*Accelerator & Technology Sector*
*Beams Department*
*Accelerator Beam Physics Group*

# Introduction to Accelerators

Foteini Asvesta

Material: F. Antoniou, B. Holzer, M. Fraser, V. Kain, Y. Papaphilippou, M. Schaumann,

images: cds.cern.ch

# Why accelerators?

**World wide about ~30,000 particle accelerators are in operation with a large variety of applications.**

**Industry**

- Material studies and processing
- ***Food sterilization***
- Ion implantation

‘Cold pasteurization’ – before packaging


The **large majority** is used in **industry** and **medicine:**

- Industrial applications: ~20,000*
- Medical applications: ~10,000*

**Sources:*
*A. W. Chao, World Scientific Revies of Accelerator Science and Technology*
*A. Faus-Golfe, The brave new world of accelerator application*
APAE report, Applications of particle accelerators in Europe
S. Sheehy, Applications of accelerators, CAS 2014

# Why accelerators?

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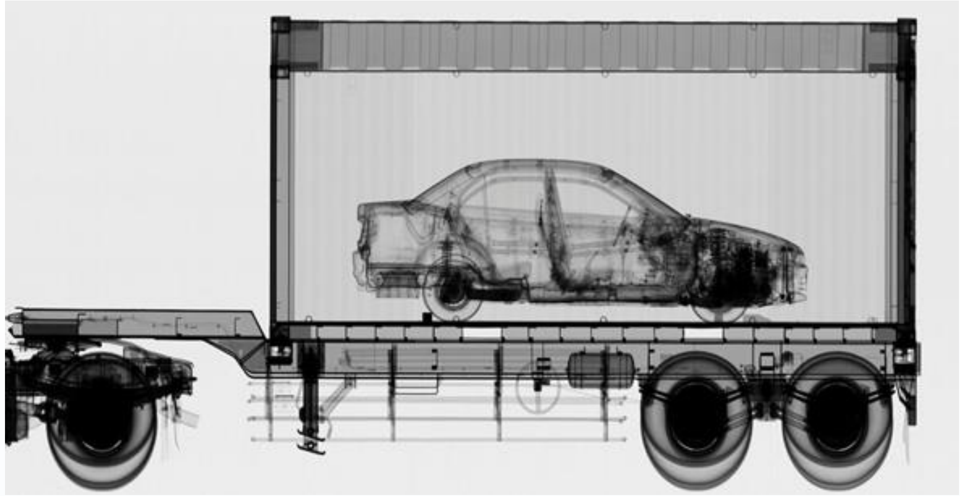
**Security**
- ***Airports & boarders***
- Nuclear security
- Imaging



- Cargo containers scanned at ports and border crossings.
- Accelerator-based sources of X-Rays can be far more penetrating (6MV) than Co-60 sources.
- Container must be scanned in 30 seconds.

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# Why accelerators?

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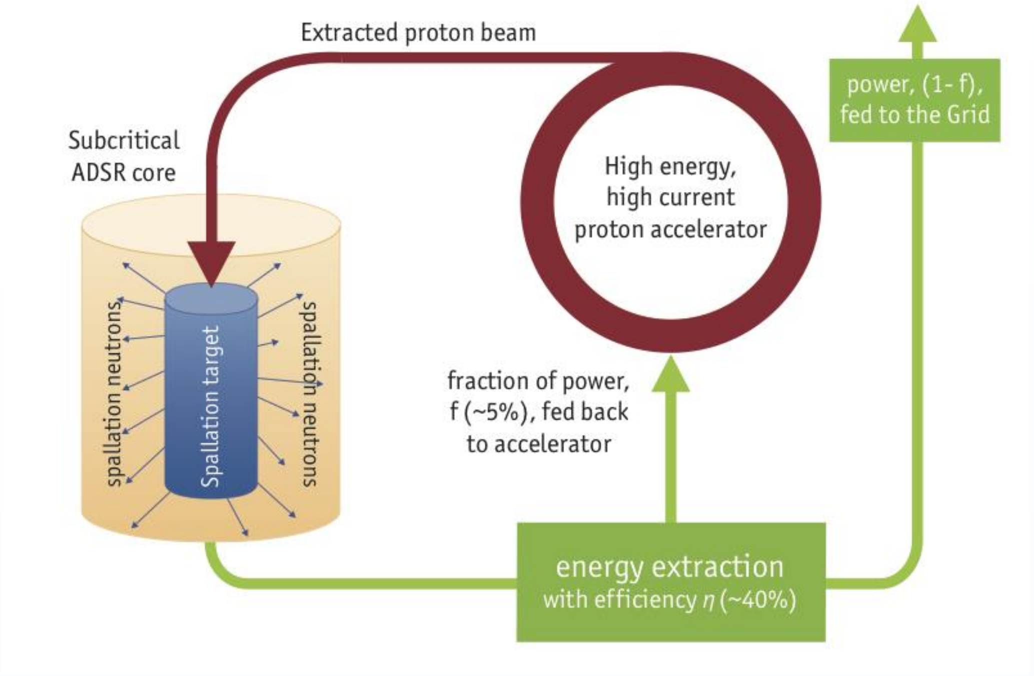
**Energy**

- Destroying radioactive waste
- ***Energy production***
- Nuclear fusion
- Thorium fuel amplifier




**Accelerator Driven System (ADS)**
Transmutation of nuclear waste isotopes or energy generation

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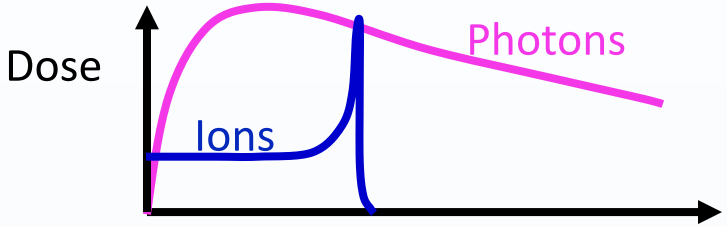
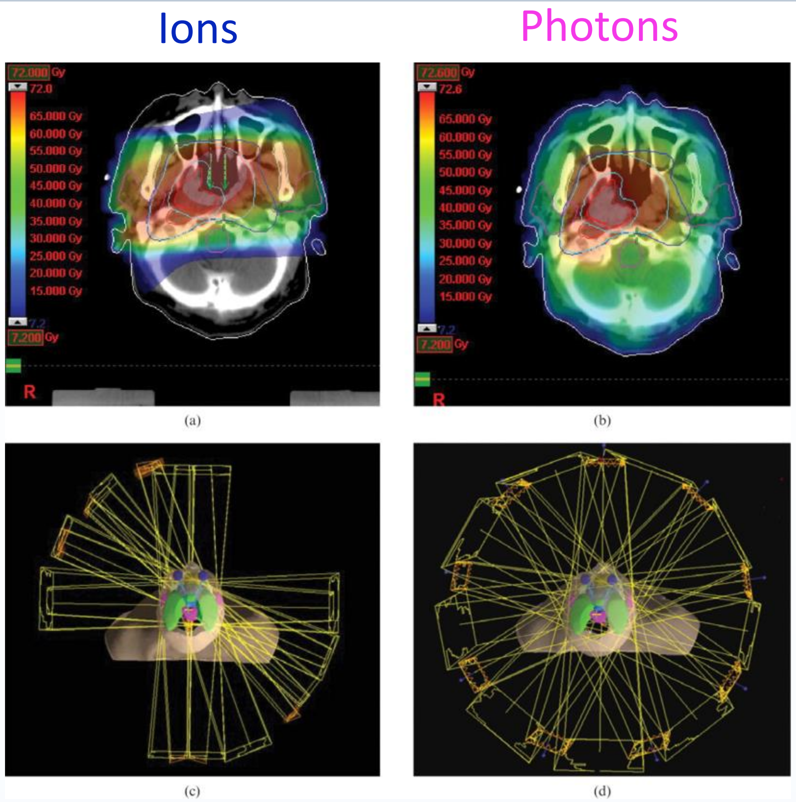
**Health**
- Diagnostic and imaging
- X-rays
- ***Cancer therapy***
- Radioisotope production

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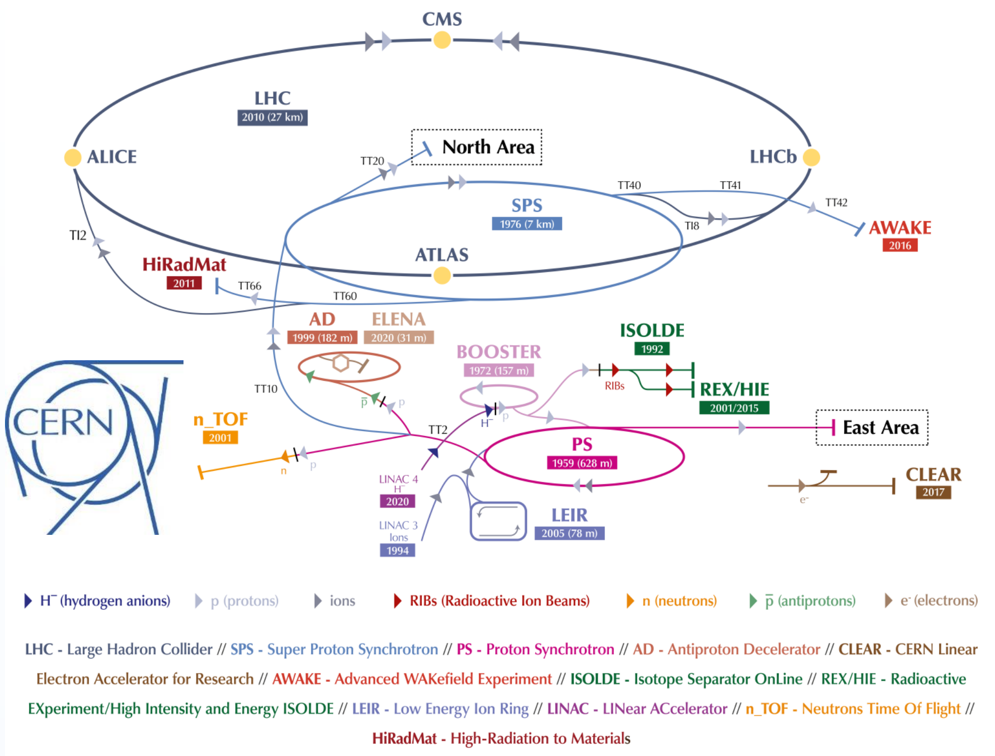
# Why accelerators?

**World wide about ~30,000 particle accelerators are in operation with a large variety of applications.**

**Less than a fraction of a percent** is used for **Research!**

- **Particle Physics**
- Storage rings & Colliders
- Material science
- Light sources
- R&D

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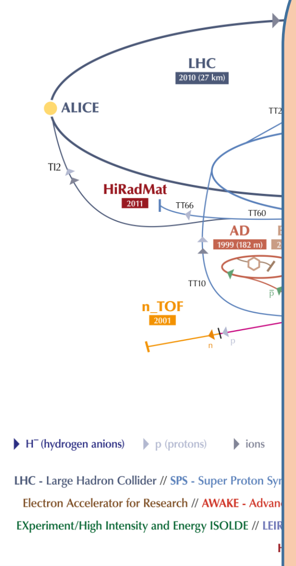
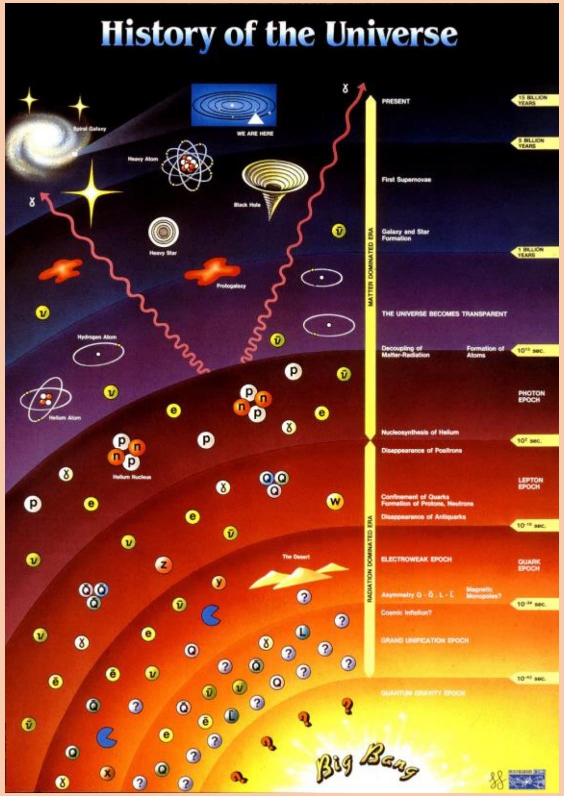
# Accelerators at CERN

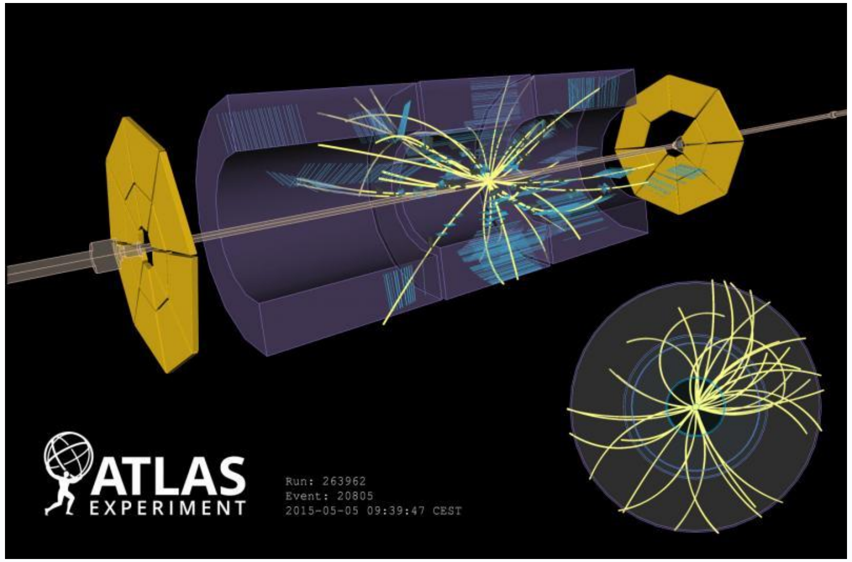
Full complex of Accelerators to give energy to particles




***Understand the laws of physics and***

***Reveal the history of the universe***




Particles produced in the collisions are observed in the detectors

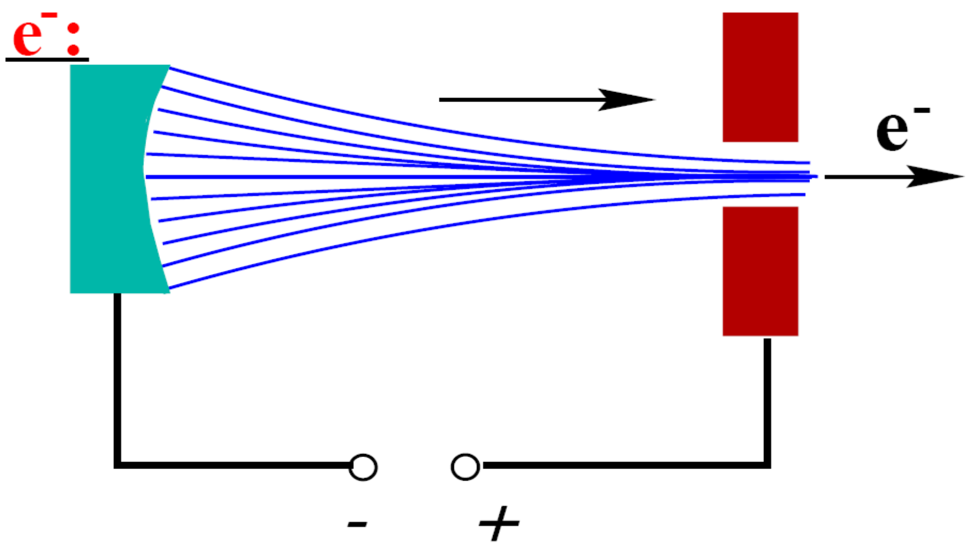
# History of Accelerators

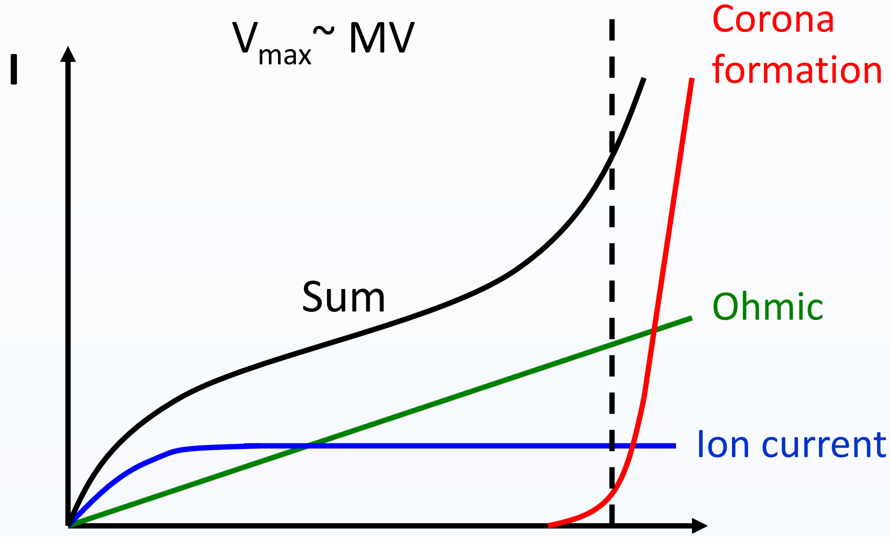
*Race for higher energies*

# Electrostatic Accelerators

The simplest of Accelerators!
(cathode ray tubes – screens...)

- Particle source – **blue** electrode, acceleration in an electric fiels, exit – **red** electrode.
- Achieved energies depend on the applied voltage.
- Current increases exponentially for large voltages creating arcs and discharge (*Corona formation*)



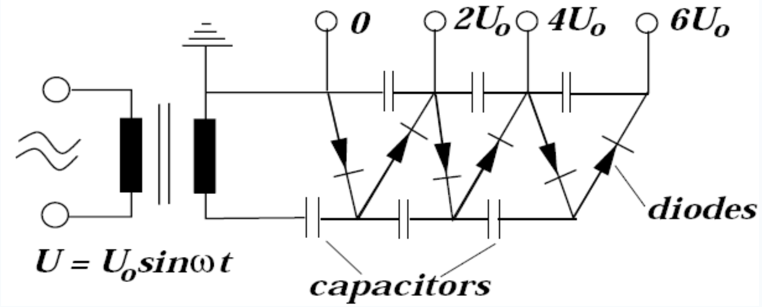



# Voltage multipliers

***Problem***: Achieve higher voltages to push to higher energies

- **Cockcroft** and **Walton**(1932) developed a cascade generator based on multiple rectifiers
- Operating principle – **Greinacker circuit**
  - AC power supply
  - 2N diods (one-way current “switch”) so that the maximum voltage on each couple of capacitors goes to $2V_0$, $4V_0$, $6V_0$, …,$2NV_0$
  - Voltages ~MV can be achieved for beams of ~100s of mA
- **Cockcroft** and **Walton** used such an accelerator to split lithium nuclei producing helium nuclei. (Nobel prize 1951)

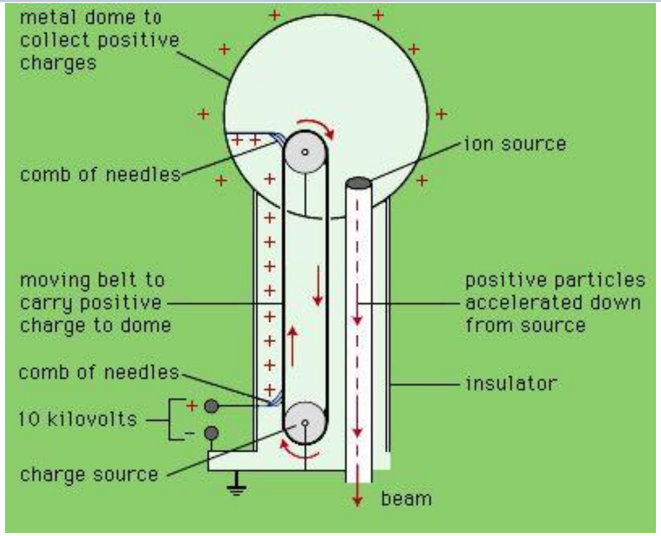
Greinacker Circuit

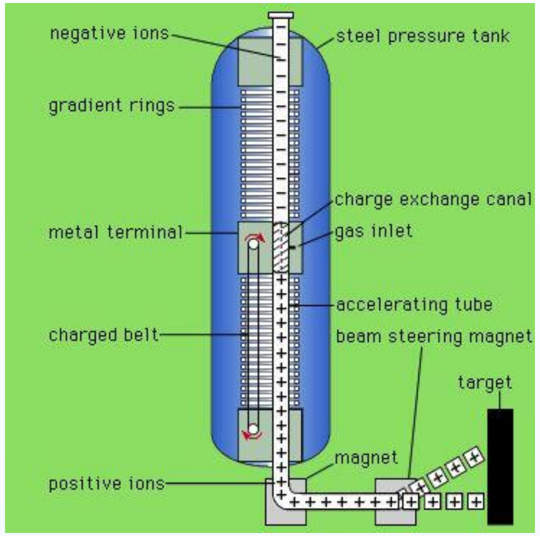



Fermilab cascade generator

# Van der Graaff Generator (1930)

- Charges from Corona formation are transferred through a band charging the dome.
- Higher voltages can be achieved within a pressure tank
- Possibility to double the voltage (Tandem)
  - Negative charge ions accelerated from 0 to V
  - Electrons absorbed from a gas and are accelerated again (from V to 0)

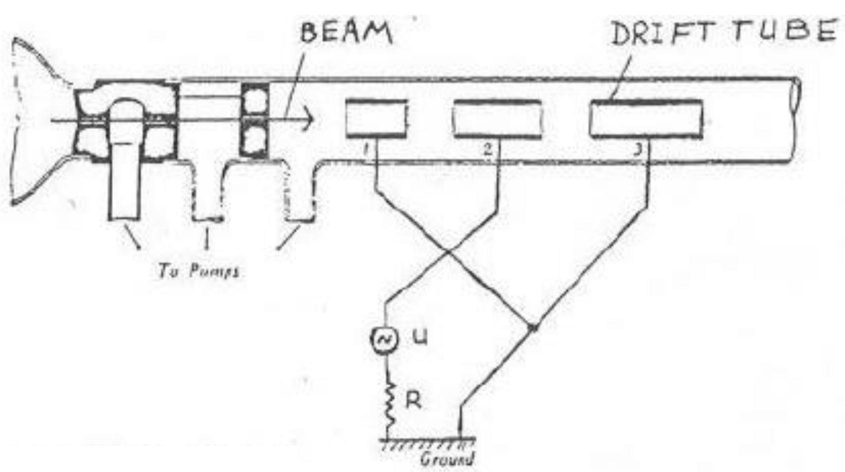



ROBERT VAN DE GRAAF DEMONSTRATES HIS FIRST GENERATOR TO KARL COMPTON

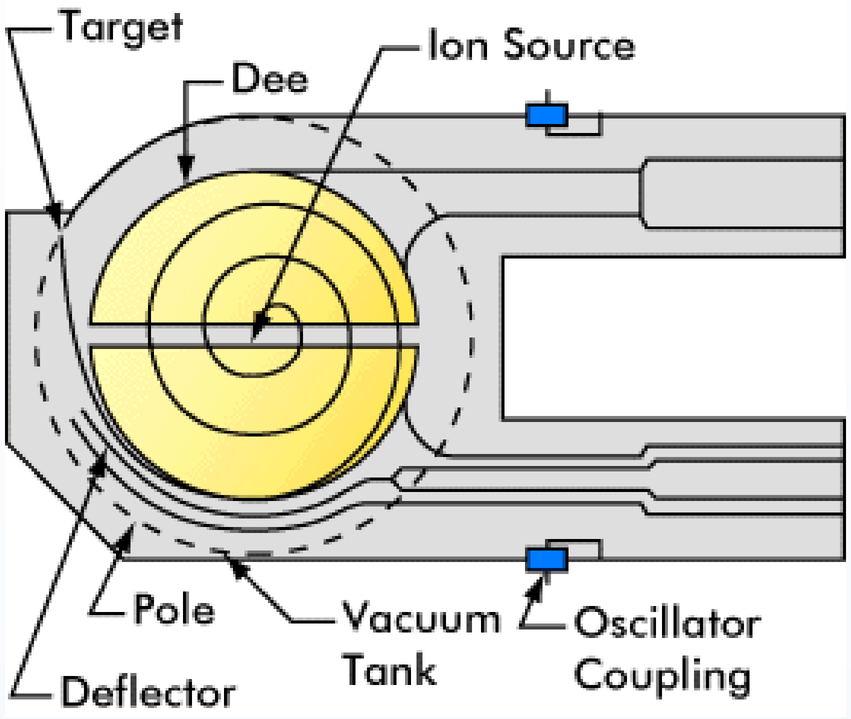
# Linear accelerators (LINAC)

- **Ising's** Original idea (1924), first built by **Wideröe** (1928) and first high energy linac (1.3MeV) built by **Sloan** and **Lawrence** (1931)
- Line of drift tubes alternatingly connected to high frequency (RF) power supplies
- Particles accelerated in the gaps, but insulated in the tubes (no field – act as a Faraday cage)
- As the voltage changes sign, the particles are accelerated every time they enter a gap
- The length of the tubes, increases with acceleration for a given/constant frequency up to the relativistic limit
- Synchronization to the field is achieved via ***phase focusing***
- **Beams** (1933) first linac with waveguides. **Hansen** and **Varian** brothers (1937) invented the **klystron** (up to 10GHz)

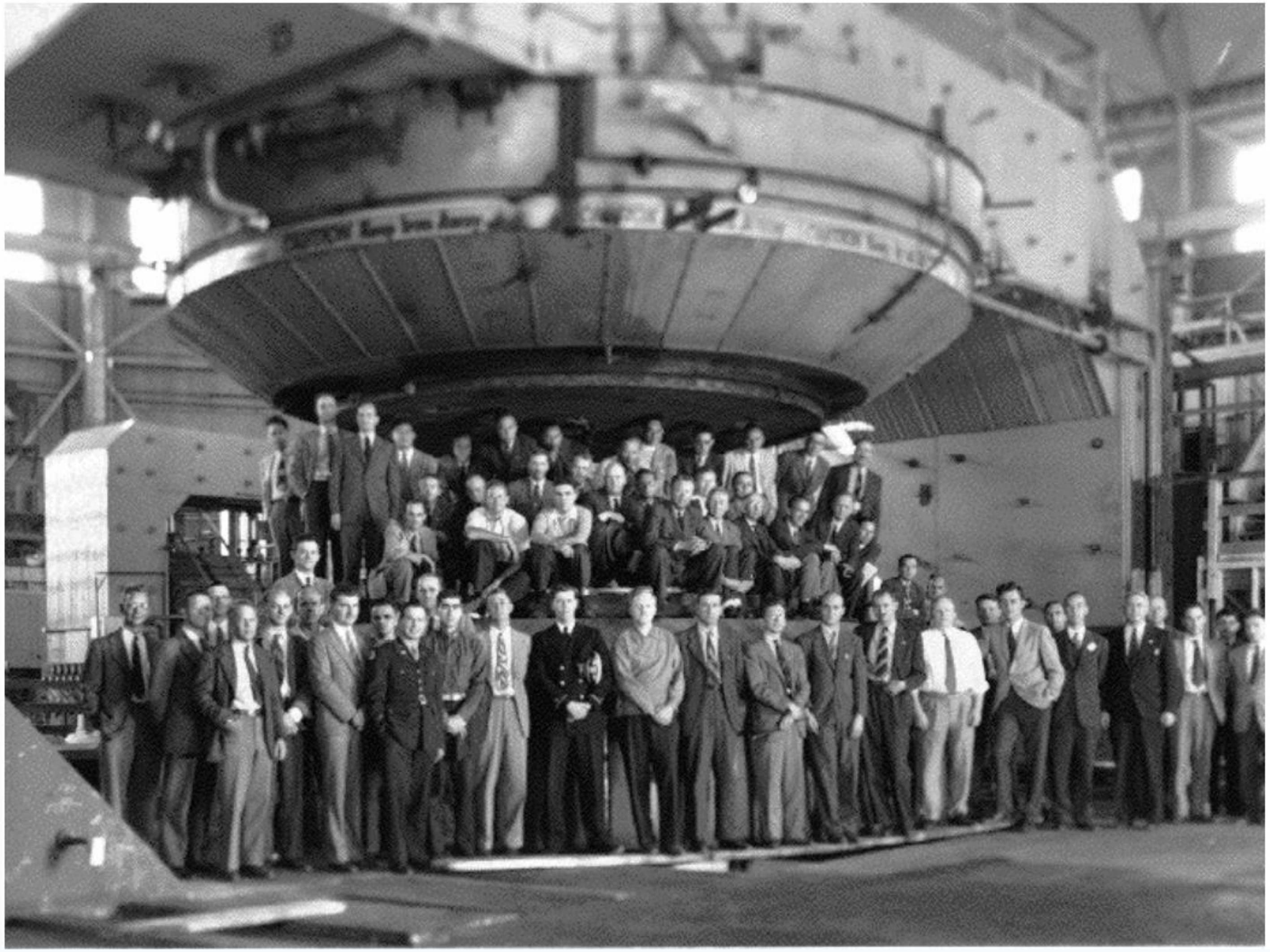



# Cyclotron

- **Lawrence's** and **Edlefsen's** original idea (1930), first built by **Lawrence** and **Livingston**(1932)
- Constant ***magnetic field B*** from an H-shaped magnet with a cyclotron frequency and a radius that increases with velocity, for non-relativistic particles: $\omega_c = qB/m$ (spiral orbits)
- The accelerating voltage is synchronous to the particles crossing the gap: $\omega_{RF} = (2n+1)\omega_c$
- Heavy particles accelerated up to ~20 MeV
- For higher energies (relativistic particles) the frequency reduces with the mass.
- **Synchro-cyclotron principle** (**McMillan** and **Veksle**r, 1945): $\omega_{RF} \propto 1/\gamma$ → different frequencies for different particle species
- **Isochronous cyclotron principle**: $\omega_{RF} \propto \mathrm{B}/\gamma$ Energies up to 600 MeV – prone to losses (field errors)

# Cyclotron



184-inch cyclotron:

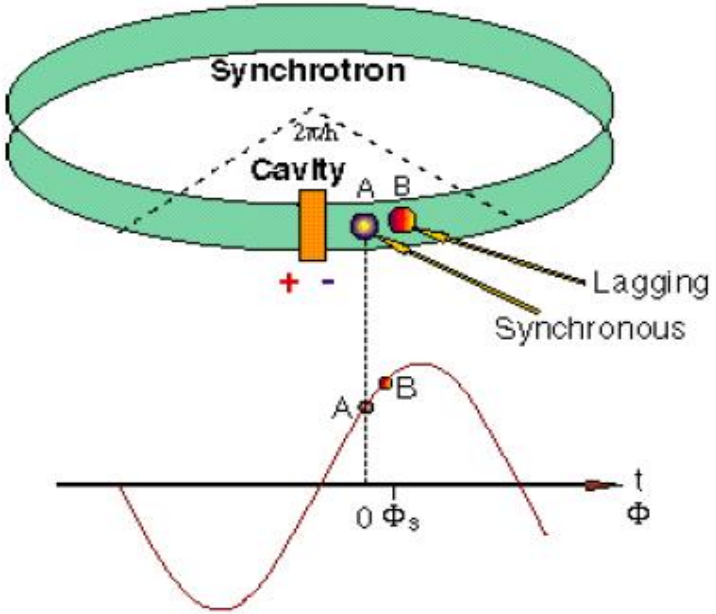
1 singly dipole with 467 cm diameter

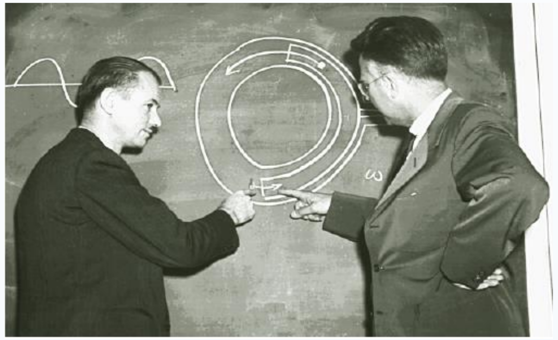
Berkeley campus, 1942

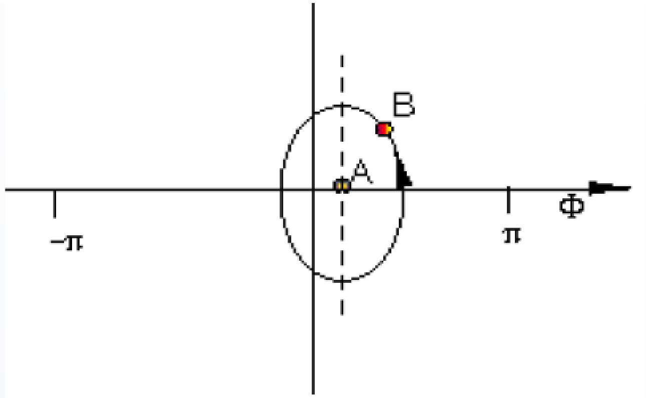
# Phase focusing

- Developed independently by **McMillan** and **Veksler** (1945)
- The **RF cavity** is set such as the particle at the centre of the **bunch** (**synchronous** particle) receives the needed energy
- Voltage in the cavity: $V = V_0 \sin(2\pi\omega_{RF}t) = V_0\, sin(\varphi(t))$
- For no acceleration, synchronous particle phase: $\varphi_s$ **= 0**
- For acceleration, synchronous particle phase: **0<**$\varphi_s$**<π** in order to achieve: $\Delta E = V_0\, sin(\varphi(t))$
- Particles arriving **late:** $\varphi > \varphi_s$, → Energy increase ***larger*** than the synchronous particle
- Particles arriving **early:** $\varphi < \varphi_s$, → Energy increase ***smaller*** than the synchronous particle

→ Particles are grouped – ***bunches!***



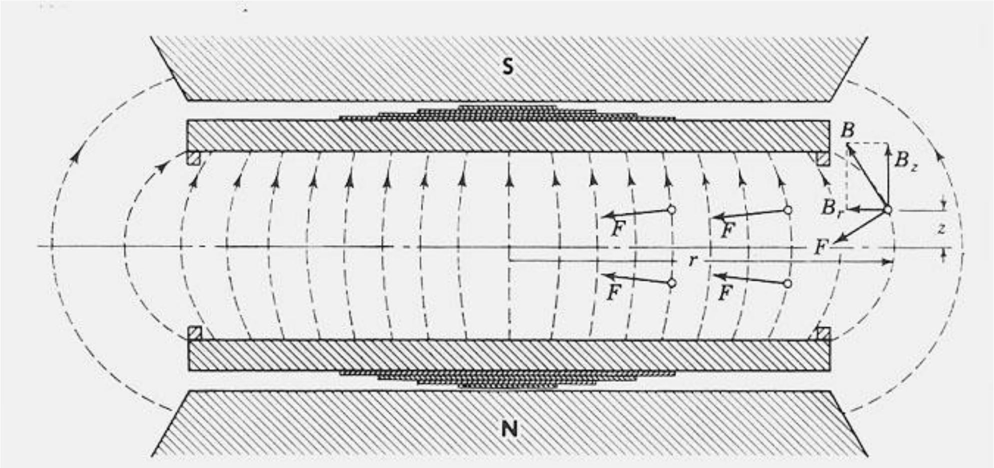





# Weak focusing

- Particles entering transversely into a homogenous magnetic field follow circular orbits
- Magnet errors can cause the particles to drift until they get lost

→ A recovering or "***focusing***" force is needed!



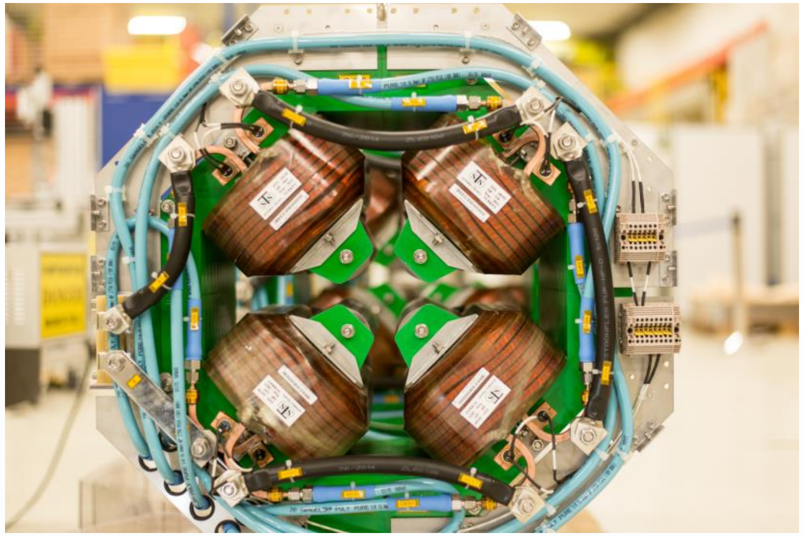

- Such a **focusing** is introduced at the edges of the magnet

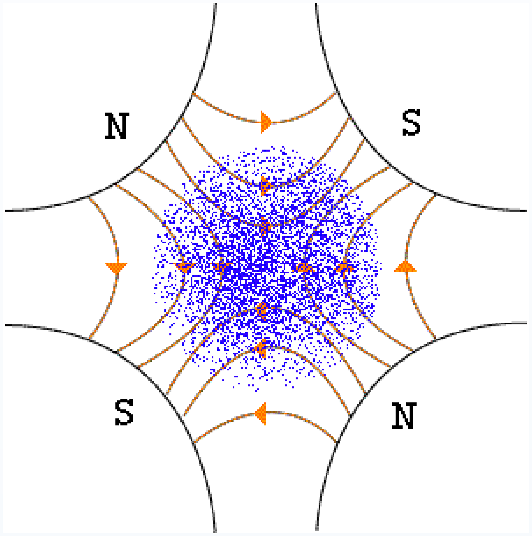
  – due to the disruption of the magnetic field

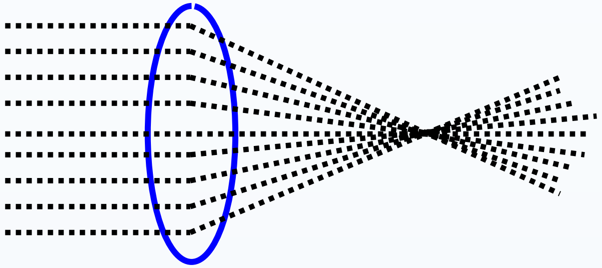
- The transverse components of the magnetic field: $\left(B_x + B_y\right) = B_0\left(-n\frac{y}{r}, 1 - n\frac{x}{r}\right)$, with $n = -\frac{r}{B_0}\frac{\partial B_y}{\partial x}$
- Particles perform linear harmonic oscillations (**betatron**) with frequencies: $\omega_x = \frac{v}{R}\sqrt{1-n}, \omega_y = \frac{v}{R}\sqrt{n}$
- For stable oscillations, **Steenbeck's** condition: 0<n<1

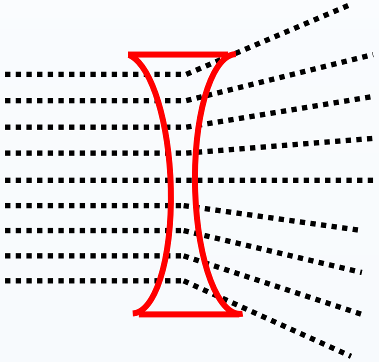
# Strong focusing

- Principle developed independently by **Christofilos** (1950) and **Courant, Livingston and Snyder** (1953)
- **No fields** can have a focusing effect in both transverse planes of motion.
- Focusing elements (quadrupoles): act as **focusing in one plane** but **defocusing in the other**
- ***A sequence of such focusing and defocusing fields can give an overall strong focusing***
- The force is proportional to the distance from the axis of the beam
- A succession of ***focusing and defocusing elements*** allow the particles to follow **stable trajectories**, performing small betatronic oscillations around the circular periodic orbit

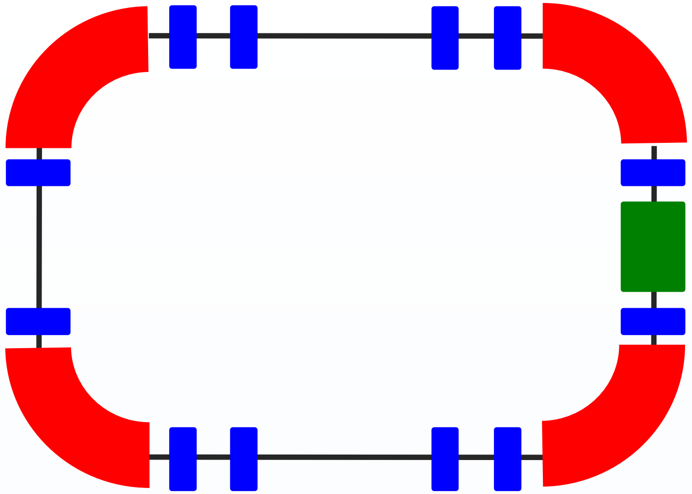






# Synchrotron



Dipole magnets to bend the beam

Quadrupole magnets to focus the beam

RF cavities to accelerate the beam

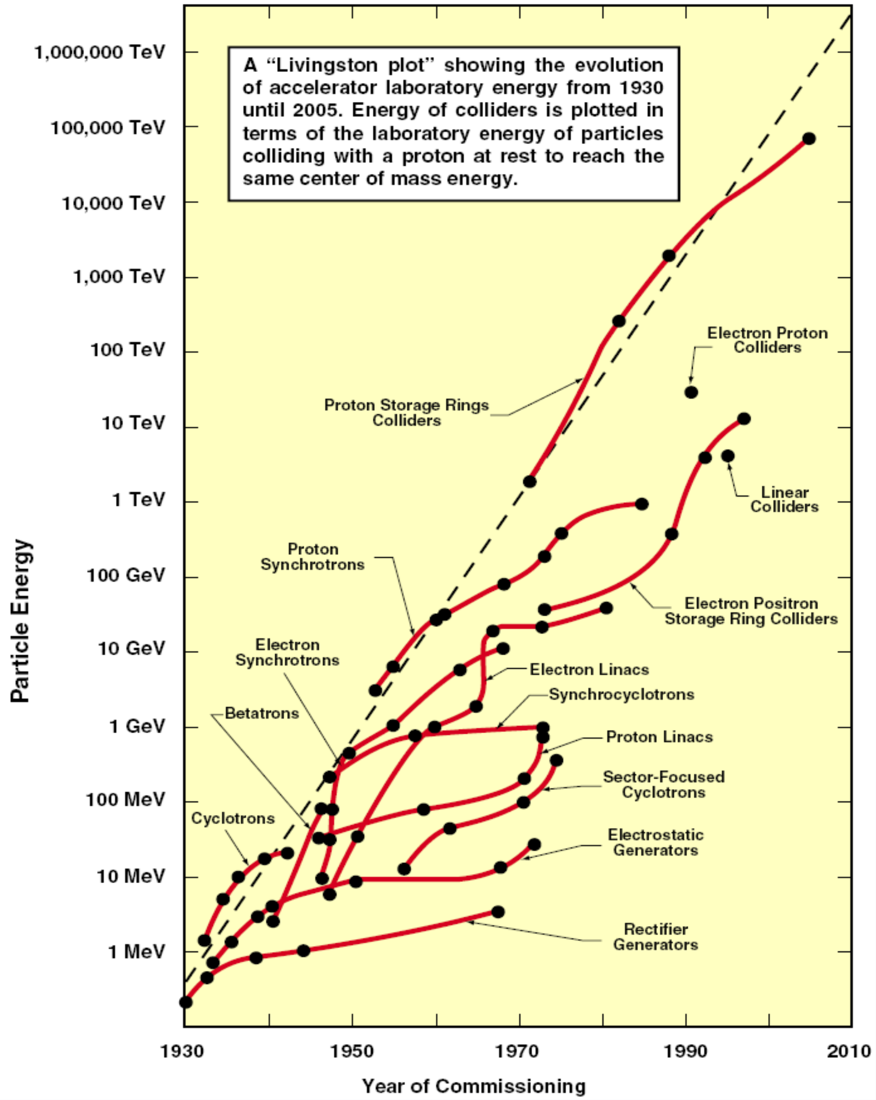
**Lorentz force**

Particle motion is described by:

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

- Electric fields used to **accelerate** and magnetic fields to steer the beam (**bending** & **focusing**)
- Magnetic field increases synchronously with the beam energy keeping the radius fixed!
- Beam rigidity: $B\rho = \frac{p}{q}$

# Livingston Plot – evolution of energy reach




- The **Livingston** plot shows an exponential increase of energy with time
- Energy is increased by one order of magnitude each 6-10 years
- New technologies replace the old ones to achieve higher energies, until saturation. By then new technological advancements allow replacing the existing ones
- *And the process continues…*

- Energy is not the only relevant figure of merit:
  - Beam intensity
  - Beam emittance (size)

# Accelerators and performance indicators

The design of an accelerator focuses on ***high performance***

- **Colliders –** high energy physics
  - **Luminosity:** *event production rate*
    - $N_b$ # of particles per bunch
    - $k_b$ # of bunches
    - $\gamma = E/(m_0 c^2)$ Lorentz factor
    - $\varepsilon_n$ normalized emittance
    - β* betatron amplitude at interaction point

$$L = \frac{N_b^2 k_b \gamma}{4\pi \epsilon_n \beta^*}$$

- **Spallation sources** – target experiments
  - **Average beam power**
    - $\bar{I}$ average current
    - **E** energy
    - $f_n$ repetition rate
    - **N** # of particles per pulse

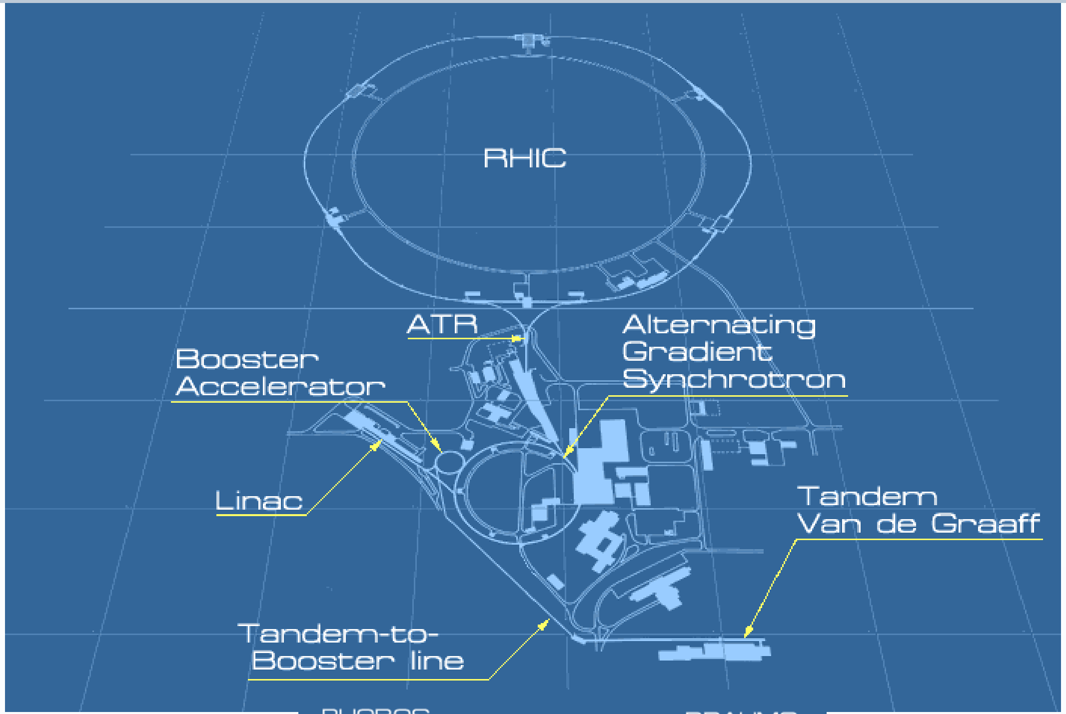
$$\bar{P} = \bar{I}E = f_N N e E$$

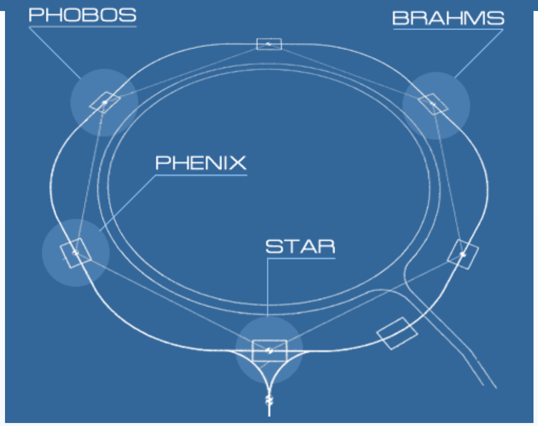
- **Synchrotron radiation sources** – spectroscopy
  - **Brightness:** *photon density*
    - $N_b$ # of photons
    - $\varepsilon_{x,y}$ horizontal and vertical emittance

$$B = \frac{N_p}{4\pi^2 \epsilon_x \epsilon_y}$$

# Relativistic Heavy Ion Collider (RHIC - BNL)

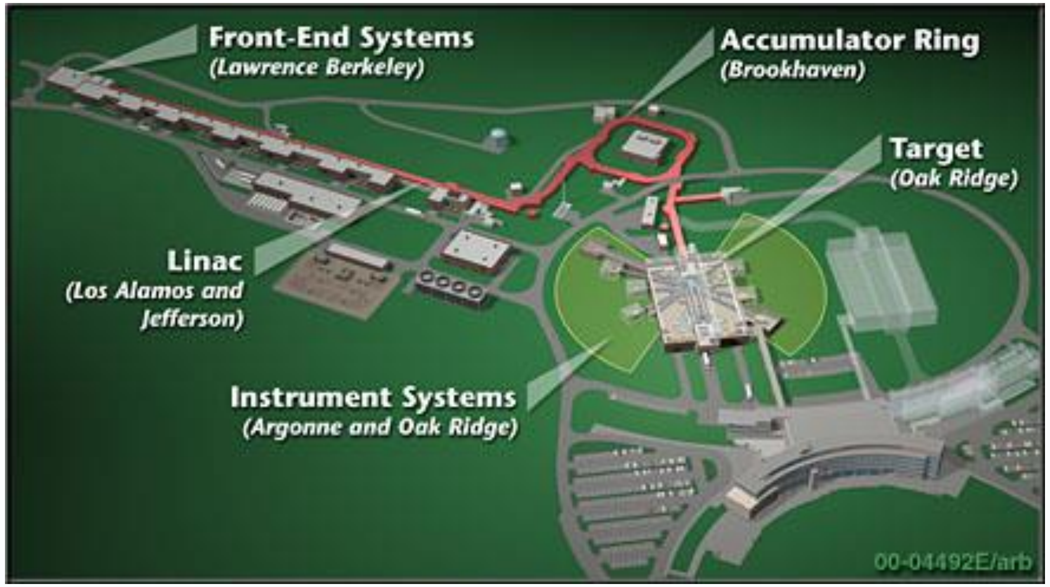
- **Ion collider** (gold, copper and polarized protons) with energies up to 100 GeV/u
- The beams are counter-rotated in a 2.4 mile (**~4km**) storage ring driven by 1740 superconducting dipoles
- The beams collide at 6 points in 4 of which the detectors of the **4 main experiments** (BRAHMS, PHENIX, PHOBOS, STAR) are placed
- The main purpose of the accelerator is the **production, detection and study of quark - gluon plasma**

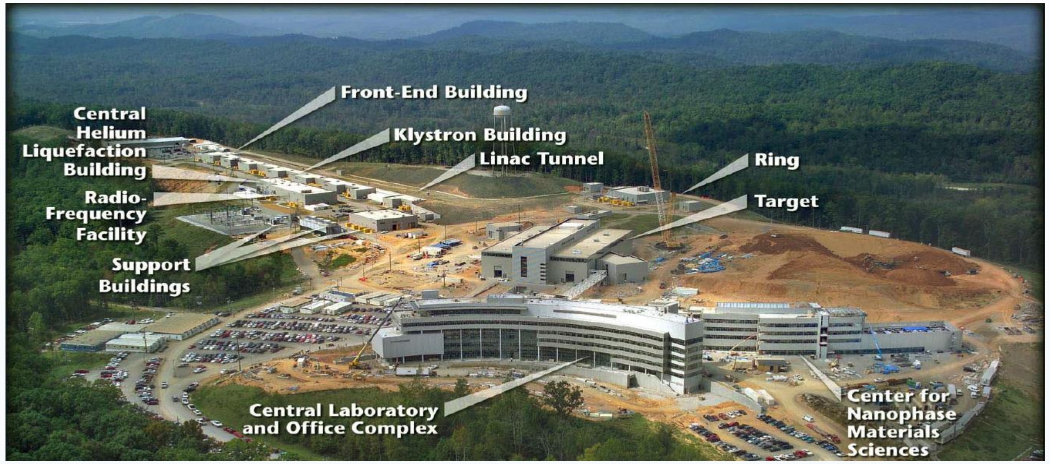


# Spallation Neutron Source (SNS - ORNL)

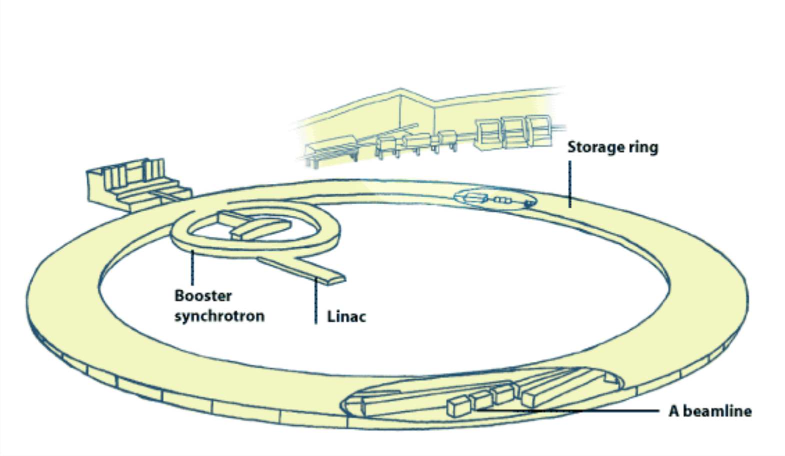
- Collaboration project of **6 laboratories** (LBNL, LANL, JLAB, BNL, ANL, ORNL)
- Spallation Neutron Source with a power of 1.4 MW
- The complex includes an **$H^-$ source**, a 300m **linear accelerator**, with superconducting RF cavities, a proton **accumulator ring** with a perimeter of 248m and a liquid mercury **target** for the production of neutrons.
- The main purpose is neutron scattering **spectroscopy experiments at 24 stations** (magnetic structure of materials, nanotechnology, etc.)



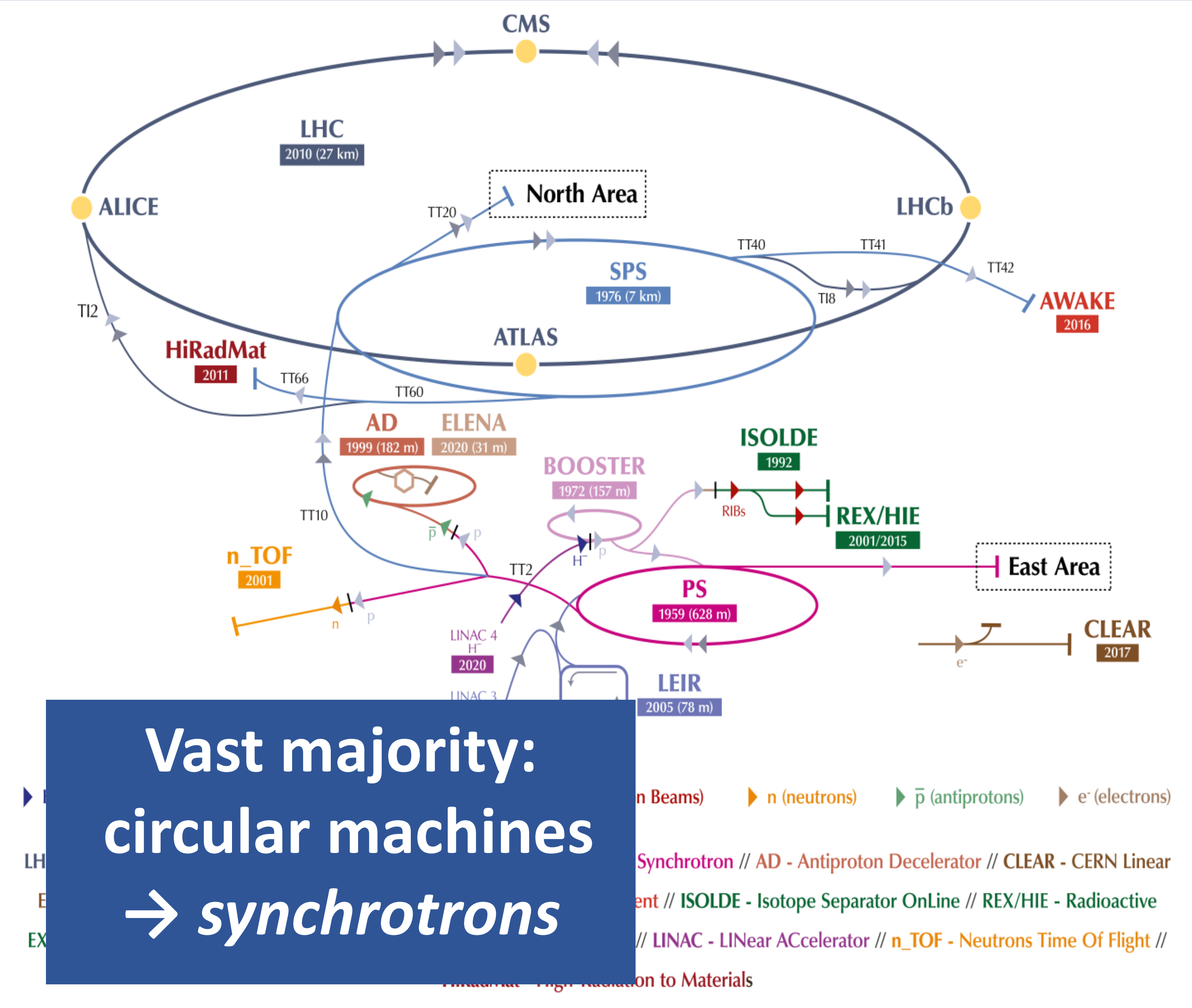



# European Synchrotron Radiation Facility (ESRF)

- The **first and brightest** 3rd generation synchrotron radiation source in Europe
- **50 experimental beamlines** using "hard" X-rays produced by interfering magnetic elements (magnetic amplifiers and oscillators) and dipole magnets
- **3500 users/year** from 14 member states perform X-ray spectroscopy experiments for materials science, chemistry, biology, geology, medicine, archaeometry, etc.
- The complex includes a **linear electron accelerator**, a 300-meter booster **synchrotron** and an 844-meter **storage ring**.
- The storage ring shows **record availability of 98%** with an average time between outages of more than 2 days.



# CERN Accelerator Complex




**Vast majority: circular machines → *synchrotrons***

## ***CERN Proton chain***

1. **LINAC-4** 160MeV (H-)
2. **Proton Synchrotron Booster** 2GeV
3. **Proton Synchtrotron** 26GeV
4. **Super Proton Synchrotron** 450 GeV
5. **Large Hadron Collider** 7Tev

## ***CERN Ion chain***

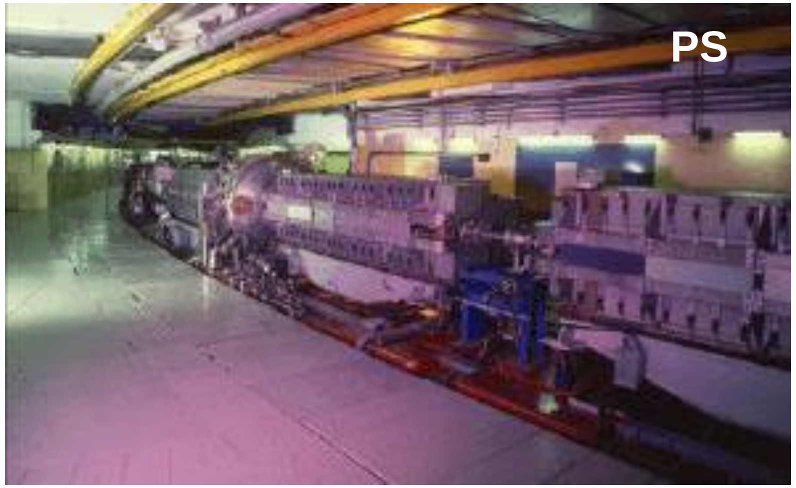
1. **LINAC-3**
2. **Low Energy Ion Ring**
3. **Proton Synchrotron**
4. **Super Proton Synchrotron**
5. **Large Hadron Collider**

***Other facilities & experiments***: n_TOF, ISOLDE, East Area, North Area, HiRadMat, AWAKE, CLEAR (electrons), AD & ELENA (Antiprotons)

# CERN Accelerator Complex

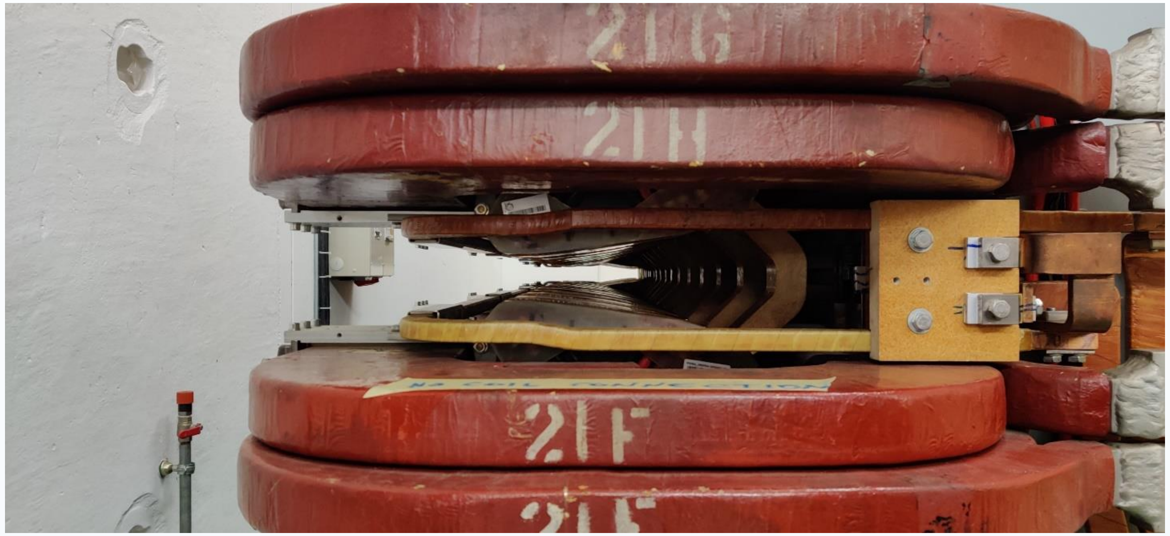
# CERN Accelerator Complex

- **PS**: Proton Synchrotron
- CERN's first accelerator
- 1st run: ***1959***
- Even today it accelerates beams (***protons and ions***) for the LHC and other CERN experiments




- Consists of 100 combined function magnets

→ ***The same magnet bends and focuses the beam!***



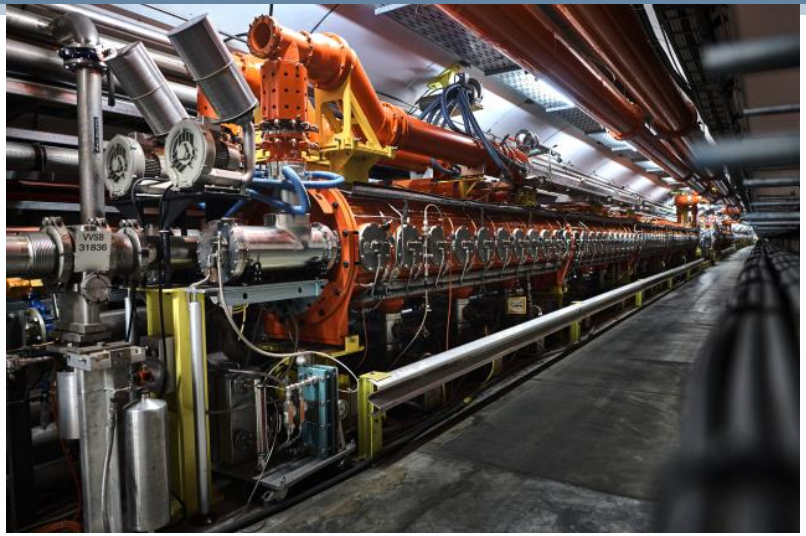
# CERN Accelerator Complex


- **PSB**: Proton Synchrotron Booster
- The first circular accelerator of the Complex
- 1$^{st}$ run: ***1972***
- Main purpose: to increase the number of protons that PS can accelerate.

- It comprises 4 superposed rings

→ ***Essentially, they are 4 different synchrotrons with common characteristics (magnets, etc.)***

# CERN Accelerator Complex




- **SPS**: Super Proton Synchrotron
- The 2nd larger accelerator at CERN with a circumference of 7km
- 1st run: ***1976***
- ***Discovery of the W and Z bosons during its operation as a collider***

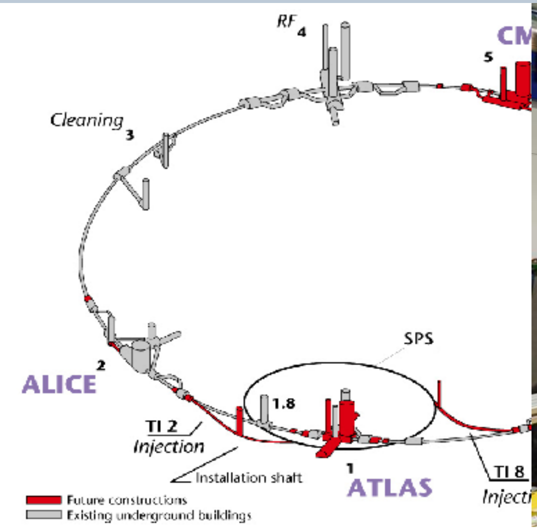
- Today it operates as an accelerator producing beams (***protons and ions***) for the LHC and other CERN experiments

# CERN Accelerator Complex

- **LHC**: Large Hadron Collides
- The largest accelerator at CERN with a circumference of **26.7km**
- 1st run: ***2008***
- The beams rotate in opposite directions driven by ***1232 superconducting dipoles***, 14.3m long with up to 8T field in temperatures of -271.3℃
- Operates with protons and ions


# CERN Accelerator Complex

- There are 8 interaction points, 4 of which the detectors of the main experiments (**ATLAS, CMS, ALICE, LHC-B**) are placed
- The main purpose: the production, detection and study of ***Higgs bosons*** (revealing the mass acquisition mechanism)

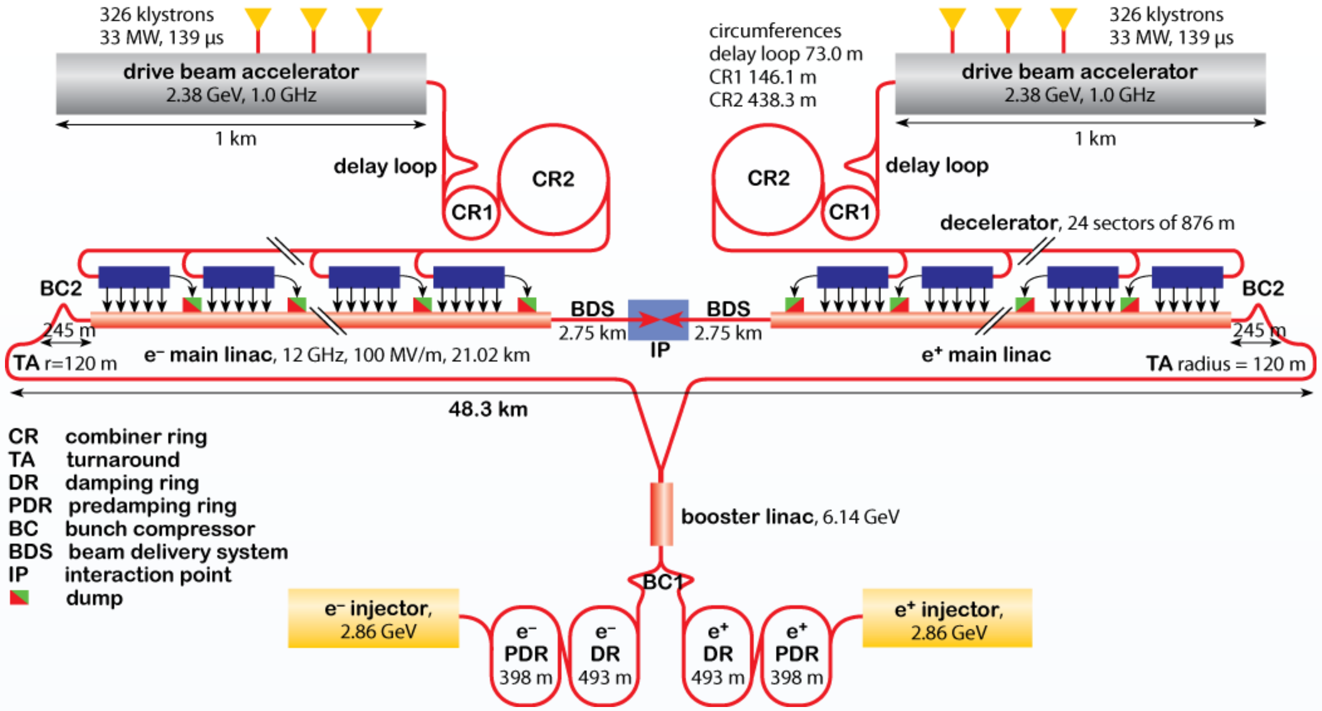




- Ongoing works for its upgrade (prototype dipole) until 2029
- *High Luminosity LHC (**HL-LHC**) to increase LHC performance (~x10)*

# CERN Future Accelerators: CLIC

- CLIC: Compact Linear Collider
- e+/e- collider (**up to 3 TeV**)
- Luminosity: 6·1034cm-2s-1 (3 TeV)
- **Normal conducting** RF accelerating structures
- Gradient 100 MV/m
- RF frequency 12 GHz
- **Two beam acceleration principle for cost minimisation and efficiency**
- Many common points with ILC, similar elements, but different parameters

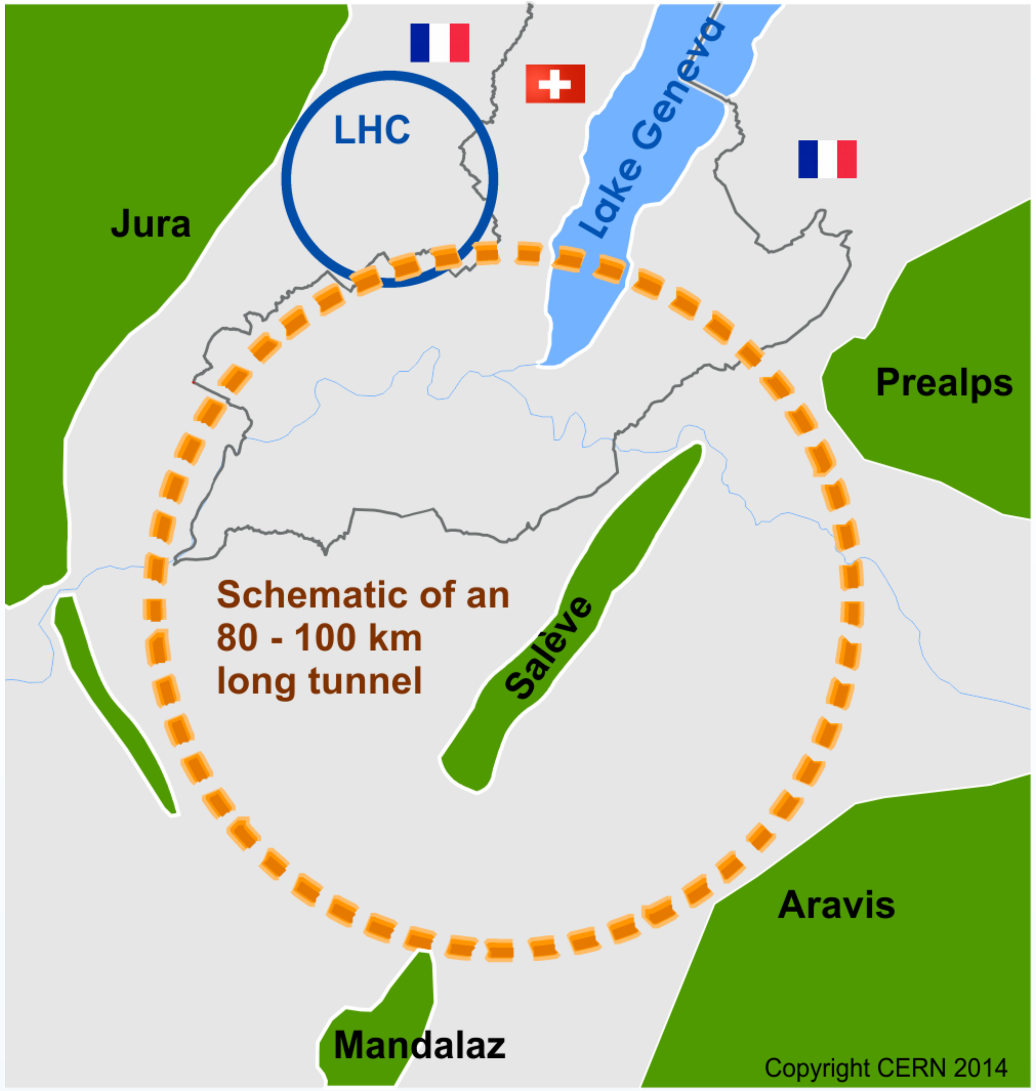


# CERN Future Accelerators: FCC

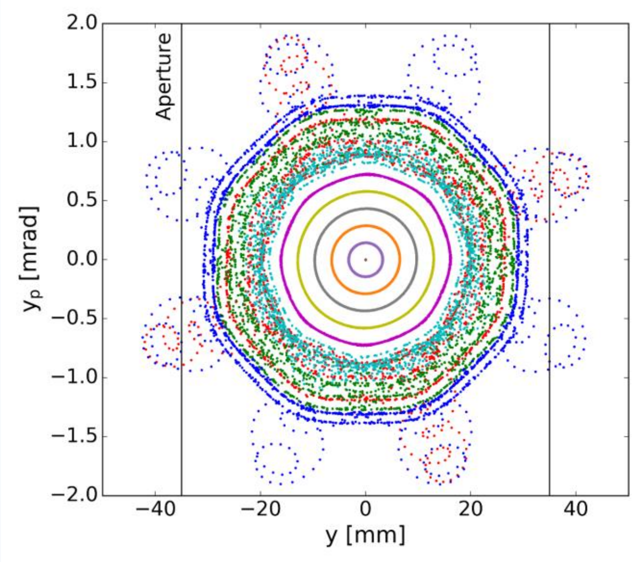
- FCC: Future Circular Collider
- Circumference: ***100 km***
- Hadron collider (FCC-hh)

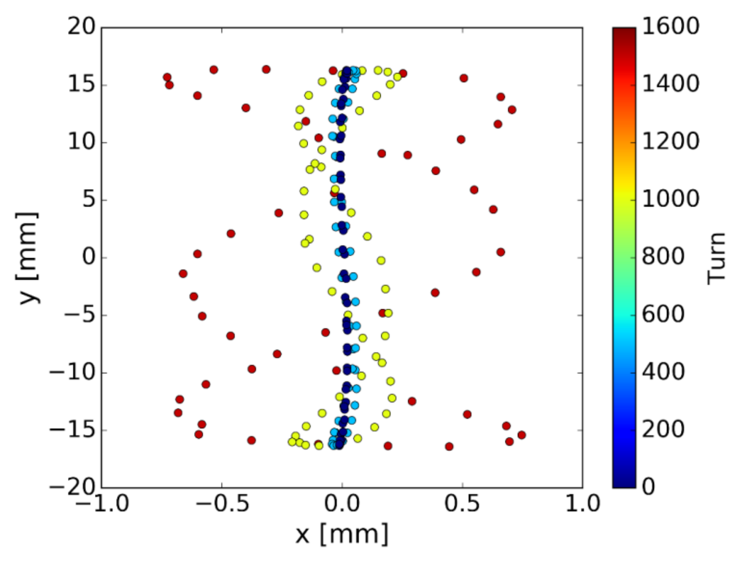
**~16 T up to 100 TeV *pp***

- Lepton collider (FCC-ee) as a first stage



# *Basic principles of accelerator beam dynamics*



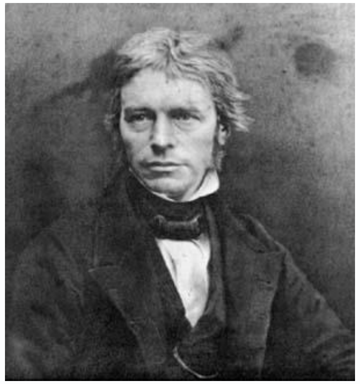



# Maxwell's equations for electromagnetism

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

**Gauss law for electricity**

electric field diverges
from electric charges



$$\nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B}$$

**Faraday's law of induction**

changing magnetic fields
produce electric fields

$$\nabla \cdot \mathbf{B} = 0$$

**Gauss law for magnetism**

no isolated magnetic
poles

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial}{\partial t}\mathbf{E}$$

**Ampere-Maxwell law**

changing electric fields and
currents produce circulating
magnetic fields

# Lorentz force

- Force acting on **charged particles** moving under the influence of **electromagnetic fields**

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

- Kinetic energy (T) change is caused by the **electric field** – ***acceleration***

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

- **Horizontal component** of the Lorentz force (particle moving on the longitudinal plane

$$\mathbf{F_x} = q(E_x - v_z B_y)$$

- For high energy (relativistic limit): $\upsilon_z \approx c$ & $\upsilon_z B_y >> E_x$ (1 T corresponding to 300 MV/m)

  → **Magnetic fields** much more efficient for ***steering***

# Dipoles

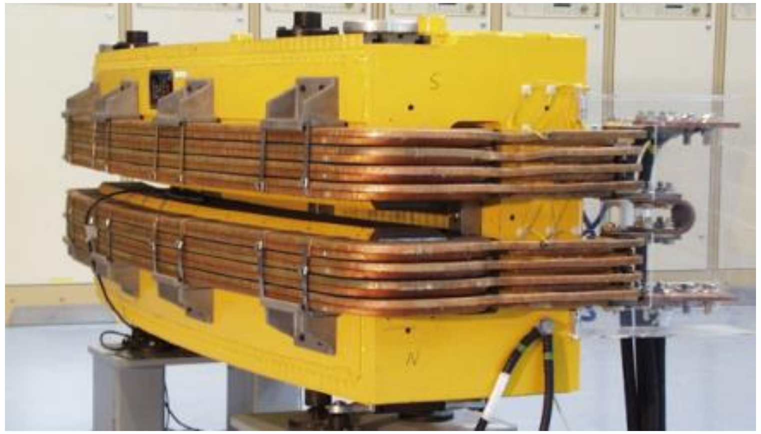
In a circular accelerator of energy ***E***, with ***N*** dipoles, each of length ***L***

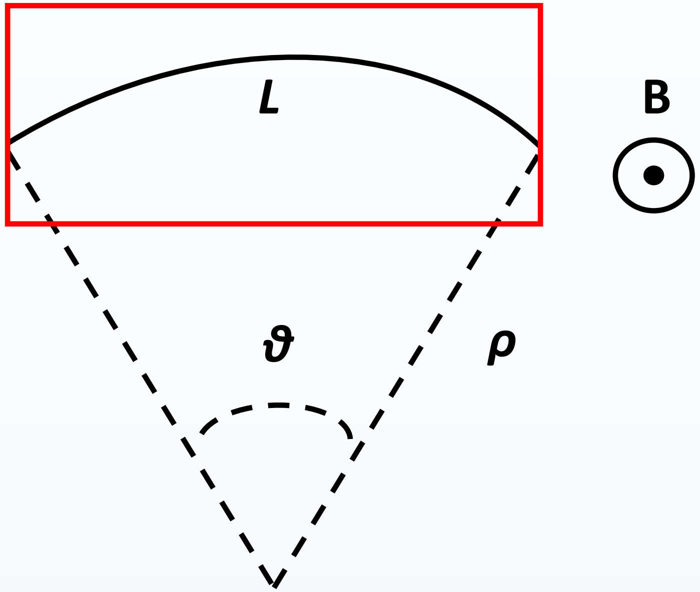
- Bending angle: $$\theta = \frac{2\pi}{N}$$
- Bending radius: $$\rho = \frac{L}{\theta}$$
- Dipole field: $$BL = \frac{2\pi}{N}\frac{\beta E}{q}$$

→ Choosing a dipole magnetic field: the length is determined (and vice versa)

→ For higher fields, smaller and fewer dipoles can be used

→Ring circumference (cost) depends on field selection





## Example LHC:

**7000 GeV proton storage ring (q = +1e)**
**1232 dipole magnets of l=15m**

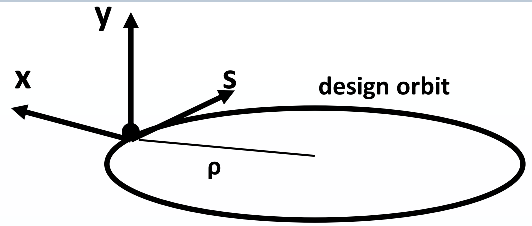
**What is the required dipole field?**

$$\beta E[GeV] = 0.2998 B\rho \; [Tm]$$

$$\theta = \frac{2\pi}{N} = \frac{l}{\rho}$$

$$B = \frac{2\pi \cdot 7000}{0.2998 \; N \cdot l} = 8.3T$$

# Beam focusing




A particle on the design orbit:

- Performs harmonic oscillations on the **horizontal plane**:

  $x = x_0 \cos(\omega t + \phi)$, where $\omega = \frac{v_s}{\rho}$

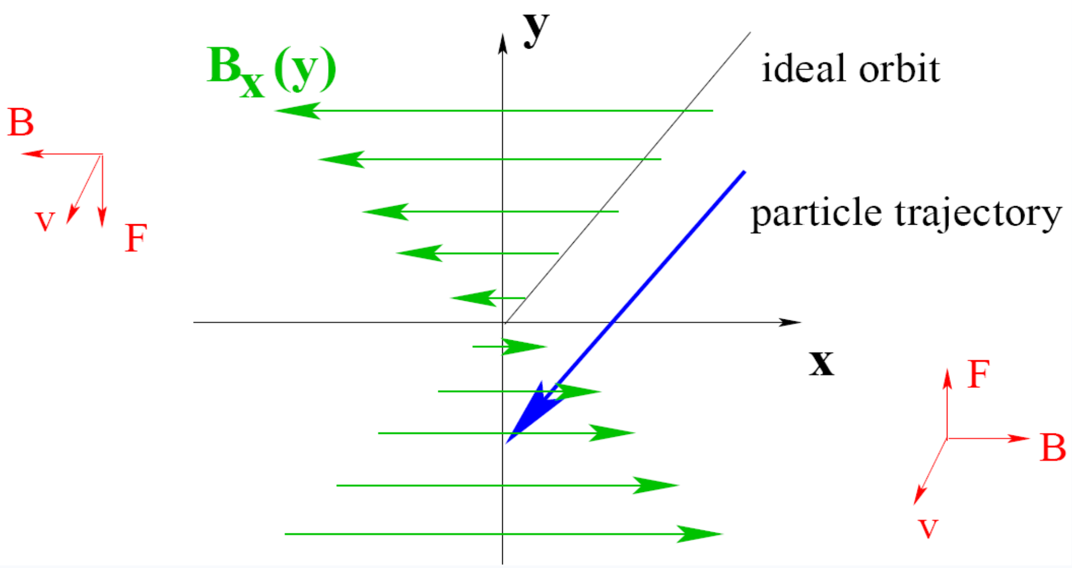
- The **horizontal acceleration** is described by: $\frac{d^2x}{ds^2} = \frac{d^2x}{v_s^2 dt^2} = -\frac{1}{\rho^2}x$

→ ***Weak focusing***

- In the **vertical plane**, only ***gravity:*** $\Delta y = \frac{1}{2} a_g \Delta t^2$

- In the LHC example:
  particles move by 18mm (dipole aperture) within 60ms (~ 100s turns)

→ ***Requires focusing***

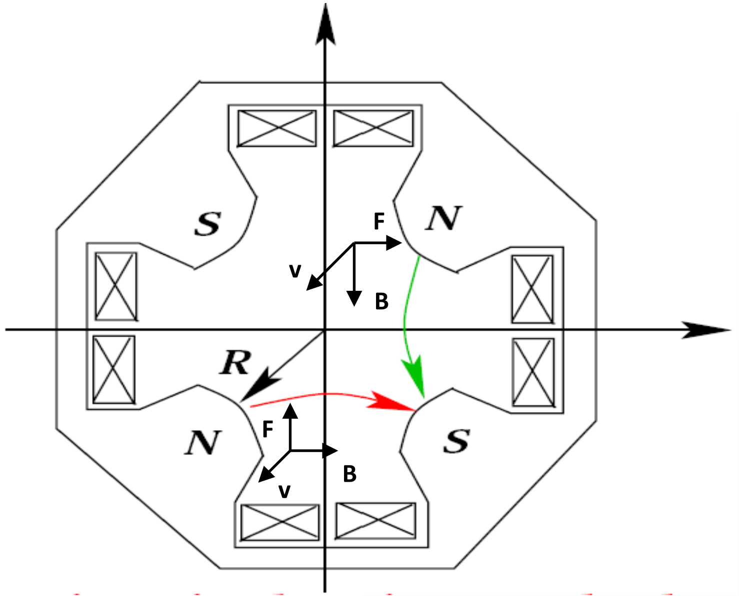


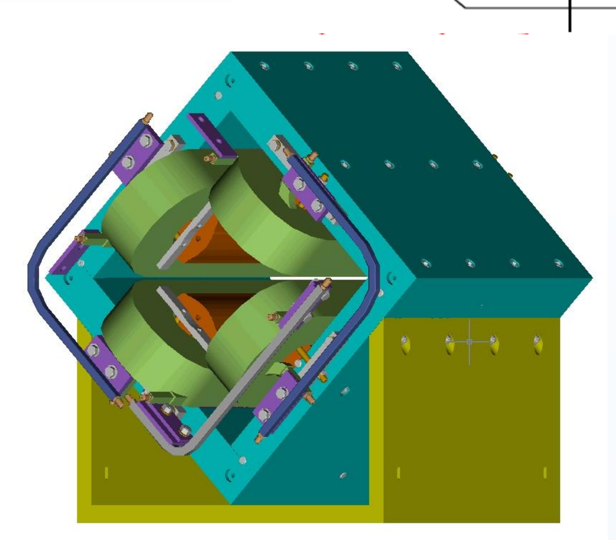
# Quadrupoles

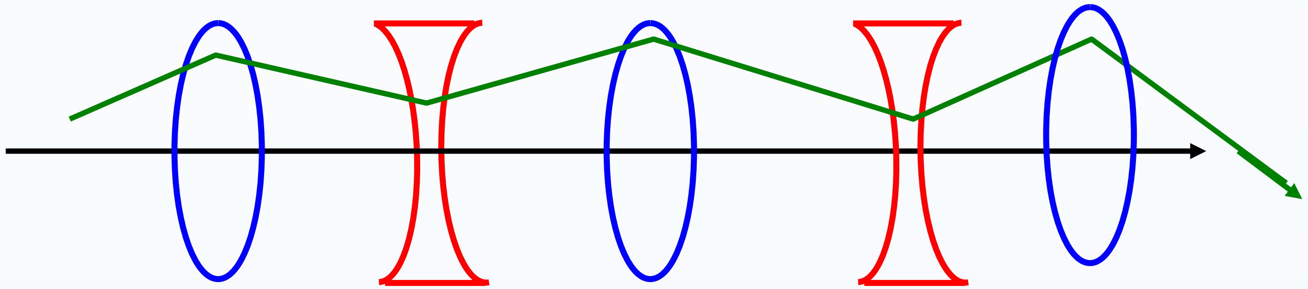
- Quadrupoles focus in one plane while they defocus in the other
- Quadrupole field: $(B_x, B_y) = g(y, x)$
- Focusing force: $(F_x, F_y) = k(y, -x)$
- **Alternating focusing and defocusing** elements needed to control the beam

→ ***alternating gradient focusing***

- Focusing as through lenses *($f_1$=-$f_2$)*: $\frac{1}{f} = |\frac{d}{f_1 \; f_2}|$



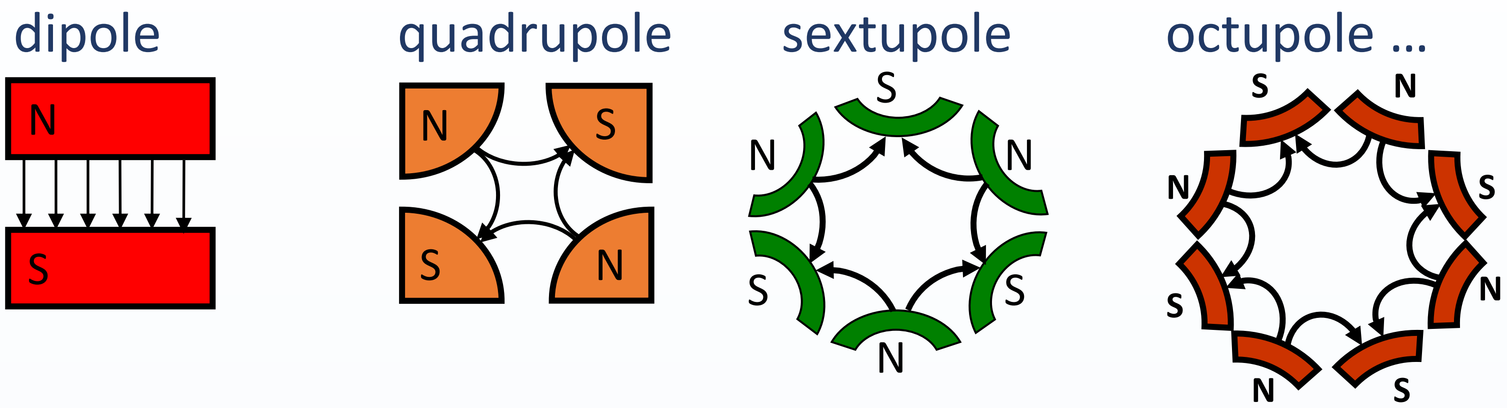





# Realistic synchrotron – Higher Order Elements

Realistically: higher order magnets are needed to correct effects such as magnet errors, misalignments etc.

- ***2n*-poles**:




| | | | | | |
|---|---|---|---|---|---|
| ***n***: | 1 | 2 | 3 | 4 | ... |

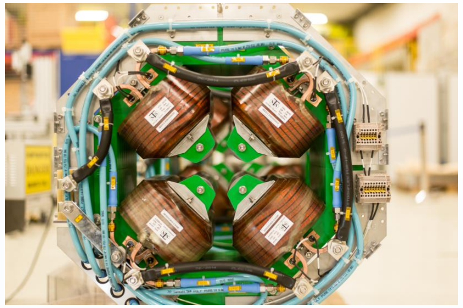
- Normal: *shown above*
- Skew: rotated by ***π/2n***
- Symmetry: rotation by ***π/n – polarity change***

# Components of a Synchrotron

***Main components:***

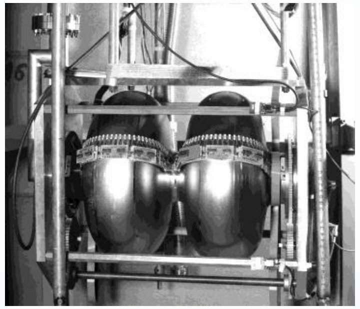
Dipole Magnets: Bending

Quadrupole Magnets: (De-)Focusing



Higher order magnets: Corrections

RF cavities: Acceleration



Kickers/Septa: Injection/extraction elements

# *Thank you!*