



Greek Teachers Programme 2022

# Efficient Powering for Research Facilities

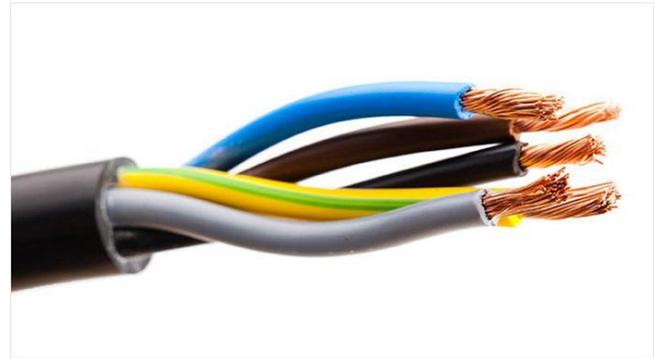
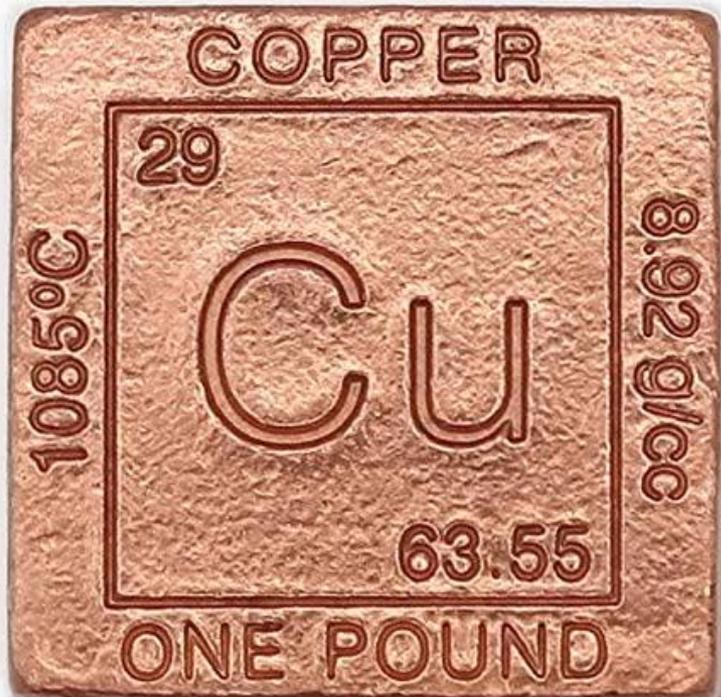
Konstantinos Papastergiou | Accelerator Systems Department  
CERN – European Organisation for Nuclear Research



# Quiz

- ➔ 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

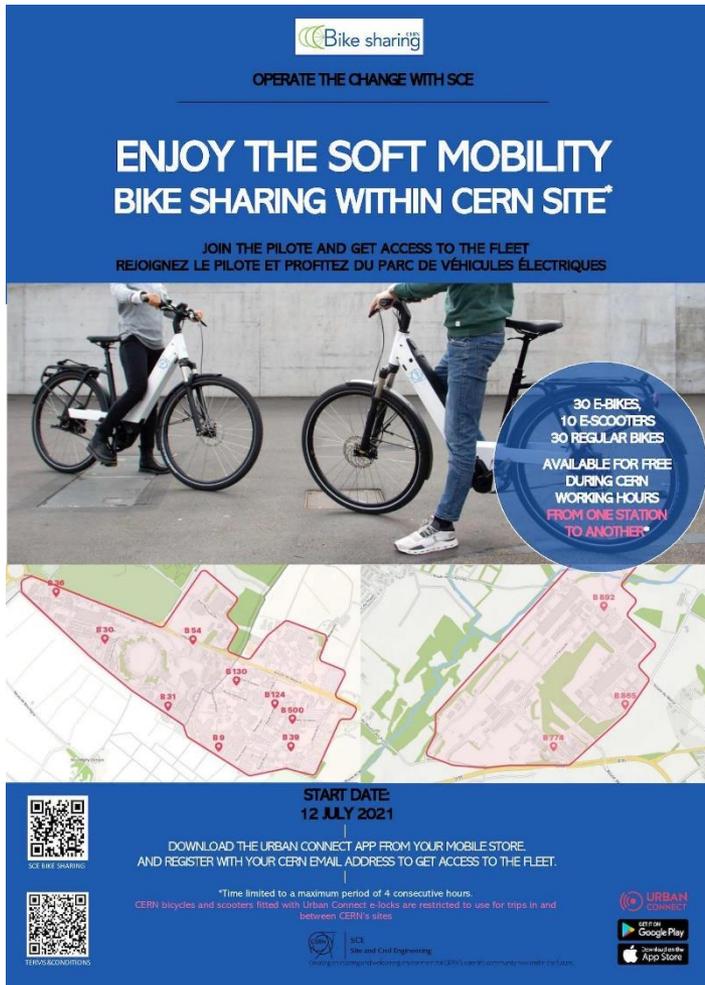
15W



Source: yootech Chargeur

# Electric scooter/bike

400W



**Bike sharing**  
OPERATE THE CHANGE WITH SCE

## ENJOY THE SOFT MOBILITY BIKE SHARING WITHIN CERN SITE\*

JOIN THE PILOTE AND GET ACCESS TO THE FLEET  
REJOIGNEZ LE PILOTE ET PROFITEZ DU PARC DE VÉHICULES ÉLECTRIQUES

30 E-BIKES,  
10 E-SCOOTERS  
30 REGULAR BIKES

AVAILABLE FOR FREE  
DURING CERN  
WORKING HOURS  
FROM ONE STATION  
TO ANOTHER\*

START DATE:  
12 JULY 2021

DOWNLOAD THE URBAN CONNECT APP FROM YOUR MOBILE STORE  
AND REGISTER WITH YOUR CERN EMAIL ADDRESS TO GET ACCESS TO THE FLEET.

\*Time limited to a maximum period of 4 consecutive hours.  
CERN bicycles and scooters fitted with Urban Connect e-locks are restricted to use for trips in and between CERN's sites.

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Site and Civil Engineering  
Contact: [urbanconnect@cern.ch](mailto:urbanconnect@cern.ch)



# Industrial Robots

10kW



Source: Le monde (Kawada Robot)

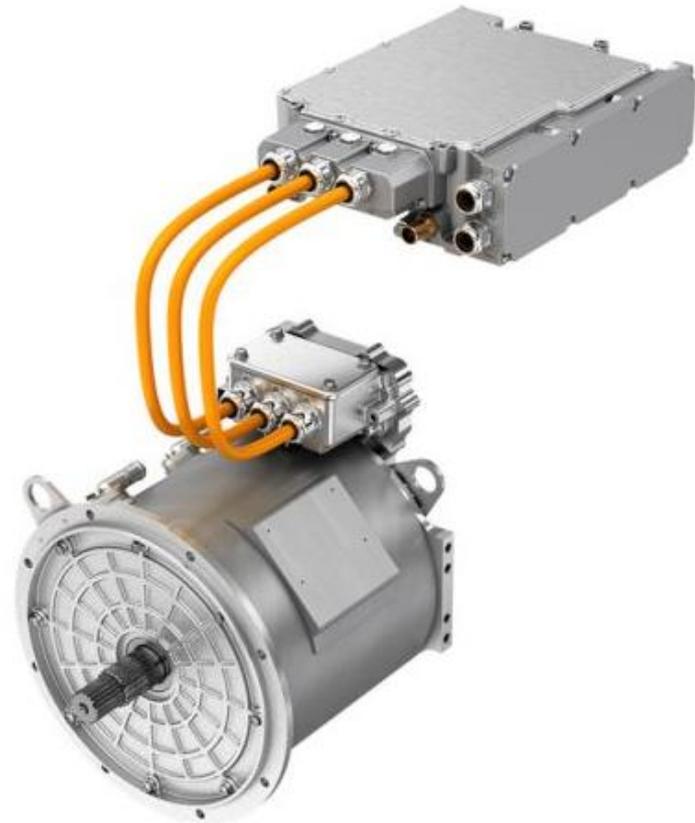
# Terrestrial/satellite

10kW



# Electric car/truck/plane

50kW



# Industrial drives

500kW



# Renewable generation

3MW

## 3MW Onshore Wind Turbine Platform

GE Renewable Energy

### Pitch System

Aerodynamic brake:  
Full feathering of  
blade pitch.  
Speed regulation;  
Electric drive  
pitch control with  
battery backup.

### Rotor

Rotor diameter ranging  
from 130 to 137 meters.

### Tower

Hub height ranging from  
85 to 164.5 meters.  
Tower made of tubular steel,  
or hybrid pre-cast concrete &  
tubular steel with logistic  
friendly tower options.

### App Suite & Predix\* Platform

GE's software applications generate smooth, predictable power, thanks to big data and the Industrial Internet. Our apps enhance annual energy production and improve wind farm predictability.

### Generator

Nameplate ranging  
from 3.2 to 3.8 MW  
at 50 or 60 Hz.



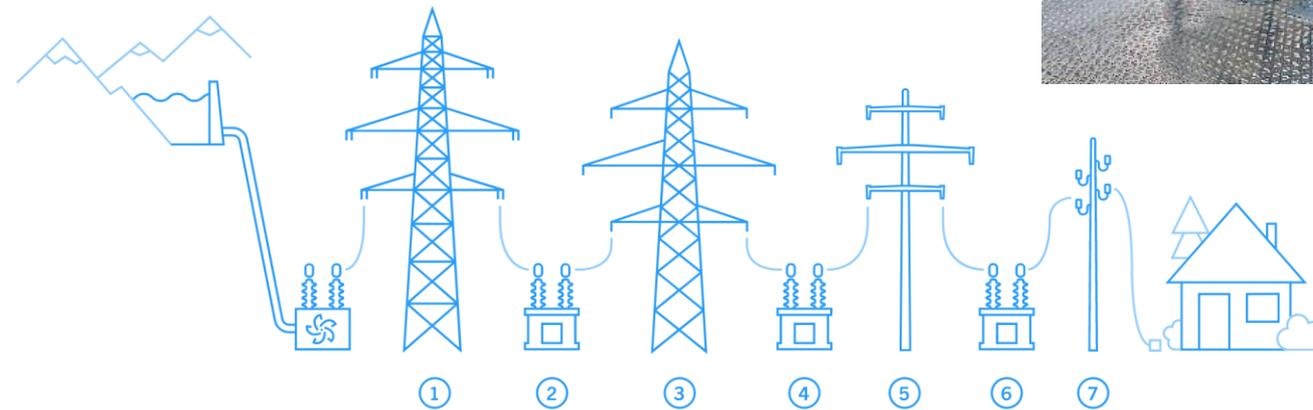
### Powerful and efficient

- GE's 3MW platform can be customized based on nameplate, rotor diameter and hub height
- The 3.6-137 is our highest performing turbine for Class III winds

Trademark of General Electric Company

# Energy Transmission

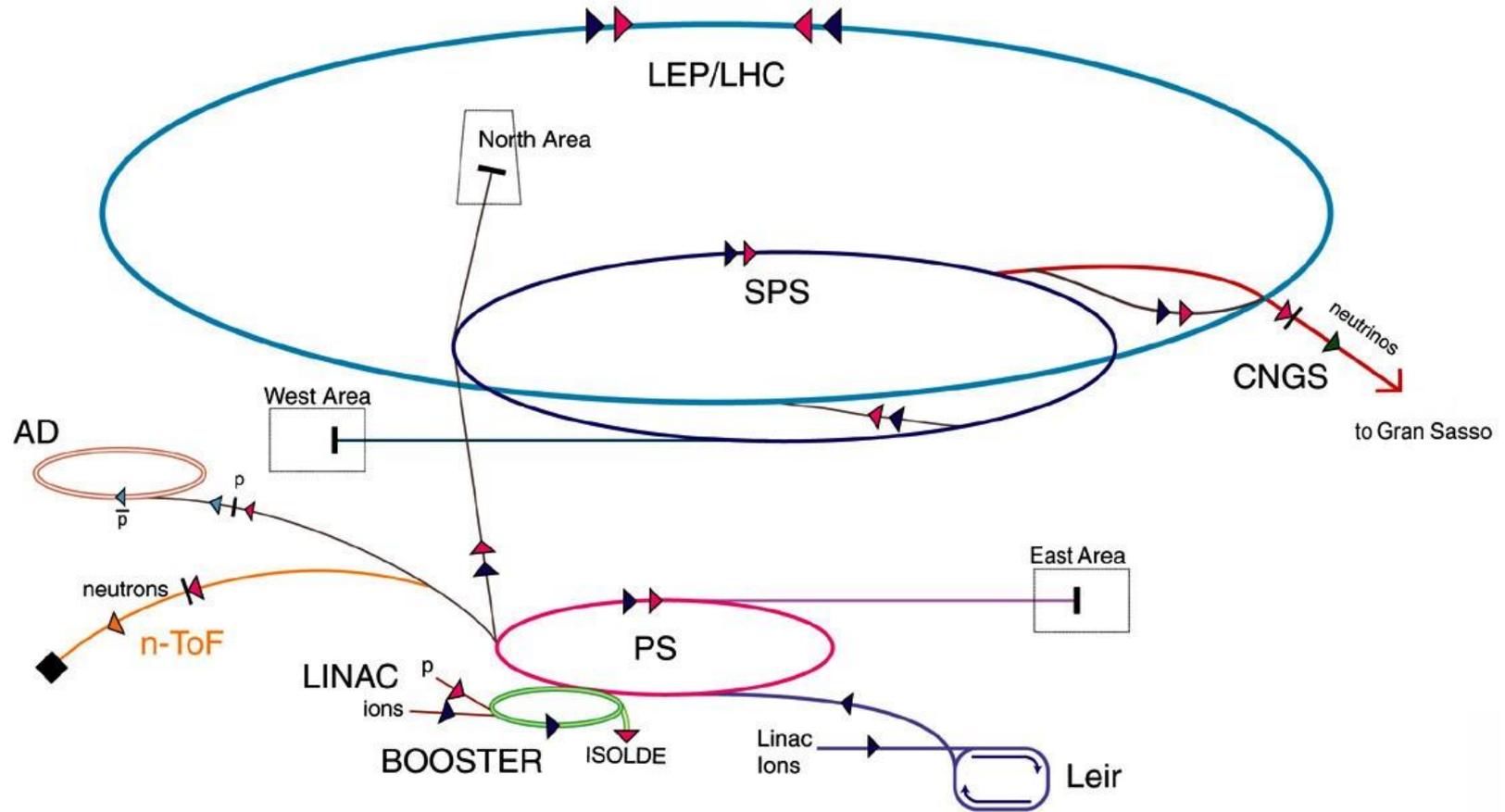
2GW



Source: Swissgrid.ch

η ενέργεια στους επιταχυντές

# Accelerators at CERN



- |   |  |  |   |
|---|--|--|---|
| <ul style="list-style-type: none"> <li> p (proton)</li> <li> ion</li> <li> neutron</li> </ul> | <ul style="list-style-type: none"> <li> <math>\bar{p}</math> (antiproton)</li> <li> proton/antiproton conversion</li> <li> neutrino</li> </ul> | <ul style="list-style-type: none"> <li>AD Antiproton Decelerator</li> <li>PS Proton Synchrotron</li> <li>SPS Super Proton Synchrotron</li> </ul> | <ul style="list-style-type: none"> <li>LHC Large Hadron Collider</li> <li>n-ToF Neutron Time of Flight</li> <li>CNGS Cern Neutrinos Gran Sasso</li> </ul> |
|---|--|--|---|

# Key Energy Consumers

## ➔ Direct Energy to the beam

⇒ RF cavities - Klystron

⇒ Magnets

## ➔ Environmental Conditioning

⇒ Cryogenics

⇒ Systems cooling

⇒ Tunnel air filtering

## ➔ Data

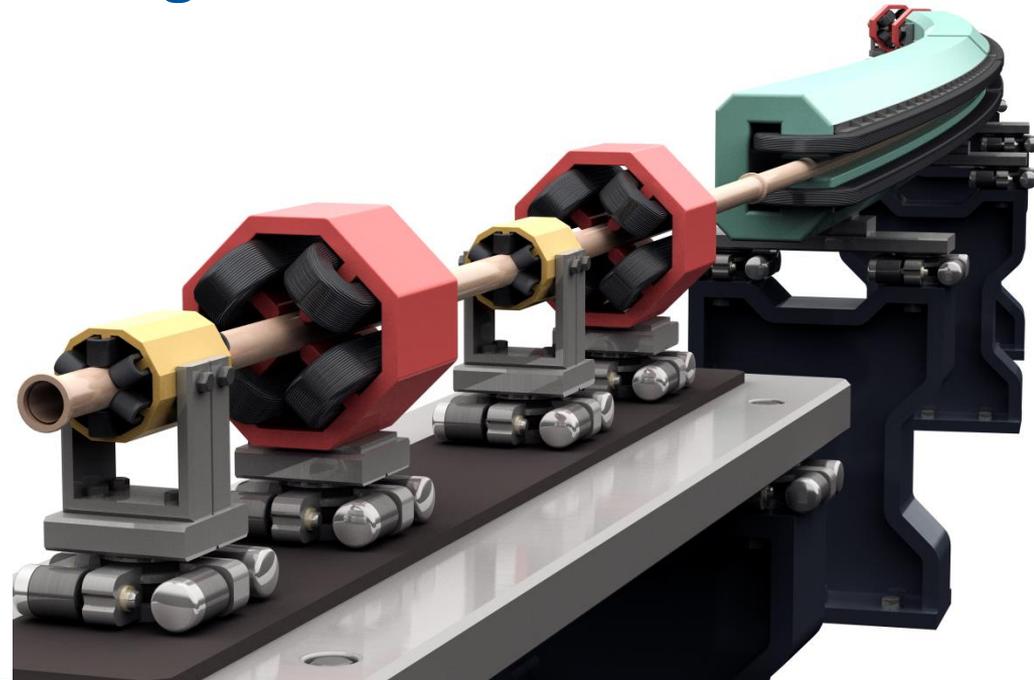
⇒ Measurements

⇒ 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:

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

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

$$q = e_0 = 1.602 \cdot 10^{-19} \text{ [C]}$$

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

$$\Delta E = \int_{s_1}^{s_2} \vec{\mathbf{F}} \cdot d\vec{\mathbf{s}}$$

by differentiating:

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

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.

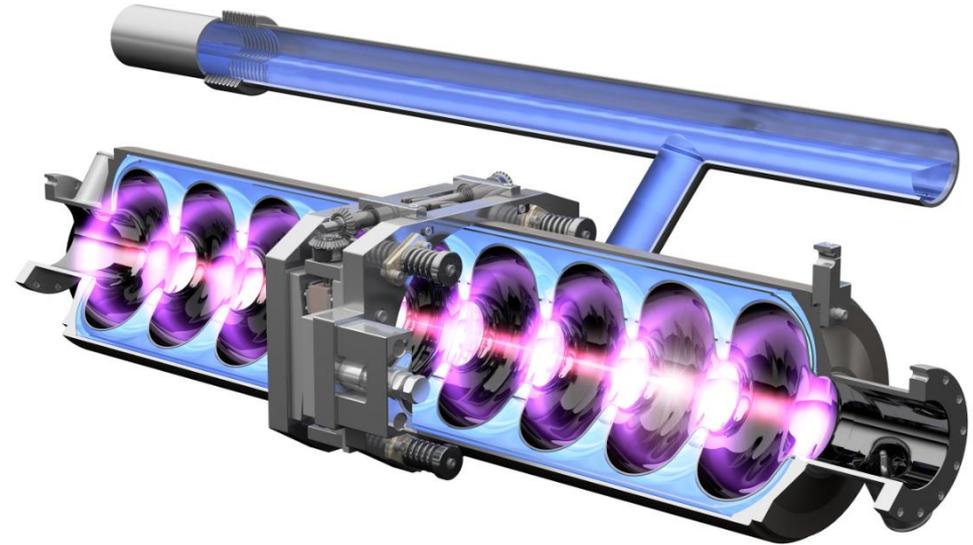
# RF Cavities - Klystron

## Functions:

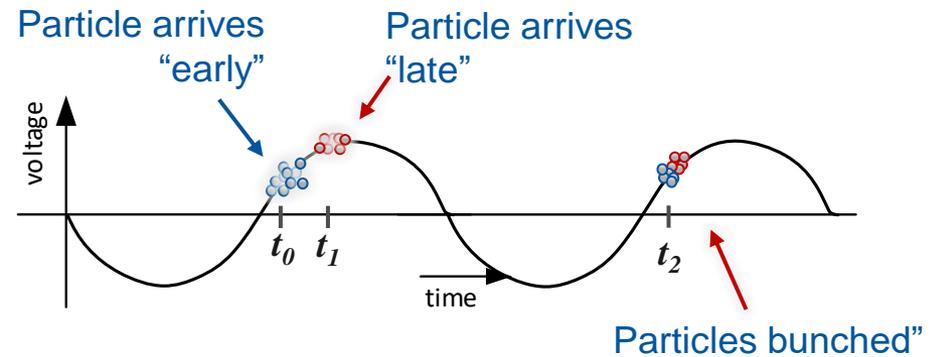
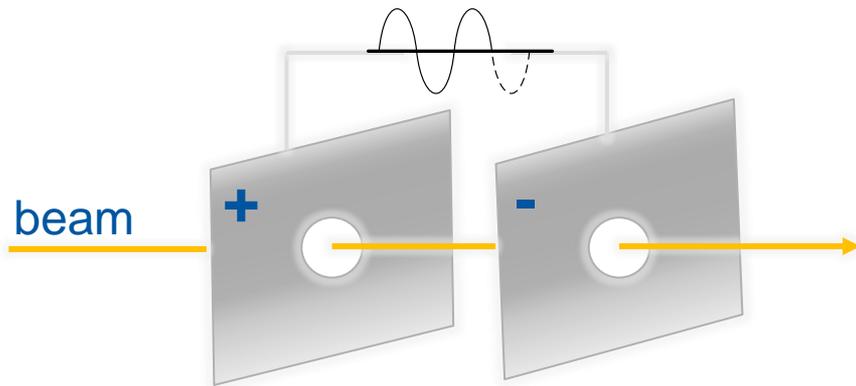
- Particle acceleration

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

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



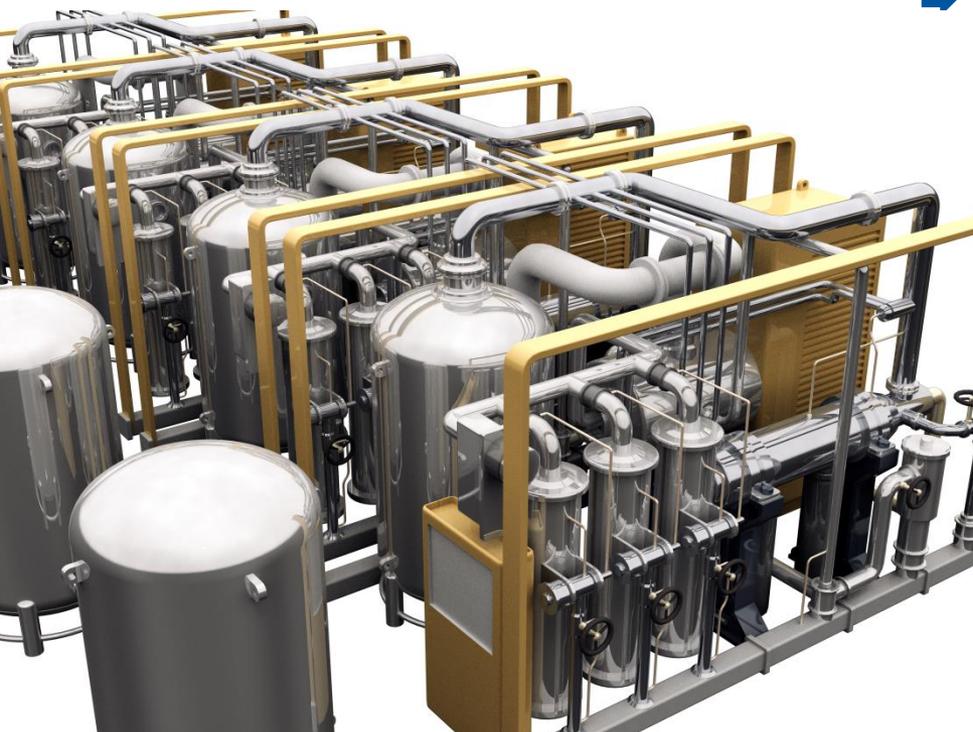
(c) Rey Hori / KEK



# Cryogenics

- ➔ Cryogenic pumps are the largest single electrical consumer at CERN
- ➔ Peak power: 50MW
- 6 weeks to cool down Helium to 1.8K

(c) Rey Hori / KEK



# Electromagnets

## Functions:

- Beam steering

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

- At first sight F is not dependent on mass
- Since v on a circle of radius  $\rho \rightarrow F = \text{centripetal force}$

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

$$m_r = \gamma \cdot m_0$$

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

- Rearranging 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

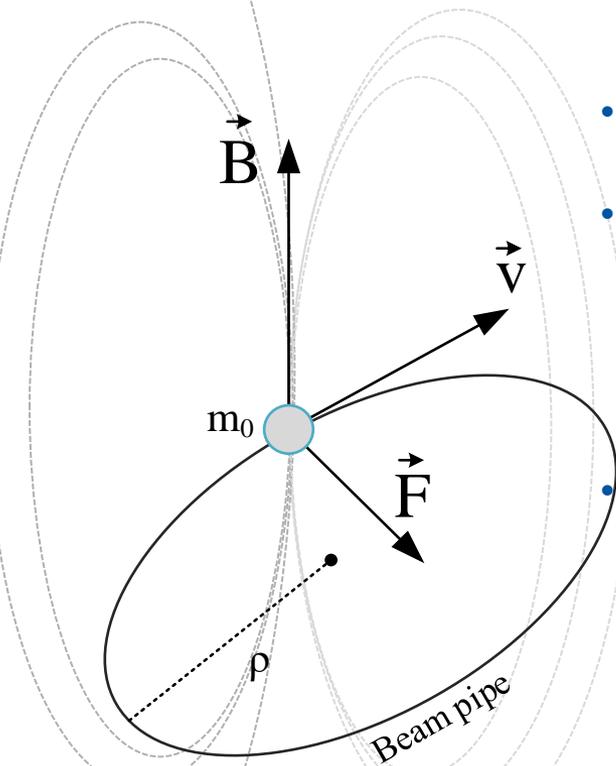
$$\vec{B} \cdot \rho = \frac{m \cdot v}{q} = \frac{p}{e}$$

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

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

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

\*  $\mu_0$ : magnetic permeability of the air



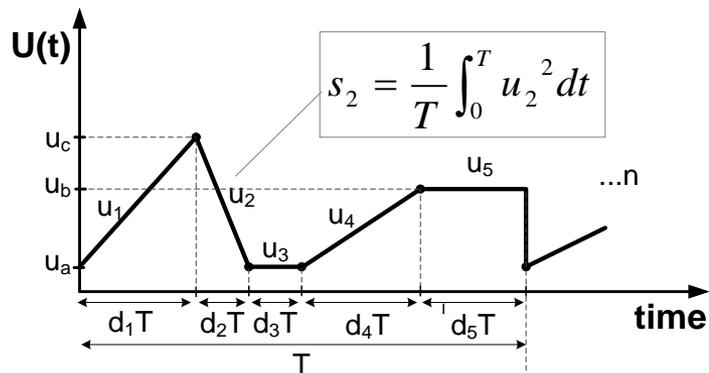
# Dipole magnet

## Functions:

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



(c) Rey Hori / KEK

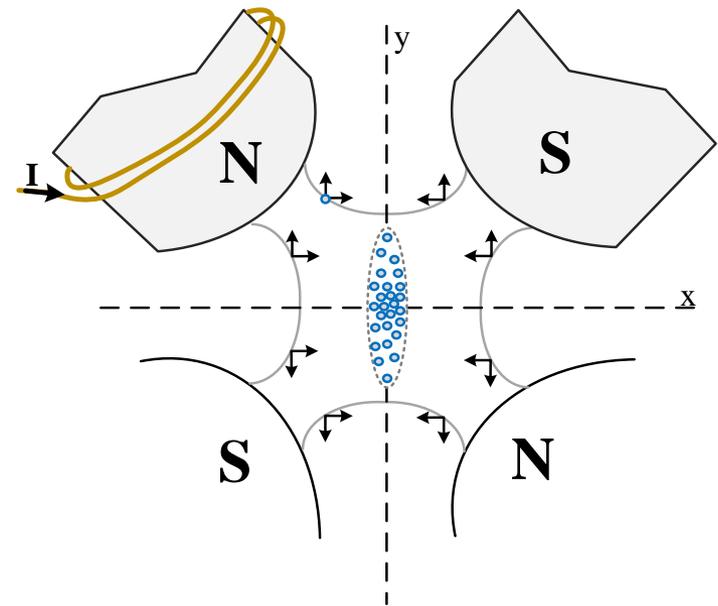
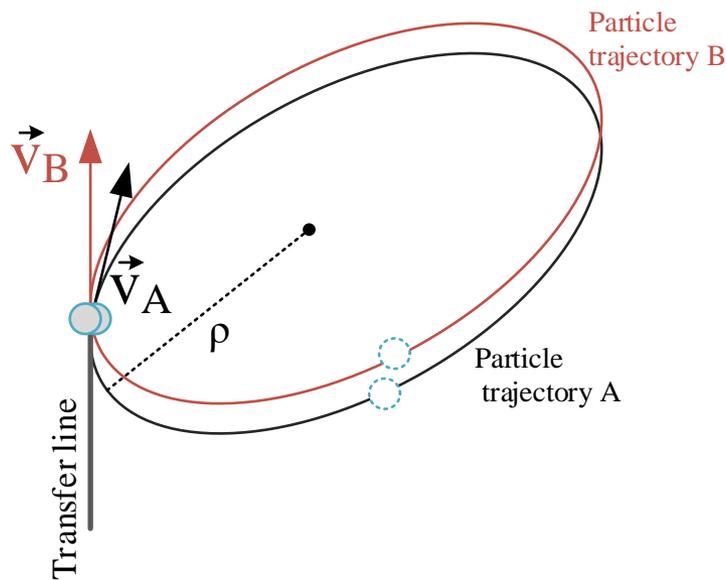


# Quadrupole magnets

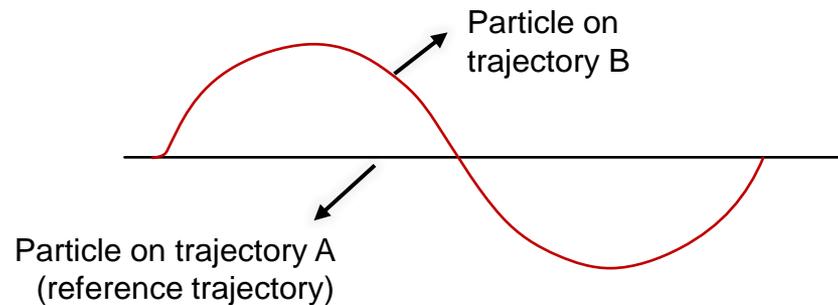
## Functions:

- Focussing-defocussing

Two particles enter in the accelerator with different velocity vectors:



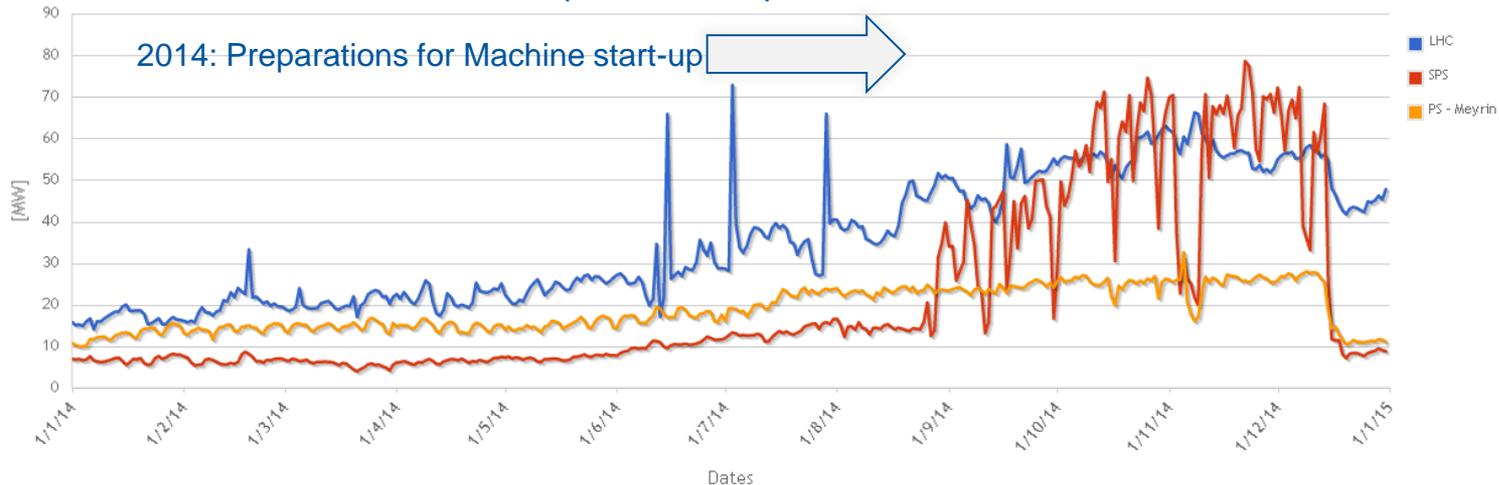
## Betatron Oscillation



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
  - ⇒ 1/10<sup>th</sup> of the canton (11.3TWh).

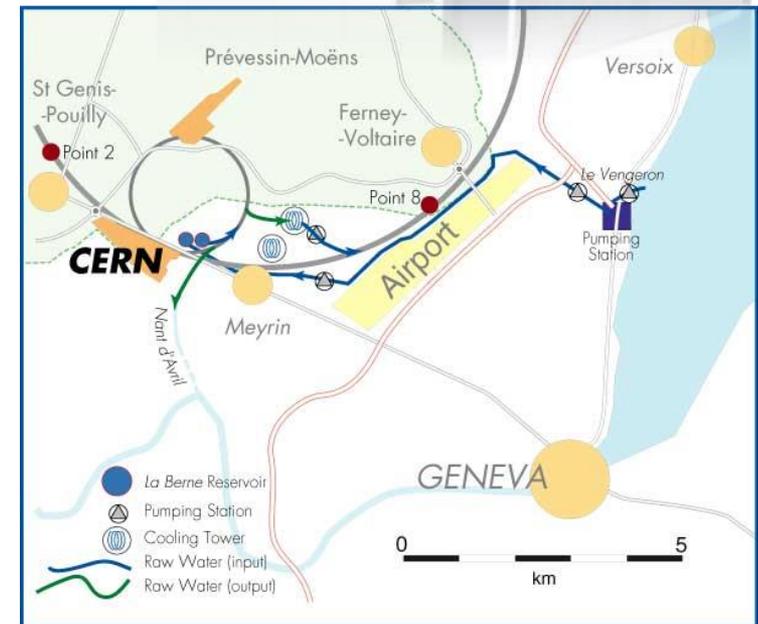


# Energy Facts & Figures

- ➔ **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 m<sup>3</sup> 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<sup>3</sup>
- ➔ Heating station at Prevechin – 1.5million m<sup>3</sup>
- ➔ Operated by external companies
  - ⇒ Monitor dust, CO, CO<sub>2</sub>, nitrogen oxides and sulphur oxides

# Steps towards more Sustainable Research Facilities

# Types of accelerators

Light sources - photon radiation for research

$P_{\text{grid}} < 5\text{MW}$

Power consumption per useful particle output is low

Examples: Swiss light source, International Spallation Source

Proton Driver Accelerators –  
sources of neutrons, muons, neutrinos

$P_{\text{grid}} < 100\text{MW}$

Losses dominated by Carnot Cycle Efficiency of cryogenic system

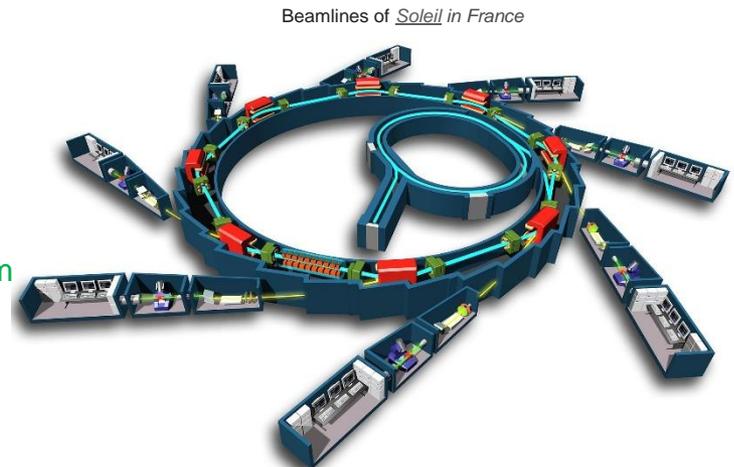
Examples: J-PARC, Spallation Neutron source, pSI cyclotron

Particle Colliders – head on collisions between beams

$P_{\text{grid}} < 500\text{MW}$

- 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

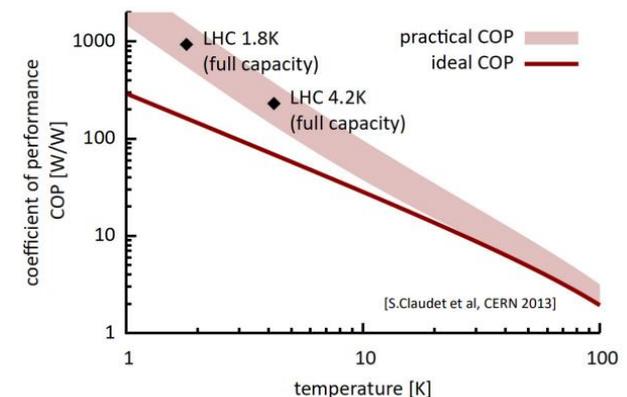
Typical efficiency <65%

### ➔ Superconducting RF cavities

- ⇒ Standard at 1.8K or new 4.2K or higher
- ⇒ Objective: high cavity quality factor/high accelerating gradient

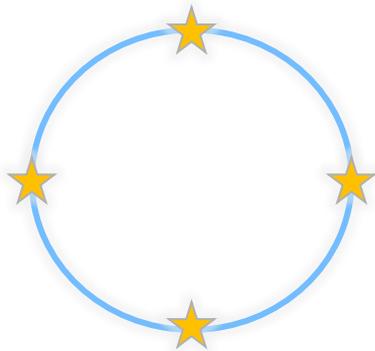
### ➔ Cryogenic systems for cooling

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



# Circular vs Linear Colliders

## Circular Colliders (FCC etc)



## Linear Colliders (CLIC, ILC etc)



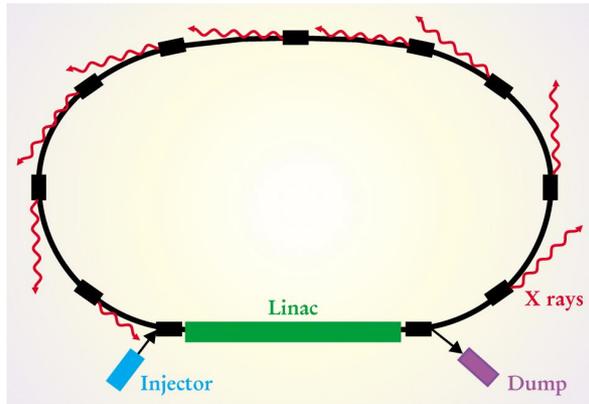
- ➔ Lower voltage gradient in RF cavity
- ➔ Beam reused for many hours
- ➔ Synchrotron radiation is important
- ➔ Complex to operate with complex beam dynamics

- ➔ 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

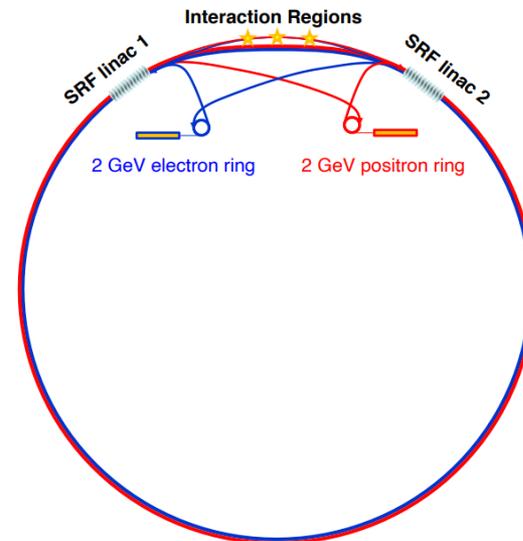
## Jefferson Lab's FEL Light Source



- ➔ 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
- ➔ Bunches 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-luminosity e-e collider using energy recover linacs, Physics Letters, [\[link\]](#)



- Ερωτήσεις;

<http://www.cern.ch/aftervisit>

# Life at CERN





[www.cern.ch](http://www.cern.ch)