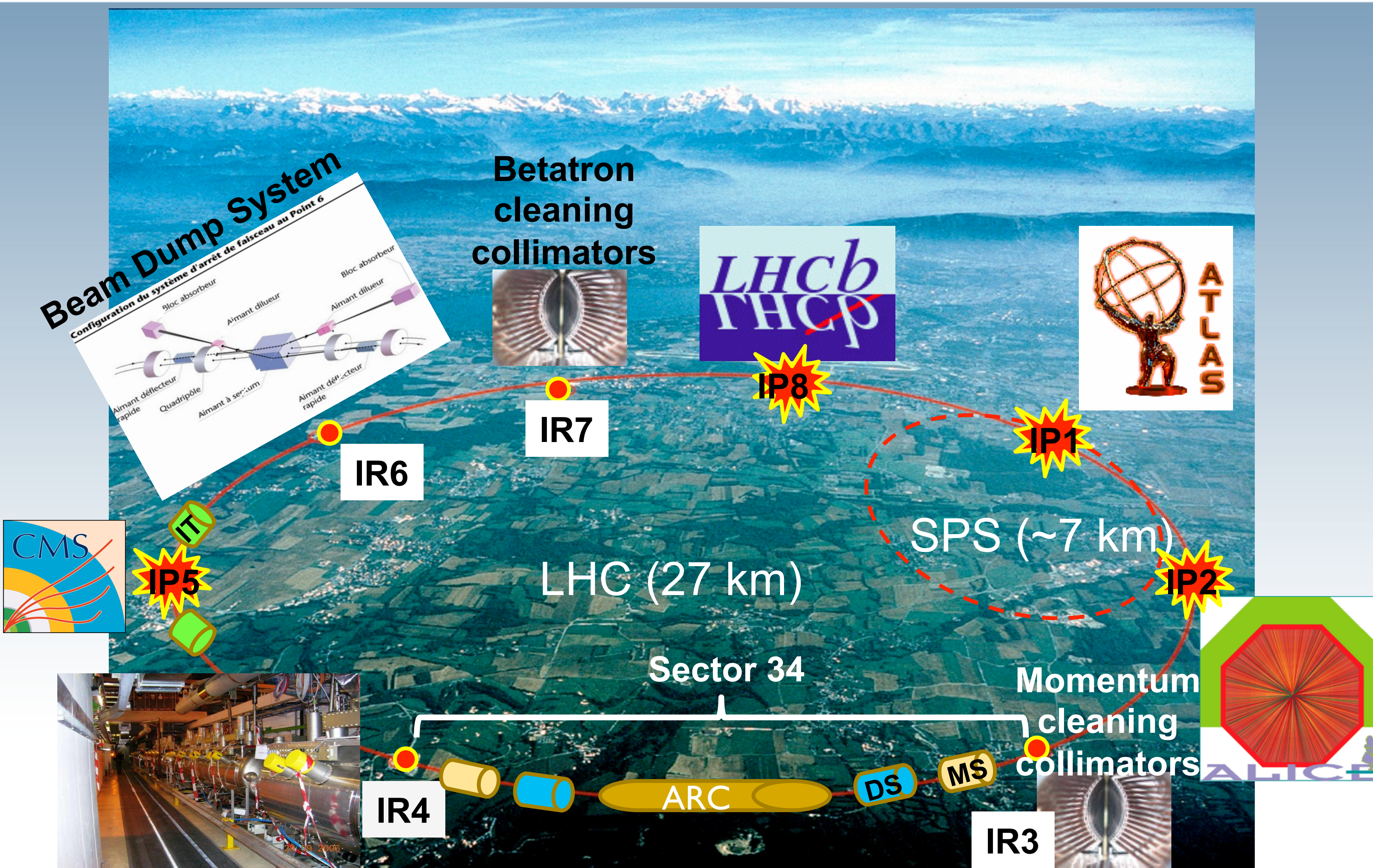
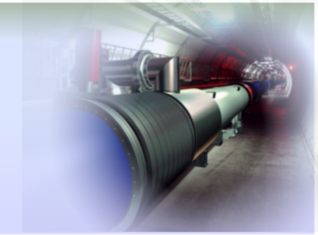
[R. Alemany]
[CERN BE/OP]
[Engineer In Charge of LHC]
Lectures JUAS (19.01.2012)

The Large Hadron Collider

Basic layout of the machine



Beam parameters (nominal)

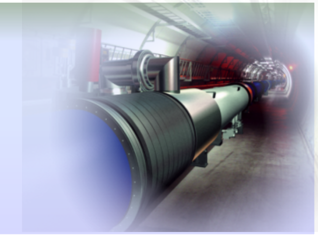


		Injection	Collision
Proton energy	GeV	450	7000
Particles/bunch		1.15×10^{11}	
Num. bunches		2808	
Longitudinal emittance (4σ)	eVs	1.0	2.5
Transverse normalized emittance	μm rad	3.5	3.75
Beam current	A	0.582	
Stored energy/beam	MJ	23.3	362
		Peak luminosity related data	
RMS bunch length	cm	11.24	7.55
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})
Instantaneous lumi/bunch crossing @IP1 & IP5	$cm^{-2}s^{-1}$		3.56×10^{30}

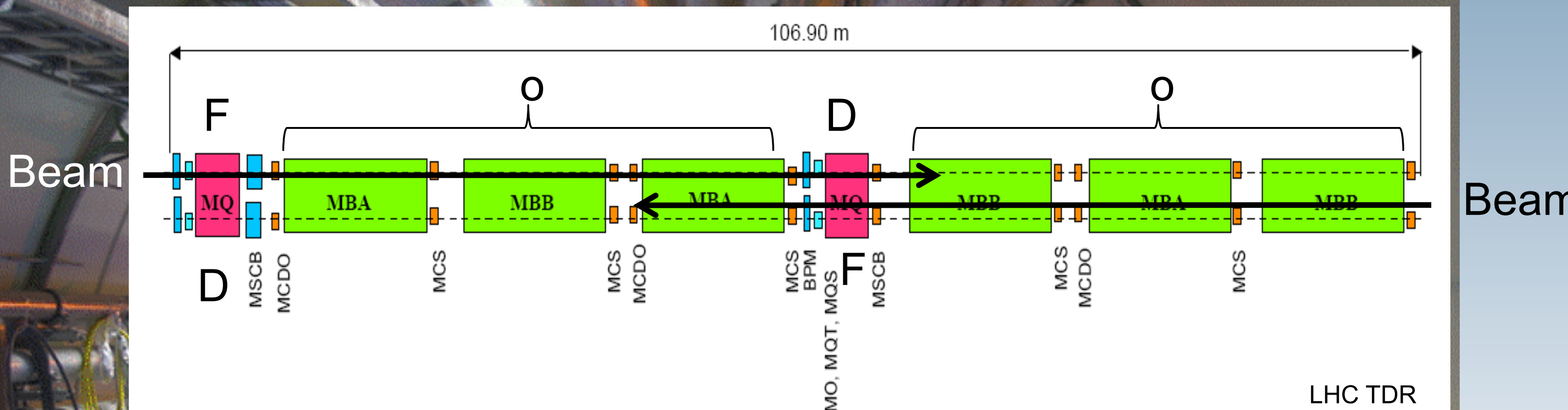
$\beta = 10$ m
$\varepsilon = 0.5$ nm rad

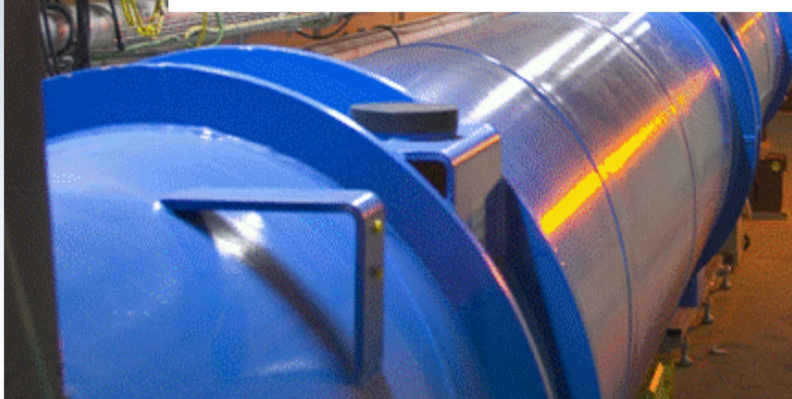
$\beta = 0.55$ m
$\varepsilon = 0.5$ nm rad

Basic layout of the machine: the arc



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

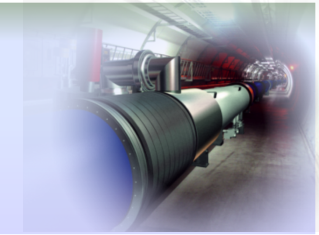




MB: main dipole
MQ: main quadrupole
MQT: Trim quadrupole
MQS: Skew trim quadrupole
MO: Lattice octupole (Landau damping)
MSCB: Skew sextupole +
Orbit corrector (lattice chroma+orbit)
MCS: Spool piece sextupole
MCDO: Spool piece octupole +
Decapole
BPM: Beam position monitor

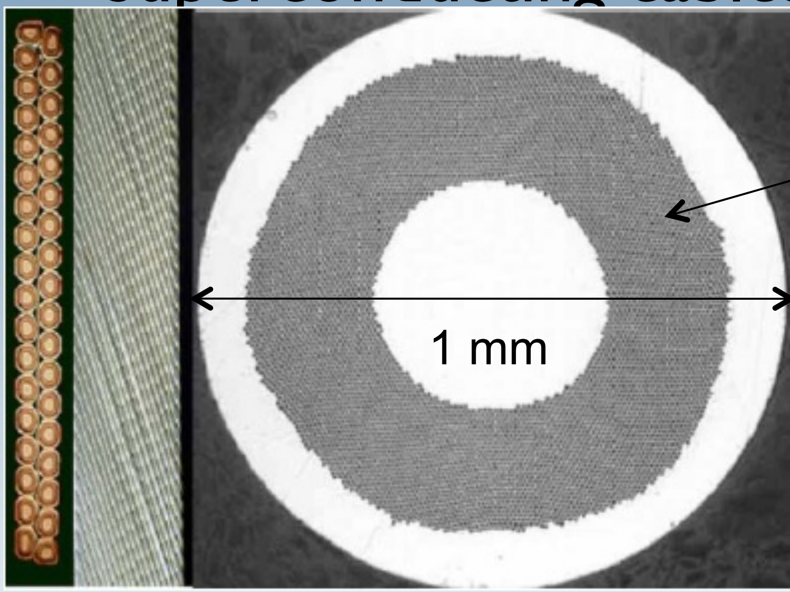
The FoDo-Lattice * BH lectures (tomorrow)

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...)



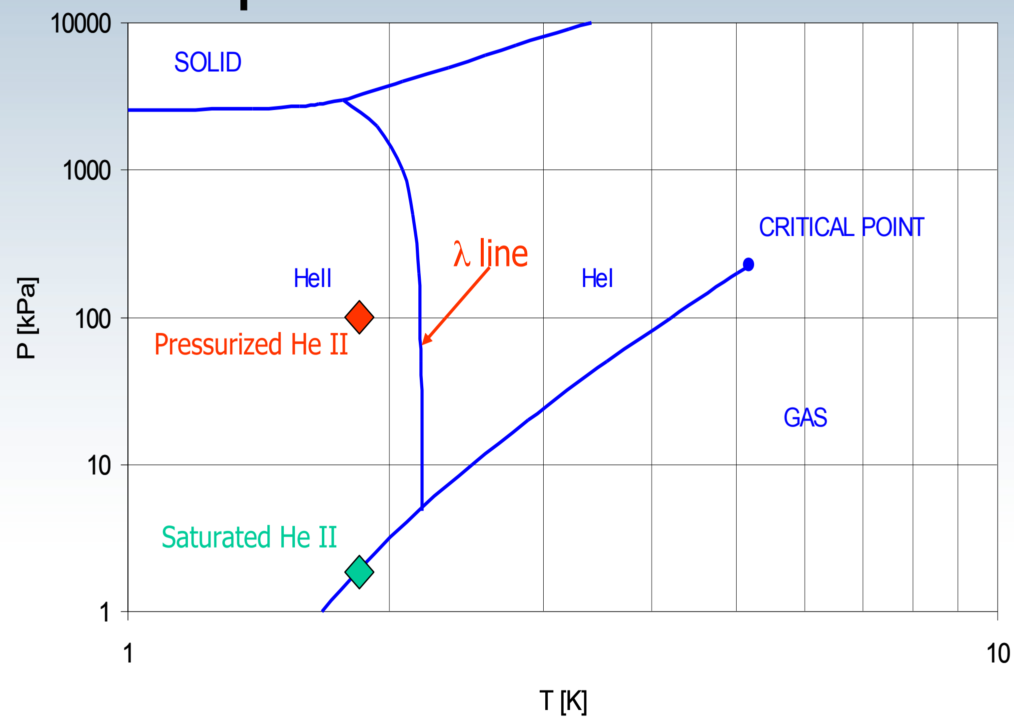
Superconducting magnets

- Superconducting cables of Nb-Ti

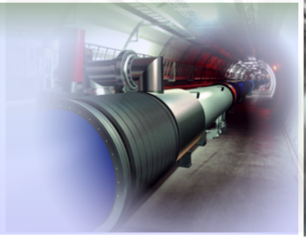


LHC ~ 27 km circumf. with 20 km of superconducting magnets operating @8.3 T. An equivalent machine with normal conducting magnets would have a circumference of 100 km and would consume 1000 MW of power ➔ we would need a dedicated nuclear power station for such a machine. LHC consumes ~ 10% nuclear power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

- Superfluid helium



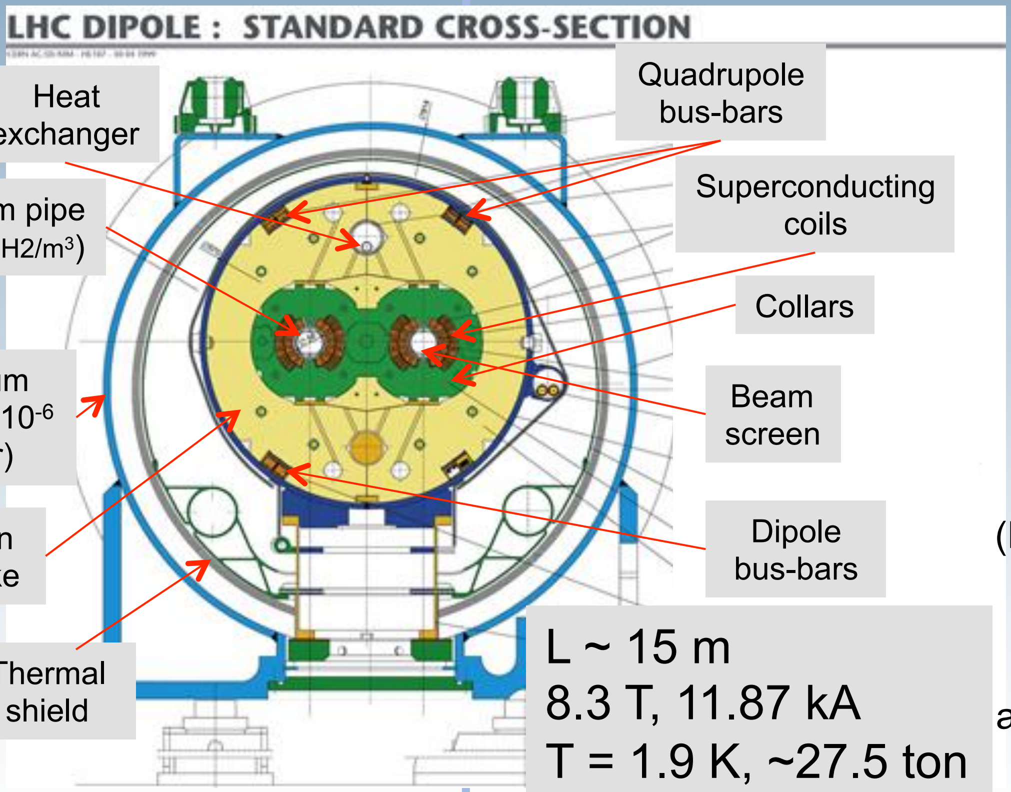
Basic layout of the machine: main cryodipoles (two dipoles in one)



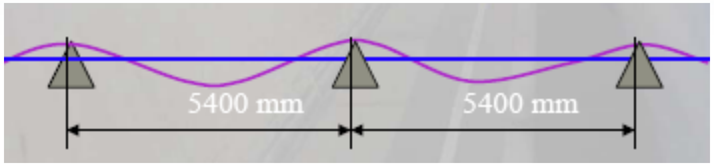
- The geometry of the main dipoles (Total of 1232 cryodipoles)

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

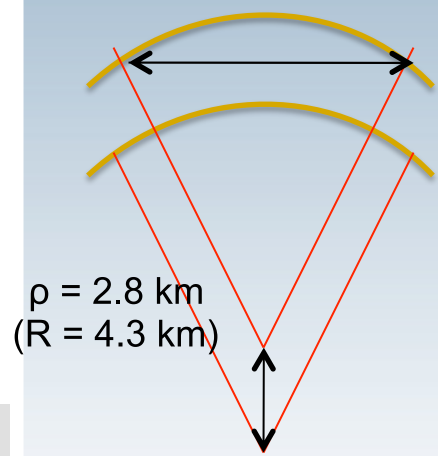


L ~ 15 m
8.3 T, 11.87 kA
T = 1.9 K, ~27.5 ton



HORIZONTAL PLANE

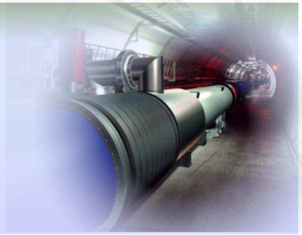
Length of the bend part =14.3 m



Distance between apertures = 194.5 mm

The active part of the cold mass is bent in the horizontal plane with an angle of 5.09 mrad with ρ = 2.8 km. The shape of the two beam channels is identical.

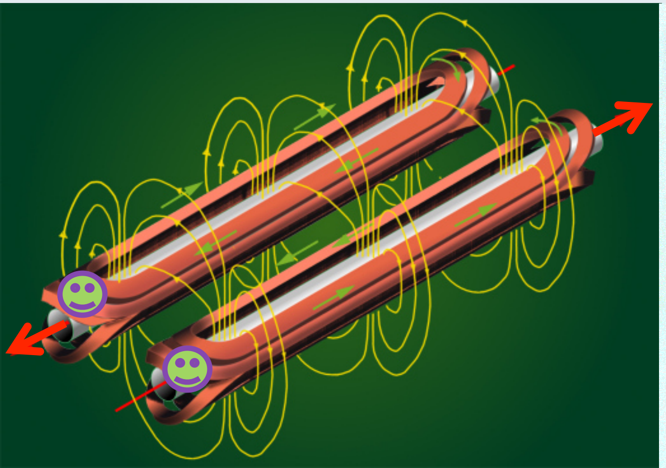
Basic layout of the machine: main dipoles

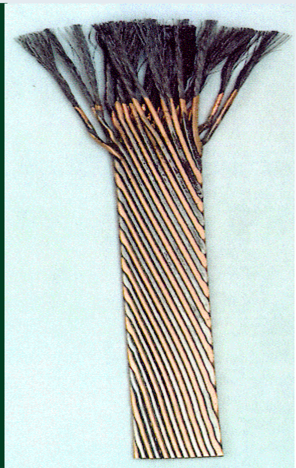


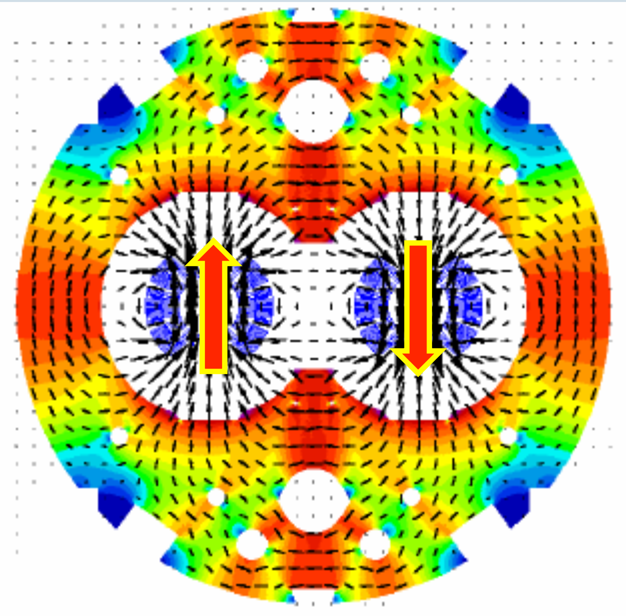
- The magnetic field of the main dipoles:

the stability of the geometry of the superconducting coils is essential to the field homogeneity. Mechanical stress during coil assembly, thermal stresses during cool-down and electromagnetic stresses during operation are the the sources of deformations of the coil geometry. Additional sources of field-shape errors are the dimensional tolerances of the magnet components and of the manufacturing and assembling tooling.

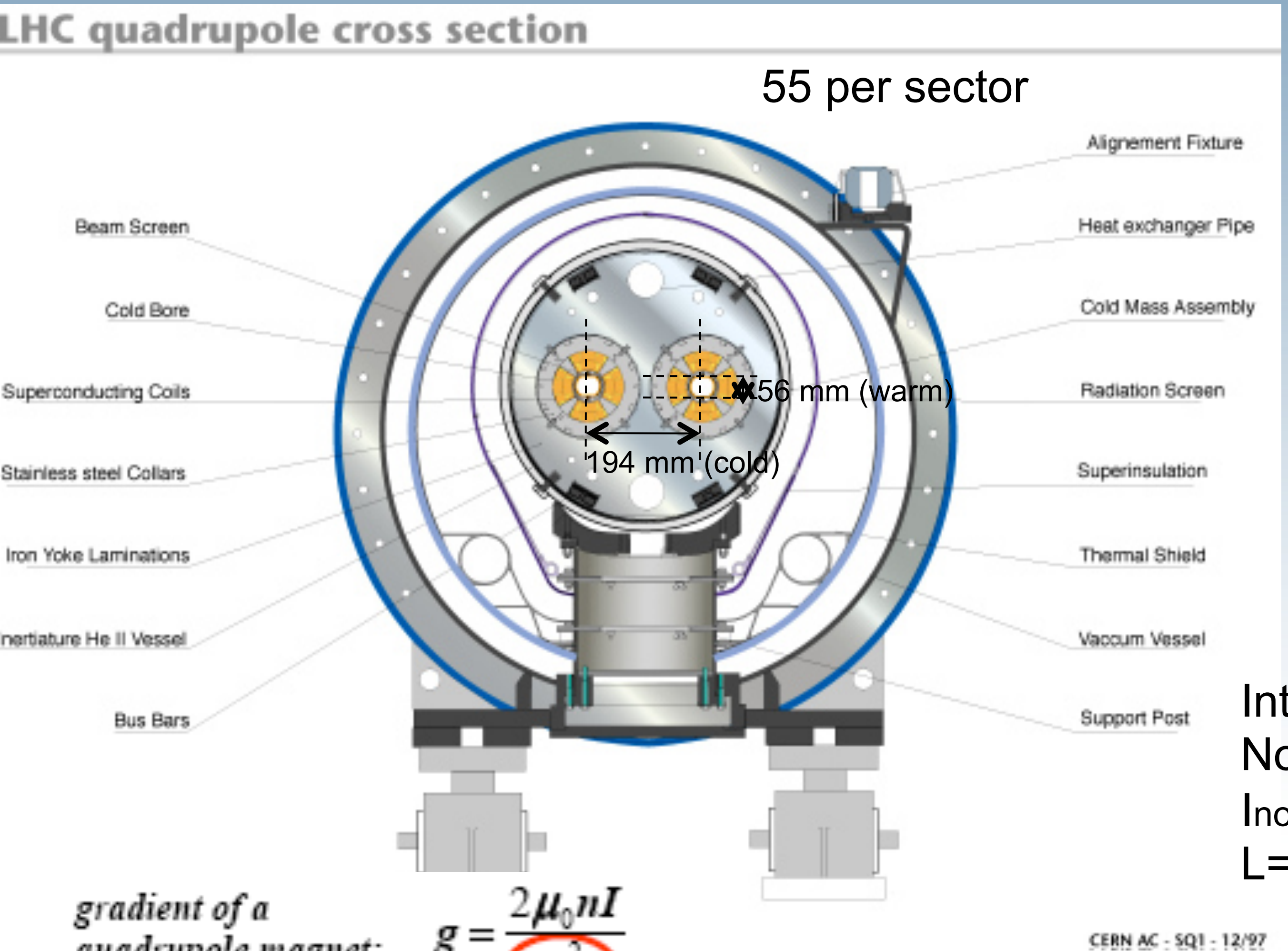
The relative variations of the integrated field and of the field shape imperfections must not exceed ~ 10^{-4} and their reproducibility better than 10^{-4} . This is possible if the coil geometry is accurate, reproducible and symmetric and if the structural stability of the magnet assembly during powering is guarantee.







I.I. Basic layout of the machine: main quadrupoles



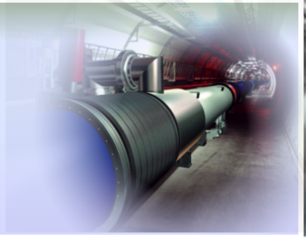
Integrated gradient = 690 T
Nominal gradient = 223 T/m
$I_{nominal}$ = 11.87 kA
L=3.1 m

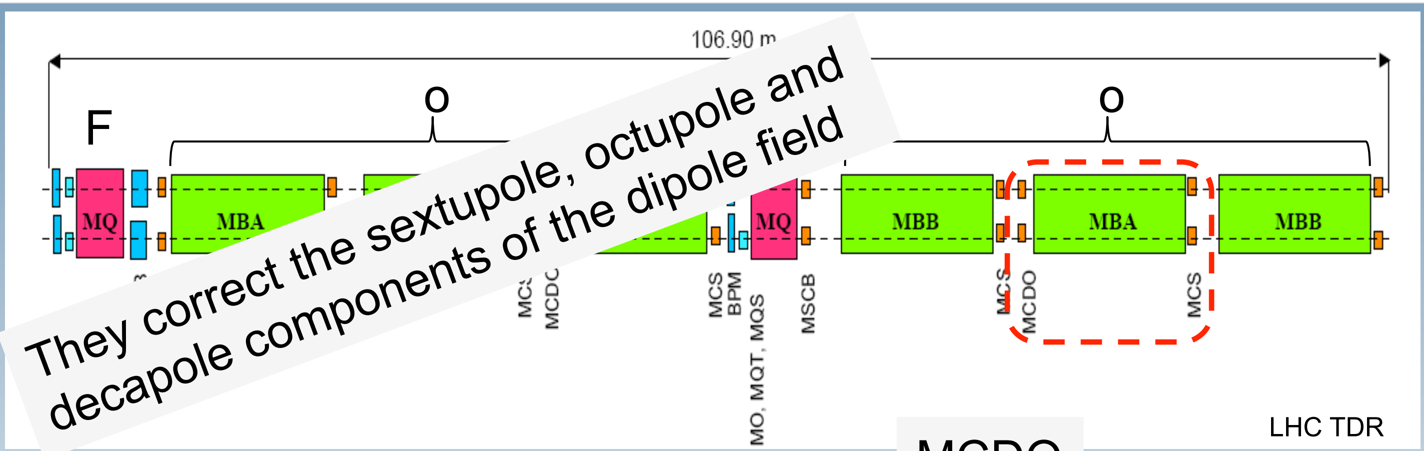
gradient of a quadrupole magnet:

$$g = \frac{2\mu_0 n I}{r^2}$$

BH Lecture

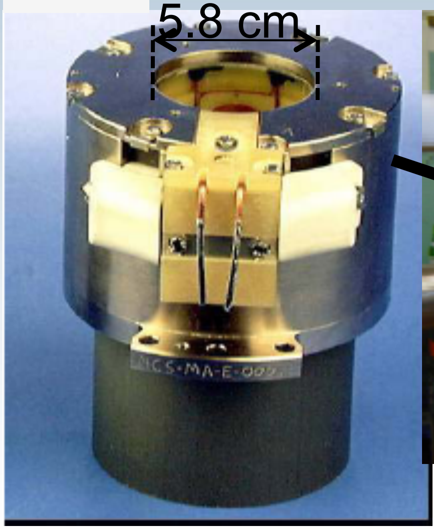
I.I. Basic layout of the machine: dipole corrector magnets

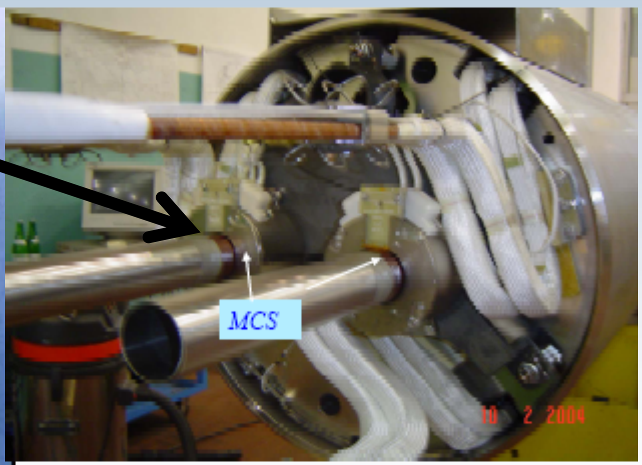




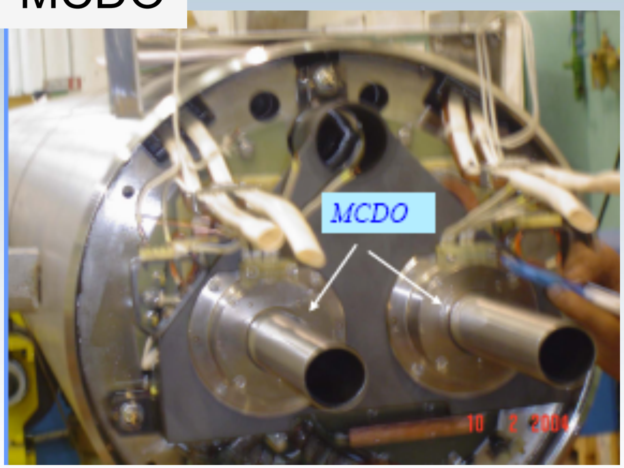
They correct the sextupole, octupole and decapole components of the dipole field

MCS





MCDO

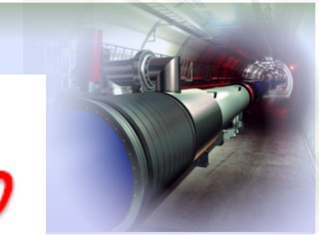


Nominal main field strength = 1630 T/m^2
Inominal = 550 A, 1.9 K,
L=15.5 cm, ~10 kg

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

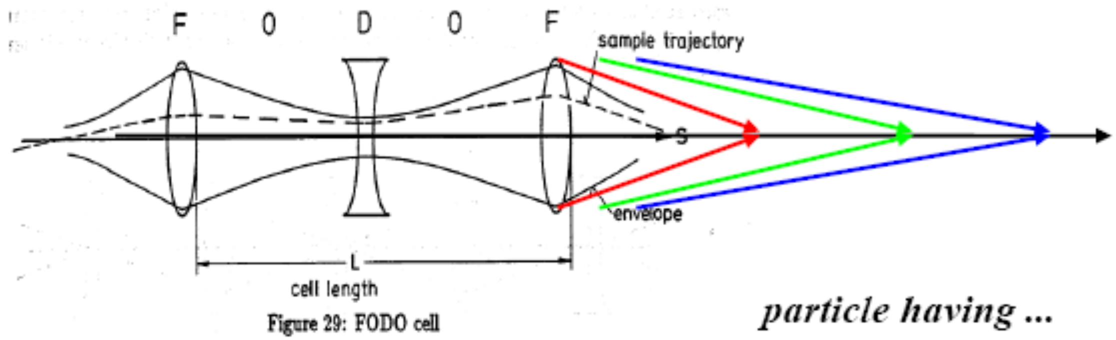
MCO:
Nominal main field strength = 8200 T/m^3
Inominal = 100 A, 1.9 K,
L=11 cm, ~6 kg

I.I. Basic layout of the machine:



20.) Chromaticity: A Quadrupole Error for $\Delta p/p \neq 0$

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

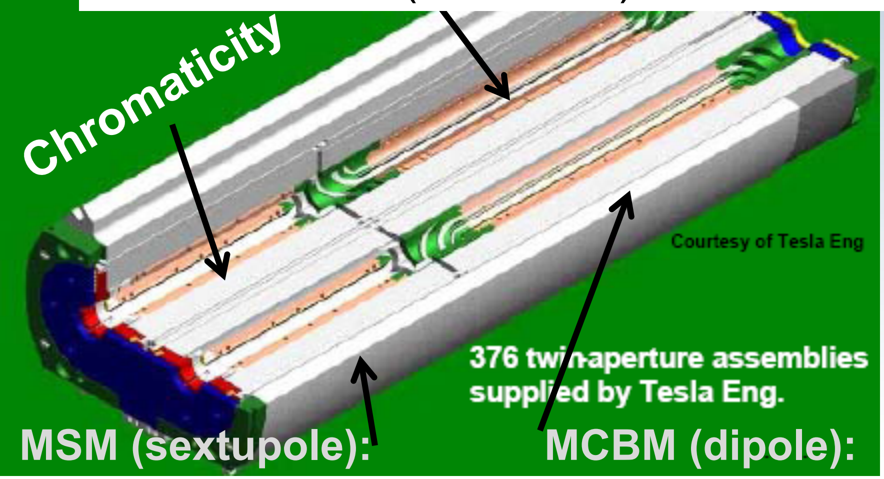


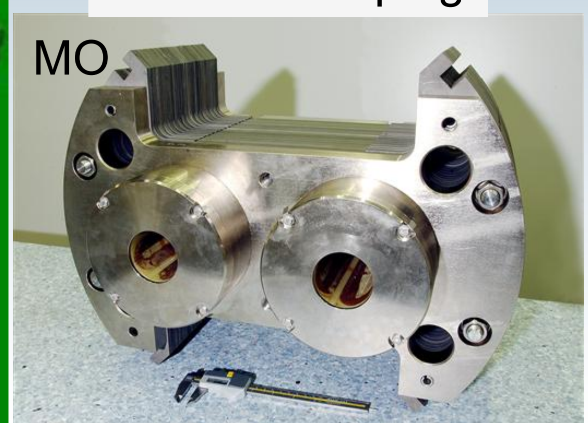
particle having ...
to high energy
to low energy
ideal energy

M

BH Lectures (tomorrow)

Landau damping





MQT/MQS:

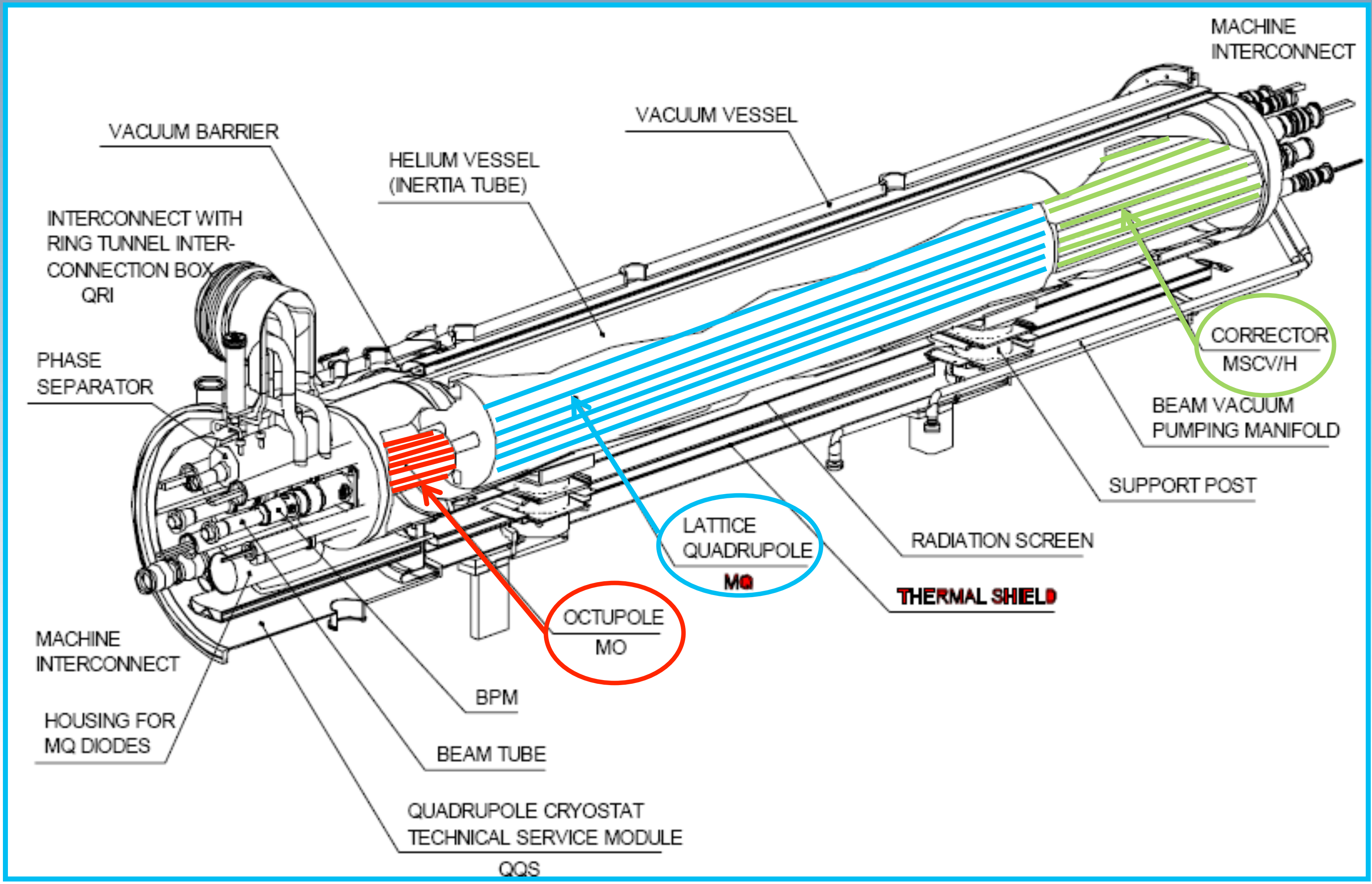
MSM (sextupole): Nominal main field strength = 4430 T/m^2
$I_{nominal}$ = 550 A, 1.9 K,
L=45.5 cm, ~83 kg

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

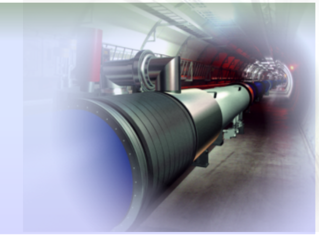
MO: Nominal main field strength = 63100 T/m^3
$I_{nominal}$ = 550 A, 1.9 K
L=38 cm, ~8 kg

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

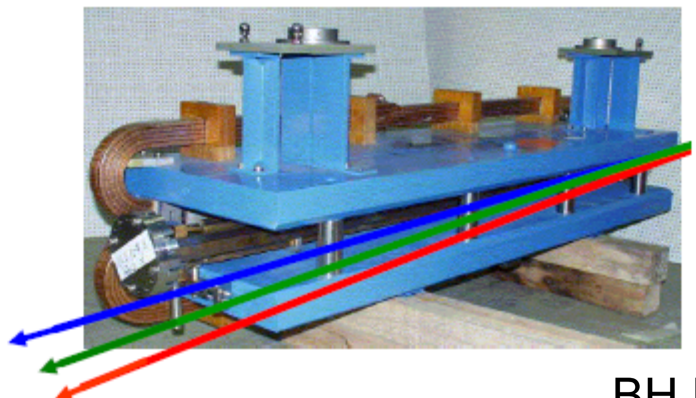
I.I. Basic layout of the machine: quadrupole corrector magnets



I.I. Basic layout of the machine: Dispersion suppression



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



$x_D(s) = D(s)\frac{\Delta p}{p}$

BH Lecture (tomorrow)

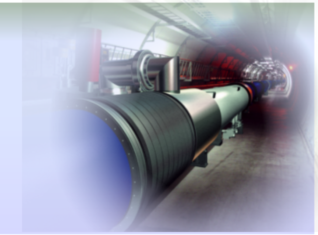
The dispersion suppression is located at the transition between the arc and the straight section. The schema above applies to all DS except the ones in IR3 and IR7.

Functions:

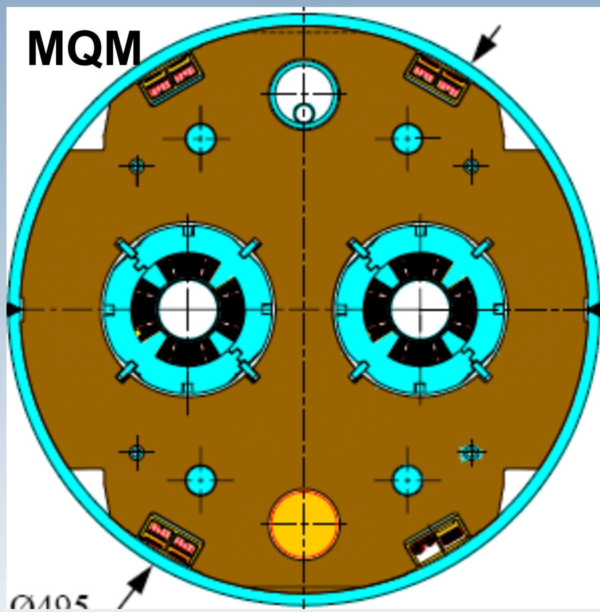
1. Adapts the LHC reference orbit to the LEP tunnel geometry
2. Cancels the horizontal dispersion generated on one side by the arc dipoles and on the other by the separation/recombination dipoles and the crossing angle bumps
3. Helps in matching the insertion optics to the periodic solution of the arc

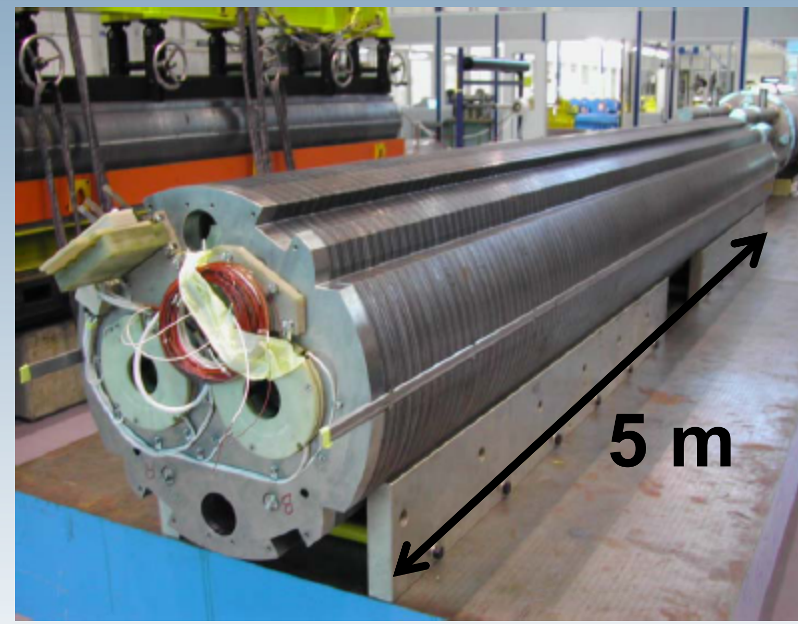
It is like an arc cell but with one missing dipole because of lack of space. If only dipoles are used they cannot fully cancel the dispersion, just by a factor 2.5. Therefore individual powered quadrupoles are required (Q8-Q11 with I ~ 6000 A).

I.I. Basic layout of the machine: Dispersion suppression



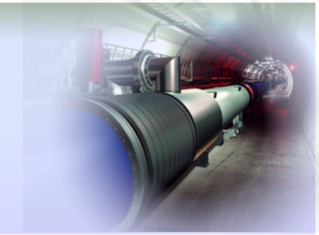
- Quadrupole types: MQ, **MQM**, MQTL

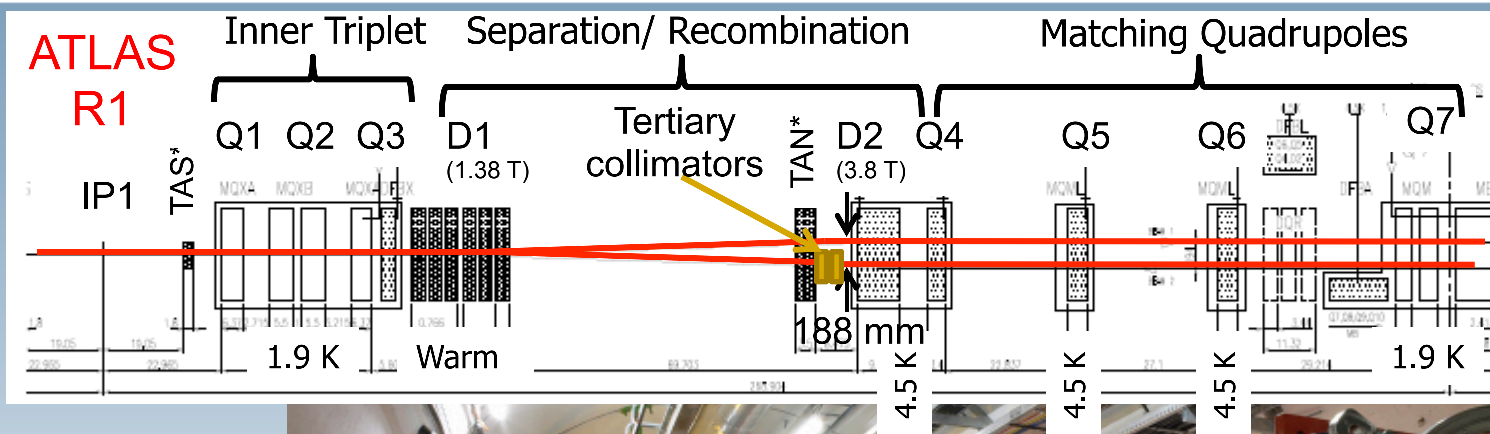




Nominal gradient = 200/160 T/m
$I_{nominal}$ = 5.4/4.3 kA
L_{mag}=2.4/3.4/4.8 m
T=1.9/4.5 K
Cold bore ∅ = 53/50 mm
Individual powered apertures

III.III. The experiments: High luminosity insertions





6.45 kA 10.63 kA

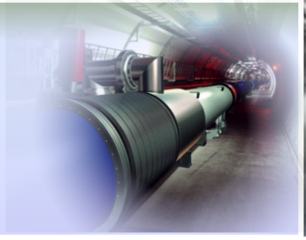
	LSS						
	low-β triplet			MS			
Magnet	Q1	Q2	Q3	Q4	Q5	Q6	Q7
#	1	2	1	1	1	1	2
Type: MQ-	XL	X	XL	Y	ML		M
L [m]	6.3	5.5	6.3	3.4	4.8	4.8	3.4
T [K]	1.9			4.5			1.9
G [T/m]	200/205			160			200
r [mm]	23.85 18.95	28.95 24.05		29.0 24.0	22.5 17.6		22.2 17.3

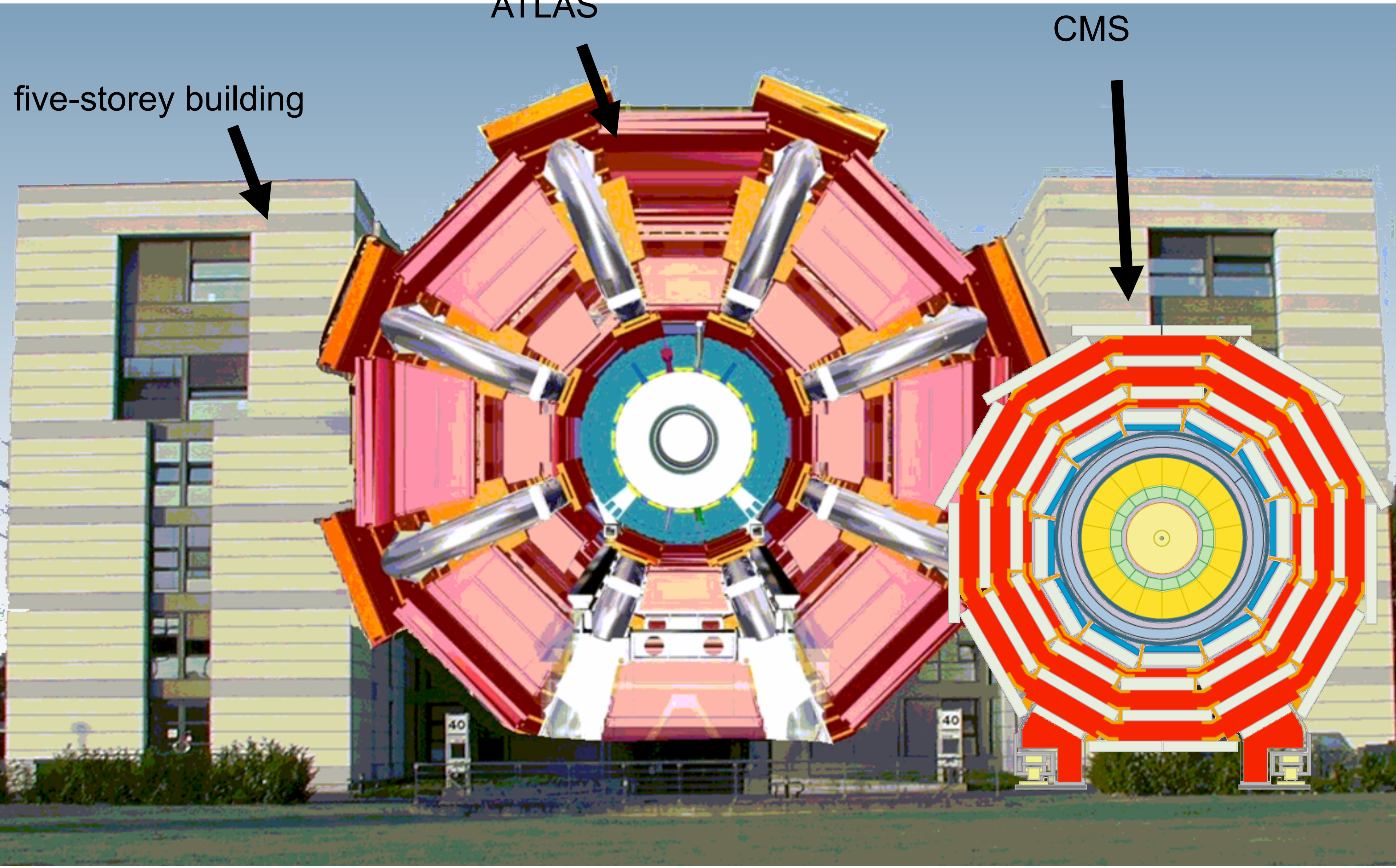
* Protect Inner Triplet (TAS) and D2 (TAN) from particles coming from the IP

→ To provide sufficient aperture for the Xangle

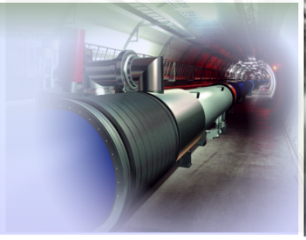
The mechanical aperture of the inner triplets limits the maximum β* @IPs and the maximum Xangle ➔ limit peak lumi

III.III. The experiments:
High luminosity insertions

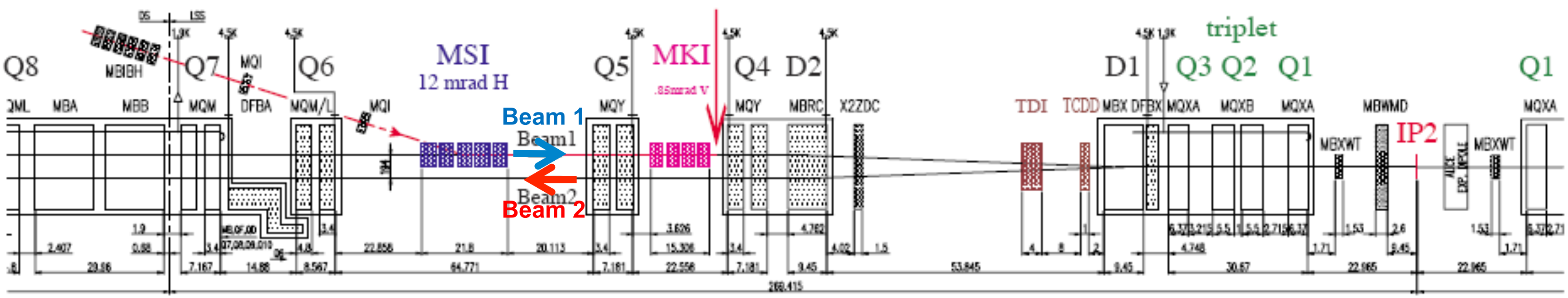




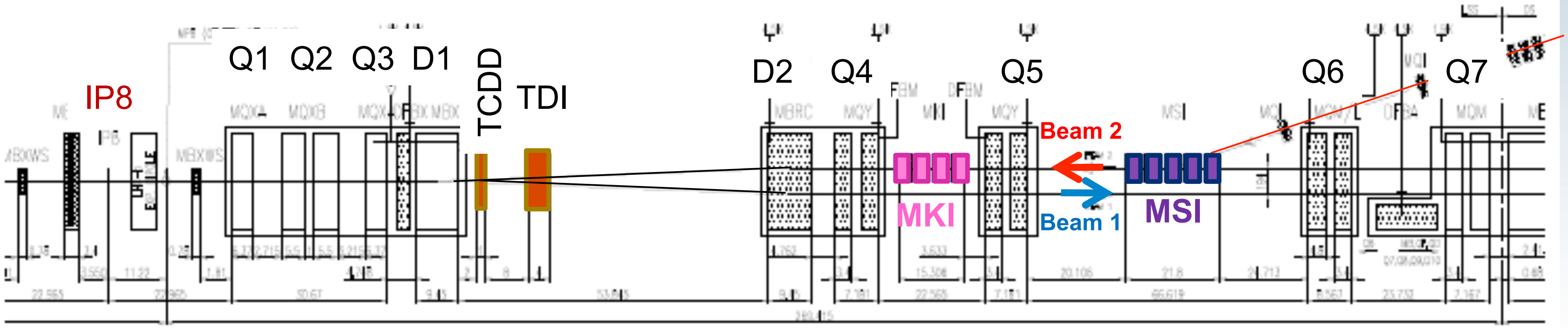
III.III. The experiments: Low luminosity insertions

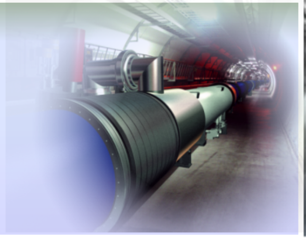


ALICE



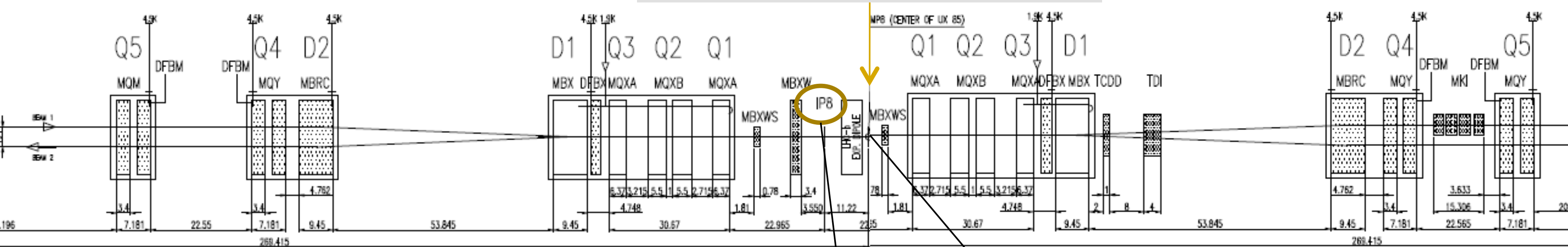
LHCb

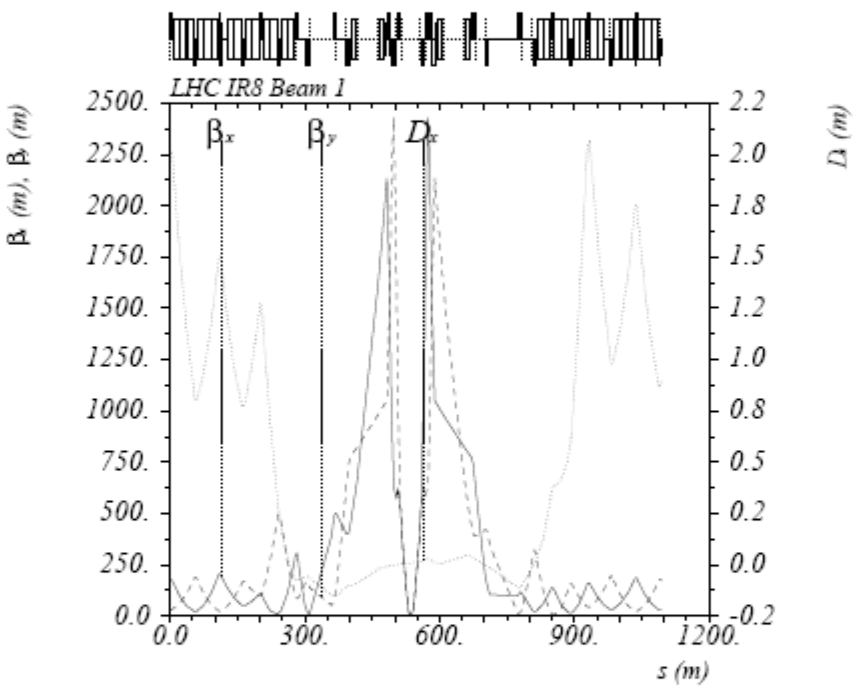




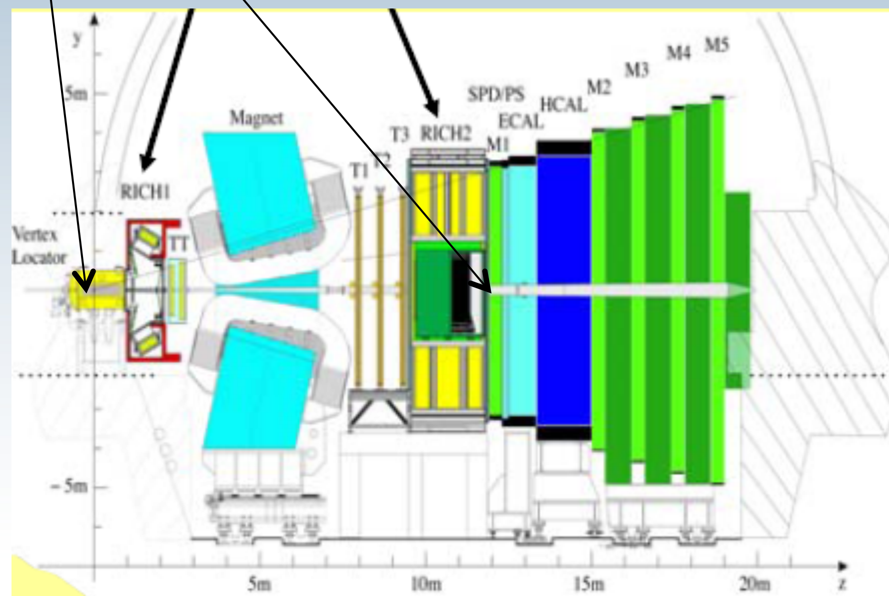
LHCb experiment

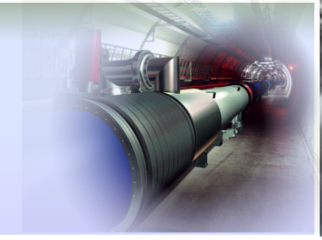
Center of the exp cavern





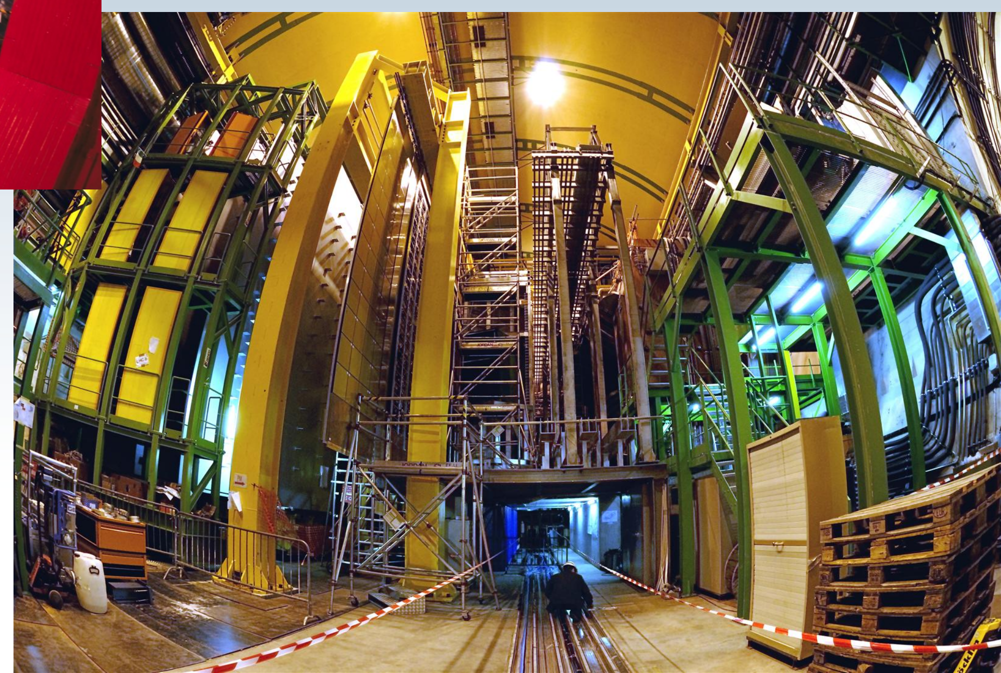
(c) Beam 1, collision optics





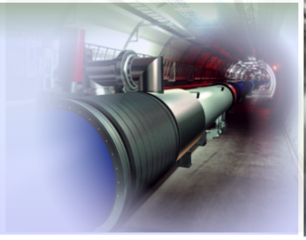
III.III. The experiments: Low luminosity insertions

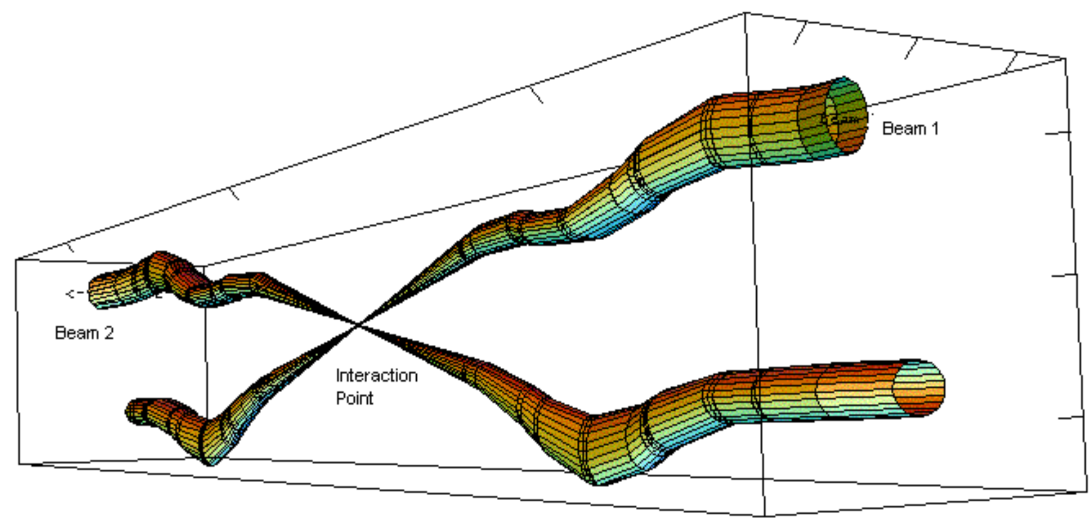
ALICE



LHCb

III.IV. Squeeze



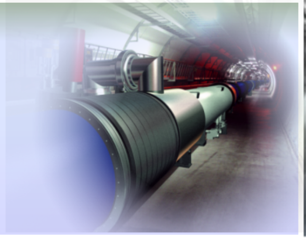


Relative beam sizes around IP1 (Atlas) in collision

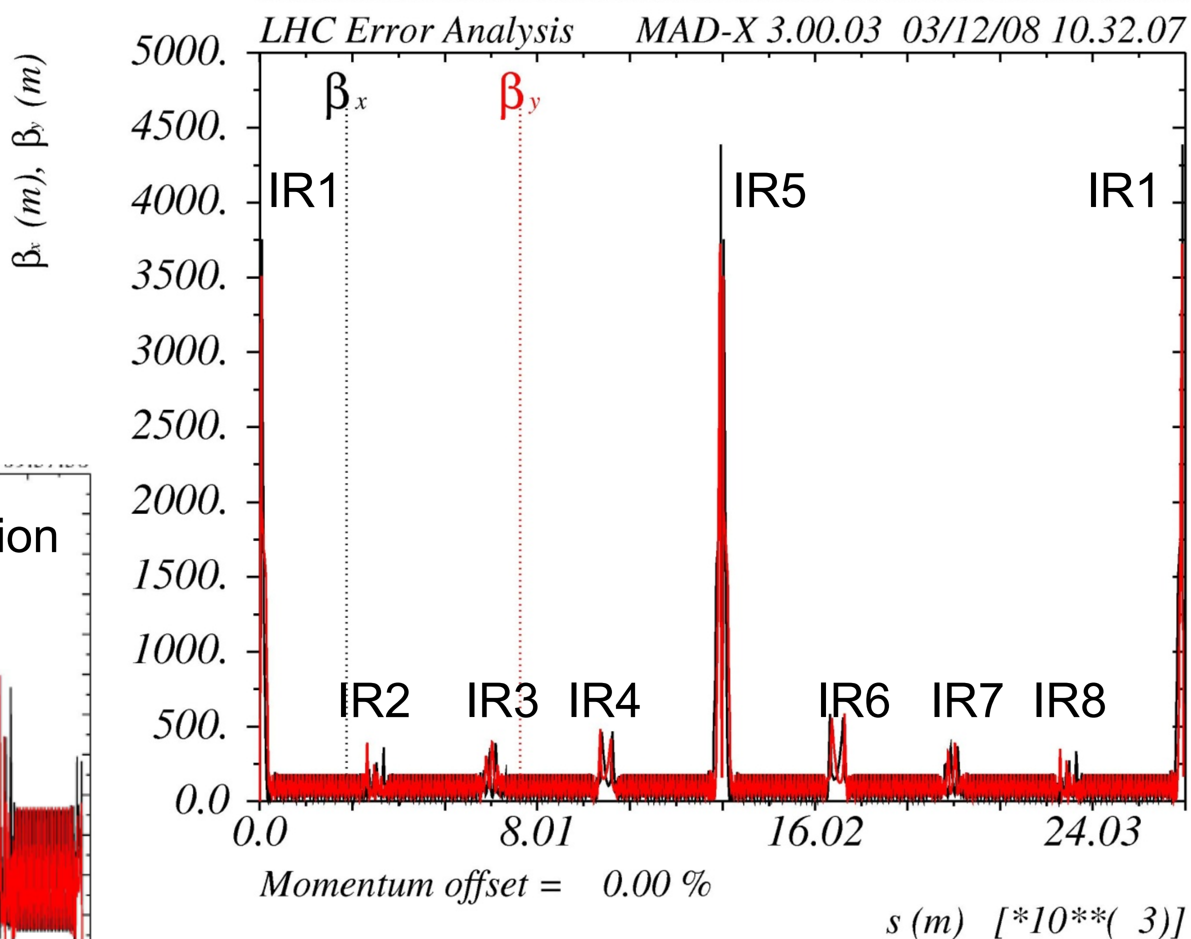
Squeeze the beam size down as much as possible at the collision point to increase the chances of a collision

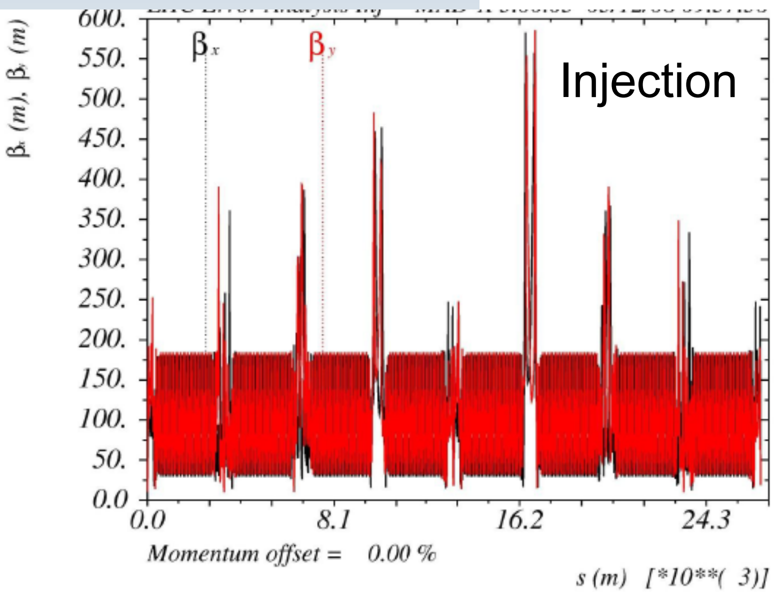
- So even though we squeeze our 100,000 million protons per bunch down to 16 microns (1/5 the width of a human hair) at the interaction point. We get only around 20 collisions per crossing with nominal beam currents.
- The bunches cross (every 25 ns) so often we end up with around 600 million collisions 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

III.IV. Squeeze

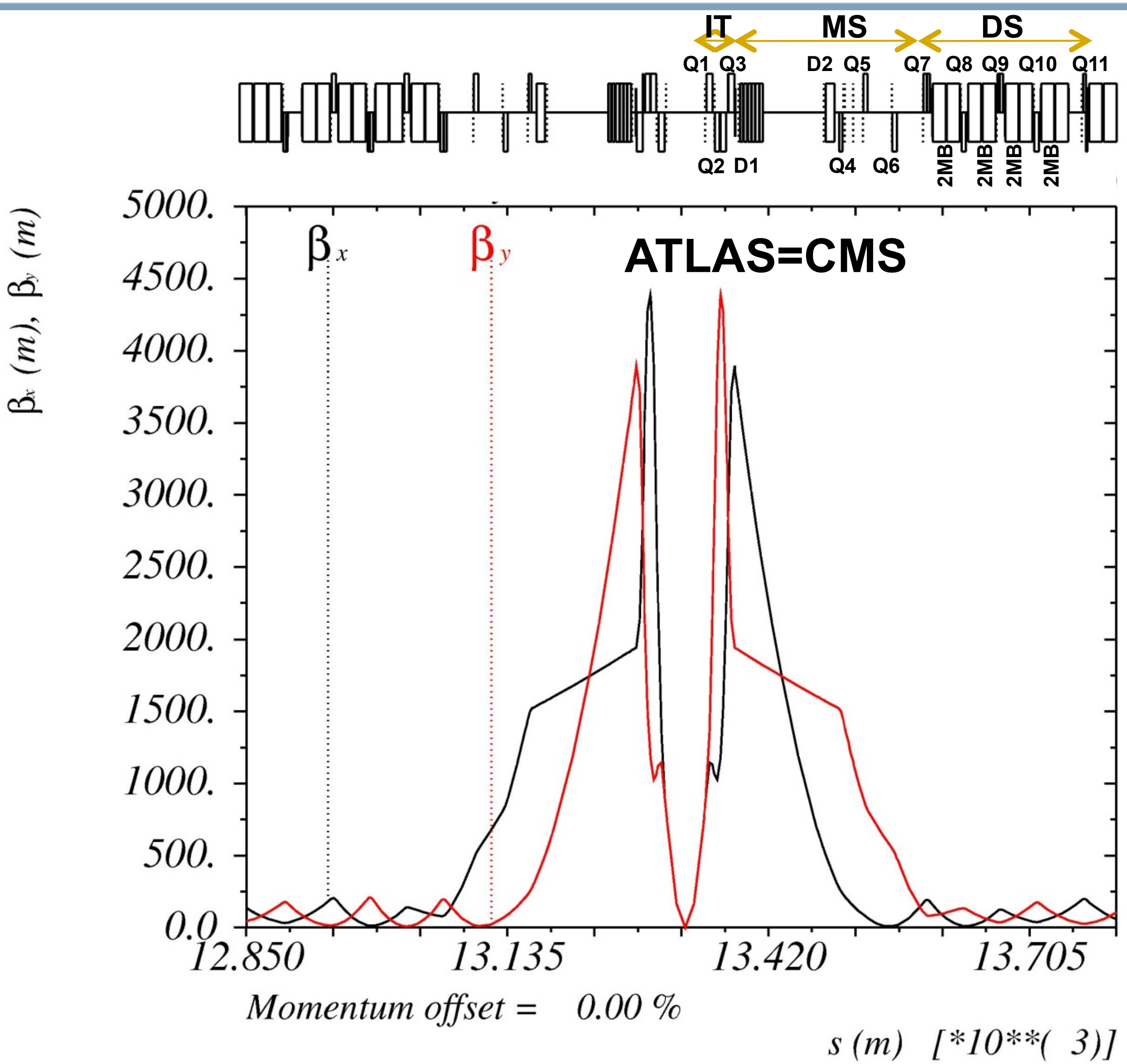


Beta function at top energy and after squeeze

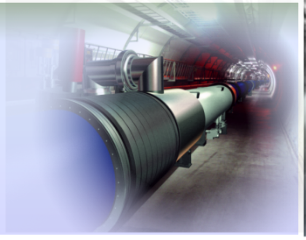


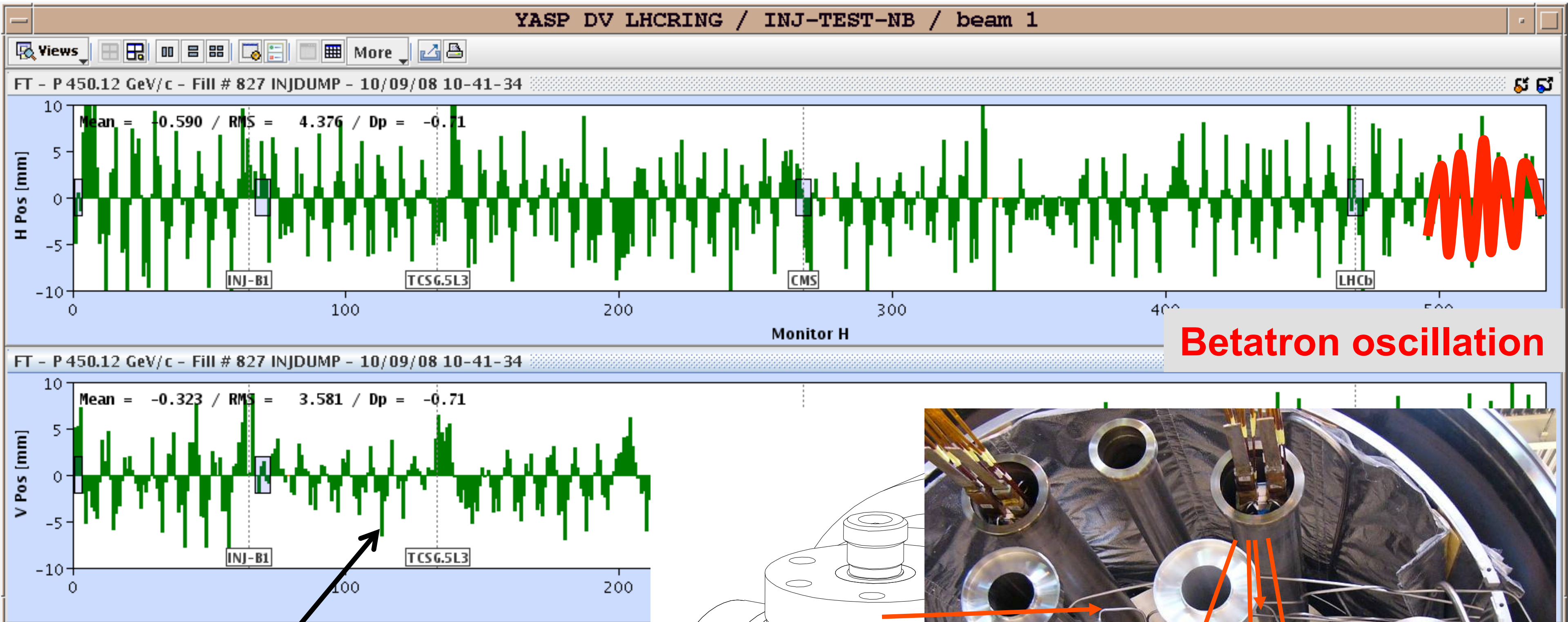


III.IV. Squeeze

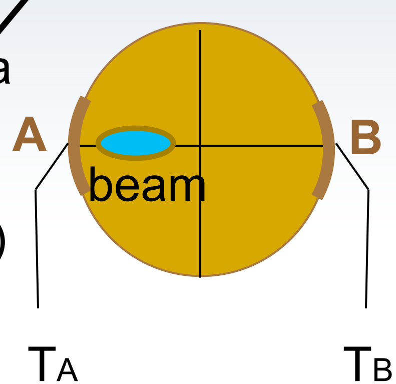


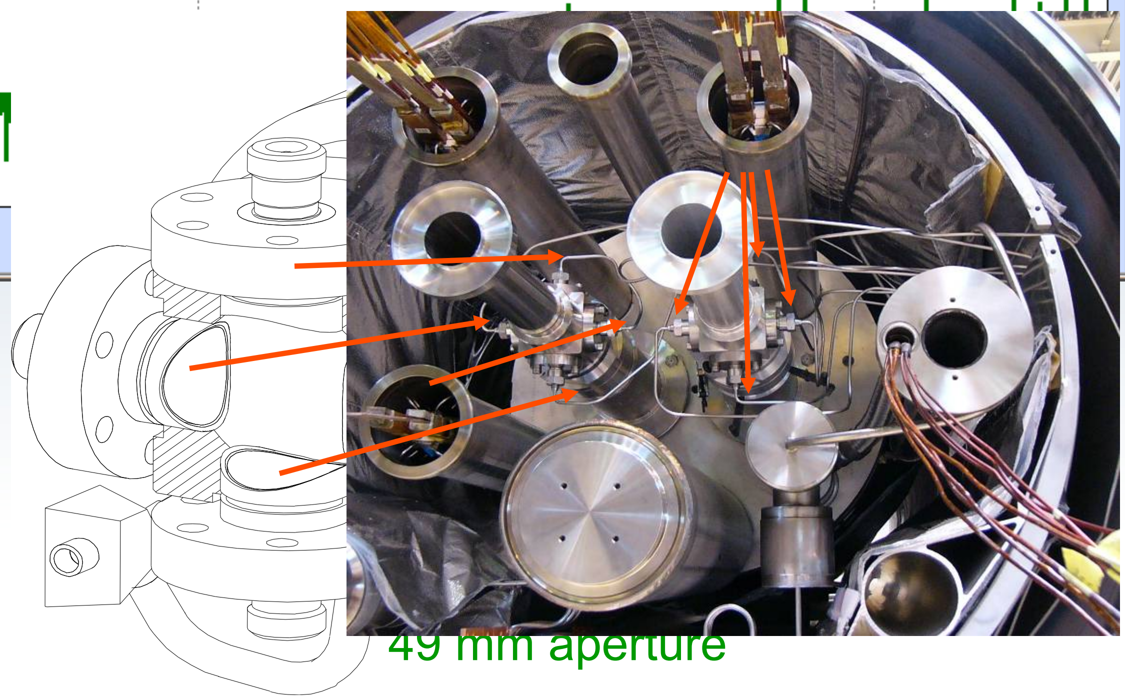
First turn trajectory (Beam 1)





Each point is a BPM (Beam Position Measurement)



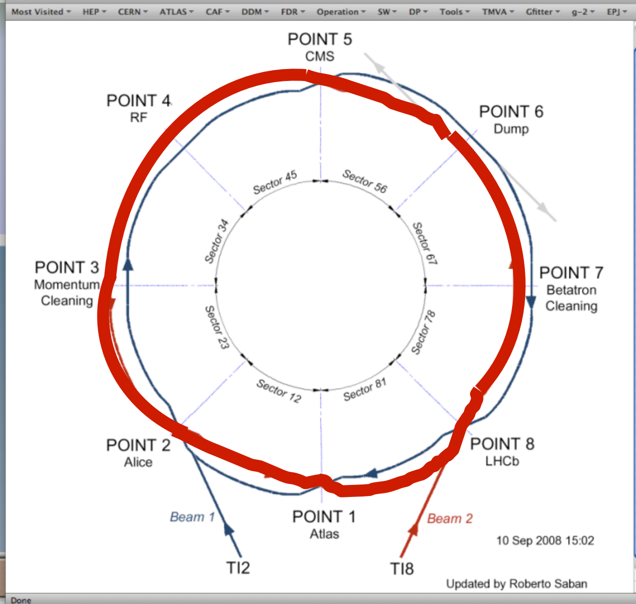


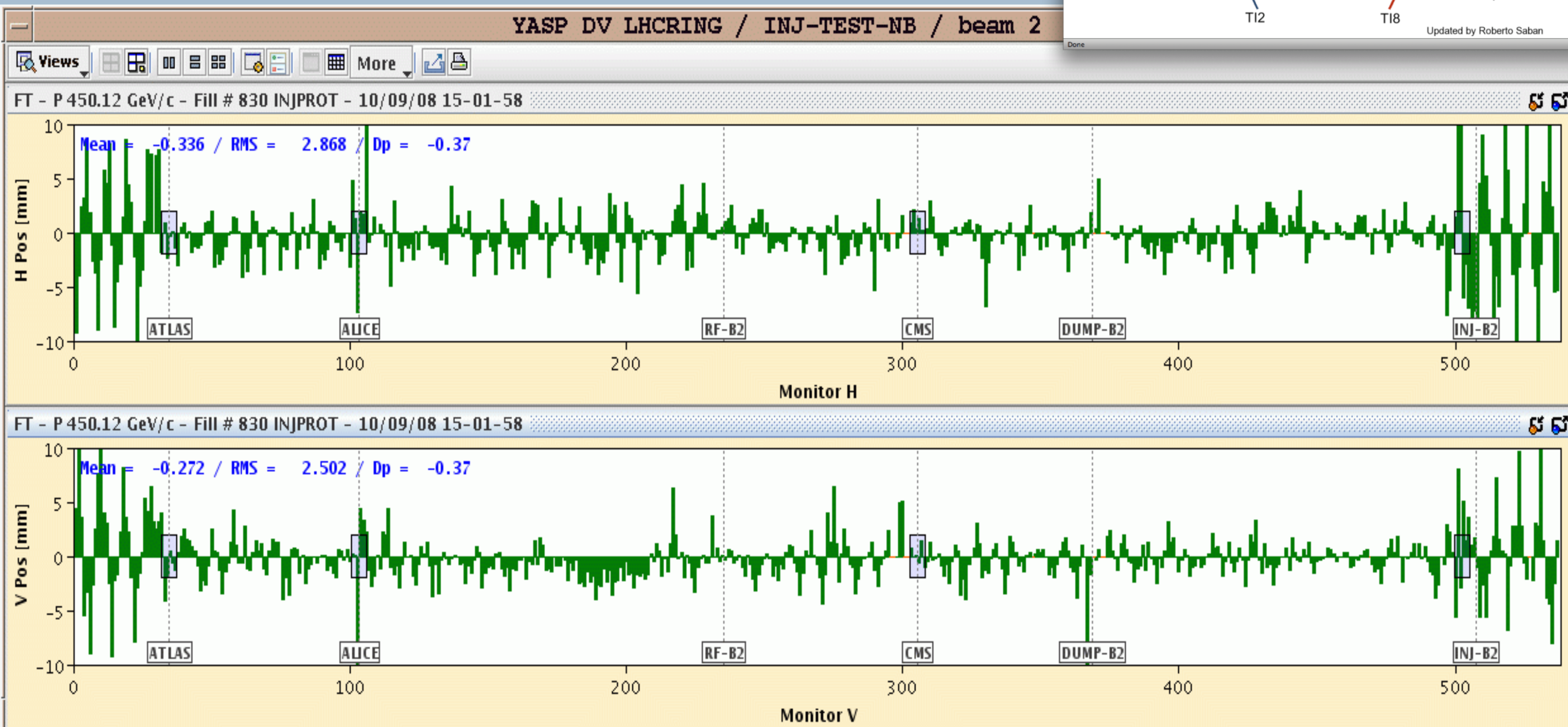
Beam threading (MCBM)

Threading by sector:

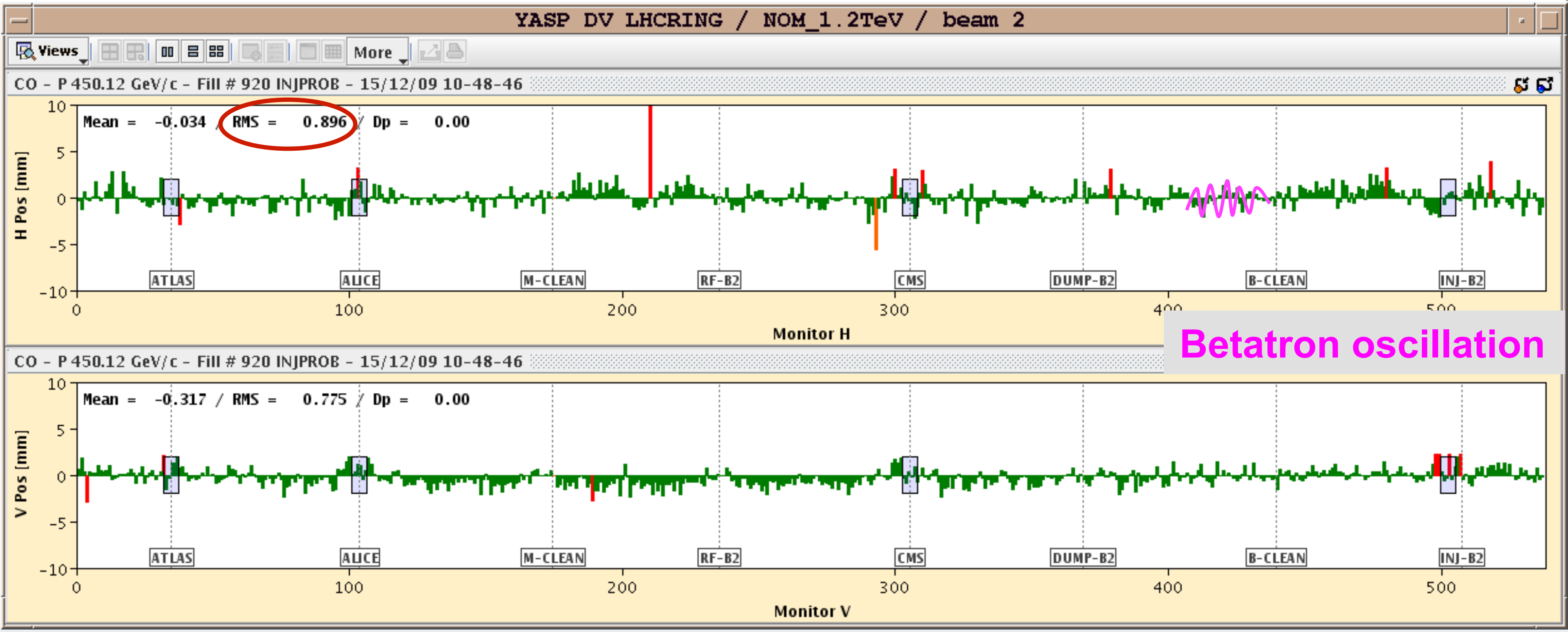
- One beam at the time
- Beam through 1 sector (1/8 ring), correct trajectory, open collimator and move on.

Beam 2 threading

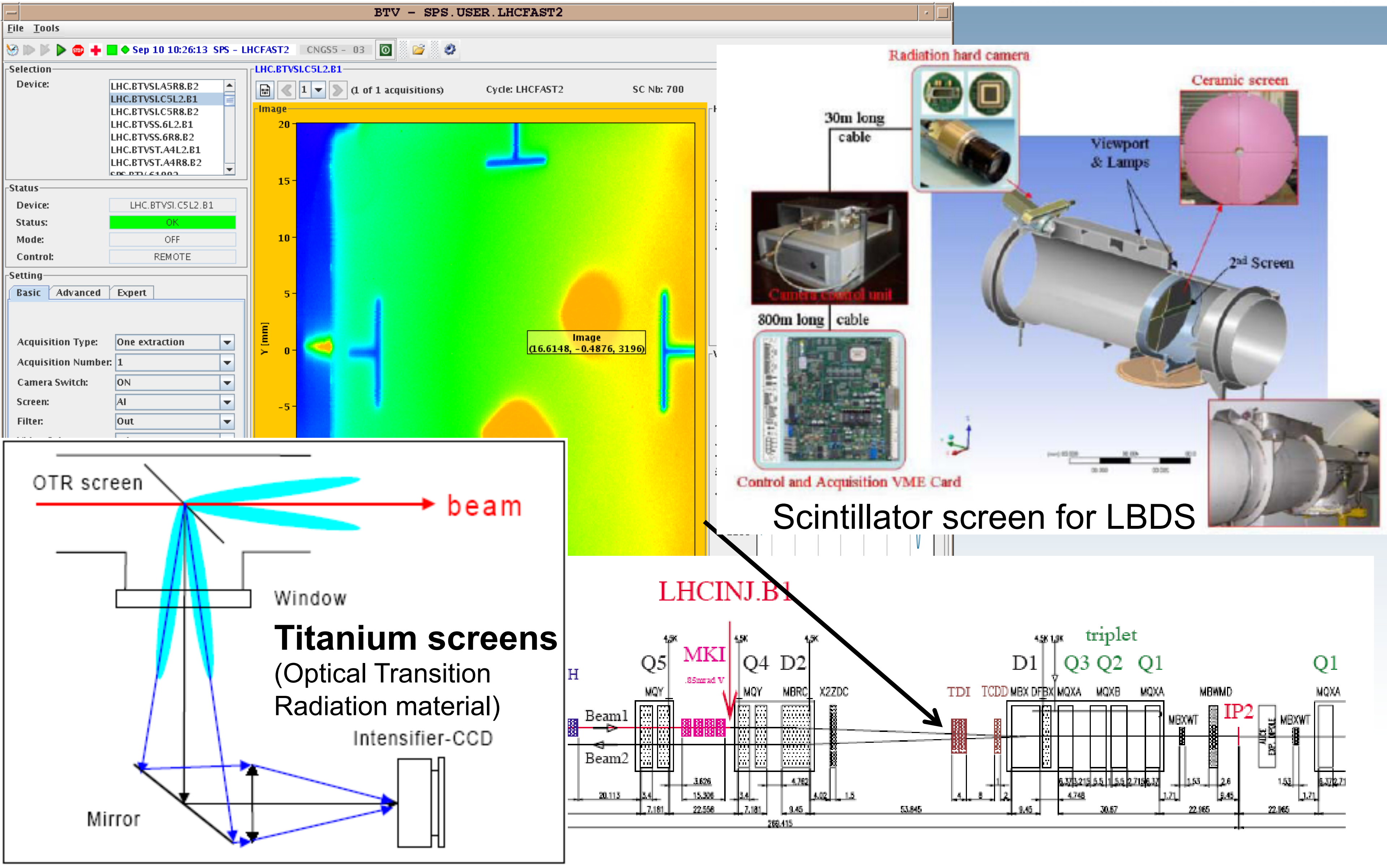




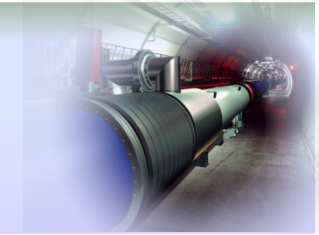
Beam threading (MCBM)

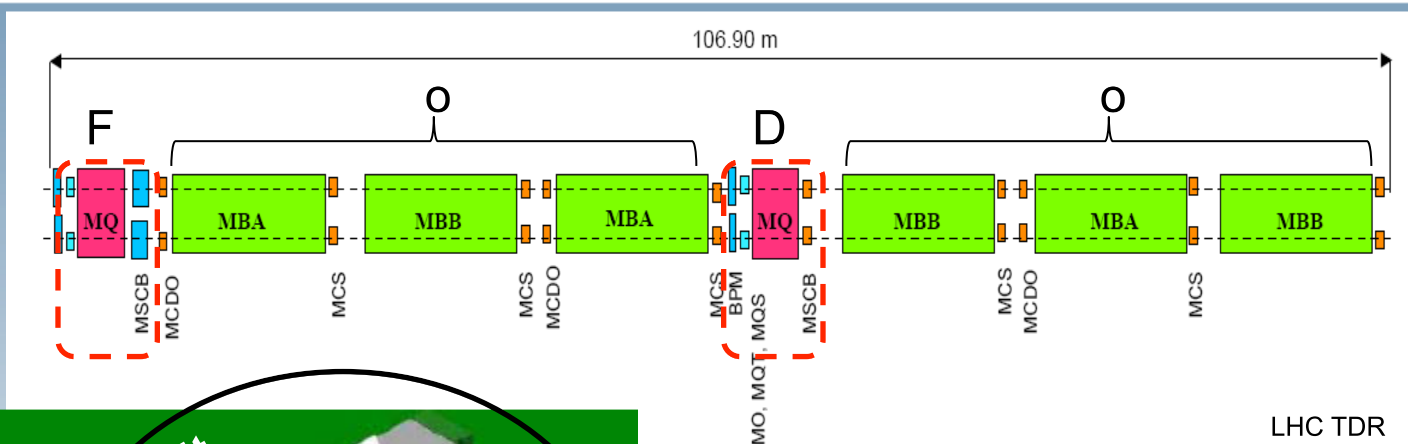


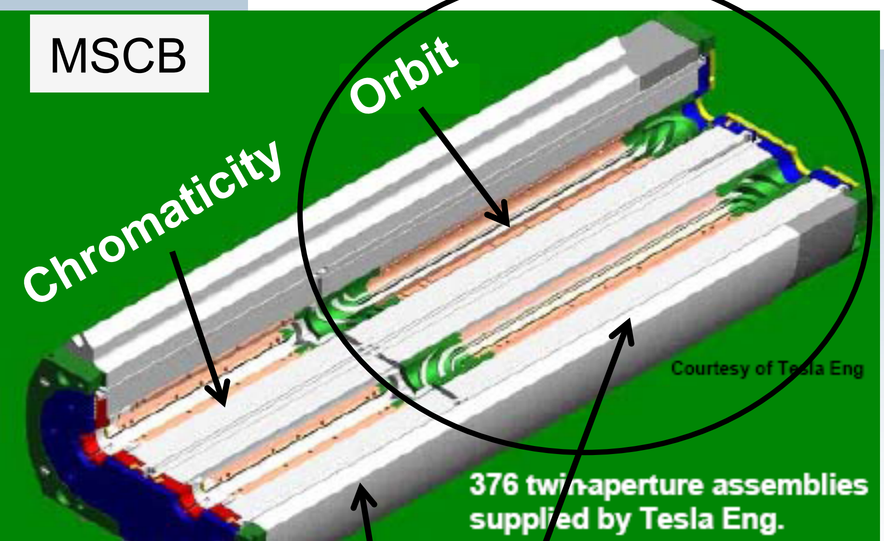
Beam 1 on TDI screen – 1st and 2nd turns



First turn trajectory (cont.)





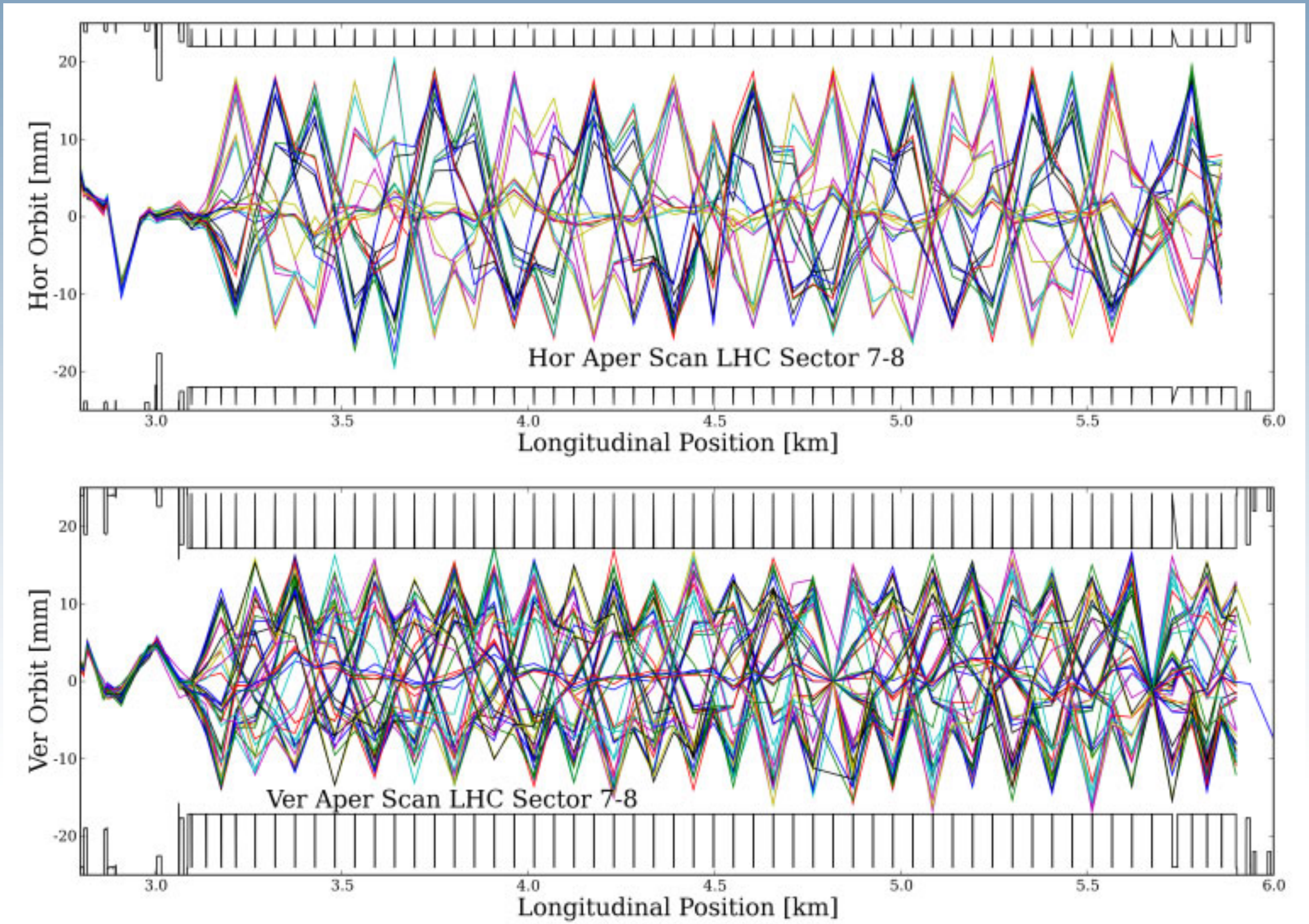


MSM (sextupole):
Nominal main field strength = 4430 T/m^2
$I_{nominal}$ = 550 A, 1.9 K,
L=45.5 cm, ~83 kg

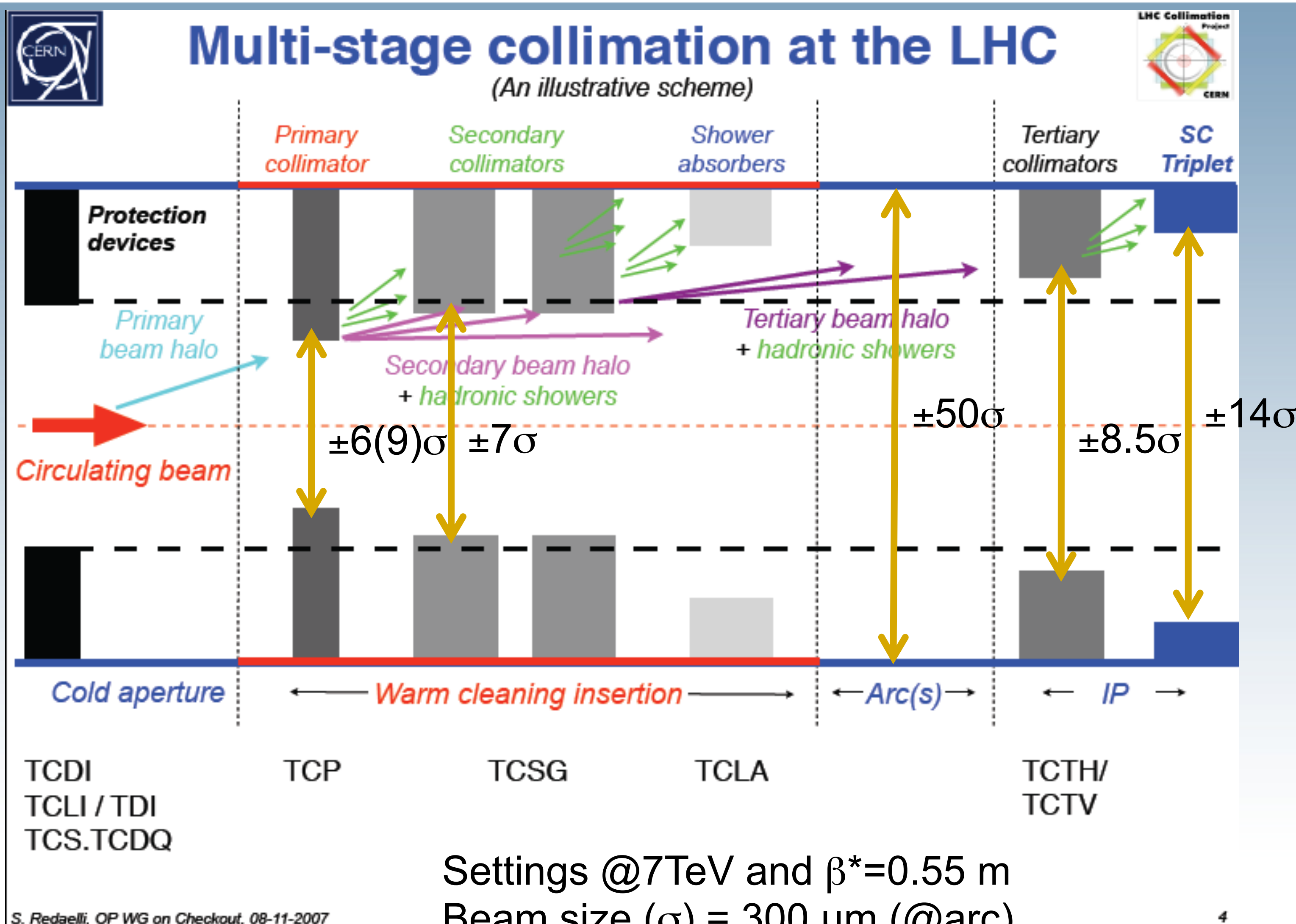
MCBM (dipole):
Nominal main field strength = 2.93 T
$I_{nominal}$ = 55 A, 1.9 K,
L=78.5 cm, ~143 kg

Explore a range of particle angles (=kick strength) with one corrector dipole, then go to the next one

Aperture scan



III.II Momentum and betatron cleaning insertions (IR3, IR7)

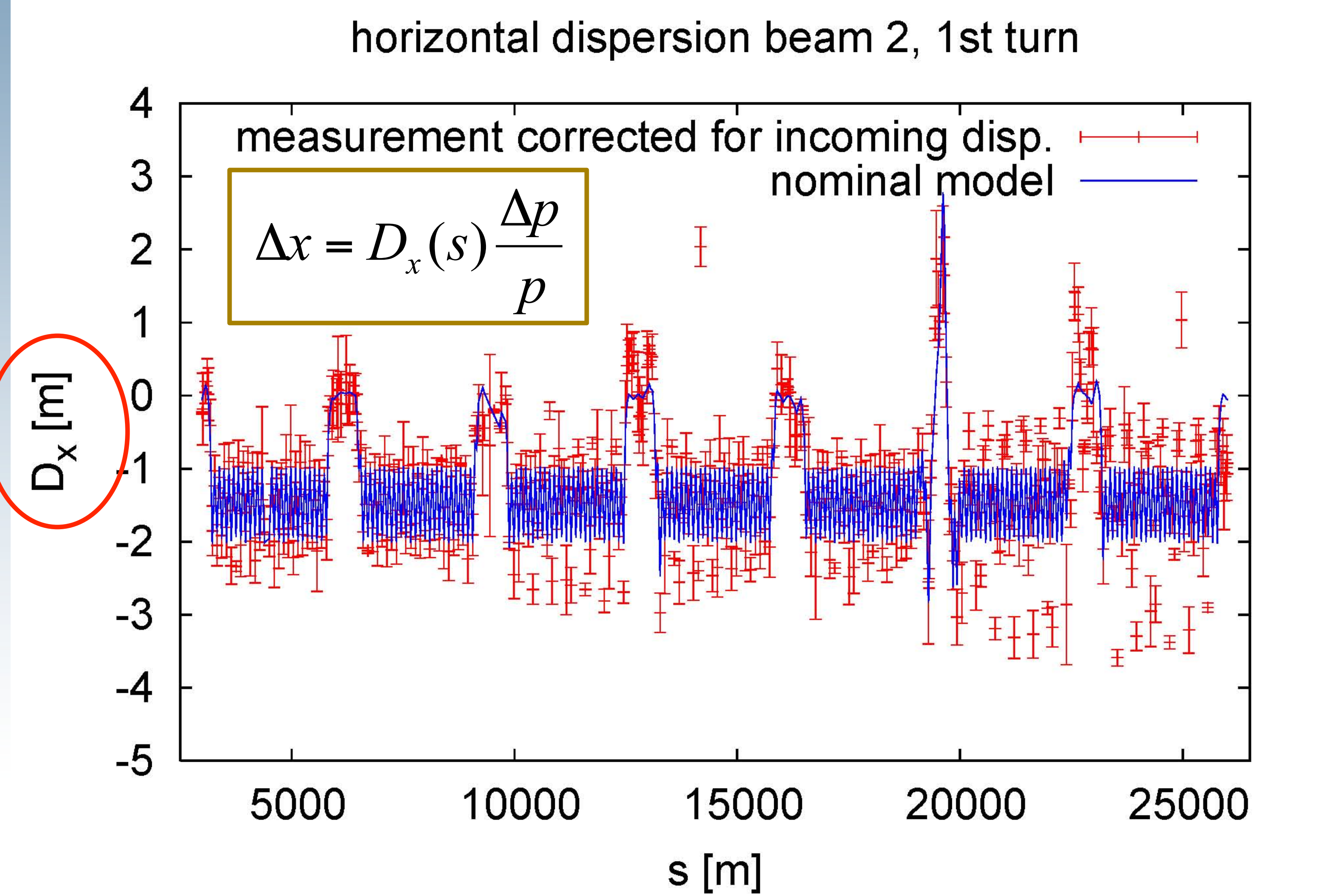


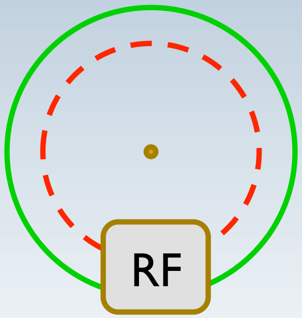
Settings @7TeV and β^*=0.55 m

Beam size (σ) = 300 μm (@arc)

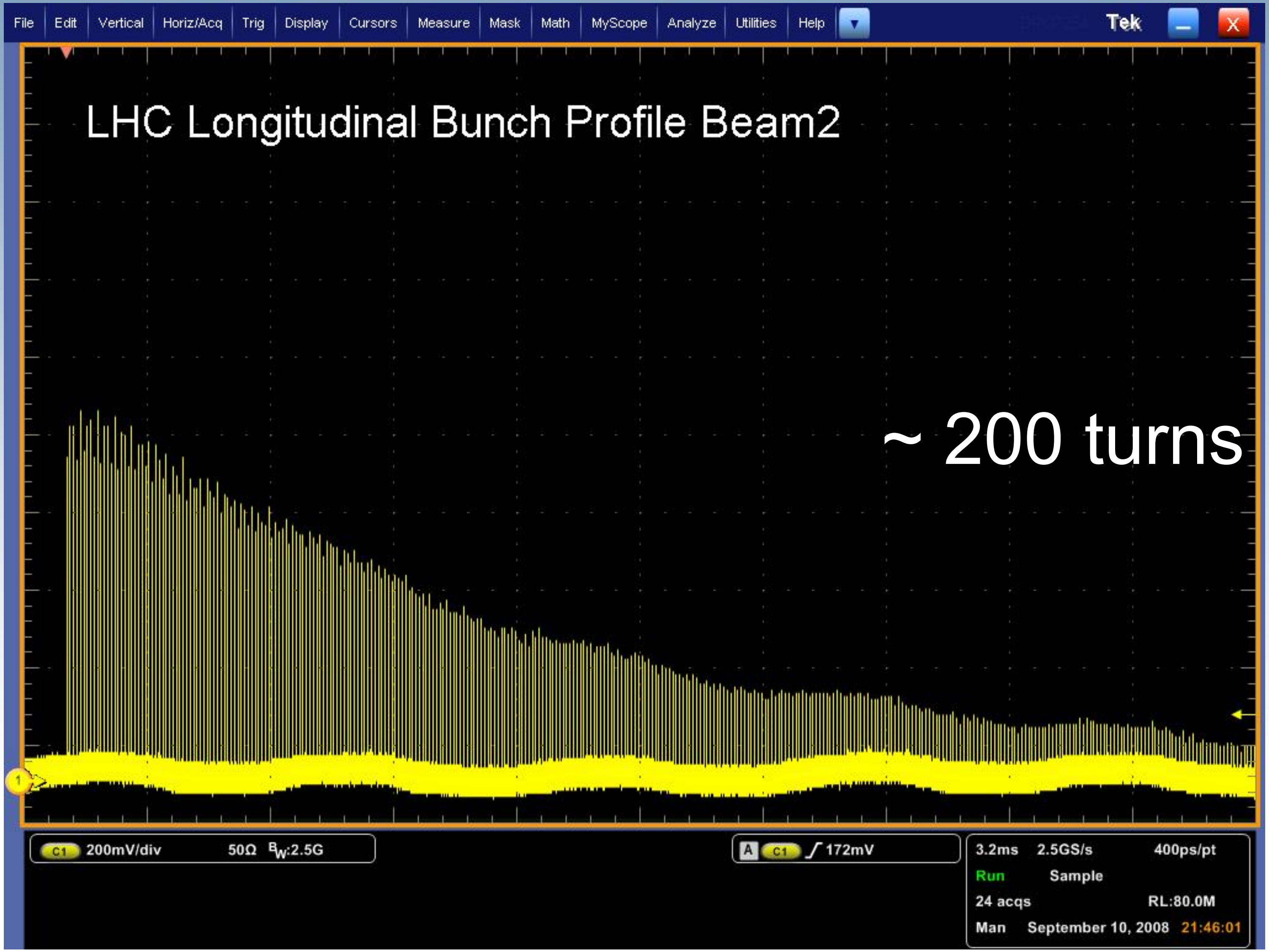
Beam size (σ) = 17 μm (@IR1, IR5)

Dispersion measurement (Beam 2 – first turn)

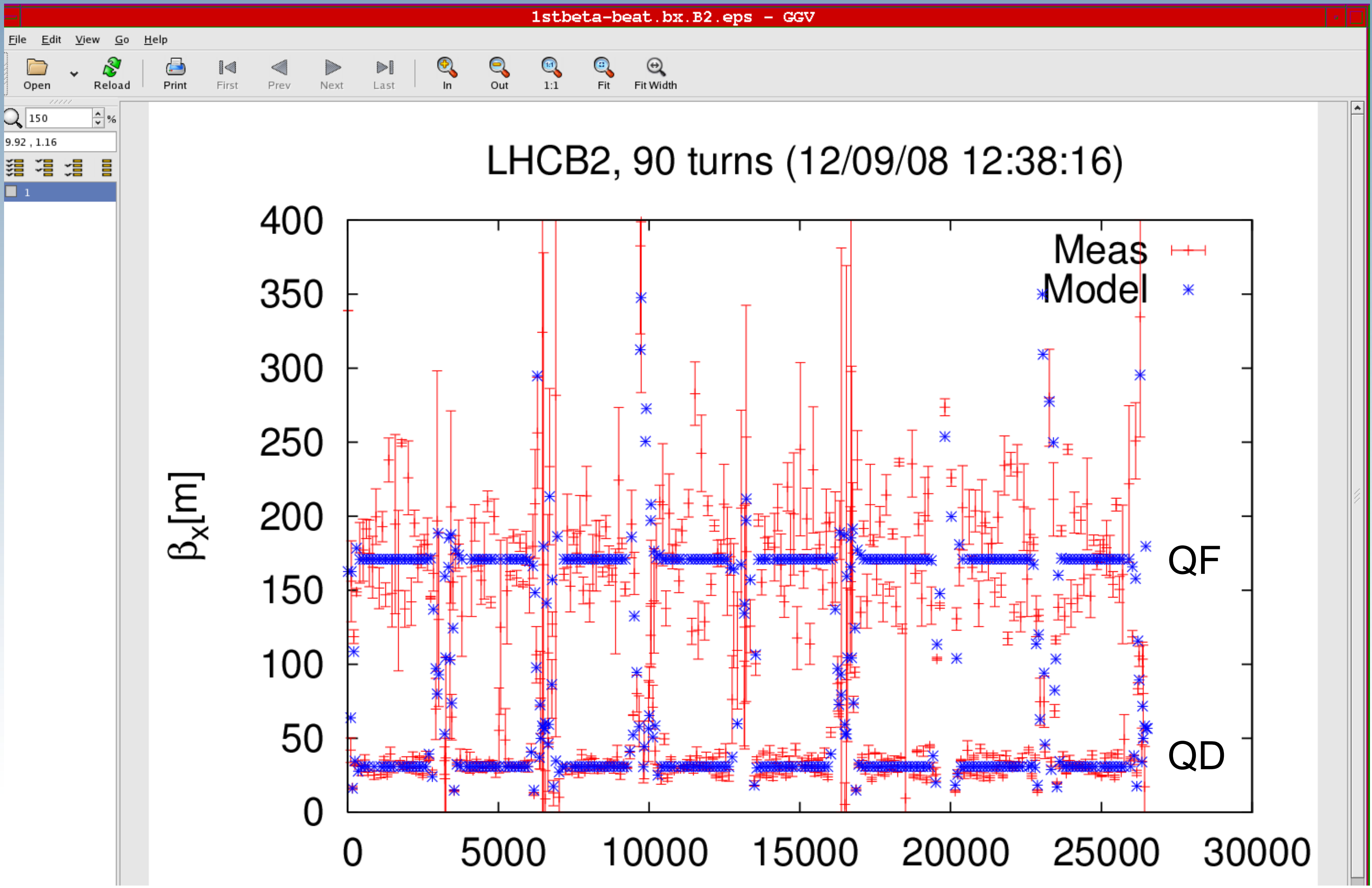




Longitudinal Bunch Profile (Beam 2)

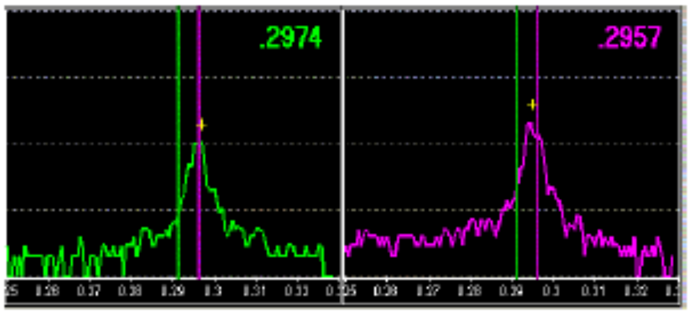


Beta measurement (Beam 2)



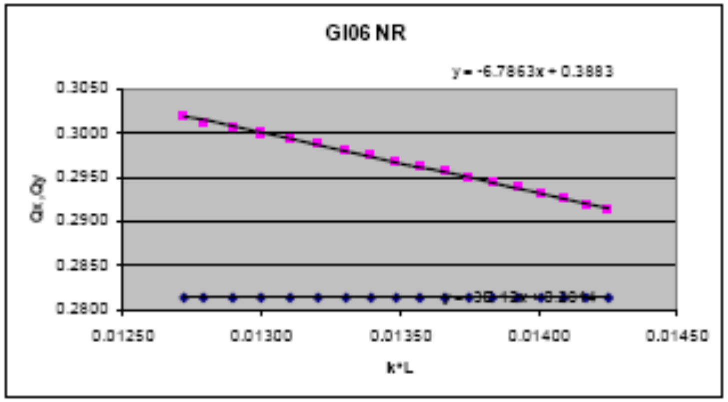
Beta measurement (Beam 2) (cont.)

a quadrupol error leads to a shift of the tune:



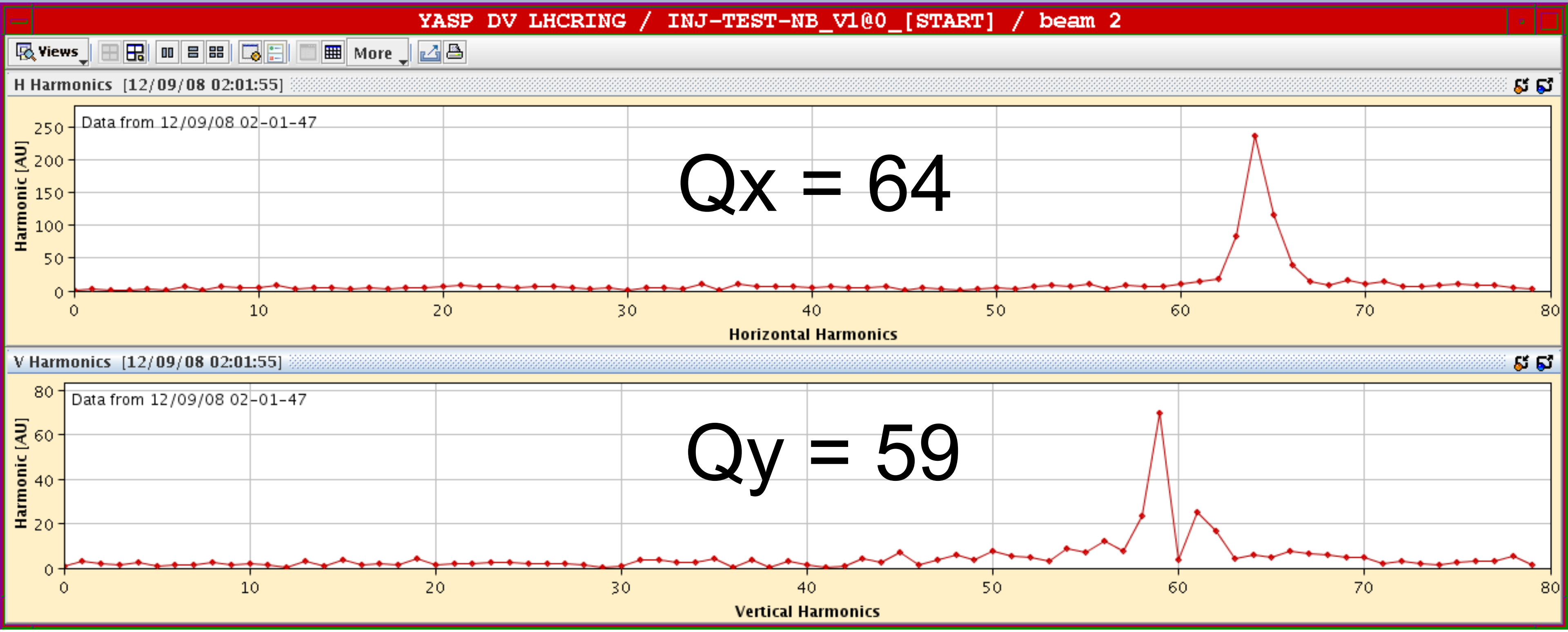
$$\Delta Q = \int_{s0}^{s0+l} \frac{\Delta k \beta(s)}{4\pi} ds \approx \frac{\Delta k l_{quad} \overline{\beta}}{4\pi}$$

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

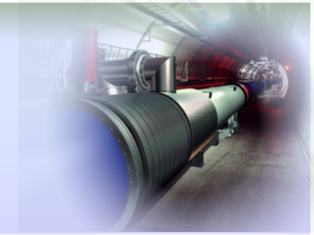


Reminder from BH lectures

Integer tunes (Beam 2)



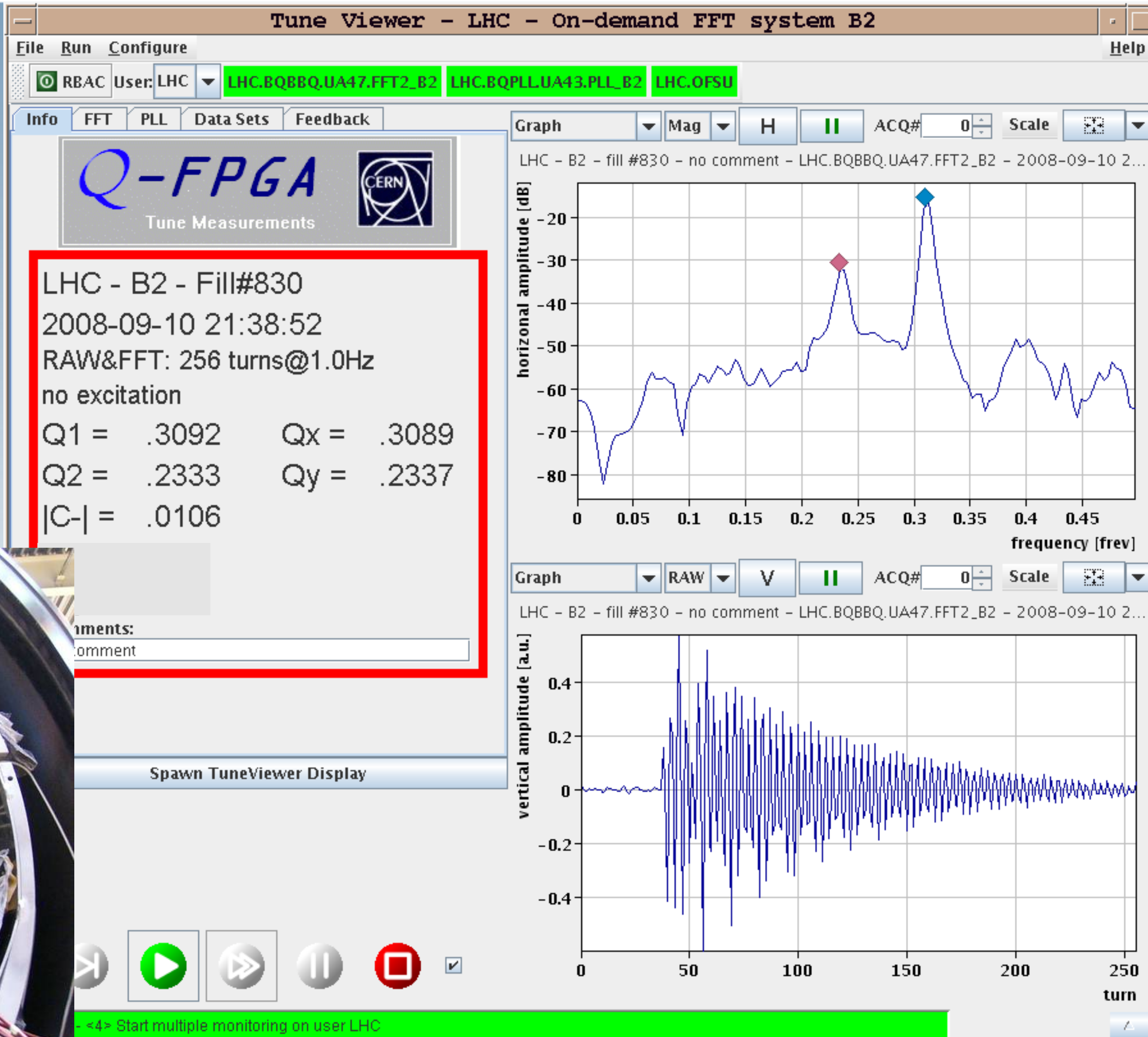
Non-integer tunes (Beam 2)

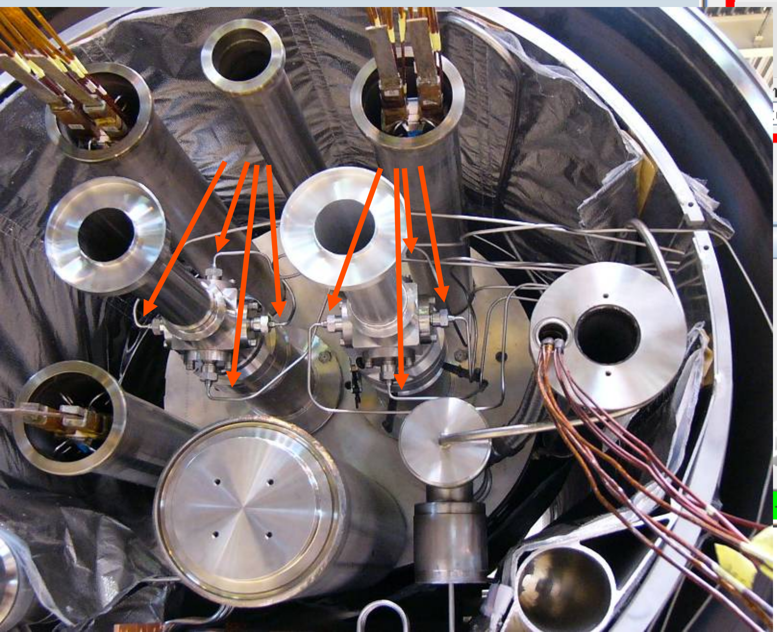


Qx = .279

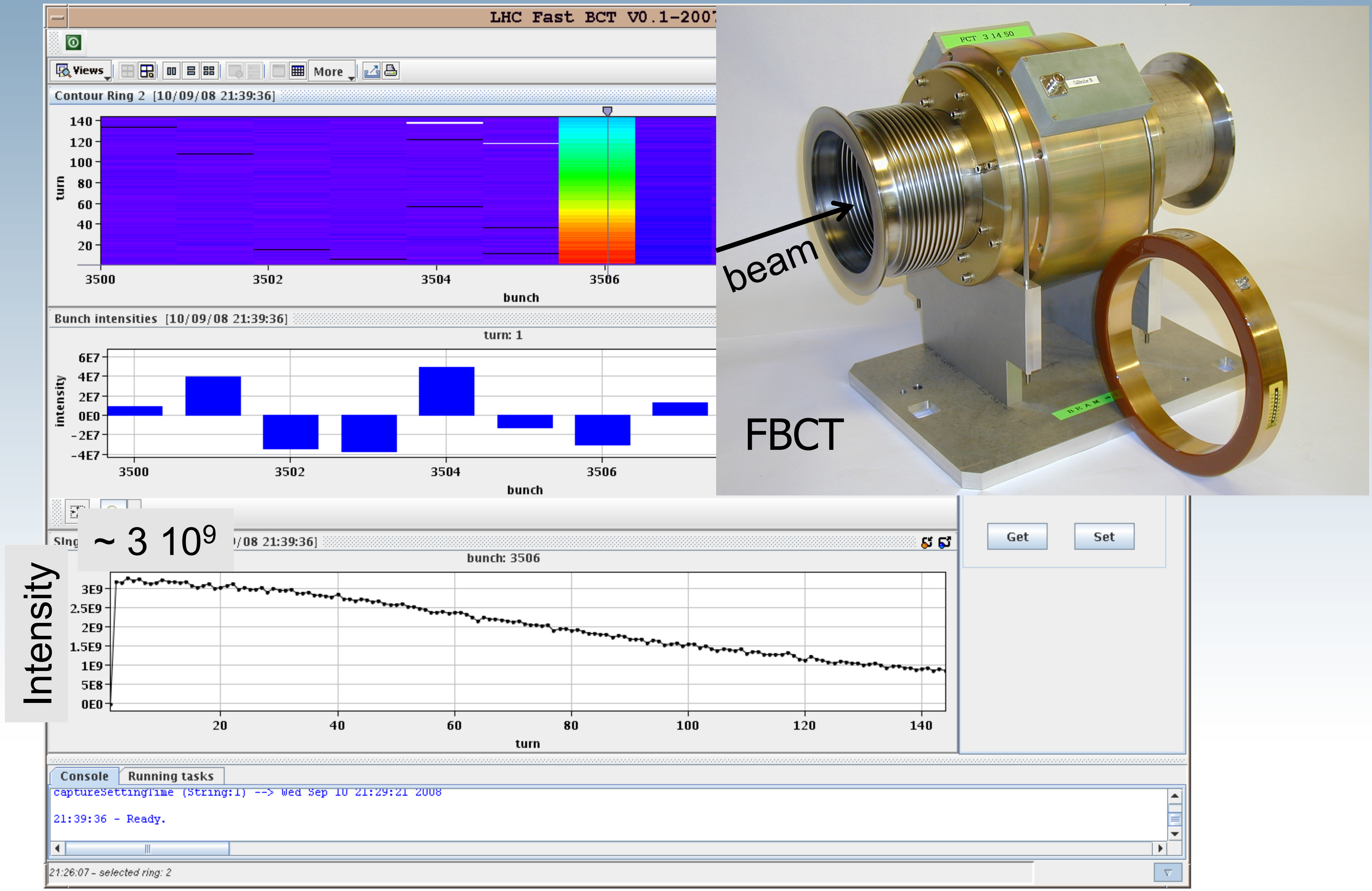
Qy = .310

BPM pos → FFT → tune

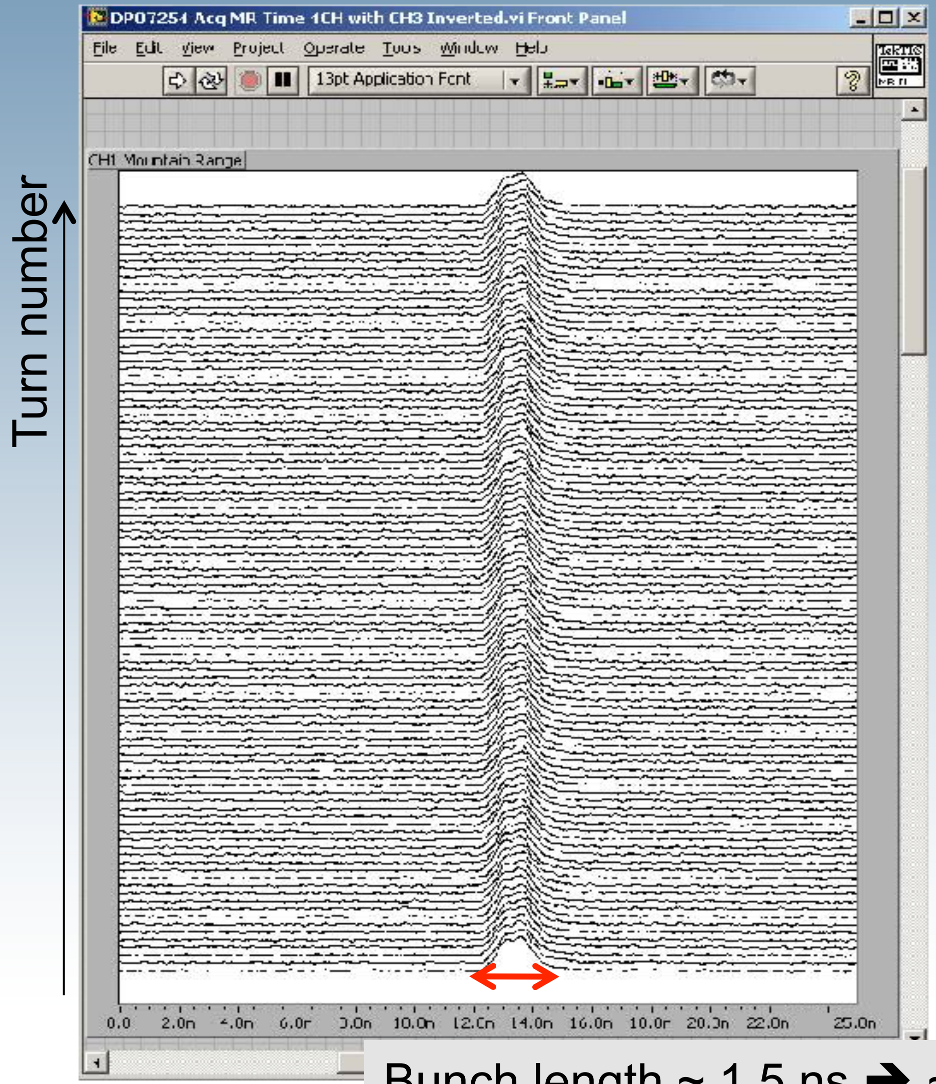




Beam 2 fast BCT (Beam Current Transformer)



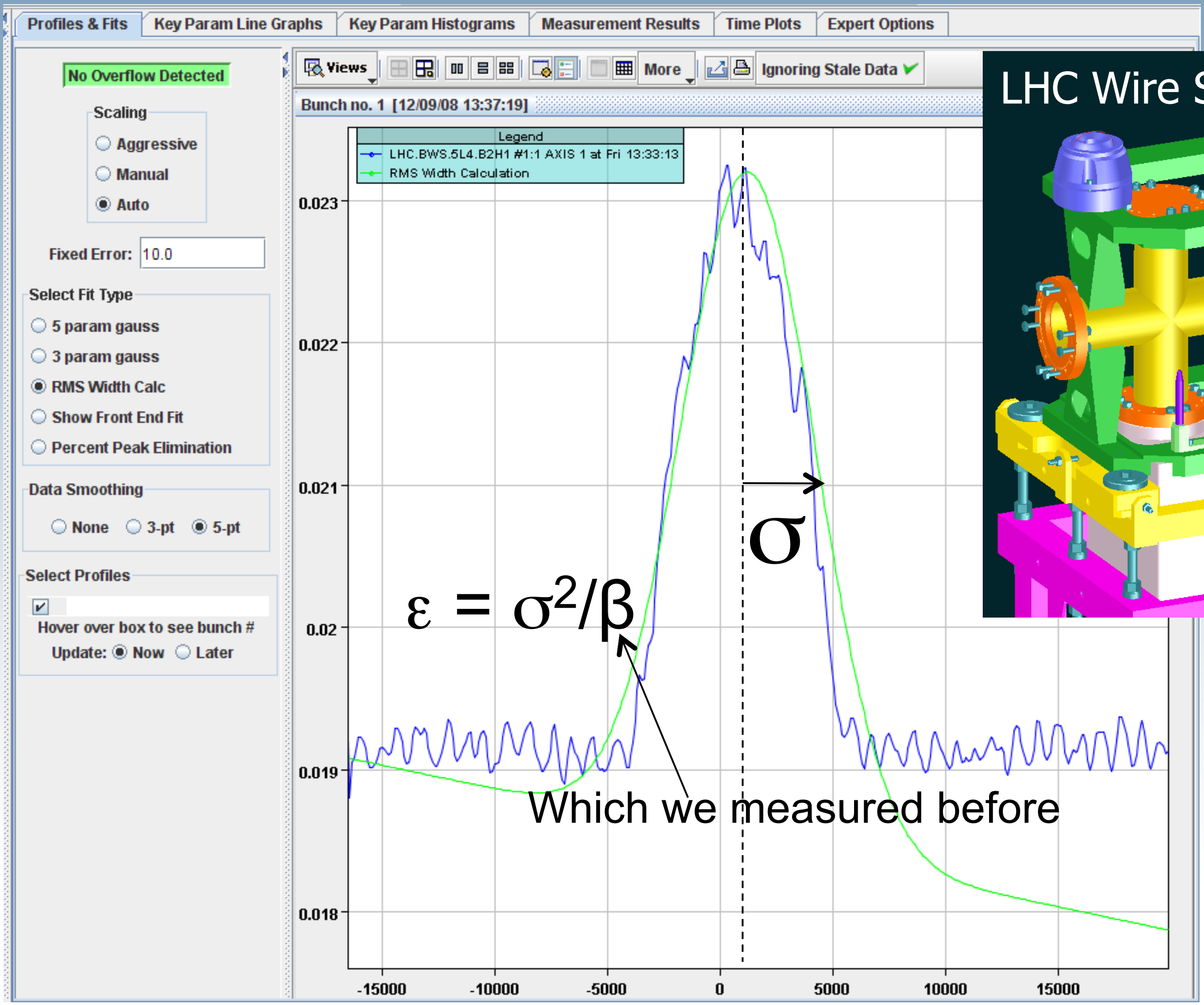
Beam 2 captured – mountain range display

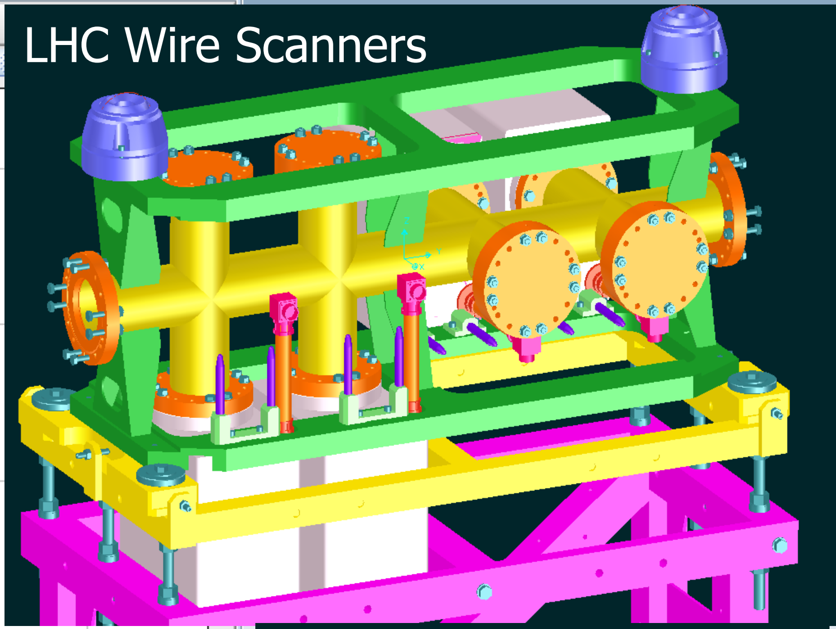


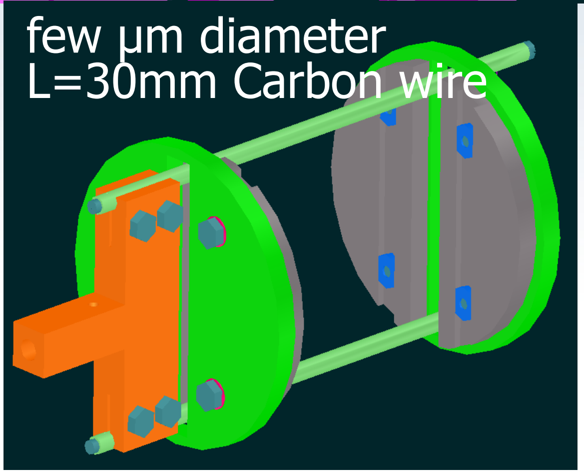
Bunch length ~ 1.5 ns → ~ 45 cm

Now RF ON

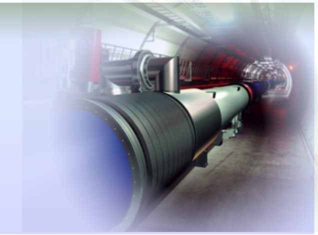
Emittance measurement (Wire scanner)

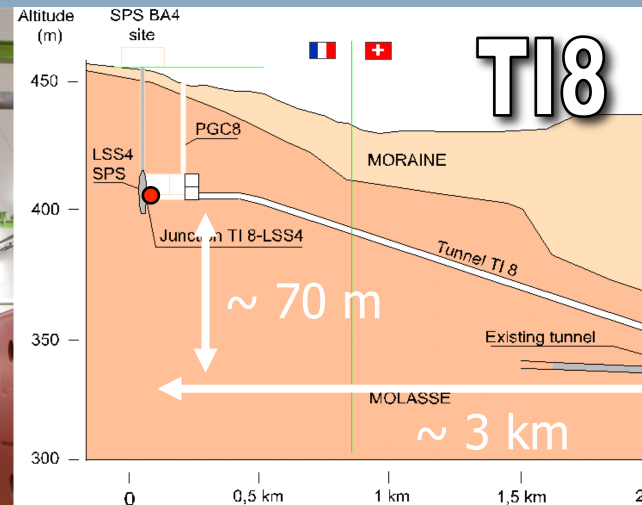


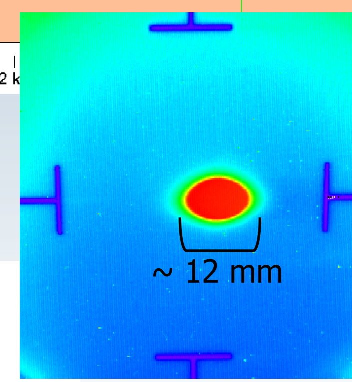


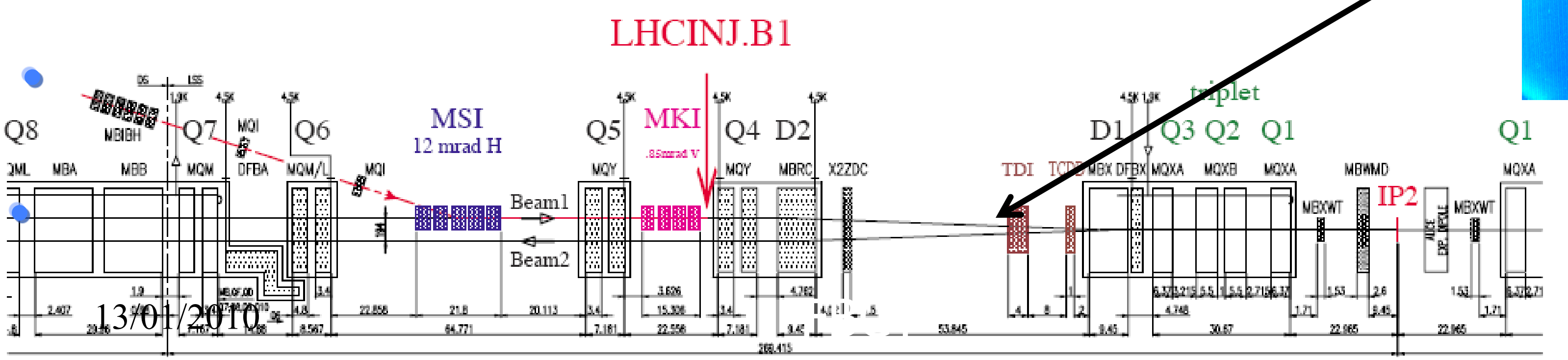


II. II. Injection mechanism: injection into LHC

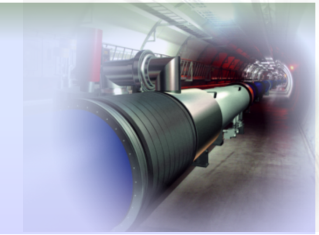








How the injection affects the beam parameters



- SPS to LHC transfer line TI 8 – beta functions

Twis parameters at start and end of the transfer line are fixed

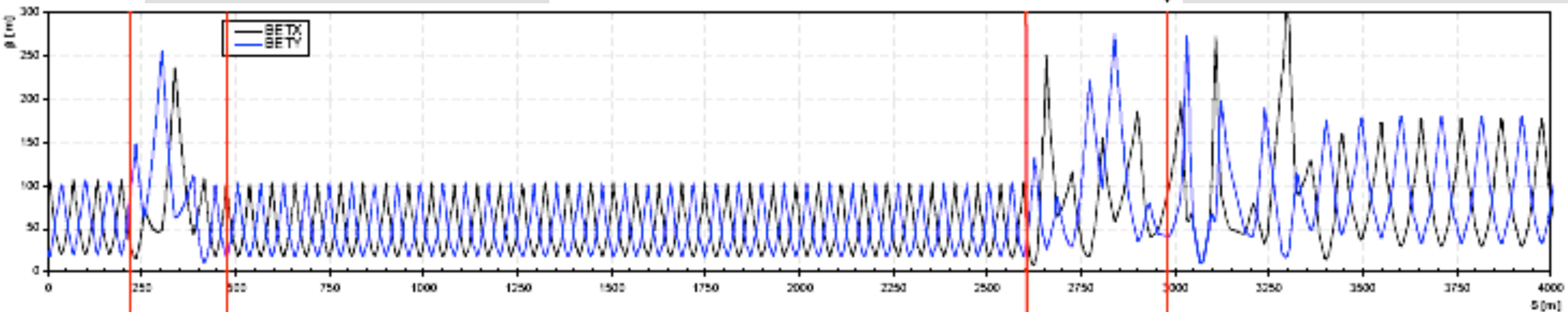
Extraction

$(\alpha_x,\beta_x,\alpha_y,\beta_y,D,D')^{ext}$

Injection

$(\alpha_x,\beta_x,\alpha_y,\beta_y,D,D')^{inj}$

β(m)



SPS ← **Transfer Line** → **LHC**

$(\alpha_x(s),\beta_x(s),\alpha_y(s),\beta_y(s),D(s),D'(s))^{trans}$

Regular FODO lattice

Initial matching section

Final matching section

II. II. Injection mechanism:

How the injection affects the beam parameters

Filamentation

Injection errors (position or angle) dilute the beam emittance

Non-linear effects (e.g. magnetic field multipoles) introduce distort the harmonic oscillation and lead to ampl dependent effects into parti

Over many tu oscillation is t increase.

verse space