Light Source Basics

Eugene Tan
Accelerator Physics and Operations

Outline

- Storage Ring based Light Sources
- Elements of a Storage Ring
- Relationship between Synchrotron Radiation and the electron beam

What is a Light Source?

- Particle accelerator dedicated to the generation of Synchrotron Radiation.

- Applications of particle accelerators:
  - Medical: Isotope production, PET, Proton/Carbon/Ion therapy.
  - Industrial: ion implantation, lithography
  - Research: high energy physics, particle based material analysis, neutron beam generation, synchrotron light generation

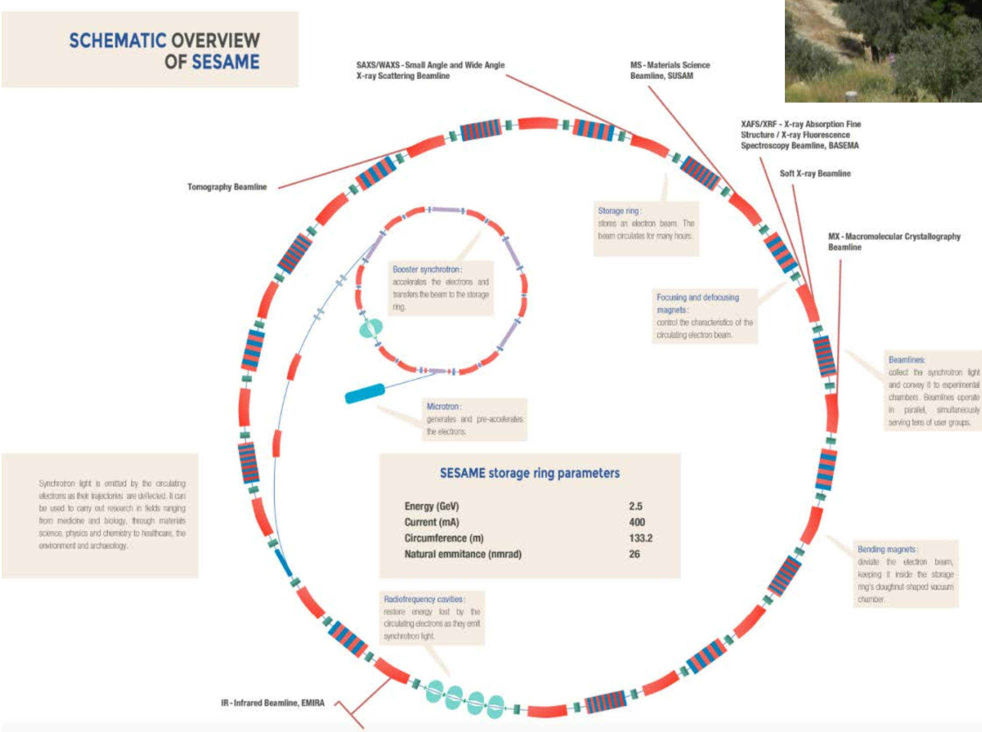
- Two types:
  - Storage Ring based light sources
  - Linac Based light sources (FELs)

Storage Ring Light Sources

- We are one of 48 storage ring based light sources around the world. Only the second in the southern hemisphere.

http://www.lightsources.org/news/2014/09/05/synchrotron-radiation-research-facility-africa

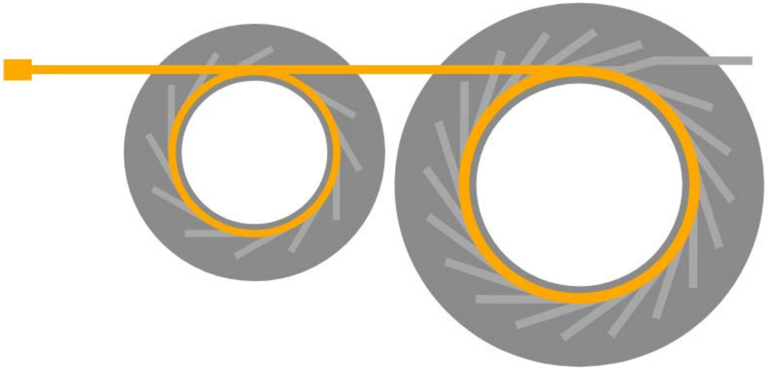
New Light Sources: Sesame (Jordan)



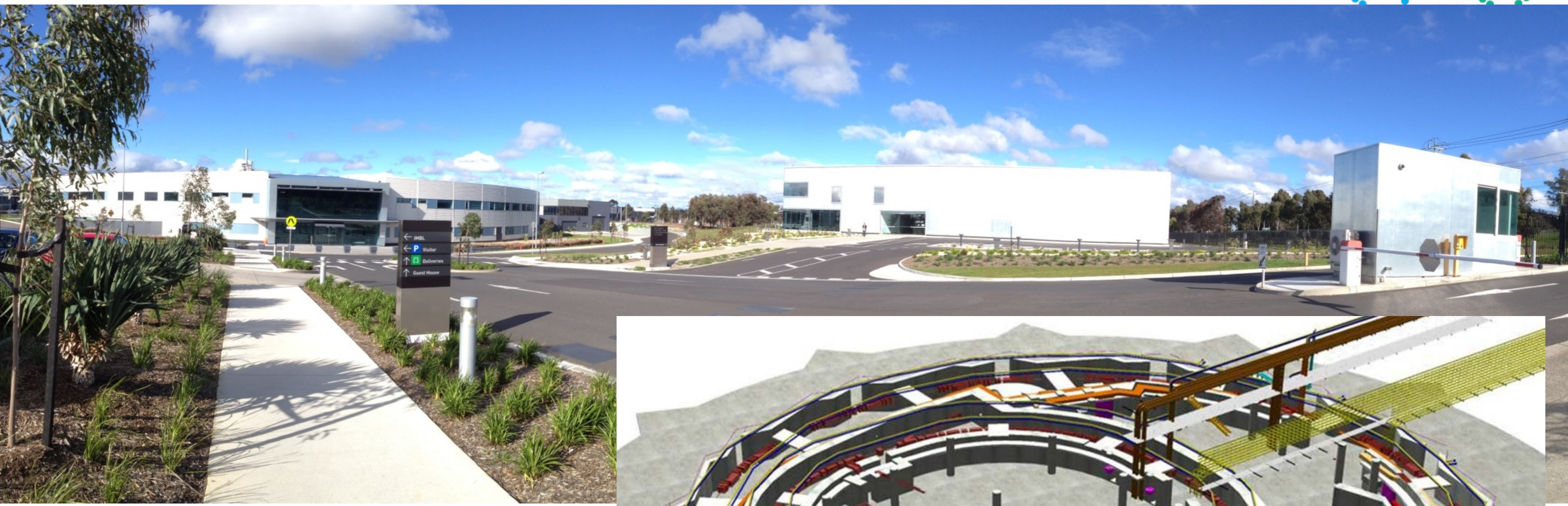
New Light Sources: Solaris(Poland)

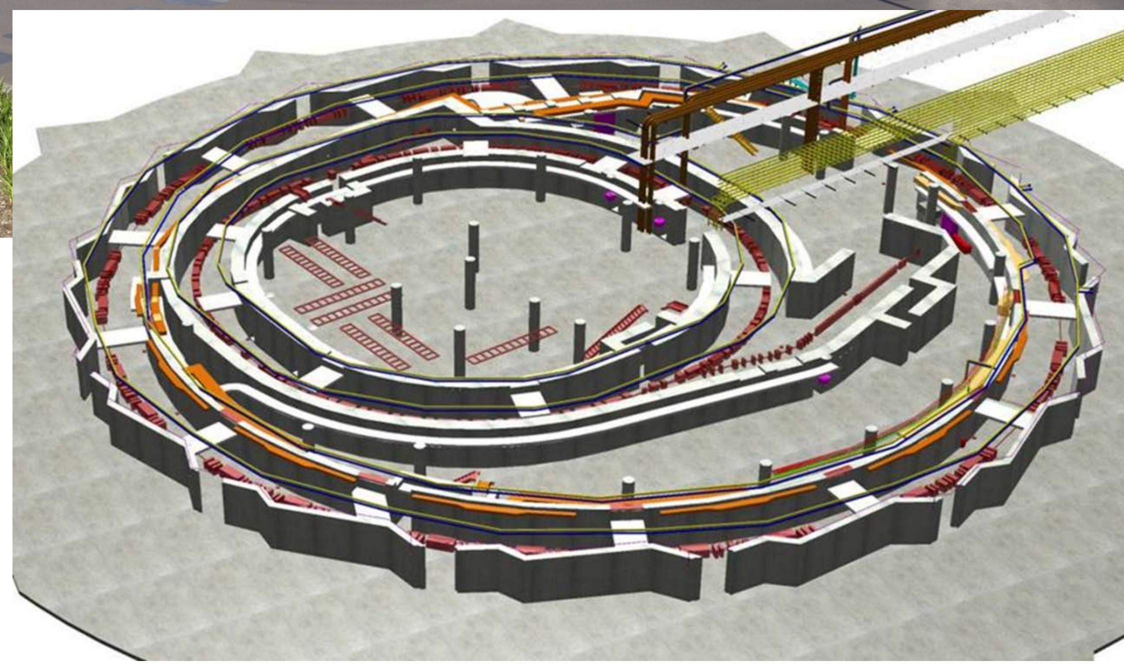
http://www.synchrotron.uj.edu.pl/en_GB/synchrotron

New Light Sources: Max IV (Sweden)



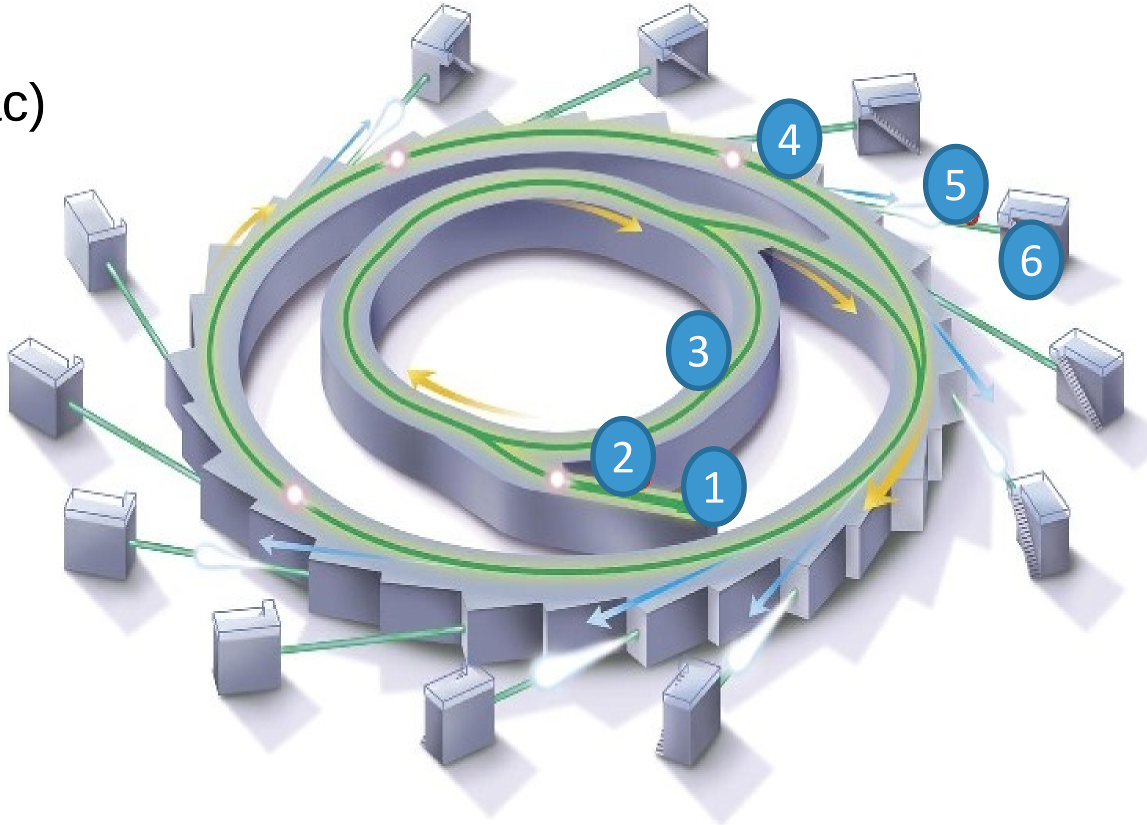
Storage Ring Light Source - Australian Synchrotron





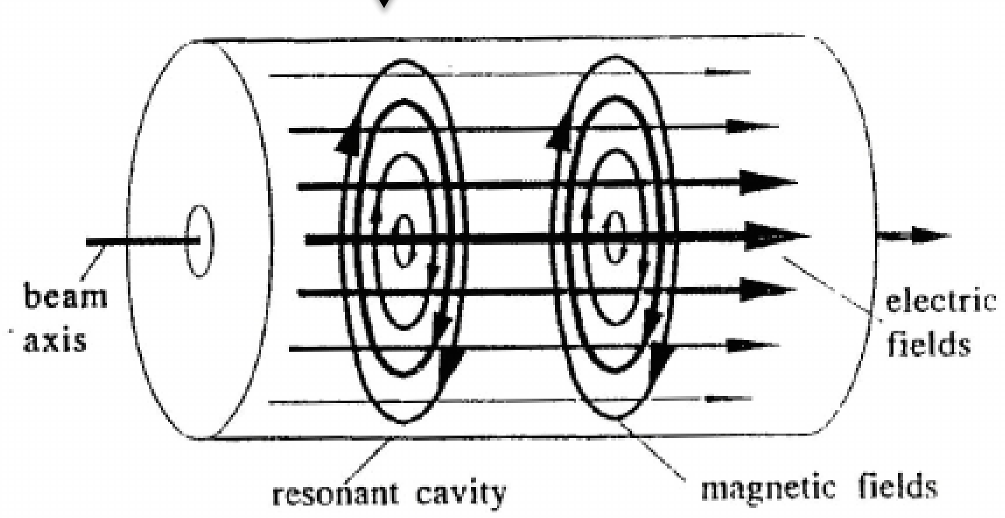
Elements of the Australian Synchrotron

1. Electron Gun
2. Linear Accelerator (Linac)
3. Booster Synchrotron
4. Storage Ring
5. Photon Transport Line
6. Photon Experiments



Lorentz Force Equation

$$\frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

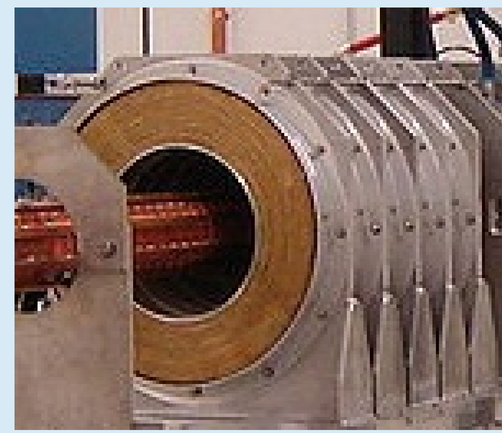


Increase kinetic energy

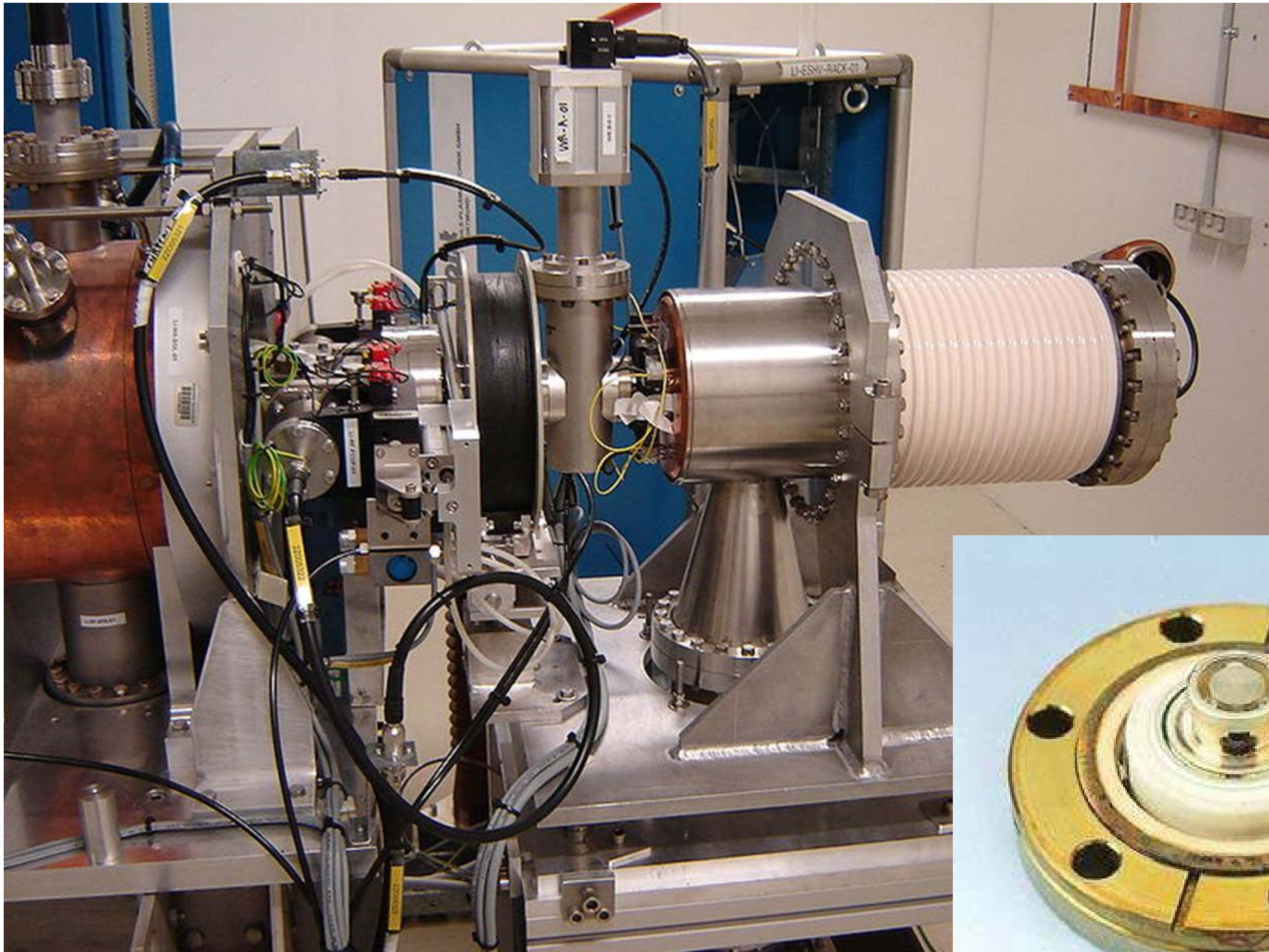
Lorentz Force Equation

$$\frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

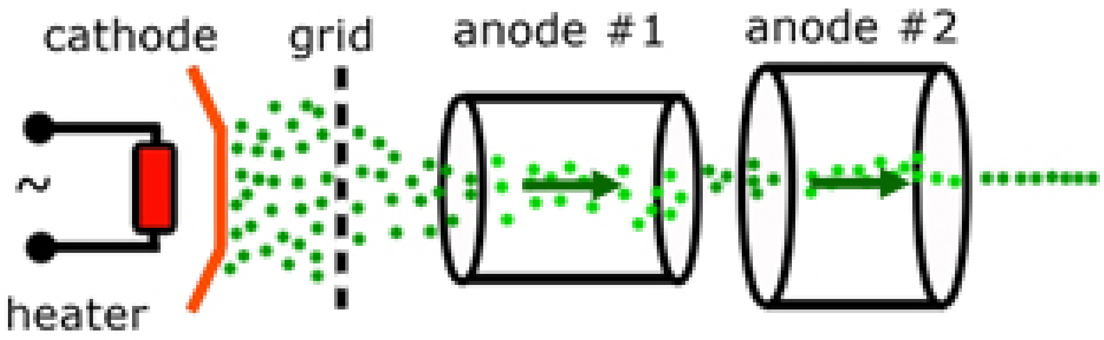
Manipulate direction



Gun → Linac → Booster → Storage Ring



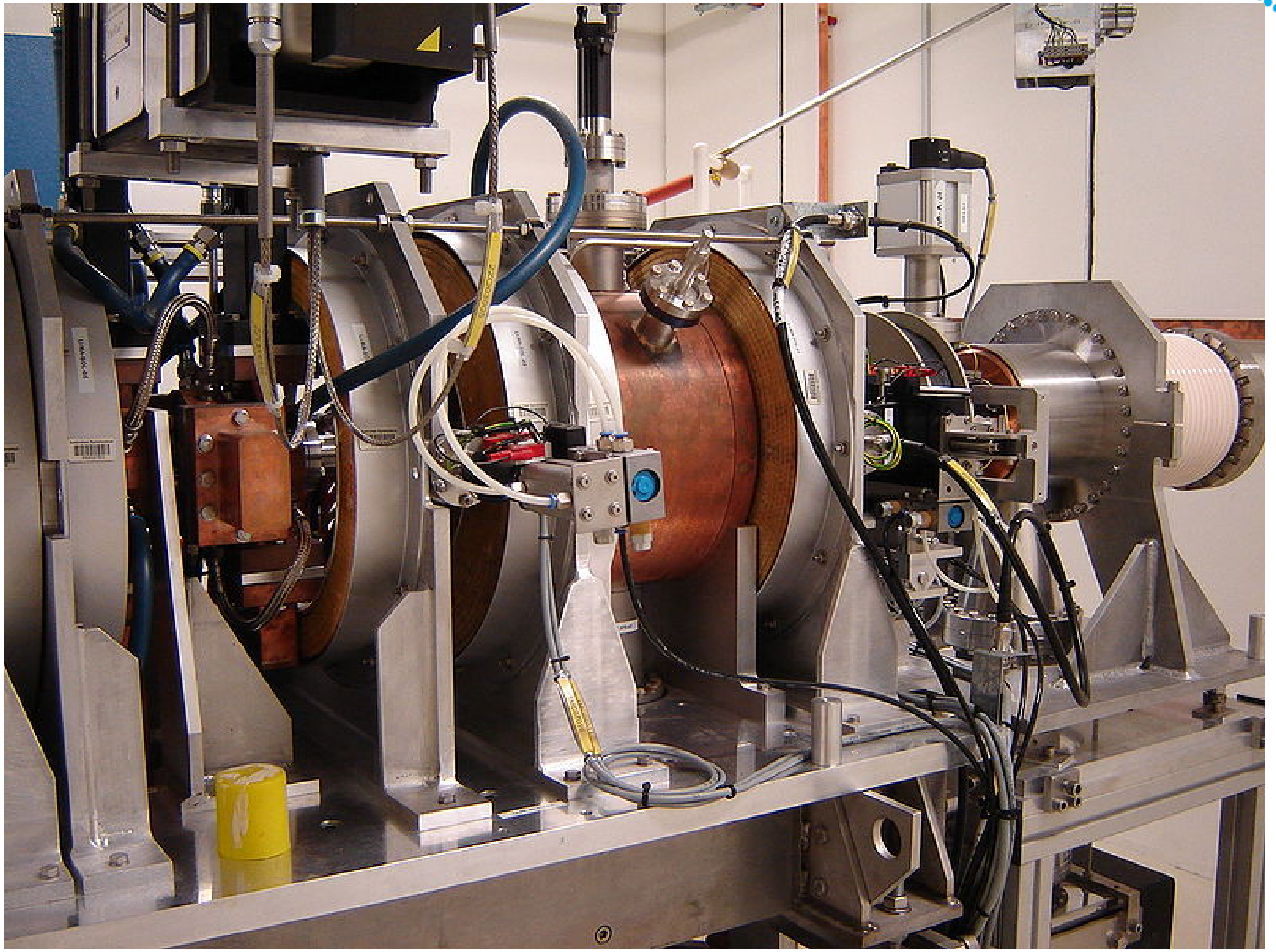
Gun → Linac → Booster → Storage Ring



- 90,000 V **- 90,100 V** **0 V**

$$
\begin{aligned}
E &= \mathbf{F} \cdot \mathbf{d} \\
&= q\mathbf{E} \cdot \mathbf{d} \\
&= q(-90kV) \\
&= 90keV
\end{aligned}
$$

Gun → Linac → Booster → Storage Ring

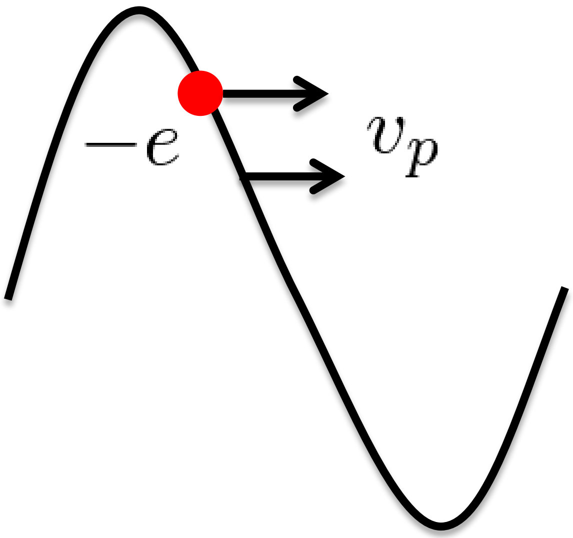


Gun → Linac → Booster → Storage Ring

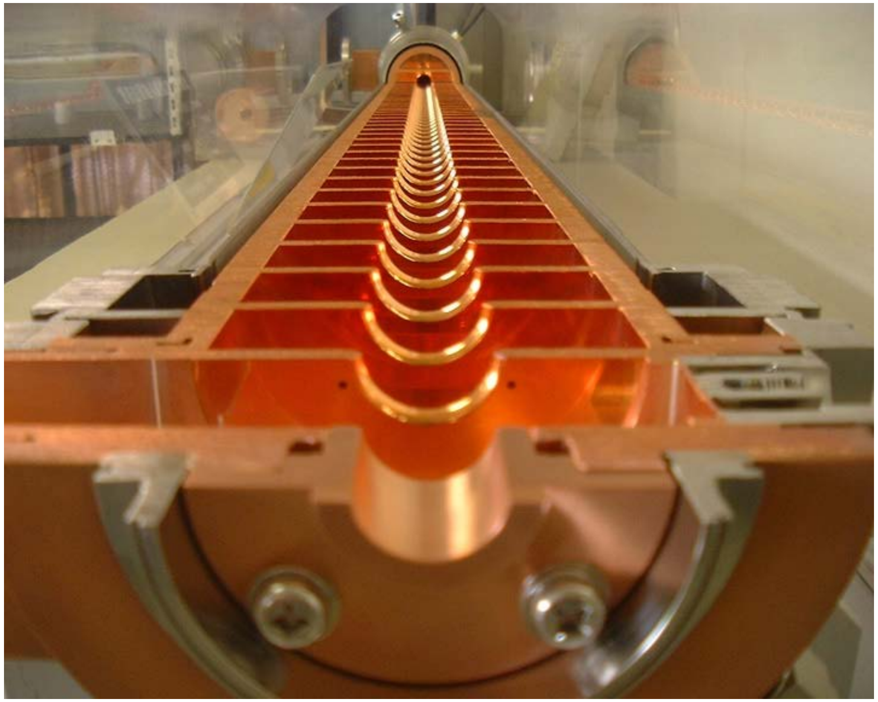
$$E_z = E_0 \cos\left(k_z z - \omega t\right)$$

$$v_p = \frac{\omega}{k_z} \rightarrow c$$

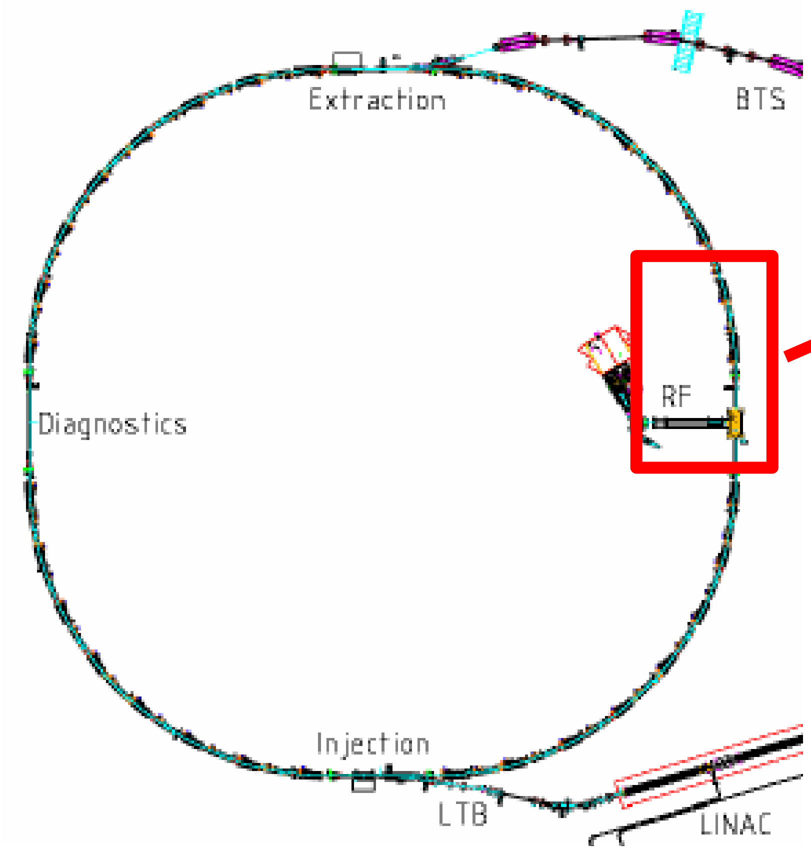
Disk loaded waveguide to manipulate RF fields to have the same phase velocity as the particles being accelerated.



Travelling Wave

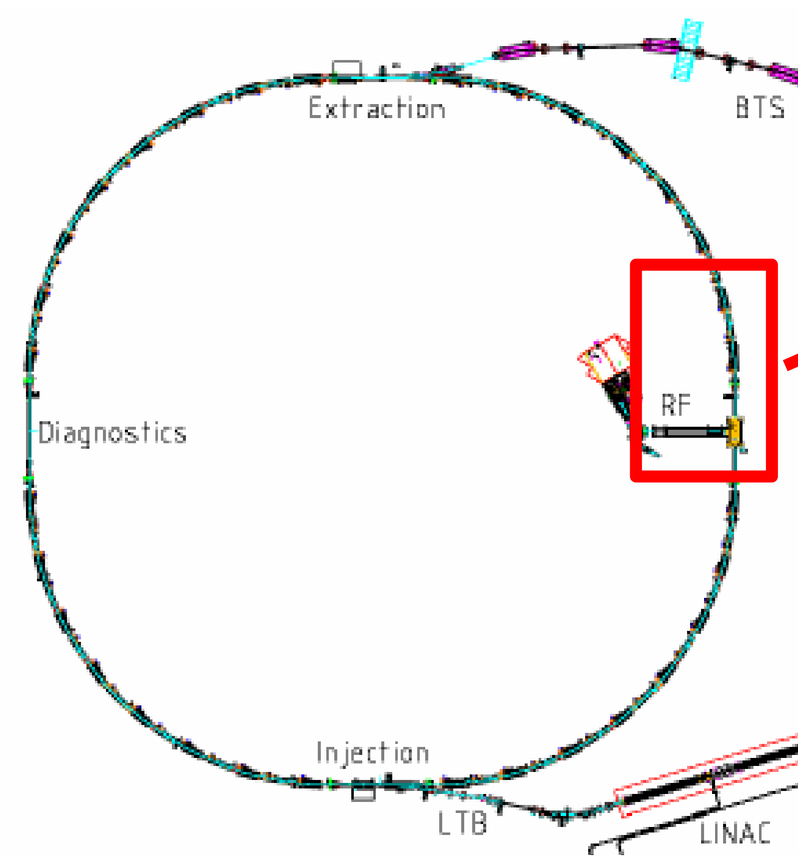


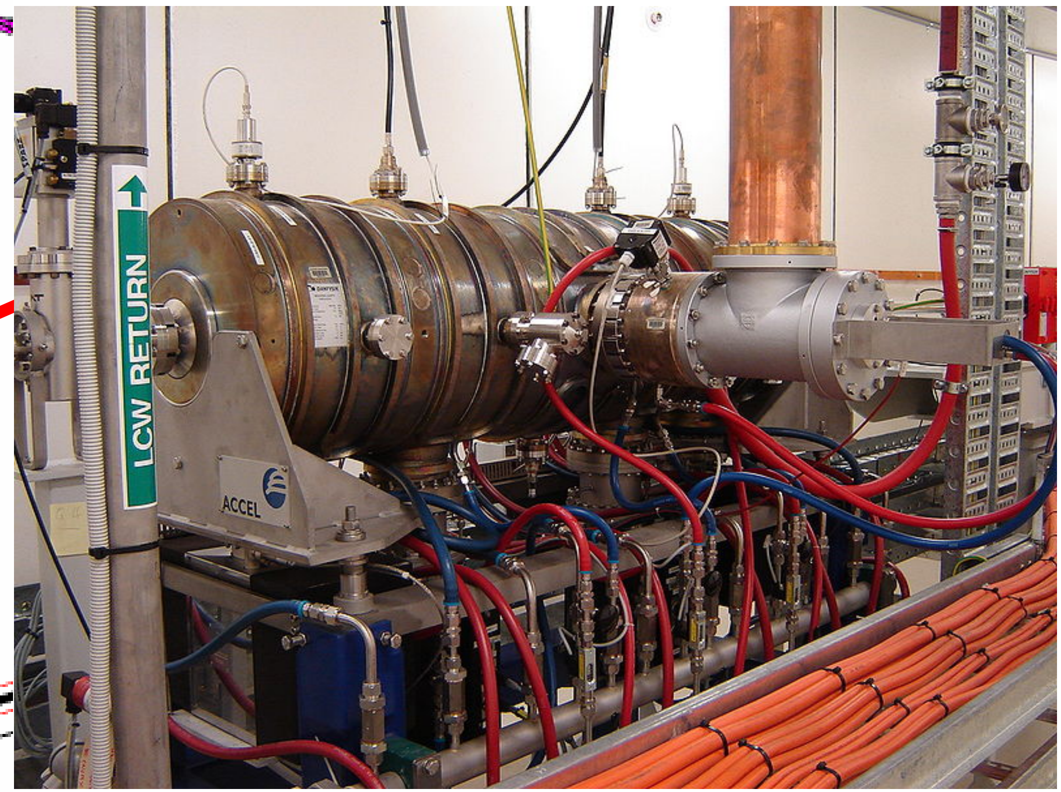
Gun → Linac → Booster → Storage Ring



Gun → Linac → Booster → Storage Ring

Standing Wave





$$\Delta E = qV(\psi) - U(E)$$

$$\psi_s = \sin^{-1}(U/qV_0) \qquad \phi = \psi - \psi_s$$

$$\ddot{\phi} + \frac{\beta c k \eta_c q}{E_0 T_0} \frac{\mathrm{d}V}{\mathrm{d}\psi}\bigg|_{\psi_s} \phi + \frac{1}{T_0} \frac{\mathrm{d}U}{\mathrm{d}E}\bigg|_{E_0} \dot{\phi} = 0$$

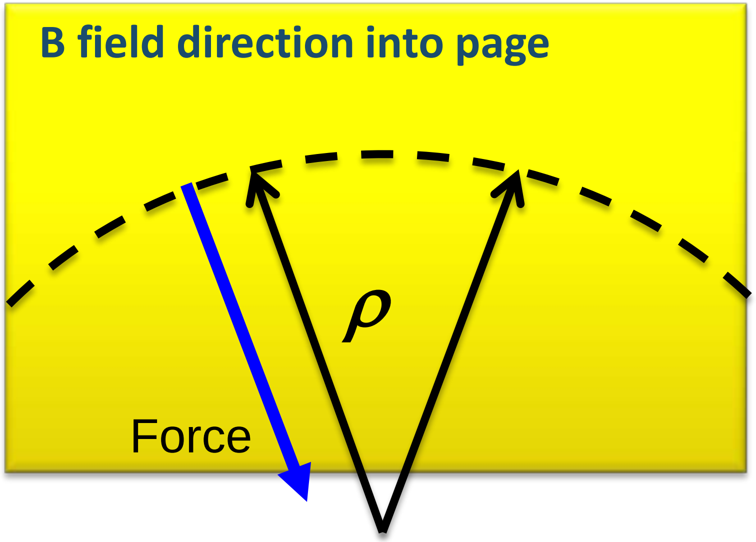
Phase focusing ensures the electron beam arrives that the same phase at the RF cavities.

Gun → Linac → Booster → Storage Ring

$$B\rho = \frac{p}{q}$$

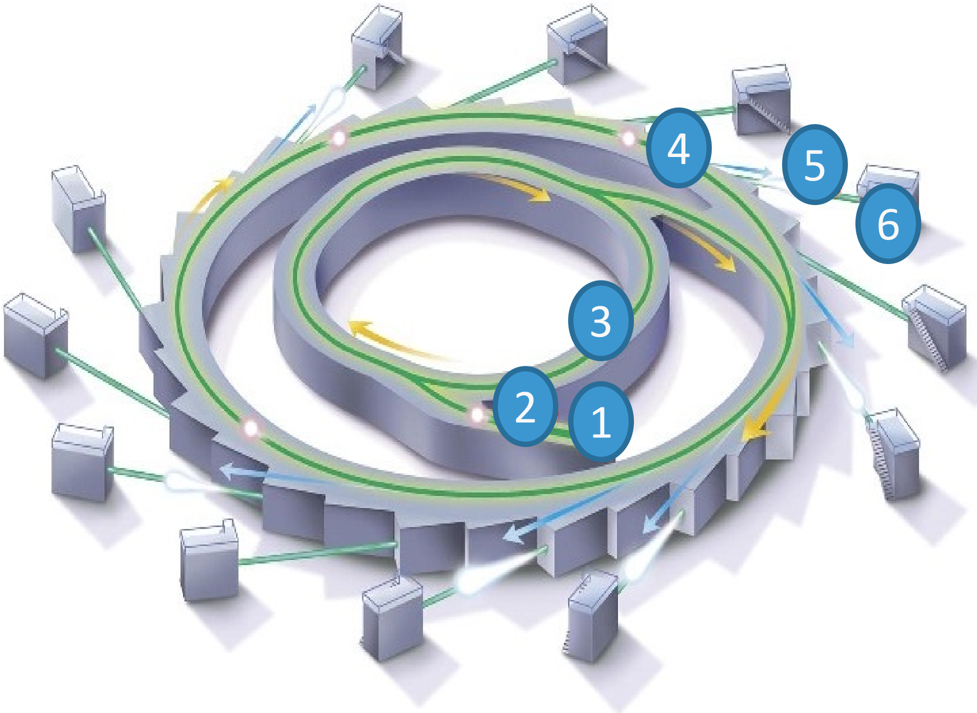
Phase focusing
→ constant circumference
→ constant ρ

Increase **B** to increase **p**



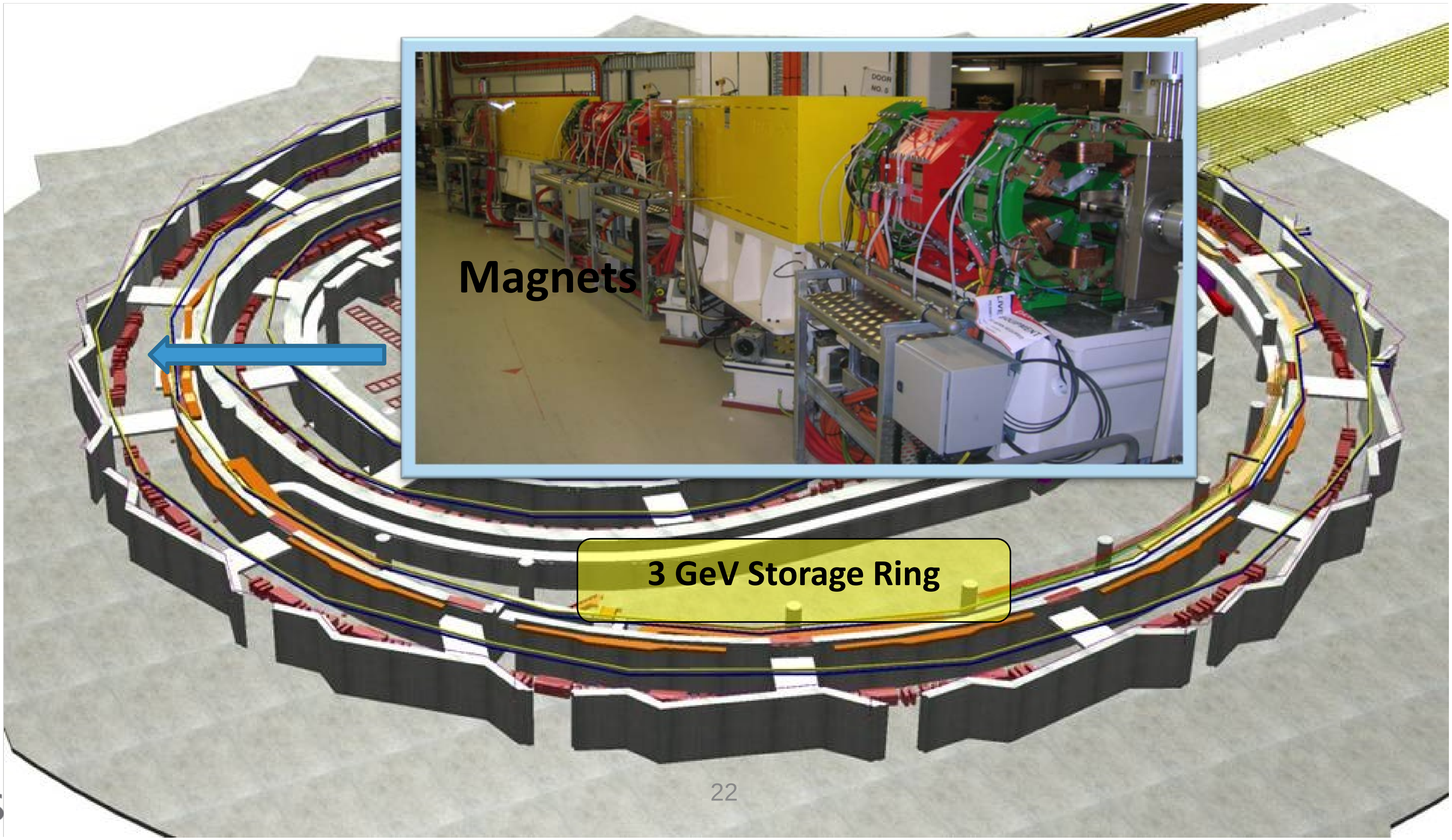
Gun → Linac → Booster → Storage Ring

1. Electron Gun (90 keV)
2. Linac (100 MeV)
3. Booster Synchrotron (3 GeV)
4. Storage Ring (3 GeV)
5. Photon Transport Line
6. Photon Experiments

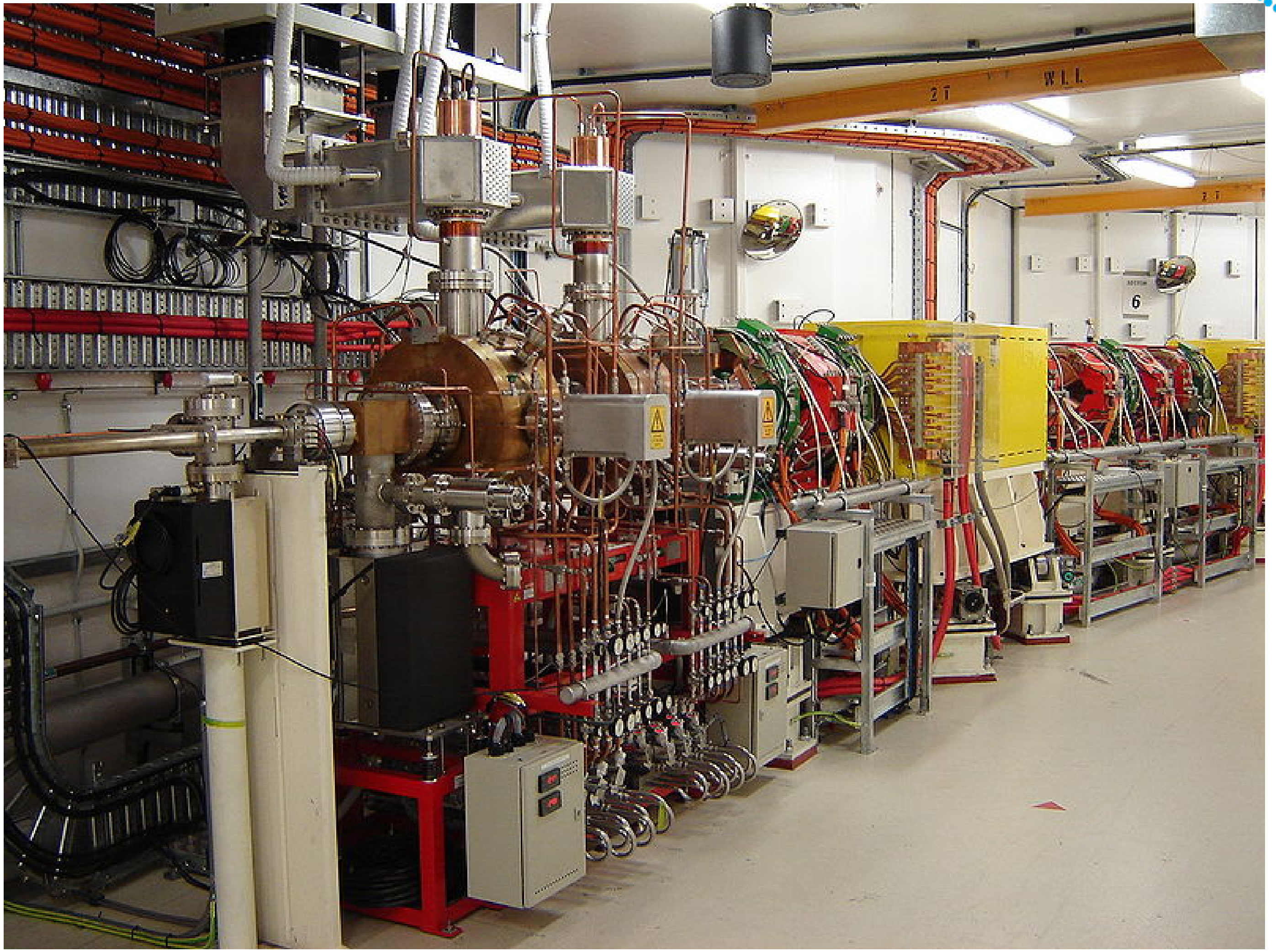


Gun → Linac → Booster → Storage Ring

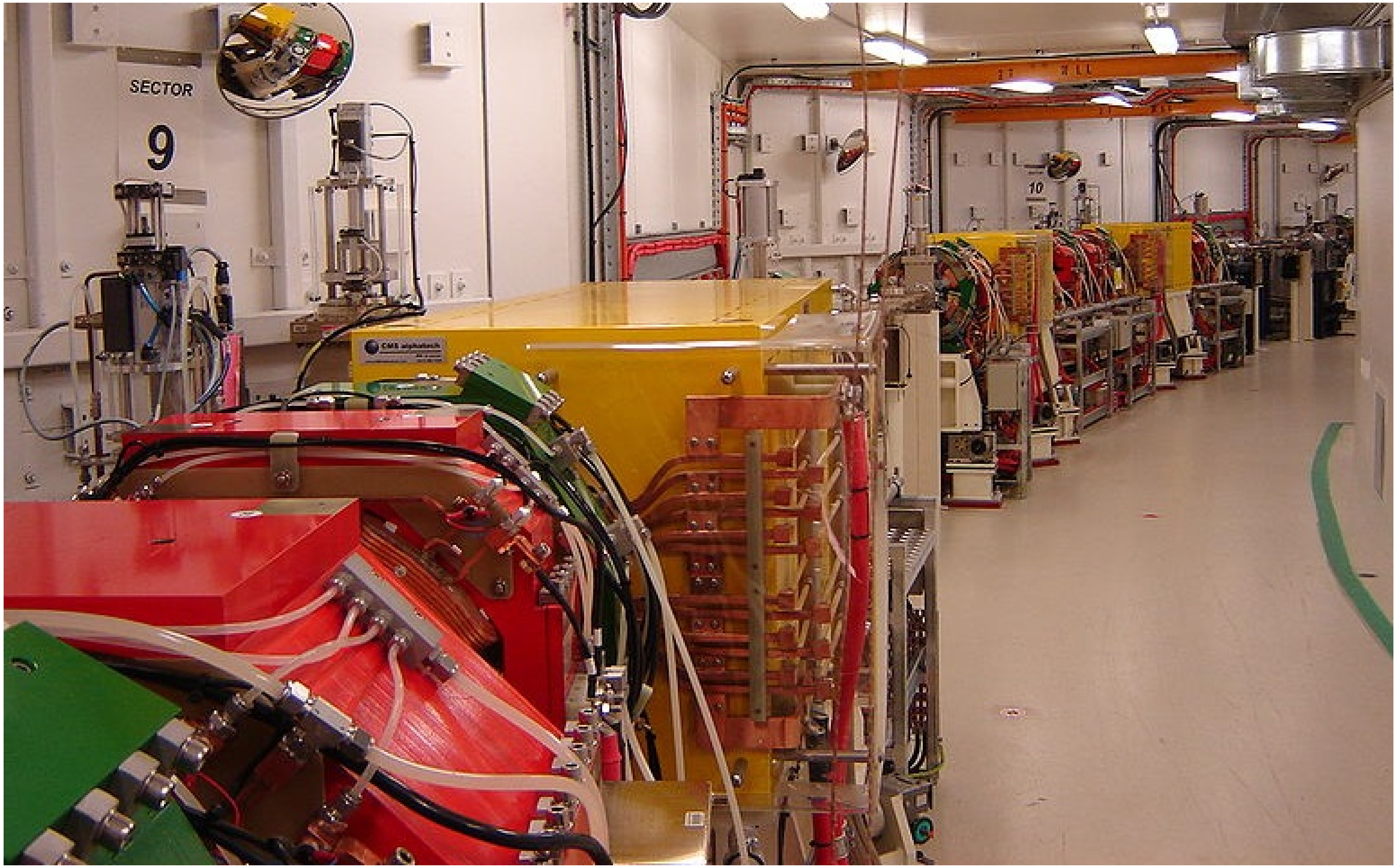
- Store electrons at 3 GeV.



Gun → Linac → Booster → Storage Ring

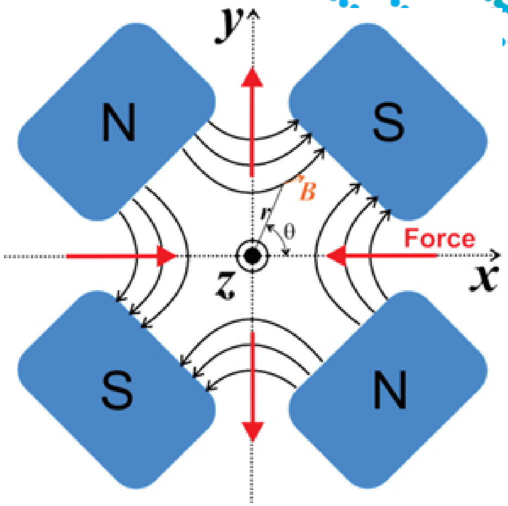


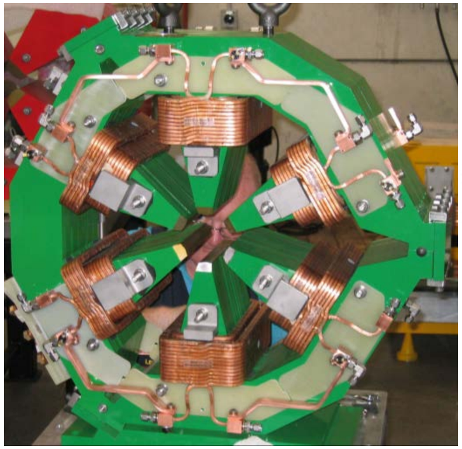
Gun → Linac → Booster → Storage Ring

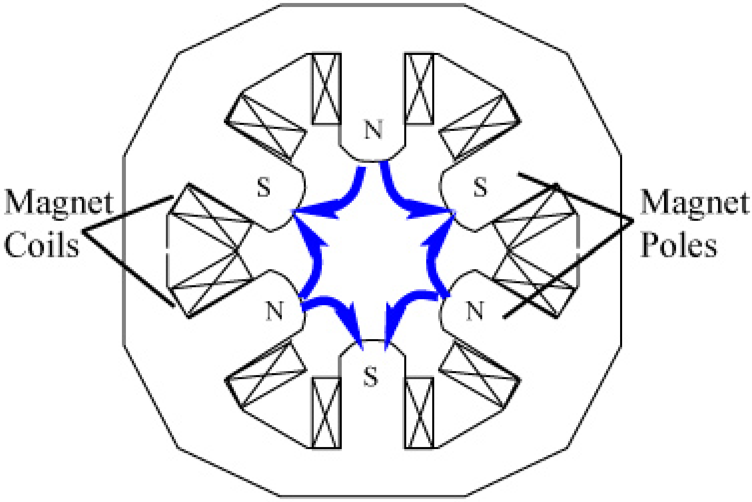


Gun → Linac → Booster → Storage Ring

- Dipole
- Quadrupole (Magnetic lens)
- Focusing quadrupole (QF)
  - Focuses horizontally
  - Defocuses vertically
- Defocusing quadrupole(QD)
  - Defocuses horizontally
  - Focuses vertically
- Sextupole
  - QF for positive x
  - QD for negative x





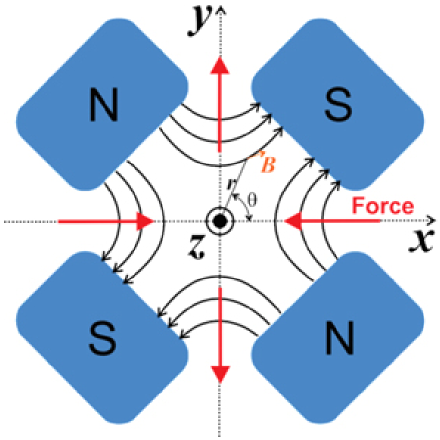


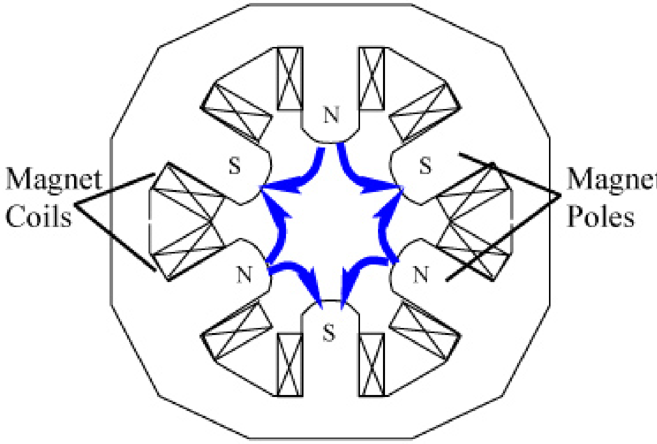
Gun → Linac → Booster → Storage Ring

- Particles with different energies will disperse horizontally when passing a dipole magnet.
- Error: dispersion

- Quadrupoles for refocus the particles
- Particles with different energies do not focus the same way
- Error: chromatic

- Sextupoles to correct for chromatic errors
- Error: geometric, …





Hill's Equation

$$x'' + \left[\frac{1}{\rho(s)^2} - \frac{1}{B\rho}\frac{dB_y(s)}{dx}\right] x = 0$$

↓

Periodic solution

$$x(s) = \sqrt{\beta(s)\epsilon}\cos\left(\theta(s) + \theta_0\right)$$

$$\theta(s) = \int_0^s \frac{ds'}{\beta(s')}$$

Also defined an arbitrary amplitude constant ε which is called emittance.

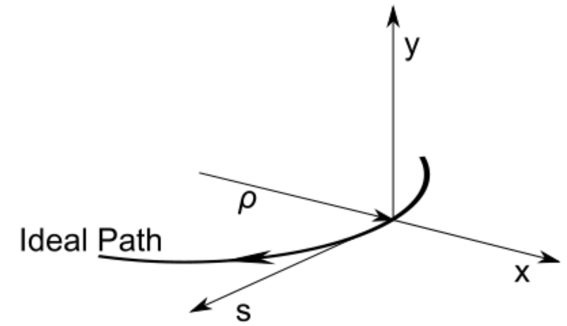
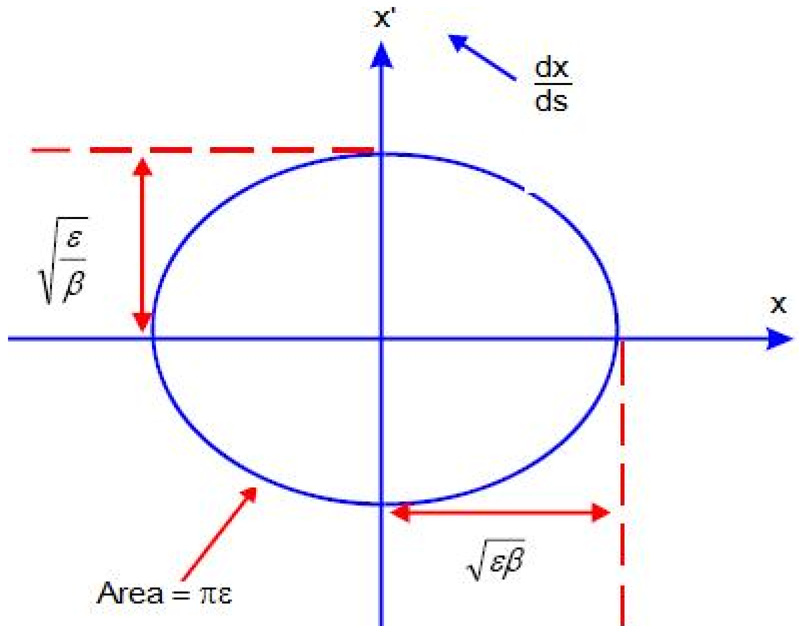
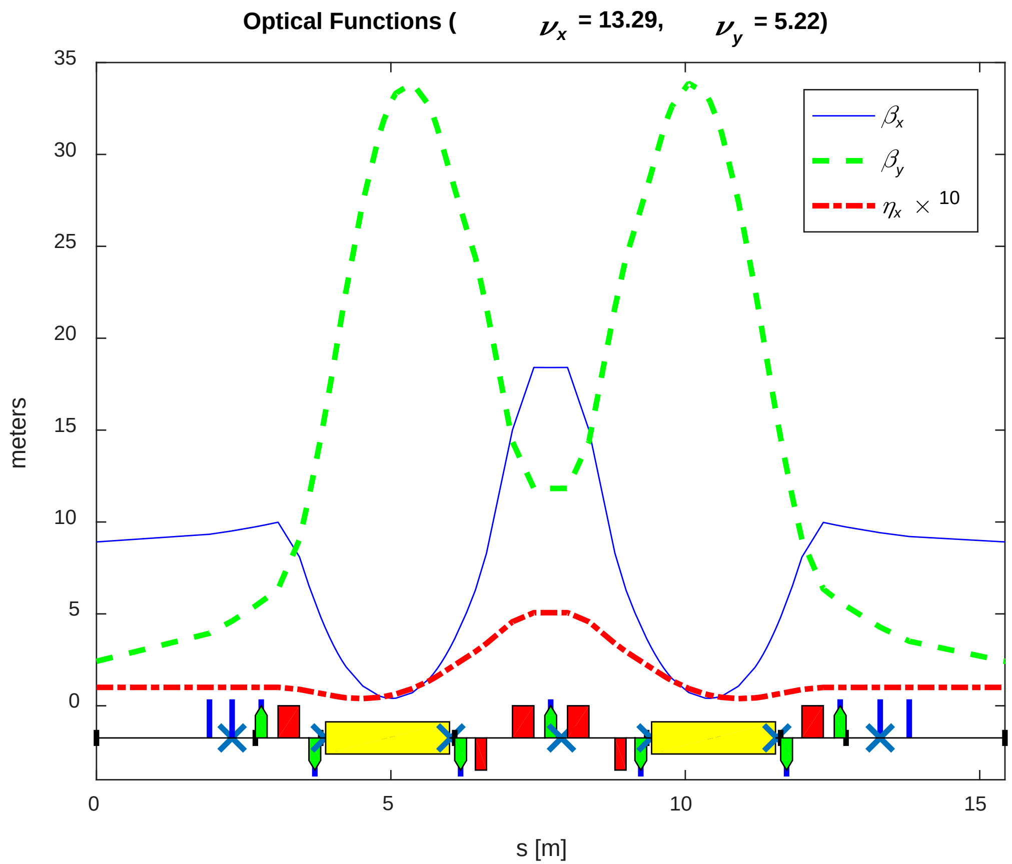


Figure 1.2: Curvilinear coordinate system with axes x (radially outwards), y (vertically up) and s that is collinear with the ideal electron path. ρ is the bending radius of the electron traversing the magnetic field of a dipole magnet.



Gun → Linac → Booster → Storage Ring

- As the magnets are discrete lumps, continuous analytical solutions are not possible.
- Matrix or numerical methods have been developed to determine the solutions.



Gun → Linac → Booster → Storage Ring

Beamsize and divergence

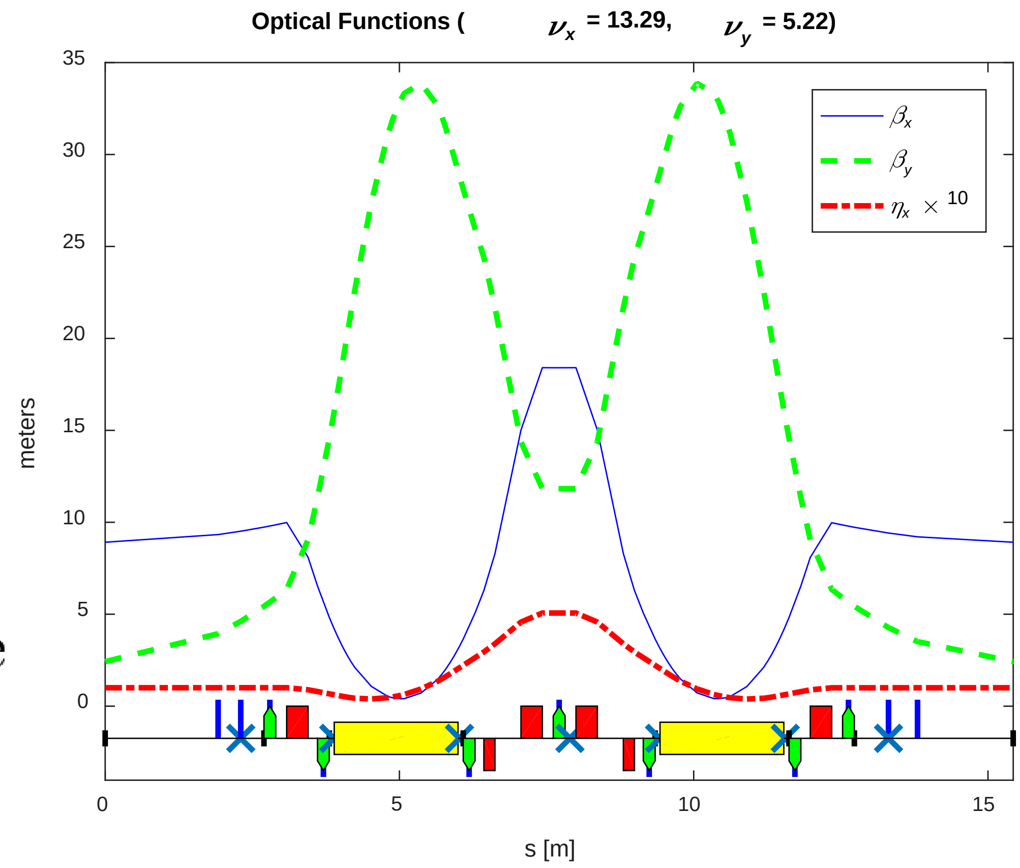
$$\sigma_x(s) = \sqrt{\beta_x(s)\epsilon_x + \eta_x(s)^2\delta^2}$$

$$\sigma'_x(s) = \sqrt{\gamma_x(s)\epsilon_x + \eta'_x(s)^2\delta^2}$$

$$\gamma_x(s) = (1 + \alpha_x(s)^2)/\beta_x(s)$$

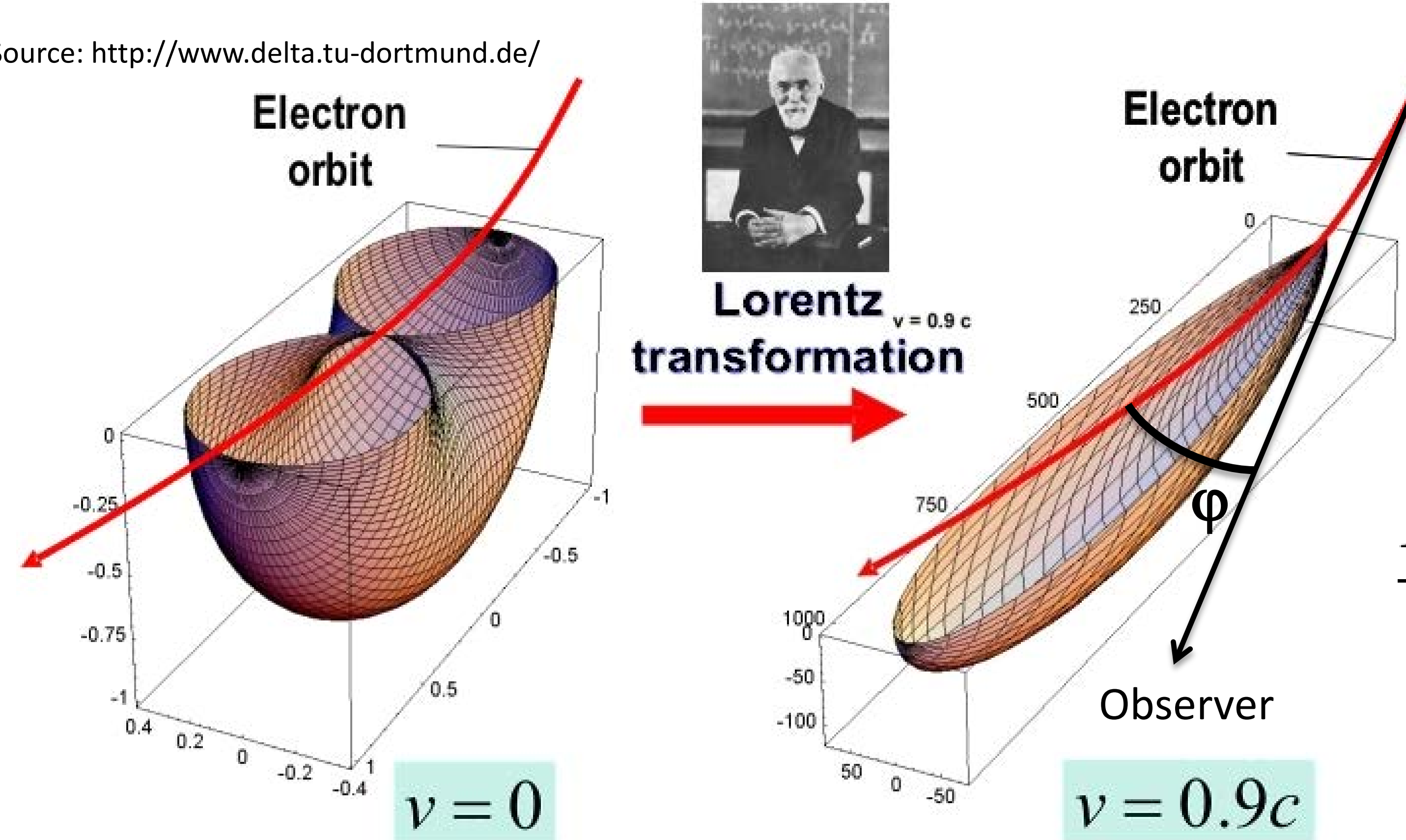
$$\alpha_x(s) = -\beta'_x(s)/2$$

$$\epsilon_x = \text{Equilibrium Emittance}$$



Synchrotron Radiation

Source: http://www.delta.tu-dortmund.de/



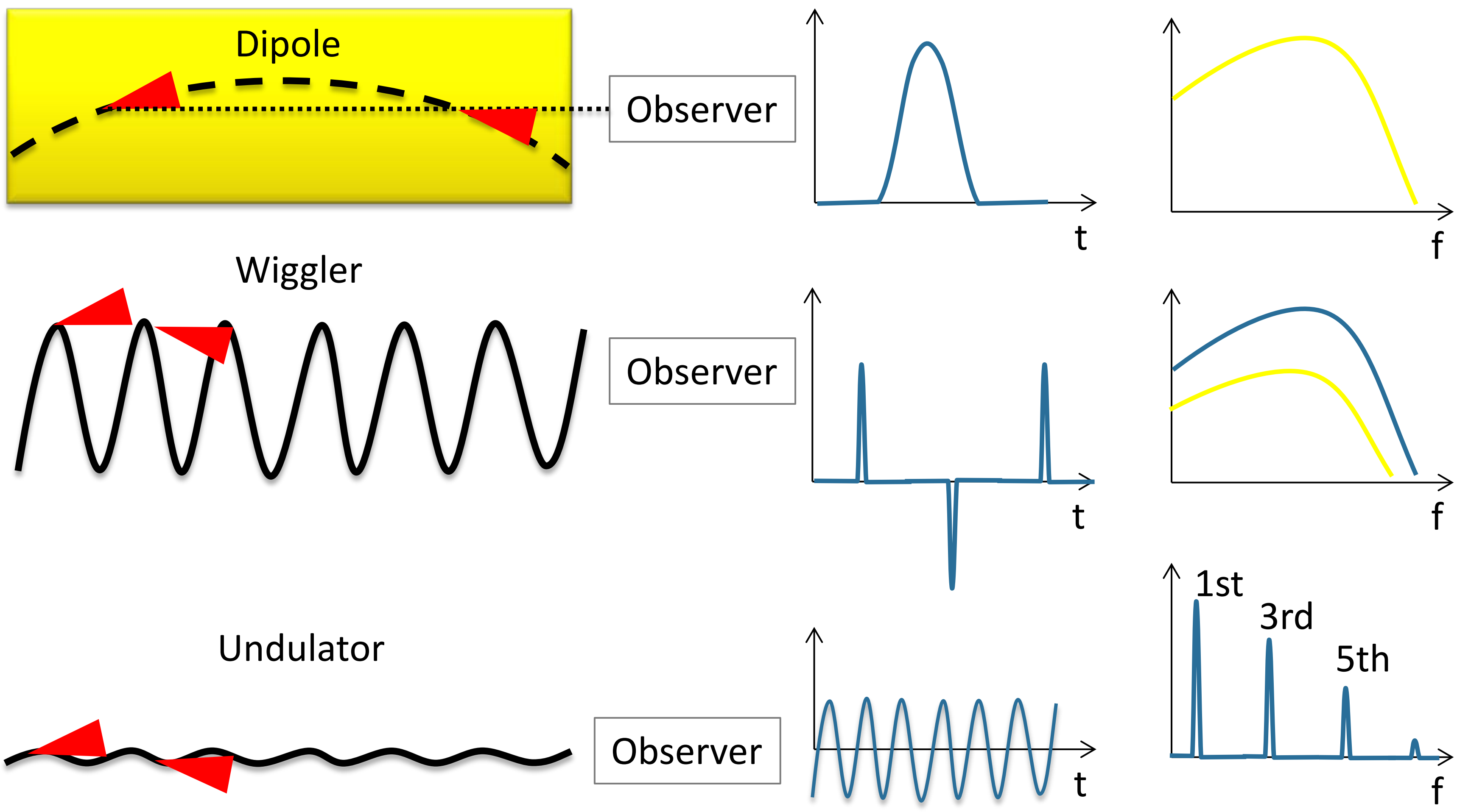
$$\frac{P|_{\varphi=1/\gamma}}{P|_{\varphi=0}} = \frac{1}{8}$$

A 3 GeV

$$\frac{1}{5800} = 172\mu rad$$

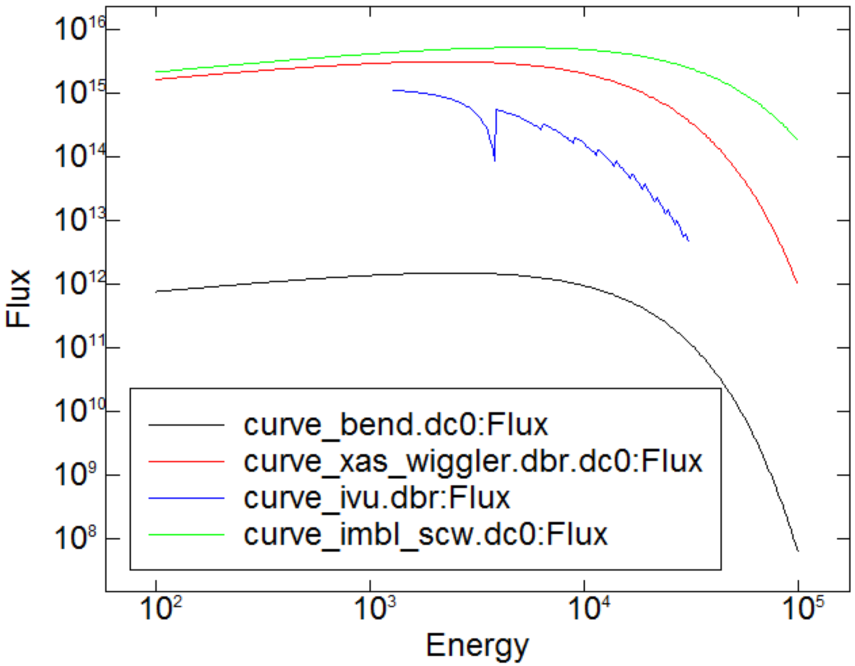
$$P \propto (\gamma^{-2} + \varphi^2)^{-3}$$

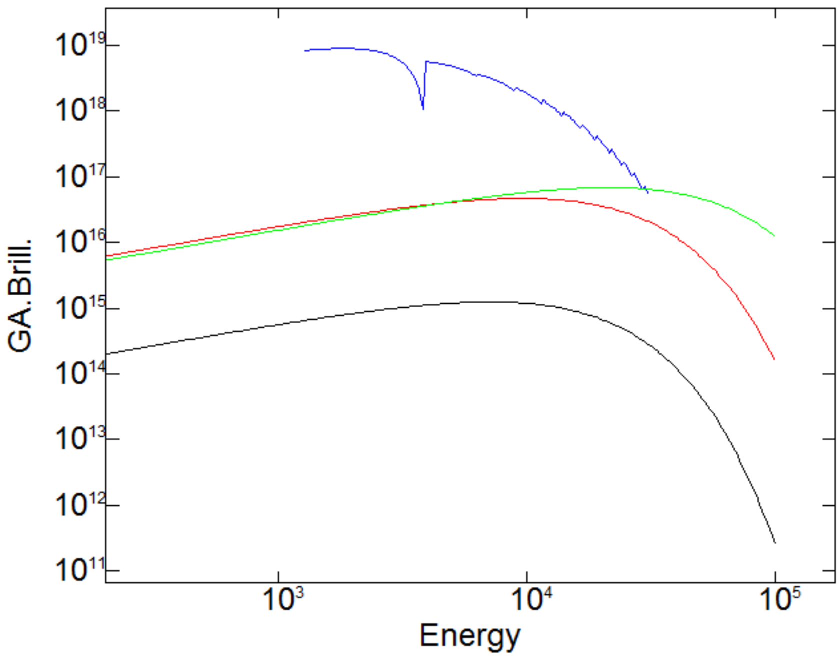
Single Particle Radiation Spectrum



Single Particle Radiation Spectrum

Comparison between bend magnet radiation, Wiggler, Super Conducting Wiggler (4.2T) and undulators.

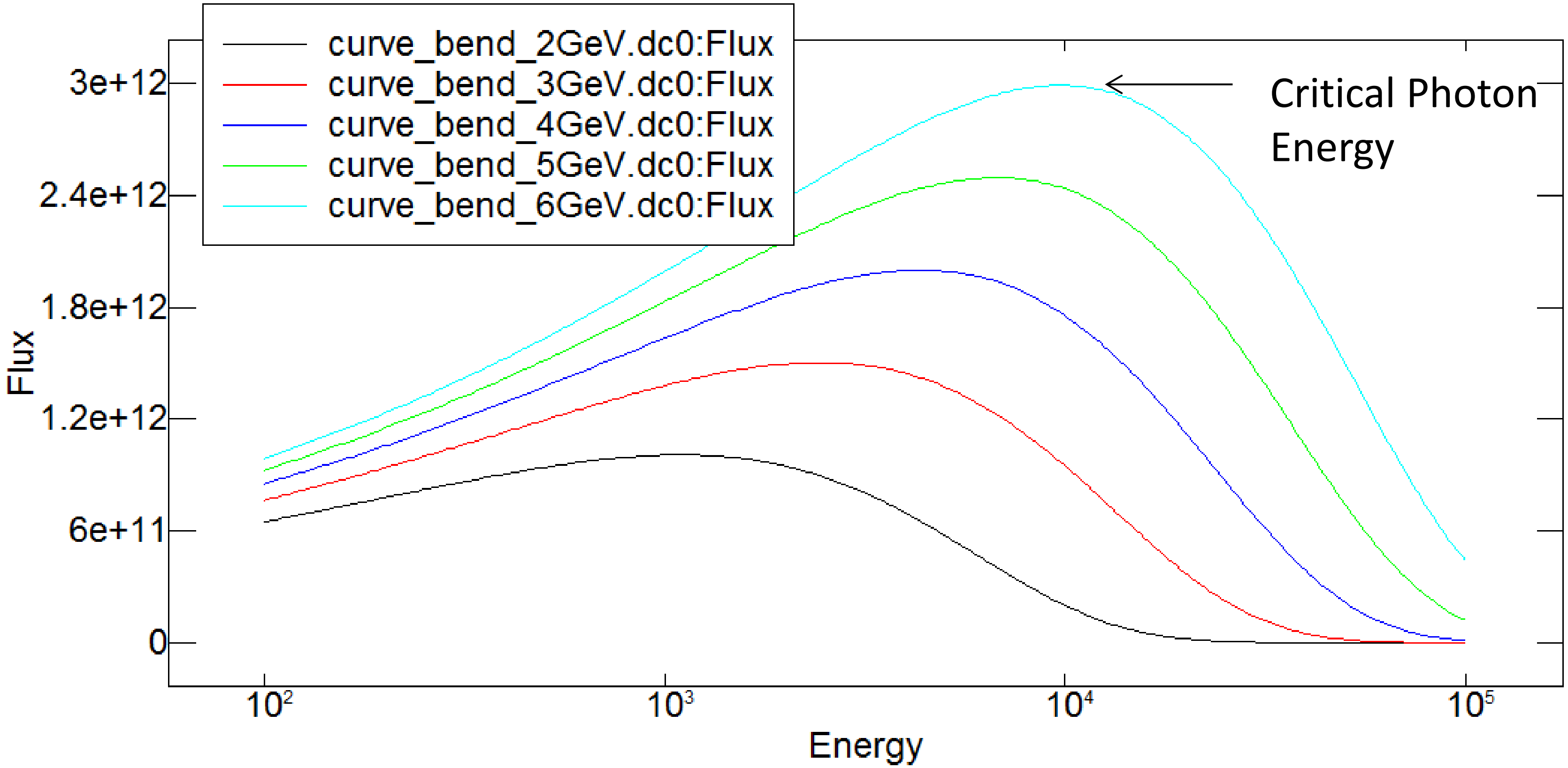




From SPECTRA

Single Particle Radiation Spectrum

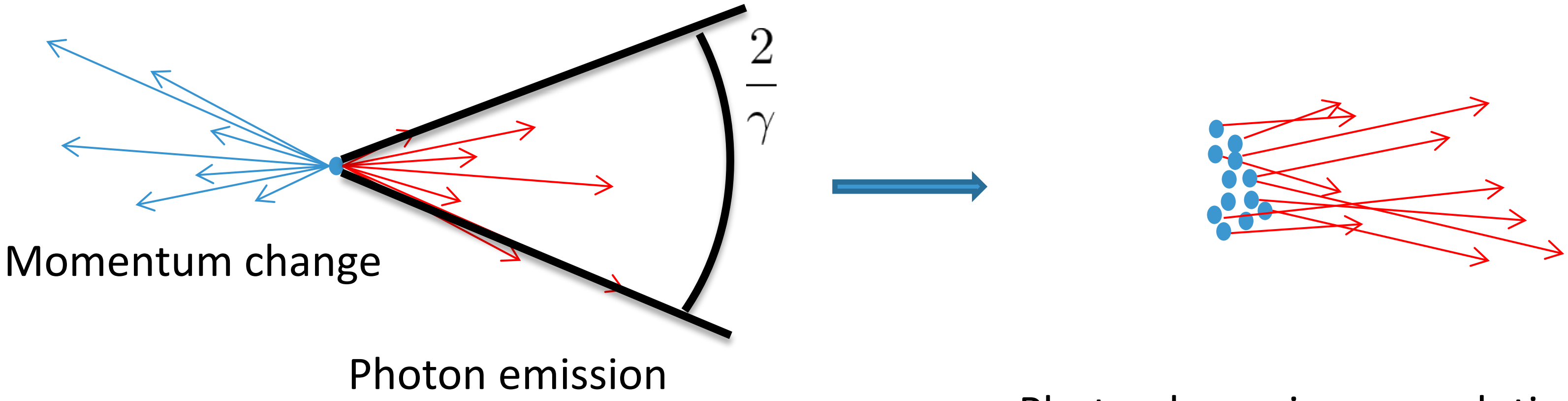
The critical energy depends on the energy of the electron beam.



From SPECTRA

Synchrotron Radiation

The emission of the photons is a stochastic process



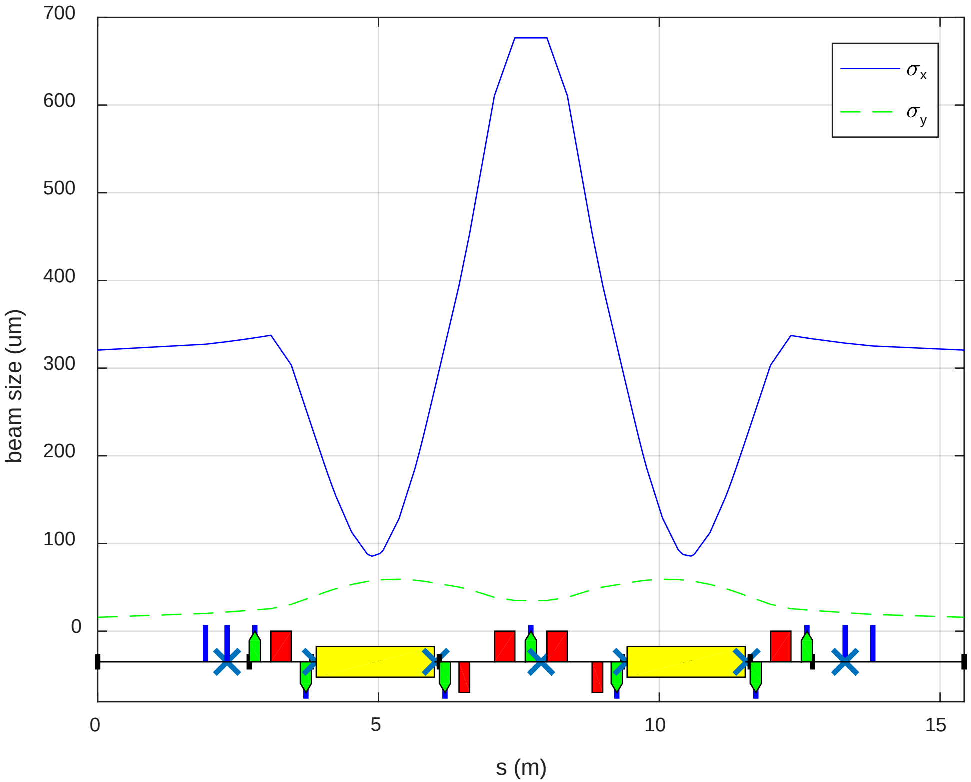
Photon beam is a convolution of the power and beam distributions.

Equilibrium emittance is the balance between:

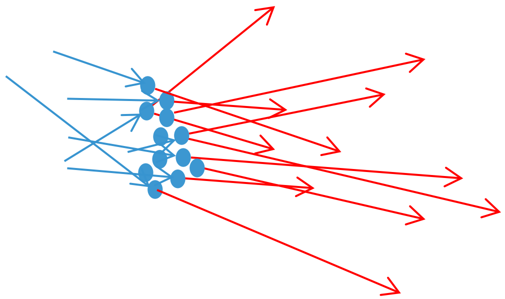
- Photon emission results a spread of momentum in 3 dimensions (quantum excitation).
- Damping effect from preferential loss in transverse momentum

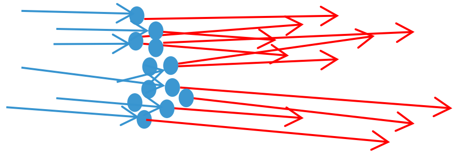
Synchrotron Radiation

ε_x = 10.00 nmrad
ε_y = 0.10 nmrad (1% coupling)
ε_y = 0.001 nmrad (min coupling)



Why do we want smaller beam emittances?





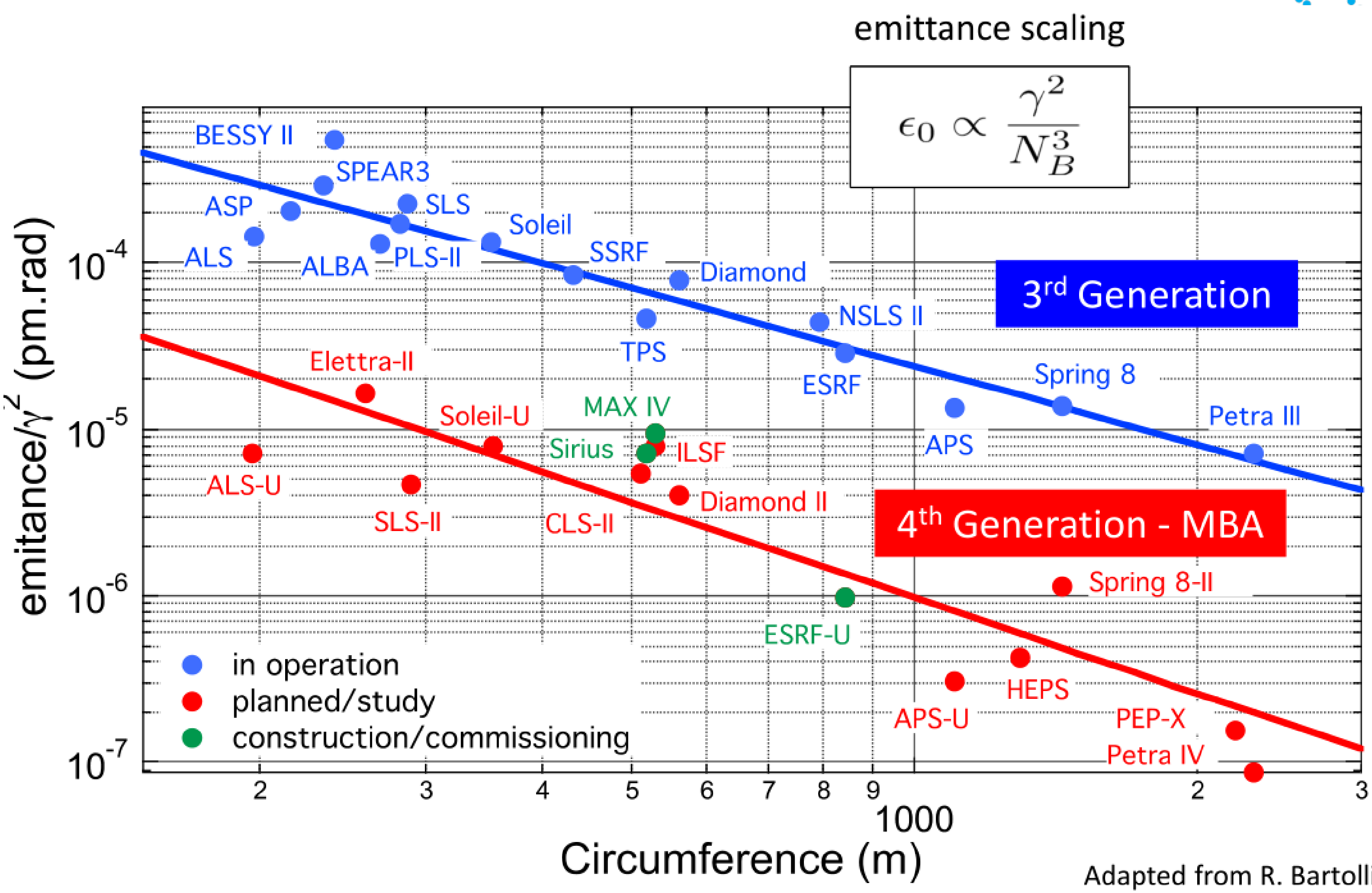
Large beam emittance
Reduced brilliance

Small beam emittance
Increased brilliance

$$\text{brilliance} = \frac{\text{photons}}{\text{second} \cdot \text{mrad}^2 \cdot \text{mm}^2 \cdot 0.1\%\ \text{BW}}$$

$$B \propto \frac{N_{photon}}{\sigma_x \sigma_y \sigma'_x \sigma'_y}$$

Synchrotron Radiation



Adapted from R. Bartollini

- Some insight into how what a is involved in building a light source
- The relationship between the electron beam and the synchrotron light that you use.

THANK YOU