Introduction to particle accelerators and beam sources

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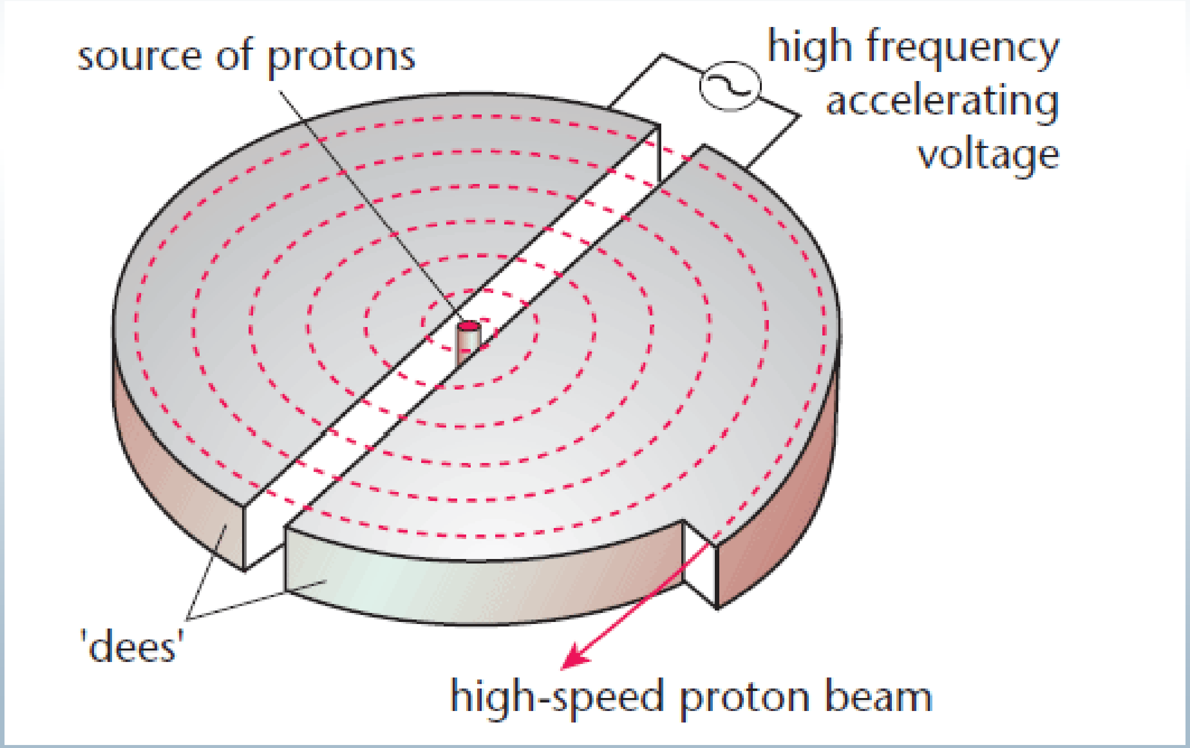
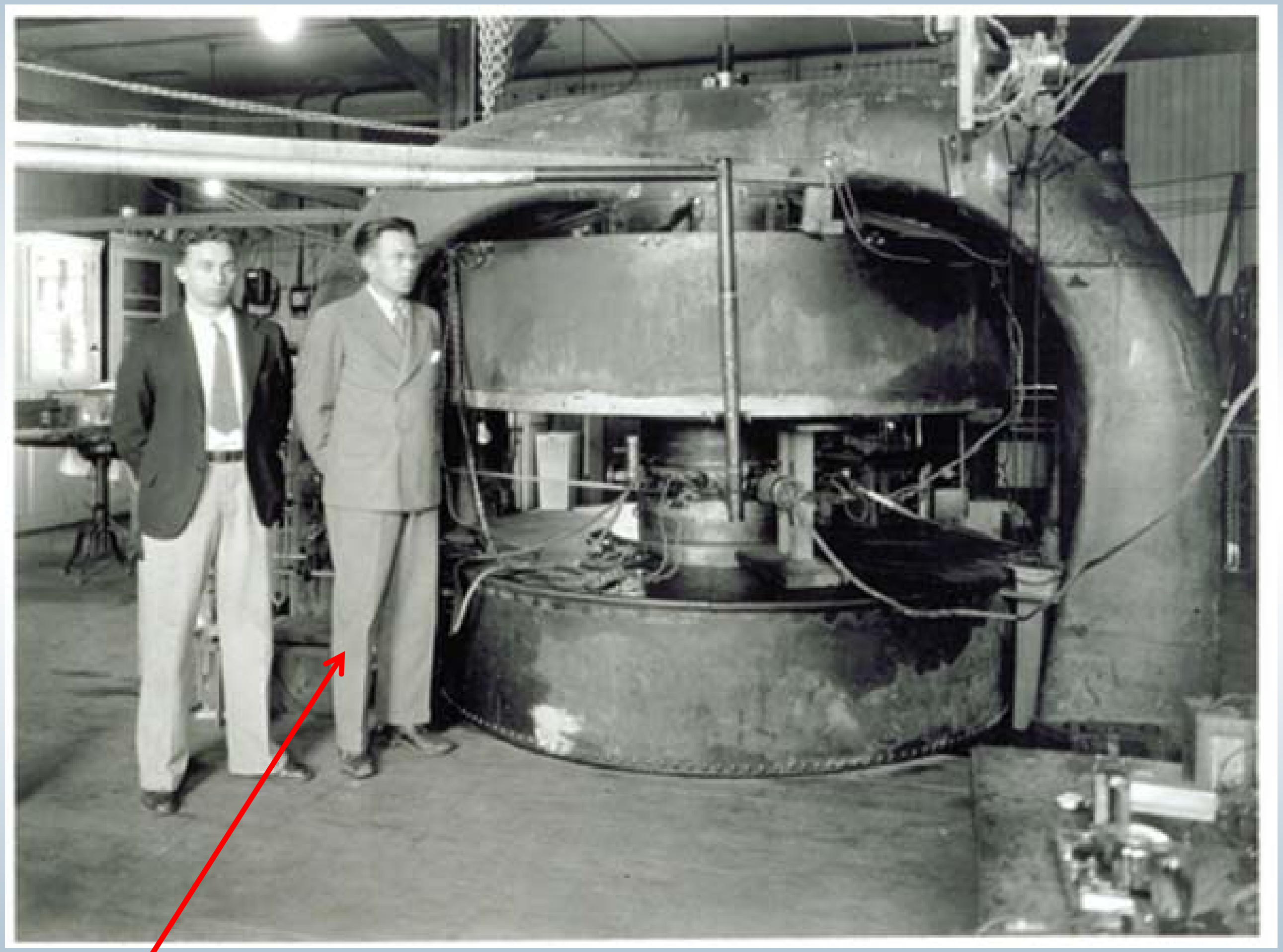
What is an accelerator?

- Accelerator is a device that uses electric fields to propel charged-particles to high-speeds and magnetic fields to contain them

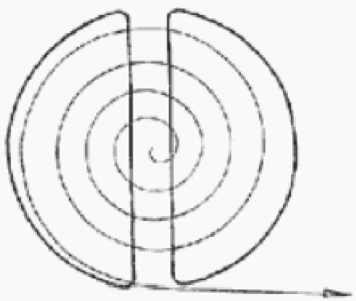


Cyclotron in 1932

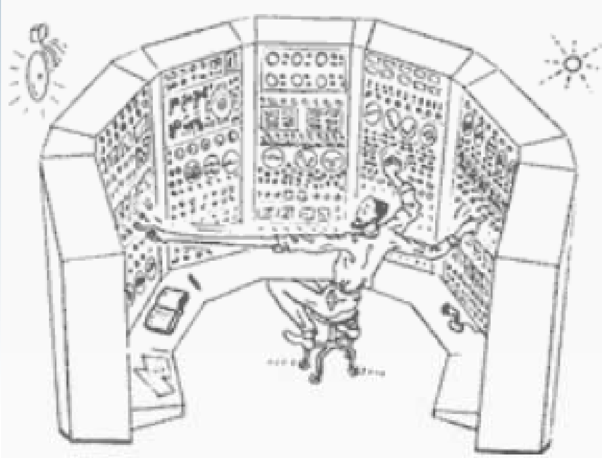


Ernest Orlando Lawrence (inventor)

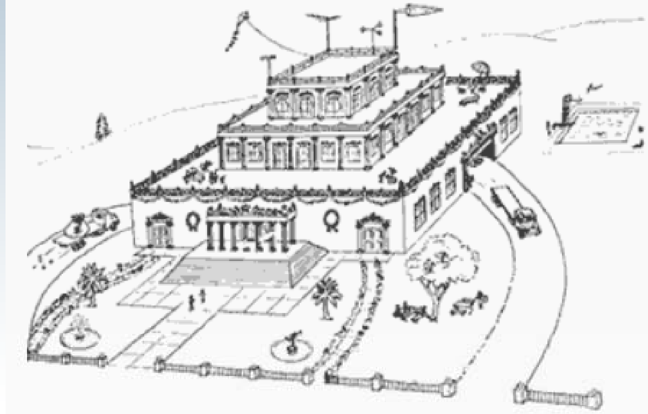
Cyclotron: Different points of view



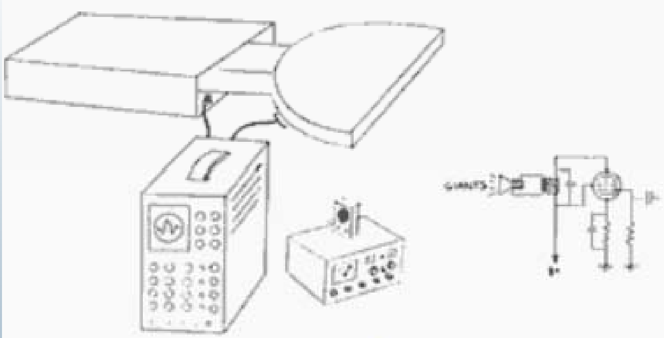
...the inventor



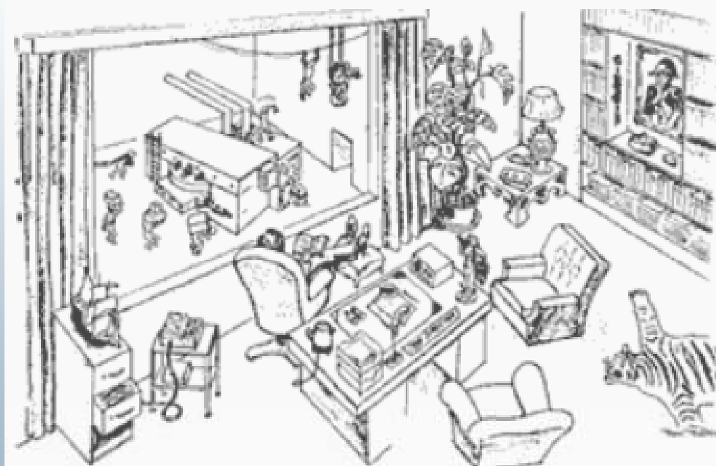
...the operator



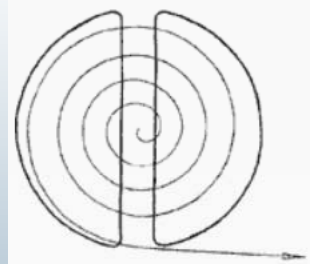
...the governmental funding agency



...the electrical engineer

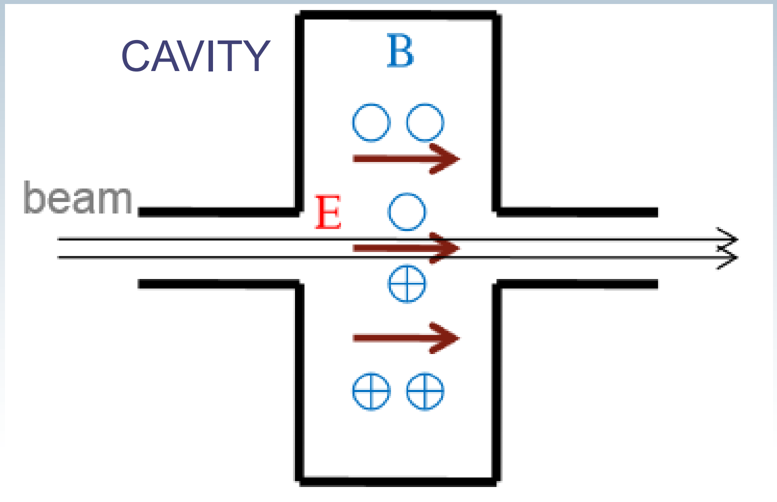


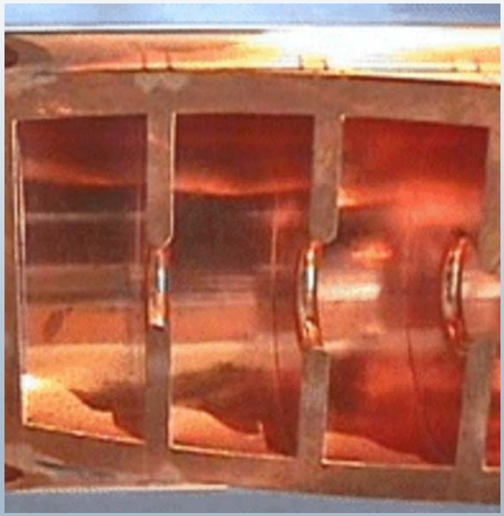
...the laboratory director

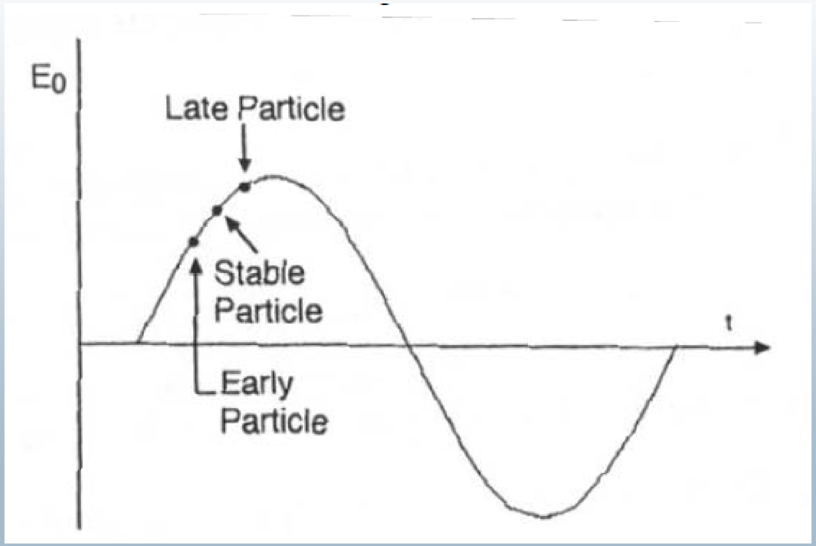


...the student

Acceleration with rf cavities



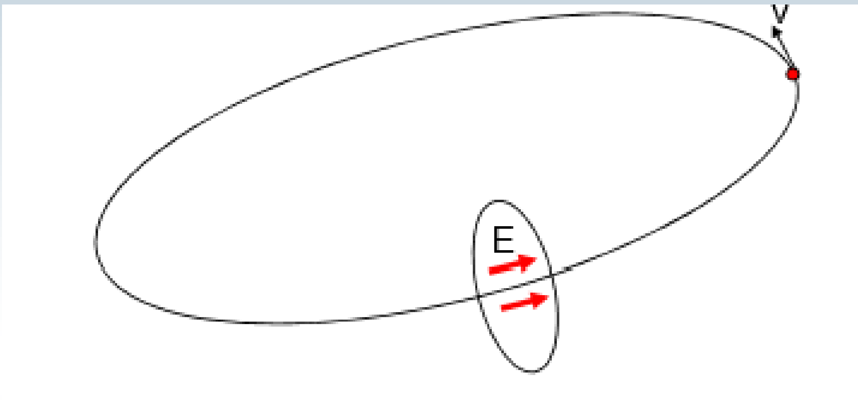


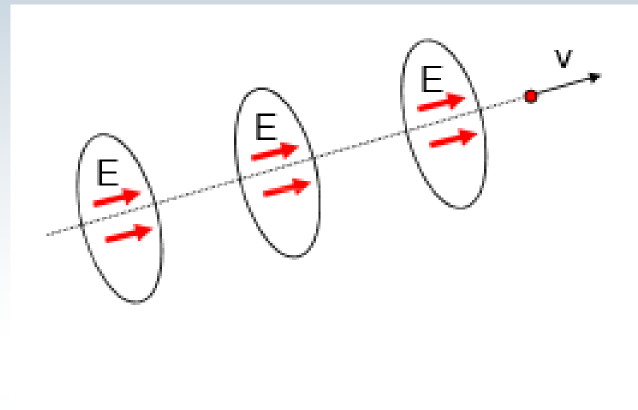


RF cavities

- Depending on the frequency, cavities can be huge!

Types of accelerators





- Circular accelerators
  - Repeated passage of beams via a series of cavities
  - Suitable for heavy particles, i.e. protons
- Linear accelerators
  - Particles pass only once through each cavity
  - Suitable for light particles, i.e. electrons

Synchrotron radiation

- Particles radiate when they are accelerated, so charged particles moving in the magnetic dipoles of a lattice in a ring (with centrifugal acceleration) emit radiation in a direction tangential to their trajectory
- After one turn totally energy lost is:

$$\Delta E\left[\mathrm{GeV}\right]=\frac{6.034\times10^{-18}}{\rho\left[\mathrm{m}\right]}\left(\frac{E\left[GeV\right]}{m_0\left[\mathrm{GeV}/c^2\right]}\right)^4$$

- Rings: Good for protons, heavy ions, muons..
- Linacs: Good for electrons

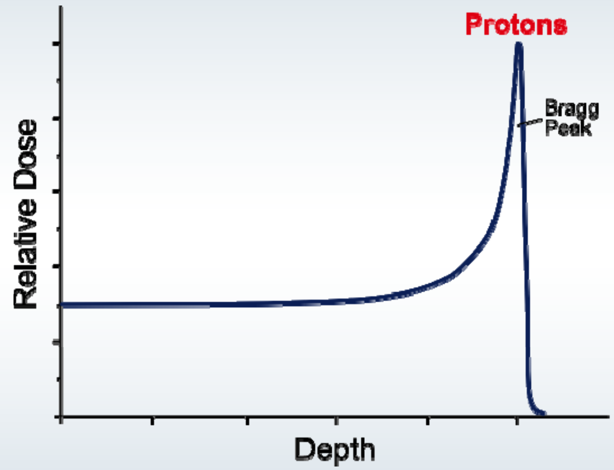
Example of a linear accelerator

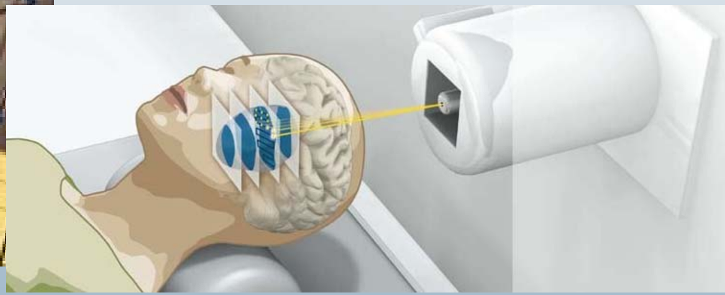
https://www6.slac.stanford.edu/

LHC – The world's largest accelerator

Accelerators for medical treatment

- Heidelberg Therapy Center, Germany
  - Treatment of cancer with heavy ions

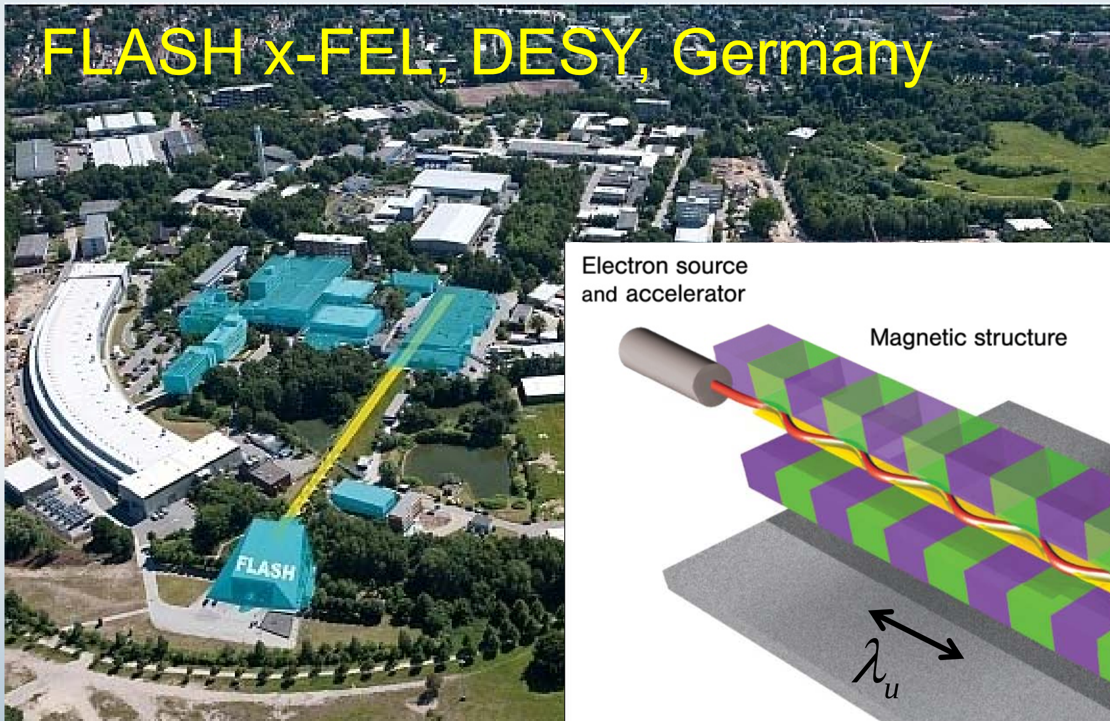




http://www.klinikum.uni-heidelberg.de

Accelerators as light sources

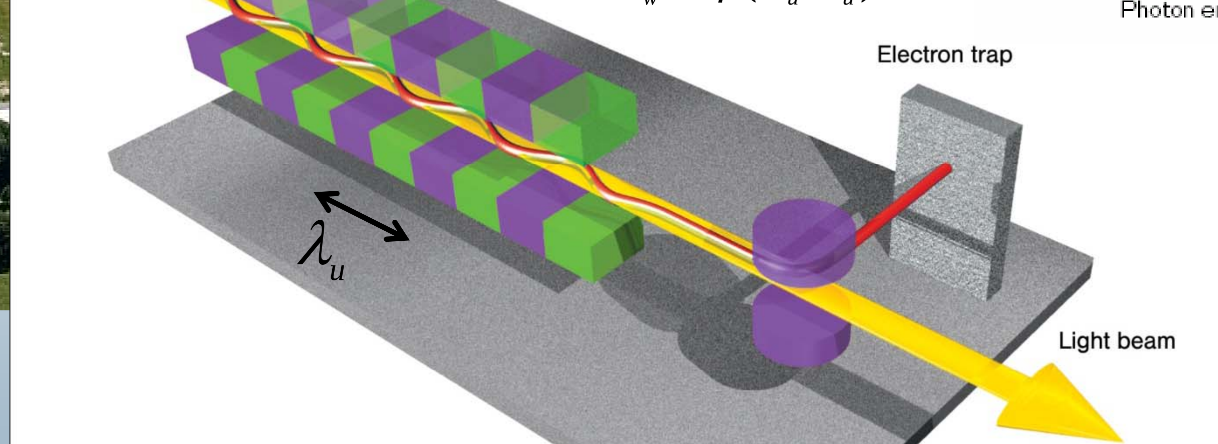
- Example: Free-electron lasers



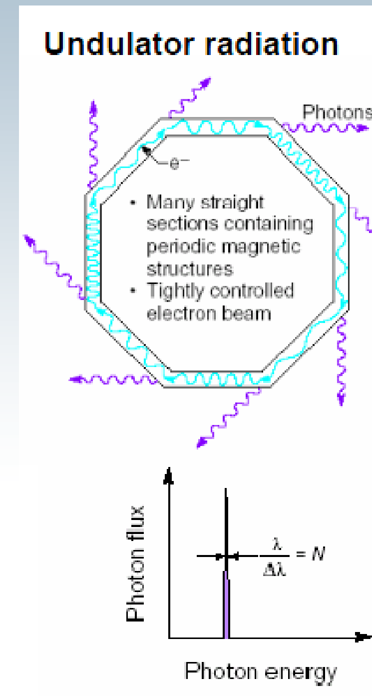
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1+K_w^2)$$

$$\gamma^2 = \frac{1}{1-v^2/c^2}$$

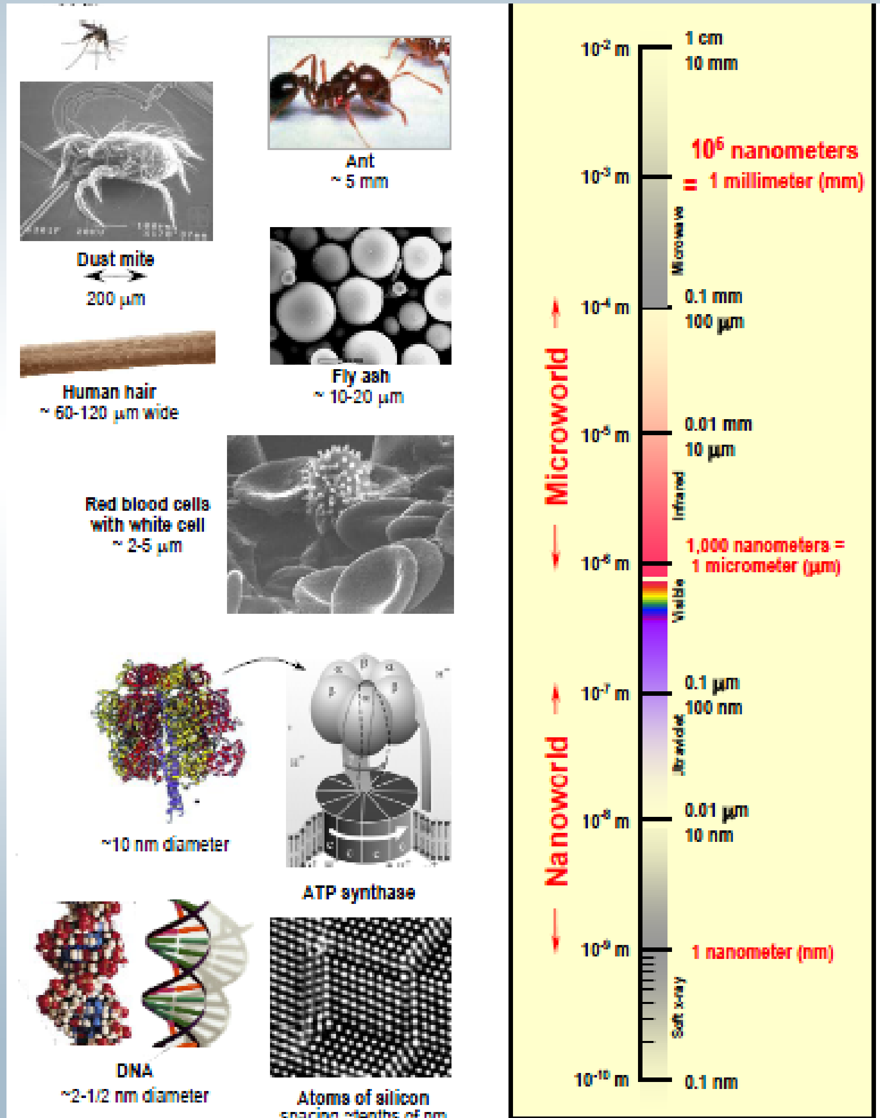
$$K_w = f(B_u, \lambda_u)$$

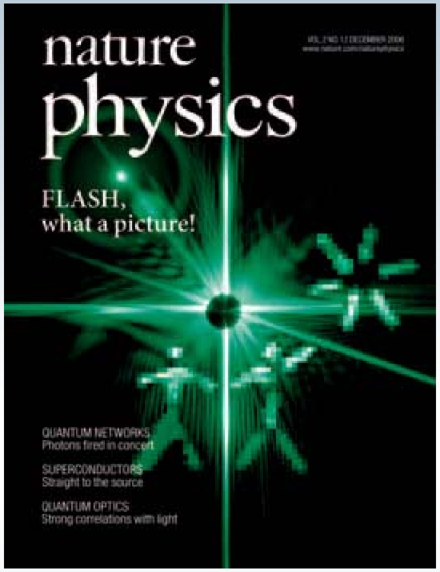


http://hasylab.desy.de

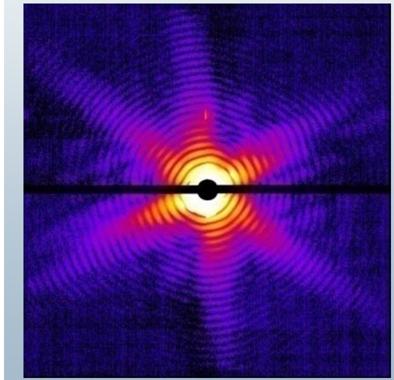


Light sources illuminate the nanoworld

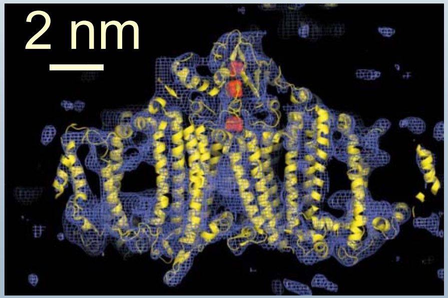




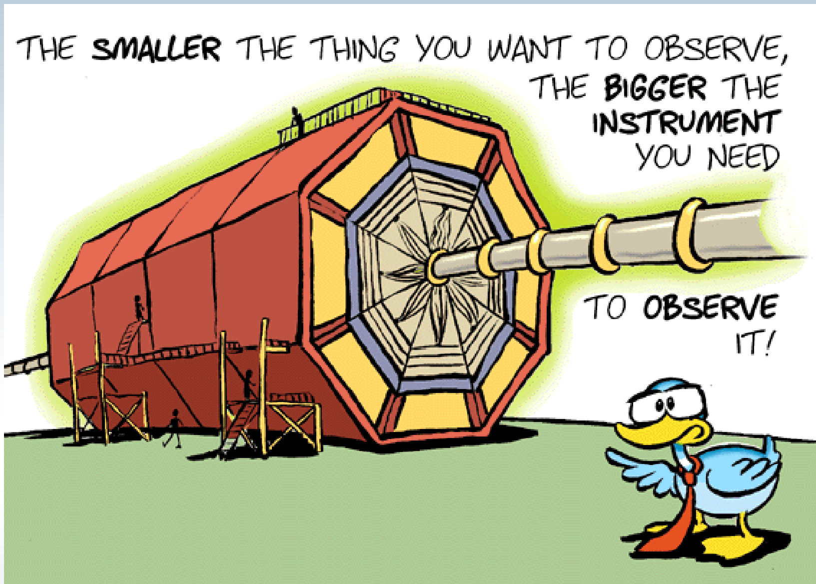
Virus image, LCLS, 2010

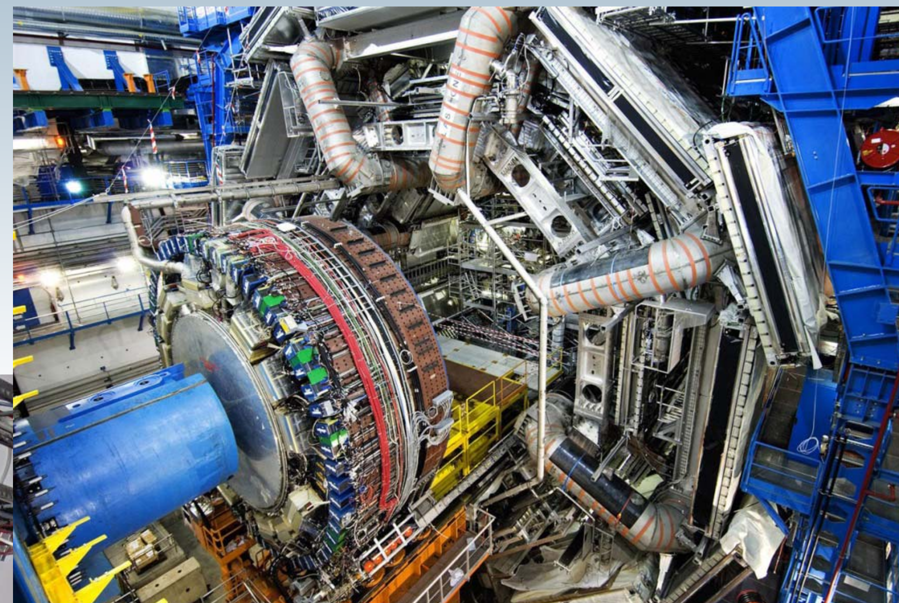


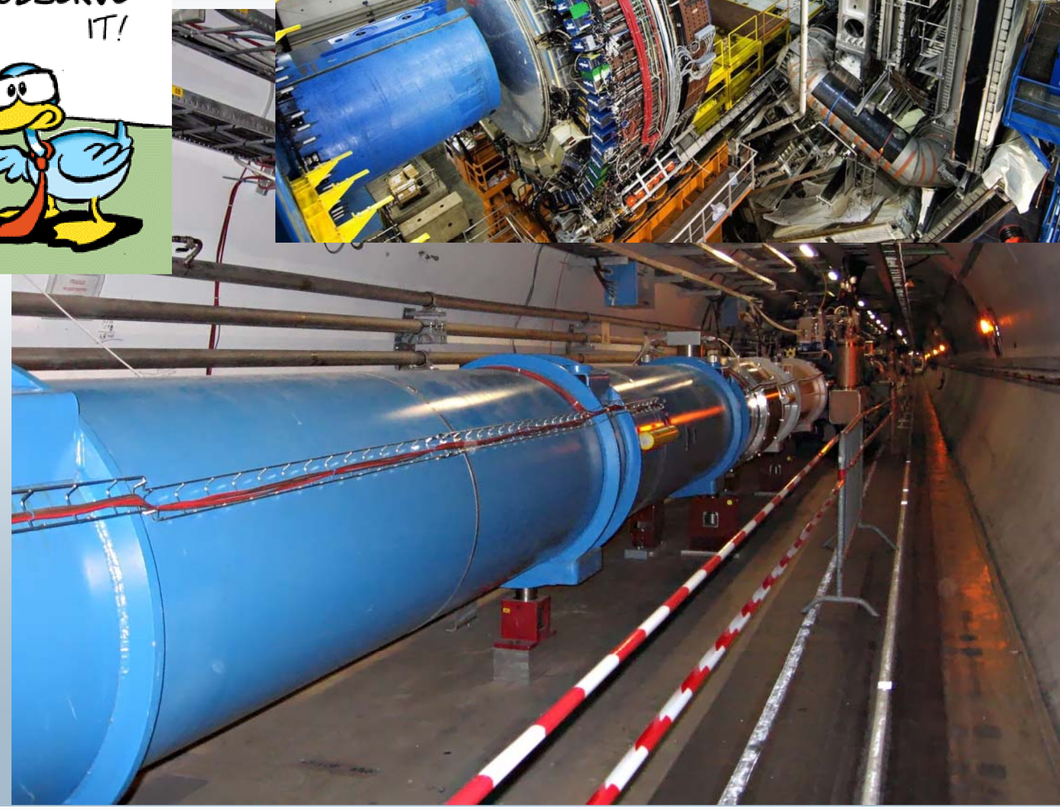
Protein image, LCLS



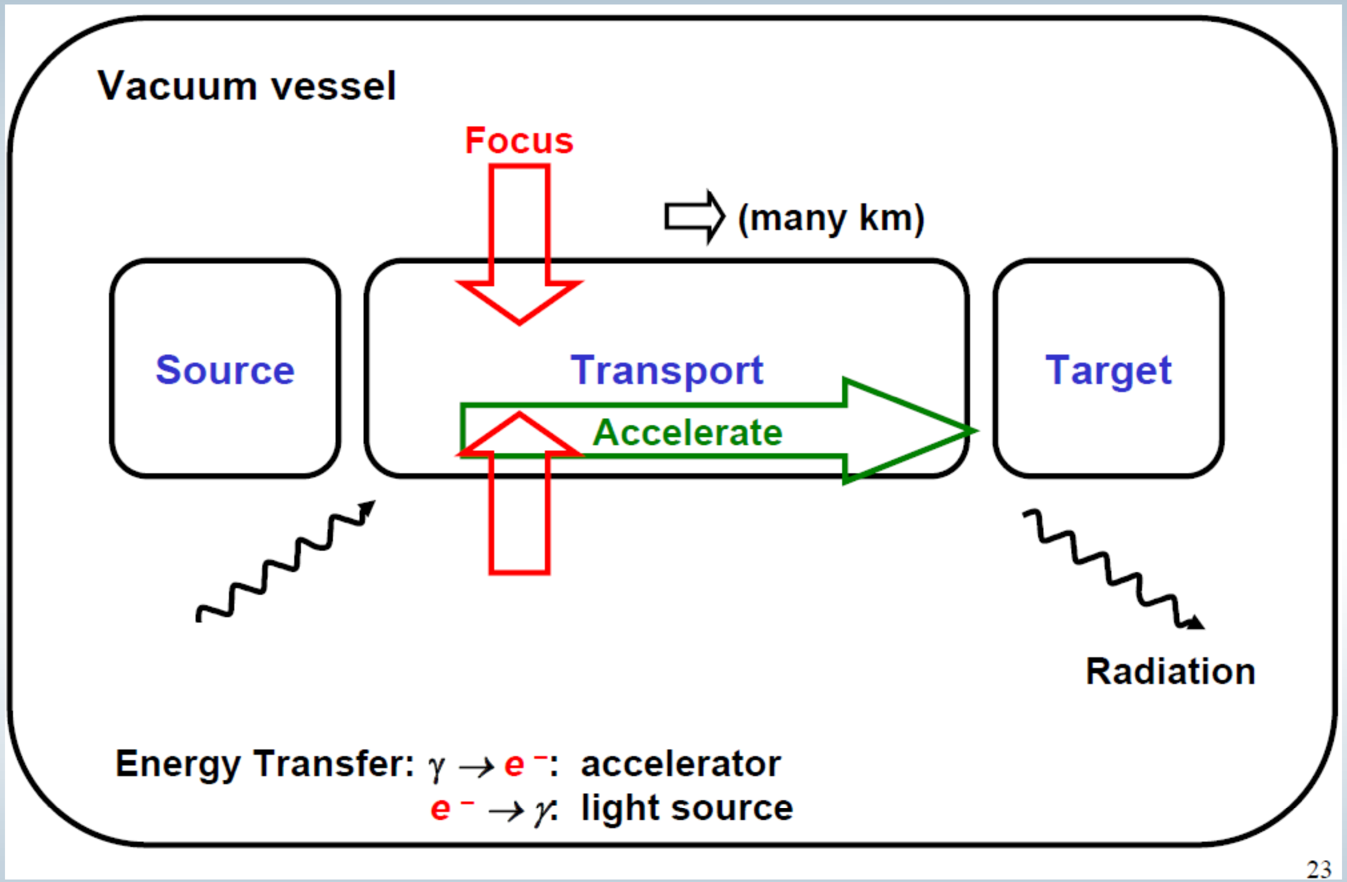
Accelerator are complex machines





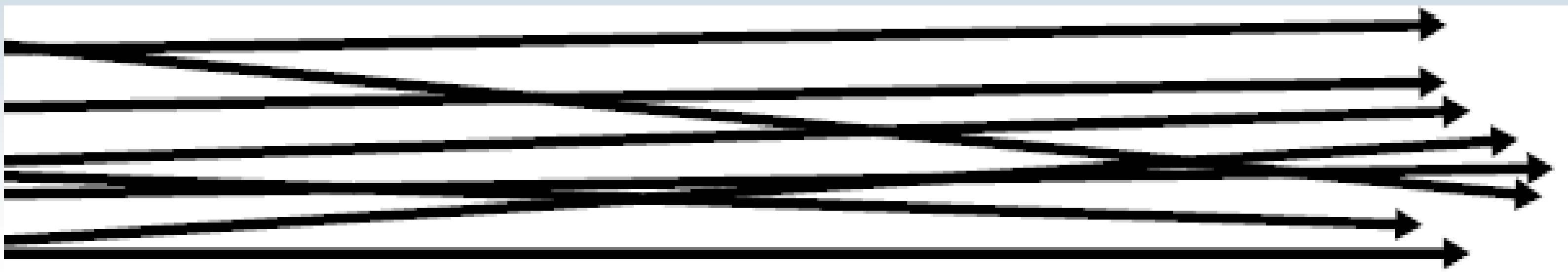


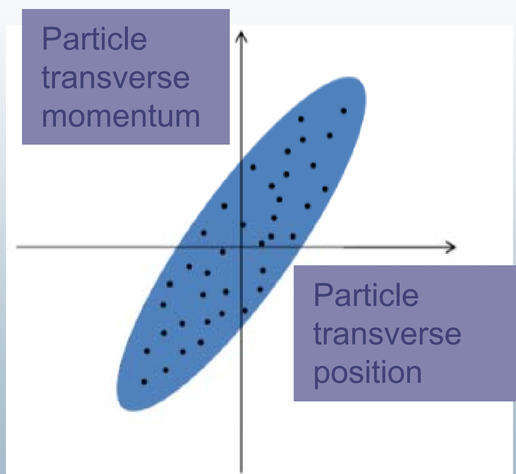
Accelerator simplified schematic



- Three main components: Source, transport, target

Defining beam quality

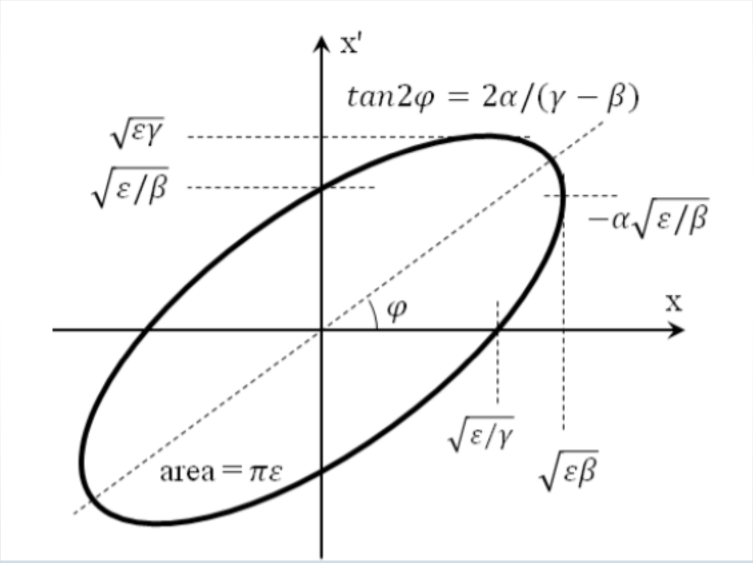




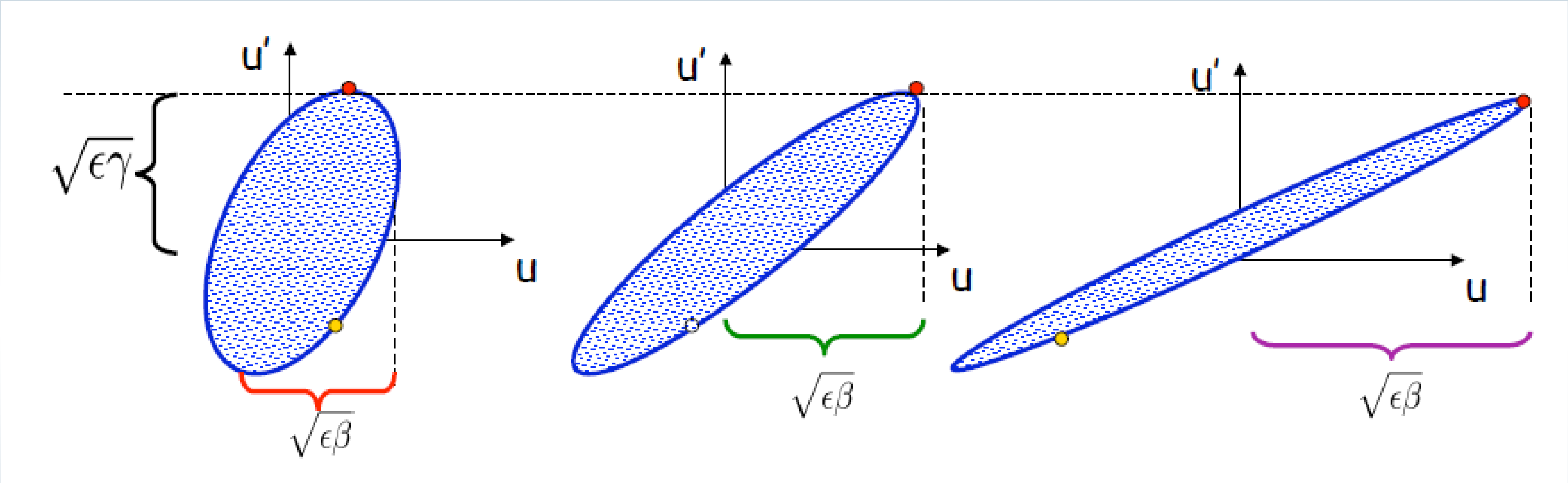
- Beam quality measures:
  - emittance (ε): volume of phase-space
  - Brightness (B): density of phase-space
- We desire high brightness & low emittance beams

Phase-space distribution

- A good approximation for the beam shape in phase space is an ellipse
- Three key parameters
  - Parameter α is related to the beam tilt
  - Parameter β is related to the size
  - Parameter ε, defines the beam quality
  - Parameter γ is just related to α and β
- The above parameters are known as Twiss parameters
- You will measure those in a later experiment



Beam ellipse in a drift

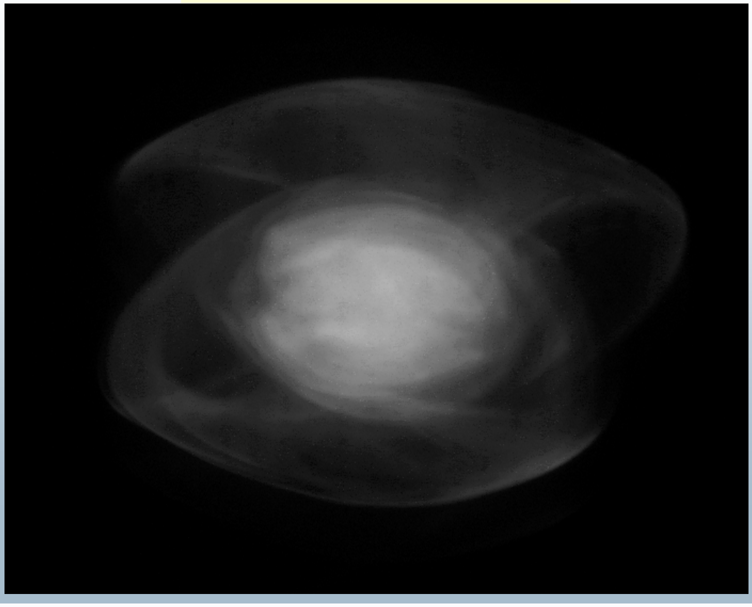


- Observation: Without focusing any beam would spread
- Magnets: Solenoids, quadrupoles
- Beam focusing will be discussed in a later lecture

Beams are complex systems

- In reality beam distribution changes
- Observe exotic phenomena
- Quality degradation mainly from mutual repulsion of particles called space-charge (SC).

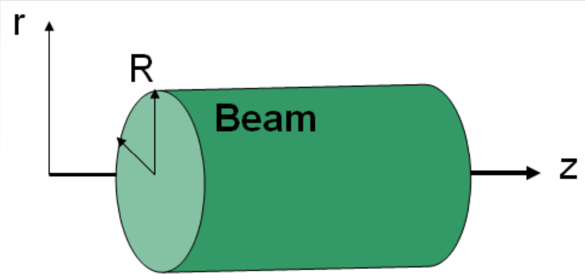
Irregular beam



Irregular galaxy

Space-charge effect

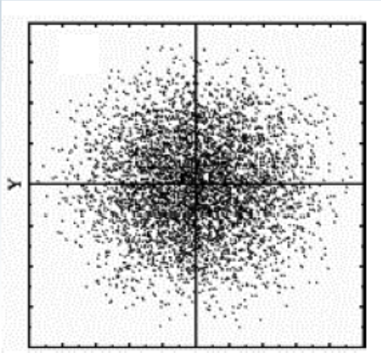
- Beam can be treated as a “continuous” charged medium



- Gauss’ Law: $E_r = \dfrac{Ir}{2\pi\varepsilon_0 R^2 v}$
- Ampere’s Law: $B_\theta = \dfrac{\mu_0 Ir}{2\pi R^2} = \dfrac{vE_r}{c^2}$
- Lorenz Force Law: $F_{r,sc} = q(E + v \times B) = \dfrac{qI}{2\pi\gamma^2\varepsilon_0 v R^2} r = C(R)r = \dfrac{qE_r}{\gamma^2}$
- SC force is pushing the particles out
- SC can be strong near the beam source (small gamma)
- SC negligible at high energies!

RMS quantities

- In reality, real beam distributions are not uniform in phase space and, in practice, it can be difficult to locate the beam edge.



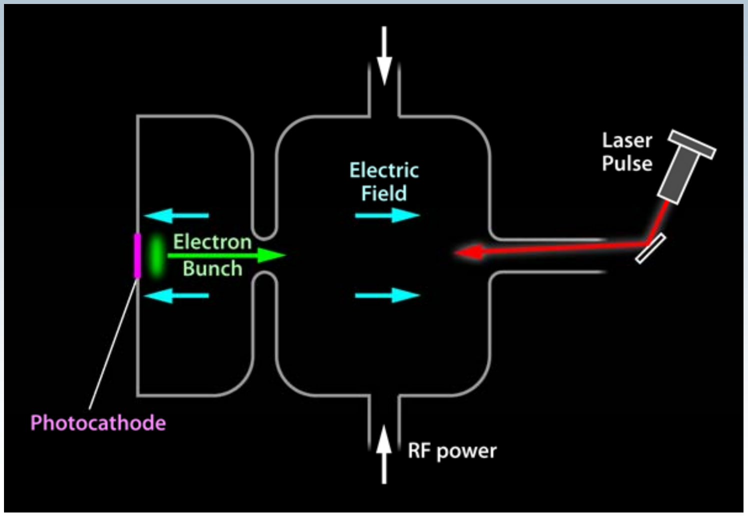
- Most often, we will deal with RMS quantities. The RMS size of a beam with N particles is defined as:

$$u_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{i}^{N}(u_i - u_{\mathrm{avg}})^2}$$

- And the RMS momentum spread, is:

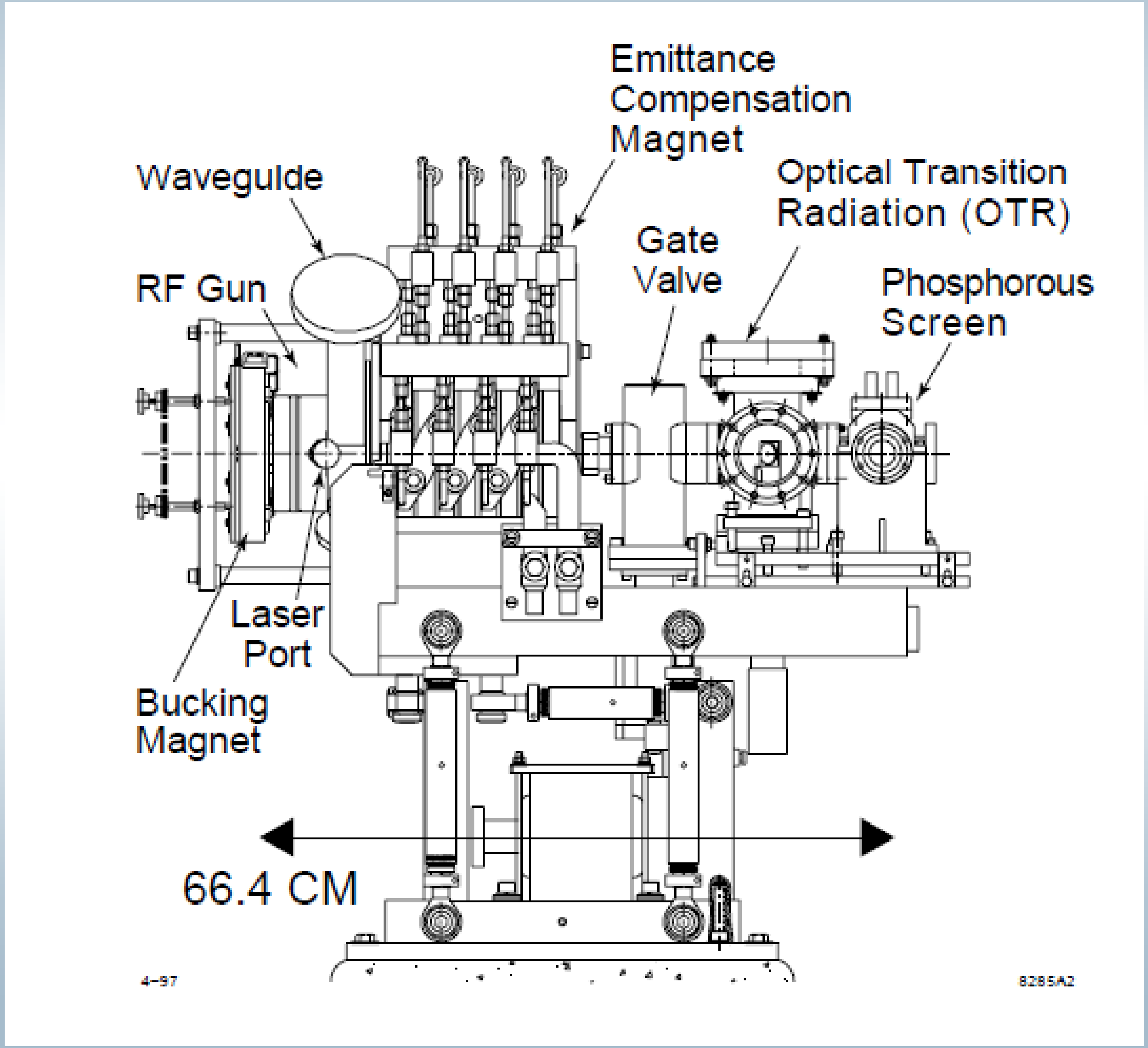
$$u'_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{i}^{N}(u_i' - u'_{\mathrm{avg}})^2}$$

Photo-injectors



- Major components:
  - **Photocathode** that releases picosecond bunches when irradiated with optical pulses from a ultrafast laser
  - **Electron gun** that acceleates electron from the rest
  - **Solenoid** to properly focus the beam
  - **Drive laser** to gate the emission of the electrons from the photocathode
  - **Linear accelerator** to further accelerate electrons
  - **Diagnostic tools** such as Faraday cup or deflecting cavity

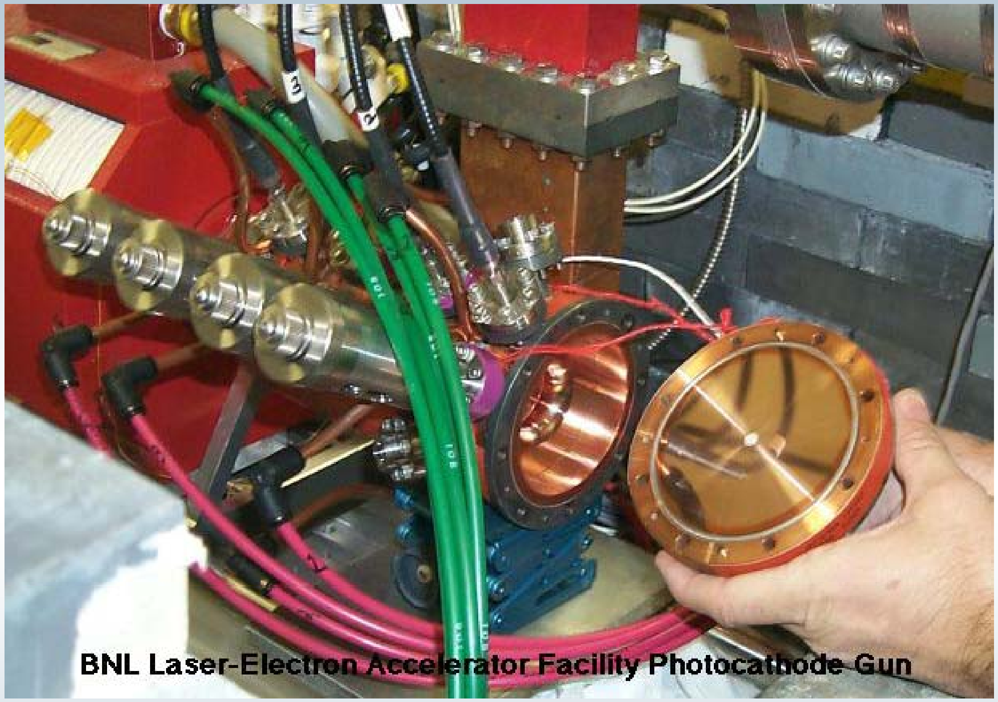
ATF photo-injector layout



ATF Parameters

- 1.6 cell copper cavity
- 2856 MHz (S-Band)
- Cu cathode with $QE=4.5\times10^{-5}$
- Max rf gradient 110-130 MV/m
- Nd:YAG laser energy 30 microJ at 266 nm
- Laser spot size on cathode: 1 mm
- Charge: 0.001 -3 Nc
- Energy: ~ 5 MeV

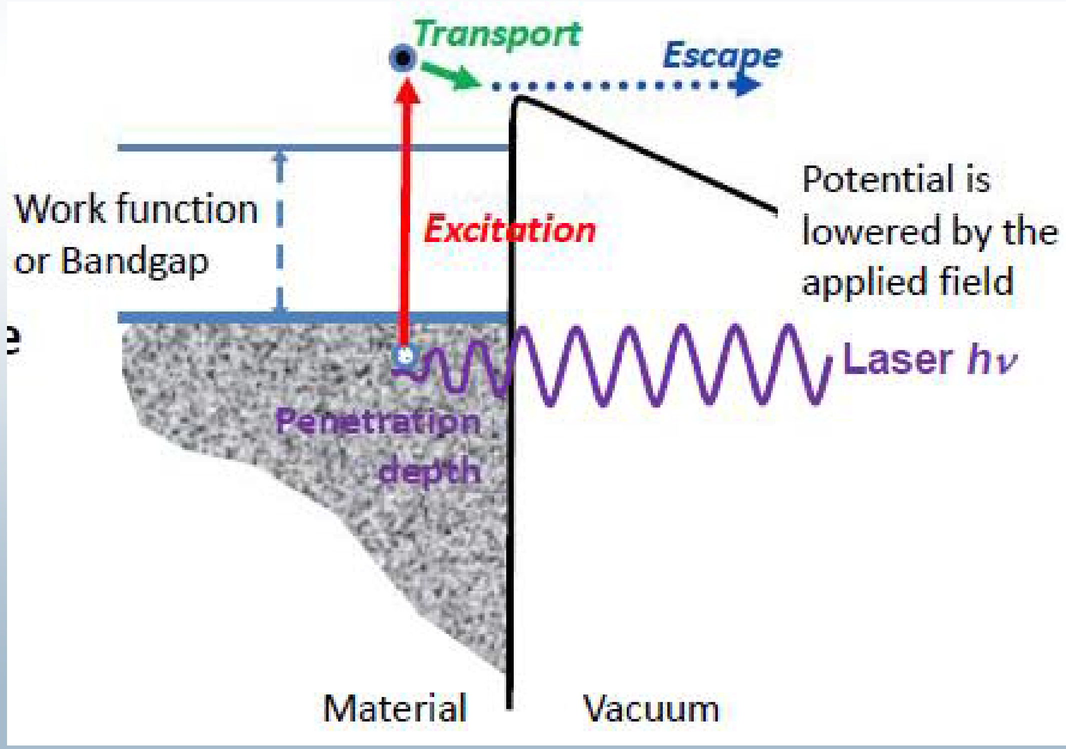
Photo-cathode



- Cathodes are a fundamental part of electron sources
- The gun performance will depend on the QE of the cathode
- QE is defined as the number of photo-emitted electrons per photon impinging ton the cathode

Photo-emission principle

- Photon absorption by electron
- Electron motion toward the crystal surface
- Electron escape through the potential barrier



Examples of photo-cathodes

- Metal: Cu
  - Low QE ~ 10^{-5}
  - Example: ATF injector at BNL
- PEA semiconductor: Cesium Telluride
  - Robust
  - High QE > 5%
- NEA semiconductor: Gallium Arsenide
  - High QE > 10%
  - Allows polarized electrons
  - Example: Gatling gun at SBU

The end…

- Questions?