Particle Accelerator Physics

How to run a Supercollider Part I

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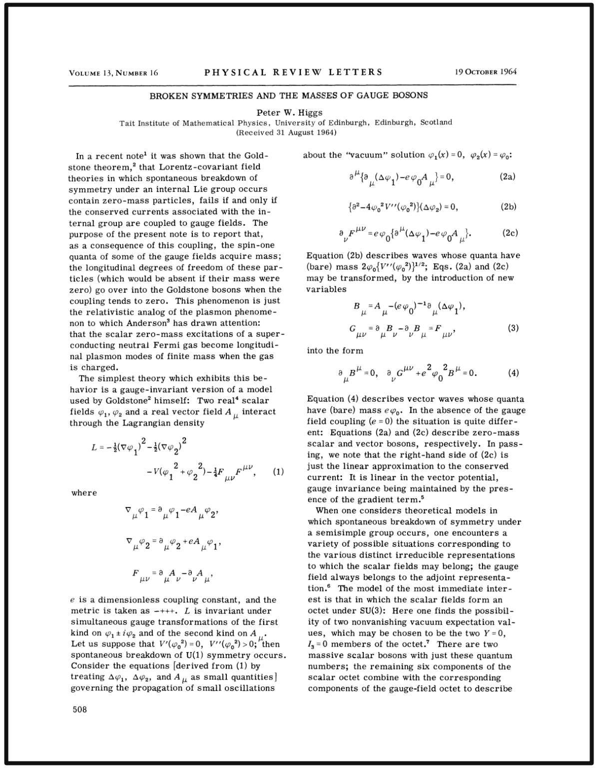
1964 – 2012: The Higgs Boson Adventure



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BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
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(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact through the Lagrangian density

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^2 + \varphi_2^2) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 \pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2) = 0$, $V''(\varphi_0^2) > 0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \qquad (2a)$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A^\mu\}. \qquad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \qquad (3)$$

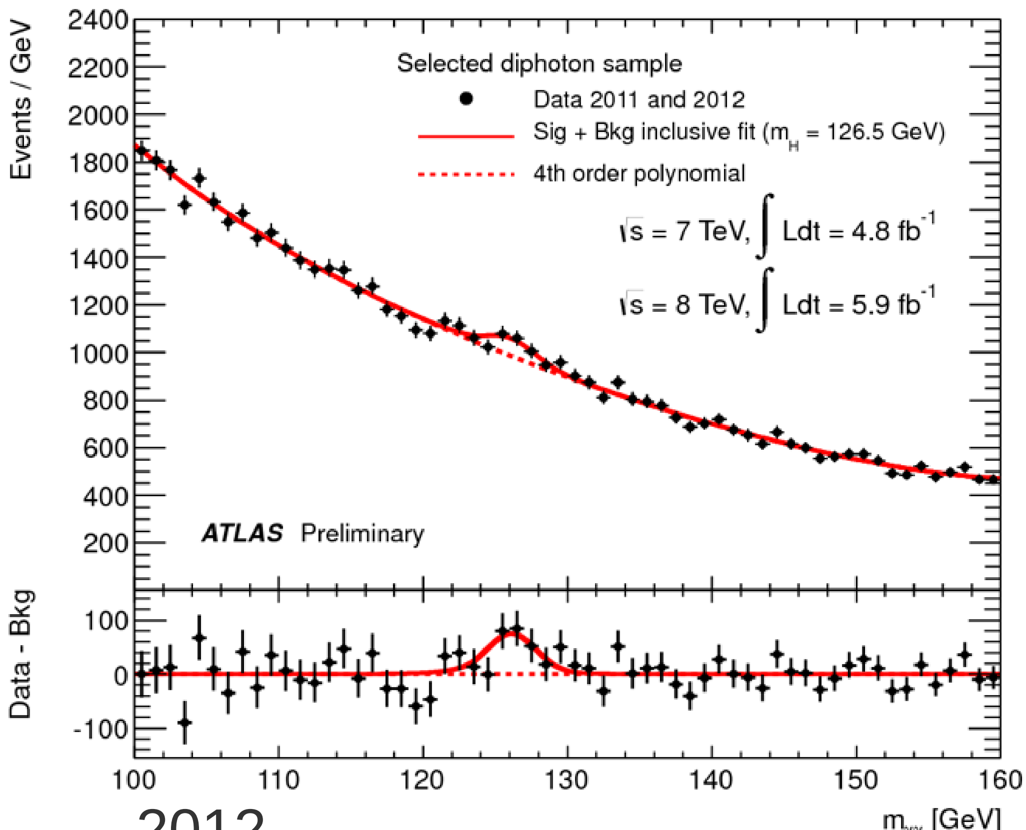
into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \qquad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e = 0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y = 0$, $I_3 = 0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

1964

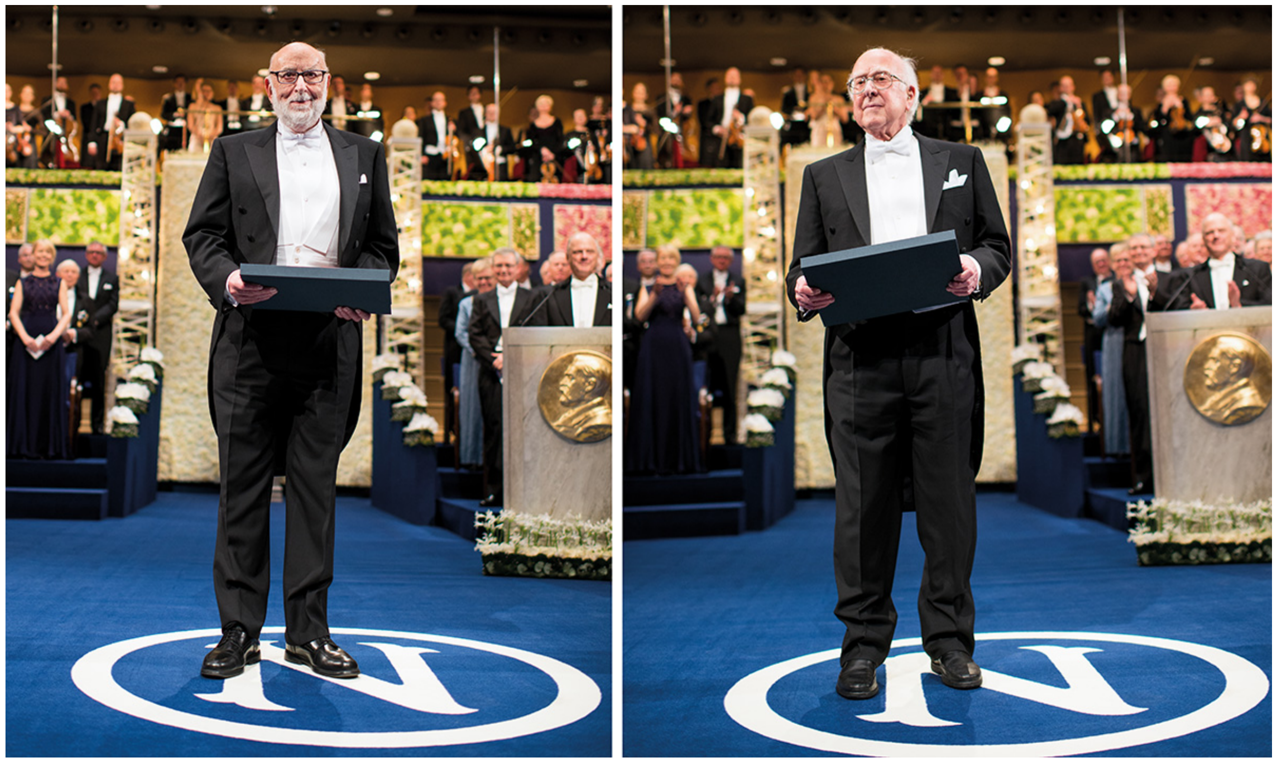


2012

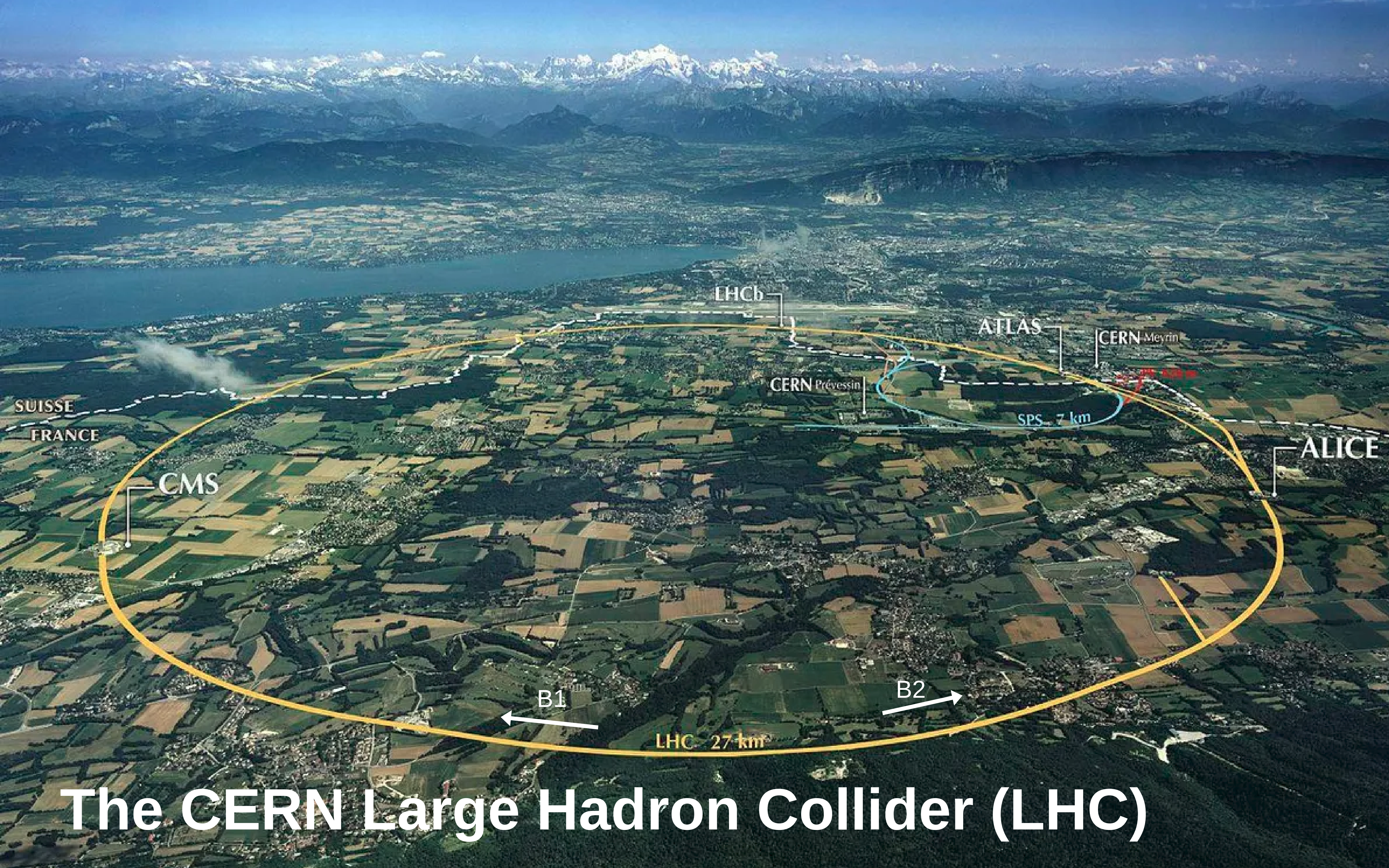
Introduction

48 years of search between prediction and discovery of the Higgs Boson

Why was it so challenging?



Credit: A. Mahmout / Nobel Media



The CERN Large Hadron Collider (LHC)

LHC Physics Goals

- What is the origin of mass? (Higgs Boson) – **ATLAS and CMS**
- Will we discover evidence for supersymmetry? - **ATLAS and CMS**
- What are dark matter and dark energy? – **ATLAS, CMS**
- Why is there far more matter than antimatter in the universe? - **LHCb**
- How does the quark-gluon plasma give rise to the particles that constitute the matter of our Universe? - **ALICE**
- Smaller experiments FASER, ATLAS-ALFA, TOTEM, LHCf...

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

LHC Design Parameters

	Unit	Protons		Lead Ions $^{208}Pb^{82+}$	
		Injection	Collision	Injection	Collision
Energy	[GeV]	450	7000	36900	574000
Relativistic γ		479.6	7461	190.5	2963.5
Max. Luminosity[a]	[$cm^{-2} s^{-1}$]	$1.0 \cdot 10^{34}$		$1.0 \cdot 10^{27}$	
Num. of bunches		2808		592	
Bunch spacing	[ns]	24.95		118.58	
Part. per bunch		$1.15 \cdot 10^{11}$		$6.7 \cdot 10^{7}$	
Beam current	[A]	0.582		0.00612	
Norm. emittance	[μm rad]	3.50	3.75	1.40	1.50
Bunch length σ_l	[cm]	11.24	7.55	9.97	7.94
Momentum spread	[10^{-3}]	1.90	0.45	0.39	0.11
β^* at IP2	[m]	10	10	10	0.55

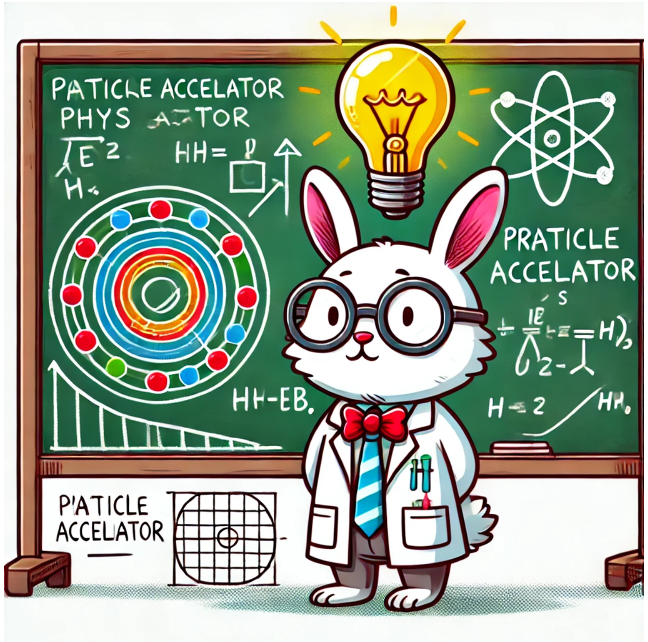
This Lecture Series: Accelerator Physics

- **What do we need to generate LHC beams needed for Higgs search et al.?**
  - Magnets for focusing and steering
  - Particle beam acceleration
  - Beam Instrumentation
  - Pre-accelerators ("Injectors")
- **What are the biggest challenges in operation of the LHC?**
  - Performance reach
  - Machine safety and operational efficiency

Main takeaways

- Concept of beam steering, focusing and acceleration
- Basics of linear accelerators and synchrotrons (like the LHC)
- Betatron motion and phase advance
- Concept of emittance
- Concept of β*, crossing angle and luminosity
- Most important beam instrumentation devices

- We will illustrate all with LHC examples!



Magnets: Dipoles

Dipole Magnets

Moving coordinate system !

Spacially homogeneous magnetic field exploiting Lorentz

$$F = q\,E + q\,(v \times B)$$

Must be identical to centrifugal force!

$$= \frac{\gamma m v^2}{\rho}$$

$$\frac{1}{\rho}\left[\mathrm{m}^{-1}\right] = 0.2995\,\frac{B_{\perp}\,[\mathrm{T}]}{cp\,[\mathrm{GV}]}$$

Bending radius ρ for perpendicular B-field

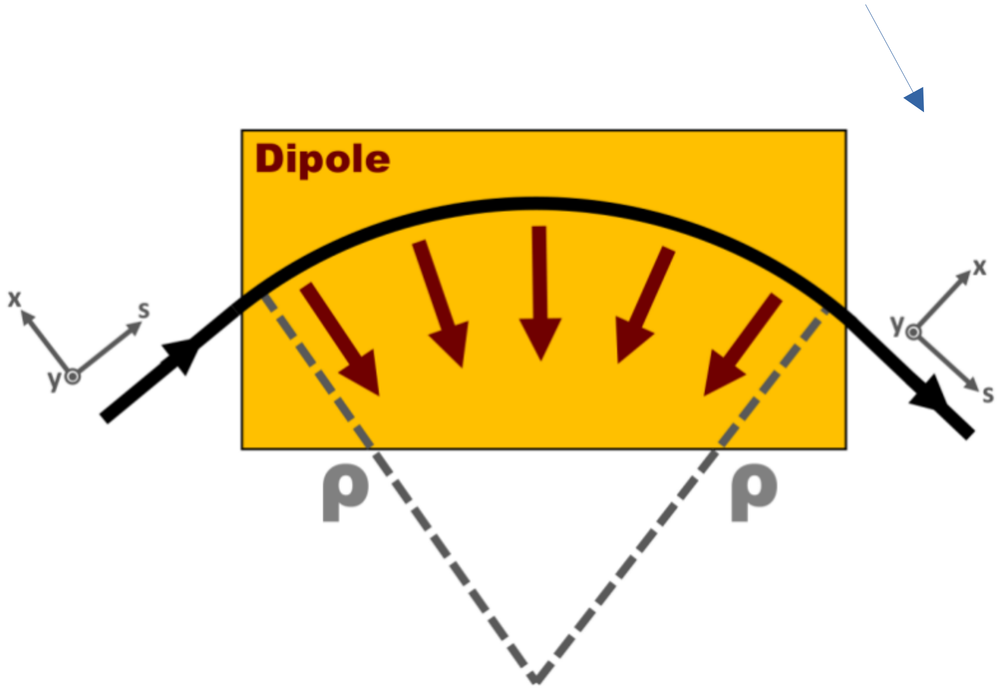
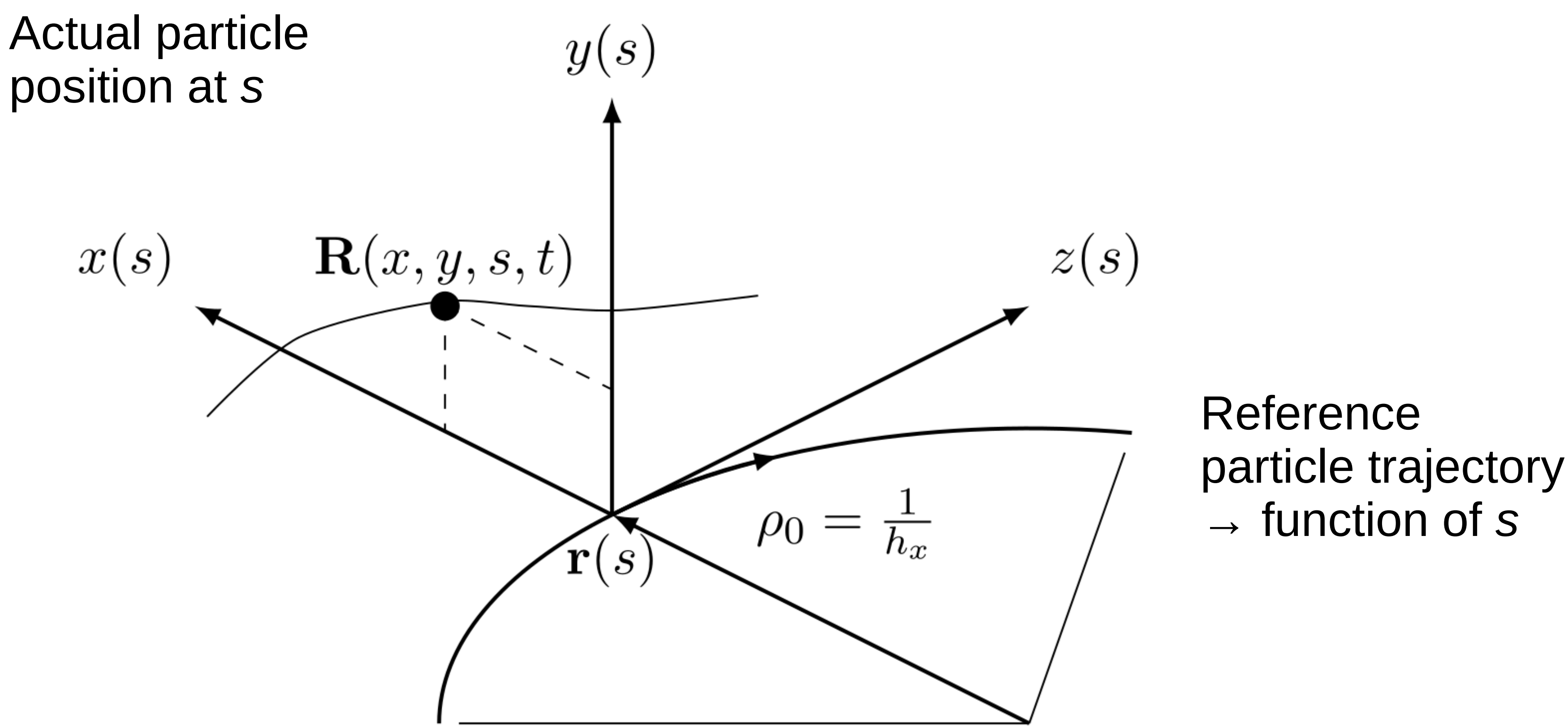


Figure courtesy of J. Dilly

Coordinate system



Dipole Magnets

Can we steer the beam also with an E-field?

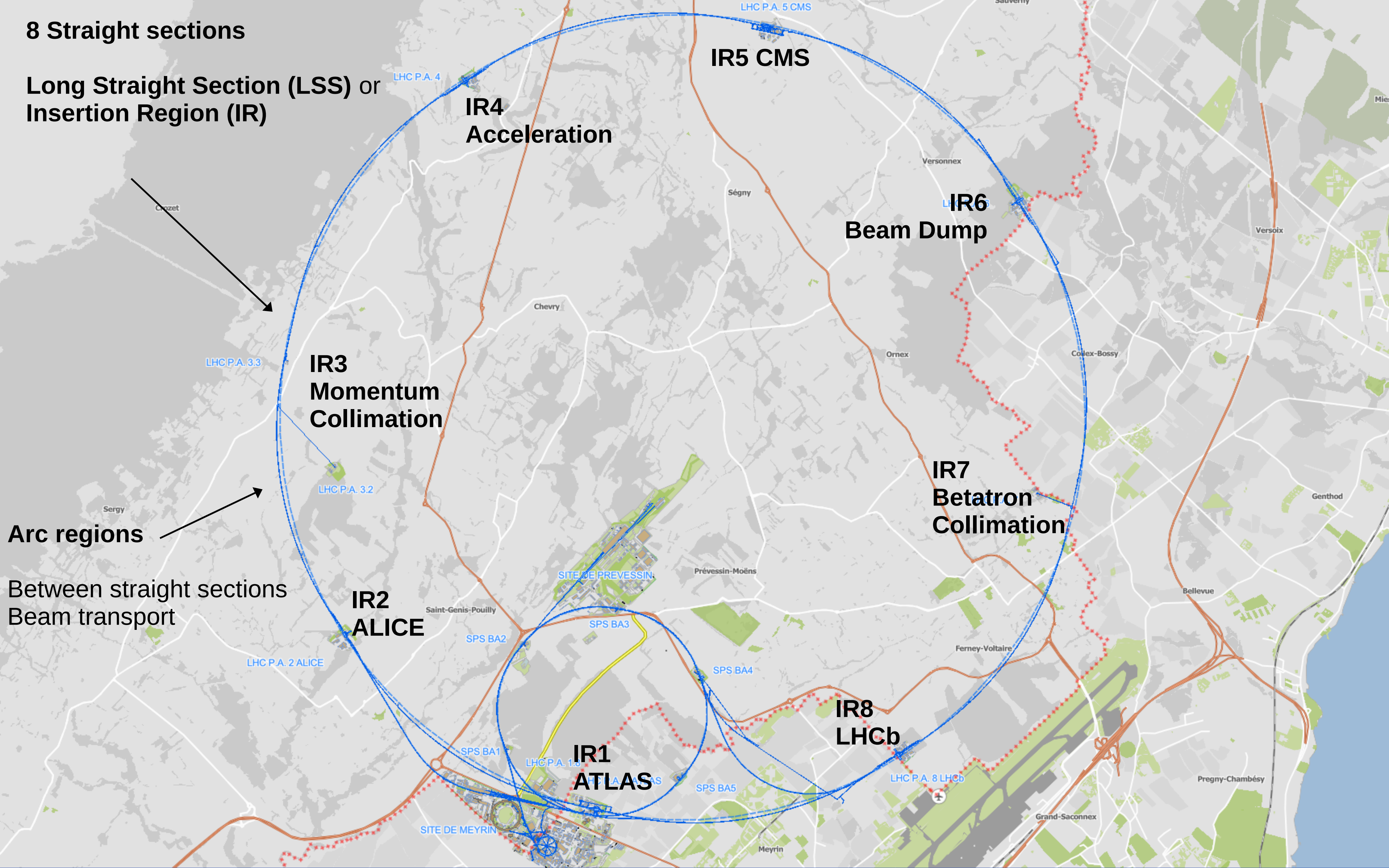
$$F = q\,E + q\,(v \times B)$$

At the LHC:

$$v \approx c = 2.998 \times 10^{8}\,\mathrm{m/s}$$

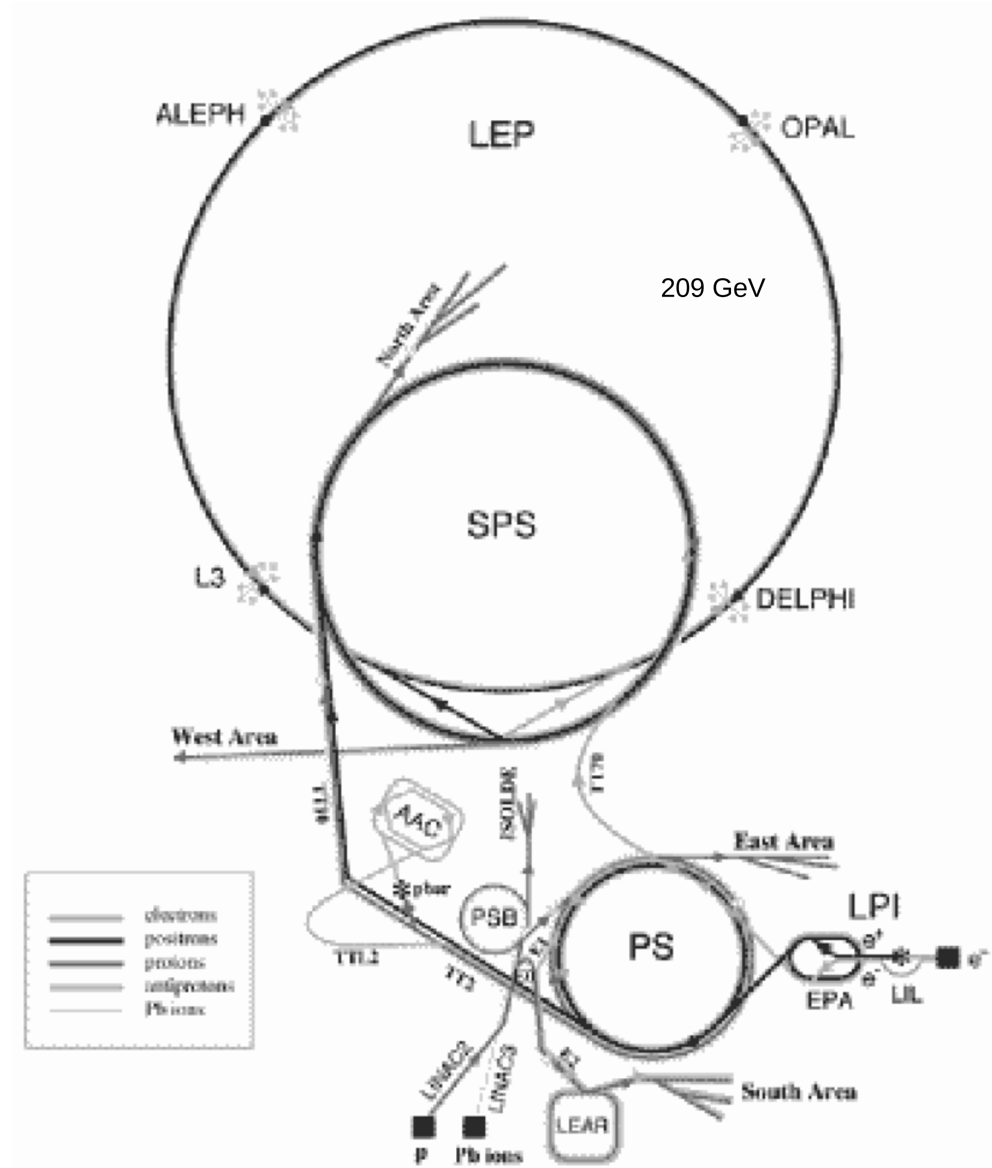
Equivalent force from electric and magnetic field → $1\,\mathrm{T} \cong 3 \times 10^{8}\,\mathrm{V/m}$

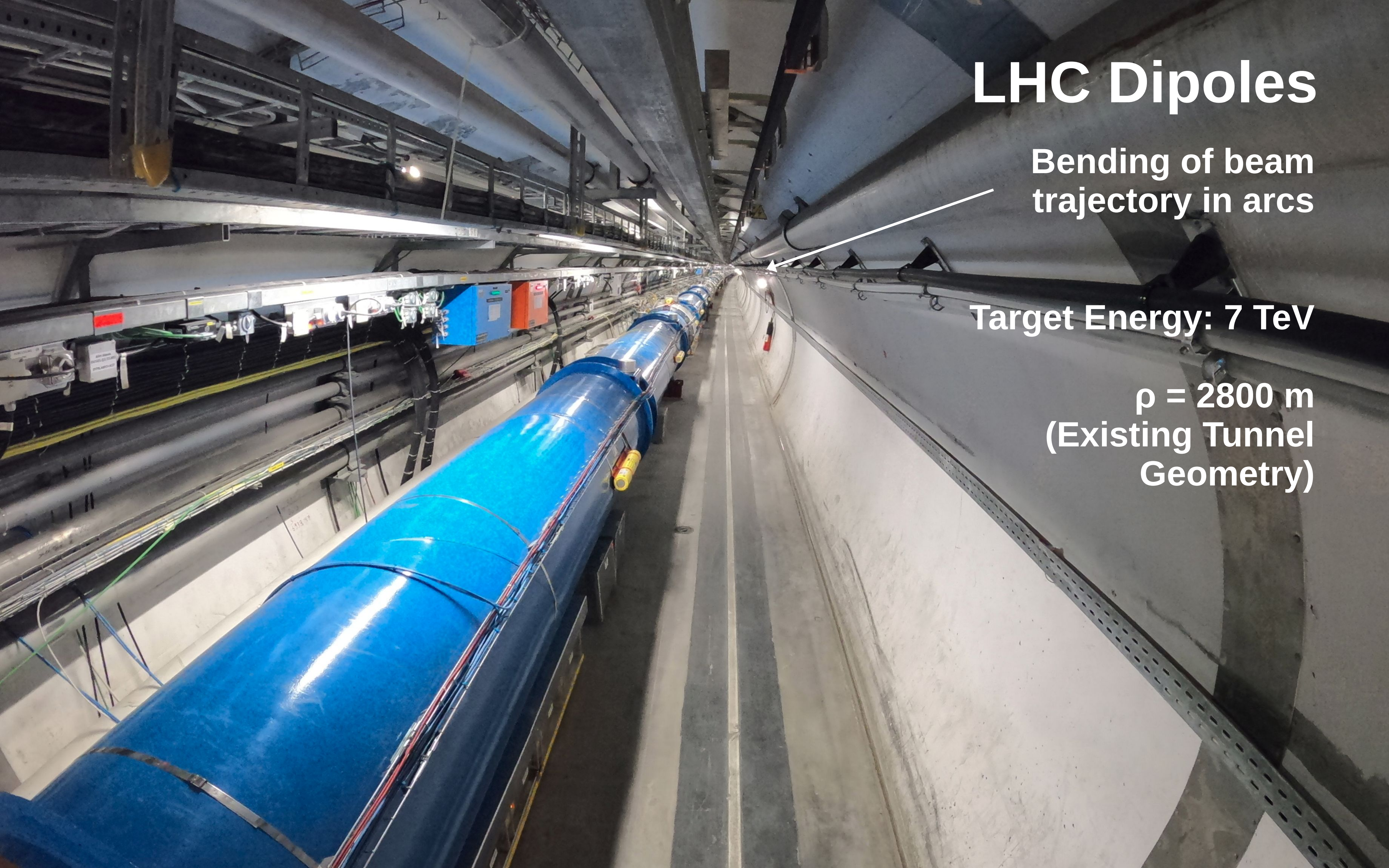
→ Only magnets are used for beam steering!


8 Straight sections
Long Straight Section (LSS) or Insertion Region (IR)
Arc regions
Between straight sections
Beam transport
IR1
ATLAS
IR2
ALICE
IR3
Momentum
Collimation
IR4
Acceleration
IR5 CMS
IR6
Beam Dump
IR7
Betatron
Collimation
IR8
LHCb
LHC P.A. 5 CMS
LHC P.A. 4
LHC P.A. 3.3
LHC P.A. 3.2
LHC P.A. 2 ALICE
LHC P.A. 8 LHCb
SITE DE PREVESSIN
SITE DE MEYRIN
SPS BA1
SPS BA2
SPS BA3
SPS BA4
SPS BA5
Versonnex
Ségny
Chevry
Ornex
Versoix
Genthod
Sergy
Prévessin-Moëns
Saint-Genis-Pouilly
Ferney-Voltaire
Bellevue
Pregny-Chambésy
Grand-Saconnex
Meyrin

The LHC Magnets

- Design of LHC was constraint by dimensions of existing LEP tunnel




LHC Dipoles
Bending of beam trajectory in arcs
Target Energy: 7 TeV
ρ = 2800 m
(Existing Tunnel Geometry)

LHC Dipole Magnets

$$\frac{1}{\rho} = 0.2995 \frac{B[T]}{cp[GeV]}$$

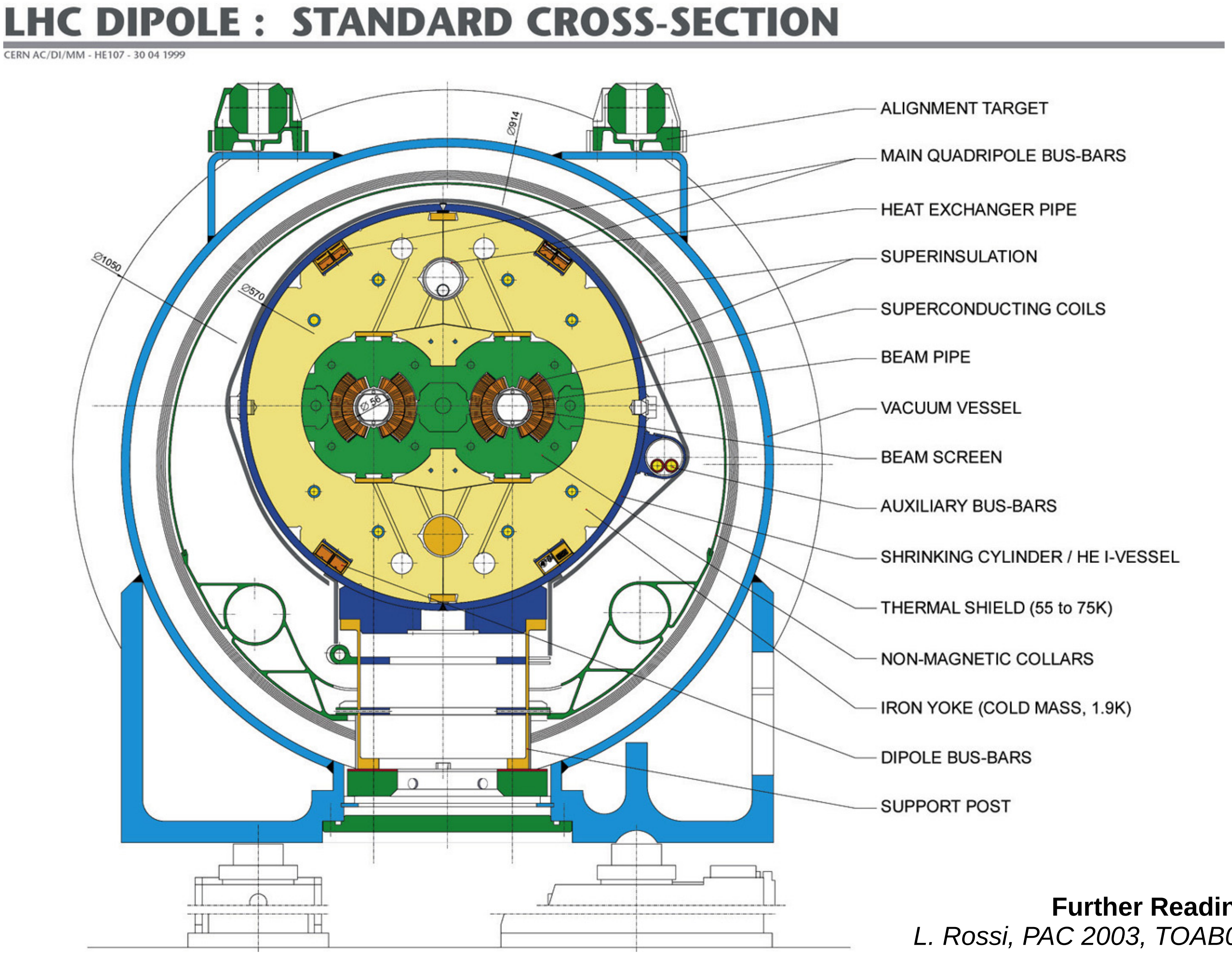
Target Proton Energy = 7 TeV

$\rho = 2800\,\mathrm{m}$

(Existing Tunnel!)

→ Required Magnetic Field of 8.3T

- Double bore magnet
- Nominal
  B-field of 8.3T
- Nominal operating
  T = 1.9K
- *I* = 11850 A
- 1232 x in the LHC
- *L* = 15m



Further Reading:
L. Rossi, PAC 2003, TOAB001

LHC Dipoles: Thermal expansion

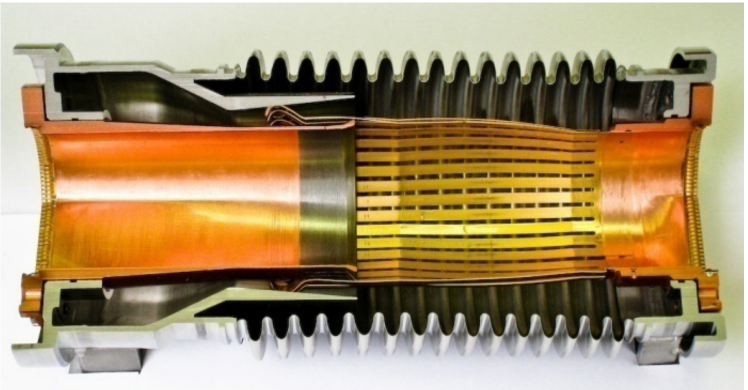
Thermal Contraction of an LHC dipole?

15m long

Thermal expansion coefficient (steel) $11 \times 10^{-6} \frac{\mathrm{m}}{\mathrm{m\,K}}$

$\Delta T \approx 291\,\mathrm{K}$

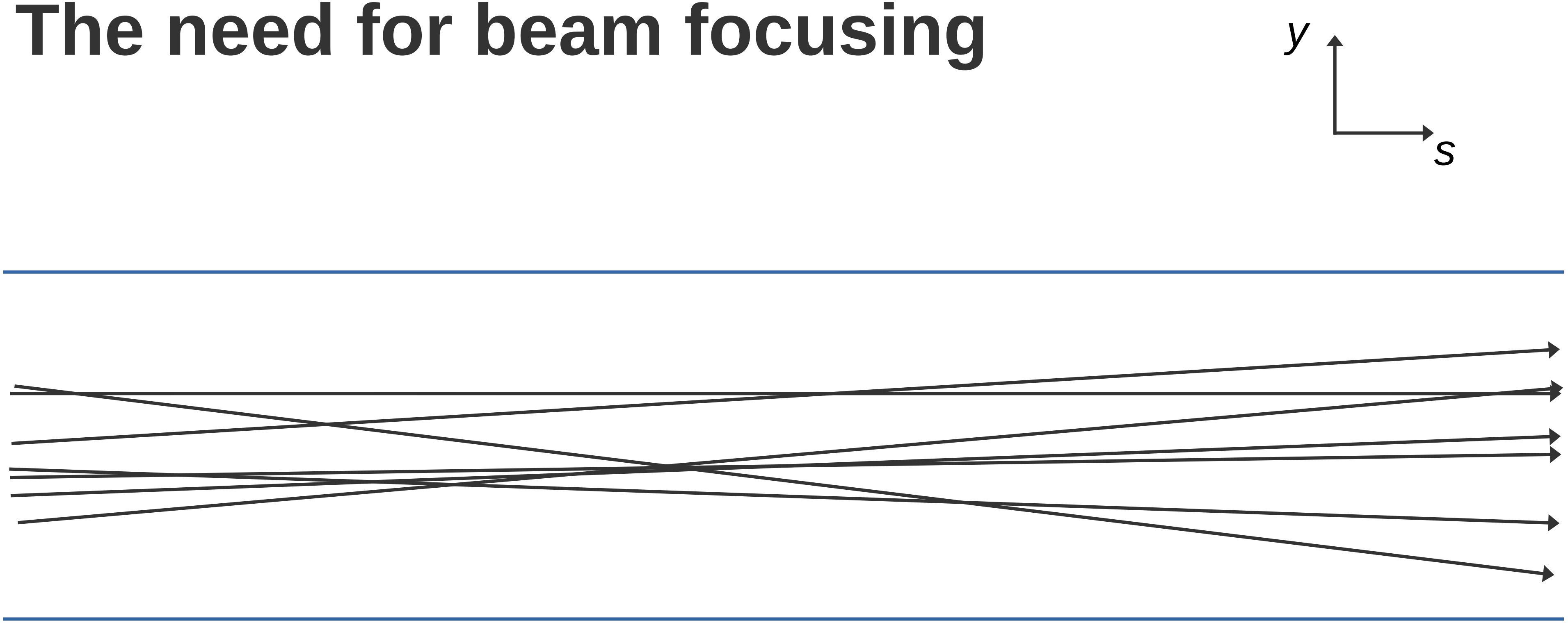
$\rightarrow \Delta L \approx 5\,\mathrm{cm}$



D. Ramos, Proceedings of EPAC08, Genoa, TUPD035

Magnets: Quadrupoles

The need for beam focusing



Beam particles will not move straight

We need focusing!

Quadrupoles

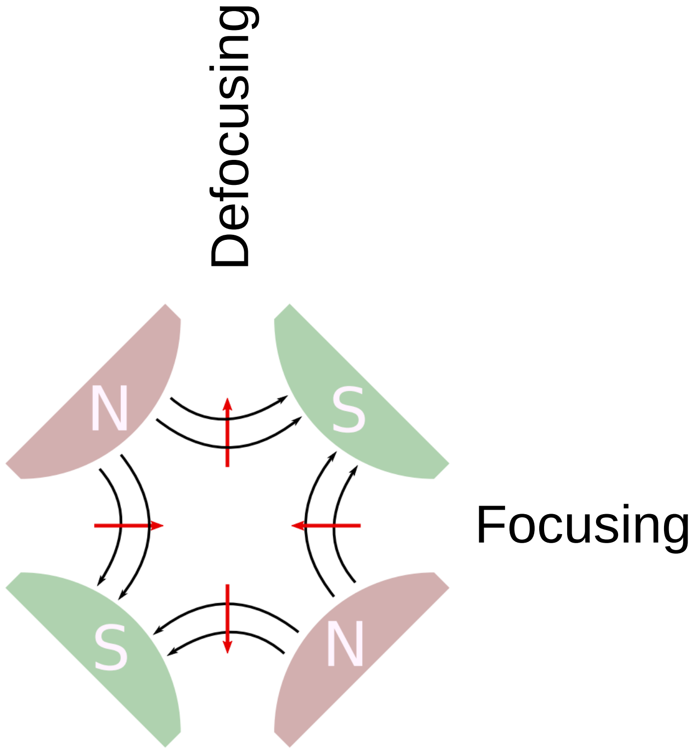
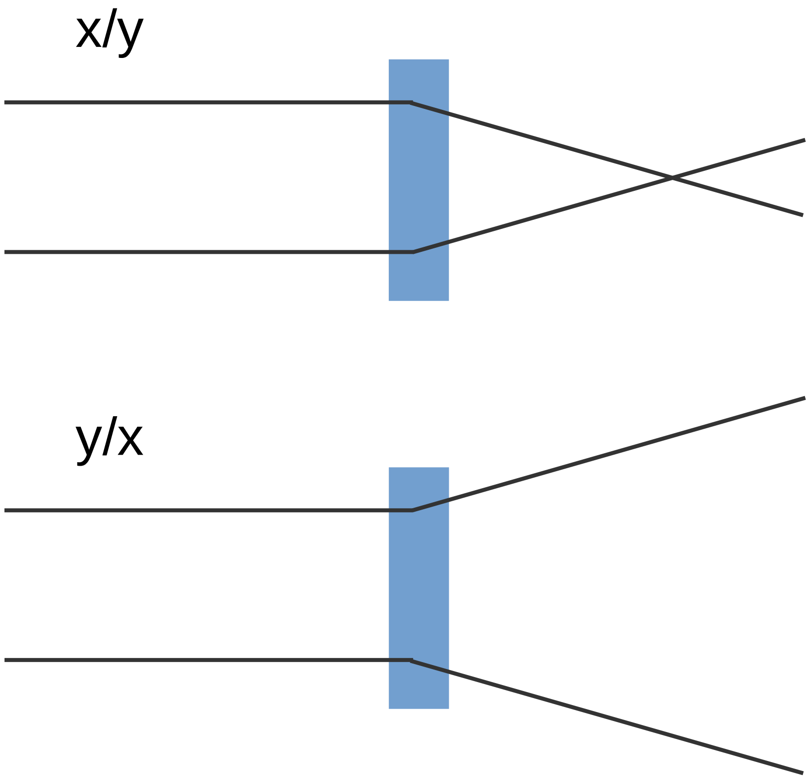
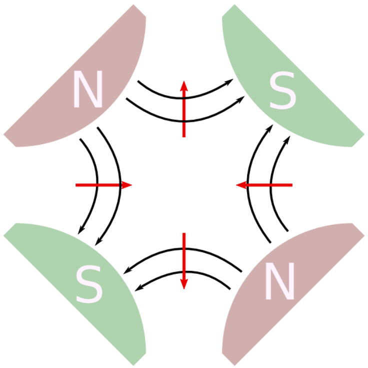


Figure: Courtesy of J. Dilly



Quadrupoles



Gradient

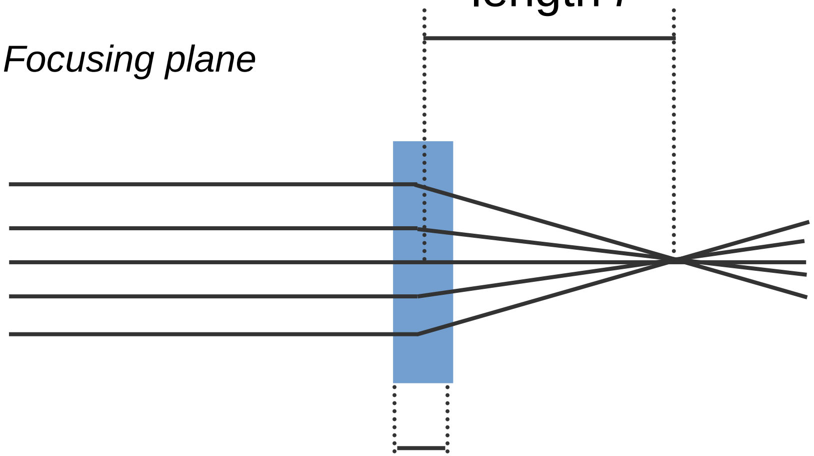
$$B_x = -g\,y$$
$$B_y = -g\,x$$

After some derivation:

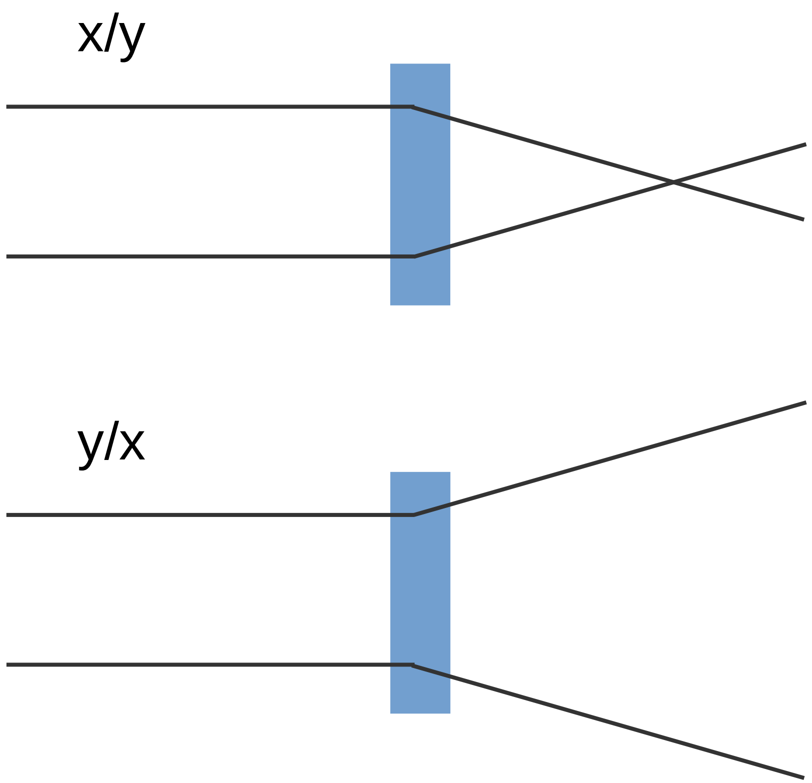
$$f_x = -\frac{p}{q\,g\,L} = -\frac{1}{k\,L}$$

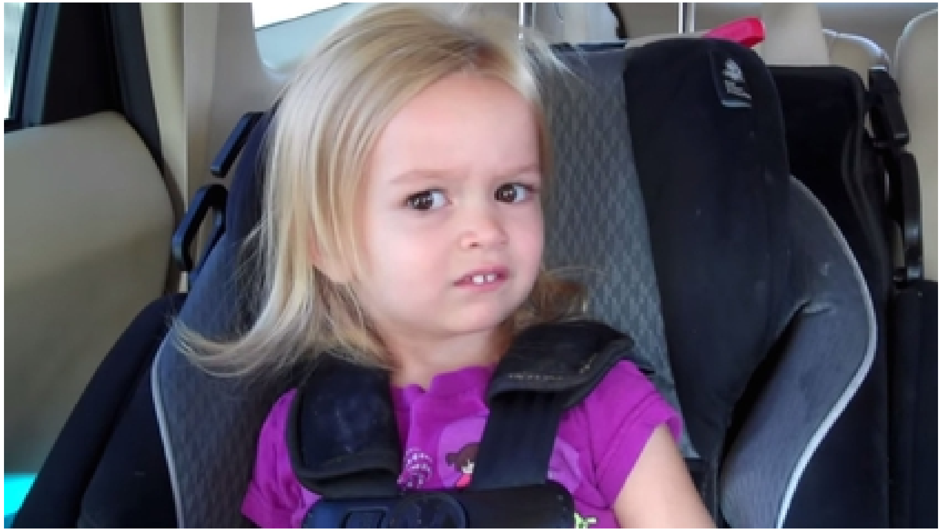
We define k as the **normalized quadrupole gradient**

- Energy independent
- Charge independent



Quadrupoles

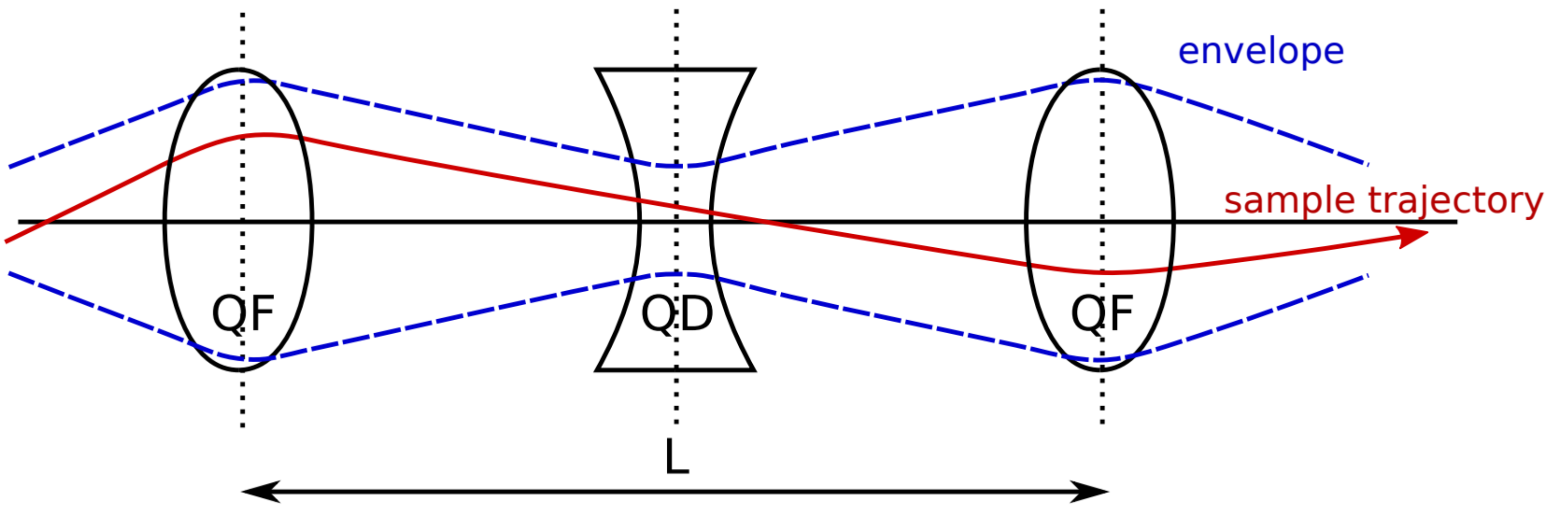




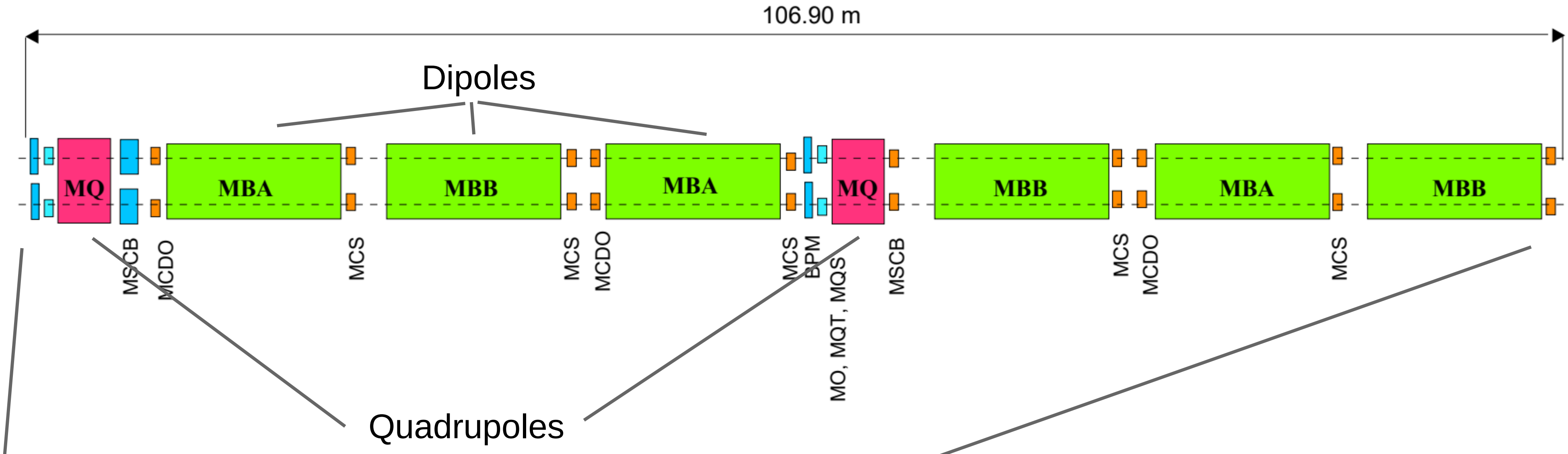
"How can we use quadrupoles for focusing if they are also defocusing in the orthogonal plane?"

Optical quadrupole lattice

Figure: Courtesy of J. Dilly



- Quadrupoles must be used in combination
- Fully analogous to an optical system for photons
- ***Beam optics***



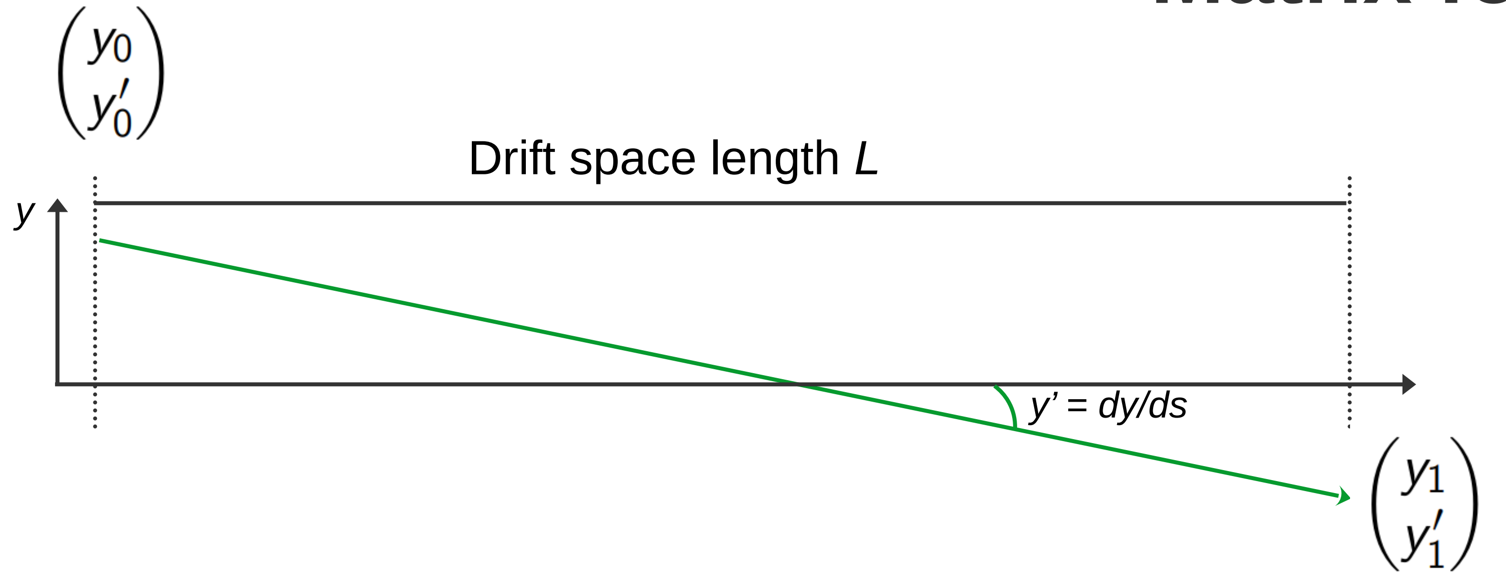
- LHC arc regions with **FODO lattice**:

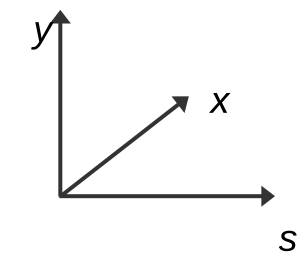
  Alternating lattice of focusing + defocusing Quads

- Used for “beam transport” between straight IRs

Matrix Formalism

Matrix formalism



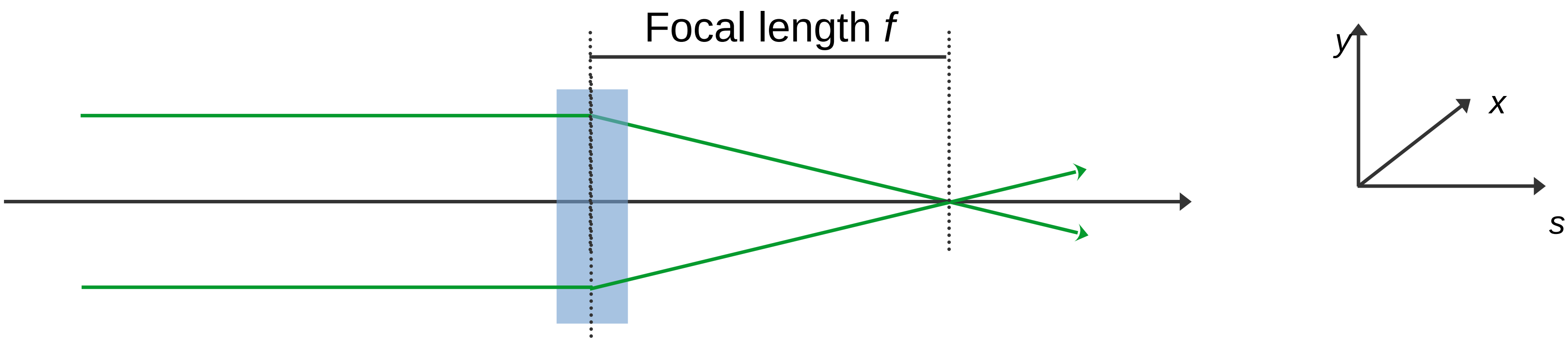


$$y_1 = y_0 + y'_0 \cdot L$$
$$y'_1 = y'_0$$

$$\begin{pmatrix} y_1 \\ y'_1 \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}$$

Transfer Matrix M_D

Matrix Formalism - Quadrupole



Thin-lens approximation

$$f = -\frac{1}{k\,L}$$

$$y_1 = y_0$$

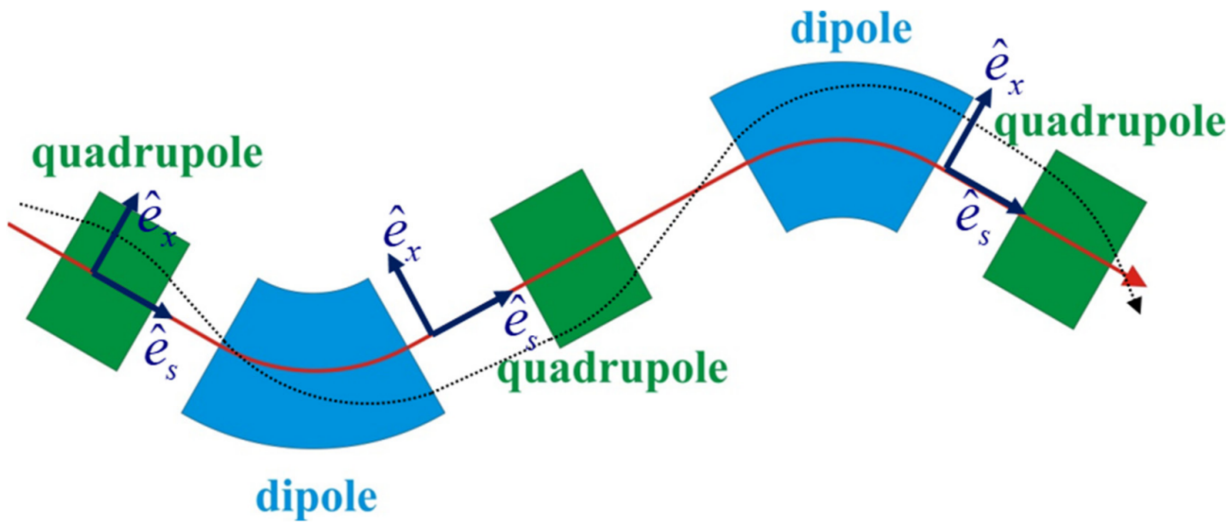
$$y_1' = y_0' \pm \frac{1}{f}\,y_0$$

$$\begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \pm\frac{1}{f} & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$

Transfer Matrix M_Q

Matrix Formalism – Transfer Matrix

Can combine matrices → calculate ***M*** for combination of elements

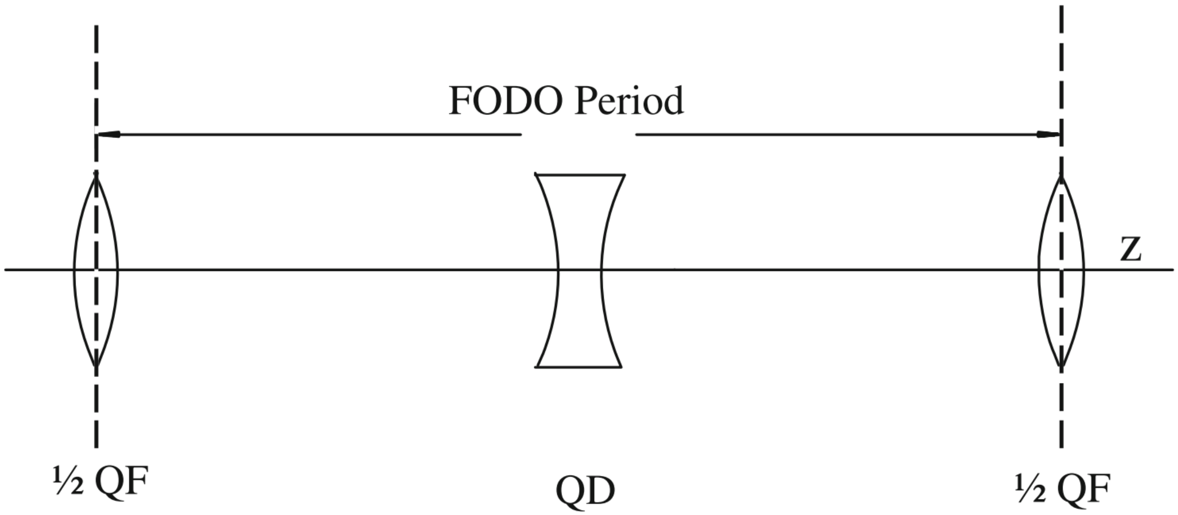


$$\vec{x} = \underbrace{\mathbf{M}_d \cdot \mathbf{M}_Q \cdot \mathbf{M}_d \cdot \mathbf{M}_D \cdot \mathbf{M}_d \cdot \mathbf{M}_Q \cdot \mathbf{M}_d \cdot \mathbf{M}_D \cdot \mathbf{M}_d \cdot \mathbf{M}_Q \cdot \mathbf{M}_d}_{= \text{Transfer Matrix } \mathbf{M}} \cdot \vec{x}_0$$

Figure: Hillert, CAS

Figure: Wiedemann

Matrix Formalism

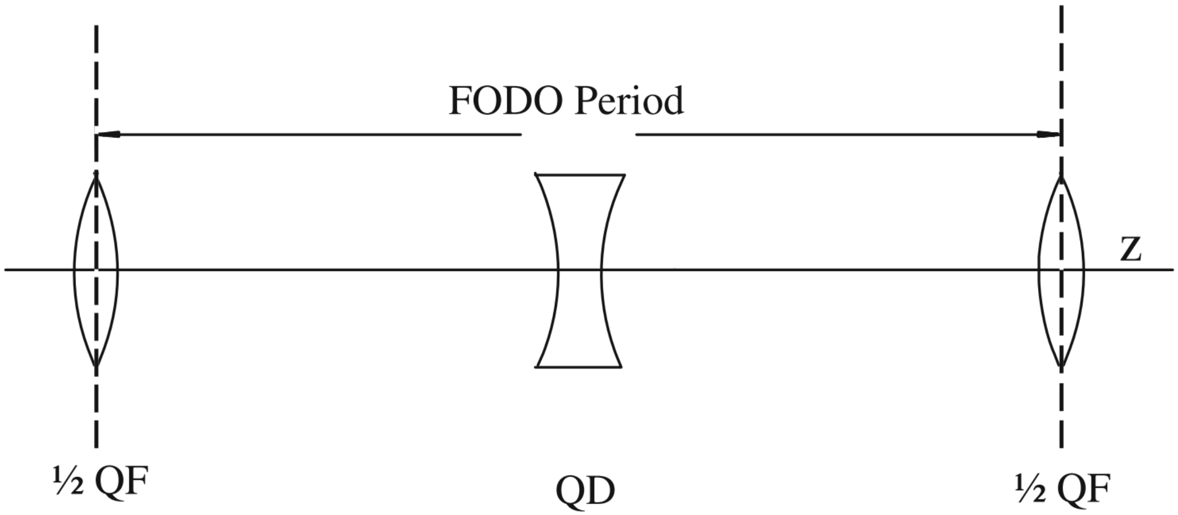


$$\begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \pm\frac{1}{f} & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$ Quad

$$\begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$ Drift

Figure: Wiedemann

Matrix Formalism



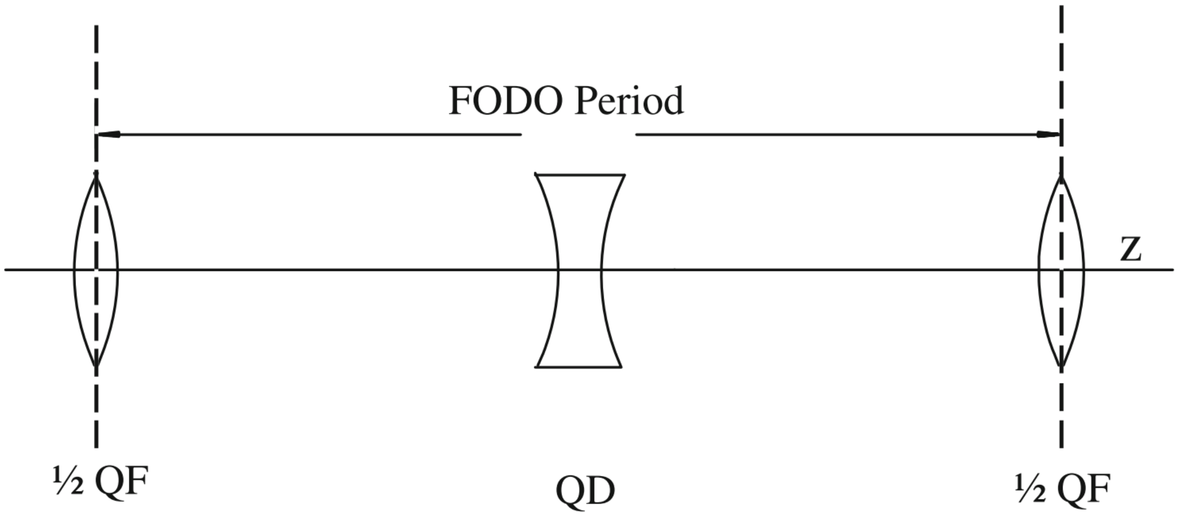
$$\begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \pm\frac{1}{f} & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$ Quad

$$\begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$ Drift

Exercise: Calculate transfer matrix for FODO cell

Figure: Wiedemann

Matrix Formalism



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$$\begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$ Drift

$$\mathcal{M}_{\mathrm{FODO}} = \begin{pmatrix} 1 - 2\frac{L^2}{f^2} & 2L\left(1 + \frac{L}{f}\right) \\ -\frac{1}{f^*} & 1 - 2\frac{L^2}{f^2} \end{pmatrix}$$

$$1/f^* = 2\,(1 - L/f)\,L/f^2$$

Equation of Motion

Equation of motion

$$x'' - k\,x = 0$$
$$y'' + k\,y = 0$$

Hill's Equation

Simplest **linear equation of motion** for particles in magnetic lattice

Simplifications:

- "Weak focusing" from dipoles ignored
- Particle momentum offsets ignored (see tomorrow)

$$f = -\frac{1}{k\,L}$$

Equation of motion: Quadrupole

Solution for quadrupole

$$x'' - k\,x = 0$$
$$y'' + k\,y = 0$$

$$\mathcal{M}_{Q,f} = \begin{pmatrix} \cos\left(\sqrt{K}L\right) & \frac{1}{\sqrt{K}}\sin\left(\sqrt{K}L\right) \\ -\sqrt{K}\,\sin\left(\sqrt{K}L\right) & \cos\left(\sqrt{K}L\right) \end{pmatrix},$$

$$\mathcal{M}_{Q,d} = \begin{pmatrix} \cosh\left(\sqrt{|K|}L\right) & \frac{1}{\sqrt{|K|}}\sinh\left(\sqrt{|K|}L\right) \\ \sqrt{|K|}\,\sinh\left(\sqrt{|K|}L\right) & \cosh\left(\sqrt{|K|}L\right) \end{pmatrix}.$$

$$L \to 0 \quad \text{with} \quad K\,L = \text{const.}$$

$$\begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \pm\frac{1}{f} & 1 \end{pmatrix} \cdot \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$

Thin lens approximation

Magnetic fields periodic with revolution length

$$k = k(z) = k(z + L_P)$$

Equation of motion: Periodic Lattice

Here: we use *z* instead of *s*

$$k = k(z) = k(z + L_P)$$

Periodicity Length L_P

$$u_1(z) = w(z)\, e^{i\mu z/L_p}\,,$$
$$u_2(z) = w^*(z)\, e^{-i\mu z/L_p}$$

Two independent solutions

$$x'' - k\,x = 0$$
$$y'' + k\,y = 0$$

Select real solutions
$w^*(z) = w(z)$

Periodic in L_P

Generalized *u*
$u = x / y$

$$w(z + L_p) = w(z)$$

Equation of motion: Periodic Lattice

$$x'' - k\,x = 0$$
$$y'' + k\,y = 0$$

$$w(z + L_\mathrm{p}) = w(z)$$

Two independent solutions

$$u_1(z) = w(z)\,\mathrm{e}^{\mathrm{i}\,\mu\,z/L_\mathrm{p}}\,,$$
$$u_2(z) = w^*(z)\,\mathrm{e}^{-\mathrm{i}\,\mu\,z/L_\mathrm{p}}$$

Transformation over one period:

$$u(z + L_\mathrm{p}) = u(z)\,\mathrm{e}^{\pm\mathrm{i}\mu} = u(z)\,(\cos\mu \pm \mathrm{i}\ \sin\mu)$$

Equation of motion: Periodic Lattice

$$x'' - k\,x = 0$$
$$y'' + k\,y = 0$$

Solution for one period

$$u(z + L_\mathrm{p}) = u(z)\,\mathrm{e}^{\pm i\mu} = u(z)\,(\cos\mu \pm \mathrm{i}\ \sin\mu)$$

Some derivation

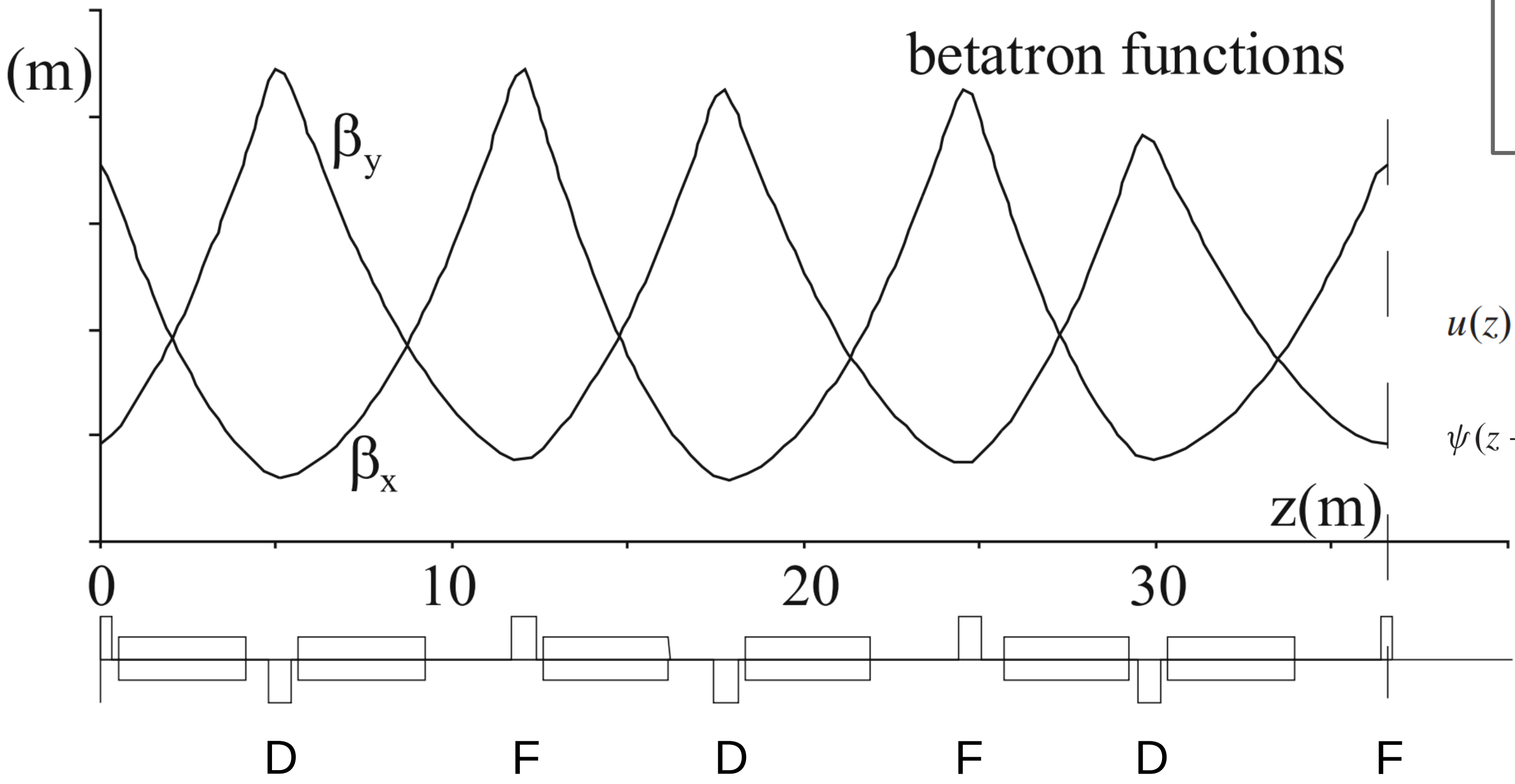
General Solution
incl. stability criterion

$$u(z) = a\,\sqrt{\beta(z)}\,\mathrm{e}^{\pm\mathrm{i}\,\psi}$$

$$\psi(z - z_0) = \int_{z_0}^{z} \frac{\mathrm{d}\zeta}{\beta(\zeta)}$$

Betatron function (FODO)

$$x'' - k\,x = 0$$
$$y'' + k\,y = 0$$



$$u(z) = a\,\sqrt{\beta(z)}\,\mathrm{e}^{\pm \mathrm{i}\,\psi}$$

$$\psi(z - z_0) = \int_{z_0}^{z} \frac{\mathrm{d}\zeta}{\beta(\zeta)}$$

Betatron function

$$u(z) = a\sqrt{\beta(z)}\, e^{\pm i\psi}$$

Maximum amplitude at *z*

$$u_{\max}(z) = a\sqrt{\beta(z)}$$

Property of the particle considered (a)

Property of the machine lattice: "optics" ($\beta(z)$)

Betatron phase

$$\psi(z - z_0) = \int_{z_0}^{z} \frac{d\zeta}{\beta(\zeta)}$$

Defines the number of betatron oscillations across a given length

Betatron function

$$\mathcal{M}(z + L_\mathrm{p} \,|\, z) = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix}$$

Individual Particles
Transfer matrix for *u, u'*

Beam lattice
Transfer matrix for *betatron parameters α, β, γ*

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix} = \begin{pmatrix} C^2 & -2CS & S^2 \\ -CC' & CS' + C'S & -SS' \\ C'^2 & -2C'S' & S'^2 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix} = \mathcal{M}_\beta \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix}$$

Twiss Parameters

$$\beta(z)$$

$$\alpha(z) = -\frac{1}{2}\frac{d\beta(z)}{dz}$$

$$\gamma(z) = \frac{1 + \alpha^2(z)}{\beta(z)}$$

Courant-Snyder Invariant

$$u(z) = \sqrt{2\,J\,\beta(z)}\,\cos(\psi(z) + \psi_0)$$

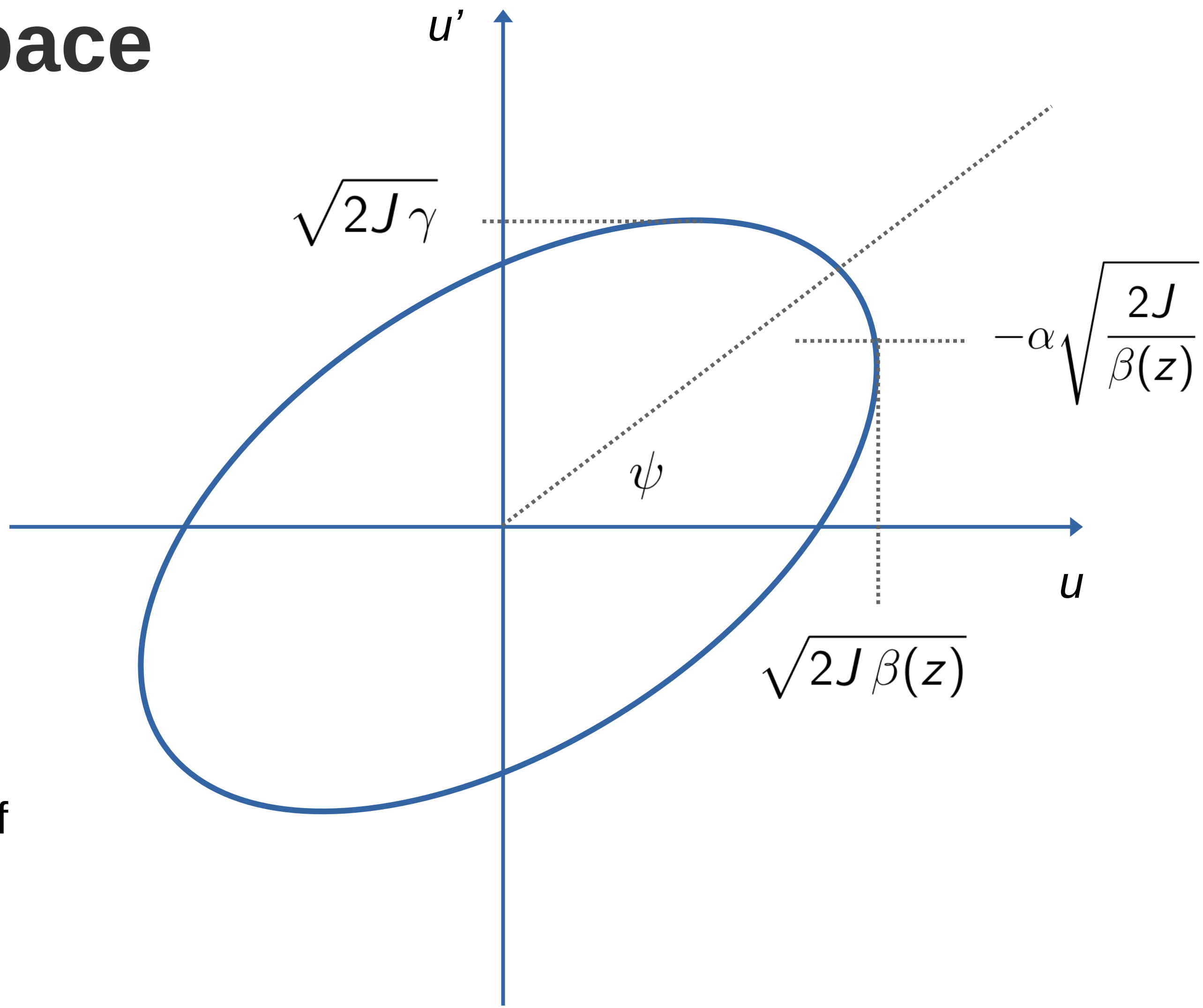
$$u'(z) = \sqrt{\frac{2\,J}{\beta(z)}}\,[\sin(\psi(z) + \psi_0) + \alpha(z)\,\cos(\psi(z) + \psi_0)]$$

$$\gamma\,u^2 + 2\alpha\,uu' + \beta\,u' = 2\,J$$

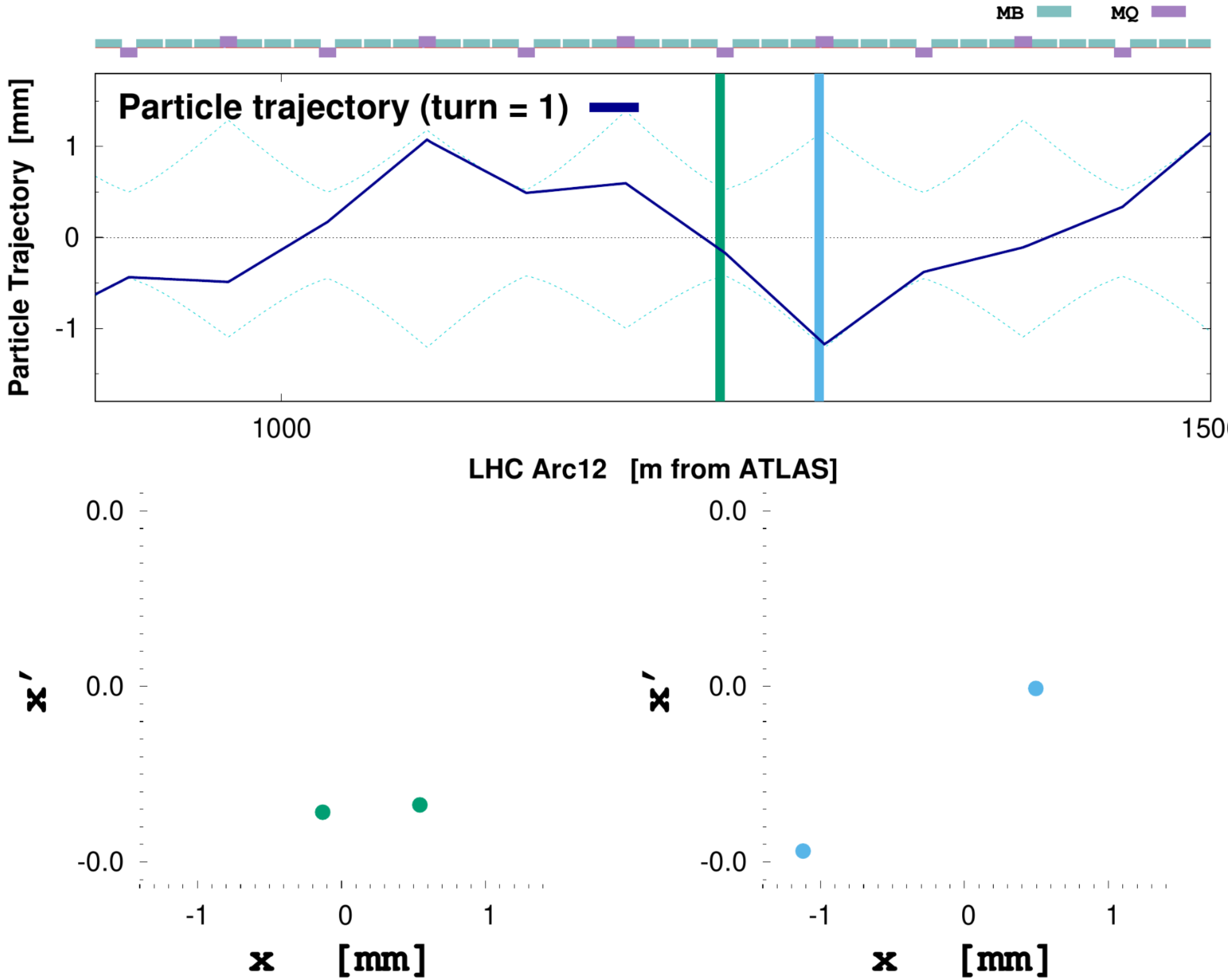
Courant-Snyder Invariant

- J is called the **particle action**
- Linear magnetic fields: constant for each particle! (Liouville theorem)

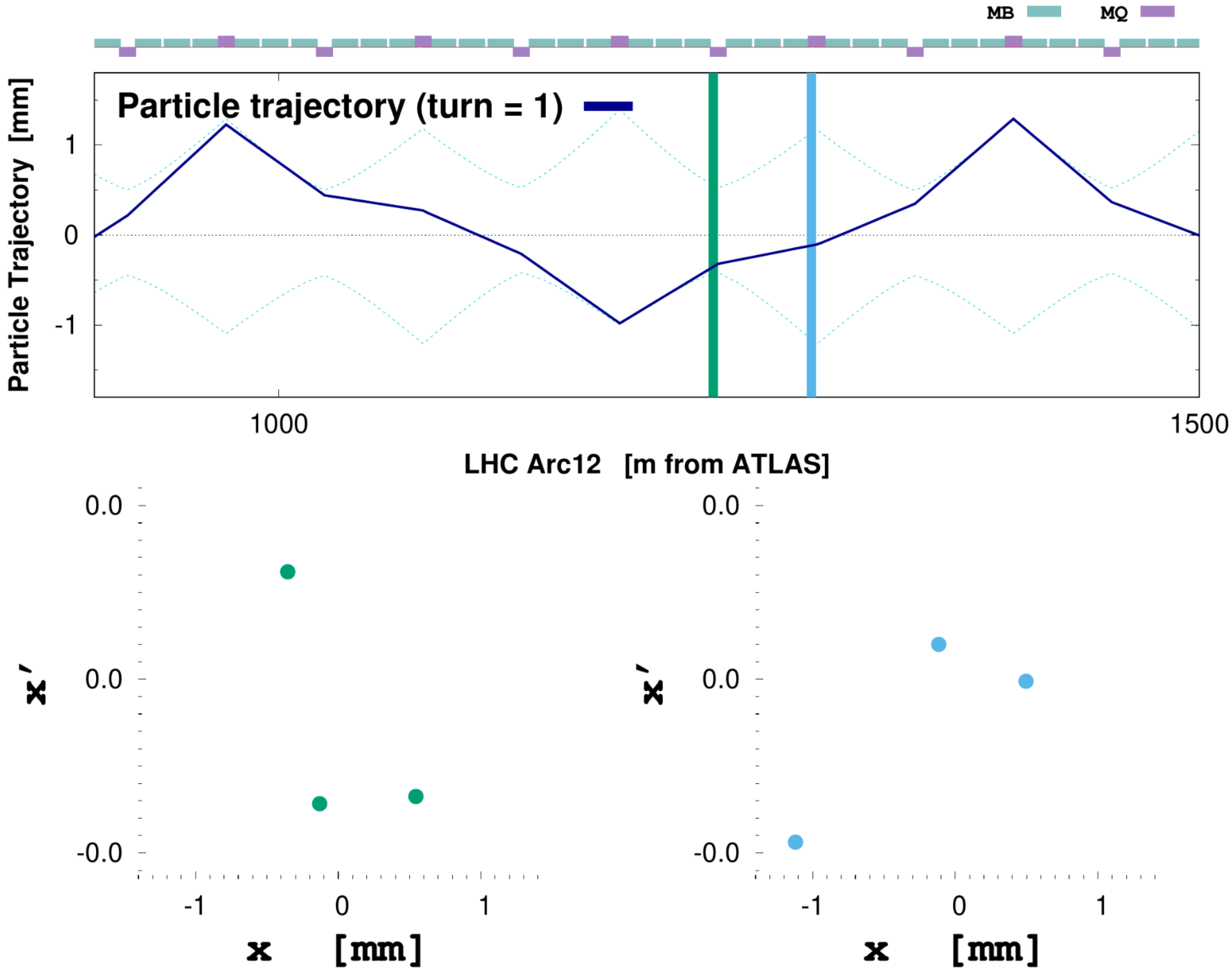
Phase space ellipse



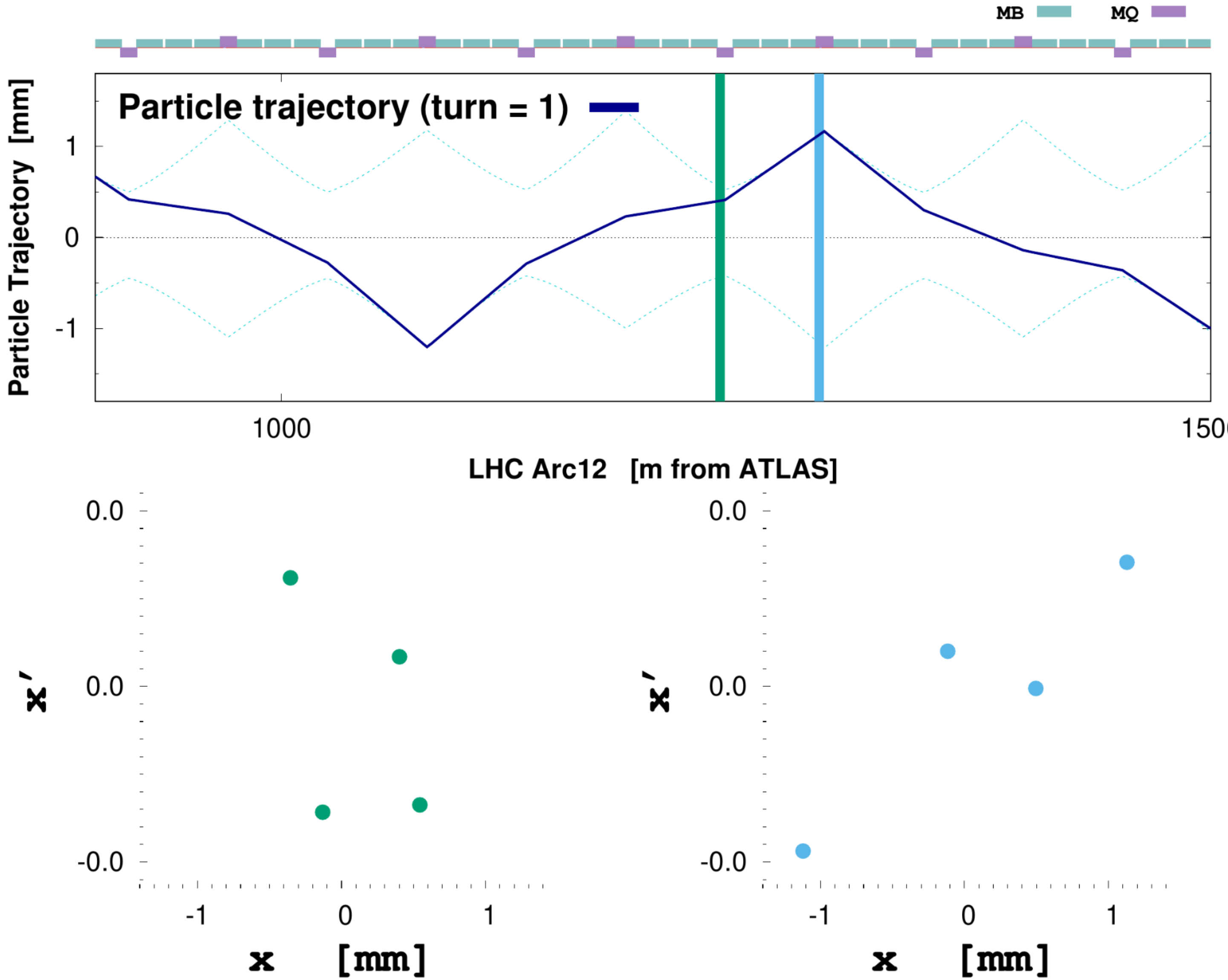
- At position z: given particle will always be on this ellipse
- Liouville: surface of the ellipse stays constant



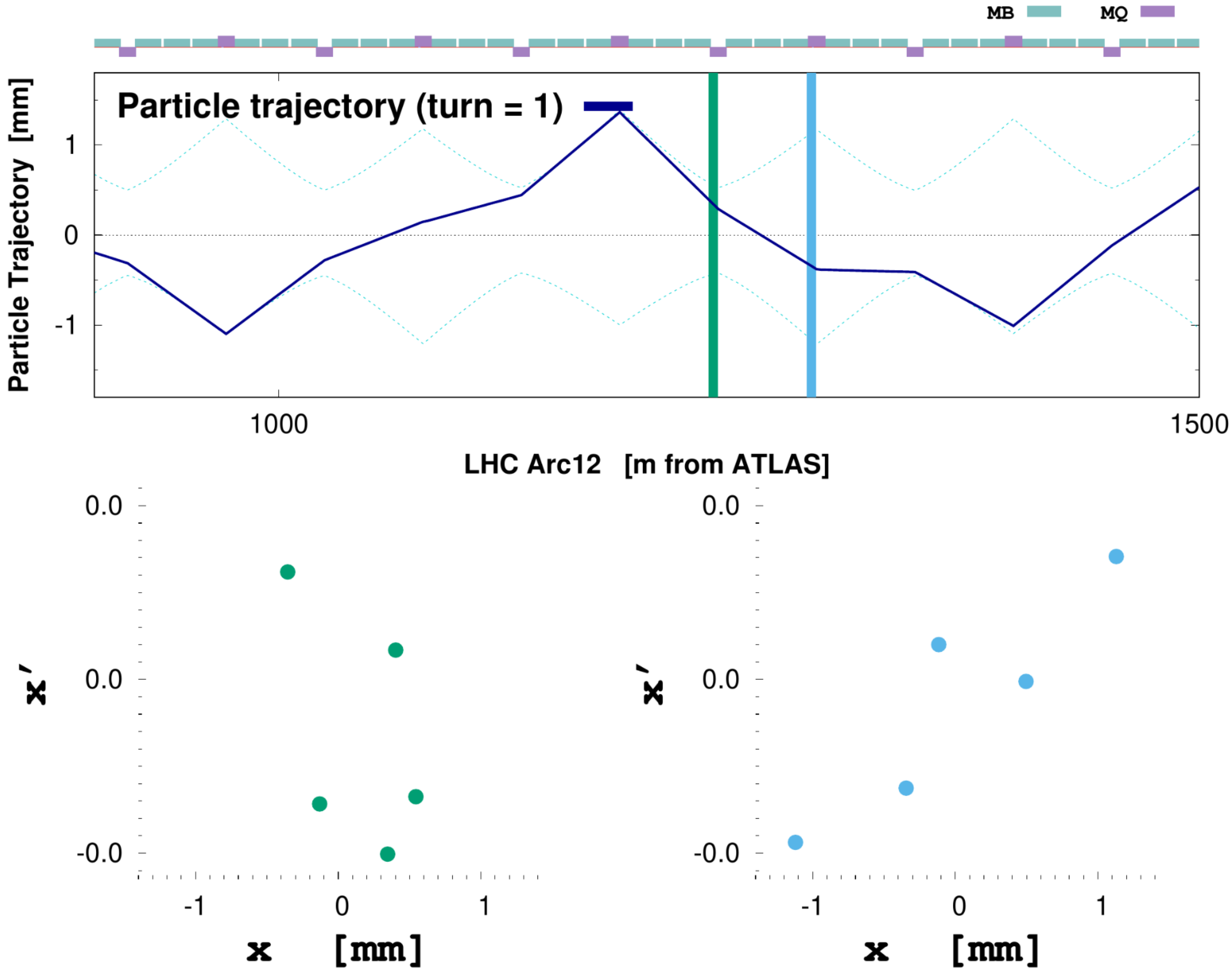
Courtesy of J. Dilly



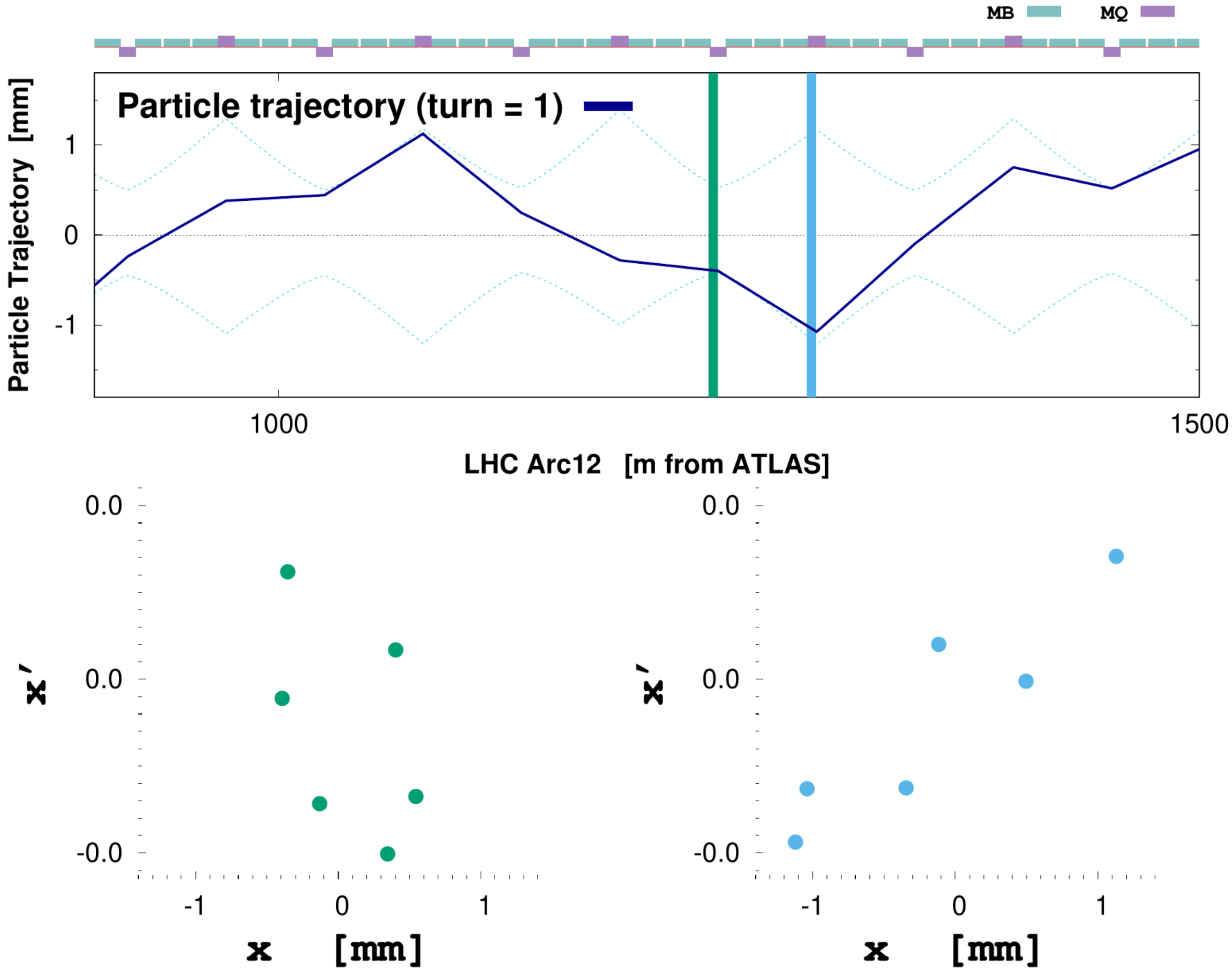
Courtesy of J. Dilly



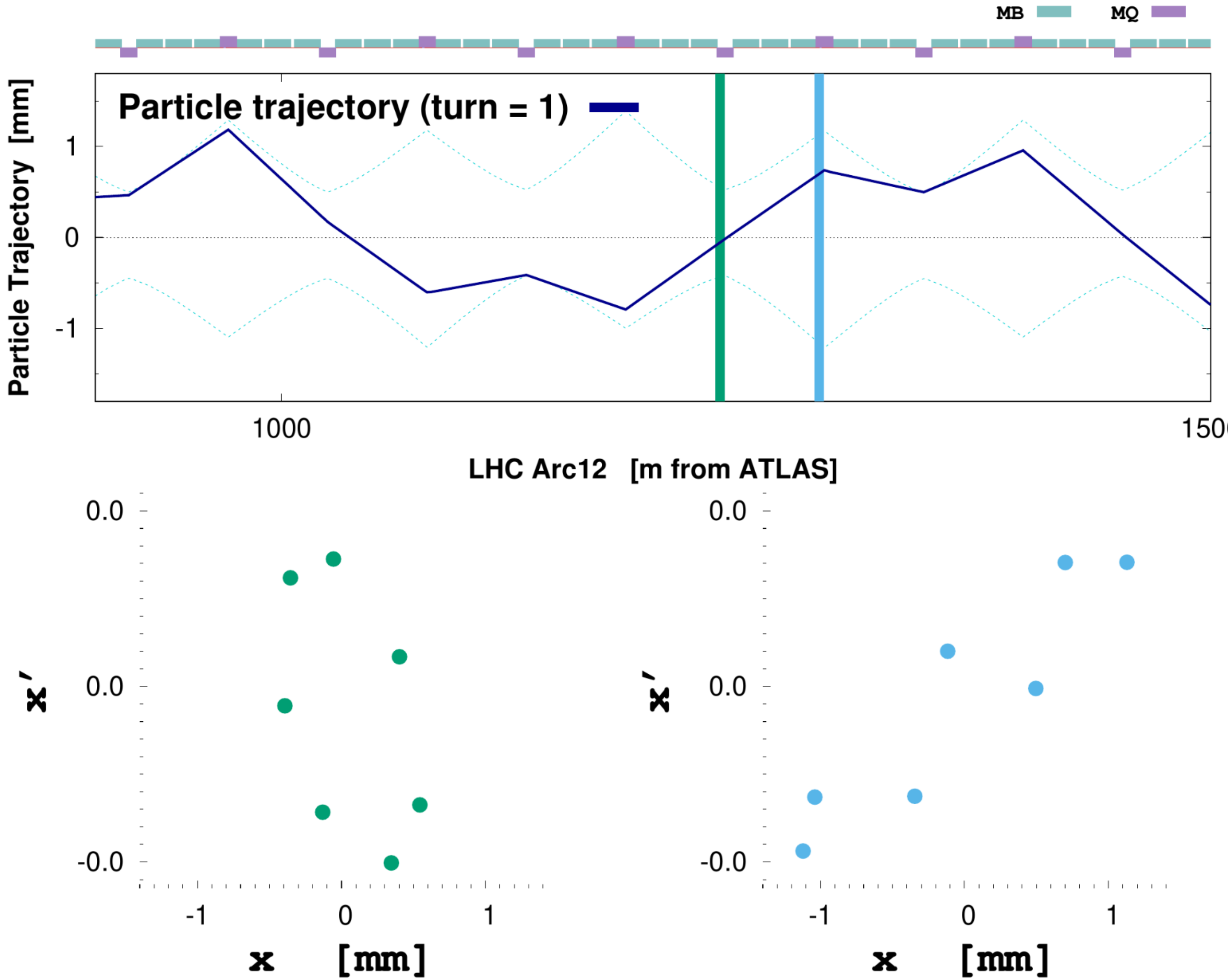
Courtesy of J. Dilly



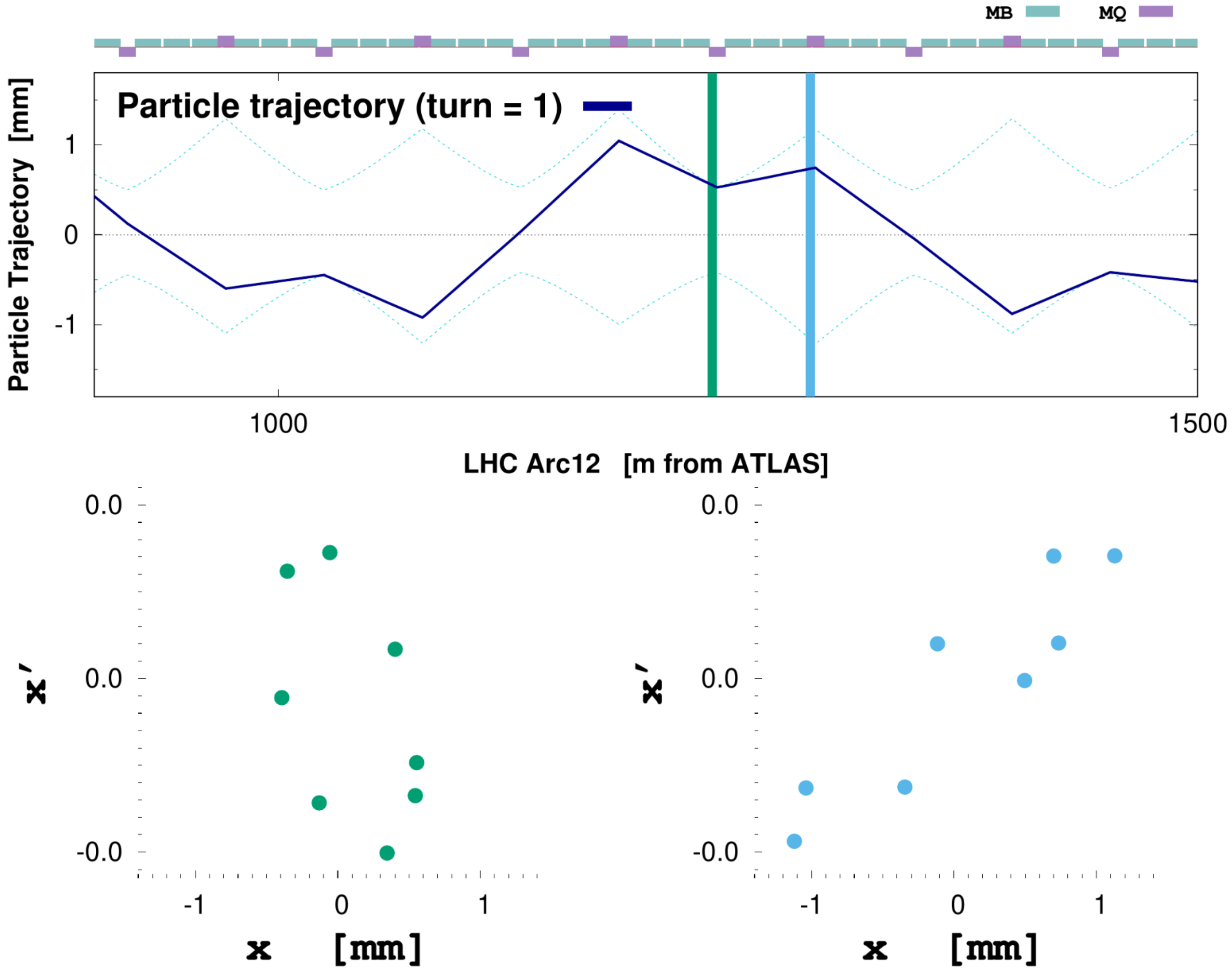
Courtesy of J. Dilly



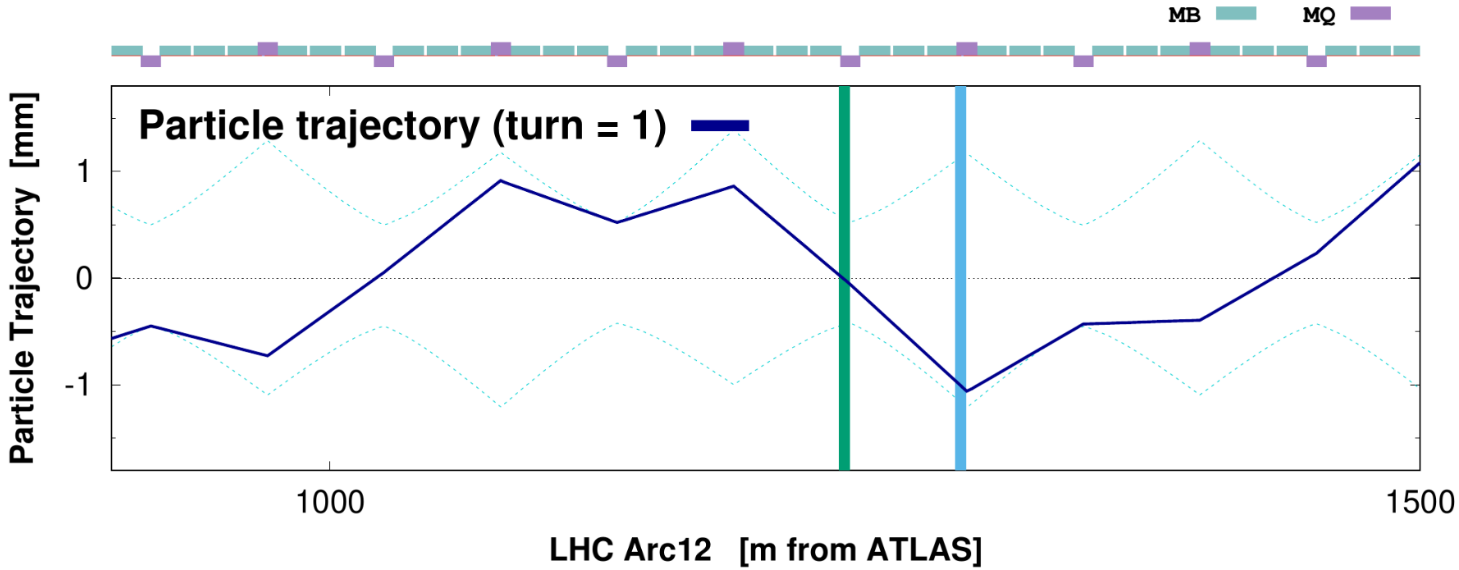
Courtesy of J. Dilly

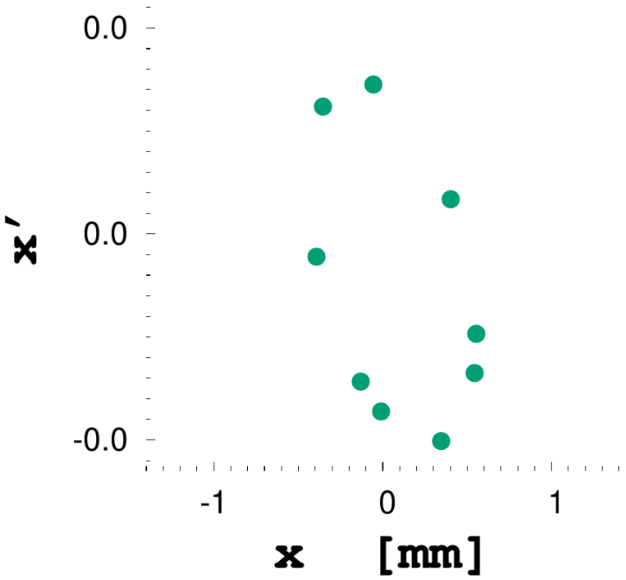


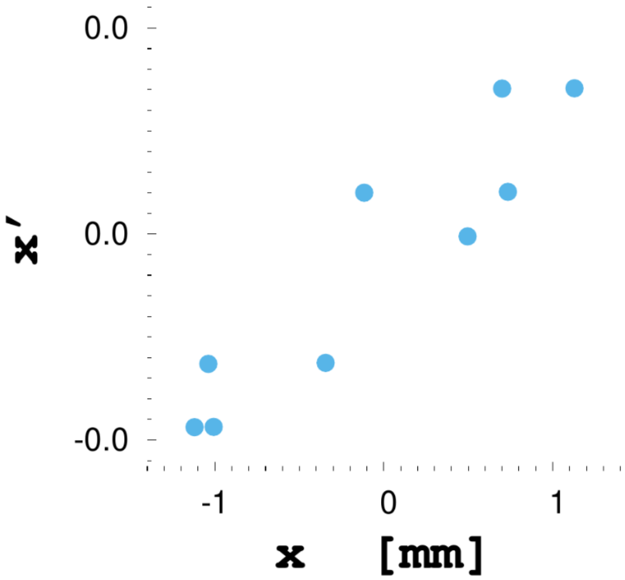
Courtesy of J. Dilly



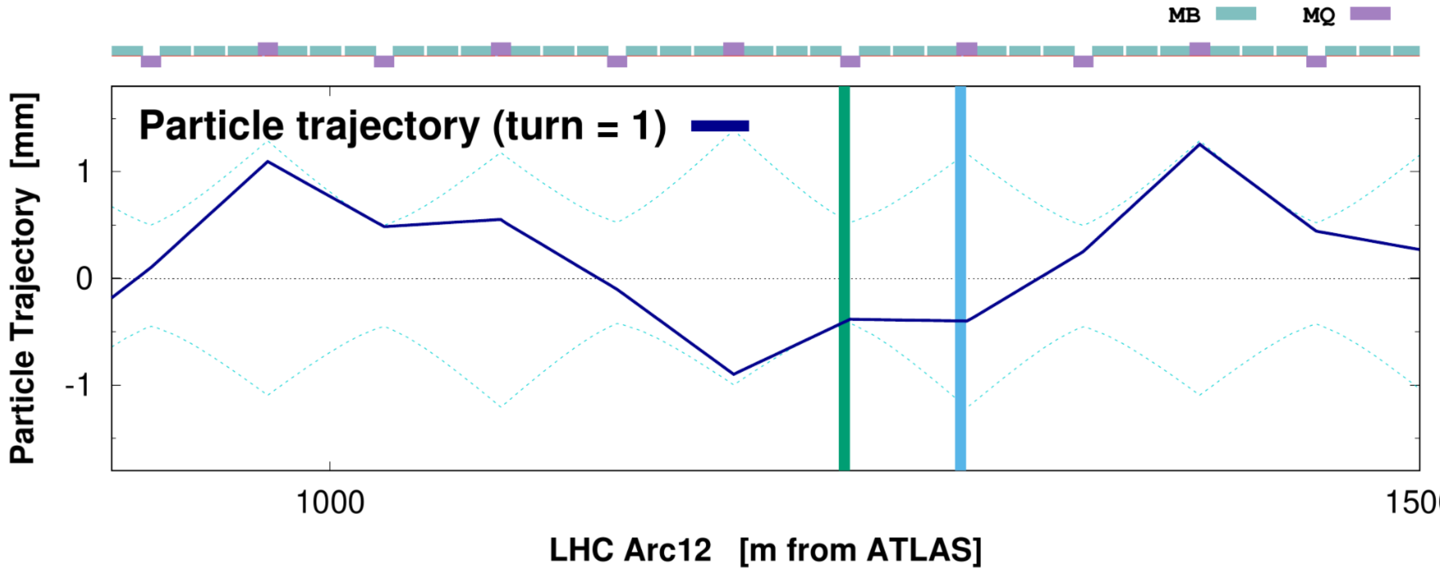
Courtesy of J. Dilly



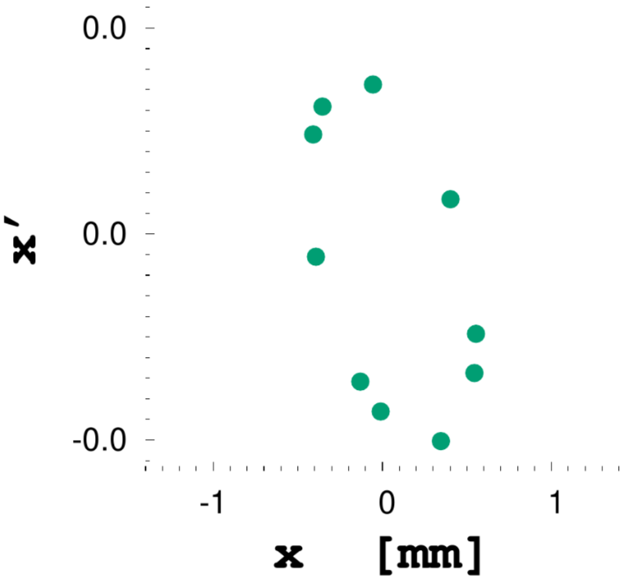


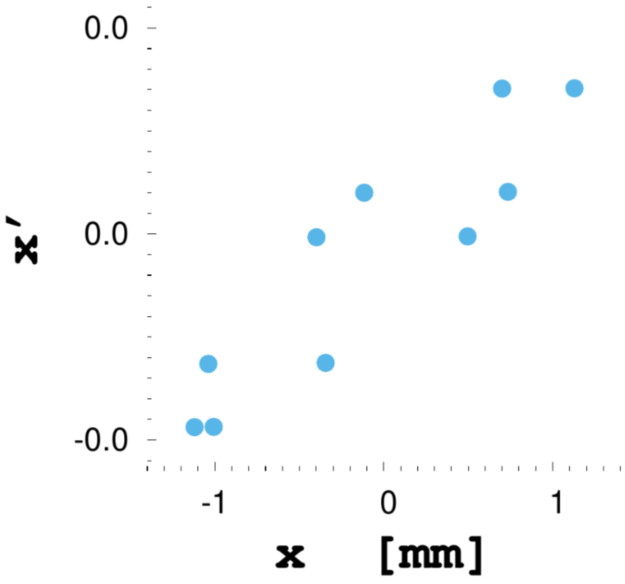


Courtesy of J. Dilly



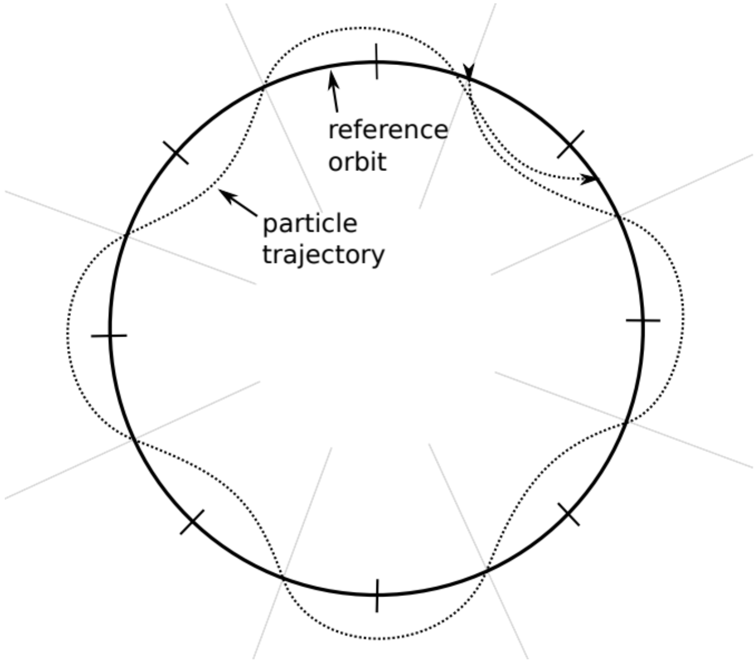
$$\sqrt{2J\,\beta(z)}$$





Courtesy of J. Dilly

Betatron function



- **"*Tune*" (ν)**: Number of betatron oscillations for one turn

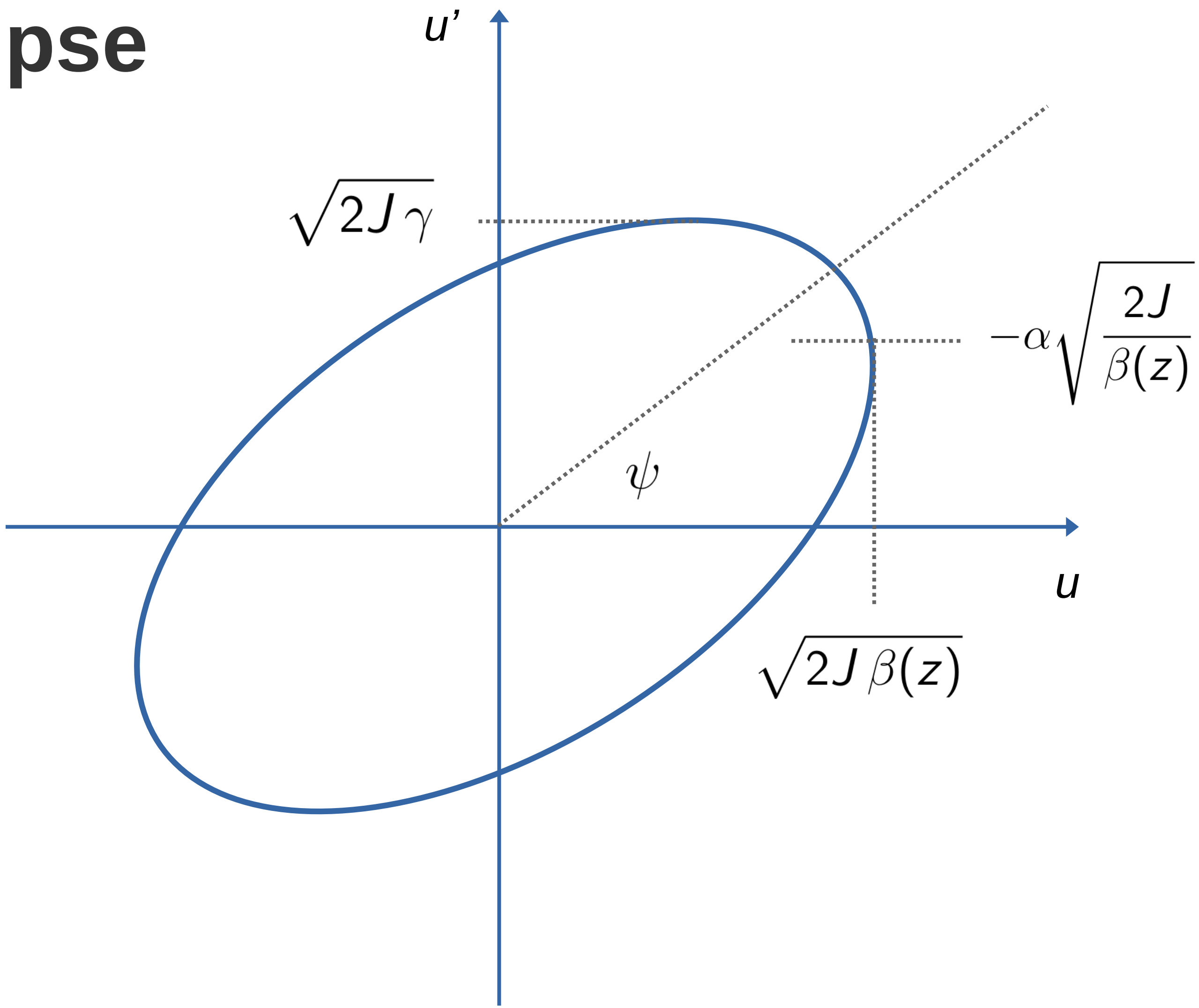
$$\psi(z - z_0) = \int_{z_0}^{z} \frac{\mathrm{d}\zeta}{\beta(\zeta)} \quad \Rightarrow \quad \boxed{\nu_{x,y} = \frac{1}{2\pi} \oint \frac{\mathrm{d}\zeta}{\beta_{x,y}(\zeta)} \,.}$$

- Fractional part of tune important to avoid resonances (can you imagine why?)

- LHC: **ν_x = 62.31 and ν_y = 60.32**

Phase space ellipse

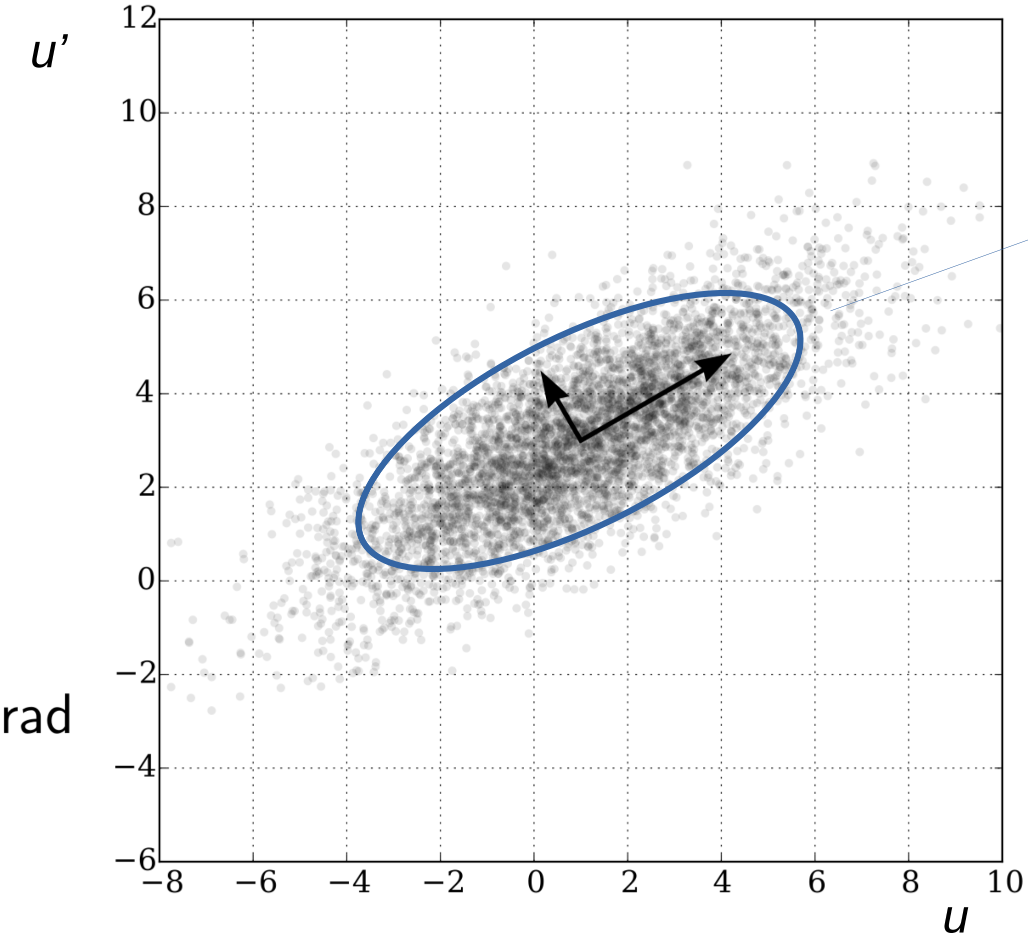
- Apparently ***J*** determines the size of the ellipse **for one particle**
- Doesn't it make sense to look at the ***J* of the entire beam**?



Emittance

LHC top energy
(6.8 TeV):

$$\epsilon = 5 \times 10^{-10}\ \mathrm{m\ rad}$$



Beam emittance

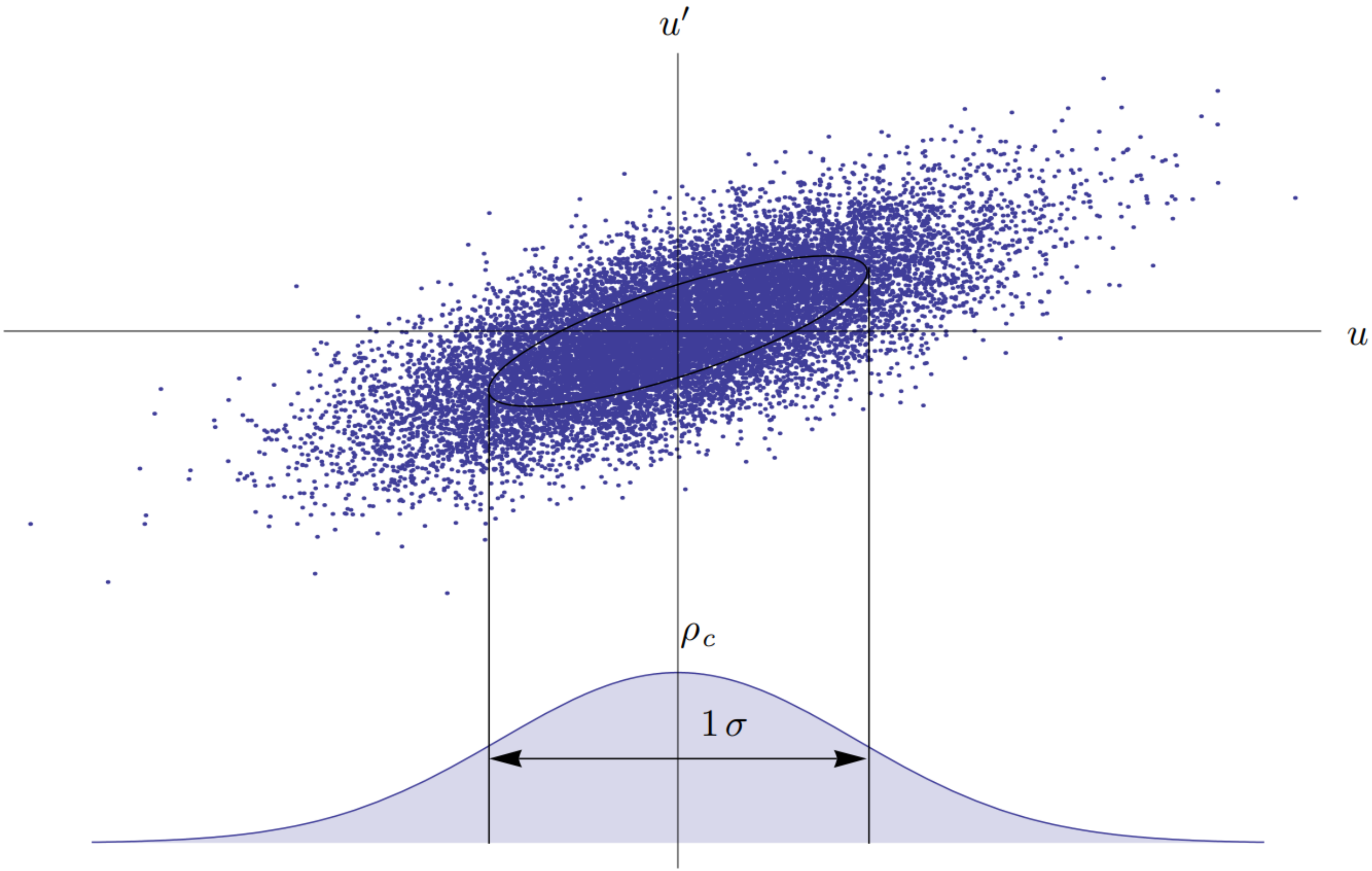
$$\epsilon = \langle J \rangle$$

Definition:
Beam size σ

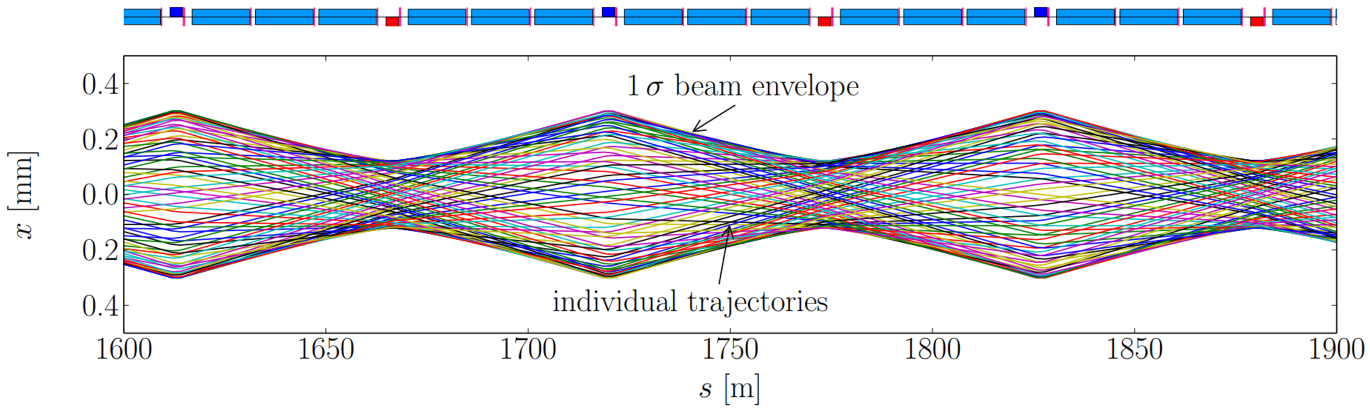
$$\sigma = \sqrt{\epsilon\,\beta(z)}$$

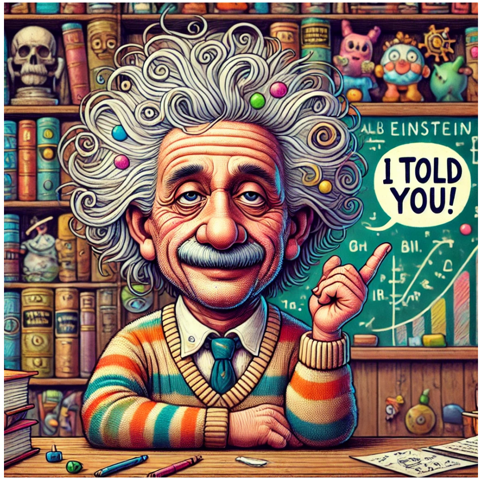
Crucial indicator for beam quality!

Emittance



Emittance





Acceleration:

- Increase of relativistic *γ* leads to beam shrinking!
- Observed *u'* in lab frame decreases
- Emittance decreases with **relativistic *βγ***

Definition

Normalized emittance

$$\epsilon_N = \beta \gamma \epsilon$$

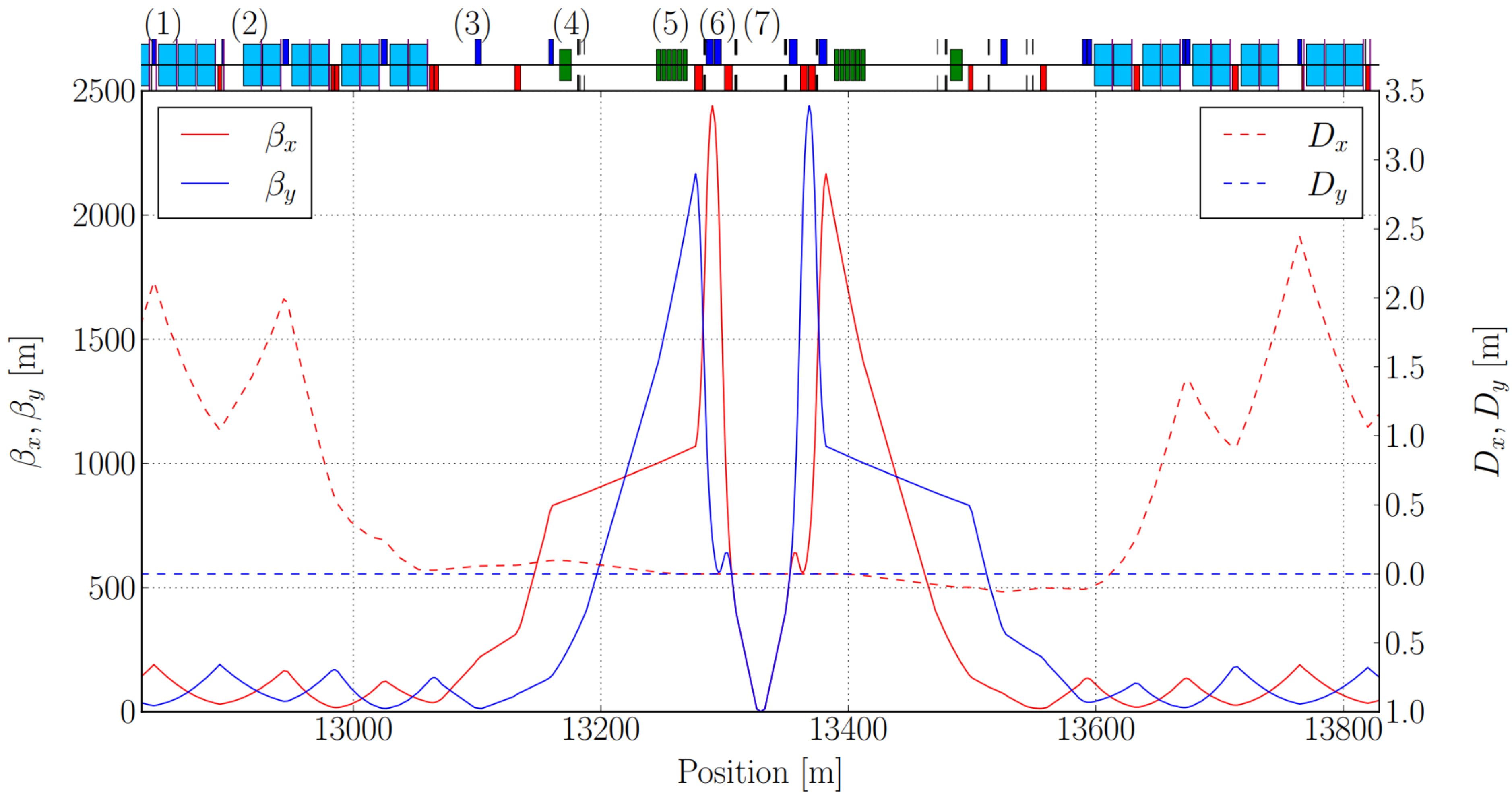
Constant!

LHC: $\epsilon_N = 3.5\,\mu\text{mrad}$

Bringing the beams into collision

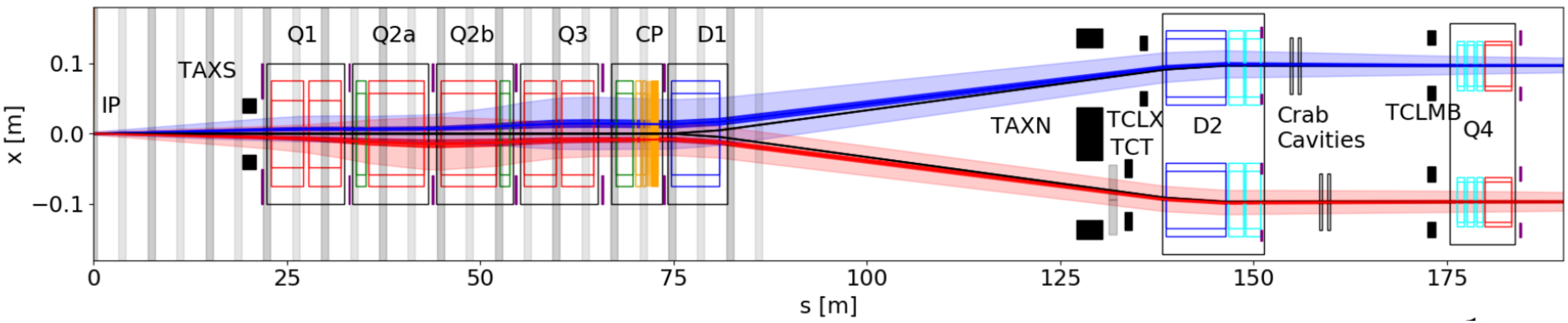
Collision Point Optics

$$\sigma = \sqrt{\epsilon\,\beta(z)}$$



Collision Point Optics

$$\sigma = \sqrt{\epsilon\,\beta(z)}$$



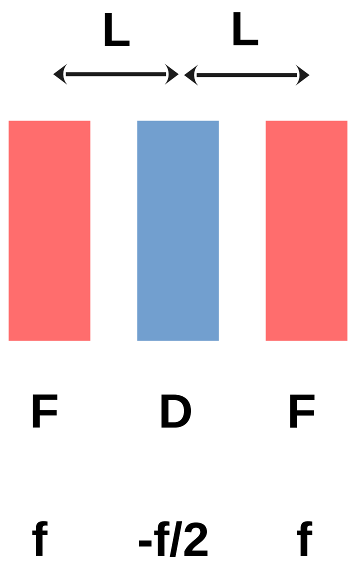
Collision Points:

- Need synchronous focusing in both planes!
- How can we achieve this?

Figure taken from HL-LHC Technical DR

Collision Point Optics: Triplet

Quadrupole triplet
for 2D focusing



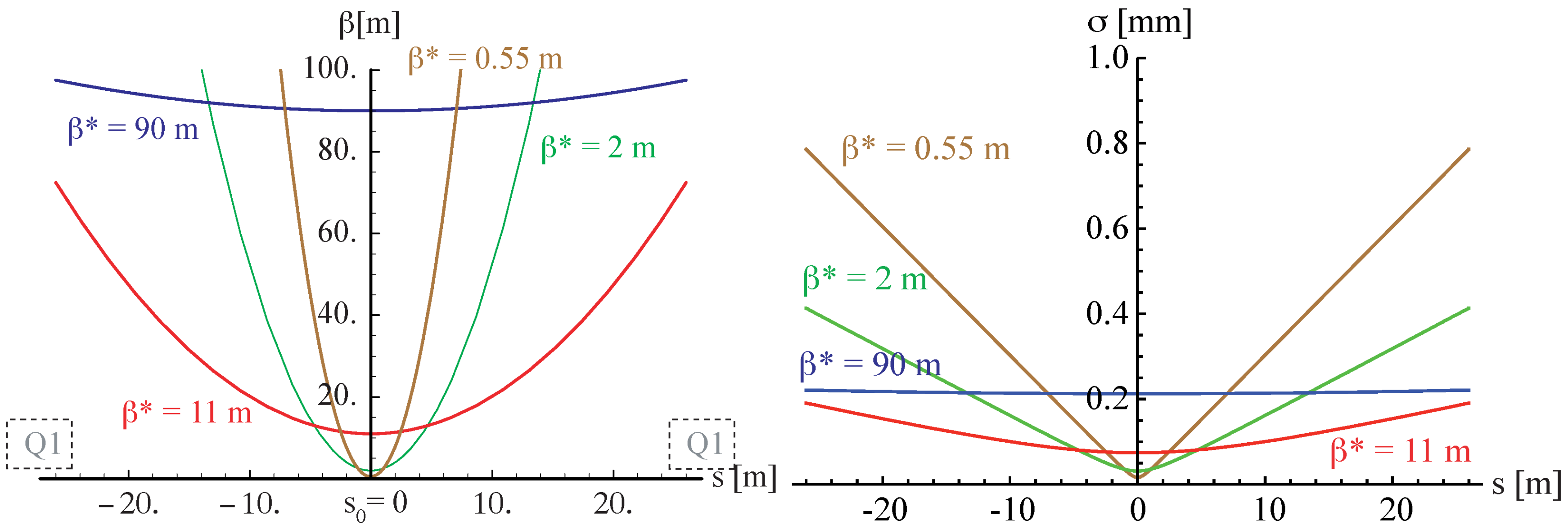
$$\mathcal{M}_{\mathrm{tr}} = \mathcal{M}_{\mathrm{r}}\,\mathcal{M} = \begin{pmatrix} 1 - 2L^2/f^{\,2} & 2L\,(1 + L/f) \\ -1/f^* & 1 - 2L^2/f^{\,2} \end{pmatrix}$$

f >> L

Lens with focal
length in x/y

$$\frac{1}{f^*} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{L}{f_1 f_2}$$

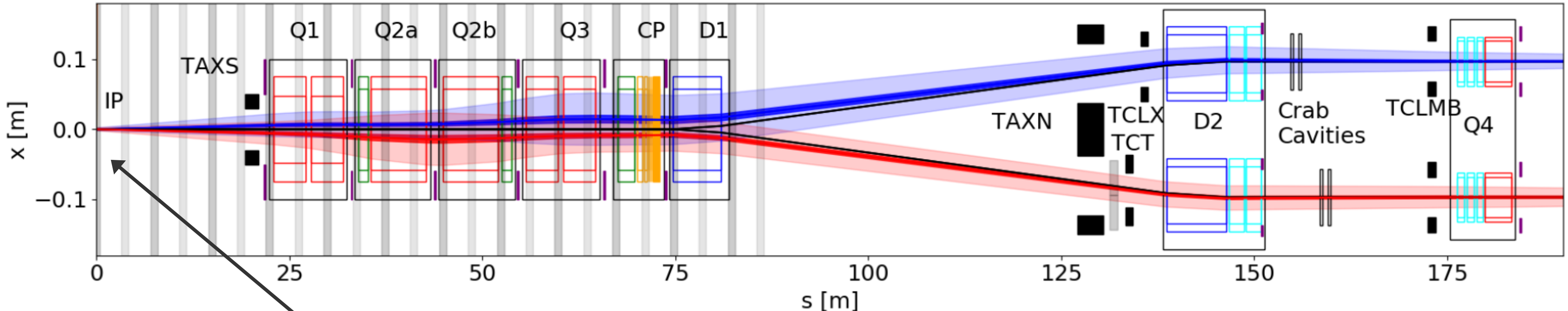
Collision Point Optics

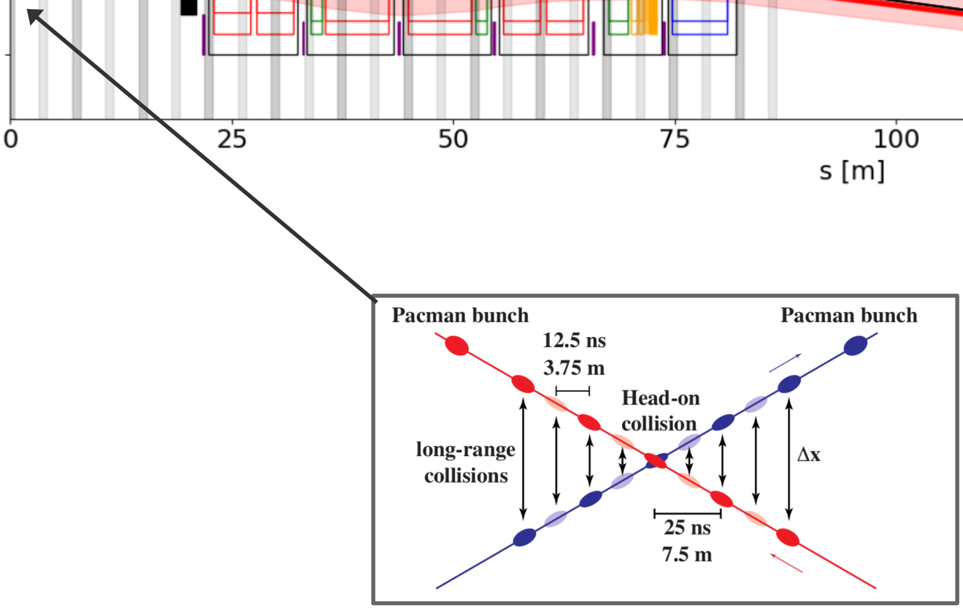


High-Beta Optics and Running Prospects by Helmut Burkhardt, Instruments 2019, 3(1), 22

Collision Point Optics

$$\sigma = \sqrt{\epsilon\,\beta(z)}$$





Crossing angle needed to avoid parasitic collisions!

Figure taken from HL-LHC Technical DR

Collision Point Optics

$$\sigma = \sqrt{\epsilon \beta(z)}$$

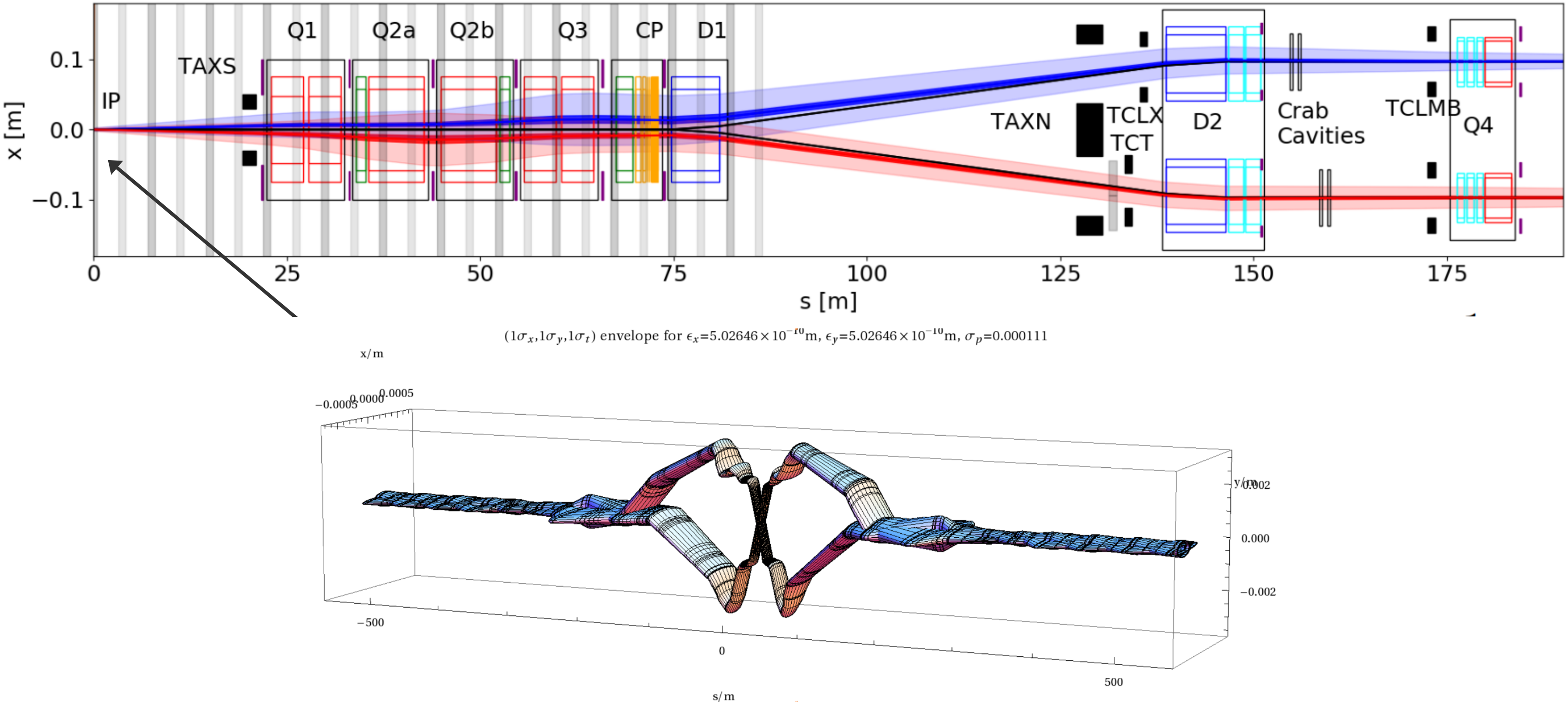


Figure taken from HL-LHC Technical DR

Luminosity

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = \mathcal{L}\,\sigma$$

Interaction rate for physics process with cross-section σ

$$\mathcal{L}_0 = f\, k_b\, \frac{N_1\, N_2}{4\,\pi\,\epsilon\,\beta^*}$$

Particles per bunch
1.6×10^{11}

Revolution Frequency
11245 Hz

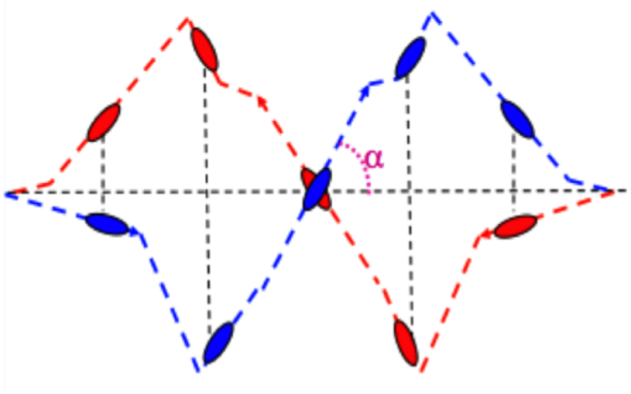
Bunch Number
~2800

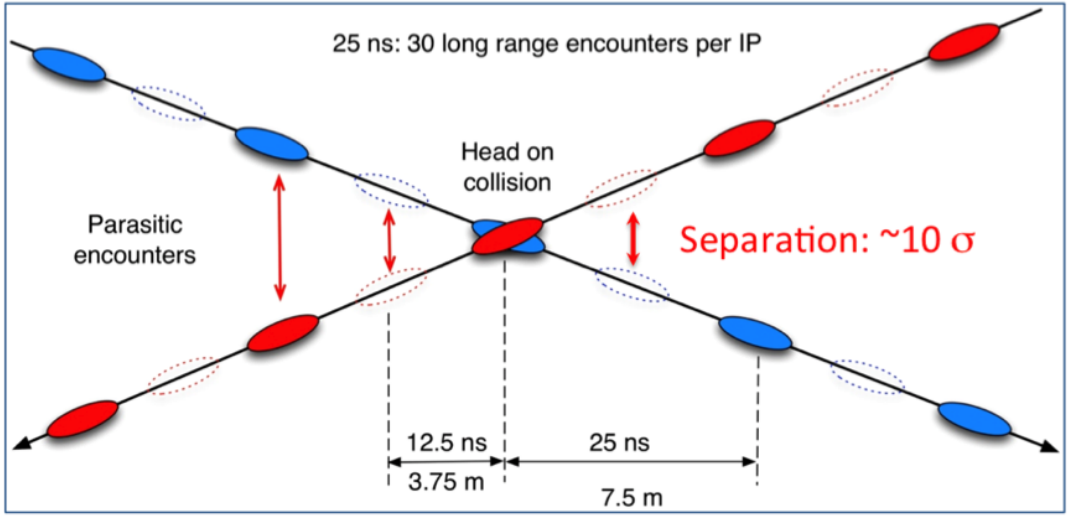
$\epsilon_N = 3.5\,\mu\mathrm{mrad}$

0.3m to 10m

Quiz: What is the luminosity with these parameters? What is the unit?

Luminosity





$$\mathcal{L} = \mathcal{L}_0 \, F_C$$

$$F_C \approx \frac{1}{1 + \left(\frac{\sigma_l}{\sigma^*} \frac{\theta_C}{2}\right)^2}$$

Luminosity is reduced to to crossing angle!

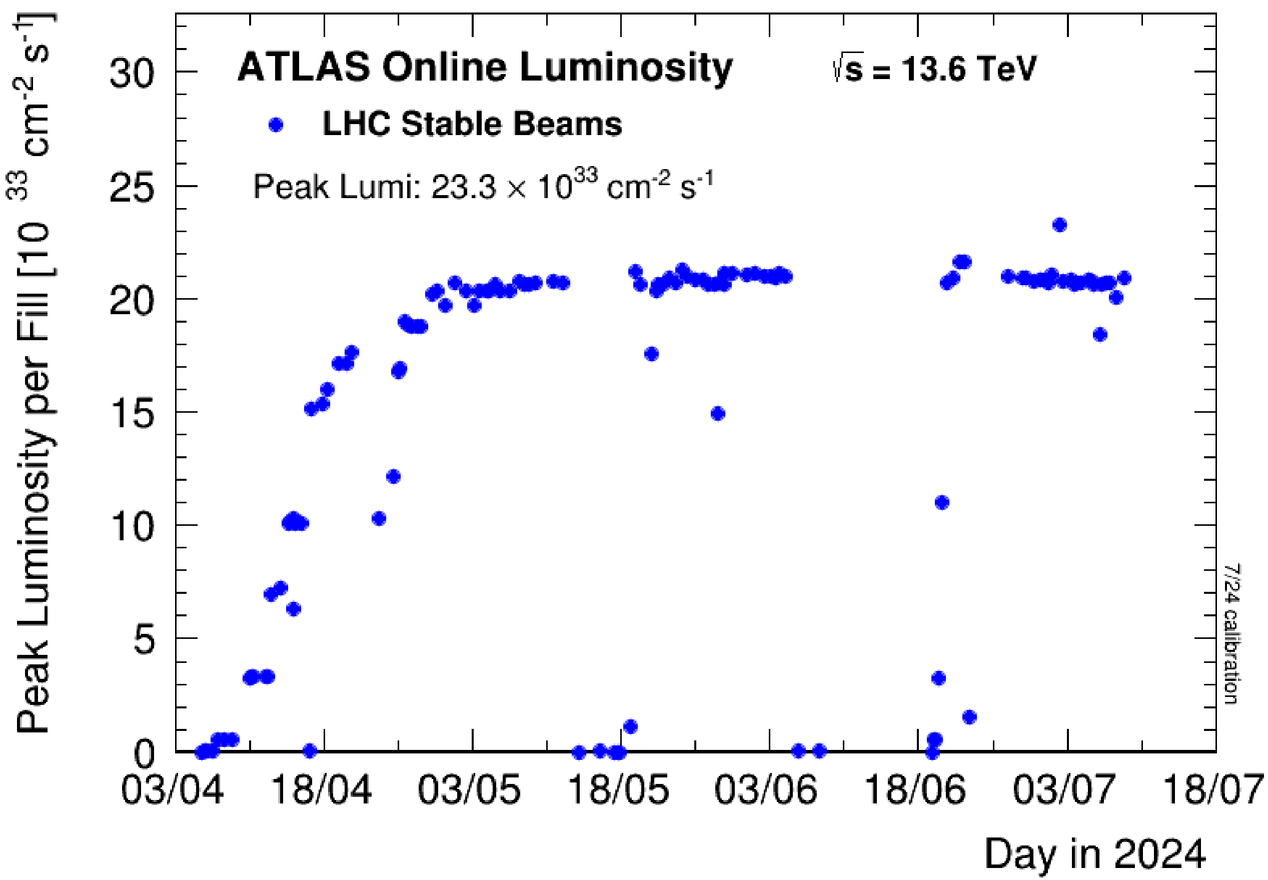
Figure taken from https://cds.cern.ch/journal/CERNBulletin/2016/38/News%20Articles/2216373

The LHC Parameters

Parameter		LHC (nominal)	HL-LHC (standard)
Beam energy in collision	[TeV]	7	7
Particles per bunch	[10^{11}]	1.15	2.2
Bunches per beam		2808	2760
Collisions in IP1 and IP5		2808	2748
Half-crossing angle in IP1 and IP5	[μrad]	142.5	250
Minimum β^*	[m]	0.55	0.15
Normalized emittance ϵ_n	[μm]	3.75	2.5
Peak luminosity w/o crab cavities	[10^{34} cm^{-2} s^{-1}]	1.00	8.11
Peak luminosity w/ crab cavities	[10^{34} cm^{-2} s^{-1}]	–	17.0
Events / Crossing		27	131

Courtesy of J. Dilly

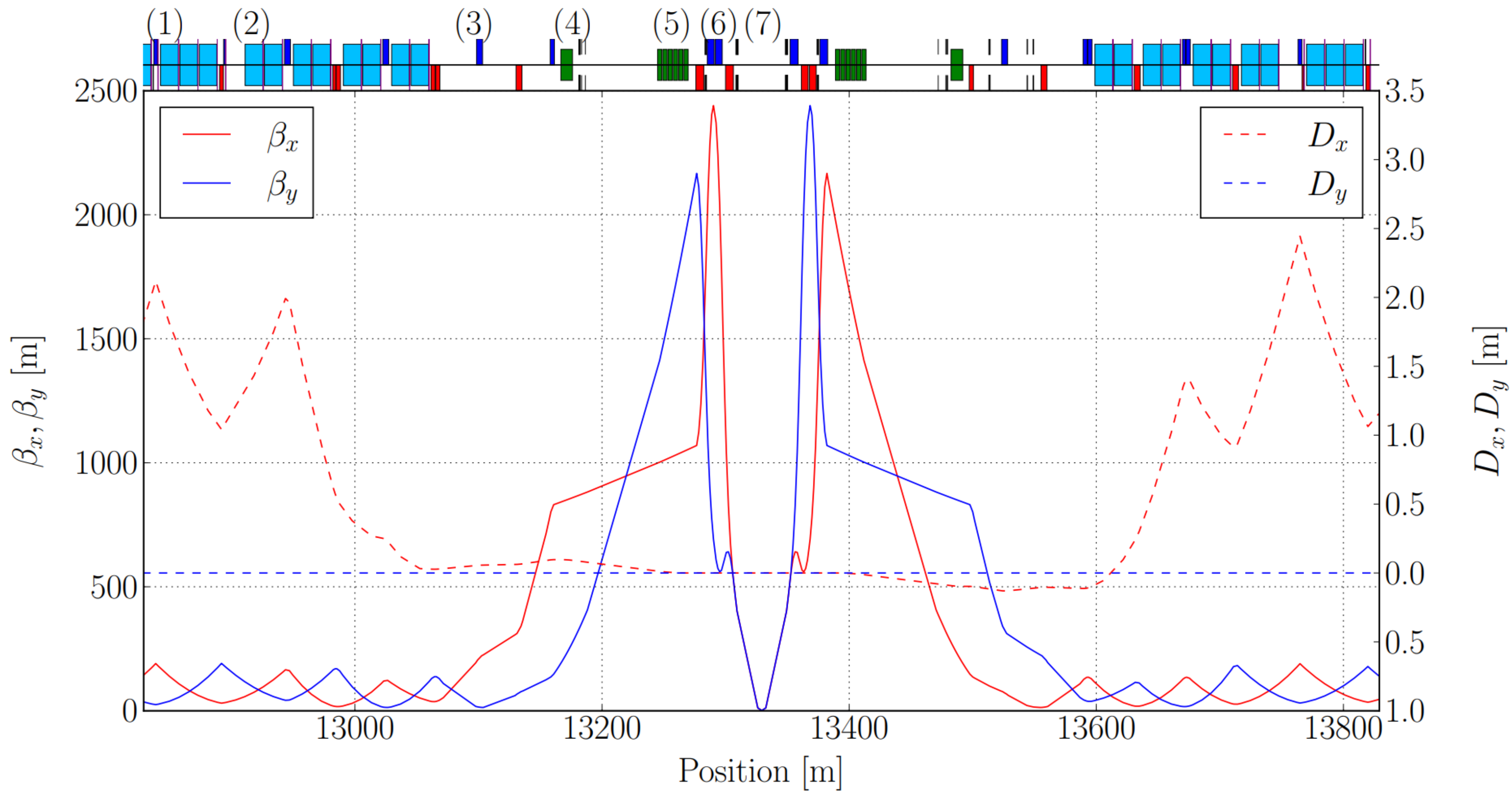
Luminosity

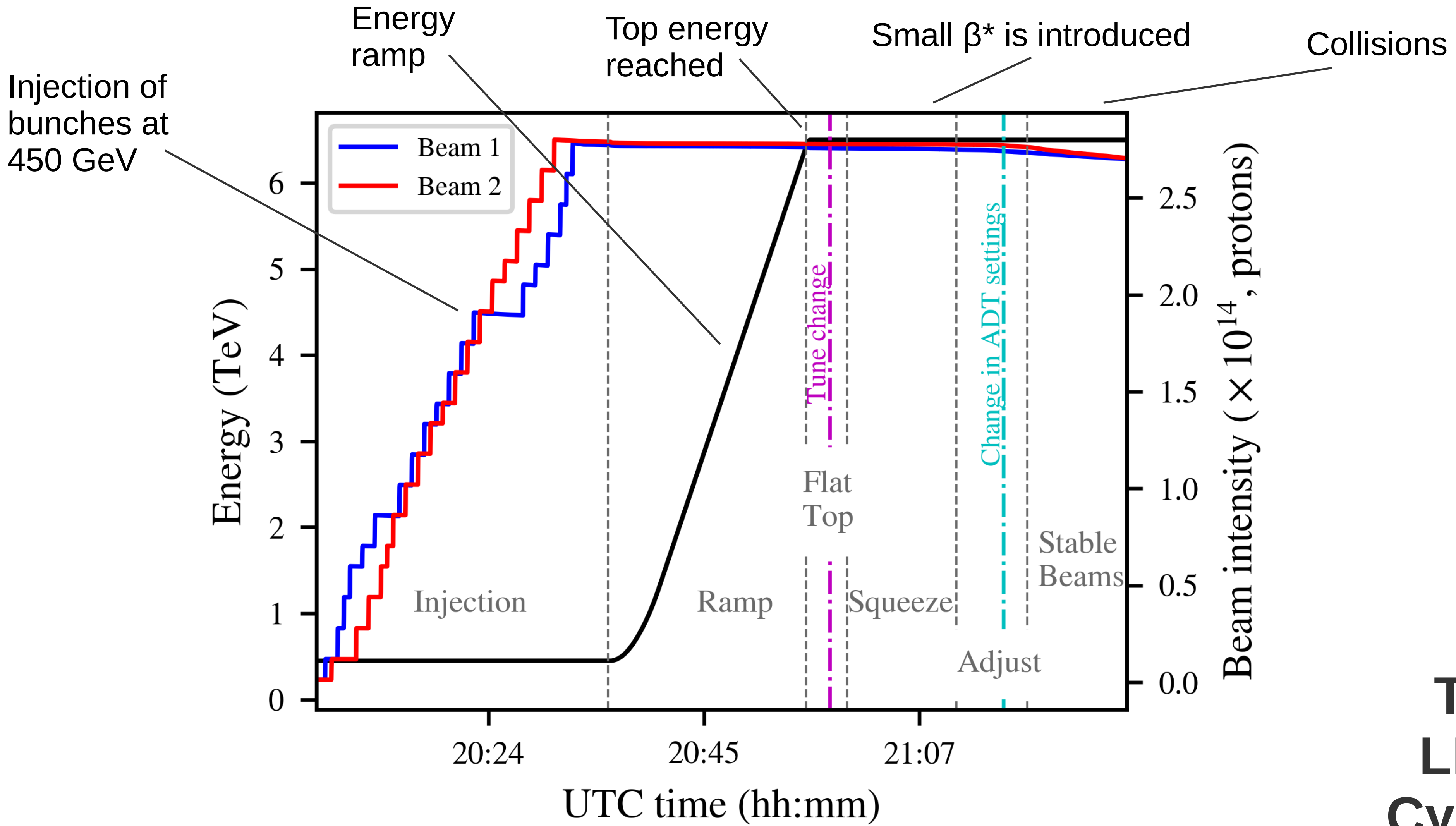


ATLAS Online Luminosity
√s = 13.6 TeV
LHC Stable Beams
Peak Lumi: 23.3 × 10^33 cm^-2 s^-1
Peak Luminosity per Fill [10^33 cm^-2 s^-1]
0
5
10
15
20
25
30
03/04
18/04
03/05
18/05
03/06
18/06
03/07
18/07
Day in 2024
7/24 calibration

Collision Point Optics

Quiz: Can we apply the "squeezed" optics from the beginning?



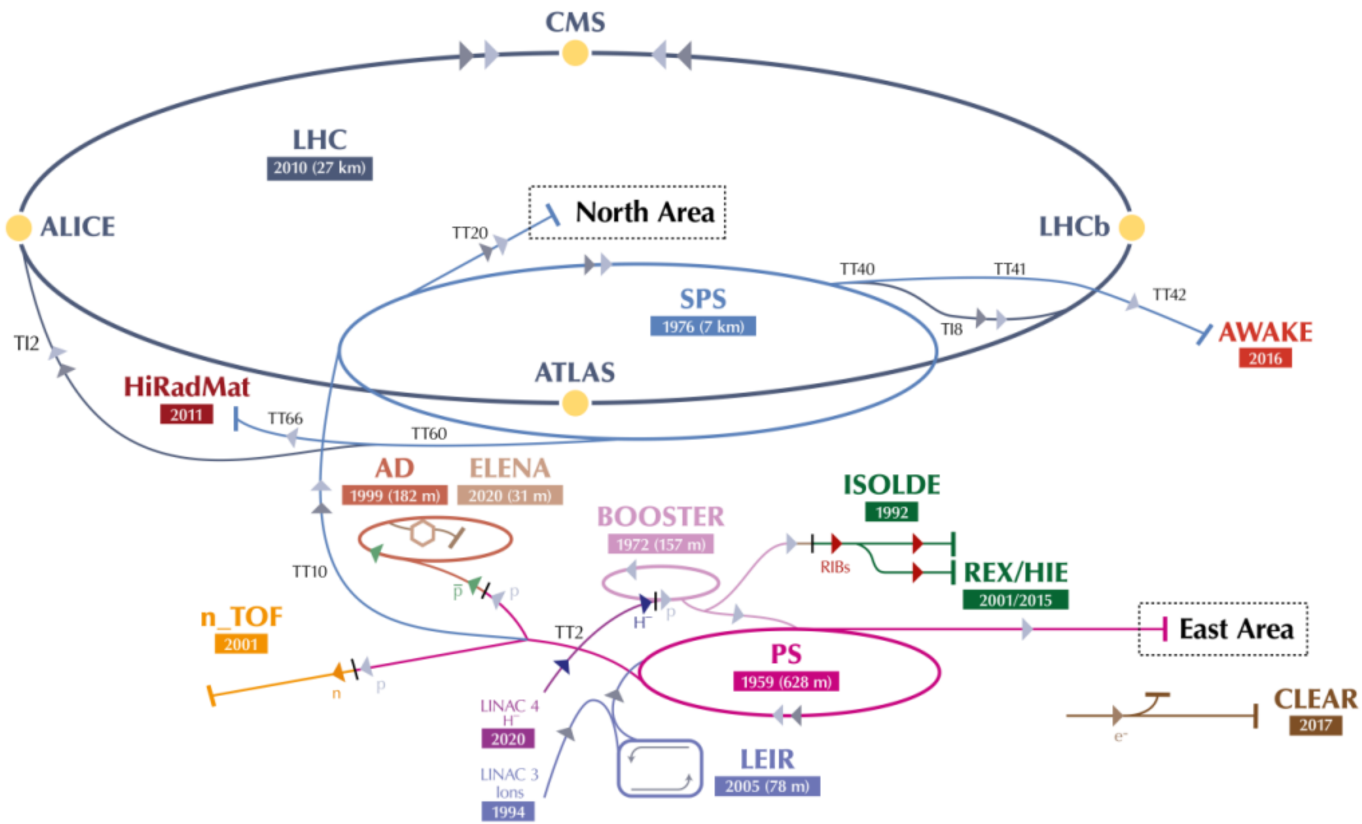


The LHC Cycle

S. Kostoglou et al., Origin of the 50 Hz harmonics in the transverse beam spectrum of the Large Hadron Collider

Outlook for tomorrow

CERN Accelerator Complex



Beam energy along the LHC injector chain

Linac 4	160 MeV
PSB	2 GeV
PS	25 GeV
SPS	450 GeV
LHC	6.5-7 TeV