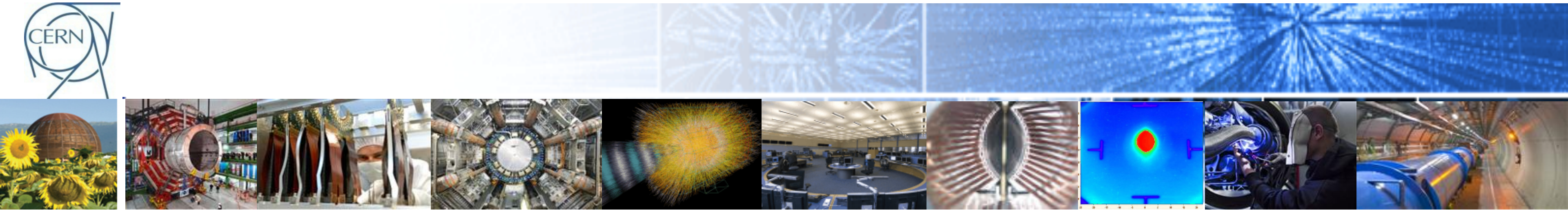
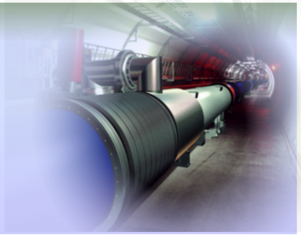
[R. Alemany]
[CERN BE/OP]
Lectures UCLouvain (30.03.2022)

Colliders and The Large Hadron Collider

1. LHC layout
2. LHC Operational cycle
3. Beam measurements



Why colliders?



What is the centre of mass energy ➔ the interesting energy because it is the only one available for the collision products ➔ when two particles of masses m1 and m2 collide?

Four-momentum

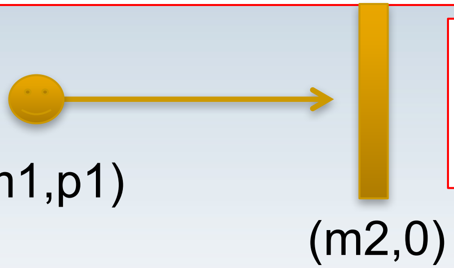
$$\mathbf{p} = (E, \vec{p})$$

Square of the four-momentum:

$$\mathbf{p}^2 = E^2 - \vec{p}^2 = m^2$$

$$(\mathbf{p}_1 + \mathbf{p}_2)^2 = E_{cm}^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

CASE 1:

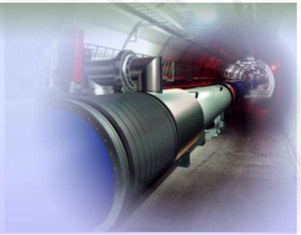


$$E_{\mathrm{cm}}^2 = (m_1^2 + m_2^2 + 2m_2 E_{1,\mathrm{lab}})$$

CASE 2:

$$E_{\mathrm{cm}}^2 = (E_1 + E_2)^2$$

Why colliders?



CASE 1:

$$E_{\mathrm{cm}}^2 = (m_1^2 + m_2^2 + 2m_2E_{1,\mathrm{lab}})$$

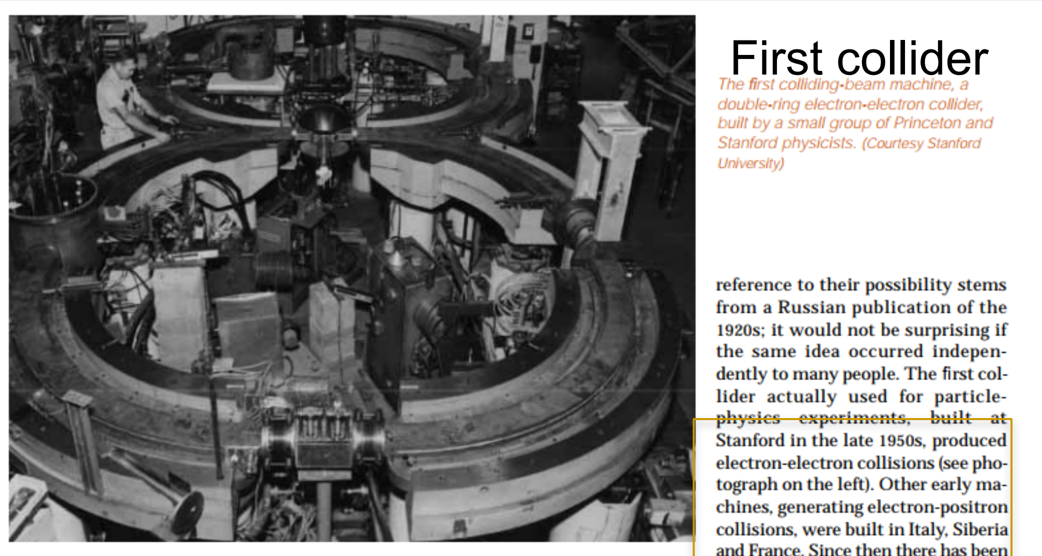
To get a Ecm = 630 GeV to do a SppS collider (SPS in the 80’s discovered the weak neutral currents with this collider), what should be the value of E1,lab?

E1,lab ~ 212 TeV

To get a Ecm = 14 TeV to do an LHC collider (LHC discovered the Higgs in 2012) what should be the value of E1,lab?

E1,lab ~ 100 PeV

If colliders would not have been invented we would not have discovered yet many particles

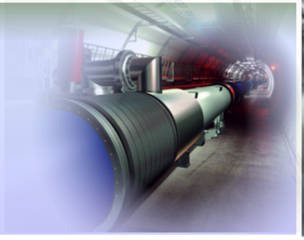


First collider

The first colliding-beam machine, a double-ring electron-electron collider, built by a small group of Princeton and Stanford physicists. (Courtesy Stanford University)

reference to their possibility stems from a Russian publication of the 1920s; it would not be surprising if the same idea occurred independently to many people. The first collider actually used for particle-physics experiments, built at Stanford in the late 1950s, produced electron-electron collisions (see photograph on the left). Other early machines, generating electron-positron collisions, were built in Italy, Siberia and France. Since then there has been

Why colliders?



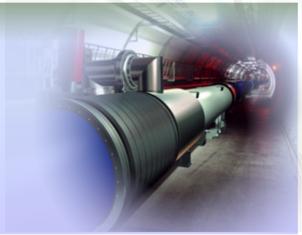
From the point of view of the energy, a collider is very very interesting
However it has some disadvantages:

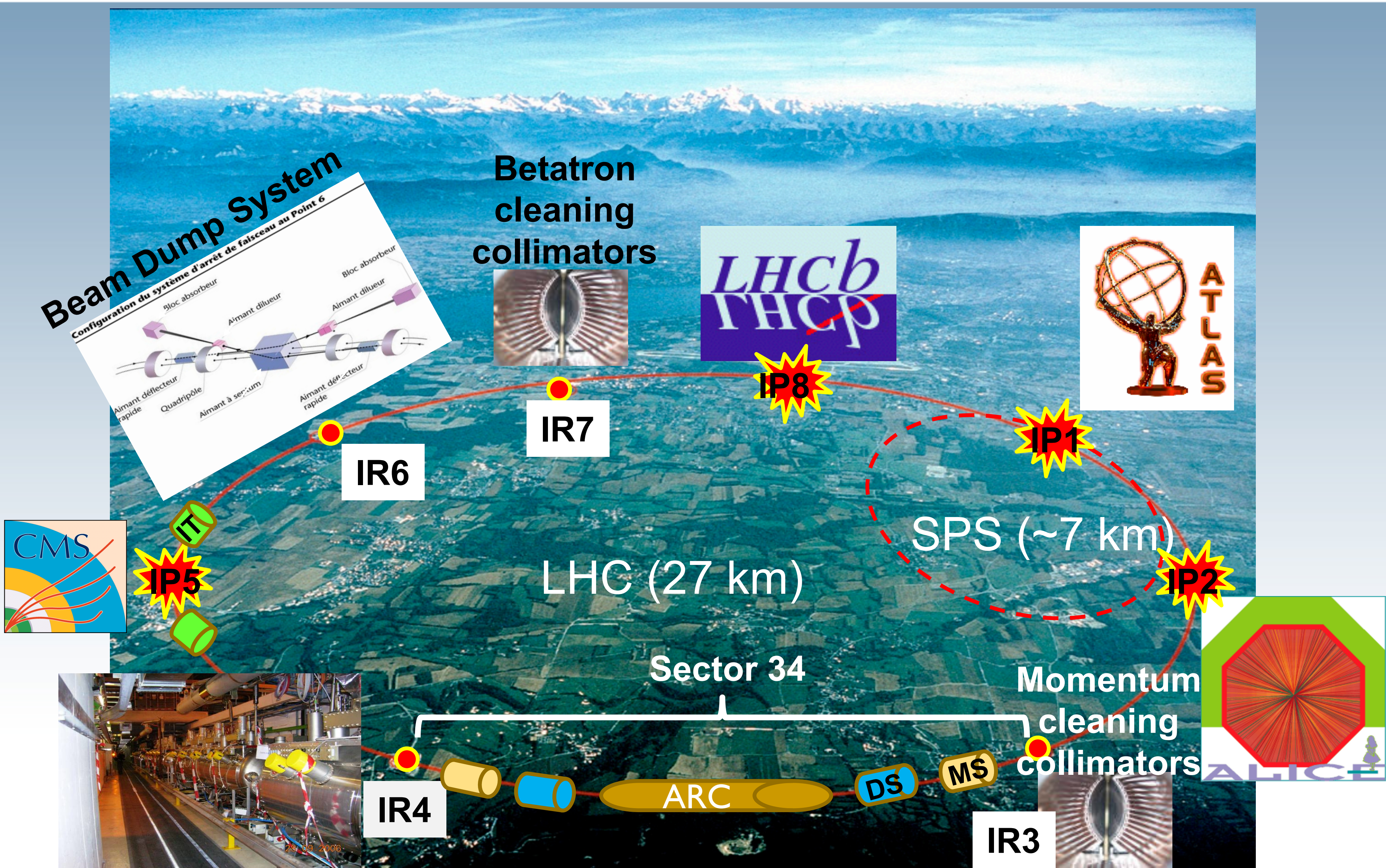
1. The beam is several orders of magnitude less dense than a fixed target ➔ less number of interactions per second
    - How do we overcome this issue?

      We collide for many hours ➔ e.g. LHC collisions ~ 12 – 15 hours

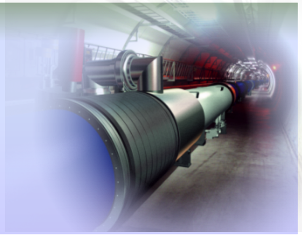
2. The collision products go out in all directions ➔ experiment has to cover all the space around the beam pipe
    - Experiments located around the beam pipe are difficult to take in/out to install a new experiment.
    - Fixed target experiments are more flexible, e.g. SPS north area: tens of experiments per year.

I. Basic layout of the machine

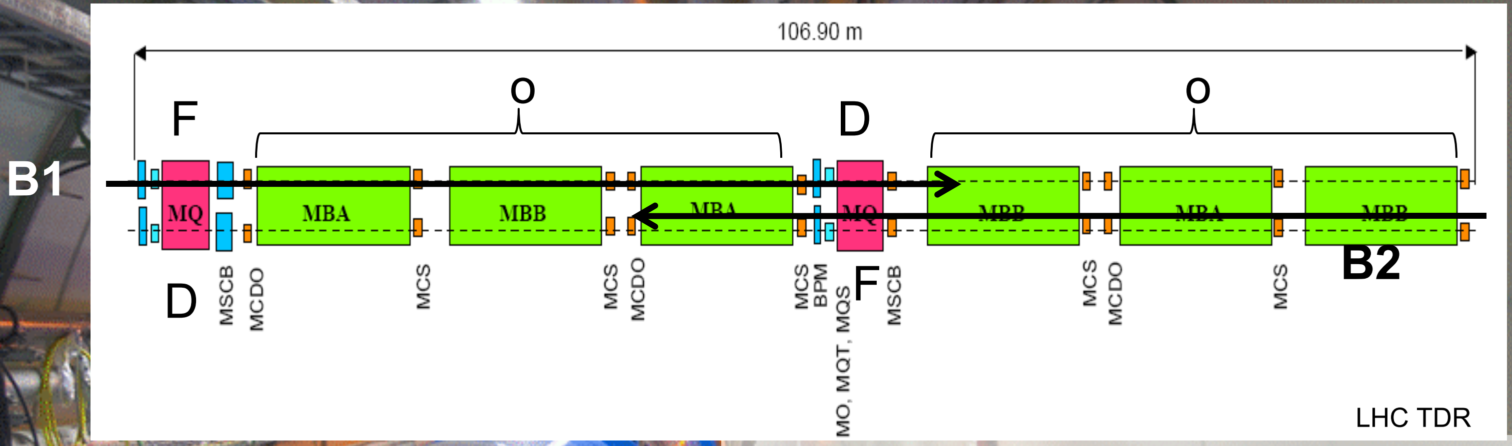




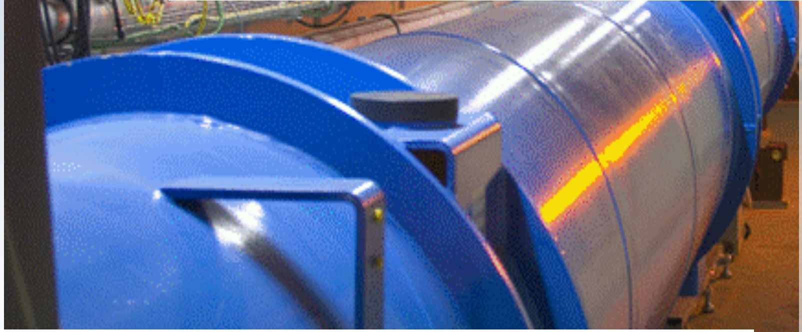
I. Basic layout of the machine: the arc



LHC arc cells = FoDo lattice* with
~ 90º phase advance per cell in the V & H plane



LHC TDR

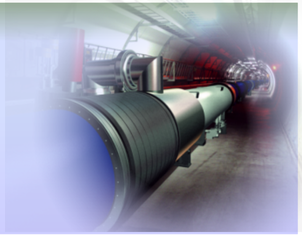


MB: main dipole
MQ: main quadrupole
MQT: Trim quadrupole
MQS: Skew trim quadrupole
MO: Lattice octupole (Landau damping)
MSCB: Skew sextupole +
Orbit corrector (lattice chroma+orbit)
MCS: Spool piece sextupole
MCDO: Spool piece octupole +
Decapole
BPM: Beam position monitor

The FoDo-Lattice

A magnet structure consisting of focusing and defocusing quadrupole lenses in alternating order with nothing in between.
(Nothing = elements that can be neglected on first sight: drift, bending magnets, RF structures ... and especially experiments...)

I. Basic layout of the machine



Golden formula (you should know by heart)

$$B\rho = \frac{p}{Ze}$$

Circumference ➔ FIXED!!! by LEP

FIXED, no choice

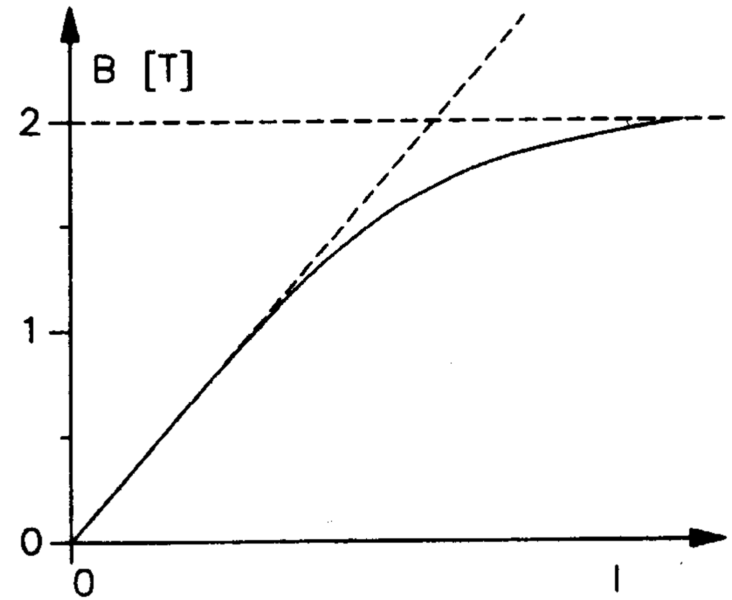
$$\rho \approx \frac{26658.9\,m}{2\pi}\cdot 66\% \approx 2780\,m$$

~ 66% of the lattice elements are dipoles

p = nucleon momentum ➔ defined by the physics case ➔ TeV range ➔ **7 TeV**

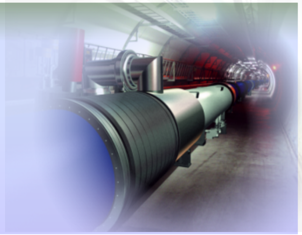
$$B = \frac{p}{\rho Z e} \approx 3.33\frac{p\left(\frac{GeV}{c}\right)}{\rho(m)} = 8.39\,T$$

We need SUPERCONDUCTING technology

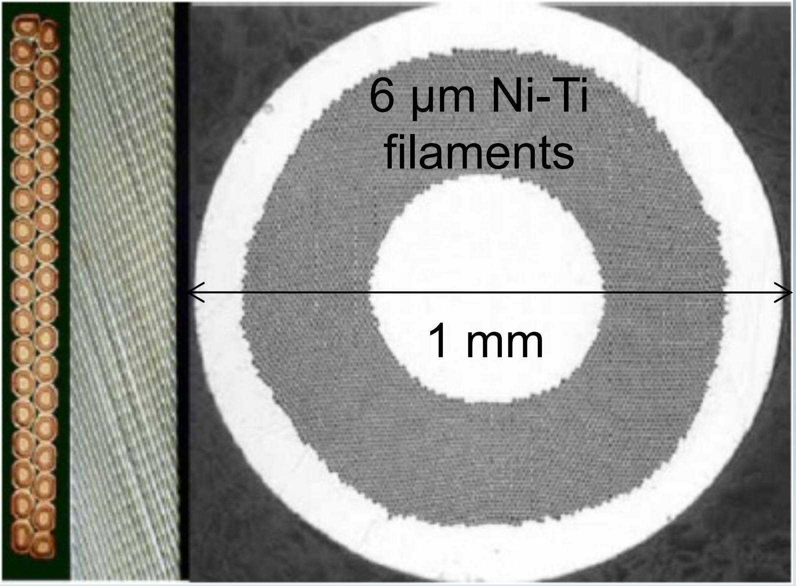


Field limit for normal conducting magnets due to saturation

I. Basic layout of the machine: Superconducting magnets

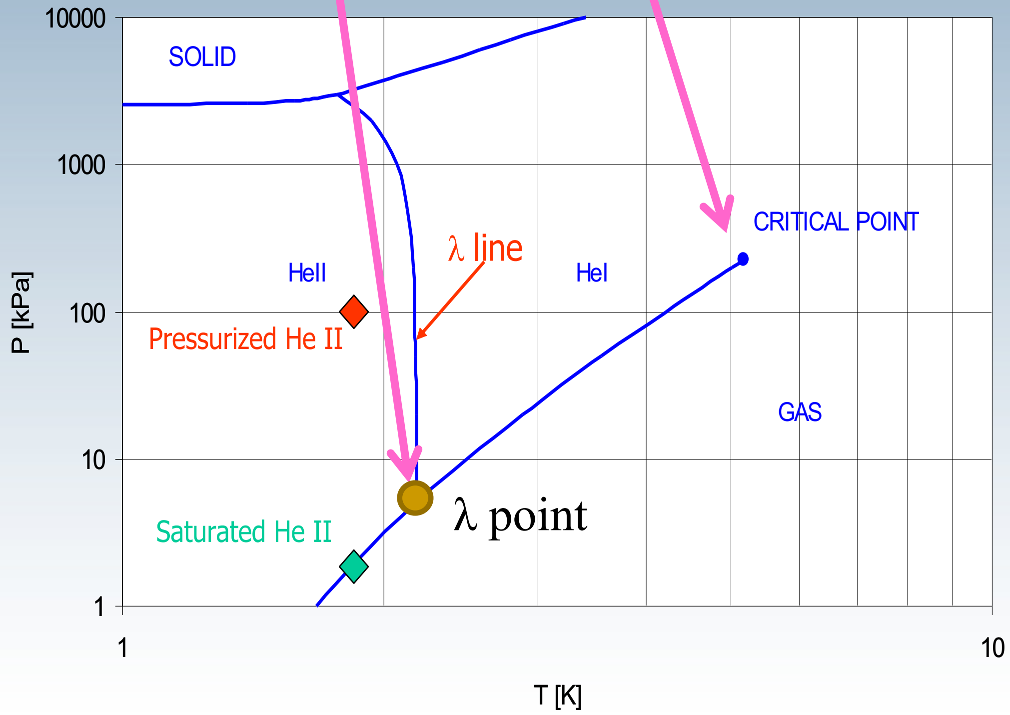


Superconducting cables of Nb-Ti



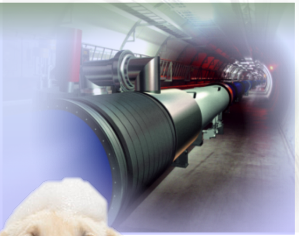
LHC ~ 27 km circumf. with 20 km of superconducting magnets operating @8.3 T. An equivalent machine with normal conducting magnets would have a circumference of 100 km and would consume 1000 MW of power ➔ we would need a dedicated nuclear power station for such a machine. LHC consumes ~ 10% nuclear power station

He gas ➔ liquid @ 4.2 K ➔ superfluid @ 2.17 K

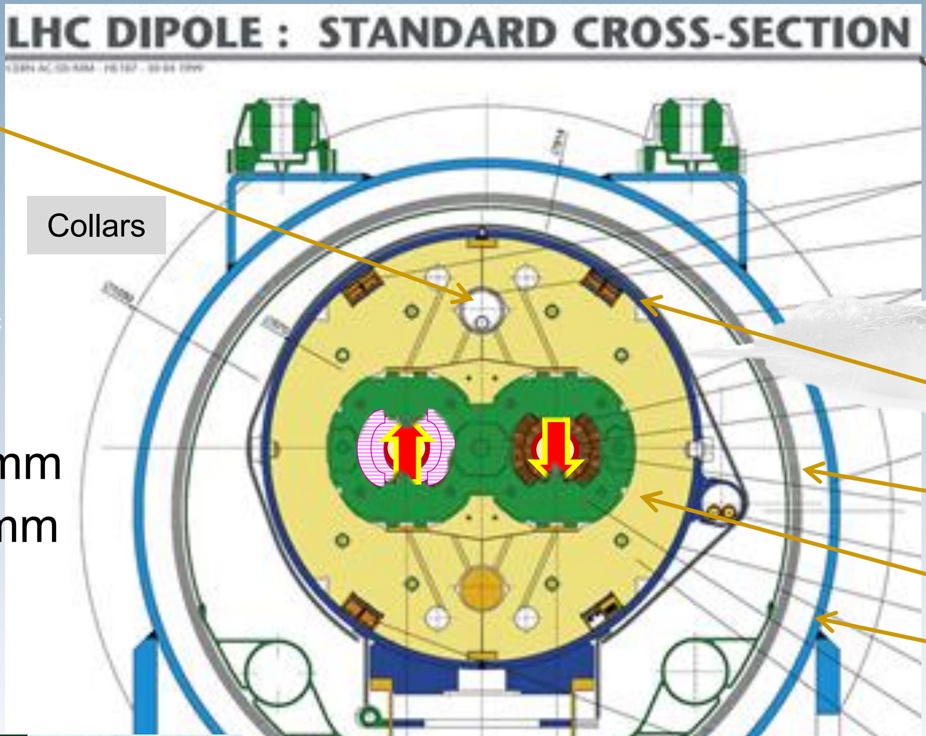


Total amount of He used @LHC ~500-700 T

I. Basic layout of the machine: main cryodipoles (two dipoles in one)



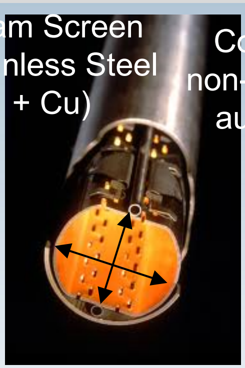
- The geometry of the main dipoles (Total of 1232 cry s)



Heat exchanger

Beam pipe (Ultrahigh **beam** vacuum 10^{-10} Torr like at 1000 km over see level)

Collars



Beam Screen (Stainless Steel + Cu)

Cold bore non-magnetic austenitic steel

36.9 mm

46.5 mm

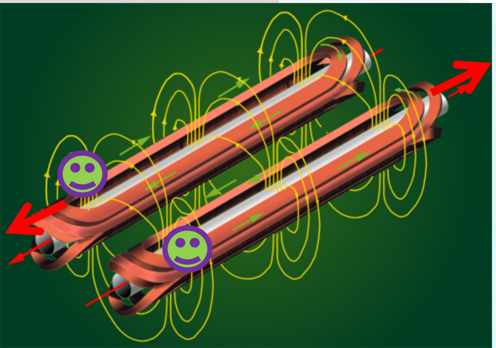
He Vessel

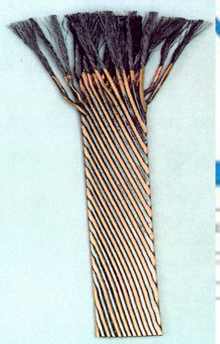
Thermal shield

Iron yoke

Vacuum vessel (10^{-6} mbar)

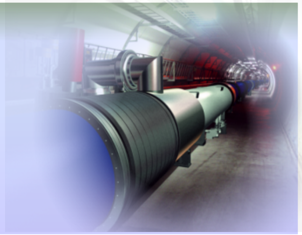
Superconducting coils





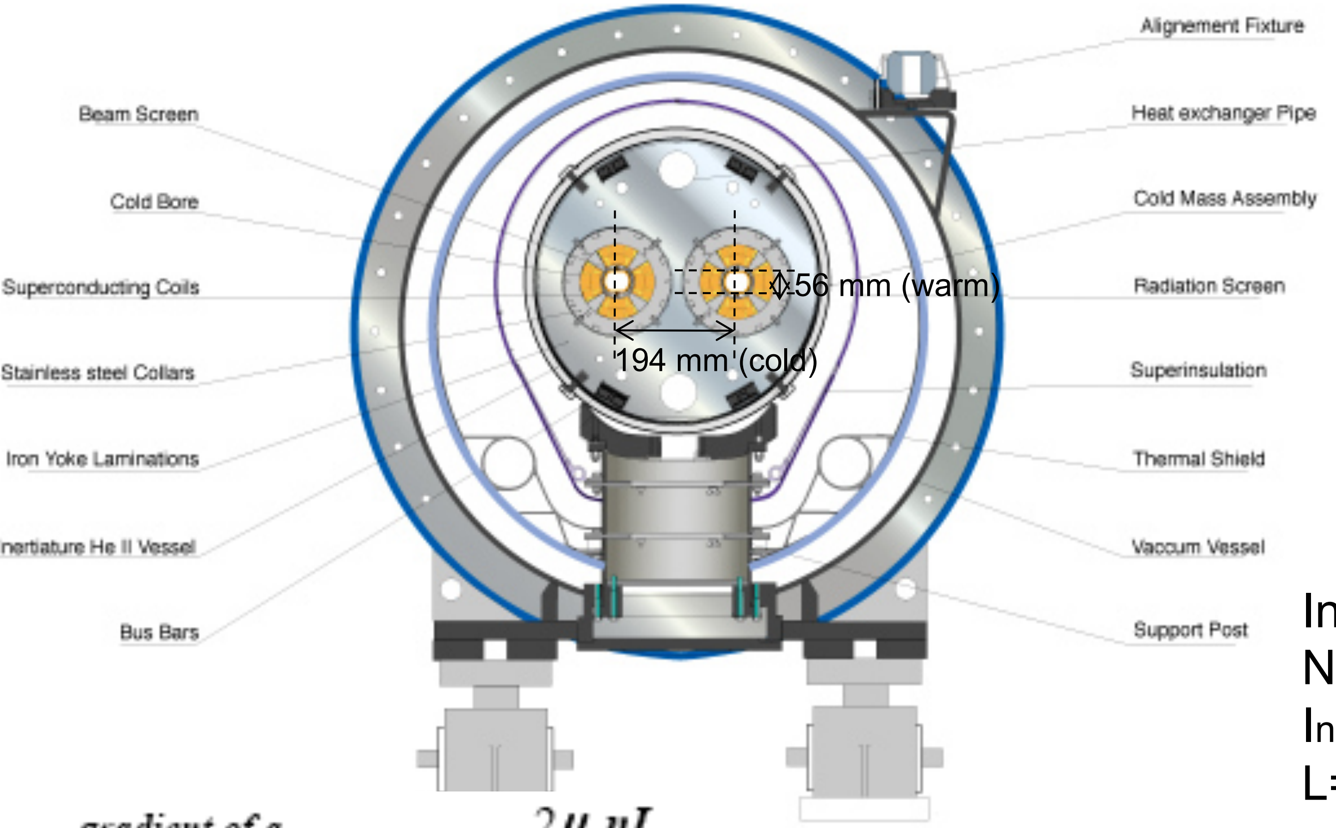
L ~ 15 m
8.3 T, 11.87 kA
T = 1.9 K, ~27.5 ton

I. Basic layout of the machine: main quadrupoles



LHC quadrupole cross section

55 per sector



Integrated gradient = 690 T
Nominal gradient = 223 T/m
$I_{nominal}$ = 11.87 kA
L=3.1 m

gradient of a quadrupole magnet: $g = \frac{2\mu_0 n I}{\boxed{r^2}}$

CERN AC - SQ1 - 12/97

I. Basic layout of the machine: main dipoles ➔Field quality

The magnetic field of the main dipoles:

The **stability** of the geometry of the superconducting coils is essential to the field quality.

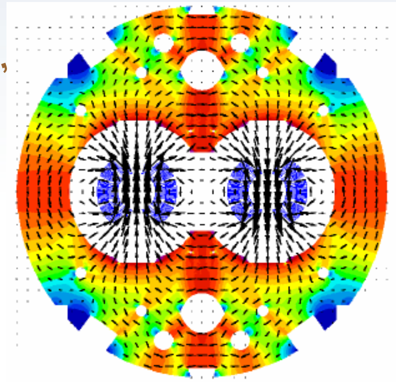
Mechanical stress during coil assembly
Thermal stresses during cool-down
Electromagnetic stresses during operation

= **sources of deformations** of the coil geometry

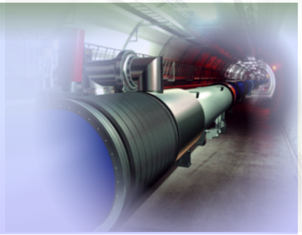
Additional sources of field errors are the **dimensional tolerances** of the magnet components and of the manufacturing and assembling tooling.

The relative variations of the integrated field and of the field shape imperfections must not exceed ~ 10 $^{-4}$ and

Reference: LHC Project Report 501
“Field Quality Specification for the LHC Main Dipole Magnets”



I. Basic layout of the machine: main dipoles ➔Field quality



Why the tolerances are so tight?

➔ Because the field quality determines how long the particles can circulate in the accelerator

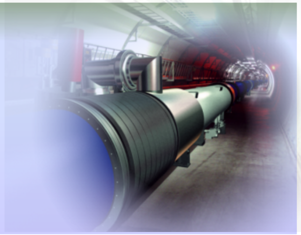
$$B_y + iB_x = B_{ref} \sum_{n=1}^{\infty} (\underset{\substack{\uparrow \\ \text{Normal harmonic}}}{b_n} + i\underset{\substack{\uparrow \\ \text{Skew harmonic}}}{a_n}) \left(\frac{x + iy}{\underset{\searrow \text{17 mm}}{R_{ref}}} \right)^{n-1}$$

n = 1 ➔ dipole
n = 2 ➔ quadrupole
n = 3 ➔ sextupole
n = 4 ➔ octupole
n = 5 ➔ decapole

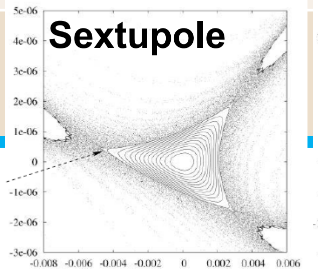
Up to which order do we care?

➔ Up to n = 7 at least ➔ $\sim 10^{-4}$

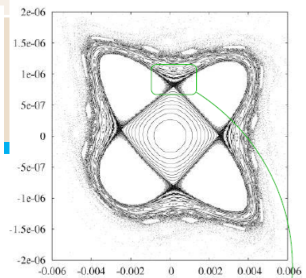
I. Basic layout of the machine: main dipoles →Field quality



Error	Side effects if error is > few 10^{-4}	Corrected with
a1 b1	Closed orbit perturbations and thus feed-down contributions from higher order multiple errors	Dipole correctors (MCB)
a2	Linear coupling and vertical dispersion	Skew quadrupoles (MQS)
b2	Tune change, β and dispersion beating	Trim quadrupoles (MQT)
a3	Chromatic coupling and Q”	Skew sextupoles (MSS)
b3	b2 feed-down at injection (persistent current effect) and off-momentum β-beat	Sextupole (MCS)
a4	Dynamic aperture (DA) at injection	
b4	DA and Q” at injection	Octupole (MCO)
a5	DA for off-momentum particles at injection	
b5	DA and Q’” at injection	Decapole (MCD)
a6 to b7	DA at injection	

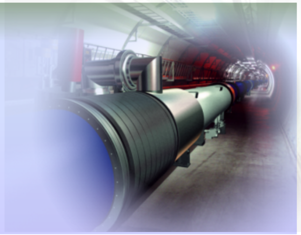


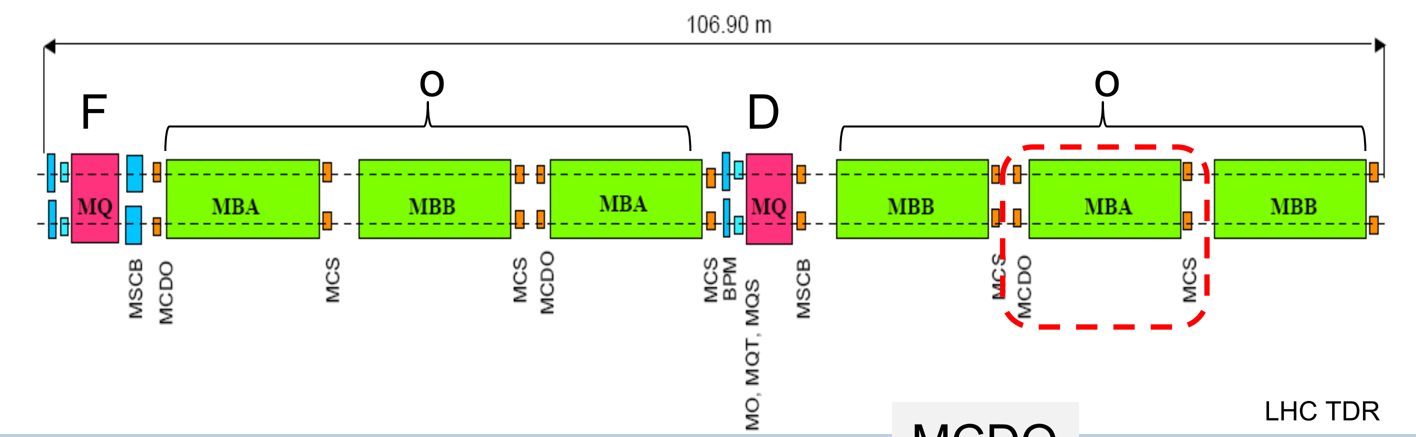
Sextupole



Sextupole+octupole

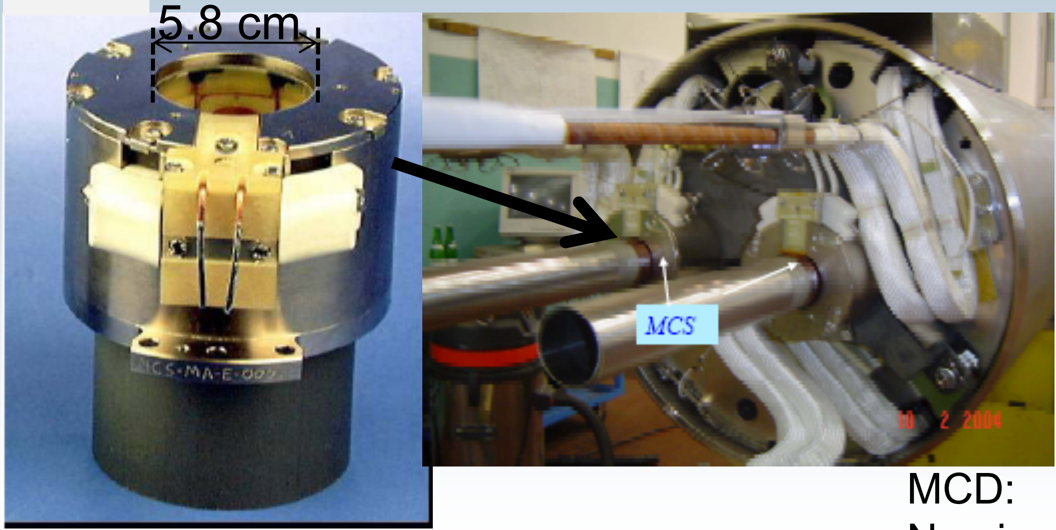
I. Basic layout of the machine: dipole corrector magnets



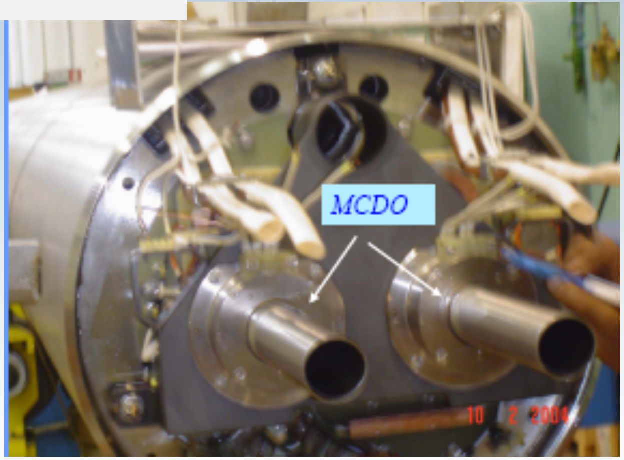


LHC TDR

MCS



MCDO

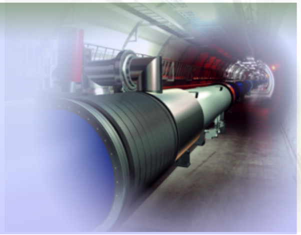


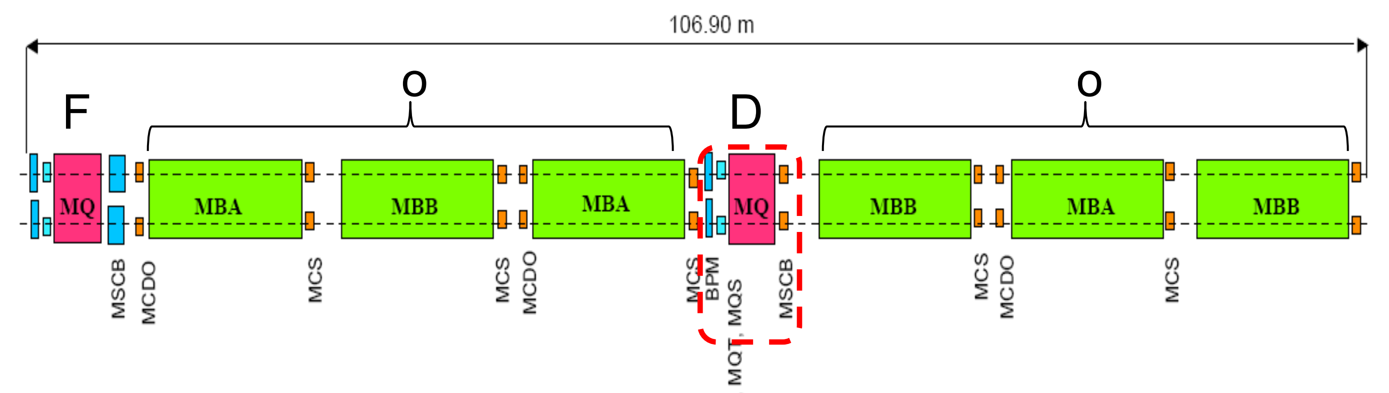
Nominal main field strength = 1630 T/m^2
Inominal = 550 A, 1.9 K,
L=15.5 cm, ~10 kg

MCD:
Nominal main field strength ~ 120 T/m^4
Inominal = 550 A, 1.9 K,
L=11 cm, ~6 kg

MCO:
Nominal main field strength = 8200 T/m^3
Inominal = 100 A, 1.9 K,
L=11 cm, ~6 kg

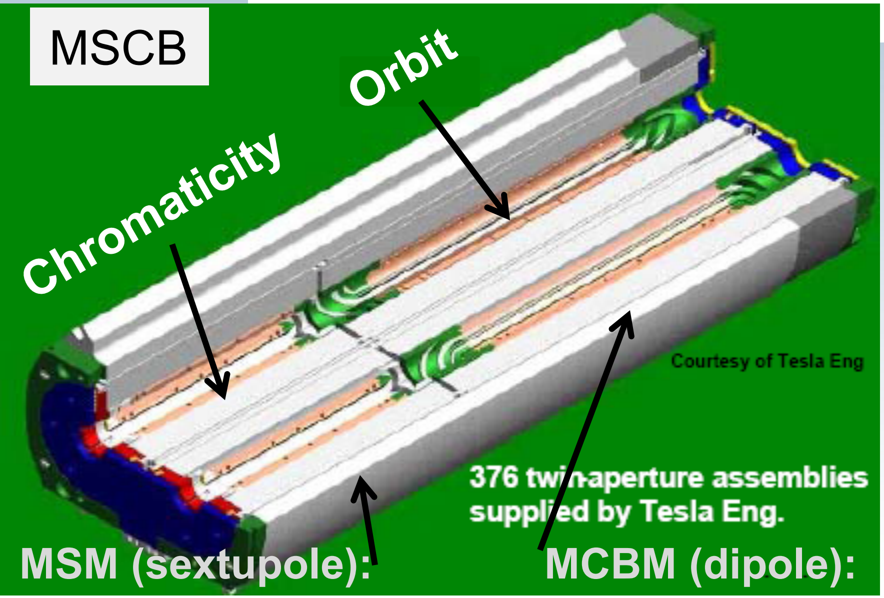
I. Basic layout of the machine: quadrupole corrector magnets





LHC TDR

MSCB



Courtesy of Tesla Eng

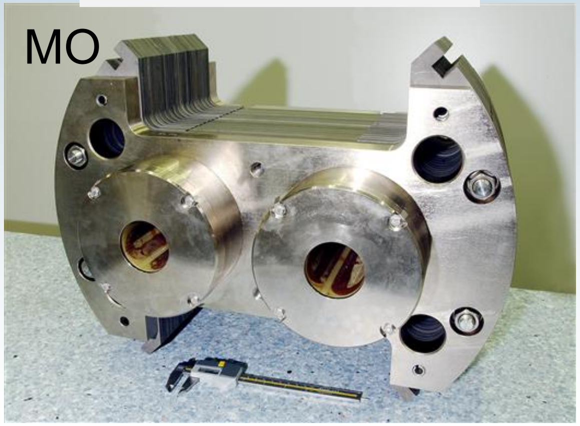
376 twin-aperture assemblies supplied by Tesla Eng.

MSM (sextupole):
Nominal main field strength = 4430 T/m^2
$I_{nominal}$ = 550 A, 1.9 K,
L=45.5 cm, ~83 kg

MCBM (dipole):
Nominal main field strength = 2.93 T
$I_{nominal}$ = 55 A, 1.9 K,
L=78.5 cm, ~143 kg

Landau damping

MO



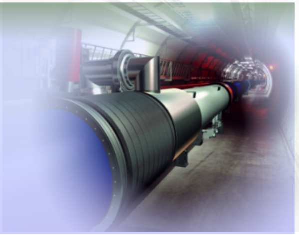
Nominal main field strength = 63100 T/m^3
$I_{nominal}$ = 550 A, 1.9 K
L=38 cm, ~8 kg

MQT/MQS

MQT: Trim quadrupole
MQS: Skew trim quadrupole

MQT/MQS:
Nominal main field strength = 123 T/m
$I_{nominal}$ = 550 A, 1.9 K
L=38 cm, ~250 kg

I. Basic layout of the machine: quadrupole corrector magnets



20.) Chromaticity: A Quadrupole Error for Δp/p ≠ 0

focusing lens $k = \frac{g}{p/e}$

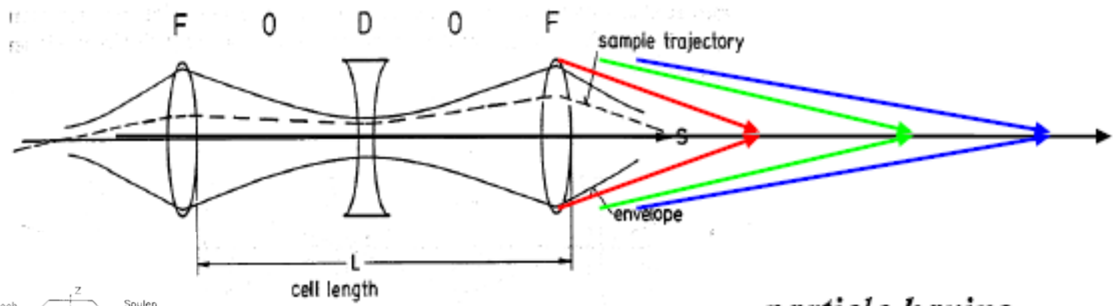
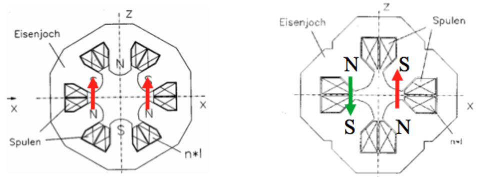


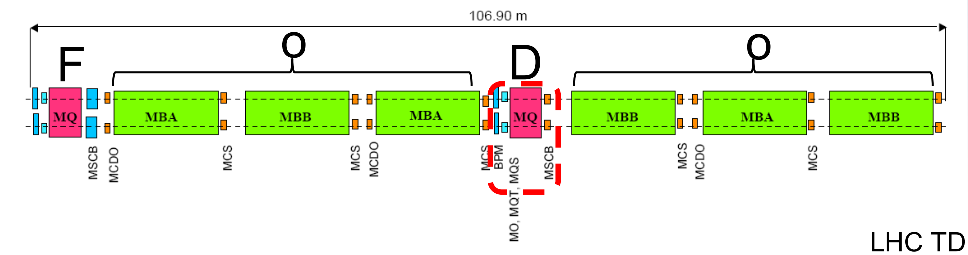
Figure 29: FODO cell

particle having ...
to high energy
to low energy
ideal energy

Sextupole Magnets:



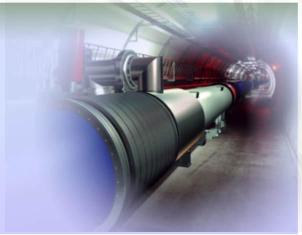
(Courtesy of B. Holzer)

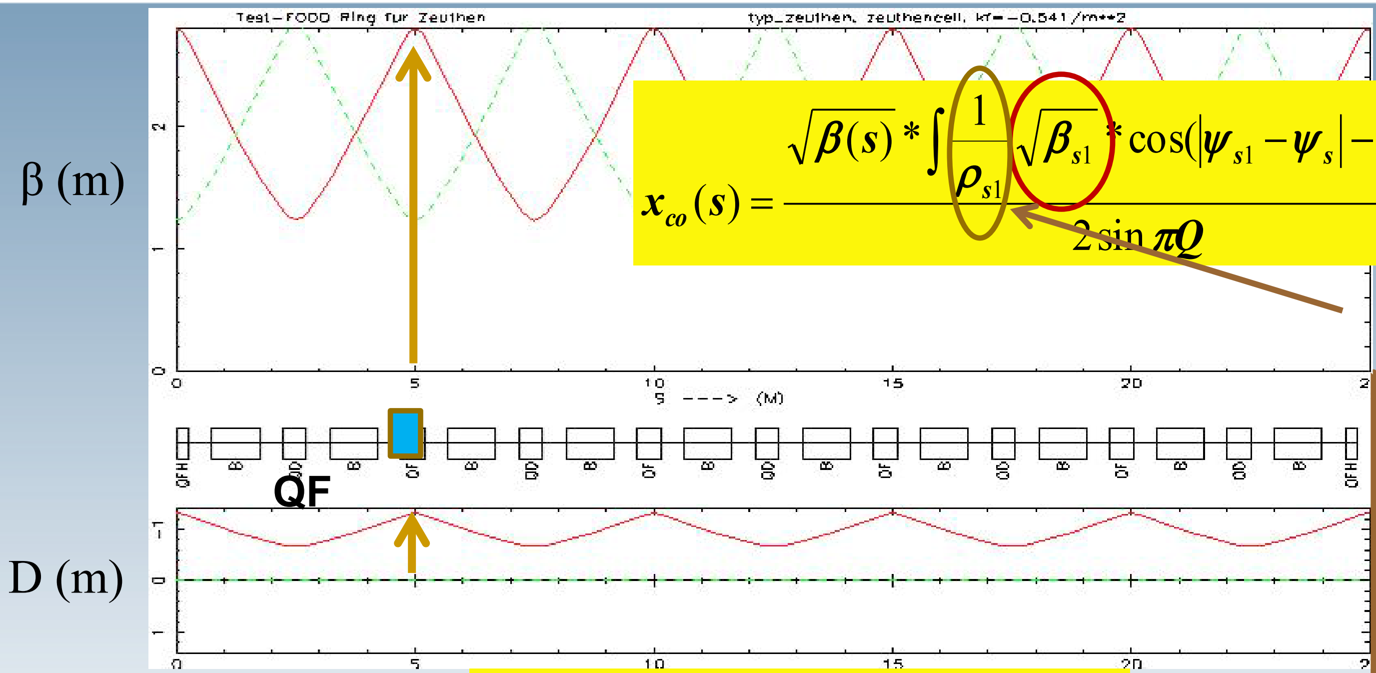


LHC TDR

Why the orbit and sextupole correctors are placed close to a quadrupole?

I. Basic layout of the machine: quadrupole corrector magnets





$$x_{co}(s) = \frac{\sqrt{\beta(s)} * \int \frac{1}{\rho_{s1}} \sqrt{\beta_{s1}} * \cos(|\psi_{s1} - \psi_{s}| - \pi Q)\, ds}{2 \sin \pi Q}$$

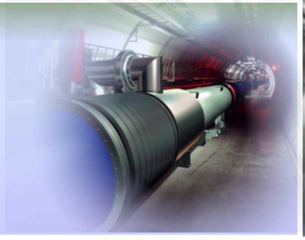
Magnet strength

$$Q' = -\frac{1}{4\pi} \oint k_{qua}(s) \beta(s) ds +$$ (Natural chromaticity term)

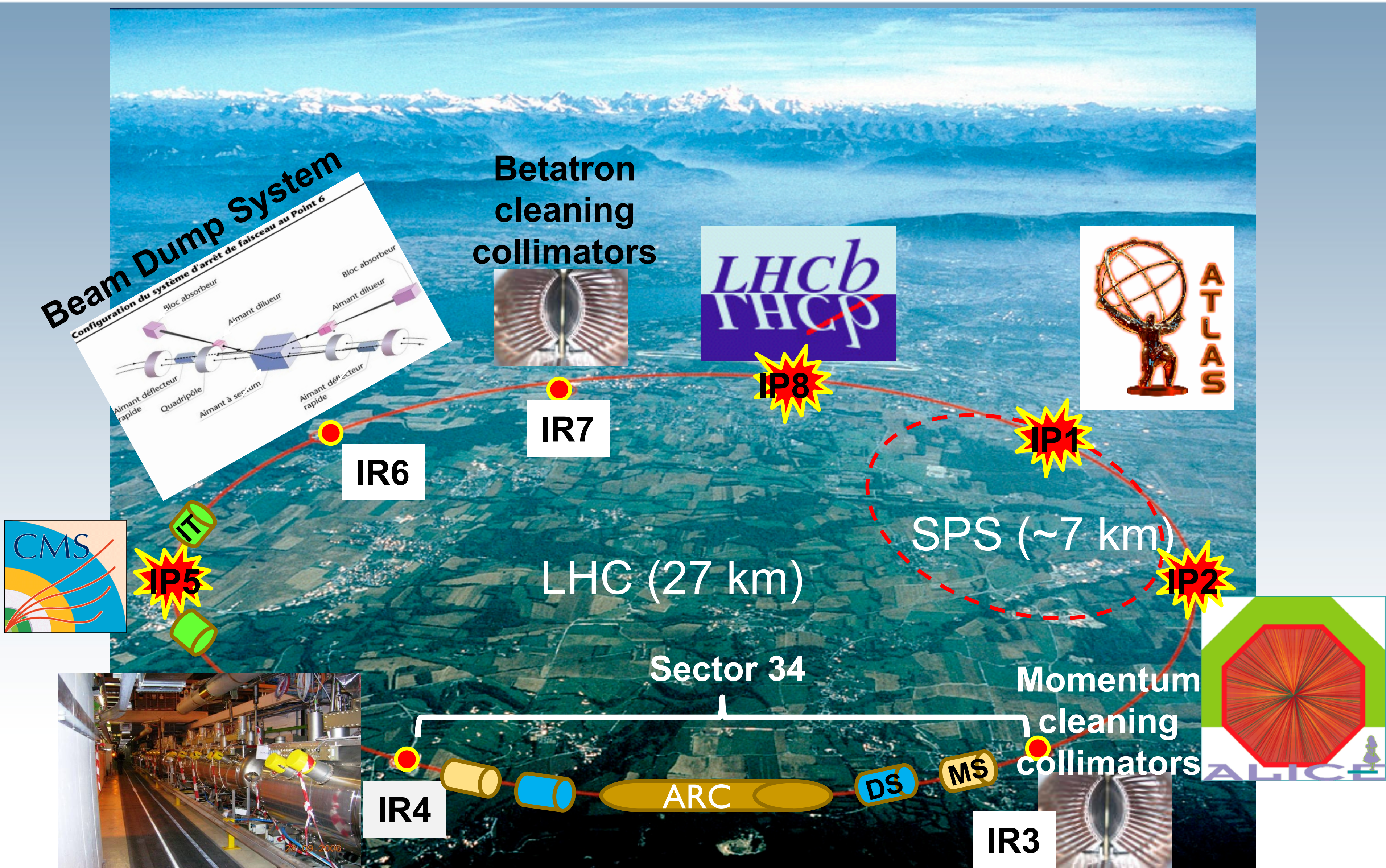
Chromaticity correction terms

$$+\frac{1}{4\pi} \sum_{FocuSext} k_{sext}^{focu} l_{sext} D_x^{focu} \beta_x^{focu} -$$

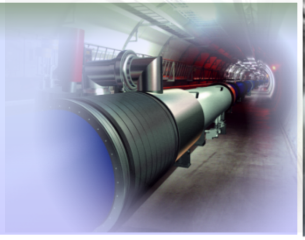
$$-\frac{1}{4\pi} \sum_{DeFocuSext} k_{sext}^{defocu} l_{sext} D_x^{defocu} \beta_x^{defocu}$$

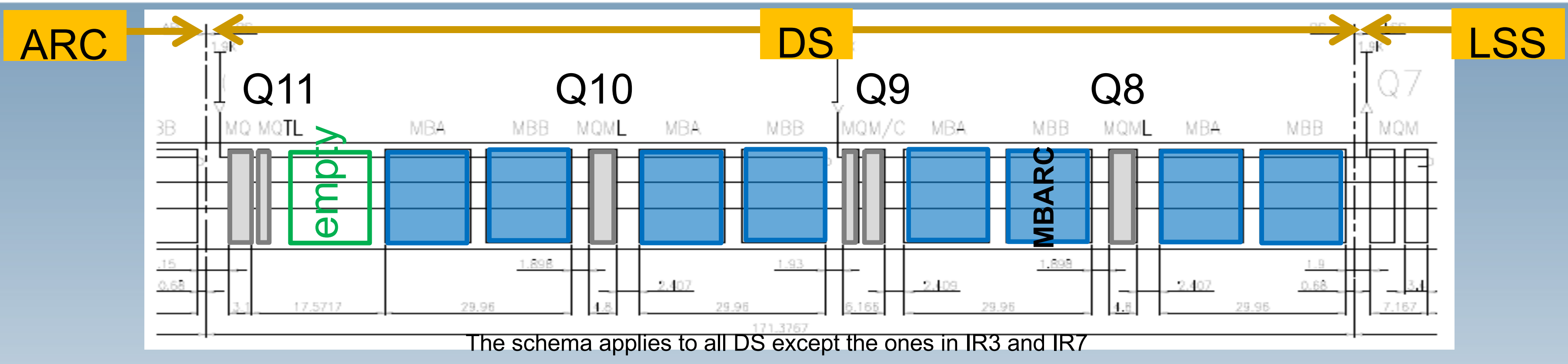


I. Basic layout of the machine



I. Basic layout of the machine: Dispersion suppression



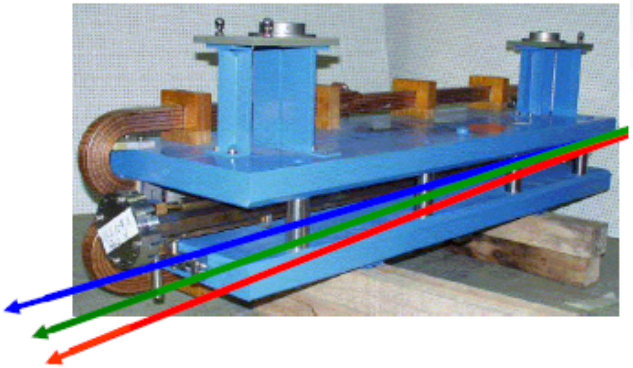


The schema applies to all DS except the ones in IR3 and IR7

- **Cancels the horizontal dispersion** generated on one side by the arc dipoles and on the other by the separation/recombination dipoles and the crossing angle bumps
- Helps in **matching** the insertion optics to the periodic solution of the arc
- If only dipoles are used they cannot fully cancel the dispersion, just by a factor 2.5. Therefore **individual powered quadrupoles are required** (Q8-Q11 with I ~ 6000 A)

dipole magnet

$$\boxed{\alpha = \frac{\int B\,dl}{p/e}}$$

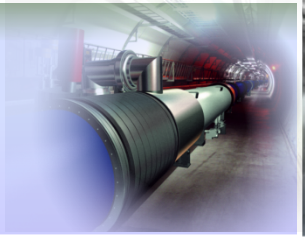


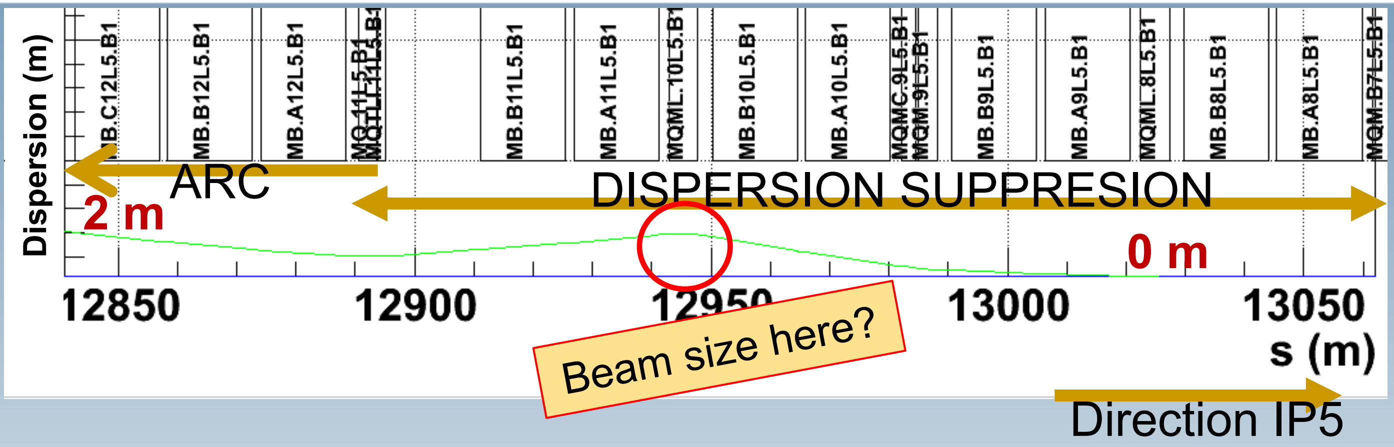
(Courtesy of B. Holzer)

$$x'' + K(s)x = \frac{1}{\rho}\frac{\Delta p}{p}$$

$$x(s) = x_\beta(s) + D(s)\frac{\Delta p}{p}$$

I. Basic layout of the machine: Dispersion suppression





D(s) is **created by the dipole magnets** and afterwards **focused by the quadrupoles**

The inhomogeneous solution **changes the beam size** …

$$\varepsilon = \frac{\varepsilon_n}{\beta_{rel}\gamma_{rel}}$$

$$\sigma = \sqrt{\sigma_\beta^2 + \sigma_D^2} = \sqrt{\varepsilon\beta + D^2\left(\frac{\Delta p}{p}\right)^2}$$

At 7 TeV in LHC: ε_n=3.5 μm rad, β=180 m, D=2 m, Δp/p ~ 10^{-3}

$$\sigma = \sqrt{3.5 \cdot 10^{-6} + 4 \cdot 10^{-6}}$$

What is the beam size at 450 GeV?

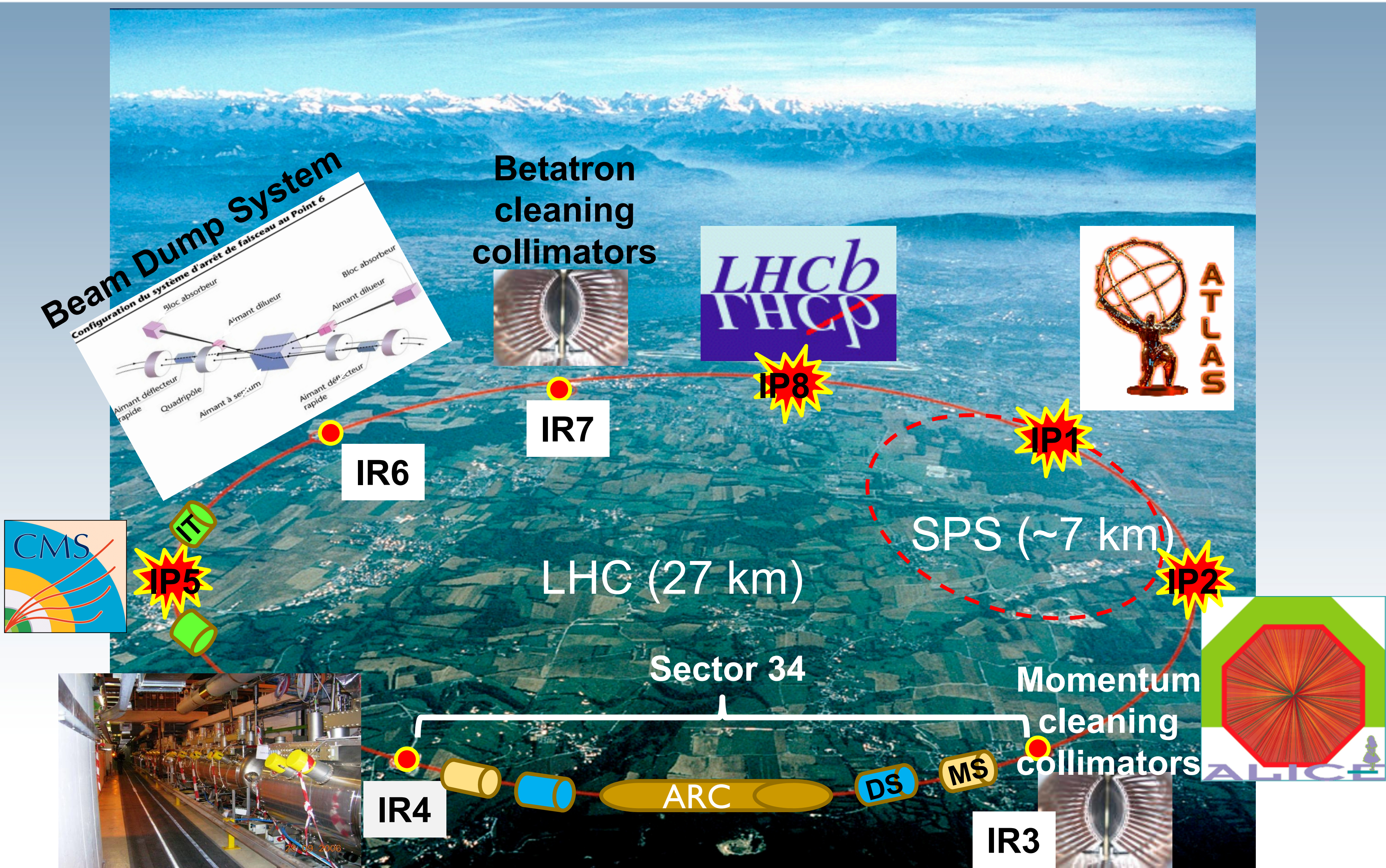
$\sigma = \sqrt{\frac{\varepsilon_n}{\beta\gamma}\beta + D^2\left(\frac{\Delta p}{p}\right)^2}$ ➔ γ(@7 TeV)~**7463** γ(@450 GeV)~**480 β≈1**

➔ $\sigma = \sqrt{1.3 \cdot 10^{-6} + 4 \cdot 10^{-6}} \cong \sigma_D + 30\%\sigma_\beta$

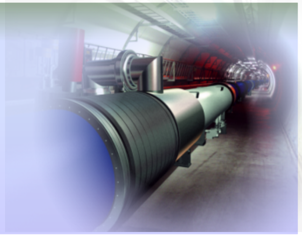
When you design your beam pipe you have to take into account the contribution of D(s)

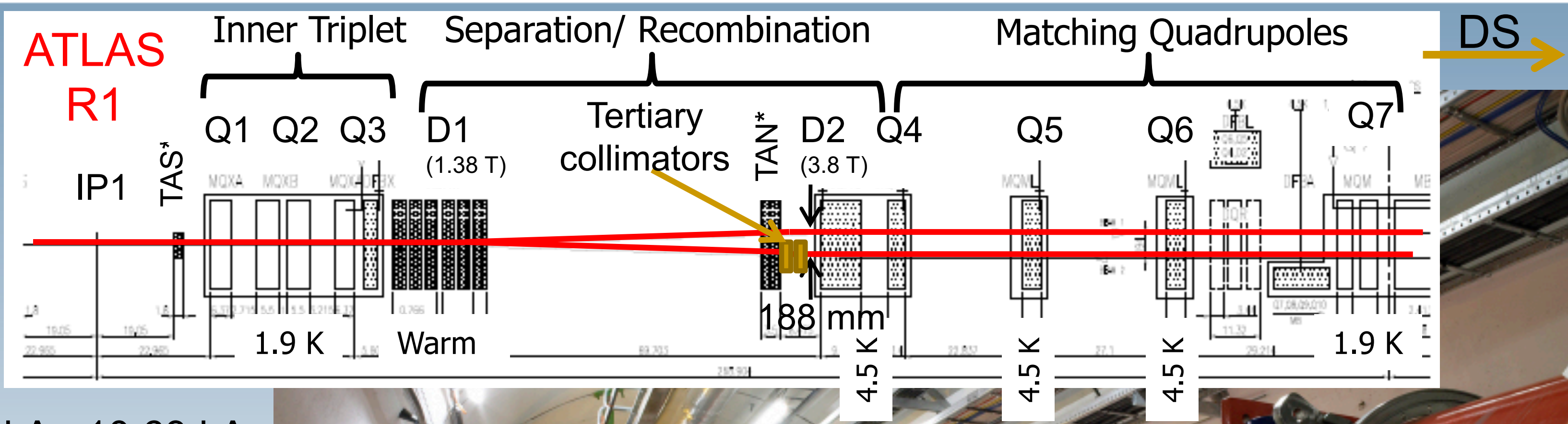
Why do we suppress dispersion before reaching the IP?

I. Basic layout of the machine



I. Basic layout of the machine: Luminosity insertions

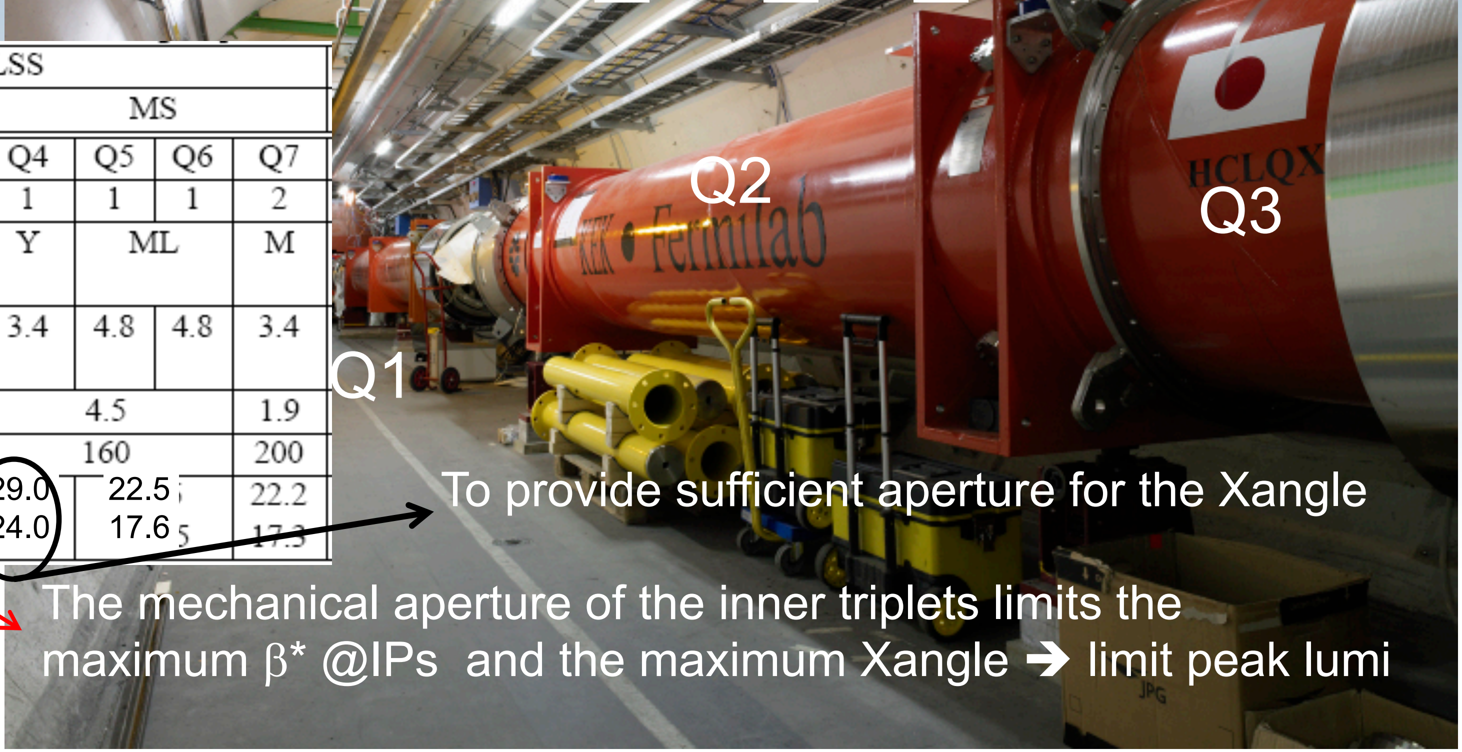




6.45 kA 10.63 kA

	LSS						
	low-β triplet			MS			
Magnet	Q1	Q2	Q3	Q4	Q5	Q6	Q7
#	1	2	1	1	1	1	2
Type: MQ-	XL	X	XL	Y	ML		M
L [m]	6.3	5.5	6.3	3.4	4.8	4.8	3.4
T [K]	1.9			4.5			1.9
G [T/m]	200/205			160			200
r [mm]	23.85 18.95	28.95 24.05		29.0 24.0	22.5 17.6		22.2 17.3

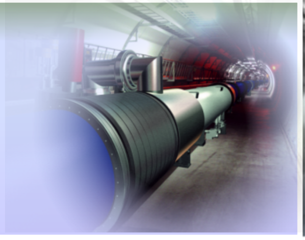
* Protect Inner Triplet (TAS) and D2 (TAN) from particles coming from the IP



To provide sufficient aperture for the Xangle

The mechanical aperture of the inner triplets limits the maximum β* @IPs and the maximum Xangle ➔ limit peak lumi

Luminosity

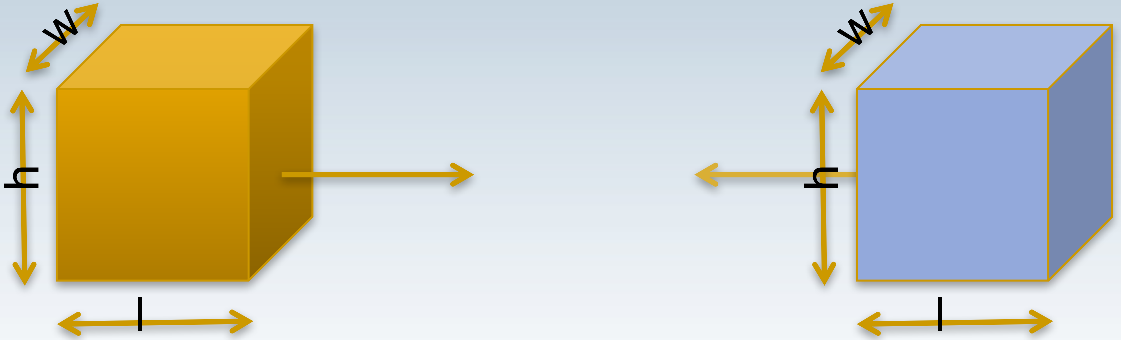


Luminosity = number of interactions per unit of time

$$\frac{dR}{dt} = \mathrm{L}\sigma$$

cross-section at the given energy of the interested physics

$$\mathrm{cm}^{-2}.\ \mathrm{s}^{-1}$$



Number of particles of the first beam in the cube:

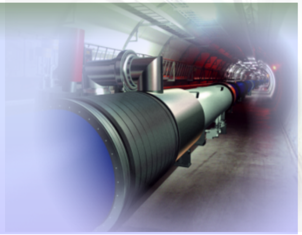
$$n_1 = \frac{I_1}{qs} \cdot \underbrace{\frac{l}{c}}_{t}$$

I/s=intensity per cm^2
with I = q/t

The orange beam is crossed by n2 particles per unit of time:

$$n_2 = \frac{I_2}{qs}$$

Luminosity



The number of events per unit of time for two beams of 1 cm2 is:

$$\frac{dn}{dt} = \frac{I_1}{qs} \cdot \frac{l}{c} \cdot \frac{I_2}{qs} \cdot \sigma$$

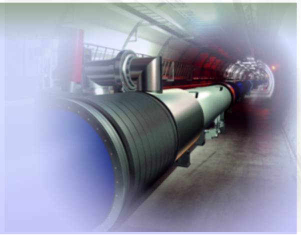
and for beams of a general area s = wh

$$L = \frac{I_1 I_2}{q^2 c} \cdot \frac{l}{wh}$$

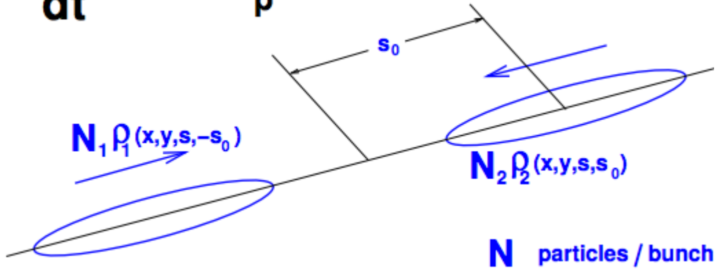
If we replace q = 1.6e-19 coulomb and c = 3e10 cm/s:

$$L \approx 1.3 \times 10^{27} \cdot I_1 I_2 \cdot \frac{l}{wh} \quad [\mathrm{cm}^{-2}.\, \mathrm{s}^{-1}]$$

Luminosity for bunched beams



$$\frac{dR}{dt} = L \, \sigma_p$$



N particles / bunch
ρ density ≠ const.

$$\mathcal{L} \propto K \cdot \iiint\!\!\int_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)\,dx\,dy\,ds\,ds_0$$

For two bunches colliding HEAD ON with Gaussian beam density distribution and equal beam sizes:

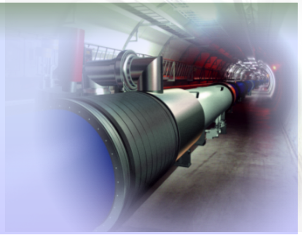
$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{2y}^2 + \sigma_{2y}^2}}$$

Ni: number of particles in one bunch
f: revolution frequency
Nb: number of bunches in one beam
sigma: beam size

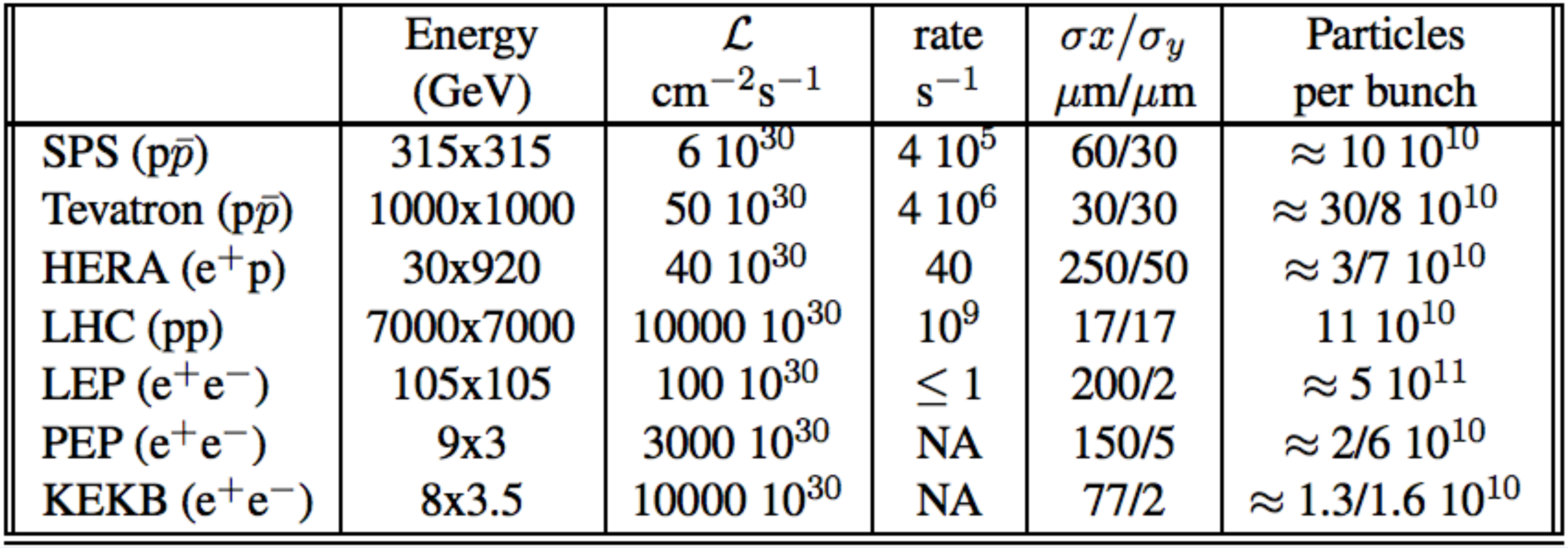
Reference:
Concept of luminosity

*Werner Herr and Bruno Muratori**
CERN, Geneva, Switzerland

Luminosity for bunched beams

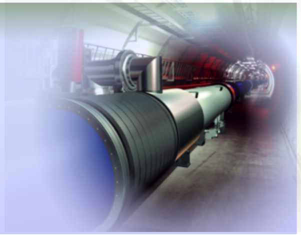


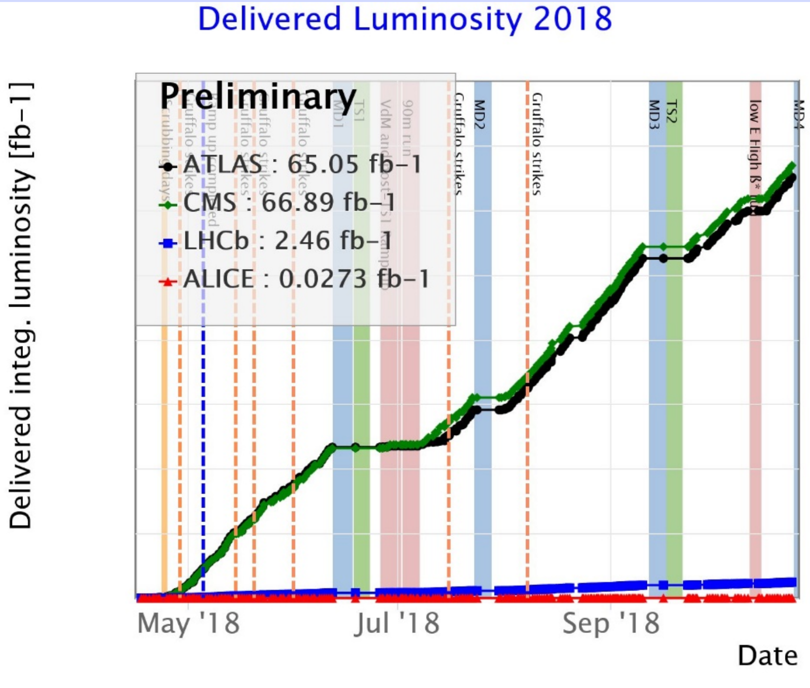
Examples:

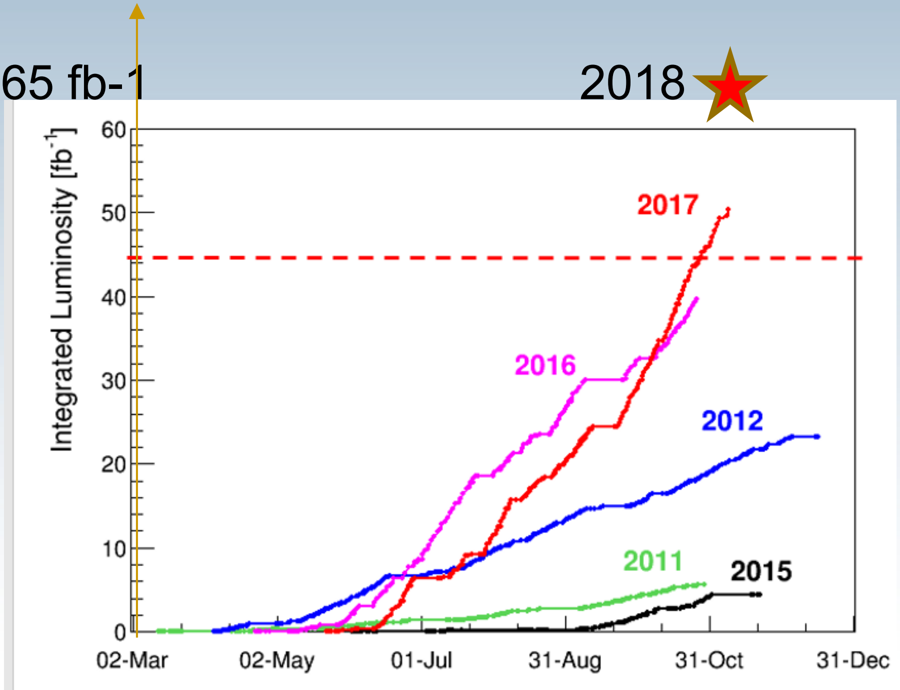


	Energy (GeV)	$\mathcal{L}$ $\text{cm}^{-2}\text{s}^{-1}$	rate s^{-1}	$\sigma x/\sigma_y$ $\mu\text{m}/\mu\text{m}$	Particles per bunch
SPS ($p\bar{p}$)	315x315	$6\ 10^{30}$	$4\ 10^{5}$	60/30	$\approx 10\ 10^{10}$
Tevatron ($p\bar{p}$)	1000x1000	$50\ 10^{30}$	$4\ 10^{6}$	30/30	$\approx 30/8\ 10^{10}$
HERA (e^+p)	30x920	$40\ 10^{30}$	40	250/50	$\approx 3/7\ 10^{10}$
LHC (pp)	7000x7000	$10000\ 10^{30}$	10^{9}	17/17	$11\ 10^{10}$
LEP (e^+e^-)	105x105	$100\ 10^{30}$	≤ 1	200/2	$\approx 5\ 10^{11}$
PEP (e^+e^-)	9x3	$3000\ 10^{30}$	NA	150/5	$\approx 2/6\ 10^{10}$
KEKB (e^+e^-)	8x3.5	$10000\ 10^{30}$	NA	77/2	$\approx 1.3/1.6\ 10^{10}$

LHC Integrated performance

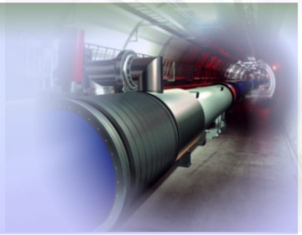


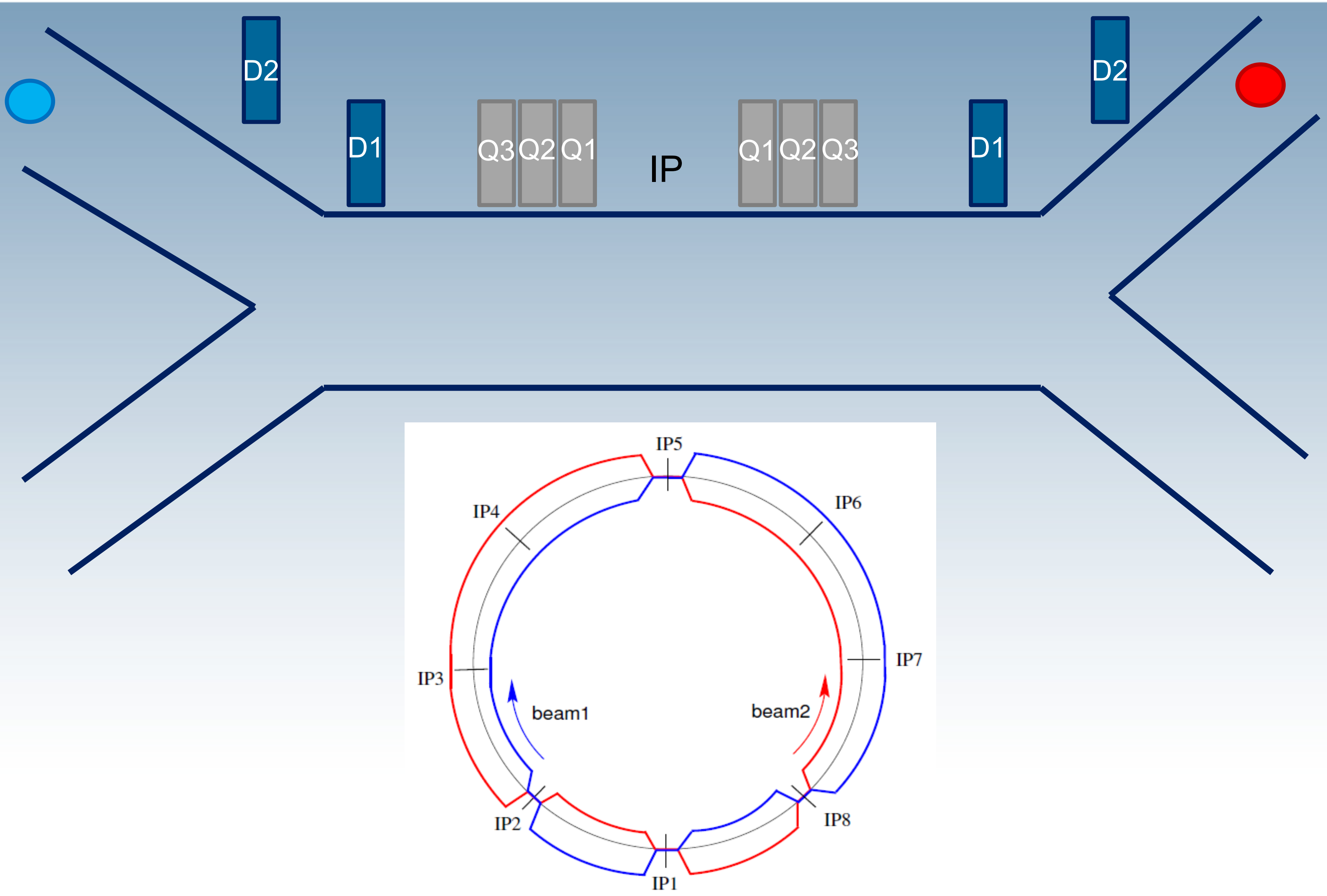

Delivered Luminosity 2018


~ 65 fb-1

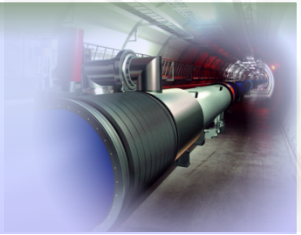
2018

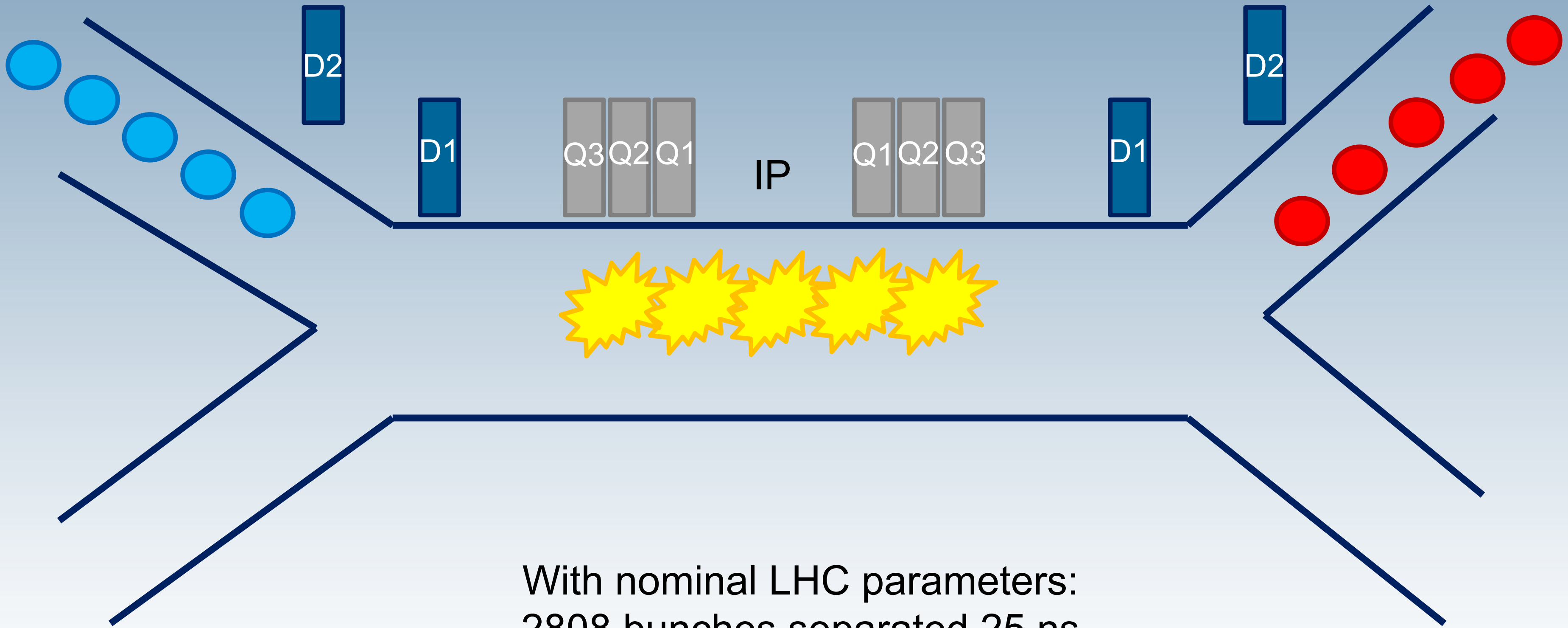
I. Basic layout of the machine: Luminosity insertions





I. Basic layout of the machine: Luminosity insertions

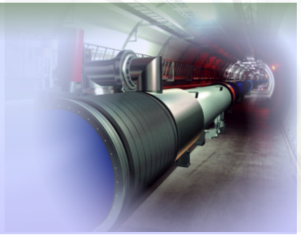


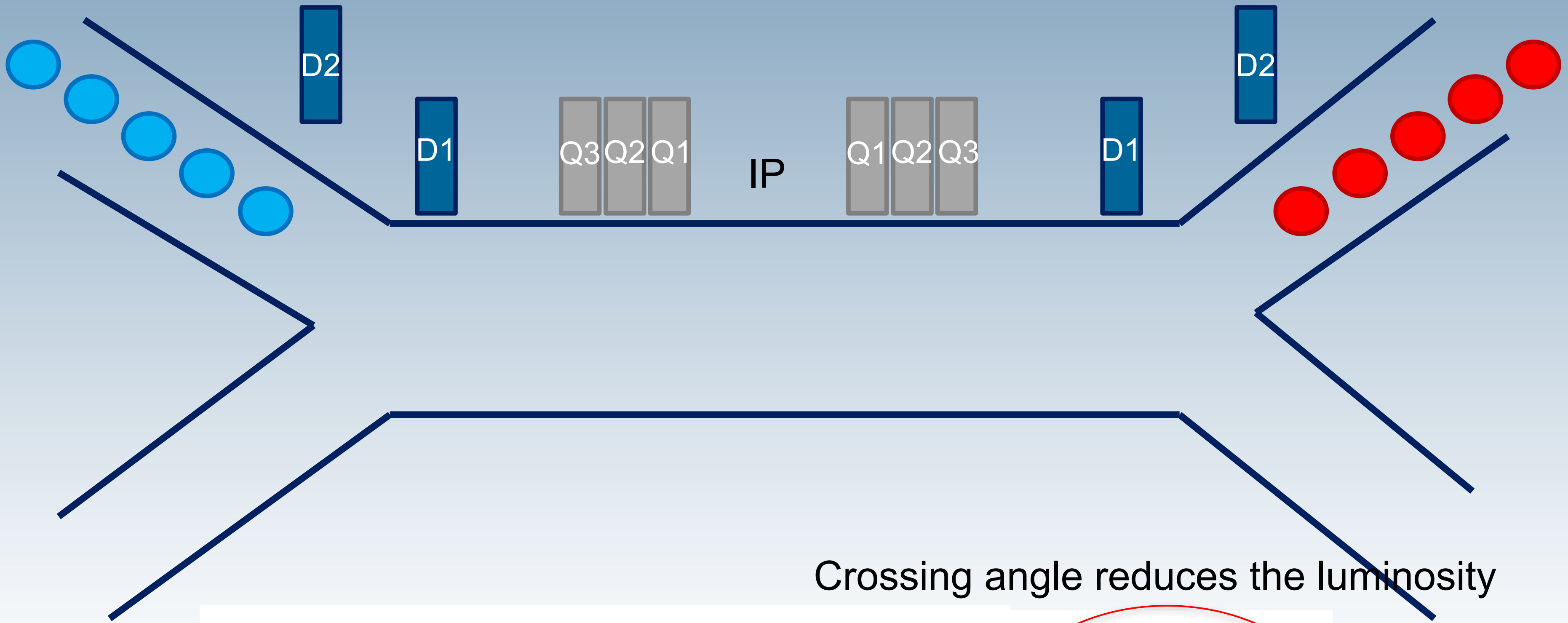


With nominal LHC parameters:
2808 bunches separated 25 ns

We can have up to **30 parasitic interactions** around the IP

I. Basic layout of the machine: Luminosity insertions

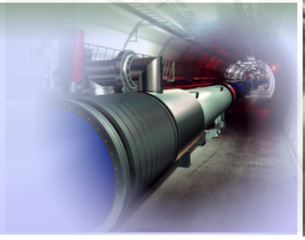


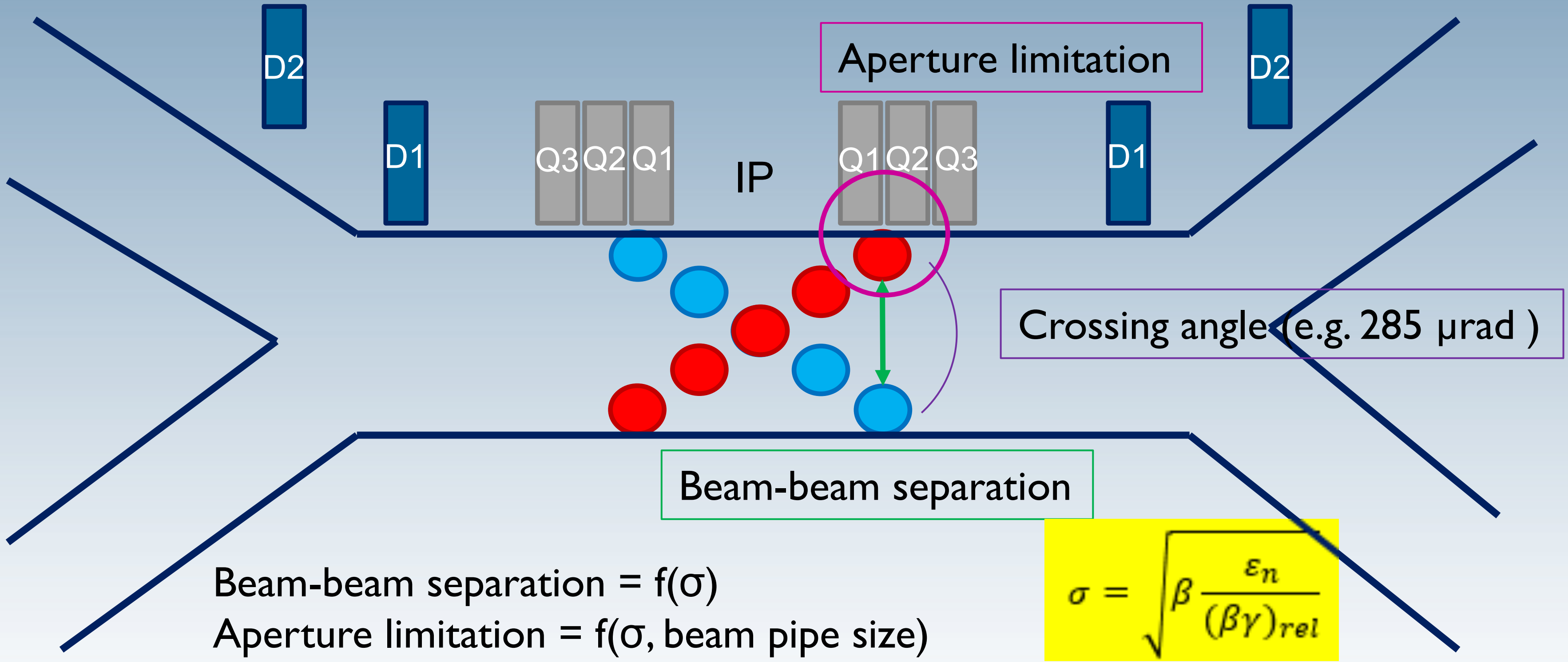


Crossing angle reduces the luminosity

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{2y}^2+\sigma_{2y}^2}} \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

I. Basic layout of the machine: Luminosity insertions





Aperture limitation

Crossing angle (e.g. 285 μrad)

Beam-beam separation

Beam-beam separation = f(σ)
Aperture limitation = f(σ, beam pipe size)

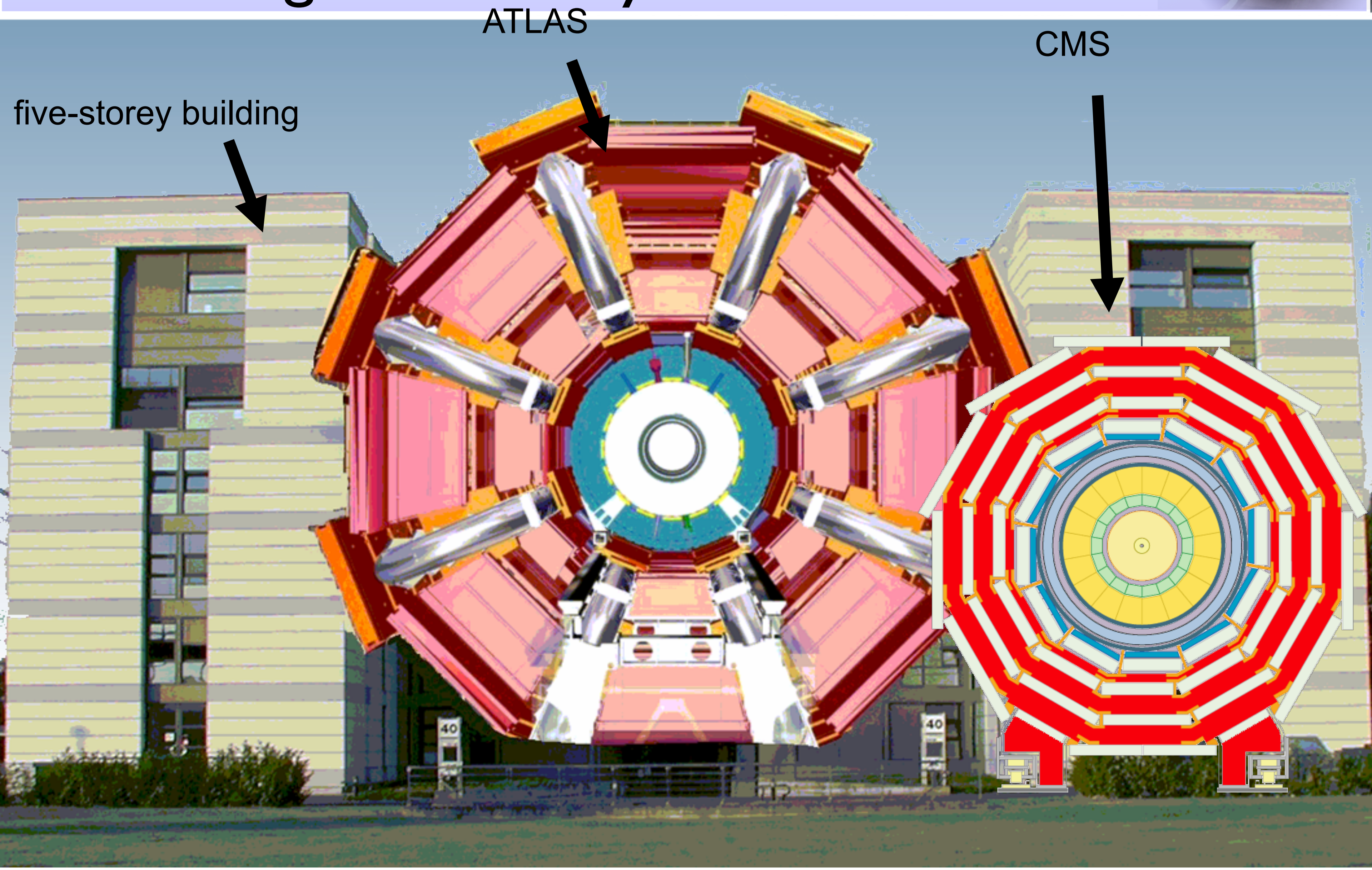
$$\sigma = \sqrt{\beta \frac{\varepsilon_n}{(\beta\gamma)_{rel}}}$$

β is very small at the IP, but very big at the Inner triplets ➔

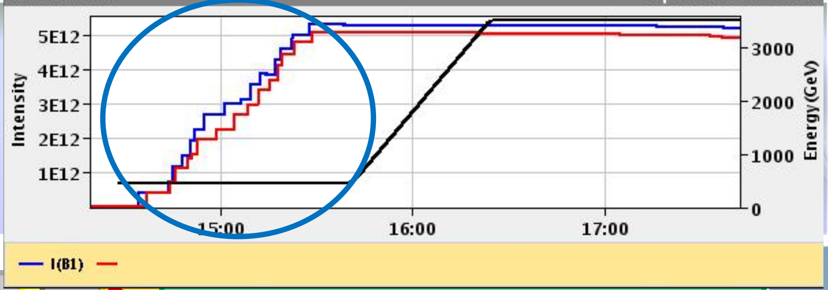
$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

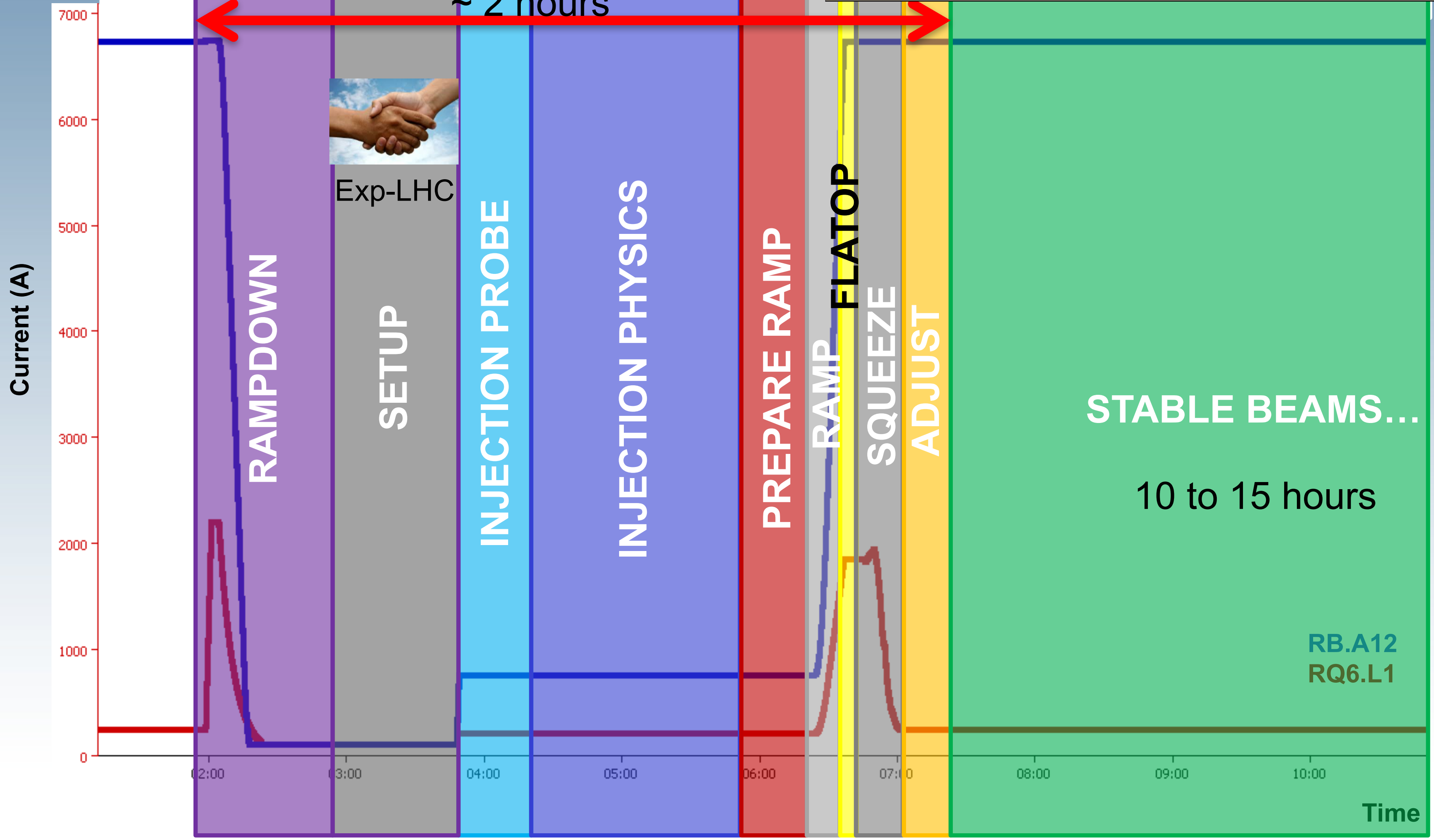
Therefore, the quadrupoles around the IP have such a big apertures

I. Basic layout of the machine: High luminosity insertions

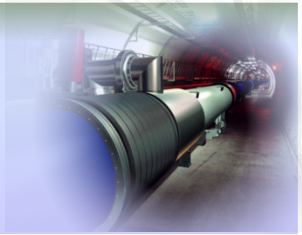


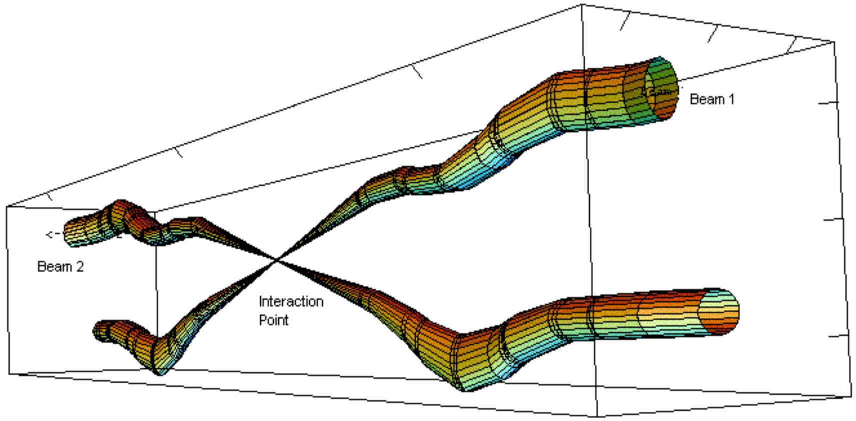
II. LHC Operational cycle





II. LHC Operational cycle:
Squeeze ➔ reduce β*





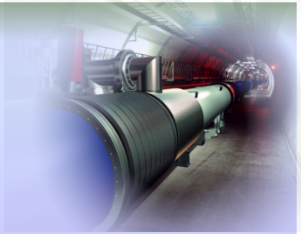
Relative beam sizes around IP1 (Atlas) in collision

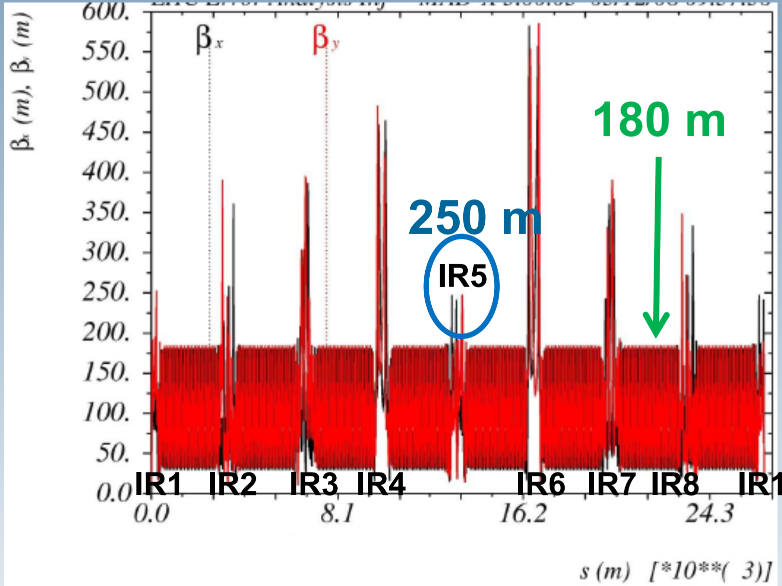
Squeeze the beam size down as much as possible at the collision point to increase the chances of a collision

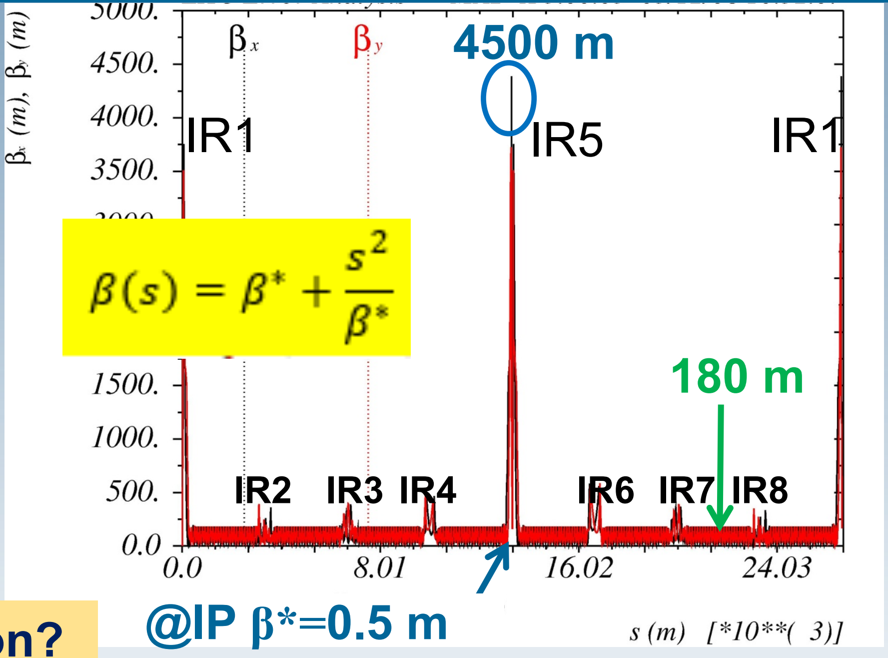
$$L \approx \frac{N_1 N_2 f_{rev} N_b}{4\pi \boxed{\sigma^2}} \longrightarrow \quad \sigma = \sqrt{\beta \frac{\varepsilon_n}{(\beta\gamma)_{rel}}}$$

- So even tough we squeeze our $N_{1,2}$=100,000 million protons per bunch down to 16 microns (1/5 the width of a human hair) **at the interaction point**. We get **only around 20 collisions per crossing** with nominal beam currents.
- The bunches cross (every 25 ns) so often we end up with around **600 million collisions per second** - at the start of a fill with nominal current.
- Most protons miss each other and carry on around the ring. The beams are kept circulating for hours ➔ 10 hours

II. LHC Operational cycle: Squeeze → reduce β* (β @IP)




Beta function at Injection


Beta function at top energy and after squeeze

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

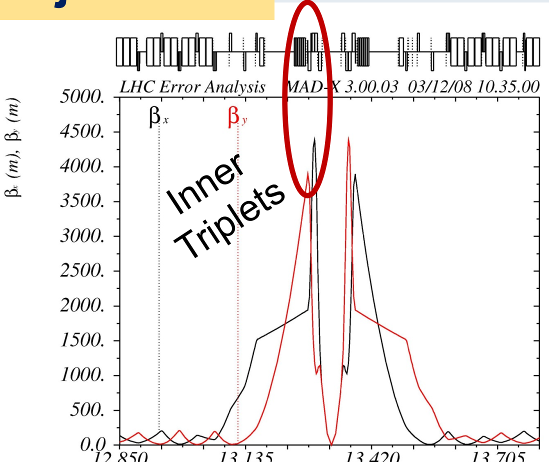
Why we cannot have β*= 0.5 m at injection?

$$\sigma = \sqrt{\beta \frac{\varepsilon_n}{(\beta\gamma)_{rel}}}$$

β=4500 m
γ(@450 GeV)~480
εn=3.5 μm rad

Remember:
there is no D(s) here

σ ~ **6 mm !!**

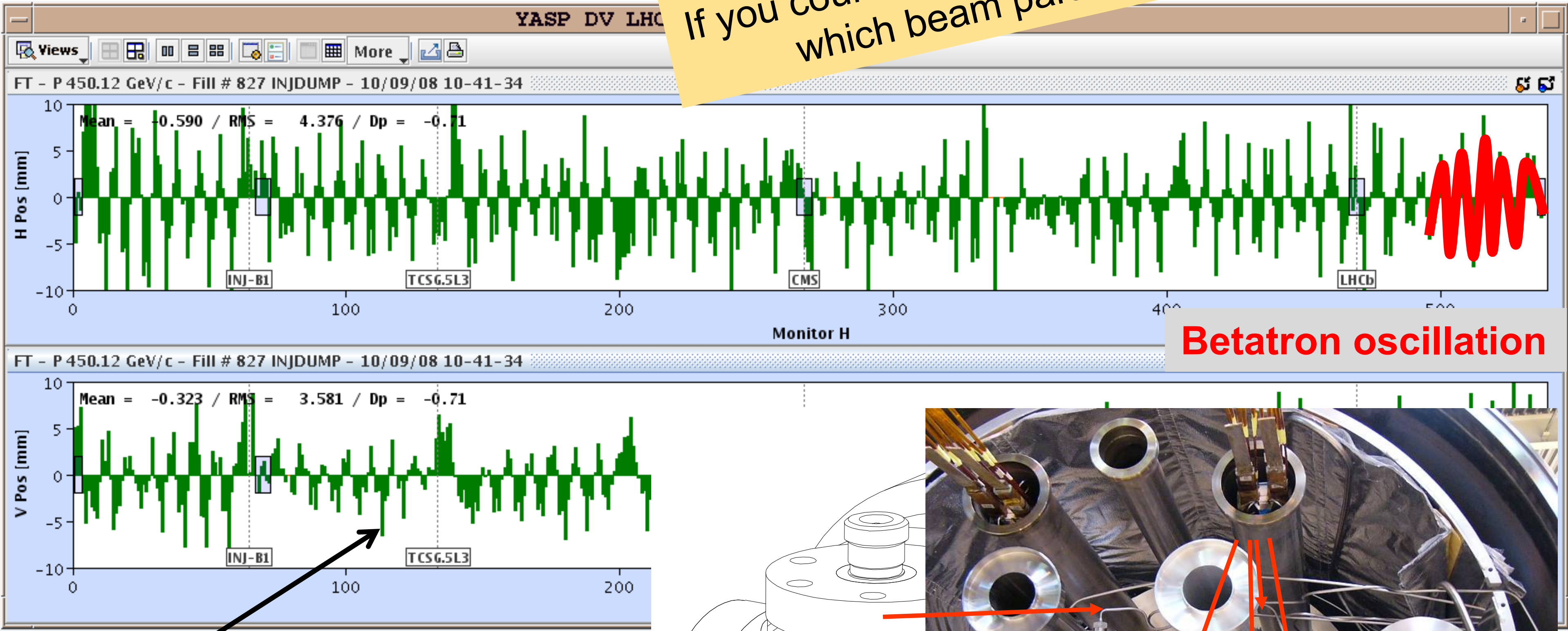


$R_{beampipe}$~29/24 mm
we could only accommodate ~ 4 times the beam size and **we need at least 7σ clearance**

@ 7 TeV
σ_{IT} ~ **1.2 mm**

II. Beam measurements: Beam trajectory

If you count the number of betatron oscillations, which beam parameter do you get?



FT – P 450.12 GeV/c – Fill # 827 INJDUMP – 10/09/08 10-41-34

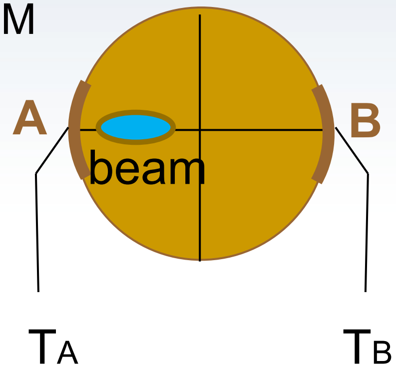
Mean = -0.590 / RMS = 4.376 / Dp = -0.71

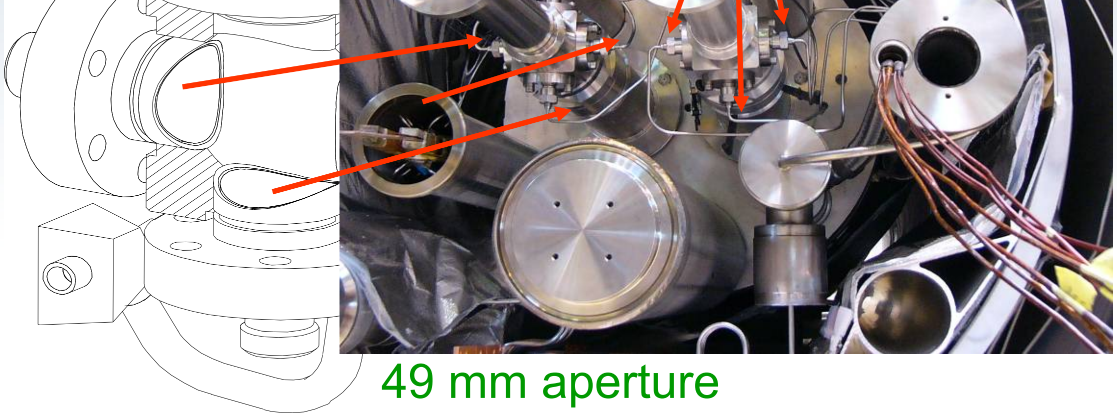
Betatron oscillation

FT – P 450.12 GeV/c – Fill # 827 INJDUMP – 10/09/08 10-41-34

Mean = -0.323 / RMS = 3.581 / Dp = -0.71

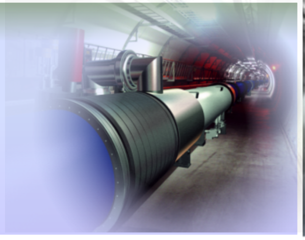
Each point is a BPM (Beam Position Measurement)

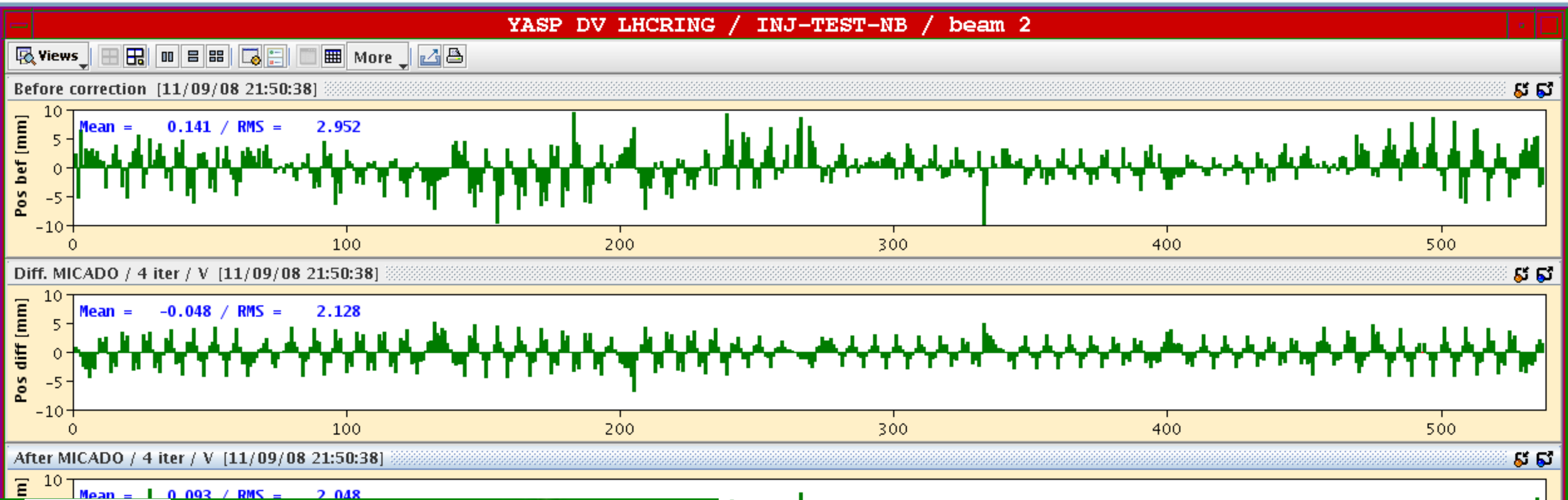




49 mm aperture

II. Beam measurements: Beam trajectory correction





YASP DV LHCRING / INJ-TEST-NB / beam 2

Before correction [11/09/08 21:50:38]

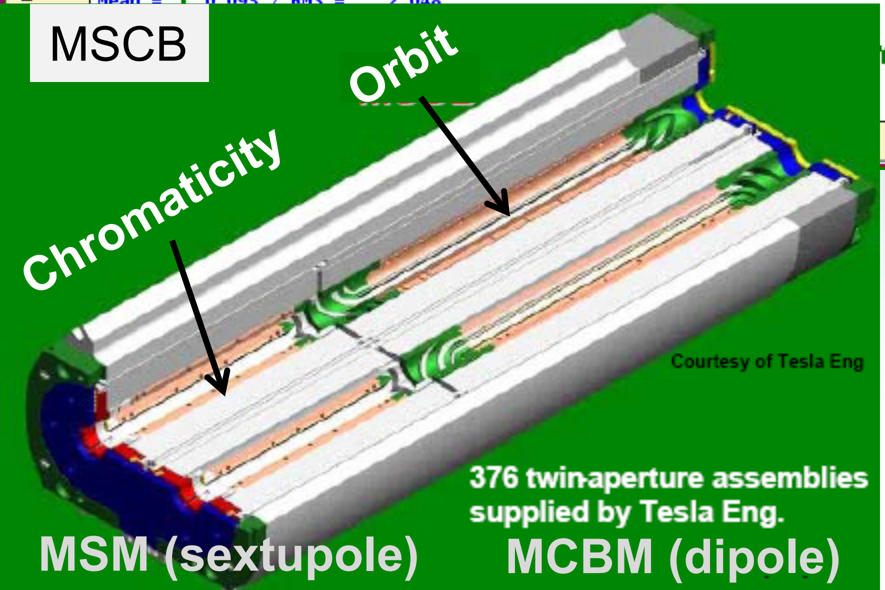
Mean = 0.141 / RMS = 2.952

Diff. MICADO / 4 iter / V [11/09/08 21:50:38]

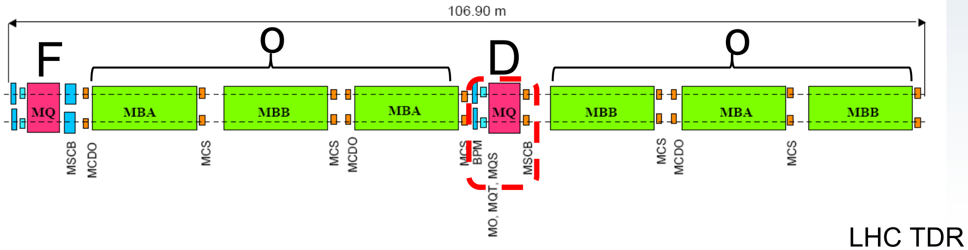
Mean = -0.048 / RMS = 2.128

After MICADO / 4 iter / V [11/09/08 21:50:38]

Mean = 0.093 / RMS = 2.048



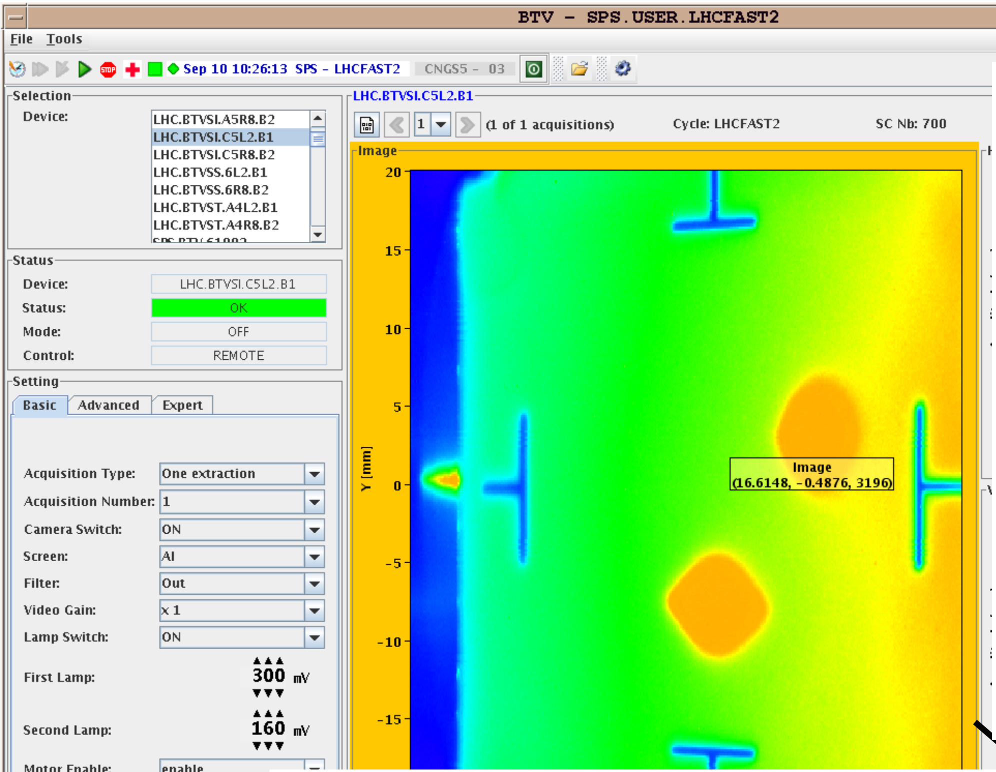
Courtesy of Tesla Eng



LHC TDR

Why the orbit and sextupole correctors are placed close to a quadrupole?

II. Beam profile measurements: Beam 1 on TDI screen – 1st and 2nd turns



BTV – SPS.USER.LHCFAST2

File Tools

Sep 10 10:26:13 SPS - LHCFAST2 CNGS5 - 03

Selection

Device:
LHC.BTVSI.A5R8.B2
LHC.BTVSI.C5L2.B1
LHC.BTVSI.C5R8.B2
LHC.BTVSS.6L2.B1
LHC.BTVSS.6R8.B2
LHC.BTVST.A4L2.B1
LHC.BTVST.A4R8.B2

Status

Device: LHC.BTVSI.C5L2.B1
Status: OK
Mode: OFF
Control: REMOTE

Setting

Basic | Advanced | Expert

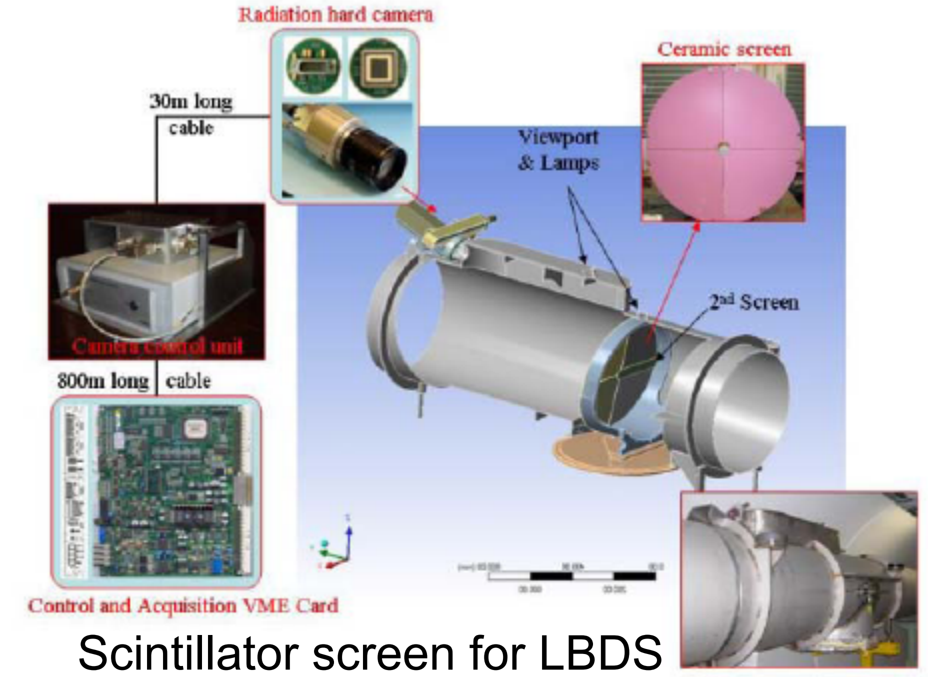
Acquisition Type: One extraction
Acquisition Number: 1
Camera Switch: ON
Screen: Al
Filter: Out
Video Gain: x 1
Lamp Switch: ON
First Lamp: 300 mV
Second Lamp: 160 mV
Motor Enable: enable
Hardware Reading:

Acquire | Start Monitoring

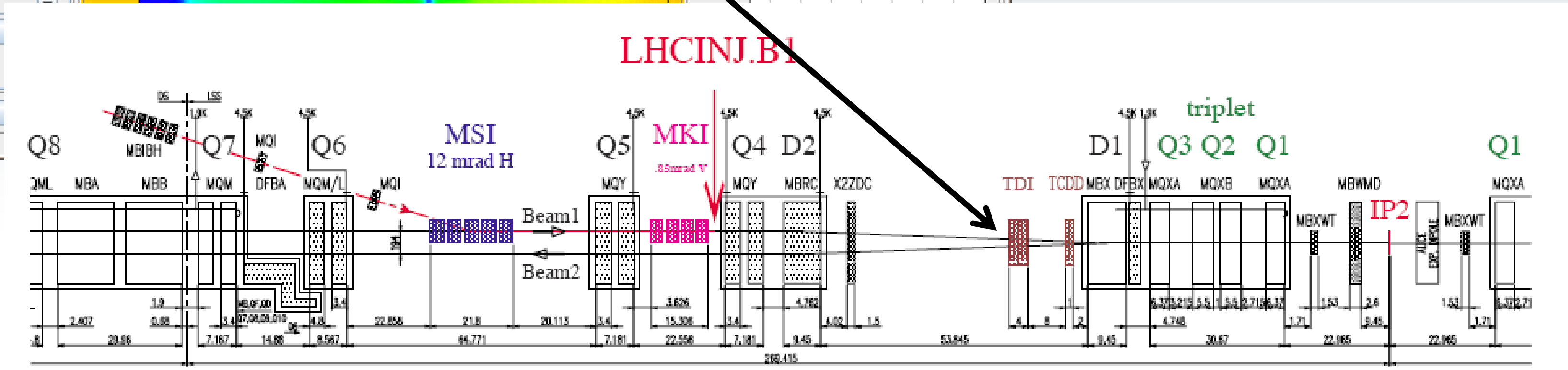
10:25:32 - Done.

LHC.BTVSI.C5L2.B1

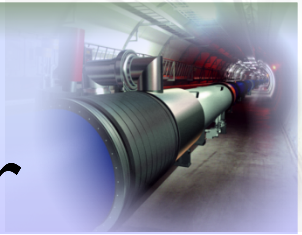
1 (1 of 1 acquisitions) Cycle: LHCFAST2 SC Nb: 700



Scintillator screen for LBDS

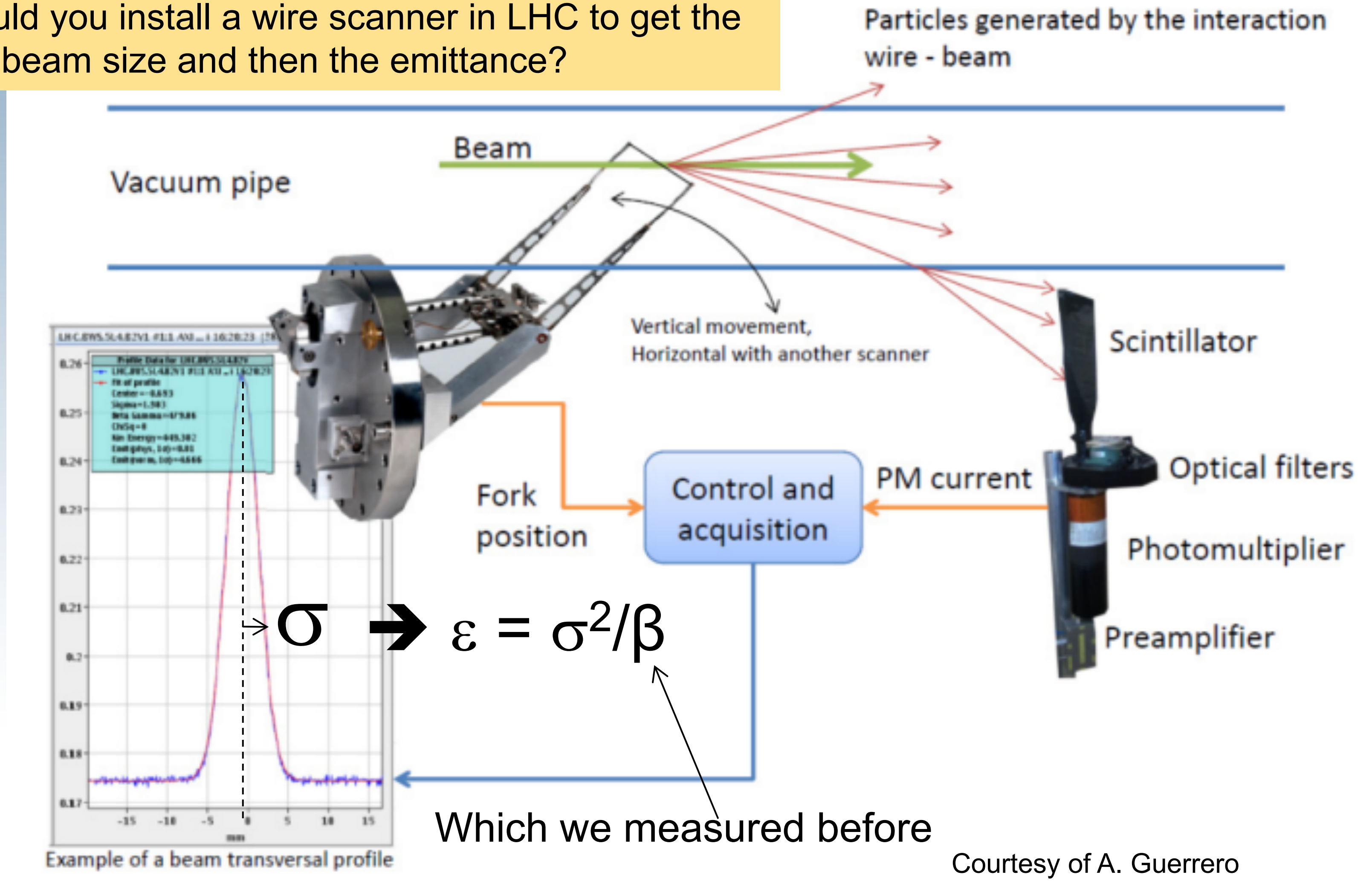


II. Beam profile measurements: Emittance measurement - Wire scanner



Emittance is the figure of merit for profile measurements.
But it is a derived quantity from the beam size ($\sigma = \sqrt{\beta\varepsilon}$)

Where would you install a wire scanner in LHC to get the beam size and then the emittance?



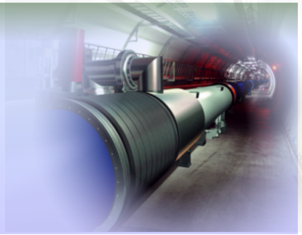
$\sigma \Rightarrow \varepsilon = \sigma^2/\beta$

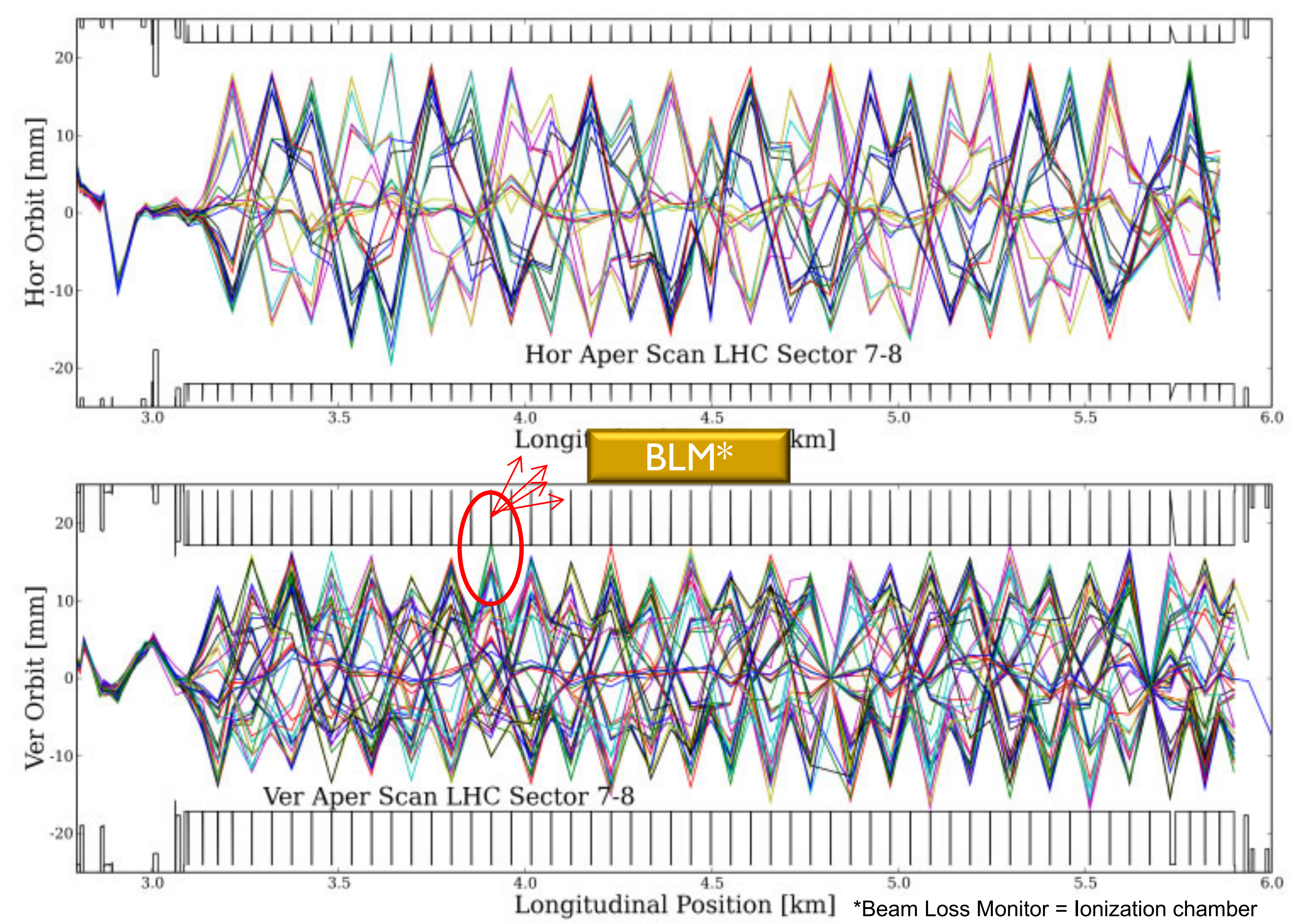
Which we measured before

Example of a beam transversal profile

Courtesy of A. Guerrero

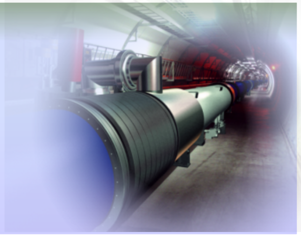
II. Beam measurements:
Aperture scan

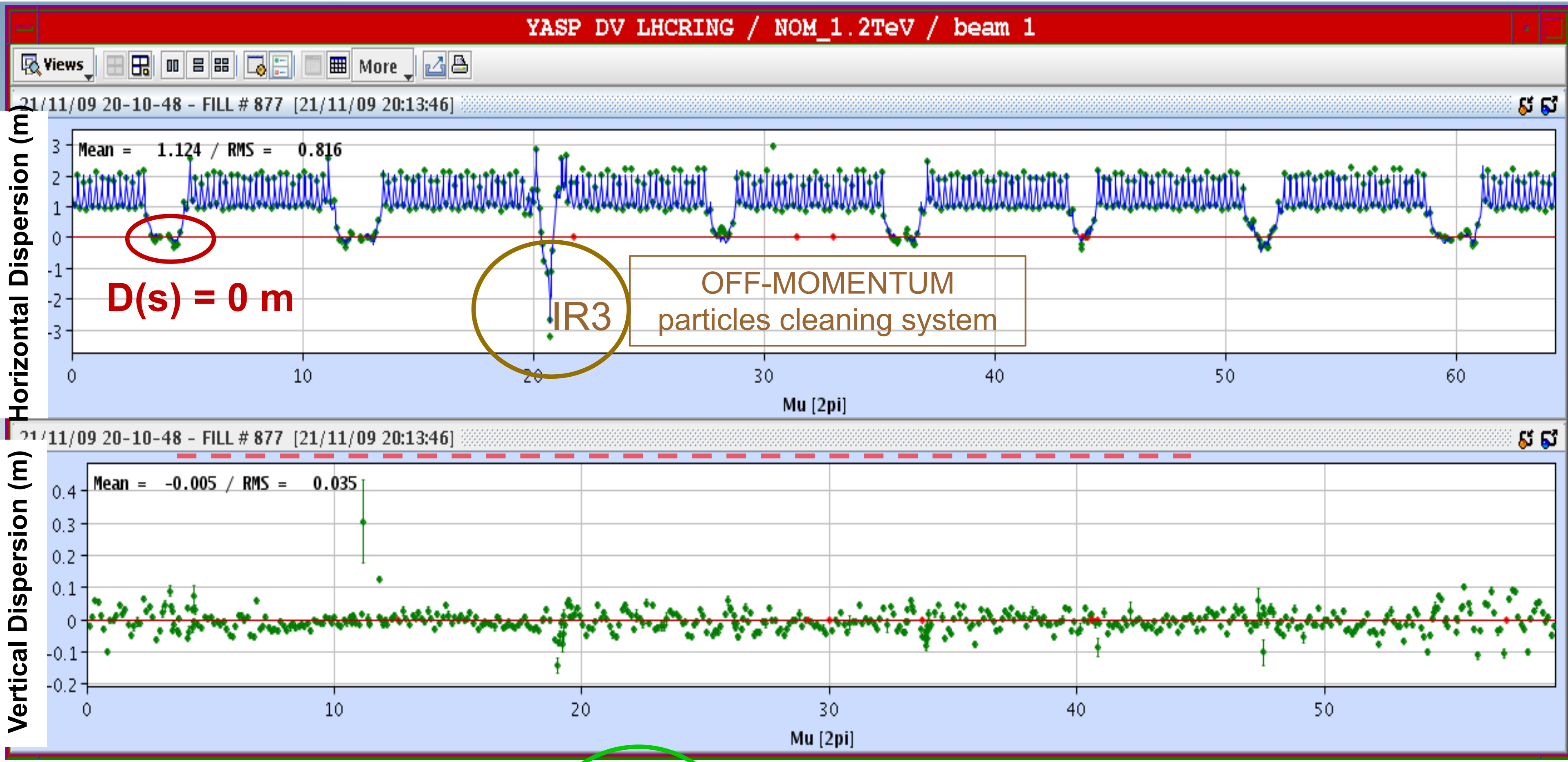




*Beam Loss Monitor = Ionization chamber

II. Beam measurements:
Dispersion measurement





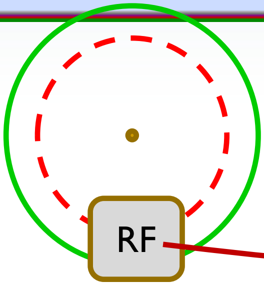
YASP DV LHCRING / NOM_1.2TeV / beam 1

21/11/09 20-10-48 - FILL # 877 [21/11/09 20:13:46]

Mean = 1.124 / RMS = 0.816

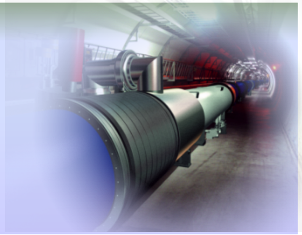
21/11/09 20-10-48 - FILL # 877 [21/11/09 20:13:46]

Mean = -0.005 / RMS = 0.035



$$\Delta x = D_x(s)\frac{\Delta p}{p}$$

II. Beam measurements: Beta measurement

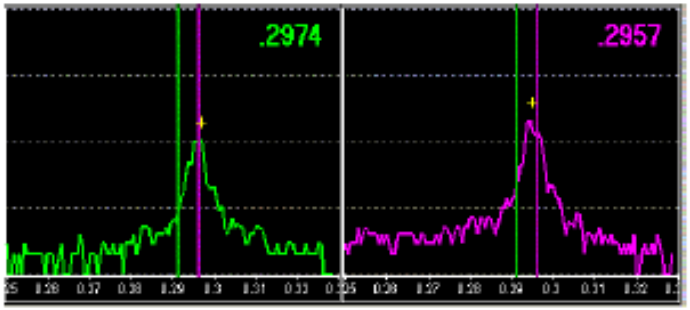


a quadrupol error leads to a shift of the tune:

1st Change quadrupole strength in steps

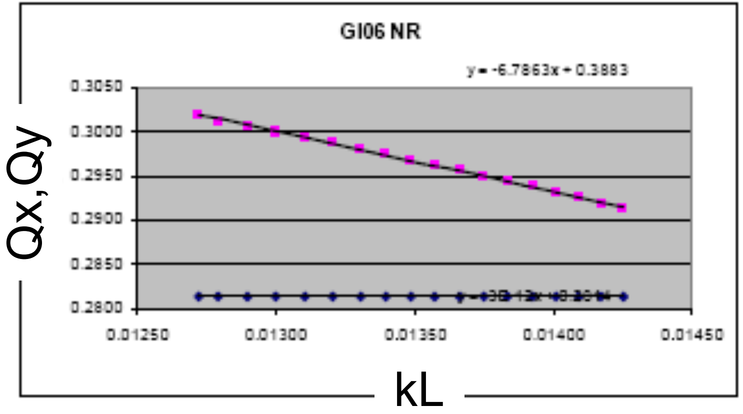
$$\Delta Q = \int_{s0}^{s0+l} \frac{\Delta k \beta(s)}{4\pi} ds \approx \frac{\Delta k l_{quad} \bar{\beta}}{4\pi}$$

2nd Measure Tune



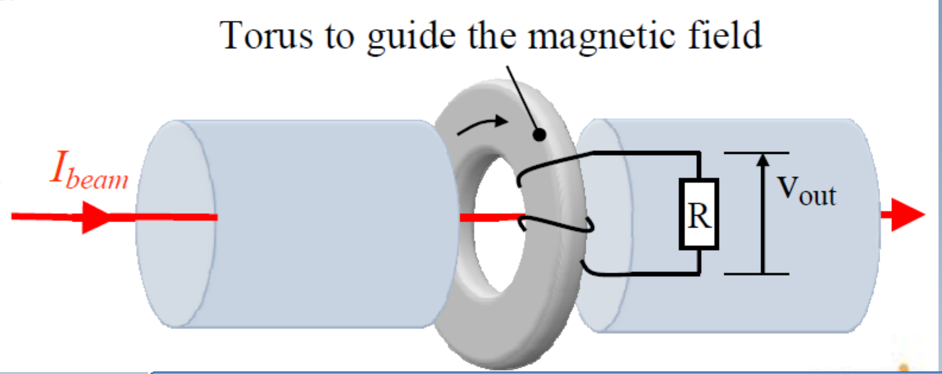
Example: measurement of β in a storage ring: tune spectrum

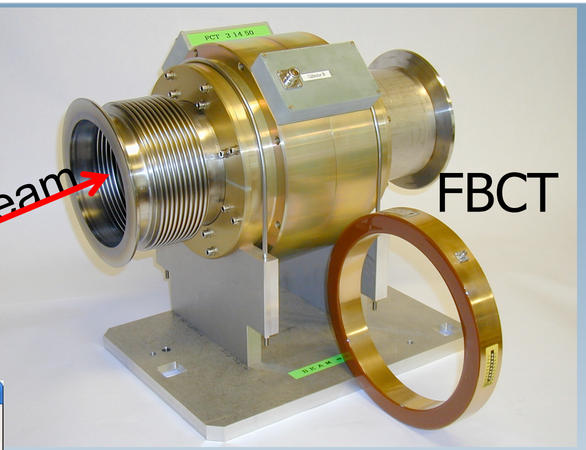
3rd Plot Tune vs Quadrupole strength

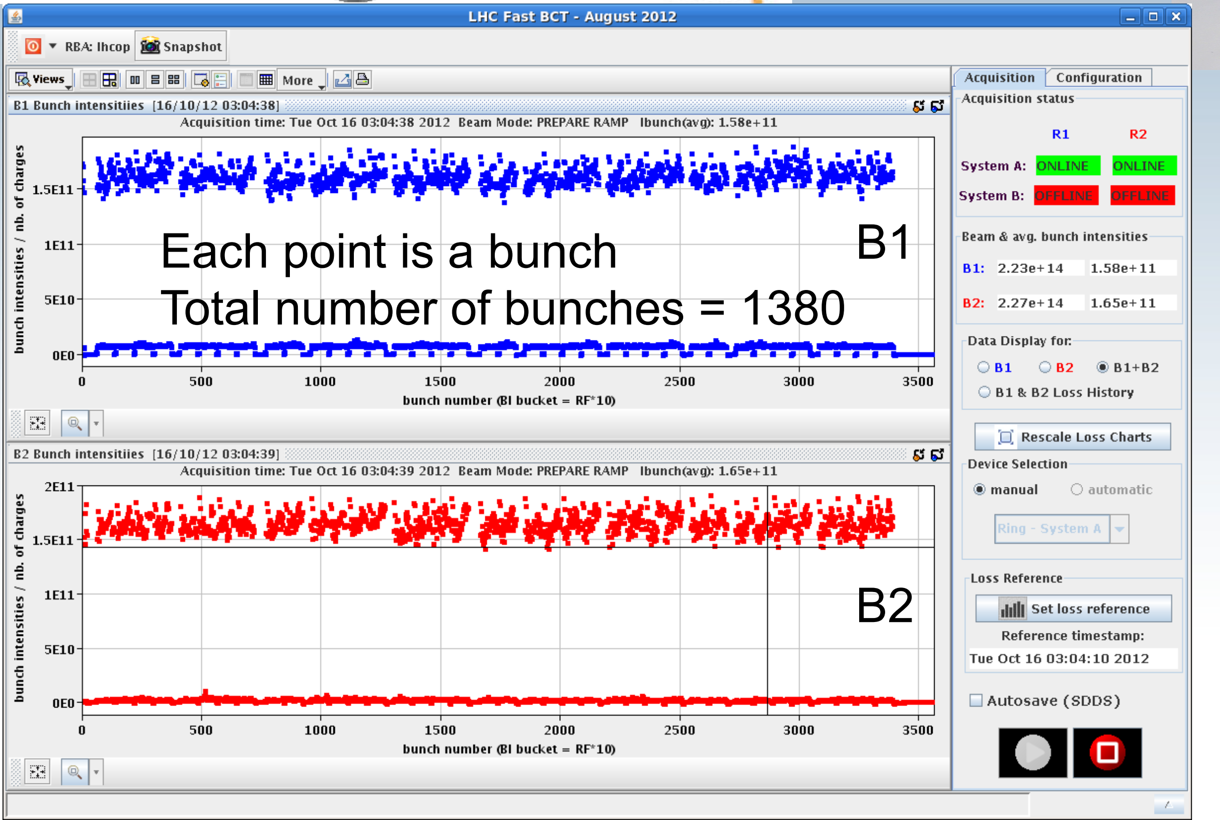


Courtesy of B. Holzer (lectures)

II. Beam measurements:
Fast BCT (Beam Current Transformer)







B1 Bunch intensitiies [16/10/12 03:04:38]

Acquisition time: Tue Oct 16 03:04:38 2012 Beam Mode: PREPARE RAMP Ibunch(avg): 1.58e+11

Each point is a bunch

Total number of bunches = 1380

B2 Bunch intensitiies [16/10/12 03:04:39]

Acquisition time: Tue Oct 16 03:04:39 2012 Beam Mode: PREPARE RAMP Ibunch(avg): 1.65e+11

Acquisition status

	R1	R2
System A:	ONLINE	ONLINE
System B:	OFFLINE	OFFLINE

Beam & avg. bunch intensities

B1:	2.23e+14	1.58e+11
B2:	2.27e+14	1.65e+11

Data Display for:
○ B1 ○ B2 ● B1+B2
○ B1 & B2 Loss History

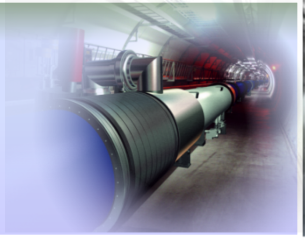
Device Selection
● manual ○ automatic
Ring - System A

Loss Reference
Reference timestamp:
Tue Oct 16 03:04:10 2012

☐ Autosave (SDDS)

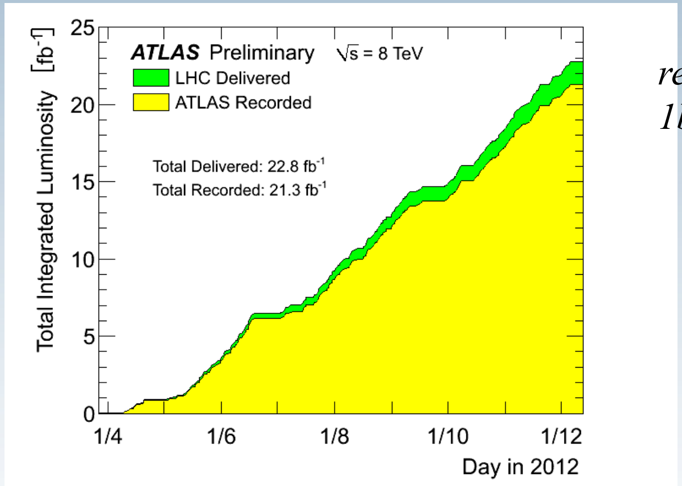
SPARE SLIDES

High Light of the LHC

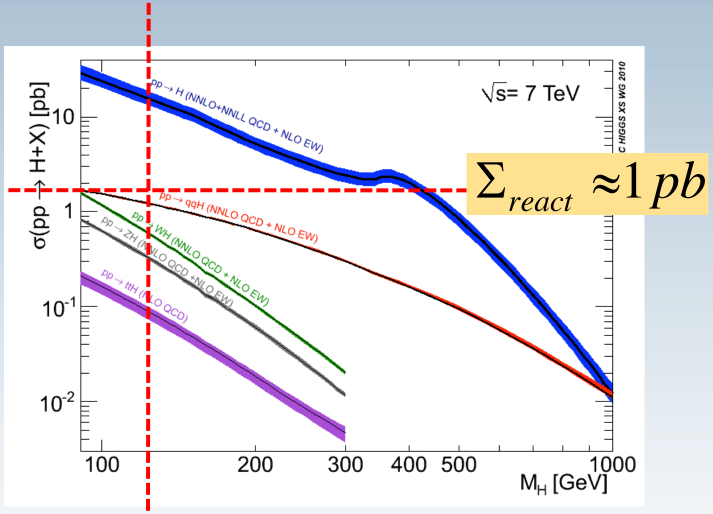


production rate of events is determined by the cross section Σ_{react} and a parameter L that is given by the design of the accelerator:
… the luminosity

$$R = L * \Sigma_{react} \approx 25 \frac{1}{10^{-15} b} 10^{-12} b = some\ 1000 H$$



remember:
$1b = 10^{-24}\,cm^2$



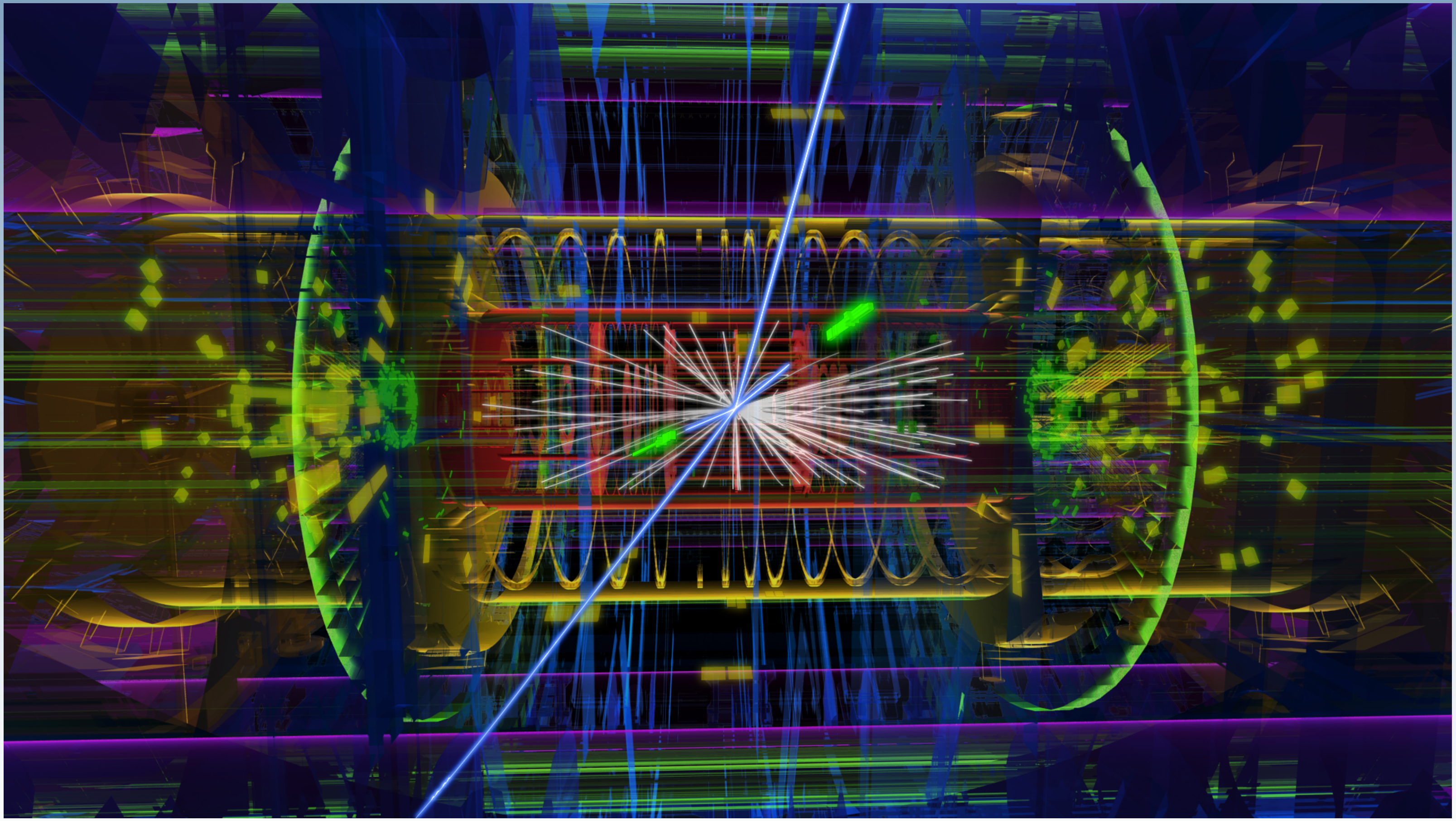
$$\Sigma_{react} \approx 1\,pb$$

Integrated luminosity during RUN I

$$\int L dt \approx 25\,fb^{-1}$$

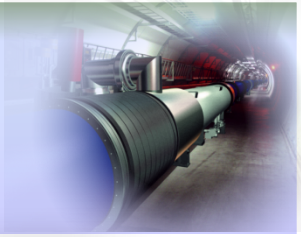
Official number: 1400 clearly identified Higgs particles "on-tape"

High Light of the HEP year



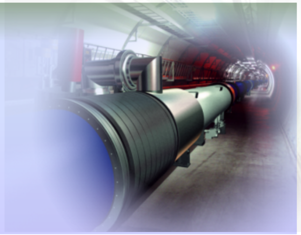
ATLAS event display: Higgs => two electrons & two muons

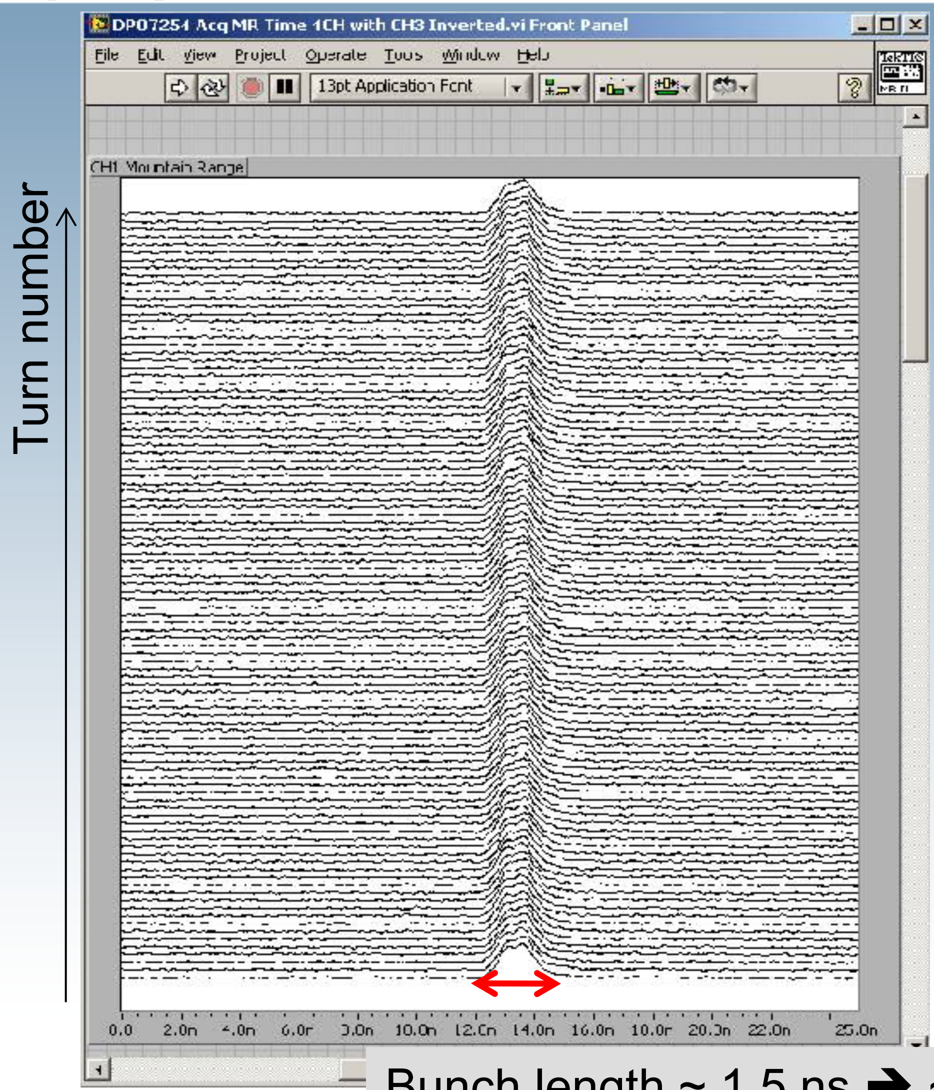
I. Basic layout of the machine: Superconducting magnets



- Superfluid helium → Why is it so great?!!
  - **very high thermal conductivity**→ is able to conduct away heat a thousand times better than a metallic conductor like copper
  - **very low viscosity coefficient** → can penetrate tiny cracks, deep inside the magnet coils to absorb any generated heat
  - **very high heat capacity** → prevents small transient temperature fluctuations

XIV. Beam captured – mountain range display

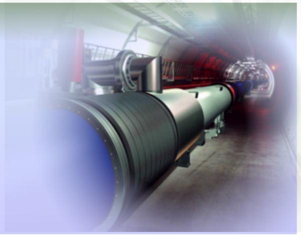




Now RF ON

Bunch length ~ 1.5 ns ➔ ~ 45 cm

Beam parameters (nominal)

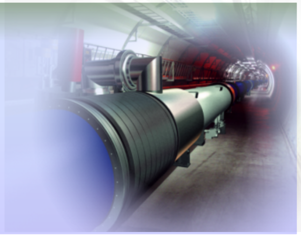


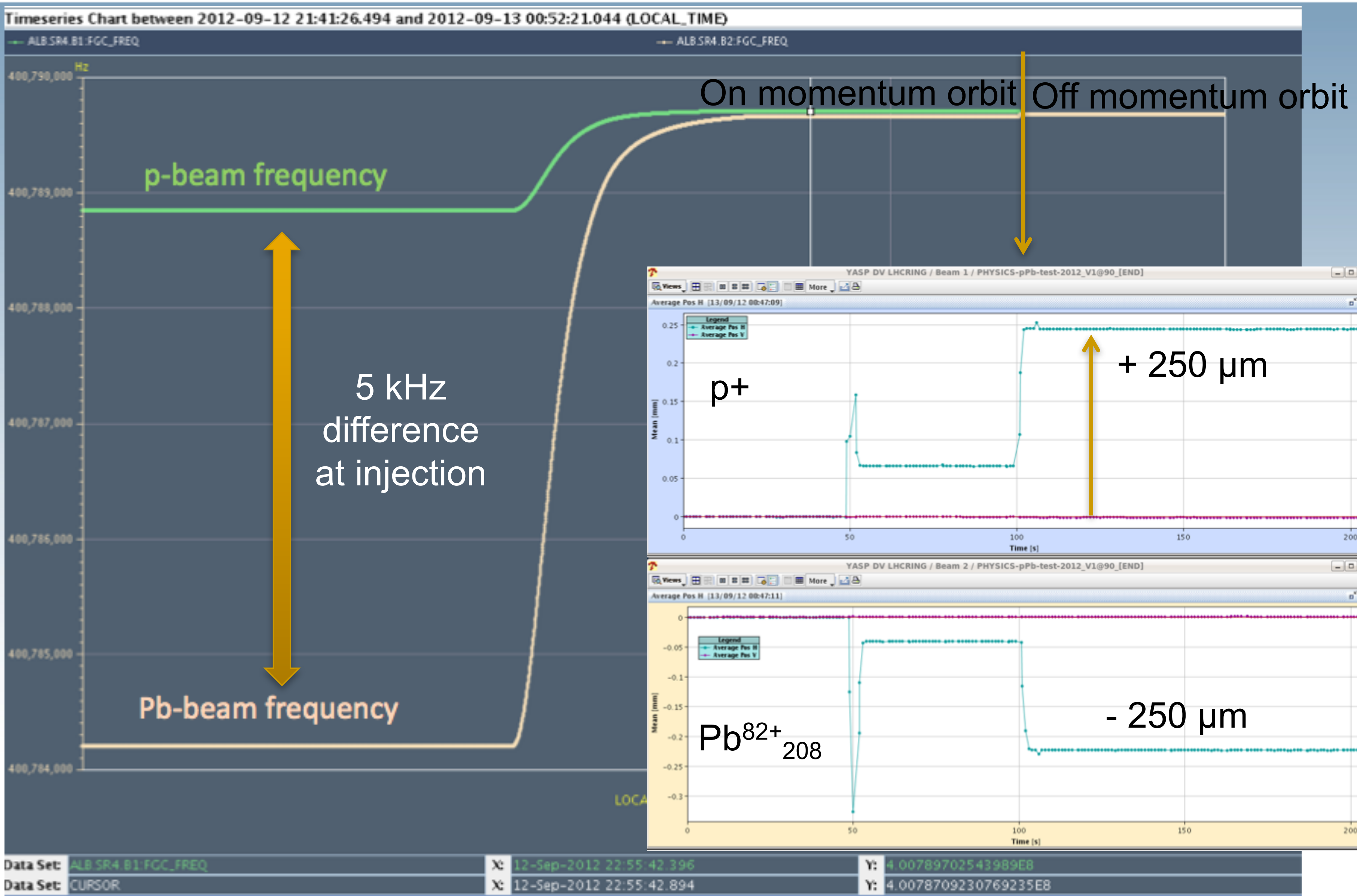
		Injection	**Collision**	**2012**
Proton energy	GeV	450	7000	4000
Particles/bunch		1.15×10^{11}		**1.6** $\times 10^{11}$
Num. bunches		2808		1380
Longitudinal emittance (4σ)	eVs	1.0	2.5	
Transverse normalized emittance	μm rad	3.5	3.75	
Beam current	A	0.582		
Stored energy/beam	MJ	23.3	362	
	Peak luminosity related data			
RMS bunch length	cm	11.24	7.55	
RMS beam size @IP1 & IP5 → $\sigma_{x,y} = \sqrt{\varepsilon\beta}$	μm	375.2	16.7	
RMS beam size @IP2 & IP8 → $\sigma_{x,y} = \sqrt{\varepsilon\beta}$	μm	279.6	70.9	
Geometric luminosity reduction factor (F)			0.836	
Instantaneous lumi @IP1 & IP5 ($IP2_{Pb-Pb}$, IP8)	$cm^{-2}s^{-1}$		10^{34} (10^{27}, 10^{32})	$7\ 10^{33}$

$\beta^* = 0.55$ m
$\varepsilon = 0.5$ nm rad

$\beta^* = 0.6$ m
$\varepsilon_n = 2.5$ μm rad

pPb physics during 2013





Data Set: ALB.SR4.B1:FGC_FREQ X: 12-Sep-2012 22:55:42.396 Y: 4.00789702543989E8

Data Set: CURSOR X: 12-Sep-2012 22:55:42.894 Y: 4.0078709230769235E8

On momentum orbit

Off momentum orbit

p-beam frequency

5 kHz difference at injection

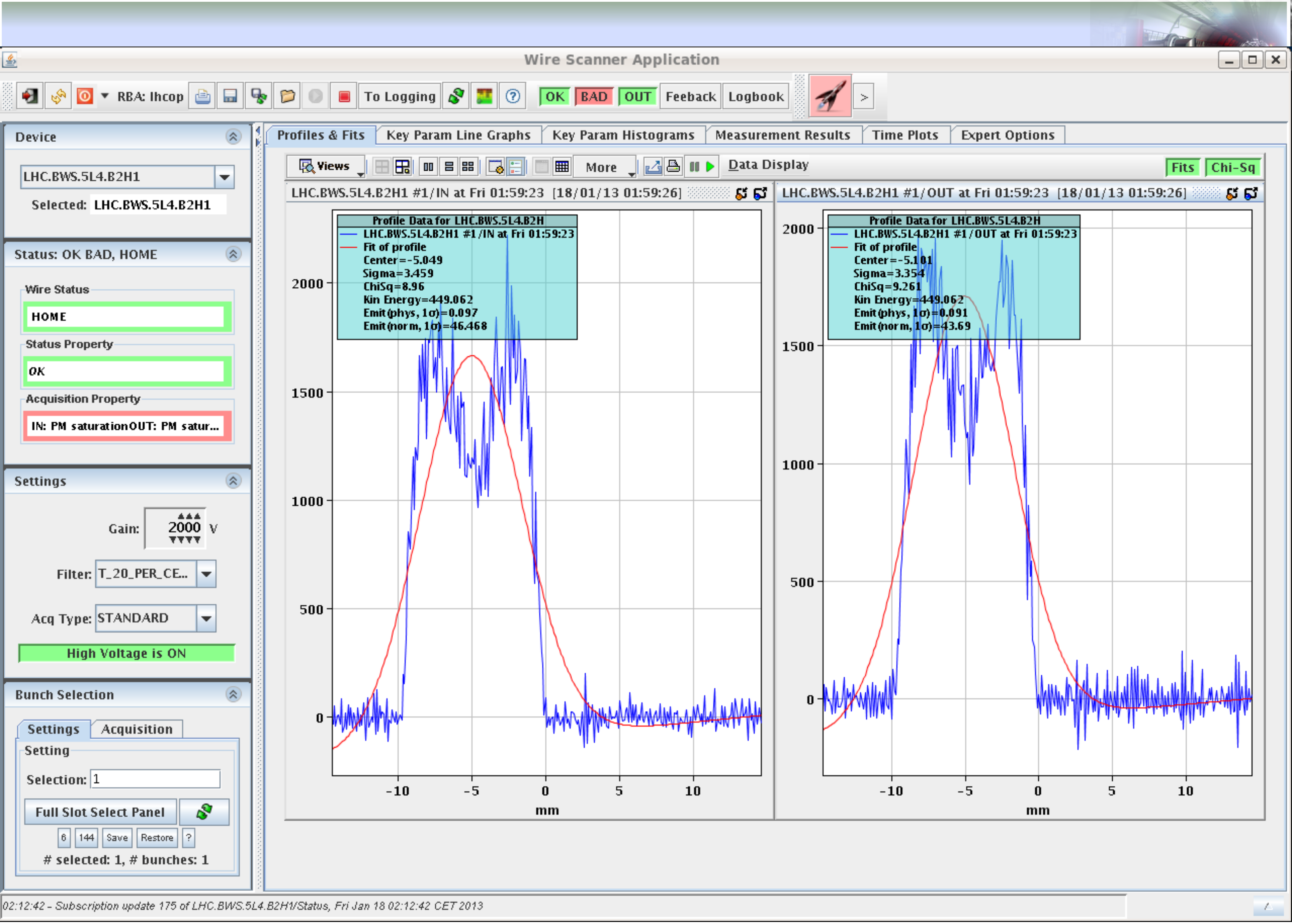
Pb-beam frequency

p+

+ 250 µm

Pb^{82+}_{208}

- 250 µm



Device: LHC.BWS.5L4.B2H1

Selected: LHC.BWS.5L4.B2H1

Status: OK BAD, HOME

Wire Status: HOME

Status Property: OK

Acquisition Property: IN: PM saturationOUT: PM satur...

Settings

Gain: 2000 V

Filter: T_20_PER_CE...

Acq Type: STANDARD

High Voltage is ON

Bunch Selection

Setting

Selection: 1

selected: 1, # bunches: 1

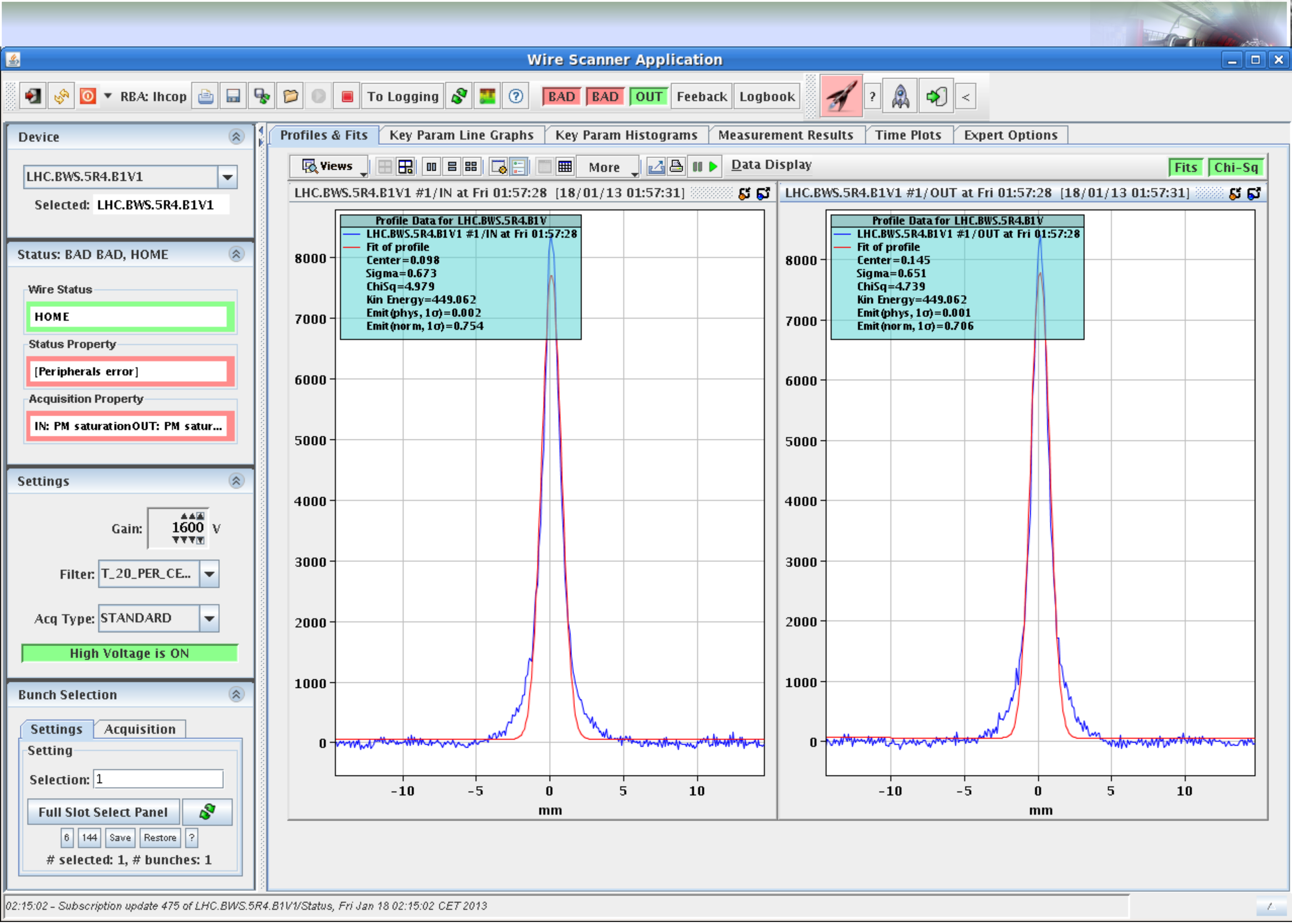
LHC.BWS.5L4.B2H1 #1/IN at Fri 01:59:23 [18/01/13 01:59:26]

Profile Data for LHC.BWS.5L4.B2H
LHC.BWS.5L4.B2H1 #1/IN at Fri 01:59:23
Fit of profile
Center=-5.049
Sigma=3.459
ChiSq=8.96
Kin Energy=449.062
Emit(phys, 1σ)=0.097
Emit(norm, 1σ)=46.468

LHC.BWS.5L4.B2H1 #1/OUT at Fri 01:59:23 [18/01/13 01:59:26]

Profile Data for LHC.BWS.5L4.B2H
LHC.BWS.5L4.B2H1 #1/OUT at Fri 01:59:23
Fit of profile
Center=-5.101
Sigma=3.354
ChiSq=9.261
Kin Energy=449.062
Emit(phys, 1σ)=0.091
Emit(norm, 1σ)=43.69

02:12:42 - Subscription update 175 of LHC.BWS.5L4.B2H1/Status, Fri Jan 18 02:12:42 CET 2013



LHC.BWS.5R4.B1V1

Selected: LHC.BWS.5R4.B1V1

Wire Status: HOME

Status Property: [Peripherals error]

Acquisition Property: IN: PM saturationOUT: PM satur...

Gain: 1600 V

Filter: T_20_PER_CE...

Acq Type: STANDARD

High Voltage is ON

Selection: 1

selected: 1, # bunches: 1

LHC.BWS.5R4.B1V1 #1/IN at Fri 01:57:28 [18/01/13 01:57:31]

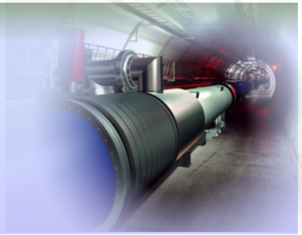
Profile Data for LHC.BWS.5R4.B1V
LHC.BWS.5R4.B1V1 #1/IN at Fri 01:57:28
Fit of profile
Center=0.098
Sigma=0.673
ChiSq=4.979
Kin Energy=449.062
Emit (phys, 1σ)=0.002
Emit (norm, 1σ)=0.754

LHC.BWS.5R4.B1V1 #1/OUT at Fri 01:57:28 [18/01/13 01:57:31]

Profile Data for LHC.BWS.5R4.B1V
LHC.BWS.5R4.B1V1 #1/OUT at Fri 01:57:28
Fit of profile
Center=0.145
Sigma=0.651
ChiSq=4.739
Kin Energy=449.062
Emit (phys, 1σ)=0.001
Emit (norm, 1σ)=0.706

```
02:15:02 - Subscription update 475 of LHC.BWS.5R4.B1V1/Status, Fri Jan 18 02:15:02 CET 2013
```

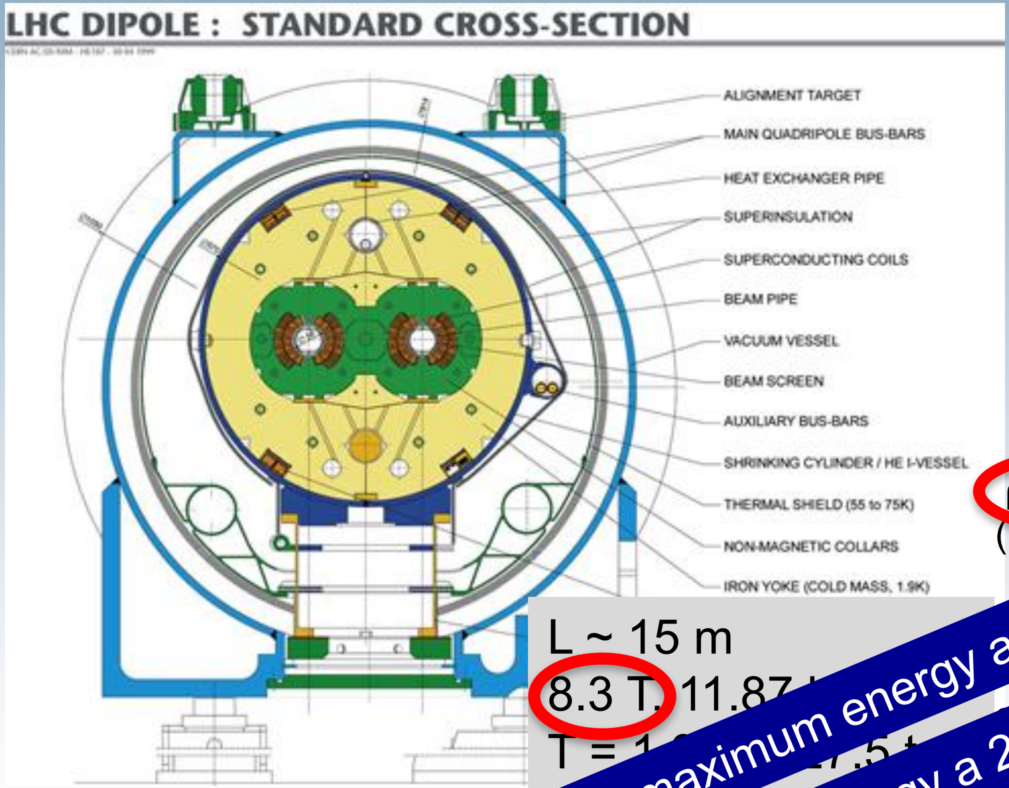
I. Basic layout of the machine: main cryodipoles (two dipoles in one)



- The geometry of the main dipoles (Total of 1232 cryodipoles)

VERTICAL PLANE

The theoretical shape of the beam channels is a straight line, while the natural shape has ~ 0.3 mm deflection between two supports at 5.4 m distance



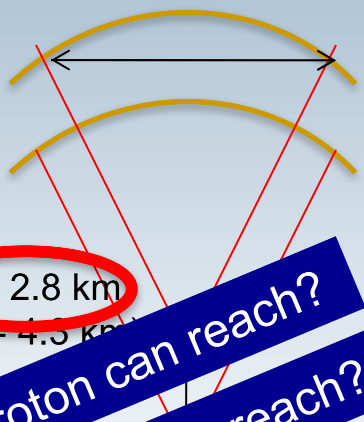
L ~ 15 m

8.3 T, 11.87

T = 1 … 27.5 t

HORIZONTAL PLANE

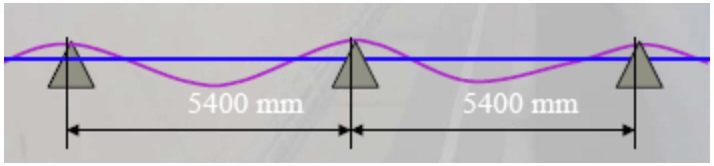
Length of the bend part =14.3 m



ρ = 2.8 km

(R = 4.3 km)

Dist… …een … 194.5 mm

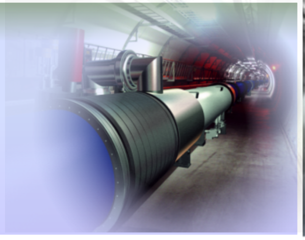


… acti… of the cold mass is bent in … …izontal plane with an angle of … mrad with ρ = 2.8 km. The shape of the two beam channels is identical.

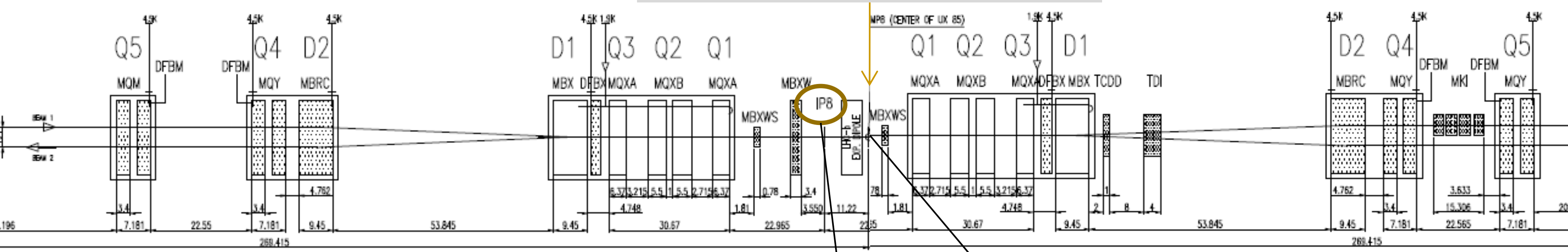
What is the maximum energy a proton can reach?

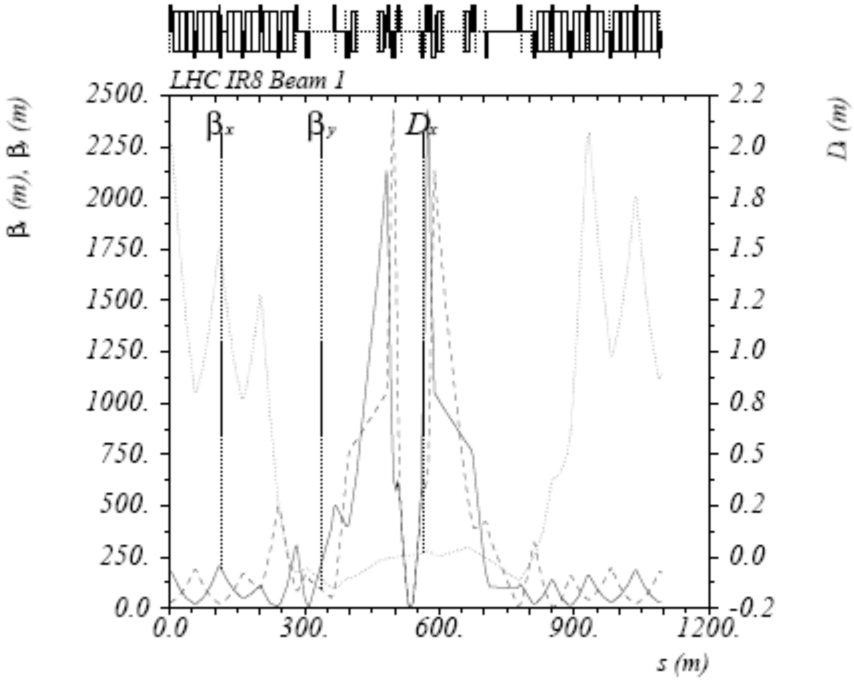
What is the maximum energy a 208Pb82+ can reach?

II. The experiments:
Low luminosity insertions: LHCb

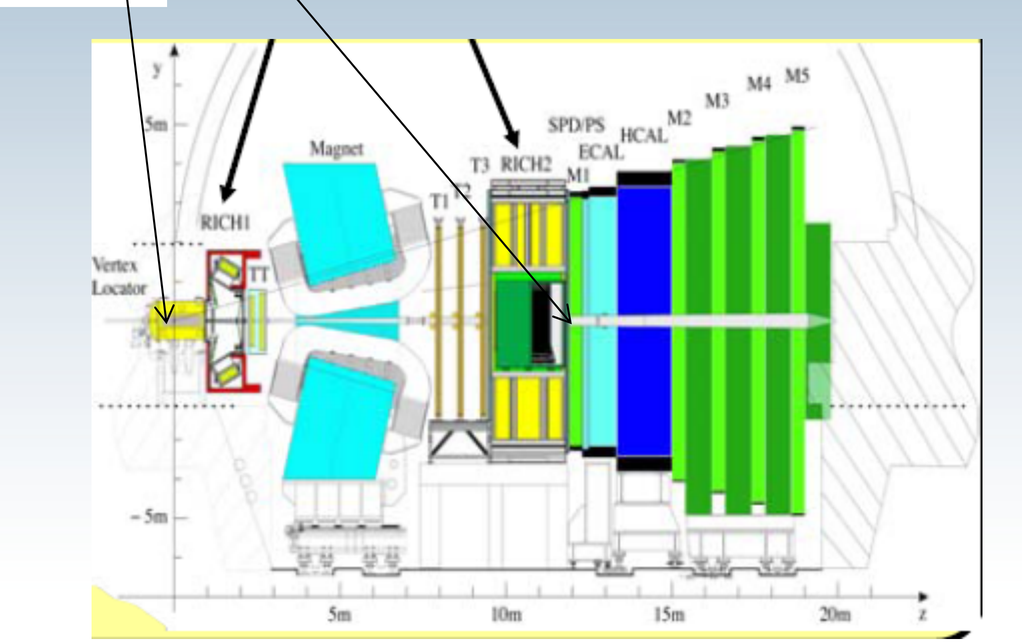


Centre of the exp cavern

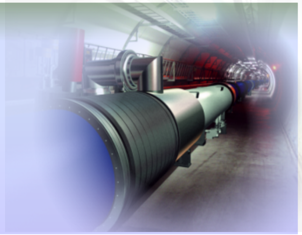


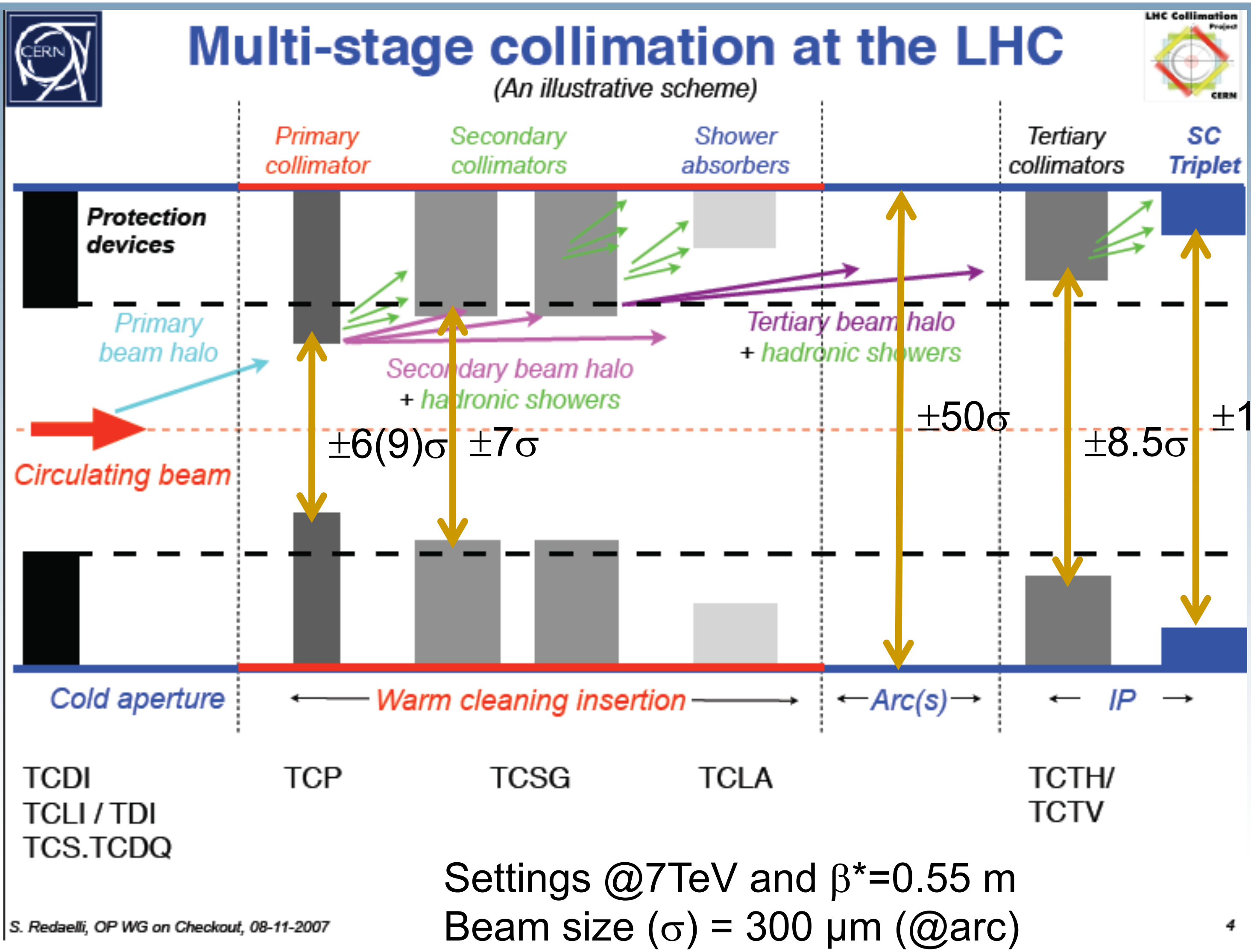


(c) Beam 1, collision optics



IV. Momentum and betatron cleaning insertions (IR3, IR7)





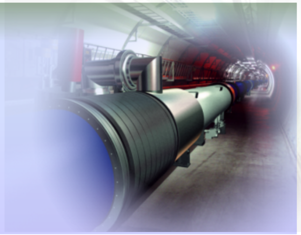
Multi-stage collimation at the LHC

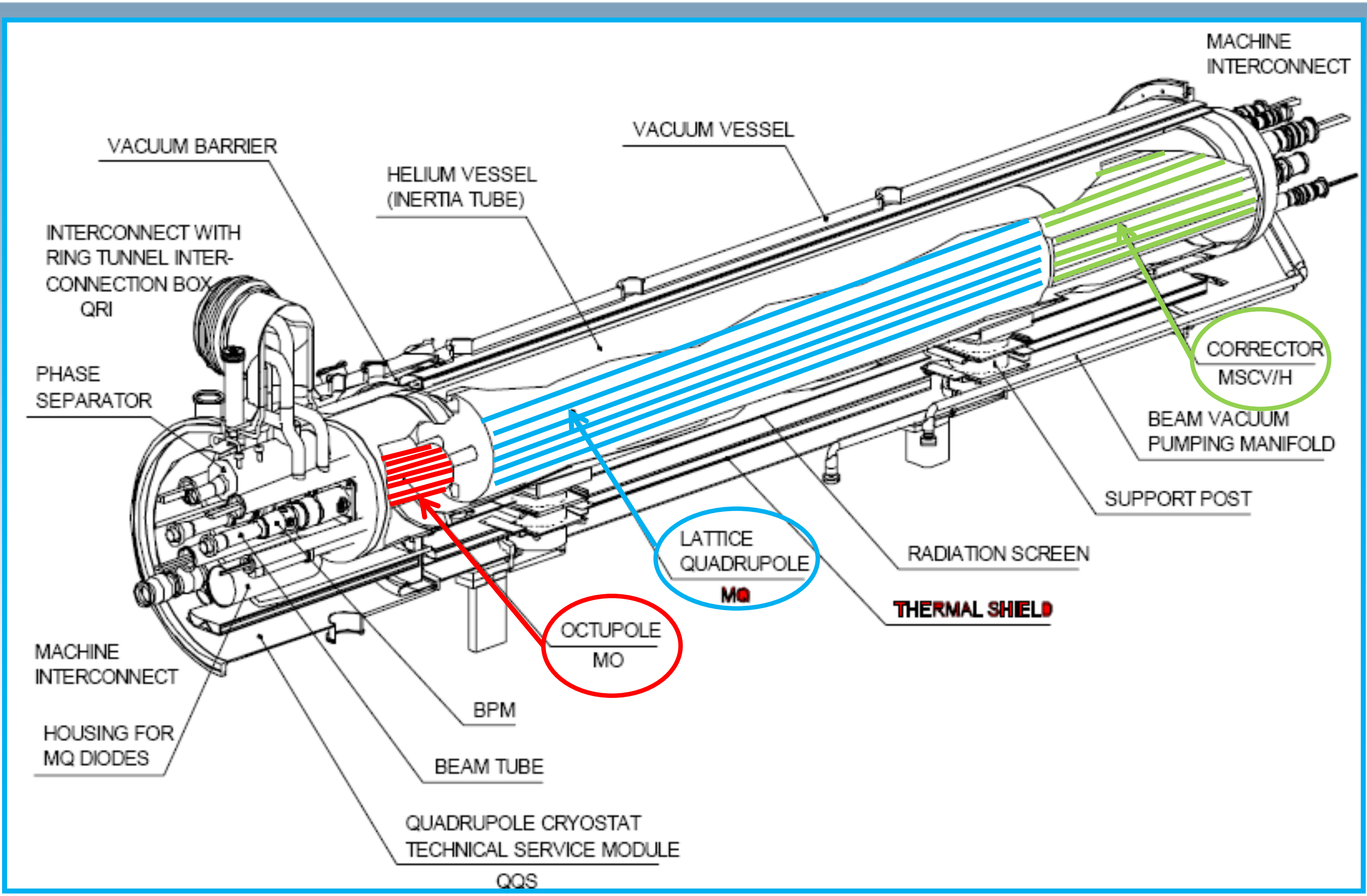
(An illustrative scheme)

S. Redaelli, OP WG on Checkout, 08-11-2007

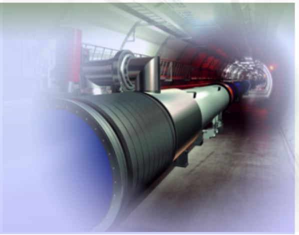
Settings @7TeV and β^*=0.55 m
Beam size (σ) = 300 μm (@arc)
Beam size (σ) = 17 μm (@IR1, IR5)

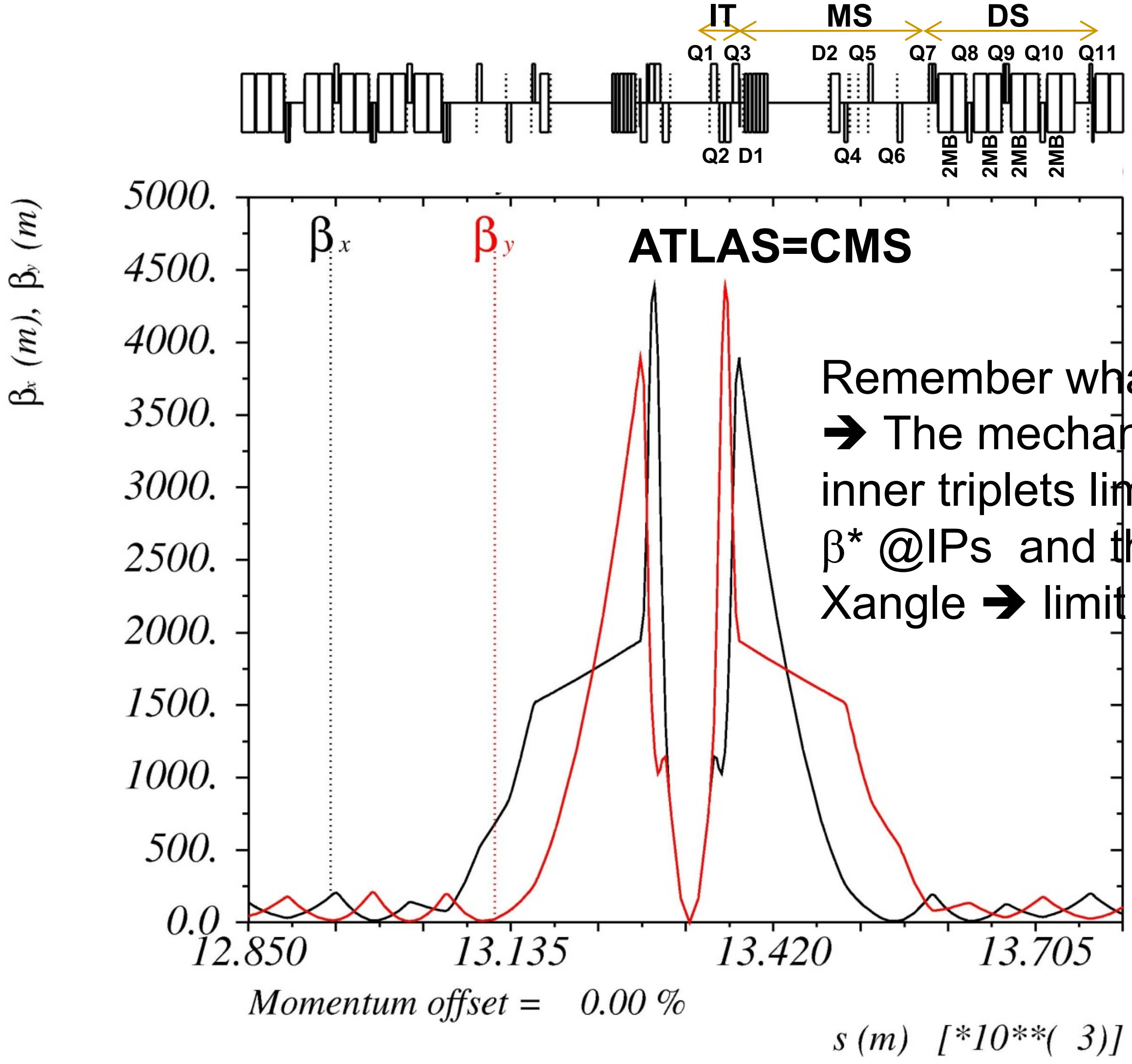
1. Basic layout of the machine: quadrupole corrector magnets





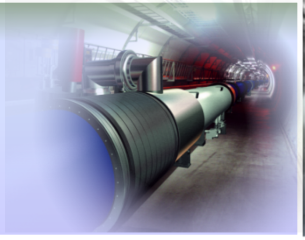
II. LHC Operational cycle:
Squeeze ➔ reduce β^*

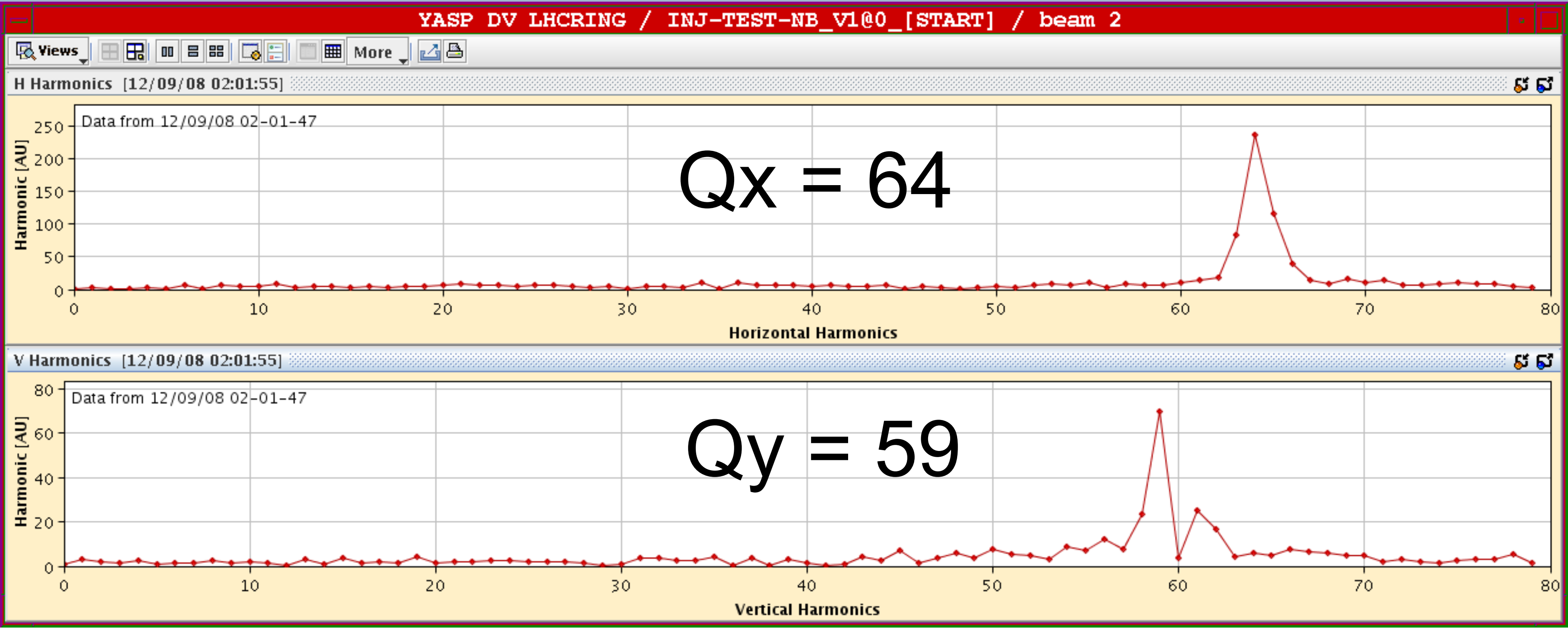




Remember what I said in slide 23 ➔ The mechanical aperture of the inner triplets limits the maximum β^* @IPs and the maximum Xangle ➔ limit peak luminosity

II. Beam measurements:
Integer tunes

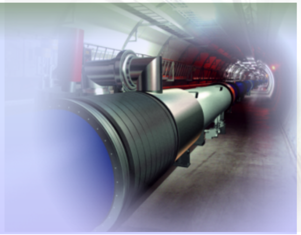




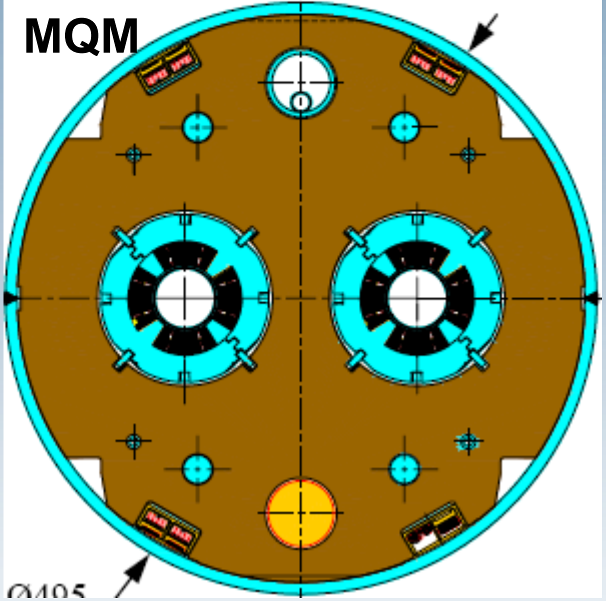
Qx = 64

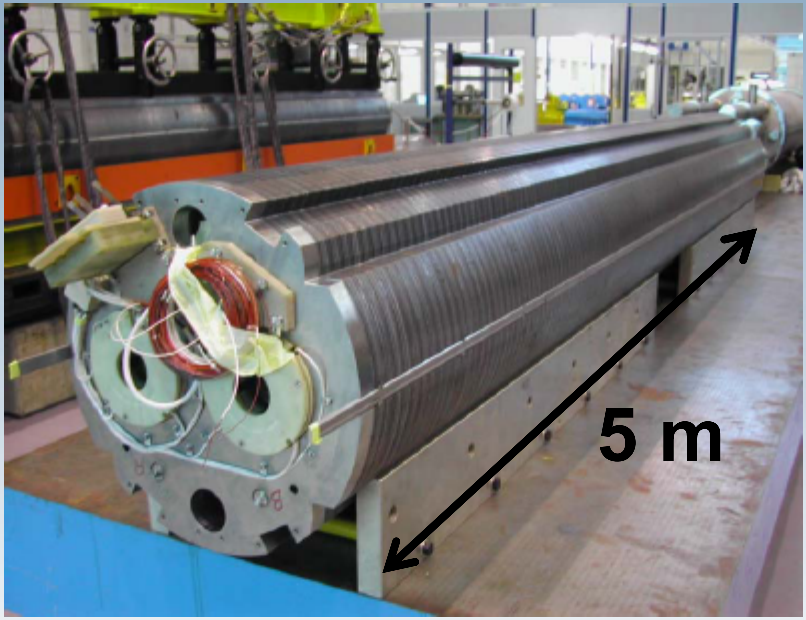
Qy = 59

I. Basic layout of the machine: Dispersion suppression



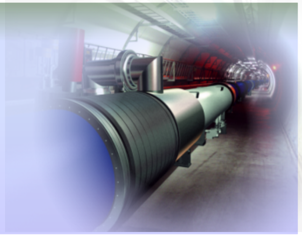
- Quadrupole types: MQ, **MQM**, MQTL

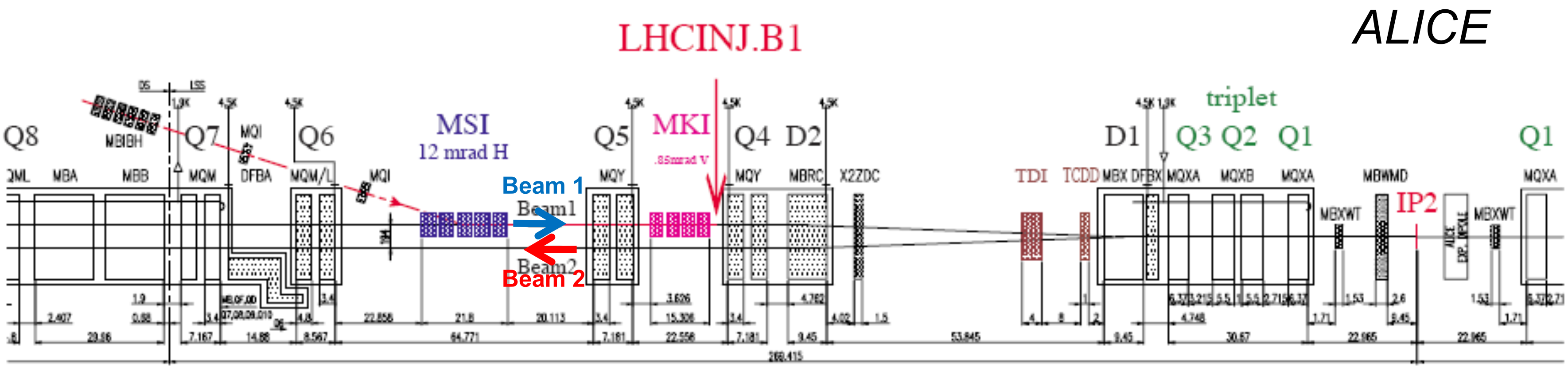


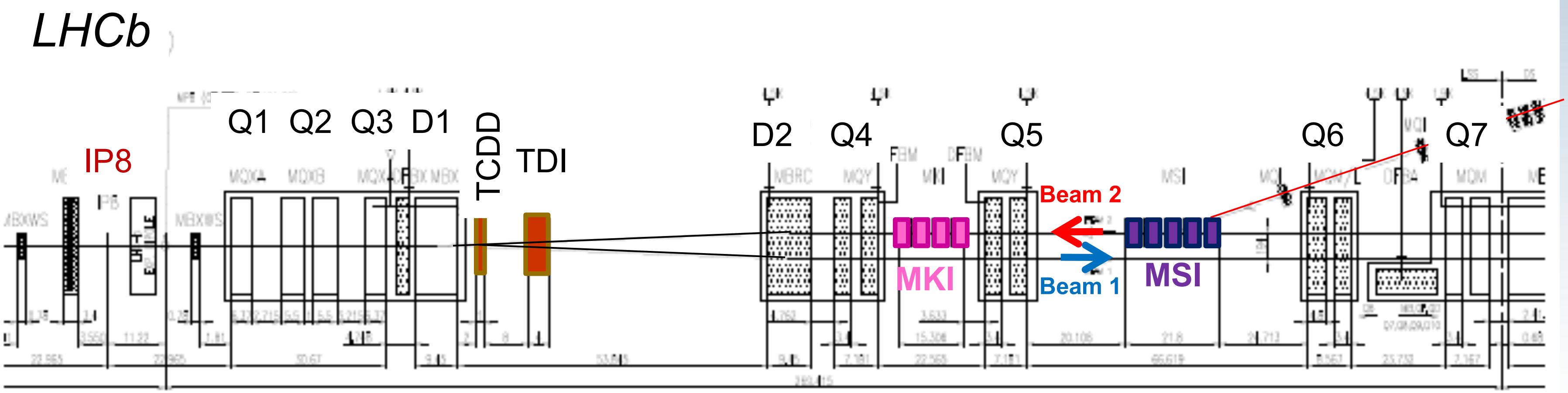


Nominal gradient = 200/160 T/m
$I_{nominal}$ = 5.4/4.3 kA
L_{mag}=2.4/3.4/4.8 m
T=1.9/4.5 K
Cold bore ∅ = 53/50 mm
Individual powered apertures

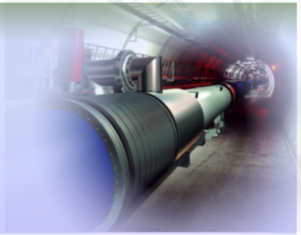
I. Basic layout of the machine: Low luminosity insertions





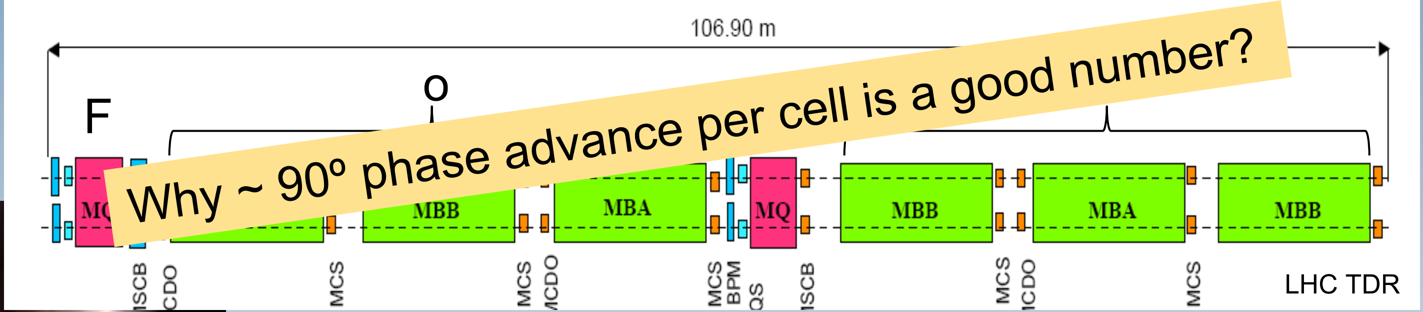


Extra challenge ➔ the lattice has to accommodate the injection region



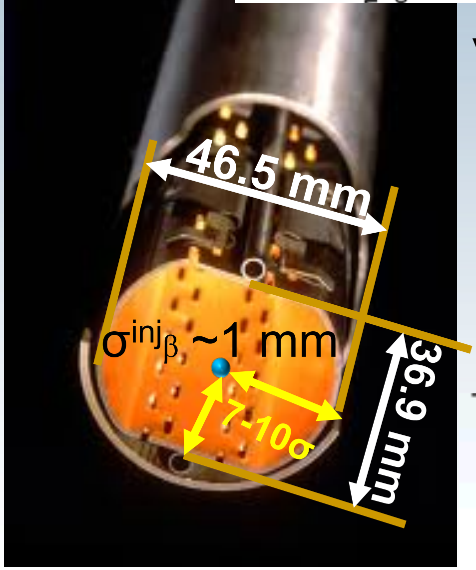
I. Basic layout of the machine

LHC arc cells = FoDo lattice* with
~ 90º phase advance per cell in the V & H plane



Why ~ 90º phase advance per cell is a good number?

LHC TDR



Which parameter determines the beam size (ignoring D(s))?

$$r^2 = \varepsilon_x\beta_x + \varepsilon_y\,\beta_y$$

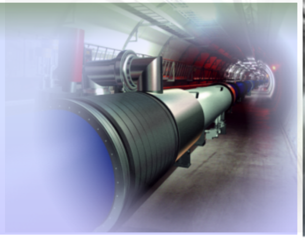
(In general in proton machines εx≈εy ➔ beams are round)

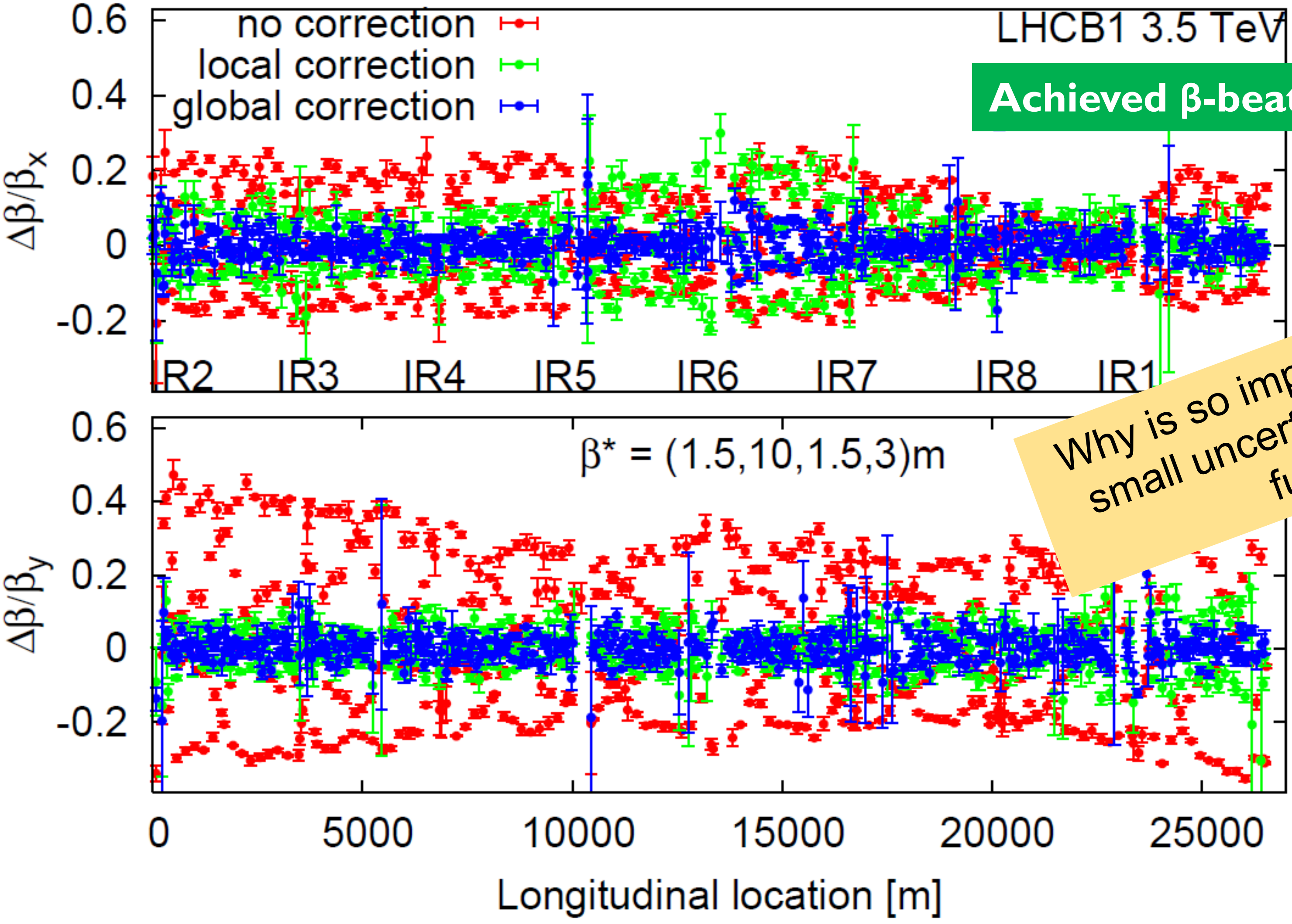
In order to get the maximum aperture possible the β(s) in both planes have to be minimized:

$$\frac{d}{d\mu}\left(\boxed{\beta_{max}} + \boxed{\beta_{min}}\right) = \frac{d}{d\mu}\left(\underbrace{\frac{\left(1+\sin\frac{\mu}{2}\right)L}{\sin\mu}}_{} + \underbrace{\frac{\left(1-\sin\frac{\mu}{2}\right)L}{\sin\mu}}_{}\right) = \frac{d}{d\mu}\left(\frac{2L}{\sin\mu}\right) = 0$$

$$\frac{L}{\sin^2\mu}\cos\mu = 0 \quad ➔ \quad \mu=90^\circ$$

II. Beam measurements: Beta measurement



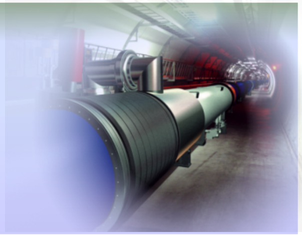


Achieved β-beating error 10% !!

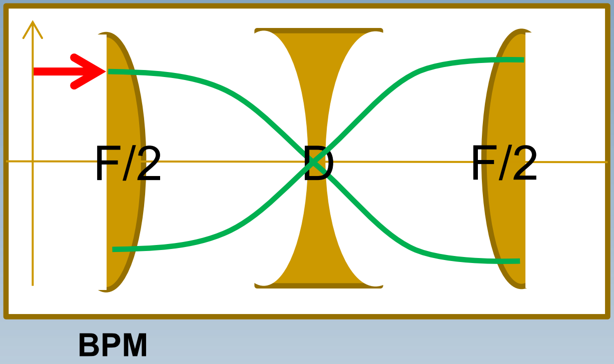
Why is so important to have a small uncertainty in the beta function?

Reference: Record low beta beating in the LHC
Tomas, R. et al. Phy. Rev. Special Topics - Accelerators and Beams15(9).

II. Beam measurements: Non-integer tunes



FODO: Ψ=180°

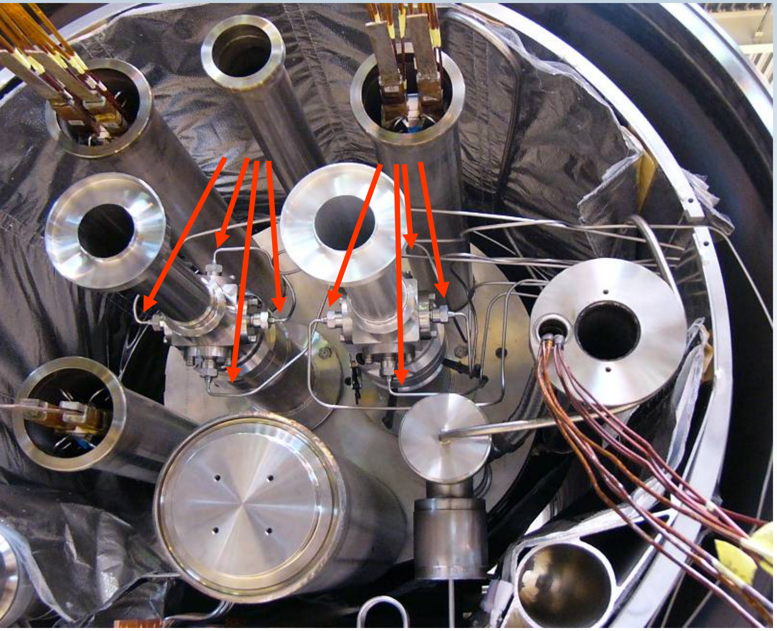


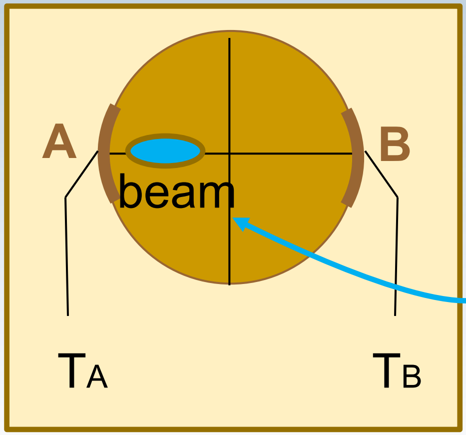
Every 2xT we measure the same position:

$$\frac{1}{2T} = f_Q = Q \cdot \frac{1}{T} = Q \cdot f_{rev}$$

$$\rightarrow Q = 0.5$$

BPM pos ➔ FFT ➔ tune





With a frequency of ~3 kHz we measure the same beam position

$Q_x \cdot f_{rev} = 3$ kHz

$Q_x = .279$ @LHC

$Q_y = .310$