# Introduction to Beam Transfer

- Types of accelerators
- Example uses of accelerators
- Transverse phase space
  - Poincare maps, phase space representation
  - Recall of accelerator lattices, Twiss parameters
- Beam ‘manipulations’ in normalised phase space
- The beam transfer process
  - Key generic requirements and performance indicators
- Conclusion

# TYPES OF ACCELERATORS

# A word about units used…

Energy: in units of eV (electron-Volts):

corresponds to the energy gained by charge of a single electron moved across a potential difference of one volt.

1 eV = 1.602176565(35) × $10^{-19}$ × 1 J

This comes from electrostatic particle accelerators.

Unit of mass m: we use

➔ Unit of mass is $eV/c^2$

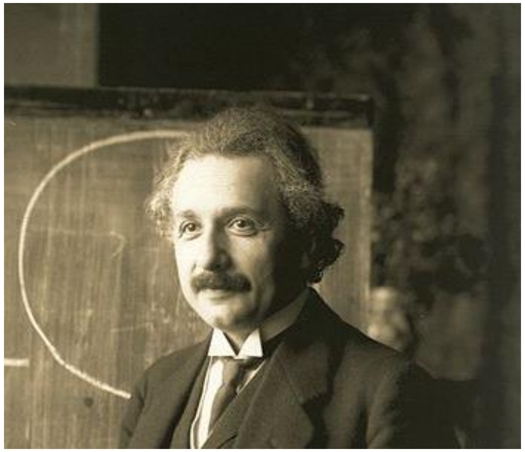
$$E = mc^2$$

Unit of momentum p:

with

➔ Unit of momentum is eV/c

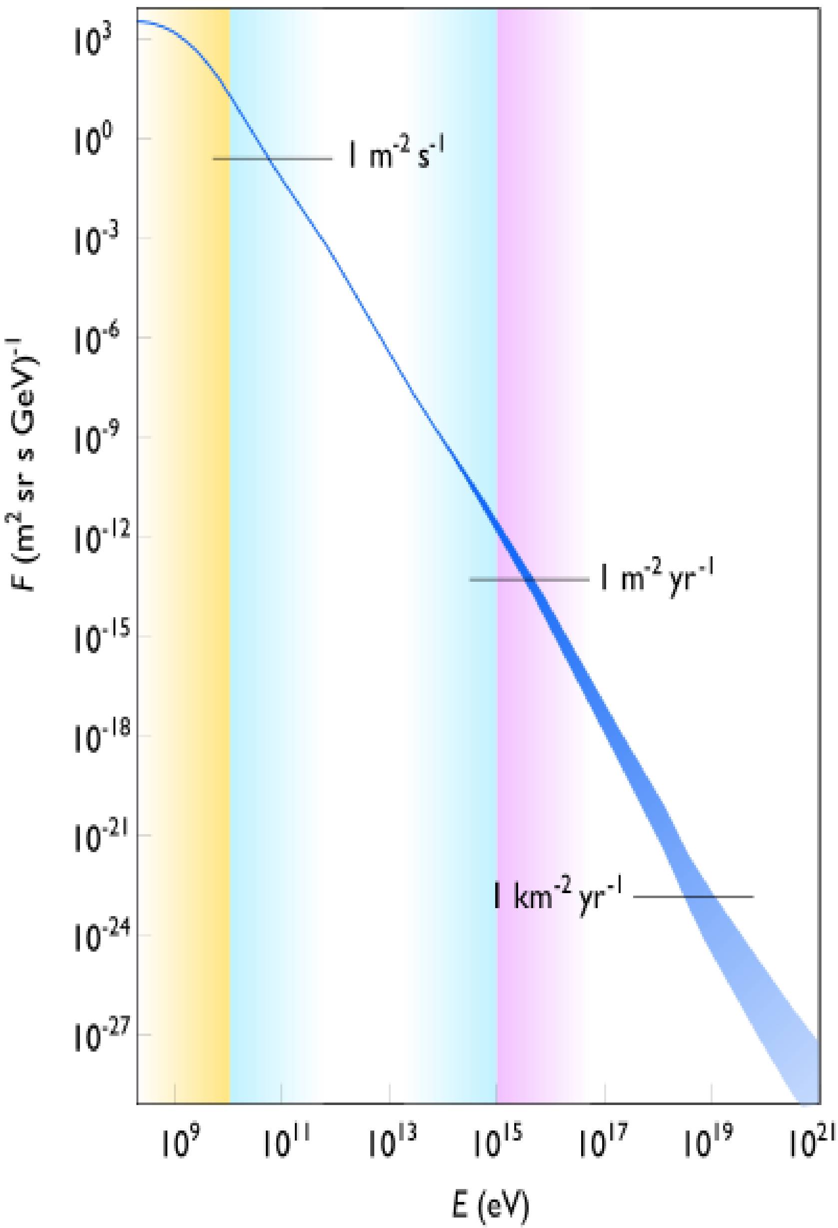
$$E^2 = (mc^2)^2 + p^2c^2$$



# Natural Accelerators exist…

- Radioactive Accelerators
  - Rutherford experiment 1911
  - Used $\alpha$ particles tunneling through the Coulomb barrier of Ra and Th to investigate the inner structure of atoms
  - Existence of positively charged nucleus, d ~ $10^{-13}$ m
  - $\alpha$ particle kinetic energy ~ 6 MeV

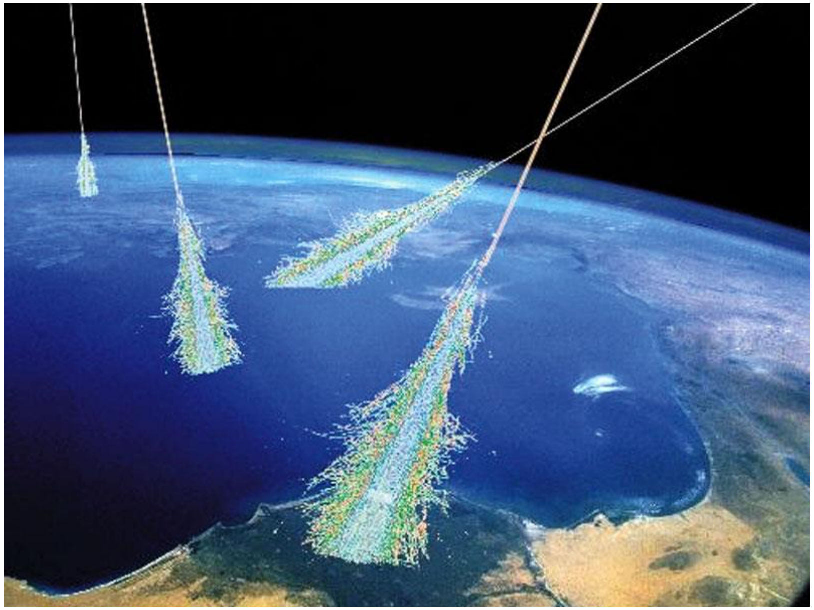
- Cosmic rays
  - Energies up to 3 x $10^{20}$ eV for heavy elements have been measured. ~ 40 x $10^{6}$ times what the LHC can do.
  - "Ultra high energy" cosmic rays are rare…



# Why build accelerators then….?

"Our" accelerators have advantages:

- High (and monochromatic) energies are possible
- High fluxes of a given particle species are possible
- Beam delivery can be controlled to a specific location with specific beam properties



# Recall: accelerating and deflecting

The Lorentz force is the force experienced by a charged particle moving in an applied electric field E and magnetic field B:

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

For particle direction $\vec{\boldsymbol{v}}$ parallel to $\overrightarrow{\boldsymbol{dr}}$ the change in energy $\Delta E$ is

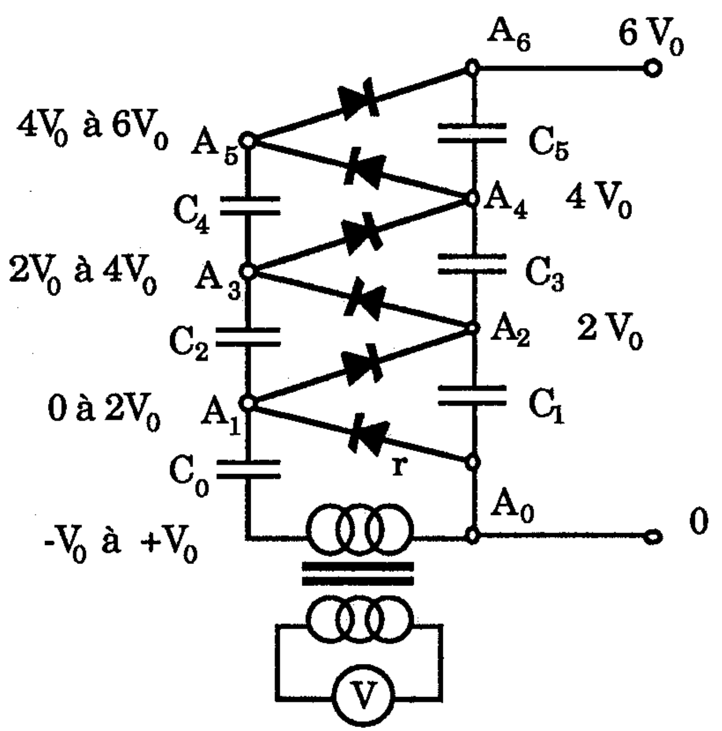
$$\Delta E = \int_{\overrightarrow{r_2}}^{\overrightarrow{r_1}} \vec{\boldsymbol{F}}\, \overrightarrow{\boldsymbol{dr}} = \int_{\overrightarrow{r_2}}^{\overrightarrow{r_1}} q\left(\vec{\boldsymbol{E}} + \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}\right)\overrightarrow{\boldsymbol{dr}} = q \int_{\overrightarrow{r_2}}^{\overrightarrow{r_1}} \vec{\boldsymbol{E}}\, \overrightarrow{\boldsymbol{dr}} = qU$$

Important consequences (in general, and for beam transfer):

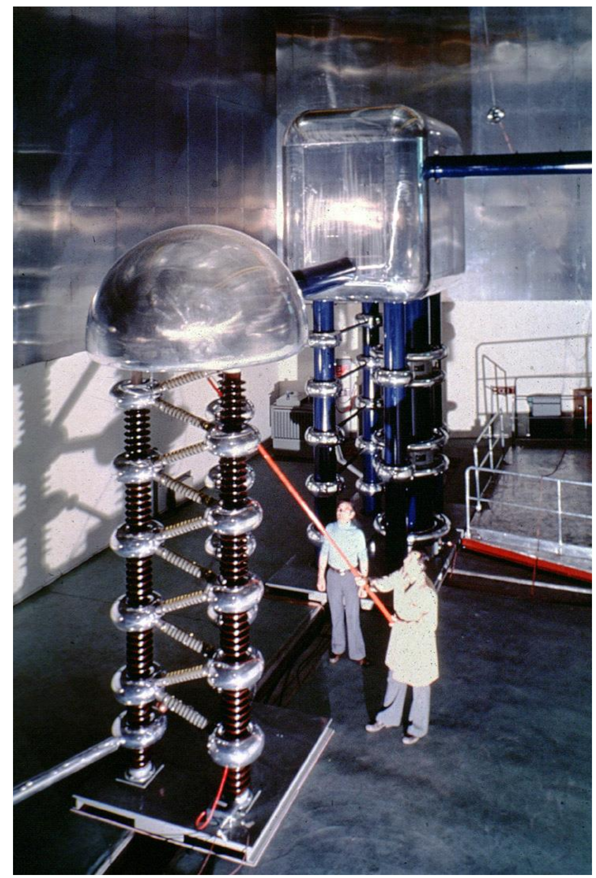
1. Magnetic field does not change Energry: so we need a need (longitudinal) electric field for acceleration.
2. Force (deflection) exerted by a magnetic field is always at right angles to field direction and particle velocity vector
3. For a relativistic particle $|\vec{\boldsymbol{v}}| \approx c$, so a 1 T magnetic field is 30 times more effective in deflecting than a 10’000,000 V/m electric field

# Electrostatic Accelerators – 1930s

- Cockcroft-Walton electrostatic accelerator
  - High voltage source by using high voltage rectifier units
  - High voltage limited due to sparking in air. Limit ~1 MV

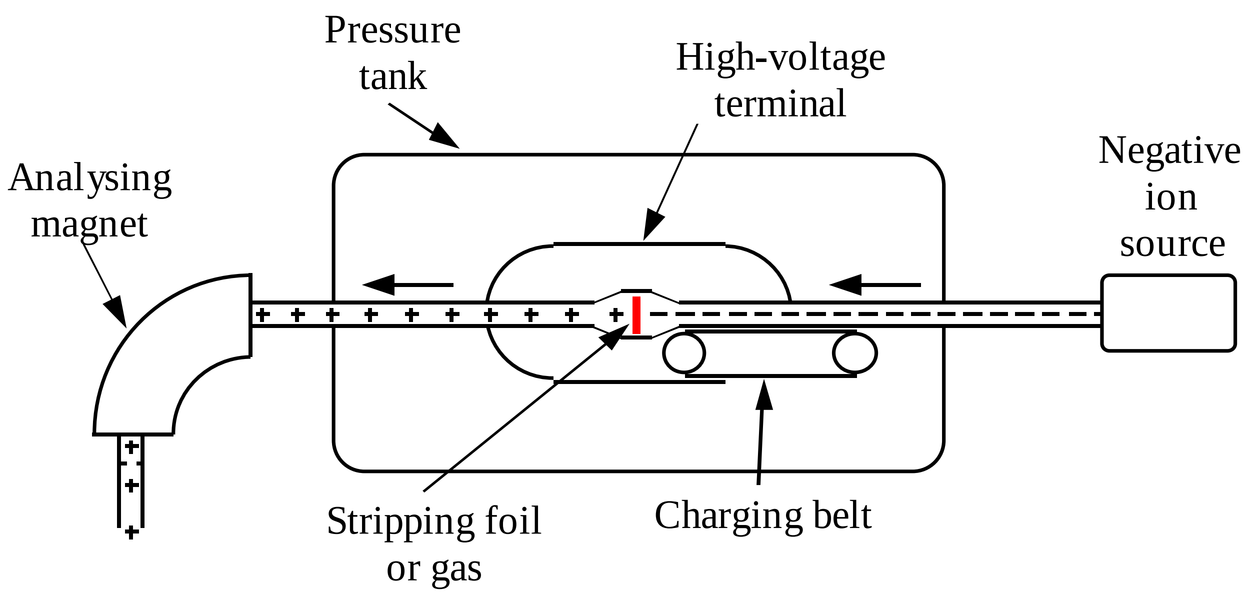



CERN used until 1993 as ion-source: 750 kV



# Tandem Van de Graaf Generator

- …use the accelerating voltage twice

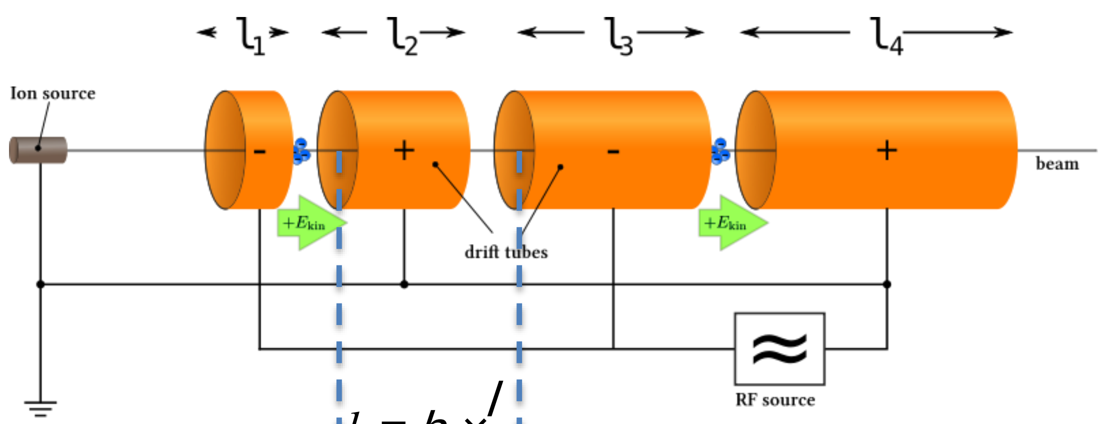



- Up to 25 MV
- Advantages of Van de Graaf:
  - Great variety of ion beams
  - Very good energy precision, small energy spread
- Applications in nuclear physics, accelerator mass spectroscopy,…

# RF Acceleration – the Revolution

Electrostatic accelerator limitation: maximum voltage before sparking for acceleration over single gap

- ➔ pass through acceleration gap of same voltage many times (Ising)
- 1928 Wideroe: first working RF accelerator




$$l_i = b_i \times \frac{l}{2}$$

Energy gain per gap:

$E = q$ **$V_{RF}$**$\sin(\phi_s)$

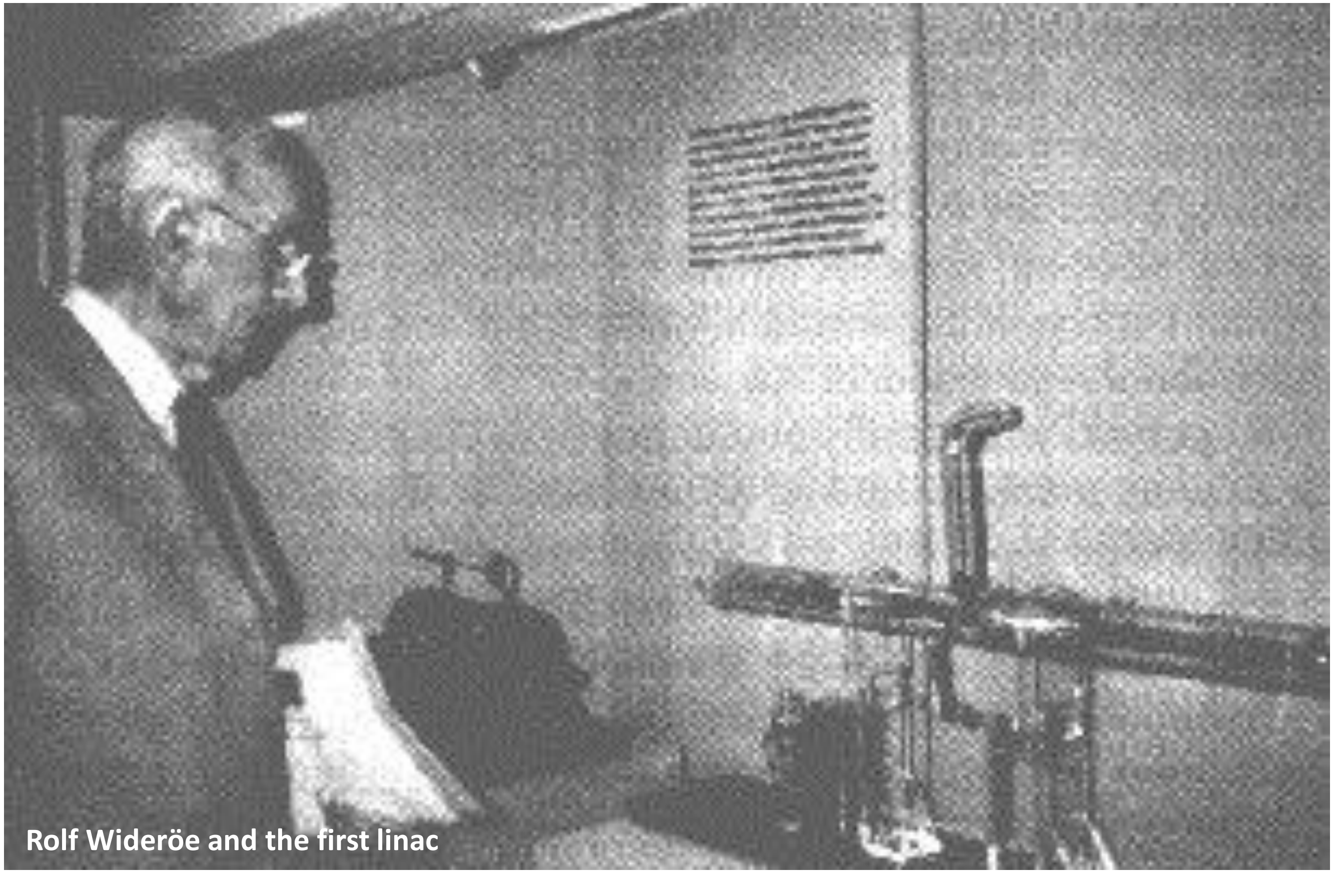
$\Phi$s...phase wrt to RF field

- Particle synchronous with field. In shielding tube when field has opposite sign. Voltage across each cell the same.

- Remark: tubes have to become longer and longer, as particles become faster and faster
- or higher frequency $\lambda = c/f_{RF}$
- But radiation power loss: $P = \omega_{RF} C V_{RF}^2$, C gap capacitance

# First Linear accelerator

- Rolf Wideröe 1927
- 50 keV, 60 cm long



Rolf Wideröe and the first linac

# Circular Accelerators

- Linear accelerators can in principle accelerate to arbitrarily high energies.
- ….but become longer and longer

- ➔ Particles on circular paths to pass accelerating gap over and over again

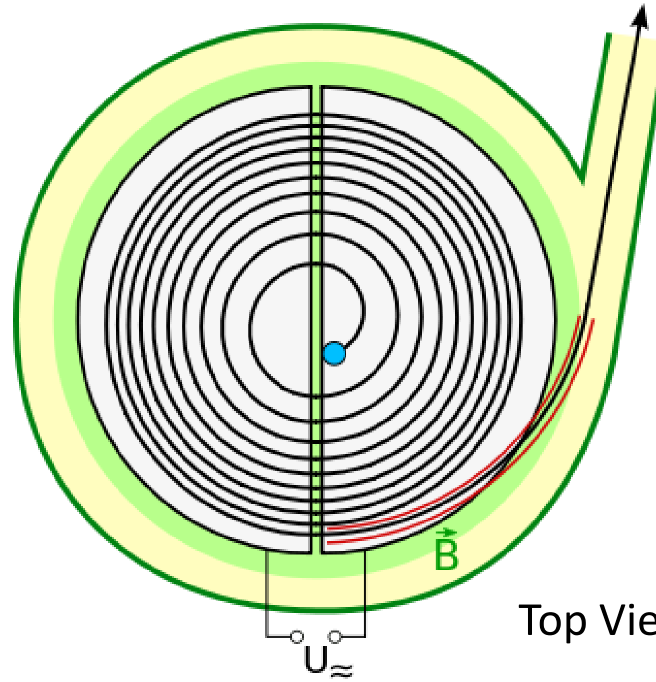
- ➔ Cyclotron proposed by E.O. Lawrence in 1929 and built by Livingston in 1931.

# Cyclotron

Particle Source in the middle

Between the two "Dees" acceleration gap connected to RF source. $\omega_{RF} = \omega_{cyclotron}$

Vertical magnetic field to guide the particles in the horizontal plane. The radius of particle trajectory becomes larger and larger with larger energy




Top View

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \longrightarrow F_L = q\, v\, B \longrightarrow$$ Vertical B No E

$$F_c = m\frac{v^2}{r} \longrightarrow$$ centrifugal force

$$F_L = F_c \longrightarrow \omega = \frac{v}{r} = \frac{qB}{m} \longrightarrow$$ revolution period

# First circular accelerator

- Ernest Lawrence 1931
- 80 keV, 4” diameter
  (10 cm for non-British)

Ernest Lawrence and the first cyclotron

# Cyclotron Limitation

- Cyclotron frequency is constant for constant mass
- But for a relativistic particles mass is not constant

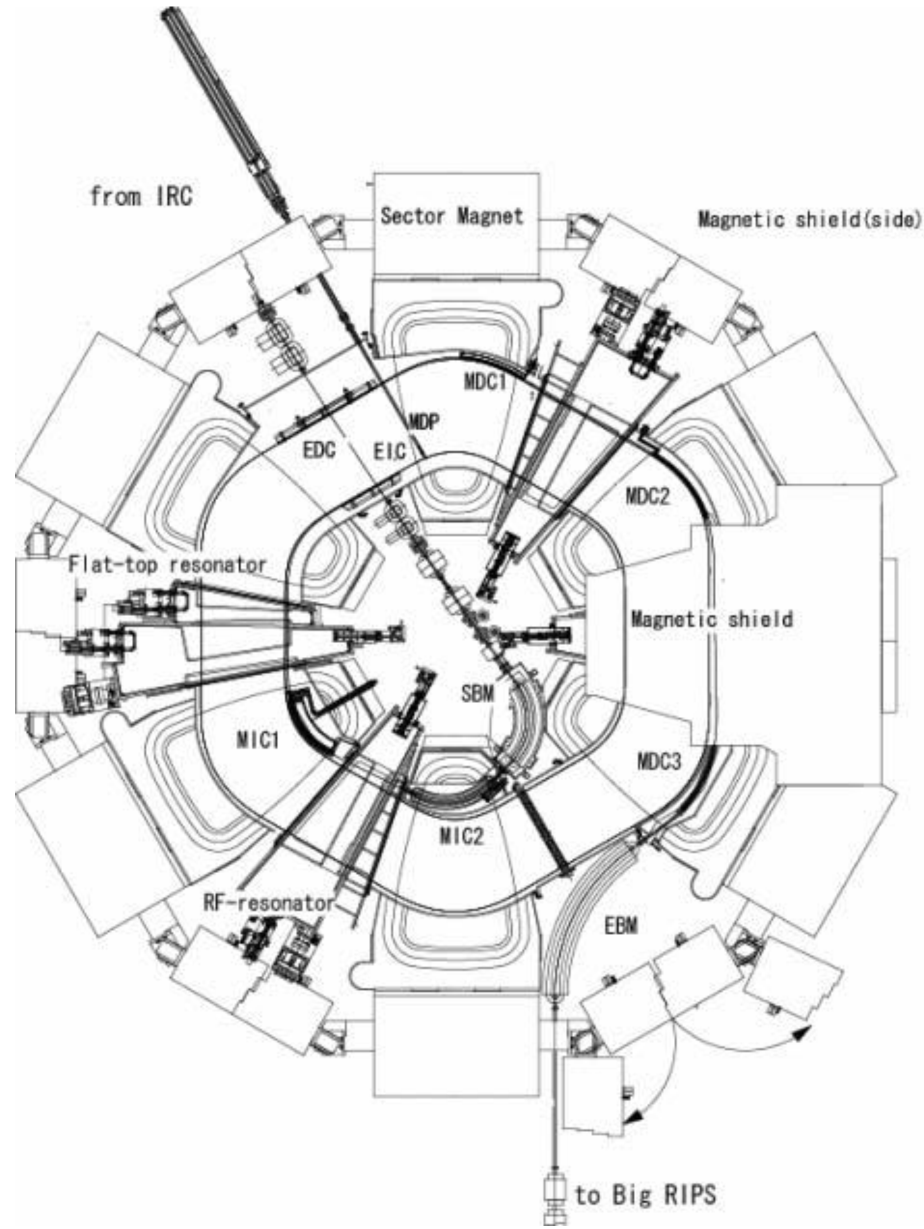
$$w = \frac{v}{r} = \frac{Bq}{m} = \frac{Bq}{m(E)}$$

- The classical cyclotron only works for particles up to few % of speed of light
  - Not useful for electrons…already relativistic at 500 keV
- Possibilities: synchrocyclotrons (change frequency (and magnetic field) with energy) or isochronous cyclotrons (increase magnetic field with r, frequency constant)
- Modern cyclotrons can reach > 500 MeV (PSI, TRIUMF, RIKEN)

# Big Cyclotron

- RIKEN, Japan
- 19 m diameter, 8 m high
- 6 superconducting sector magnets, 3.8 T each
- Heavy ion acceleration

- Uranium ions accelerated up to 345 MeV/u



# PSI cyclotron

High intensity beam: $P_{max}$ = 1.3 MW

# Synchrotron

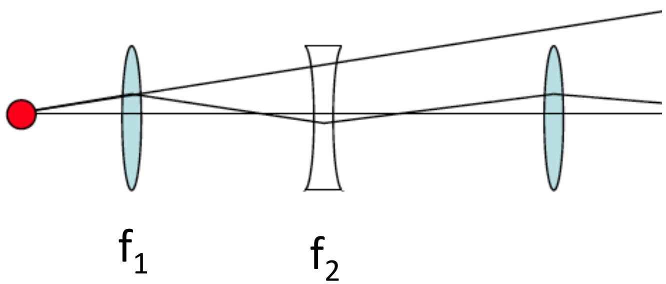
- Higher and higher energies – larger and larger radii, limited B fields – cannot stay compact
- Fix trajectory ➔ R = constant; R can be large
- Dipole magnets with field only where the beam is
  - "small" magnets
- R= constant ➔B field increases **synchronously** with beam energy
- Synchrotron - all big modern machines are synchrotrons

# Strong Focusing

Idea by E. Courant, M. Livingston, H. Snyder in 1952 and earlier by Christofilos

**Alternating gradient focusing**

– Analogous to geometrical optics: a series of alternating focusing and defocusing lenses will focus.

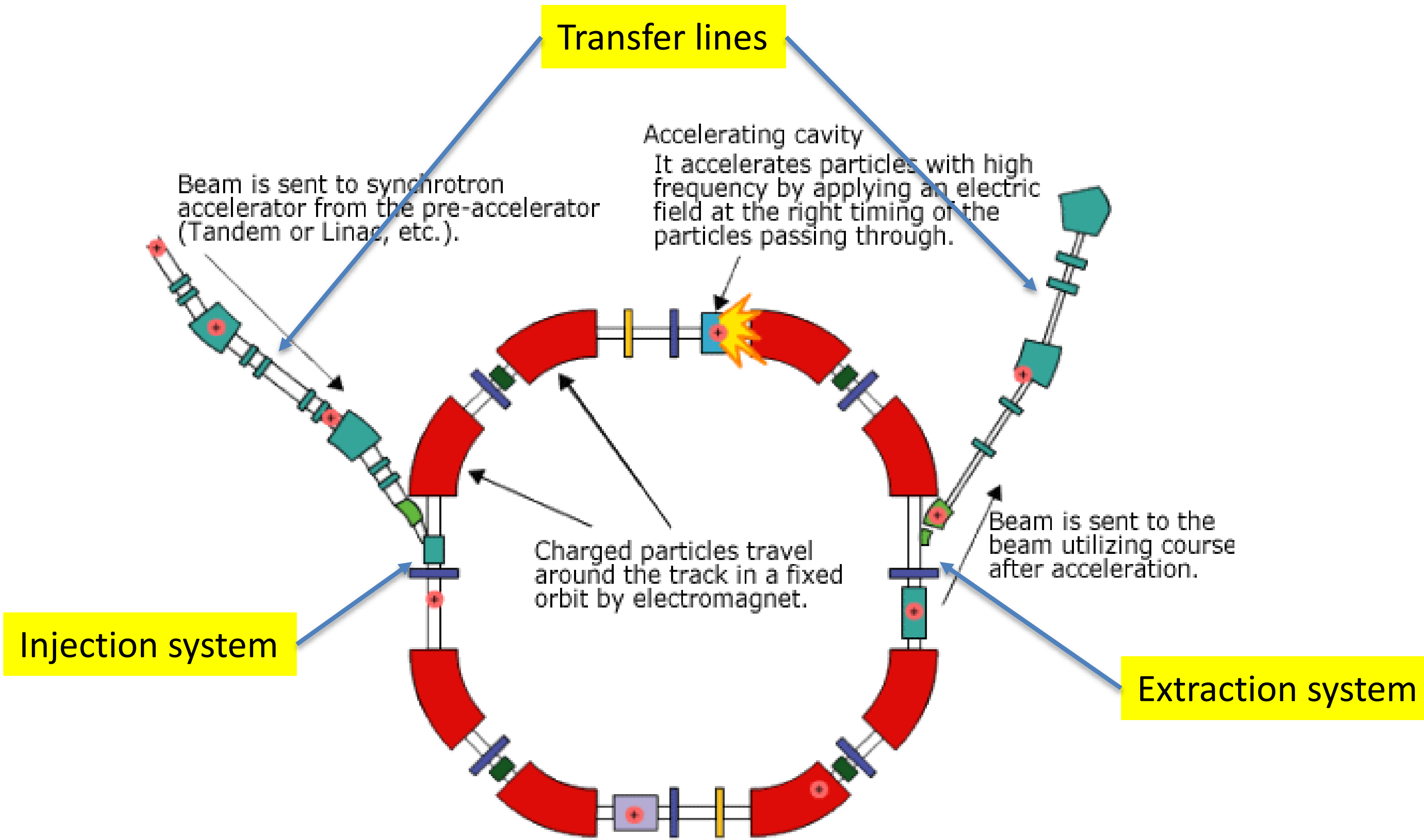



$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

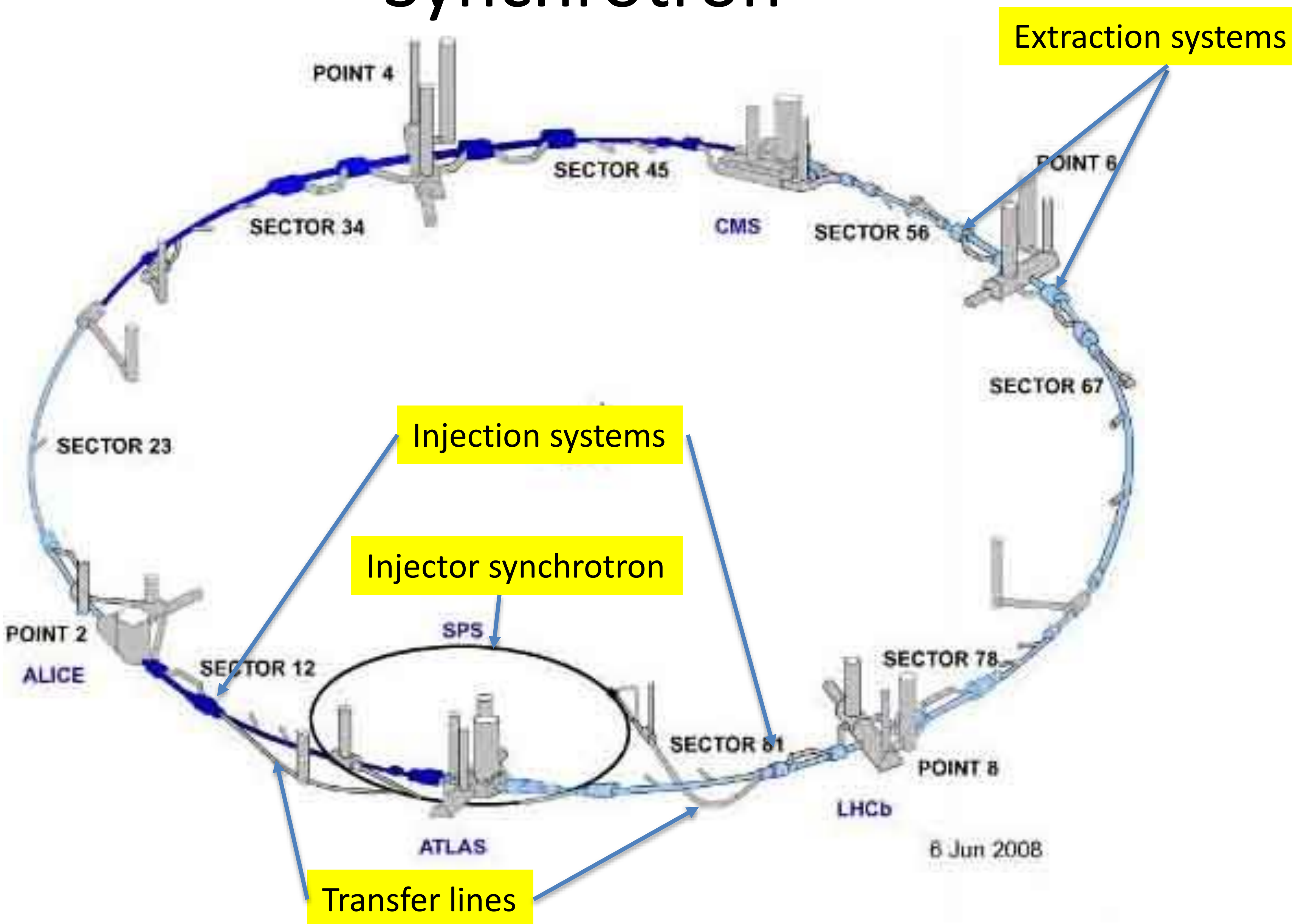
Consider $f_1=f$, $f_2 = -f$ ➔ $F = f^2/d > 0$

In our case the lenses will be magnets with alternating gradients

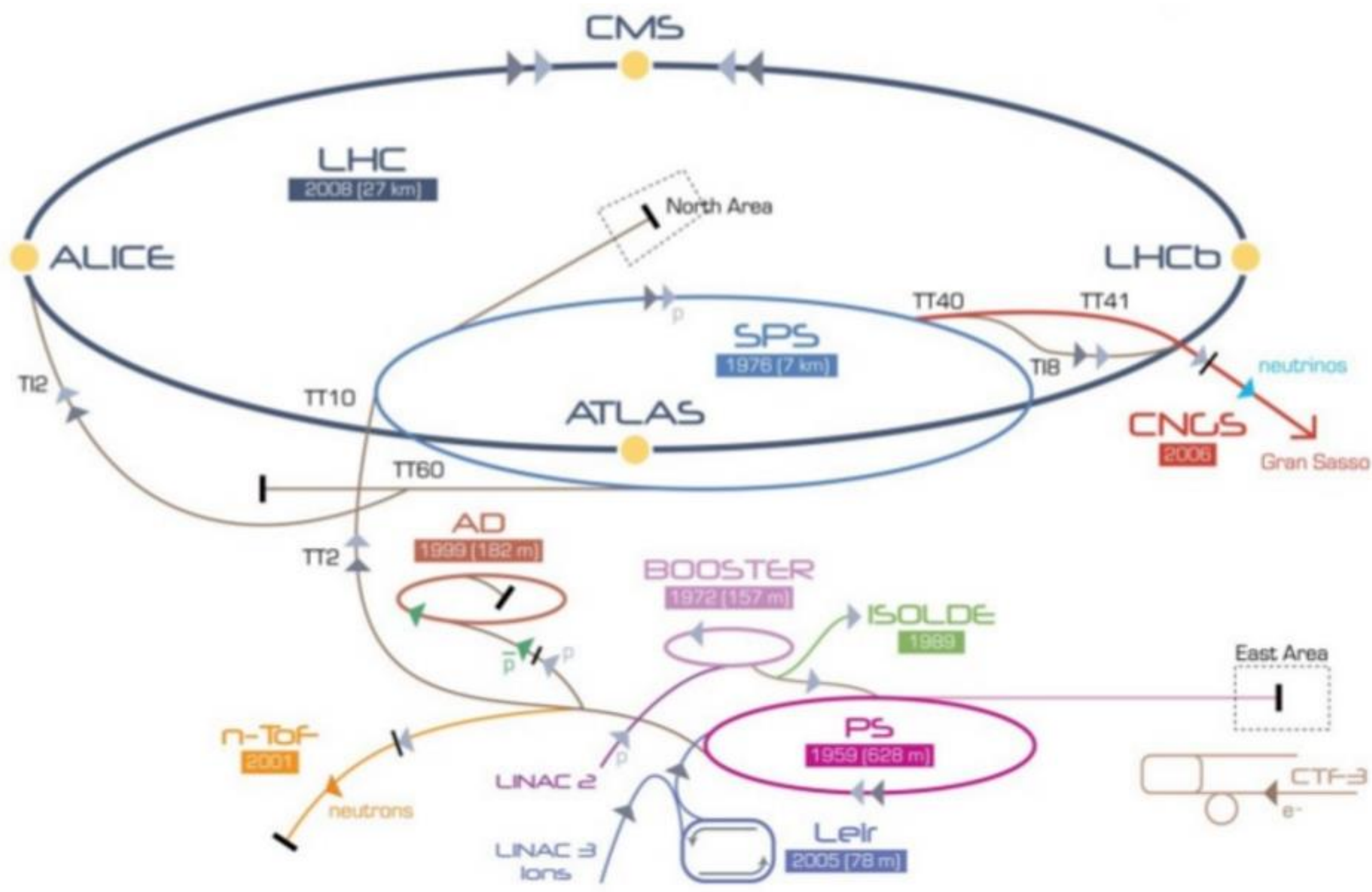
# Basic Layout of a small Alternating Gradient Synchrotron



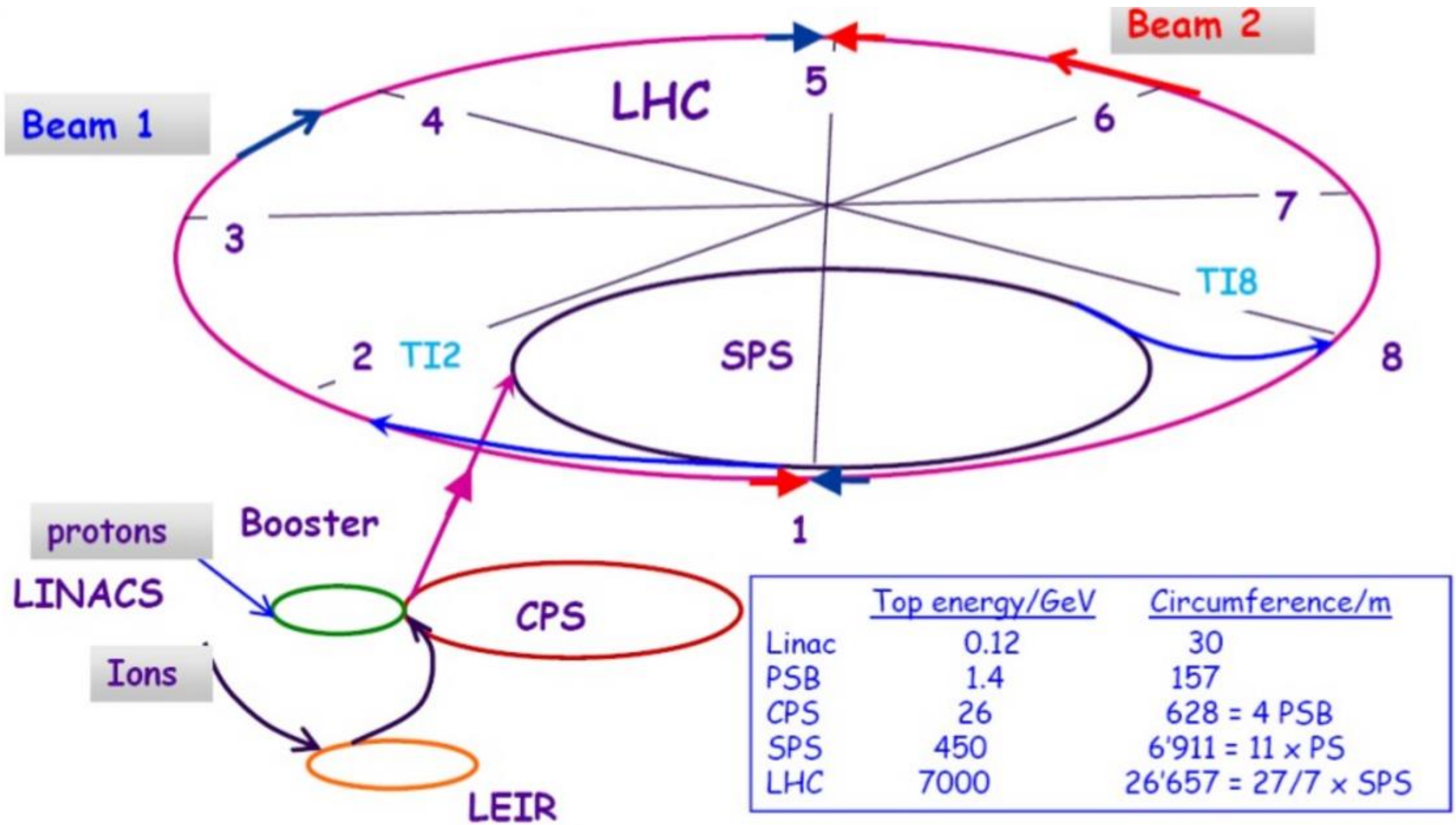
# Layout of a large Alternating Gradient Synchrotron



# CERN accelerator complex



# CERN LHC injector chain



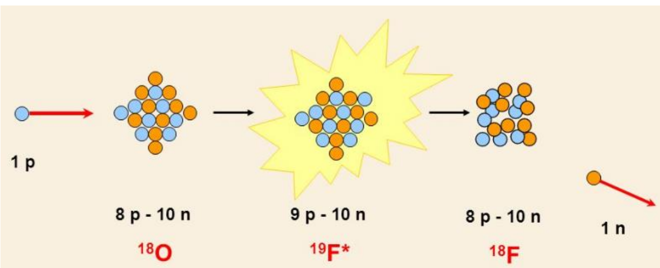

| | Top energy/GeV | Circumference/m |
|---|---|---|
| Linac | 0.12 | 30 |
| PSB | 1.4 | 157 |
| CPS | 26 | 628 = 4 PSB |
| SPS | 450 | 6'911 = 11 x PS |
| LHC | 7000 | 26'657 = 27/7 x SPS |

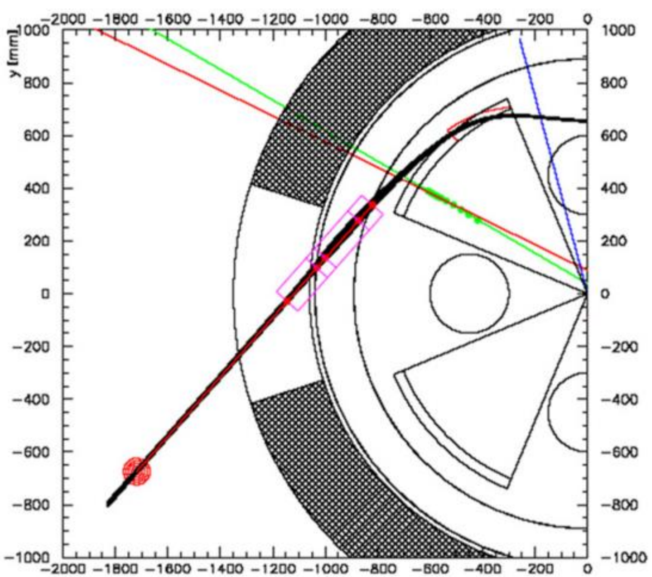
# USES OF ACCELERATORS

# Use of particle accelerators

**Medical diagnostics**: Accelerators are used to produce a wide range of radioisotopes for medical diagnostics and treatments, which are in routine use at hospitals worldwide for millions of medical procedures per year.

Most existing commercial suppliers of medical isotopes use 10-70 MeV $H^-$ cyclotrons, with **charge-exchange extraction**.

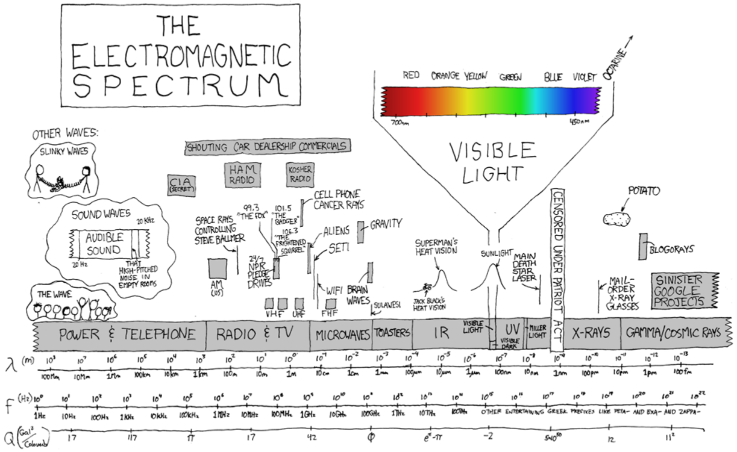


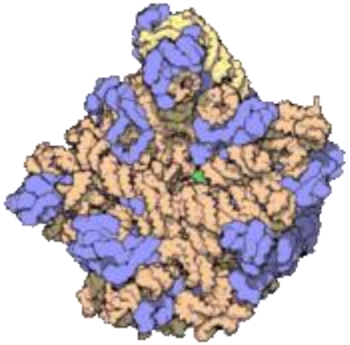



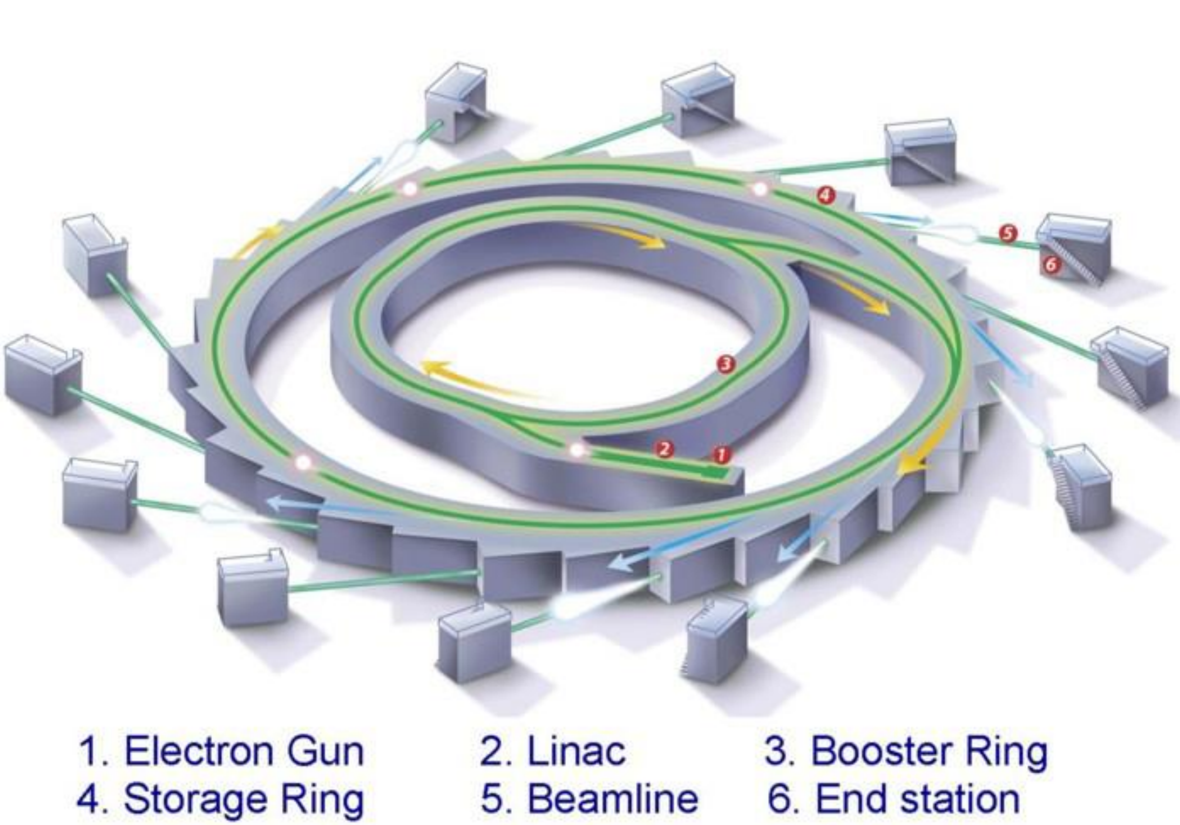

# Use of particle accelerators

**Synchrotron light sources**: Many uses for intense X-ray beams from synchrotron light sources, e.g. for pharmaceutical research to analyse protein structures quickly and accurately, or to define how the ribosome translates DNA information into life, earning the 2009 Nobel Prize in Chemistry.

Electron storage rings, often with sophisticated **top-up injection** systems.



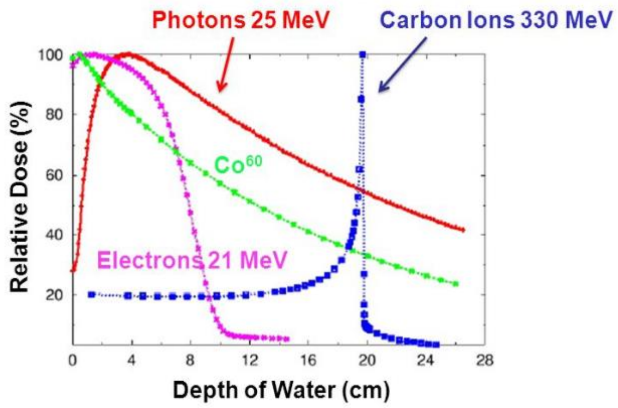



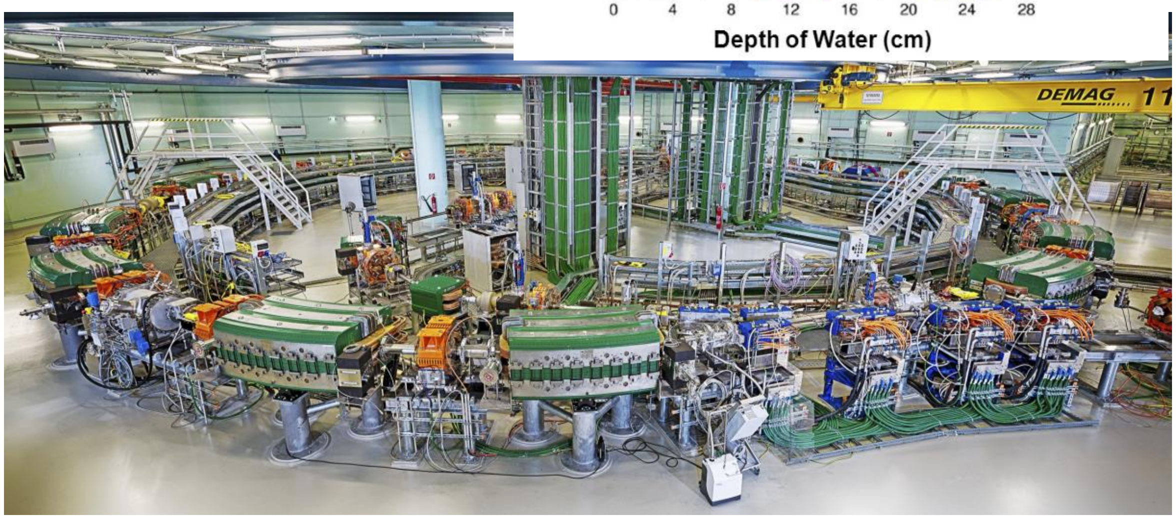


# Use of particle accelerators

**Cancer therapy**: An accelerated particle beam is the best tool for some cancer types. Hospitals use particle accelerators to treat thousands of patients per year, with fewer side effects than traditional chemical or radiation treatment.

Proton or carbon ions commonly accelerated and then **slow-extracted** over several seconds. Huge gantries are needed for **beam delivery**.

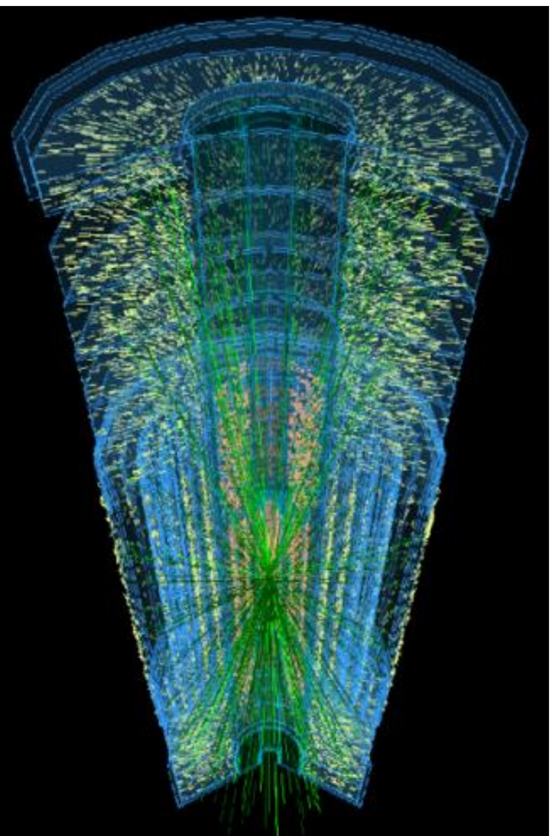


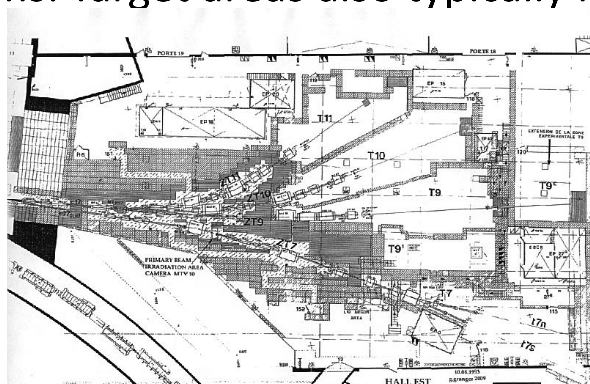



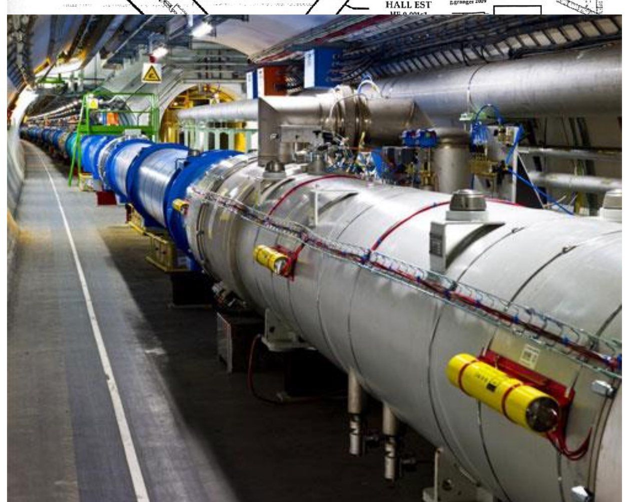
# Use of particle accelerators

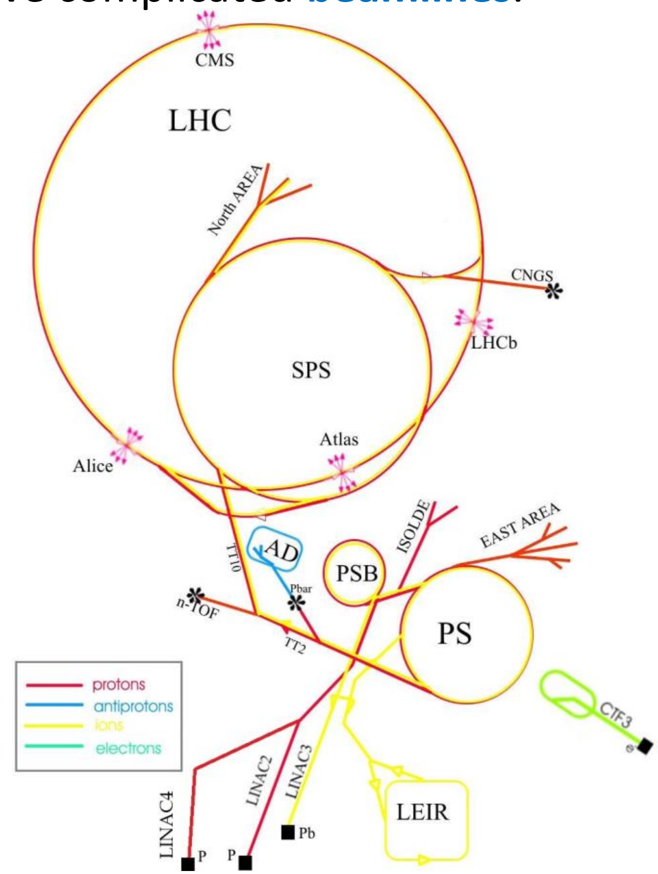
**High Energy/Nuclear Physics**: Particle accelerators are used to study smaller and smaller structures and create heavy short-lived objects in collisions, leading to the discovery of new physics phenomena like the Higgs boson, which earned the 2013 Nobel Prize in Physics.

Highest energy accelerators need a whole chain of injectors with associated **injection, extraction and transfer** systems. Target areas also typically have complicated **beamlines**.





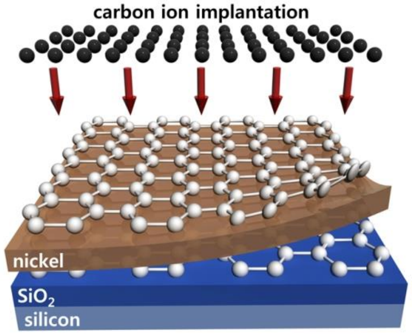



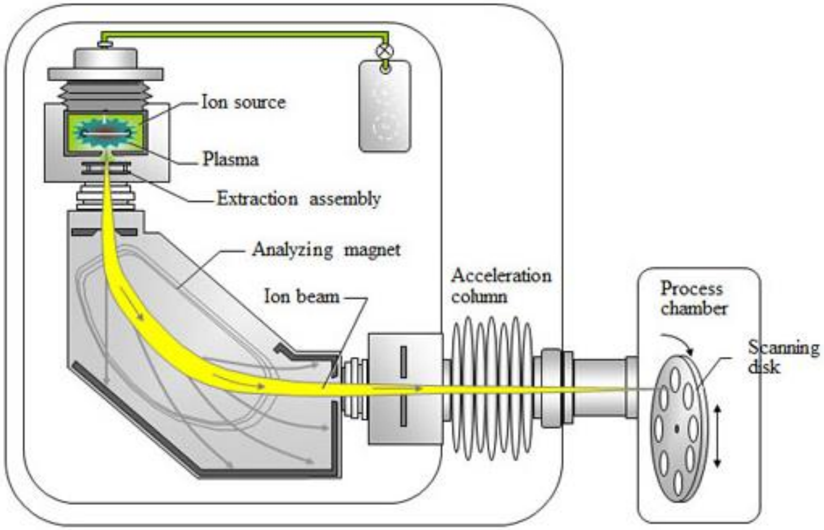


# Use of particle accelerators

**Materials processing**: Accelerators are widely used in the semi-conductor industry, in different materials technologies, and also in the food industry. Used for semiconductor doping, metal hardening, mesotaxy, sterilisation, …

Typically electrostatic acceleration to 10-500 keV with high current, and straightforward **low energy beam transport**




# Ubiquity of particle accelerators

This brief overview has just scratched the surface

Particle accelerators are widespread in many scientific, engineering and medical domains…

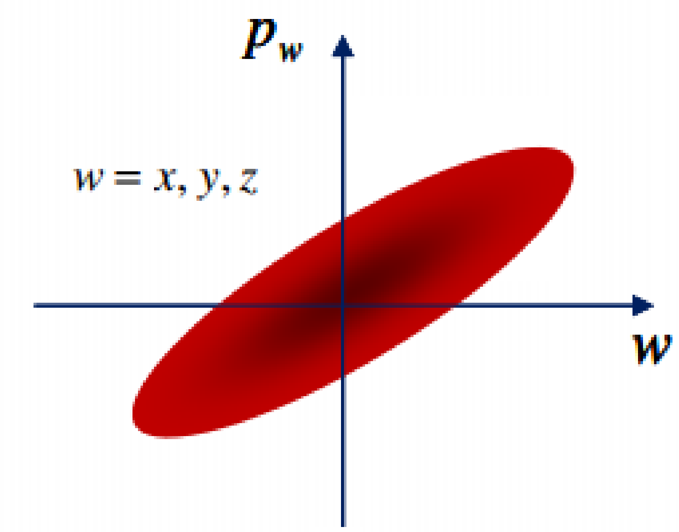
…there are an estimated 18’000 in use worldwide…

…and the particle beam has to be **injected and extracted** from (almost) all of them!

# TRANSVERSE PHASE SPACE

# Phase space

- An accelerated beam typically consists of $10^6 – 10^{13}$ particles
- We can apply the methods of statistical mechanics, and treat properties of the statistical ensemble, not of individual particles
- This is a useful concept for representation of many common beam ‘manipulations’ and hence for helping the understanding of injection and extraction processes



# Phase space

- In relativistic classical mechanics, motion of single particle fully defined at any instant *t*, if position *r*, momentum *p* of particle are given with the *forces* (fields) acting on i^th particle

$$\vec{r}_i = x_i\hat{x} + y_i\hat{y} + z_i\hat{z}$$

$$\vec{p}_i = p_{xi}\hat{x} + p_{yi}\hat{y} + p_{zi}\hat{z}$$

$$\vec{F}_i = F_{xi}\hat{x} + F_{yi}\hat{y} + F_{zi}\hat{z}$$

- It is (very) convenient to use 6D "phase space" representation, where $i^{th}$ particle has coordinates:

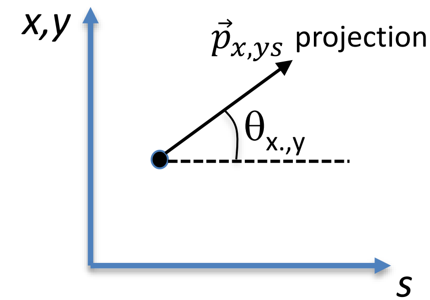
$$P_i \equiv \{x_i, p_{xi}, y_i, p_{yi}, z_i, p_{zi}\}$$

- Generally, the 3 planes can be considered decoupled (but you will see some exceptions to this), and it's (very) convenient to study particle evolution separately in each plane

$$\{x_i, x_{yi}\} \qquad \{y_i, p_{yi}\} \qquad \{z_i, z_{yi}\}$$

# Transverse phase space

- For transverse planes, we generally use a modified phase space where the transverse momentum coordinates $p_{xi}$ and $p_{yi}$ are replaced by angles x' and y'




$$p_x \rightarrow x' = \frac{dx}{ds} = \tan\theta_x \qquad p_y \rightarrow y' = \frac{dy}{ds} = \tan\theta_y$$

- The angle is related to the momentum by:

$$p_x = \gamma_r m_0 \frac{dx}{dt} = \gamma_r m_0 v_s \frac{dx}{ds} = \beta_r \gamma_r m_0 c x'$$

$$p_y = \gamma_r m_0 \frac{dy}{dt} = \gamma_r m_0 v_s \frac{dy}{ds} = \beta_r \gamma_r m_0 c y'$$

- Note: $x$ and $p_x$ are canonical conjugate variables, while $x$ and $x'$ are not, unless $\gamma_r$ and $\beta_r$ remain constant (i.e no acceleration)

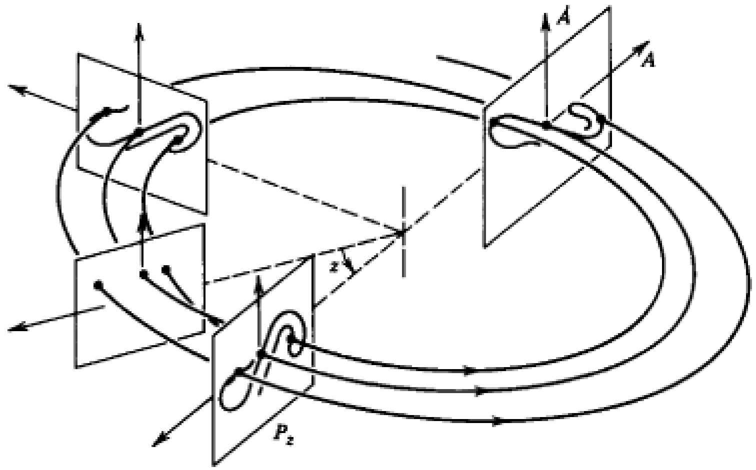
# Poincaré map

- A first recurrence map or Poincaré map, is the intersection of a periodic orbit in the state space of a continuous dynamical system with a certain lower-dimensional subspace, called the Poincaré section, transversal to the flow of the system

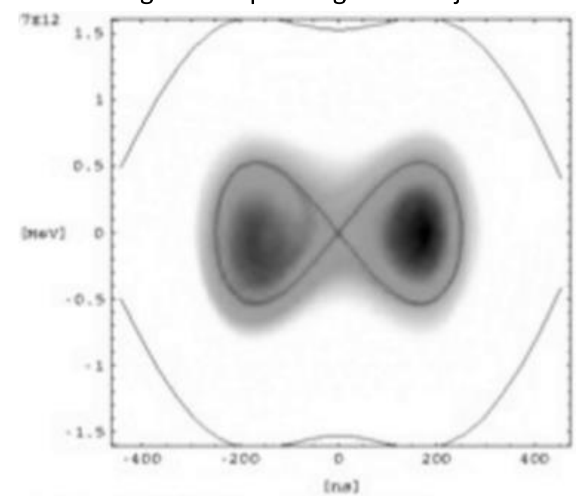
- Translation: plot the phase space coordinates at one physical location over time

# Poincaré map

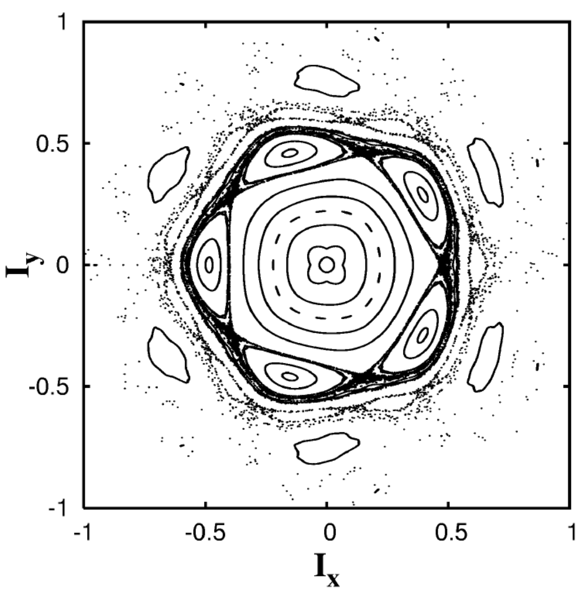
## Widespread representation method for non-linear systems…



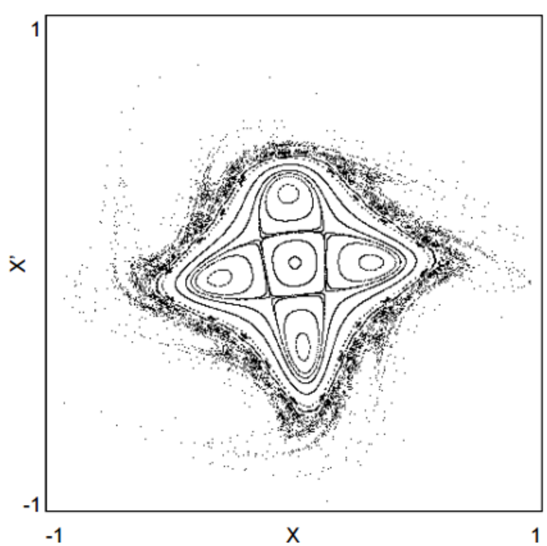

Longitudinal painting in PSB injection



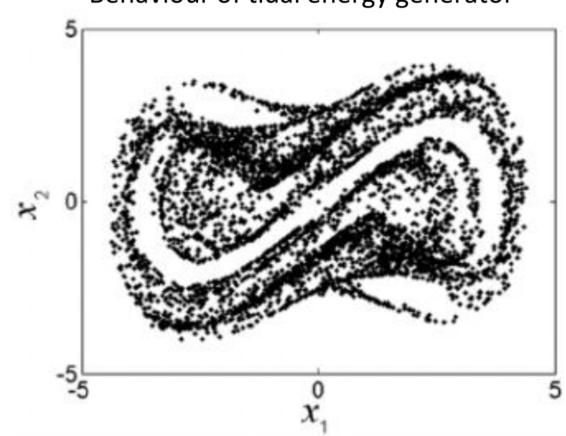

Ray propagation in a deep-ocean waveguide




Transverse phase space for PS multi-turn extraction

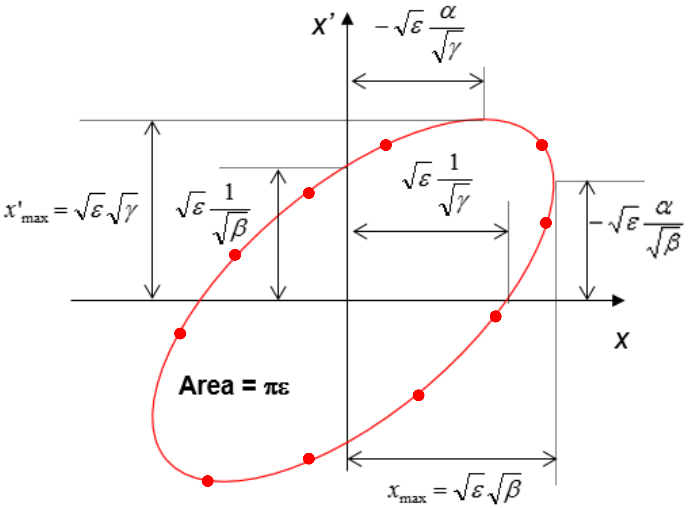



Behaviour of tidal energy generator

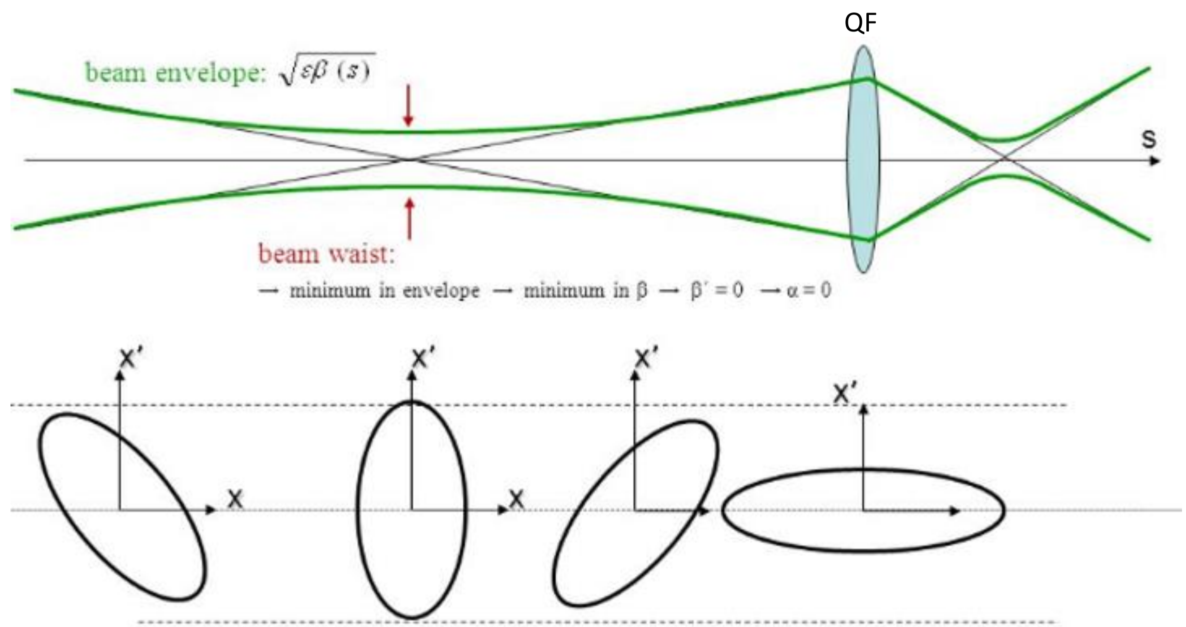


# Phase space ellipses

- For a circular accelerator, if we make (x,x’) or (y,y’) Poincaré map for any single particle at one location over many turns, it traces an ellipse
- This ellipse at this location always has same shape and orientation for all particles – the local ellipse form is a property of focussing lattice
- The ellipse changes shape and orientation as it propagates along accelerator – but the area is preserved. The specific area (emittance) is a property of the beam.




$$\varepsilon = \gamma \cdot x^2 + 2\alpha \cdot x \cdot x' + \beta \cdot x'^2 = x_{max}^2 / \beta_x$$



# Normalised transverse phase space

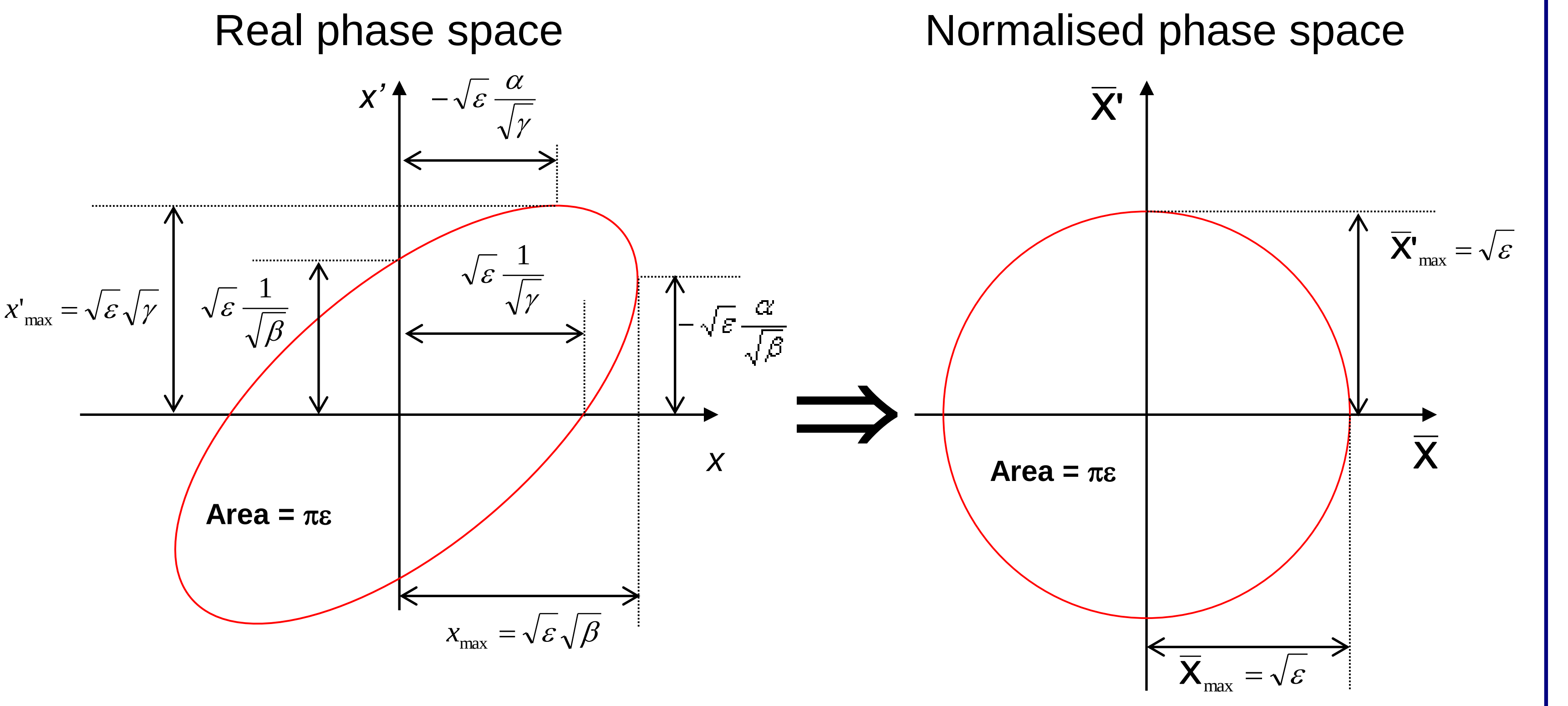
- Transform ‘real’ transverse coordinates *x*, *x’* by

$$\begin{bmatrix} \overline{\mathsf{X}} \\ \overline{\mathsf{X}}' \end{bmatrix} = \mathbf{N} \cdot \begin{bmatrix} x \\ x' \end{bmatrix} = \sqrt{\frac{1}{\beta_S}} \cdot \begin{bmatrix} 1 & 0 \\ \alpha_S & \beta_S \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \end{bmatrix}$$

$$\overline{\mathsf{X}} = \sqrt{\frac{1}{\beta_S}} \cdot x$$

$$\overline{\mathsf{X}}' = \sqrt{\frac{1}{\beta_S}} \cdot \alpha_S x + \sqrt{\beta_S}\, x'$$

# Normalised phase space




$$\varepsilon = \gamma \cdot x^2 + 2\alpha \cdot x \cdot x' + \beta \cdot x'^2$$

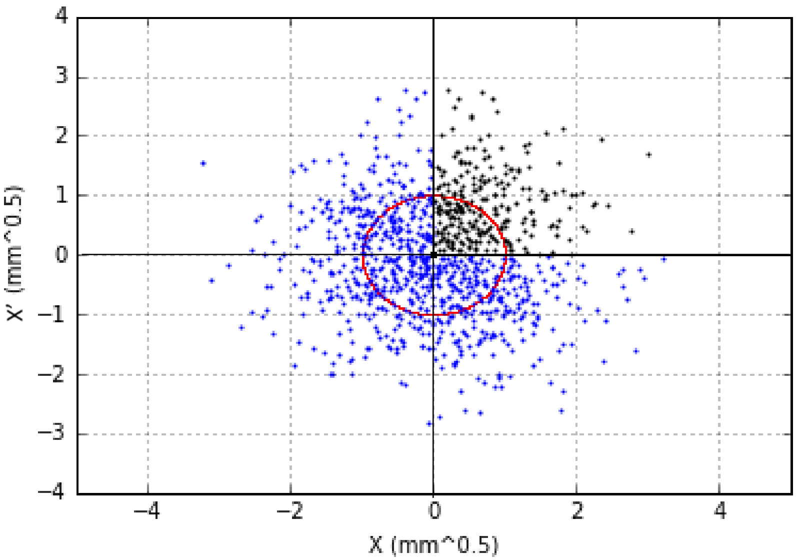
$$\varepsilon = \overline{X}^2 + \overline{X}'^2$$

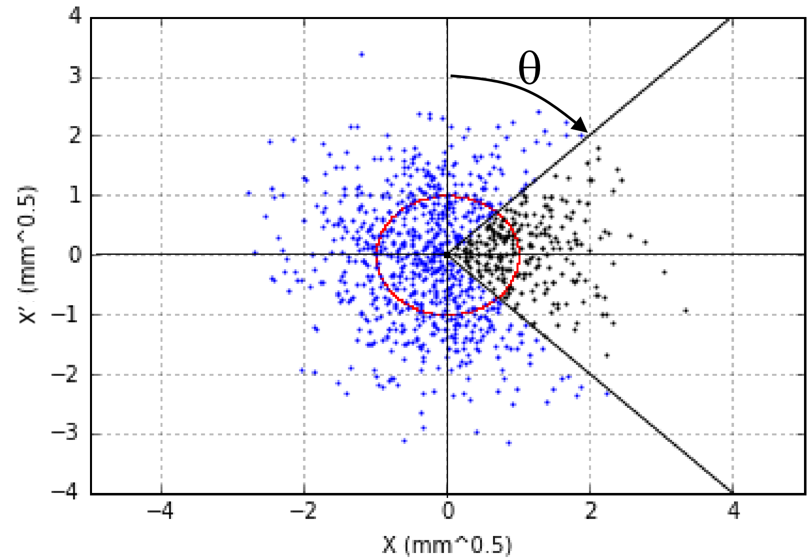
# COMMON BEAM ‘MANIPULATIONS’ IN NORMALISED PHASE SPACE

# Transport along lattice

- In normalised phase space this is just a rotation of the distribution around the origin by a phase advance θ

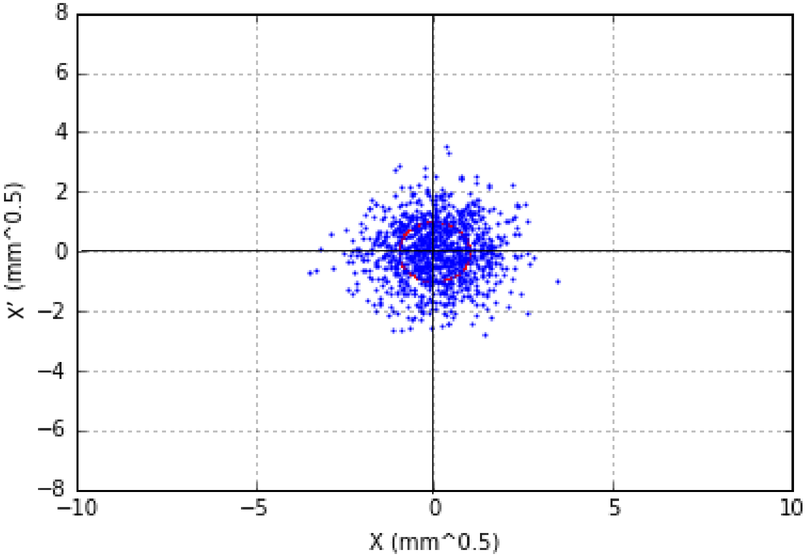
$$\begin{pmatrix} X \\ X' \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} X_0 \\ X'_0 \end{pmatrix}$$

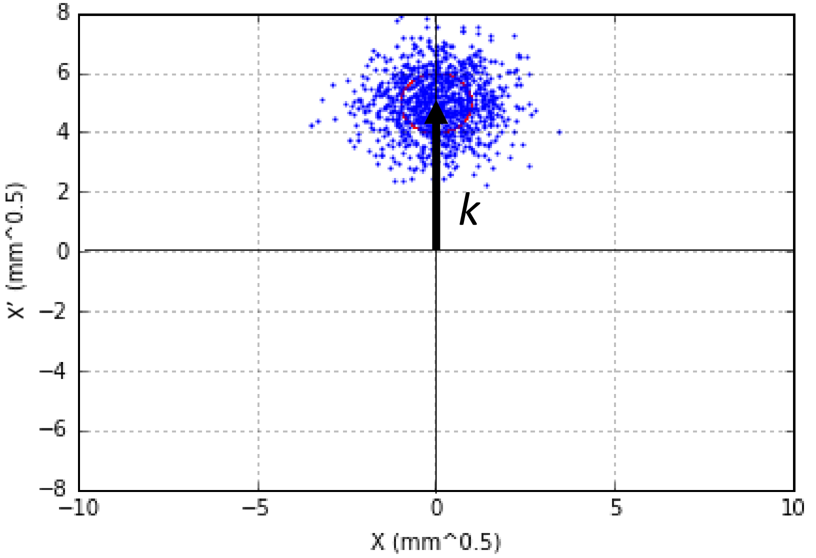


# Dipole deflection (thin lens)

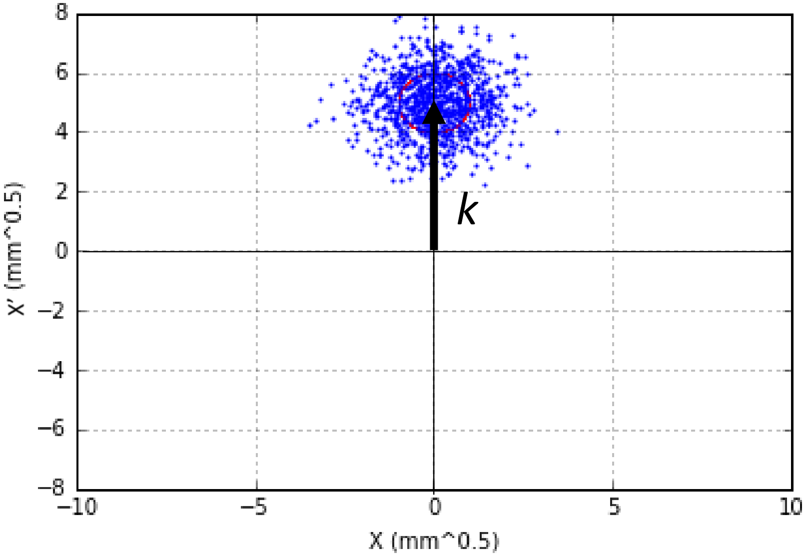
- A dipole deflection (kick) *k* is a vertical displacement in normalised phase space

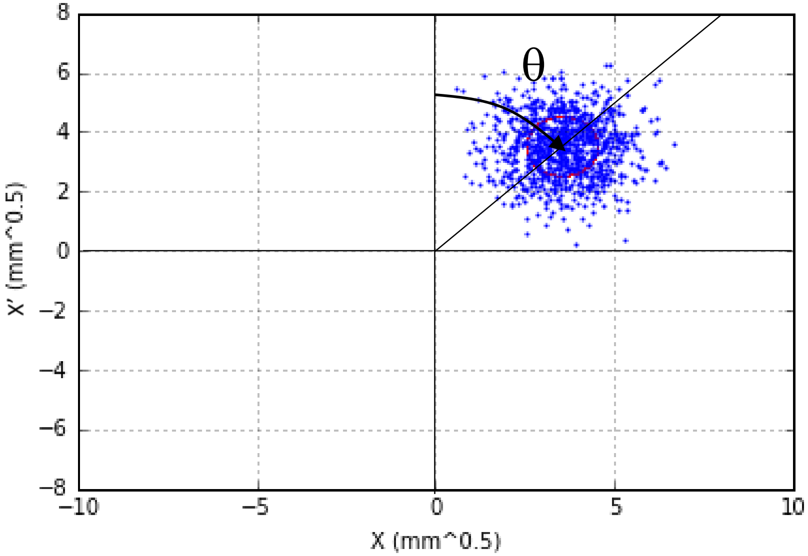


# Transport kicked beam along lattice

- Again, apply a rotation by $\theta$, but this time to the displaced distribution

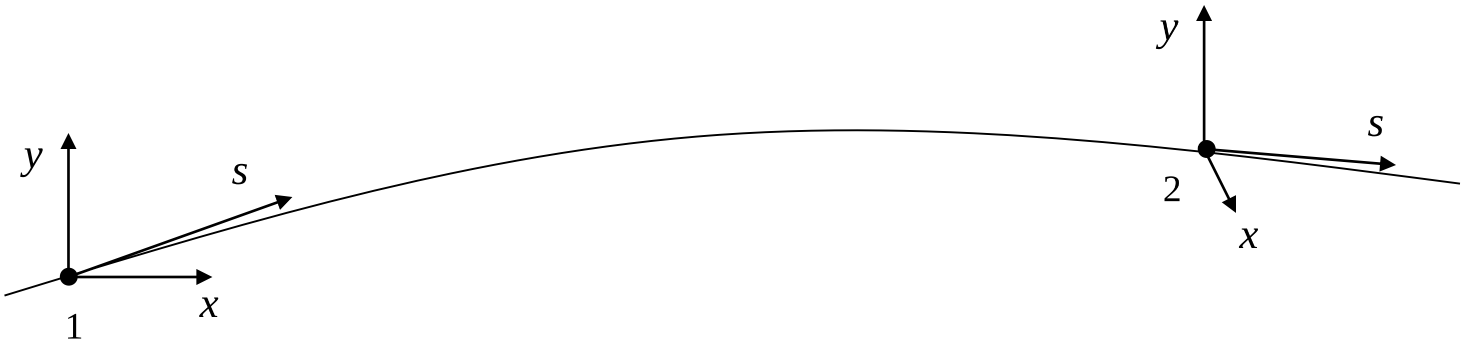


# A WORD ON BEAM TRANSPORT

# General transport

Beam transport: moving from $s_1$ to $s_2$ through *n* elements, each with transfer matrix $M_i$

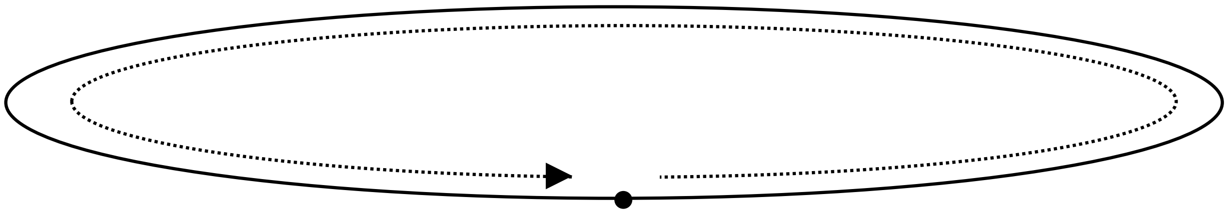



$$\begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = \mathbf{M}_{1\to 2} \cdot \begin{bmatrix} x_1 \\ x'_1 \end{bmatrix} = \begin{bmatrix} C & S \\ C' & S' \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x'_1 \end{bmatrix} \qquad \mathbf{M}_{1\to 2} = \prod_{i=1}^{n} \mathbf{M}_n$$

Twiss parameterisation

$$\mathbf{M}_{1\to 2} = \begin{bmatrix} \sqrt{\beta_2/\beta_1}\left(\cos\Delta\mu + \alpha_1 \sin\Delta\mu\right) & \sqrt{\beta_1\beta_2}\,\sin\Delta\mu \\ \sqrt{1/\beta_1\beta_2}\left[(\alpha_1-\alpha_2)\cos\Delta\mu - (1+\alpha_1\alpha_2)\sin\Delta\mu\right] & \sqrt{\beta_1/\beta_2}\left(\cos\Delta\mu - \alpha_2\sin\Delta\mu\right) \end{bmatrix}$$

# Circular Machine




One turn

$$\mathbf{M}_{1\to 2} = \mathbf{M}_{0\to L} = \begin{bmatrix} \cos 2\pi Q + \alpha \sin 2\pi Q & \beta \sin 2\pi Q \\ -\frac{1}{\beta}\left(1+\alpha^2\right)\sin 2\pi Q & \cos 2\pi Q - \alpha \sin 2\pi Q \end{bmatrix}$$

- The solution is *periodic*
- Periodicity condition for one turn (closed ring) imposes $\alpha_1=\alpha_2$, $\beta_1=\beta_2$, $D_1=D_2$
- This condition *uniquely* determines $\alpha(s)$, $\beta(s)$, $\mu(s)$, $D(s)$ around the whole ring

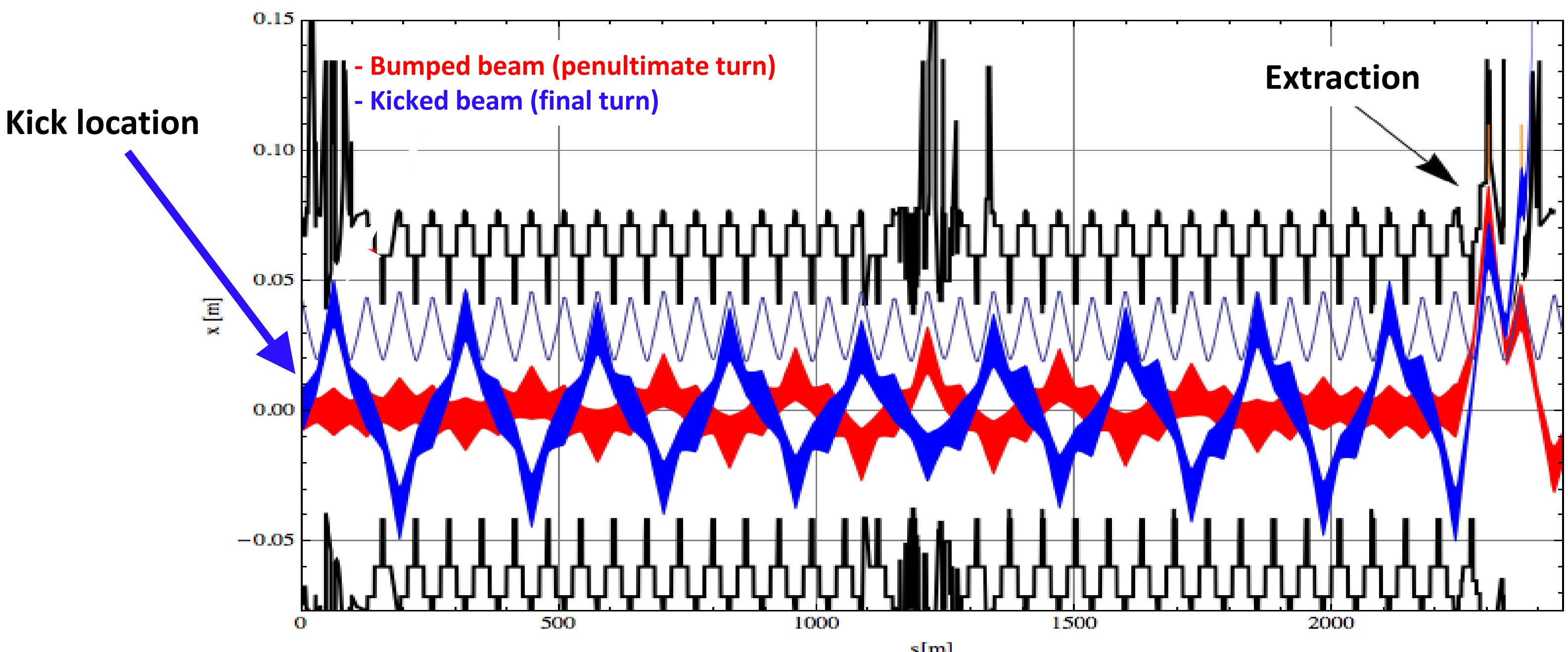
# Effect of dipole deflection ('kick')

- Can calculate downstream position x (or y) and angle x' (or y') as a function of initial coordinates and lattice functions
  - Often, for beam transfer, initial x (or y) = 0, which gives:

$$x_s = x'_0 \sqrt{\beta_0 \beta_s} \sin \Delta\mu$$

  - 90° phase advance $\Delta\mu$ and large $\beta$ give maximum deflection $x_s$
  - Beam as a whole performs transverse *betatron oscillations* after a kick

2.2 km betatron oscillation from SPS kicker



# THE BEAM TRANSFER PROCESS

# Beam transfer is a process

- By definition a pulsed / transient process
- A critical event (or series of events) in accelerator cycle
- Requires speciliased equipment (you'll hear about)
- If badly designed or not optimised it can have a large negative impact on 'downstream' beam performance
  - emittance, intensity, stability
  - often needs operational adjustment to optimise
- For high energy/high intensity beams, control of beam losses becomes critical
  - To avoid excessive irradiation and activation
  - To avoid direct damage from beam impact

# Injection : common desiderata

- Low fraction of beam lost (for injected beam and any already circulating beam)
- Maintain large filling factor (i.e. injection process does not cause too much ‘empty’ ring circumference)
- Precise beam delivery onto reference orbit
- Minimum perturbation to any circulating beam
- As high energy as possible (sometimes full ring energy)
- Minimum effect on overall ring performance (e.g. impedance, aperture, …)
- Simple setup and operation
- Reliable, reproducible, stable

# Extraction : common desiderata

- Low fraction of beam lost
- A precise delivery onto target, dump or into transfer line
- Minimum perturbation to any remaining circulating beam
- Minimum effect on overall ring performance (e.g. impedance, aperture, …)
- Simple setup and operation
- Reliable, reproducible, stable

# Transfer lines : common desiderata

- Low fraction of beam lost
- A precise delivery onto target, dump or to next injection system
- Precise optical matching to ring optics (and minimum optical perturbation)
- Easy steering and trajectory control
- Filtering of different beam energies or ion species
- Achromatic transport
- Accurate beam characterisation
- Reliable, reproducible, stable
- Low operation cost

# CONCLUSION

# Beam transfer is special

- (In general) needed for all accelerators
- A pulsed / transient process
- Requires specialised equipment
- Has lots of associated constraints
- Gives scope for very creative and elegant solutions
- Why we're here this week!

# Acknowledgements

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The end