Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

DAΦNE: the circular *Crab-Waist* Collider

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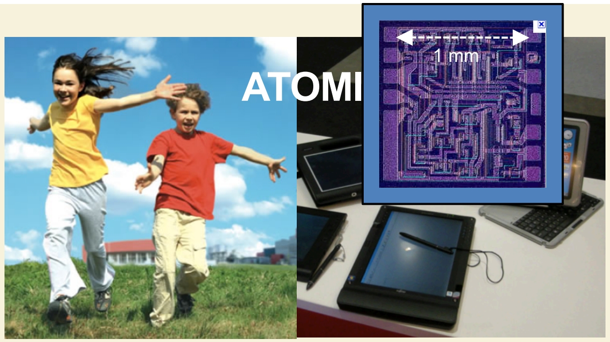
LNF, Frascati, April 2024

Particle Accelerator Physics

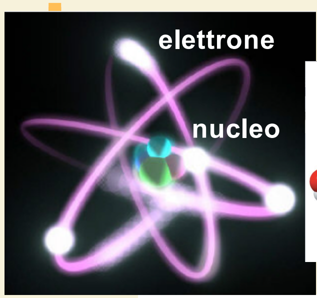
Particle Accelerators

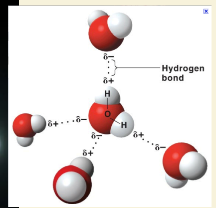


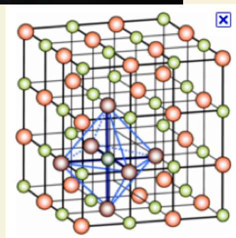
MATERIA animata ed inerte

Strumenti per:
Diagnostica Medica
Terapia Oncologica

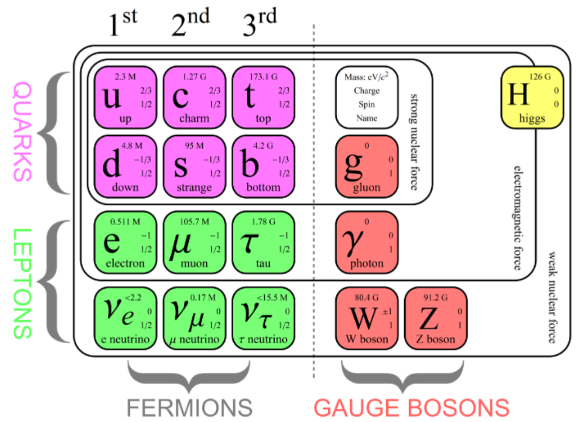
Produzione di componenti avanzate per l'elettronica

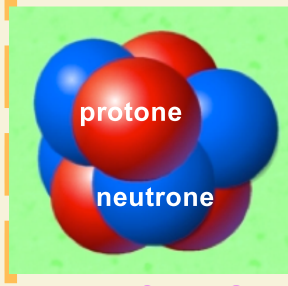






ATOMI variamente organizzati





NUCLEO

NUCLEONE

Presently in the world there are ***30000*** operating particle accelerators

Proprietà atomiche e molecolari
Studio delle strutture cristalline

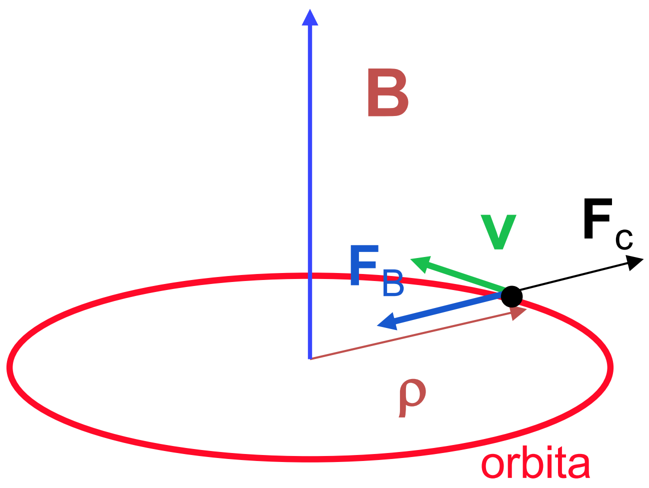
Struttura del nucleo
Studio delle particelle elementari

Topics

- *Transverse beam dynamics*
- *Longitudinal beam dynamics*

Particle motion in a uniform magnetic field

A uniform magnetic field **B** can be used to maintain a particle on a circular orbit



- charge q

$$\boldsymbol{F}_c = \frac{m\boldsymbol{v}^2}{\rho}$$ centrifugal force

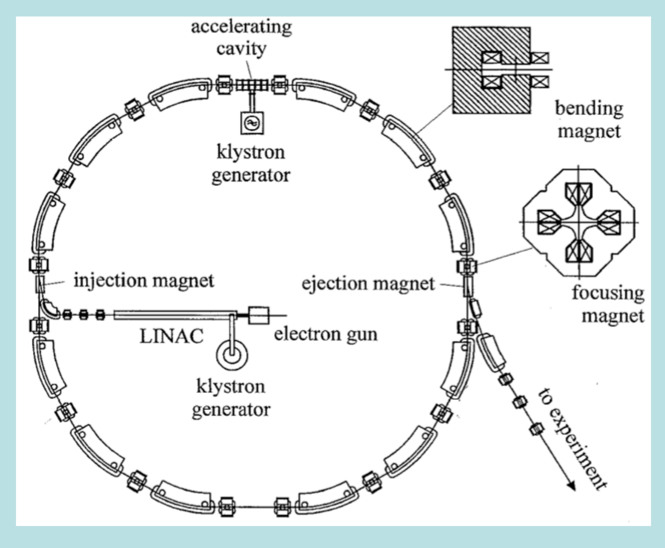
$$\boldsymbol{F}_B = q\boldsymbol{v}\times\boldsymbol{B}$$ Lorentz force

$$qvB = \frac{mv^2}{\rho}$$ equilibrium condition

$$\rho = \frac{mv}{qB} = \frac{p}{qB}$$ bending radius

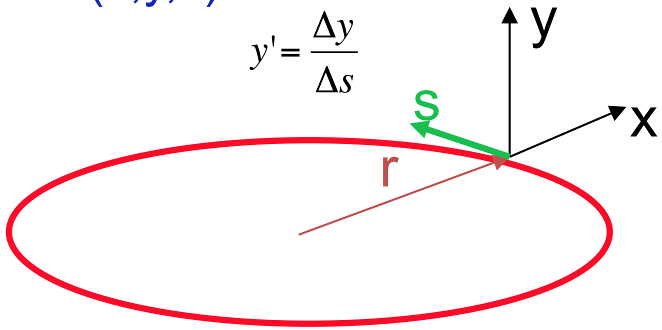
$$\rho[m]B[T] = \frac{p}{q}$$ magnetic rigidity

Transverse Dynamics of a Particle in a Storage Ring



Reference System (x,y,s)

$$x' = \frac{\Delta x}{\Delta s} \qquad y' = \frac{\Delta y}{\Delta s}$$



the nominal orbit corresponds to the design energy E_0

Main concepts:

nominal orbit

revolution period ***T***

revolution frequency f_r

$$T = \frac{2\pi r}{v} \qquad f_r = \frac{1}{T} = \frac{v}{2\pi r}$$

A particle injected on the nominal orbit with initial conditions:

$x_0 = 0 \quad x'_0 = 0 \quad y_0 = 0 \quad y'_0 = 0 \quad E = E_0$

stays on the nominal orbit ideal particle

As soon as one of the parameters: x_0 , x'_0, y_0 , y'_0 , E is different from zero the particle starts to oscillate

Linear Beam Optics

Assumptions

- Cartesian coordinate system whose origin moves along the beam orbit → $\boldsymbol{K} \equiv (x,z,s)$
- Particles move mainly along *s* direction → $\boldsymbol{v} \equiv (0,0,v_s)$
- Magnetic field only has transverse components → $\boldsymbol{B} \equiv (B_x, B_z, 0)$
- Magnetic field is constant with time and is symmetric w.r.t. the orbit plane
- Equilibrium condition between Lorentz and centrifugal forces:

$$\frac{1}{R(x,z,s)} = \frac{e}{p} B(x,z,s)$$

Magnetic field can be expanded around the nominal trajectory since transverse beam dimension are small w.r.t R and multiplying by e/p

$$\frac{e}{p} B_z(x) = \frac{e}{p} B_{z0} + \frac{e}{p}\frac{dB_z}{dx} x + \frac{1}{2!}\frac{e}{p}\frac{d^2 B_z}{dx^2} x^2 + \frac{1}{3!}\frac{e}{p}\frac{d^3 B_z}{dx^3} x^3 + \cdots$$

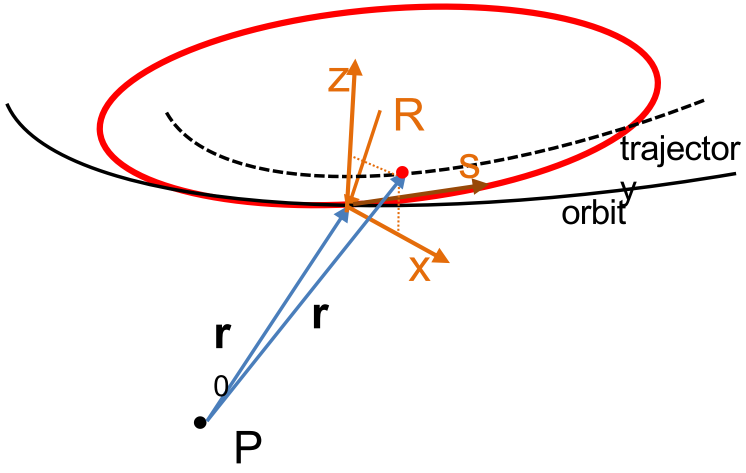
$$= \frac{1}{R} + kx + \frac{1}{2!} m x^2 + \frac{1}{3!} o x^3 + \cdots$$

Linear Beam Optics as far as the first two terms are taken into account

Linear Beam Optics

Assumptions:

Cartesian coordinate system whose origin moves along the beam orbit → $\boldsymbol{K} \equiv (x,z,s)$
Particles move mainly along *s* direction → $\boldsymbol{v} \equiv (0,0,v_s)$
Magnetic field only has transverse components → $\boldsymbol{B} \equiv (B_x, B_z, 0)$
Magnetic field is constant with time and is symmetric w.r.t. orbit plane i.e. $\boldsymbol{B}(z) = \boldsymbol{B}(-z)$
Equilibrium condition between Lorentz and centrifugal forces:



Rotating co-moving reference system named also Frenet-Serret reference system

K rotates when the beam is steered and the unit vector $\mathbf{x}_0$ and $\mathbf{s}_0$ transform as:

$$\boldsymbol{x}_0 = \boldsymbol{x}_{0a}\cos\varphi + \boldsymbol{s}_{0a}\cos\varphi$$
$$\boldsymbol{s}_0 = -\boldsymbol{x}_{0a}\cos\varphi + \boldsymbol{s}_{0a}\cos\varphi$$

unit vector derivatives

$$\frac{ds_0}{d\varphi} = -x_0 \qquad \frac{dx_0}{d\varphi} = s_0$$
$$ds = R\, d\varphi \qquad \frac{d\varphi}{dt} = \frac{1}{R}\frac{d\varphi}{dt}$$

unit vector time derivatives

$$\dot{x_0} = \frac{dx_0}{d\varphi}\frac{d\varphi}{dt} = \frac{1}{R}\dot{s}\boldsymbol{s}_0$$
$$\dot{s_0} = \frac{ds_0}{d\varphi}\frac{d\varphi}{dt} = -\frac{1}{R}\dot{s}\boldsymbol{x}_0 \qquad \dot{z_0} = 0$$

K origin moves as

$$d\boldsymbol{r}_0 = \boldsymbol{s}_0 ds \qquad \dot{\boldsymbol{r}}_0 = \dot{s}\boldsymbol{s}_0$$

General expression for the particle position on the trajectory

$$\boldsymbol{r} = \boldsymbol{r}_0 + x\boldsymbol{x}_0 + z\boldsymbol{z}_0$$

Linear Beam Optics

Equations of motion

To determine $\dot{\boldsymbol{r}}$ and $\ddot{\boldsymbol{r}}$ is useful to set:

$$\dot{x} = \frac{dx}{ds}\frac{ds}{dt} = x'\dot{s} \qquad \ddot{x} = x''\dot{s}^2 + x'\ddot{s}$$

then

$$\dot{\boldsymbol{r}} = x'\dot{s}\boldsymbol{x}_0 + z'\dot{s}\boldsymbol{z}_0 + \left(1+\frac{x}{R}\right)\dot{s}\boldsymbol{s}_0$$

$$\ddot{\boldsymbol{r}} = \left[x''\dot{s}^2 + x'\ddot{s} - \left(1+\frac{x}{R}\right)\frac{\dot{s}^2}{R}\right]\boldsymbol{x}_0 + (z''\dot{s}^2 + z'\ddot{s})\boldsymbol{z}_0 + \left[\frac{2}{R}x'\dot{s}^2 + \left(1+\frac{x}{R}\right)\ddot{s}\right]\boldsymbol{s}_0$$

The Lorentz force in presence of $\boldsymbol{B} \equiv (B_x, B_z, 0)$ is

$$\ddot{\boldsymbol{r}} = \frac{e}{m}(\dot{\boldsymbol{r}} \times \boldsymbol{B})$$

Computing the vector product, using the expressions for $\dot{\boldsymbol{r}}$ and $\ddot{\boldsymbol{r}}$ and considering only the transverse components

$$x''\dot{s}^2 + x'\ddot{s} - \left(1+\frac{x}{R}\right)\frac{\dot{s}^2}{R} = \frac{e}{m}B_z\left(1+\frac{x}{R}\right)\dot{s}$$

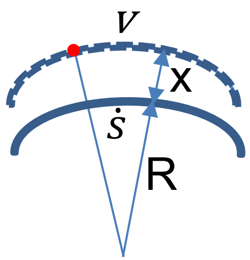
$$z''\dot{s}^2 + z'\ddot{s} = \frac{e}{m}B_x\left(1+\frac{x}{R}\right)\dot{s}$$

Assuming

$\ddot{s} \approx 0 \qquad p = mv$ and writing $v = \left(1+\frac{x}{R}\right)\dot{s}$

$$x'' - \left(1+\frac{x}{R}\right)\frac{1}{R} = -\frac{v}{\dot{s}}\frac{e}{p}B_z\left(1+\frac{x}{R}\right)$$

$$z'' = \frac{v}{\dot{s}}\frac{e}{p}B_z\left(1+\frac{x}{R}\right)$$



Linear Beam Optics

Equations of motion

Writing the beam momentum p as

$p = p_0 + \Delta p$ with Δp of the order of few $/_{00}$ –> $\frac{1}{p} = \frac{1}{p_0}\left(1 - \frac{\Delta p}{p}\right)$

And using the expressions for the dipolar component of the B field

$$\frac{e}{p_0} B_z = \frac{1}{R} - kx \qquad \frac{e}{p_0} B_x = -kz$$

$$x'' - \left(1 + \frac{x}{R}\right)\frac{1}{R} = -\left(1 + \frac{x}{R}\right)^2 \left(\frac{1}{R} - kx\right)\left(1 - \frac{\Delta p}{p}\right)$$

$$z'' = -\left(1 + \frac{x}{R}\right)^2 kx \left(1 - \frac{\Delta p}{p}\right)$$

Since $x \ll R$, $z \ll R$ and $\frac{\Delta p}{p} \ll 1$

All the higher order terms in x, z and $\frac{\Delta p}{p}$ can be ignored

$$x''(s) + \left(\frac{1}{R^2(s)} - k(s)\right) x(s) = \frac{1}{R}\frac{\Delta p}{p}$$

$$z'' = k(s) z(s) = 0$$

Hill's equations describe the linear motion of a particle in a storage ring:

- they are non-linear
- focusing terms have opposite sign in the transverse planes
- In first approximation $\frac{\Delta p}{p}$ affects the horizontal motion only
- they looks like harmonic oscillator
- are the starting point for any calculations in the beam optics field

Linear Beam Optics

General solution of the motion equations

Aiming at computing the motion properties of a beam (many particles)

Betatron oscillations:

Starting from

$$x''(s) + \left(\frac{1}{R^2(s)} - k(s)\right)x(s) = \frac{1}{R}\frac{\Delta p}{p} \qquad (a)$$

assuming 1/R = 0 and $\Delta p/p_0$ =0

$$x''(s) - k(s)x(s) = 0$$

harmonic oscillator having a restoring term depending on s

solution can be obtained by the trial function

$x(s) = Au(s)\cos[\psi(s) + \varphi]$ with *A* and ϕ set by initial conditions

computing x'', substituting in (a) and grouping all the terms in $A\cos[\psi(s) + \varphi]$and $A\sin[\psi(s) + \varphi]$ it gets to an equation which can only be satisfied if :

$$u'' - u\psi'^2 - k(s)u = 0 \qquad \text{(b)}$$

$2u'\psi' + u\psi'' = 0$ -> $2\frac{u'}{u} + \frac{\psi''}{\psi'} = 0$ integrating $\psi(s) = \int_0^s \frac{d\sigma}{u^2(s)}$ ins. in (b)

$$u'' - \frac{1}{u^3} - k(s)u = 0$$

Non-linear differential equation, having no general analytical solution, which can be solved numerically only

Linear Beam Optics

Betatron oscillations:

Replacing

$$A = \sqrt{\varepsilon} \qquad \text{and} \qquad \beta(s) = u^2(s)$$

$$x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cos[\psi(s) + \varphi]$$

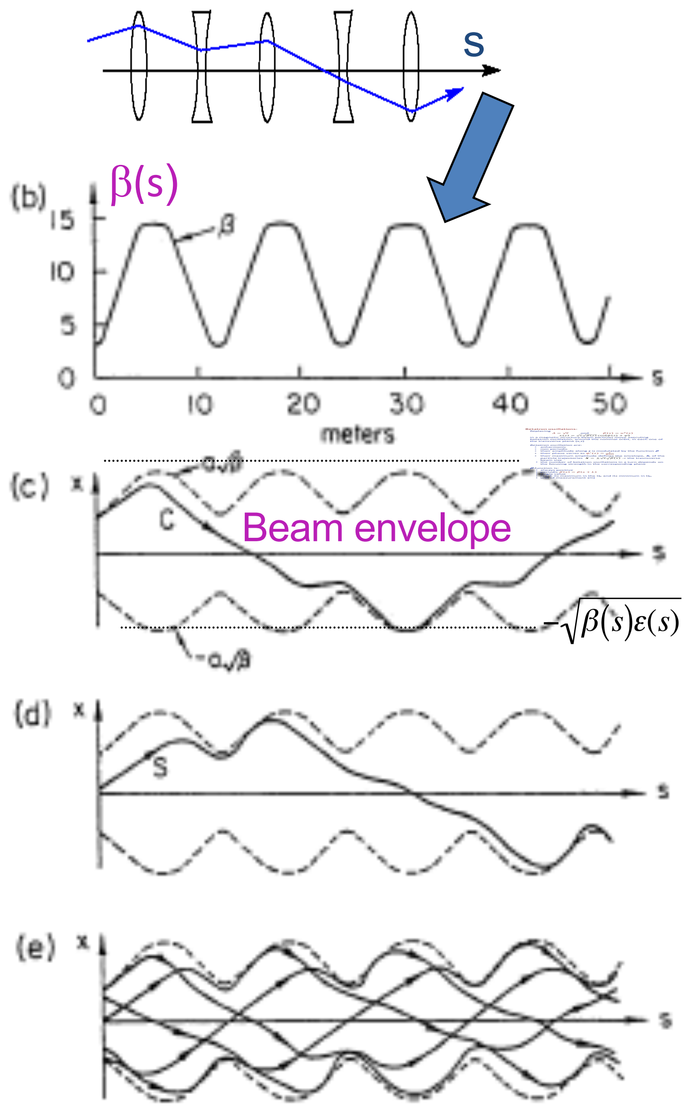
in a magnetic structure beam particles move executing betatron oscillation, around the nominal orbit, in each one of the transverse plane (x,z)

Betatron oscillation are:

- anharmonic
- non periodic
- their amplitude along ***s*** is modulated by the function β
- their phase varies as $\psi'(s) = \frac{1}{\beta(s)}$
- their maximum amplitude defines the envelope, ***X,*** of the particle trajectories $X = \pm\sqrt{\varepsilon}\sqrt{\beta(s)}$ -> the transverse beam size
- the number of betatron oscillations in a turn depends on the focusing strength in the corresponding plane

β function is:

- always positive
- periodic $\beta(s) = \beta(s + L)$
- single value
- reach its maximum in the Q_F and its minimum in Q_D
- unit of measurement [m]



All the stable trajectories lie within the envelope

Betatron Oscillation Phase Advance

$$\psi(s) = \int_0^L \frac{1}{\beta(s)} ds$$

As far as a circular accelerator is considered:

consisting of N cells

having a total circumference C

The phase change per revolution becomes:

$$N\psi(s)$$

From operative point of view becomes very useful to define the ***betatron phase advance per turn***

$$\boldsymbol{\mu} = \frac{N\psi(s)}{\boldsymbol{2\pi}}$$

$$\boldsymbol{\mu} = \frac{1}{\boldsymbol{2\pi}} \int_{\boldsymbol{s}}^{\boldsymbol{s+C}} \frac{1}{\beta(s)} ds \qquad \boldsymbol{tunes} \quad \boldsymbol{\mu_x, \mu_z}$$

Tunes:

must avoid integer values

are dimensionless and measurable parameters (principally their fractional part)

Betatron Oscillation Amplitude β

Can be easily measured, since a focusing error induces $\Delta\mu$

$$\Delta\mu = \frac{1}{4\pi}\beta\Delta k \mathrm{ds}$$

Quadrupole strength is varied by modifying the current I of the magnet power supply

To measure β it's necessary to know the calibration constant

k = cst * I

QUAI1023 (ks100, ci1023)

ks100= (ci1023/ABS(ci1023))*(c1s*(ABS(ci1023)+eps+di1023)+c2s)/en

c1s = 9.1277

c2s = 4.53

Betatron Tune

One defines the tune per lattice as :

$$Q = \frac{\bar{\mu}}{2\pi} = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

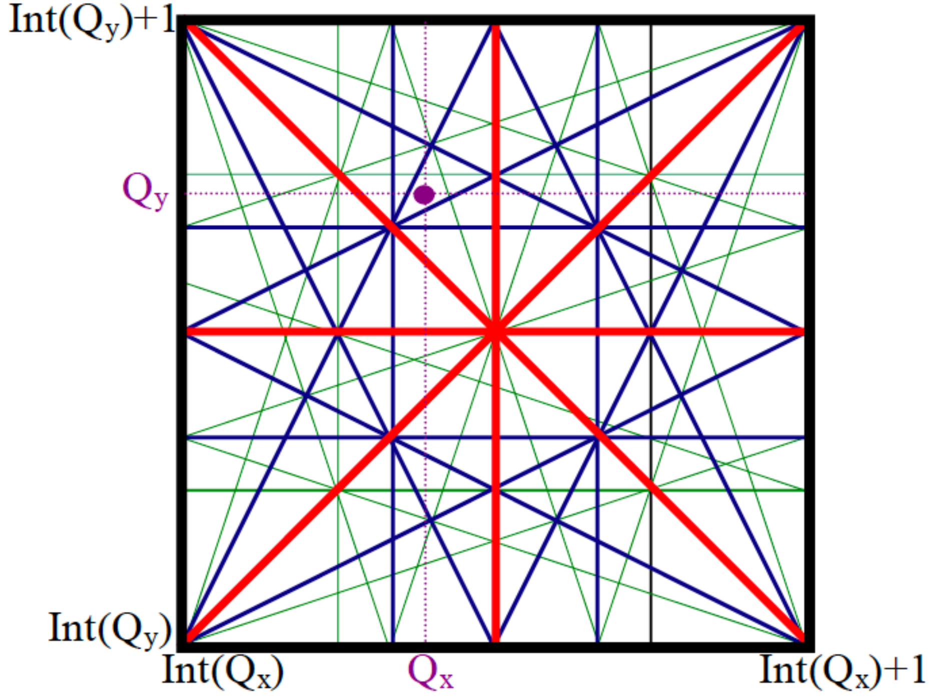
In synchrotron, the ***tune*** is the number of betatron oscillations over one turn.

Resonance :

$$n_x \cdot Q_x + n_y \cdot Q_y = n$$

Resonance's order :

$$|n_x| + |n_y|$$



Avoid resonances :
find the best working point in tune diagram

Linear Beam Optics

Emittance

To unveil ε properties it's worth writing an expression for the particle motion in *x(s)* and *x'(s)*

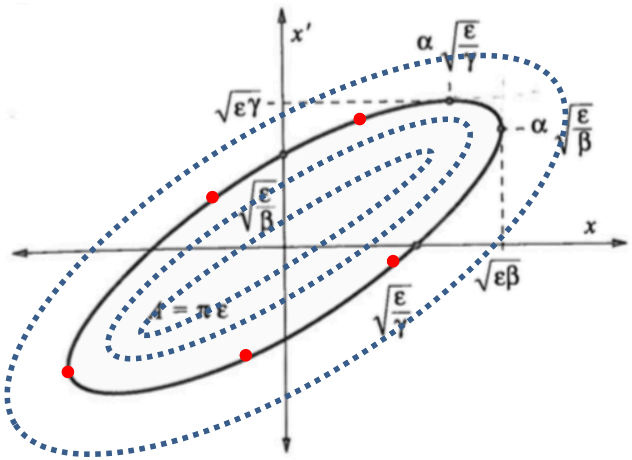
$$x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cos[\psi(s)+\varphi]$$

$$x'(s) = -\frac{\sqrt{\varepsilon}}{\sqrt{\beta(s)}}[\alpha(s)\cos[\psi(s)+\varphi] + \sin[\psi(s)+\varphi]] \qquad \alpha(s) = -\frac{\beta'}{2}$$

Eliminating the terms depending on the phase $\psi(s)$

$$\frac{x^2}{\beta(s)} + \left(\frac{\alpha(s)}{\sqrt{\beta(s)}}x + \sqrt{\beta(s)}x'\right)^2 = \varepsilon \qquad \gamma(s) = \frac{1+a^2(s)}{\beta(s)}$$

$$\gamma(s)x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'$$



Courant-Snyder invariant

This is the general equation for the area of an ellipse A_{ell}

$$A_{ell} = \varepsilon\pi$$

A beam contains many particles so it's necessary to understand which is the ellipse to associate to the beam emittance

Linear Beam Optics

Liouville's Theorem

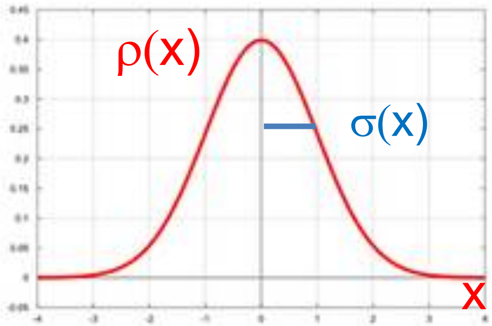
Consider an ensemble obeying canonical equations, the volume element defined by any trajectory in the phase space is invariant w.r.t. time

For a particle accelerator this holds if:

- energy = constant
- synchrotron radiation emission and space charge related effects are negligible

In the case of a lepton beam the charge density distribution function is Gaussian in the transverse and longitudinal dimension

$$\rho(x,z) = \frac{Ne\ \beta\gamma}{2\pi\sigma_x\sigma_z} e^{\left(-\frac{x^2}{2\sigma_x^2}-\frac{z^2}{2\sigma_z^2}\right)}$$



It's reasonable to take **1 σ_x** of the statistical particle distribution as reference emittance value for the whole beam

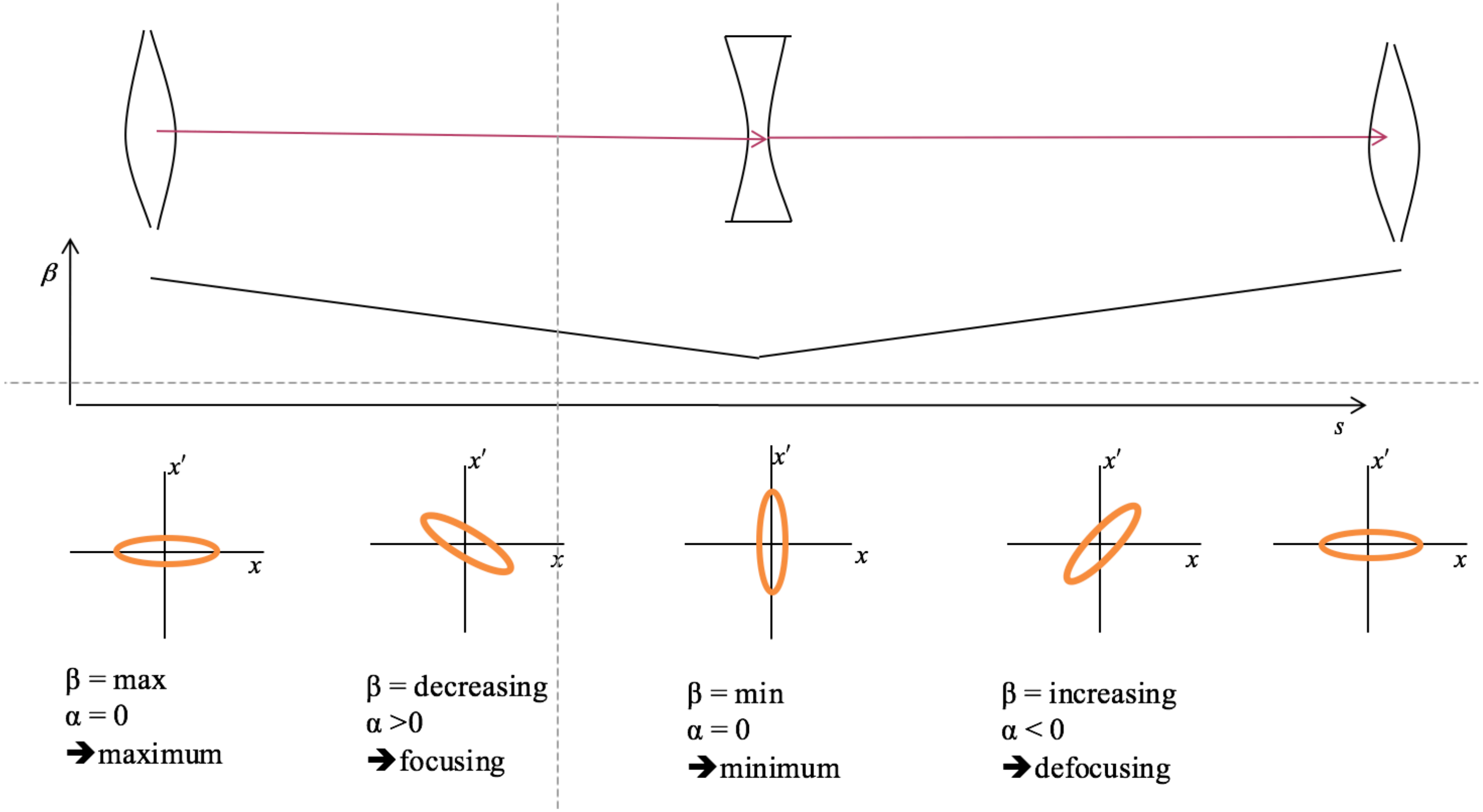
$$\sigma_x = \sqrt{\varepsilon_{ave}\beta(s)} \qquad \pi\varepsilon_{ave} = [mm\ mrad]$$

synchrotron radiation emission determines fluctuations in ε_{ave}

In the case of accelerated particles, the Liouville's theorem can be still used after applying a canonical transformation to the motion equation

Linear Beam Optics

Emittance evolution through a storage ring cell



Ellipse shape and orientation vary along the storage ring cell, but its area remains constant as far as the beam energy is constant

Particle Accelerator basic components

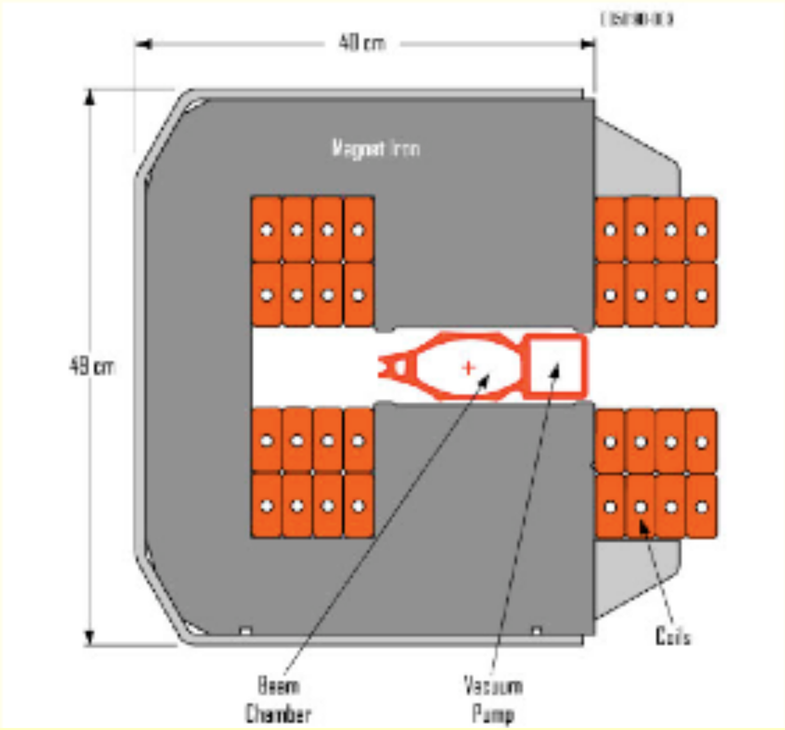
- *Bending magnets*
- *Quadrupoles*
- *Sextupoles*
- *RF cavity*

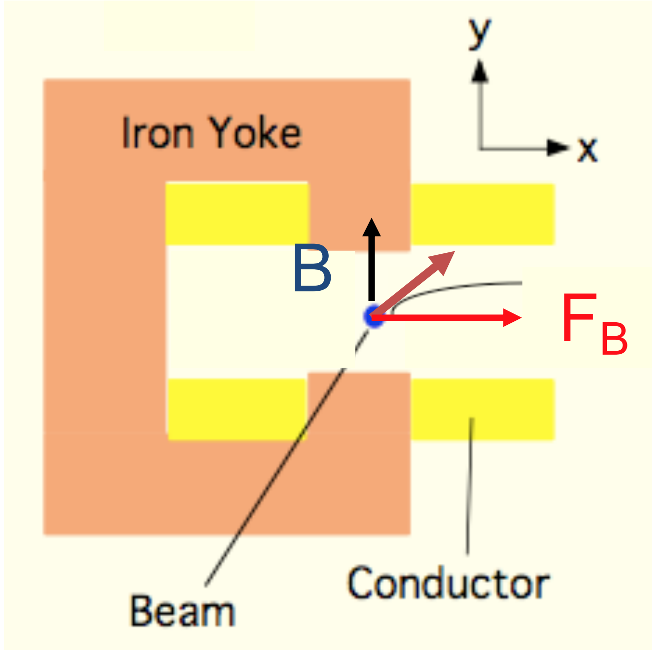
Magnete curvante dipolo

Consentono di curvare la traiettoria delle particelle
Dipolo elettromagnetico

Rigidità magnetica $\rho B[Tm] = \frac{p}{q} = \frac{E}{cq}$

$$\frac{1}{\rho} \approx 0.3 \frac{B[T]}{p[GeV/c]}$$





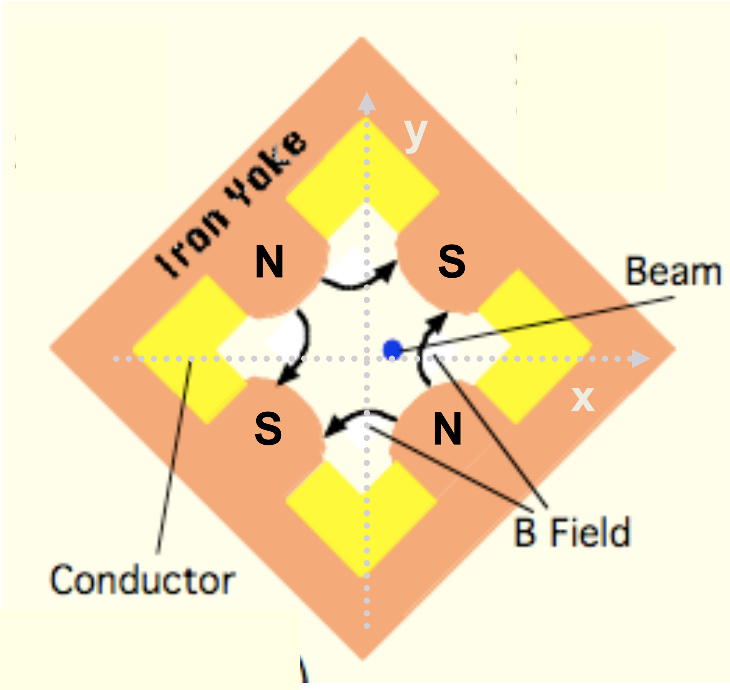
i dipoli elettromagnetici vengono usati per produrre B non oltre

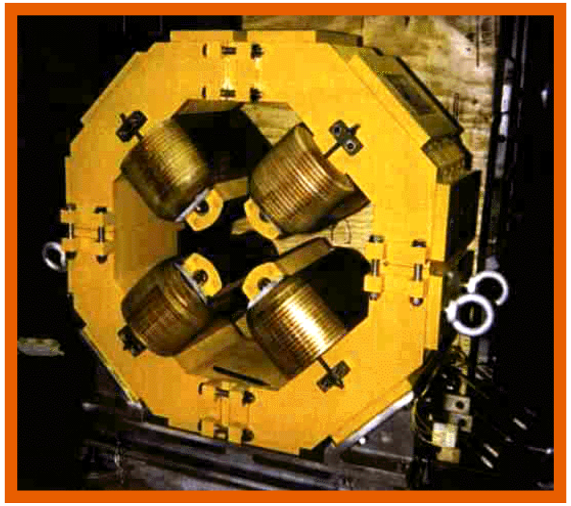
$B_{MAX} \leq 2$ T

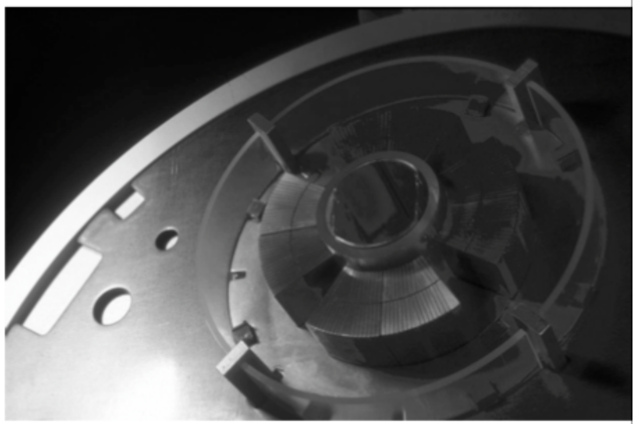
Cosa fare per ottenere campi magnetici più intensi?

B = 1 ÷ 8 T

Quadrupole Magnets





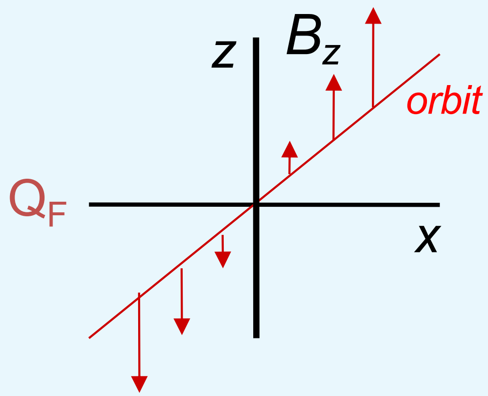


LHC main quadrupole magnet

$g \approx 25 \ldots 220 \;\; T/m$

B

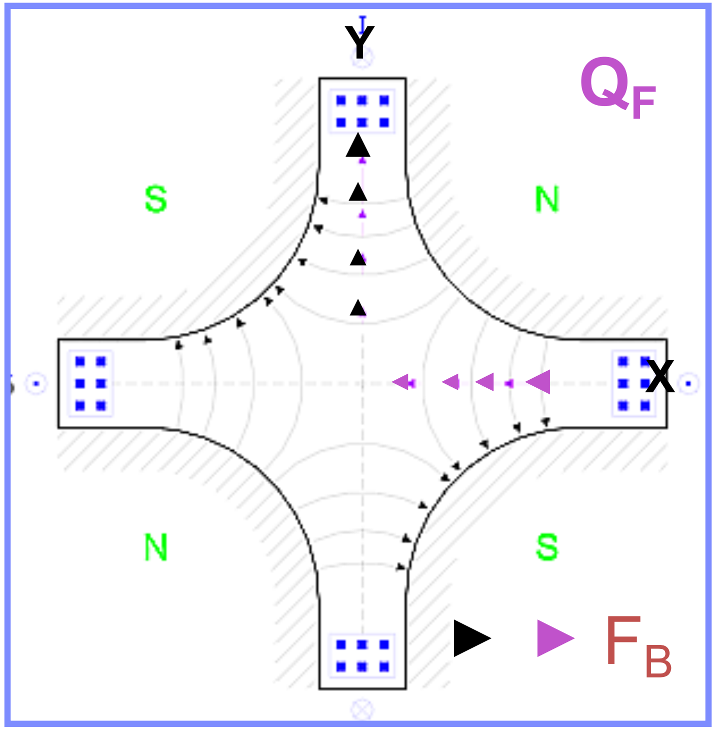
- B=0 at x=0 z=0
- **B** strength grows linearly with the displacement w.r.t. the reference axis

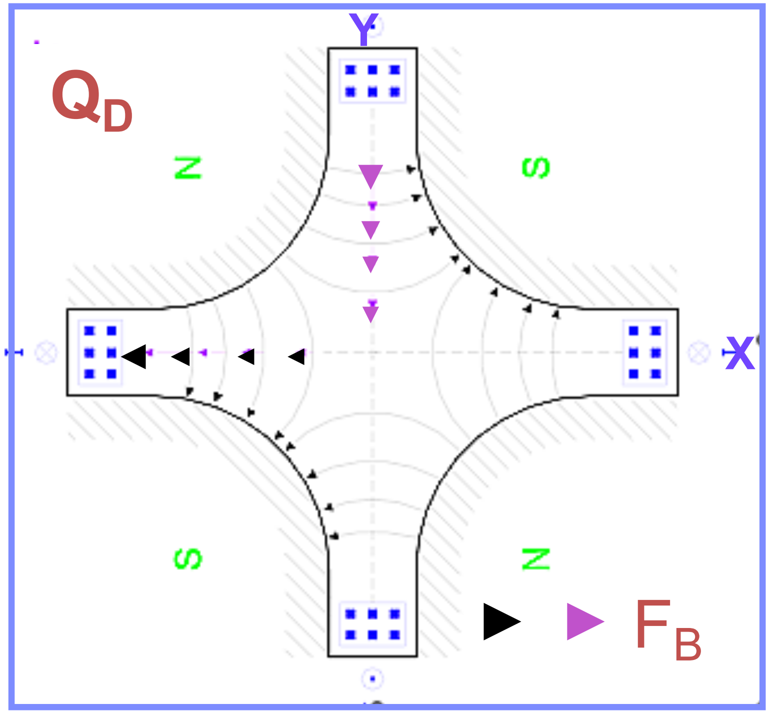


$$F_x = -gx$$
$$F_z = gx$$

$$g = \left[\frac{T}{m}\right]$$

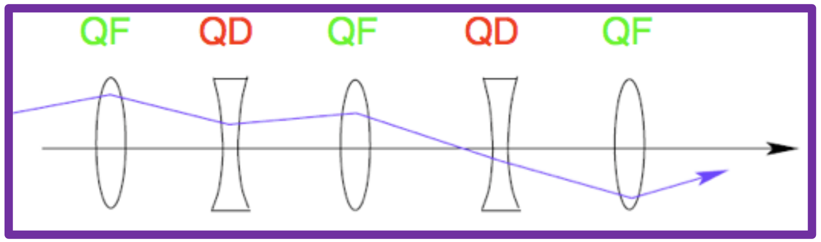
Alternating Gradient Focusing





Strong Focusing

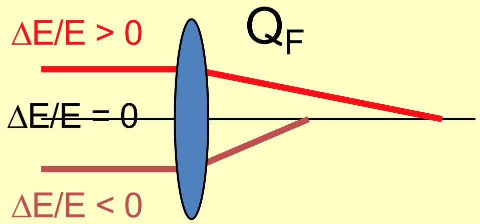
Per ottenere il focheggiamento complessivo di un fascio di particelle lungo un canale di trasporto o in un acceleratore circolare bisogna usare una sequenza di quadrupoli con il segno alternato



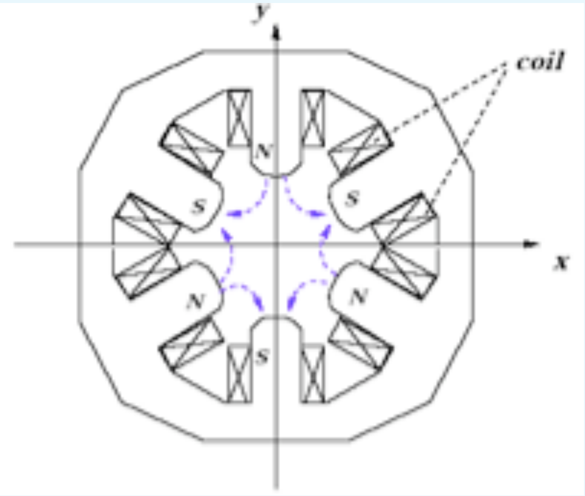
Tale configurazione è in grado di garantire traiettorie stabili con piccole deviazioni dai valori nominali

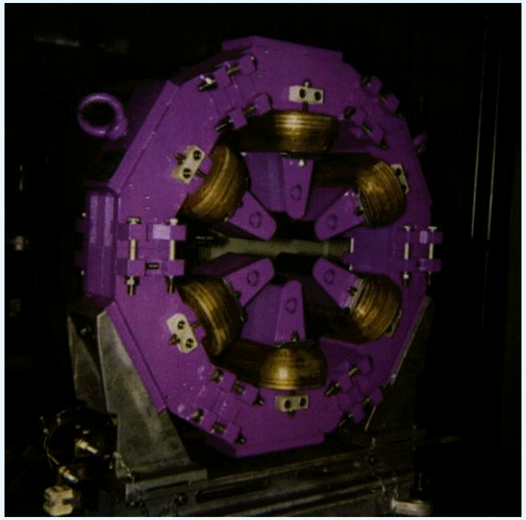
Sestupolo

Abberrazioni cromatiche:
I quadrupoli focheggiano in maniera diversa particelle con diversa energia



Sestupolo
Genera un campo nullo nel centro del magnete
La variazione del campo magnetico dipende quadraticamente dallo spostamento trasversale



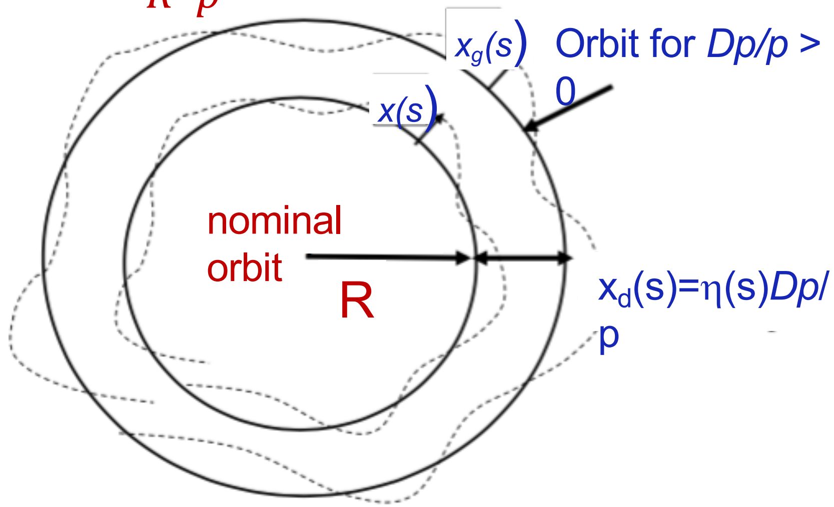


Trajectories for $\Delta p/p \neq 0$

Particles with different momentum passing through bending magnets follow different orbit or trajectory

$$x''(s) + \left(\frac{1}{R^2(s)} - k(s)\right)x(s) = \frac{1}{R}\frac{\Delta p}{p}$$

inhomogeneous differential equations



Considering a $x_d(s)$

$$x_d''(s) + \left(\frac{1}{R^2(s)}\right)x_d(s) = \frac{1}{R}\frac{\Delta p}{p}$$

normalizing by *$\Delta p/p$ and defining*

$$\eta(s) = \frac{x_d(s)}{\frac{\Delta p}{p}}$$

$$\eta''(s) + \left(\frac{1}{R^2(s)}\right)\eta(s) = \frac{1}{R} \qquad (a)$$

Assuming a constant particular solution of (a) η_p

$$\eta_p = R$$

In analogy with what seen for a dipole

$$\eta(s) = A\cos\frac{s}{R} + B\sin\frac{s}{R} + R \qquad \eta(0) = \eta_0 \qquad \eta_0'(0) = \eta_0' \qquad A = \eta_0 - R \qquad B = \eta_0' R$$

$$\eta'(s) = -\frac{A}{R}\sin\frac{s}{R} + \frac{B}{R}\cos\frac{s}{R}$$

$$\eta(s) = \eta_0\cos\frac{s}{R} + \eta_0' R\ \sin\frac{s}{R} + R\left(1 - \cos\frac{s}{R}\right)$$

$$\eta'(s) = -\frac{\eta_0}{R}\sin\frac{S}{R} + \eta_0'\cos\frac{S}{R} + \sin\frac{S}{R}$$

Dispersion Function η

The function η at a point s can be computed knowing its value at *s=0* by using the matrix

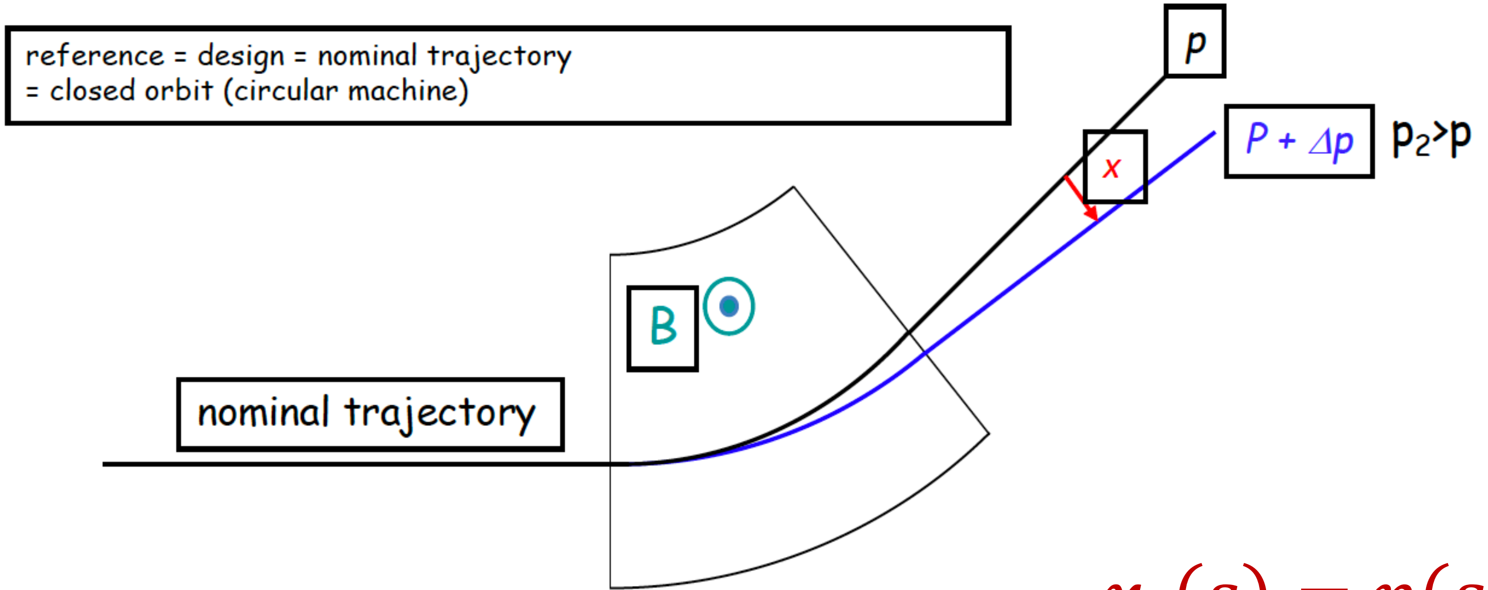
$$\begin{pmatrix} \eta(s) \\ \eta'(s) \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\frac{s}{R} & R\sin\frac{s}{R} & R\left(1-\cos\frac{s}{R}\right) \\ -\frac{1}{R}\sin\frac{s}{R} & \cos\frac{s}{R} & \sin\frac{s}{R} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \eta_0 \\ \eta'_0 \\ 1 \end{pmatrix}$$

The general equation for the trajectory of a particle having a momentum different from the nominal one is

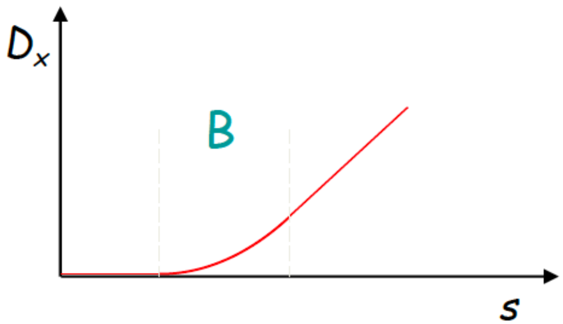
$$x_g(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cos[\psi(s)+\varphi] + \eta(s)\frac{\Delta p}{p}$$

η function can be regarded as the orbit corresponding to a particle having Dp/p = 1
the orbit of a particle is the sum of *x(s)* plus η
Unit measurement [m]

Dispersion Function η

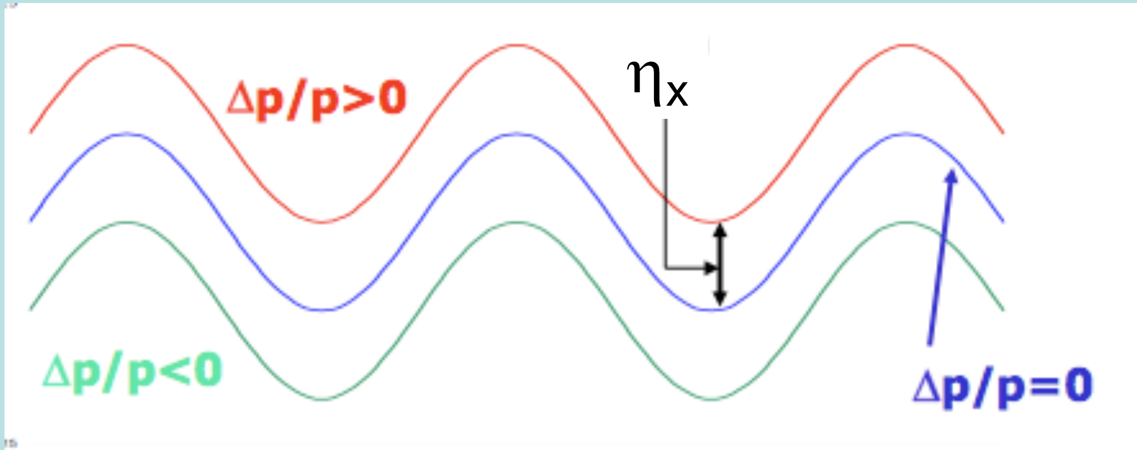


$$x_\eta(s) = \eta(s)\frac{\Delta p}{p}$$



Effetto dei dipoli sul moto trasverso di particelle con energia **E** diversa da quella nominale $\mathbf{E_0}$

Per particelle ultrarelativistiche $E = p \cdot c$



La particella con Dp/p ≠ 0 compie oscillazioni di betatrone intorno ad un'orbita diversa da quella nominale

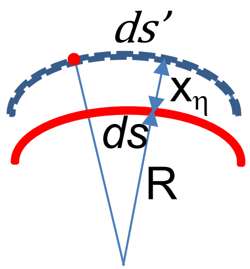
La funzione che decrive di quanto l'orbita fuori energia si discosta da quella nominale si chiama dispersione

$\eta(s)$ *[m]*

Momentum Compaction Factor α_c

It's important to study the dependence of the relative variation of the orbit length on the relative variation of momentum

$$\frac{ds'}{R + x_\eta} = \frac{ds}{R}$$



$$\oint ds' = \oint \frac{R + x_\eta}{R} \mathrm{ds}$$

$$L' = L_0 + \frac{\Delta p}{p} \oint \frac{\eta(s)}{R(s)} \mathrm{ds}$$

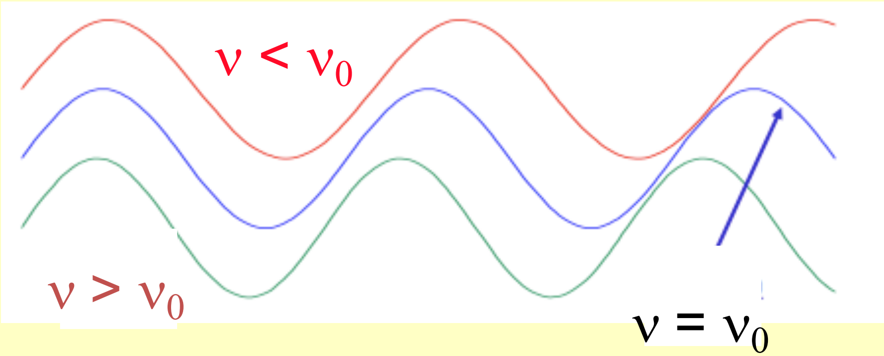
$$\frac{\frac{\Delta L}{L_0}}{\frac{\Delta p}{p_0}} = \frac{1}{L_0} \frac{\Delta p}{p} \oint \frac{\eta(s)}{R(s)} \mathrm{ds}$$

$$\alpha_c = \frac{1}{L_0} \frac{\Delta p}{p} \oint \frac{\eta(s)}{R(s)} \mathrm{ds}$$

$$\frac{\Delta L}{L_0} = \alpha_c \frac{\Delta p}{p_0}$$

Effetto dei quadrupoli sul moto trasverso di particelle con energia **E** diversa da quella nominale $\mathbf{E_0}$

Dp/p > 0 le particelle sentono un focheggiamento minore --> $\nu < \nu_0$
Dp/p < 0 le particelle sentono un focheggiamento maggiore --> $\nu > \nu_0$



cromatismo

$$\frac{\Delta\nu}{\nu_0} = \xi \frac{\Delta p}{p_0}$$

La dipendenza del numero di oscillazione di betatrone delle particelle accumulate dall'energia è cruciale per la stabilità del fascio

ξ deve essere corretto accuratamente

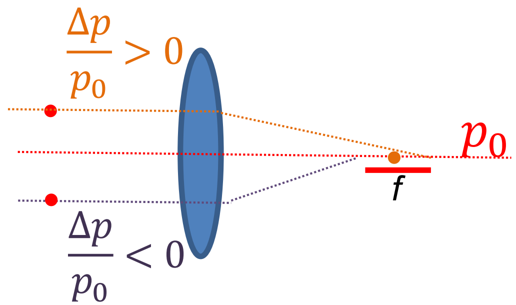
Chromaticity ξ

Consider a particle having $\Delta p \ll p_0$ passing through a quadrupole magnet

$$k(p) = -\frac{e}{p_0} g = \frac{e}{p_0 + \Delta p} g$$

$$k(p) \simeq -\frac{e}{p_0} g \left(1 - \frac{\Delta p}{p_0}\right) \qquad k(p) = k_0 + \Delta k \qquad \Delta k = k_0 \frac{\Delta p}{p_0}$$

A momentum error induces a focusing error -> Δμ



$$\Delta\mu = \frac{1}{4\pi} \beta \Delta k ds \qquad \Delta\mu = \frac{1}{4\pi} \beta k_0 \frac{\Delta p}{p_0} ds$$

Since the particle maintain the same Δp for several turns it's possible to integrate the r.h.s. over all the quadrupoles

$$\frac{\Delta\mu}{\Delta p / p_0} = \frac{1}{4\pi} \oint \beta k_0 ds \qquad \xi = \frac{\Delta\mu}{\Delta p / p_0}$$

Properties of *ξ:*

- measurable and dimensionless quantity
- generated always when a particle is focused $\xi = f(k(s))$
- Is due to the lattice elements → ξ_n **natural chromaticity**
- It indicates the size of the tune spot in the tune diagram
- For an accelerator based on strong focusing ξ_n will be predominantly < 0

Chromaticity Correction

Can be implemented by means of magnet elements having:

B=0 on the nominal orbit

focusing strength depending quadratically on x (z)

SEXTUPOLES

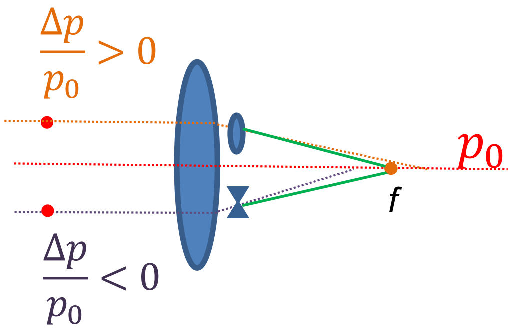
$$k_{sxt} = \frac{e}{p} g' x = m_{sxt}(s) x \qquad x_g = x(s) + \eta(s)\frac{\Delta p}{p} \qquad x_d(s) = \eta(s)\frac{\Delta p}{p}$$

Sextupoles should be installed at place where there is dispersion

$$\xi_{tot} = \frac{1}{4\pi} \oint [m_{sxt}(s)\eta(s) + k(s)]\, \beta(s) ds$$

Chromaticity must be corrected to avoid to incur in resonances and must be moved to values >0 to avoid the head-tail instability

However too high Sextupole gradients can lead to lose particles



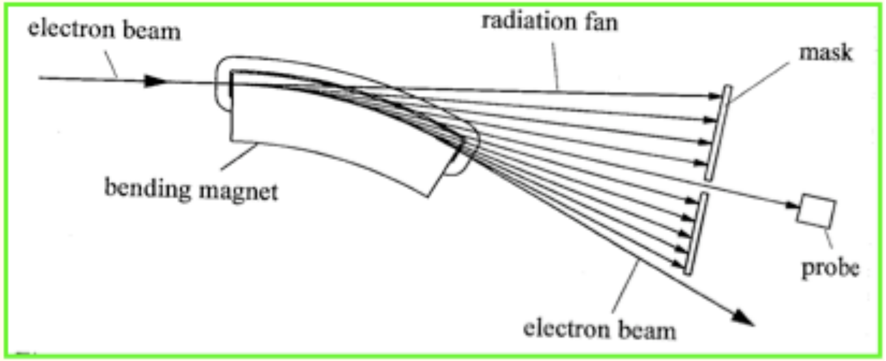
Radiazione di Sincrotrone

Particelle in moto su un'orbita circolare quando passano all'interno di un magnete curvante emettono radiazione in direzione tangente alla loro traiettoria

U energia persa per giro

$$U = \frac{4\pi}{3} \frac{r_o}{(m_0 c^2)^3} \frac{E^4}{\rho}$$

E energia dela particella
ρ raggio di curvatura
m_0 massa della particella



$$\frac{m_p}{m_e} = 1836$$

$$\frac{U_{e^-}}{U_p} = \frac{m_p^3}{m_e^3} \approx 10^{13}$$

- *A parità di* ***E*** *e ρ un elettrone emette molta più radiazione di sincrotrone di un protone*
- *La radiazione di sincrotrone emessa da protoni è stata osservata per la prima volta al Tevatron*

Limiti imposti dalla Radiazione di Sincrotrone

L'energia persa per emissione di radiazione di sincrotrone viene reintegrata mediante una **cavità a Radio Frequenza**

$$U_{MAX} = P_{MAX}^{RF}$$

$$E_{MAX}[GeV] \propto \left(\rho[m]U_{MAX}\right)^{1/4}$$

- *Data una certa potenza RF si può costruire un acceleratore con energia maggiore aumentandone il raggio*
- *Raddoppiare l'energia a parità di potenza RF richiede un acceleratore con raggio 16 volte maggiore*

$e^+ e^-$	DAΦNE	U ~ 9.7 KeV	E = .51 GeV	L = 97.58 m
$e^+ e^-$	LEP	U ~ 700 MeV	E = 70 GeV	L = 27 Km
p p	LHC	U ~ 7 KeV	E = 7000 GeV	L = 27 Km

Acceleratori con energia E >> 200 GeV è preferibile che usino adroni (protoni, antiprotoni o ioni) oppure che siano acceleratori lineari

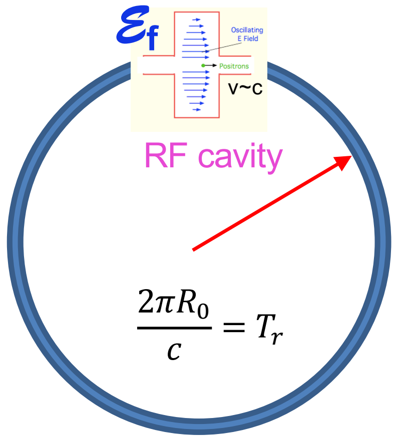
Longitudinal Dynamics

Circular accelerators use powerful **R**adio **F**requency structure to generate high intensity $\mathcal{E}_f$ with frequency f_{RF} in the range: 100 MHz ≤ f_{RF} ≤ GHz

The field $\mathcal{E}_f$ is intended to restore the energy lost by synchrotron radiation emission

E_0 nominal energy

W_0 average energy lost per turn



$$V = V_0 \sin(\omega t + \omega_0)$$

$$\omega = 2\pi f_{RF}$$

$$f_{RF} = n f_r = n\frac{2\pi}{T_r}$$

Energy balance for a nominal particle over a turn

$$E_0 = eV_0 \sin\psi_0 - W_0 \qquad (a)$$

Energy balance for a particle with small Δp -> $\Delta\psi$

$$E = eV_0 \sin(\psi_0 + \Delta\psi) - W \qquad (b)$$

Subtracting *(a)* from *(b)* and considering

$$\Delta\dot{E} = \frac{\Delta E}{T_r}$$

$$E - E_0 = eV_0[\sin(\psi_0 + \Delta\psi) - \sin\psi_0] - \frac{\Delta W}{dE}\Delta E$$

$$\Delta\dot{E} = \frac{eV_0}{T_r}[\sin(\psi_0 + \Delta\psi) - \sin\psi_0] - \frac{\Delta W}{dE}\frac{\Delta E}{T_r}$$

How does T_r changes with Δp?

Longitudinal Dynamics

How does T_r changes with Δp?

$$T_r = \frac{2\pi R_0}{\beta c} \qquad\qquad \beta = \frac{v_0}{c} \quad \text{(beware!!!!)}$$

$$\frac{\Delta T}{T_r} = \frac{dR}{R_0} - \frac{d\beta}{\beta_0} \qquad\qquad \frac{dR}{R_0} = \alpha_c \frac{\Delta p}{p} \quad and \quad \frac{d\beta}{\beta_0} = \frac{1}{\gamma^2}\frac{\Delta p}{p}$$

being $f_r = 1/T_r$

$$f_r = \frac{\beta c}{2\pi R_0} \qquad\qquad \frac{\Delta f}{f_r} = \frac{d\beta}{\beta_0} - \frac{dR}{R_0} = \frac{1}{\gamma^2}\frac{\Delta p}{p} - \alpha_c \frac{\Delta p}{p}$$

defining

$$\eta_c = \frac{\frac{\Delta f}{f_r}}{\frac{\Delta p}{p}} \qquad \textit{phase slip factor} \qquad \eta_c = \left(\frac{1}{\gamma^2} - \alpha_c\right)$$

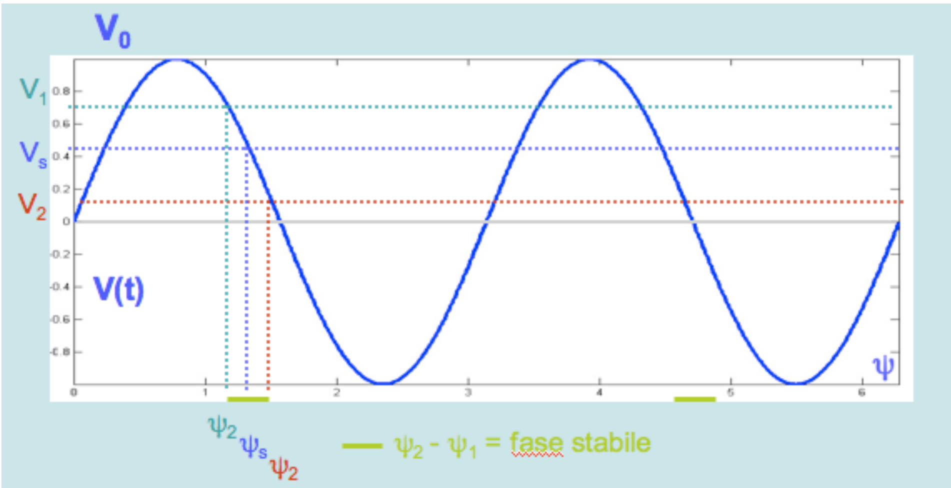
in a lepton storage ring $\eta_c = -\alpha_c$

linear accelerator structures $\alpha_c = 0$

in a synchrotron may happen $\eta_c = 0$

Phase Focusing Effect

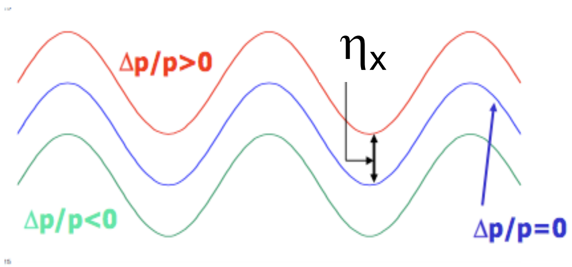
$$V(t) = V_0 \sin \omega t = V_0 \sin \psi$$



$$\omega = 2\pi f_{RF} = 2\pi n f_r$$

f_r revolution frequency
f_{RF} RF frequency
n harmonic number

$$n = \frac{f_{RF}}{f_r}$$



$\Delta p/p = 0$ $V = V_0$ synchronous particle, unchanged
$\Delta p/p > 0$ $V_2 < V_0$ slowed
$\Delta p/p < 0$ $V_1 > V_0$ accelerated

Particles undergo energy oscillation SYNCHROTRON OSCILLATION
n_s = number of oscillation per turn
Particles arriving in the RF cavity at t:

$$t \notin t_2 - t_1$$

are lost -> **BUNCHES**

Longitudinal Dynamics

Let us writing the **longitudinal motion equation** going back to the equation

$$\Delta\dot{E} = \frac{eV_0}{T_r}[\sin(\psi_0 + \Delta\psi) - \sin\psi_0] - \frac{\Delta W}{dE}\frac{\Delta E}{T_r}$$

Since $\Delta\psi << \psi_0$

$$\sin(\psi_0 + \Delta\psi) - \sin\psi_0 \approx \Delta\psi\cos\psi_0$$

an expression for $\Delta\psi$ is required

$$\Delta\psi = \frac{2\pi\Delta t}{T_{RF}} = \omega_{RF}\Delta t \qquad \frac{\omega_{RF}}{\omega_r} = n$$

$$\Delta\psi = n\omega_r\,\Delta t \qquad \Delta\psi = 2\pi n\frac{\Delta t}{T_r} \qquad \Delta\psi = 2\pi n\left(\alpha_c - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p}$$

$$\Delta\dot{\psi} = \frac{2\pi n}{T_r}\left(\alpha_c - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p} \qquad \frac{\Delta p}{p} = \frac{1}{\beta^2}\frac{\Delta E}{E}$$

$$\Delta\dot{\psi} = \frac{2\pi n}{\beta^2 T_r}\left(\alpha_c - \frac{1}{\gamma^2}\right)\frac{\Delta E}{E}$$

$$\Delta\dot{E} = \frac{eV_0}{T_r}\Delta\psi\cos\psi_0 - \frac{\Delta W}{dE}\frac{\Delta E}{T_r}$$

differentiating again w.r.t. time

$$\Delta\ddot{E} = \frac{eV_0}{T_r}\Delta\dot{\psi}\cos\psi_0 - -\frac{\Delta W}{dE}\frac{\Delta E}{T_r} \qquad \Delta\ddot{E} + 2\alpha_s\Delta\dot{E} + \Omega^2\Delta E = 0$$

Longitudinal Dynamics

$$\Omega^2 = \frac{1}{T_r}\left[-\frac{2\pi n e V_0}{\beta^2 E}\cos\psi_0\left(\alpha_c - \frac{1}{\gamma^2}\right)\right]^{1/2}$$ Synchrotron frequency

$$\alpha_s = \frac{1}{2T_r}\frac{\Delta W}{dE}$$ *damping term usually small* $\alpha_s \ll \Omega$

and the solution

$$\Delta E(t) = \Delta E_0 e^{-\alpha_s t} e^{i\Omega t}$$

There are **stable longitudinal oscillation only if** $\Omega \in \Re$

$$\cos\psi_0\left(\alpha_c - \frac{1}{\gamma^2}\right) < 0$$

which defines two stable phase areas

$$\frac{\pi}{2} < \psi_0 < \frac{3\pi}{2} \quad when \quad \alpha_c > \frac{1}{\gamma^2}$$

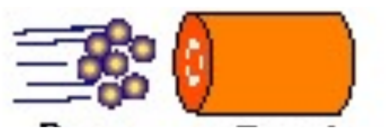
$$-\frac{\pi}{2} < \psi_0 < \frac{\pi}{2} \quad when \quad \alpha_c < \frac{1}{\gamma^2}$$

When $\gamma_{tr} = \frac{1}{\sqrt{\alpha_c}}$ $\quad \Omega \to 0$ $\quad$ *the longitudinal focusing effect vanishes*

Colliders

Cinematica delle collisioni tra fasci

VANTAGGI



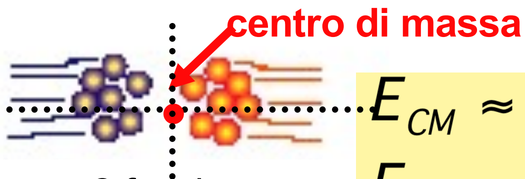
fascio
E = 600 MeV

targhetta
fissa

$$E_{CM} \approx \sqrt{2E_1 m_2}$$

$$E_{CM} \approx 279\,MeV$$

Parte dell'energia del fascio incidente è spesa nel loro rimbalzo sulla targhetta



2 fasci
E1 = E2 = 600 MeV

$$E_{CM} \approx 2E$$

$$E_{CM} = 1200\,MeV$$

Tutta l'energia dei due fasci è a disposizione per realizzare le collisioni

LIMITE

La densità dei fasci relativistici che si sanno realizzare è molto bassa rispetto a quella della materia condensata di una targhetta.

Uno dei fasci circolanti in DAFNE contiene un numero di particelle n_p

$N_p = 100 \cdot 10^{10}$

Il CONCETTO di SEZIONE D'URTO

Due particelle che collidono possono produrre tipi diversi di eventi, alcuni più probabili di altri

la *sezione d'urto* $\boldsymbol{\sigma}$ di un determinato evento
è proporzionale alla probabilità che l'evento avvenga
si misura in cm^2

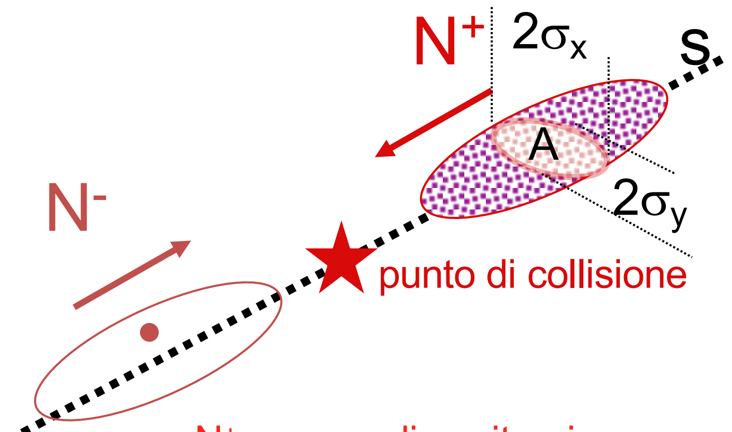
Luminosità *L*

Come ottenere il più alto numero di eventi possibili?

N_e è il numero di eventi prodotti dalle collisioni

σ_p è la probabilità di ottenere un dato evento dall'urto tra particelle collidenti (sezione d'urto del processo da studiare)

L è il numero di collisioni realizzate per unita' di superficie A per unità di tempo



N^+ numero di positroni
N^- numero di elettroni

$$\frac{\Delta N_e}{\Delta t} = \sigma_p L$$

Numero di eventi nell'unità di tempo

$$\frac{\Delta N_e}{\Delta t} = \sigma_p \frac{f_r b N^+ N^-}{4\pi\sigma_x\sigma_y}$$

$$L = \frac{f_r b N^+ N^-}{4\pi\sigma_x\sigma_y}$$

$$I = Nbf_r e$$

$$L = \frac{I^+ I^-}{4\pi e^2 f_r b \sigma_x \sigma_y}$$

$$L_{integrata} = L\Delta t$$

Unità di misura

$L[\mathrm{cm}^{-2}\mathrm{s}^{-1}] = L[10^{33}\ \mathrm{nb}^{-1}\mathrm{s}^{-1}]$

$1\ \mathrm{b} = 10^{-24}\ \mathrm{cm}^2$

$\mathrm{nb} = 10^{-9}\ \mathrm{b}$

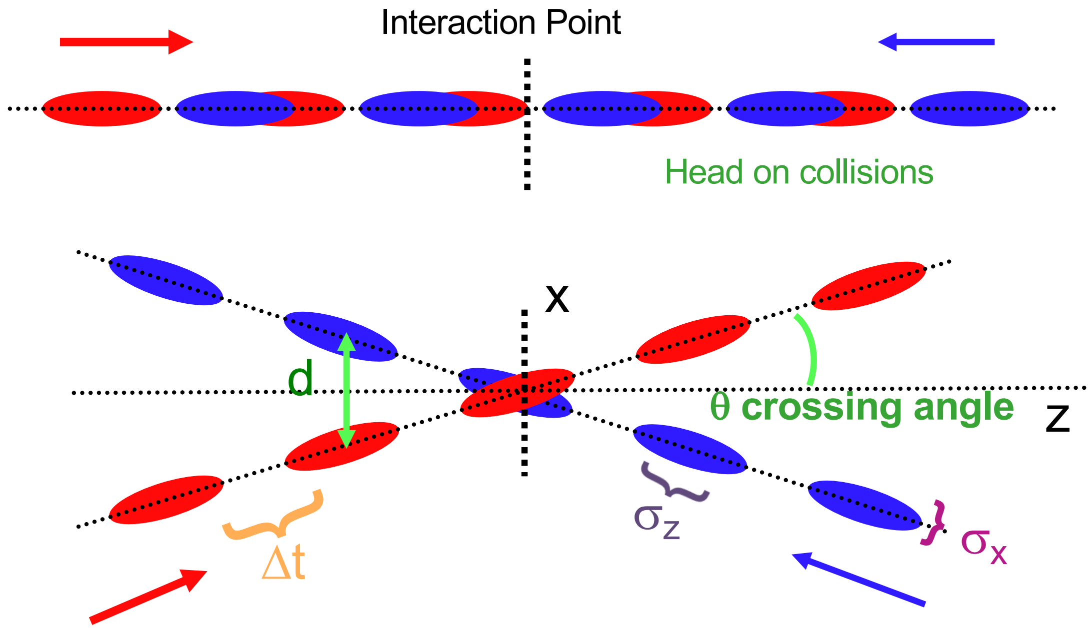
$f_r = c/L$ frequenza di rivoluzione

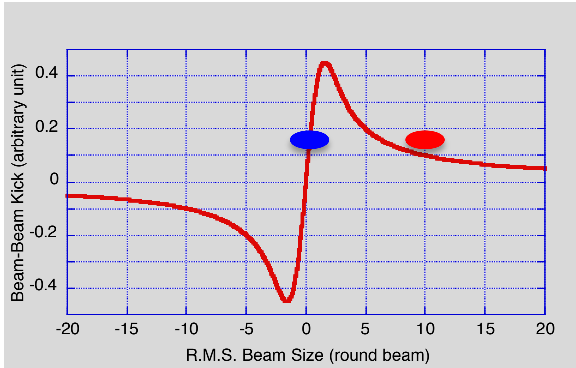
b numero dei pacchetti

$f_r b$ frequenza di collisione

Parasitic Crossings

Colliding beams consist of many bunches
Head on collisions determine many parasitic crossings
Crossing angle is introduced to minimize *parasitic crossings*





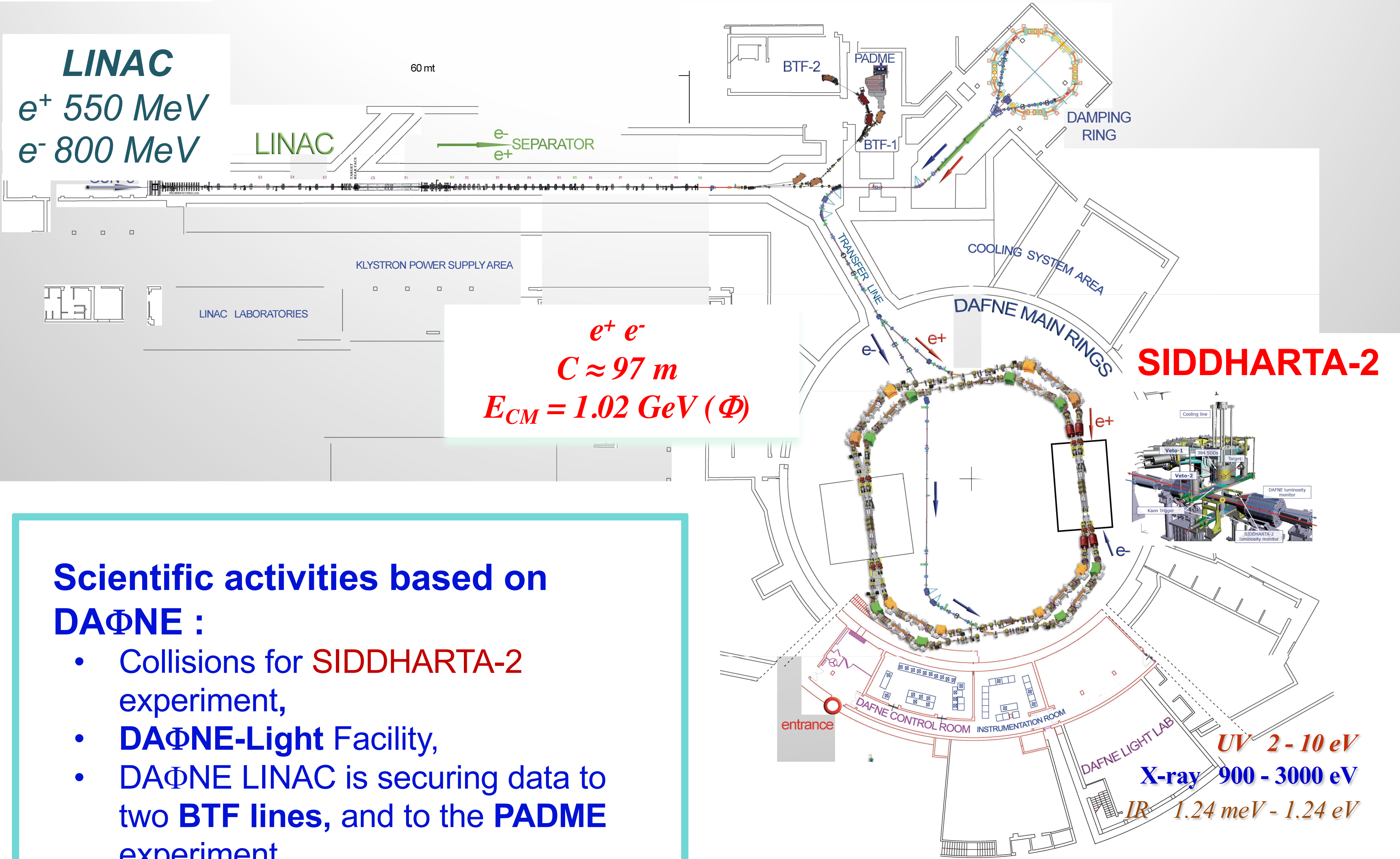
$$\Phi \approx \frac{\sigma_z}{\sigma^*_x} tg\left(\frac{\theta}{2}\right) < 1$$

Still ***Long Range Beam-Beam (LRBB) interactions*** is not negligible in fact it cause:

- closed orbit distortion
- correlation between the transverse and longitudinal motion
- excite dangerous resonances

The DAΦNE Accelerator Complex

LINAC
e^+ 550 MeV
e^- 800 MeV



$e^+ e^-$
$C \approx 97$ m
$E_{CM} = 1.02$ GeV (Φ)

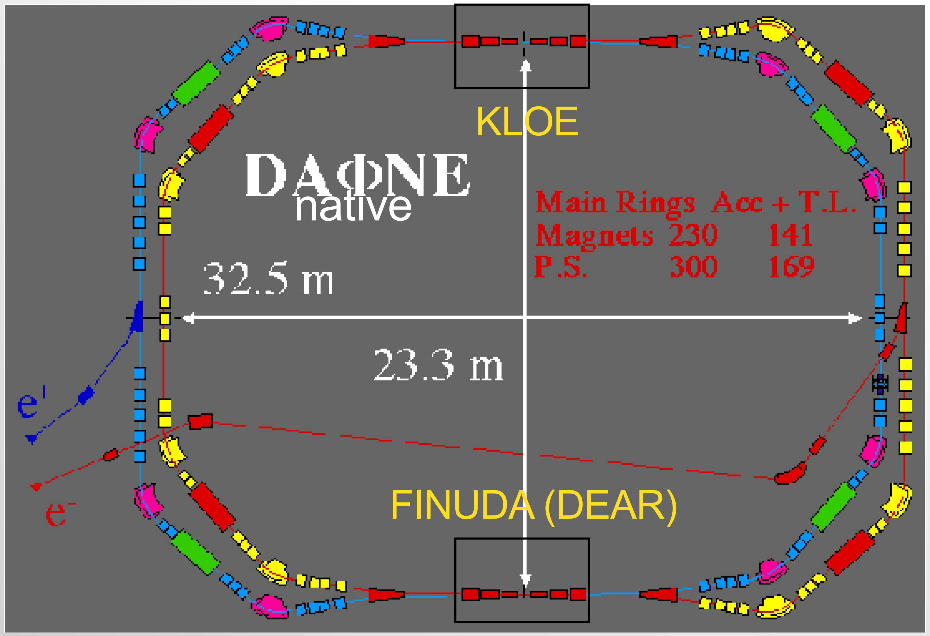
Scientific activities based on DAΦNE :

- Collisions for SIDDHARTA-2 experiment,
- **DAΦNE-Light** Facility,
- DAΦNE LINAC is securing data to two **BTF lines,** and to the **PADME** experiment.

Outline

- *DAΦNE*
- *path toward higher luminosity*
- *Crab-Waist Collision Scheme*
- *Performances of Crab-Waist collisions with:*
  - *SIDDHARTA*
  - *KLOE-2*
- *Preparation for SIDDHARTA-2 run*
- *Conclusions*

DAΦNE Main Ring Layout and Parameters



"Proposal for a Φ-factory", LNF-90/031 (IR),1990.

	DAΦNE native	DAΦNE Crab-Waist
Energy (MeV)	510	510
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mm•mrad)	0.34	0.28
β_x^* (cm)	160	23
σ_x^* (mm)	0.70	0.25
$\Phi_{Piwinski}$	0.6	1.5
β_y^* (cm)	1.80	0.85
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	13
σ_z (mm)	25	15
N_b	120	120

Colliding Beams have:
- *low E*
- *high currents*
- *short bunch spacing 2.7 nsec*
- *long damping time*

Conventional Approach to High Luminosity

$$L = N_b f_0 \frac{N^2}{4\pi\sigma_x^*\sigma_y^*} \qquad \xi_{x,y} = \frac{N r_e}{2\pi\gamma} \frac{\beta_{x,y}^*}{\sigma_{x,y}^*\left(\sigma_x^* + \sigma_y^*\right)} \qquad L = N_b f_0 \frac{\pi\gamma^2 \xi_x \xi_y \varepsilon_x}{r_e^2 \beta_y^*}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)^2$$

Small $\boldsymbol{\beta_y^*}$

Higher number of particle per bunch $\boldsymbol{N}$

More bunches $\boldsymbol{N_b}$

Higher tune shift $\boldsymbol{\xi_{x,y}}$

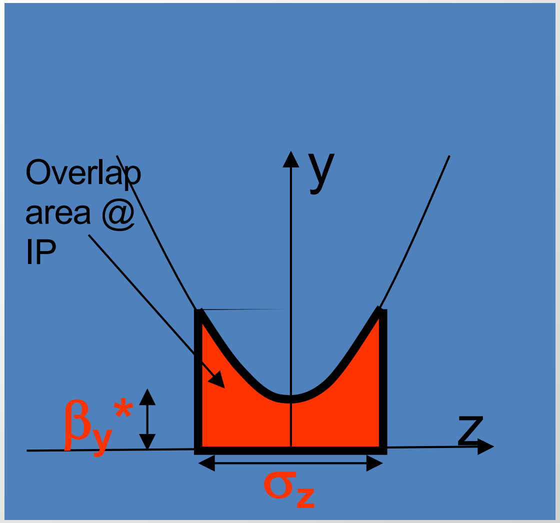
Greater horizontal rms beam size $\boldsymbol{\sigma_x}$

Small crossing angle $\boldsymbol{\theta_x}$

Small Piwinsky angle $\boldsymbol{\Phi = \frac{\sigma_z}{\sigma_x}\tan\frac{\theta_x}{2} < 1}$

Conventional Approach Meets Limitations

$\beta_y^* \sim \sigma_z$ to avoid hourglass effect

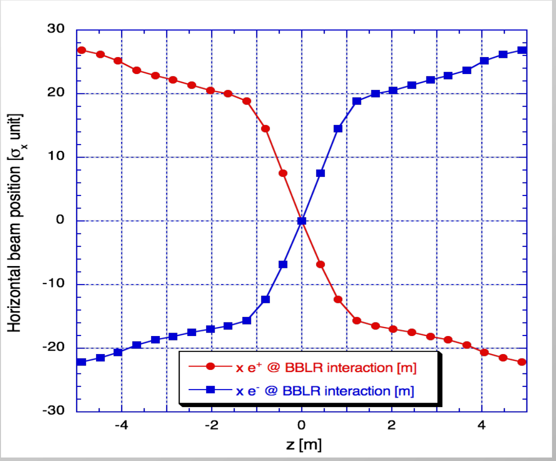


σ_z reduction led to:

- single bunch instability
- bunch lenghtening and microwave instabilityies
- CSR production

Higher N and N_b

- led to enhanced power losses
- increase wall plug power requirements
- causes coupled bunch instabilities



Tune shifts $\xi_{x,y}$ are constrained by beam-beam limit

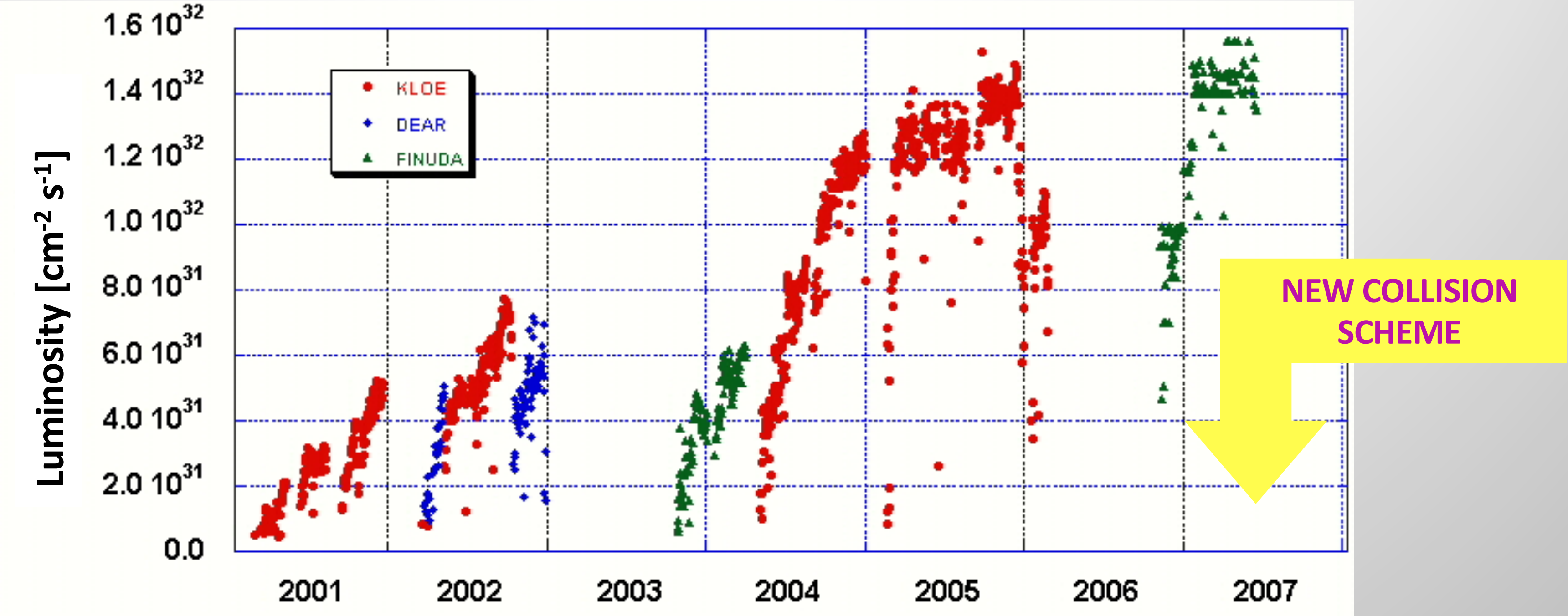
Larger σ_x conflicts with

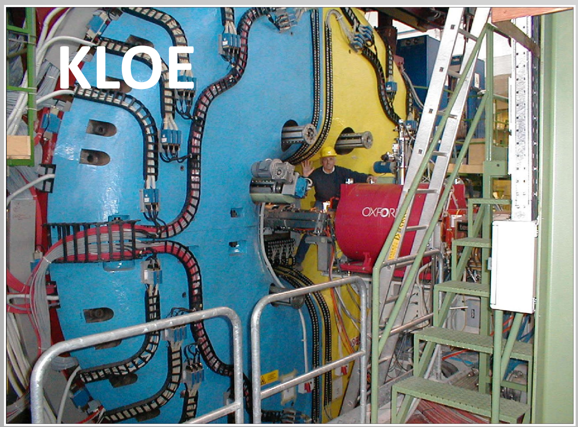
- beam stay clear and dynamical aperture requirements

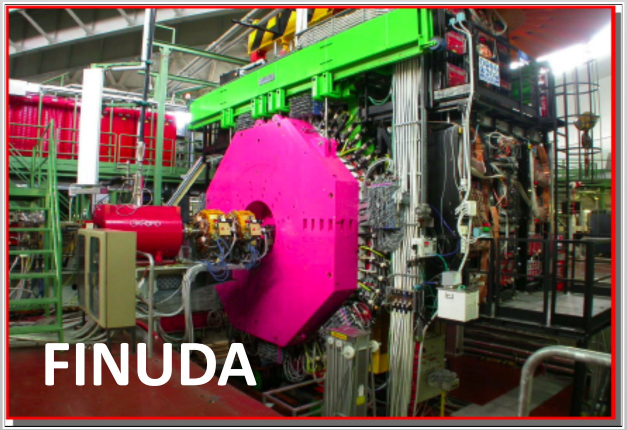
Long-range beam-beam interactions causing τ^+ τ^- reduction limiting I^+_{MAX} I^-_{MAX} and -> L_{peak} and $L_\int$

L_{peak} at DAΦNE 2001 ÷ 2007

L_{peak} had a remarkable evolution mainly due to several machine upgrades
Experiments took data one at the time, although DAΦNE had been originally conceived as collider with two IRs







L_{logged} (fb^{-1}) 2001÷2007

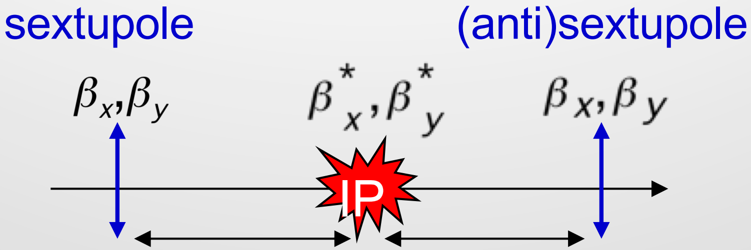
KLOE	3.0
FINUDA	1.2
DEAR	0.2

Crab-Waist Collision Scheme

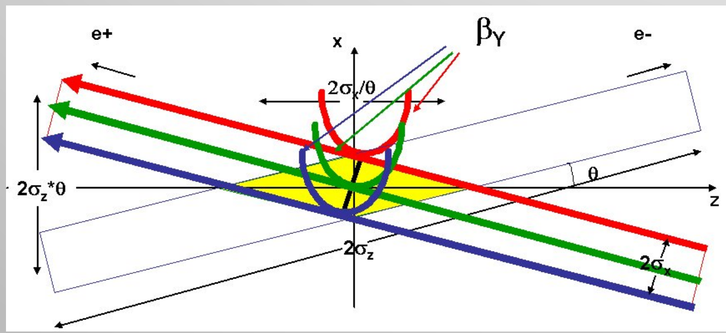
The innovative approach to the beam-beam interaction

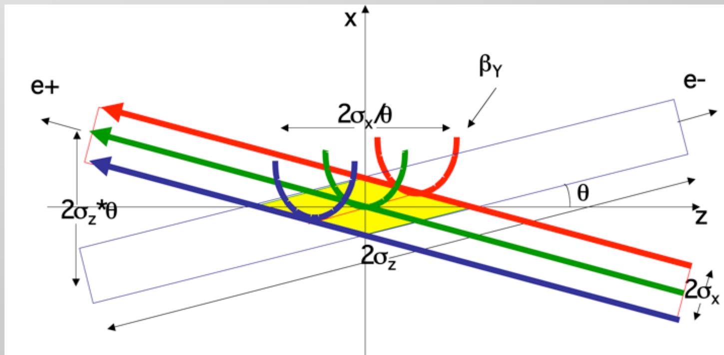
Crab-Waist Collision Scheme

Large horizontal crossing angle.
Large Piwinsky angle.
Overlap area, no longer bunch length, is the limit to avoid hourglass effect, this allows to have a *lower β^*_y at IP.*
Beam-beam non-linear resonances suppressed by a *pair of Crab-Waist Sextupole*



$$\Delta\nu_x = \pi$$
$$\Delta\nu_y = \frac{\pi}{2}$$





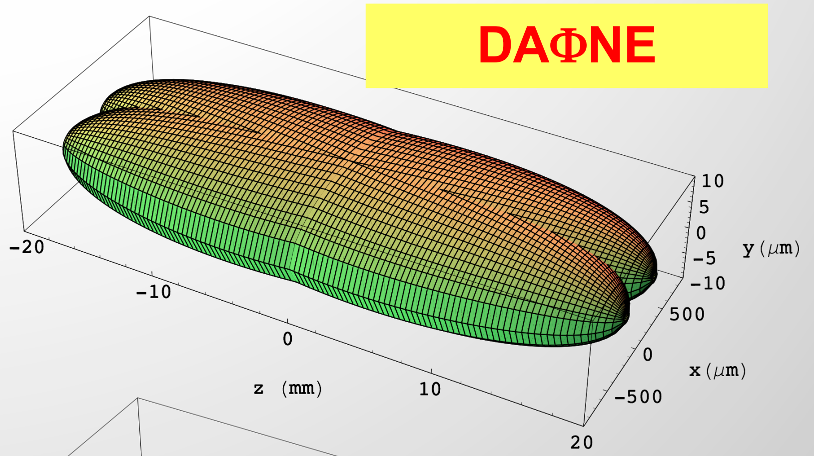
Crab-Waist transformation

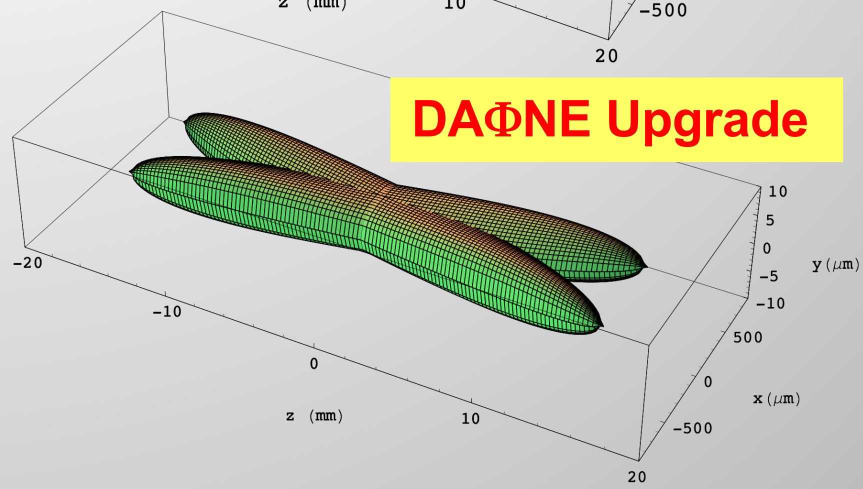
P. Raimondi , 2° *SuperB Workshop, March 2006,*
M.Zobov et al., Phys.Rev.Lett. 104 (2010) 174801,
C. Milardi et al., Int.J.Mod.Phys.A24, 2009.

DAΦNE Upgrade Parameters

	DAΦNE KOE	DAΦNE Upgrade
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mmxmrad)	0.34	0.26
β_x^* (cm)	160	26
σ_x^* (mm)	0.70	0.26
$\Phi_{Piwinski}$	0.6	1.9
β_y^* (cm)	1.80	0.85
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
I_{bunch} (mA)	13	13
σ_z (mm)	25	20
N_{bunch}	110	110
L ($cm^{-2}s^{-1}$) x10^{32}	1.6	5

Beam distribution @ IP



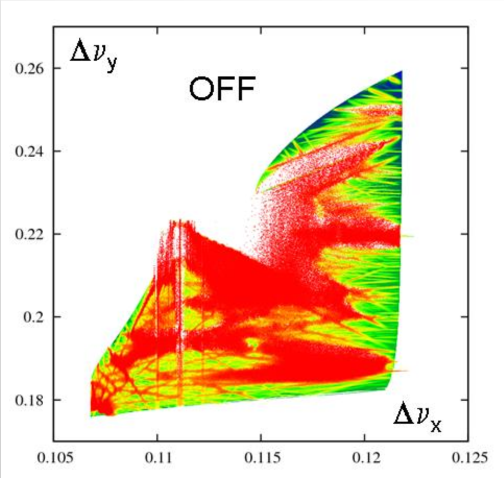


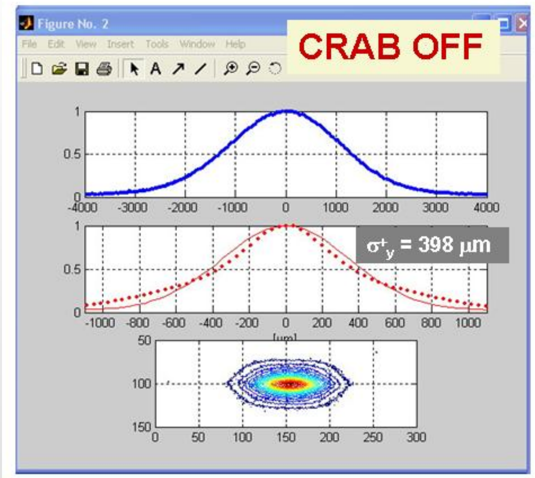
- *In 2007 the DAΦNE accelerator complex has been upgraded in order to implement a new collision scheme based on **large Piwinski angle, low–β** and **Crab-Waist compensation** of the synchrobetatron resonances*
- *The upgrade took ~ **five months***
- ***Since May 2008** DAΦNE is delivering luminosity to the SIDDHARTA experiment.*

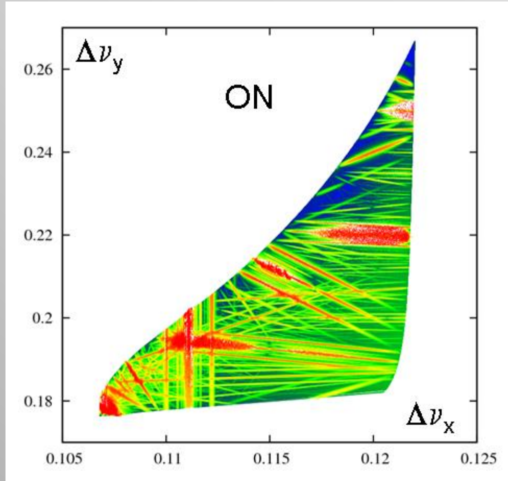
Suppression of beam-beam resonances at DAΦNE

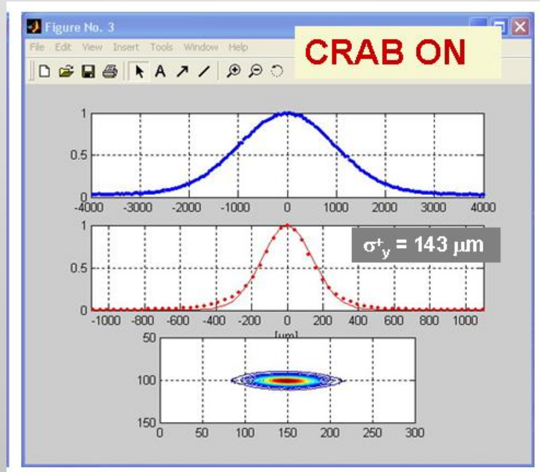
Frequency map analysis

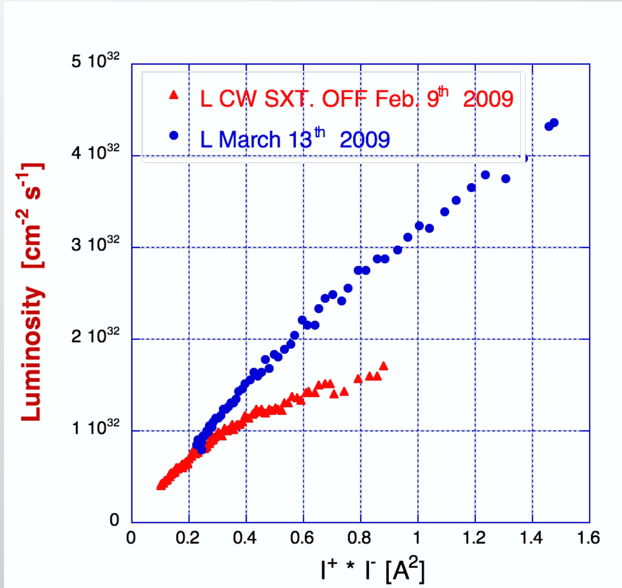
Images from SLM







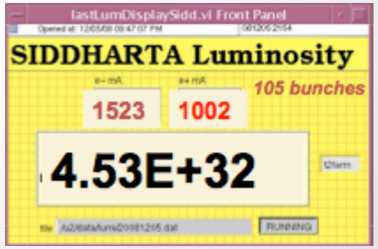




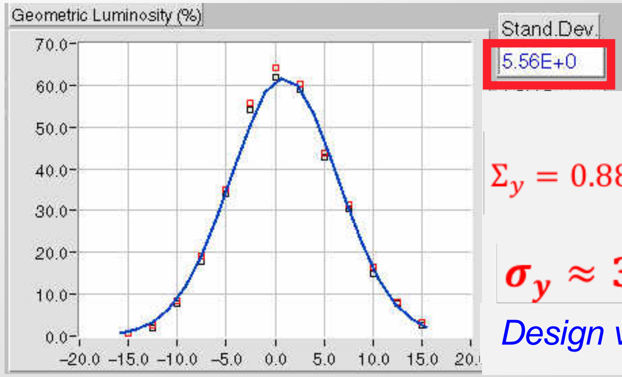
Crab-Waist Achievements during SIDDHARTA Run

Crab-Waist collisions and SIDDHARTA

- Large crossing angle and *Crab-Waist* collisions proved to be effective in *increasing luminosity by a factor 3*
- The DAΦNE collider, based on the new collision scheme including Large Piwinski angle and *Crab-Waist*, has been successfully commissioned achieving record performances



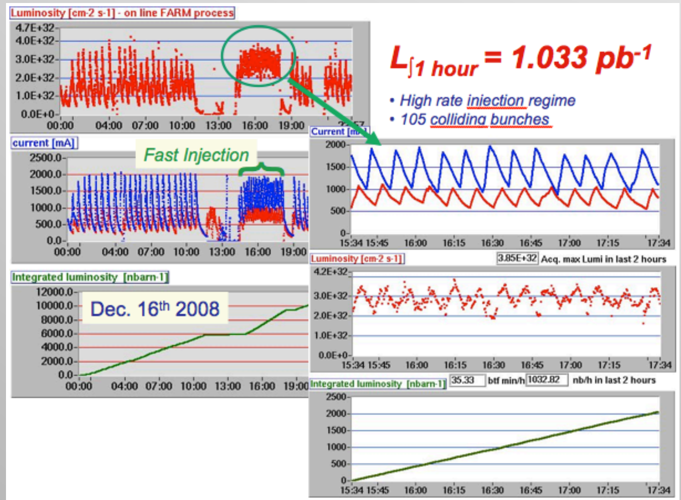
L_{peak}= 4.5*10^{32} cm^{-2} s^{-1}
$L_{\int 1\ day}$= 15.0 pb^{-1}
$L_{\int 1\ hour}$ = 1.033 pb^{-1}
$L_{\int run}$~ 2.8 fb^{-1} (delivered in 18 months)

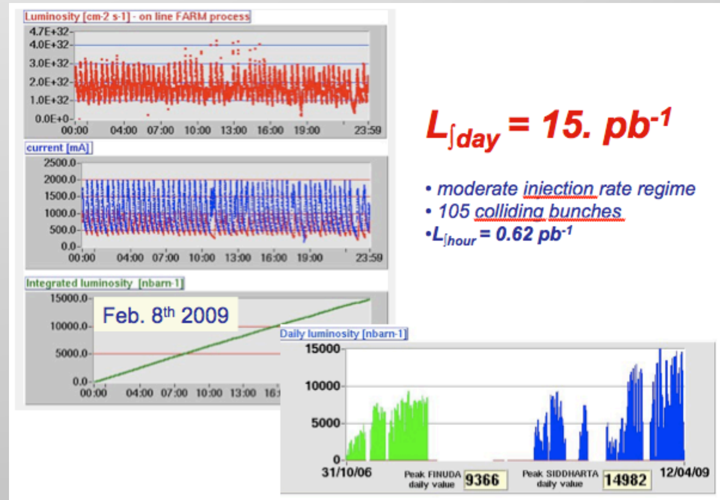


$$\Sigma_y = 0.88\sqrt{\sigma_{Ypos}^2 + \sigma_{Yele}^2}$$

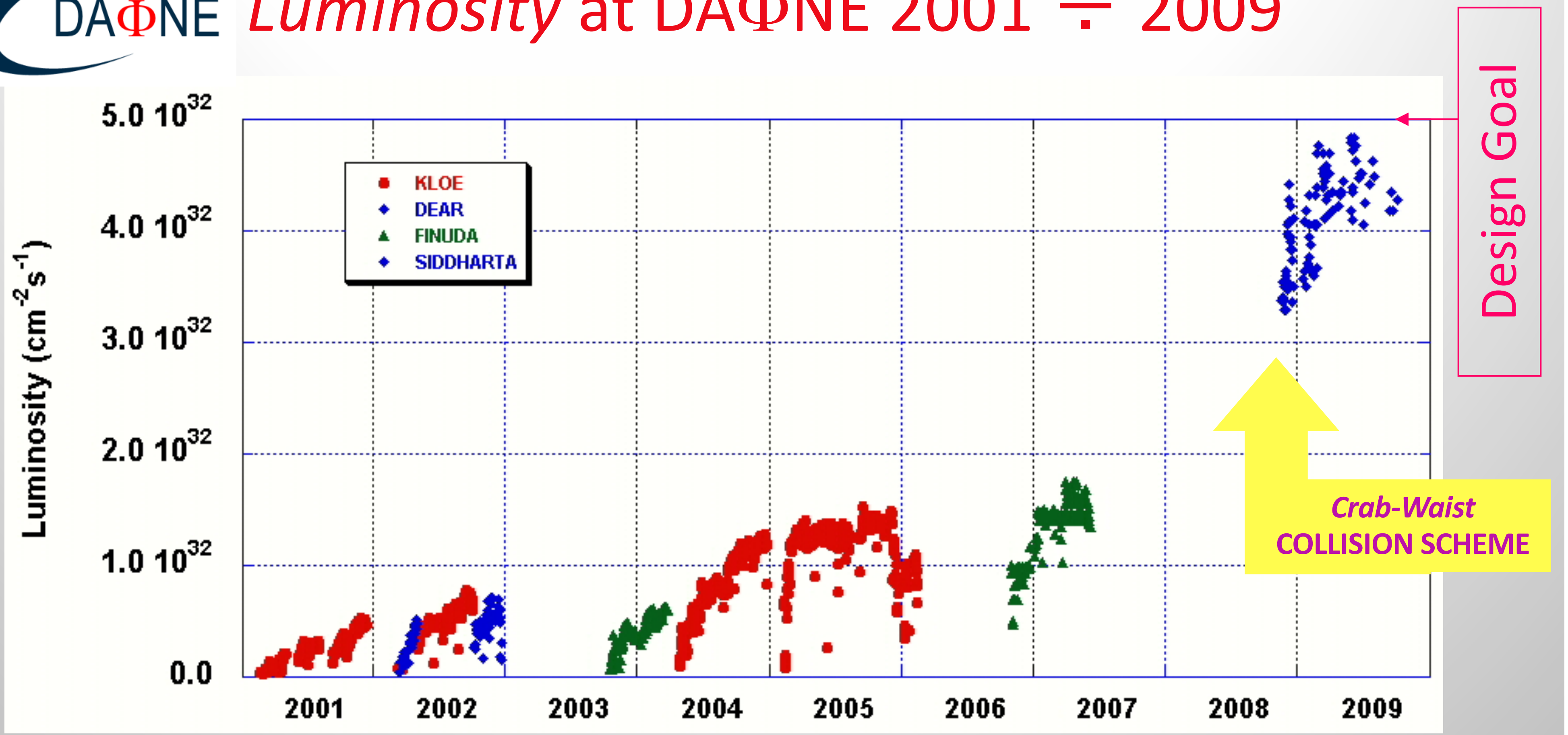
$$\boldsymbol{\sigma_y \approx 3.5\mu m}$$

Design value 3.1μm





Luminosity at DAΦNE 2001 ÷ 2009



A factor 3 higher luminosity achieved without increasing beam currents

No evidence of vertical BB saturation with *CW-Sextupoles* on (ξ_y = 0.044)

LRBB interaction cancelled

Crab-Waist Achievements during KLOE-2 Run

CW-Collision scheme for the KLOE detector

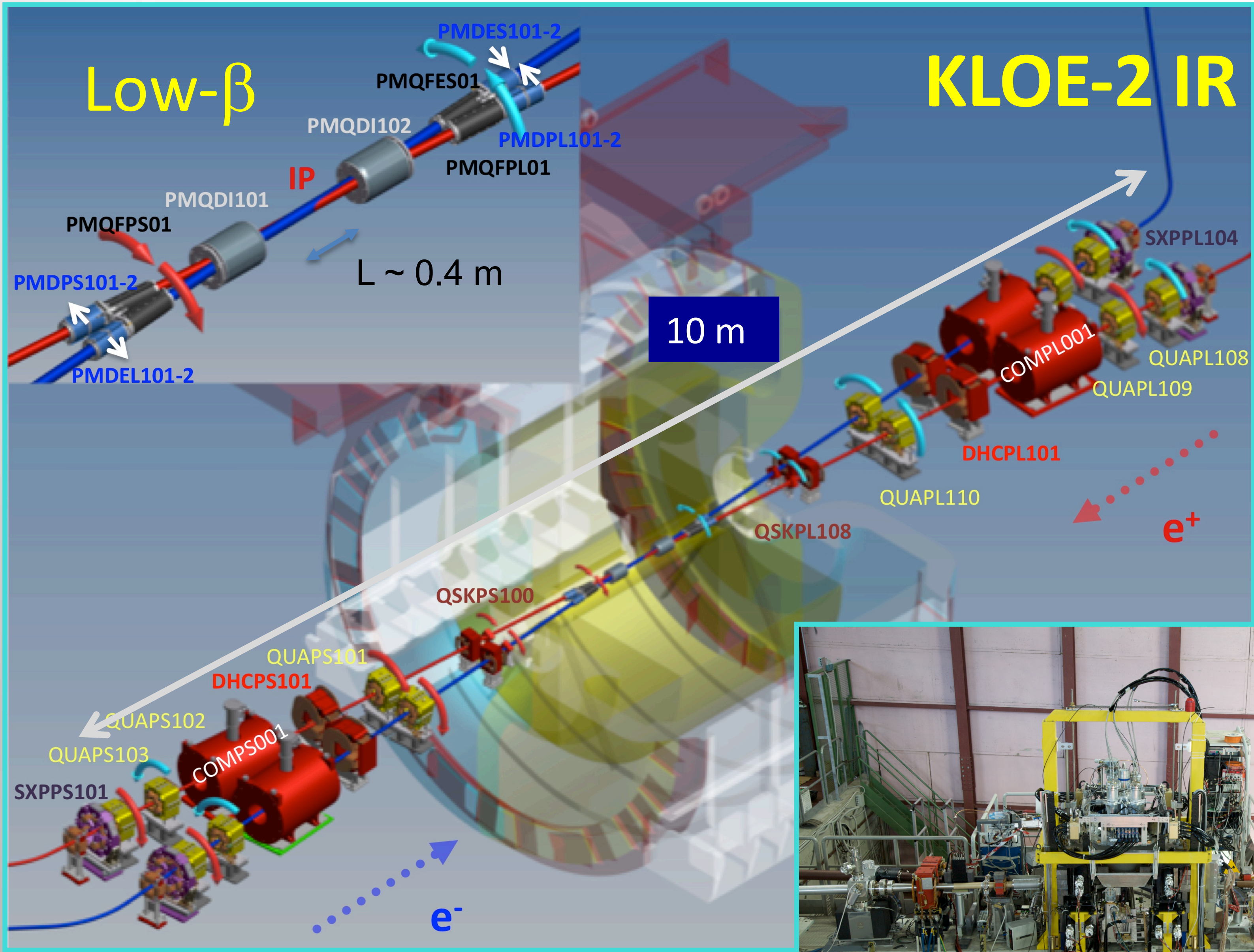
Integrating the high luminosity collision scheme with a large experimental detector introduces new challenges in terms of IR layout, optics, beam acceptance, coupling correction

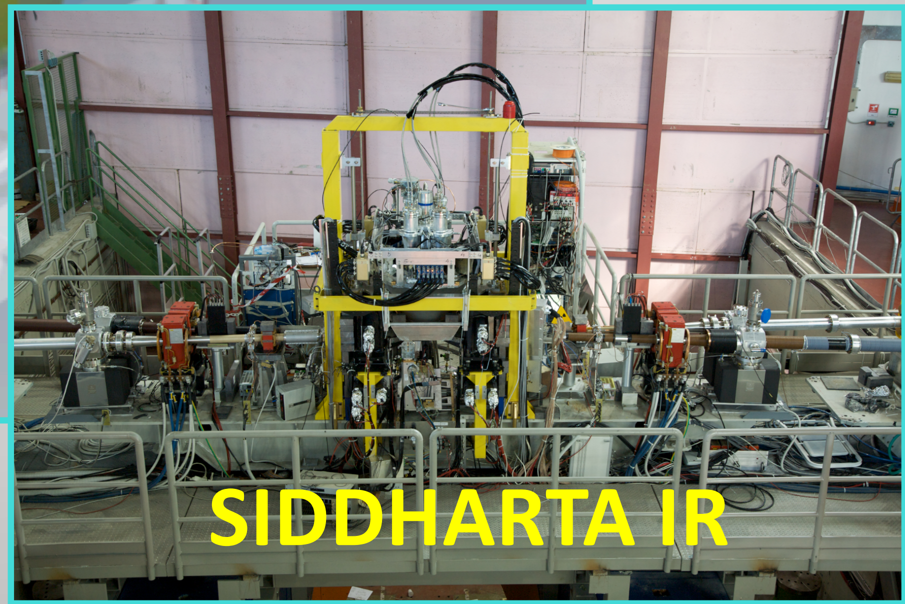
Crucial Points:

IR optics complying with:
- Low-β
- ***Crab-Waist*** collision scheme
- Coupling compensation
- Beam trajectory control

IR mechanical design allowing:
- Large crossing angle
- Early vacuum pipe separation after IP
- Mechanical stability of the low-β doublet

DAΦNE





C. Milardi *et al 2012 JINST 7 T03002.*

Betatron Coupling correction

$\int_{KLOE} B \bullet dl$ *canceled by 2 anti-solenoids for each beam*

$$\int_{KLOE} B \cdot dl = 2.048 \quad [Tm] \quad \rightarrow \quad I_{KLOE} = 2300.[A]$$

$$\int_{comp} B \cdot dl = \pm 1.024 \quad [Tm] \quad \rightarrow \quad I_{comp} = 86.7[A]$$

In order to have coupling compensation also for off-energy particles

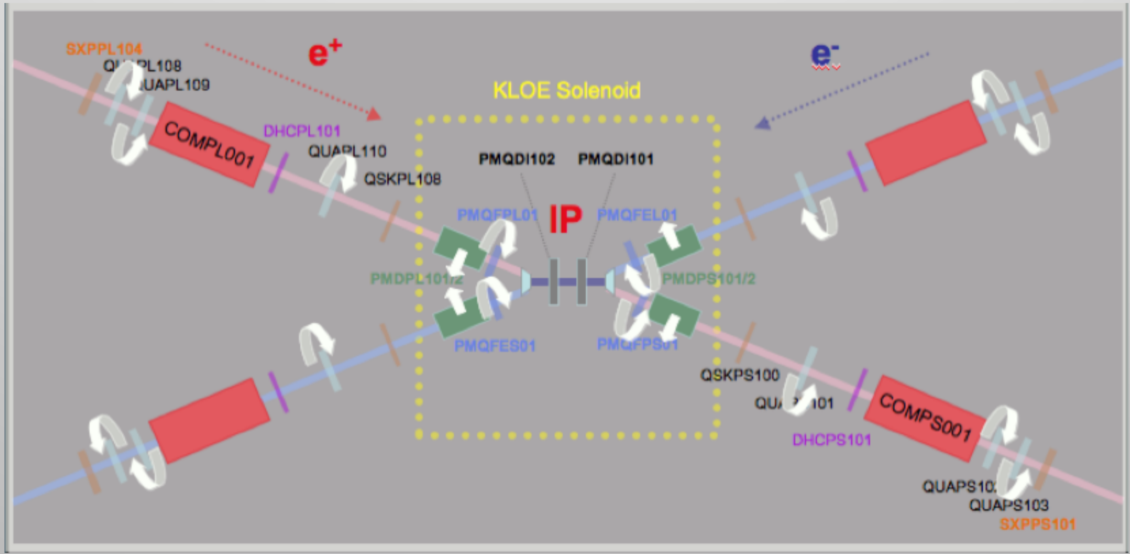
Fixed QUAD rotations

K is expected to be lower than for KLOE past

$$K_{KLOE1} = 0.2 \div 0.3\ \%$$

	Z from the IP [m]	Quadrupole rotation angles [deg] *Anti-solenoid current [A]*
PMQDI101	0.415	0.0
PMQFPS01	0.963	-4.48
QSKPS100	2.634	used for fine tuning
QUAPS101	4.438	-13.73
QUAPS102	8.219	0.906
QUAPS103	8.981	-0.906
COMPS001	*6.963*	*72.48 (optimal value 86.7)*

C. Milardi *et al 2012 JINST 7 T03002.*



DAΦNE Activity Program for KLOE-2

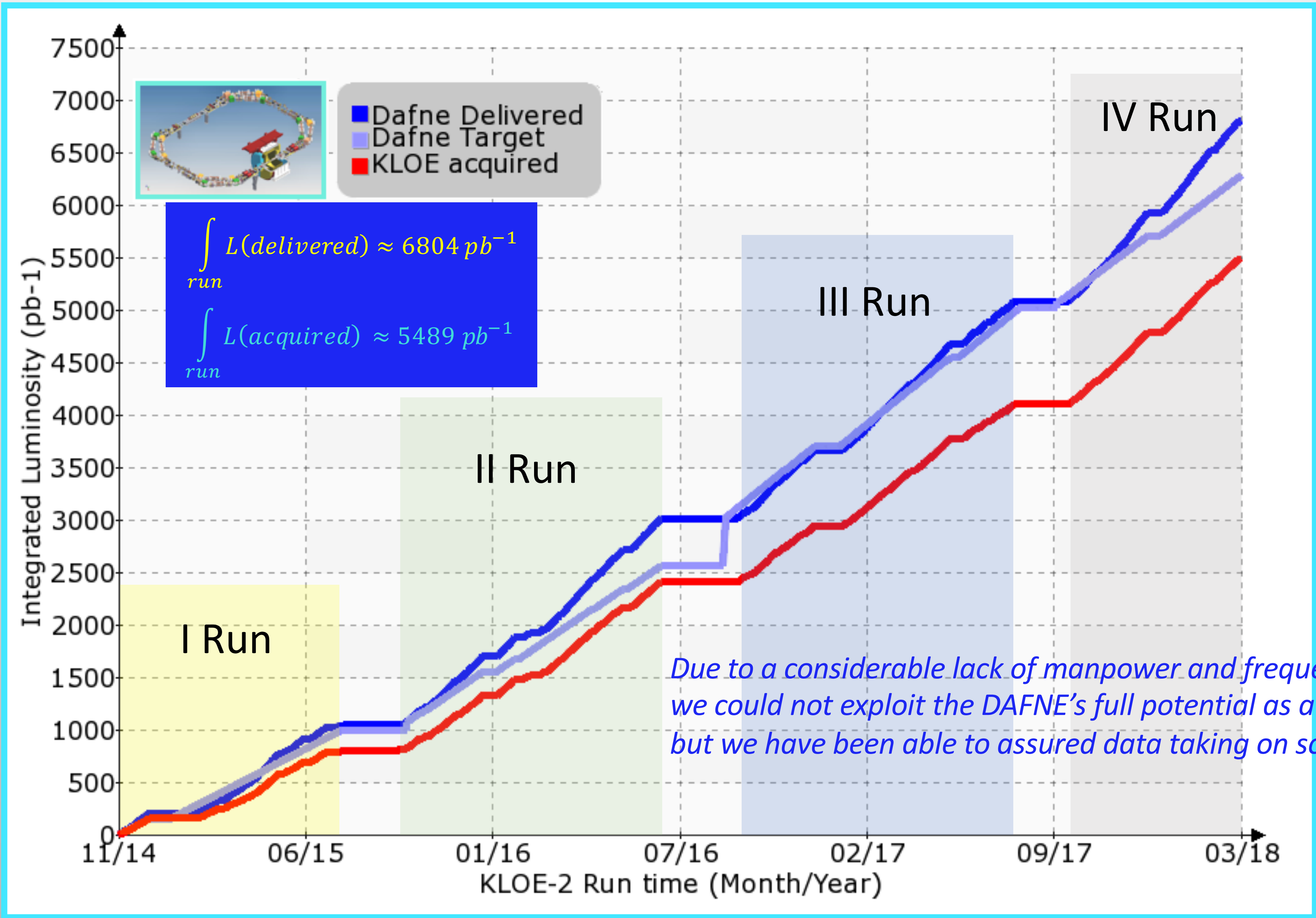
Preliminary Test Phase *fall 2010 ÷ Dec 2012*

Collider Consolidation
KLOE-2 detector layers installed *Dec 2012 ÷ Jun 2013*

KLOE-2 data taking

I Run *Nov 16th 2014 ÷ Jul 3rd 2015*
goal 1 fb^{-1}
II Run *Spt 28th 2015 ÷ Jun 29th 2016*
goal 1.5 fb^{-1}
III Run Spt 12nd 2016 ÷ Aug 1st 2017
goal 2 fb^{-1}
IV Run *Spt 6th 2017 ÷ Mar 31st 2018*
goal 1.5 fb^{-1}

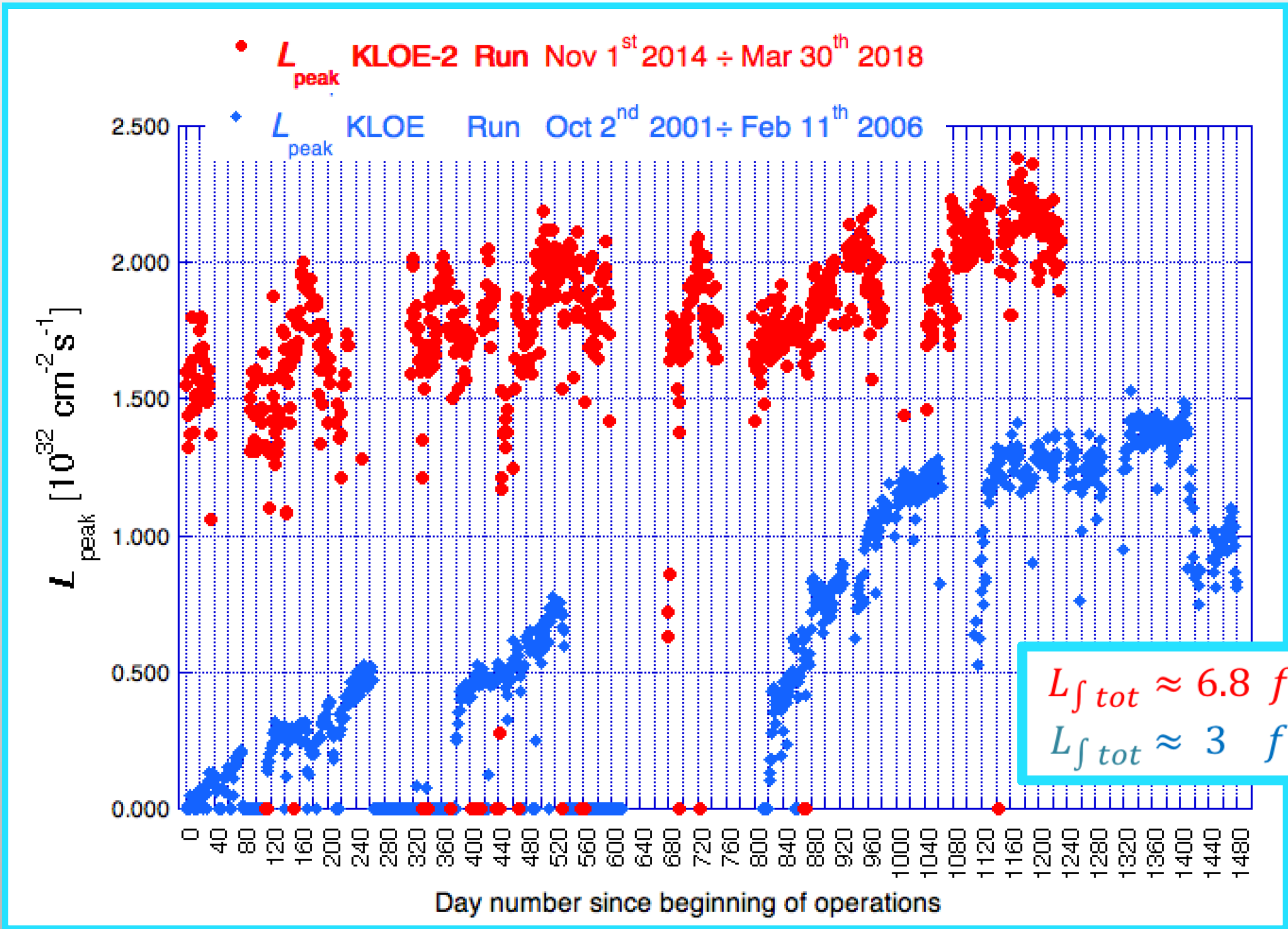
KLOE-2 Run Overview



Due to a considerable lack of manpower and frequent faults we could not exploit the DAFNE's full potential as a collider, but we have been able to assured data taking on schedule.

Crab-Waist Luminosity Gain

Crab-Waist provides a 59% increase in terms of peak luminosity as evidenced by data taken by the same detector with the same accuracy



$L_{\int tot} \approx 6.8 \ fb^{-1}$

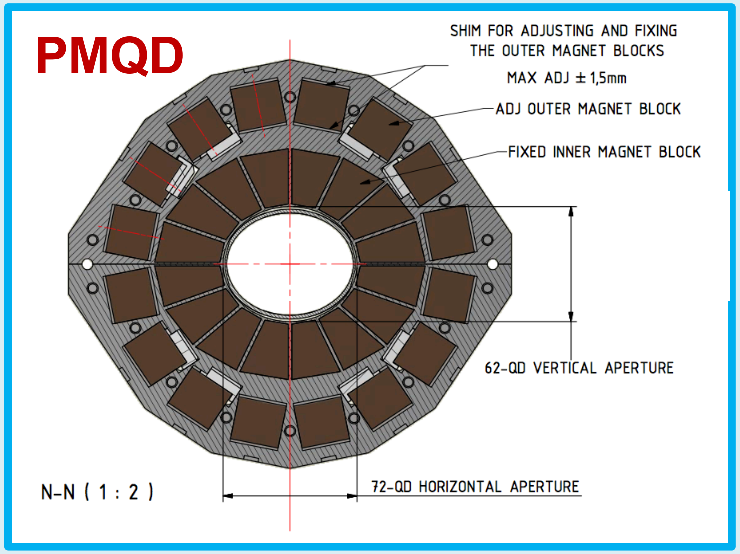
$L_{\int tot} \approx 3 \ fb^{-1}$

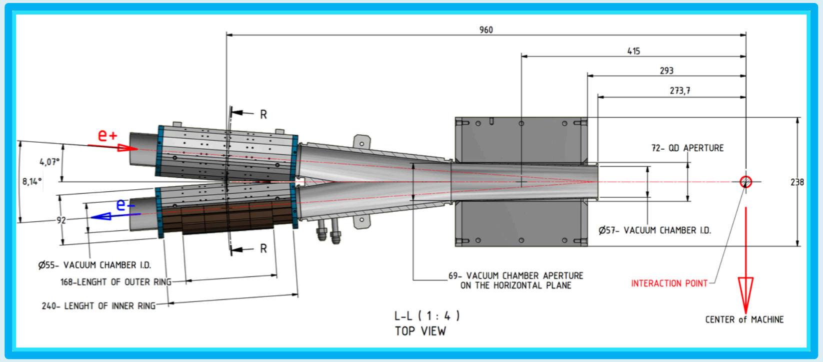
Crab-Waist Interaction Region for SIDDHARTA-2 Run

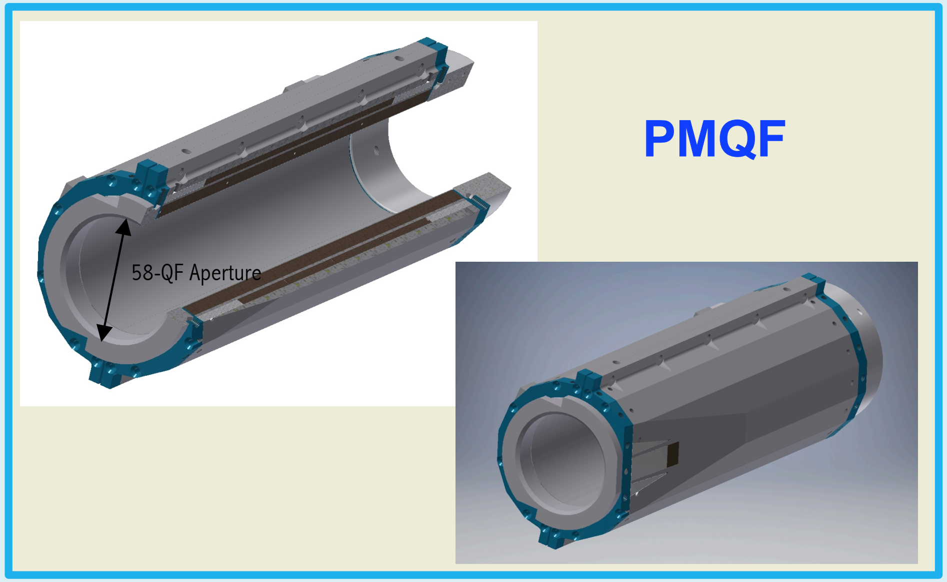
PMQs specifications

New PMQs are Halbach type magnets made of SmCo2:17

PMQs have been designed in collaboration with the ESRF magnet group.







	PMQD	PMQF
Beam Pipe Aperture H-V (mm) at IP (I row) and at Y (II row) side	57 69 - 55	54
Inner Apert. With Case H-V (mm)	72 - 62	58
Outer Diameter H-V (mm)	238 - 220	95.6
Mech. Length Inner-Outer (mm)	220	168 - 240
Nominal Gradient (T/m)	29.2	12.6
Integrated Gradient (T)	6.7	3.0
Good Field Region (mm)	±20	±20
Integrated Field Quality |dB/B|	5.00E-4	5.00E-4
Magnet Assembly	2 halves	2 halves

DAΦNE IR and SIDDHARTA-2

SIDDHARTA-2 Run Timeline

Spt – Dec 2019 collider commissioning for SIDDHARTA-2

Mid Jan – March 2020 (pandemic)

February – Jul 2021

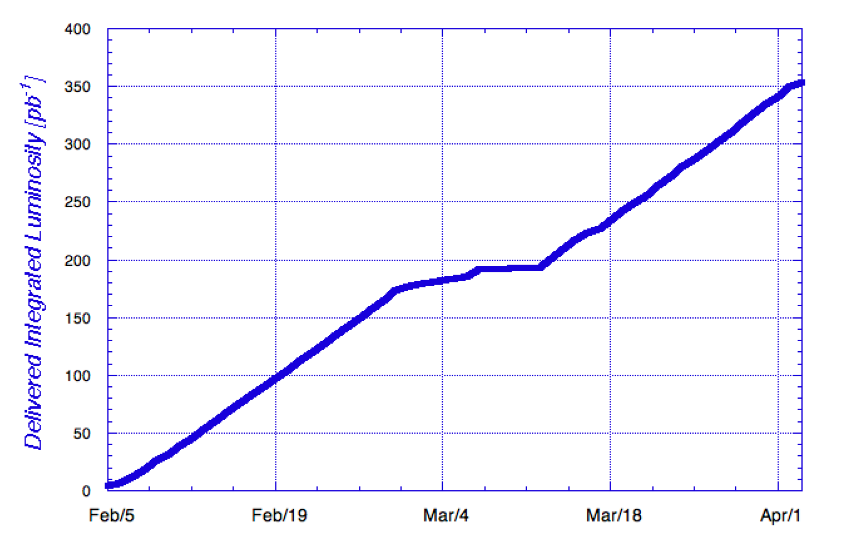
Apr – Jul 2022 SIDDHARTINO run completed, *and preliminary run with Deuterium target*

Apr – Jul 2023 *Neon run*

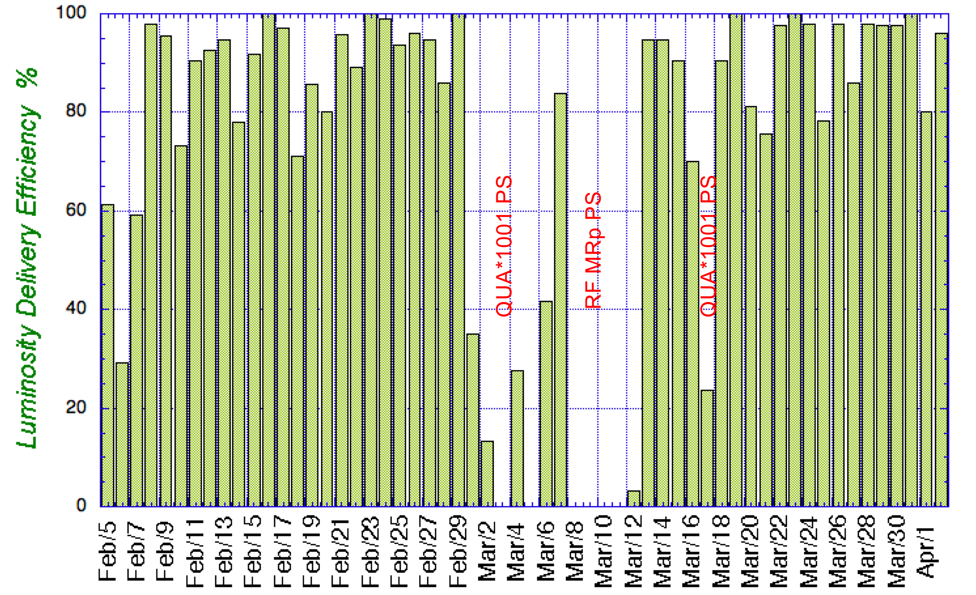
Sep 15th – Dec 19th 2023
Periodical maintenance, and winter shutdown

Jan 18h – Jul 2024
Data taking with deuterium target

Present Run with Deuterium target

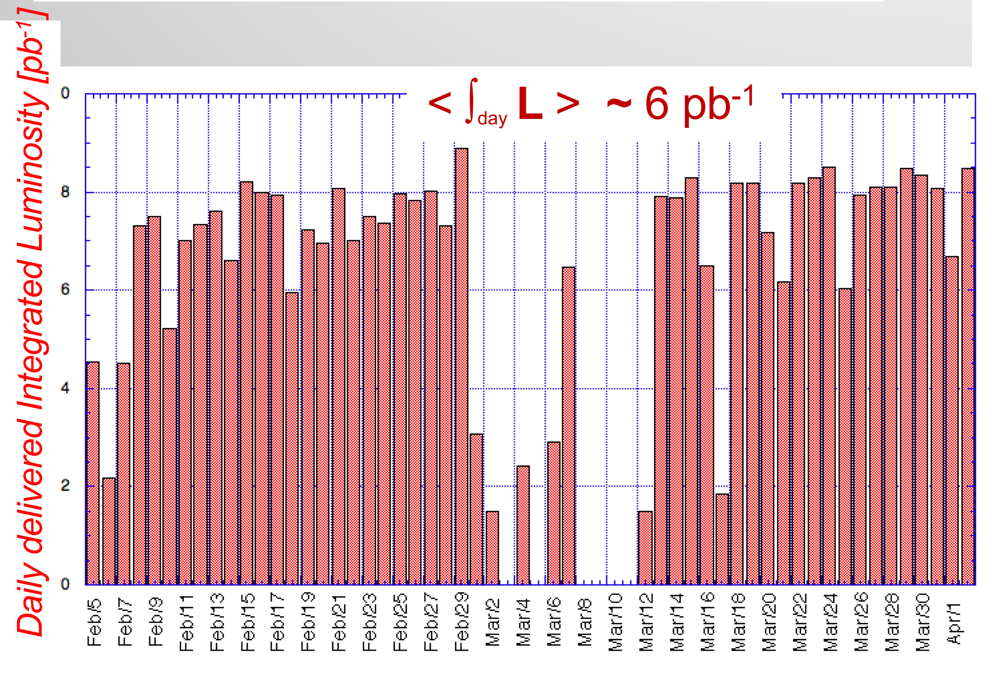


$< L_{del.Eff.} > \sim 72$ %



Percentance of the 24h DAFNE was delivering a $L_{peak} \geq 1 \cdot 10^{32}$ cm^{-2}s^{-1}

Few localized faults occurred.



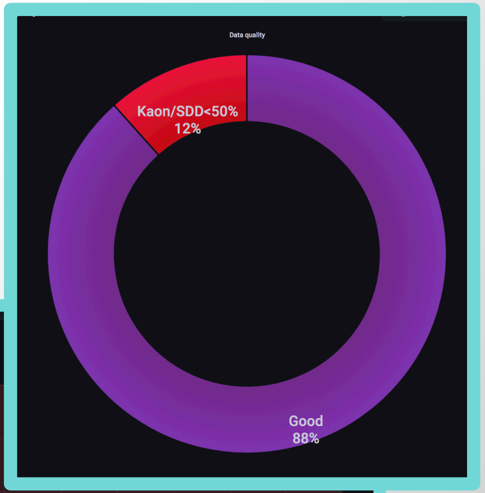
Data range Feb 5th – Apr 2nd 2024

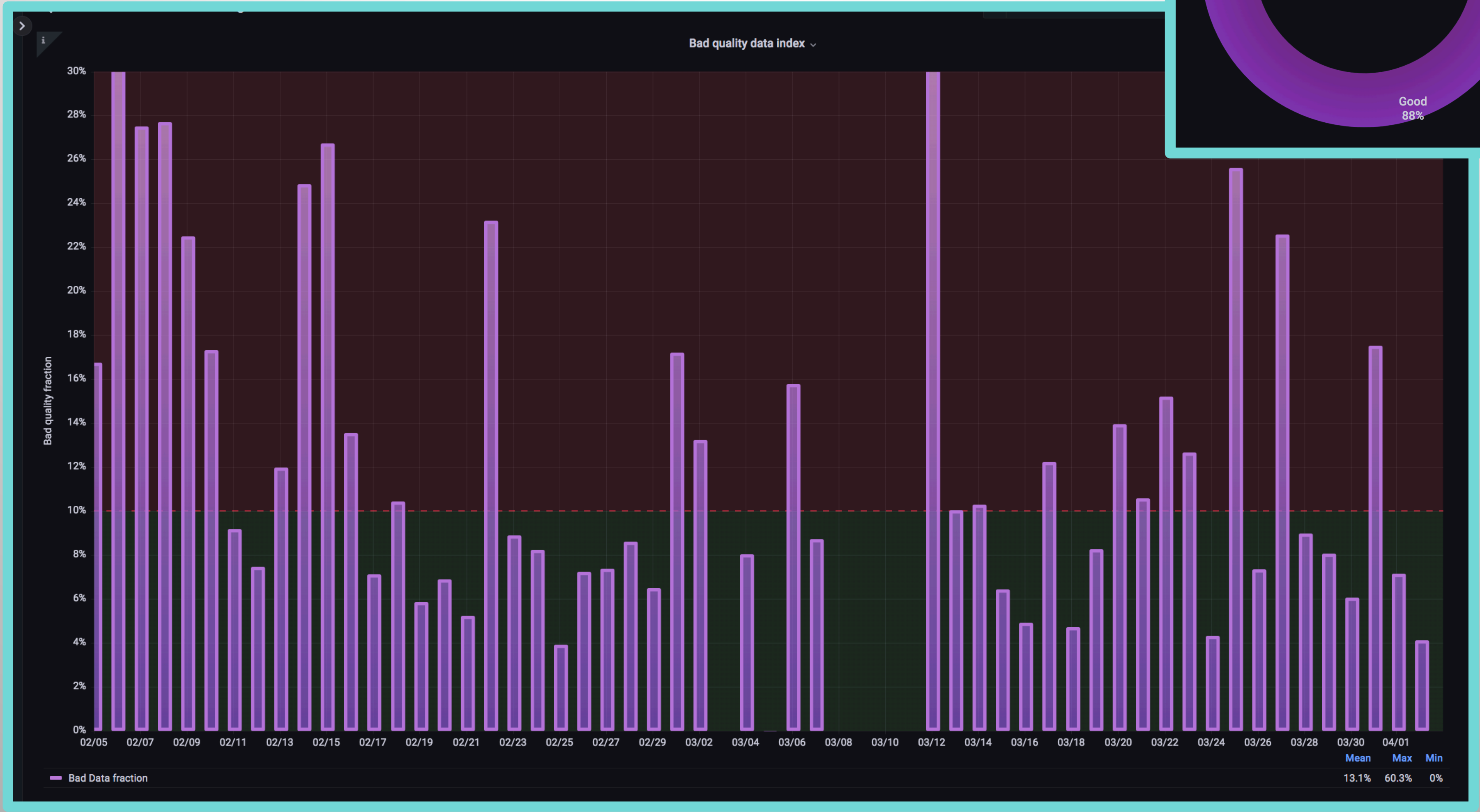
Integrated luminosity delivered to the SIDDHARTA experiment to detect the kaonic deuteriumX-ray transition is:

$\int L \sim 349{,}86$ pb^{-1}

Data Quality

Kaon/SDD ratio ≥ 50% assures that data acquired can be used for physics.





(C. Milardi for the DAΦNE Team)

The Enduring interest in DAΦNE

The DAΦNE lepton collider has been powering physics research at the LNF since almost 20 years.

This has been possible because DAΦNE implemented and successfully tested, with detectors of different complexity, a new collision scheme: the ***Crab-Waist Collision Scheme***.

The *Crab-Waist* concept was conceived, implemented, and tested in about two years, and allowed to increase the DAΦNE luminosity by about a factor three, reducing at the same time the background on the detector.

SuperKEKB adopted Crab-Waist in 2020 achieving world record luminosity securing the BELLE-II detector data taking as well.

Crab-Waist Colliders

Nowadays Crab-Waist has become the main approach to collision for present and future lepton colliders.

Colliders	Location	Status
DAΦNE	Φ-Factory Frascati, Italy	In operation (SIDDHARTA, KLOE-2, **SIDDHARTA-2**)
SuperKEKB	B-Factory Tsukuba, Japan	Adoped CW collision in 2020
SuperC-Tau	C-Tau-Factory Novosibirsk, Russia	Russian mega-science project
SuperCharmTau	Tau-Charm Factory Sarov, Russia	Design study
SuperTauCharm	Tau-Charm Factory Hefei, China	Proposed, significant R&D funding
FCC-ee	Z,W,H,tt-Factory CERN,Switzerland	91 km, CDR
CEPC	Z,W,H,tt-Factory China	100 km, CDR released in September 2018

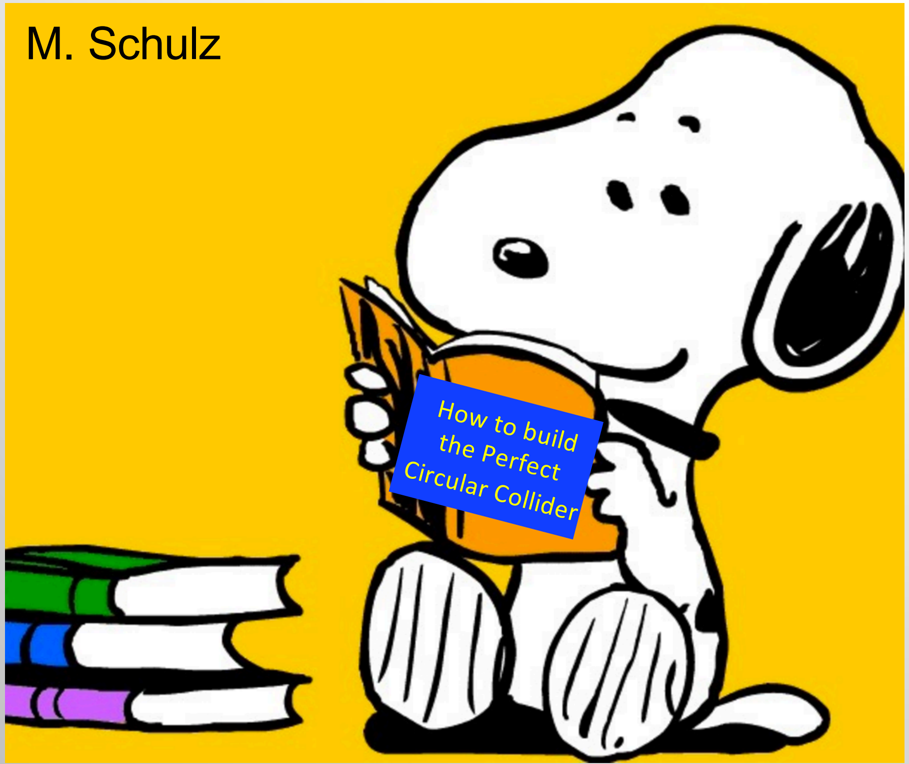
Conclusions

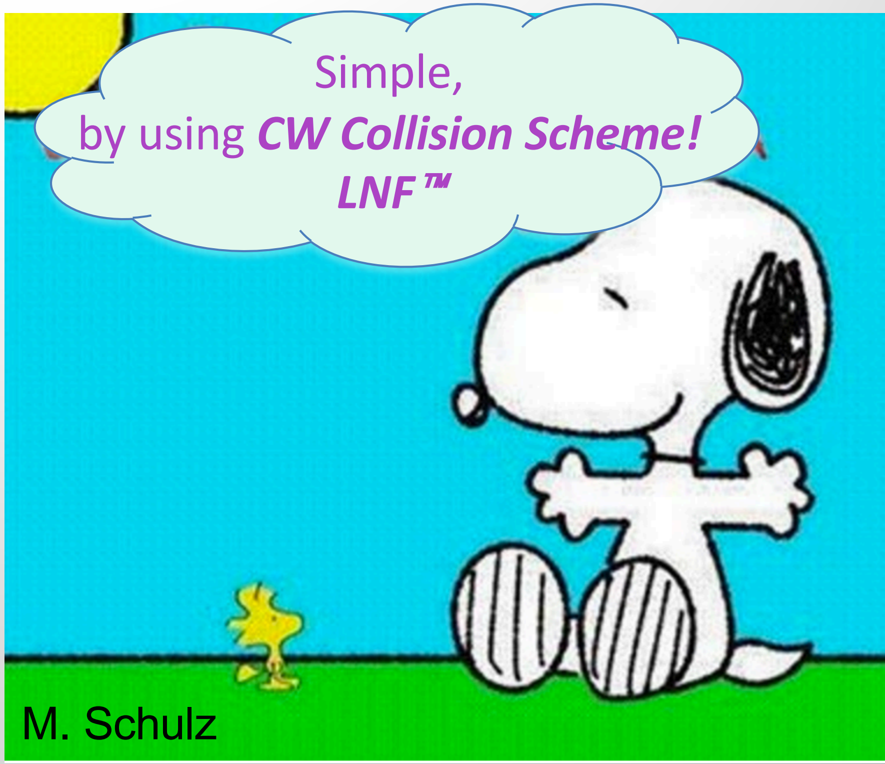
DAFNE is the first and only Collider running with the *Crab-Waist* Collision Scheme, presently the third different detector is preparing to take data.

The new collision scheme including Large Piwinski angle and Crab-Waist compensation of the beam-beam interactions has proved to be a viable approach to increase the luminosity

- *It has been succesfully tested and routinelly used during the SIDDHARTA run when a factor ~3 higher instantaneous luminosity has been measured*
- *Crab-Waist collision scheme has also been the leading concept in designing the new IR for the KLOE-2 experiment. KLOE-2 data-taking profited from a daily integrated luminosity comparable with the best ever measured at DAΦNE, despite the instantaneous luminosity gain was a factor 2 lower wrt the one measured with the SIDDHARTA configuration. NO TIME for MD!*
- *KLOE-2 run has clearly stated the Crab-Waist* collision scheme effectiveness even in presence of a large detector including high intensity longitudinal field at low energy colliding beams
- Presently DAFNE operations are finalized to provide data to the SIDDHARTA-2 experiment.

…. *let me joke*





Thank you for your attention

Spare Slides

The DAΦNE Accelerator Complex

LINAC
e^+ 550 MeV
e^- 800 MeV

$e^+ e^-$
$C \approx 97$ m
$E_{CM} = 1.02$ GeV (Φ)