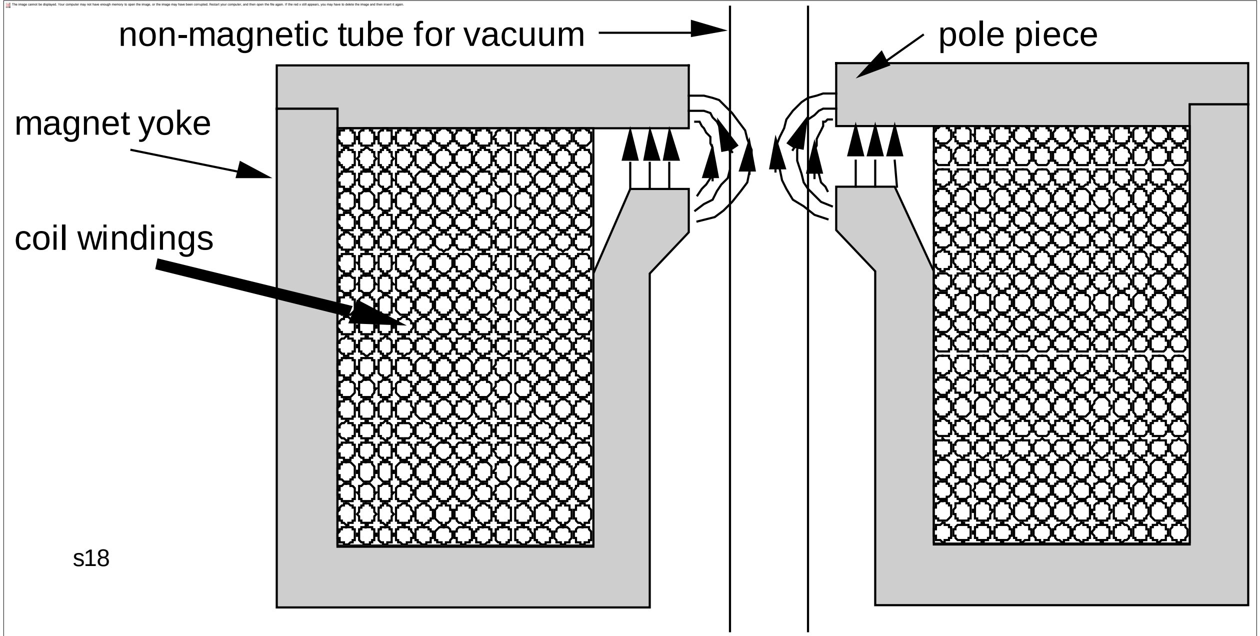
Nanometer Scale Patterning and Processing

Spring 2016

Lecture 17

Electron Optics and Lithography (continued)

Magnetic Lenses for charged particles



Axially symmetric field distribution

No contamination build up: can be outside vacuum.

Weak focusing, proportional to q/m, can not focus heavy ions in FIB

Electrons in Magnetic Fields: The Left hand Rule

•An electron moving through a magnetic field receives an accelerating force which is:

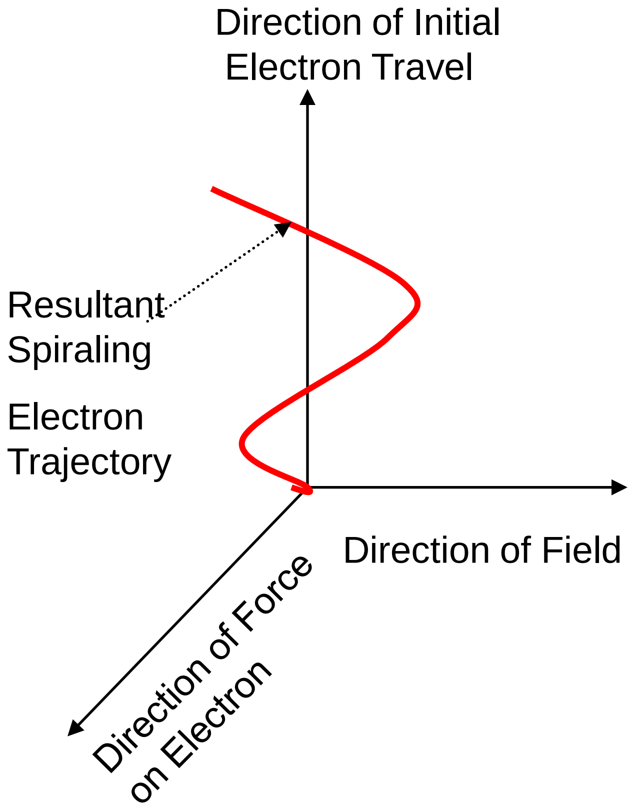
- perpendicular to the direction of the field
- perpendicular to the direction of the electron
- proportional to the flux density in the field
- proportional to the speed of the electron

•**The velocity of the electron is not altered**.

•This means:

•Electrons travelling parallel to the field are not affected.

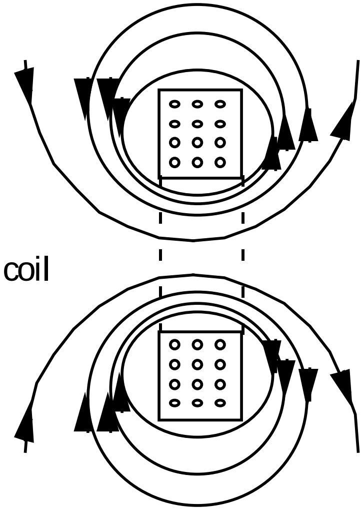
•In general, electrons travel through the field in some
form of corkscrew path.



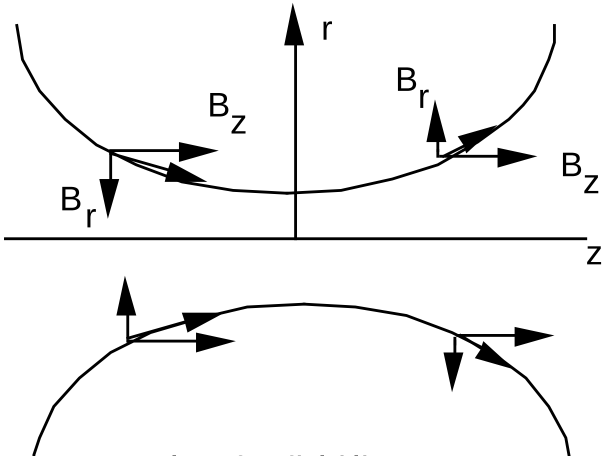
$$F \propto q\left(\bar{v} \times \bar{B}\right)$$

How do Magnetic Lenses work?

s5



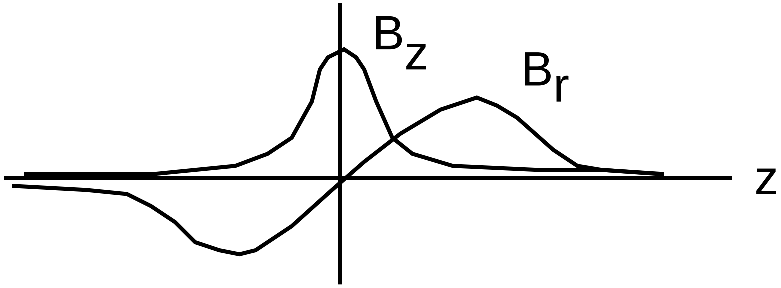
cross section of coil



plot of B field lines

The axial and radial magnetic fields vary along the lens axis; roughly sketched as the following:

s6



“Hand waving” Explanation

Lorentz force $F \propto q\left(\bar{v} \times \bar{B}\right)$

$\left|\bar{v}\right|$ is unchanged by the magnetic field.

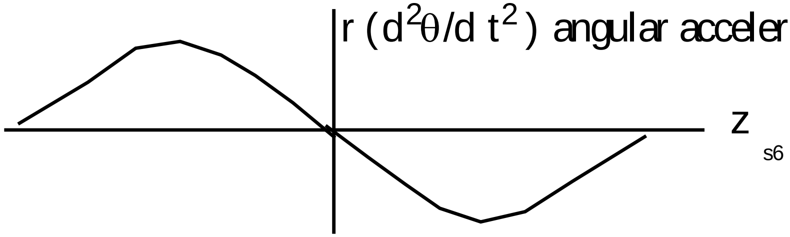
The angular acceleration due to B_r is proportional to

$$(v_z \bullet B_r) \qquad a = \frac{d^2x}{dt^2} \quad x = r\theta$$

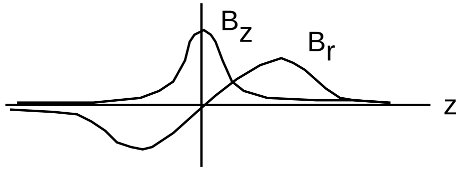
Therefore $m \; r\left(d^2\theta / dt^2\right) \propto v_z \bullet B_r (-e)$

The angular acceleration as a function of distance along the lens axis varies somewhat like

s7

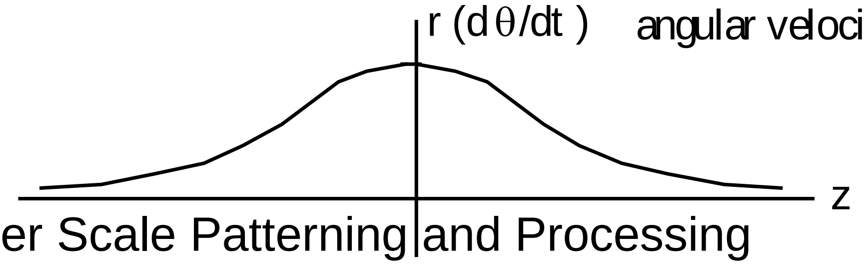


s6



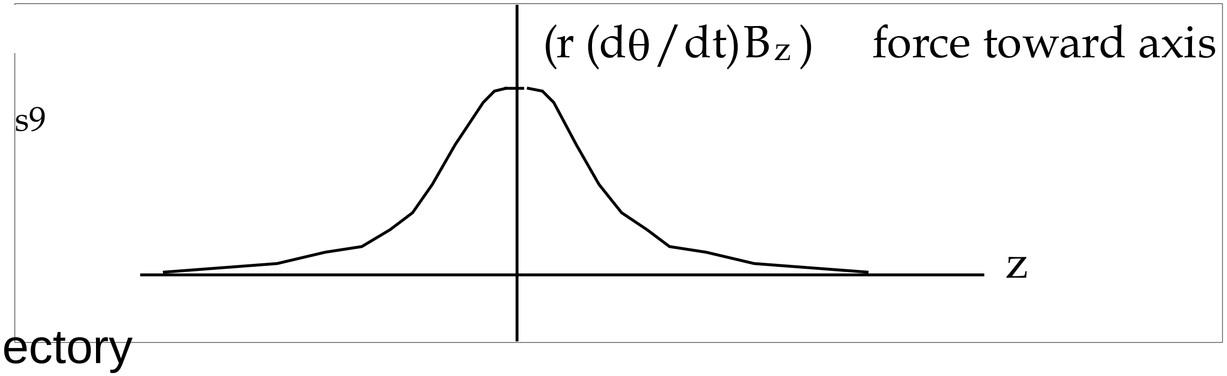
Angular velocity as a function of distance along the lens axis (taking integration)

s8

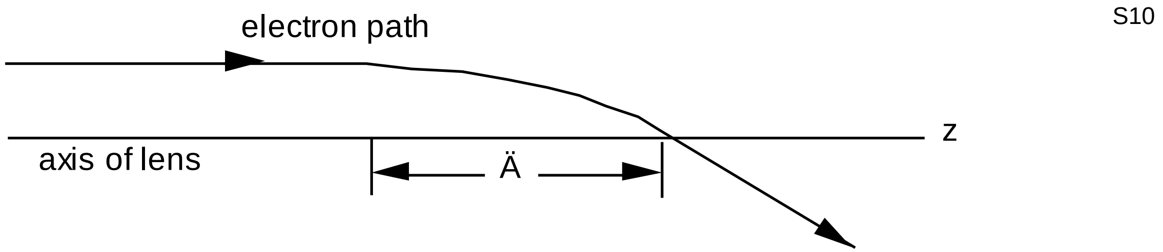


Spiral focusing

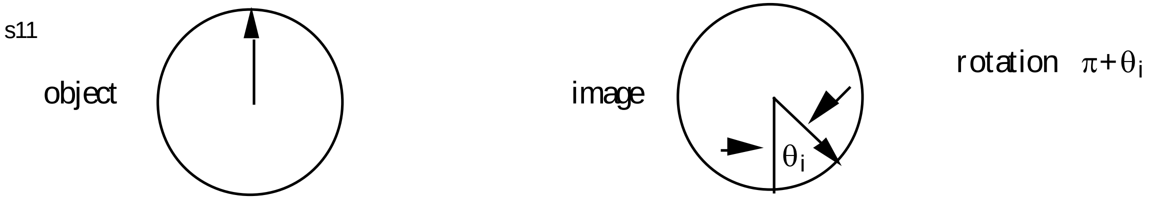
$r(d\theta/dt)B_z$: the radial force on the electron is directed toward the axis.



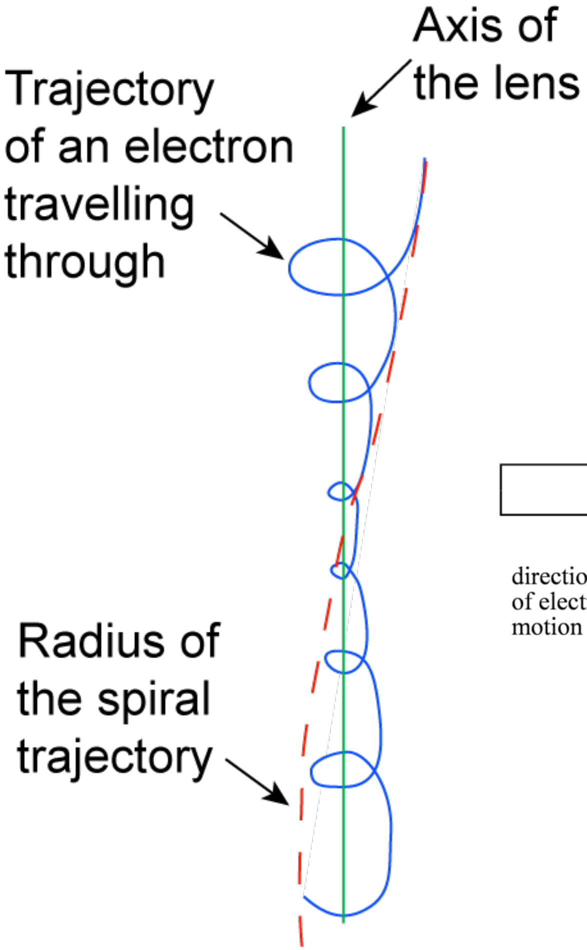
Electron trajectory

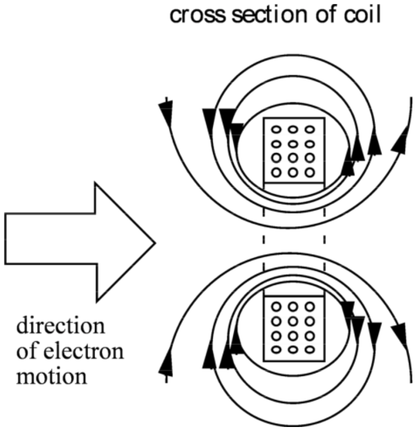


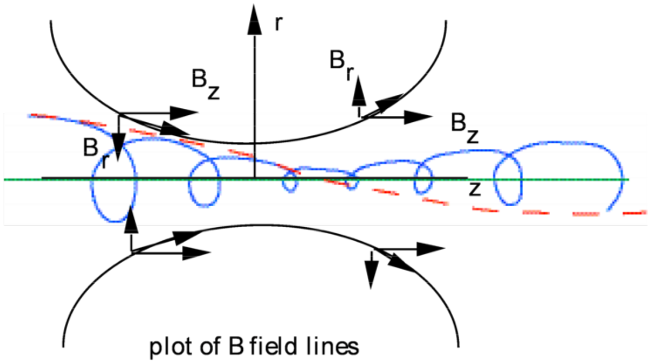
Along the axis, image field would be inverted and rotated relative to the object.



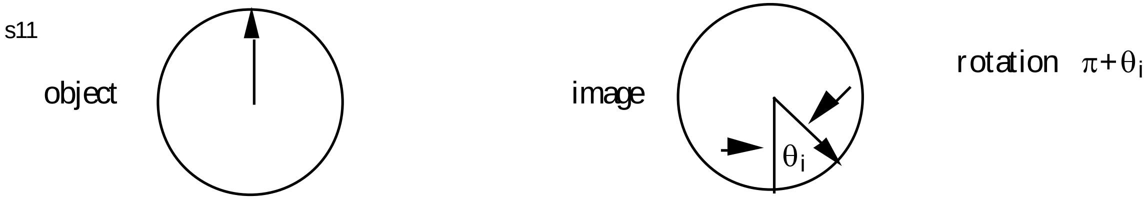
Trajectory of an electron through a magnetic lens



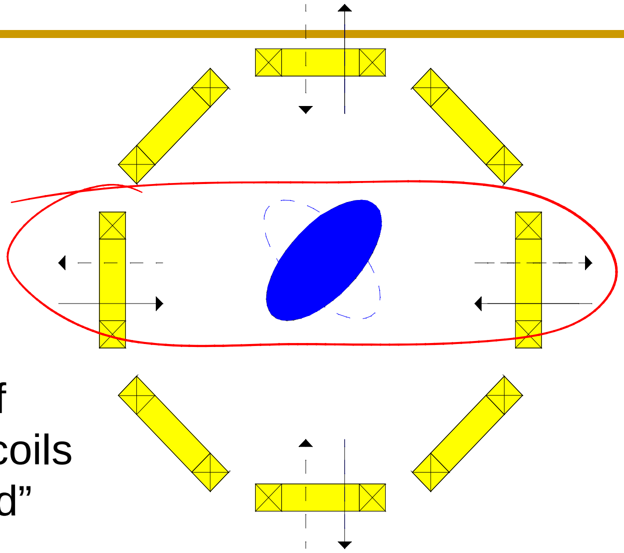




Along the axis, image field would be inverted and rotated relative to the object.

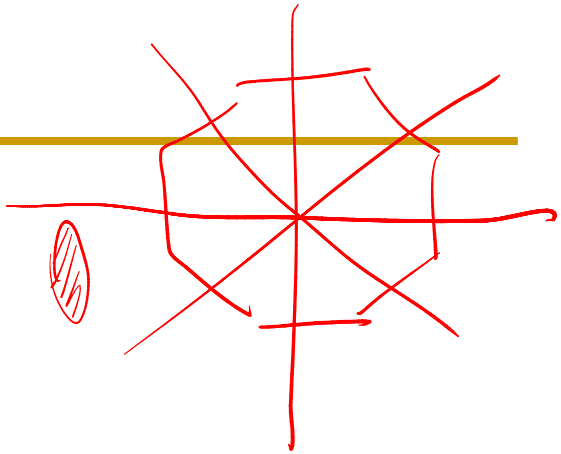


Stigmation Correction

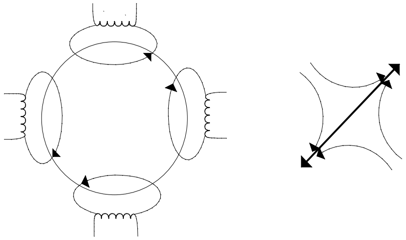


STIGMATOR COILS

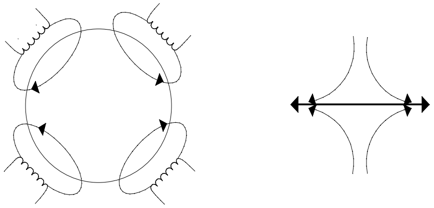
By adjusting the strength of the magnetic field in the 8 coils the beam can be “squeezed” in the direction required for correcting the astigmatic beam.



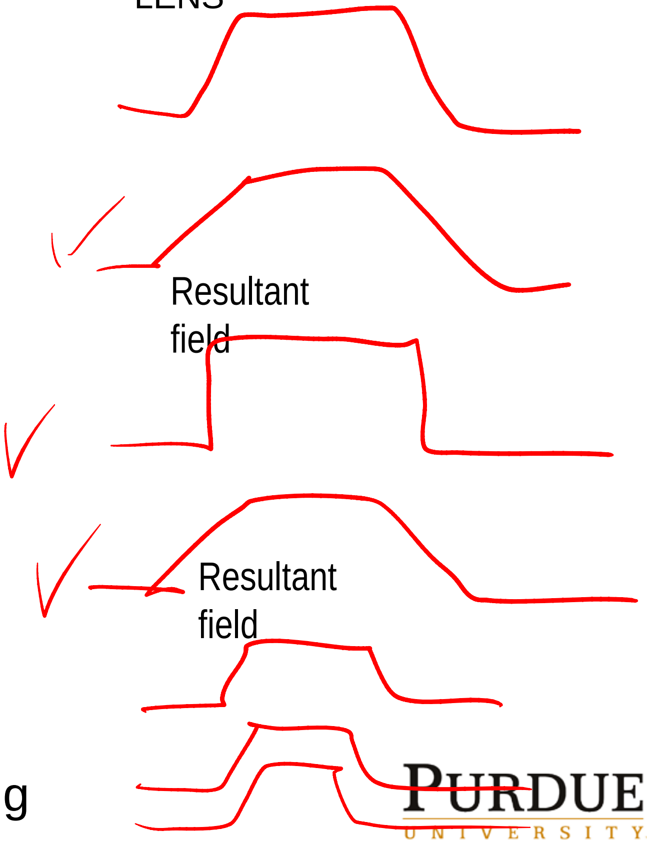
2x4 STIGMATOR COILS IN FINAL LENS



Diagonal stigmator coils



Axis stigmator coils



Resultant field

Resultant field

Aberrations in Electromagnetic Lens

- Spherical aberrations

$$d_s = B * \sqrt[4]{\lambda^3 * C_s}$$

B is a numerical value of the order of 1

λ is the electron wavelength

C_s the spherical aberration coefficient

- Chromatic aberrations

$$d_c = A * \sqrt[4]{\lambda * \frac{\Delta E}{E} * C_C}$$

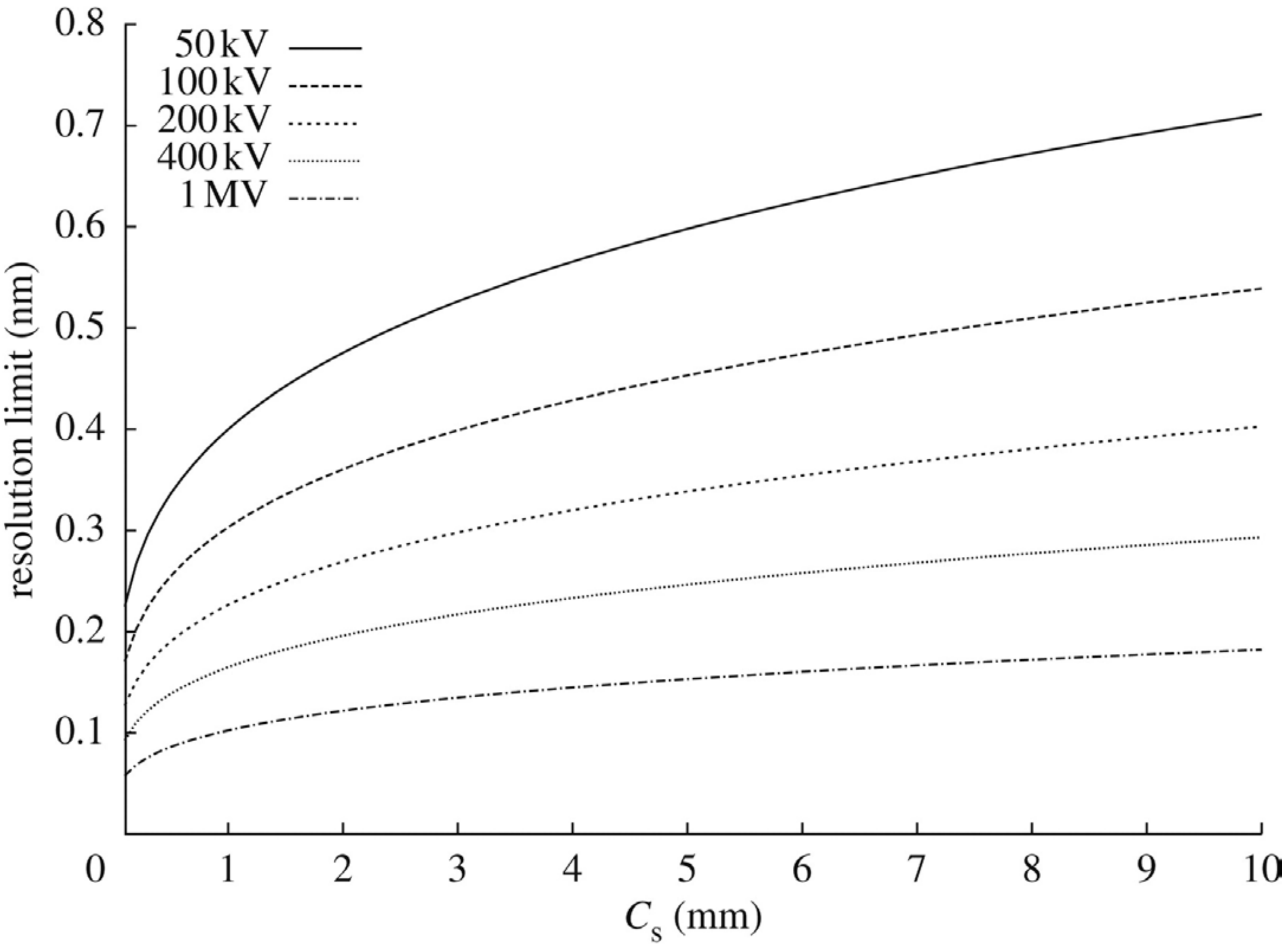
A is a numerical value of the order of 1

E and ΔE the mean energy and energy width of the beam

C_C the chromatic aberration coefficient

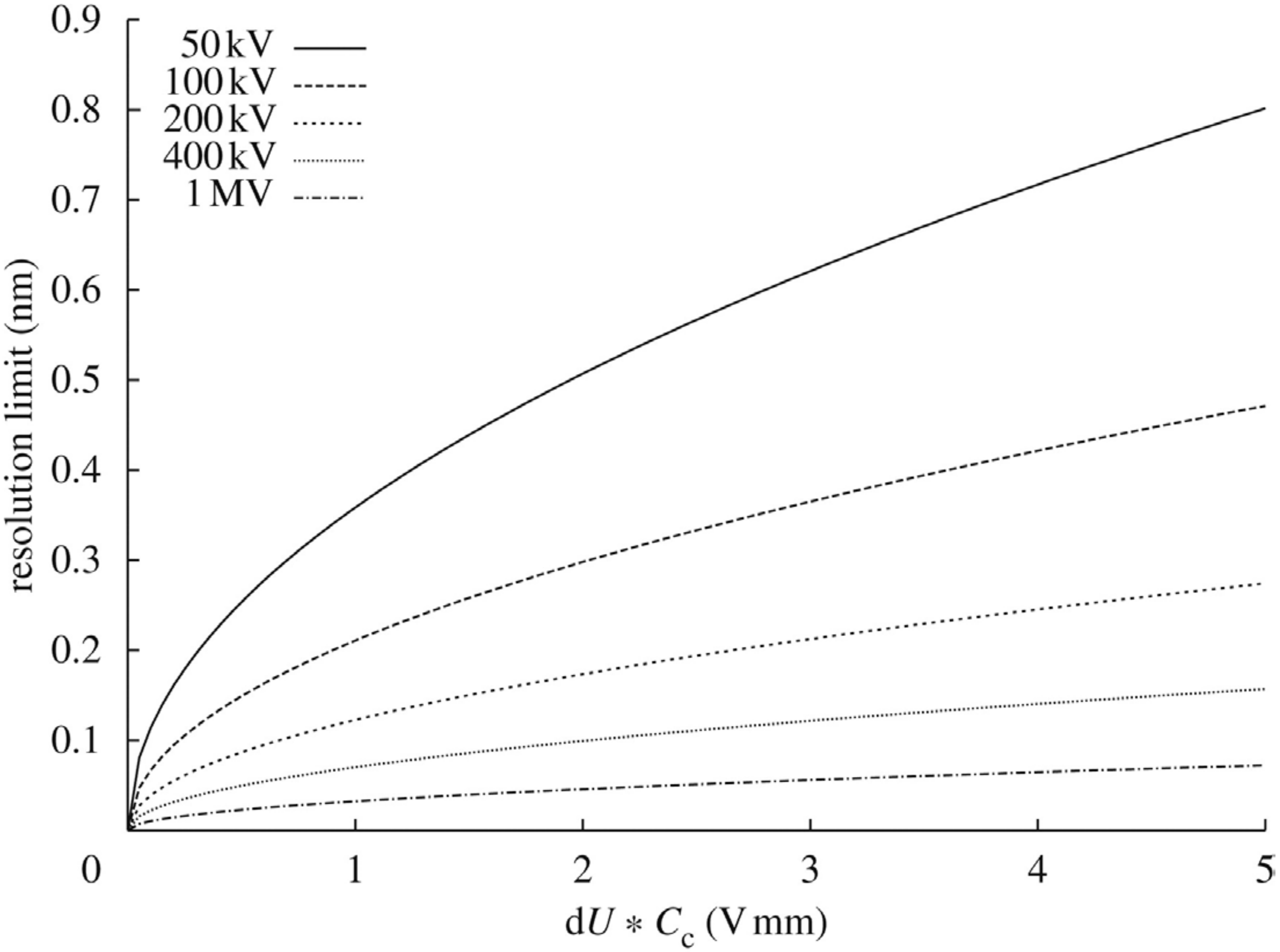
- Reducing aberrations → finer beam spot
  - – Higher resolution in (transmission) electron microscopy
  - – For lithography, resolution is generally not limited by focused electron beam spot size

Achievable resolution in spherical aberration limited microscopes



J. Zach Phil. Trans. R. Soc. A 2009;367:3699-3707

Achievable resolution with chromatic aberration



J. Zach Phil. Trans. R. Soc. A 2009;367:3699-3707

Summary of Electron optics

- Any axially symmetric magnetic or electrostatic field has the property of a lens for paraxial rays.
- All such lenses are convergent.
- Focusing of a magnetic lens depends on *q/m*.
- Focusing of an electrostatic lens is independent of *m*.
- The image is inverted and rotated in the case of a magnetic lens and merely inverted in the case of an electrostatic lens.

- **Some Comments on Diverging Electron Lenses**
  To get a diverging electron lens one can: (1) violate axial symmetry; or (2) introduce field shorting planes or grids. N. Wittels, (Ph.D., MIT 1976) demonstrated a diverging electrostatic lens through the use of thin electron-transparent carbon foils. Neither of these approaches has proven to be practical.

- Higher acceleration voltages can increase resolution, but makes the beam difficult to deflect
  - More immune to environmental stray EM fields or deflection noises
  - An optimal acceleration voltage is 100 kV