Colliders – part 2

Accelerator physics - Colliders

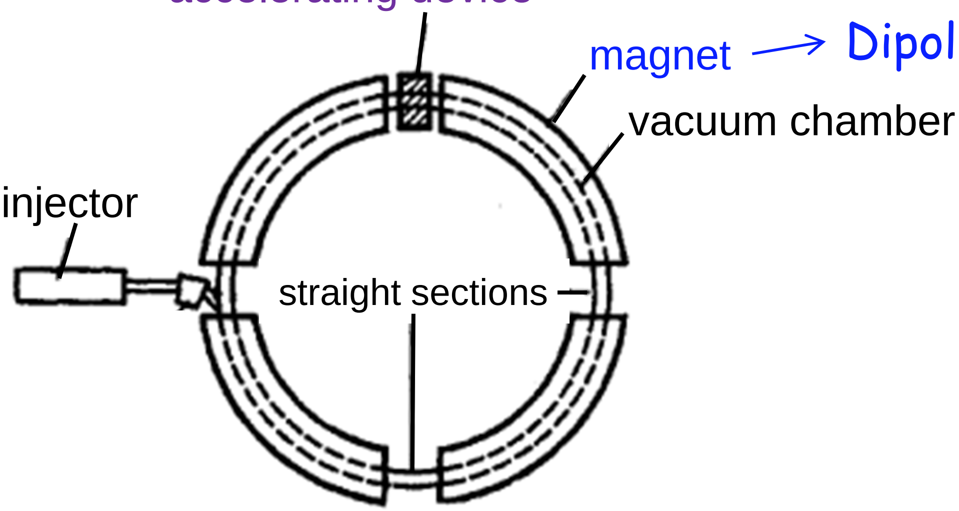
Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics
DESY, 31st July 2012

HELMHOLTZ ASSOCIATION

DESY

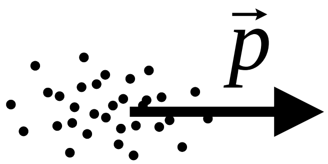
From part 1

RF cavities:
- pill-box cavity
- superconducting cavities

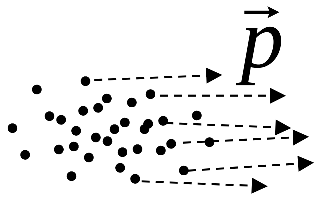


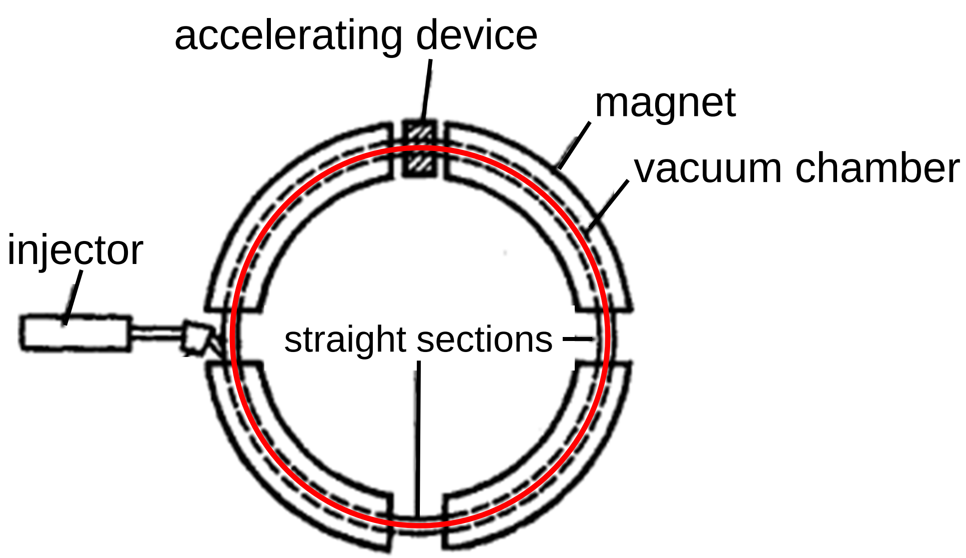
magnet → Dipole magnets:
- normal conducting dipoles
- superconducting dipoles

Need of focusing

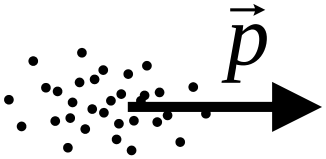


beam / bunch

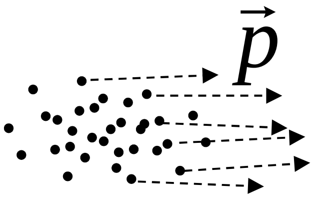


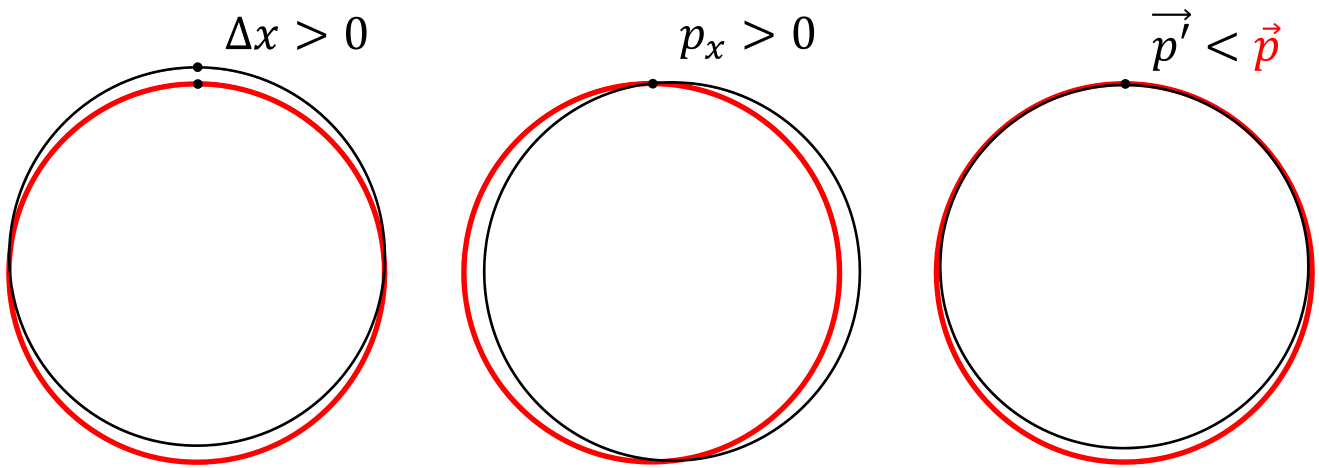


Need of focusing

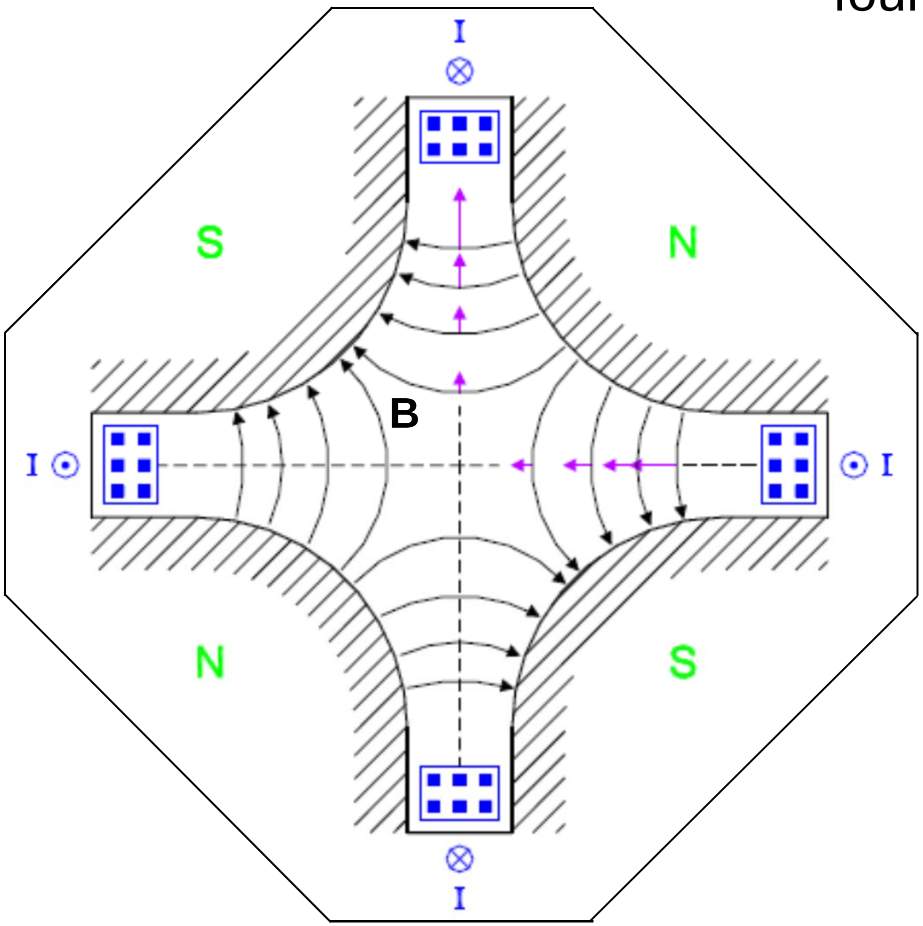


beam / bunch





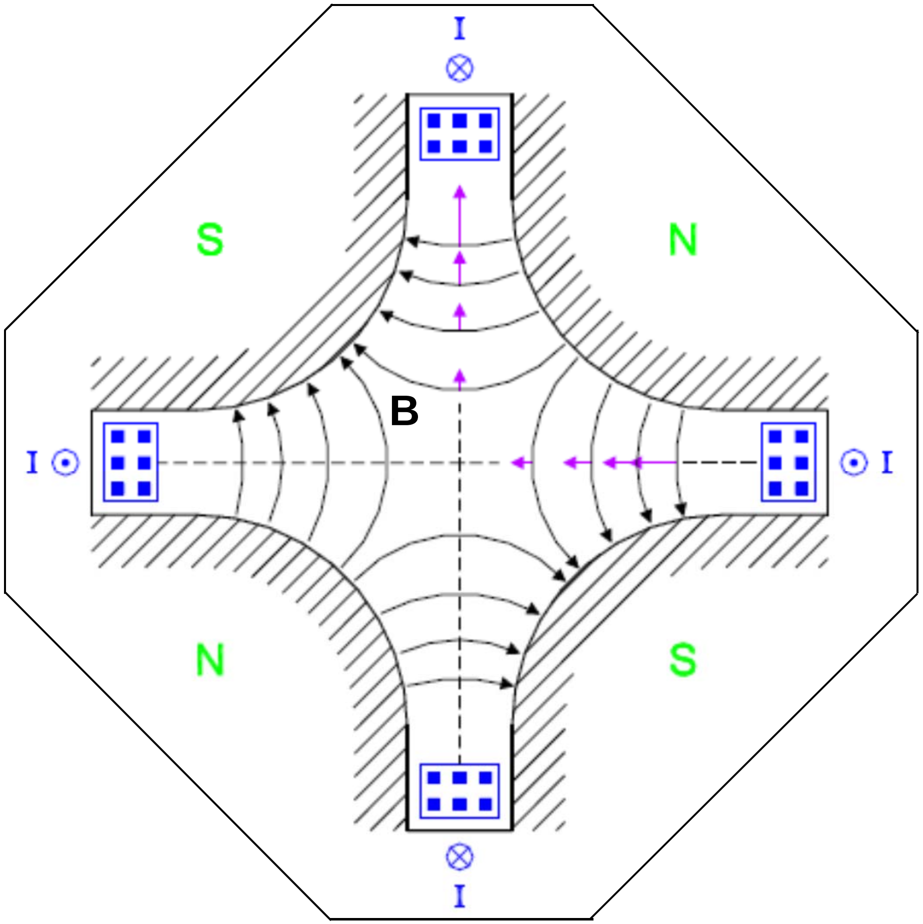
Need of focusing



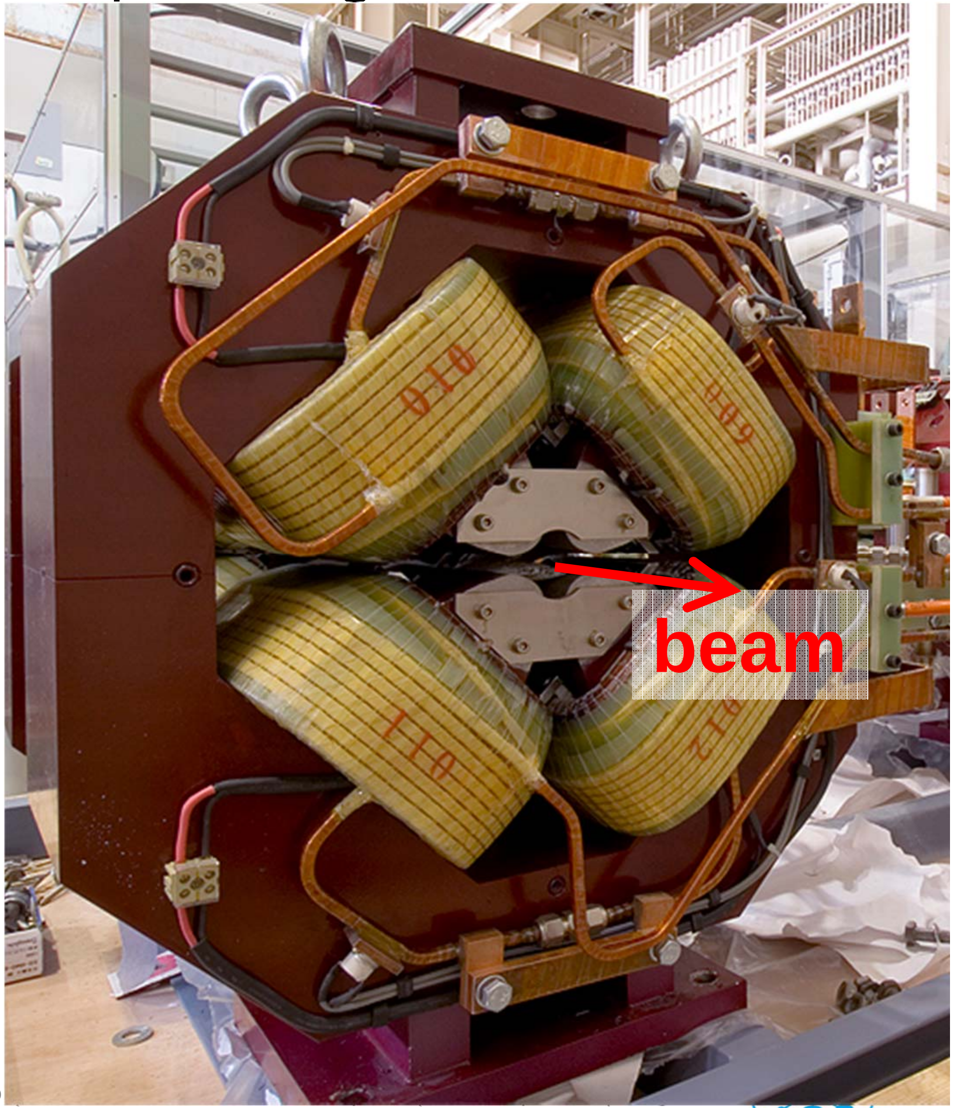
quadrupole magnet:

four iron poles

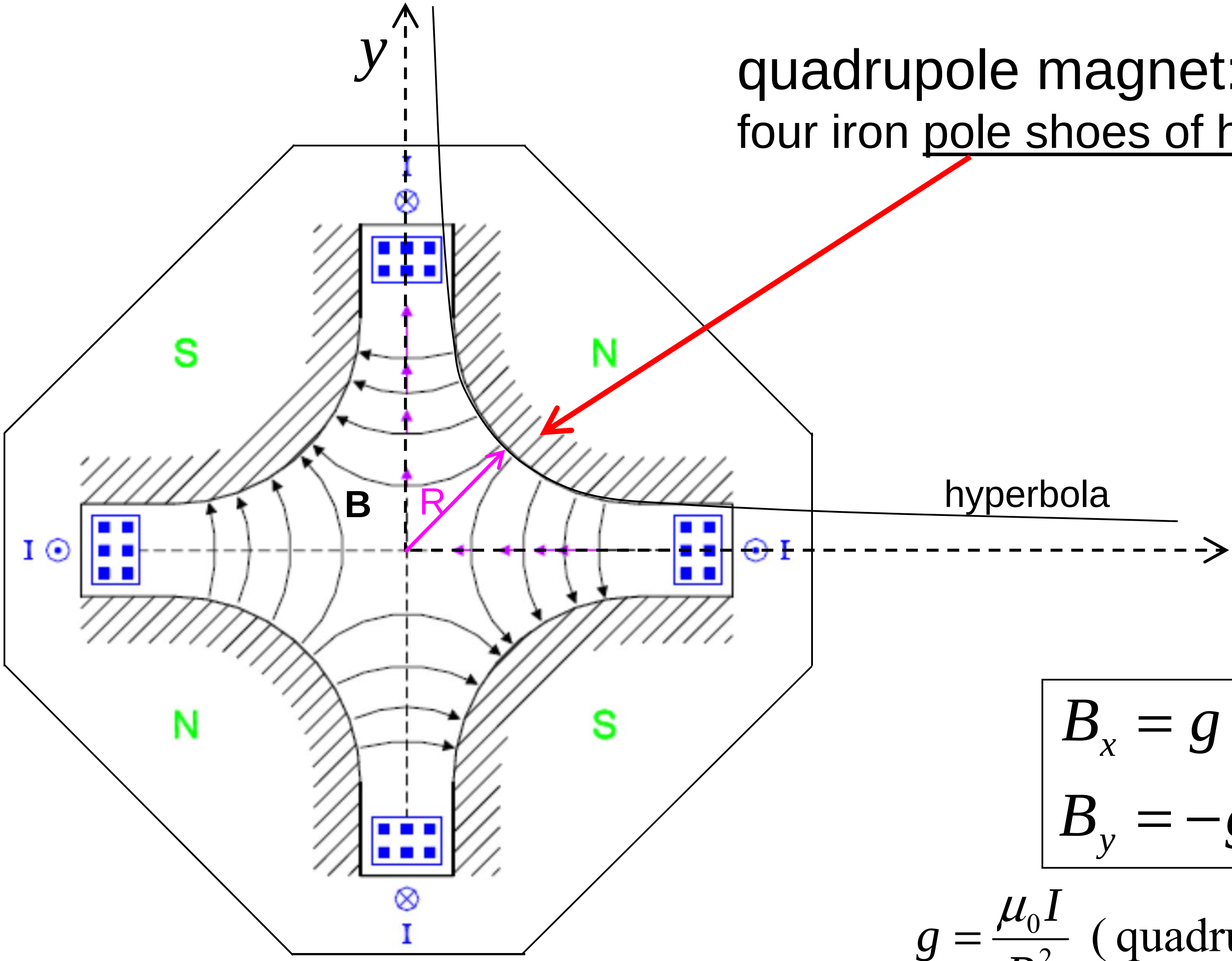
Quadrupole magnets



quadrupole magnet:



Quadrupole magnets



quadrupole magnet:

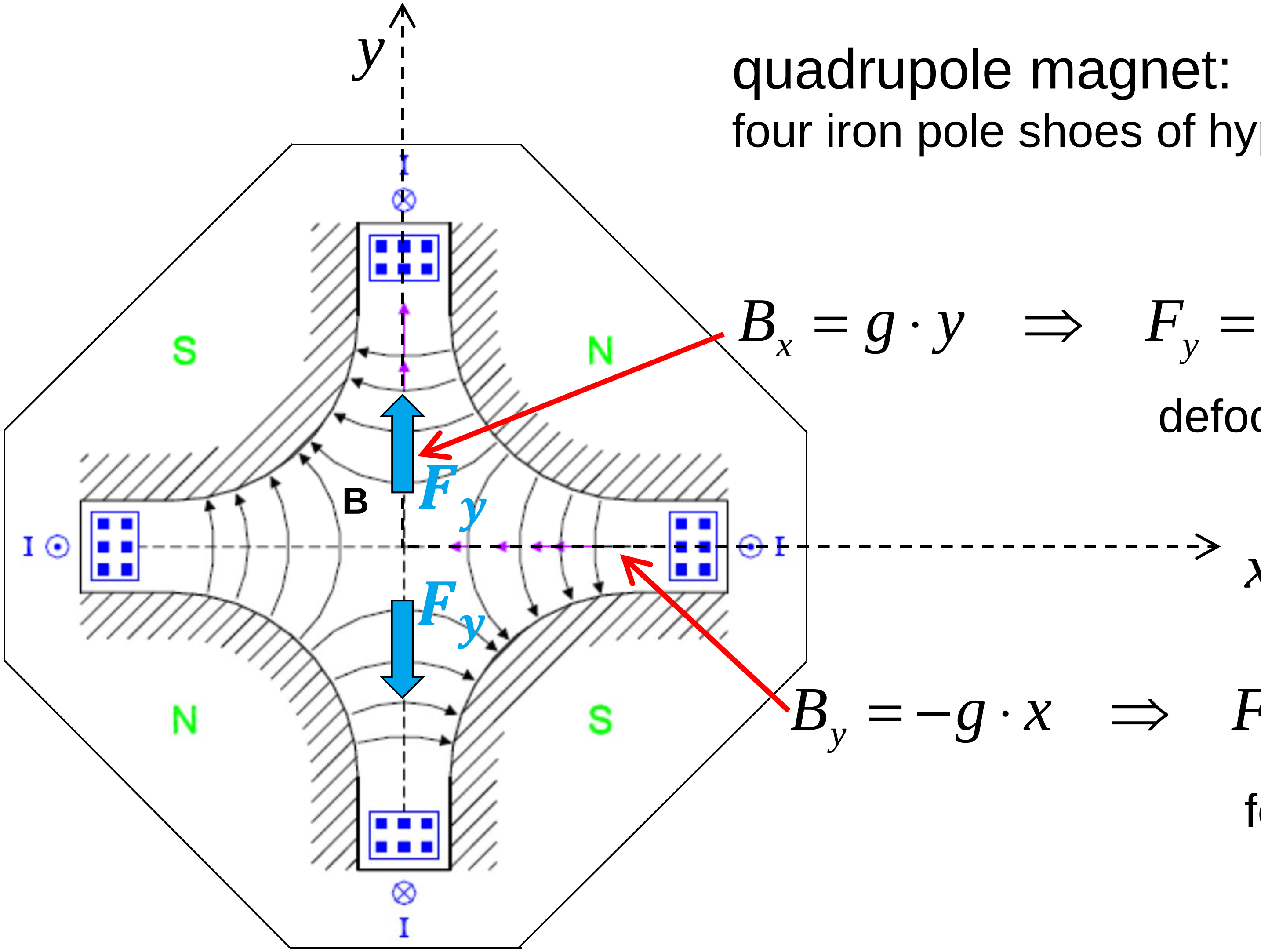
four iron pole shoes of hyperbolic contour

$$B_x = g \cdot y$$

$$B_y = -g \cdot x$$

$$g = \frac{\mu_0 I}{R^2} \quad \text{(quadrupole gradient)}$$

Quadrupole magnets



quadrupole magnet:
four iron pole shoes of hyperbolic contour

$$B_x = g \cdot y \quad \Rightarrow \quad F_y = g \cdot y$$

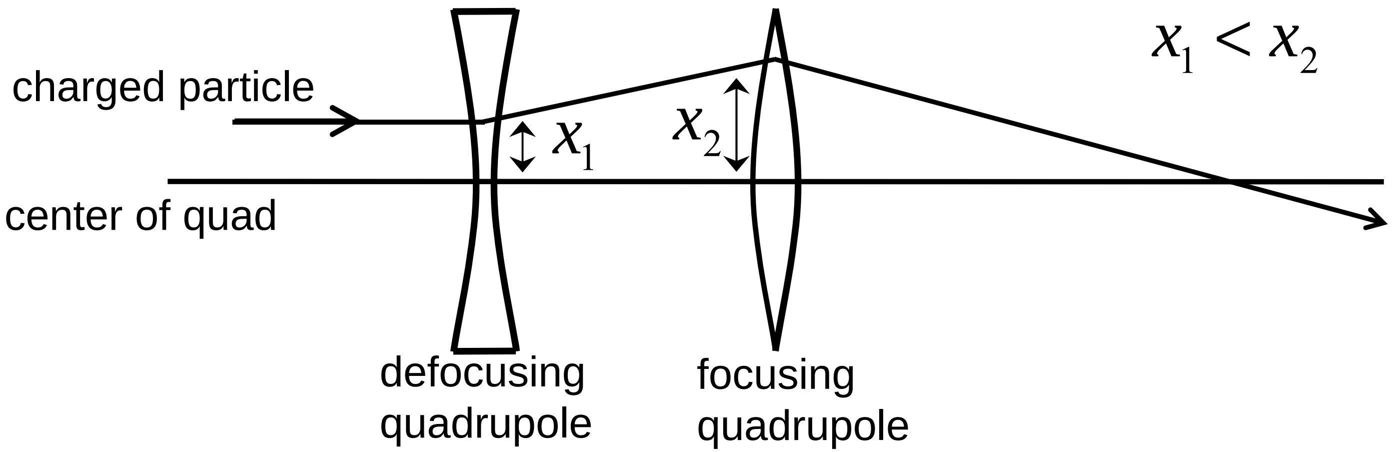
defocusing

$$B_y = -g \cdot x \quad \Rightarrow \quad F_x = -g \cdot x$$

focusing !

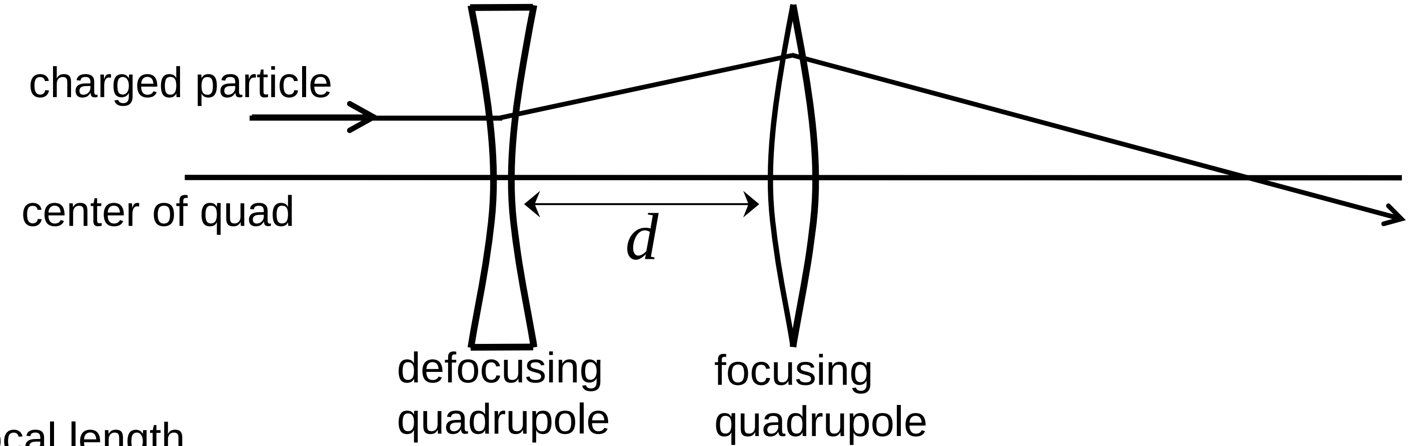
Quadrupole magnets

QD + QF = net focusing effect:



Quadrupole magnets

QD + QF = net focusing effect:



f: focal length

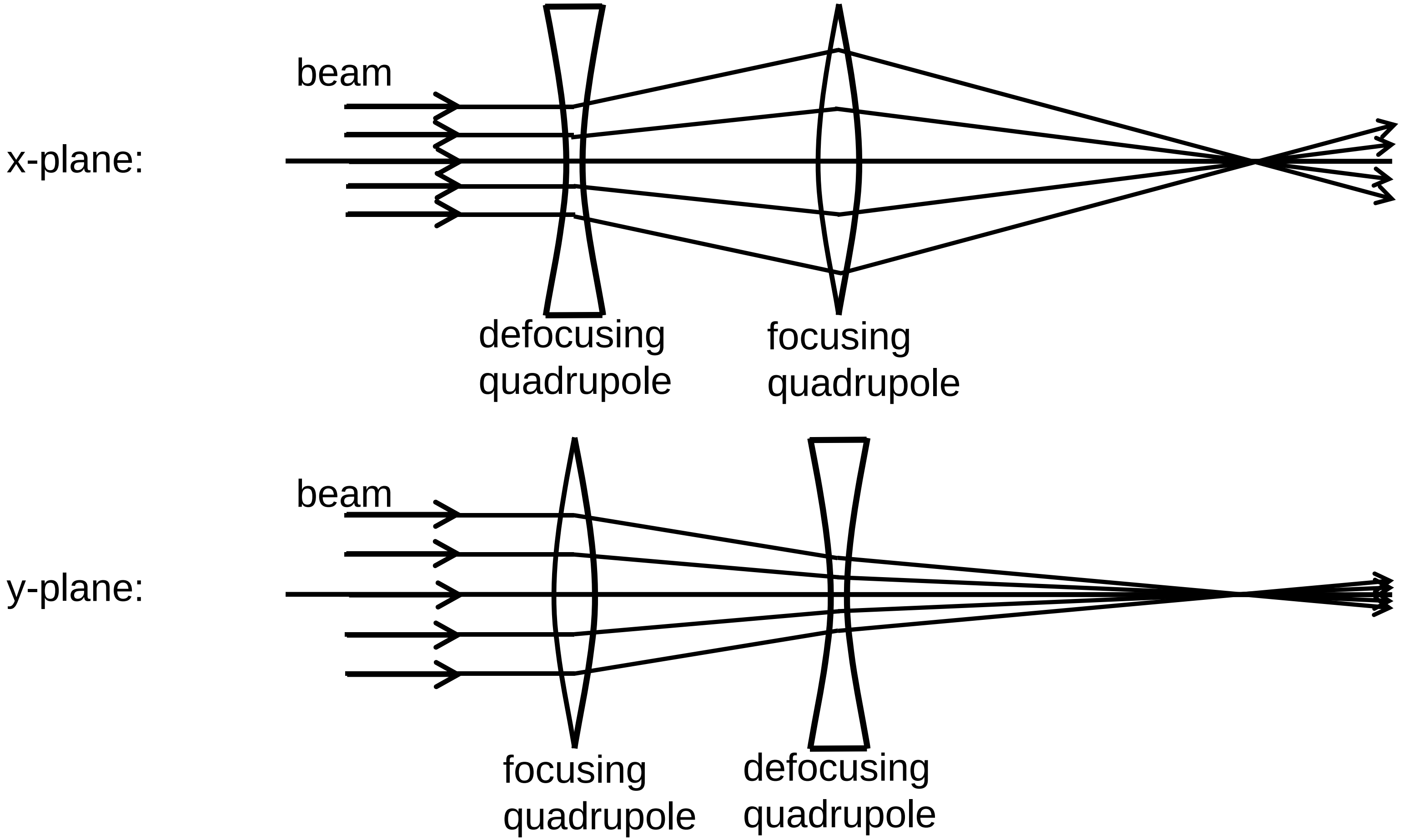
$$\frac{1}{f^*} = \frac{1}{f_D} + \frac{1}{f_F} - \frac{d}{f_D f_F}$$ (light optics)

if $f_D = -f_F = f$

$$\frac{1}{f^*} = \frac{d}{f^2} > 0$$

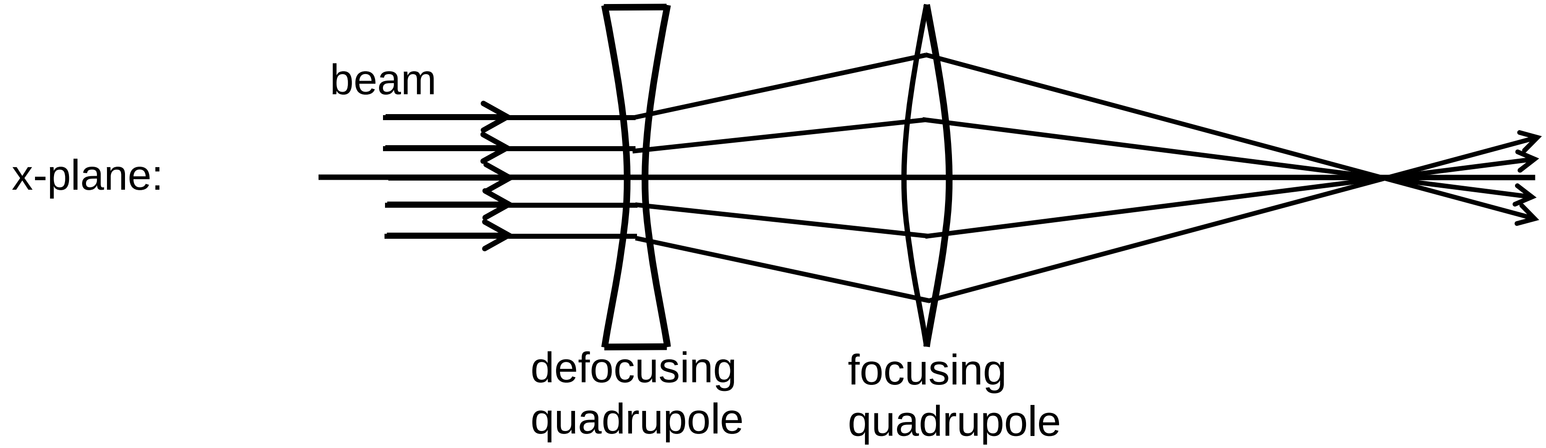
Quadrupole magnets

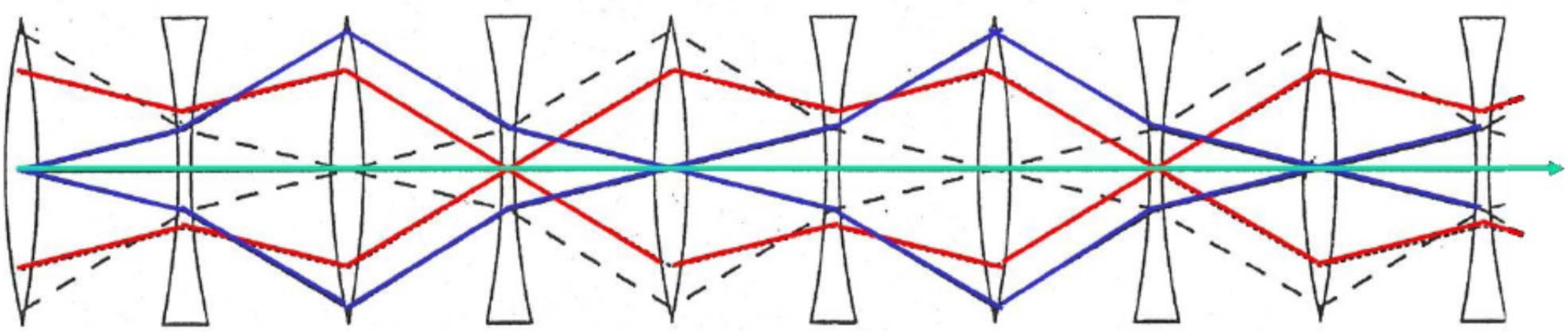
QD + QF = net focusing effect:



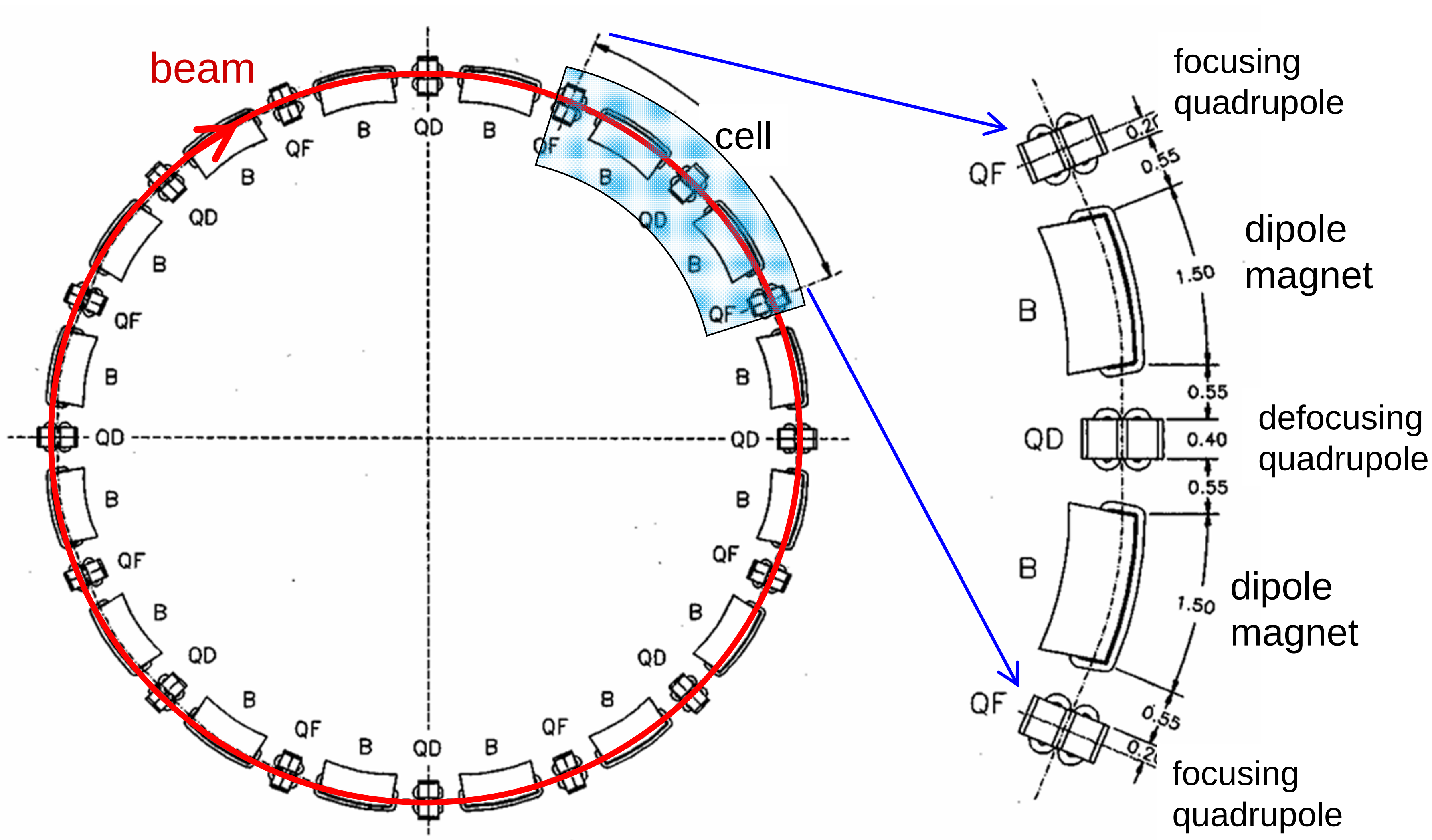
Quadrupole magnets

QD + QF = net focusing effect:



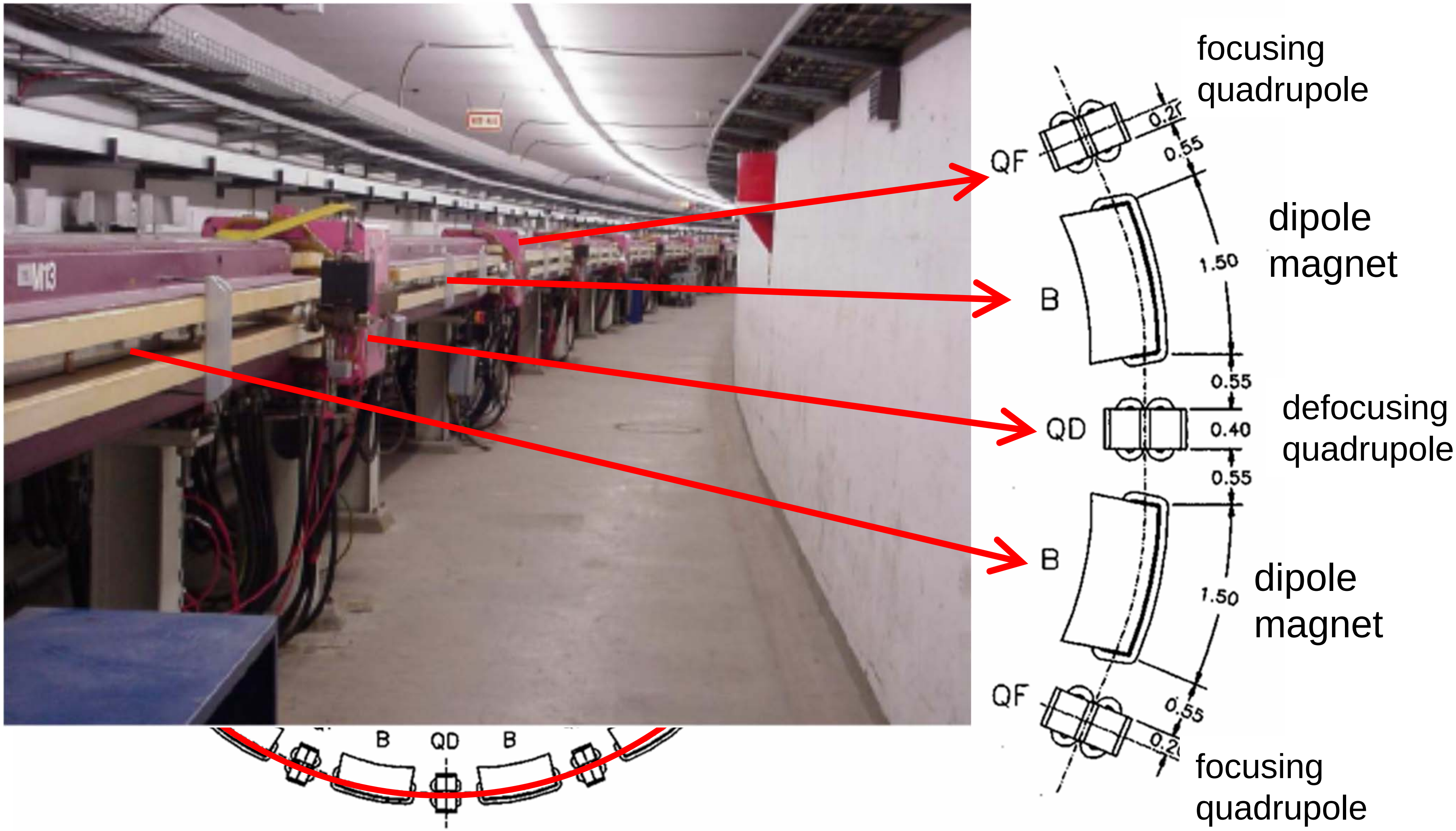


Circular accelerator



Circular accelerator

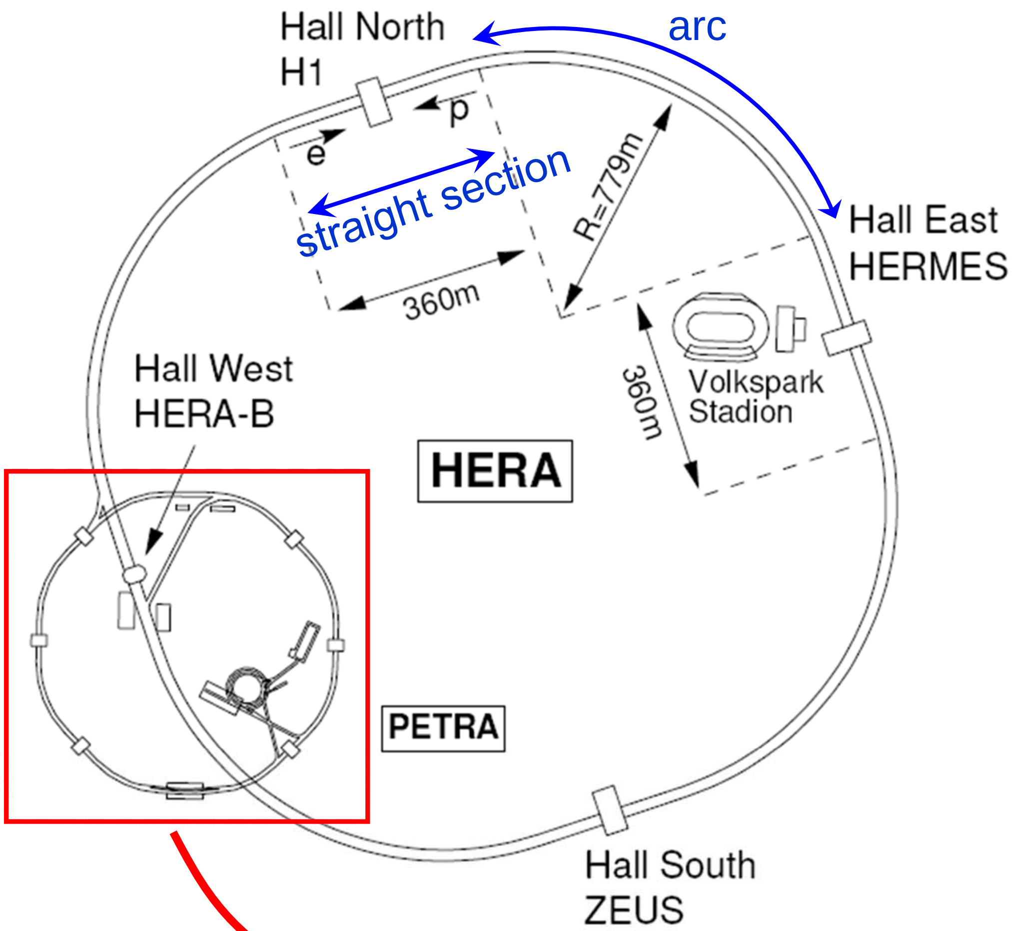
PETRA

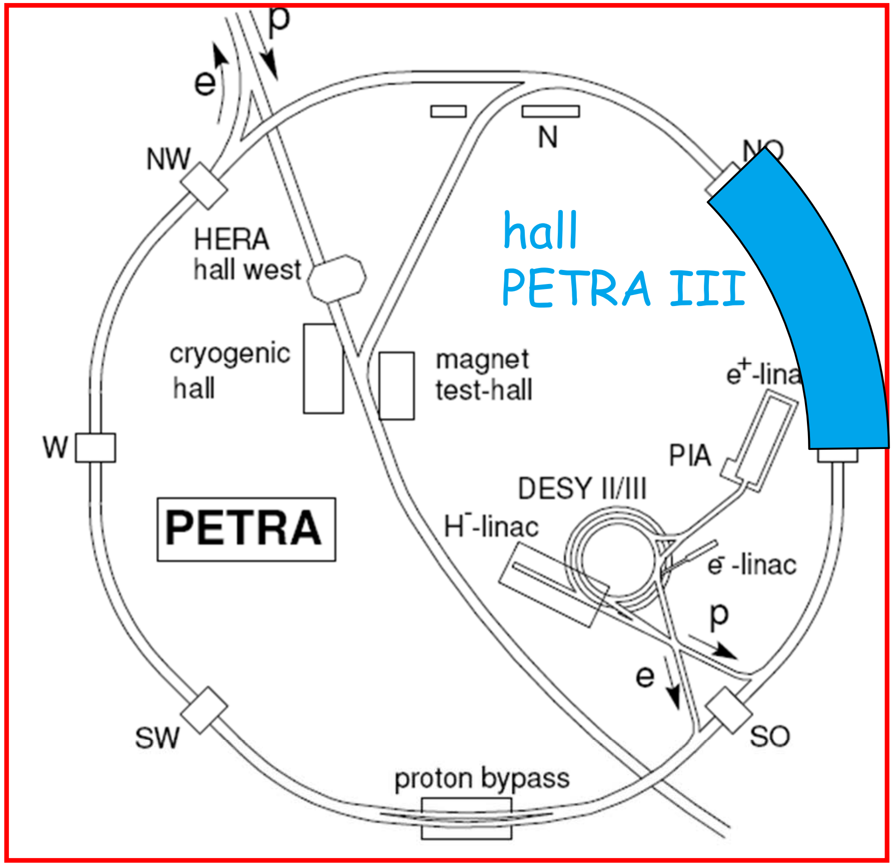


HERA collider and injector chain

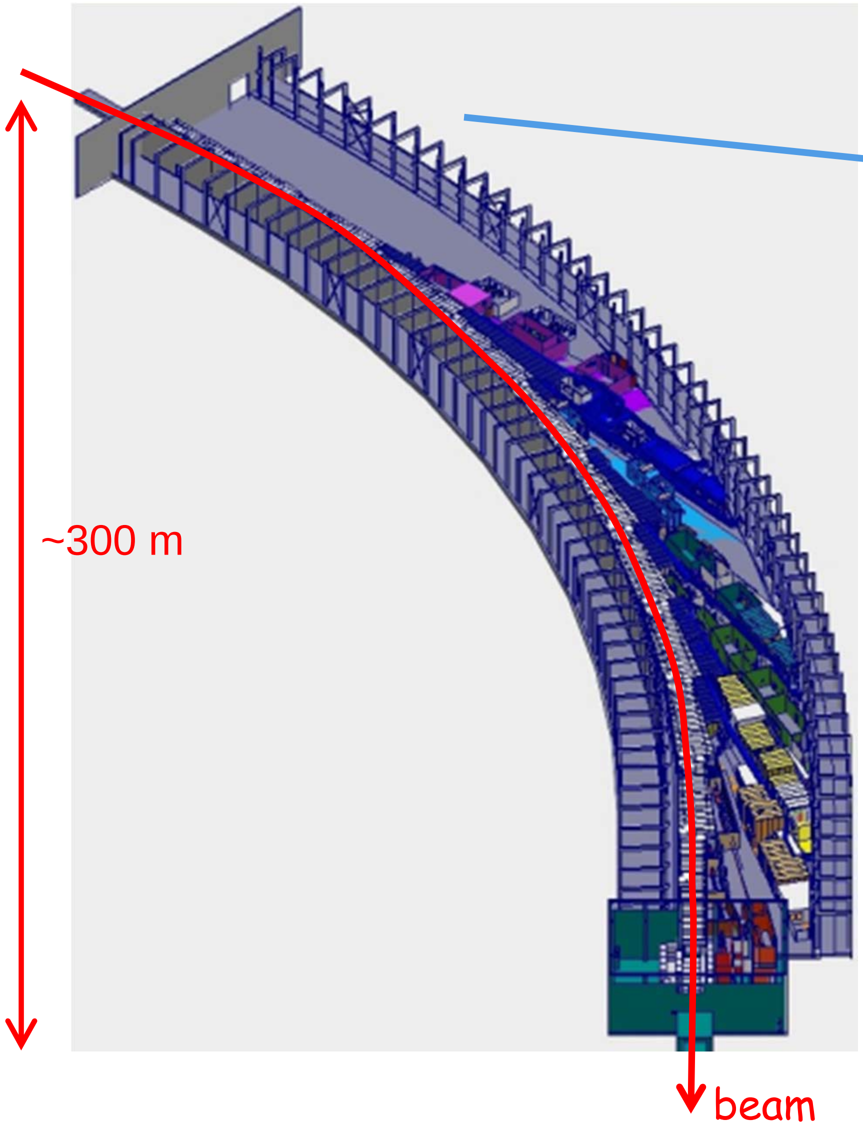
HERA: 4 arcs + 4 straight sections

PETRA: 8 arcs + 8 straight sections



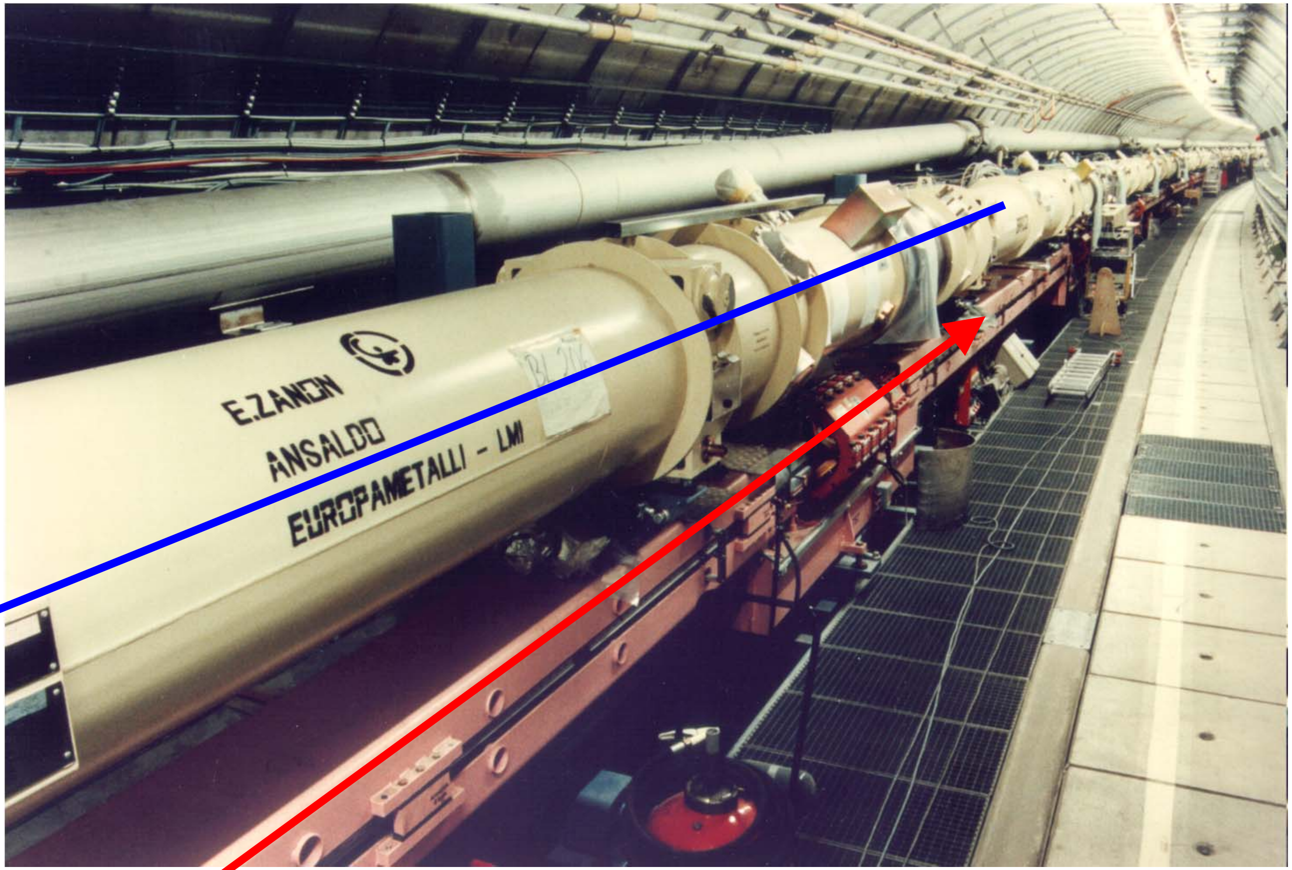


PETRA III



Why are the energies so different?

HERA (Hadron Electron Ring Accelerator) tunnel:

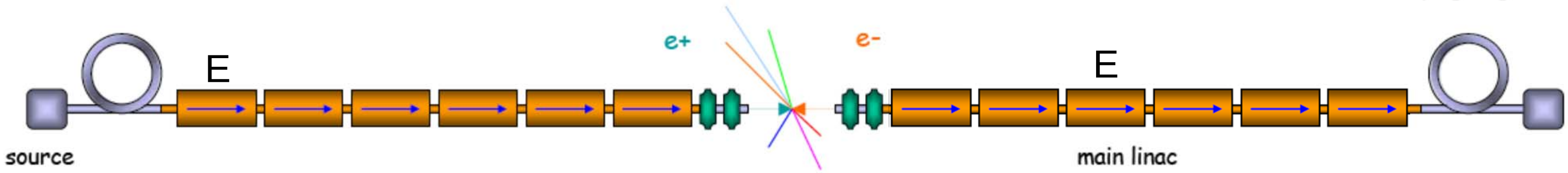


protons
at 920 GeV

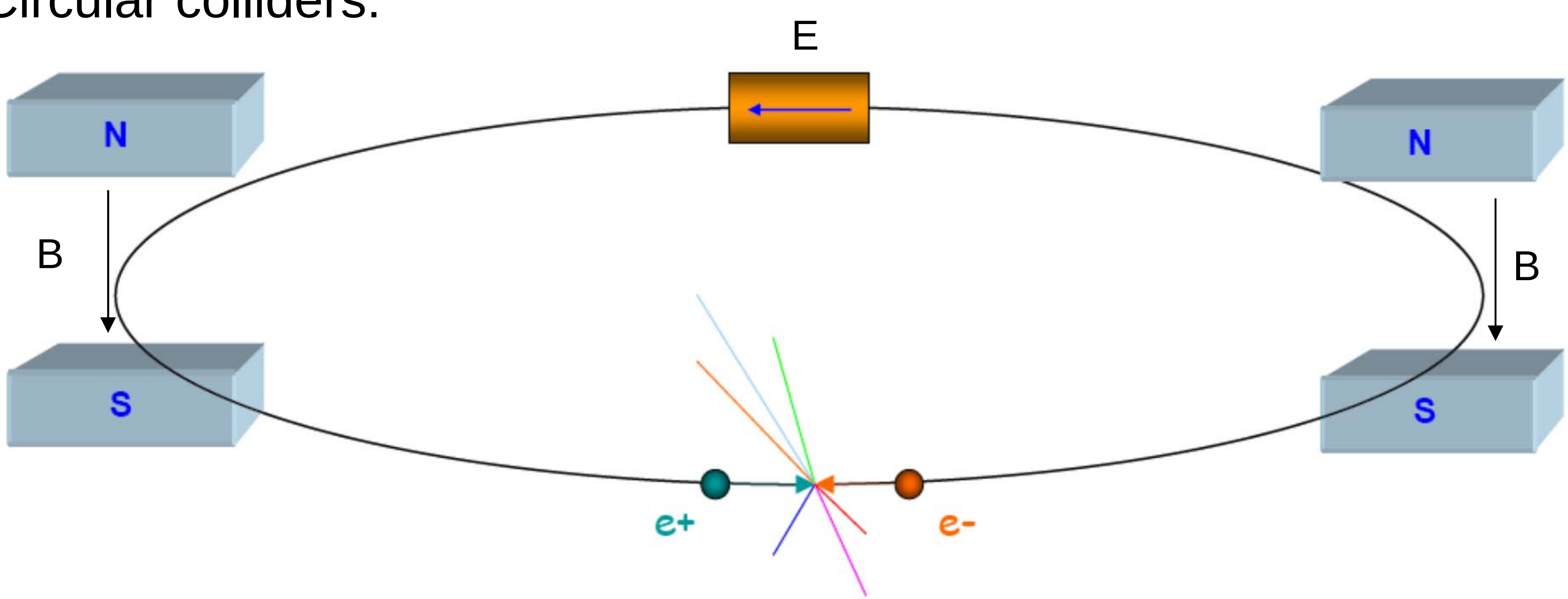
electrons at 27.5 GeV

Circular and linear colliders

Linear colliders:

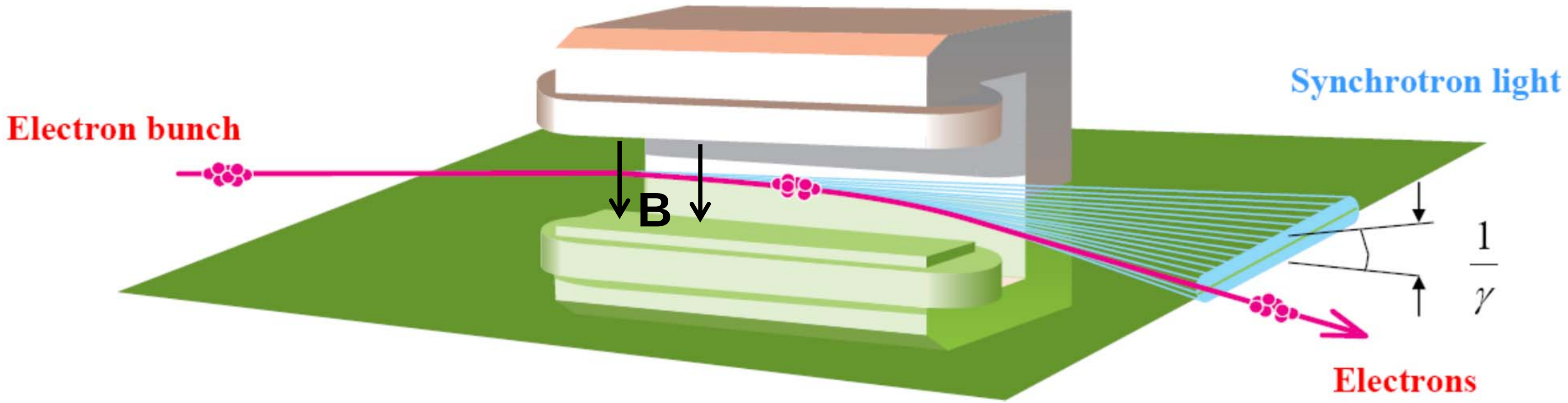


Circular colliders:



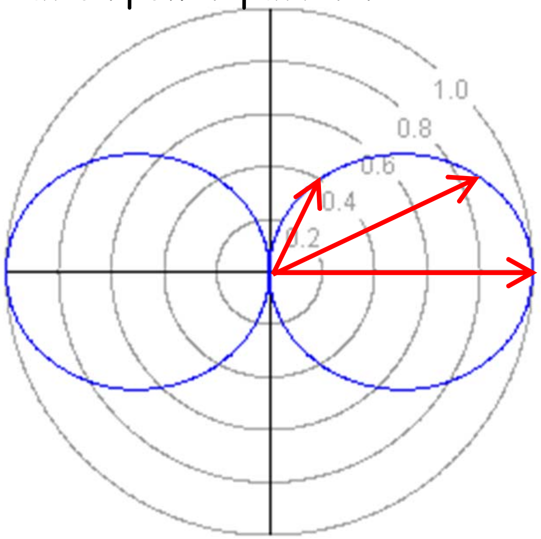
Synchrotron radiation

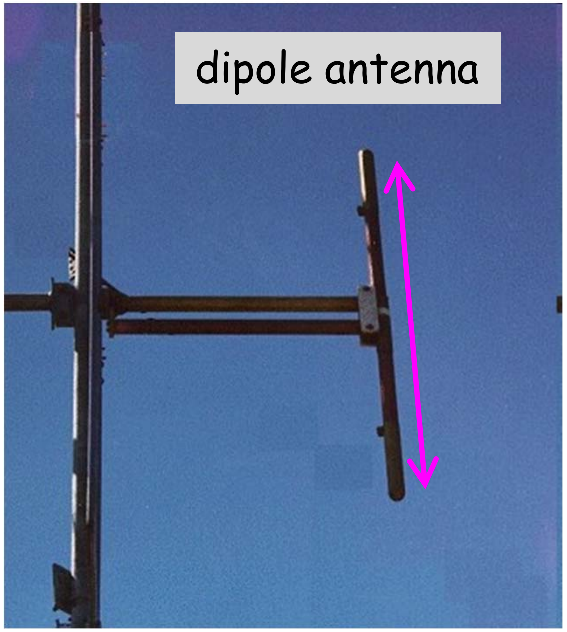
Dipole magnet

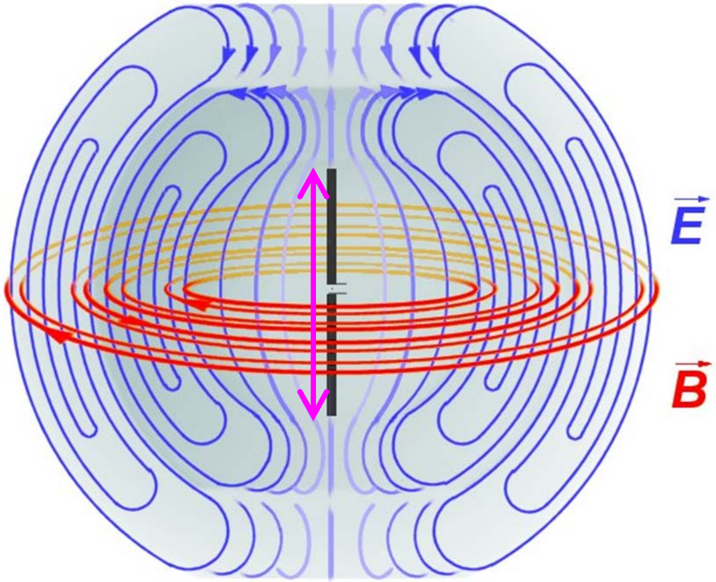


Radio antenna

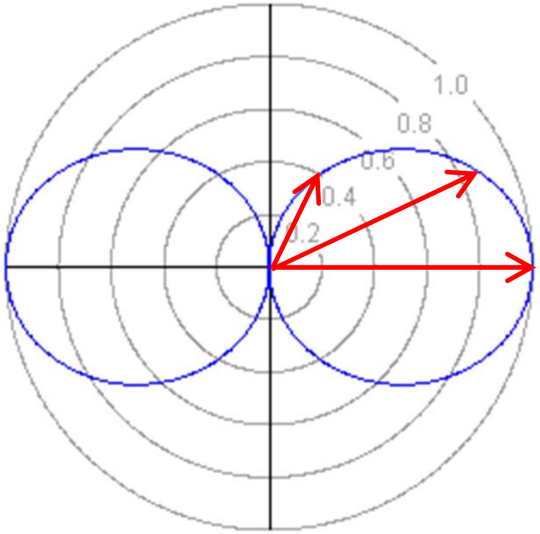
radiation power pattern:



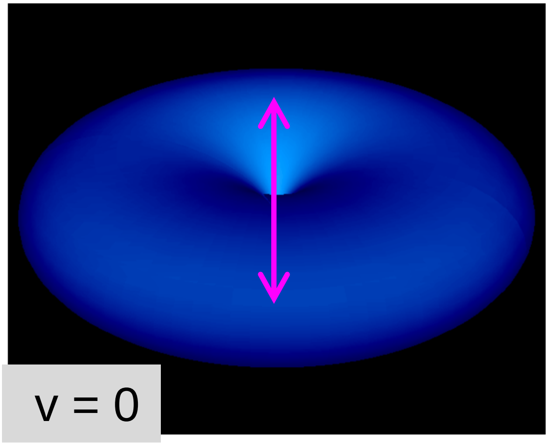




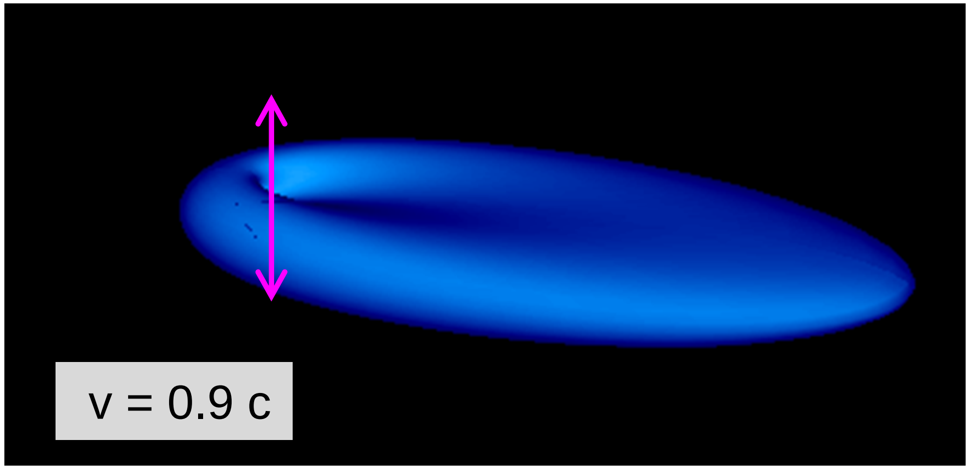
Radiation of a dipole antenna



Radiation of an oscillating dipole



Radiation of a moving oscillating dipole



Radiation of a dipole antenna

local oscillator:

$$P = \frac{q^2 a^2}{12\pi\varepsilon_0 c^3}\omega^4$$

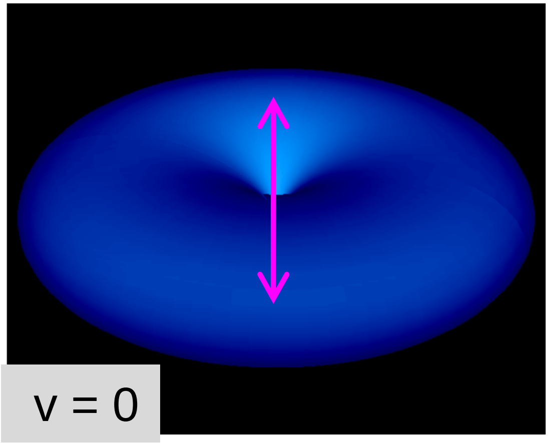
$$(\text{oscillation amplitude} : a < \lambda)$$

moving oscillator:

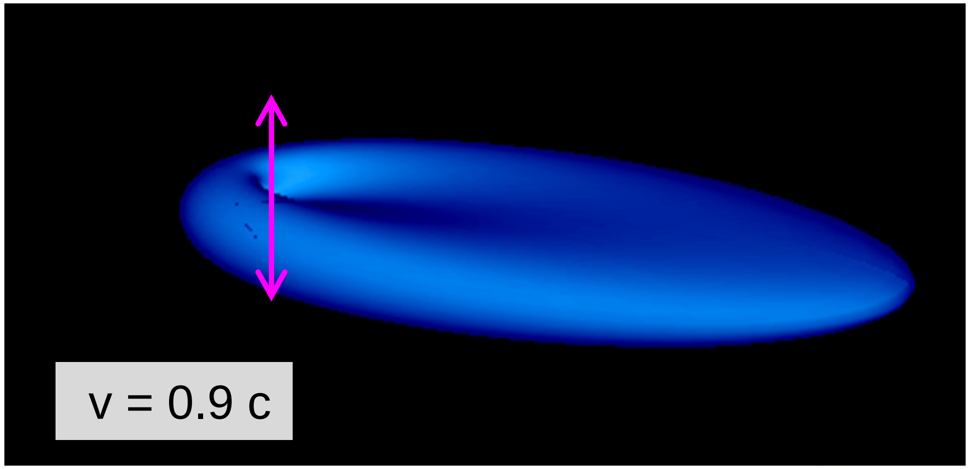
$$P = \frac{q^2 a^2}{12\pi\varepsilon_0 c^3}\gamma^4\omega^4$$

$$\gamma = \frac{E}{m_0 c^2}$$

Radiation of an oscillating dipole

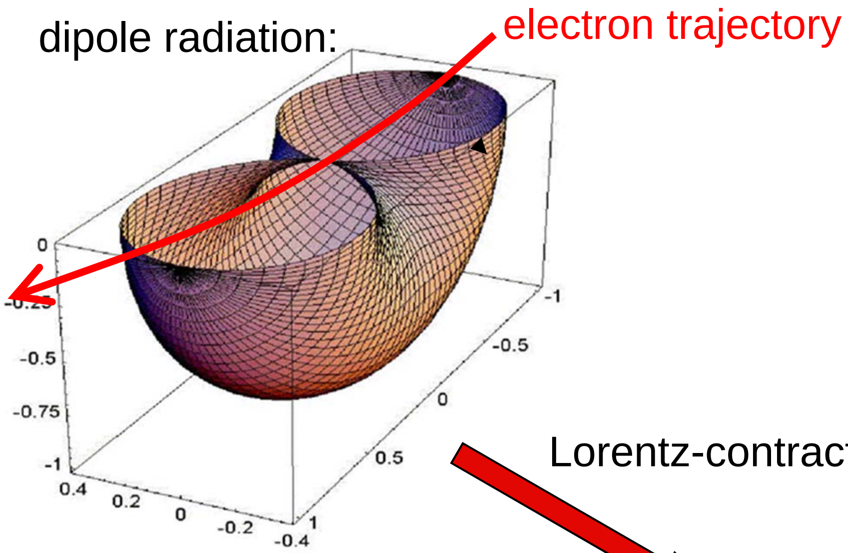


Radiation of a moving oscillating dipole



Radiation of a oscillating dipole under relativistic conditions

dipole radiation:



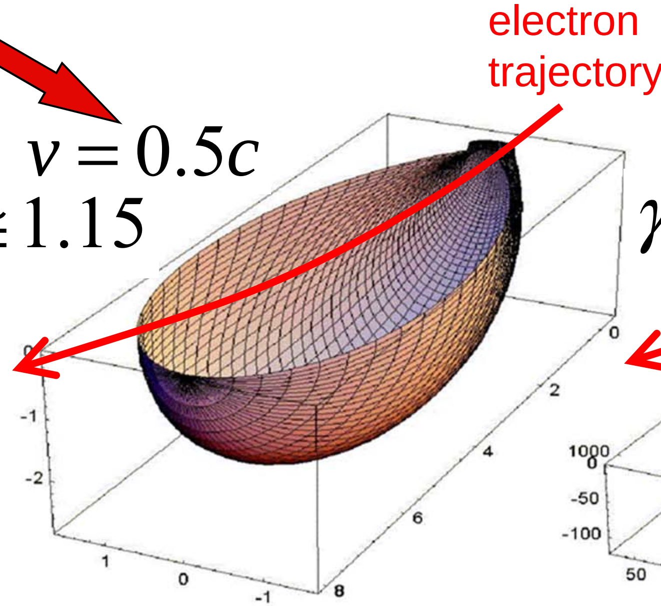
DORIS: $\gamma = 8900$

PETRA: $\gamma = 12000$

Lorentz-contraction

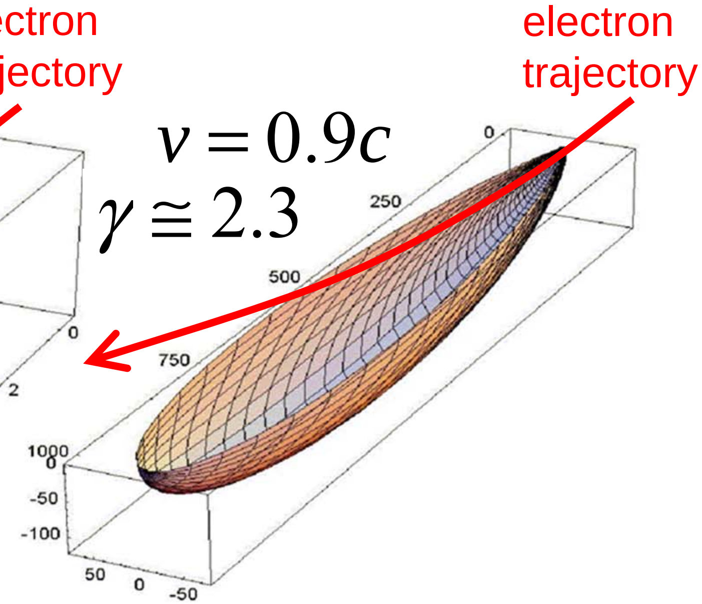
$v = 0.5c$

$\gamma \cong 1.15$



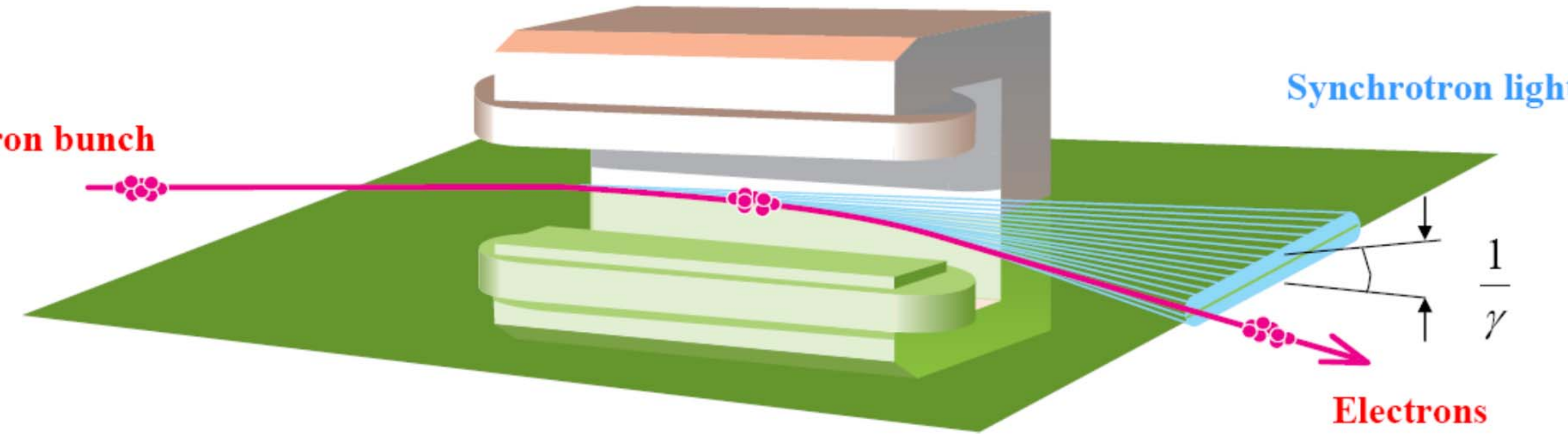
$v = 0.9c$

$\gamma \cong 2.3$



Synchrotron radiation

Dipole magnet



Power radiated by one electron in a dipole field *B*:

$$P = \frac{c\,q^2}{6\pi\,\varepsilon_0}\,\frac{\gamma^4}{r^2}$$

$$\gamma = \frac{E}{m_0 c^2}$$

$$\frac{1}{r} = \frac{q\,B}{p}$$

vacuum permitivity

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$r = 580\text{ m}$

$E = 27.5\text{ GeV}$

$\gamma = 54000$

$\Delta E_{turn} = 87\text{ MeV } (0.3\%)$

need acceleration = 87 MV per turn

HERA proton ring:

$r = 580\text{ m}$ (same as electron ring)

$E = 920\text{ GeV}$

$\gamma = 980$

$\Delta E_{turn} \cong 10\text{ eV } (10^{-9}\%)$

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$$r = 580\ \text{m}$$

$$E = 27.5\ \text{GeV}$$

$$\gamma = 54000$$

$$\Delta E_{turn} = 87\ \text{MeV}\ (0.3\%)$$

need acceleration = 87 MV per turn

same

HERA proton ring:

$$r = 580\ \text{m}$$

$$E = 920\ \text{GeV}$$

$$\gamma = 980$$

the limit is the max. dipole field = 5.5 Tesla

$$\frac{1}{r} = \frac{qB}{p}$$

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$r = 580$ m

$E = 27.5$ GeV

$\gamma = 54000$

$\Delta E_{turn} = 87$ MeV (0.3%)

need acceleration = 87 MV per turn

x5 →

LEP collider:

$r = 2800$ m

$E = 105$ GeV

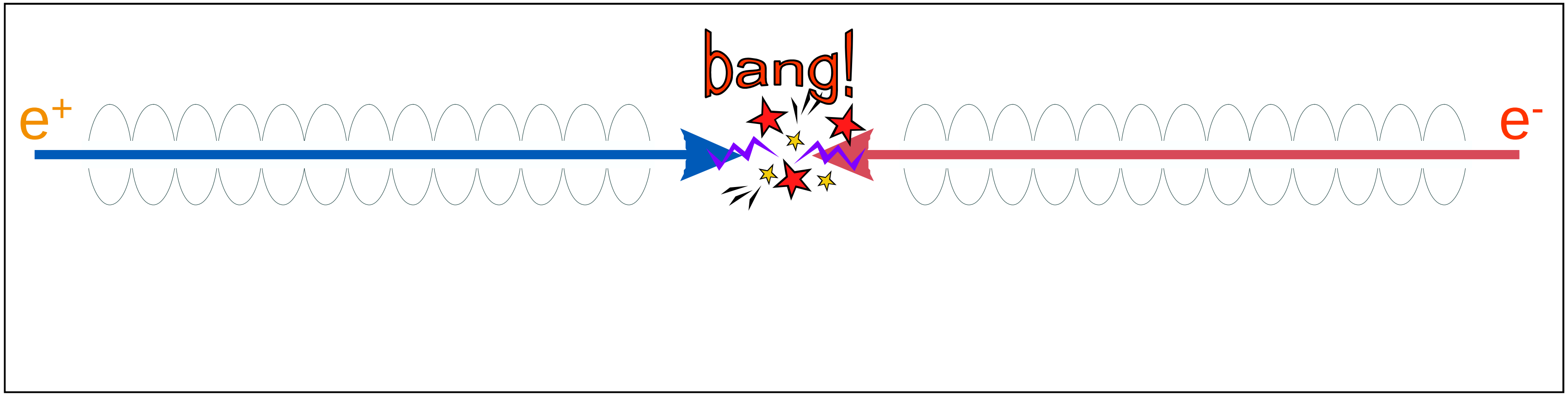
$\gamma = 205000$

$\Delta E_{turn} \cong 4$ GeV (4%)

need 4 GV per turn !!

Project for a future e-e+ collider: ILC

The International Linear Collider

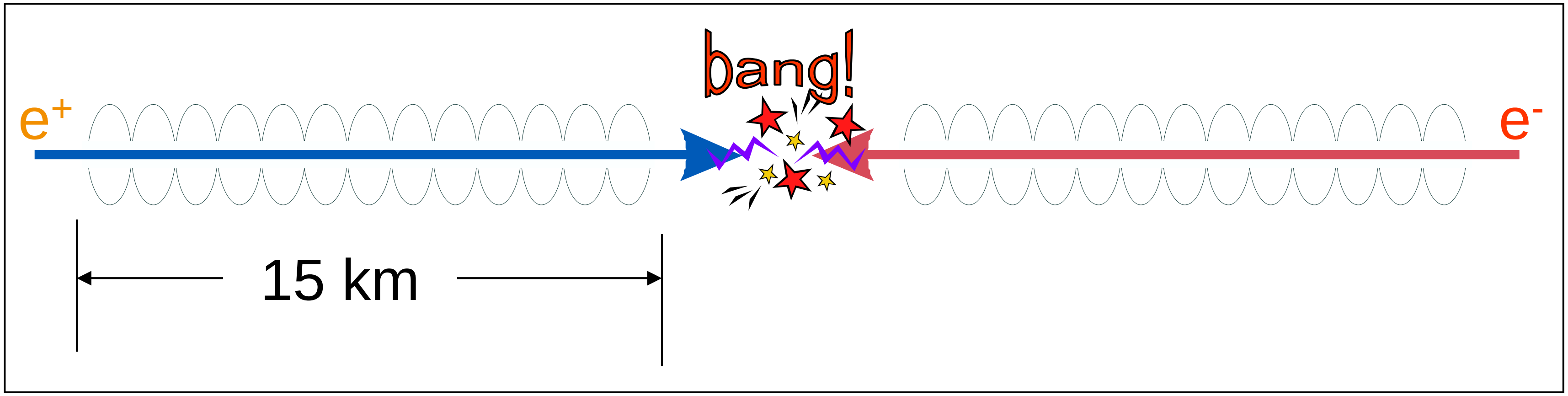


Colliding beams with $E_{CM} = 500$ GeV

more about ILC: lecture on ‘Linear Collider’ by S. Riemann (24th Aug.)

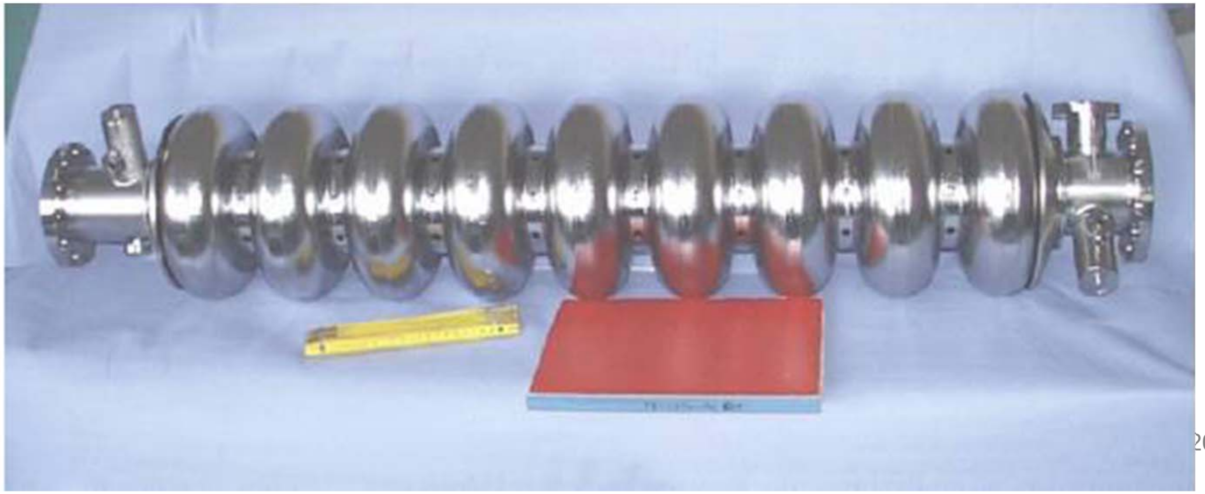
Project for a future e-e+ collider: ILC

The International Linear Collider



Colliding beams with $E_{CM} = 500$ GeV

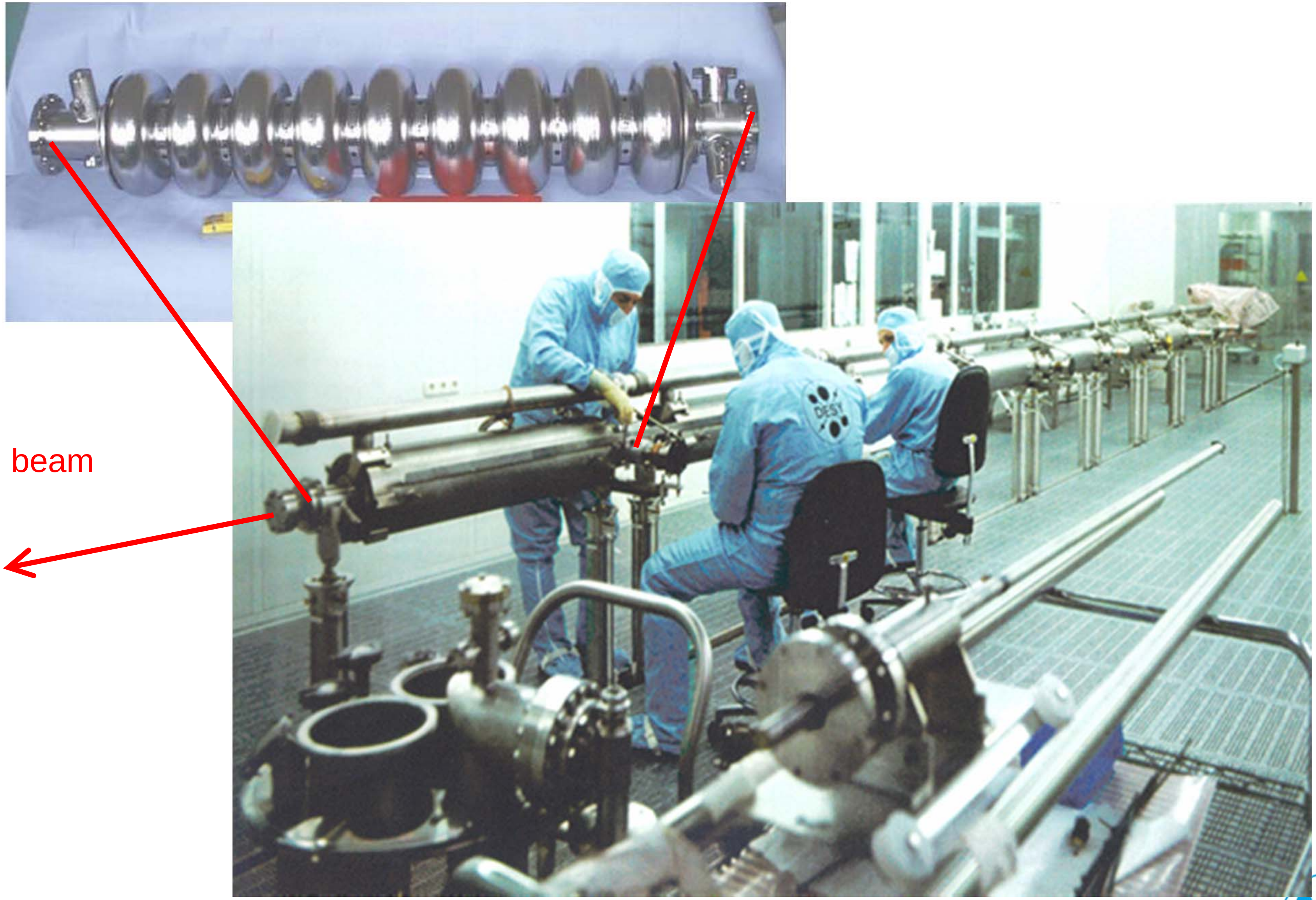
using superconducting cavities for acceleration:

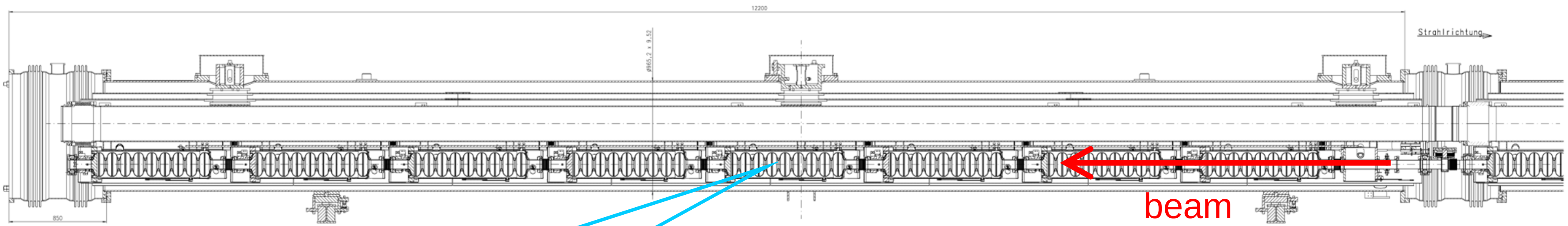


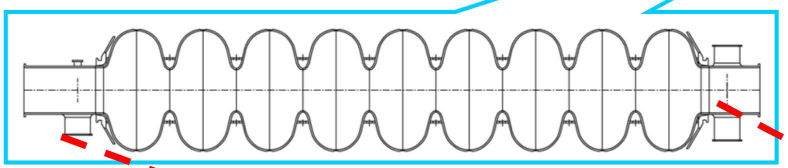
Superconducting cavities for acceleration

- International Linear Collider (ILC)
  (future project)
- European X-ray Free-Electron Laser (XFEL)
  (in construction)
- Free-electron LASer in Hamburg (FLASH)
  (in operation)

Cavities inside a cryostat

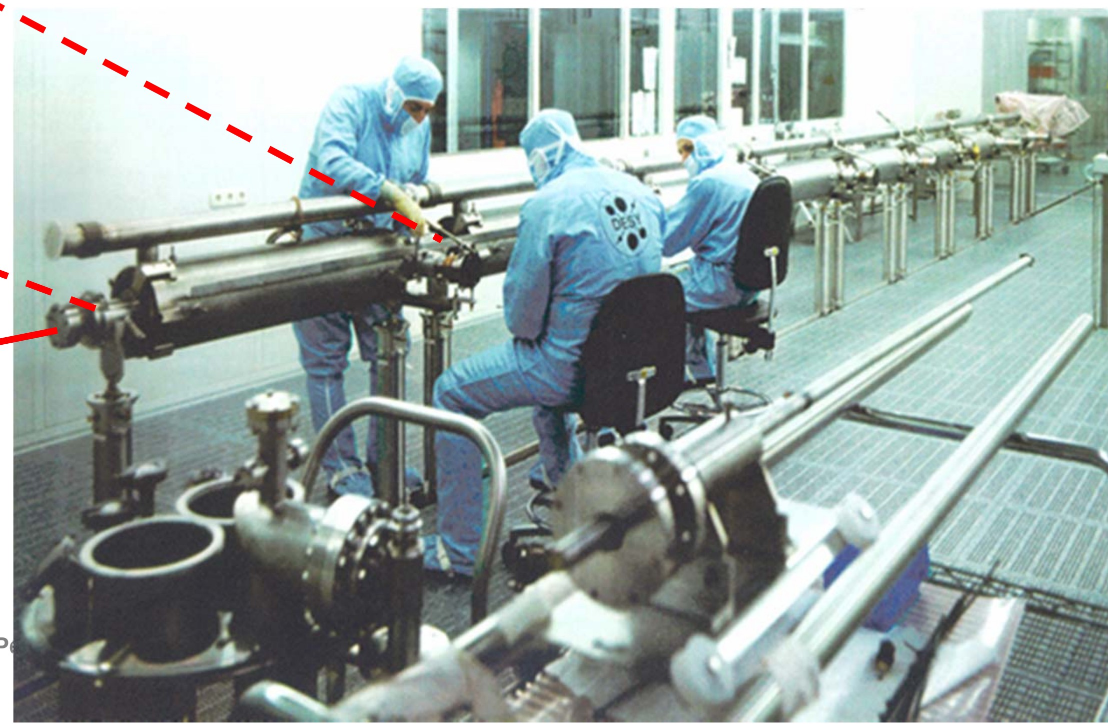




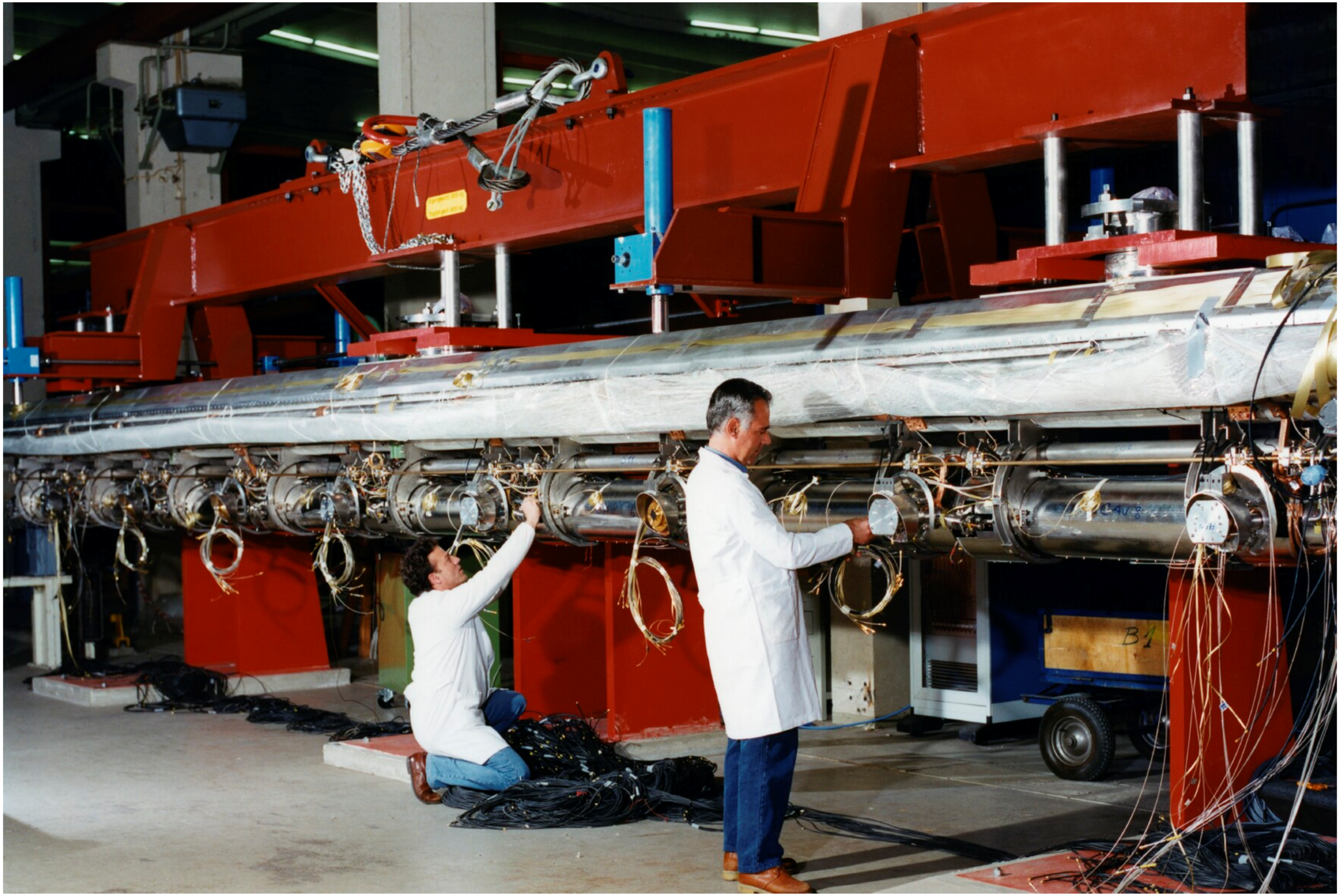


Number of cavities	8
Cavity length	1.038 m
Operating frequency	1.3 GHz
Operating temperature	2 K
Accelerating Gradient	23..35 MV/m

beam

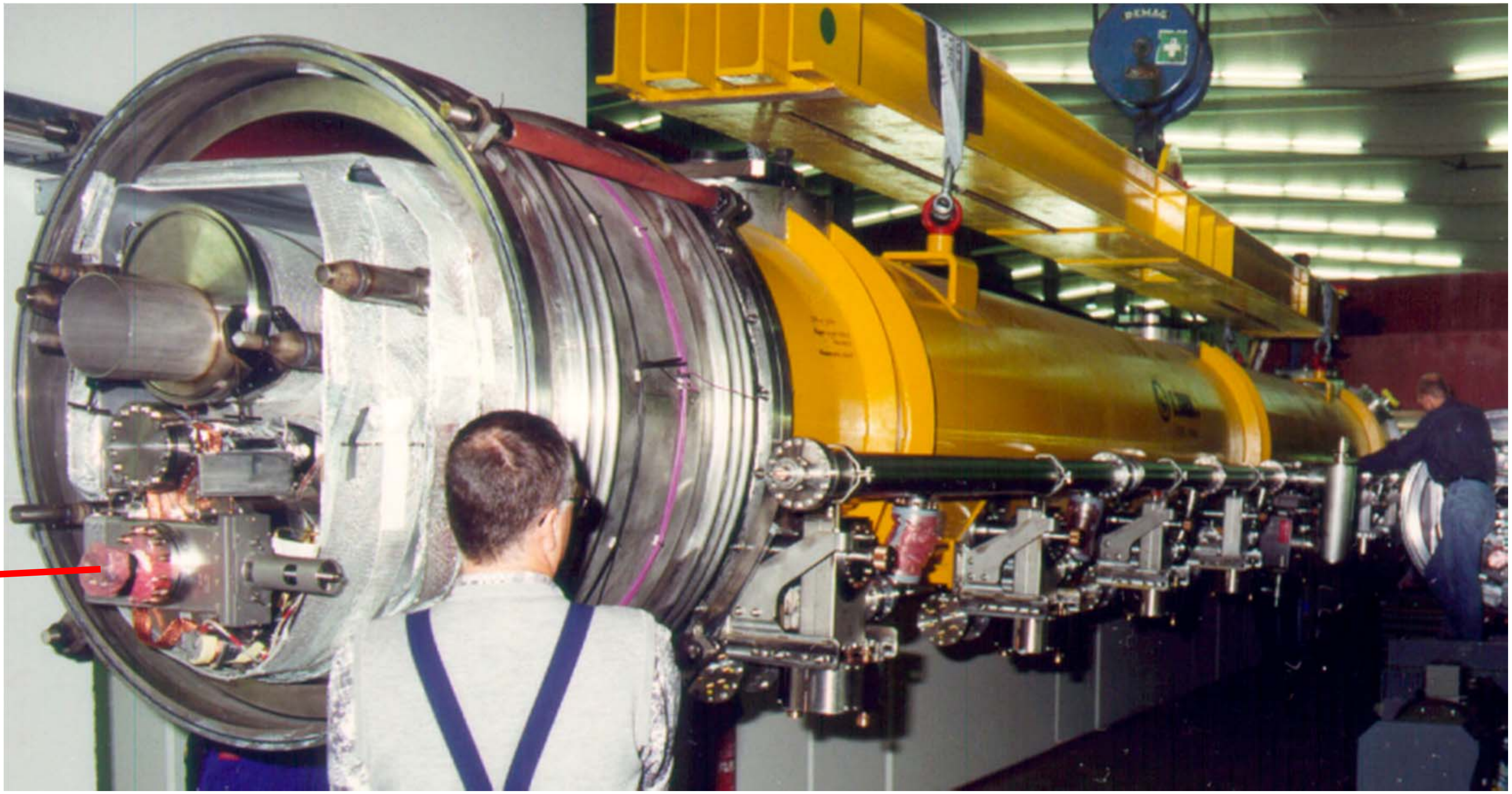


Cavities inside a cryostat



Cavities inside a cryostat

beam

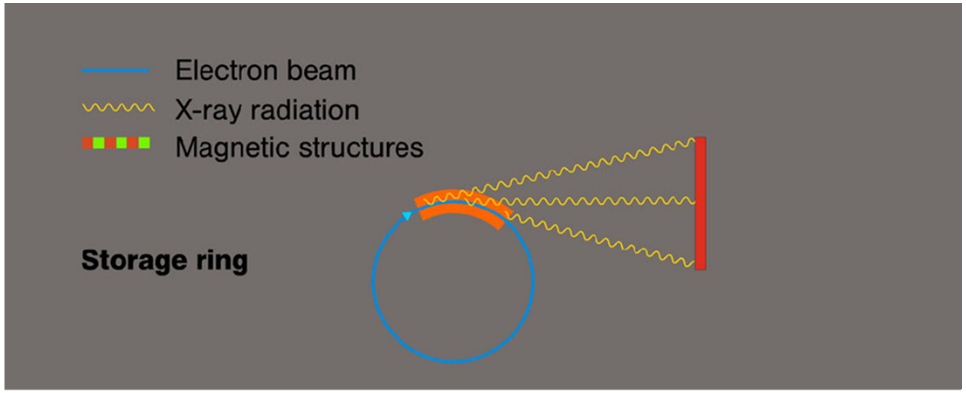


module installation in FLASH (2004)

Undulators for Free-Electron Laser

- International Linear Collider (ILC) (future project)
- European X-ray Free-Electron Laser (XFEL) (in construction)
- Free-electron LASer in Hamburg (FLASH) (in operation)

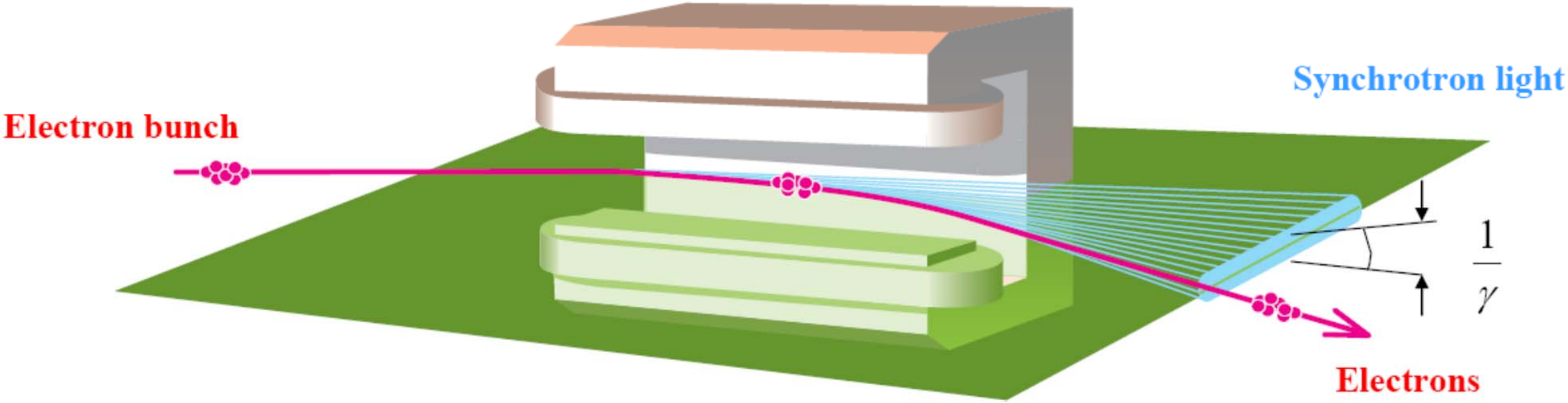
Increase of number of photons



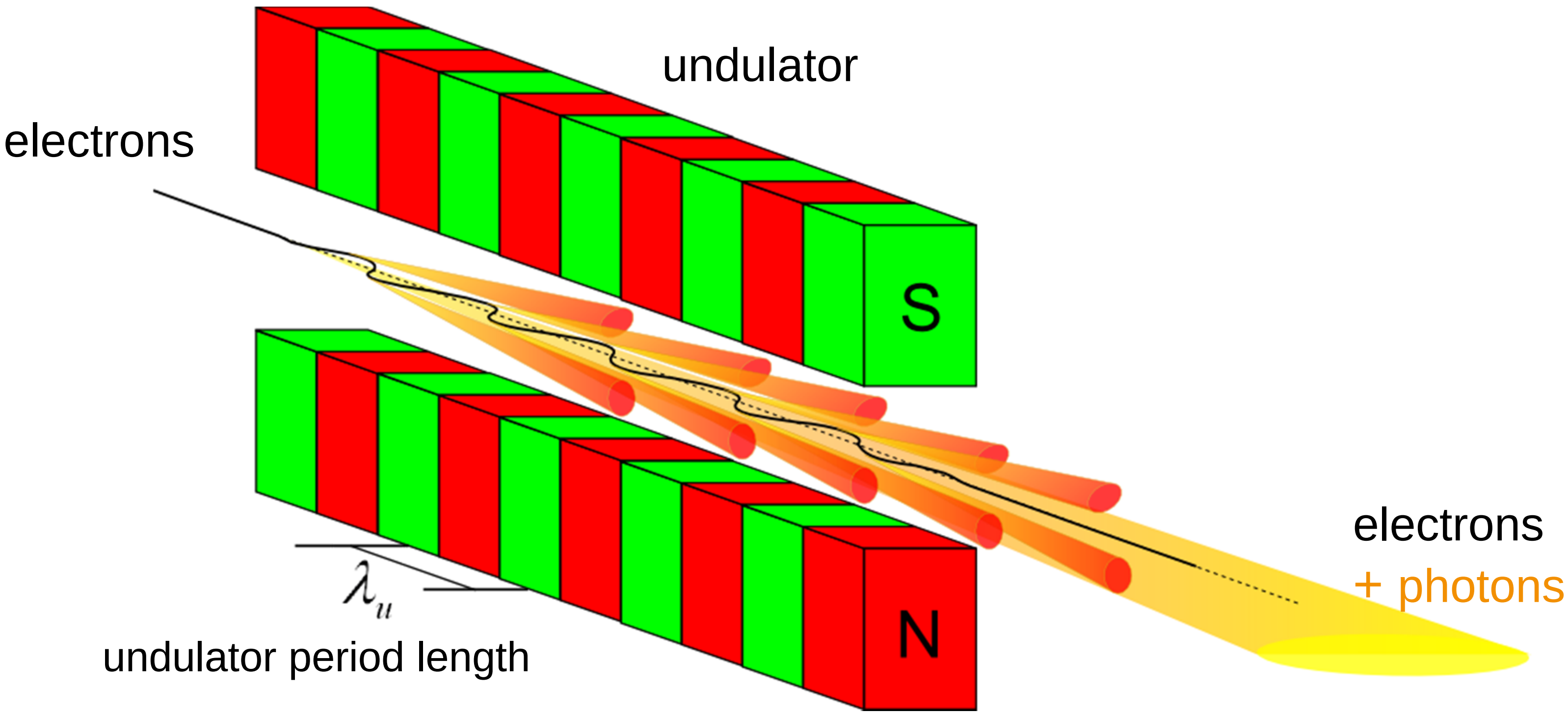
Power radiated by one electron in a dipole field

$$P_{\text{ph}} = N_{\text{e}} \times P_{\text{dipole}}$$

Bending Magnet

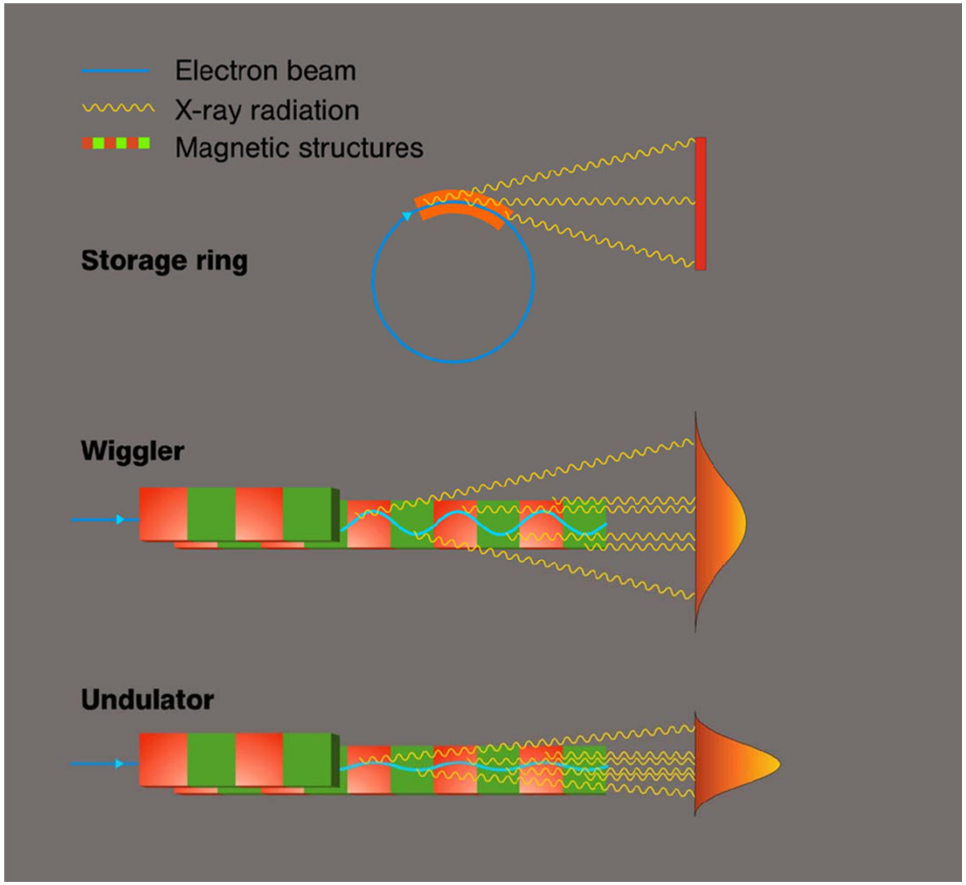


Motion of electrons inside an undulator magnet



Example: undulator at FLASH: $\lambda_u = 27\ \text{mm}\,,\quad \hat{x} = 2.6\ \mu\text{m}$

Increase of number of photons



Photon brilliance emitted by an electron bunch in a dipole field

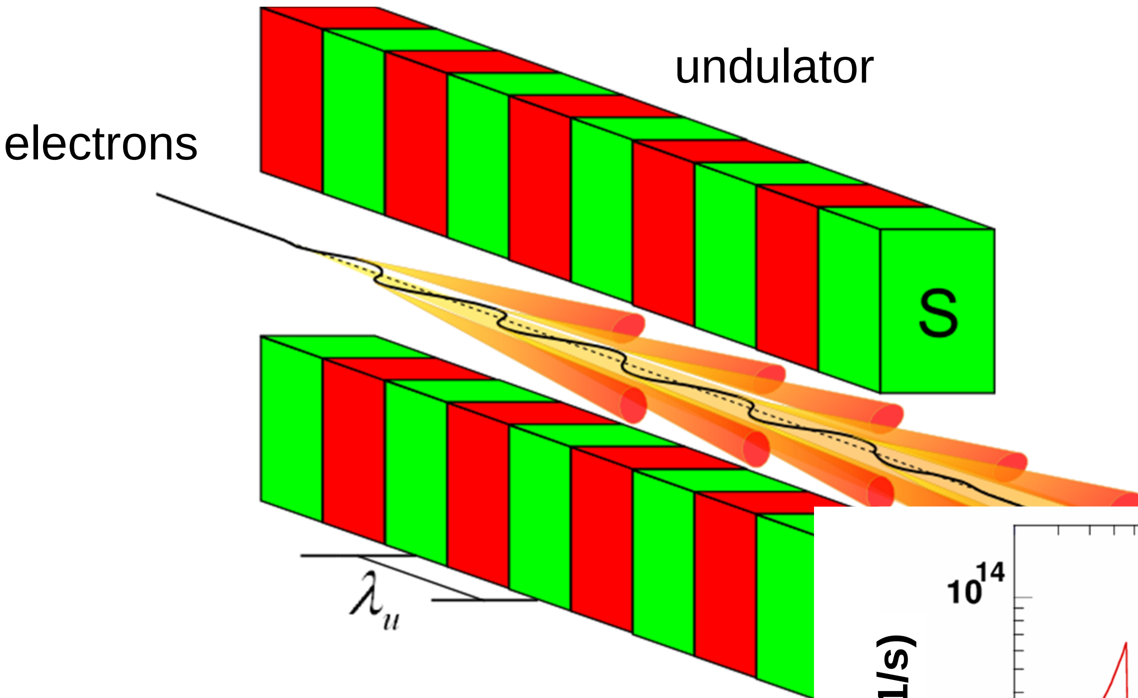
$$B_{\text{dipole}}$$

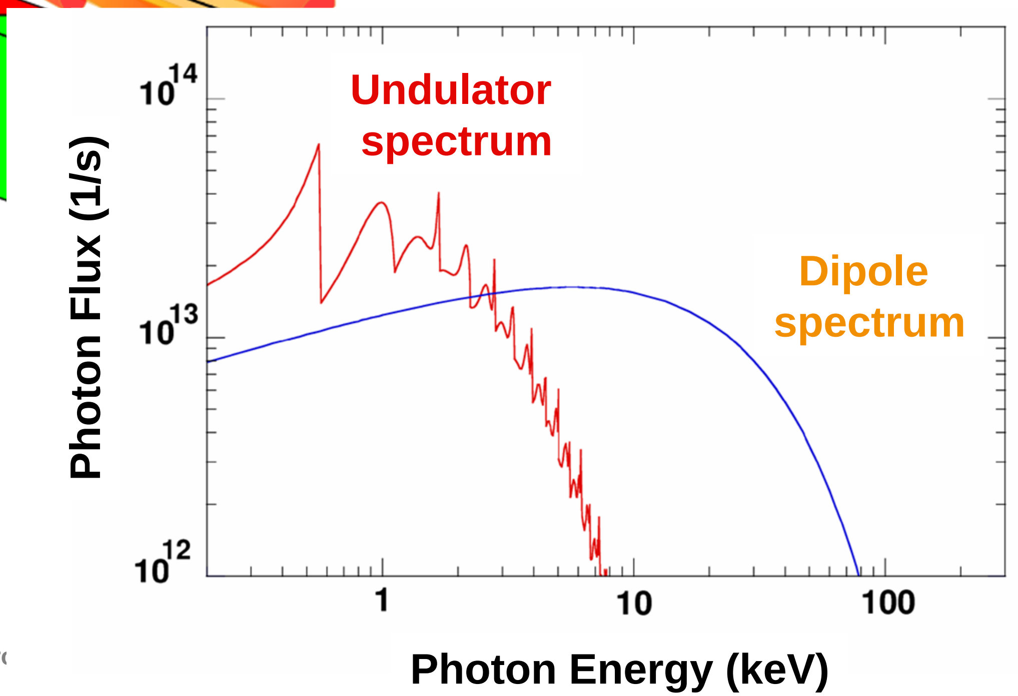
$$B = B_{\text{dipole}} \times N_{\text{dipole}}$$

$$B \propto B_{\text{dipole}} \times N_{\text{dipole}}^{2}$$

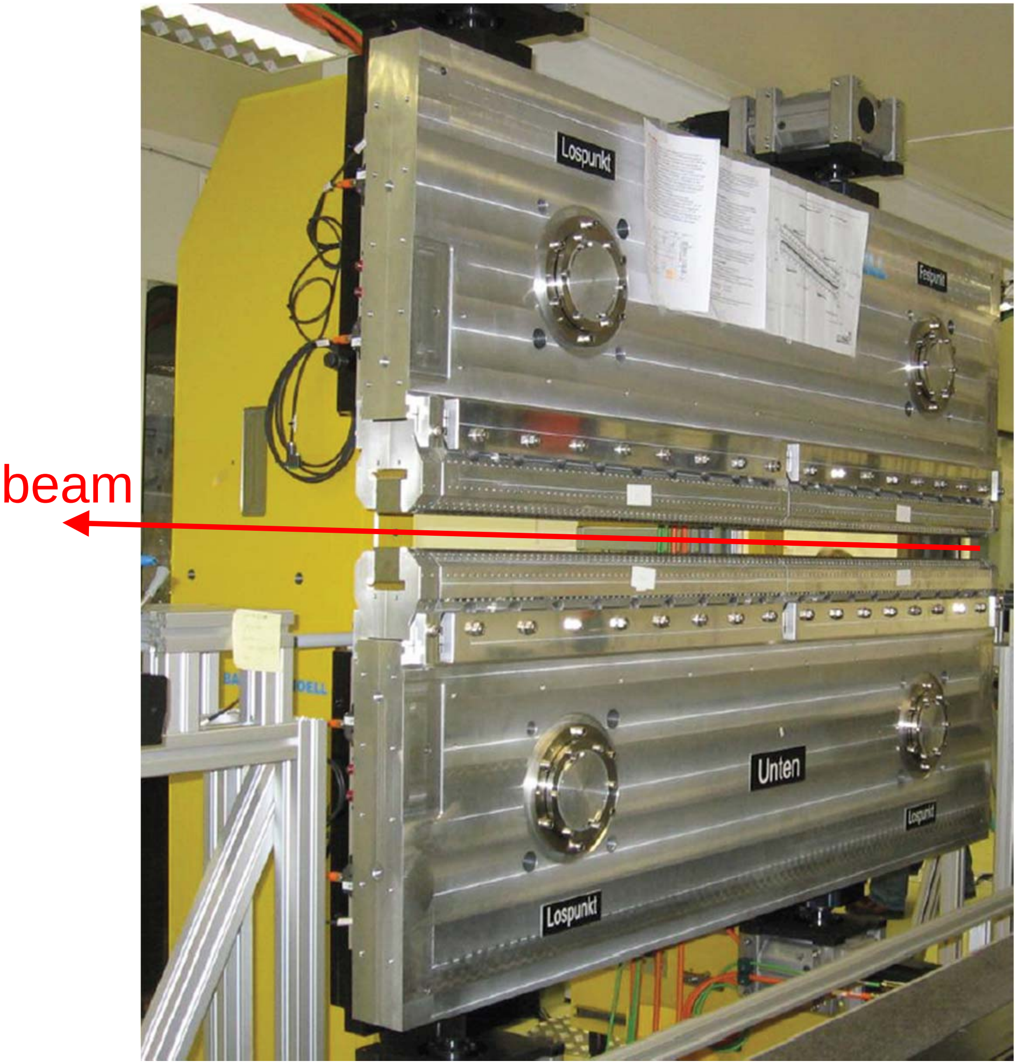
$$\text{Brilliance} = \frac{\text{photons / s / 0.1\% bandwidth}}{\text{source area} \times \text{solid angle}} = \frac{\text{spectral flux}}{\text{source area} \times \text{solid angle}}$$

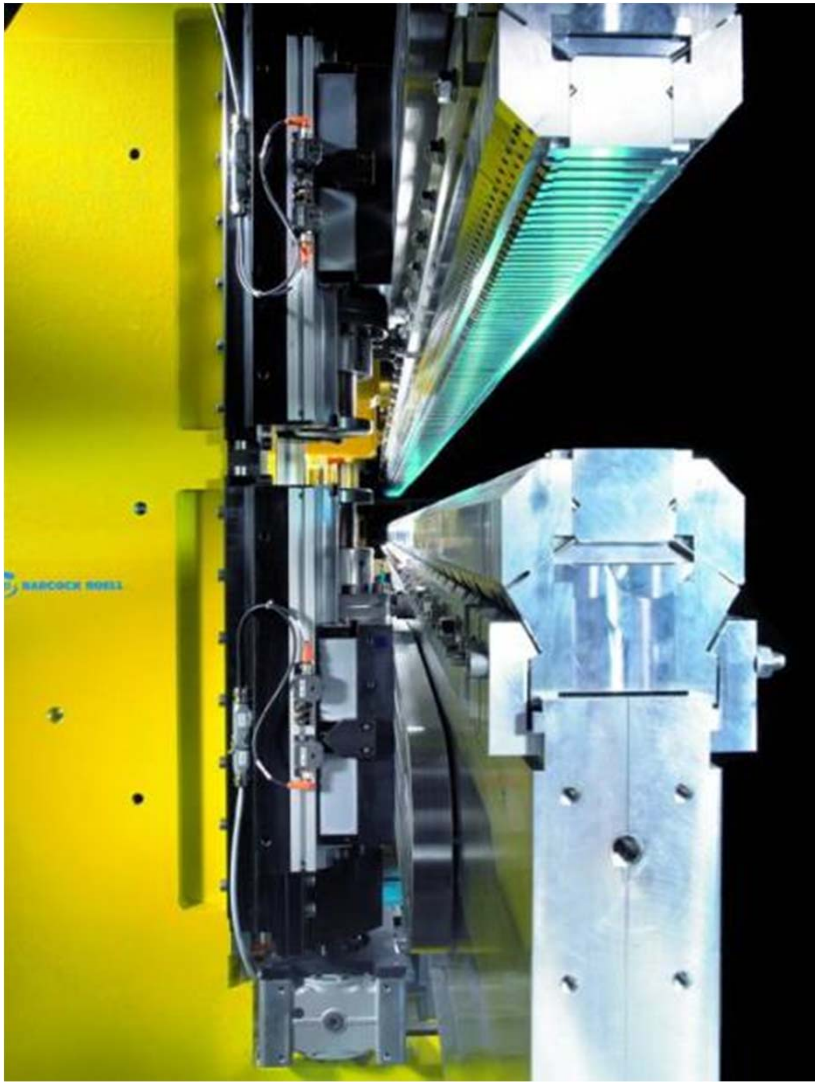
Motion of electrons inside an undulator magnet



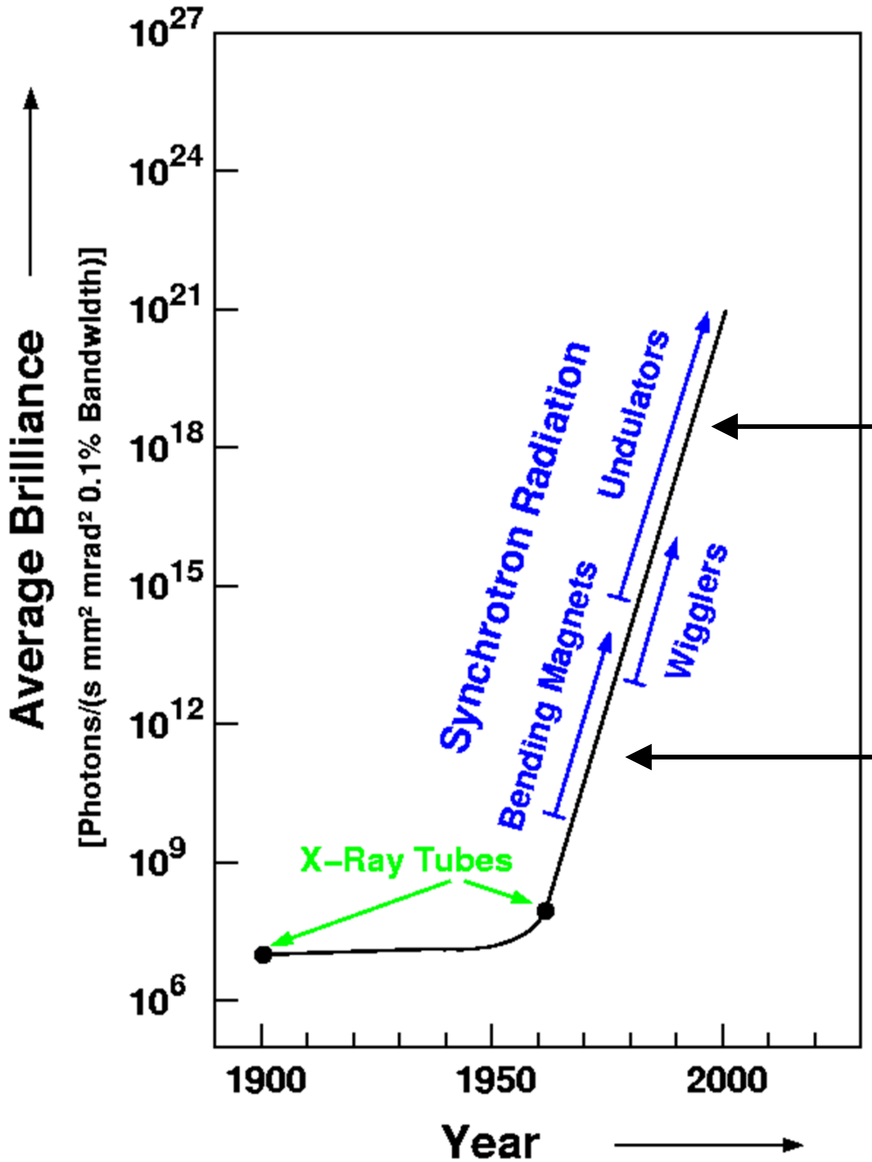


Undulators

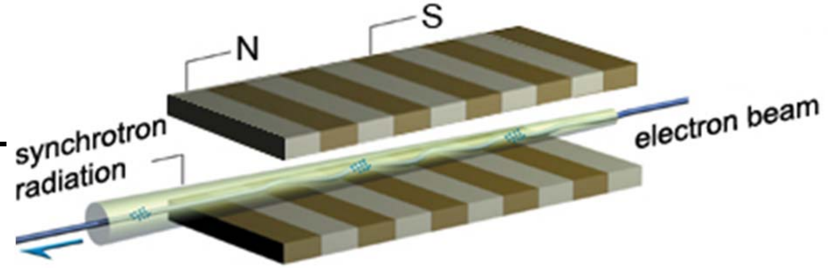


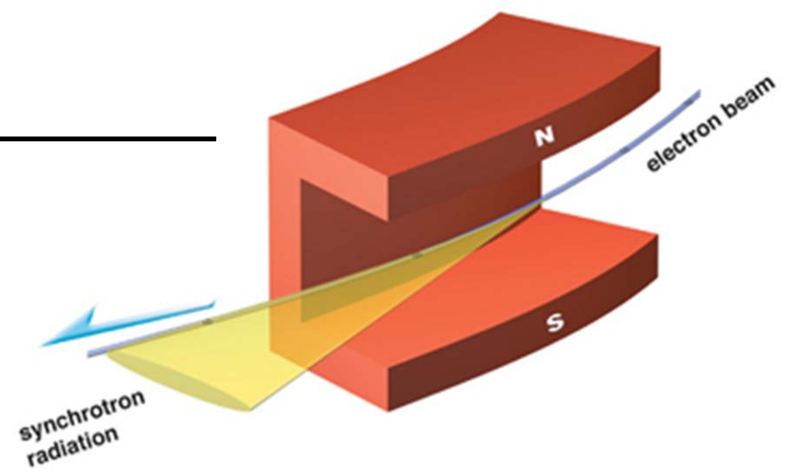


Development of synchrotron light sources

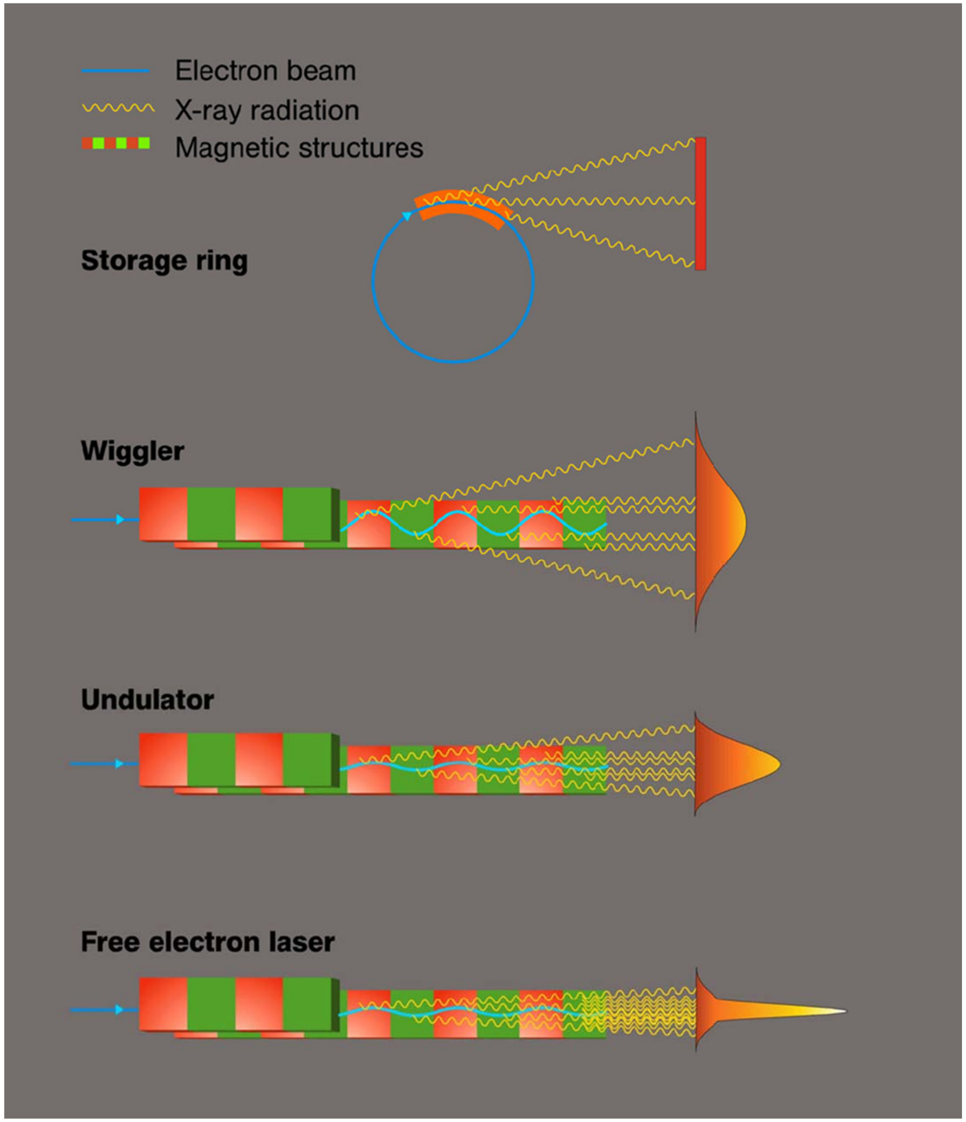


$$\text{Brilliance} = \frac{\text{photons / s / 0.1\% bandwidth}}{\text{source area} \times \text{solid angle}}$$





Increase of number of photons



Photon brilliance emitted by an electron bunch in a dipole field

$$B_{\mathrm{dipole}}$$

$$B = B_{\mathrm{dipole}} \times N_{\mathrm{dipole}}$$

$$B \propto B_{\mathrm{dipole}} \times N_{\mathrm{dipole}}^{2}$$

$$B \propto N_{e} \times B_{\mathrm{dipole}} \times N_{\mathrm{dipole}}^{2}$$

… and you need a very long undulator

6 undulators (4.5 m long) at FLASH

- European X-ray Free-Electron Laser (XFEL)
  (in construction)

  3.4 km, 18 GeV,   0.1 nm

- Free-electron LASer in Hamburg (FLASH)
  (in operation)

  300 m, 1.2 GeV,   4.1 nm

http://xfel.desy.de

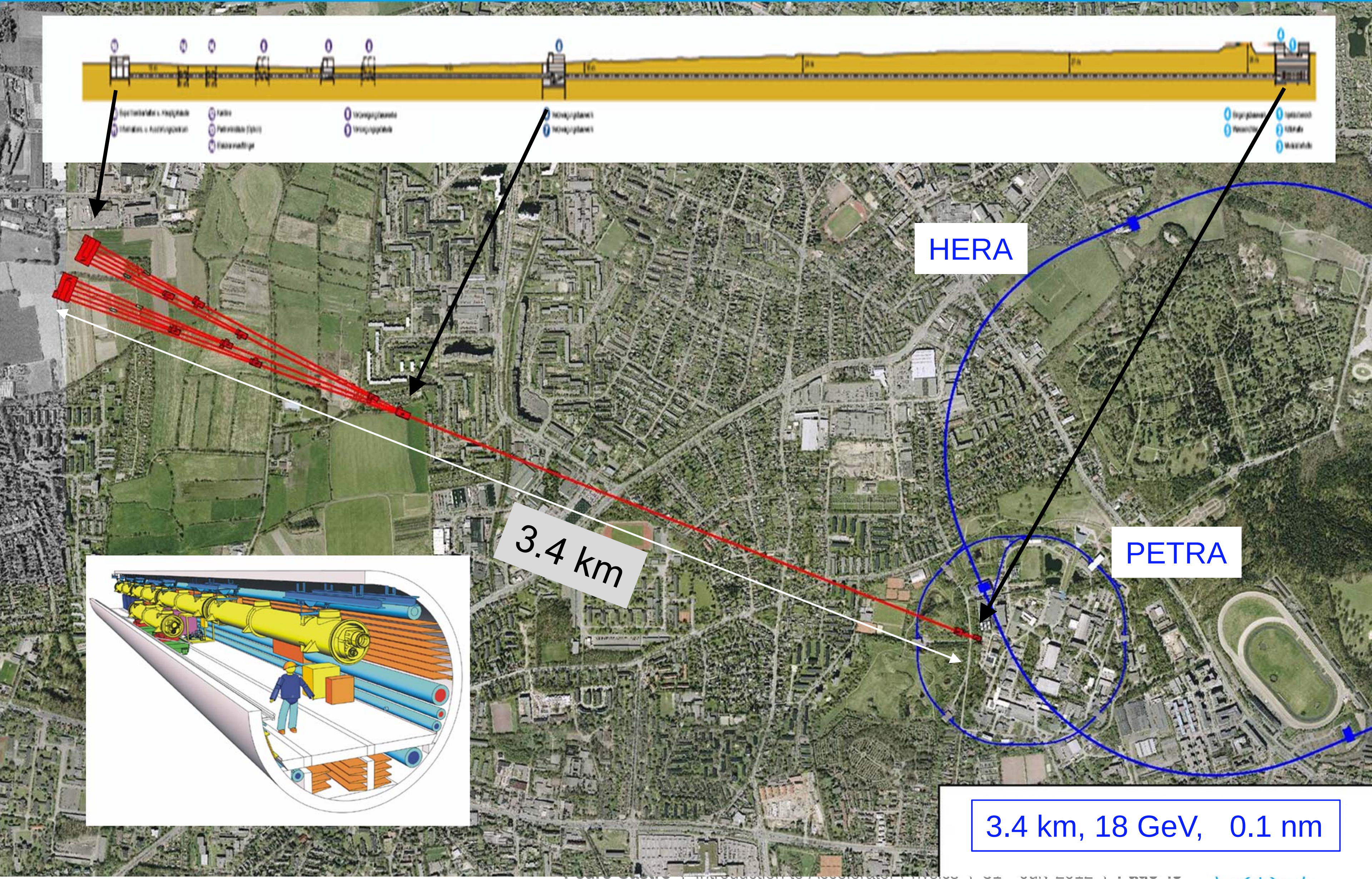
http://flash.desy.de

Free-electron LASer in Hamburg (FLASH)

300 m, 1.2 GeV, 4.1 nm

accelerator control room

European X-Ray Free Electron Laser (XFEL)



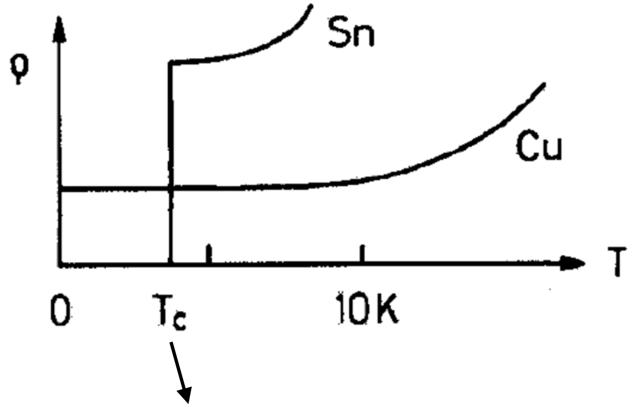
Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	0 ??	56 kW / m	dissipated at the cavity walls

Advantages of RF superconductivity

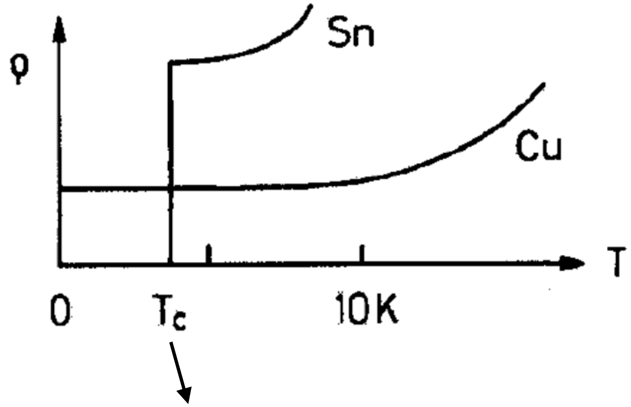
resistance



critical temperature (Tc):

Advantages of RF superconductivity

resistance



for DC currents !

critical temperature (Tc):

at radio-frequencies, there is a "microwave surface resistance"

which typically is 5 orders of magnitude lower than R of copper

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	1.5 W / m	56 kW / m	dissipated at the cavity walls

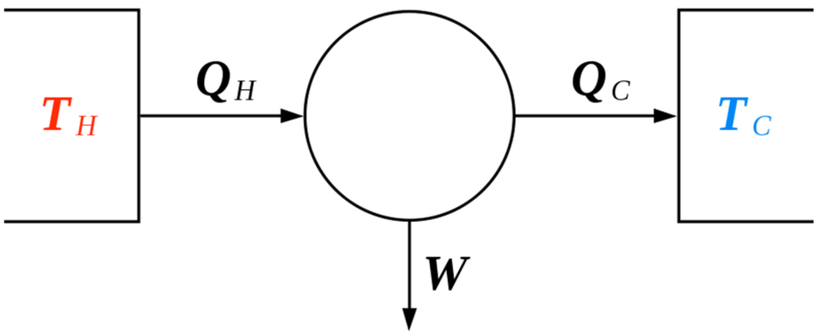
Advantages of RF superconductivity

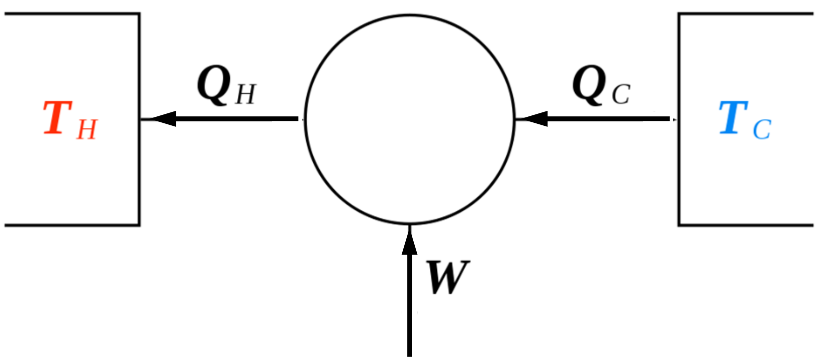
Example: comparison of 500 MHz cavities:

	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	1.5 W / m at 2 K	56 kW / m	dissipated at the cavity walls

2nd law of Thermodynamics

"Heat cannot spontaneously flow from a colder location to a hotter location"





max. efficiency	most common applications
$\eta_c = \frac{T_H - T_C}{T_H}$	thermal power stations, cars, …
$\eta_c = \frac{T_C}{T_H - T_C}$	air conditioners, refrigerators, …

Carnot efficiency:

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

	superconducting cavity	normal conducting cavity	
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Carnot efficiency: $\eta_c = \dfrac{T}{300-T} = 0.007$ x cryogenics efficiency 20-30%

Advantages of RF superconductivity

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for E = 1 MV/m	1 kW / m	56 kW / m

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Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

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for E = 1 MV/m	1 kW / m	56 kW / m	
for E = 1 MV/m	1 kW / m	112 kW / m	including RF generation efficiency (50%)

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

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>100 (electrical) power reduction factor

Third summing-up

Beam focusing in synchrotrons: quadrupole magnets

Circular colliders (synchrotrons with R=const.):

	limitation
• proton synchrotrons	dipole magnet
• electron synchrotrons	synchrotron radiation

Linear accelerators:

- International Linear Collider (ILC)
- European X-ray Free-Electron Laser (XFEL)
- Free-electron LASer in Hamburg (FLASH)

} based on S.C. cavities

Thank you for your attention

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