



Accelerator & Technology Sector

Beams Department

Accelerator Beam Physics Group

Particle Accelerators and Beam Dynamics

Foteini Asvesta

Eurolabs 2024

Disclaimer

Based on:

- Y. Papaphilippou : “Introduction to Accelerators”
- Summer student lectures:
 - B. Holzer, V. Kain, and M. Schaumann
- CERN accelerator school (CAS):
 - F. Tecker: “*Longitudinal beam dynamics*”
 - S. Sheehy: “*Applications of accelerators*”
- Joint Universities Accelerator School (JUAS):
 - F. Antoniou, H. Bartosik and Y. Papaphilippou: “*Linear imperfections*” and “*nonlinear dynamics*”
- Books:
 - K. Wille: “*The Physics of Particle Accelerators*”
 - S.Y. Lee: “*Accelerator Physics*”
 - A. Wolski: “*Beam Dynamics in High Energy Particle Accelerators*”

Images: cds.cern.ch

Overview

I. Introduction to Accelerators

- Applications
- Accelerator types (historic overview)
- Accelerator performance indicators & examples
- Synchrotrons

II. Accelerator beam dynamics

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 Review 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

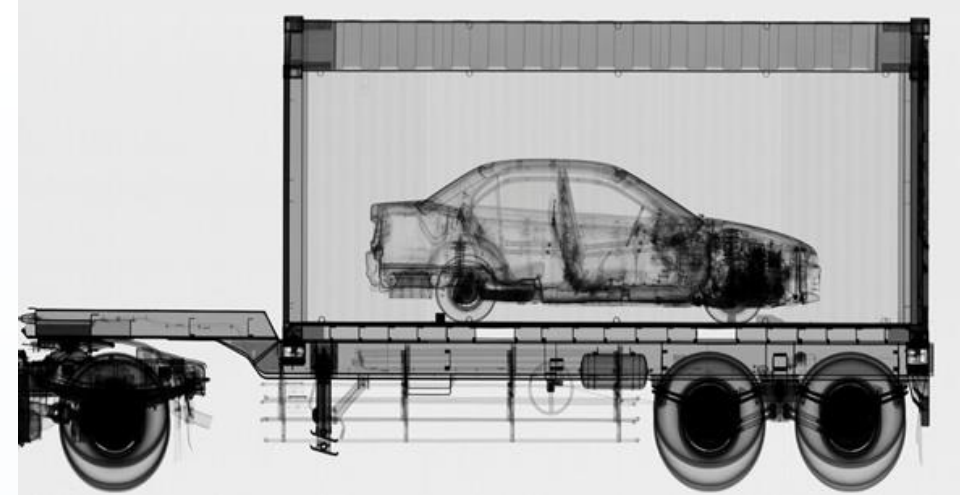
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Security

- **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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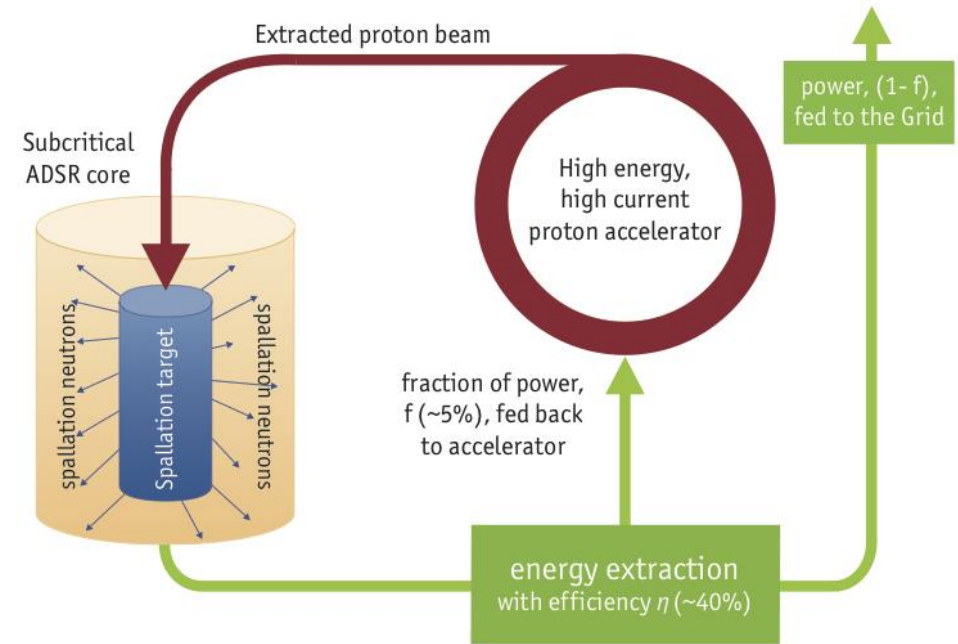
Why accelerators?



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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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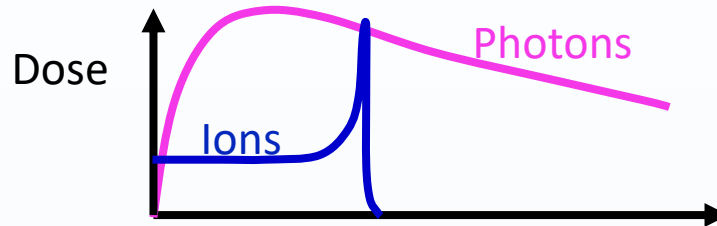
Why accelerators?



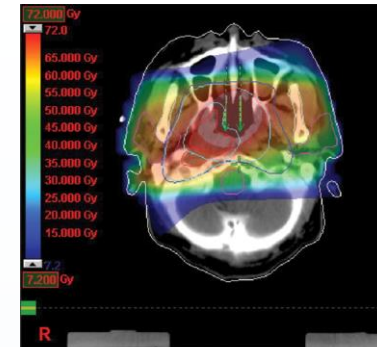
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Health

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

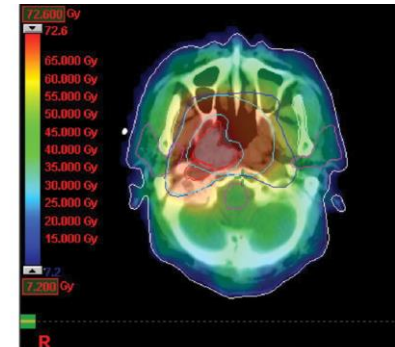


Ions

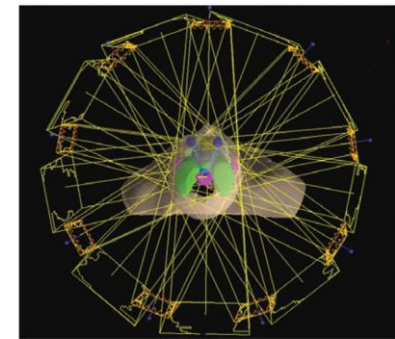
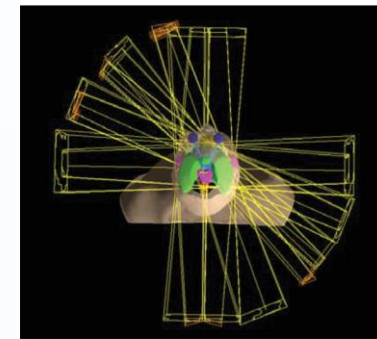


(a)

Photons



(b)



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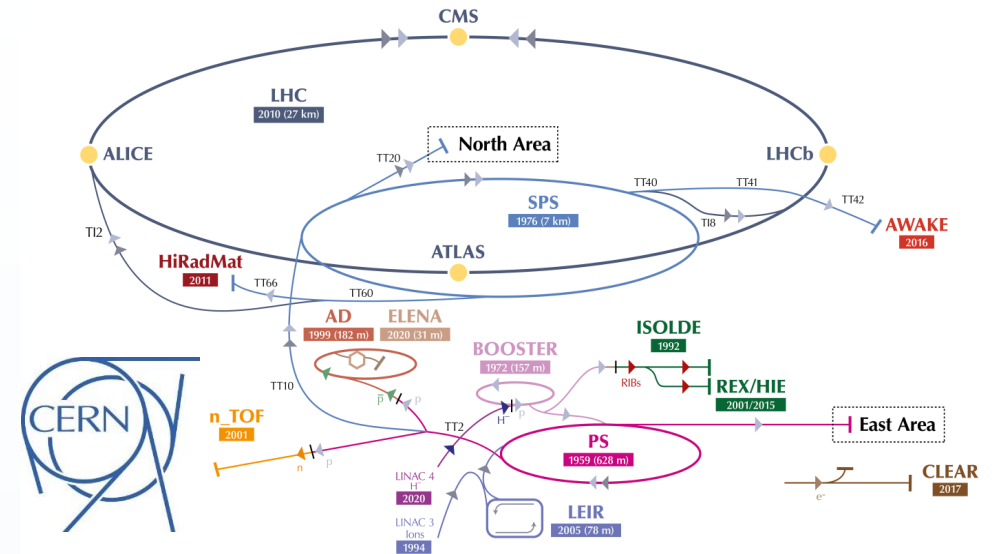
Why accelerators?



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



▶ H⁻ (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ \bar{p} (antiprotons) ▶ e⁻ (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive Experiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LInear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

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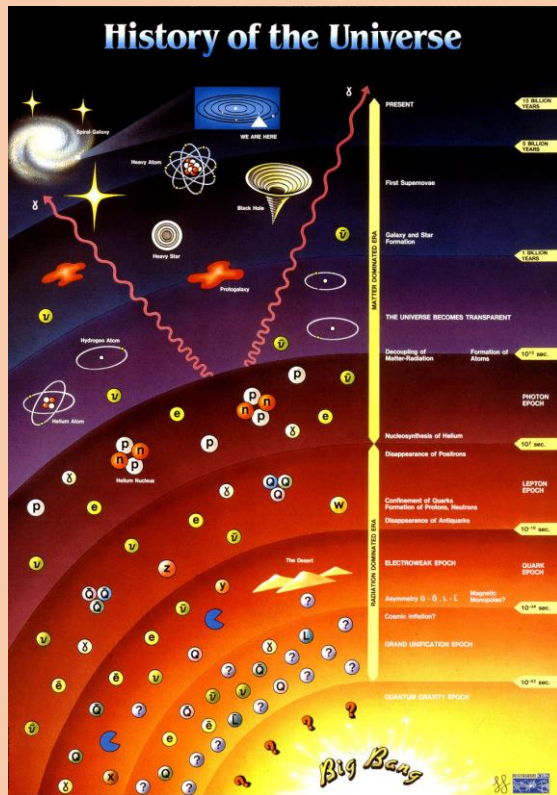
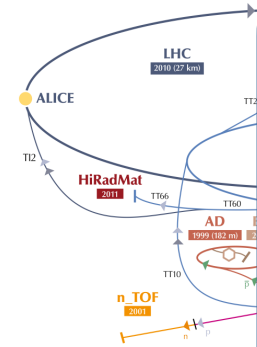
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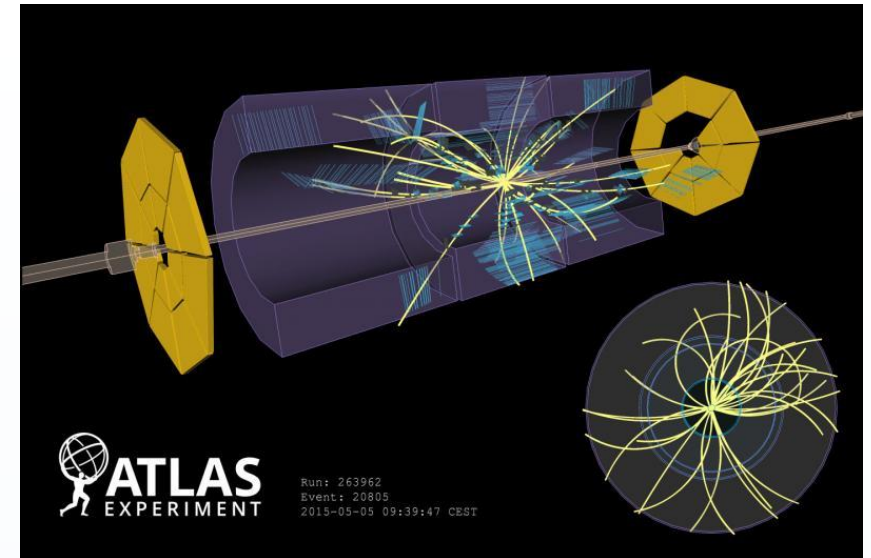
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Accelerators at CERN

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

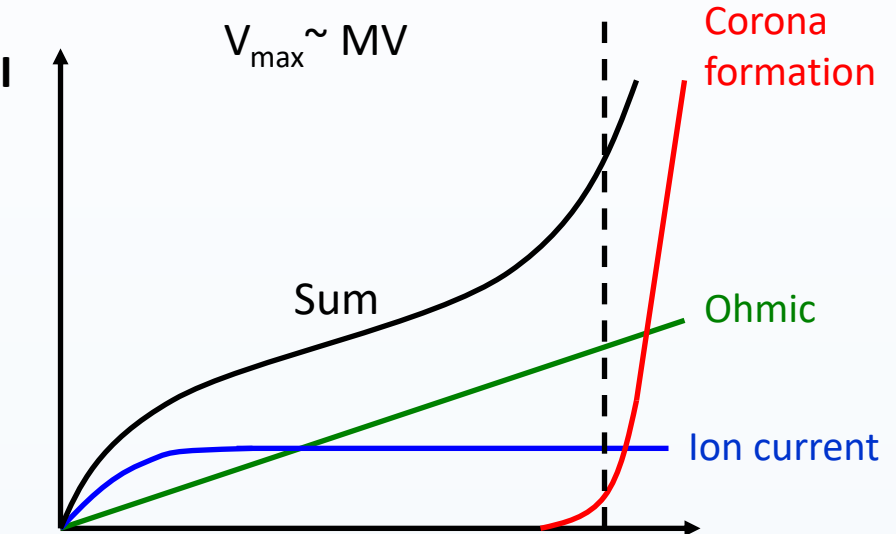
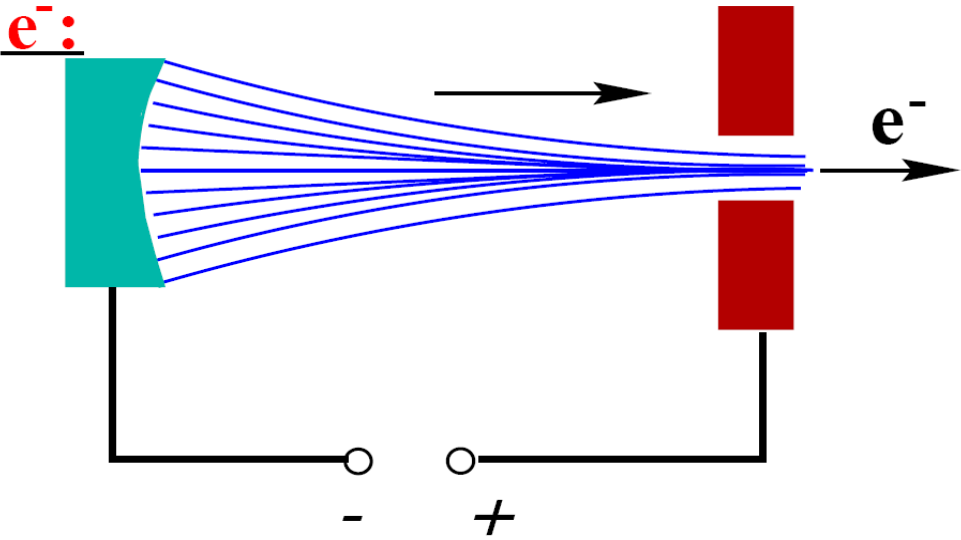
Race for higher energies



Electrostatic Accelerators

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

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



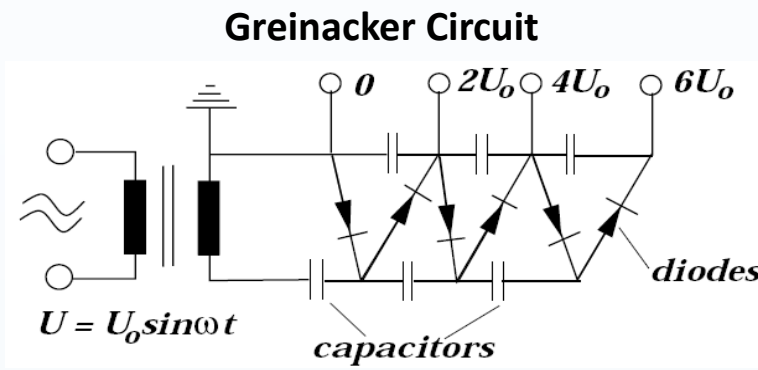
Voltage multipliers

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 diodes (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 \sim MV can be achieved for beams of \sim 100s of mA
- **Cockcroft and Walton** used such an accelerator to split lithium nuclei producing helium nuclei. (Nobel prize 1951)

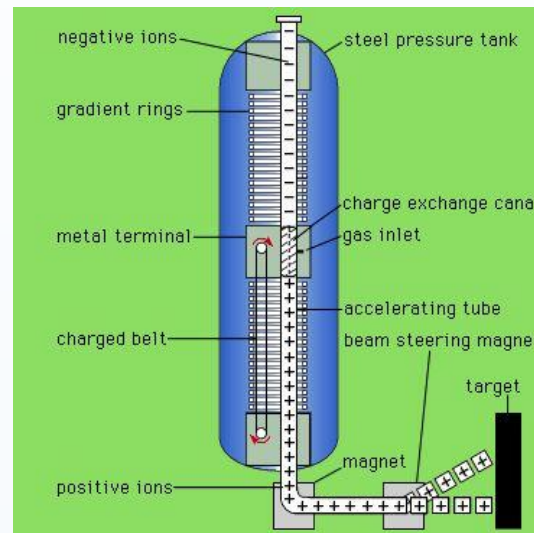
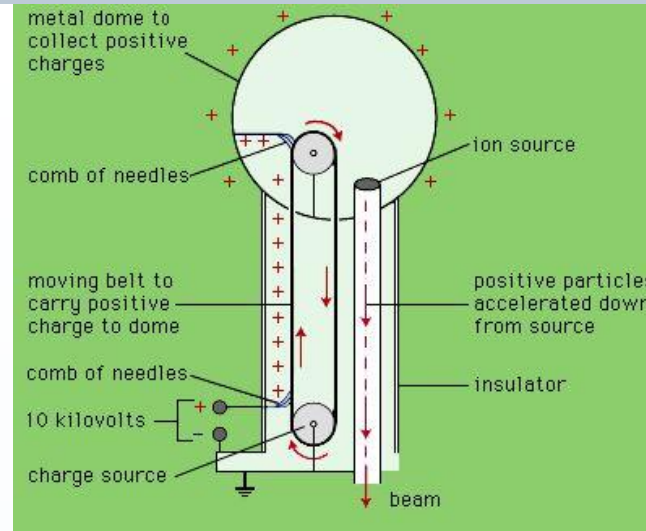


Fermilab cascade generator



Van de Graaff Generator (1930)

- Charges are accumulated through a moving belt charging the dome.
- Higher voltages can be achieved within a pressure tank – Paschen's law: Break down voltage depends on gas pressure & gap
- 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)

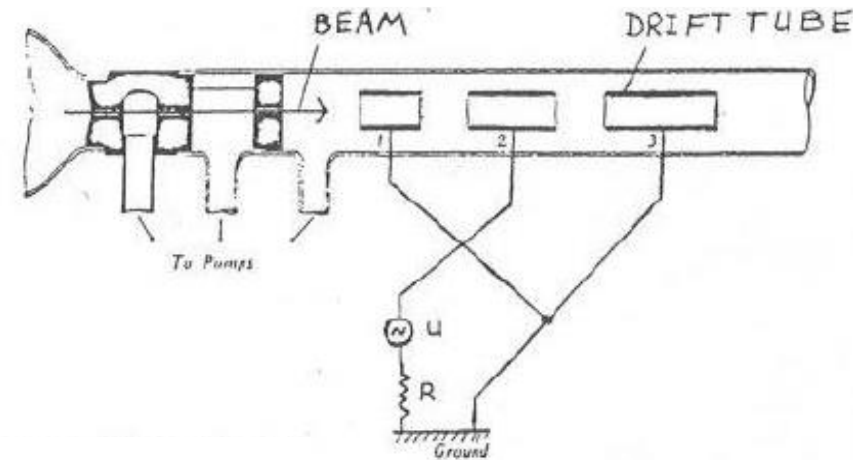


ROBERT VAN DE GRAAF DEMONSTRATES HIS FIRST GENERATOR TO KARL COMPTON

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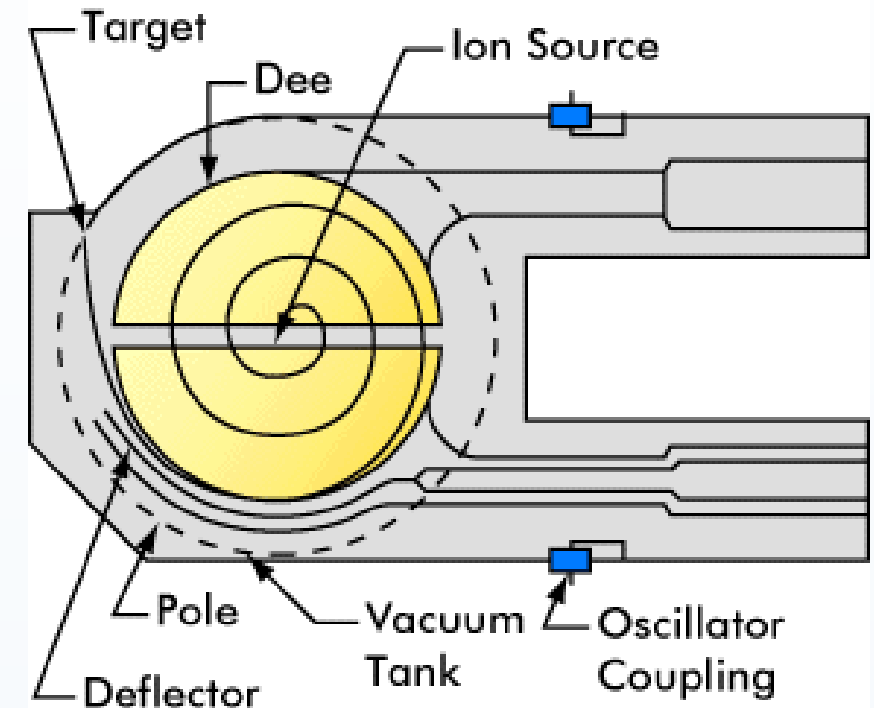
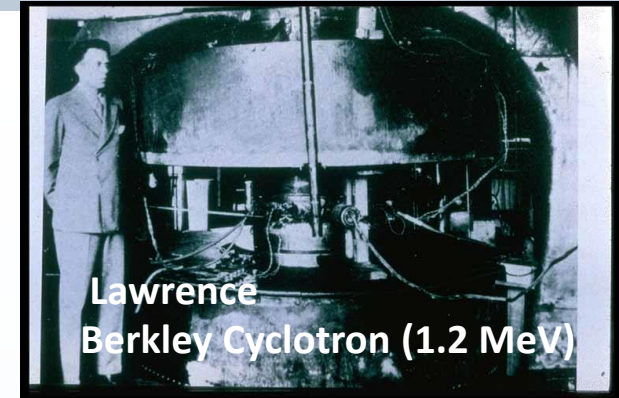
Linear accelerators (LINAC)

- **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:
(spiral orbits)
$$\omega_c = qB/m$$
- 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 Veksler, 1945):**
$$\omega_{RF} \propto 1/\gamma \rightarrow$$
 different frequencies for different particle species | compensation for relativistic effects
- **Isochronous cyclotron principle:** $\omega_{RF} \propto B/\gamma \rightarrow$ Magnetic field increases with radius | Energies up to 600 MeV – prone to losses (field errors)

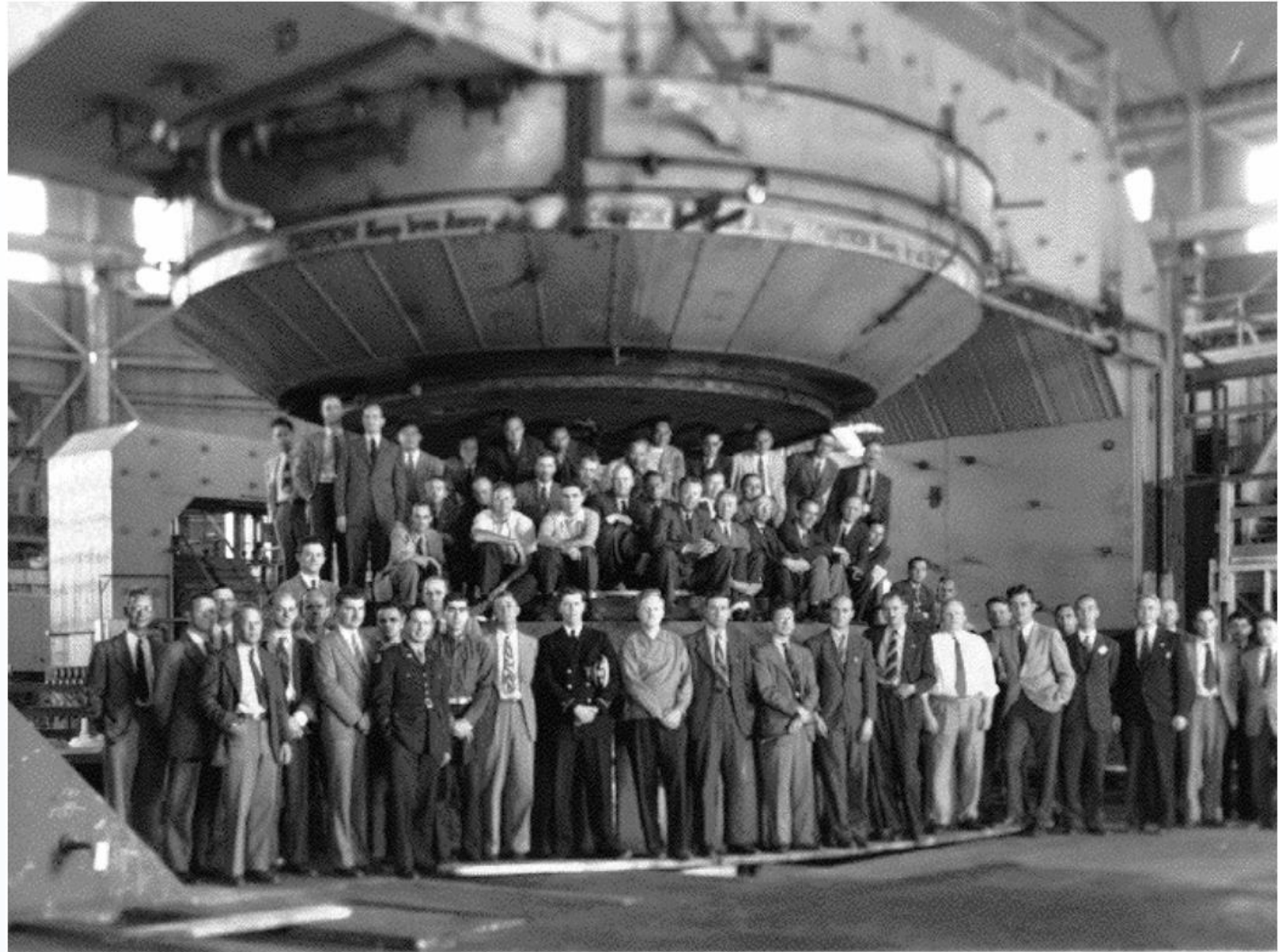


Cyclotron

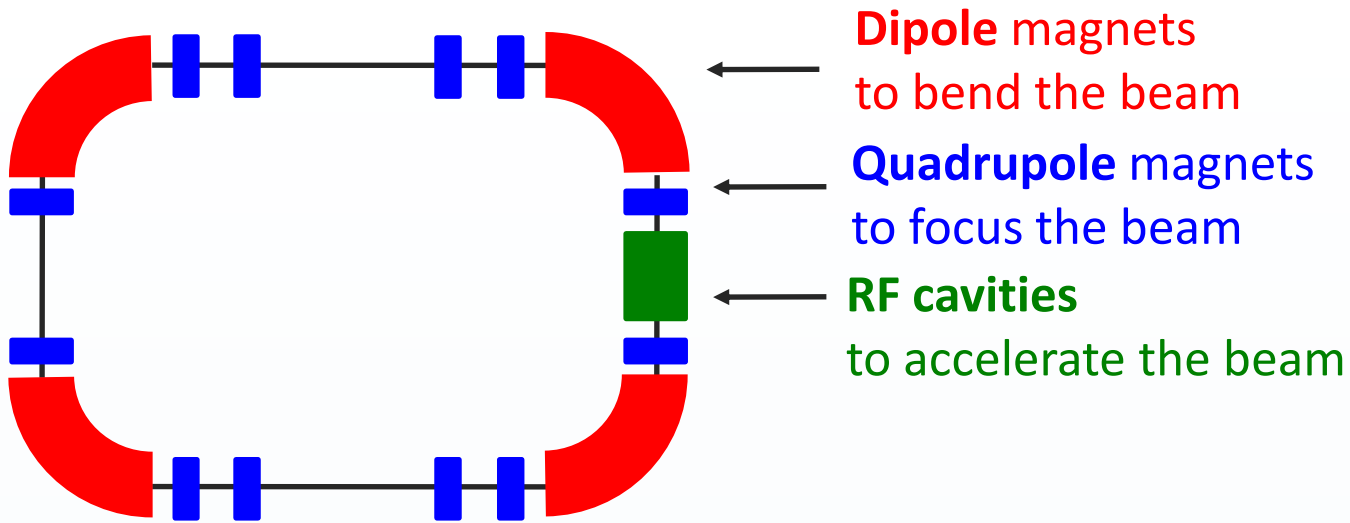
184-inch cyclotron:

1 single dipole with 467 cm diameter

Berkeley campus, 1942



Synchrotron



Could we further push the energy?

Colliders

- Two beams circulating at the Synchrotron's energy
- The beams are brought to collision
- ✓ energy at the *centre of mass* gets **double**

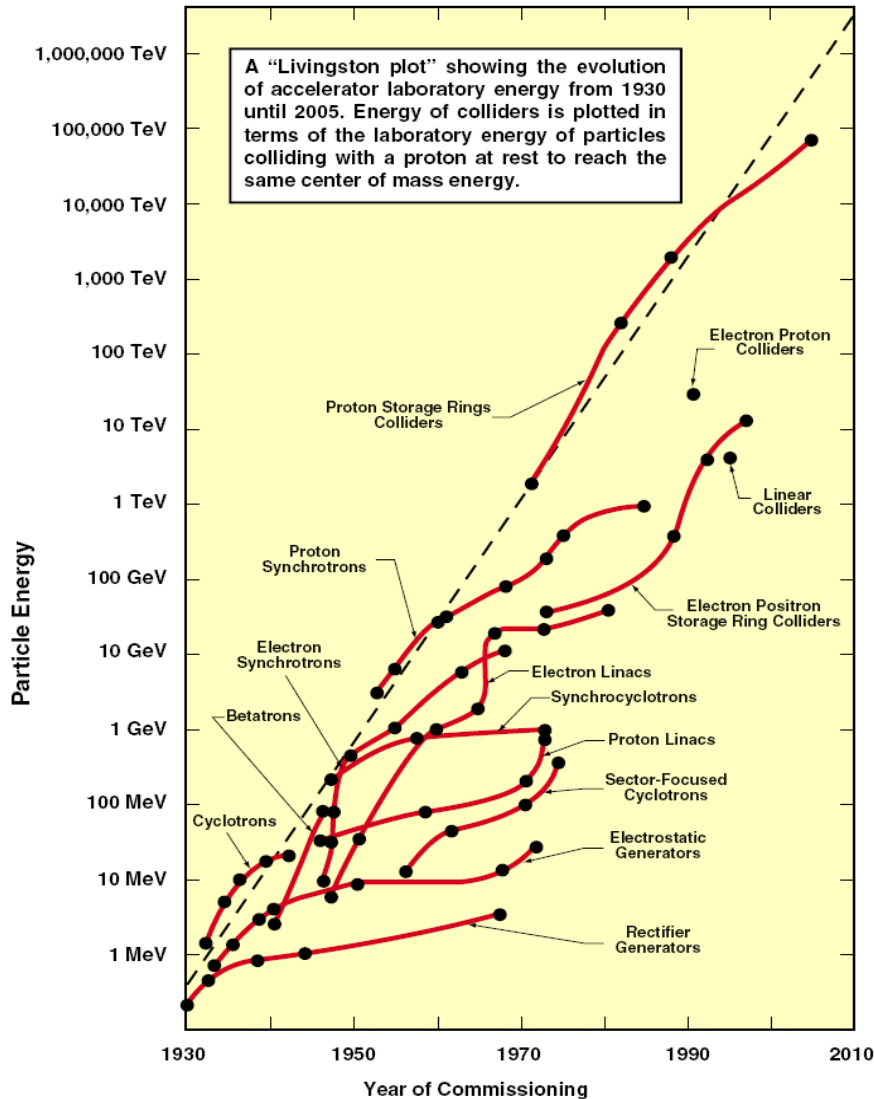
Developed in the 1950s | The CERN PS built in 1959 is still in operation!

Fixed trajectory: $R = \text{constant}$

Magnets only in the vicinity of the beam

- 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
 - $\gamma = E/(m_0c^2)$ Lorentz factor
 - ϵ_n normalized emittance
 - β^* betatron amplitude at interaction point
- **Spallation sources** – target experiments
 - **Average beam power**
 - \bar{I} average current
 - E energy
 - f_n repetition rate
 - N # of particles per pulse
- **Synchrotron radiation sources** – spectroscopy
 - **Brightness:** *photon density*
 - N_p # of photons
 - $\epsilon_{x,y}$ horizontal and vertical emittance

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

Energy

Intensity

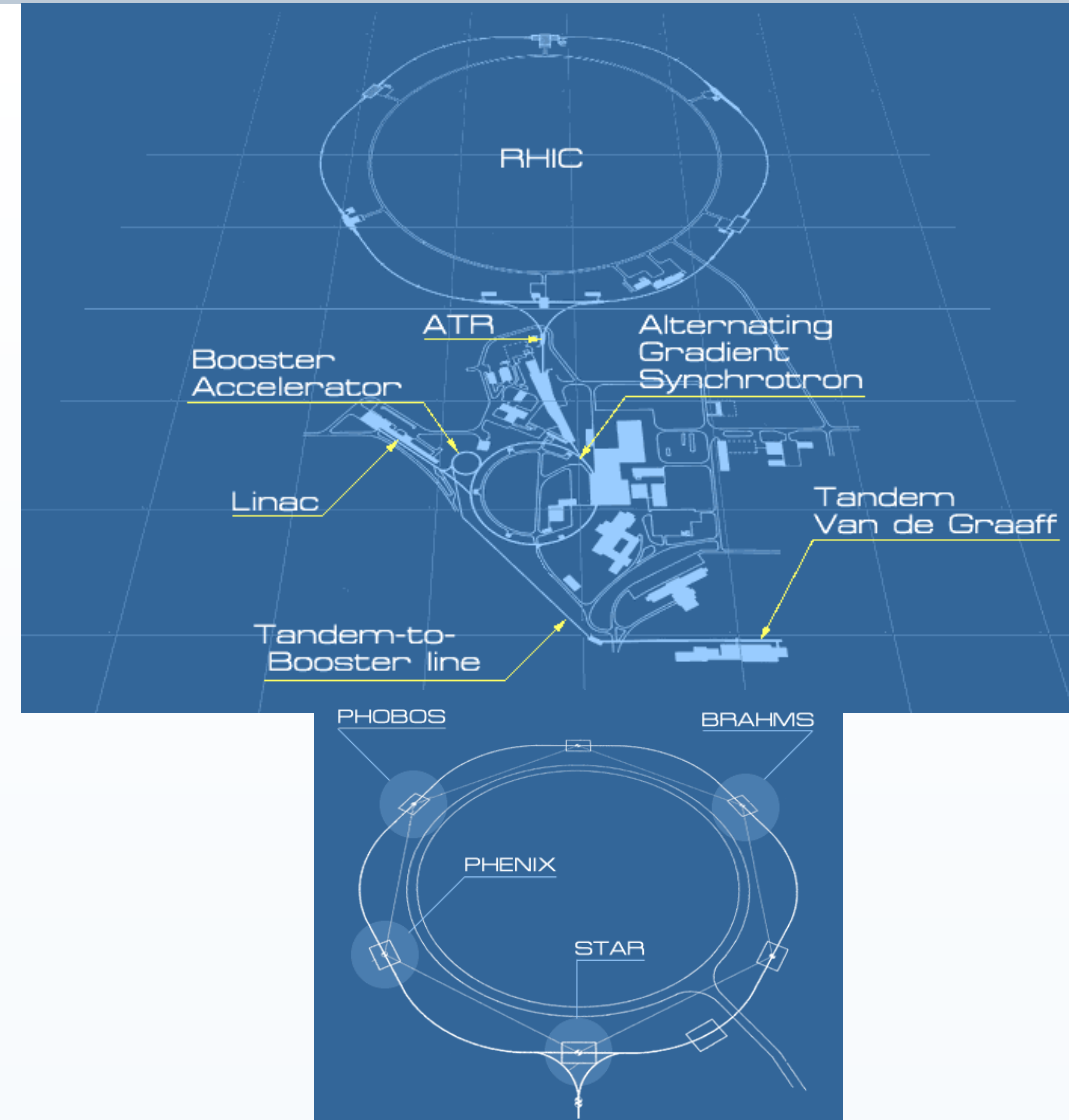
$$\bar{P} = \bar{I} E = f_n N E$$

Beam size

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

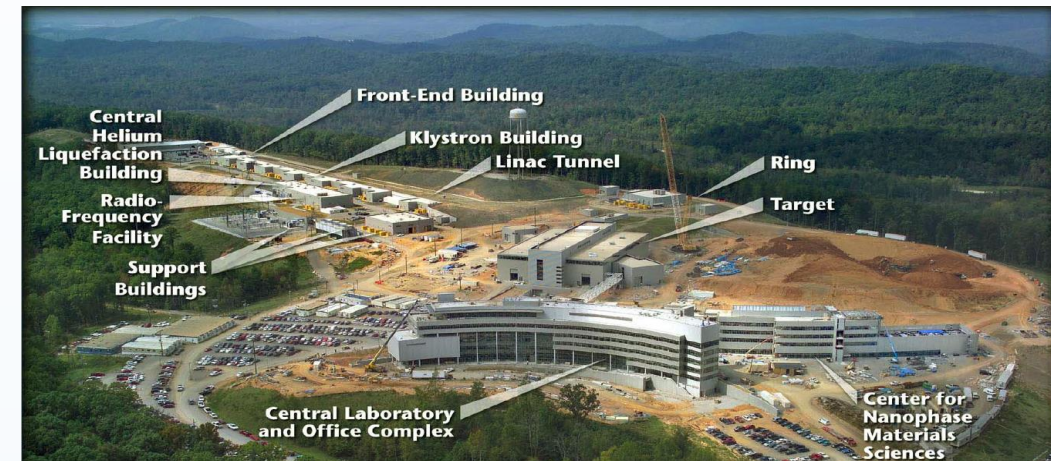
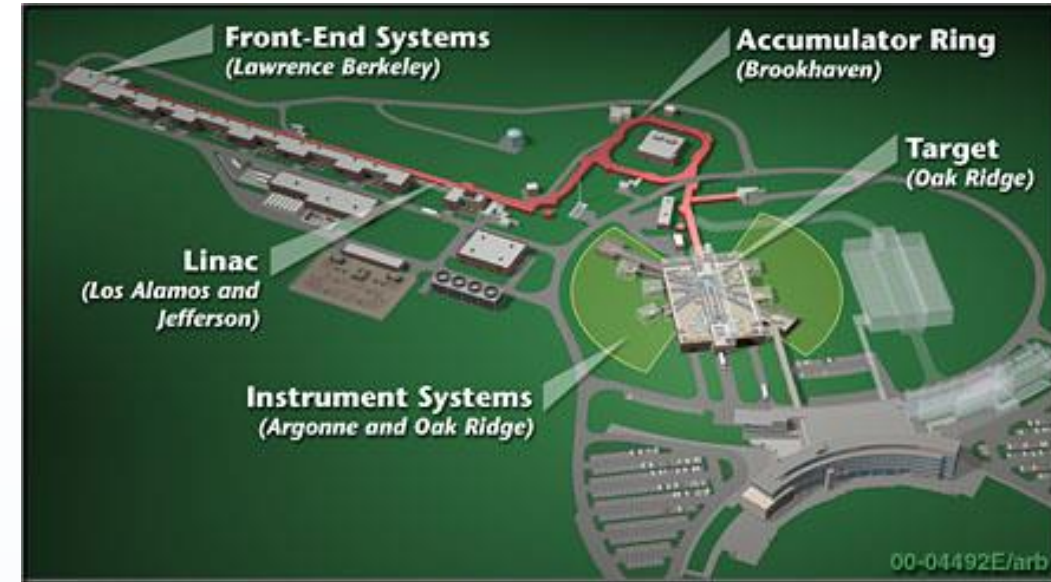
Relativistic Heavy Ion Collider (RHIC - BNL)

- **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**



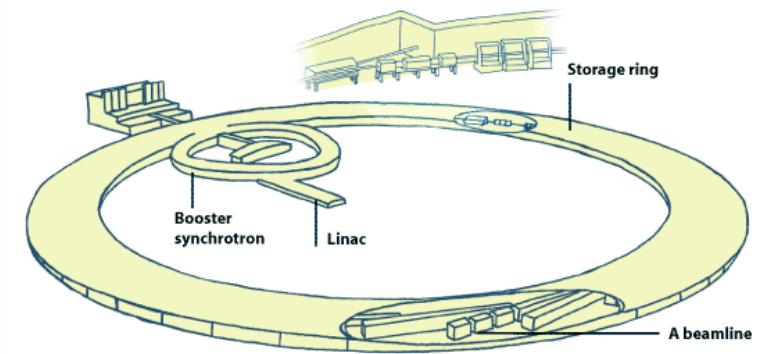
Spallation Neutron Source (SNS - ORNL)

- 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.)

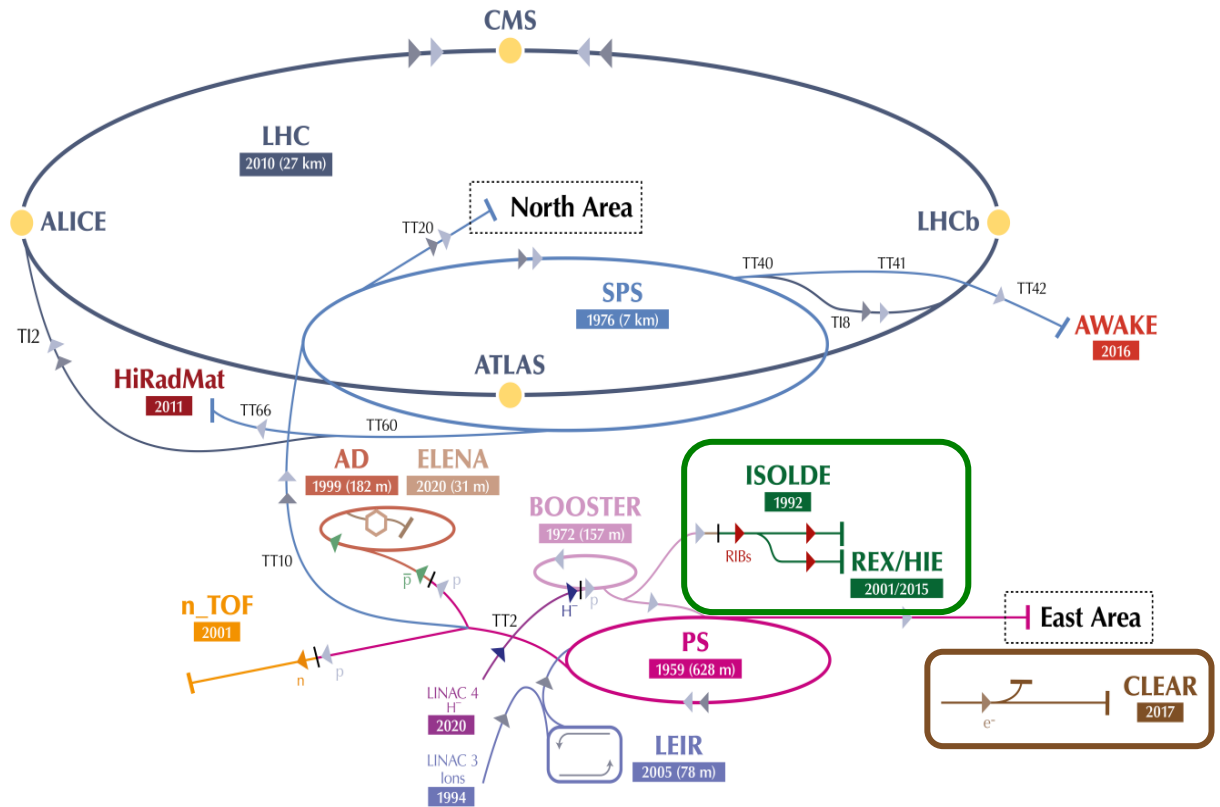


European Synchrotron Radiation Facility (ESRF)

- 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



▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ \bar{p} (antiprotons) ▶ e^- (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive Experiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

CERN Proton chain

1. **LINAC-4** 160MeV (H^-)
2. **Proton Synchrotron Booster** 2GeV
3. **Proton Synchrotron** 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**

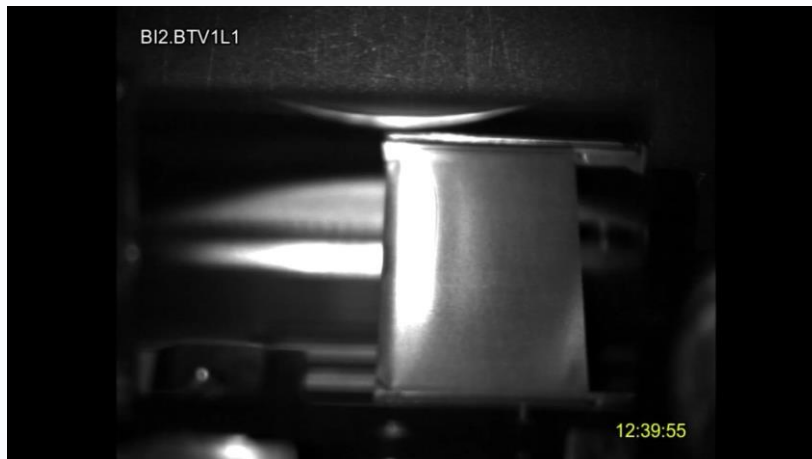
Other facilities & experiments: n_TOF, **ISOLDE**, East Area, North Area, HiRadMat, AWAKE, **CLEAR** (electrons), AD & ELENA (Antiprotons)

CERN Accelerator Complex – Linac 4



- **Linac 4:** Linear Accelerator 4
- CERN's newest accelerator
- 1st run: **2019**
- Main purpose: to increase the injection energy of the PSB to 160 MeV.

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 - 1st run: **2019**
 - Main purpose: to increase the injection energy of the PSB to 160 MeV.
-
- It accelerates negative hydrogen ions, H^- , to 160 MeV.
→ ***H^- beam guided through a stripping foil at PSB injection to produce the protons: "Charge exchange injection".***

CERN Accelerator Complex



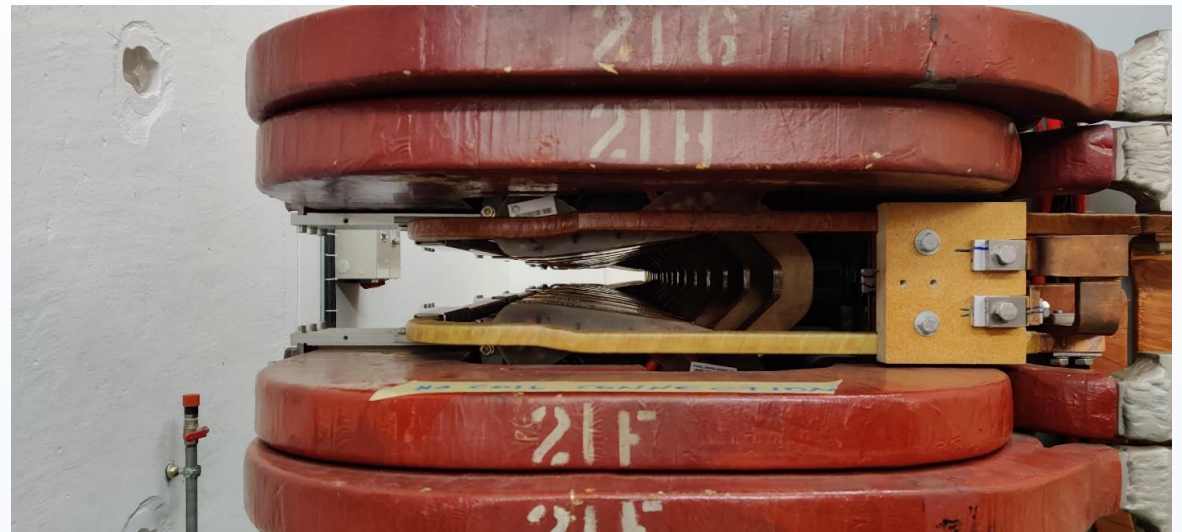
- **PSB**: Proton Synchrotron Booster
- The first circular accelerator of the Complex
- 1st run: **1972**
- Main purpose: to increase the number of protons that PS can accelerate.



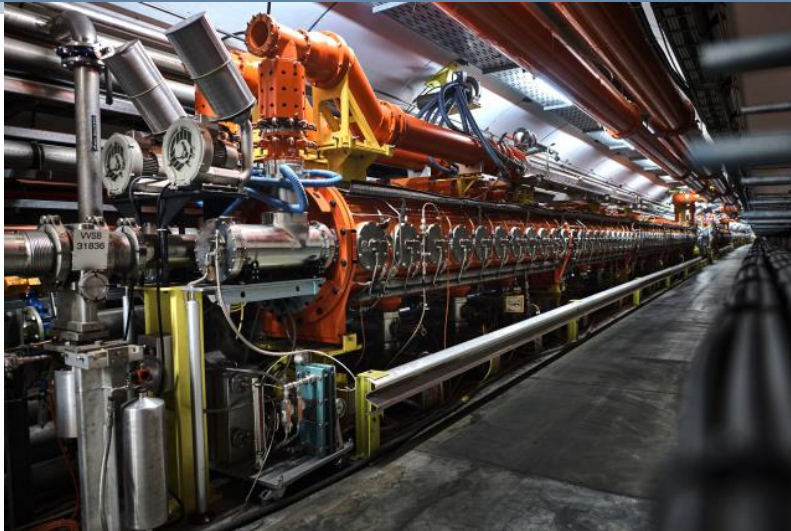
- It comprises 4 superposed rings
→ *Essentially, they are 4 different synchrotrons with common characteristics (magnets, etc.)*

CERN Accelerator Complex

- **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



- **SPS:** Super Proton Synchrotron
 - The 2nd largest 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

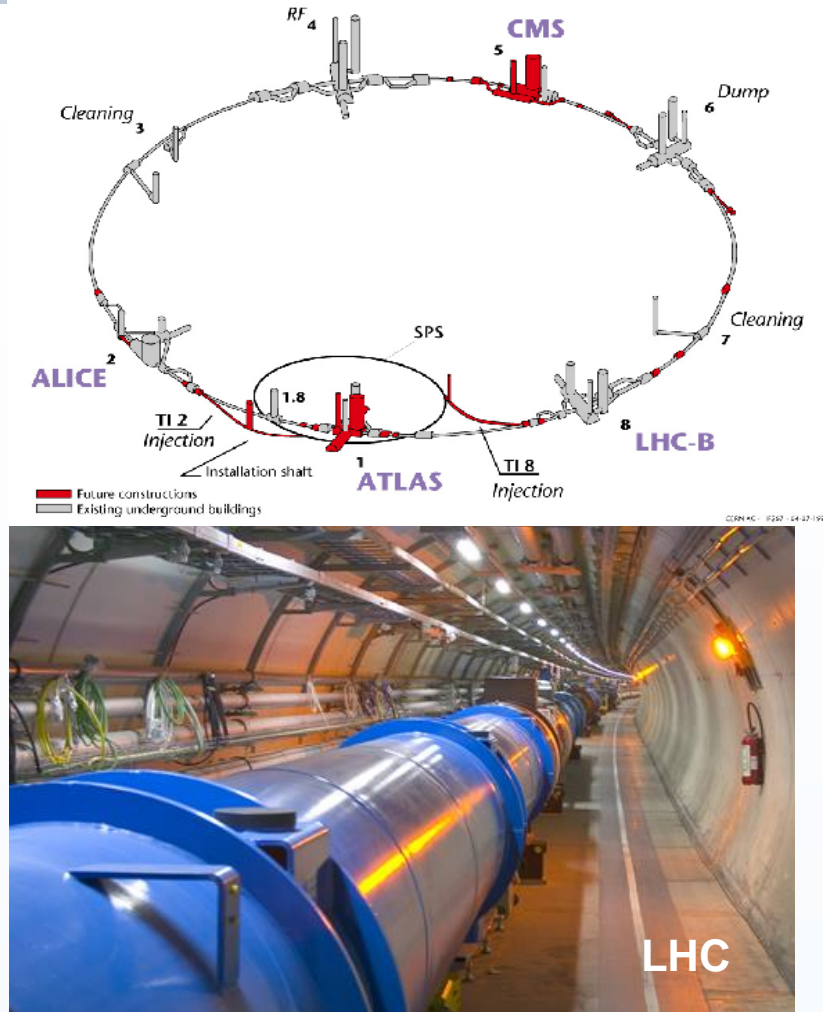
CERN Accelerator Complex

- **LHC**: Large Hadron Collider
- 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°C
- Operates with protons and ions

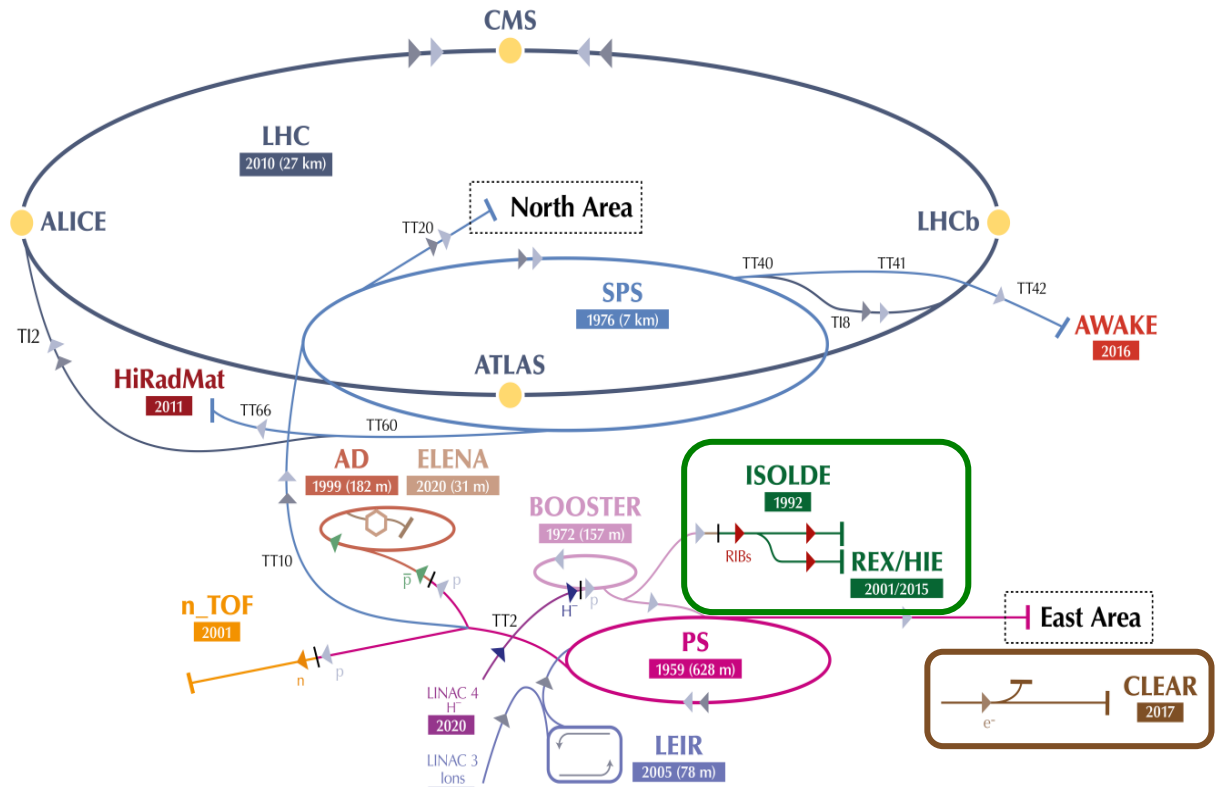


CERN Accelerator Complex

- 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)



CERN Accelerator Complex



Vast majority:
circular machines
→ *synchrotrons*

▶ Heavy Ion Beams
 ▶ n (neutrons)
 ▶ \bar{p} (antiprotons)
 ▶ e^- (electrons)

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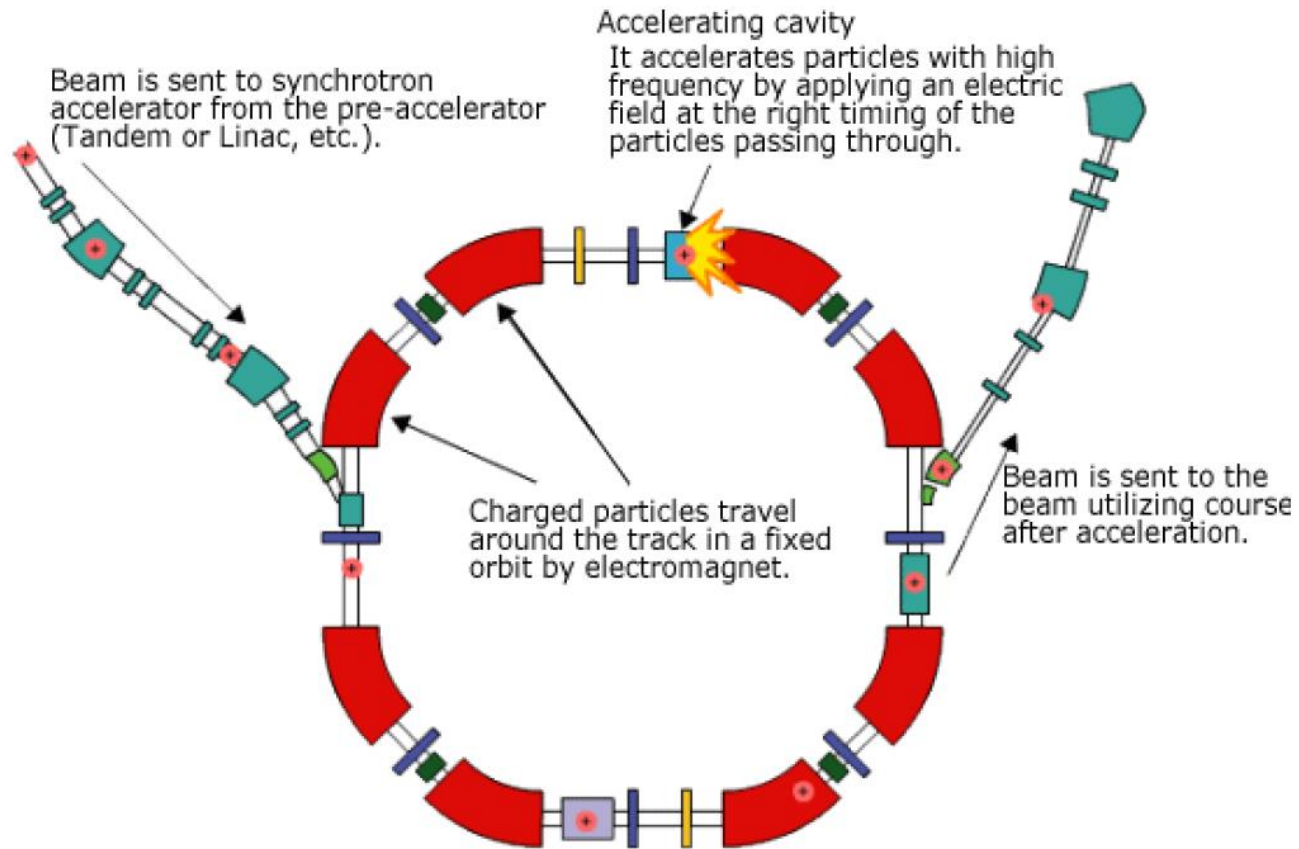
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Main principles of a Synchrotron



The beam needs to be controlled to allow:

- Long storage times
- Preservation of beam quality

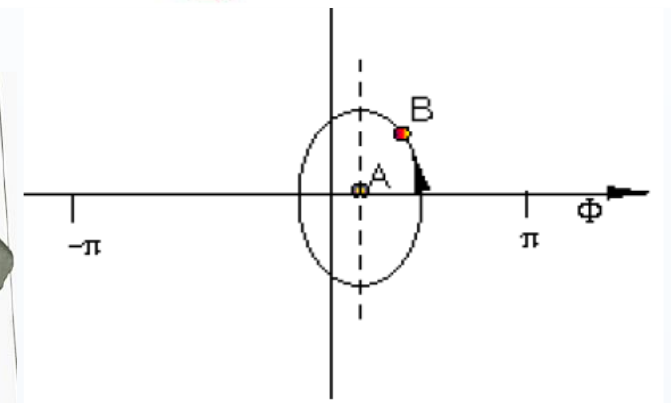
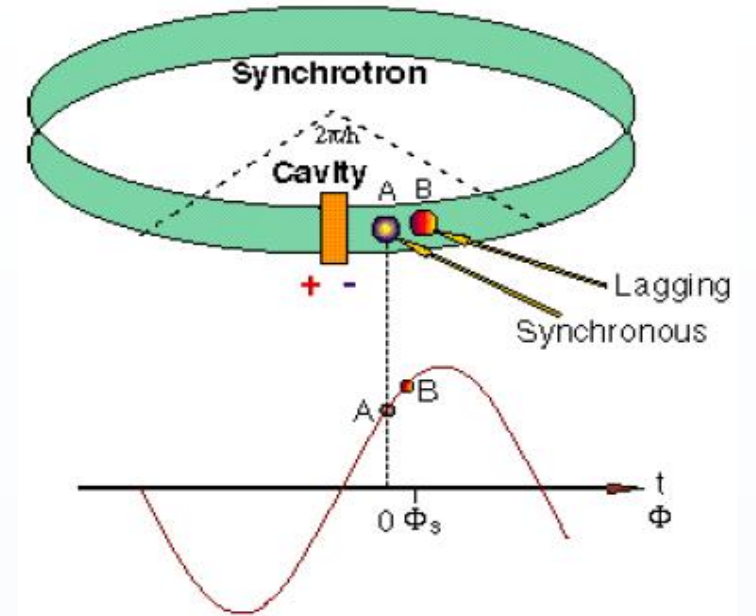
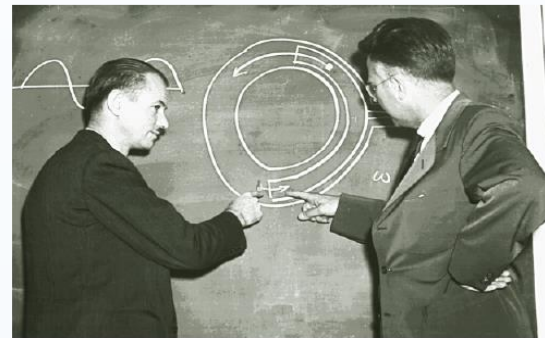
Focusing allows better control:

- **Phase focusing** | RF cavities
- **Weak focusing** | Dipoles
- **Strong focusing** | Quadrupoles

Phase focusing

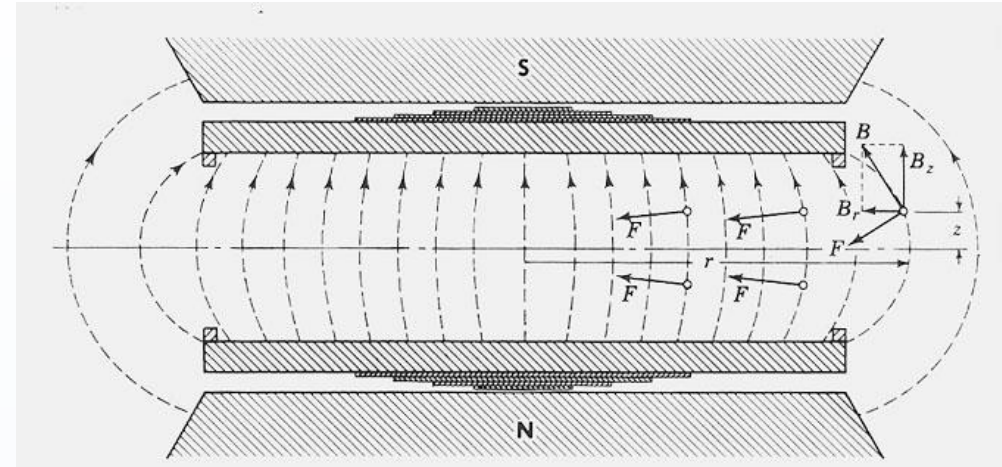
- Developed independently by **McMillan** and **Veksler** (1945)
- The **RF cavity** is set such as the particle at the centre of the **bunch** (**synchronous** particle) receives the needed energy
- Voltage in the cavity: $V = V_0 \sin(2\pi\omega_{RF}t) = V_0 \sin(\varphi(t))$
- For no acceleration,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

\rightarrow 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!

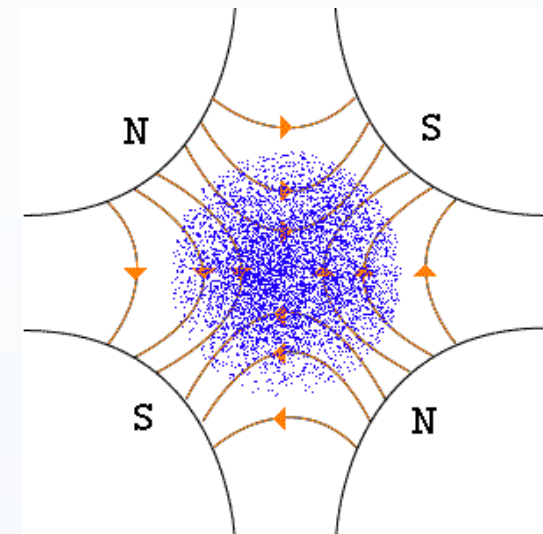
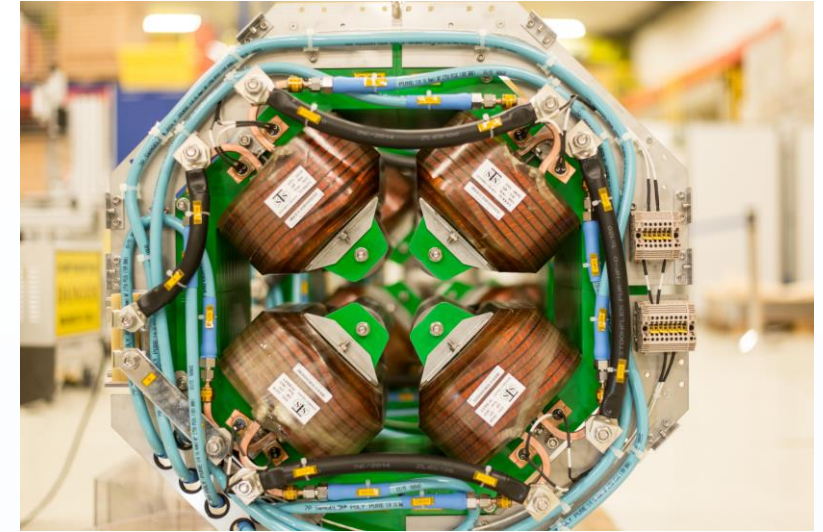
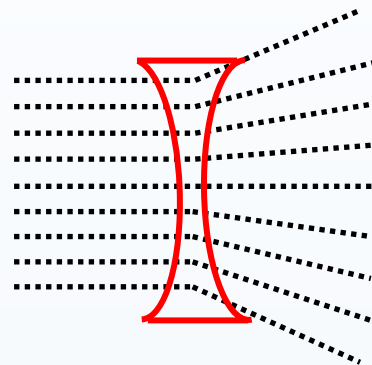
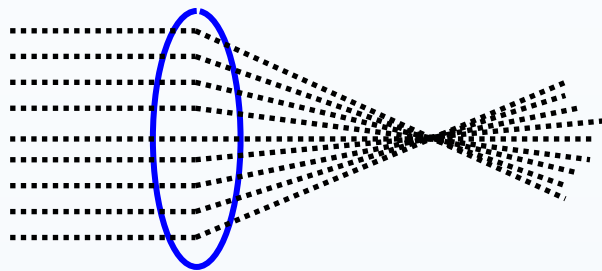


- Such a **focusing** is introduced at the edges of the magnet – due to the disruption of the magnetic field

- The transverse components of the magnetic field: $(B_x + B_y) = B_0 \left(-n \frac{y}{r}, 1 - n \frac{x}{r} \right)$, 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



Building Blocks of a Synchrotron

Main components:

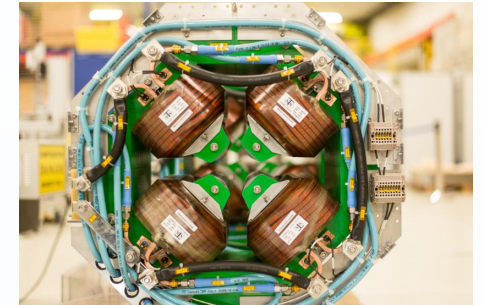
Dipole Magnets:

Bending



Quadrupole Magnets:

(De-)Focusing



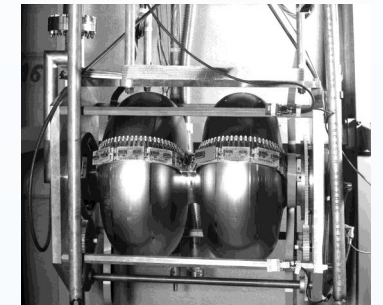
Higher order magnets:

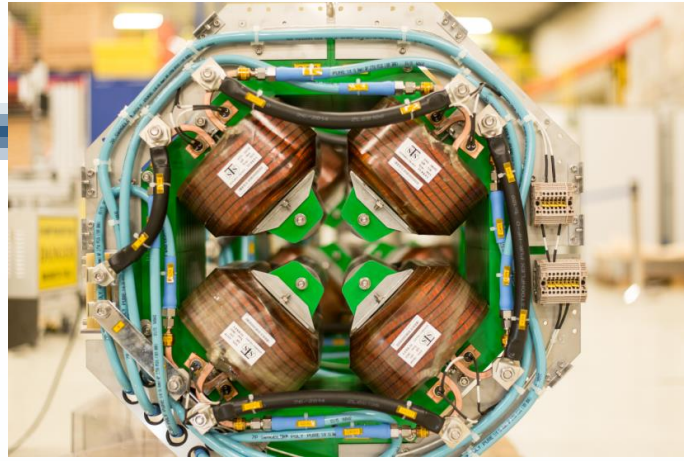
Corrections



RF cavities:

Acceleration





How do particles move under the influence of these elements?

→ Transverse & Longitudinal Beam Dynamics

