Class Procedure for March 2

- Short lecture on accelerators with emphasis on beam sources. Discuss how a electron beam is born in a accelerator (photo-injector).
- Will take a break
- Then, you will be divided into two groups
- Group A will learn about photo-injectors in the experiment (~50 min)
- Group B will simulate a photo-injector (~50 min)
- You will switch

Introduction to particle accelerators with emphasis on beam sources

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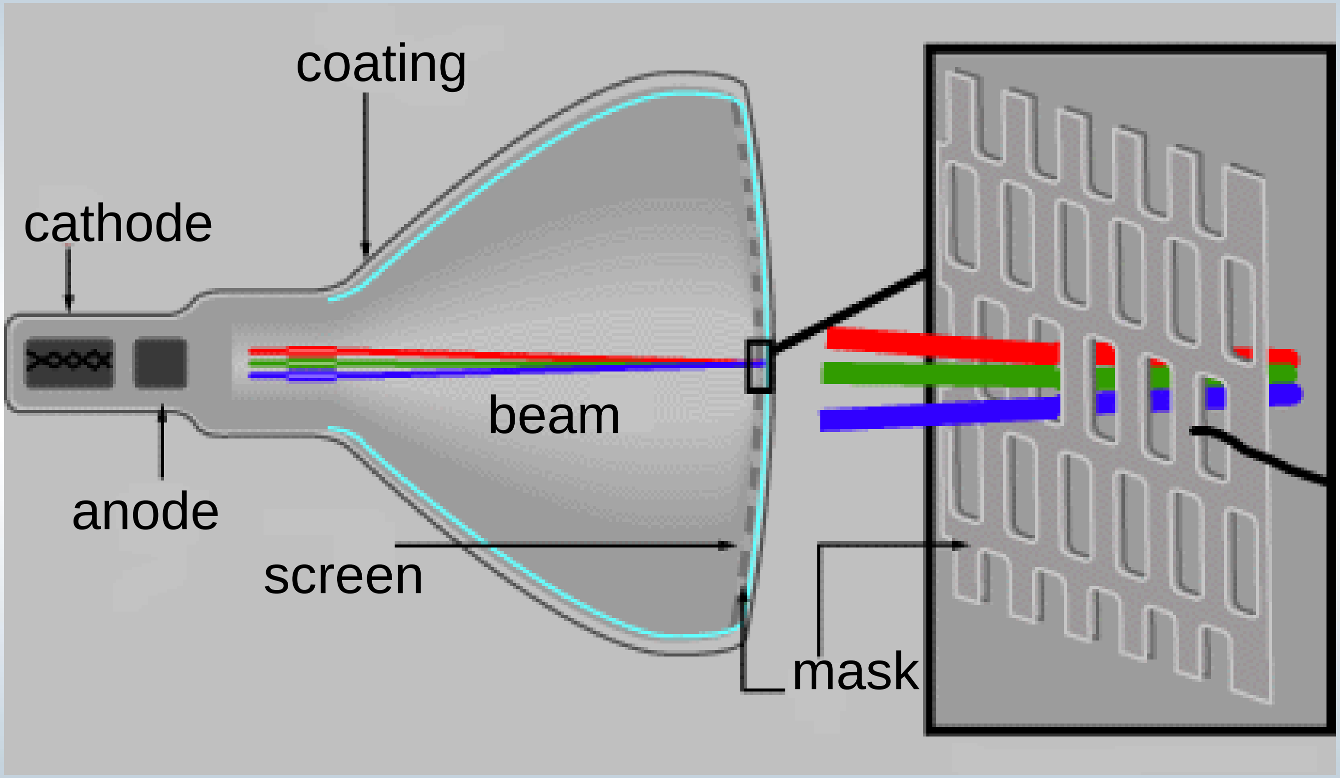
PHY 542

March 02, 2015

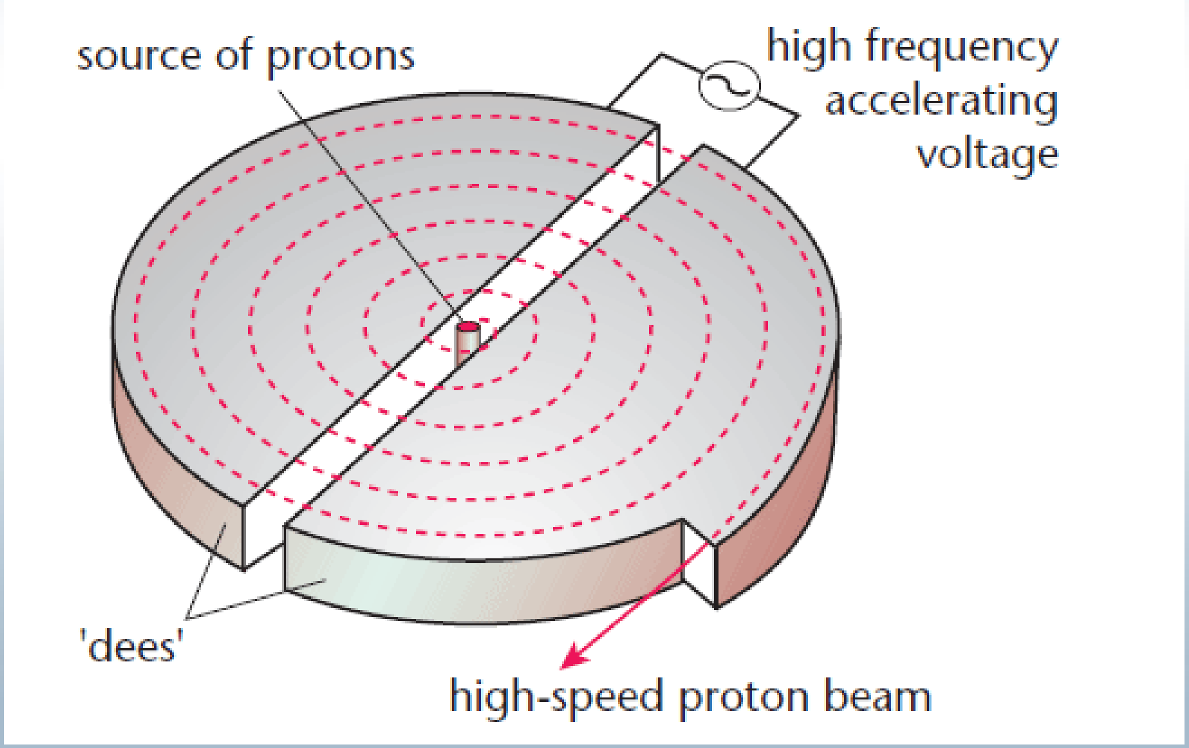
Do you know how a TV works?



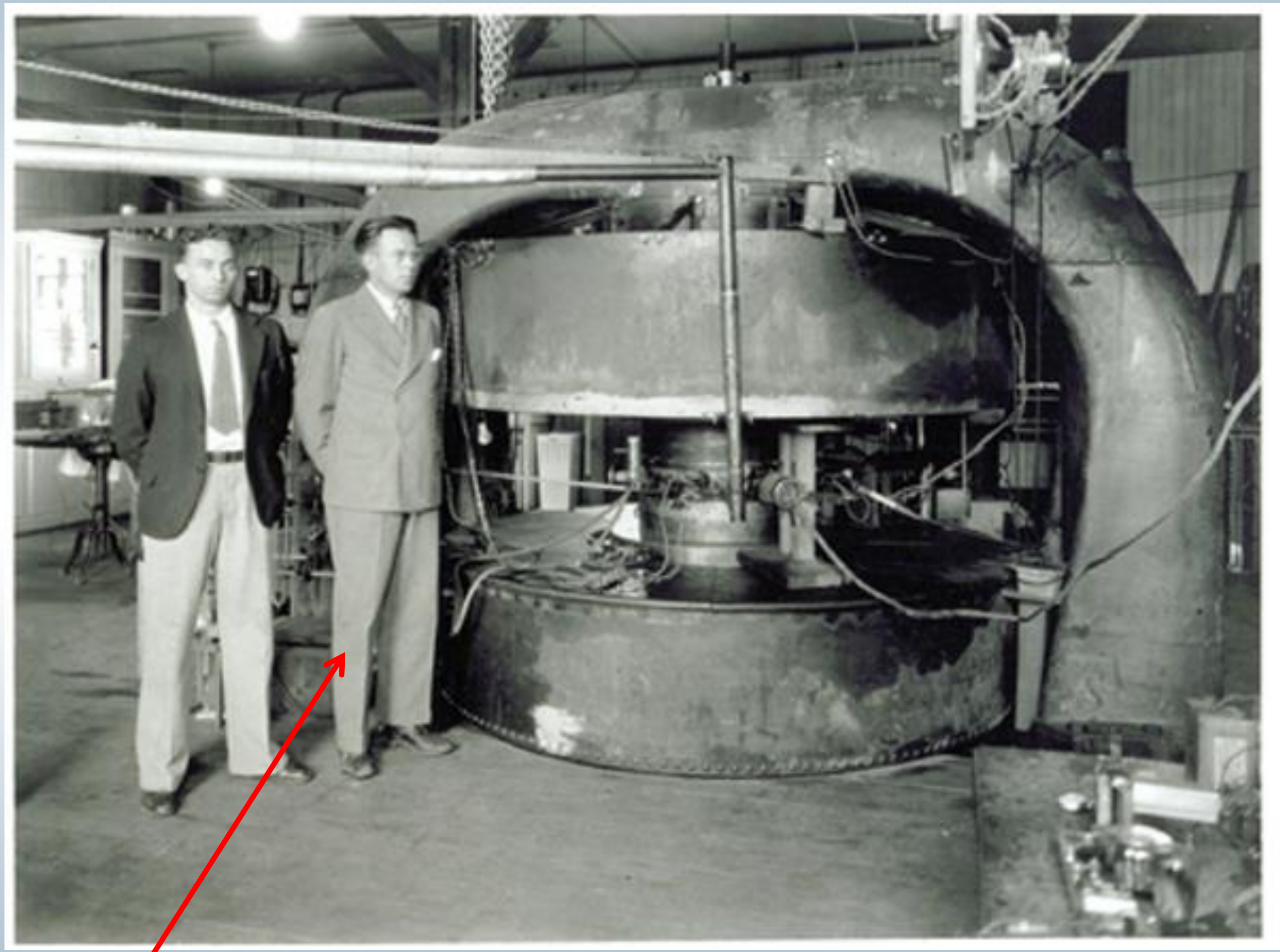
- Did you know that you have (or used to have) a type of particle accelerator in your house?

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

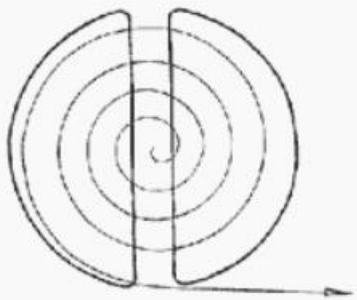


Cyclotron in 1932

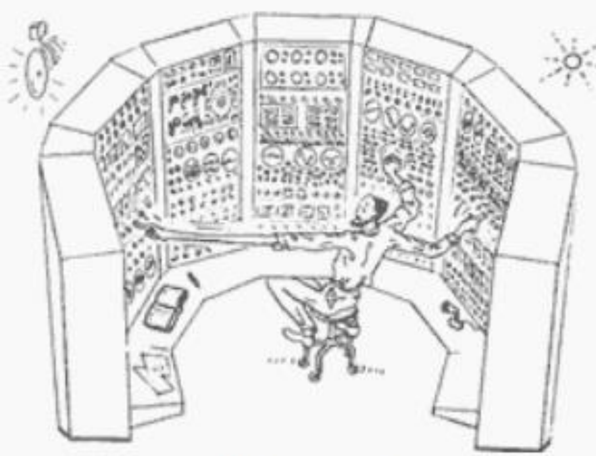


Ernest Orlando Lawrence (inventor)

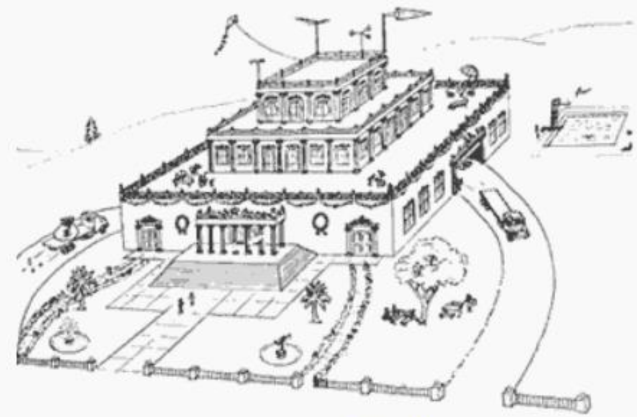
Cyclotron: Different points of view



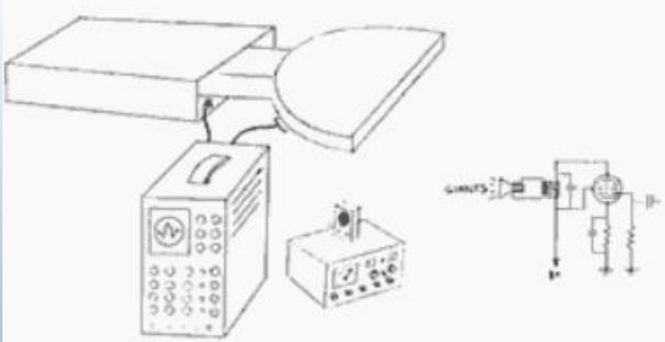
...the inventor



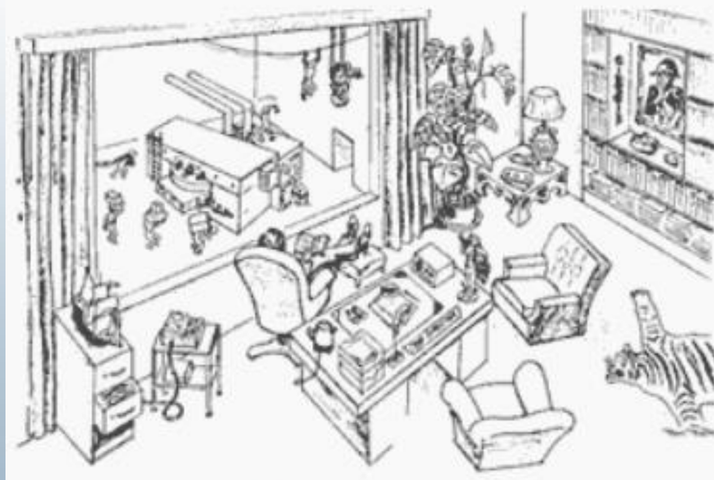
...the operator



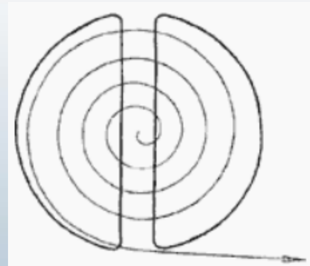
...the governmental funding agency



...the electrical engineer

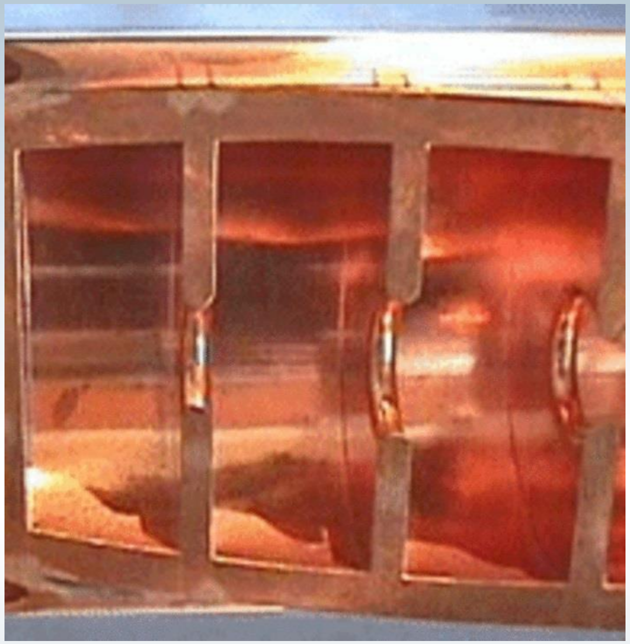


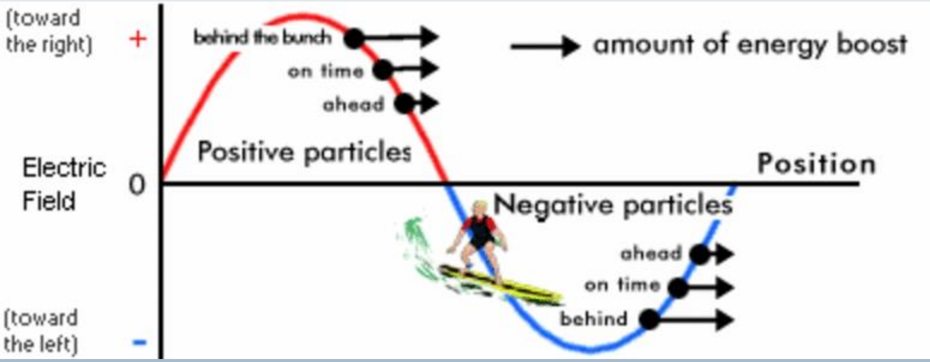
...the laboratory director



...the student

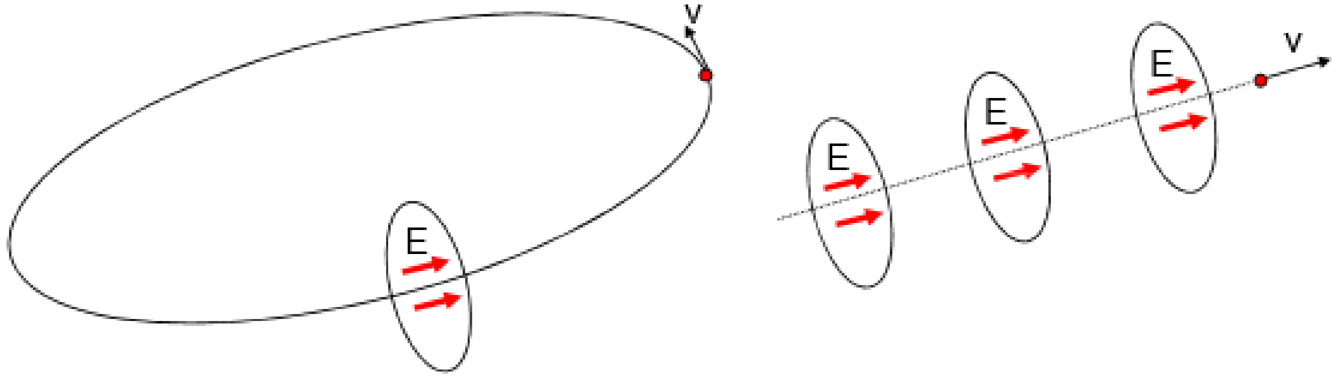
RF Cavities: Wave acceleration





Types of accelerators

- Two approaches for accelerating with time-varying fields
- Make an electric field along the direction of particle motion with Radio-Frequency (RF) Cavities



Circular Accelerators

Use one or a small number of Radio-frequency accelerating cavities and make use of repeated passage through them.

This approach leads to circular accelerators: Cyclotrons, synchrotrons, and their variants.

Linear Accelerators

Use many accelerating cavities through which the particle passes only once:

These are linear accelerators.

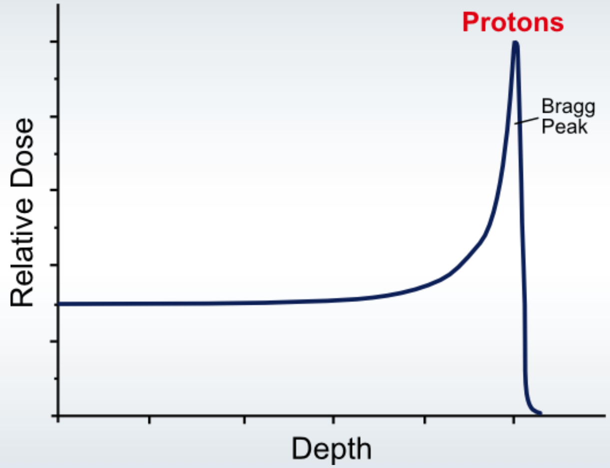
Suitable for heavy particles i.e protons

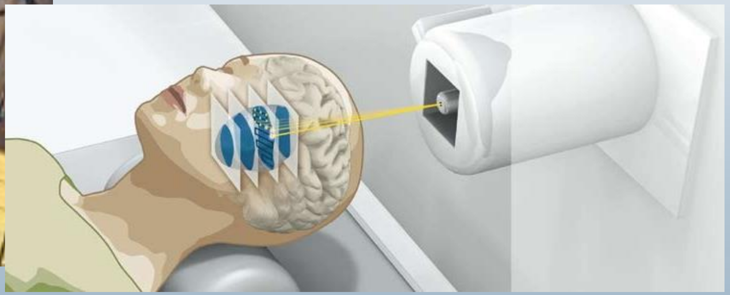
Suitable for light partcles, i.e Electrons. Can you guess why?

LHC – The world’s largest accelerator

Accelerators for medical treatment

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

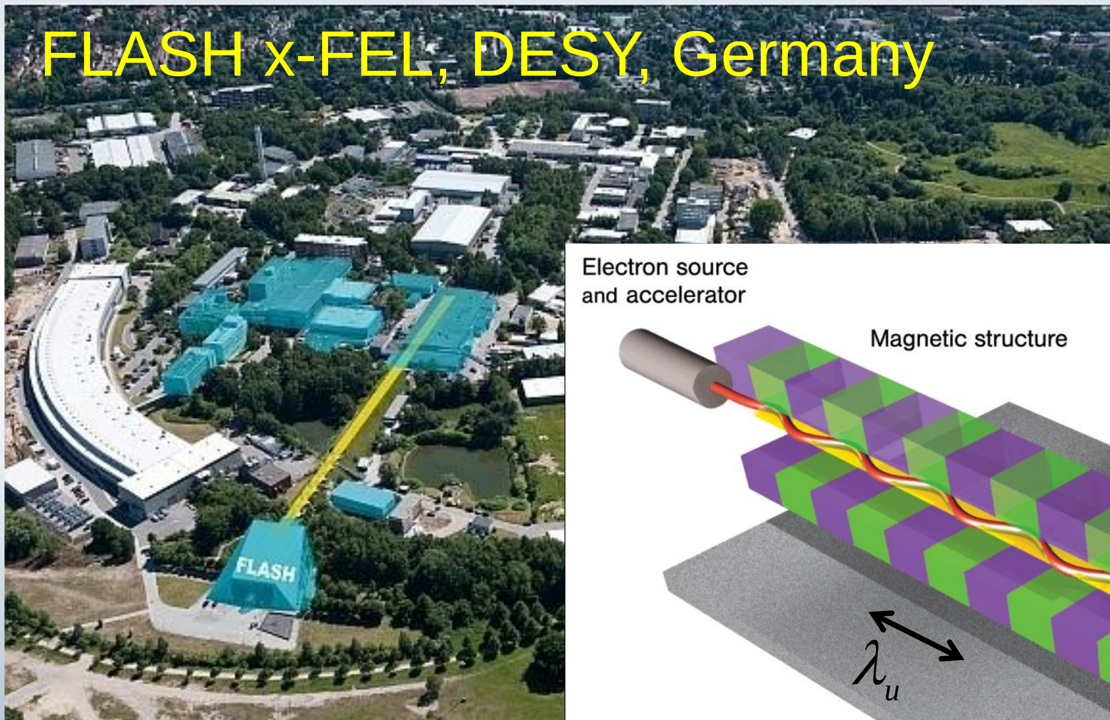




http://www.klinikum.uni-heidelberg.de

Accelerators as light sources

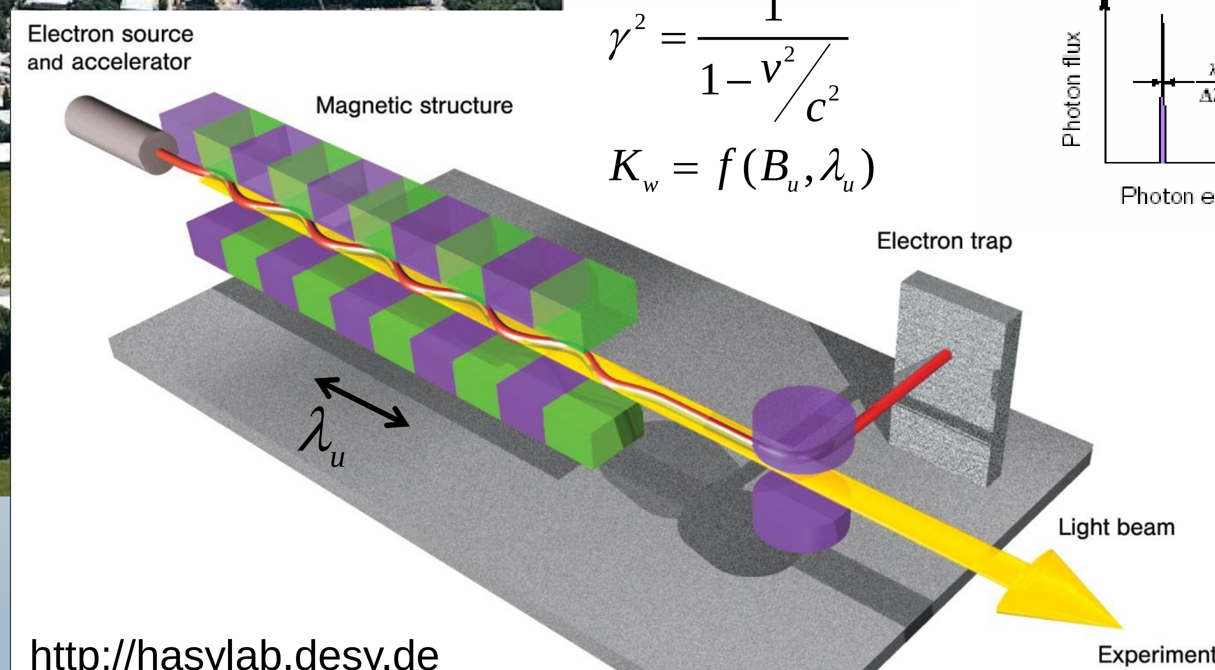
- Example: Free-electron lasers



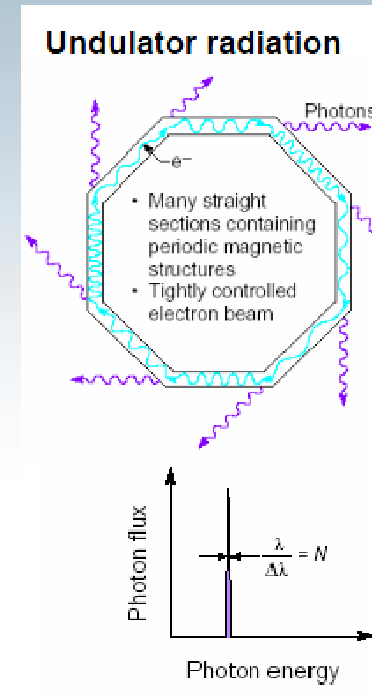
$$\boxed{\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K_w^2\right)}$$

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

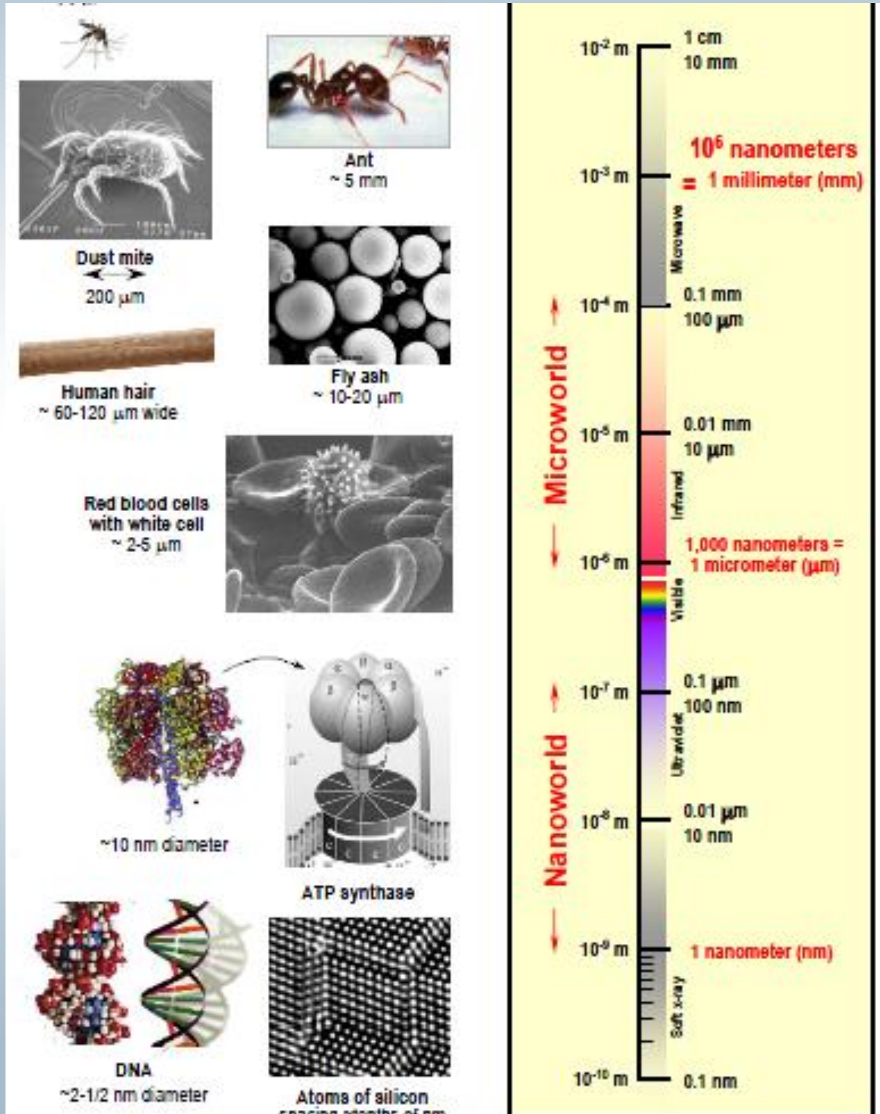
$$K_w = f\left(B_u, \lambda_u\right)$$

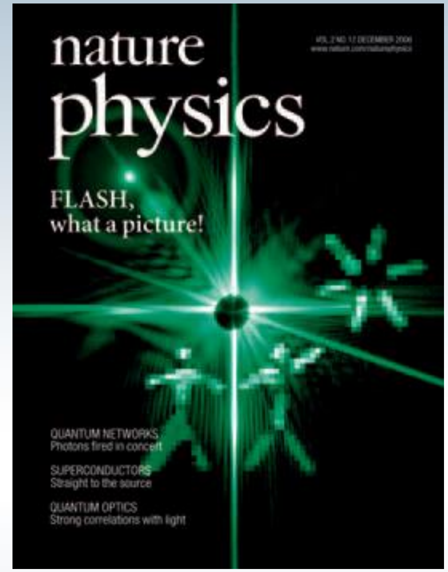


http://hasylab.desy.de

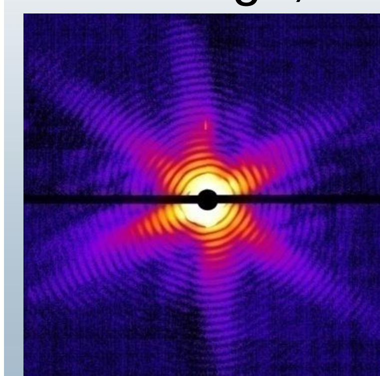


Light sources illuminate the nanoworld

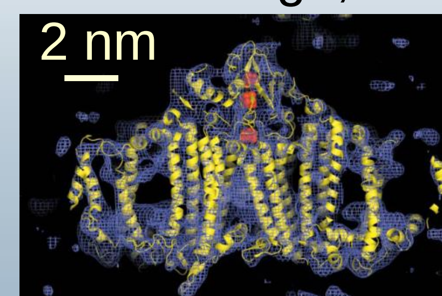




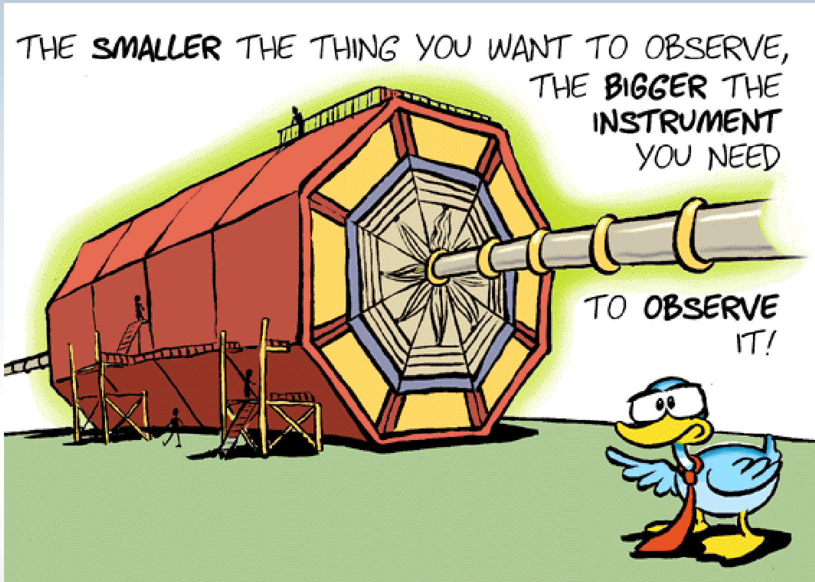
Virus image, LCLS, 2010

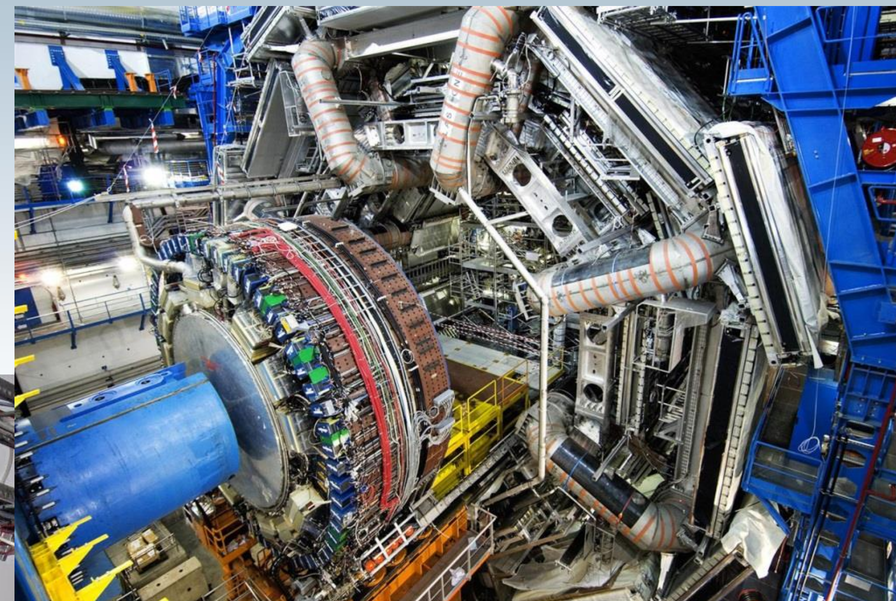


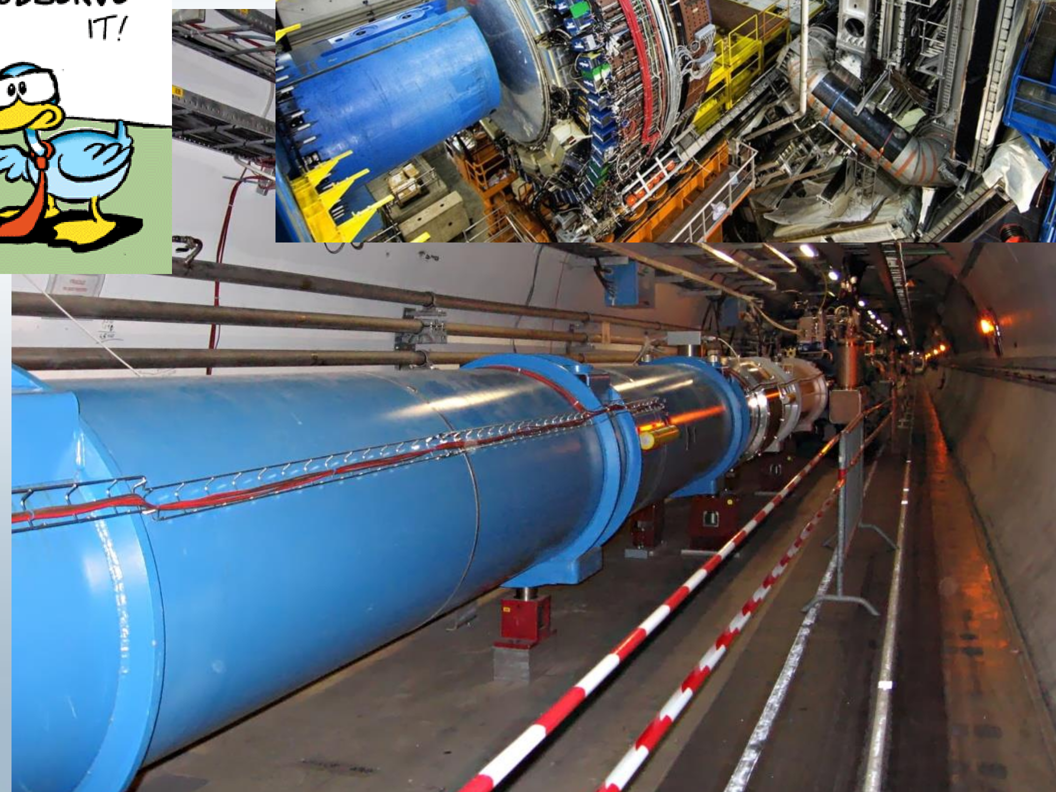
Protein image, LCLS



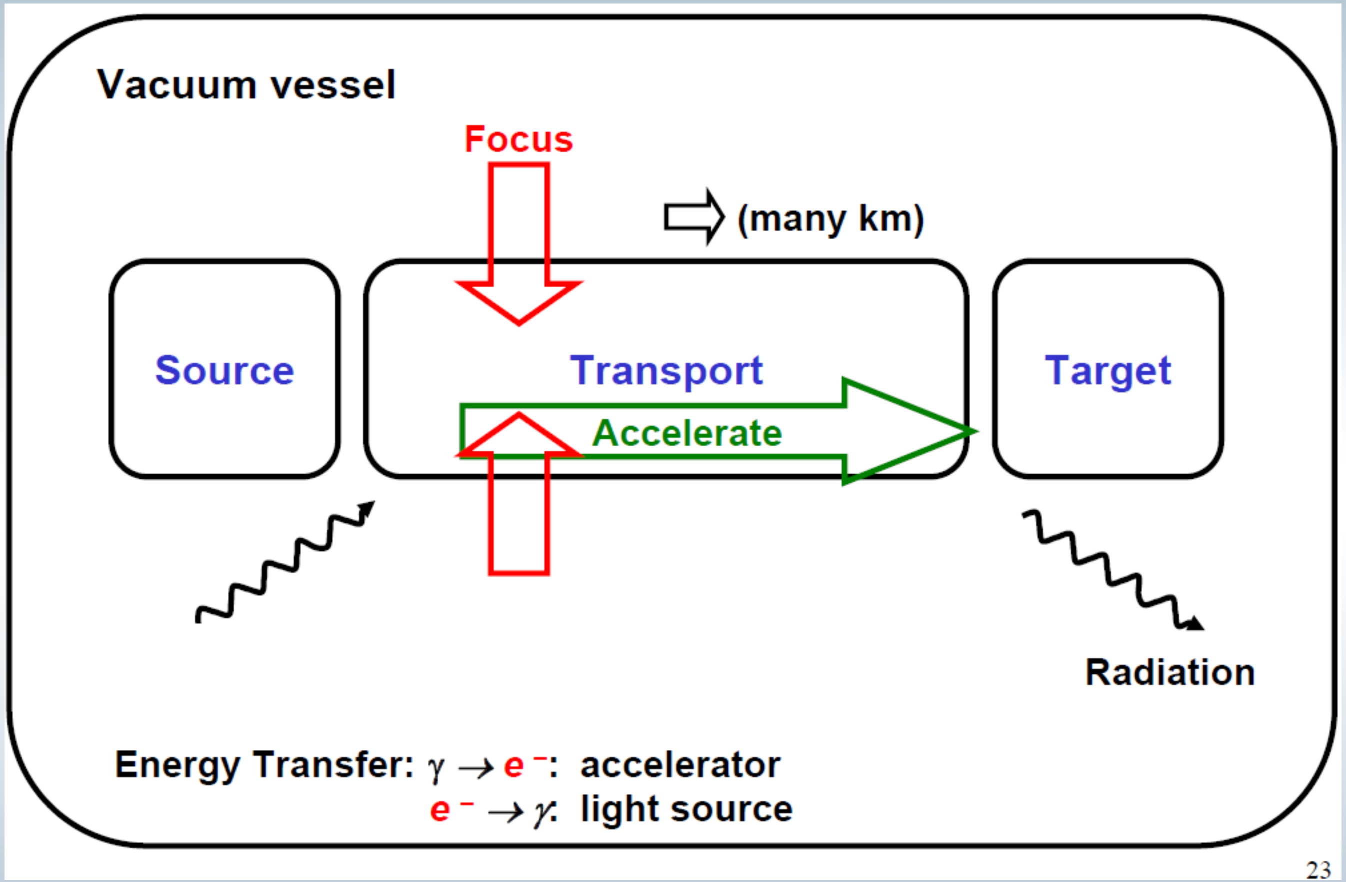
Accelerator are complex machines





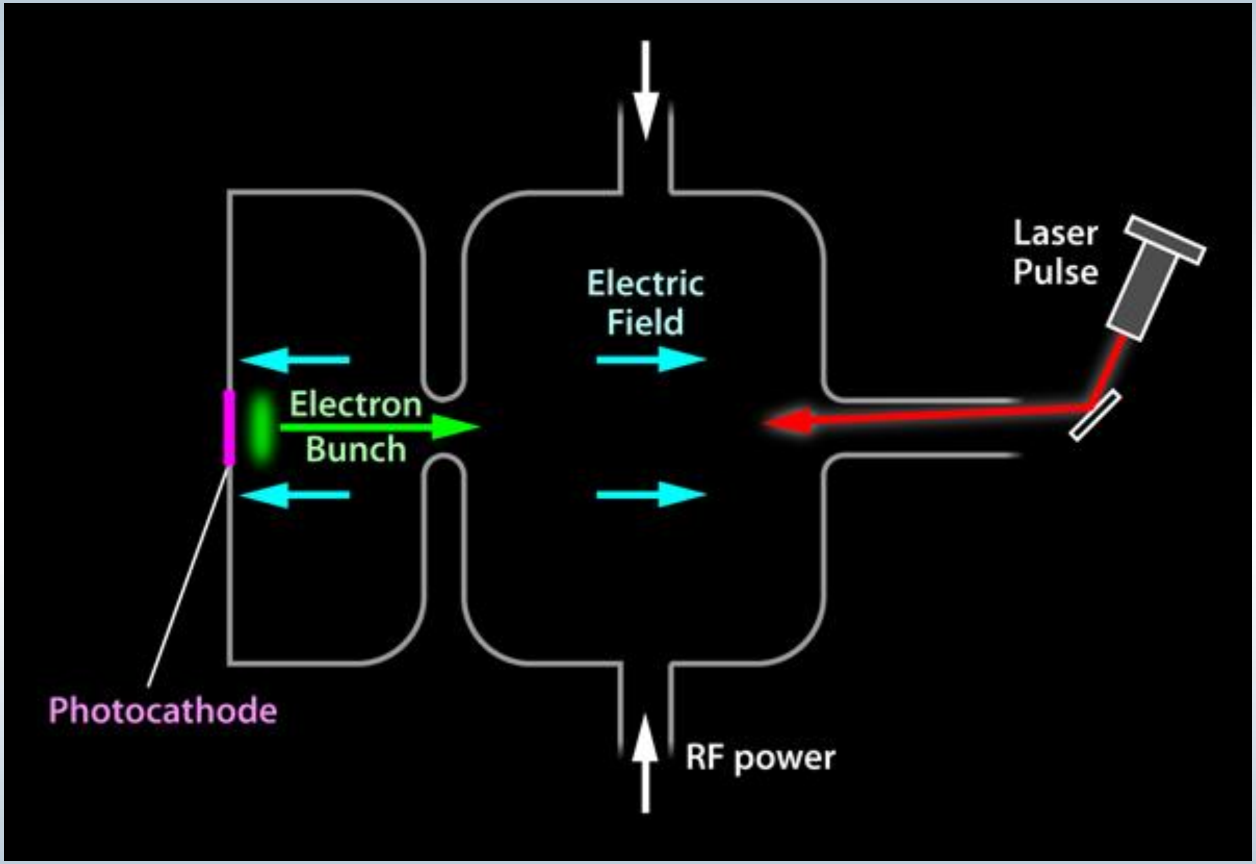


Accelerator simplified schematic



- Three main components: Source, transport, target
- Today we will focus on the source

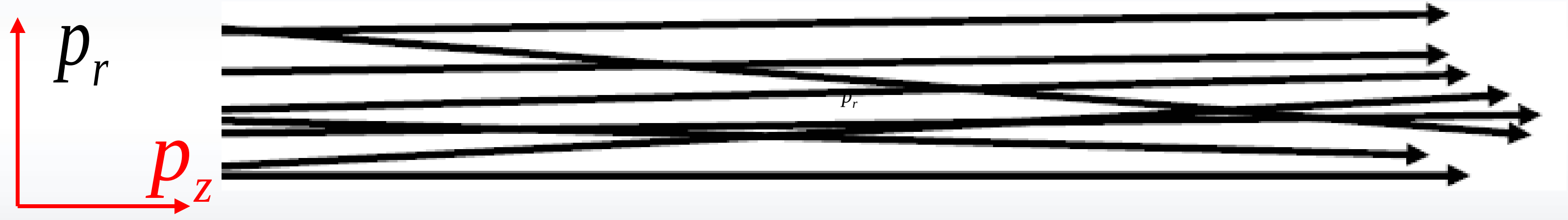
How particles are born: Photo-cathodes

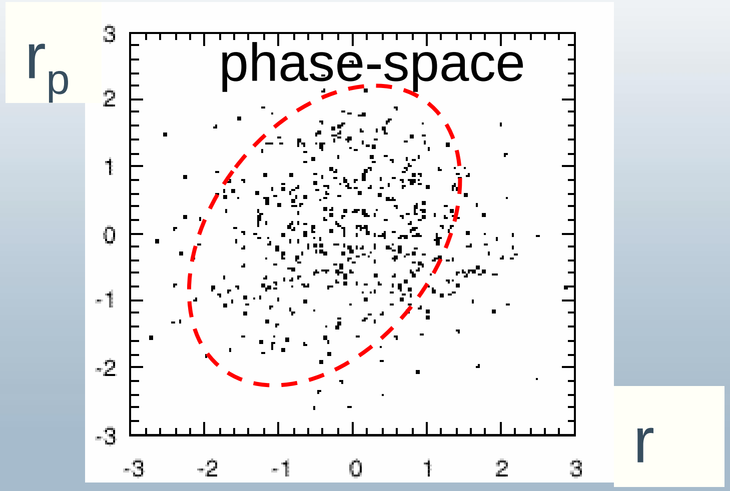


- Your experiment and simulation exercise will be on that
- We will come back into this subject shortly

Main Goal: Preservation of beam quality

- In reality beams are not perfect laminar
- Paraxial approximation: $p_r << p_z$ and $r_p = p_r/p_z \approx p_r/p$





Ideal beam distribution

A good approximation for the beam shape in phase space is an ellipse. Any ellipse can be defined by specifying:

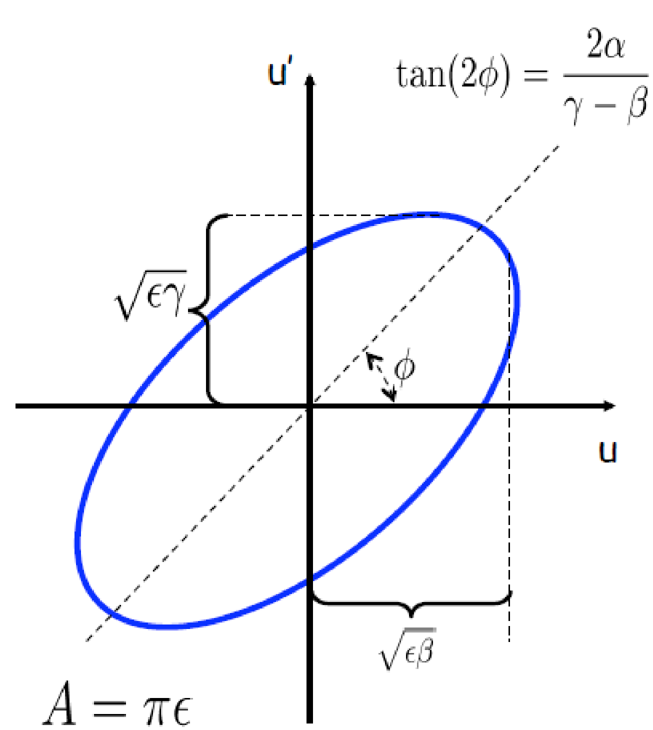
- ✓ Area
- ✓ Shape
- ✓ Orientation

We choose 4 parameters – 3 independent, 1 dependent:

α - related to beam tilt
β - related to beam shape and size
ε - related to beam size
γ - dependent on α and $\boldsymbol{\beta}$.

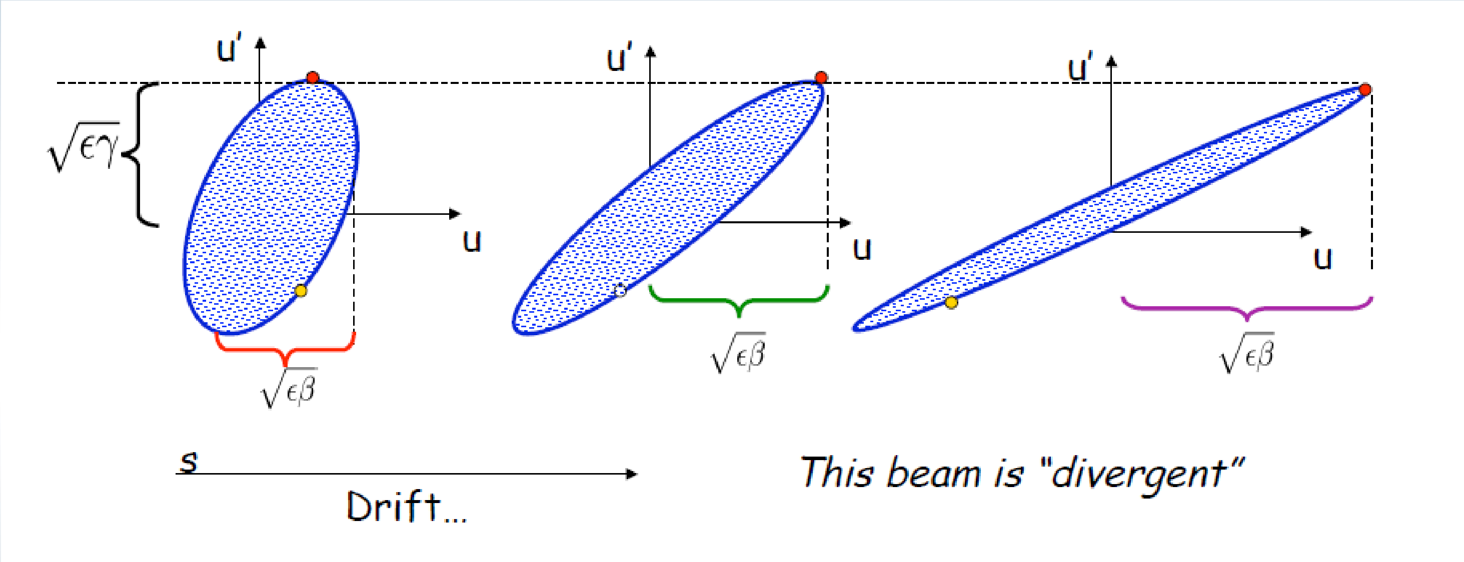
These are the "Twiss Parameters" (or "Courant-Snyder Parameters")

Beam Ellipse in Phase Space:



- The phase space area of the beam is called emittance. **Emittance is a parameter used to gauge beam quality**.

Beam ellipse in a drift

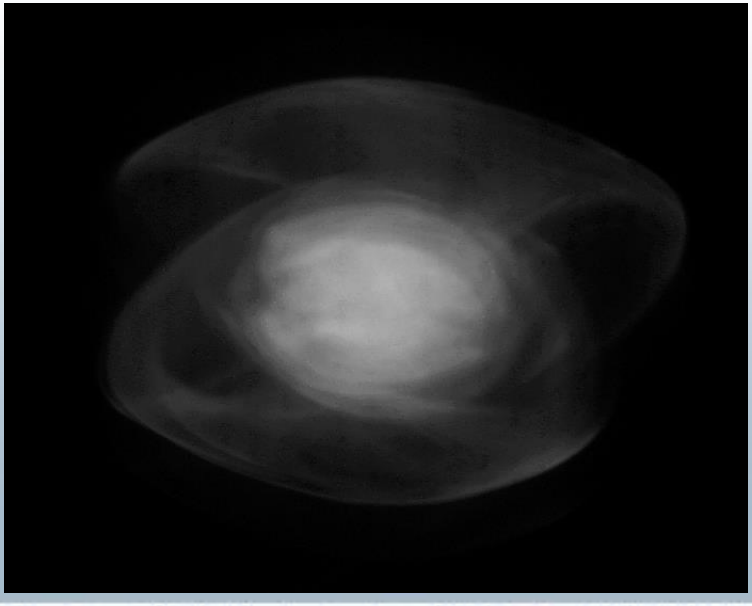


- Observation: Without focusing any beam would spread
- Magnets: Solenoids, quadrupoles
- Beam focusing will be discussed in a later lecture

Beams are complex systems

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

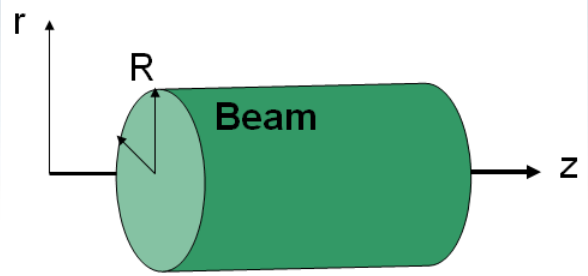
Irregular beam (from my PhD thesis)



Irregular galaxy

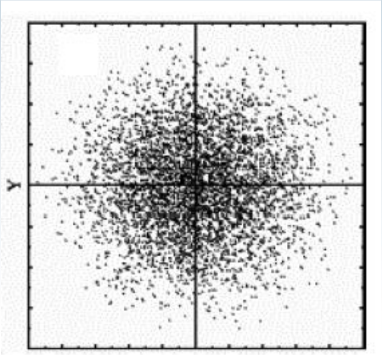
Space-charge effect

- 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:

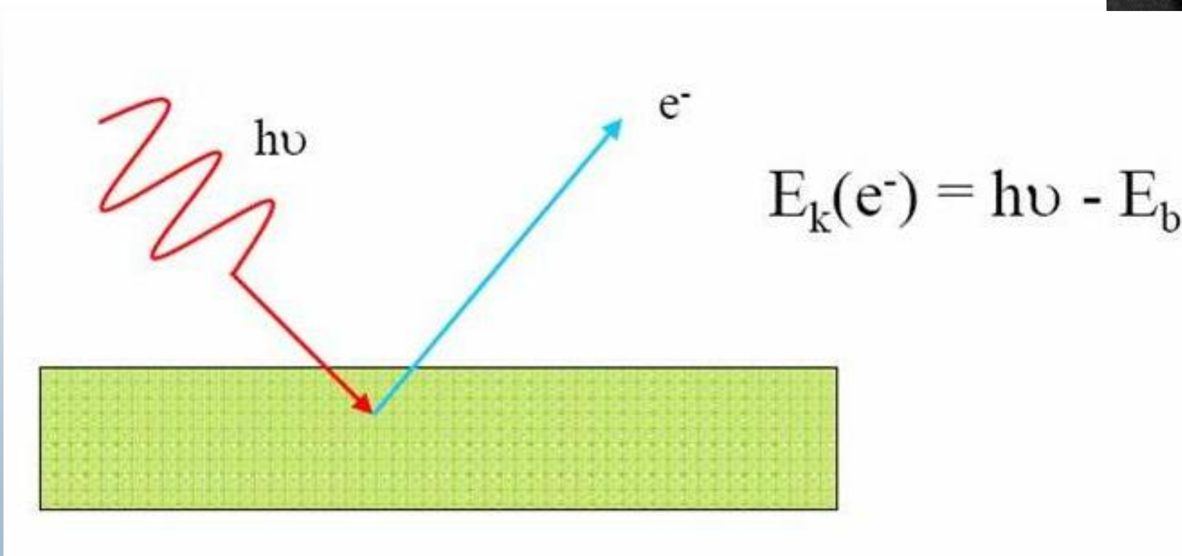
$$u_{\text{RMS}} = \sqrt{\frac{1}{N}\sum_{i}^{N}(u_i - u_{\text{avg}})^2}$$

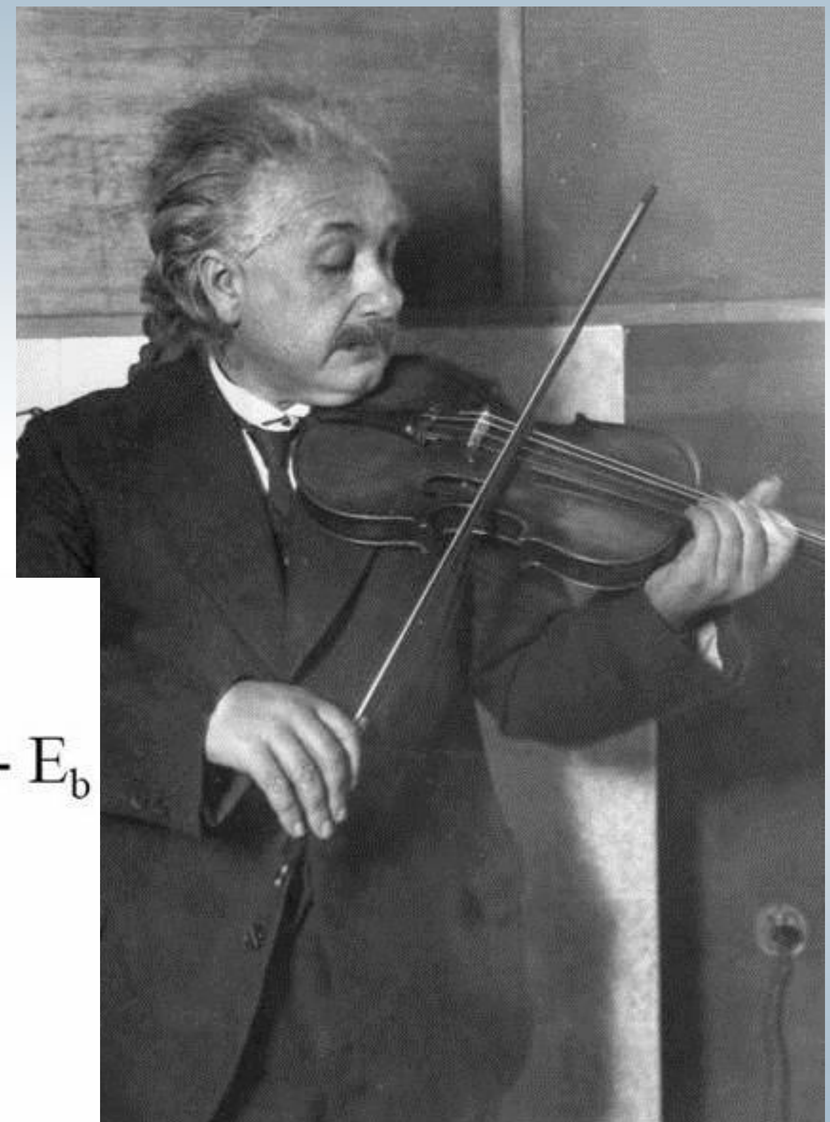
- And the RMS momentum spread, is:

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

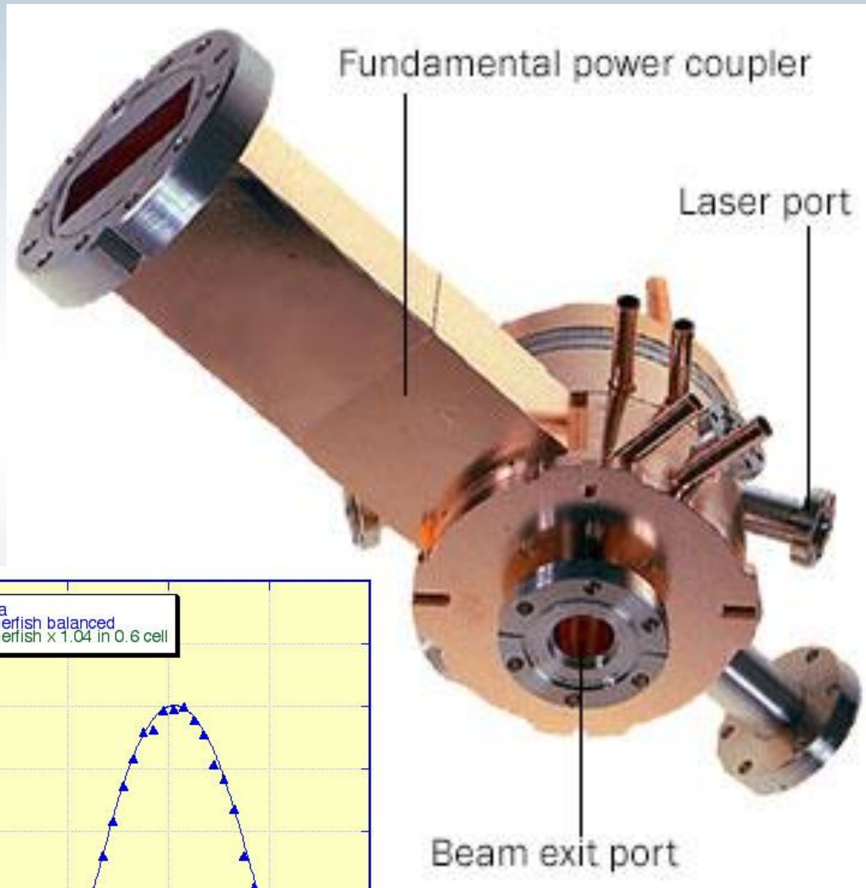
Photo-injectors

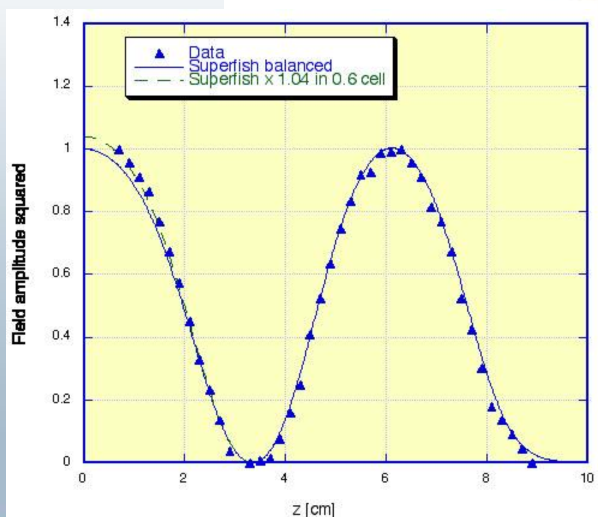
- Main principle: Photo-electric effect





Back to beam sources….





Time structure of the electron beam is controlled by the laser

Laser to cathode

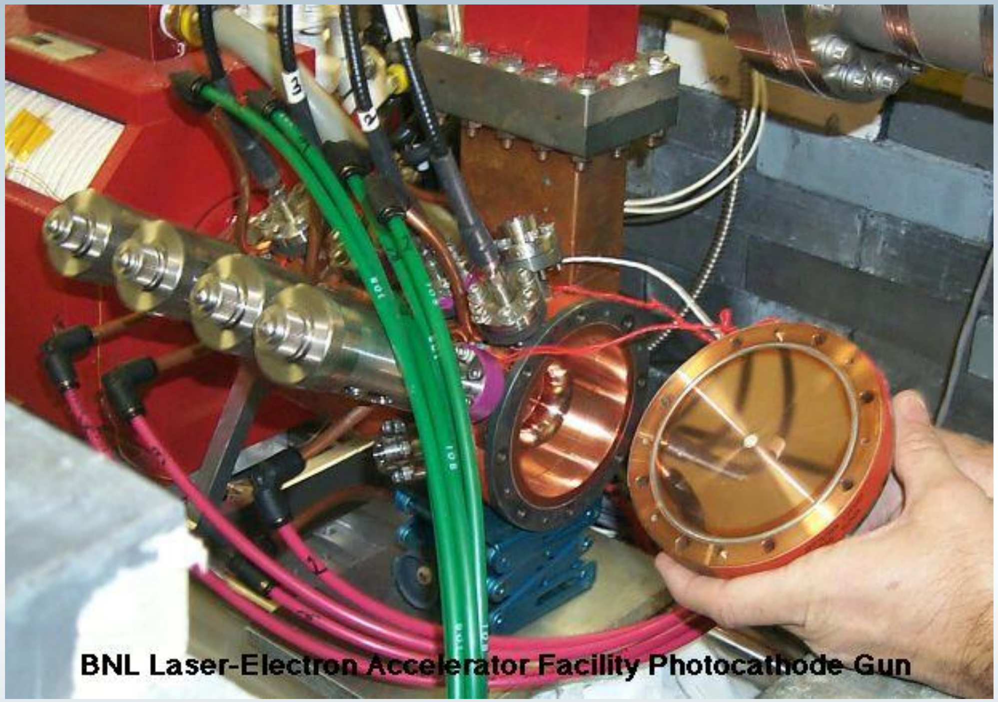
Photo-electric effect

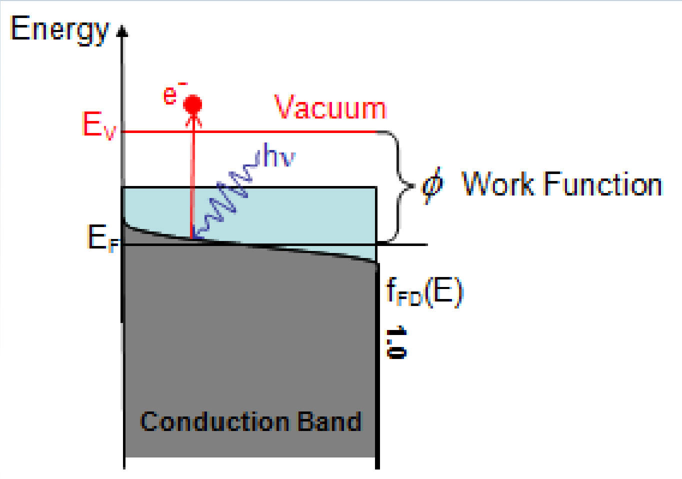
Electron emission

Acceleration through rf field

Focusing with magnets

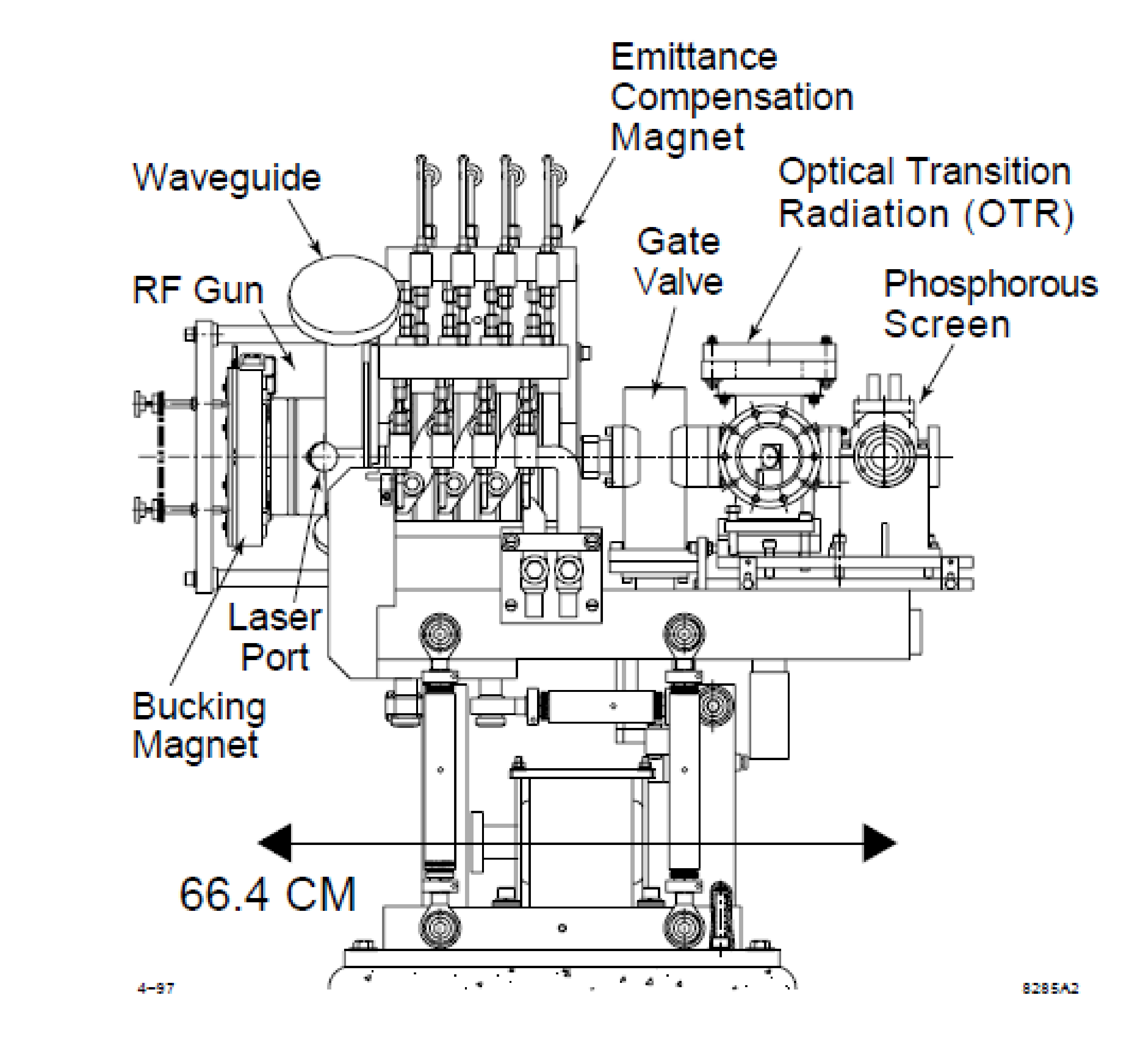
Cathodes



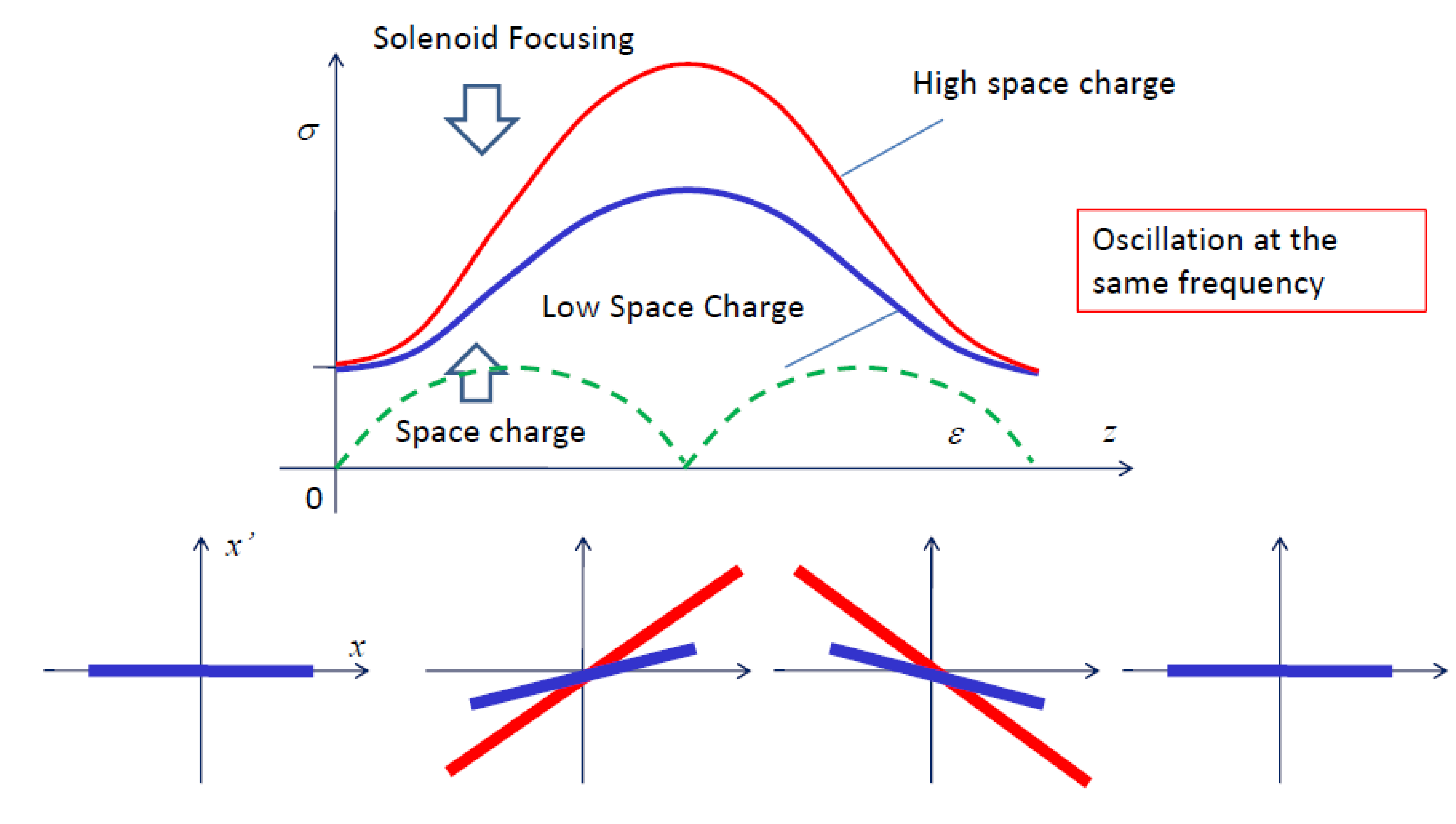


- The gun performance heavily depends on cathodes.
- Cathodes with high quantum efficiency and lifetime preferred.
- ATF is using a Cu cathode

ATF photo-injector layout



Focusing: Emittance compensation



The end…

- Any questions?