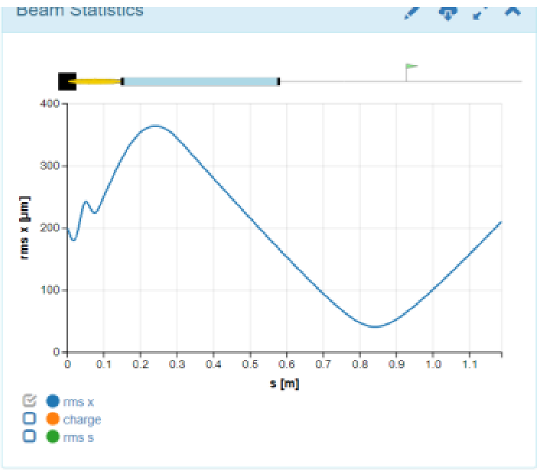
Today schedule:

1. Questions/discussion from previous classes
2. Transport line components intro
3. Emittance measurements techniques short lecture
4. Break.
5. Demonstration of energy measurements using crystal diffraction
6. Demonstration of QE measurements
7. Demonstration of emittance measurements:
   - Solenoid scan and single profile monitor
   - and/or using 4 profile monitors

6. if time is allowed measure energy using diffraction

Short recap



- So far, you have learned how to setup and run beam dynamic simulation
- For offline using ASTRA (very basic interface but fast simulation)
  - ATF injector, ATF injector+ LINAC
    - What is the best 2 LINACs phases setup for the smallest final emittance for the fixed final energy?
- For online simulation with SIREPO (with GUI and some additional controls)
- Now you should be able to setup and optimize RF photo injectors with and without LINAC
- Do you have any trouble to set up UED beam line simulation? Maybe next time we can compare your simulation results (plot of min. bunch size vs bunch charge) vs measurements in the control room

Any questions ?

Main accelerators components

- Source
- Beam Acceleration
- Beam transport

- Each particle is defined in 6-D space (coordinates and momentums) $\vec{x} = (x, p_x, y, p_y, z, p_z)$

- In accelerators physics is more convenient to use reference particle and paraxial approximation pz>>px,py then:

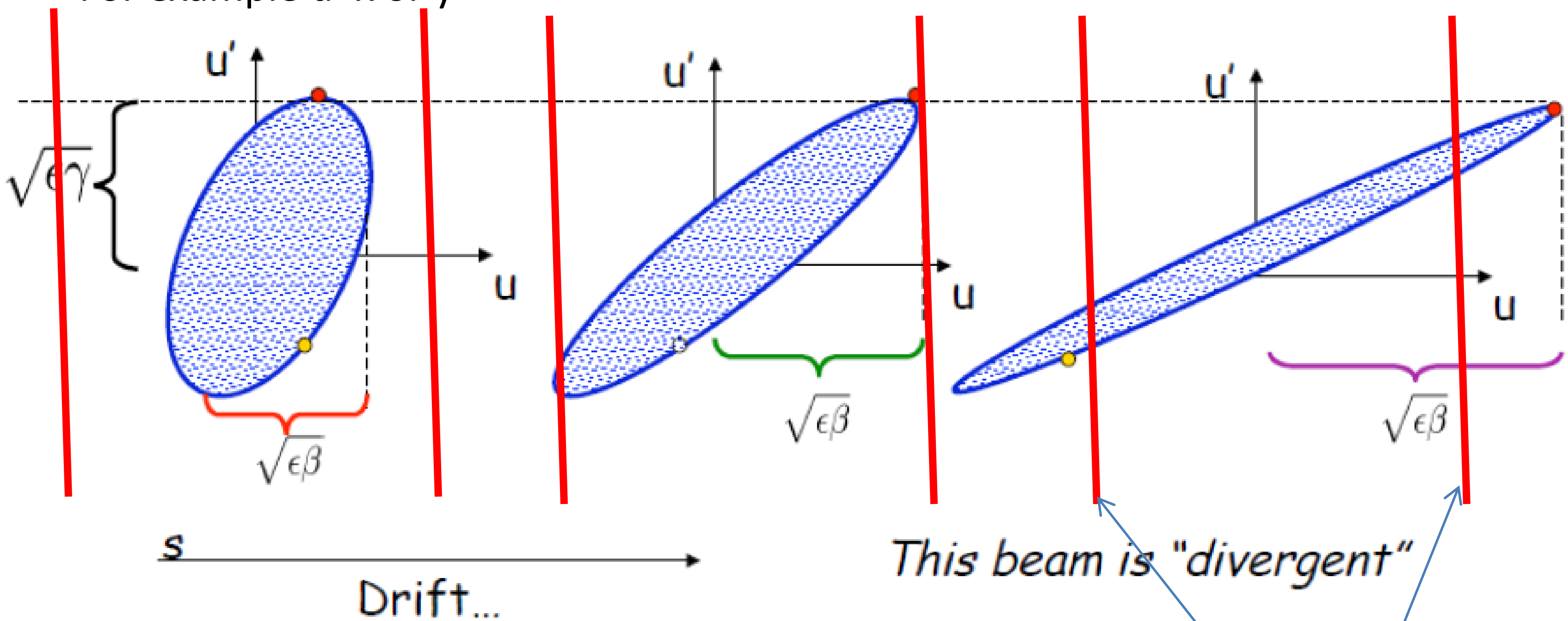
$$\vec{x} = (x, x', y, y', c\Delta t, \Delta E/E)$$

$$x' = \frac{p_x}{p_z} \quad y' = \frac{p_y}{p_z}$$

- $\Delta t, \Delta E$-it s time and energy difference energy from reference particle.

Beam phase space modification drift space only

If there is no coupling between X and Y we can work with 2D phase spaces
For example u=x or y

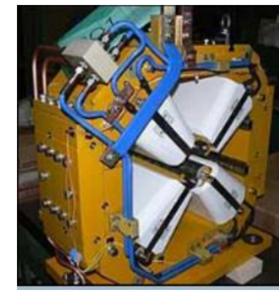


Eventually beam spreads out and hits the aperture
Focusing is needed.

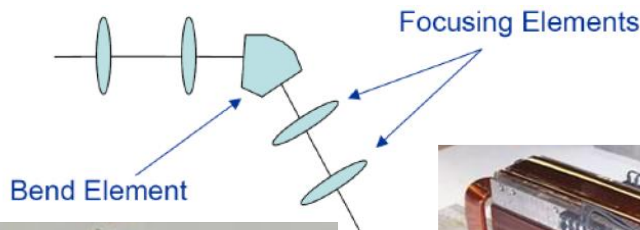
Vacuum pipe aperture
radius=a (+/- a)

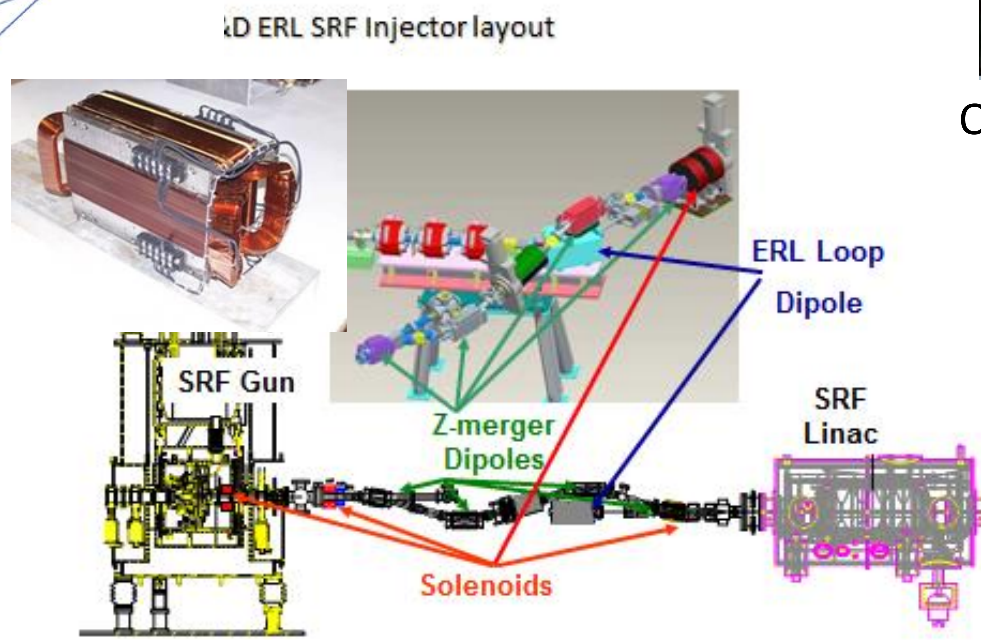
Magnetic lattice

- Usually the set of different kind of magnets is needed in order to successfully propagate charge beam through the system.



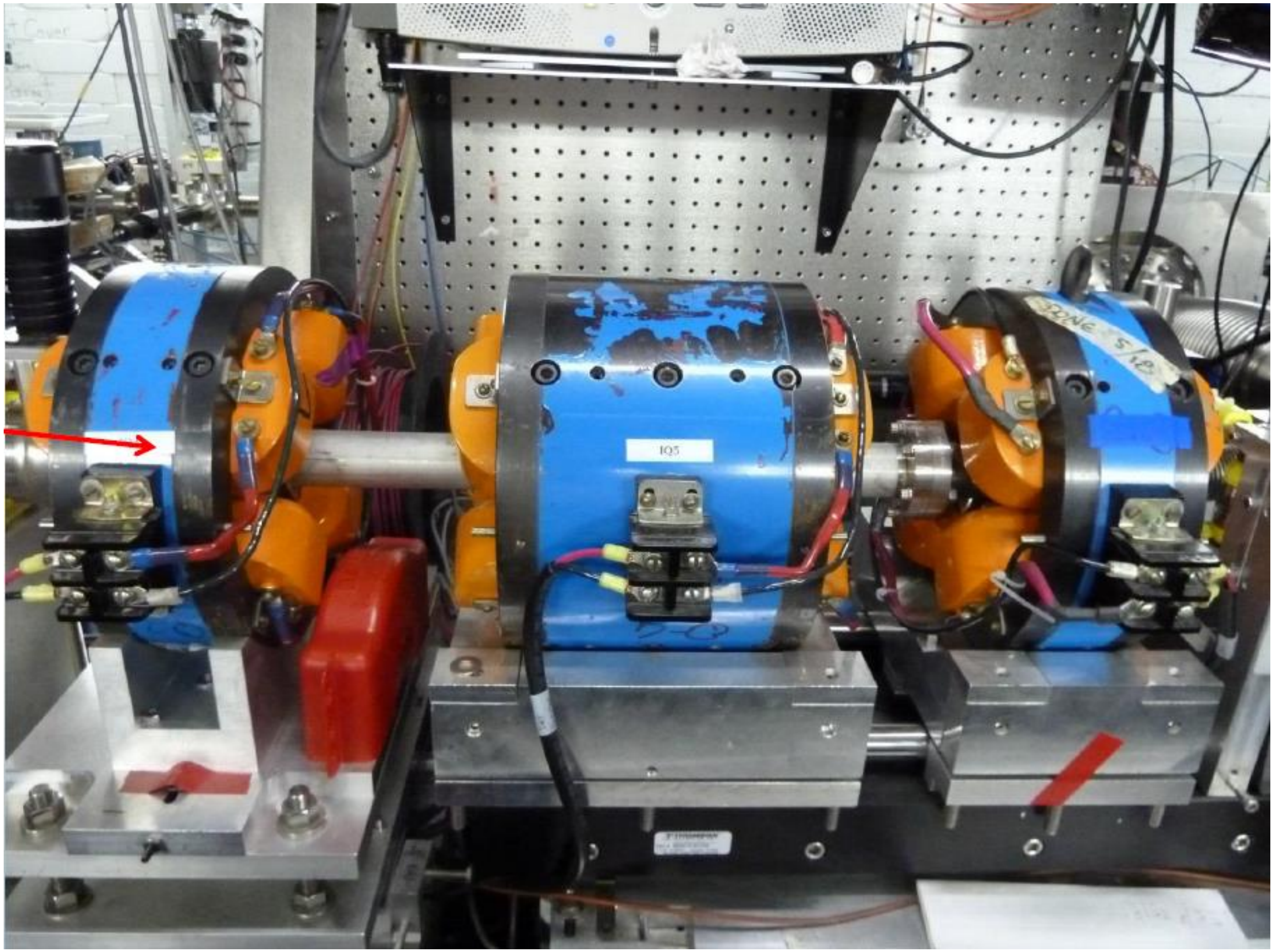
Quadrupoles





Dipoles

ATF qudrupoles



How can we say that these are quadrupoles?

Why magnetic field not electric field?

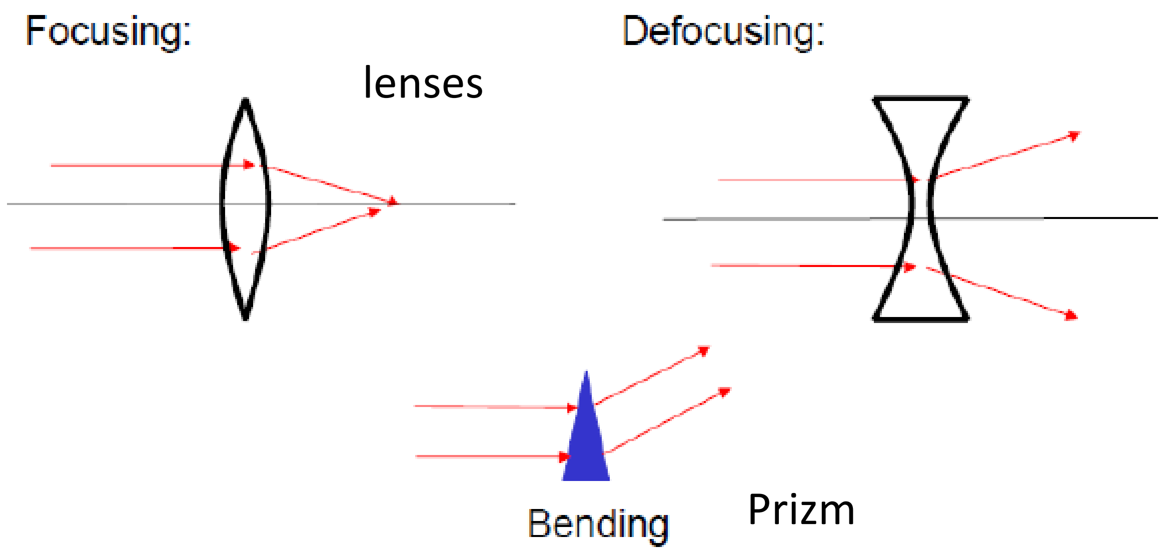
Ratio of magnetic and electric forces

$$F = q(E + v \times B) \Rightarrow \frac{F_M}{F_E} = \frac{vB}{E} \Rightarrow \frac{F_M}{F_E} = 1 \Rightarrow E = vB$$

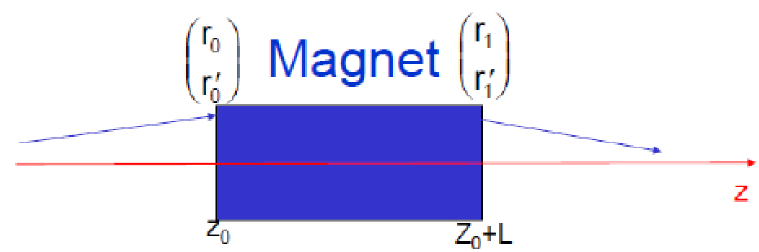
- For ultra-reletivistic particles v~c
  - B=1T is equivalent to E=300MV/m!!!!
- For low energy (v=0.01c)
  - B=1T is equivalent of E=3MV/m

- Electrostatic accelerators existed but the use of such systems are very limited of low energy!!

The light optics similarity



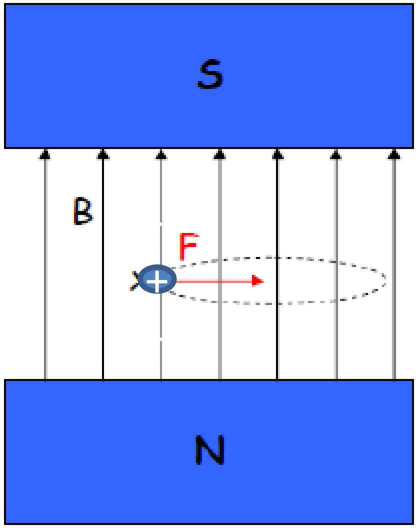
The same matrix formalism can be adopted in first order and linear approximation.
Vectors (x,x’) and (y, y’)

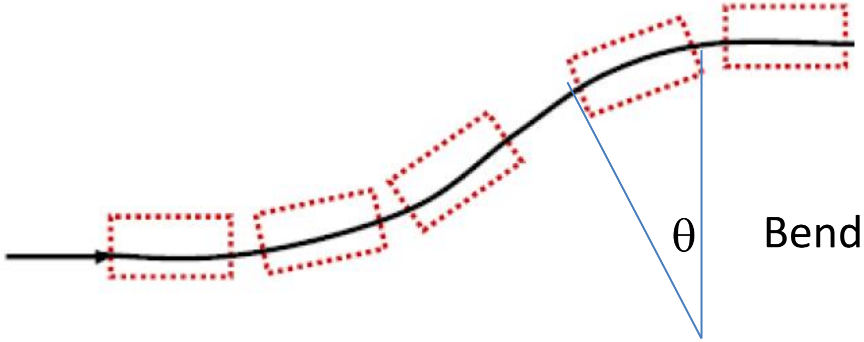


$$\begin{pmatrix} r_1 \\ r_1' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} r_0 \\ r_0' \end{pmatrix} = \mathbf{M} \begin{pmatrix} r_0 \\ r_0' \end{pmatrix}$$

Bending magnets

- A dipole magnet with constant magnetic field
- Positive particle coming in the screen will bend to the right.
- Using combination of the dipoles one could create any kind of transport lines.





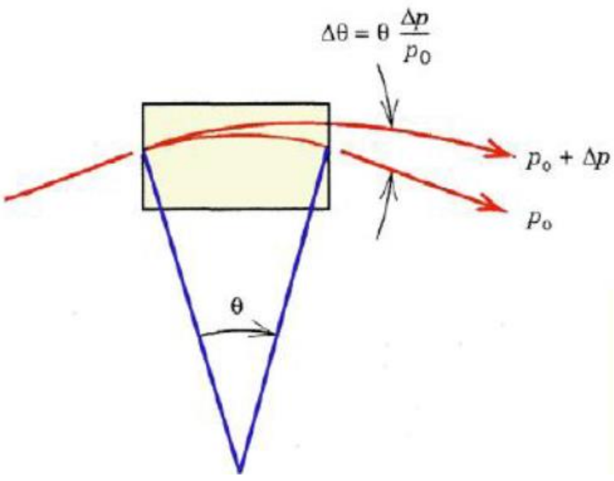
Bending angle

$$\theta = \frac{e}{p_0}\int_{s_1}^{s_2} B\,dl = \frac{e}{B\rho}\int_{s_1}^{s_2} B\,dl$$

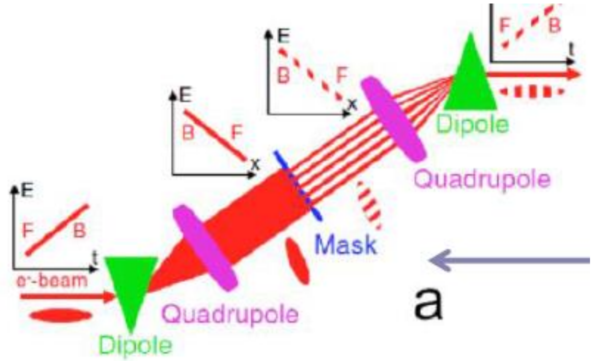
Where, p_0 is the momentum and $B\rho = p_0/e$ is the momentum 'rigidity' of the beam.

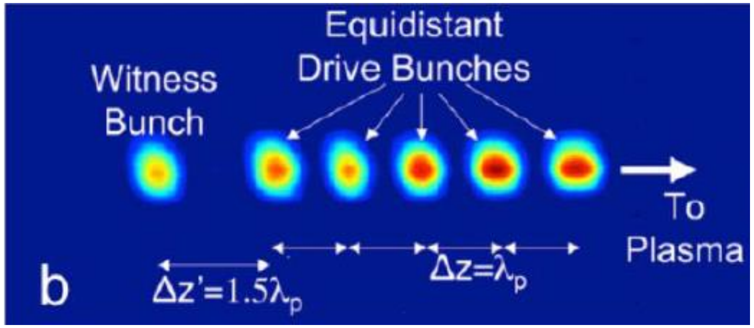
Dispersion

- Particle with different momentum will be bend on different angle
- Can cause beam quality degradation but also used for some experiments.

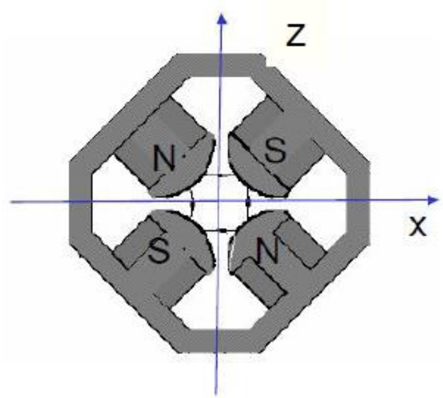


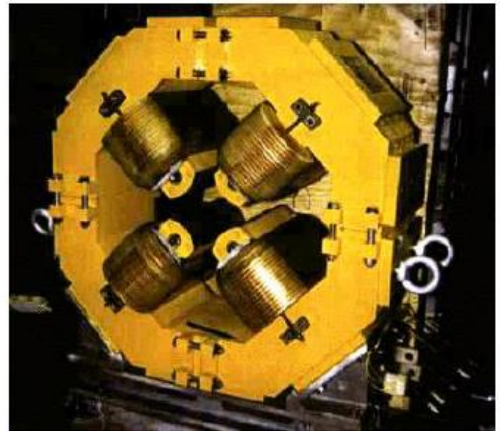
- Mask at ATF

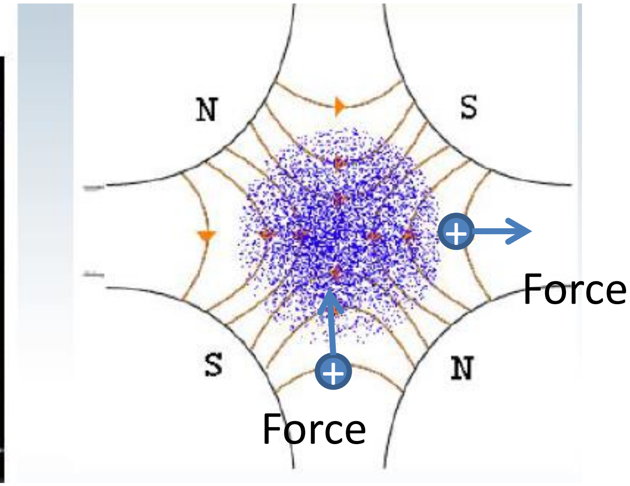




Quadrupoles



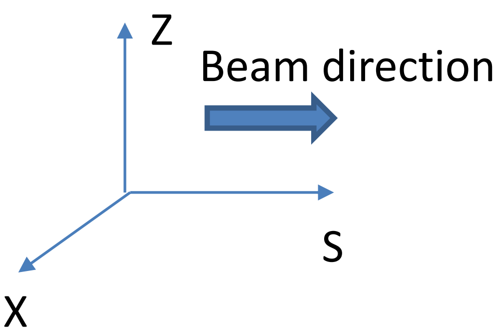




$$B = B_1 \left(z\hat{x} + x\hat{z} \right)$$

- Due to special field symmetry focus beam in one direction but defocus in other.
- Particles moving at axis are not experienced any force.

Sometimes in accel. physics especially in circular accel. (X,Z, S) coordinates are used



Quadrupoles(cont.)

- Particle displaced by (x,z) from the center

$$\boxed{B = B_1\left(z\hat{x} + x\hat{z}\right)}$$

$$\vec{F} = evB_1\hat{s}\times\left(z\hat{x} + x\hat{z}\right) = -evB_1 z\hat{z} + evB_1 x\hat{x}$$

the equations of motion become:

$$\frac{1}{v^2}\frac{d^2x}{dt^2} = \frac{eB_1}{\gamma m v}x, \quad \frac{1}{v^2}\frac{d^2z}{dt^2} = -\frac{eB_1}{\gamma m v}z$$

or $$\frac{d^2x}{ds^2} = x'' = \kappa x \quad \frac{d^2z}{ds^2} = -\kappa z$$ where $$\kappa = \frac{eB_1}{\gamma m v}$$

When matrix transformation from entrance to exit of quadrupole :

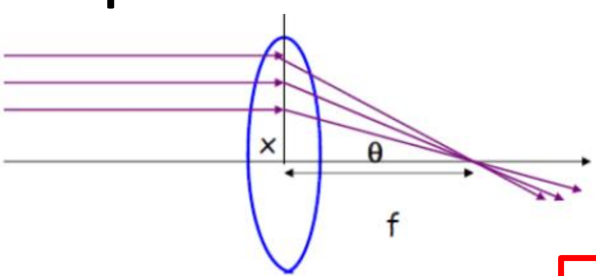
$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\sqrt{\kappa}L & \frac{1}{\sqrt{\kappa}}\sin\sqrt{\kappa}L \\ -\sqrt{\kappa}\sin\sqrt{\kappa}L & \cos\sqrt{\kappa}L \end{pmatrix}\begin{pmatrix} x_0 \\ x0' \end{pmatrix} \quad \begin{pmatrix} z \\ z' \end{pmatrix} = \begin{pmatrix} \cosh\sqrt{\kappa}L & \frac{1}{\sqrt{\kappa}}\sinh\sqrt{\kappa}L \\ \sqrt{\kappa}\sinh\sqrt{\kappa}L & \cosh\sqrt{\kappa}L \end{pmatrix}\begin{pmatrix} z_0 \\ z0' \end{pmatrix}$$

Thin lens approximation

- For thin lens when K<<1/L^2

$$\begin{pmatrix} \cos(\sqrt{K}L) & \frac{1}{\sqrt{K}}\sin(\sqrt{K}L) \\ -\sqrt{K}\sin(\sqrt{K}L) & \cos(\sqrt{K}L) \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 \\ -KL & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{F} & 1 \end{pmatrix}$$

- If the quadrupole is thin enough, the particles coordinate doesn’t change while momentum change. The quad works almost as a optical lens…



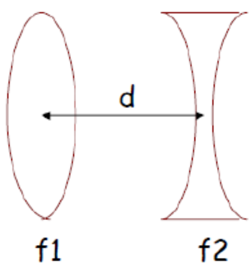
$$\Delta x' = \frac{x}{f}$$

- With only one difference:

It Focus in the one plane and defocus in the other plane

Focus the beam in both directions.

- Using doublets
- Using optical analogy one can calculate



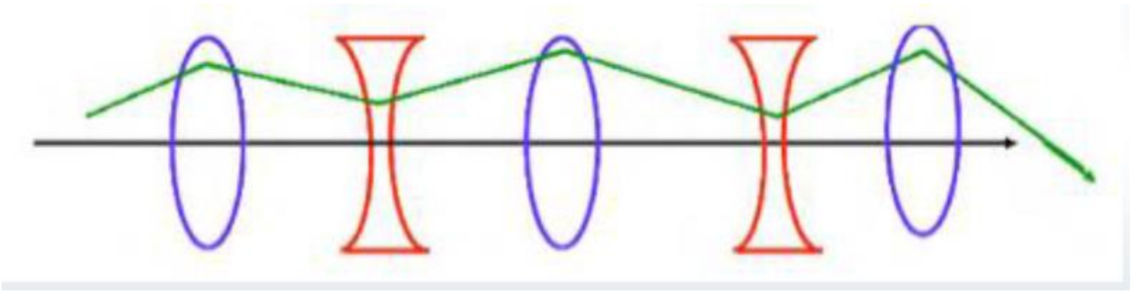
The combined f is:

$$\frac{1}{f_{combined}} = \frac{1}{f1} + \frac{1}{f2} - \frac{d}{f1 f2}$$

What if f1 = -f2?

$$f_{combined} = \frac{f1^2}{d}$$

- A quadrupole doublet is focusing in both planes.
- Strong focusing by sets of quadrupole doublets with alternative gradient. Could keep beam inside vacuum chamber.



Solenoid

- A solenoid is a set of helical coils.
- Typically, solenoid radius is smaller than the its length.
- Magnetic field is generated along the axis line.
- Solenoid couples X and Y motion.
- Solenoid produced focusing in both direction

$$1/f = e\int Bz^2 dz/(2pc)^2$$

$$\begin{pmatrix} 1 & 0 \\ -\frac{1}{F} & 1 \end{pmatrix}$$

- Solenoids are preferable at low energy