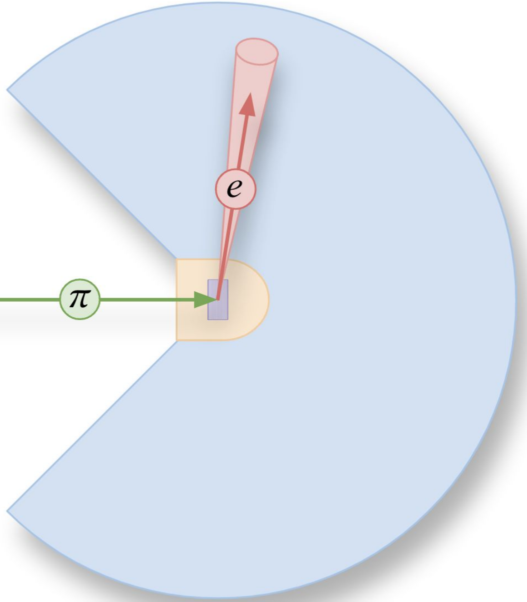
# Particle Beams

## An introduction to accelerator physics and the PSI beamlines




**PIONEER Collaboration meeting**


Stefan Hochrein


Seattle, 19.06.2024

# Why do we need particle accelerators?

## Natural particle sources:

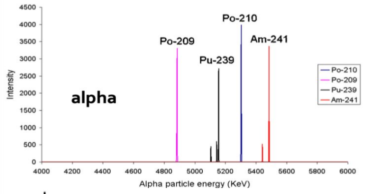
- Cosmic rays
- Natural radiation (alpha/beta/gamma)

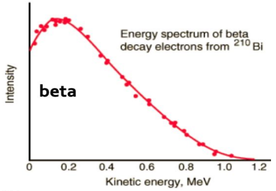
➔ Hard to gain control: e.g. change energy or intensity, select particle species

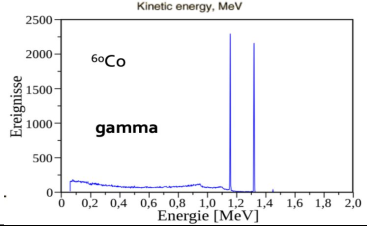
**Accelerators are needed to produce precise initial states with variable energies and high intensities:**

## Radioactive sources:

- Limited energies (up to a few MeV)

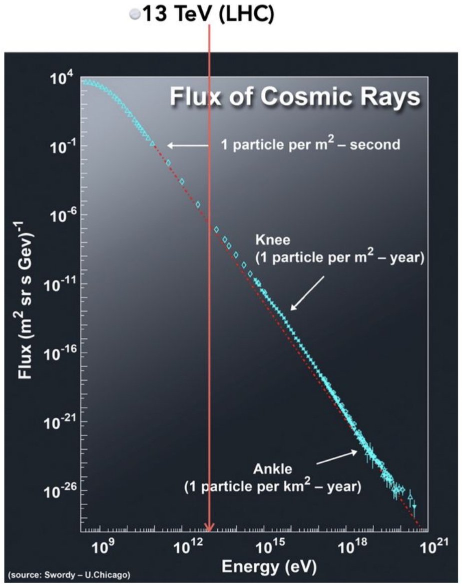



## Cosmic rays:

- Low intensity at high energies

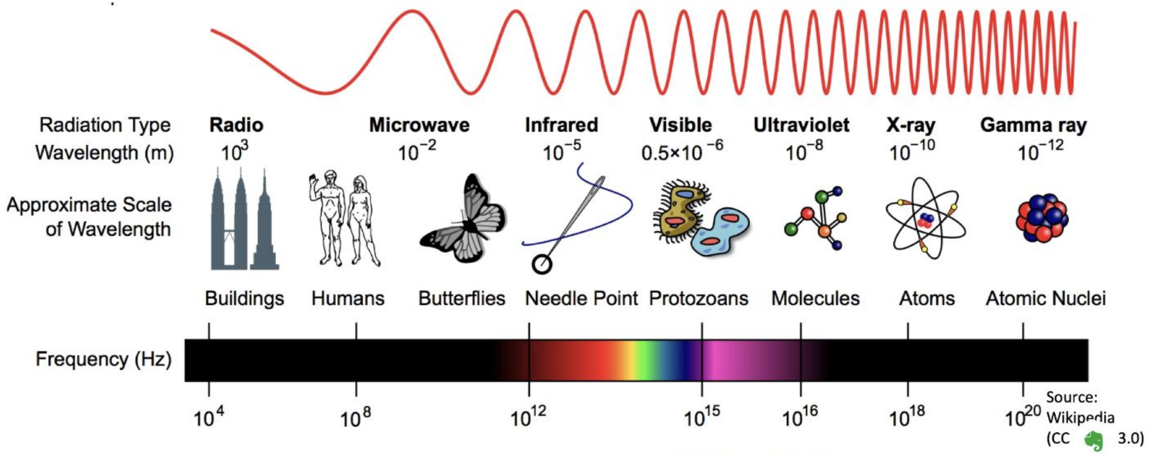


# Why do we need particle accelerators?

**View into smaller dimensions:**

- Energy is directly linked to the size of structures one can resolve

**We need high energies to study small things like elementary particles**




$$\lambda = \frac{hc}{E}$$

Visible
$\lambda$ = 400 ➔ 700 nm

X-ray
$\lambda$ = 0.01 ➔ 10 nm

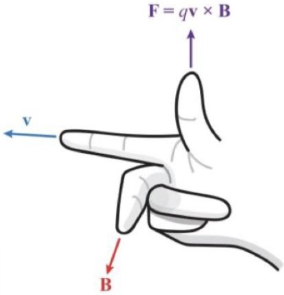
**Particle accelerators**
$\lambda$ < 0.01 nm

# Basics of particle accelerators

### How do we accelerate particles?

- charged particles travelling through an electro-magnetic field feel the Lorentz force

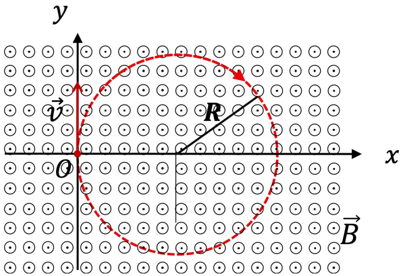
$$\vec{F} = q(\vec{v} \times \vec{B} + \vec{E})$$

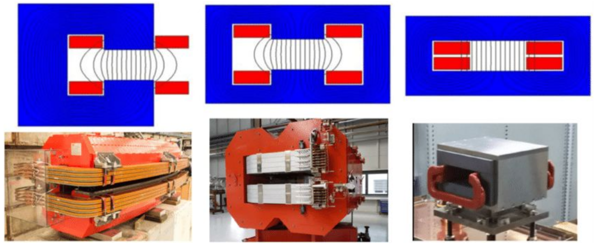



### Magnetic field B:

Force acts perpendicular to path

- Can change direction of path
- Cannot accelerate

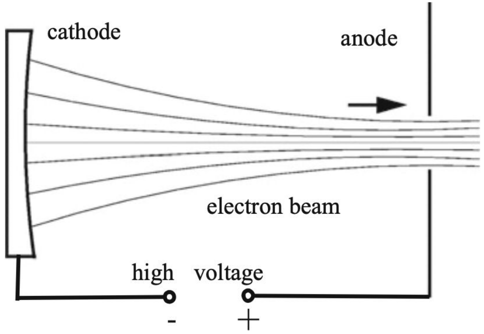


### Electric field E:

Force acts parallel to path

- Can accelerate
- not optimal for deflection

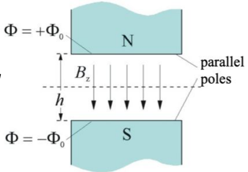



**Numerical example:**
v = c, B = 1T,
E = vB = $3 \times 10^8$ m/sxT = 300 MV/m
**Technical limit: ~ 1 MV/m**

# How to steer and focus a beam

## Dipole magnets:

- Bend the beam in one plane, free drift in the other
- $B(\vec{x}) = B_y$
  $F_L = q \cdot v \cdot B_y$
  $F_Z = \frac{\gamma m v^2}{\rho}$



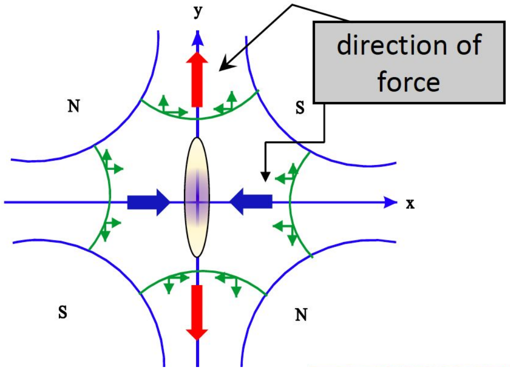

- Beam rigidity:
  $\rightarrow p/q = \rho \cdot B$

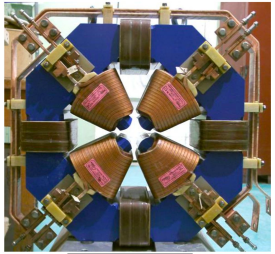
**Iron dominated:**
field determined by geometry of poles
→ 2 flat poles

**Superconducting:**
field determined by geometry of coils
→ $j(\phi) \sim \cos\phi$

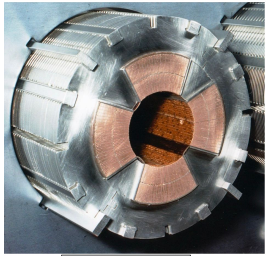
## Quadrupole magnets:

- Focus the beam in one plane but defocus in the other
  - ➔ Usually quadruple doublets or triplets are used
- Sextupole/ octupole magnets are used in precision beamlines
- Field gradient *g*:
  $F(x,y) = q \cdot v \cdot B(x,y)$
  $B_x = g \cdot y$
  $B_y = g \cdot x$
- Quadrupole strength *k*:
  $\ddot{x} + kx = 0$ ← Harmonic oscillator
  $\ddot{y} - ky = 0$



**Iron dominated:**
field determined by geometry of poles
→ 4 hyperbolic poles



**Superconducting:**
field determined by geometry of coils
→ $j(\phi) \sim \cos 2\phi$

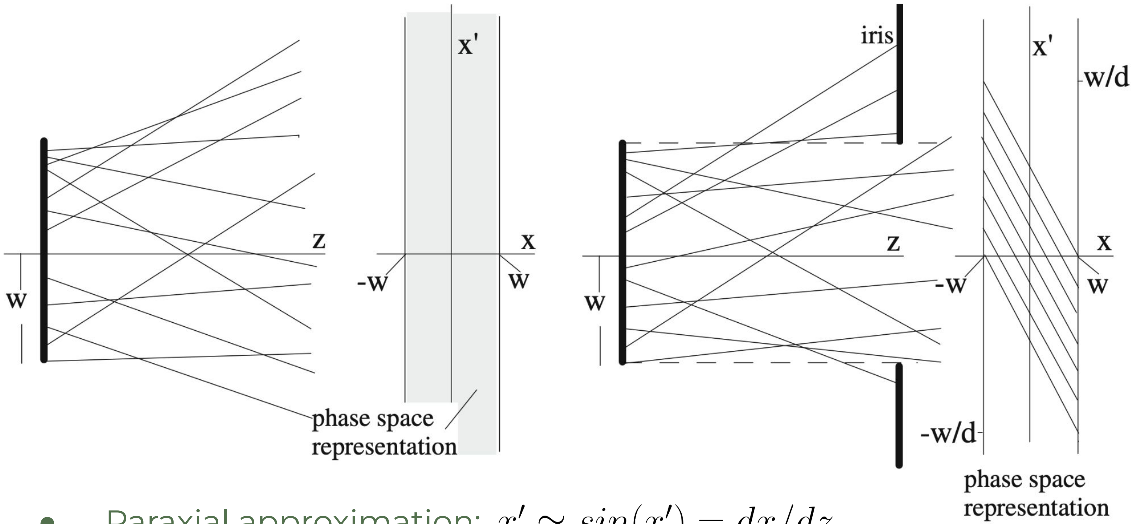
# Basics of particle beams

**What is a beam:**

- Bundle of particles
- Every particle follows its own trajectory described by the equations of motion
- Can be statistically described by position and momentum distribution in 2-d phase space
- Independent description of x, y & z

**Basic beam example:**

- Isotropic disc-source with a collimator




- Paraxial approximation: $x' \simeq sin(x') = dx/dz$

Wiedemann, H. (2019). *Particle accelerator physics*. Springer International Publishing.

# Basics of particle beams

**Gaussian beam** (“ideal”)**:**

- Position and momentum follow Gaussian distribution
- Particle distribution in phase space can be described by an ellipse

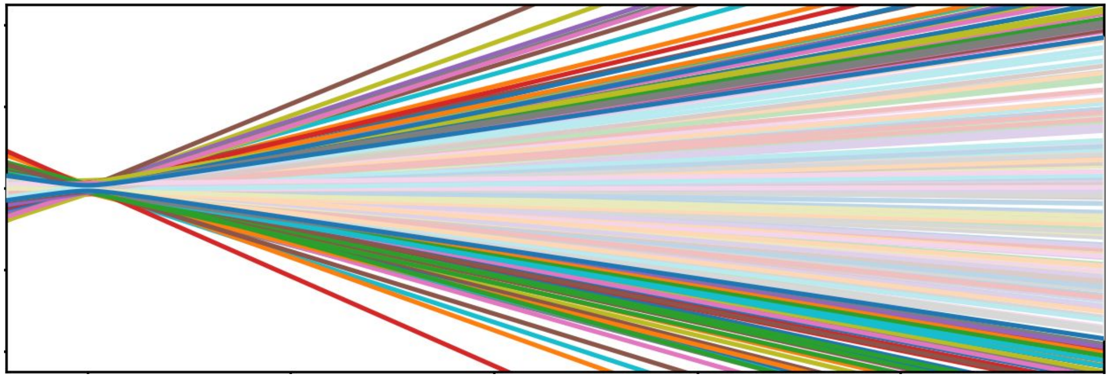
**Liouville’s theorem:**

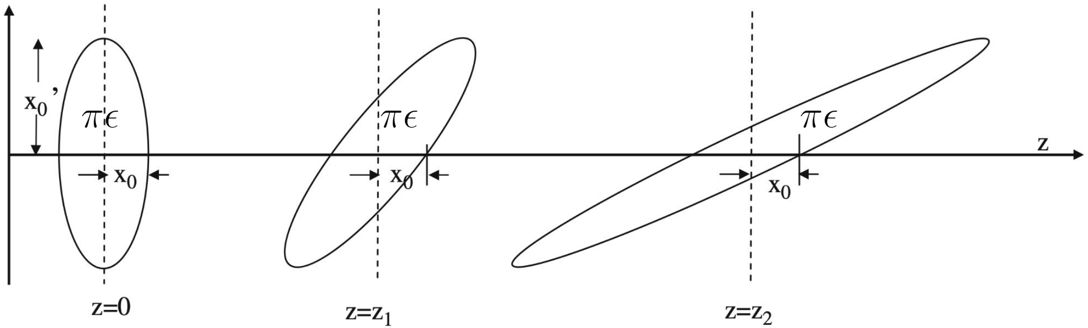
- Particle density in phase space stays constant if only conservative forces act on beam

➔ Area of ellipse stays constant

**Beam emittance:**

$$\epsilon = A/\pi$$



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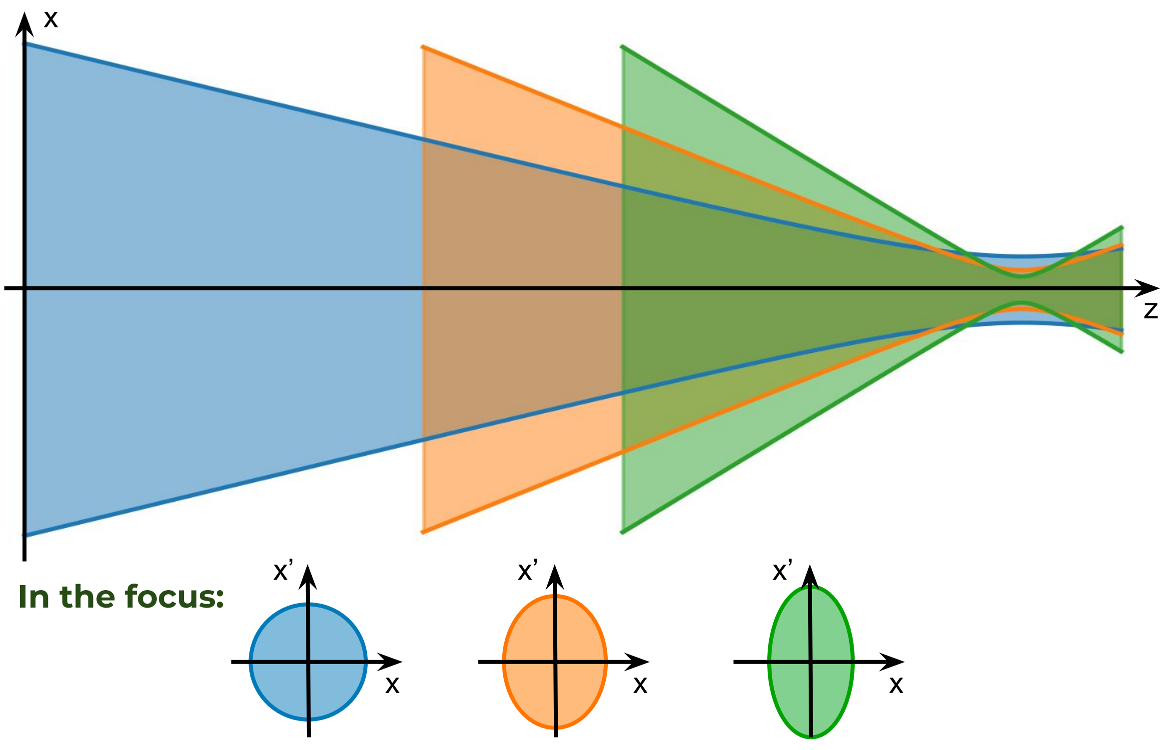
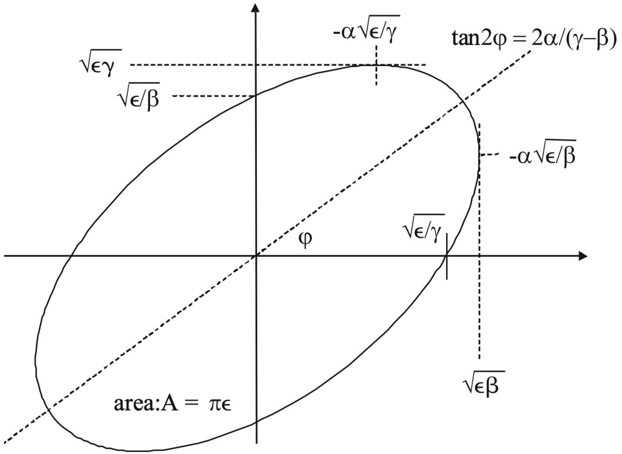
$$A = \pi \epsilon$$



# Beam parameters and matrix formalism

**Have a look at Twiss parameters:**

- Parameters that describe the beam ellipse:
  - $\alpha$: correlation between x & x'
  - $\beta$: beam width in x
  - $\gamma$: beam width in x'




**Beam matrix formalism:**

Beam phase-space, free beam transport and magnets can be described by matrices:

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

- Free beam transport:

$$\mathcal{M}_f = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

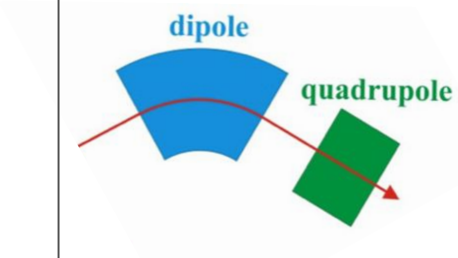
- Dipole magnet:

$$\mathcal{M}_d = \begin{pmatrix} cos(L/\rho) & \rho sin(L/\rho) \\ -1/\rho sin(L/\rho) & cos(L/\rho) \end{pmatrix}$$

- Focusing/ defocusing quadrupole magnet:

$$\mathcal{M}_q = \begin{pmatrix} cos(\sqrt{k}L) & \frac{1}{\sqrt{k}} sin(\sqrt{k}L) \\ -\sqrt{k} sin(\sqrt{k}L) & cos(\sqrt{k}L) \end{pmatrix} \quad \mathcal{M}_q = \begin{pmatrix} cosh(\sqrt{k}L) & \frac{1}{\sqrt{k}} sinh(\sqrt{k}L) \\ \sqrt{k} sinh(\sqrt{k}L) & cosh(\sqrt{k}L) \end{pmatrix}$$

- Then: $\sigma = \mathcal{M}\sigma_0\mathcal{M}^T$




$$\mathcal{M} = \mathcal{M}_f \cdot \mathcal{M}_q \cdot \mathcal{M}_f \cdot \mathcal{M}_d \cdot \mathcal{M}_f$$

$$\sigma_{End} = \mathcal{M}\sigma_{Start}\mathcal{M}^T$$

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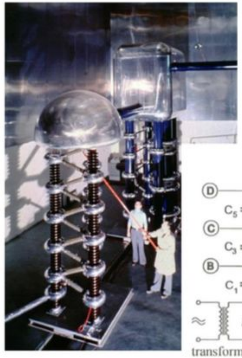
# Electrostatic accelerators

## Cockroft-Walton

1928



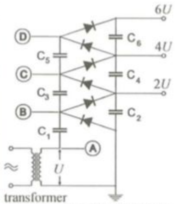



Image Credit: K. Wille

*Concept:*
rectifier circuit, built of capacitors and diodes
(Greinacker circuit)

*Limitation:*
Electrical discharge in air
(Paschen Law)

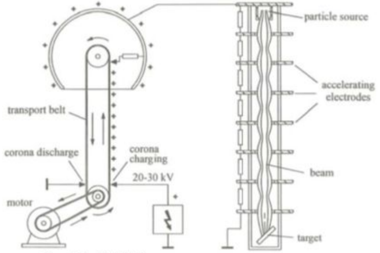
Max. Voltage ~ 1 MV

## 1930 Van de Graaff accelerator

*Concept:*
mechanical transport of charges via rotating belt

Electrode in high pressure gas to suppress discharge ($SF_6$)

Max. Voltage ~ 1- 10 MV




## 1936 Tandem Van de Graaff

at MPI Heidelberg

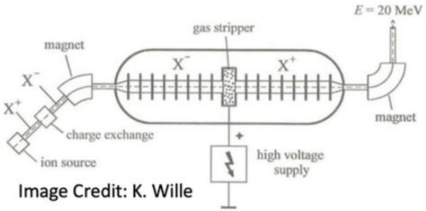


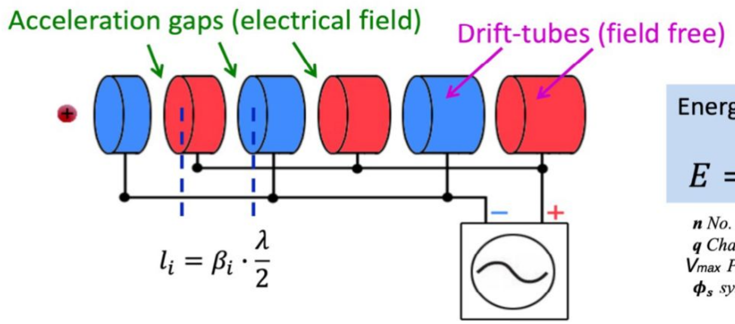

Image Credit: K. Wille

*Concept:*
Generate negative ions, strip off electrons in the center, use voltage a 2nd time with now positive ions

# Linear accelerators

**Working principle:**

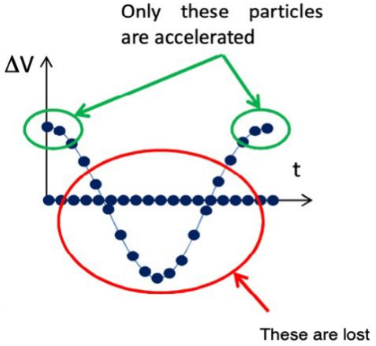
- High-frequency (RF) field
- Particle should only feel the field when the field direction is synchronized
  - ➔ Drift-tubes screen the field while the field has the reversed polarity
- The more energy the particle gains, the faster it becomes
  - ➔ Drifts tubes have to increase in length
- Only particles in phase with the RF are accelerated
  - ➔ Particles will be clustered in packages (bunches)




Energy gain after *n* gaps:

$$E = n\, q\, V_{max} \sin \phi_s$$

*n* No. of acceleration gaps
*q* Charge of the particle
$V_{max}$ Peak voltage of RF System
$\phi_s$ synchronous phase w.r.t. RF field




**Linear accelerators:**

- Still widely used for medium energy experiments or as injectors

**But:**
Particles pass accelerator only once

# Circular orbit: Cyclotrons

## Classical Cyclotron:

- Classical (non-relativistic) connection between velocity, field strength and radius:

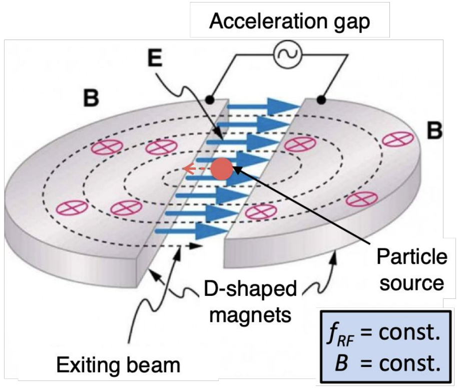
$$m\frac{v^2}{r} = qvB$$

- Revolution period does not depend on the velocity (isochronous)

$$\omega = \frac{v}{r} = \frac{qB}{m}$$

- Output particle energy classically limited by the magnetic field strength and radius:

$$E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$




**Limitation:**
Dephasing via relativistic effects! Classical cyclotron only works for particles up to few % of speed of light. Not very useful for electrons (already relativistic at ~500 keV)

## Modified cyclotrons:

Compensate for relativistic effects!

### Synchro-cyclotron:

- With acceleration, RF field frequency (sometimes also B-field) are increased
  - ➔ run in pulsed mode

| Synchro-cyclotron | Isochronous cyclotron |
| --- | --- |
| $f_{RF}(E)$<br>$B(E)$ or $B$ = const. | $f_{RF}$ = const.<br>$B(r)$ |

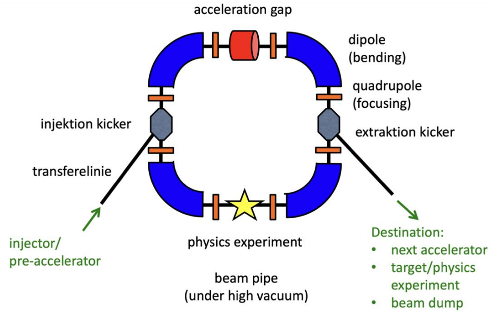
### Isochronous cyclotron:

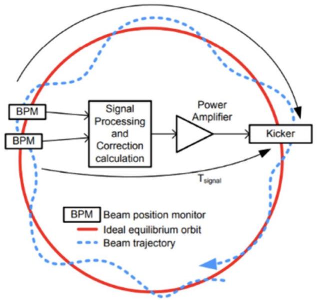
- B-field increases with radius
  - ➔ Orbits are more complicated but can produce a continuous beam

# Synchrotrons

## Working principle:

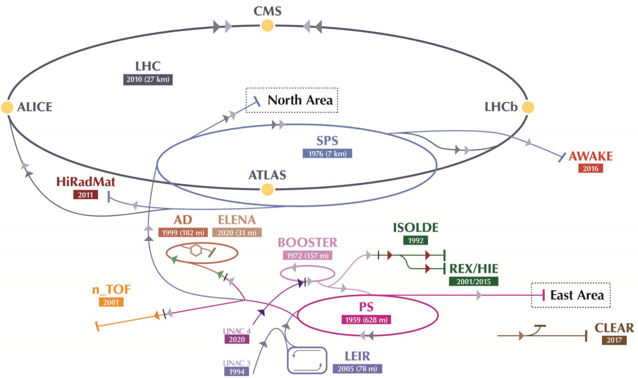
- Place dipole bending magnets between elements of a short linac to make it a "circle"
- Actively synchronize accelerator parameters (magnetic fields, RF) continuously to keep accelerating particles in phase
  - ➔ Allows multiple turns in the same device for a limited amount of bunches
  - ➔ Challenging control: correction signals have to travel faster than the particles!




## Most famous synchrotron: LHC

- 27 km circumference, 100km underground
- Accelerates protons and heavy-ions to E = 6.5 Z TeV (2018), 13 TeV center of mass
- Collides 2 counter-rotating beams in 4 physics experiments



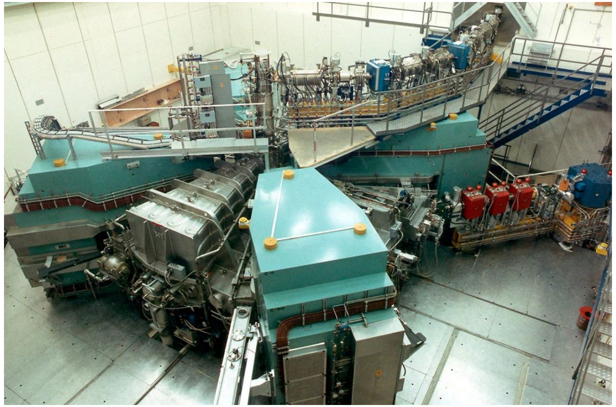
# The High Intensity Proton Accelerator at PSI

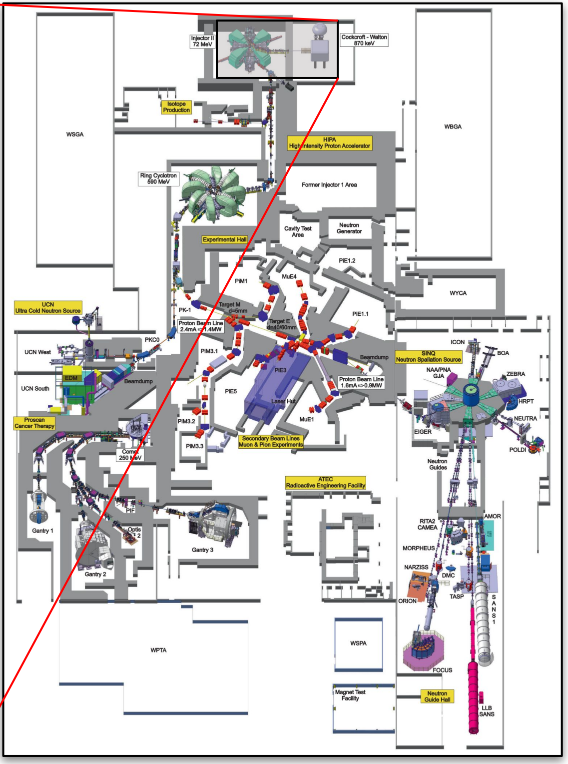
**Cockroft-Walton:**

- Accelerates protons from a hydrogen source to 870 keV

**Injector II:**

- Isochronous cyclotron
- Accelerates protons to 72 MeV





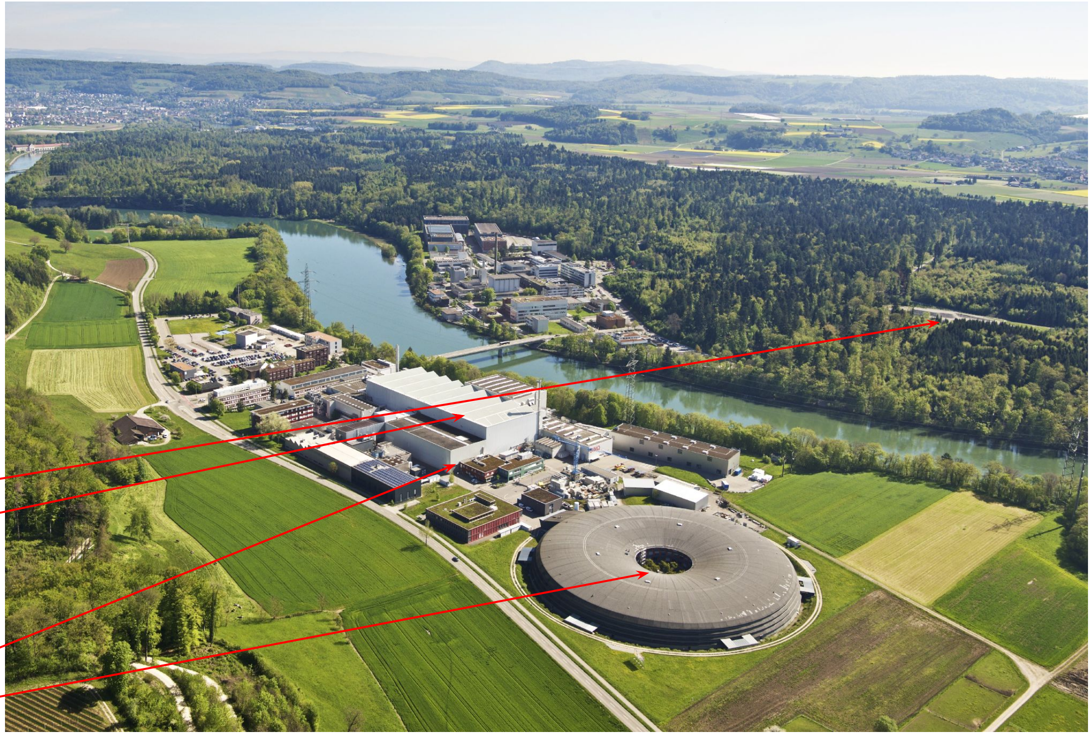
# Paul Scherrer Institute (PSI)

**PSI facility:**

- Located in Villigen, Switzerland
- Large scale research facility
    - 35 % material science
    - 25 % life sciences
    - 19 % general energy
    - 13 % nuclear energy
    - 8 % particle physics

**PSI:**

- Free electron laser SwissFEL
- **Proton accelerator HIPA**
    - Secondary Beamlines
    - Muon source S$\mu$S
    - Neutron source SINQ
- Proton Therapy (COMET)
- Swiss light source SLS

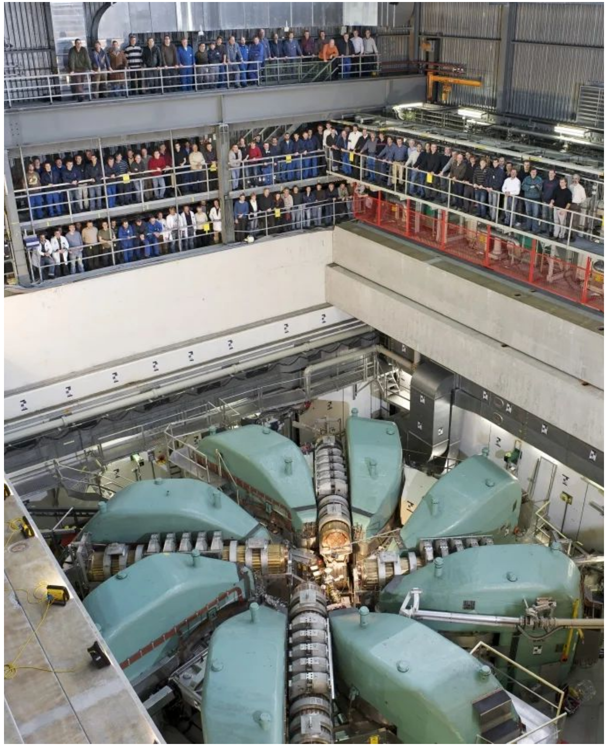


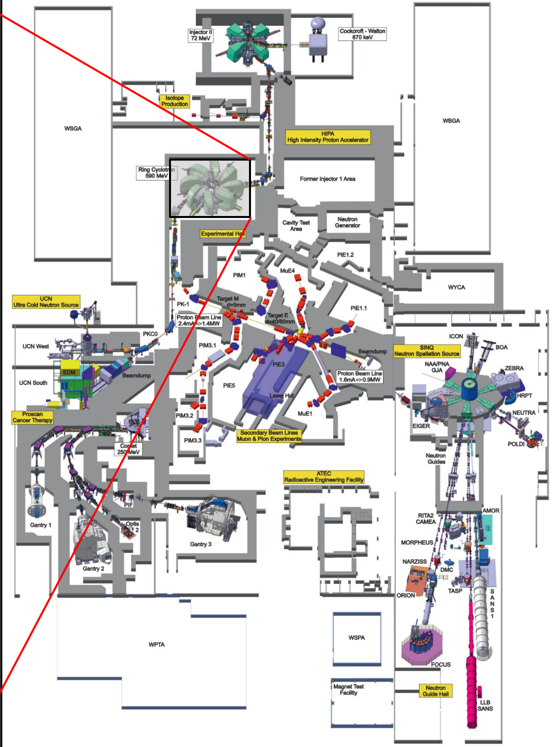
Pictures: https://www.psi.ch/

# The High Intensity Proton Accelerator at PSI

## Ring Cyclotron:

- Started operating 1974
- Isochronous cyclotron
- 8 magnets
- 4 cavities at 850 kV with RF 50.6 MHz
- Produces 590 MeV proton beam, 1.3 MW




Pictures: https://www.psi.ch/

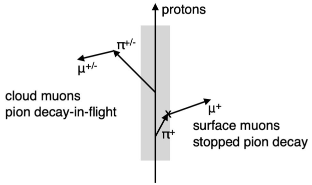
# The High Intensity Proton Accelerator at PSI

## Carbon targets M and E:

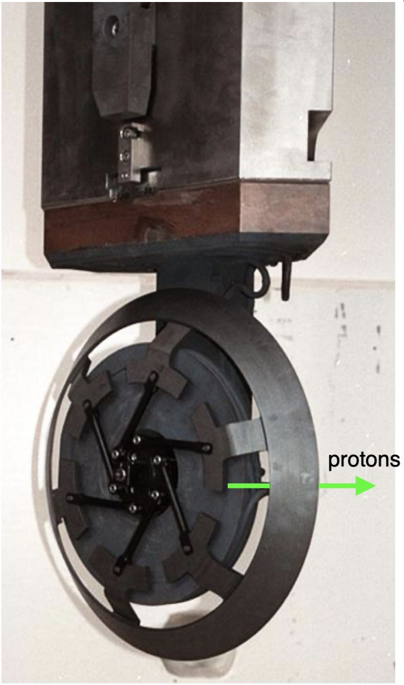
- **Target M** (mince): 5 mm
- **Target E** (epaisse): 40/ 60 mm
- Rotating carbon disk for heat dissipation
- Pions are produced via interaction of protons with target ($\Delta$-resonance)

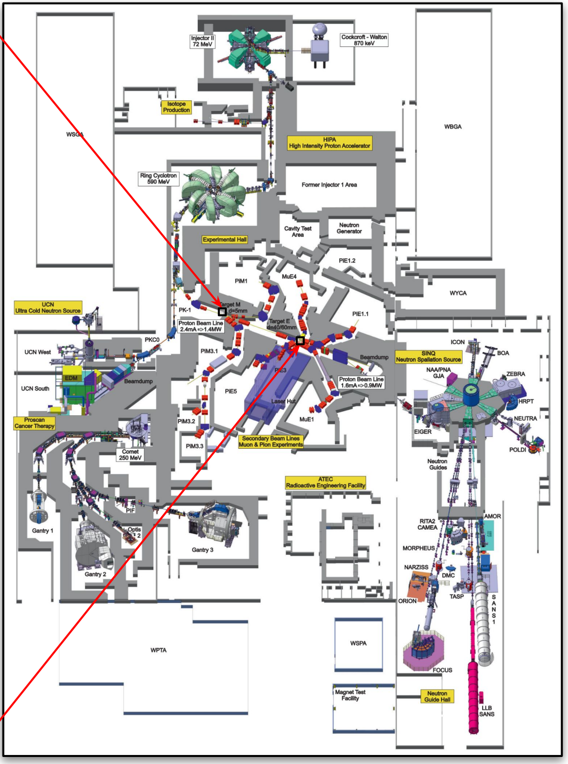
$$p + p \rightarrow p + n + \pi^+ \qquad p + n \rightarrow p + n + \pi^0$$
$$p + p \rightarrow p + p + \pi^0 \qquad p + n \rightarrow p + p + \pi^-$$
$$p + p \rightarrow d + \pi^+ \qquad p + n \rightarrow n + n + \pi^+$$
$$p + n \rightarrow d + \pi^0.$$

- Muons (and positrons) are produced from pion decay
- Surface muons: 28 MeV/c muons from pion decays near target surface




Carbon target E



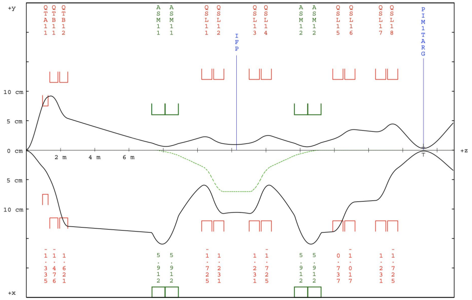



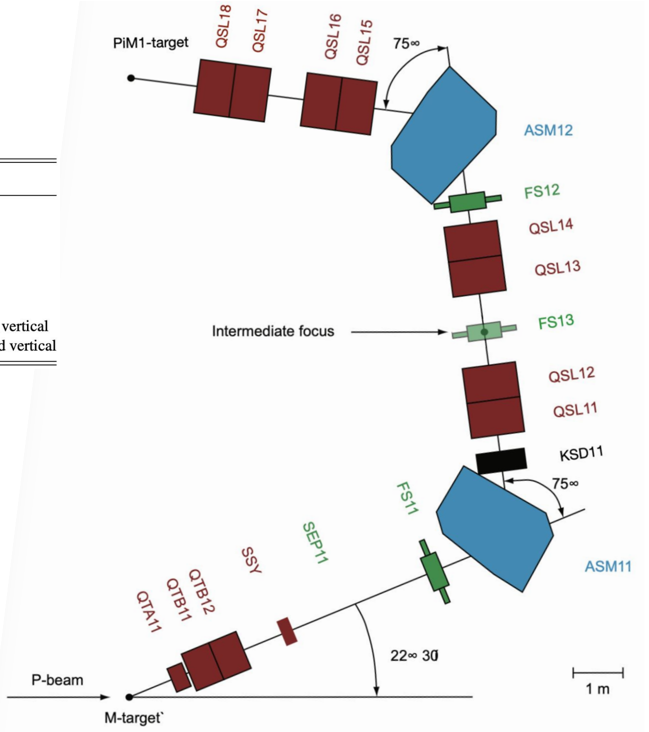
# The High Intensity Proton Accelerator at PSI

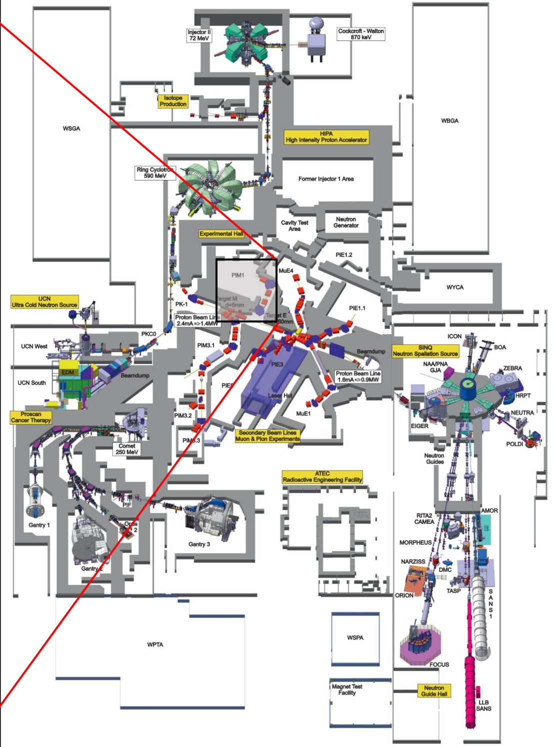
## PiM1 beamline:

- Optimized for a narrow momentum bite

| Property | Value |
|---|---|
| Total path length | 23.12 m |
| Momentum range | 100 – 500 MeV/$c$ |
| Solid angle | 6 msr |
| Momentum acceptance (FWHM) | ±1.5% |
| Momentum resolution | 0.1% |
| Dispersion at the IFP | 7 cm/% |
| Spot size on target (FWHM) | 15 mm horizontal by 10 mm vertical |
| Angular divergence on target (FWHM) | 35 mrad horizontal by 75 mrad vertical |



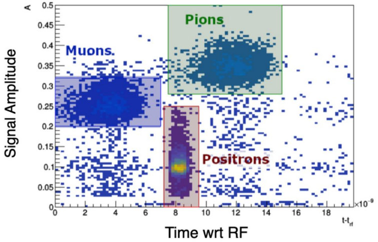



# The High Intensity Proton Accelerator at PSI

**PiE5 beamline:**

- Optimized for high pion (and muon) rates




**Key parameters (measured 2022):**

- Pion rate @65 MeV: $R_{\pi}$ = 633 kHz (~300 kHz in target area)
- Momentum bite $\Delta p/p < 2\%$
- Particle contamination 32% muons, 25% positrons
- Spot size in beam focus $\sigma_x = 23$ mm, $\sigma_y = 10$ mm
- Beam emittance $\varepsilon_{x/y} = 617/232$ mm mrad