

# *Choices for the LHC*

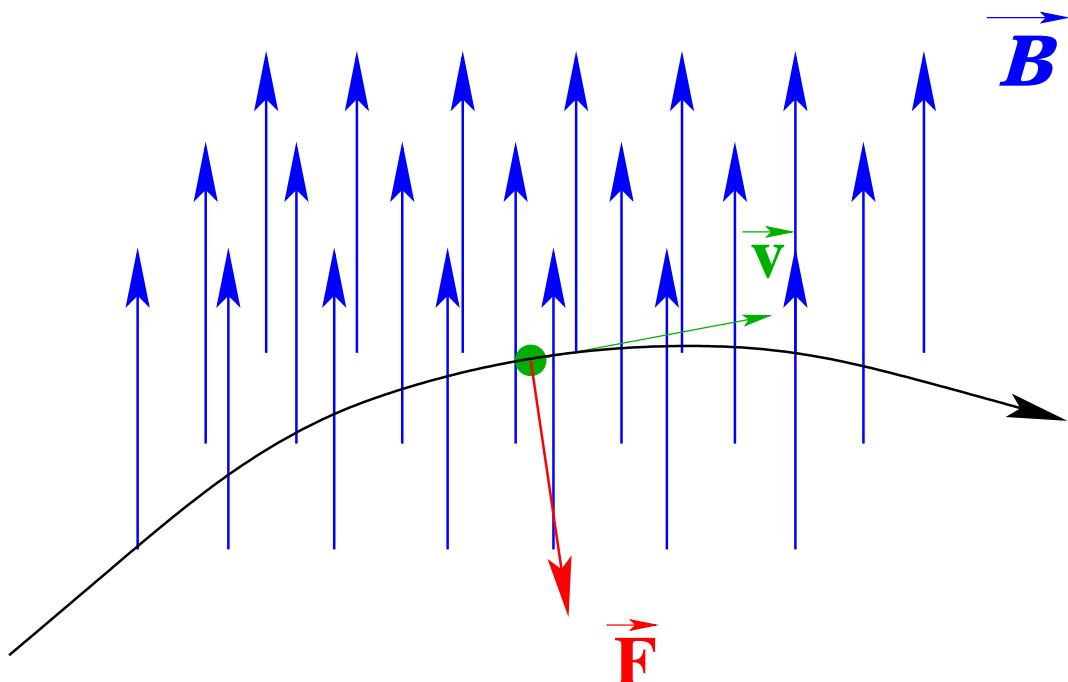
---

- super conducting magnet technology
- FODO lattice
- dipole packing factor
- field quality and resonances
- 2 in 1 magnet design
- synchrotron radiation
- beam screen
- electron cloud
- 2808 bunches with  $10^{11}$  particles per bunch
- luminosity insertions
- luminosity lifetime and operation cycle

## ● Lorentz Force:

$$\frac{d\vec{p}}{dt} = Q * (\vec{E} + \vec{v} \times \vec{B})$$

## ■ **magnetic fields:**



→ **Trajectory curvature due to  $B$  field!**

→ **Energy gain only due to  $E$  field!**

# Circular Accelerators

## ■ **Cyclotron:**

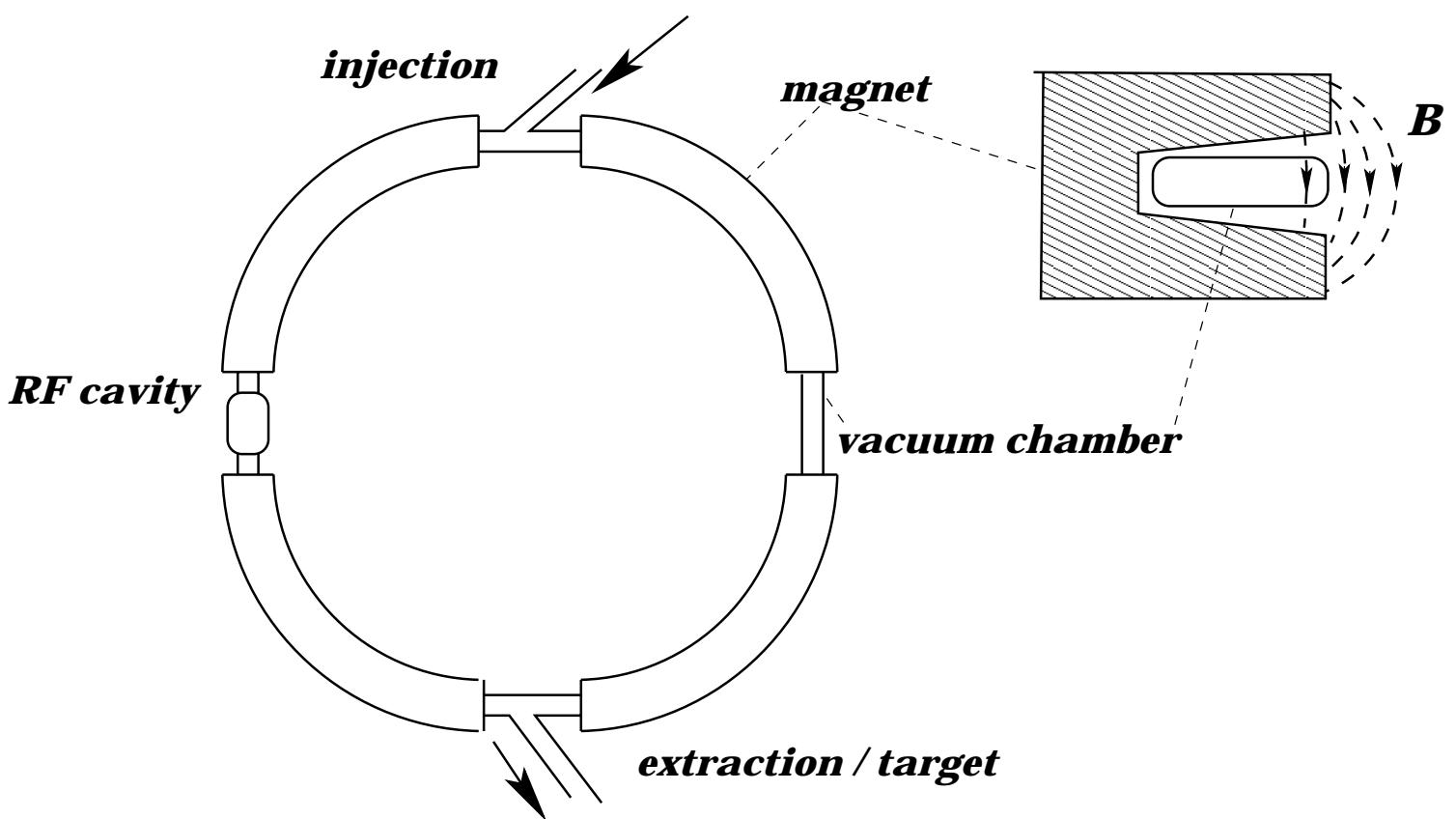
$$\omega_0 = \frac{Q}{m_0} \bullet \frac{B}{\gamma}$$

$$r = \frac{m_0}{Q} \bullet \frac{\gamma}{B} \bullet v$$

## ■ **Synchrotron:**

**$R = \text{const.}$**

→  **$B \neq \text{const.}$**



(LHC/LEP:  $\omega_0 = 11.3 \text{ kHz}$ )

# Circular Accelerators

■ **uniform  $B$ -field:**  $R = \text{const.}$

$$\mathbf{p} = Q \cdot \frac{\mathbf{B} \cdot \mathbf{L}}{2\pi}$$

$$\approx E/c \quad \text{for } E \gg E_0$$

■ **realistic synchrotron:**

B-field is not uniform: –drift space for installation  
–different types of magnets  
–space for experiments etc

$$E = \frac{Q \cdot c}{2\pi} \cdot \underbrace{\oint}_{\text{circle}} \vec{B} \cdot d\vec{l}$$

→ high beam energy requires:

- high magnetic field
- large packing factor 'F'

# **Why 8.4 Tesla?**

---

■ **required maximum dipole field:**

$$\mathbf{B} \propto \gamma$$



$$B[T] = \frac{2\pi}{0.3} \cdot \frac{p[\text{GeV}/c]}{F \cdot L[\text{meter}]}$$

■ **Physics:** →  $p = 7000 \text{ GeV}/c$

■ **LEP tunnel:**  $L = 27000 \text{ meter}$

→ arcs:  $L = 22200 \text{ meter}$

■ **only 80% of the arc are filled with dipoles:**

→  $F = 0.8$



$$B_{\max} = 8.38 \text{ T}$$

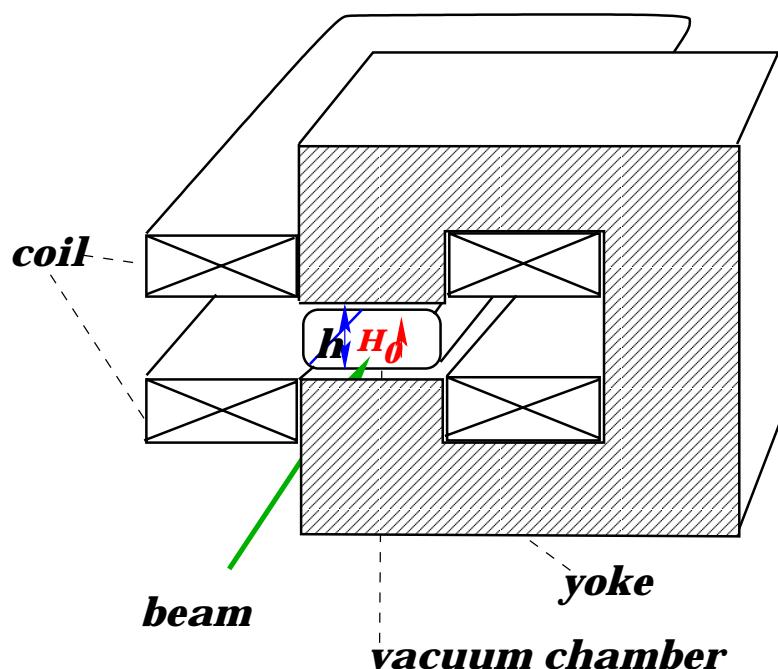
*iron saturation: 2 Tesla  
earth:  $0.3 \cdot 10^{-4}$  Tesla*

# Bending Magnet

■ Amperes Law:

$$\oint \mathbf{H} = \mathbf{I} \cdot \mathbf{N}$$

$$\mathbf{B} = \mu_0 \cdot \mu \cdot \mathbf{H}$$



■ field amplification with iron core

→ **Ferro magnetic material**       $\mu \gg 1$

■ field quality is determined by the pole face shape

■ this design principle was used for the LEP magnets

# **Power Consumption**

---

## **LEP:**

$B = 0.135 \text{ Tesla}$

$$I = 4500 \text{ A}; R = 1 \text{ m}\Omega \quad \rightarrow \quad P = 20 \text{ kW / magnet}$$

$$\text{ca. 500 magnets} \quad \rightarrow \quad P = 10 \text{ MW}$$

$$P = R \cdot I^2$$

## **LHC:**

$$B \propto I$$

$$\rightarrow B_{\max} = 8.38 \text{ T} \rightarrow I = 280000 \text{ A} \\ (\text{current density!})$$

$$\rightarrow P > 78 \text{ MW / magnet}$$

$$\text{ca. 500 magnets} \rightarrow$$

$$P > 39 \text{ GW}$$

***superconducting technology!***

8.4 T is at the limit of available technology!  $\rightarrow$  L. Rossi

# **Other Collider Synchrotrons**

---

- **LEP2:**       $e^-/e^+$        $E = 0.1 \text{ TeV}$     **1989**  
*CERN*  
 **$27 \text{ km}; B = 0.1 \text{ T}$**
  
- **Tevatron:**     $p^-/p^+$        $E = 1 \text{ TeV}$       **1985**  
*Chicago, USA*  
 **$6.3 \text{ km}; B = 4.5 \text{ T}; T = 4.2 \text{ K}$**
  
- **HERA:**       $e^-/p^+$        $E = 0.9 \text{ TeV}$       **1991**  
*Hamburg, Germany*  
 **$6.3 \text{ km}; 2 \text{ rings}; B = 5.5 \text{ T}; T = 4.4 \text{ K}$**
  
- **RHIC:**       $Au/Au; p^-/p^+$   
*New York, USA*                           $E = 0.25 \text{ TeV}$       **1999**  
 **$3.8 \text{ km}; 2 \text{ rings}; B = 3.5 \text{ T}; T = 4 \text{ K}$**
  
- **LHC:**       $E = 7 \text{ TeV}$   
*CERN*  
\* 2                          \* 0.5                          \* 4  

$B = 8.4 \text{ T}$

$T = 1.9 \text{ K}$

$L = 27 \text{ km}$

P. Lebrun

# Trajectory Stability



## Vertical Plane:

■ **gravitation:**

$$\Delta s = \frac{1}{2} \cdot g \cdot \Delta t^2$$

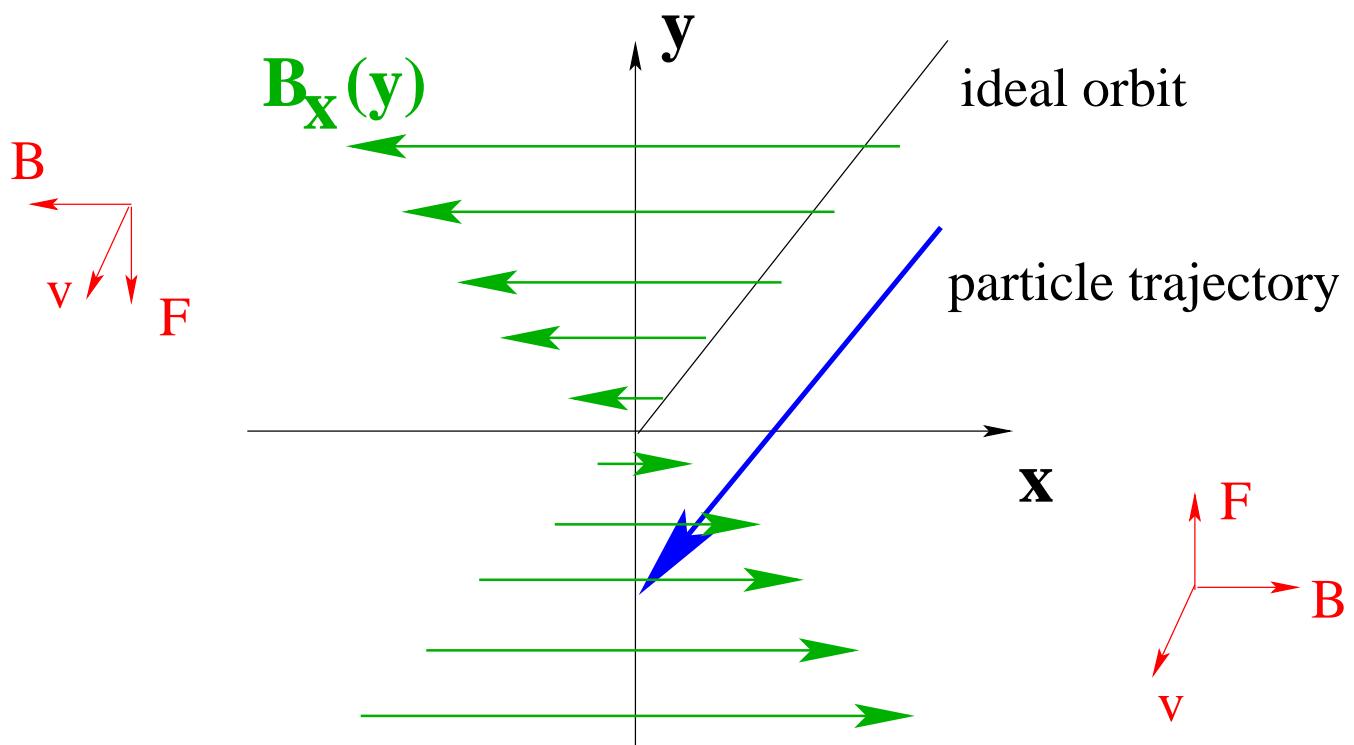
$$g = 10 \cdot m \cdot s^{-2}$$

$$\Delta s = 18 \text{ mm}$$

$$\Delta t = 60 \text{ msec}$$

→ **660 Turns!**

→ **requires focusing!**



# Quadrupole Focusing



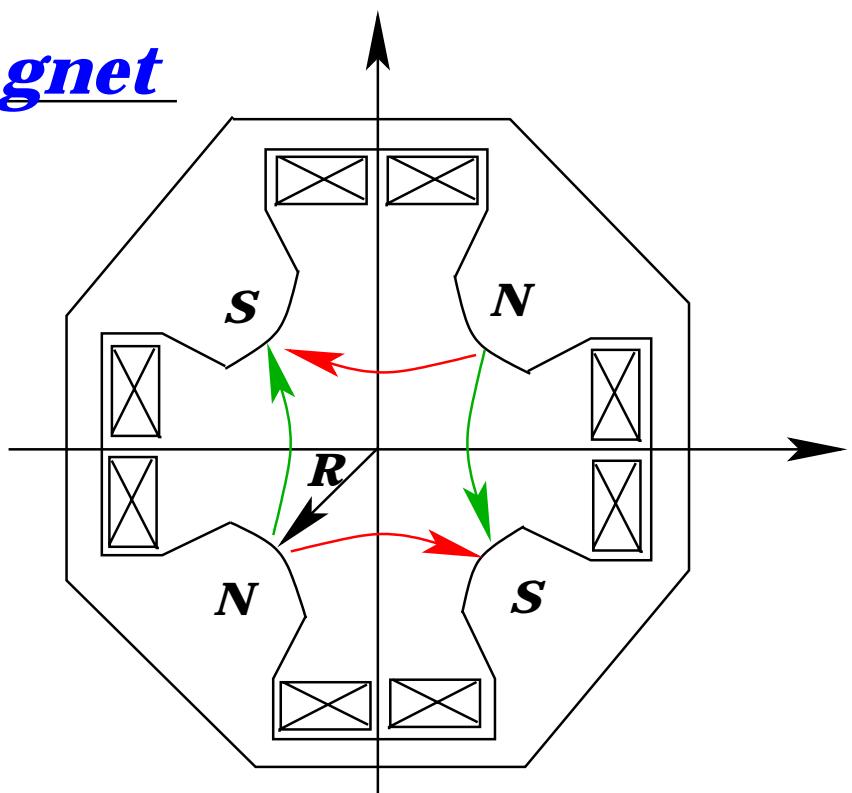
## Quadrupole Magnet

$$\mathbf{B}_x = -\mathbf{g} \cdot \mathbf{y}$$

$$\mathbf{B}_y = -\mathbf{g} \cdot \mathbf{x}$$

$$\mathbf{F}_x = \mathbf{g} \cdot \mathbf{x}$$

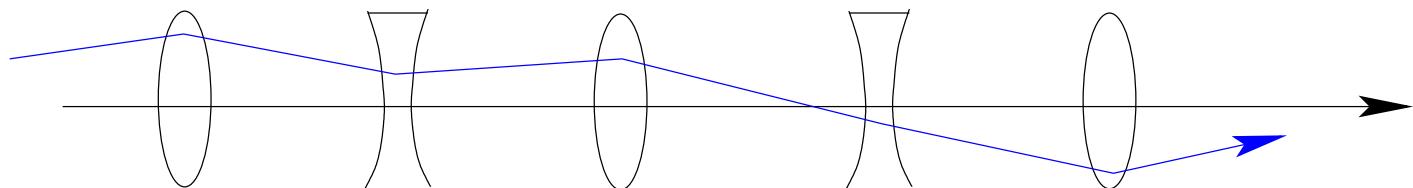
$$\mathbf{F}_y = -\mathbf{g} \cdot \mathbf{y}$$



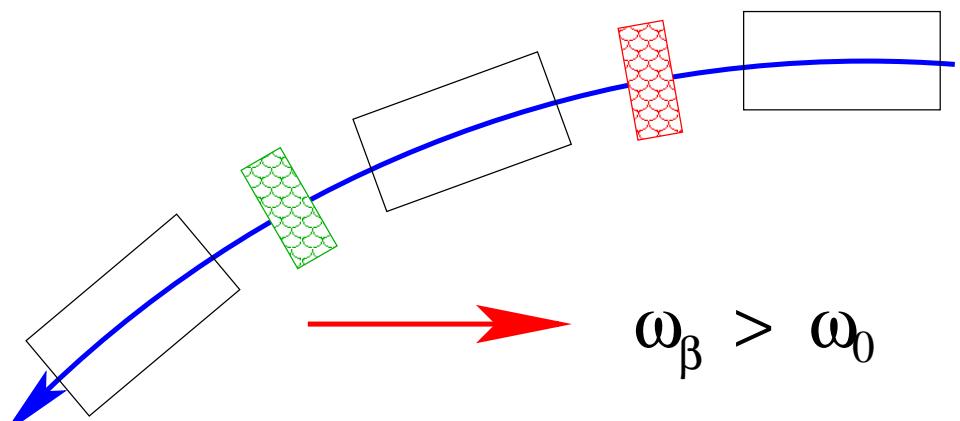
→ **defocusing in horizontal plane!**



## Alternate Gradient Focusing

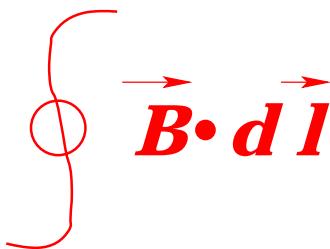


**Idea:** *cut the arc sections in focusing and defocusing elements*



# LHC Lattice Cell Design

■ maximum beam energy implies maximum



- maximize peak dipole field for each dipole
- peak field limited by quench behaviour
- critical surface of a superconductor
- maximize the area occupied by dipole magnets
  - decreases with number of quadrupoles and number of interconnects
  - large beam size!
    - requires large magnet bore diameter
    - increased dipole magnet cost
    - reduced quadrupole strength

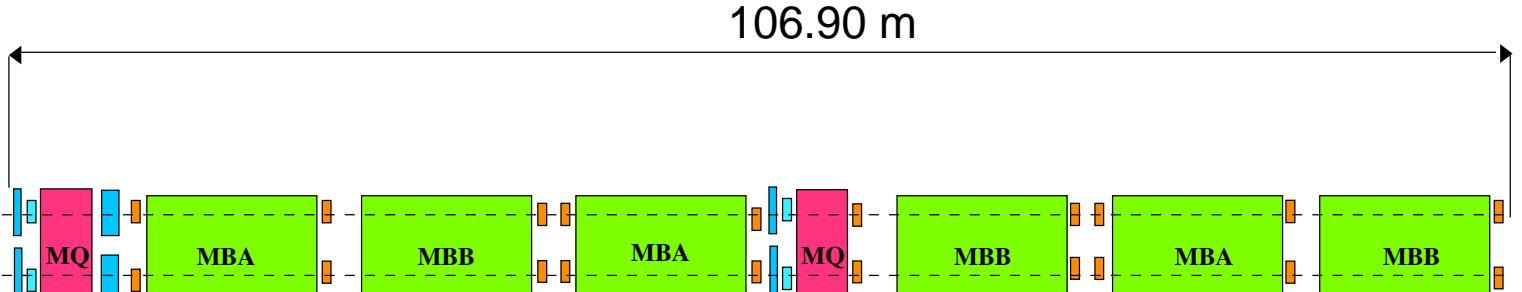
■ quadrupole strength:

limited by peak field at the coils

- large quadrupole diameter  $\rightarrow$  small gradient

# LHC ARC CELL

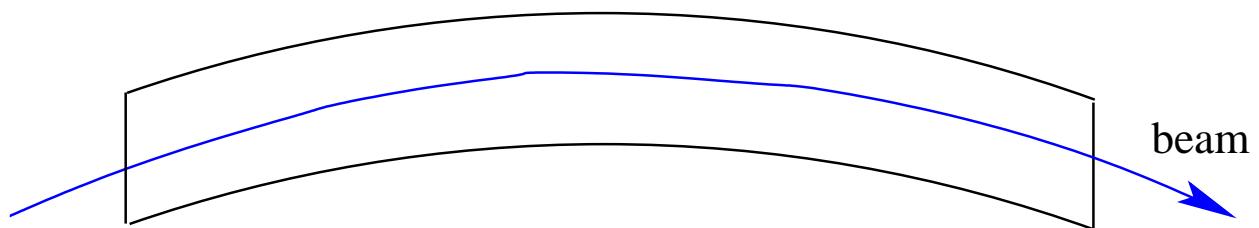
■ schematic layout of one LHC cell (23 cells per arc)



■ dipole deflection angle

14.4 meter long dipoles with a peak field of 8.4T

- 4 cm change of the trajectory along 1 dipole!  
compared to a vacuum chamber diameter of 4cm
- build curved dipole magnets ( ca 2cm sagitta)



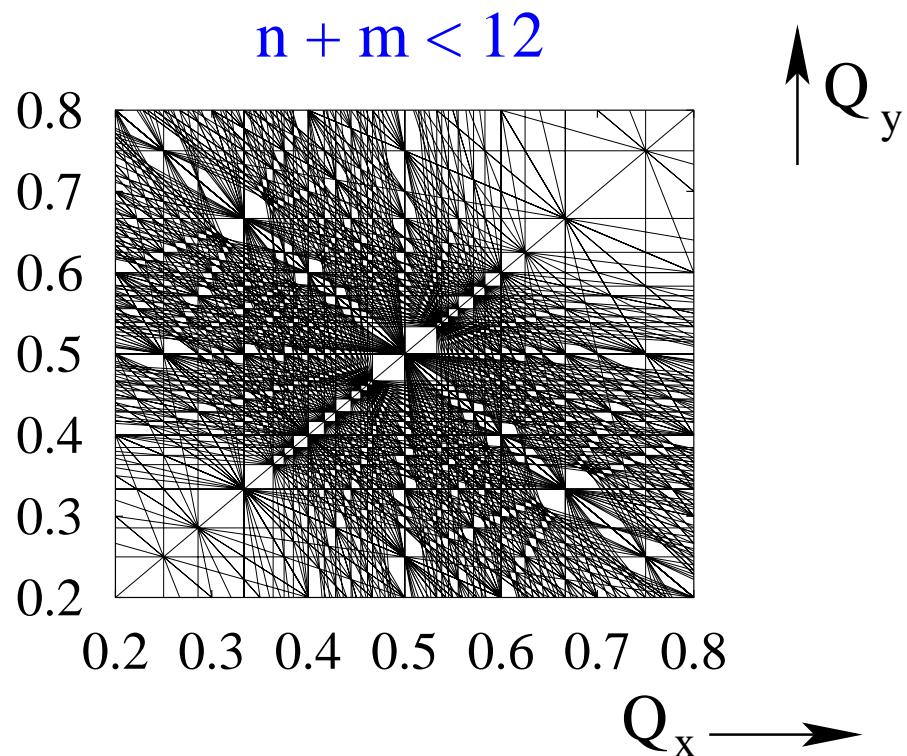
new design concept (does not exist in other machines)!

stability of the dipole geometry!??

# Resonances and Non-Linear Field Errors

■ resonances in the tune diagram:

$$n \cdot Q_x + m \cdot Q_y = r$$



magnetic field imperfections drive resonances!

■ resonances limit the long term stability of the protons:

$$h_{n,m} \propto A^{n+m}$$
 → avoid 'low order' resonances

■ experience from SppS, Tevatron and HERA:

avoid resonances  $< 11^{\text{th}}$  order!

→ requires high precision magnet field quality

→ dipole field error change in time! (L. Rossi)

# Cold Machine

- **Quench level:** (L. Rossi and P. Lebrun)

$$N_{\text{lost}} < 7.0 \cdot 10^8 \text{ m}^{-1} \longleftrightarrow \boxed{0.02\% \text{ of beam}}$$

→ ***minimize losses (resonances)!***

***machine protection at all times!***

(R. Schmidt)

- **field errors change in time**

■ ***injection:***

→ ***persistent current decay***

■ ***ramp:***

→ ***snap back***

- **active correction circuits**

ca 500 orbit corrector and 100 other correction circuits

# Other Superconducting Machines

● **Tevatron:**  $\bar{p}/p^+$   $E = 1 \text{ TeV}$  **1985**  
*Chicago, USA*

**$L = 6.3 \text{ km}$  magnet range: 6  $\xi(b3) = 120$**

beam losses not critical at injection

● **HERA:**  $e/p^+$   $E = 0.9 \text{ TeV}$  **1991**  
*Hamburg, Germany*

**$L = 6.3 \text{ km}$  magnet range: 20  $\xi(b3) = 300$**

magnet quench limit = 20% total beam

● **RHIC:**  $Au/Au; p^+/p^+$   
*New York, USA*  $E = 0.25 \text{ TeV}$  **1999**

**$L = 3.8 \text{ km}$  magnet range: 7  $\xi(b3) = 35$**

beam losses not critical at injection

● **LHC:** *CERN*  $E = 7 \text{ TeV}$

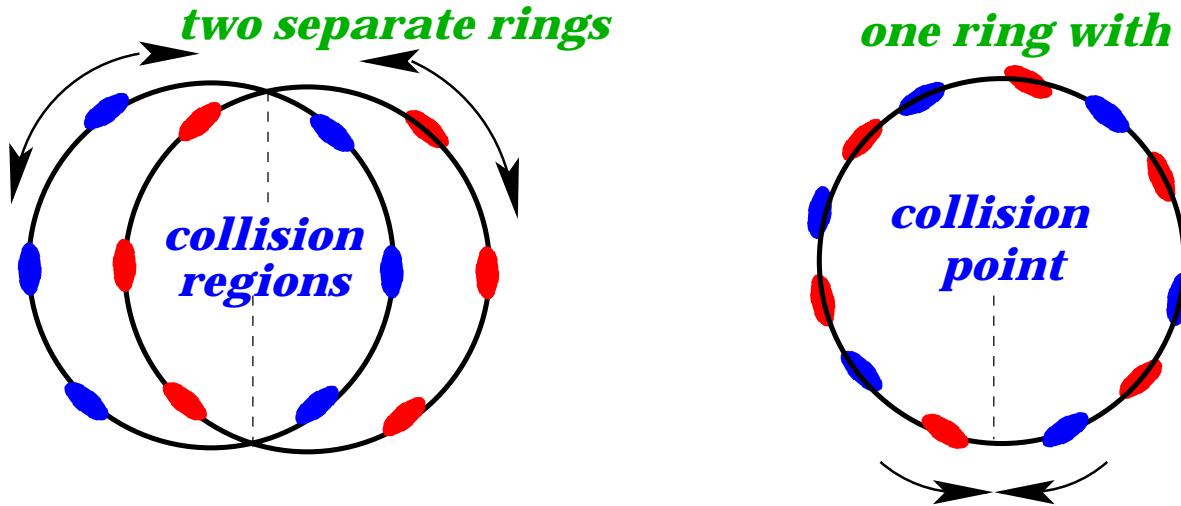
**$L = 27 \text{ km}$  magnet range: 16  $\xi(b3) = 300$**

magnet quench limit = 0.02% total beam

P(7TeV)!!!!

# **2-in-1 Magnet Design**

- collider ring design requires 2 beams:  $E_{CM} = 2 \cdot E_p$



- design with only one aperture requires particles and anti-particles:

$$F = q \cdot v \cdot B$$

→ LEP:  $e^+ / e^-$       Tevatron:  $p^+ / p^-$

- limited by beam-beam interactions (# bunches)
- limited by anti-particle production

- 2-ring design implies twice the hardware

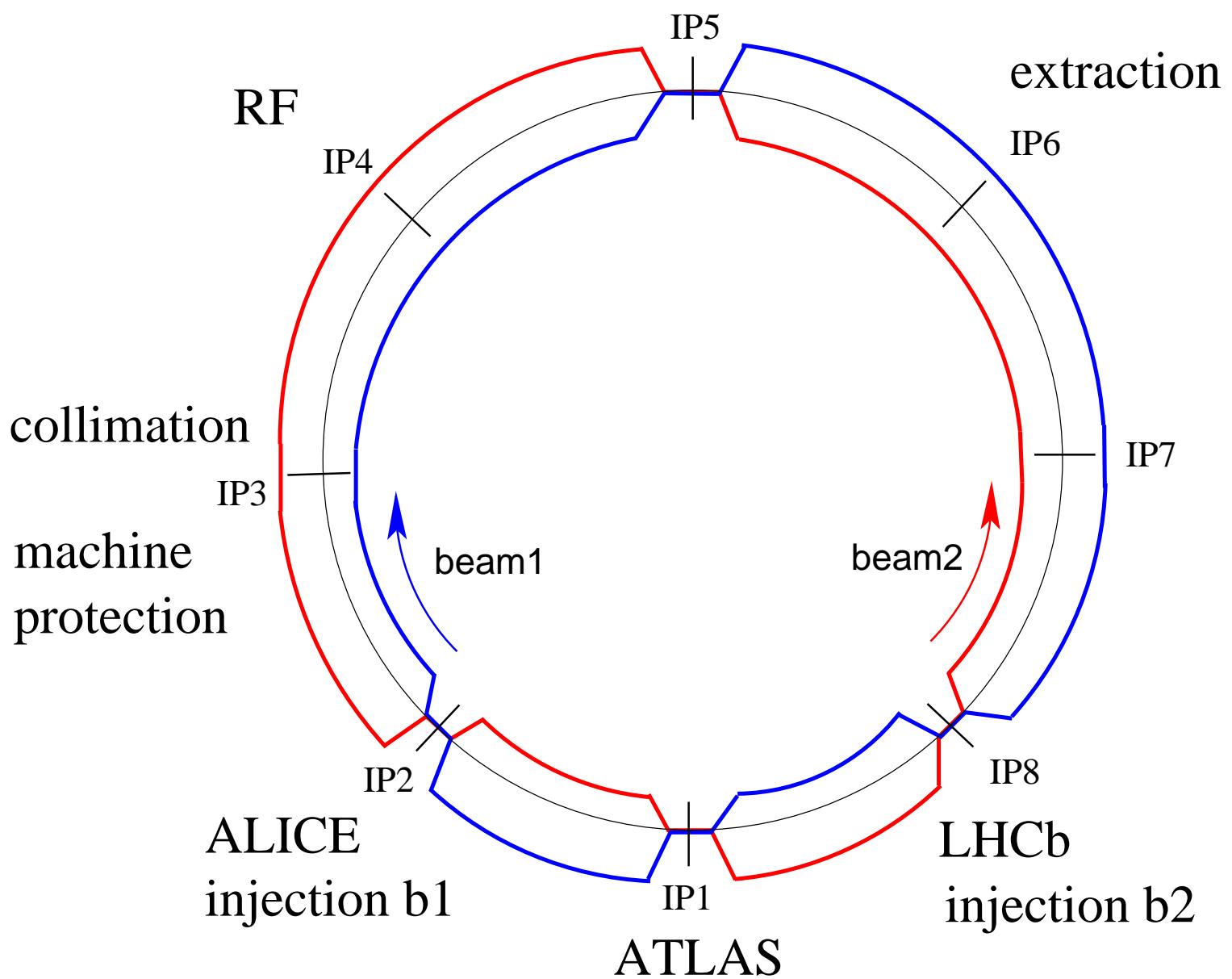
LHC 2-in-1 design is a compromise between the two

such a magnet design has never been done before

# **LHC Layout**

## **2 Ring Layout:**

CMS  
TOTEM



- 2-in-1 magnet design
  - more than 10GJ stored electromagnetic energy
- > 4000Kg TnT → powering in 8 independent octants

P. Lebrun, F. Bordry and K.H. Mess

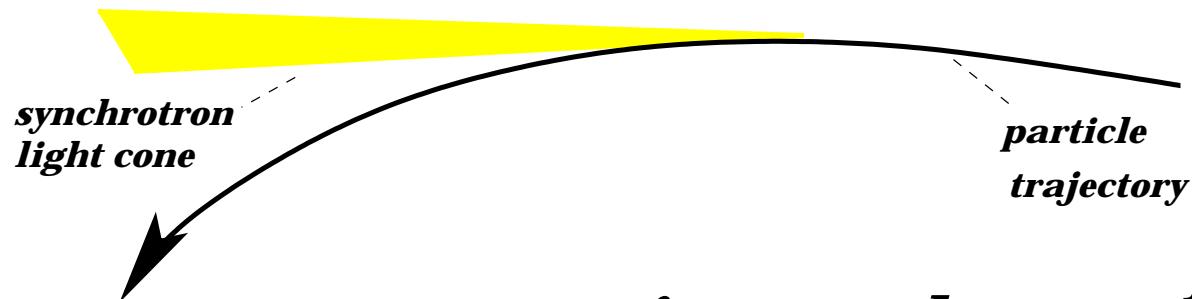
# Synchrotron Radiation

- **accelerated charge emits electro-magnetic waves**

→ **radio signal**

→ **X-rays**

- **radiation fan in bending plane bending plane**



$$\text{opening angle} \propto \frac{1}{\gamma}$$

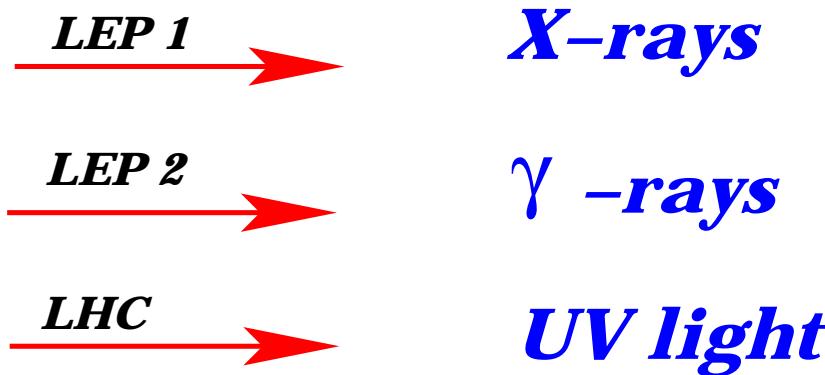
- $\mathbf{P} \propto \frac{\gamma^4}{\rho^2}$

(LEP:  $\gamma = 200000$ )  
(LHC:  $\gamma = 7000$ )

- $\langle E_\gamma \rangle \propto \frac{\gamma^3}{\rho}$

# Examples

	$E$ [GeV]	$\rho$ [km]	$N$ [ $10^{12}$ ] J	$U$ [MeV]	$P$ [MW]	$u_c$ [keV]
<b>LEP 1</b>	<b>45</b>	<b>3.1</b>	<b>4.7</b>	<b>260</b>	<b>1.2</b>	<b>90</b>
<b>LEP 2</b>	<b>100</b>	<b>3.1</b>	<b>4.7</b>	<b>2900</b>	<b>30</b>	<b>715</b>
<b>LEP2+</b>	<b>110</b>	<b>3.1</b>	<b>312</b>	<b>3900</b>	<b>44</b>	<b>952</b>
<b>LHC</b> p / p	<b>7000</b>	<b>3.1</b>	<b>312</b>	<b>0.007</b>	<b>0.005</b>	<b>0.04</b>

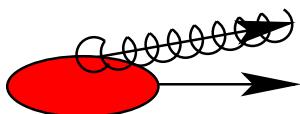


first super conducting machine with synchrotron radiation

- protect the cold bore of the superconducting magnets from synchrotron radiation!
- beam screen in the LHC

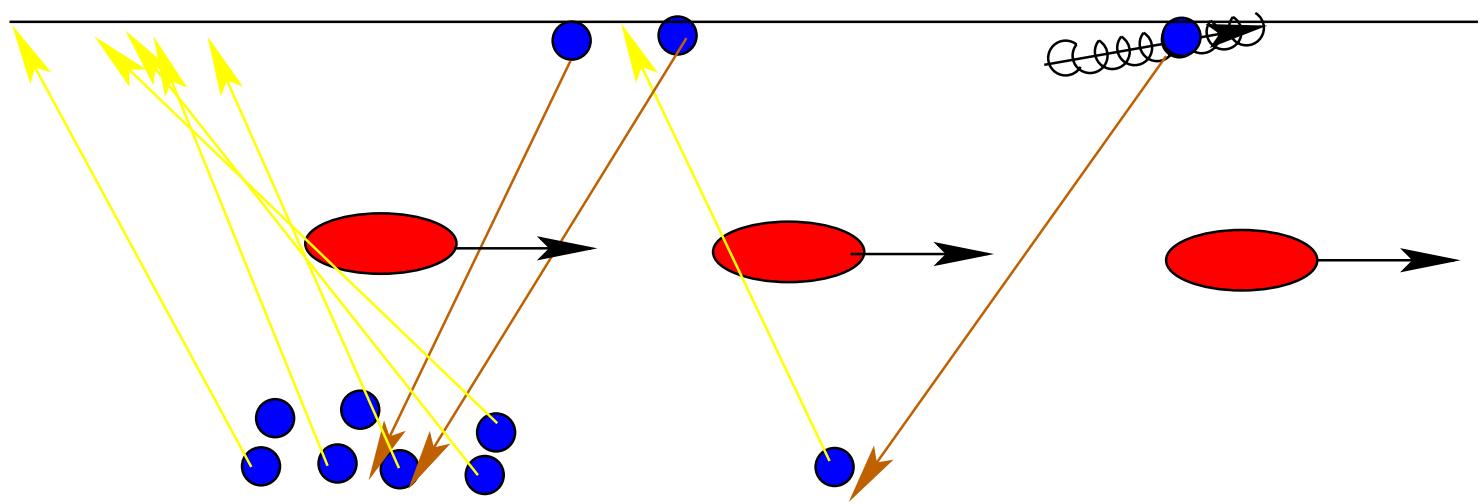
# Electron Cloud Instability

- Synchrotron light removes electrons from chamber



→ synchrotron light hits vacuum chamber next to the bunch

- Electrons are accelerated by the next bunch
- Electrons hit vacuum chamber and generate more  $e^-$
- Electrons are accelerated by the next bunch
- Electron cloud



→ ***instability and heat loss!***

# LHC – Hardware

## ● 7 TeV $p\text{-}p$ Collider:

→ *discovery potential (Higgs)*

## ● LEP Tunnel: $(2\pi R = 27 \text{ km})$

→  $B = 8.4 \text{ T}$

## ● Superconducting Magnets:

■  $f(T, B, I) \quad I = 11700 \text{ A} \quad T = 1.9 \text{ K}$

→ *magnet quench!*

■ **double bore;  $L = 15 \text{ m}$**

■ **field quality** (L. Rossi)

## ● Cooling:

■ **superfluid He at 1.9K** (P. Lebrun)

*30 kTons coldmass; 90 Tons He*

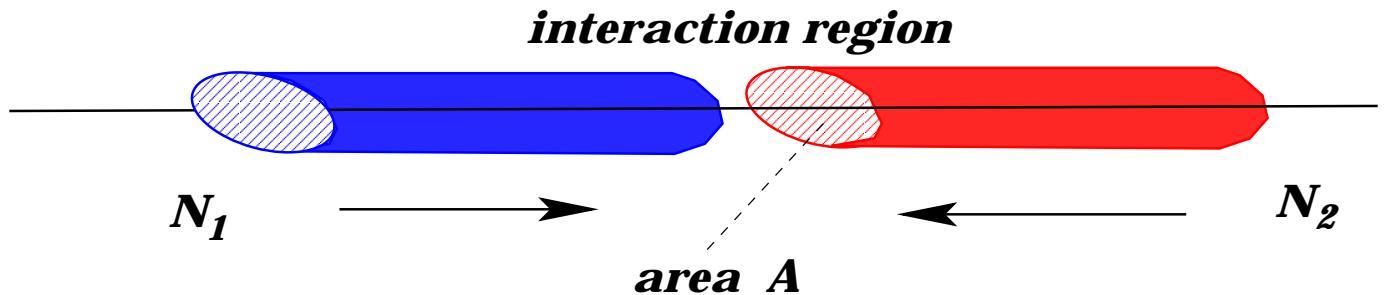
■ **beam screen at 10K to 20K**

## ● $p\text{-}p$ and Ion Beams: ( $\text{Pb}; \text{Ca}$ )

# Luminosity



$$N_{ev}/sec = \sigma \cdot L \quad [L] = cm^{-2} \cdot s^{-1}$$



$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A}$$

- **high bunch current**  
**beam-beam; collective effects**
- **many bunches**  
**total current (RF); collective effects**
- **small beam size**  
**coupling; dispersion; hardware**

# Beam-Beam Parameter

the electro-magnetic fields of beam2 act on the particles of beam1

→ transform into moving frame of test particle  
and calculate Lorentz force

$$\vec{F} = q \cdot (\vec{E} + v \times \vec{B}) = q \cdot (E_r + \beta c B_\phi) \cdot \vec{r}$$

Gauss theorem and Ampere's law:

→

$$2\pi \cdot r \cdot E_r = \frac{1}{\epsilon_0} \cdot \int_0^r 2\pi r' \cdot \rho(r') dr'$$

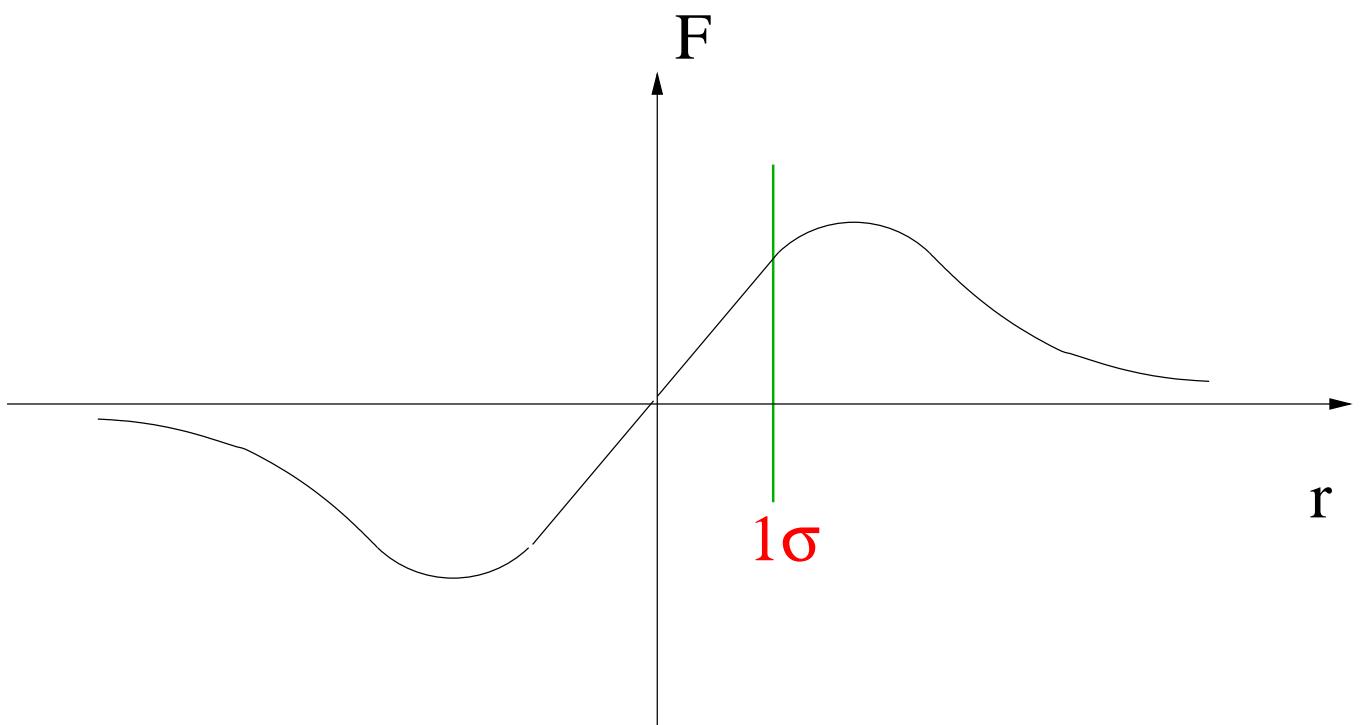
$$2\pi \cdot r \cdot B_\phi = \mu_0 \int_0^r 2\pi r' \cdot \beta c \cdot \rho(r') dr'$$

Gaussian distribution for round beam:

$$F(r) = \frac{N_2 q_1 q_2}{2\pi\epsilon_0} \cdot \frac{(1 + \beta^2)}{r} \cdot \left[ 1 - \exp\left(-\frac{r^2}{2\sigma^2}\right) \right]$$

→ force acts in the radial direction

# Beam-Beam Parameter



■ small amplitudes (with  $v \approx c$ ):

$$\frac{F}{v \cdot p} \approx \frac{N_2 \cdot r_p}{\gamma} \cdot \frac{r}{\sigma^2} \quad \xrightarrow{\text{quadrupole}}$$

with:  $r_p = \frac{e^2}{4 \cdot \pi \cdot \epsilon_0} \cdot \frac{1}{m_p \cdot c^2}$

■ strong non-linear field:

tune depends on oscillation amplitude

strong non-linear field

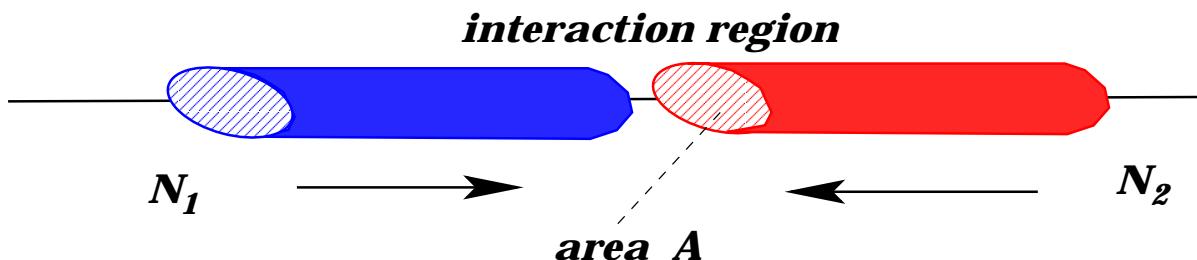
→ bunch intensity limited by non-linear resonances

# Number of Bunches

- bunch intensity:

$$N < 1.7 \cdot 10^{11} \text{ protons per bunch}$$

- luminosity



$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A} \quad \underline{A = 4\pi \cdot \beta \cdot \varepsilon}$$

→ **maximize the number of bunches**

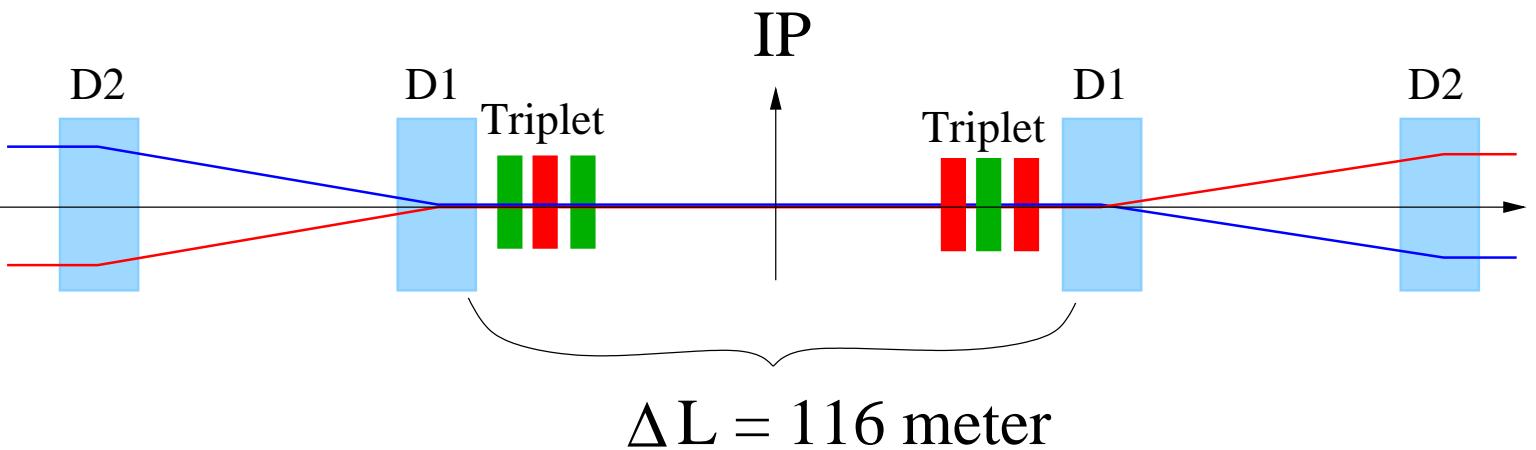
- avoid unwanted head on collisions!

- watch out for total beam power!

# **Long Range Beam-Beam**

---

## **IR layout:**



→ additional head on collisions for a bunch separation of less than 232 meter

## **maximum number of bunches:**

$$C = 26.7 \text{ km} \quad \rightarrow \quad n_b < 115$$

→  $L_{\max} < 4.9 \cdot 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$

→ too small!

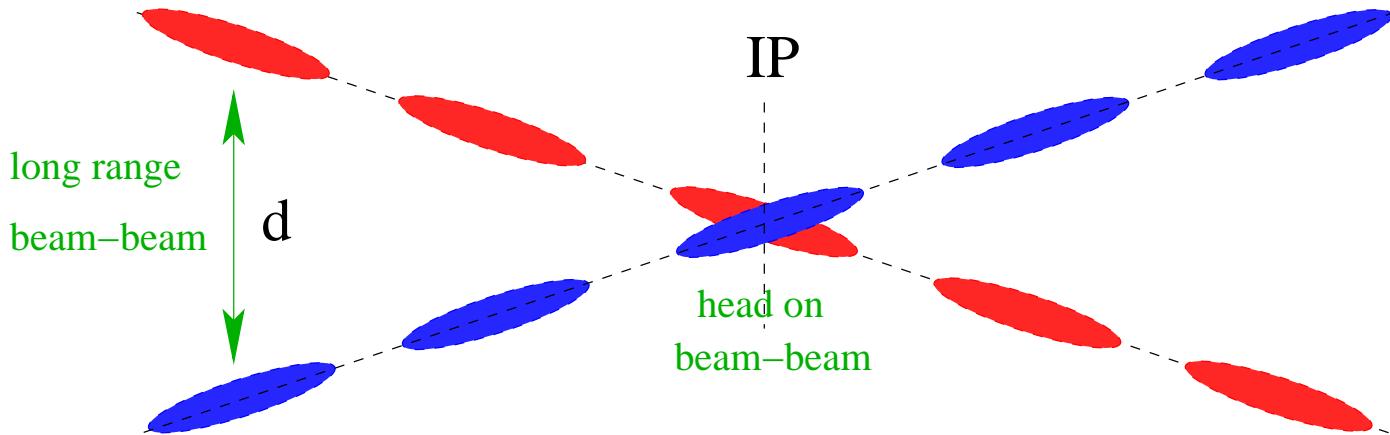
## **crossing angle:**

→ separate the two beams left and right from the IP with additional orbit bumps

# **Long Range Beam-Beam**

---

■ crossing angle:



■ pro's:

- avoids additional head-on collisions

■ con's:

- generates additional tune shift
- requires larger triplet magnet aperture
- increases interacting cross section
- breaks the bunch symmetry
- breaks symmetry between x,y planes
- odd order resonances are excited
- couples longitudinal and transverse motion

$$n \cdot Q_x + m \cdot Q_y + p \cdot Q_s = r$$

# LHC – Beam Parameter

## ● Beam-Beam Interaction:

$$\Delta Q \propto \frac{N_b}{\varepsilon} < 5 \cdot 10^{-3}$$

$N_p = 10^{11}$

**magnet quality + aperture** →  $\varepsilon$

## ● number of bunches:

**long range beam-beam+ beam power**

$$\rightarrow n_b = 2808$$

$$\rightarrow I_{beam} = 0.5 \text{ A}$$

### **Beam Power**

$$E = 300 \text{ MJ}$$

$$\hat{=} 120 \text{ kg TnT}$$

### **Synchrotron Radiation**

$$P = 0.5 \text{ W/m}$$

(R. Schmidt)

→ radiation dose in detector and insertion regions!

# Other Superconducting Machines

- **Tevatron:**  $p^+ / p^-$   $E = 1 \text{ TeV}$  **1985**  
*Chicago, USA*

$$n_b = 6 \leftrightarrow 36; I_{beam} = 2 \text{ mA}; \text{range: } 6$$

beam losses are not critical at injection

- **HERA:**  $e / p^+$   $E = 0.9 \text{ TeV}$  **1991**  
*Hamburg, Germany*

$$n_b = 180; I_{beam} = 0.5 \text{ mA}; \text{range: } 20$$

magnet quench limit = 20% of total beam

- **RHIC:**  $Au/Au; p^+ / p^+$   
*New York, USA*  $E = 0.25 \text{ TeV}$  **1999**

$$n_b = 57 \leftrightarrow 114; I_{beam} = 13 \mu A; \text{range: } 7$$

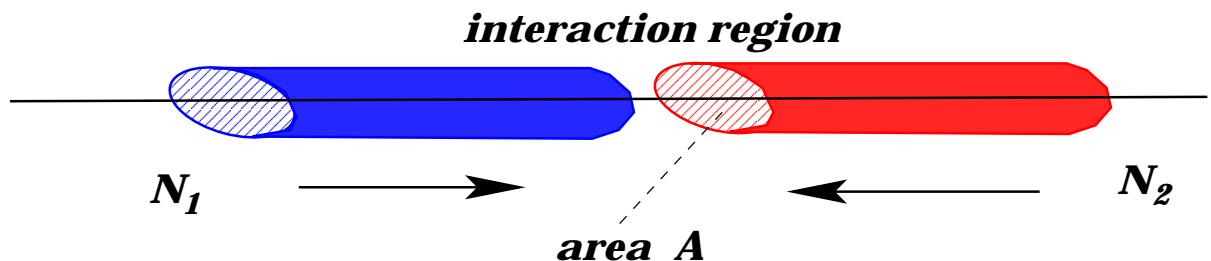
beam losses are not critical at injection

- **LHC:**  $n_b = 2808$   
 $B = 8.4 \text{ T}; T = 1.9 \text{ K}; \text{range} = 16; I_{beam} = 0.5 \text{ A}$

→ beam losses must be smaller than  $2 \cdot 10^{-6} \cdot N_{\text{tot}}$

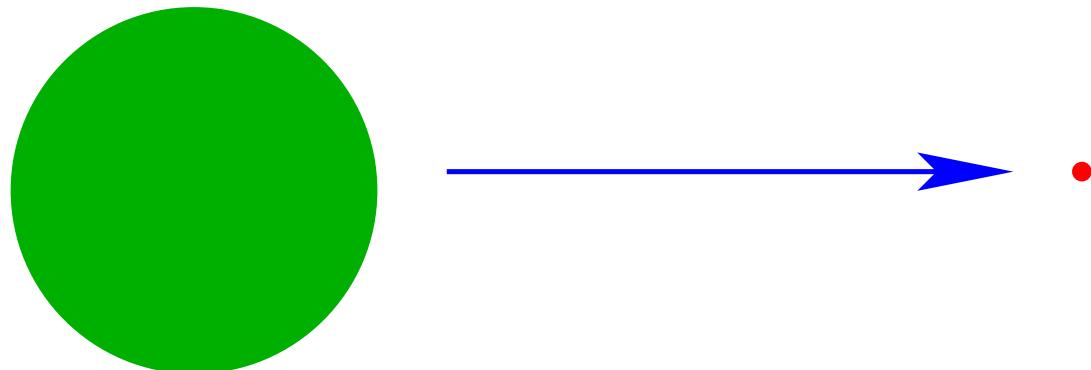
# Beam Size

## Luminosity:



$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A} \quad \underline{A = \pi \cdot \beta \cdot \varepsilon}$$

## LHC:



$\langle \beta \rangle_{arc} = 80 \text{ meter}$

$\beta_{IP} = 0.5 \text{ meter}$

## Limit:



***magnet strength***



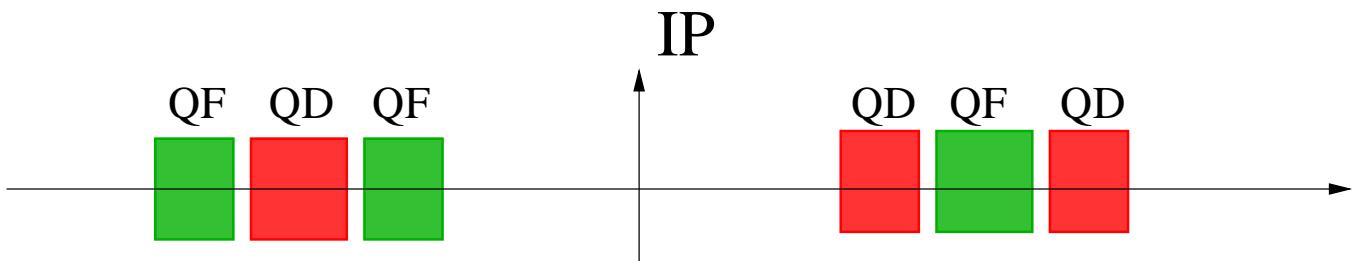
***aperture***

$$\sigma = \sqrt{\varepsilon \cdot \beta}$$

$$\sigma' = \sqrt{\frac{\varepsilon}{\beta}}$$

# Low $\beta$ Insertion

■ triplet assembly:



■ limit: → quadrupole aperture

→ large aperture triplet quadrupoles  
(strength!)

→ small distance from the IP

■ LHC parameters: →  $L^* = 23 \text{ m}$

$\beta^* = 0.5 \text{ m}$   $\beta_{\max} = 4.7 \text{ km}$

→  $\sigma^* = 16 \mu \text{m}$

■ bunch luminosity:

$$N = 1.1 \cdot 10^{11} \leftrightarrow 1.5 \cdot 10^{11} \quad A = 4\pi \cdot \sigma^2$$

→  $L_{\text{bunch}} = 4.25 \cdot 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$

→ **ca 20 events per crossing!**

# Average Luminosity

$$L \propto n_b \cdot \frac{I_{e^+} \cdot I_{e^-}}{\sigma_x \cdot \sigma_y}$$

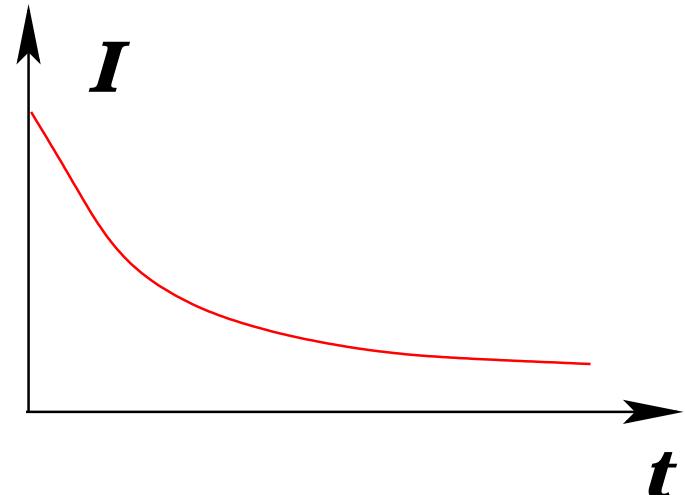
## ■ **beam size changes during operation**

collective effects and instabilities, electron–cloud  
and non–linear resonances

→ luminosity decrease

## ■ **Beam Lifetime:**

$$I(t) = I_0 \cdot e^{-t/\tau}$$



## ■ **Residual gas pressure**

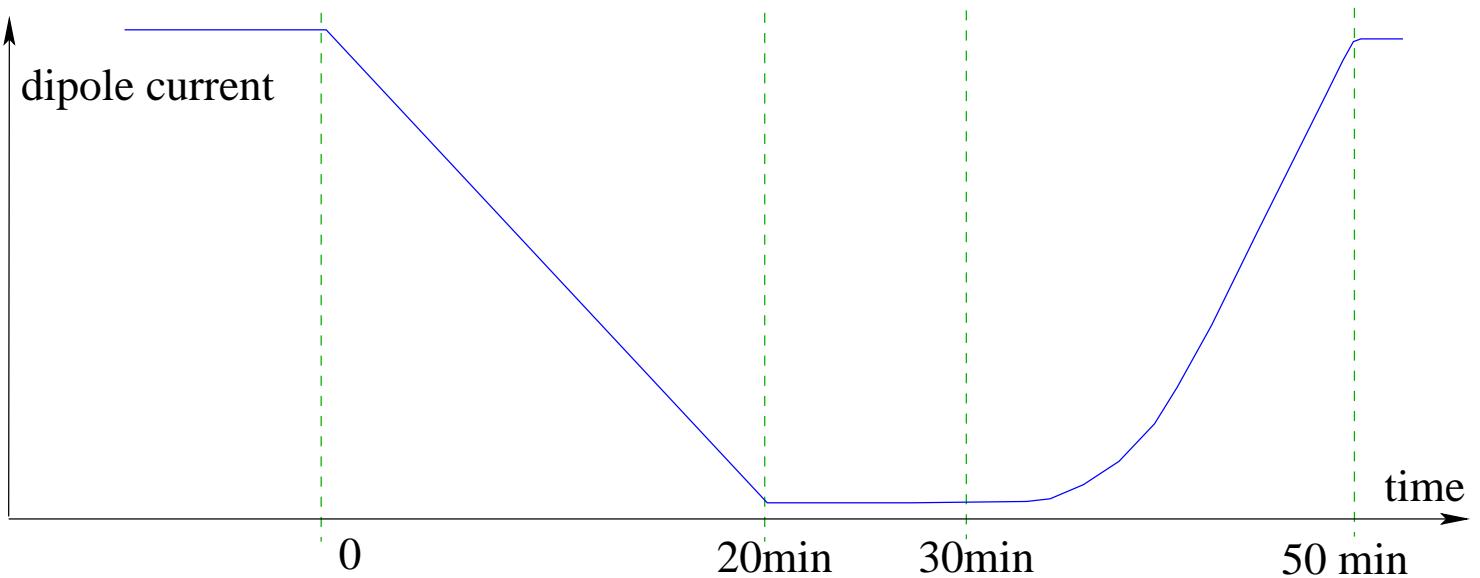
$$P < 10^{-8} \text{ Torr}$$

[atmosphere:  $P = 750 \text{ Torr}$ ]

## ■ **Luminosity Lifetime:** ca 10 hours

# Main Dipole Cycle

## magnet cycle:



max. ramp speed limited by magnet inductance

→ Total: ca 60 minutes + physics time

beam abort due to failure or beam losses

- each unscheduled abort implies at least 1 hour delay
- avoid beam losses and magnet quenches!

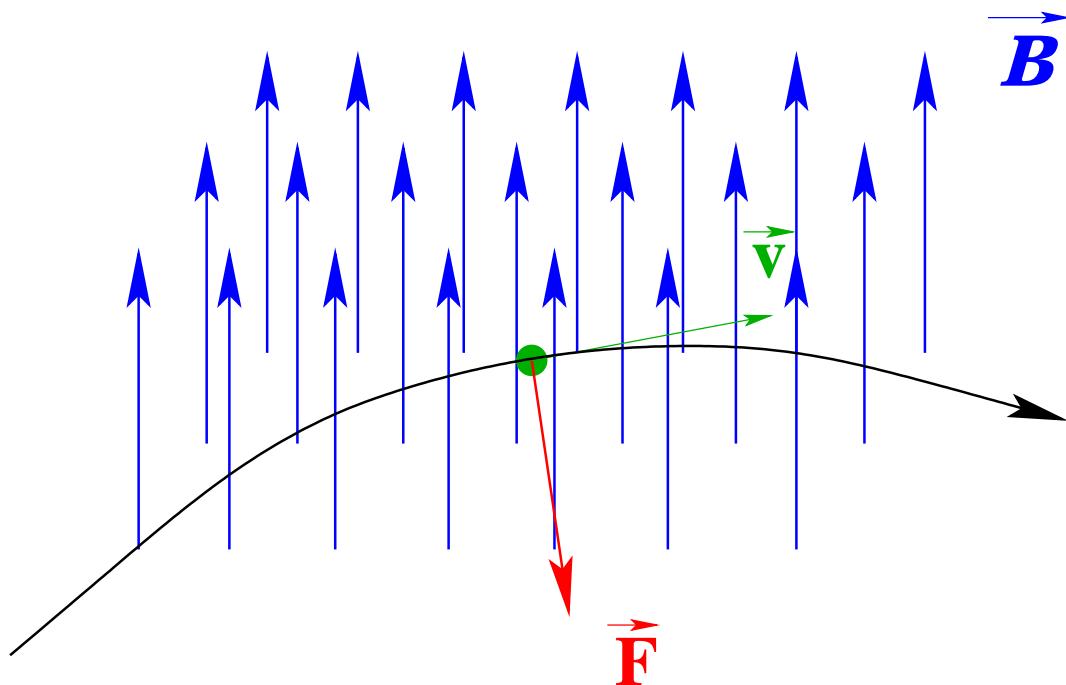
experience from HERA (after 10 years)

- on average 6 attempts per physics fill
- on average 6 hours between two physics fills  
(assume 10 hours for the LHC)

## ● Lorentz Force:

$$\frac{d\vec{p}}{dt} = Q * (\vec{E} + \vec{v} \times \vec{B})$$

## ■ **magnetic fields:**



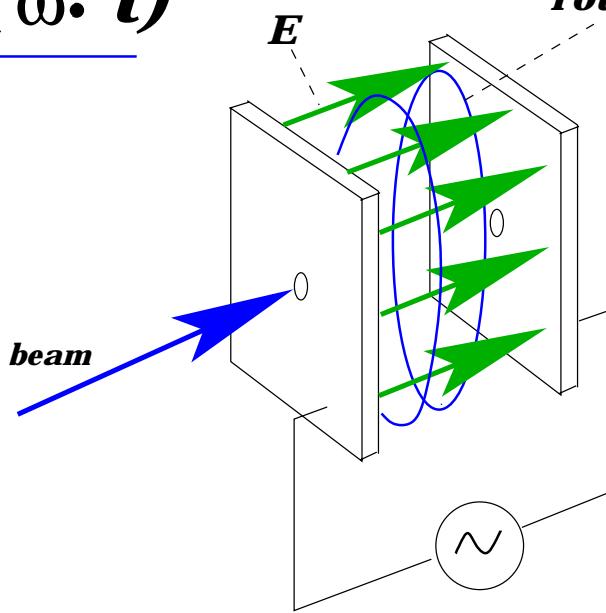
→ **Trajectory curvature due to  $B$  field!**

→ **Energy gain only due to  $E$  field!**

# Time Varying Fields

●  $E = E \cdot \sin(\omega \cdot t)$

$$\text{rot } \mathbf{B} = \frac{\mu \epsilon}{c} \frac{\partial \mathbf{E}}{\partial t}$$



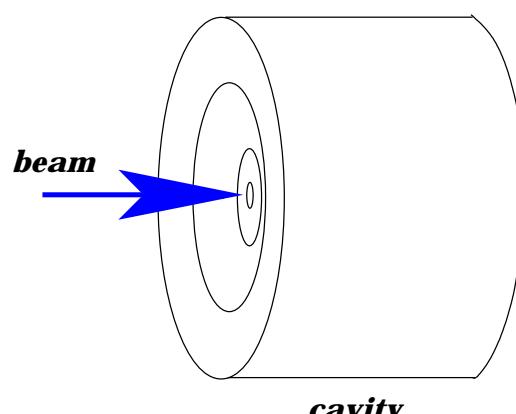
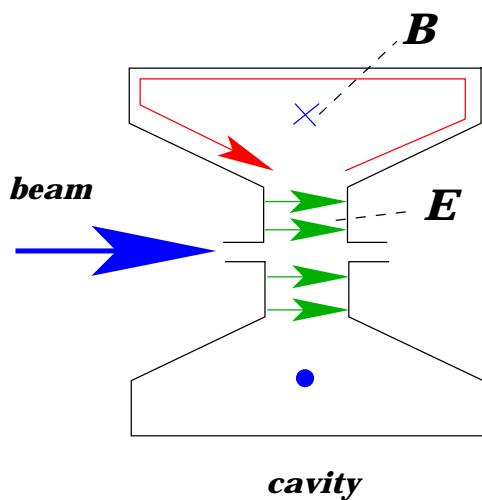
→ **bunched beam**

● Cavity:

**vacuum requirements + resonator**



**close gap of capacitor**



**f; Q; R**



**superconducting cavities**

# Optic Functions

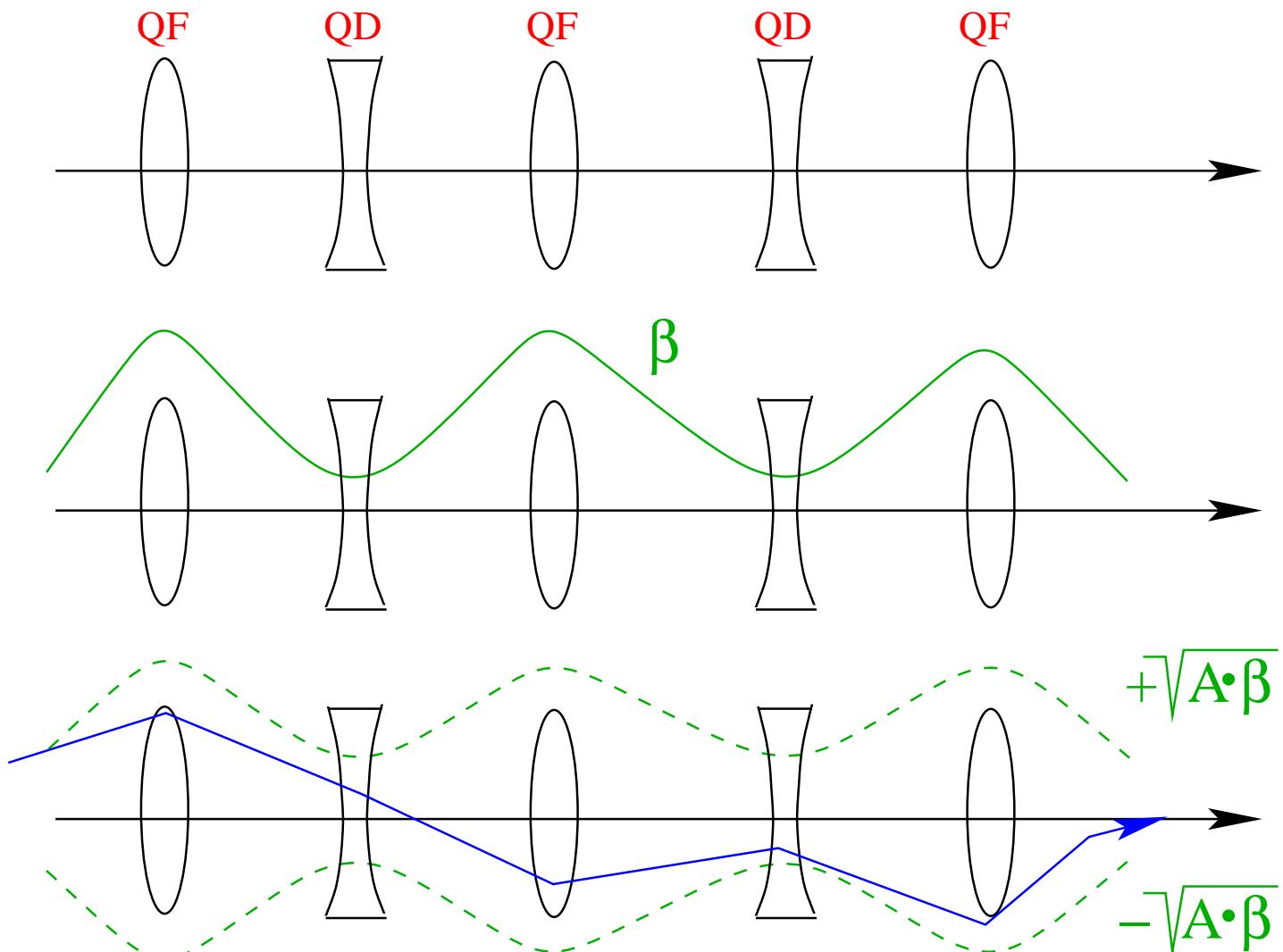
## transverse oscillations:

$$x = \sqrt{A \cdot \beta(s)} \cdot \sin(\phi(s) + \phi_0)$$

$$\beta(s) = \beta(s + L); \quad \phi(s) = \int \frac{1}{\beta} ds$$

→  $x = \sqrt{\frac{A}{\beta(s)}} \cdot \cos(\phi(s) + \phi_0)$

## FODO structure:

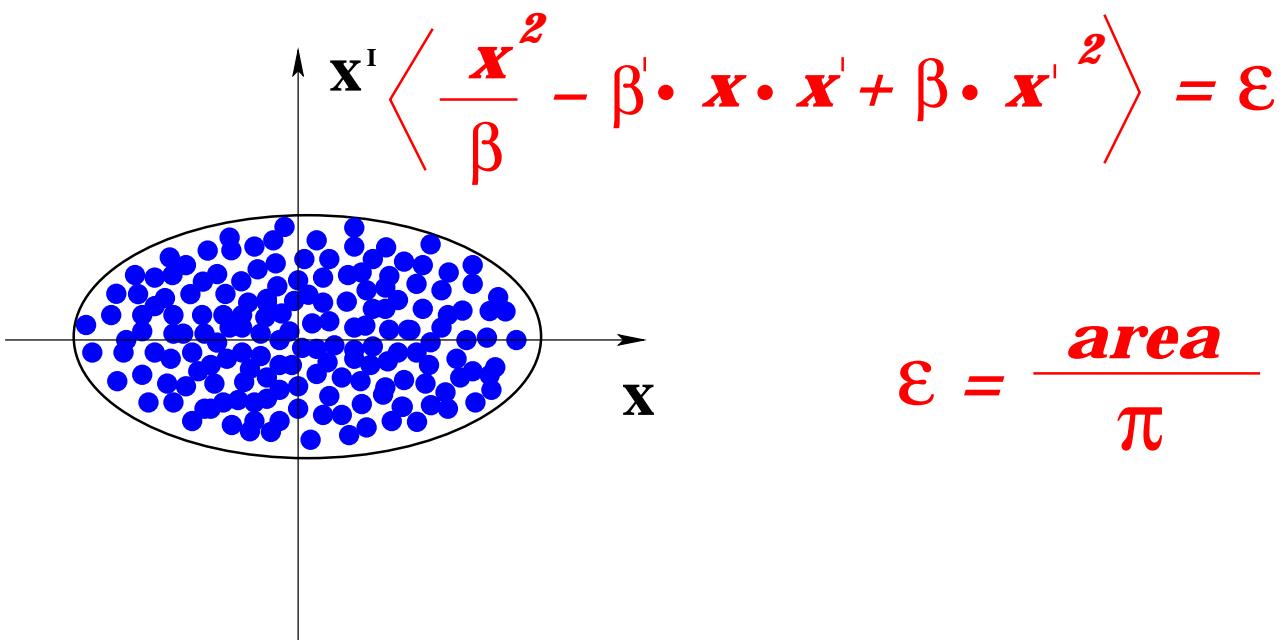


●  $\beta$  and  $\phi$  are determined by the arrangement of the magnets in the tunnel

●  $Q$ : # of oscillations per turn

● individual trajectories are determined by  $A$  and  $\phi_0$

● beam ensemble:



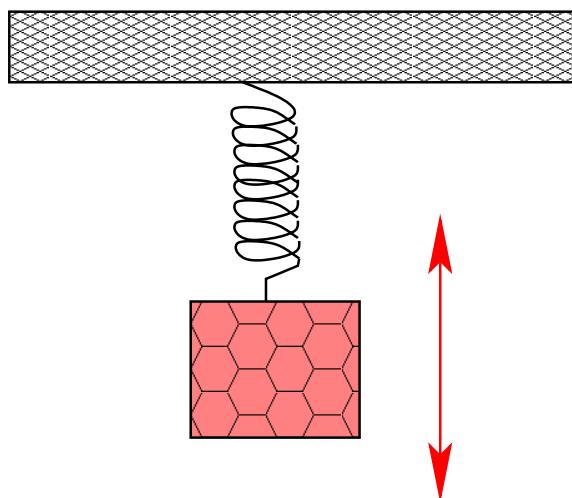
→  $\varepsilon$  describes the beam quality

→  $\sigma = \sqrt{\varepsilon \cdot \beta}$  describes the beam size

# **Strong Focusing**

---

## **oscillator (spring):**



$$\mathbf{F} = -\mathbf{g} \quad y$$



$$\Omega^2 \propto g$$

$$A \propto \frac{1}{g}$$

for a fixed energy

## **strong focusing:**



**small amplitudes**



**small vacuum chamber**



**efficient magnets**

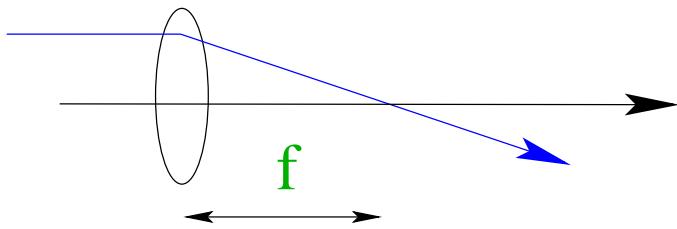


**high oscillation frequency**

# Quadrupole Focusing

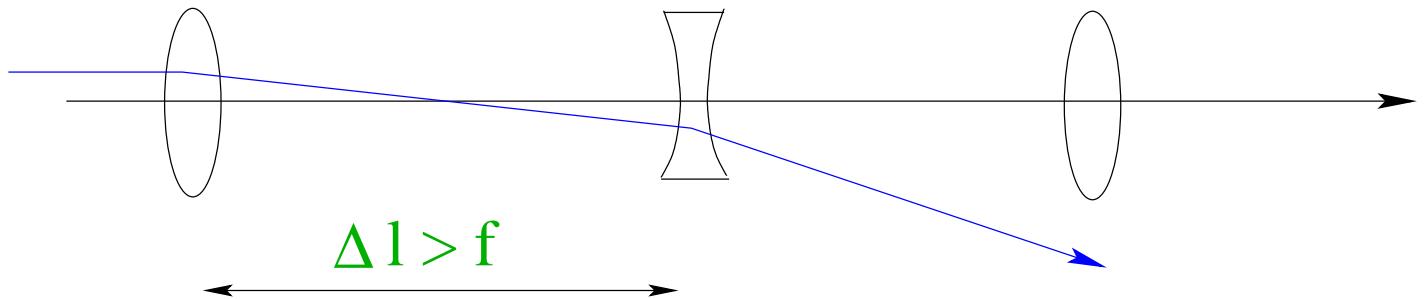
■ effective quadrupole strength:  $k = 0.3 \cdot \frac{g[\text{T/m}]}{p[\text{GeV}]}$

■ focal length:



$$f = \frac{1}{1 \cdot k}$$

■ trajectory stability:



stability requires:

$$\Delta l < f$$



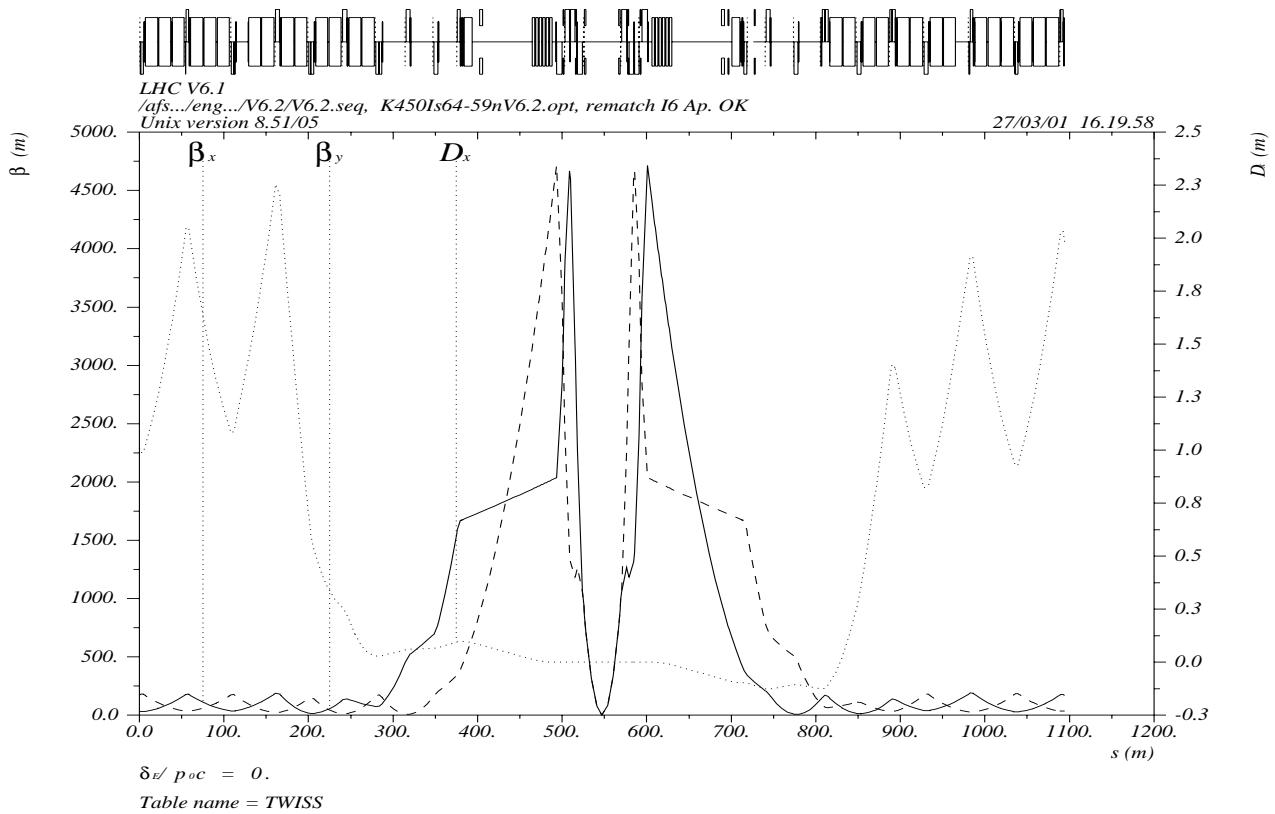
strong focusing requires many quadrupole magnets with short spacing



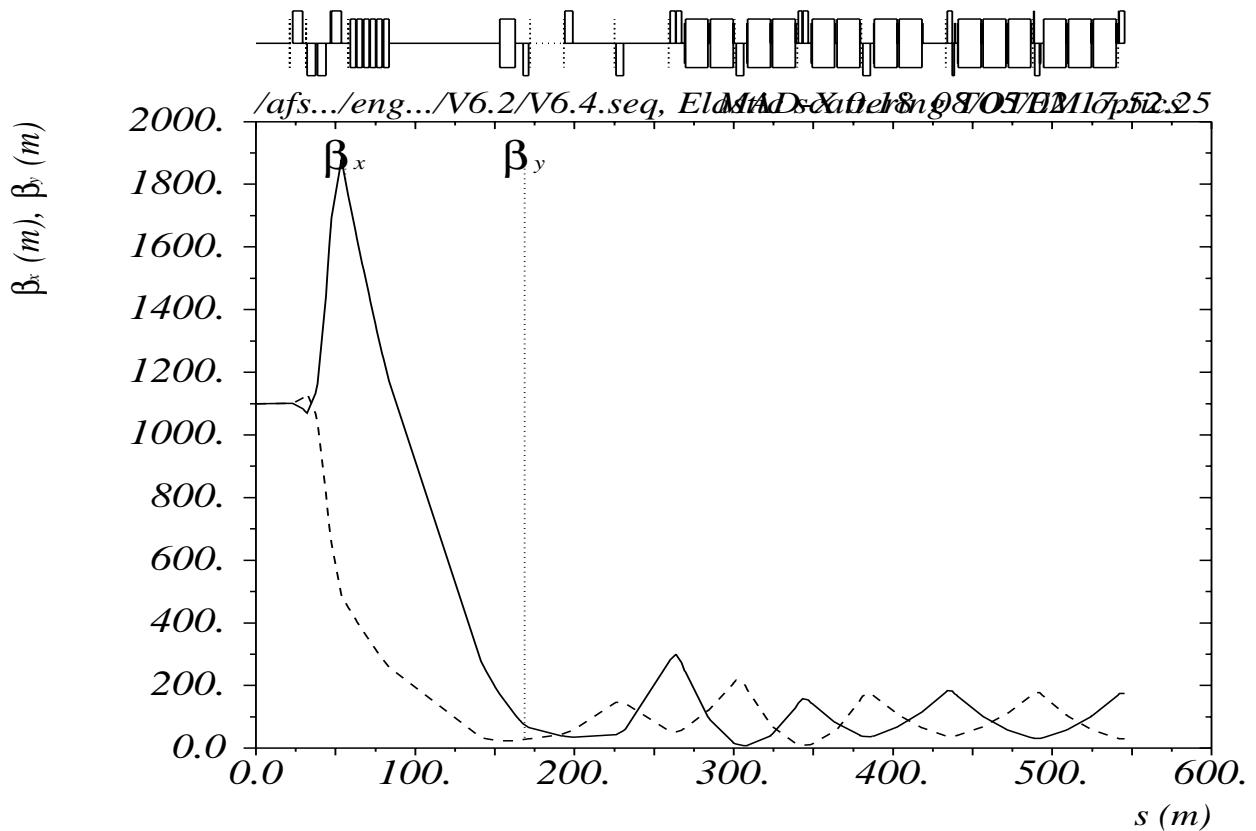
reduction of

$$\oint \vec{B} \cdot d\vec{l}$$

# **Low $\beta$ Optics**

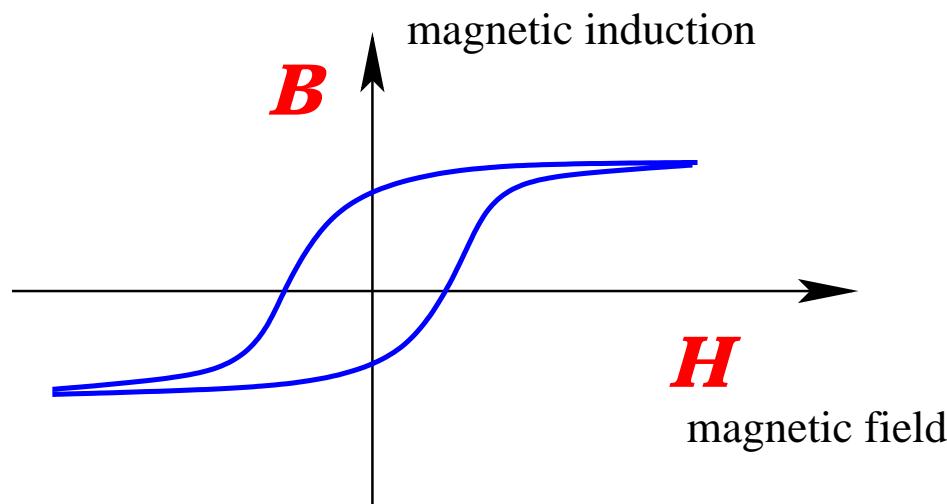


# **Large $\beta$ Optics**



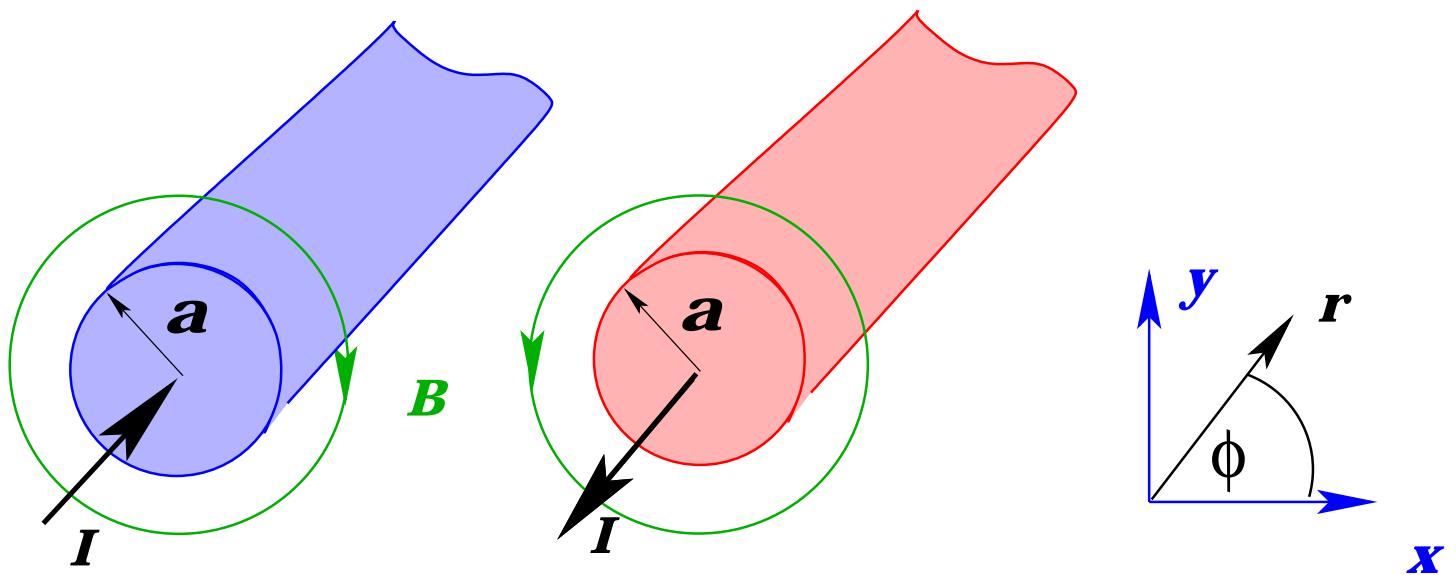
# Bending Magnet

saturation



- amplification process does not work for fields above 2 Tesla!
- field quality control via pole face shape does not work for the LHC magnets!
- use the coil design to determine the field quality
  - cosine field distribution in the magnet cross section generates a uniform vertical dipole field
  - coil precision and stability is a major concern for superconducting magnets!

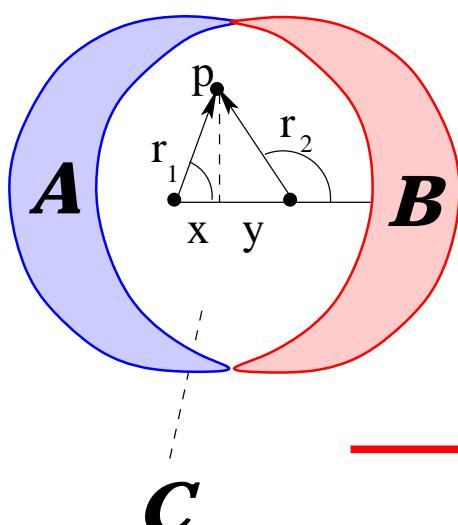
# Superconducting Magnets



■  $r > a$ :  $\vec{B} = \frac{\mu_0 \cdot I}{2\pi r} \cdot [-\sin(\phi), \cos(\phi), 0]$

■  $r < a$ :  $\vec{B} = \frac{\mu_0 \cdot j \cdot r}{2} \cdot [-\sin(\phi), \cos(\phi), 0]$

■ Overlap the two cylinders:



$$r_1 \cdot \cos(\phi_1) - r_2 \cdot \cos(\phi_2) = d$$

$$r_1 \cdot \sin(\phi_1) - r_2 \cdot \sin(\phi_2) = 0$$

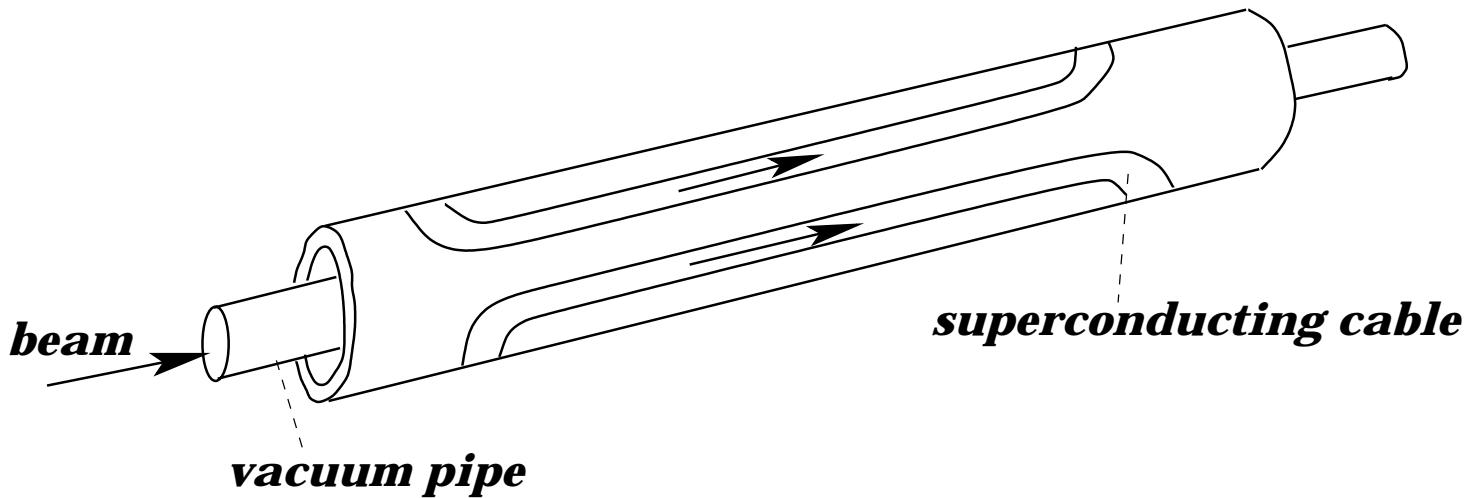
$$B_y = \text{const.}$$

$$B_x = 0$$

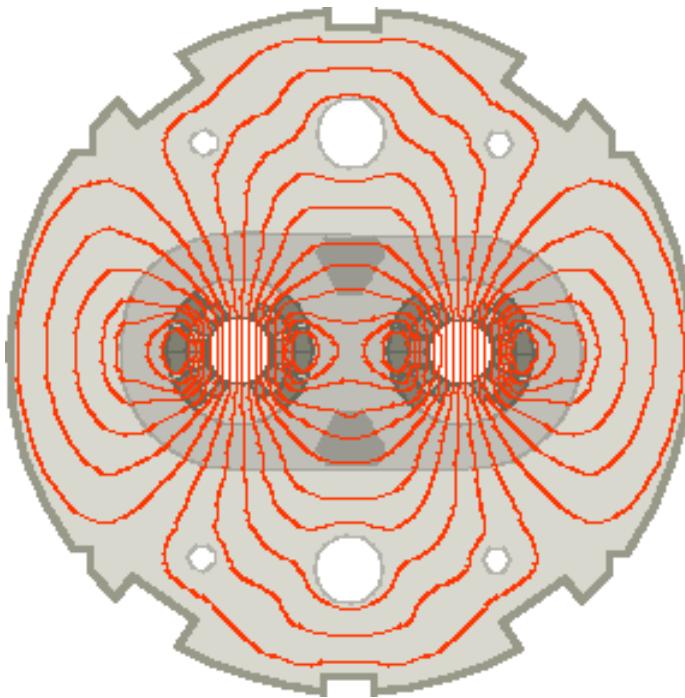
$$j = 0$$

in C

## **Coil Winding:**



## **Magnet Cross Section:**



iron only used to  
guide the magnetic  
return flux

## **Persistent Currents:**

$$\frac{\partial \mathbf{B}}{\partial t} = -\mathbf{c} \cdot \text{rot} \mathbf{E}$$

