Introduction to Accelerators and Accelerator Physics

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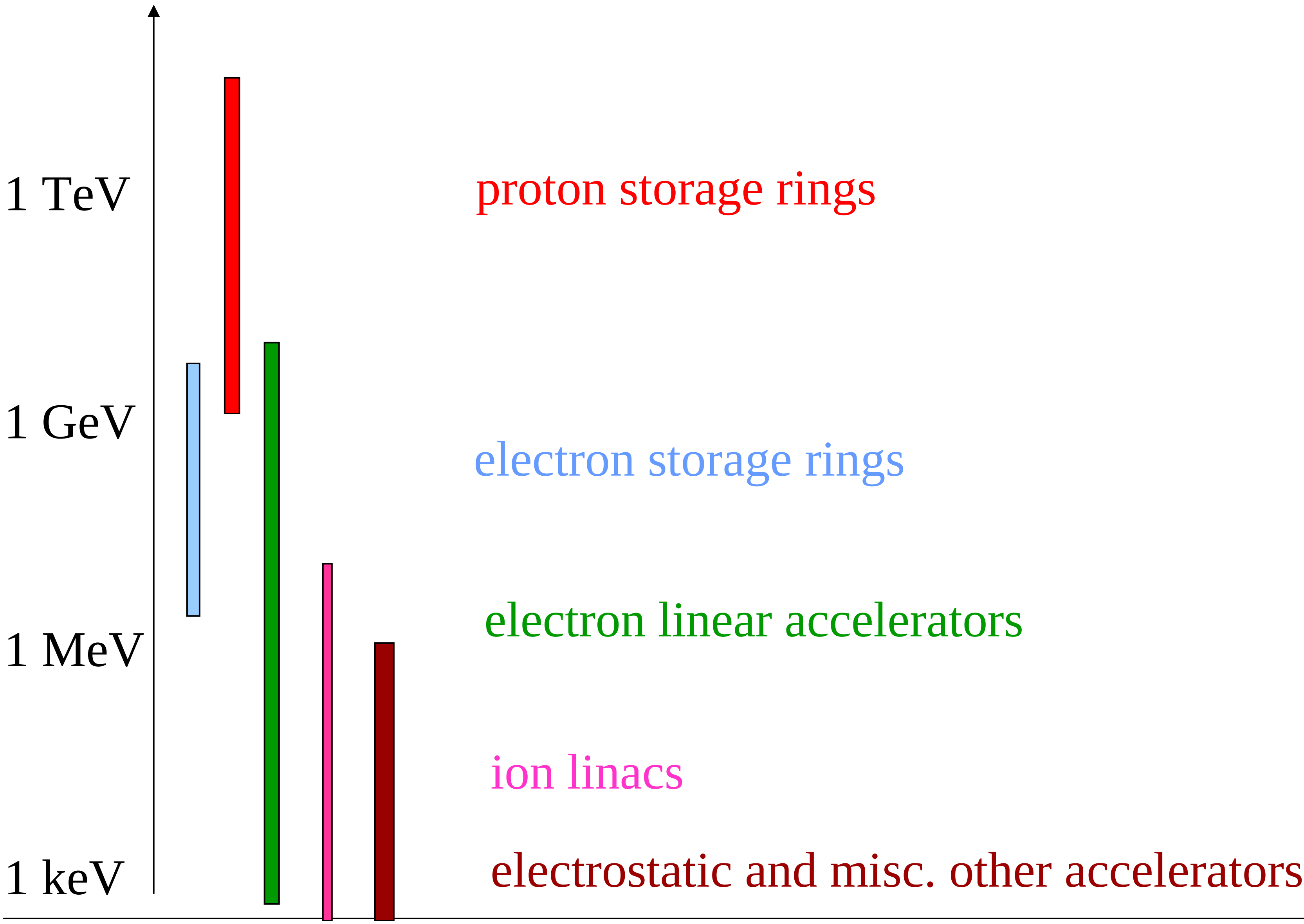
Accelerator Physics

- Accelerators are devices which accelerate charged particles like electrons, protons and ions
- means of acceleration range from static electric fields, pulsed electric fields, varying magnetic fields and microwaves
- the energy of accelerated particles are measured in eV or for ions in eV/nucleon
- a particle gains the energy of 1 eV while traveling in the field between two electrodes with a potential difference of 1 Volt
- we use also units of keV, MeV, GeV and TeV

the beam current is measured in Ampere or mAmpere

- the beam current in microwave accelerators is bunched
- bunches are typically ~1/20th of the microwave wavelength
- there are several definitions of beam currents used
- instantaneous current or peak current is the current within a bunch, $dI/dt = eN_p\, c/l_b$ where l_b is the bunch length
- pulsed current is measured as the average current in a (linac) pulse. $I = en_b N_p/\tau_p$ where n_b in the number of bunches in the pulse, N_p the number of particles per bunch and τ_b the duration of the pulse
- average current is the current averaged over some longer time

Accelerator Physics



most particles travel close to the speed of light:

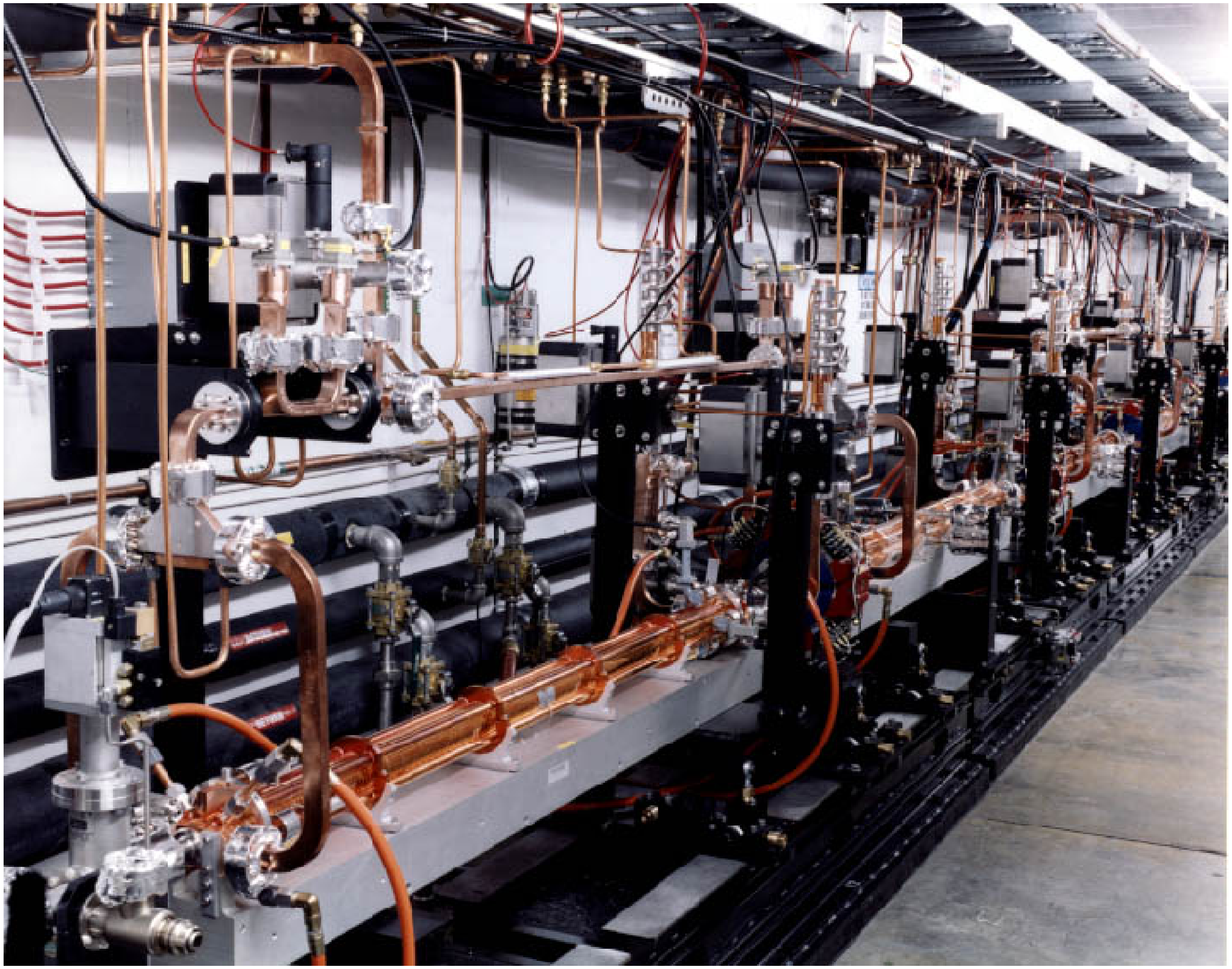
- 40 keV/u Ar ion beam $\beta = 0.0092447$
- 50 keV electrons $\beta = 0.4126858$
- 25 MeV protons (cyclotron) $\beta = 0.2266106$
- 3 GeV electrons (DIAMOND) $\beta = 0.9999999861$
- 8 TeV protons in LHC $\beta = 0.99999999315$
- 50 GeV electrons (SLAC) $\beta = 0.9999999999478$

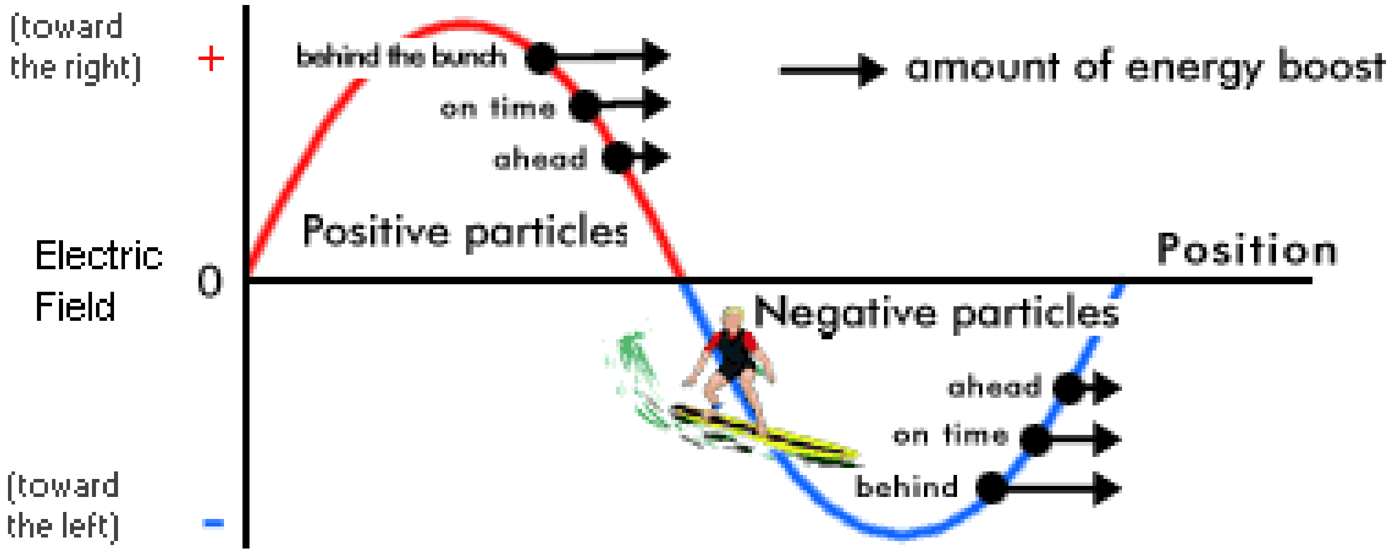
- simplest accelerator is the electrostatic accelerator (e-guns, Van de Graaf, Tandem)
- varying magnetic field in betatron
- pulsed electric fields in Tesla transformer
- most accelerators rely on microwaves to accelerate particles

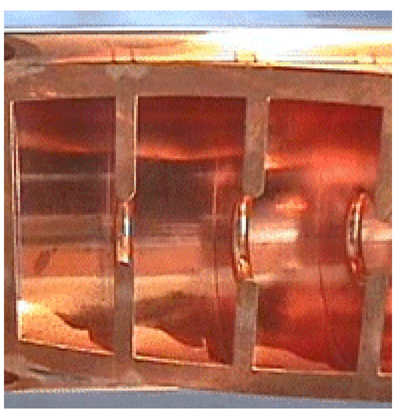
  cyclotron, linear accelerator, synchrotron, storage ring
- time is too short to cover all
- we concentrate on

  linear accelerator, synchrotron, storage ring

Linac:

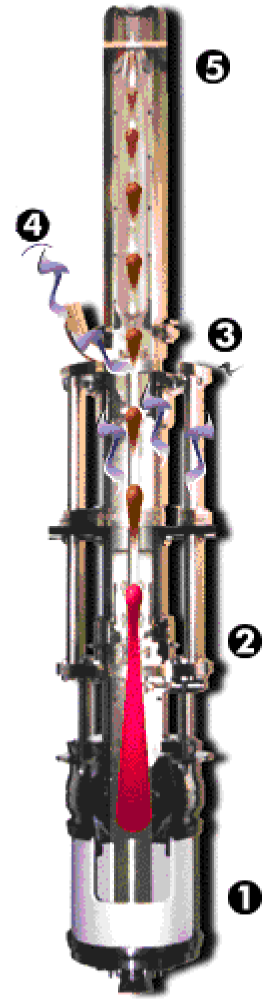






→ 3 cm ←

1 of 10,000 SLAC linac cells
operating at 3 GHz



klystron

a synchrotron is a “wound-up” linear accelerator

employing one or few cavities many times

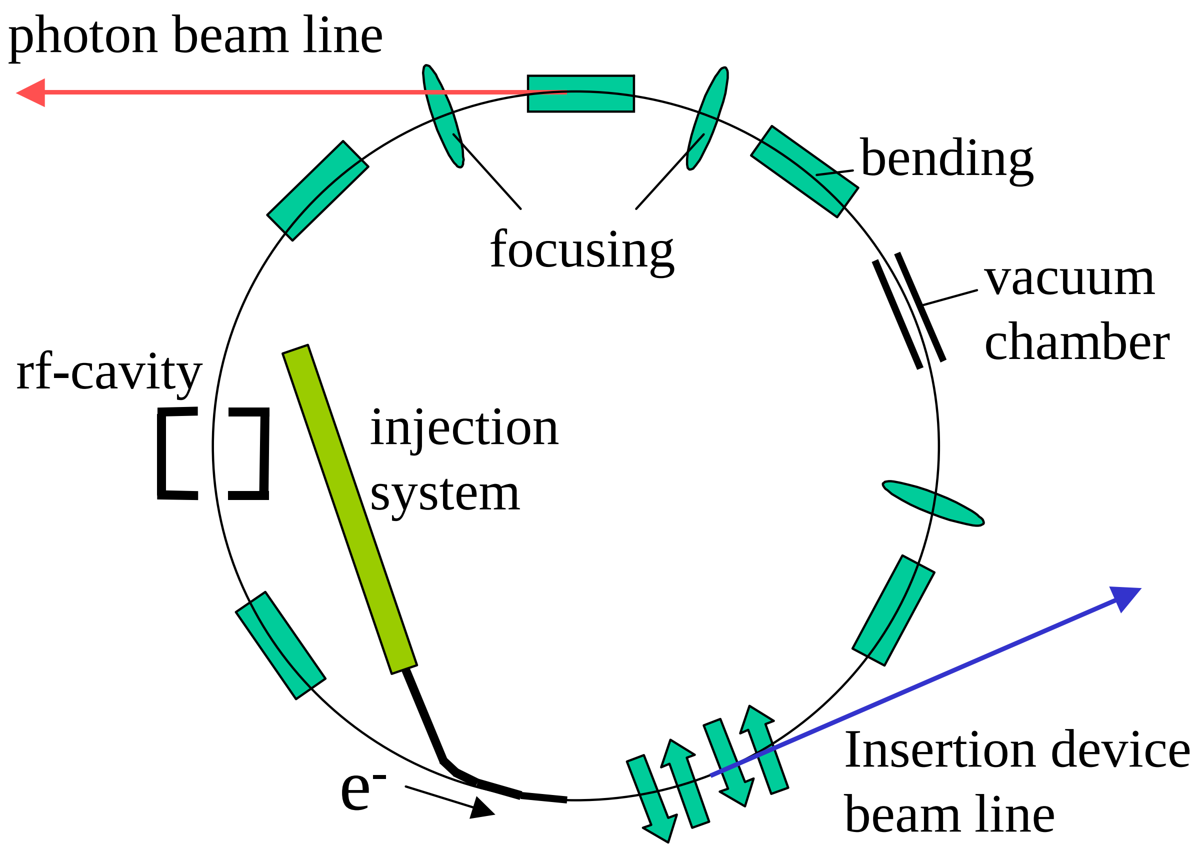
what is a storage ring?

basically a synchrotron which is used

NOT to accelerate, but only

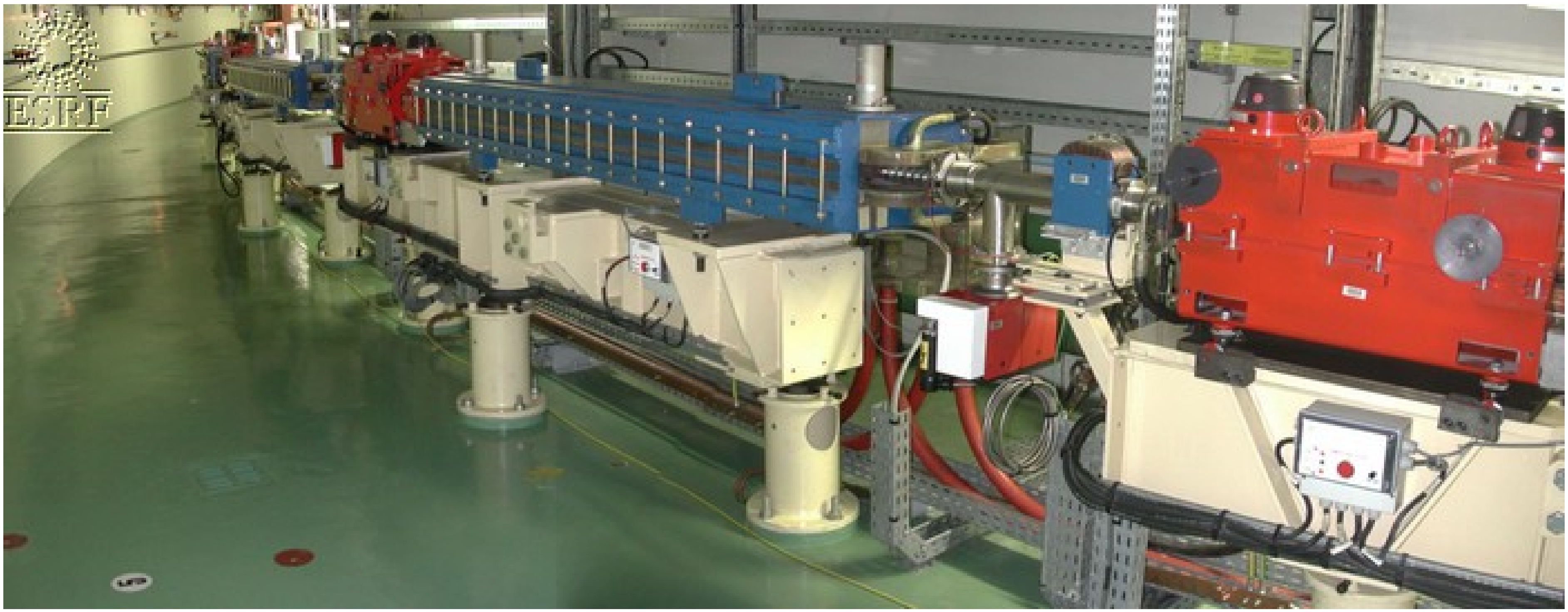
to store a particle beam at a constant energy

main storage ring components



Storage ring ADONE

ESRF Booster



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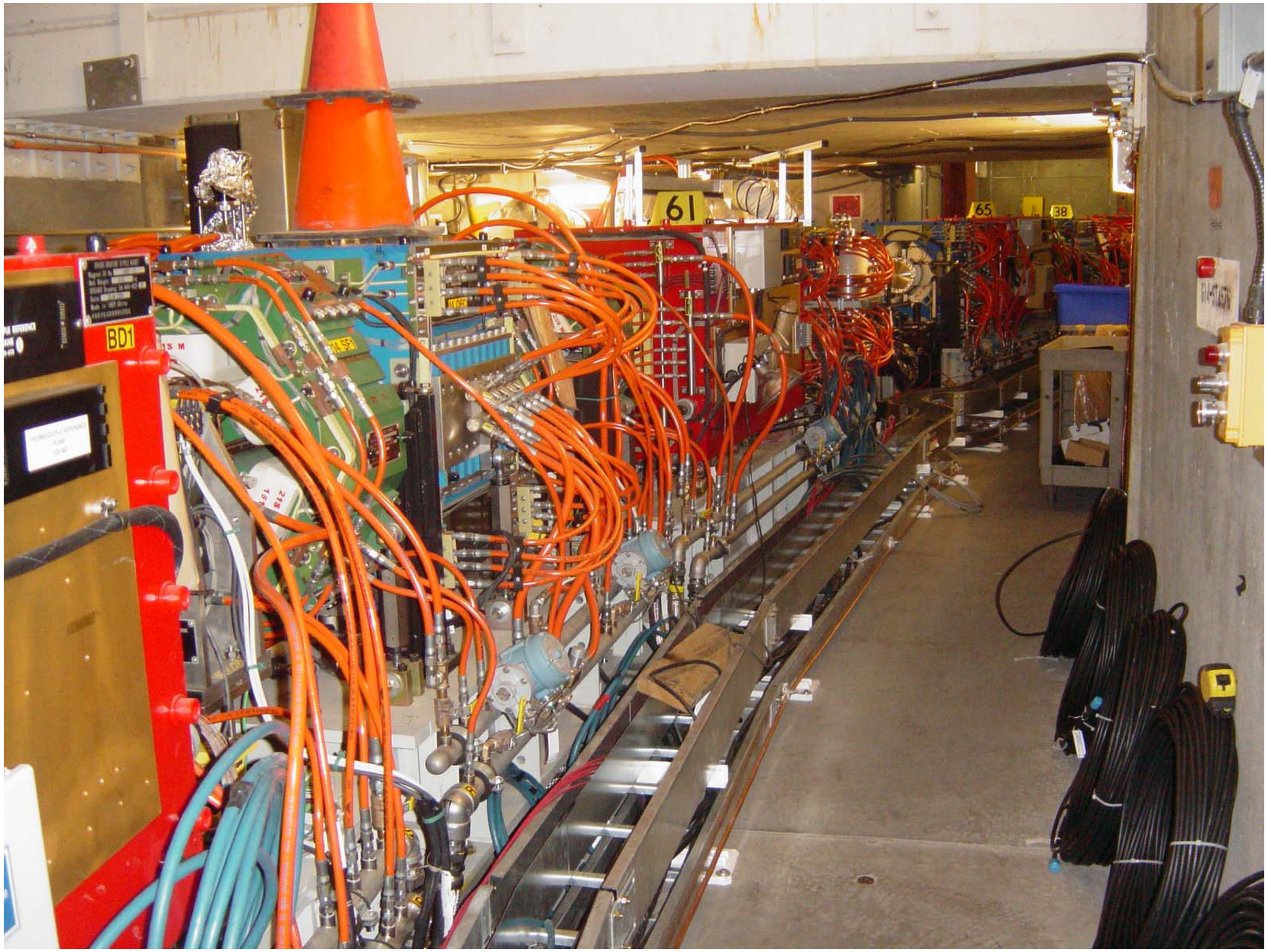

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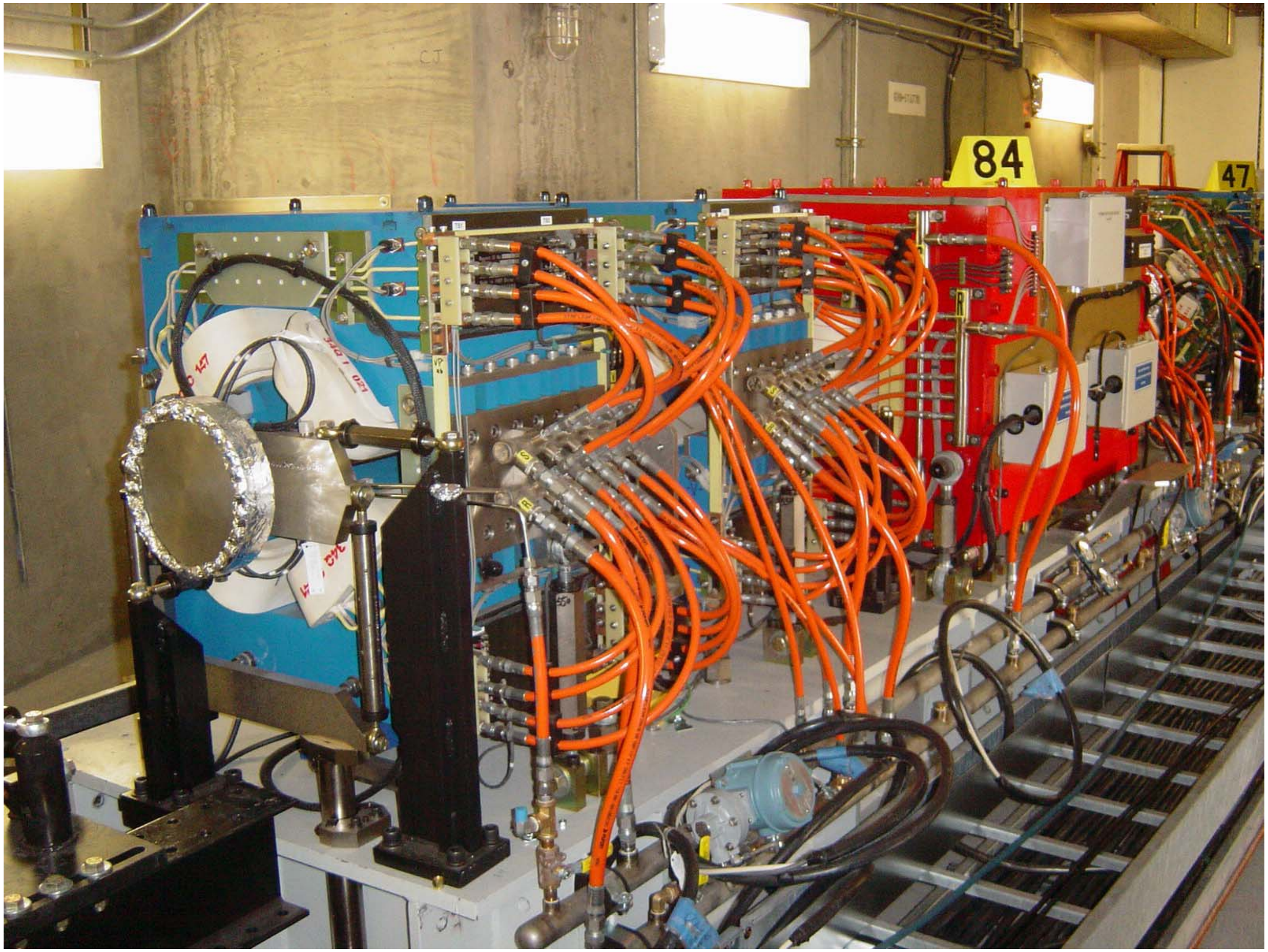
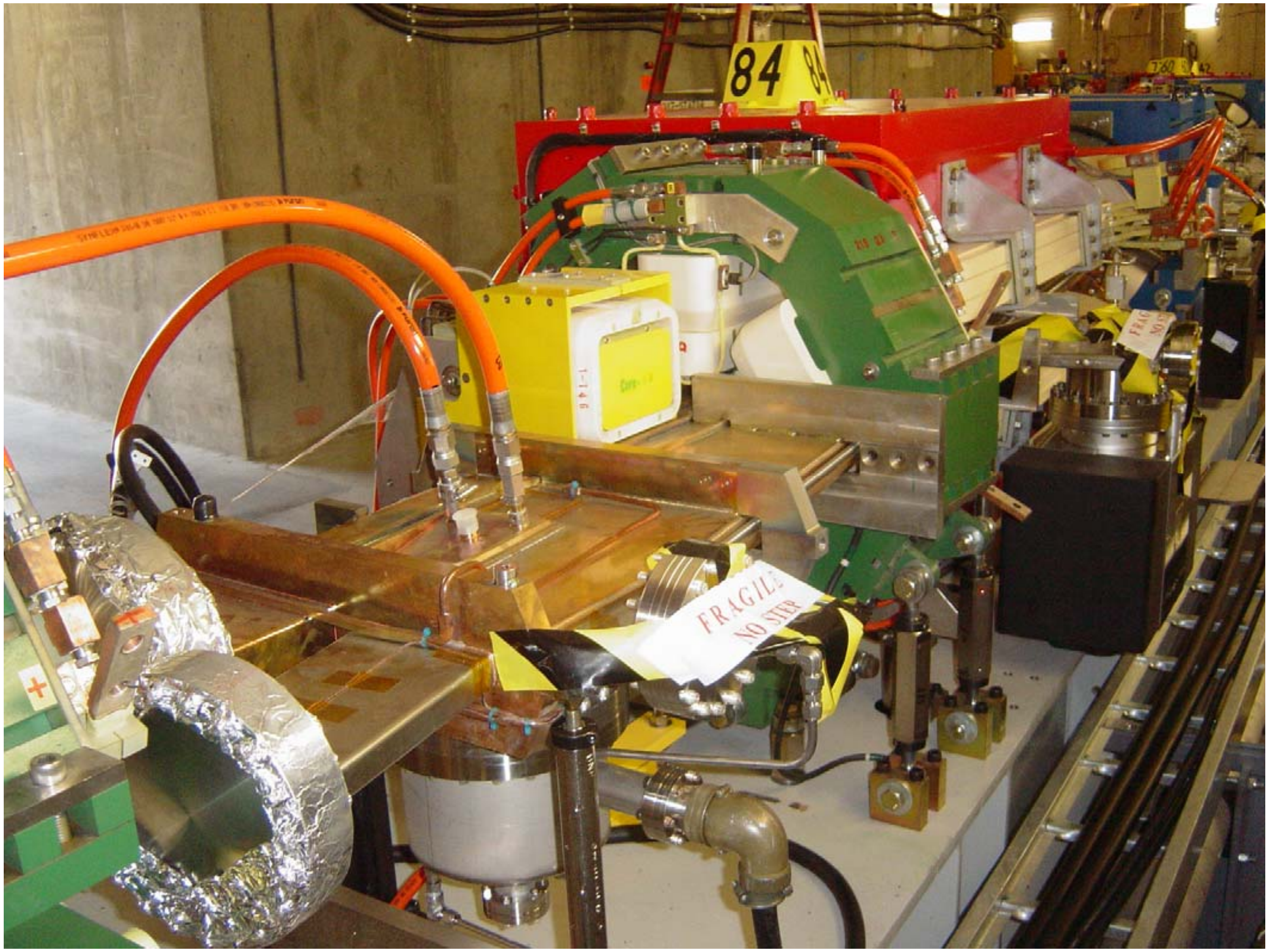


SPEAR-3

SPEAR-3



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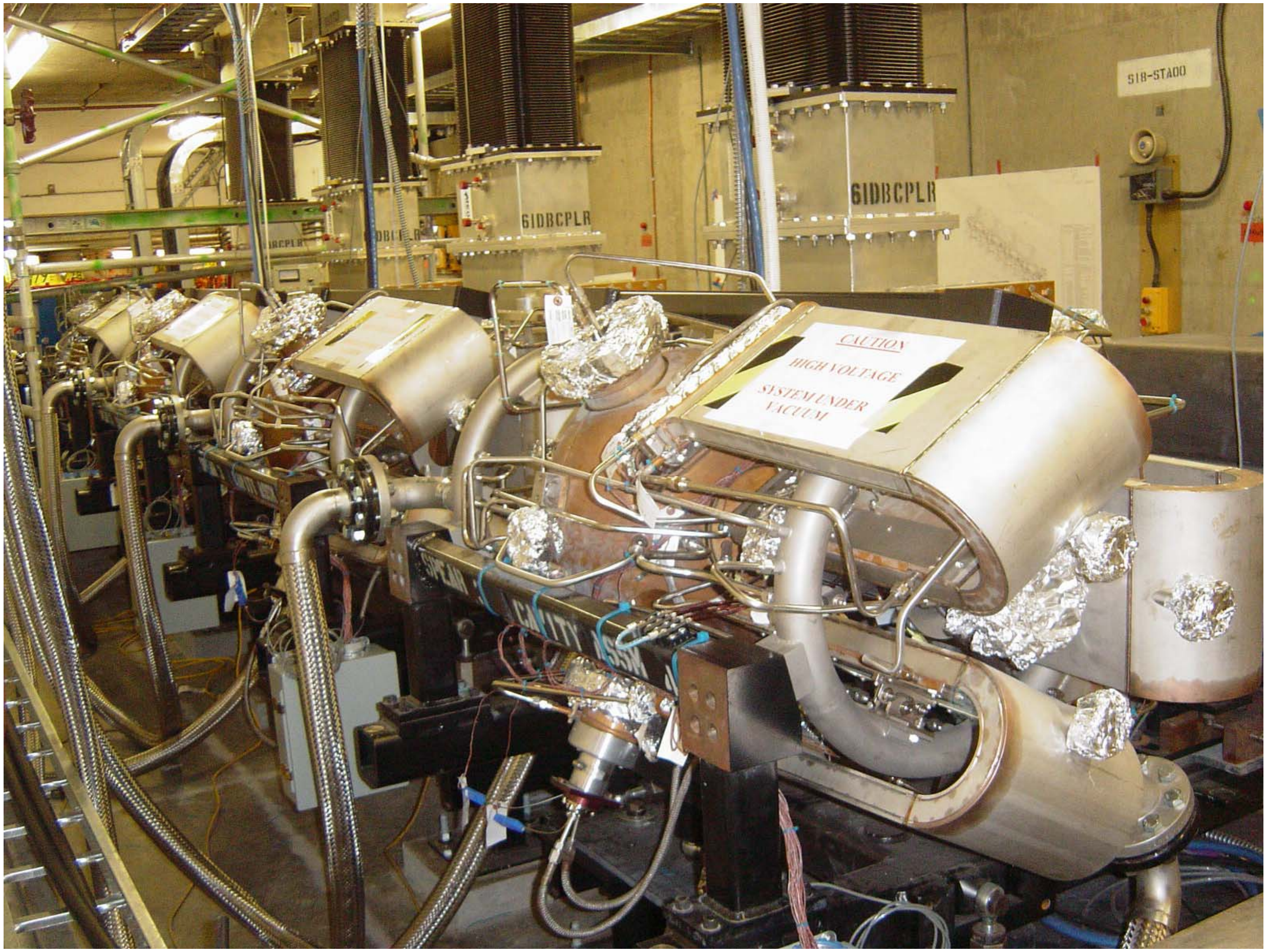

S18-STADD
6IDBCPLR
6IDBCPLR
CAUTION
HIGH VOLTAGE
SYSTEM UNDER
VACUUM

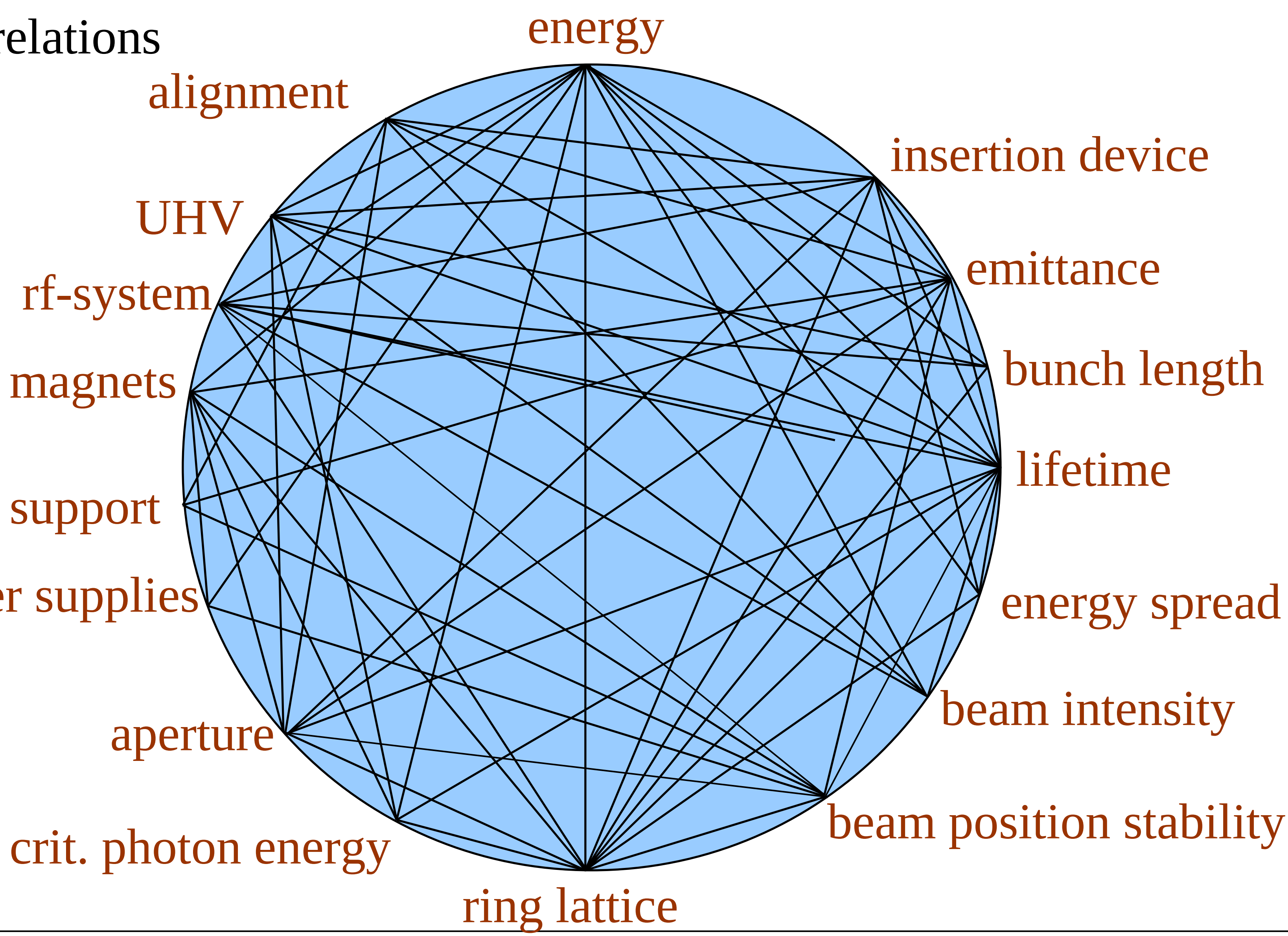
SUBARU undulator

SUBARU : 2.3 m undulator, λ_p = 7.6 cm, 30 periods

Accelerator Physics

- in a storage ring, particles travel along the orbit for many hours at the speed of light (well, very close to it)
- during 15 hours this is a distance of 16.200.000.000.000 m or 16.200.000.000 km or 16.2 billion km or 108 times from earth to sun
- in modern storage rings, particles travel this distance within < 100 μm of the ideal orbit
- in linear colliders nano-beams from independent accelerators must be made to collide
- this cannot be achieved by steering alone !
- we must employ stability principles for beam dynamics and very accurate components and diagnostics
- modern accelerators are not possible without team work involving many skills

interrelations



- need ultra high vacuum UHV (~ 10^{-9} Torr) to avoid loss of particles due to scattering

bending magnets for beam guidance

why magnets? why not electric fields?

Lorentz force: $\boldsymbol{F}_{\mathrm{L}} = e\boldsymbol{E} + e[\boldsymbol{v} \times \boldsymbol{B}]$

should we use *electrical* or *magnetic* fields?

for equal force: $E(\mathrm{V/m}) = \beta c B(\mathrm{T})$

or for $\beta = 1$: $1\ \text{Tesla} \equiv 3 \times 10^{8}\ \mathrm{V/m}$

a 1 Tesla magnet is much easier to built than is plates holding 300 MV/m !

not true if $\beta << 1$

beam deflection

centrifugal force = Lorentz force $$\frac{\gamma A m v^2}{\rho} = eZvB$$

where A is the atomic number (for electrons $A = 1$) and Z the charge multiplicity

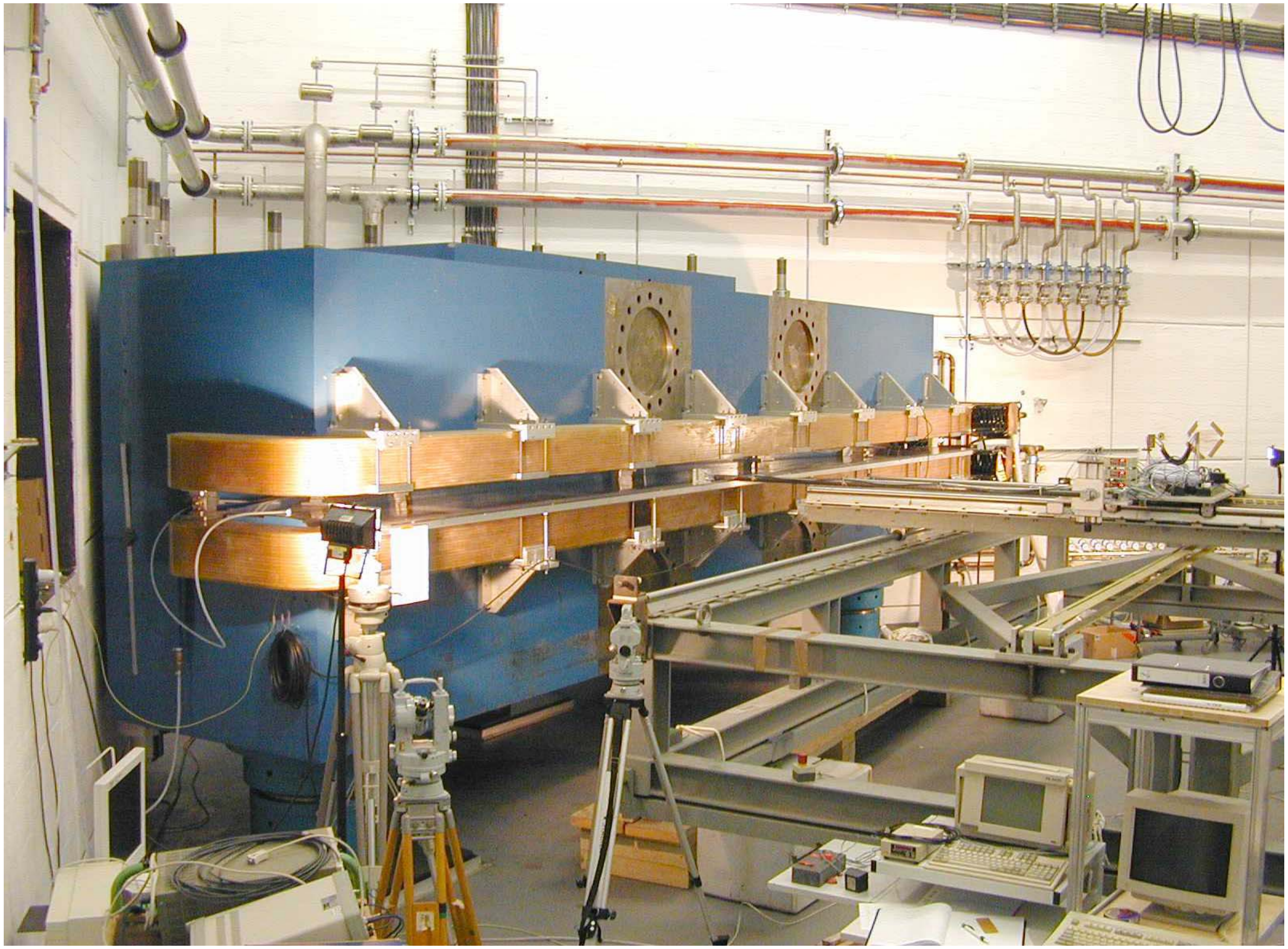
$$\frac{1}{\rho} = \frac{B}{(B\rho)} \quad \text{where} \quad (B\rho) = \frac{\beta\gamma A m c^2}{eZc} = \frac{\beta}{c}\frac{AE_{\mathrm{u}}}{Z} \approx 3.333\frac{\beta A E_{\mathrm{u}}}{Z}$$

is the beam rigidity

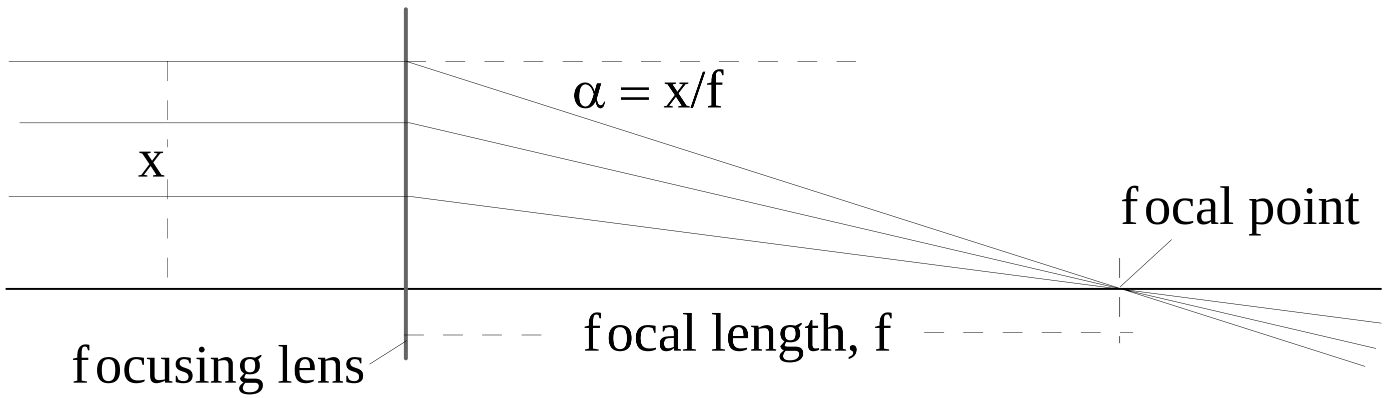
bending radius $$\frac{1}{\rho}\left(\mathrm{m}^{-1}\right) = 0.29979\,\frac{Z}{A}\,\frac{B\left(\mathrm{T}\right)}{\beta E\left(\mathrm{GeV}\right)}$$

deflection angle $$\psi = \frac{\ell_{\mathrm{b}}}{\rho}$$

bending magnet during measurements



principle of focusing



$$\alpha = \frac{l_m}{\rho} = \frac{eBl_m}{cp} \propto x$$

$$B = B_o + gx$$

$$\alpha = \frac{egl_m}{cp} x = kl_m x$$

quadrupole magnet

focal length: $\frac{1}{f} = k\ell_q$

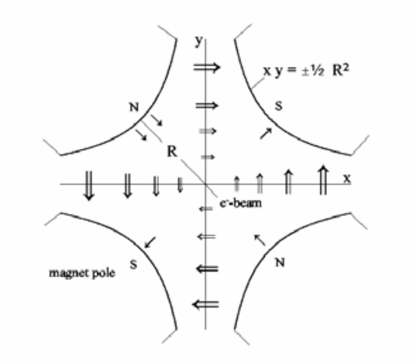
quadrupole strength: $k(\mathrm{m}^{-2}) = 0.3\,\frac{g(\mathrm{T/m})}{cp\,(\mathrm{GeV})}$

derive field from potential: $V = -gxy$

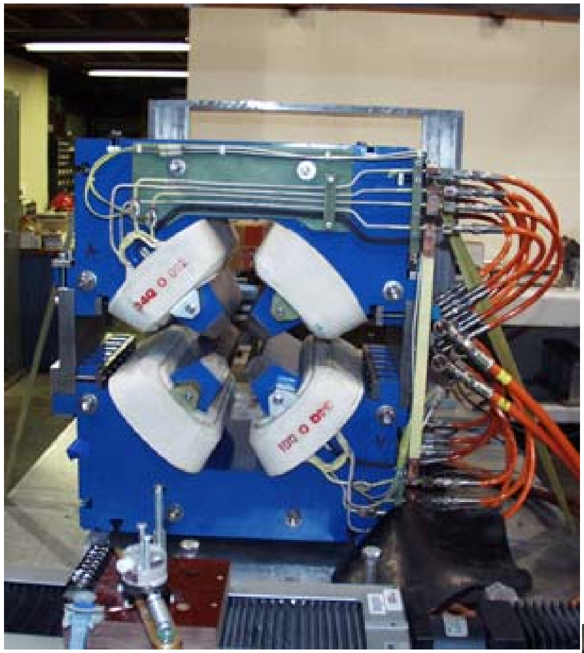
$$B_y = \frac{\partial V}{\partial y} = gx\,, \quad \text{and} \quad B_x = \frac{\partial V}{\partial x} = gy$$

pole profile:

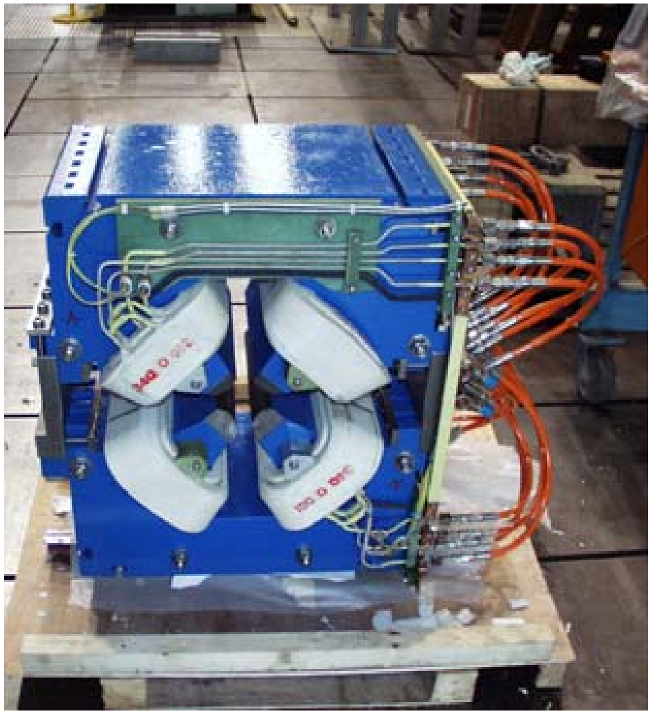
$$x \cdot y = \pm\frac{1}{2}R^2$$



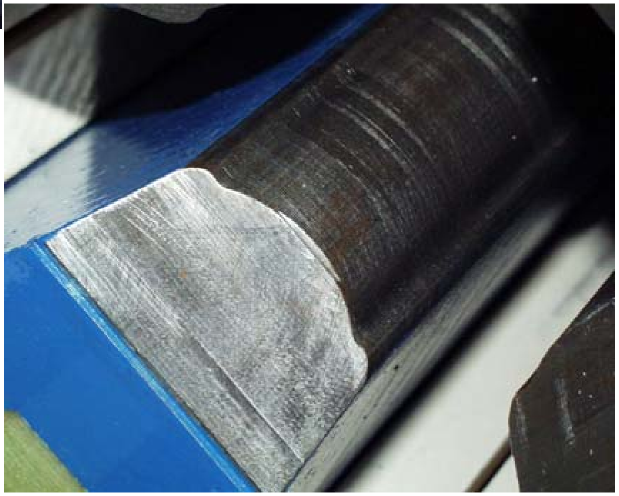
quadrupoles



storage ring
quadrupoles

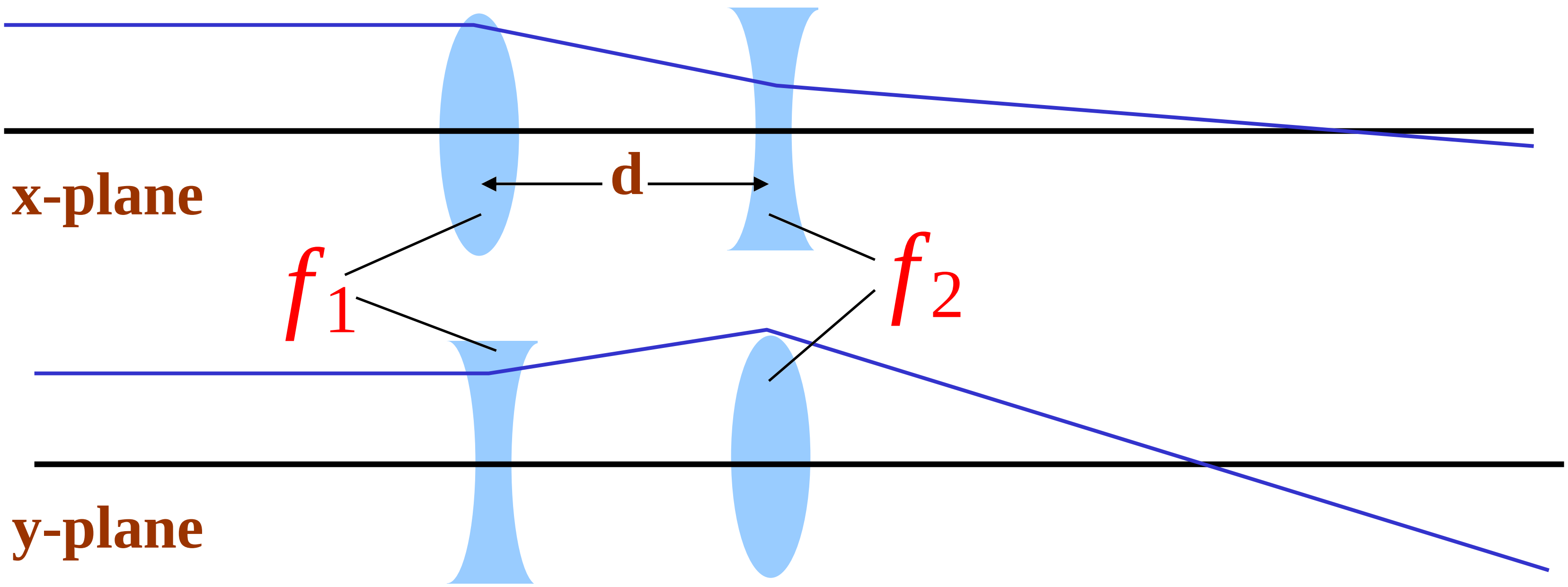


pole profile



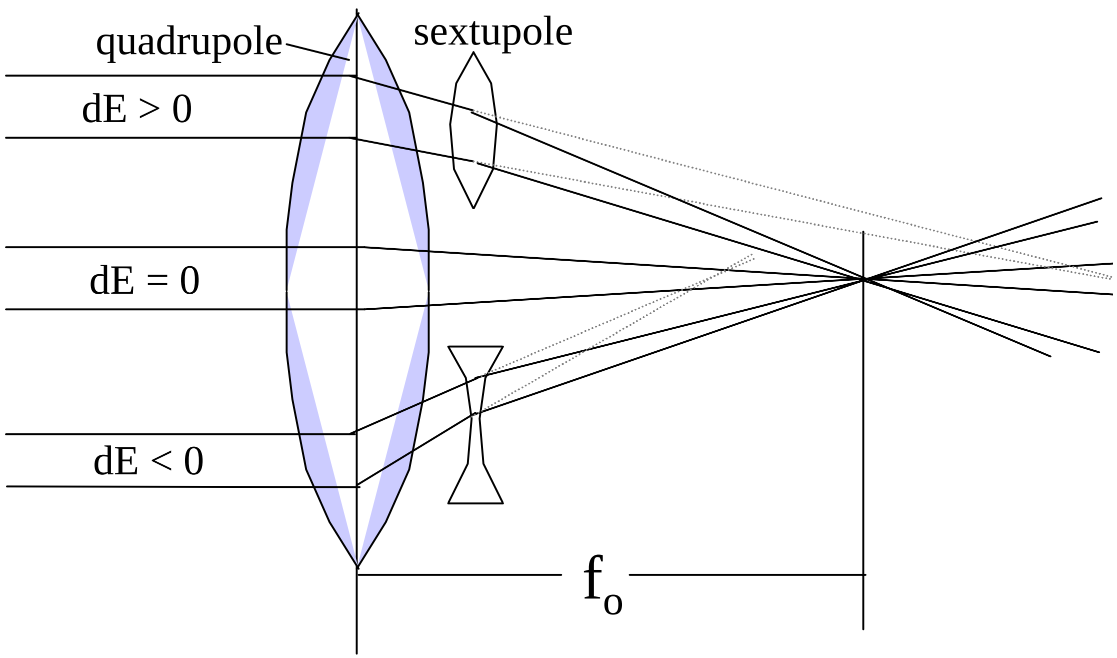
Quadrupole is focusing in one plane defocusing in other plane

How do we get focusing in both planes ?



$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

chromatic and geometric aberrations



need sextupoles to correct for chromatic aberrations, but get now geometric aberrations limiting the dynamic aperture to construct a circular accelerator

- we place all magnets along an ideal orbit
- the excitation of all bending magnets deflect the beam by 360 deg
- the excitation of the quadrupoles defines the focusing or beam dynamics configurations – the lattice
- a correct lattice ensures beam stability in the transverse planes (x,y)
- particles are not forced to travel along ideal orbit, but oscillate about the ideal orbit (betatron oscillations)
- the number of oscillations per turn are called the tunes (Q_x , Q_y)
- they may not be equal to *n*, *n*/2, *n*/3, *n*/4…..where n is an integer
- resonances !

all particles are contained within an envelope given by

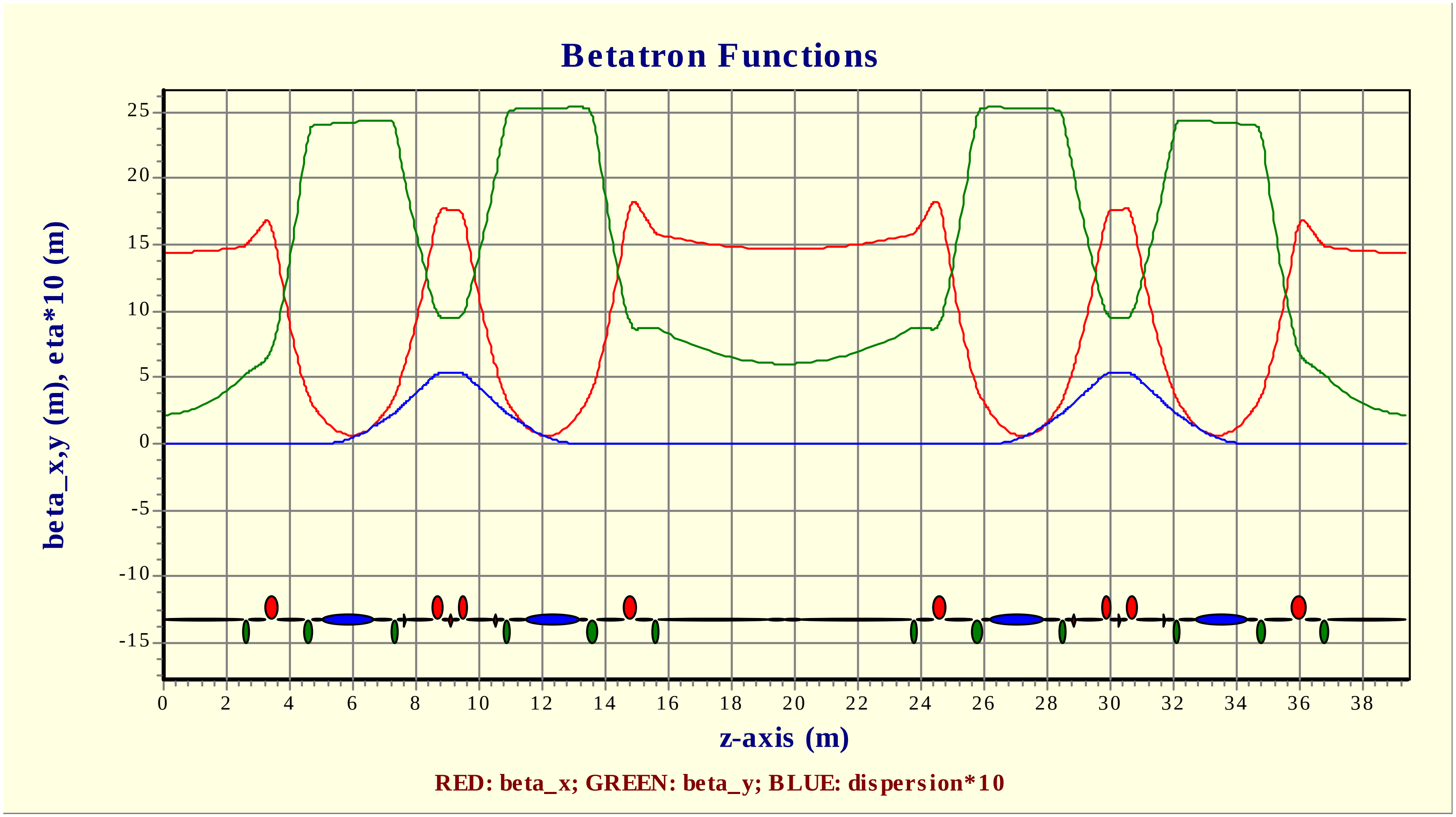
$$E_{x,y}(z) = \sqrt{\epsilon_{x,y}\beta_{x,y}(z)}$$

where $\epsilon_{x,y}$ is the emittance of the beam in the x- or y-plane

and $\beta_{x,y}(z)$ is the betatron function

- the emittance is a constant around the circular accelerator
- the betatron function is defined by the lattice (quadrupoles)
- there is only one betatron function per plane and configuration
- its values are tabulated

periodic betatron and dispersion functions



particles are expected to travel along to the ideal orbit

- well, close
- not all particles have the correct energy
- not all magnets have the ideal field or are aligned ideally
- we get dispersion
- on top of dispersion we also get orbit distortion
- both dispersion and orbit distortion define reference orbits
- particles with different energies follow different reference orbits

$$x_{\mathrm{ref}}(z) = x_{\mathrm{d}}(z) + \eta(z)\frac{\Delta p}{p_0}$$

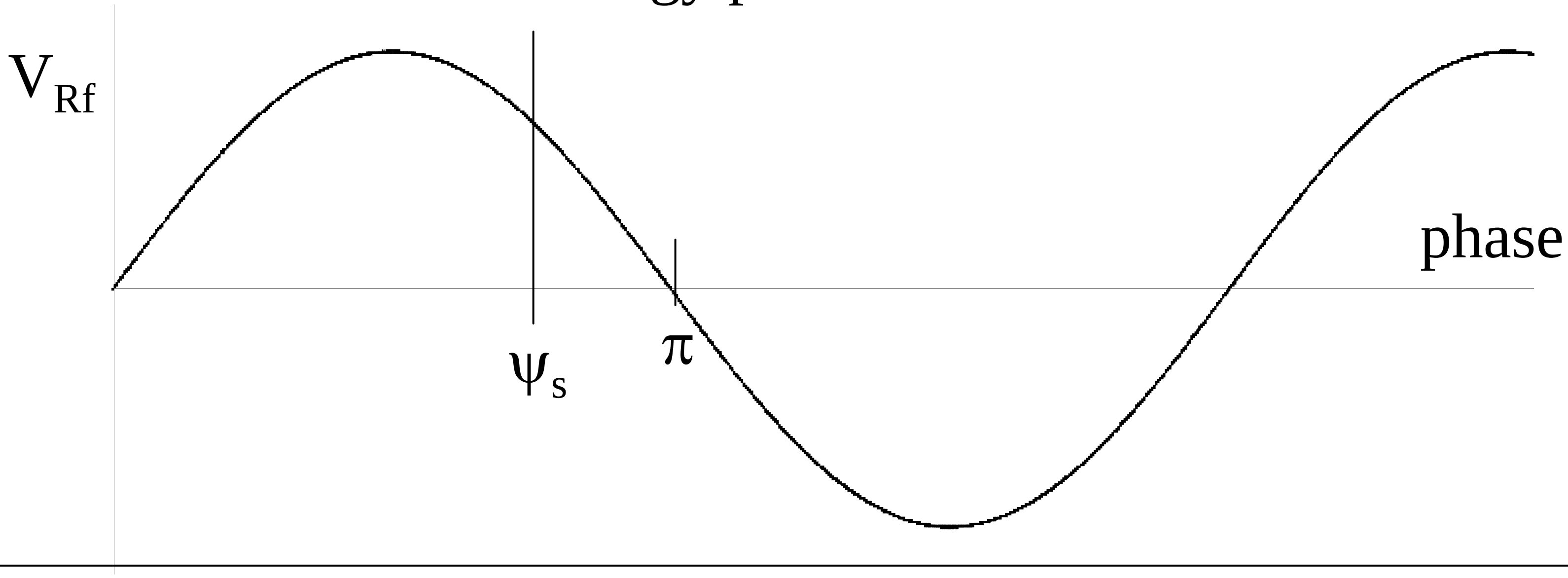
- for perfect ring and energy $x_{\mathrm{ref}}(z) \equiv 0$

- orbit distortion must be corrected absolute to < 100 μm
- need beam position monitors and steering magnets
- relative sensitivity of BPMs < 1μm
- need sensitivity for beam stability and reproducibility
- and for diagnostic purpose – transfer matrix

longitudinal motion and stability

principle of phase stability (Veksler, McMillan 1946)

- for proper interaction of beam with cavity, revolution time must be integer multiple of Rf-period
- ok for ideal energy particle
- what about non-ideal energy particles?



Accelerator Physics

- periodic focusing solutions for the transverse planes and
- principle of phase focusing
- together with precisely built components
- and diagnostic instruments

allows us to design accelerators and be confident a beam will survive on a precise orbit for more than

16.2 billion km

or collide nano-meter beams from two independent accelerators