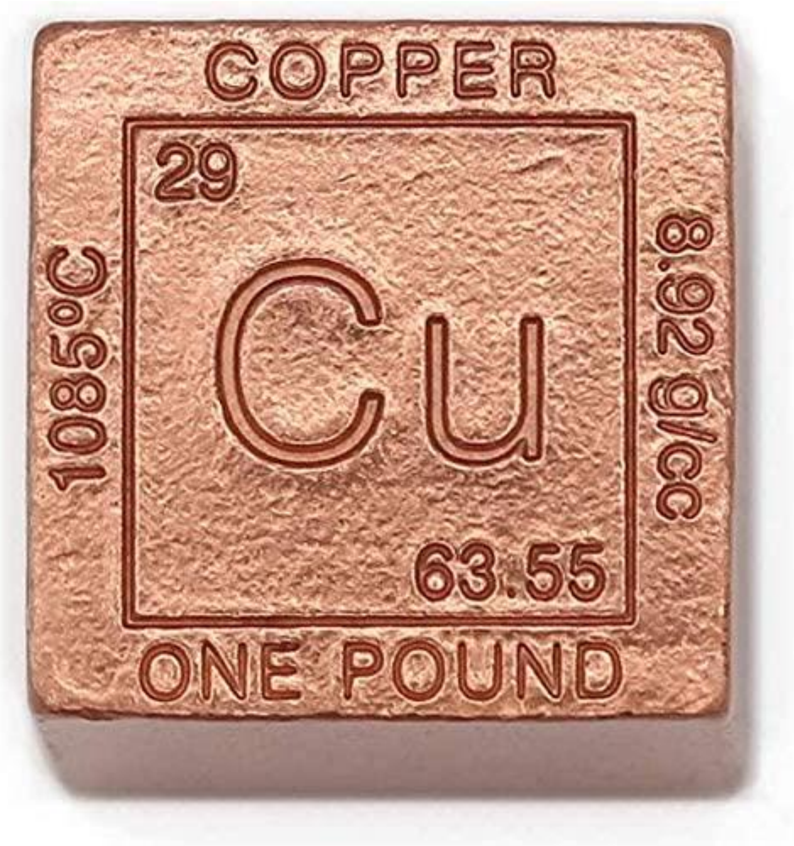
Efficient Powering for Research Facilities

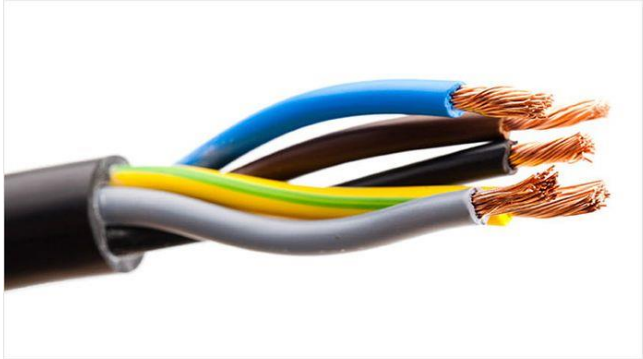
Konstantinos Papastergiou | Accelerator Systems Department
CERN – European Organisation for Nuclear Research

Quizz

- Gold contains some of it.
- A household contains 180 kg of this
- The average car contains about 20kg
- It is naturally antibacterial
- 100% recyclable used since ancient times
- It is located in the middle of the periodic table of elements
- Price increased about 30% this year alone
- More than 80kg will be needed for each electric car
- The demand is expected to increase from 40 to 600m tones in 15 years.

Copper





Quizz

- Has 14 protons in the nucleus
- It is called a metalloid
- It is extracted from the sand
- Dangerous if inhaled – can cause xxx-cosis
- Combined with carbon it makes xxx-carbide the hardest substance after diomond
- Plants use it to strengthen their cell walls
- California xxx-valey is a famous user of the element

Silicon

Semiconductors

Applications of power electronics

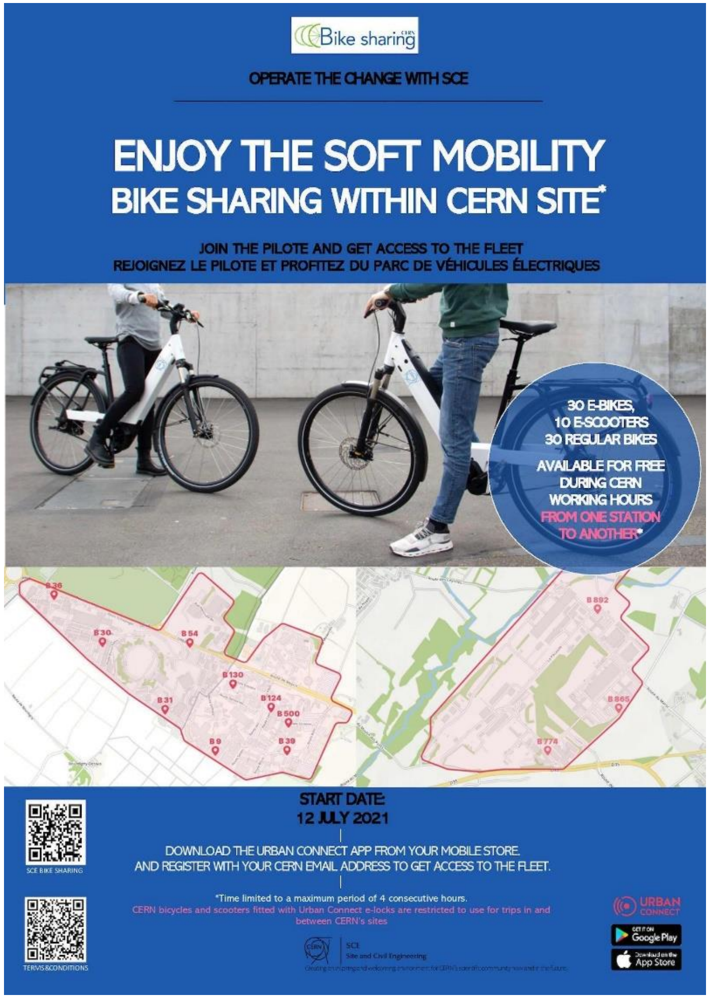
Power supply/chargers

15W

Source: yootech Chargeur

Electric scooter/bike

400W



Industrial Robots

10kW

Source: Le monde (Kawada Robot)

Terrestrial/satellite

10kW

Electric car/truck/plane

50kW

Industrial drives

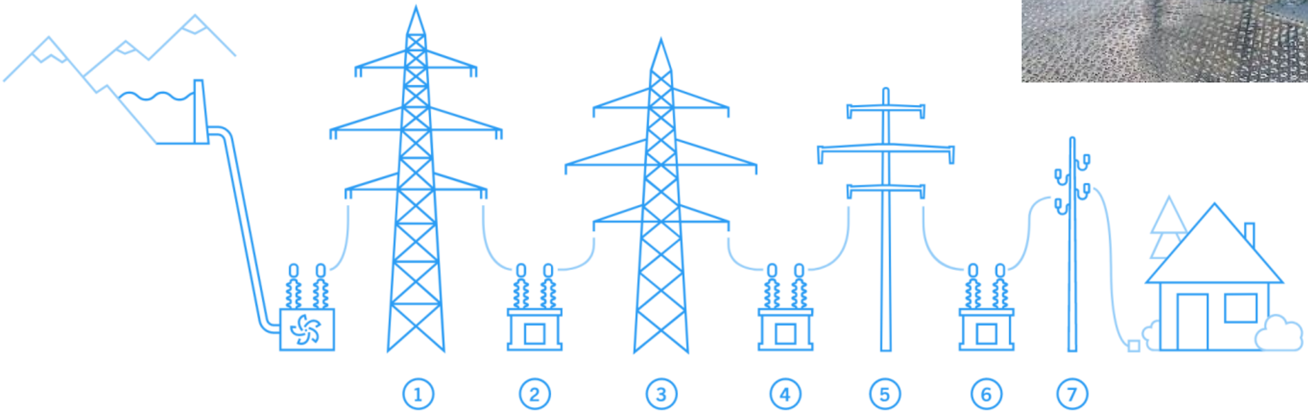
500kW

Renewable generation

3MW

Energy Transmission

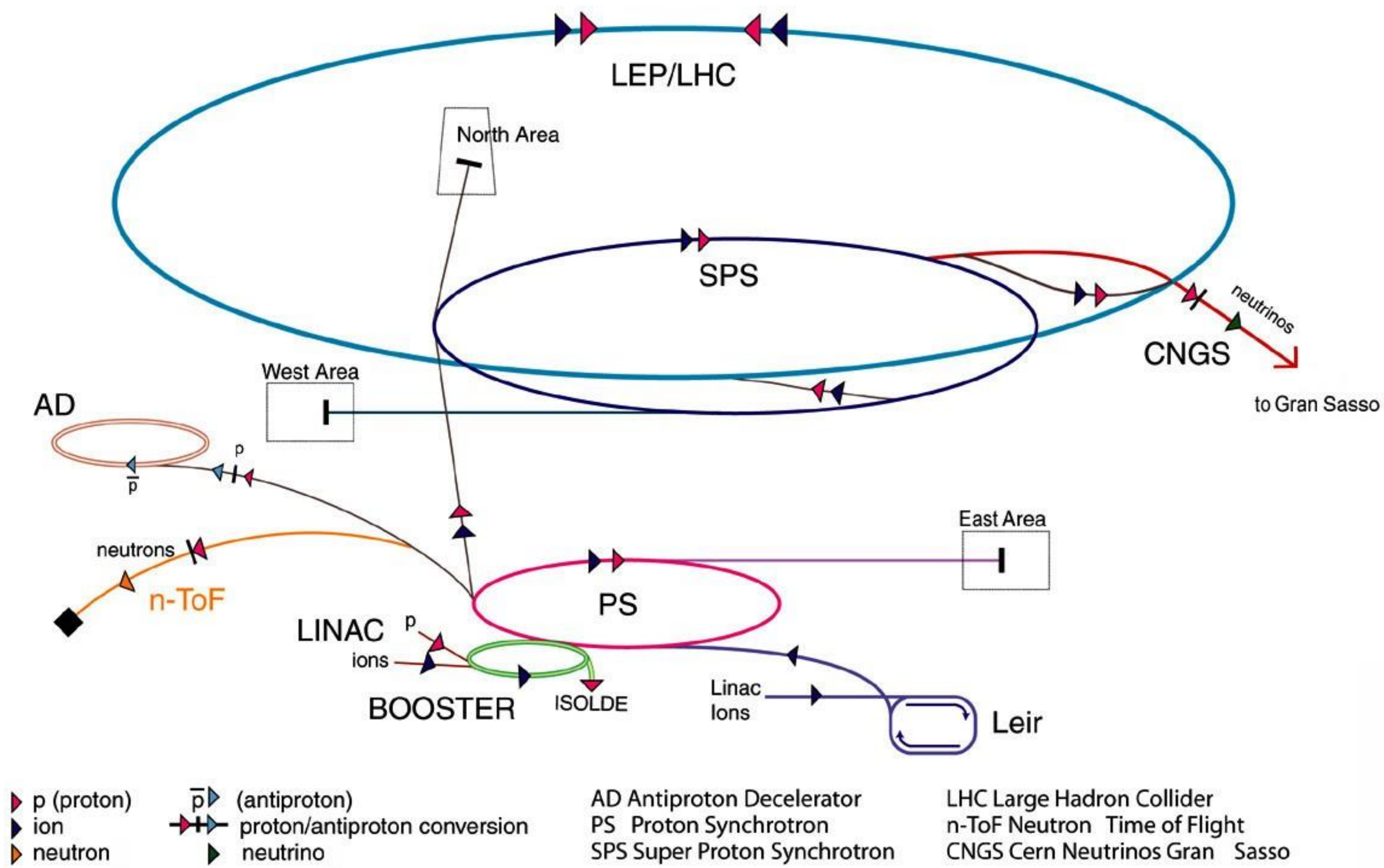
2GW



Source: Swissgrid.ch

η ενέργεια στους επιταχυντές

Accelerators at CERN



Key Energy Consumers

- **Direct Energy to the beam**
  - RF cavities - Klystron
  - Magnets
- **Environmental Conditioning**
  - Cryogenics
  - Systems cooling
  - Tunnel air filtering
- **Data**
  - Measurements
  - Processing
- **Infrastructure**
- **Other**

(c) Rey.Hori / KEK

What component accelerates the charged particles?

What component steers the charged particles in their trajectory?

Force on Charged Particle

The force on a charged particle is proportional to the charge, the electric field, and the cross product of the velocity vector and magnetic field:

Lorenz force:

$$\boxed{\vec{\mathbf{F}} = q\cdot(\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})}$$

Where q is the electrons' (positrons', protons'…) elementary charge:

$$\mathrm{q} = \mathrm{e}_0 = 1.602\cdot 10^{-19}\ [\mathrm{C}]$$

For conservative forces (work done independent of the path) the work done by a force F along the path s_1->s_2 transversed by the particle is:

$$\boxed{\Delta E = \int_{s1}^{s2} \vec{\mathbf{F}}\cdot \mathbf{d}\vec{\mathbf{s}}}$$

by differentiating:

$$\boxed{\Delta E \big/ dt = q\cdot(\vec{\mathbf{v}}\cdot\vec{\mathbf{E}} + \vec{\mathbf{v}}\cdot(\vec{\mathbf{v}}\times\vec{\mathbf{B}})) = q\cdot\vec{\mathbf{v}}\cdot\vec{\mathbf{E}}}$$

Conclusion the magnetic field does not produce any work on the direction of the vector travelled by the charged particle. Energy (acceleration) is only gained under the effect of electric field.

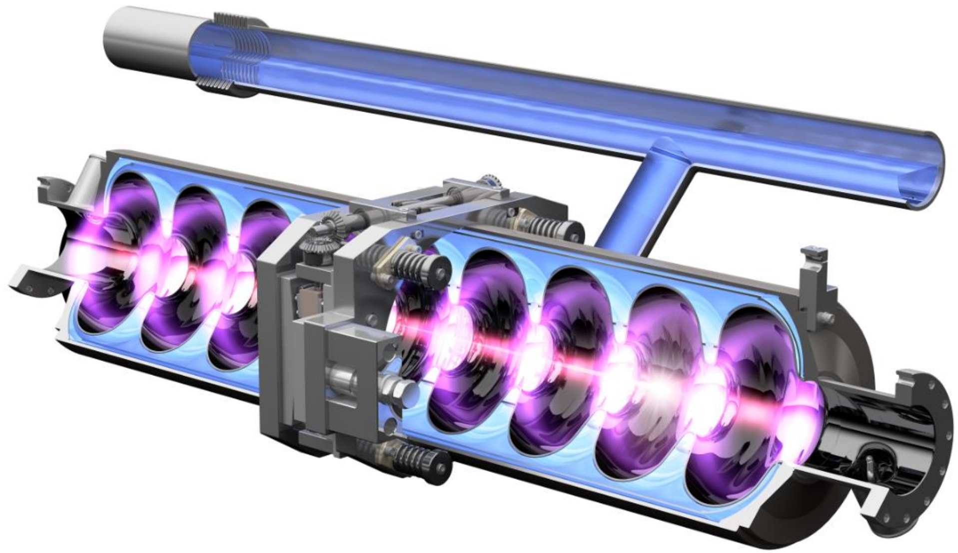
RF Cavities - Klystron

Functions:

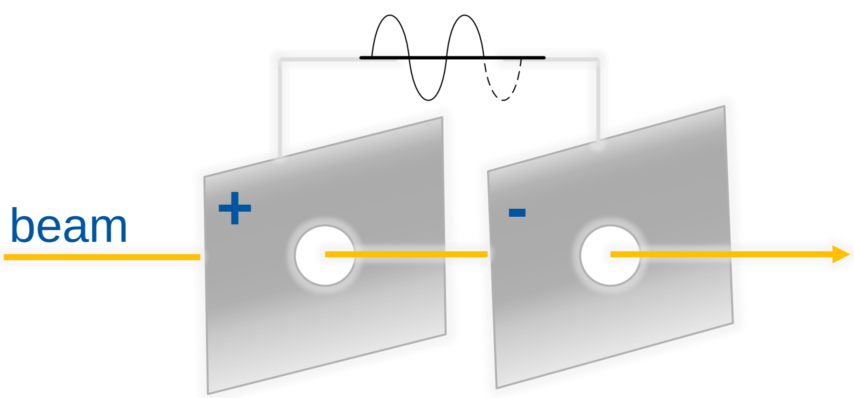
- Particle acceleration

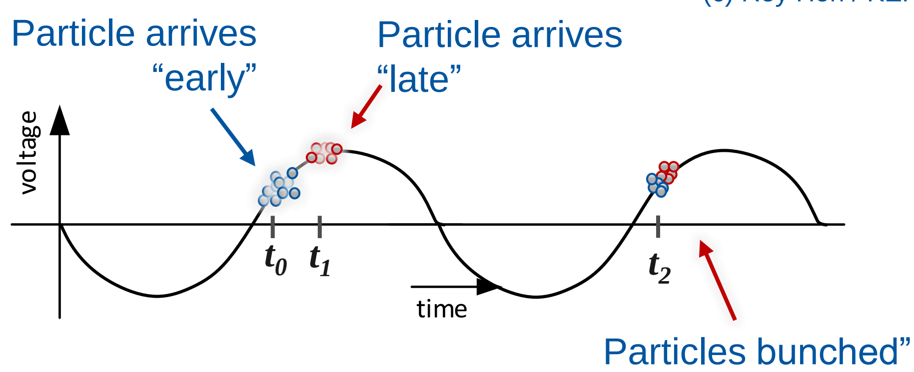
$$\Delta E = \int_{s1}^{s2} \vec{F} \cdot d\vec{s} = q \cdot \int_{s1}^{s2} \vec{E} \cdot d\vec{s} = q \cdot U$$

* The rythm of energy build up depends on the particles' charge and the electric field voltage



(c) Rey Hori / KEK





Cryogenics

(c) Rey Hori / KEK

- Cryogenic pumps are the largest single electrical consumer at CERN
- Peak power: 50MW

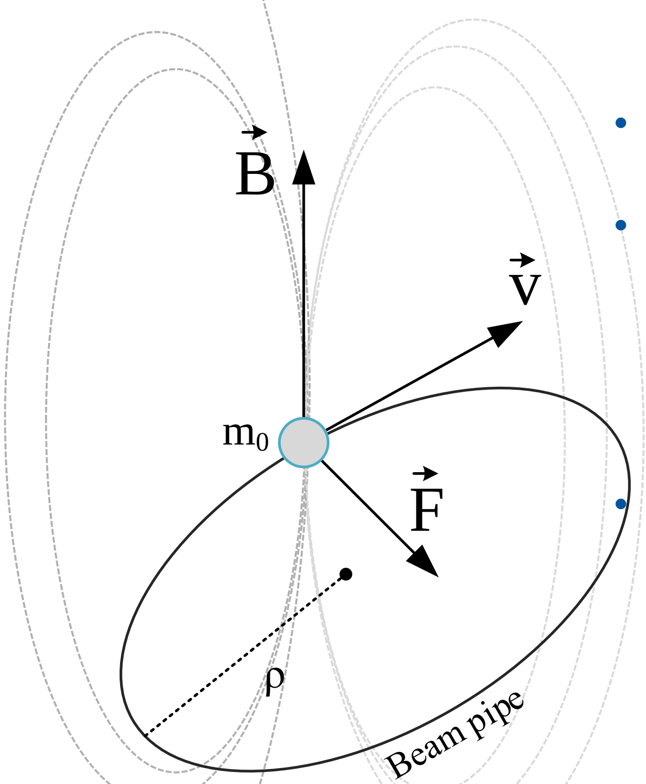
  6 weeks to cool down Helium to 1.8K

Electromagnets

Functions:

- Beam steering

$$\boxed{\vec{\mathbf{F}} = q\cdot(\vec{\mathbf{v}}\times\vec{\mathbf{B}})}$$



- At first sight F is not dependent on mass
- Since v on a circle of radius ρ-> F = centripetal force

$$\boxed{\vec{\mathbf{F}} = q\cdot(\vec{\mathbf{v}}\times\vec{\mathbf{B}}) = m_r\cdot\vec{a}_C = \frac{m_r\cdot\vec{v}^{\,2}}{\rho}}$$

$$\boxed{m_r = \gamma\cdot m_0}$$

* γ : lorenz factor ($\gamma=1/(1-v^2/c^2)$)

- Rearanging yields the beam rigidity i.e. a measure of the force needed to bend the charge direction
- And the bending angle inside a magnet field

$$\boxed{\vec{B}\cdot\rho = \frac{m\cdot\vec{v}}{q} = \frac{\vec{p}}{e}}$$

$$\boxed{a = \frac{\int\vec{B}\cdot ds}{B\cdot\rho}}$$

- The integrated field is a magnet property also given by Amperes law:

$$\boxed{\oint_C \vec{B}\cdot ds = \mu_0\cdot\iint_A \vec{J}\cdot dA = \mu_0\cdot I_C}$$

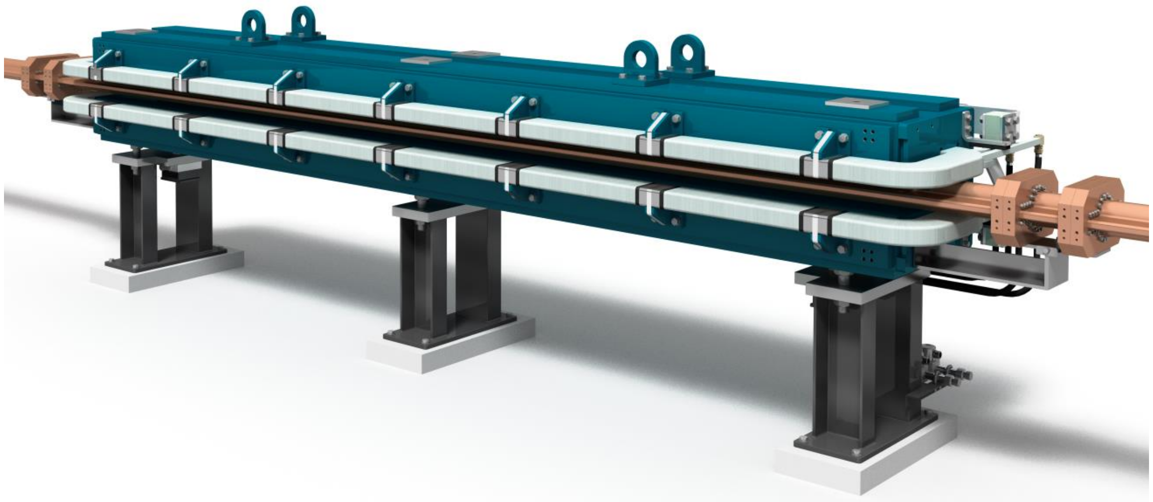
*μ_0: magnetic permeability of the air

Dipole magnet

Functions:

- Beam steering

- Stores energy $E=0.5\ L\ I^2$
- Consumes power $P=I^2\ R$



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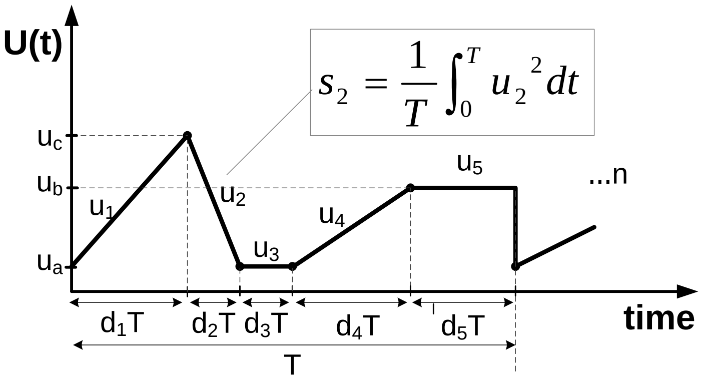
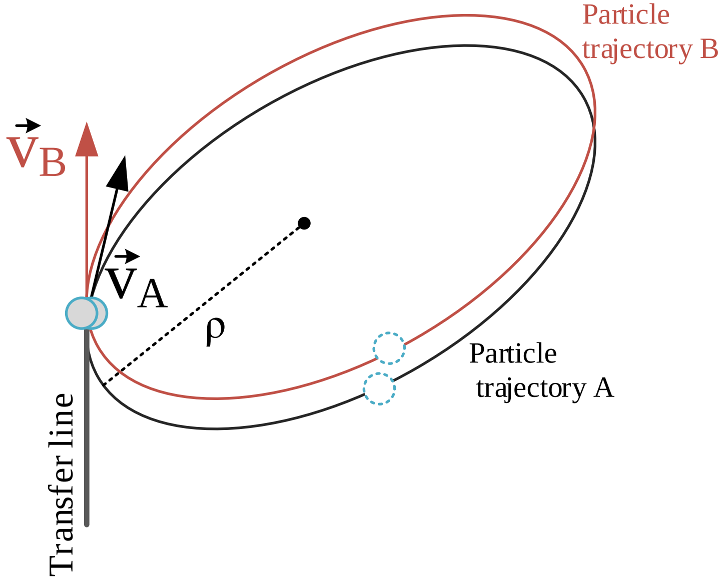


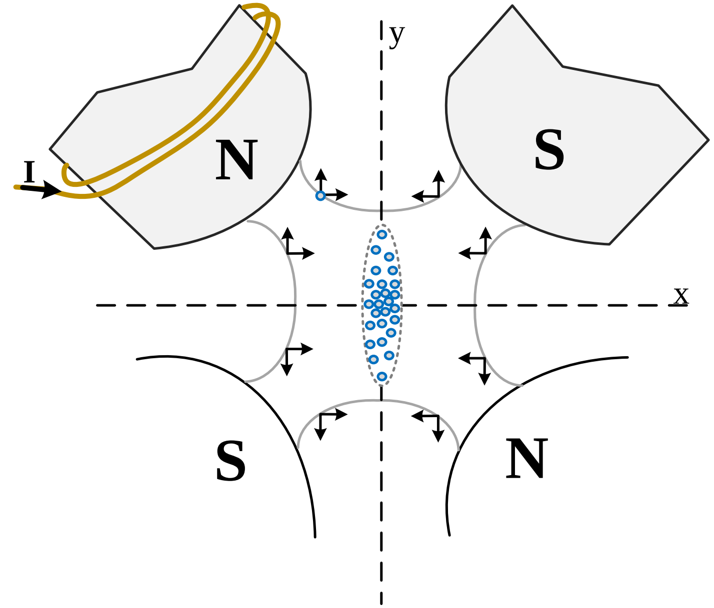
Quadrupole magnets

Functions:

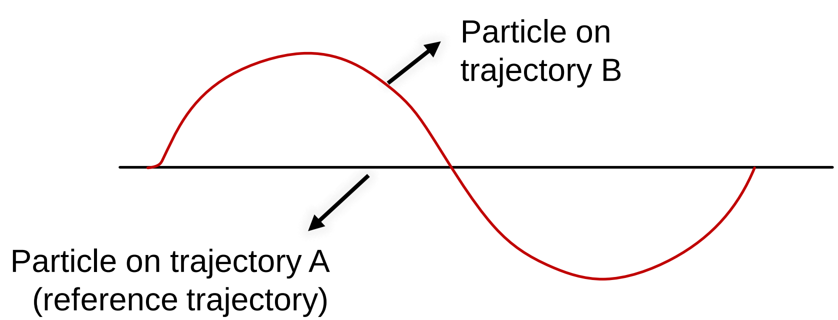
- Focussing-defocusing

Two particles enter in the accelerator with different velocity vectors:





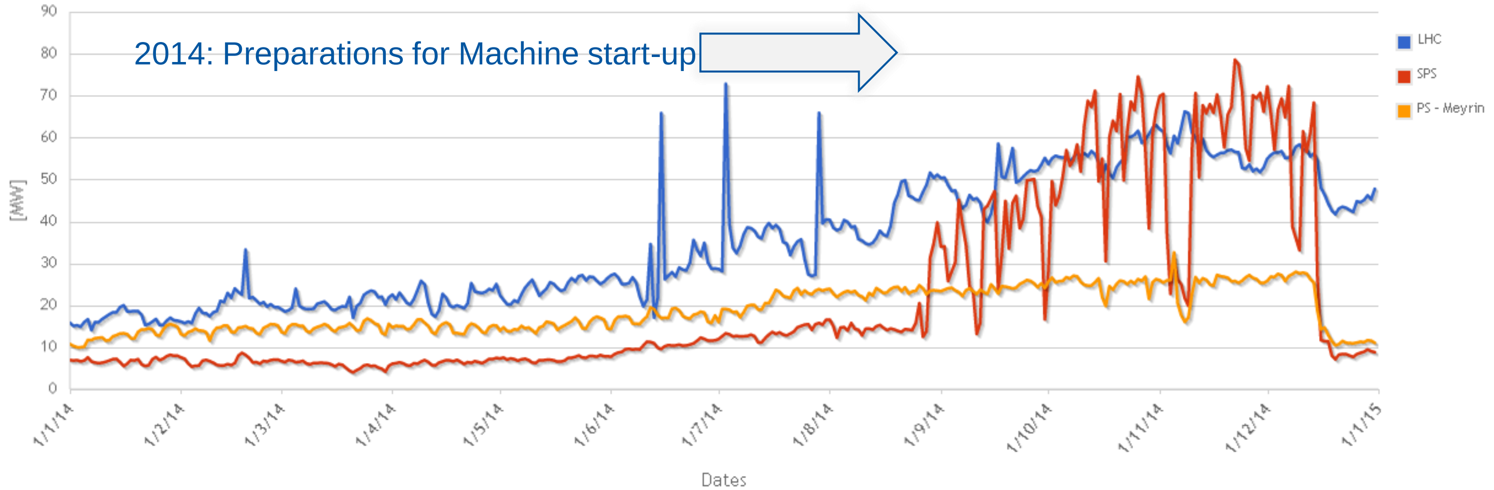
Betatron Oscillation



CERN και ενέργεια

Electricity at CERN

- Interconnections to both France and Switzerland
- Approximately 80% of electricity from France
  - French Energy mix: 75%Nuclear,16% Hydro, Thermal 9%
- 1000 high voltage circuit breakers in operation
- Consumption
  - as high as all households in Geneva area
  - 1/10th of the canton (11.3TWh).

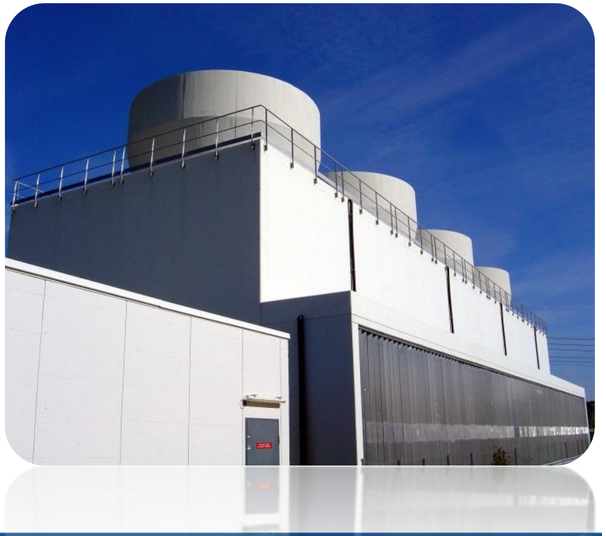


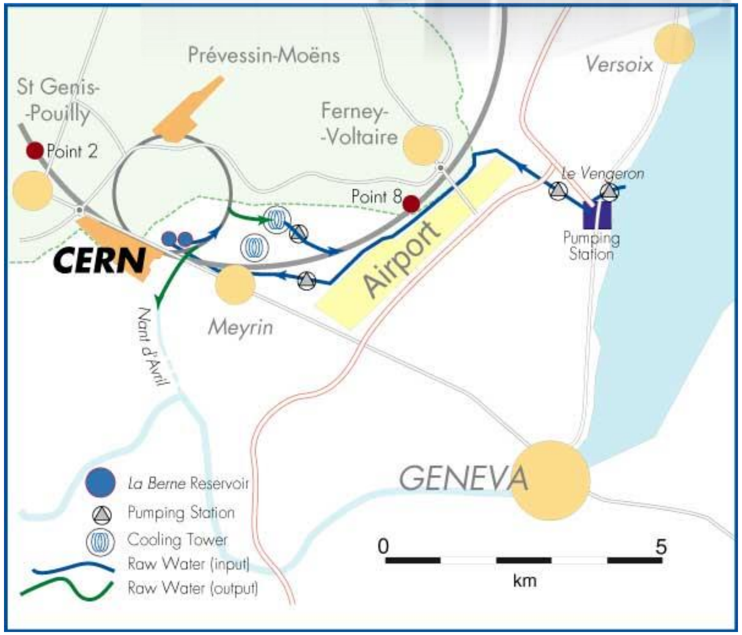
Energy Facts & Figures

- **Total consumption 1 230 000 000 kWh/yr (at home ~ 11 000kWh/yr)**
  - 43% consumed by the LHC
    - Up to 14% by superconductive magnet cooling
    - Up to 9% equipment cooling and tunnel ventilation
  - 11% by its Experiments
  - 30% by SPS
    - 7% at its Experiments
  - 3% PS-booster-Linac
  - 6% Data Centres
  - 7% in offices, restaurants etc.

Water

- 5 million m³ of water mainly from the lake
- Closed circuit of demineralised water and secondary circuit of raw water cooled in cooling towers.
- Industrial process water
  - Surface treatment
  - Production of demineralised water





Natural Gas

- Heating stations at Meyrin 8 million m^3
- Heating station at Prevessin – 1.5million m^3
- Operated by external companies
  - Monitor dust, CO, CO_2, nitrogen oxides and sulphur oxides

Steps towards more Sustainable Research Facilities

Types of accelerators

Light sources - photon radiation for research

P_{grid}<5MW

Power consumption per useful particle output is low

Examples: Swiss light source, International Spallation Source

Beamlines of *Soleil* in France

Proton Driver Accelerators – sources of neutrons, muons, neutrinos

P_{grid}<100MW

Losses dominated by Carnot Cycle Efficiency of cryogenic system

Examples: J-PARC, Spallation Neutron source, pSI cyclotron

Particle Colliders – head on collisions between beams

P_{grid}<500MW

- Synchrotron radiation from light particles (i.e leptons)
- Magnet strength due to rigid hadron beams
- Cooling of superconducting equipment

Examples: LHC

With acknowledgement to M.Seidel, Towards Efficient Particle Accelerators – A Review, presented in IPAC 2022 Conference

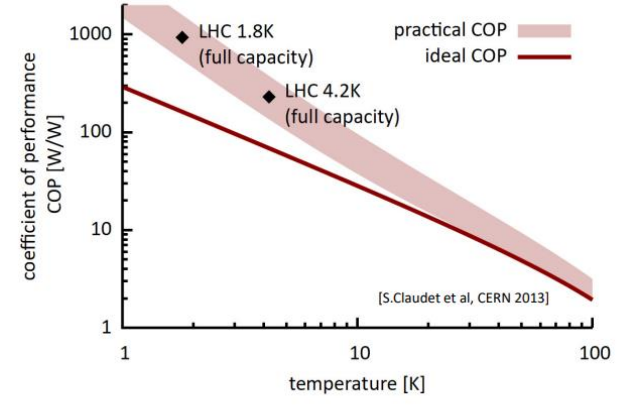
Dominant consumers

Accelerating structures:

- Radio frequency sources
  - Klystrons and Magnetrons tubes
  - Solid state amplifiers
- Superconducting RF cavities
  - Standard at 1.8K or new 4.2K or higher
  - Objective: high cavity quality factor/high accelerating gradient
- Cryogenic systems for cooling

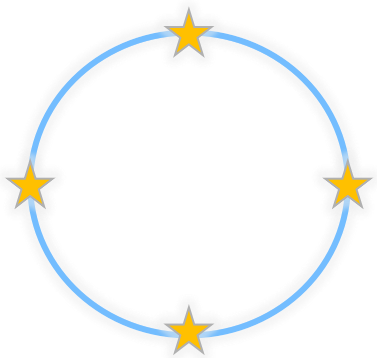
Typical efficiency <65%

$$COP_{refrigerator} = \frac{T_C}{T_H - T_C} = \frac{1.8K}{273K + 35K - 1.8\,K} = 1/170$$



Circular vs Linear Colliders

Circular Colliders (FCC etc)



- Lower voltage gradient in RF cavity
- Beam reused for many hours
- Synchrotron radiation is important
- Complex to operate with complex beam dynamics

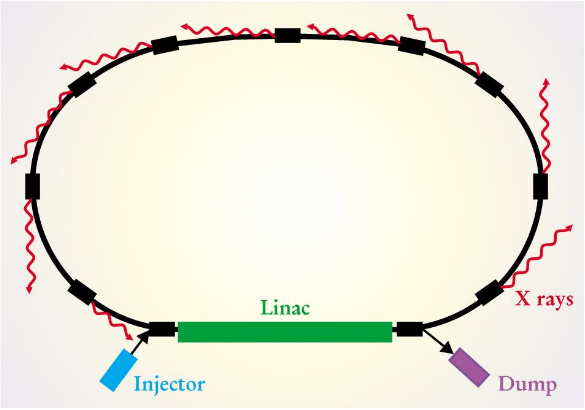
Linear Colliders (CLIC, ILC etc)

- Significant voltage gradients for acceleration
- Beam wasted after collision
- No Synchrotron radiation
- Better (easier) beam dynamics

With acknowledgement to M.Seidel, Towards Efficient Particle Accelerators – A Review, presented in IPAC 2022 Conference

Energy efficient concepts

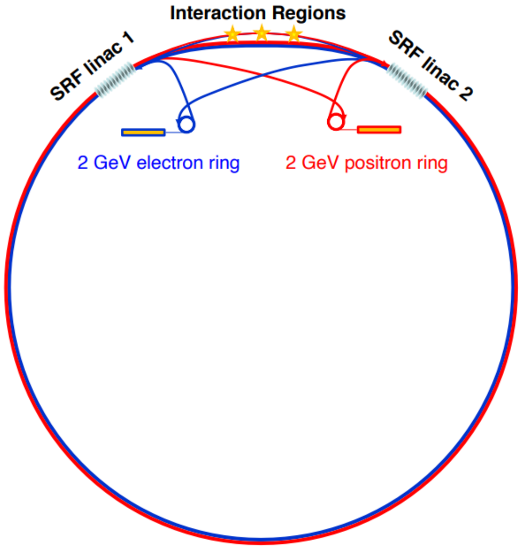
Jefferson Lab's FEL Light Source



- Lower emittance, shorter pulses (single turn)
- Recovery of spent energy

Source: Barbara Goss Levi, Physics today [link]

Circular Energy Recovery Collider



- Flat beams stored in 2GeV rings
- Buches ejected with collision frequency
- Beams accelerated by SRF linacs over 4km
- After collision rf phases are changed to decelerating recovering most energy
- Decelerated beams are reinserted in 2GeV rings

Source: V.N Litvinenko et al, High-energy high-luminocity e-e collider using energy recover linacs, Physics Letters, [link]

- Ερωτήσεις;

http://www.cern.ch/aftervisit

Life at CERN

CERN

www.cern.ch