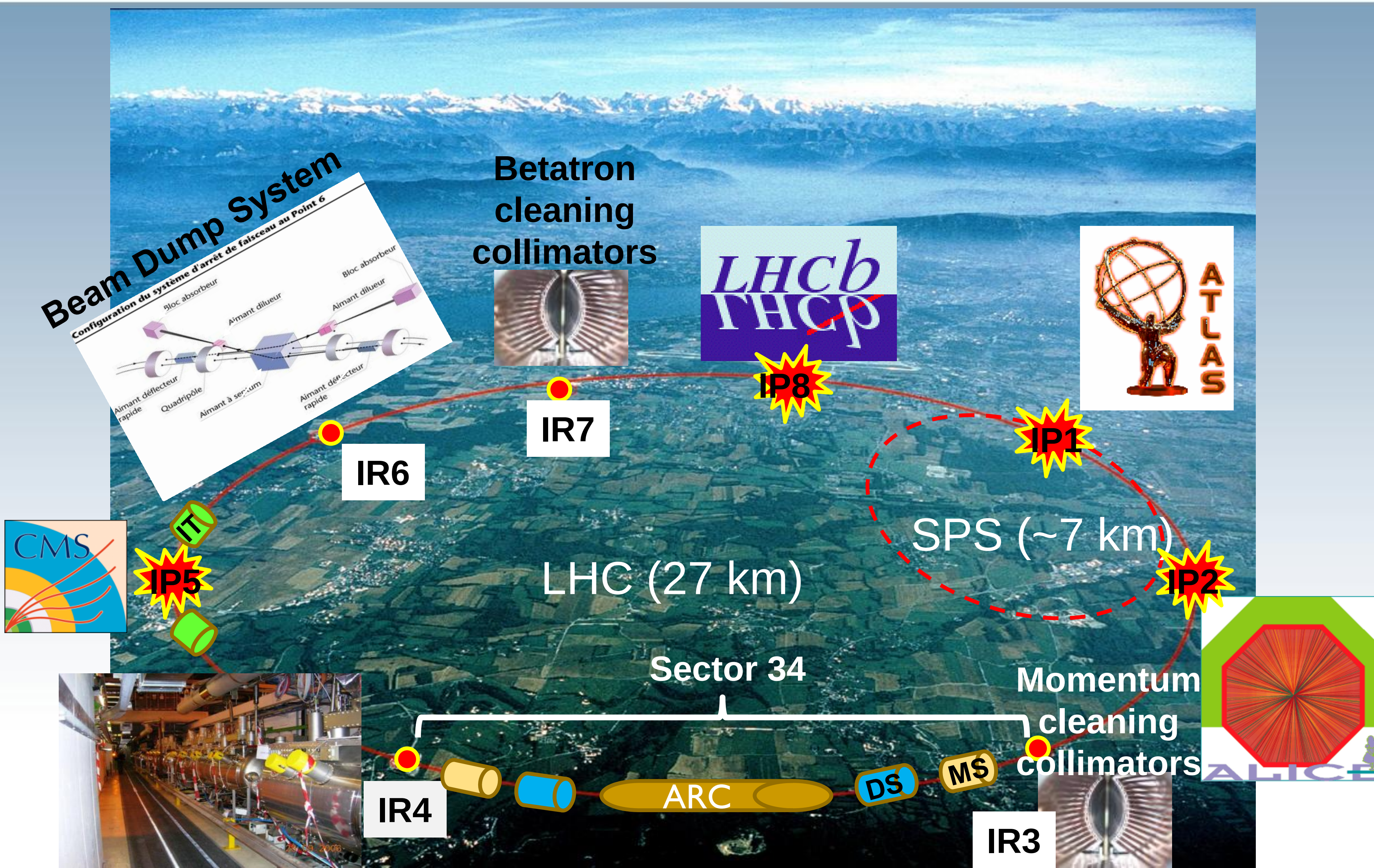
[R. Alemany]
[CERN BE/OP]
[Engineer In Charge of LHC]
Lectures JUAS (18.01.2013)

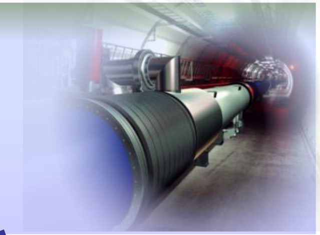
The Large Hadron Collider

LHC layout
Beam measurements
LHC performance in 2012
pPb run 2013

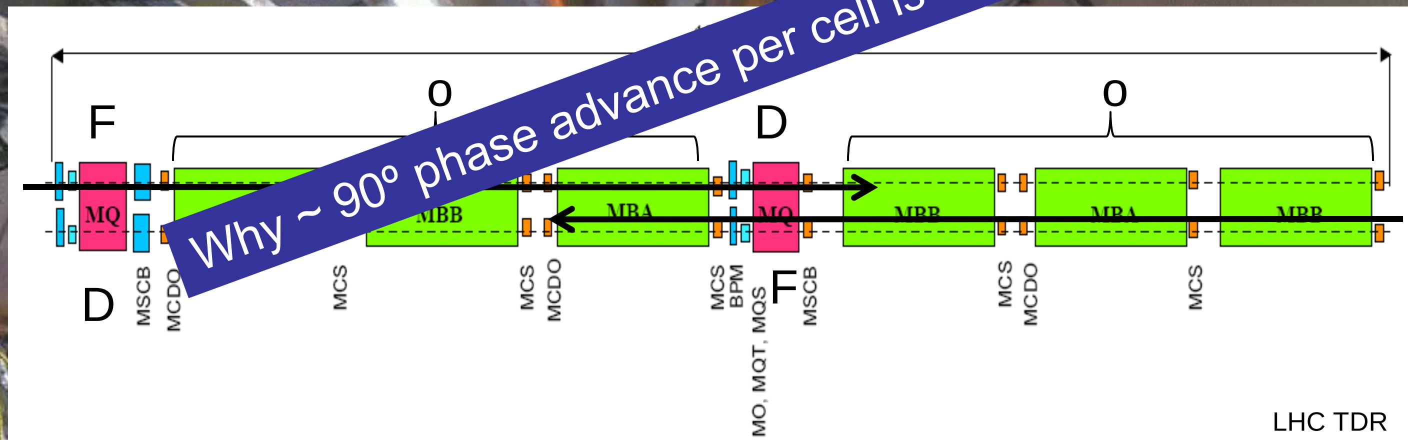
I. Basic layout of the machine



I. Basic layout of the machine: the arc



LHC arc cells = FoDo lattice* with
~ 90º phase advance per cell in th… plane

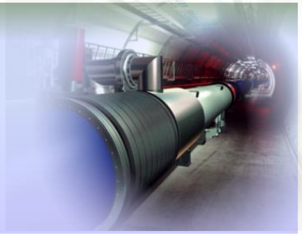


MB: main dipole
MQ: main quadrupole
MQT: Trim quadrupole
MQS: Skew trim quadrupole
MO: Lattice octupole (Landau damping)
MSCB: Skew sextupole + Orbit corrector (lattice chroma+orbit)
MCS: Spool piece sextupole
MCDO: Spool piece octupole + Decapole
BPM: Beam position monitor

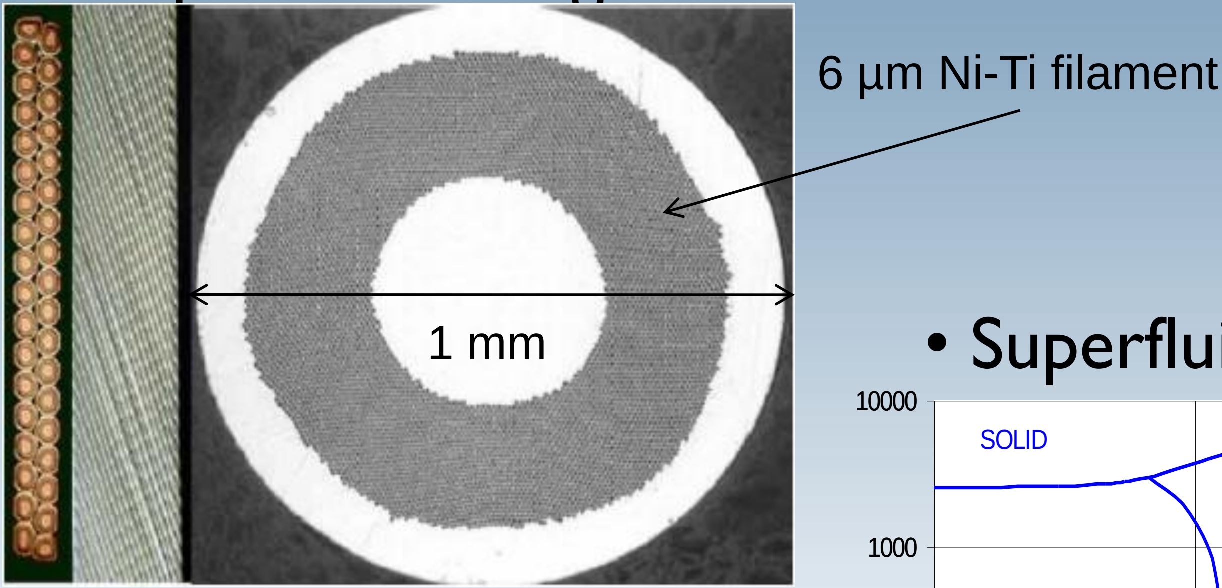
The FoDo-Lattice

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: Superconducting magnets

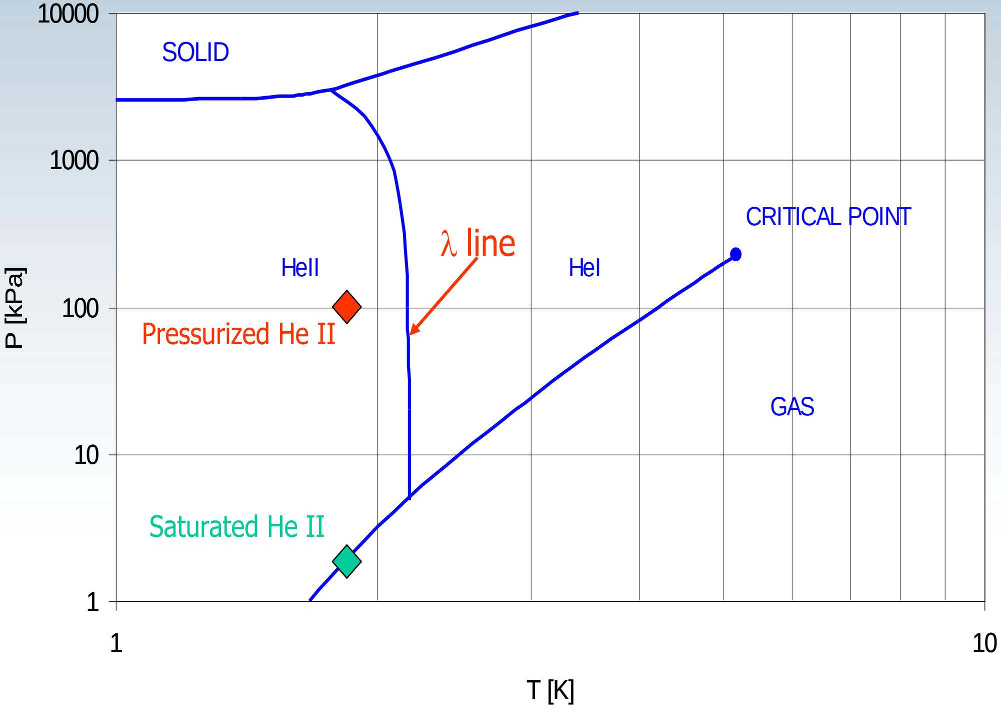


- Superconducting cables of Nb-Ti

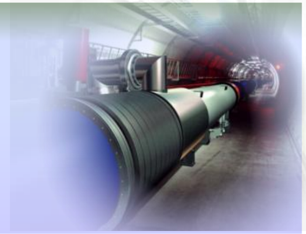


LHC ~ 27 km circumf. with 20 km of superconducting magnets operating @8.3 T. An equivalent machine with normal conducting magnets would have a circumference of 100 km and would consume 1000 MW of power ➔ we would need a dedicated nuclear power station for such a machine. LHC consumes ~ 10% nuclear power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

- Superfluid helium



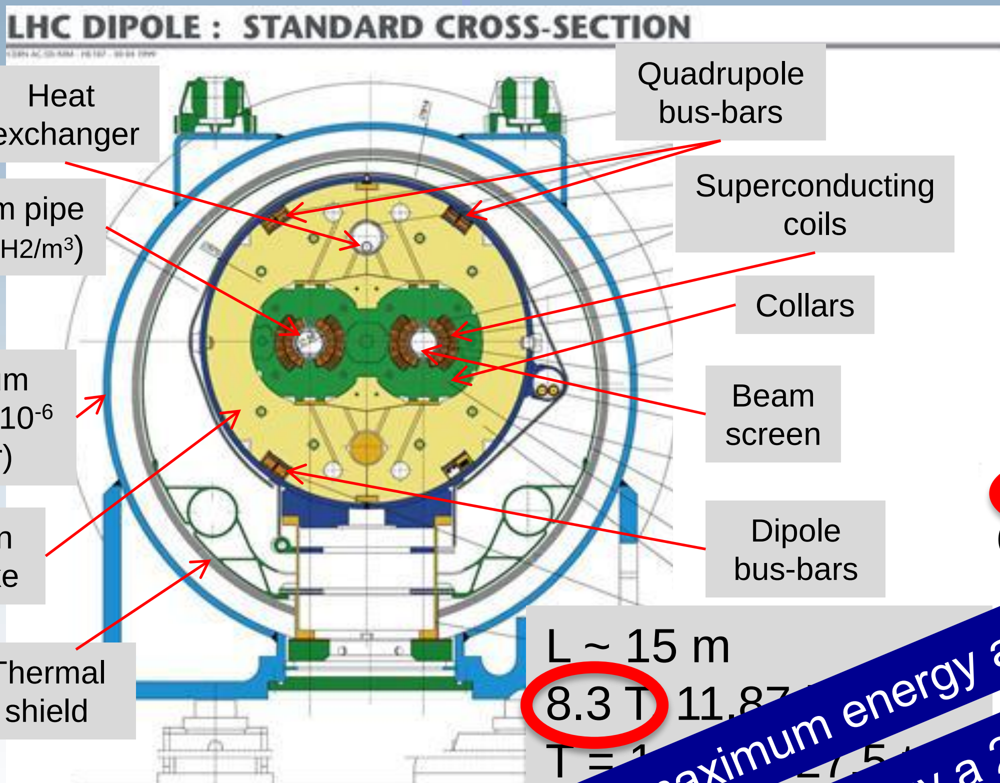
I. Basic layout of the machine: main cryodipoles (two dipoles in one)



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

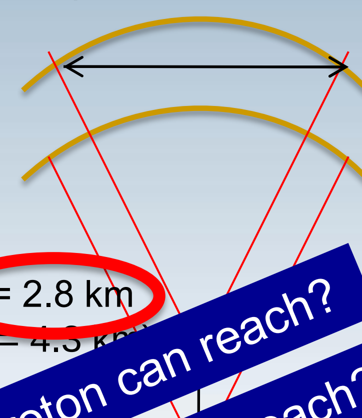
VERTICAL PLANE

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



HORIZONTAL PLANE

Length of the bend part =14.3 m



ρ = 2.8 km

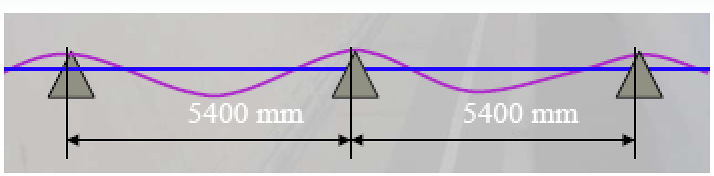
(R = 4.3 km)

Dista… …en … 194.5 mm

L ~ 15 m

8.3 T 11.87 …

T = 1… 27.5 …

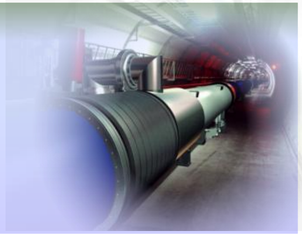


…e acti… of the cold mass is bent in … horizontal plane with an angle of … mrad with ρ = 2.8 km. The shape of the two beam channels is identical.

What is the maximum energy a proton can reach?

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

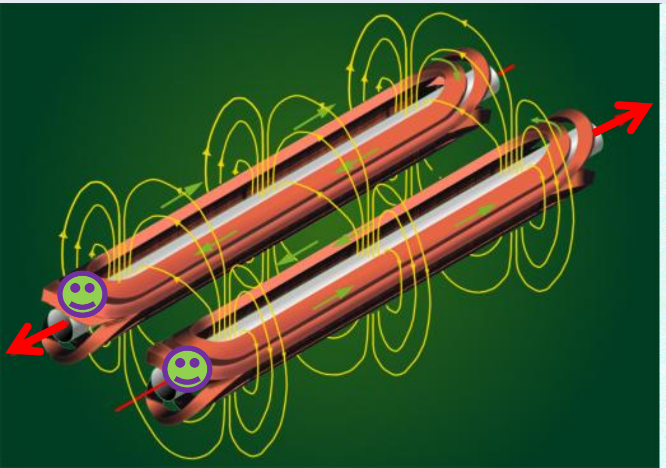
I. Basic layout of the machine: main dipoles

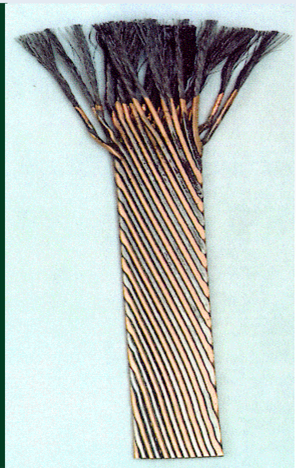


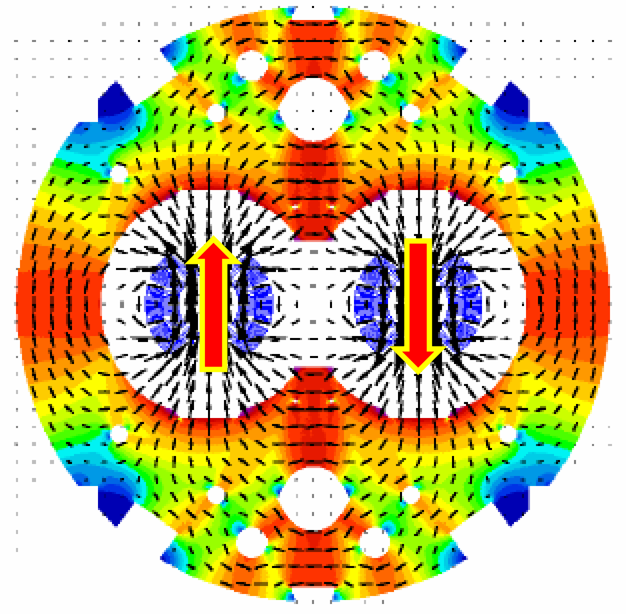
- The magnetic field of the main dipoles:

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.

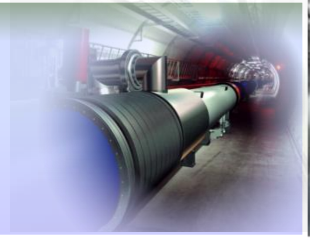
The relative variations of the integrated field and of the field shape imperfections must not exceed ~ 10^{-4} and their reproducibility better than 10^{-4}. This is possible if the coil geometry is accurate, reproducible and symmetric and if the structural stability of the magnet assembly during powering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

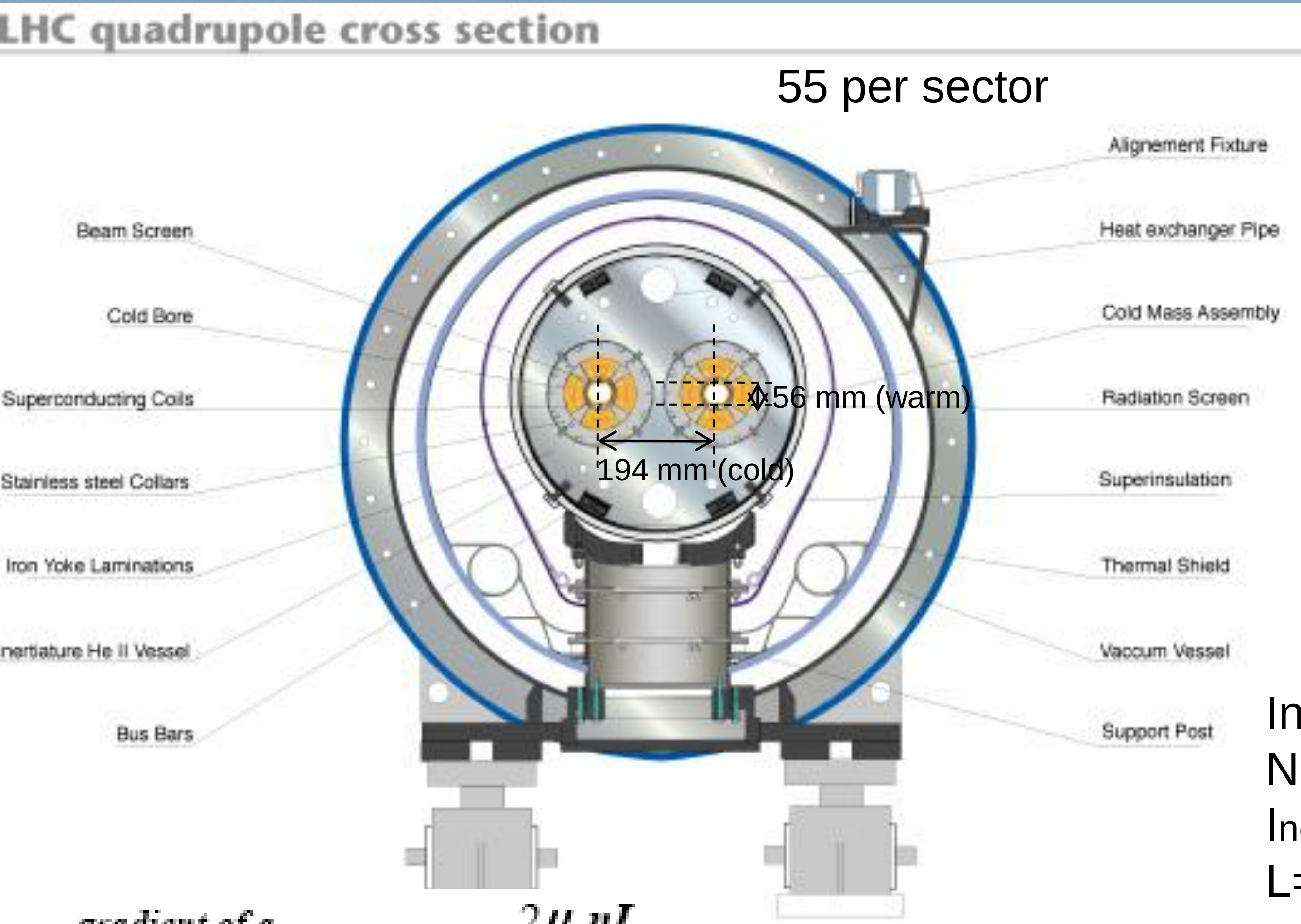






I. Basic layout of the machine: main quadrupoles





CERN AC - SQ1 - 12/97

gradient of a quadrupole magnet:

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

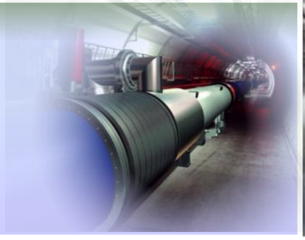
Integrated gradient = 690 T

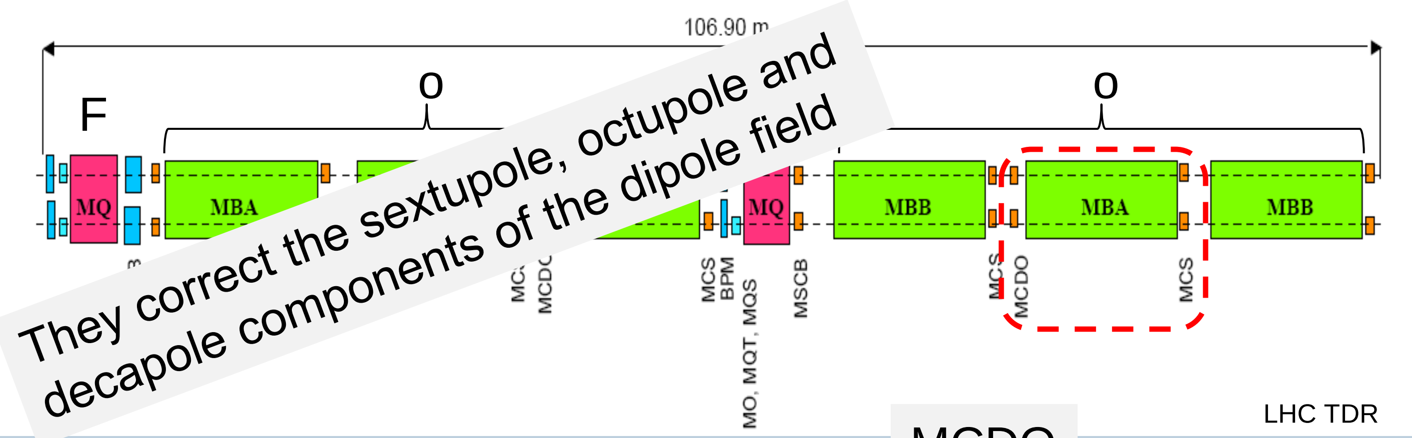
Nominal gradient = 223 T/m

$I_{nominal}$ = 11.87 kA

L=3.1 m

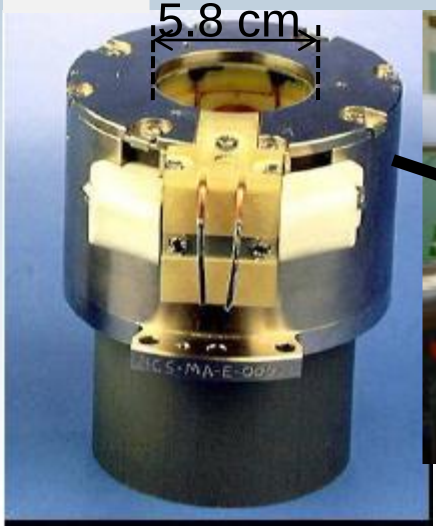
I. Basic layout of the machine: dipole corrector magnets

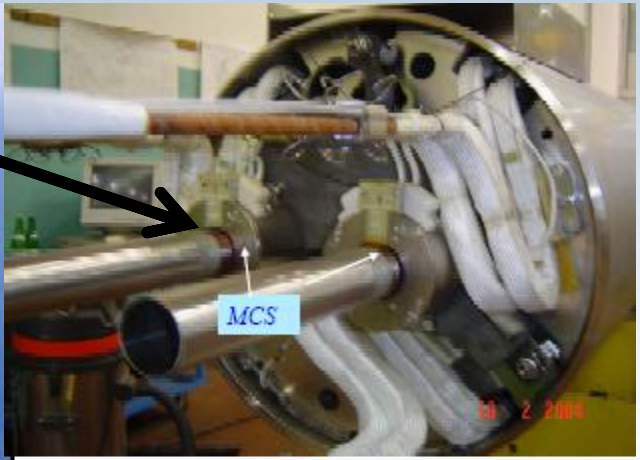




They correct the sextupole, octupole and decapole components of the dipole field

MCS





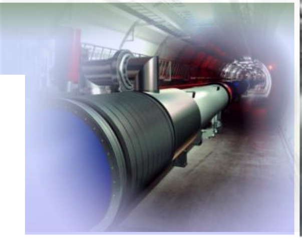
MCDO

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

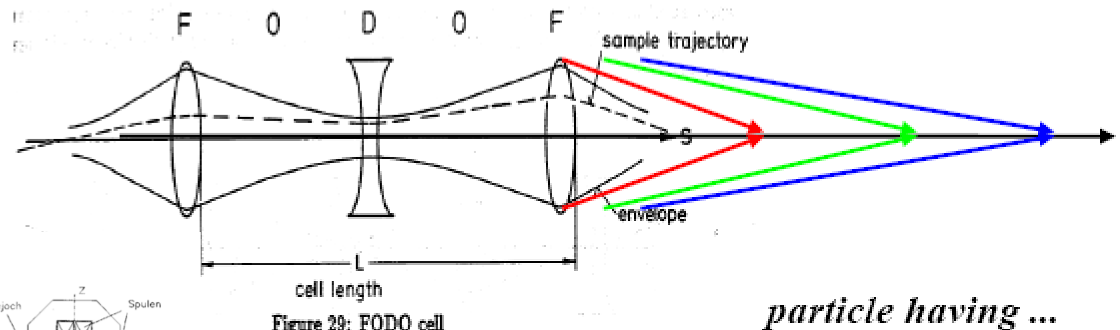
MCO:
Nominal main field strength = 8200 T/m^3
Inominal = 100 A, 1.9 K,
L=11 cm, ~6 kg

I. Basic layout of the machine:



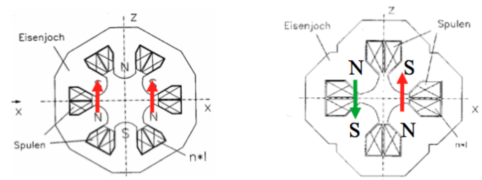
20.) Chromaticity: A Quadrupole Error for $\Delta p/p \neq 0$

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



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

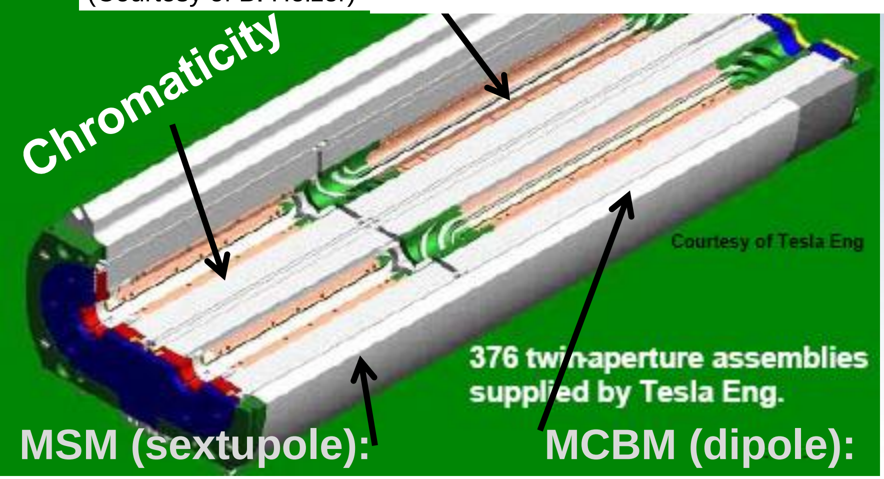
Sextupole Magnets:

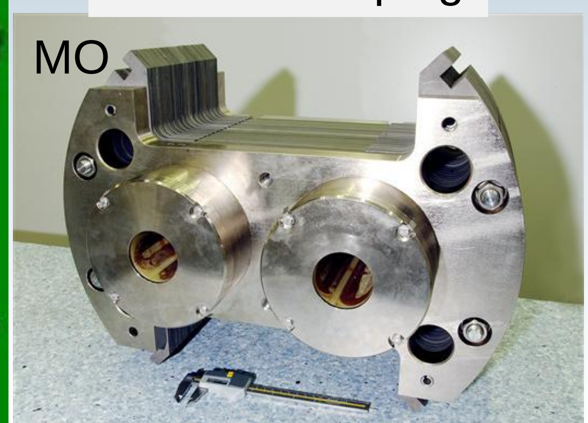


(Courtesy of B. Holzer)

M

Landau damping





MQT: Trim quadrupole
MQS: Skew trim quadrupole

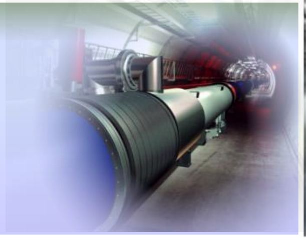
MSM (sextupole):
Nominal main field strength = 4430 T/m^2
$I_{nominal}$ = 550 A, 1.9 K,
L=45.5 cm, ~83 kg

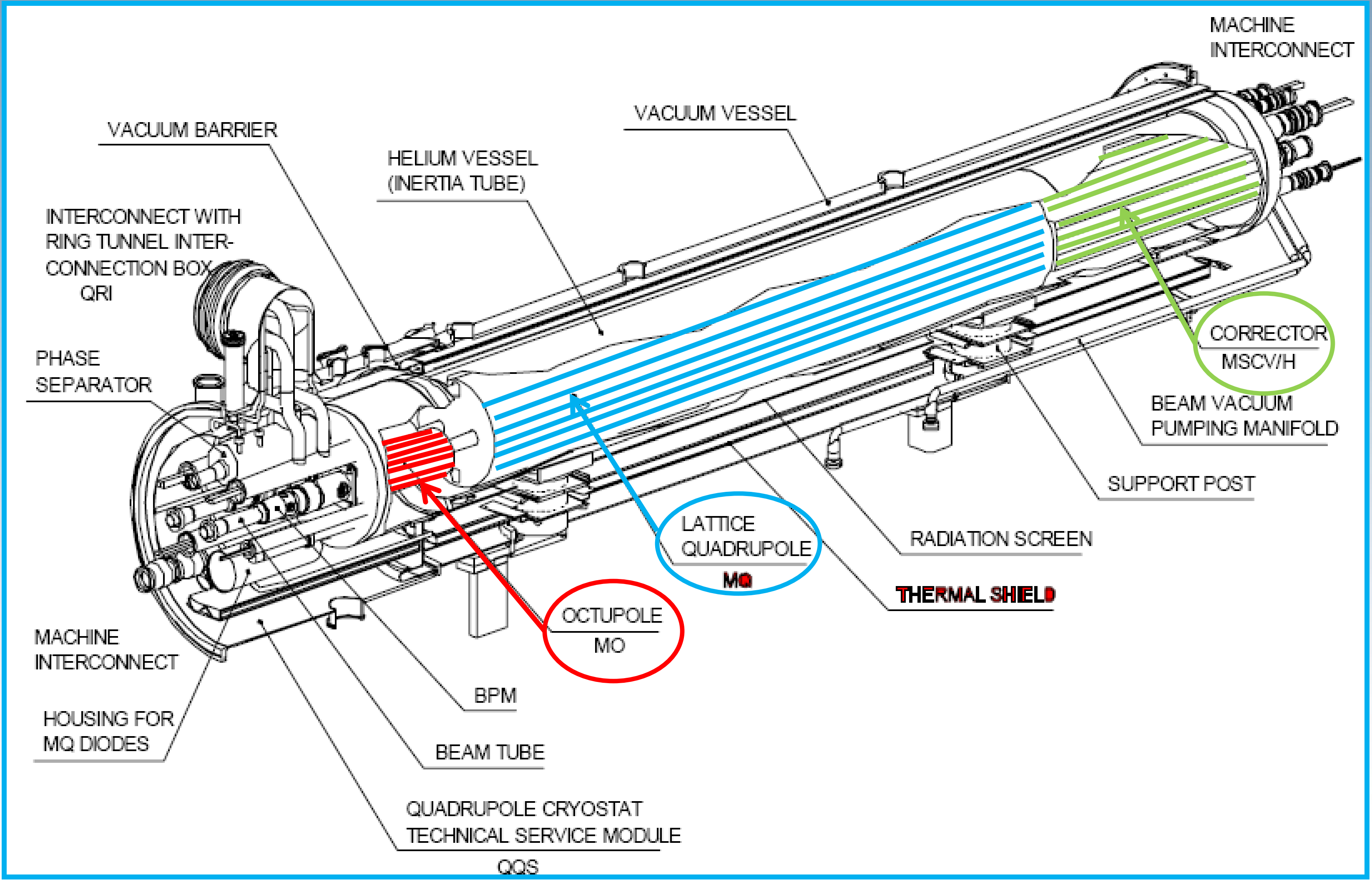
MCBM (dipole):
Nominal main field strength = 2.93 T
$I_{nominal}$ = 55 A, 1.9 K,
L=78.5 cm, ~143 kg

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

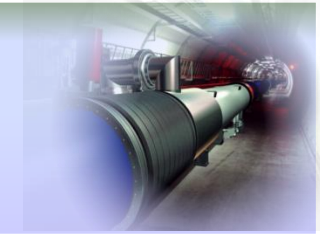
MQT/MQS:
Nominal main field strength = 123 T/m
$I_{nominal}$ = 550 A, 1.9 K
L=38 cm, ~250 kg

I. Basic layout of the machine: quadrupole corrector magnets



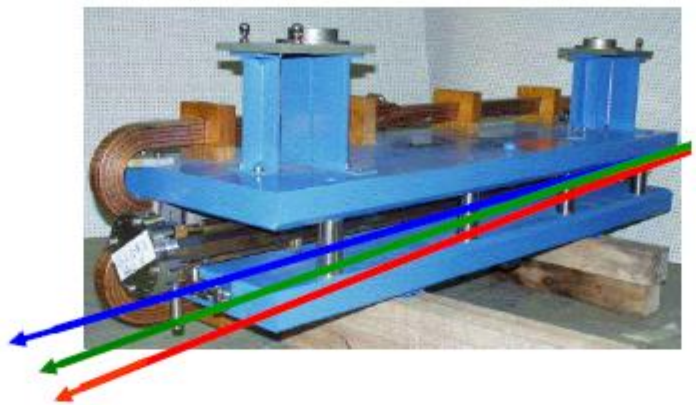


I. Basic layout of the machine: Dispersion suppression



ARC → ← DS → ← LSS

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



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

(Courtesy of B. Holzer)

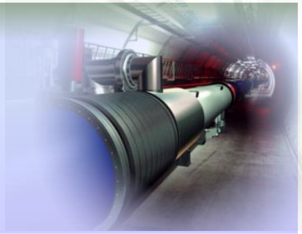
The dispersion suppression is located at the transition between the arc and the straight section. The schema above applies to all DS except the ones in IR3 and IR7.

Functions:

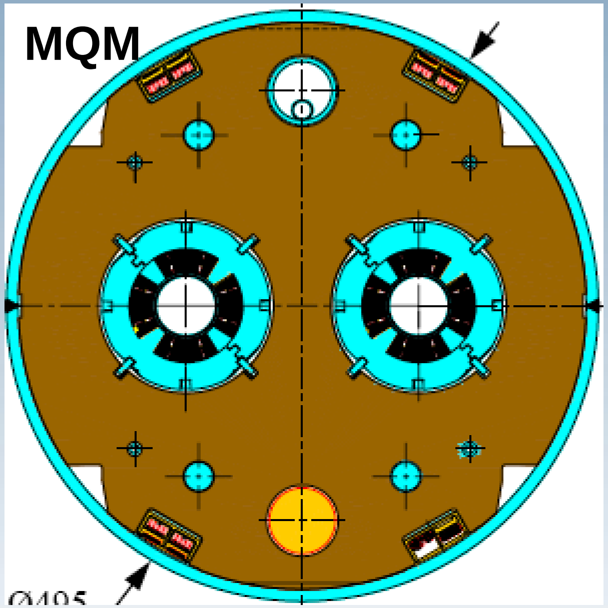
1. Adapts the LHC reference orbit to the LEP tunnel geometry
2. Cancels the horizontal dispersion generated on one side by the arc dipoles and on the other by the separation/recombination dipoles and the crossing angle bumps
3. Helps in matching the insertion optics to the periodic solution of the arc

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. Basic layout of the machine: Dispersion suppression

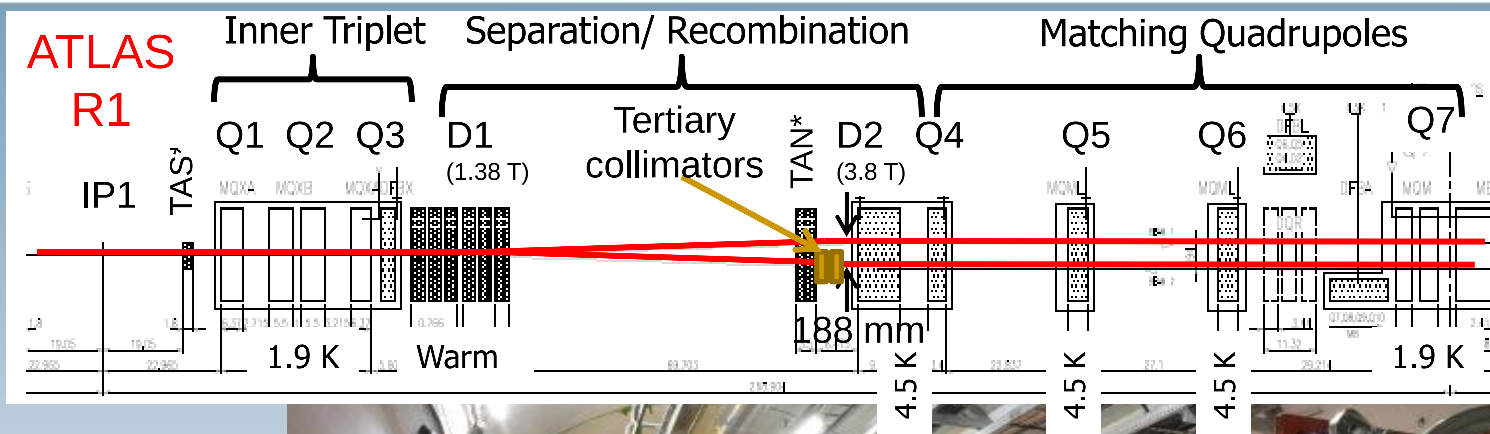


- Quadrupole types: MQ, **MQM**, MQTL



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

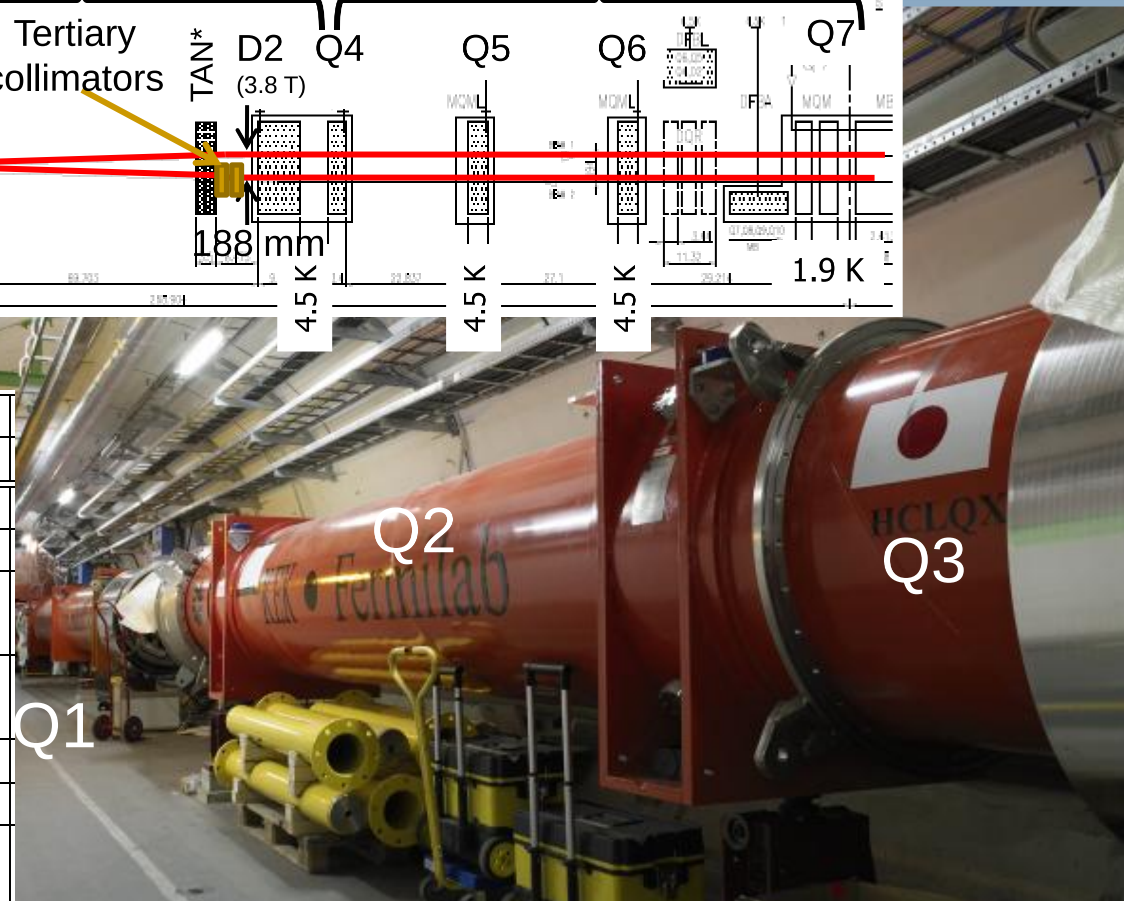
II. The experiments:
High luminosity insertions



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

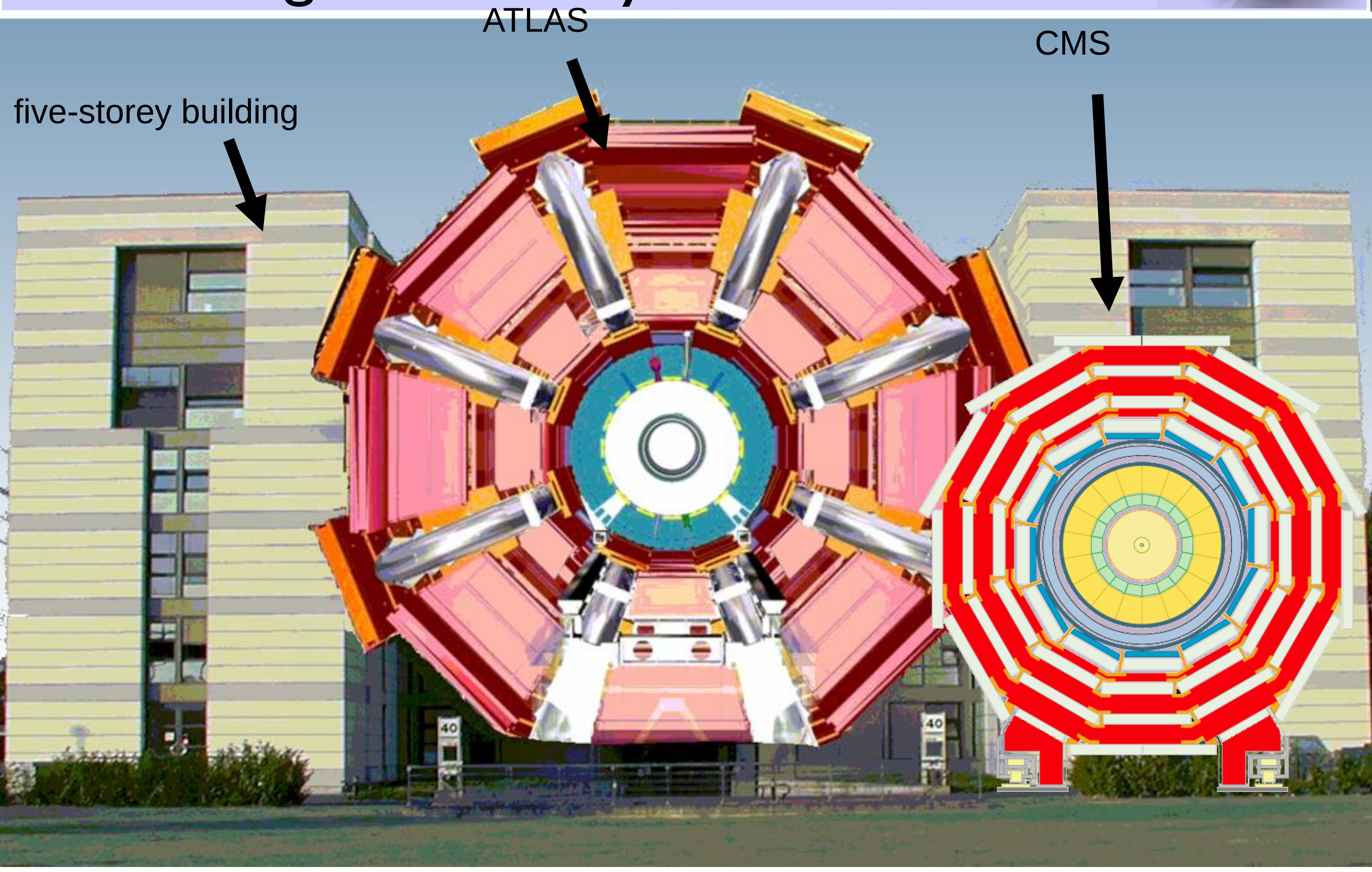
* Protect Inner Triplet (TAS) and D2 (TAN) from particles coming from the IP



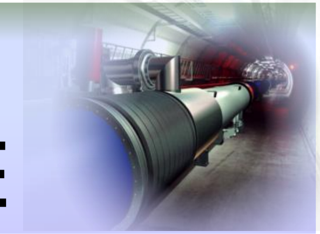
➔ To provide sufficient aperture for the Xangle

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

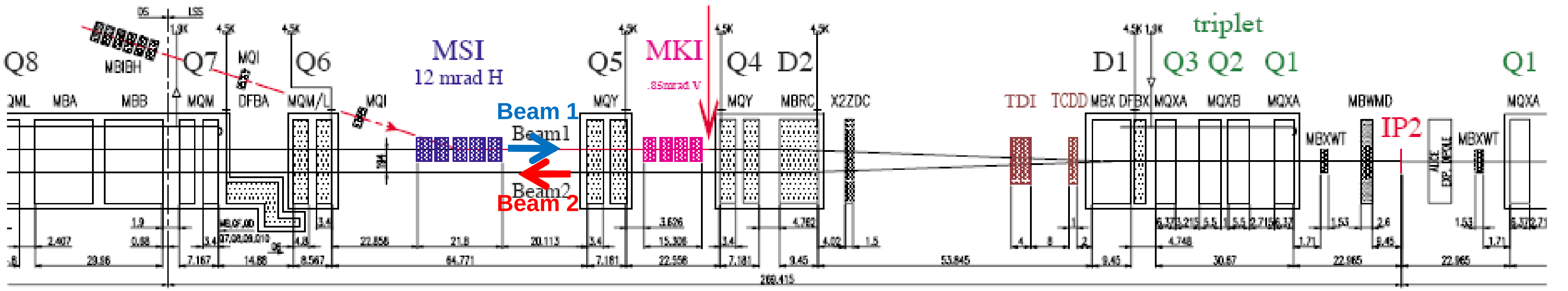
II. The experiments:
High luminosity insertions



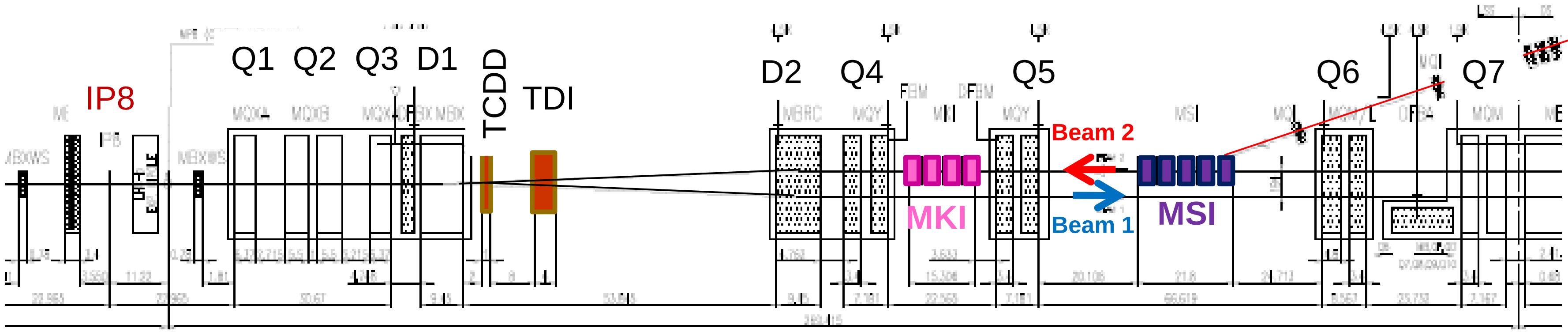
II. The experiments:
Low luminosity insertions: ALICE



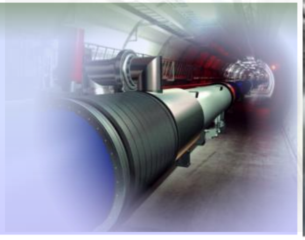
ALICE



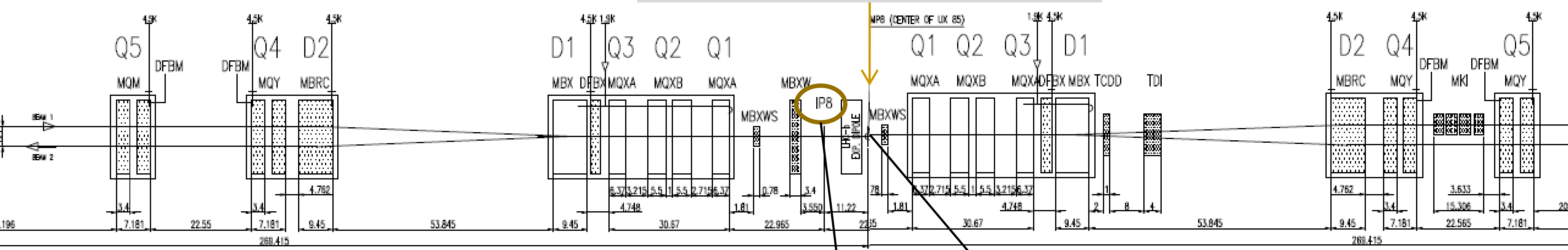
LHCb

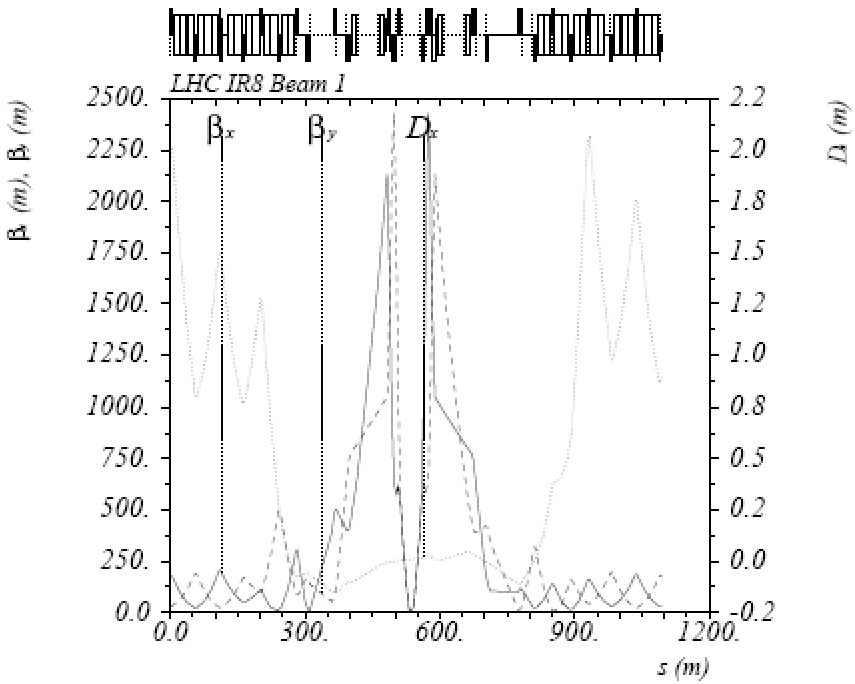


II. The experiments:
Low luminosity insertions: LHCb

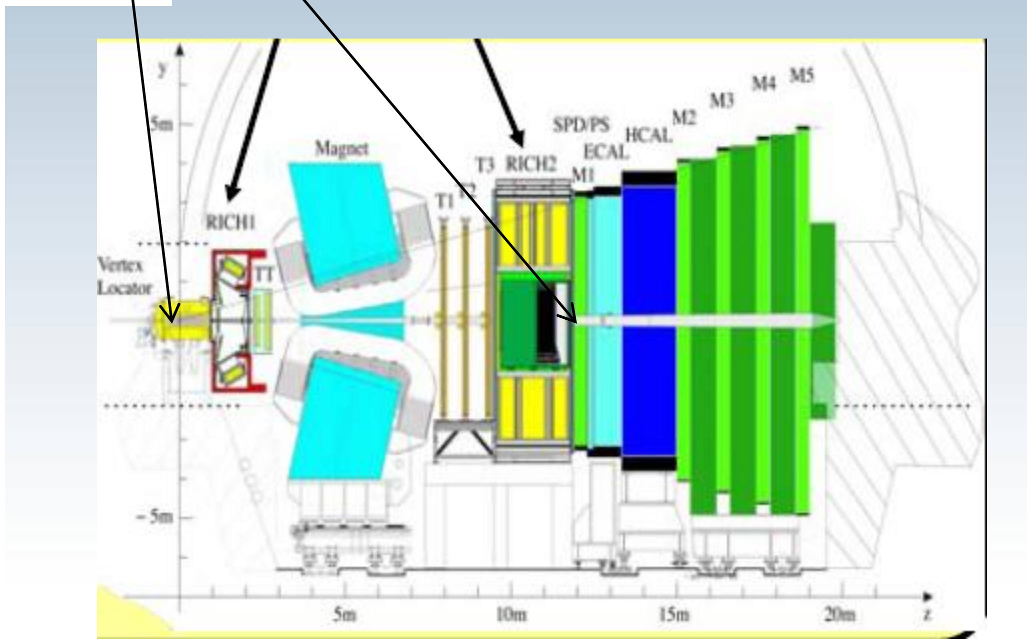


Centre of the exp cavern

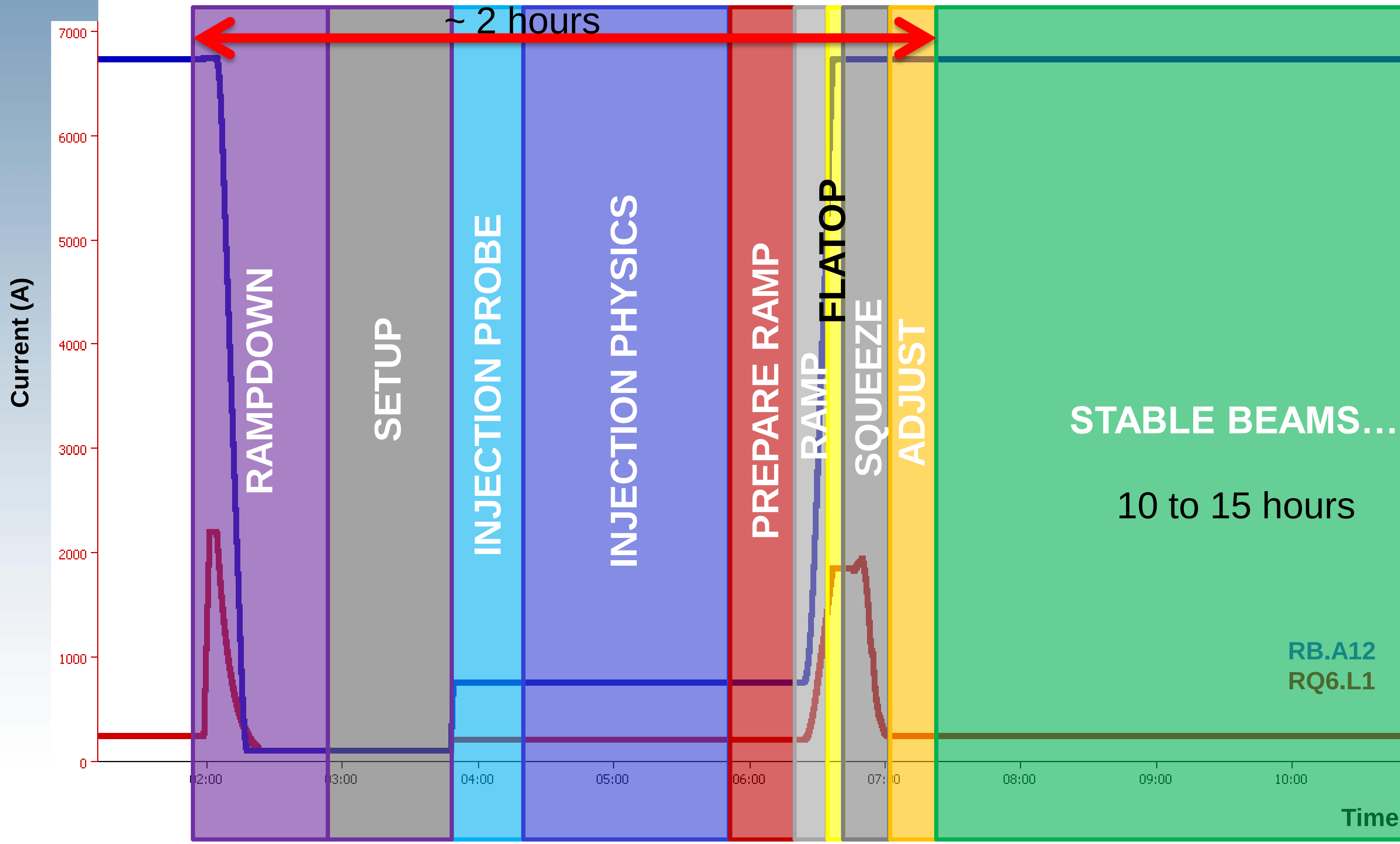




(c) Beam 1, collision optics

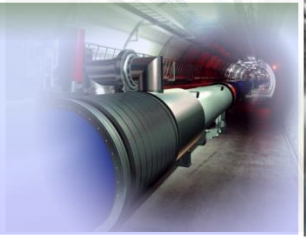


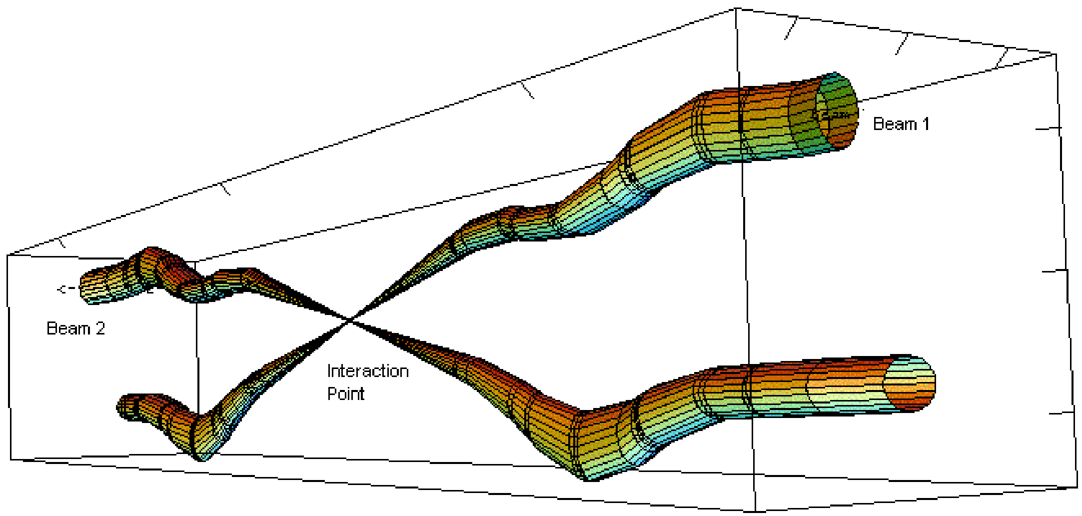
III. LHC Operational cycle



M. Solfaroli Evian 2012

III. LHC Operational cycle: Squeeze ➔ reduce β*



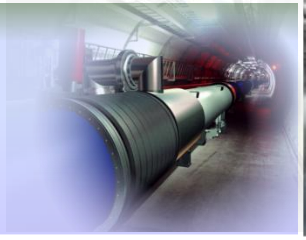


Relative beam sizes around IP1 (Atlas) in collision

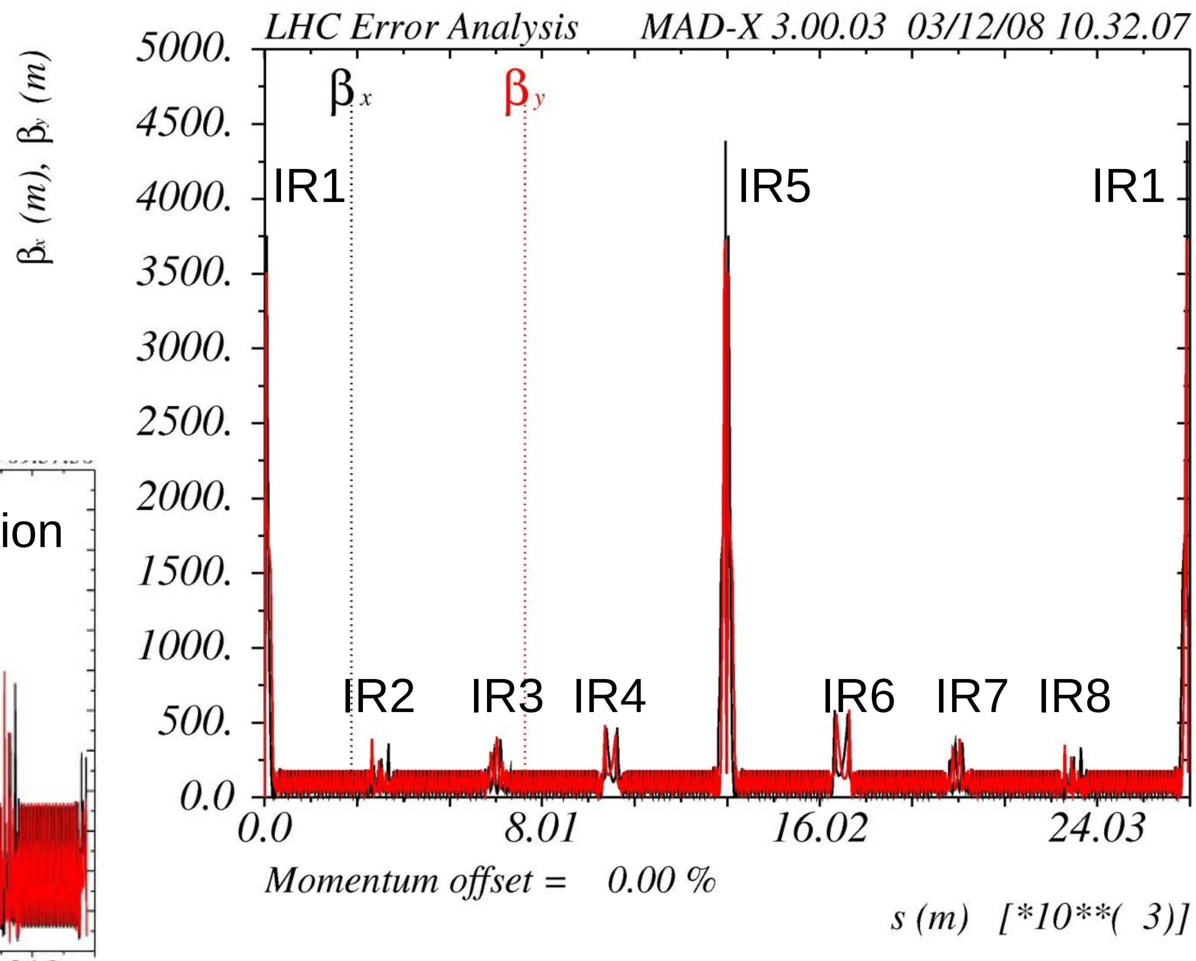
Squeeze the beam size down as much as possible at the collision point to increase the chances of a collision

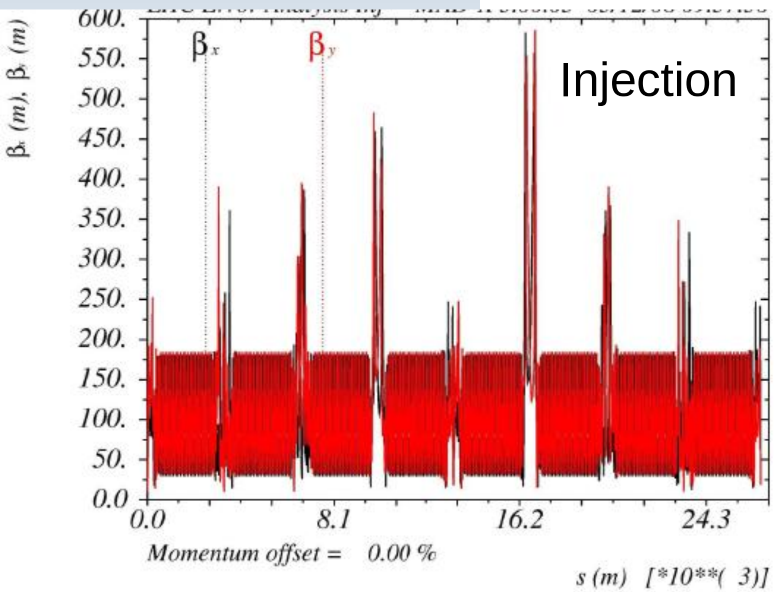
- So even though we squeeze our 100,000 million protons per bunch down to 16 microns (1/5 the width of a human hair) at the interaction point. We get only around 20 collisions per crossing with nominal beam currents.
- The bunches cross (every 25 ns) so often we end up with around 600 million collisions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

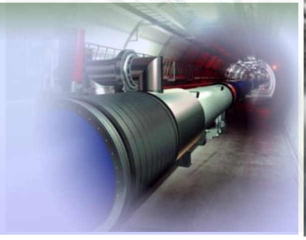


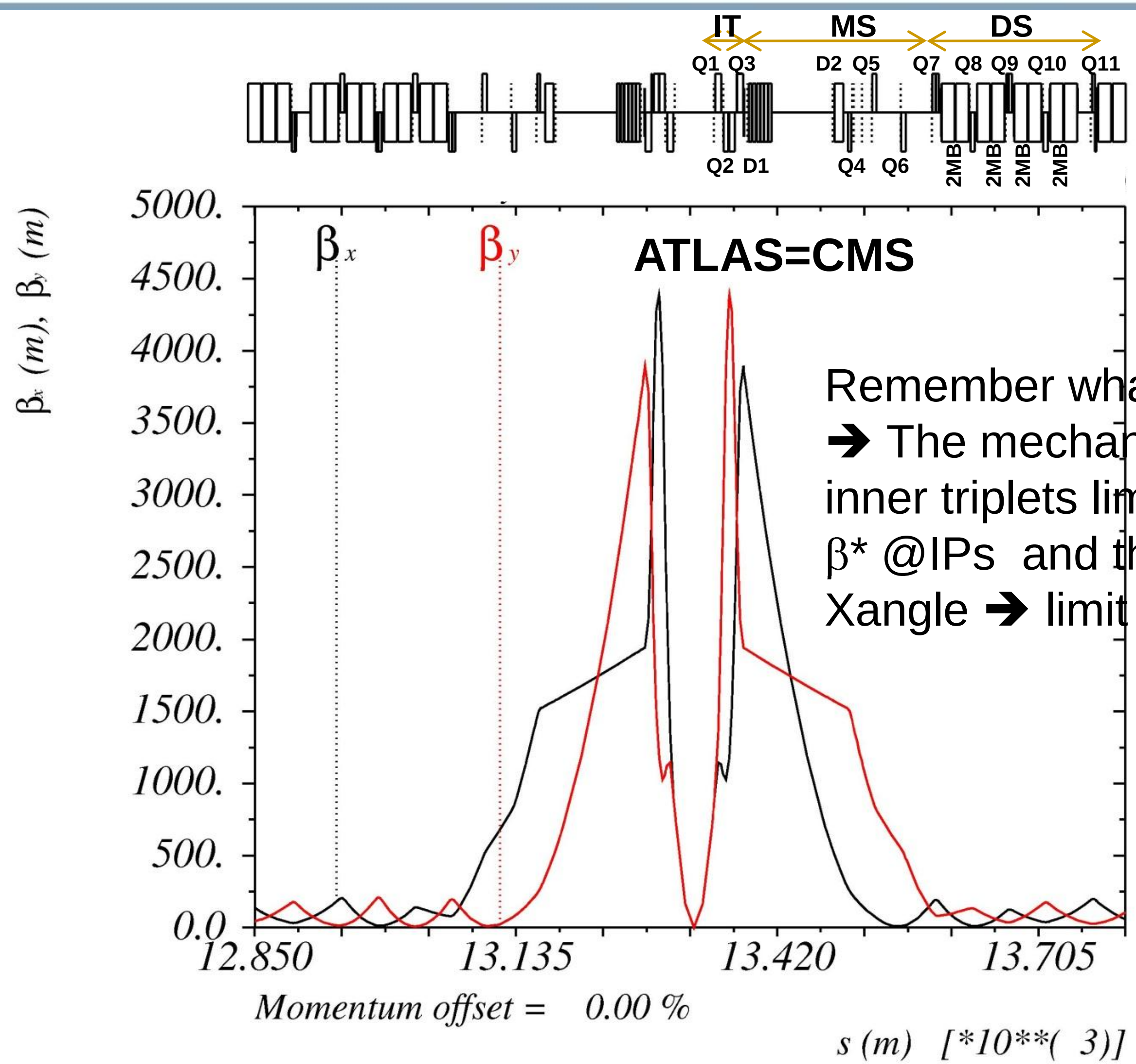
Beta function at top energy and after squeeze





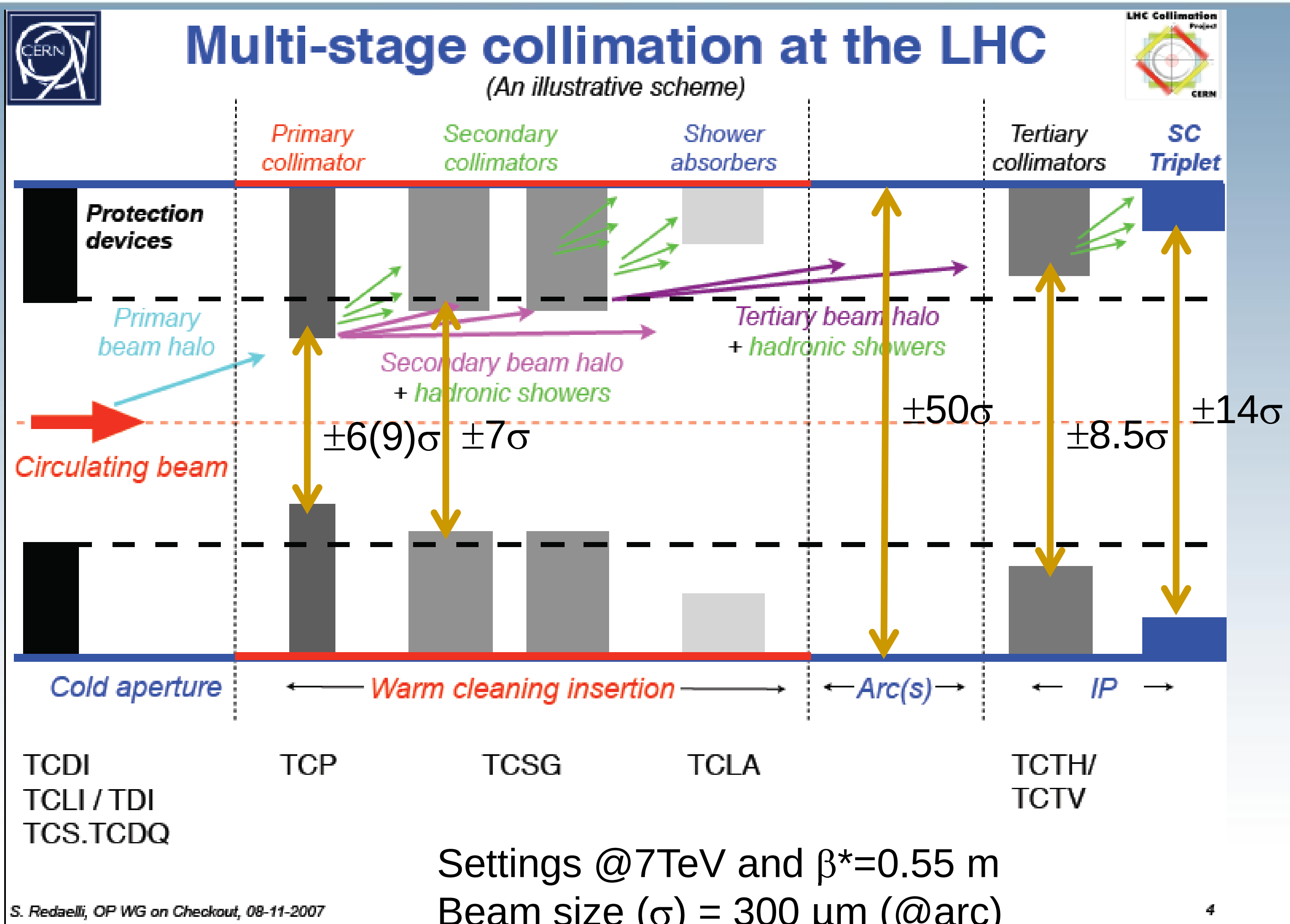
III. LHC Operational cycle: Squeeze ➔ reduce β*





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

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

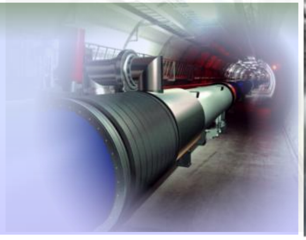


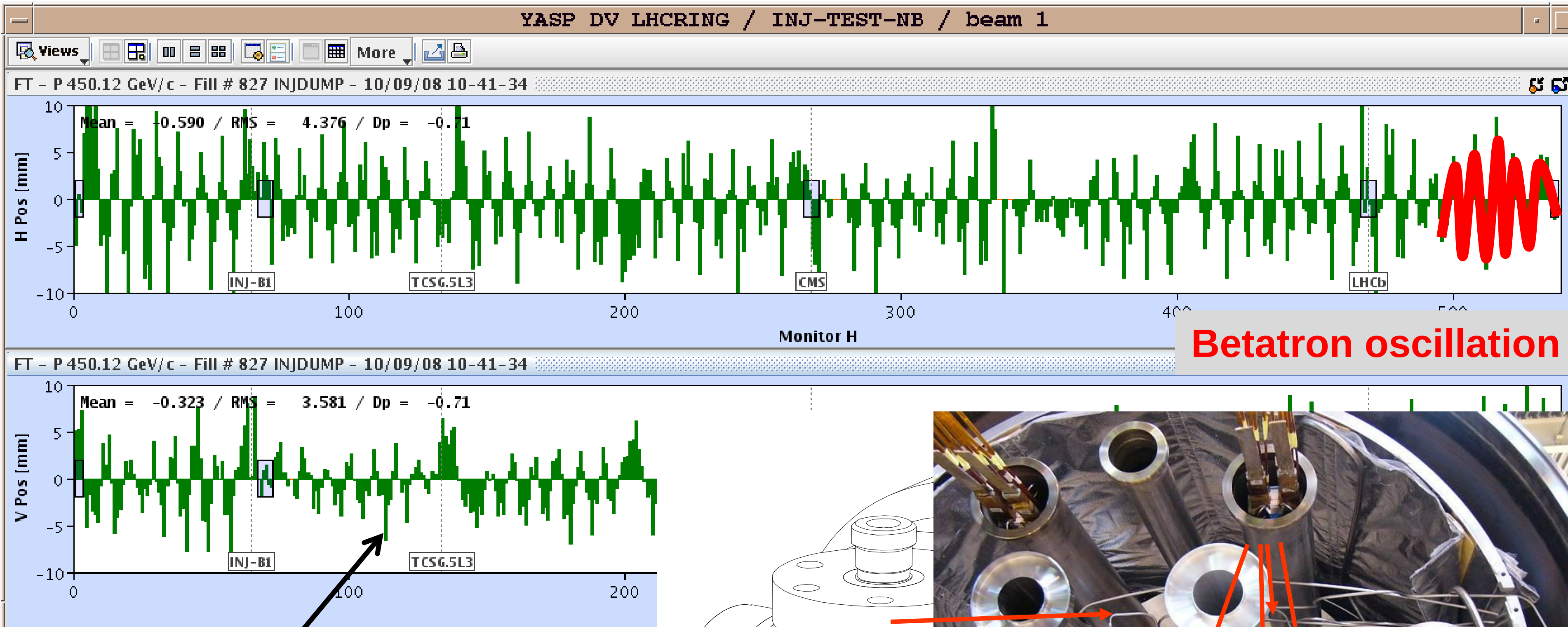
Settings @7TeV and β^*=0.55 m

Beam size (σ) = 300 μm (@arc)

Beam size (σ) = 17 μm (@IR1, IR5)

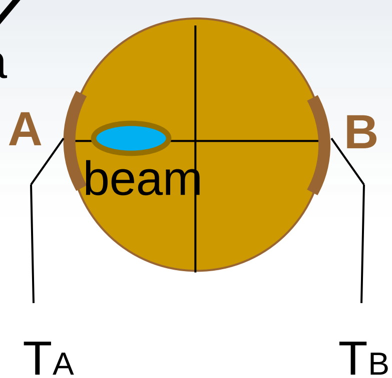
V. Beam trajectory

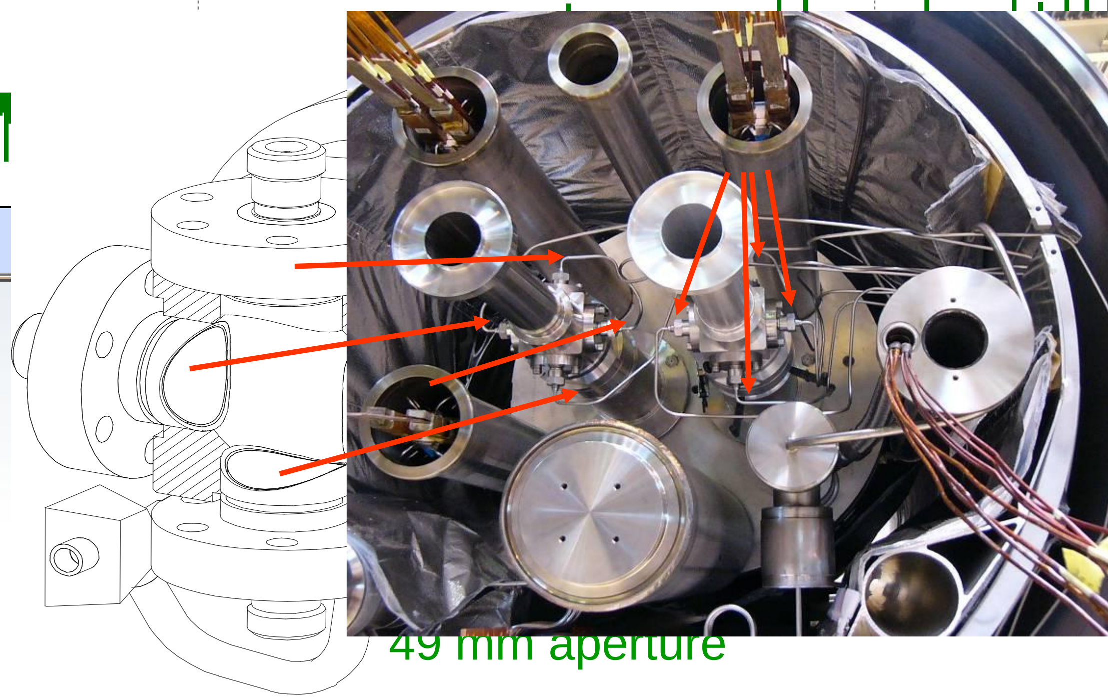




Betatron oscillation

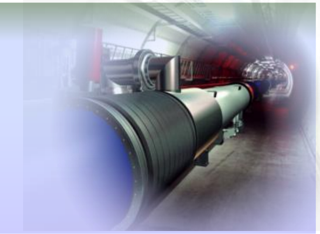
Each point is a BPM (Beam Position Measurement)

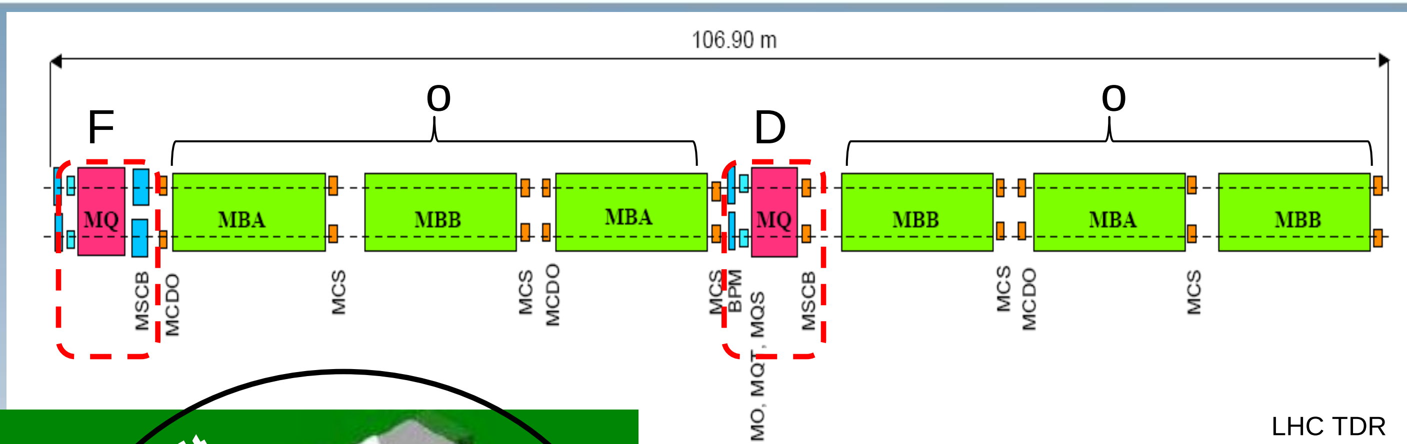


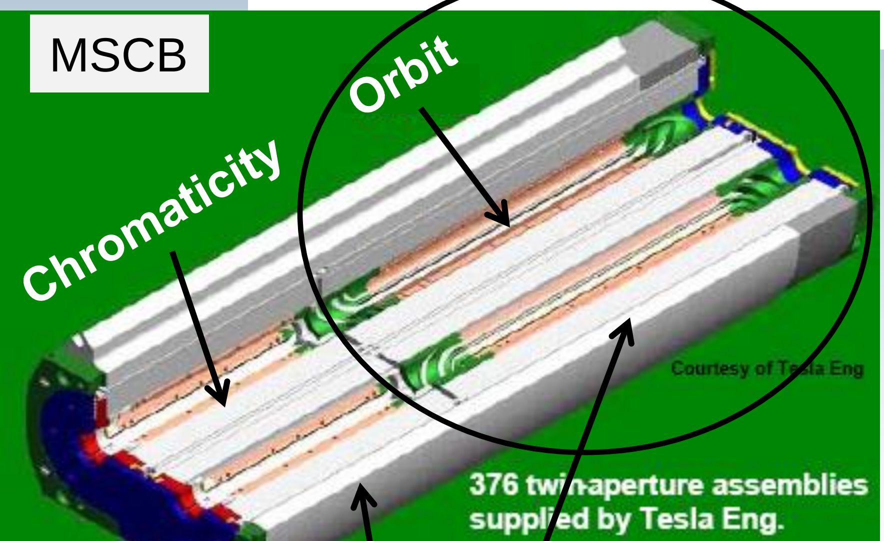


49 mm aperture

V. Beam trajectory



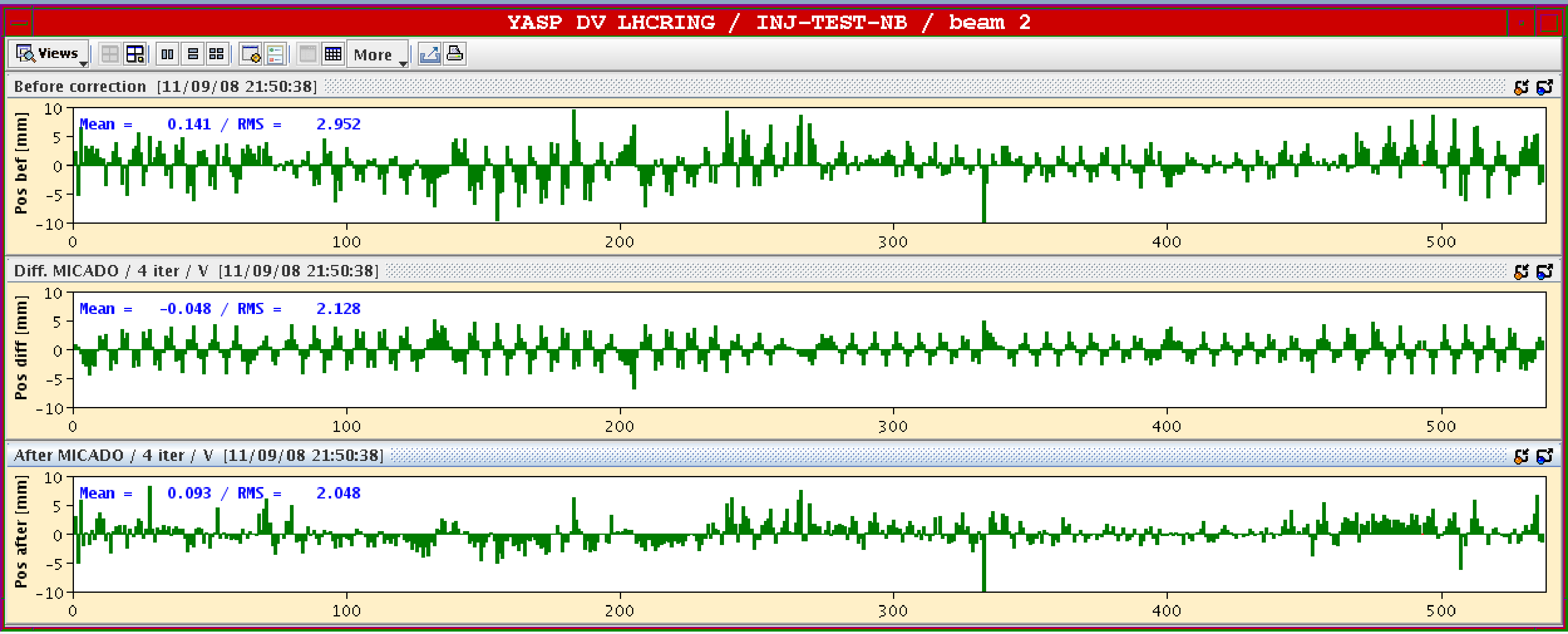




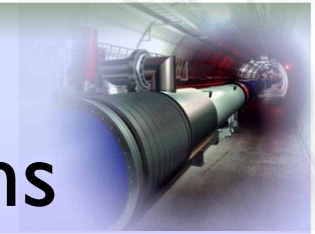
MSM (sextupole):
Nominal main field strength = 4430 T/m^2
$I_{nominal}$ = 550 A, 1.9 K, L=45.5 cm, ~83 kg

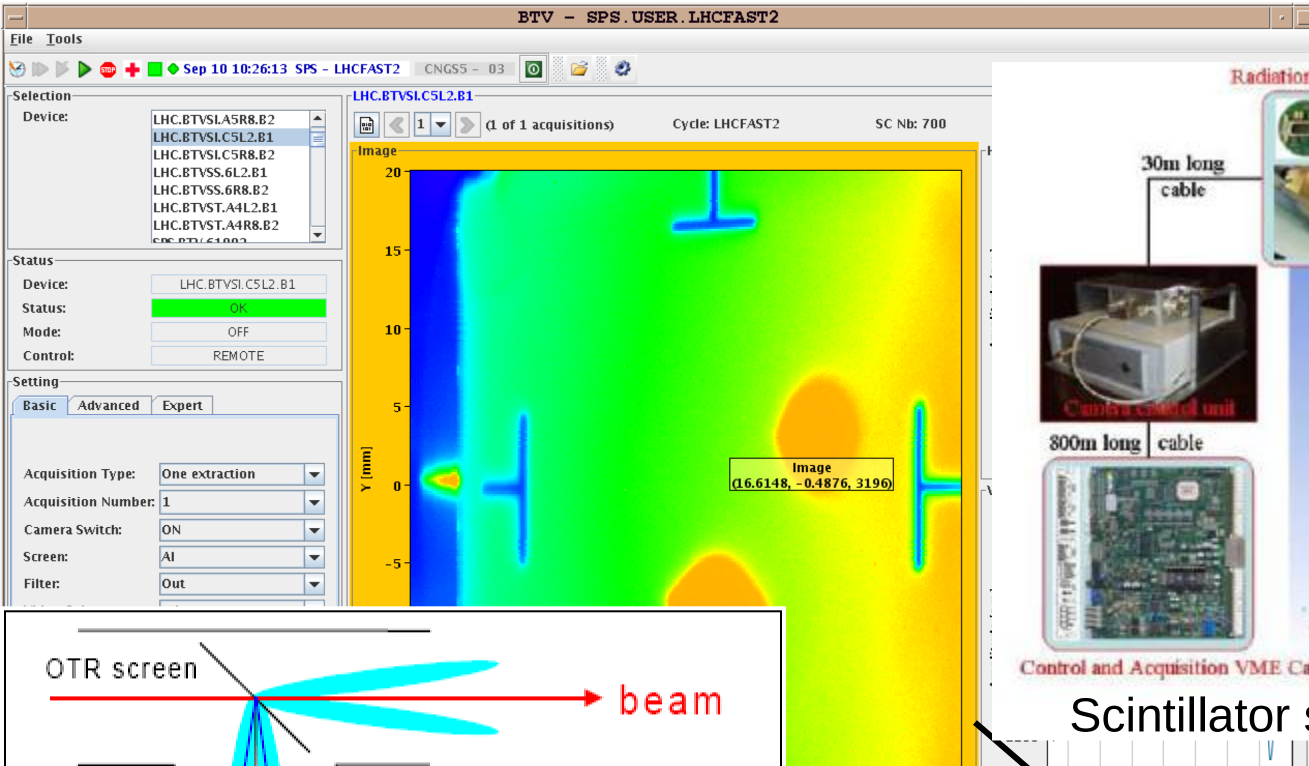
MCBM (dipole):
Nominal main field strength = 2.93 T
$I_{nominal}$ = 55 A, 1.9 K, L=78.5 cm, ~143 kg

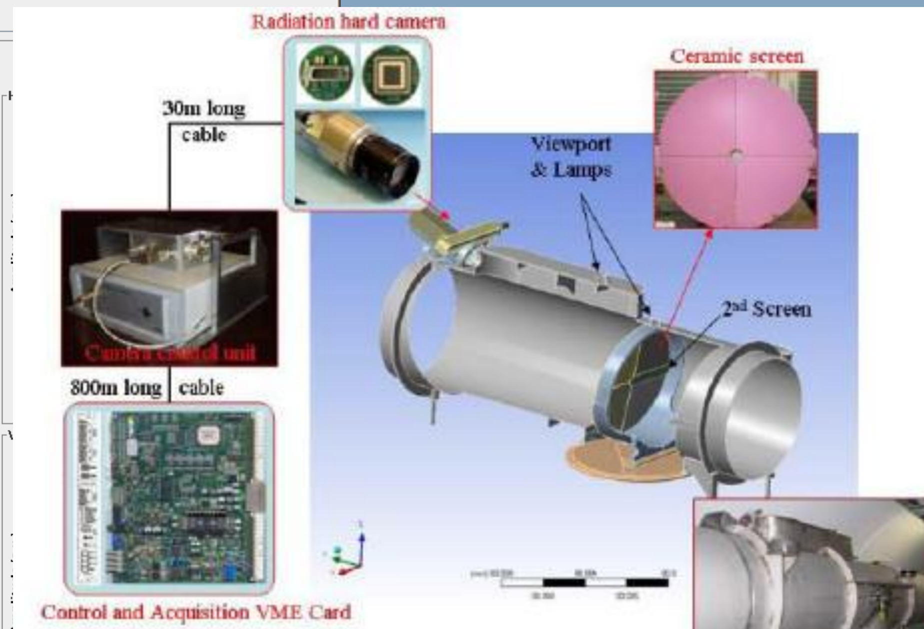
V. Beam trajectory



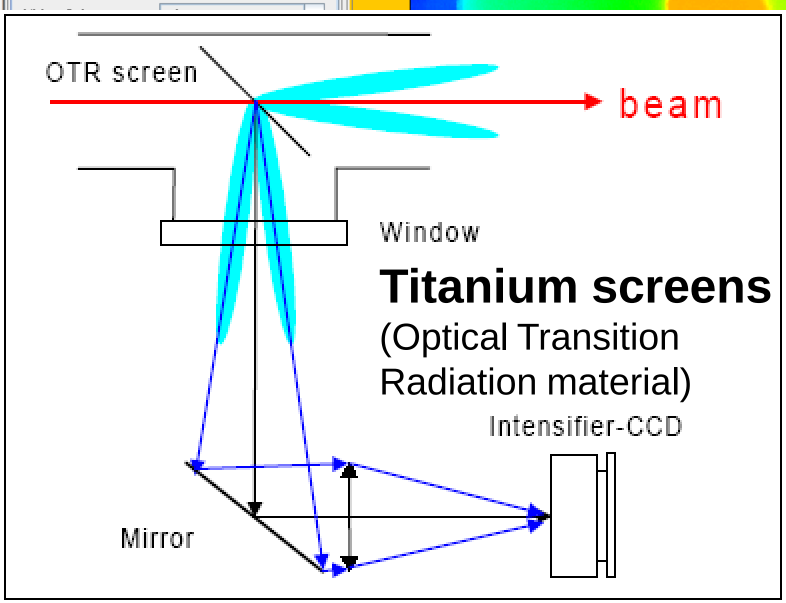
V. Beam profile measurements: Beam 1 on TDI screen – 1st and 2nd turns



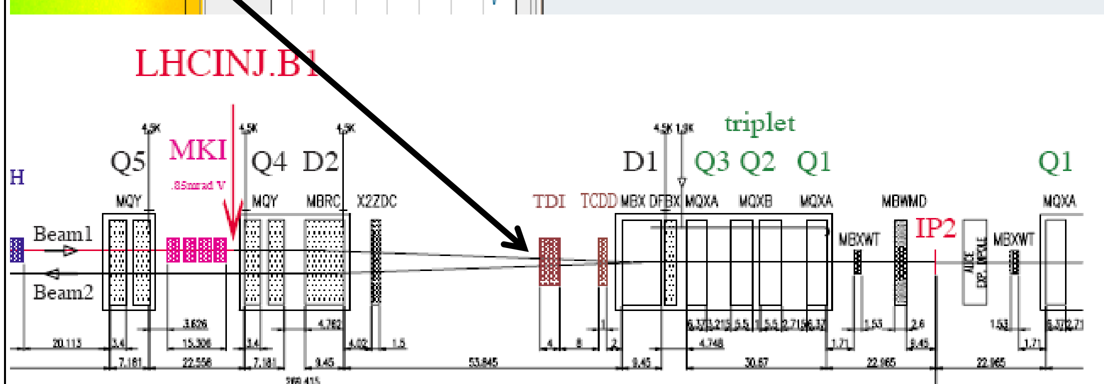




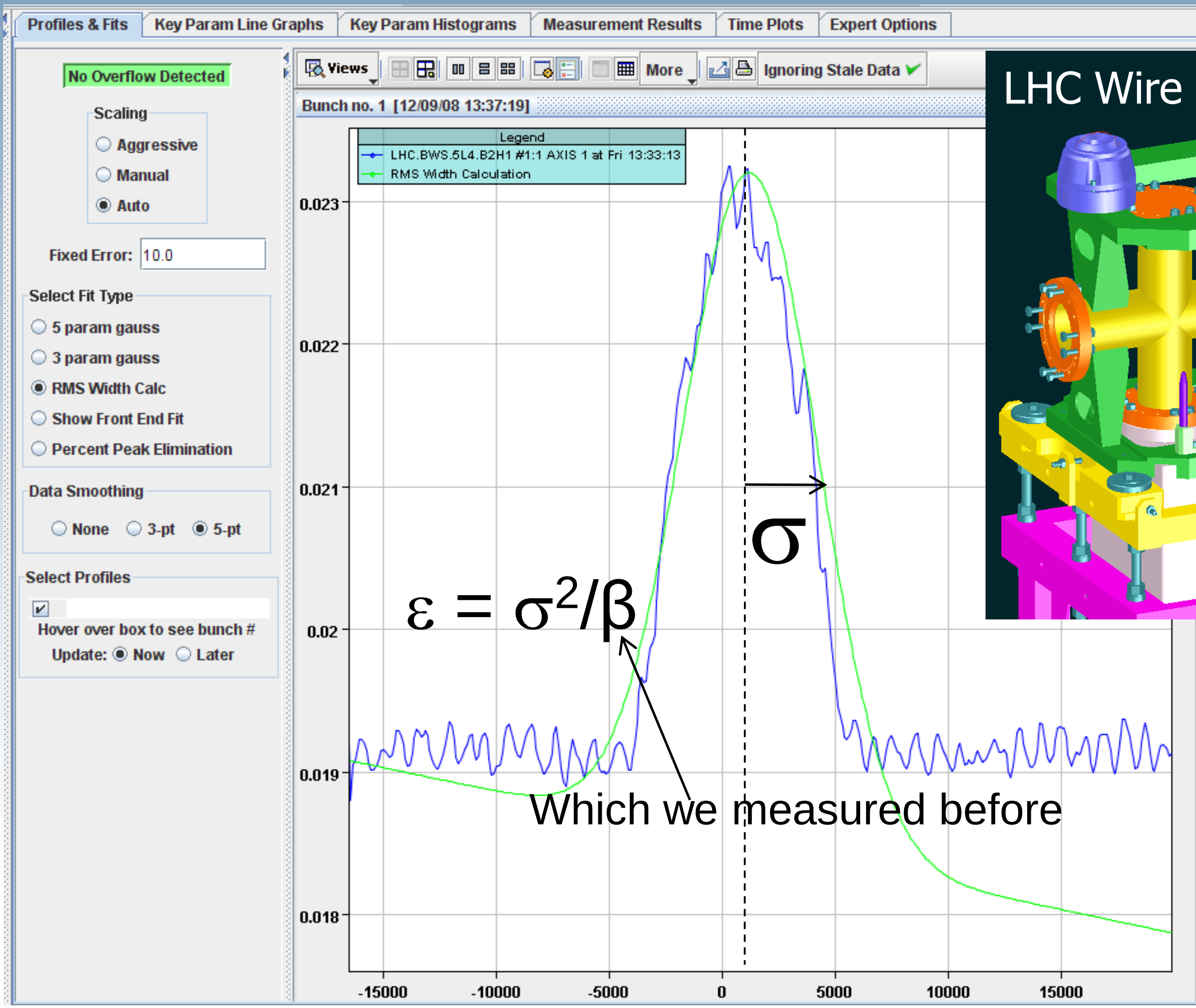
Scintillator screen for LBDS

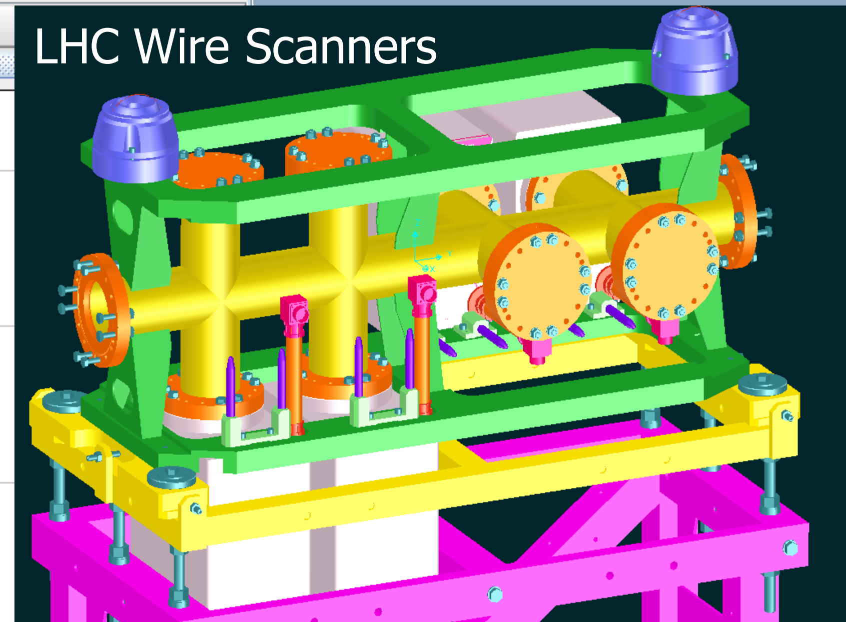


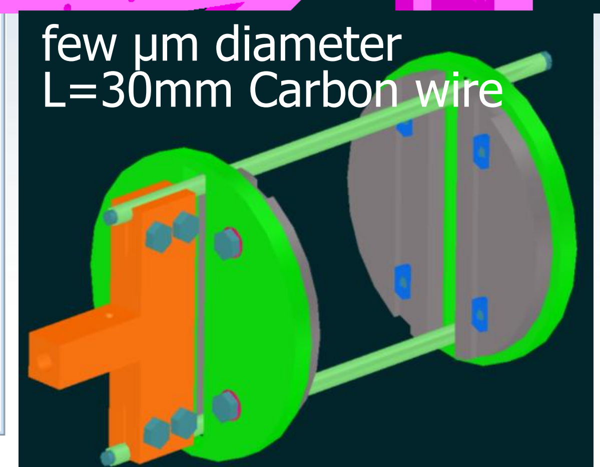
Titanium screens
(Optical Transition Radiation material)



V. Beam profile measurements: Emittance measurement - Wire scanner

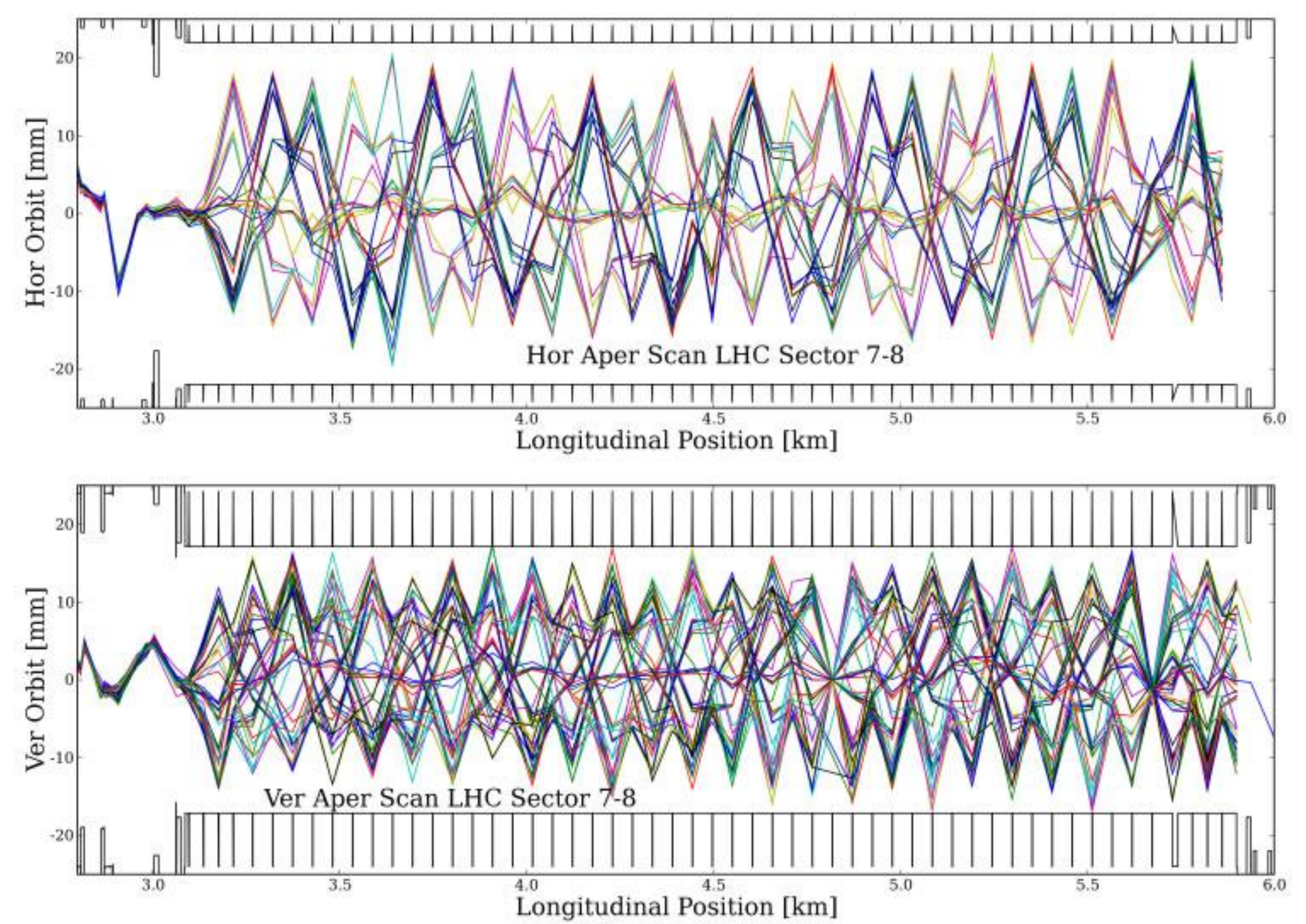




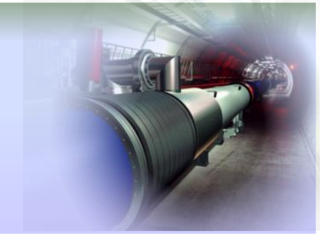


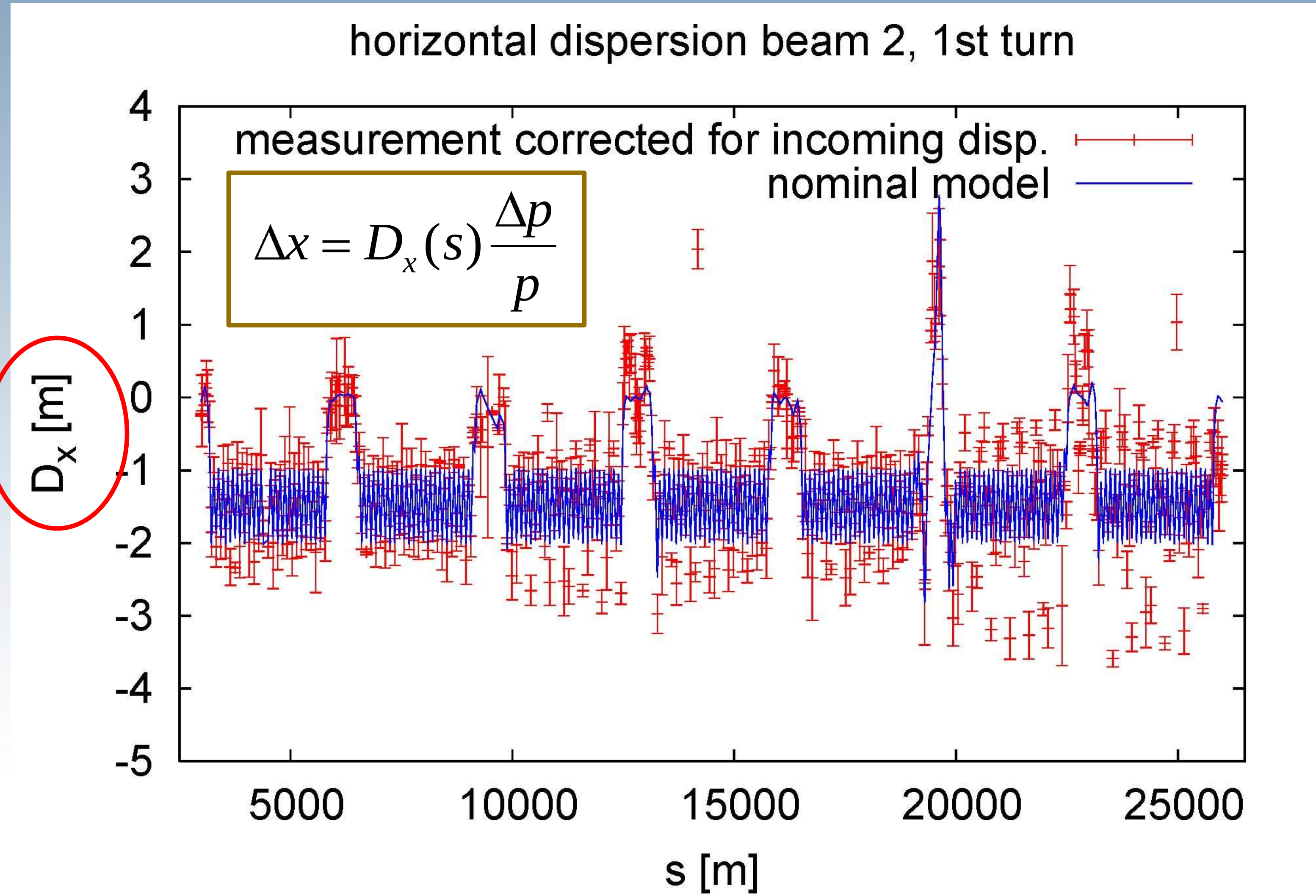
VI. Aperture scan

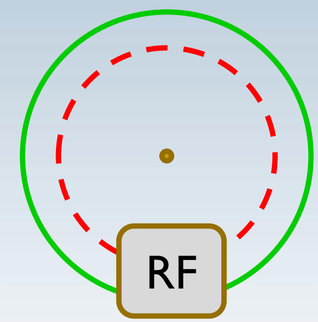
Explore a range of particle angles (=kick strength) with one corrector dipole, then go to the next one



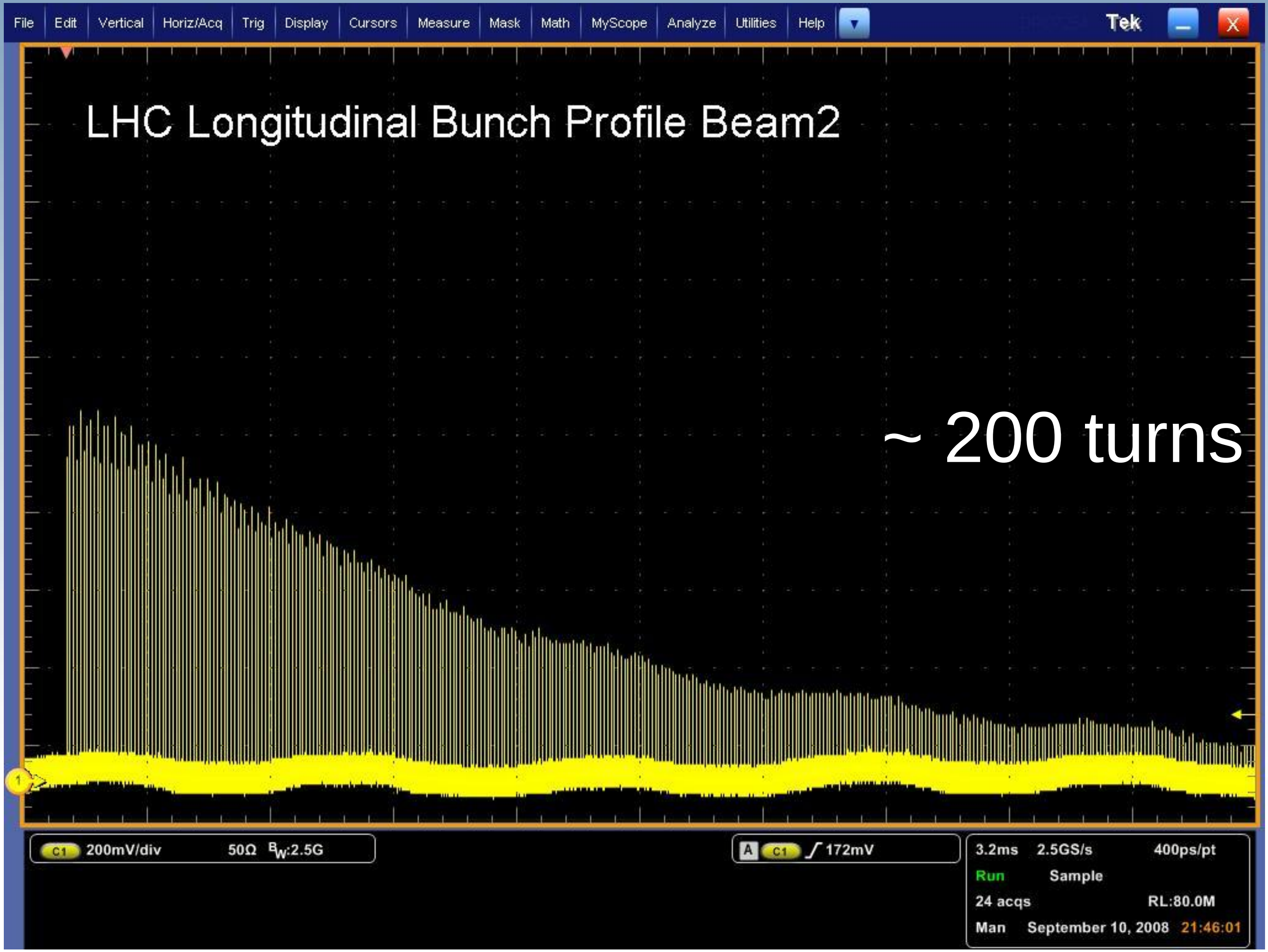
VII. Dispersion measurement



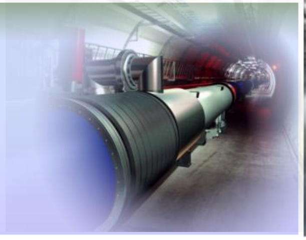


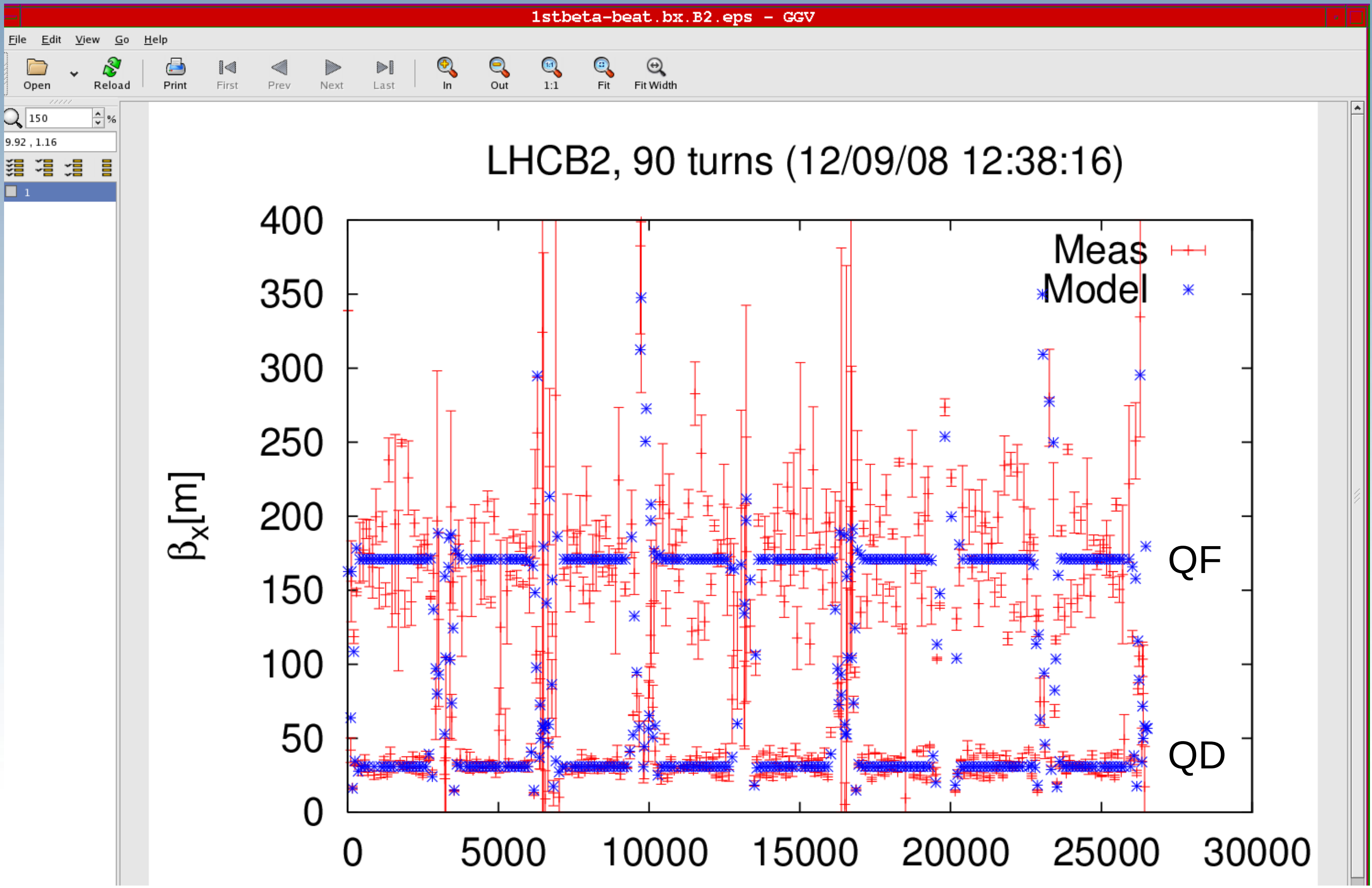


VIII. Longitudinal Bunch Profile



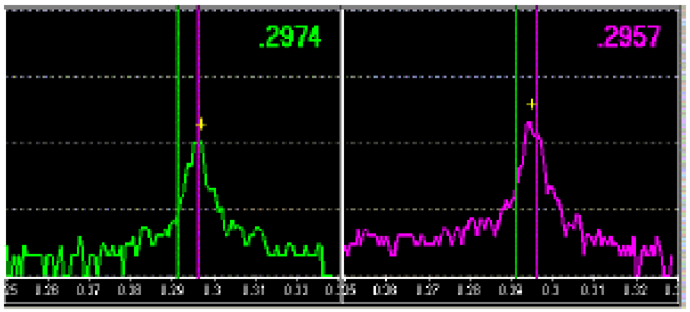
IX. Beta measurement





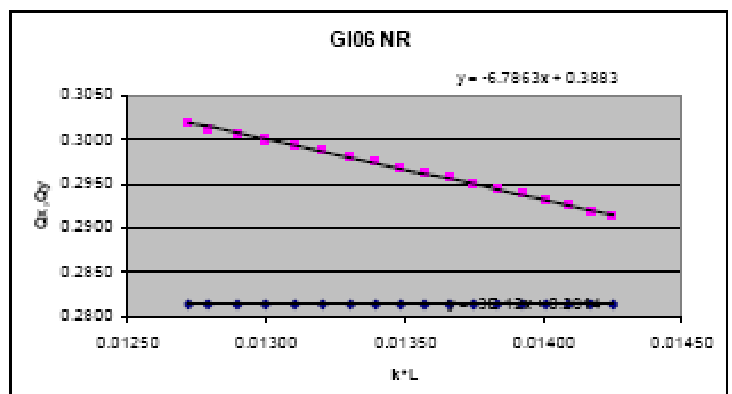
X. Beta measurement

a quadrupol error leads to a shift of the tune:



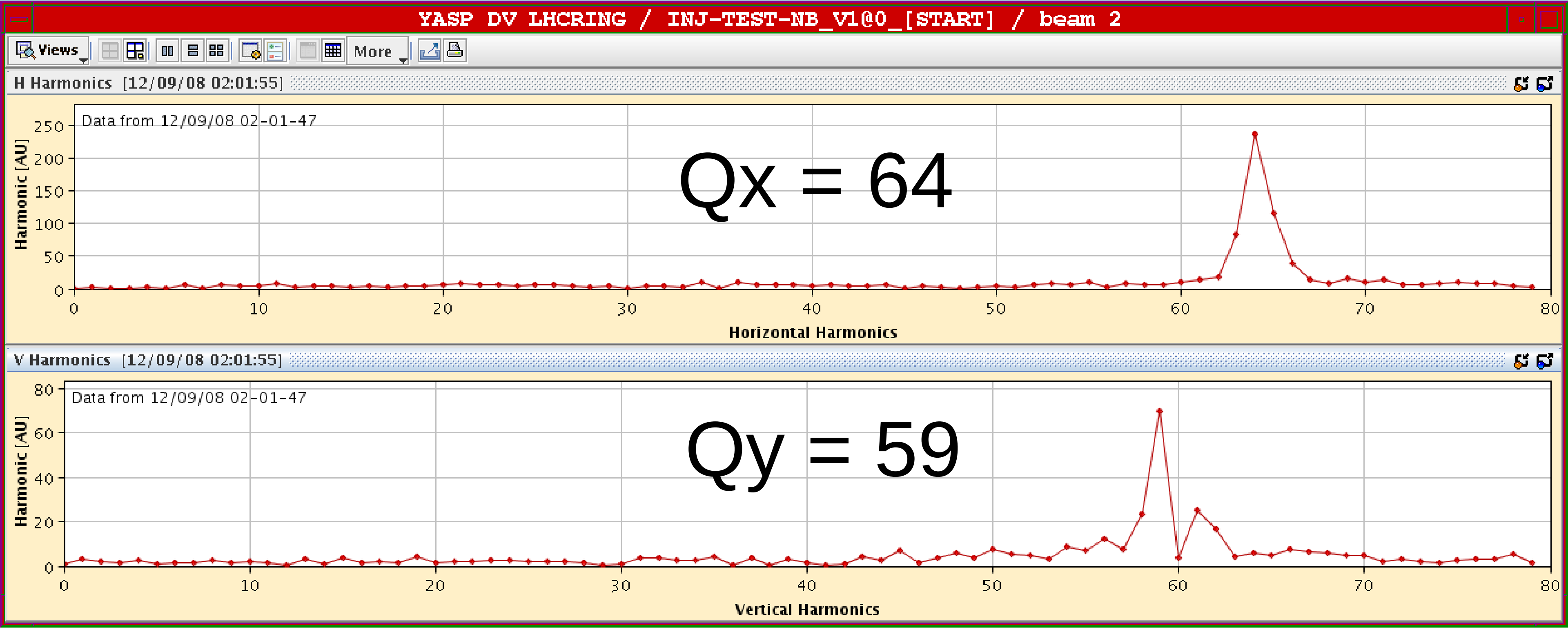
$$\Delta Q = \int_{s0}^{s0+l} \frac{\Delta k \beta(s)}{4\pi} ds \approx \frac{\Delta k l_{quad} \overline{\beta}}{4\pi}$$

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



Courtesy of B. Holzer (lectures)

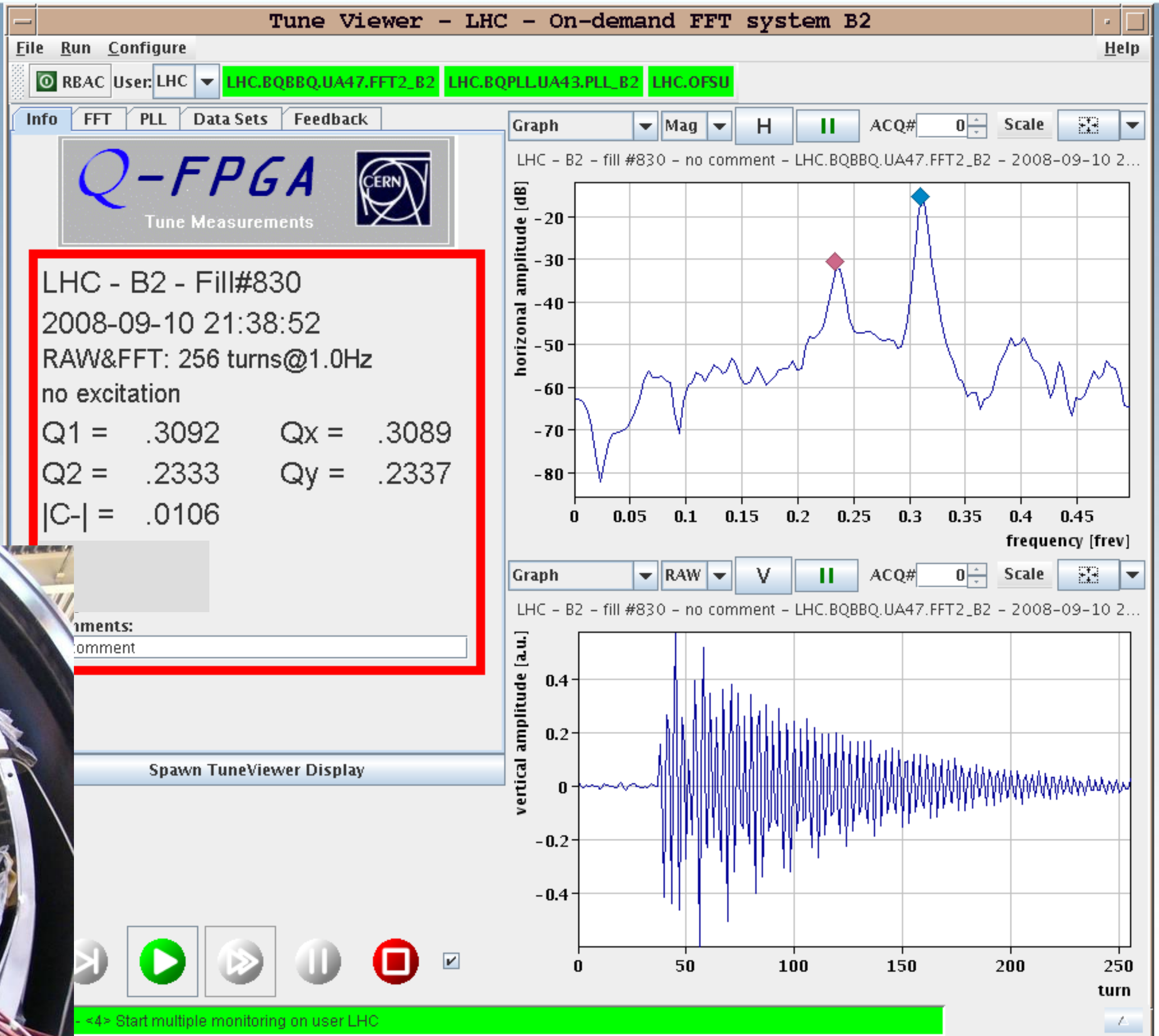
XI. Integer tunes



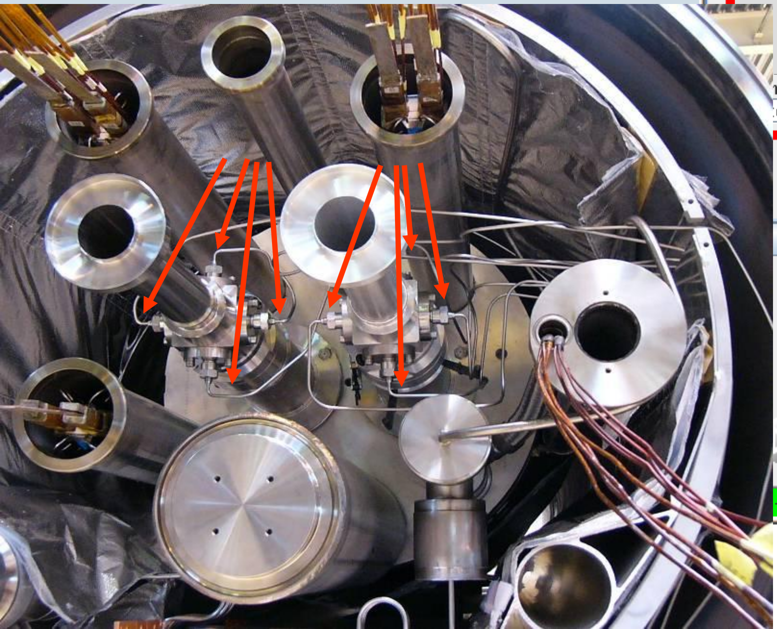
XII. Non-integer tunes

Qx = .279

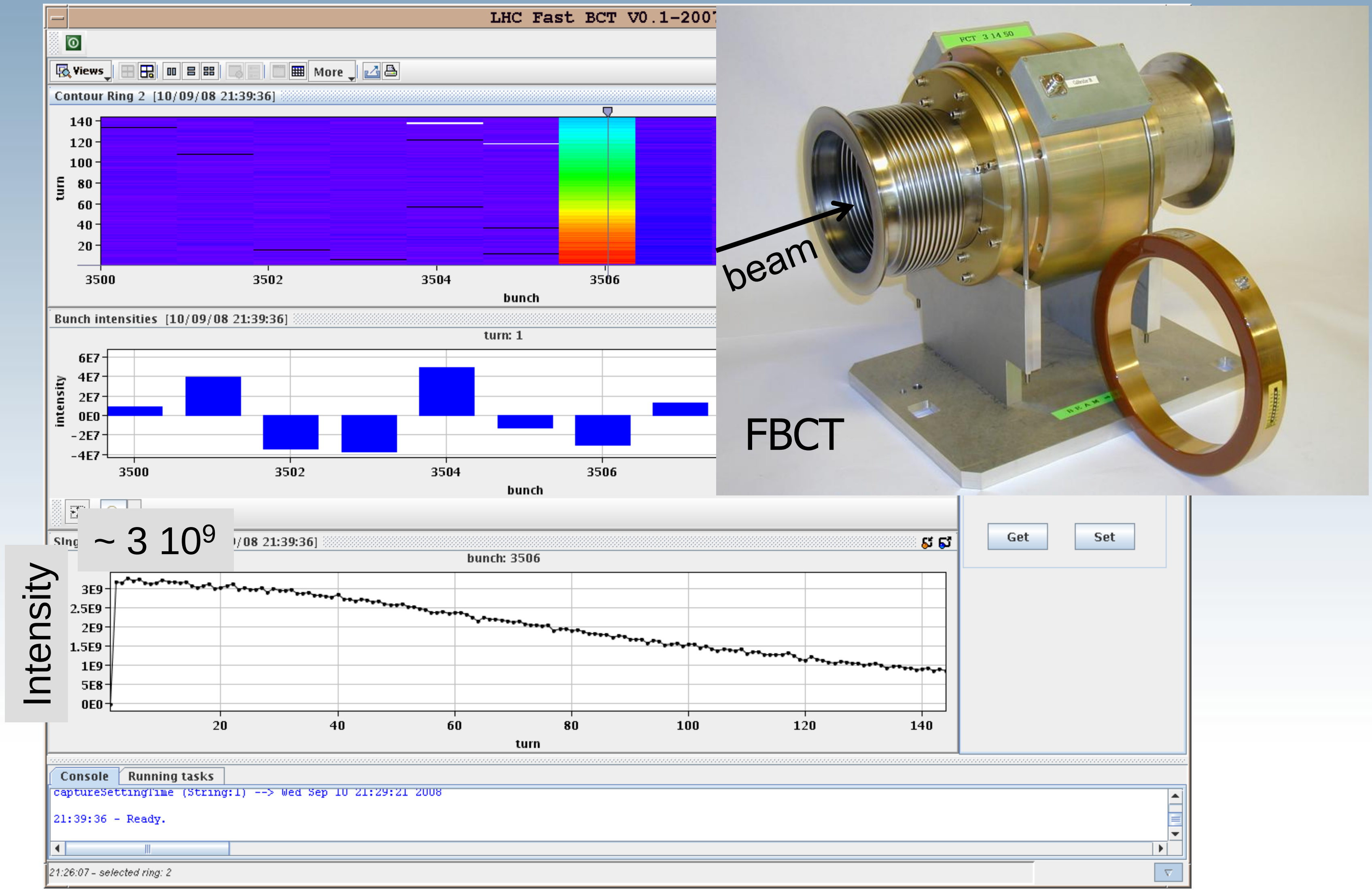
Qy = .310



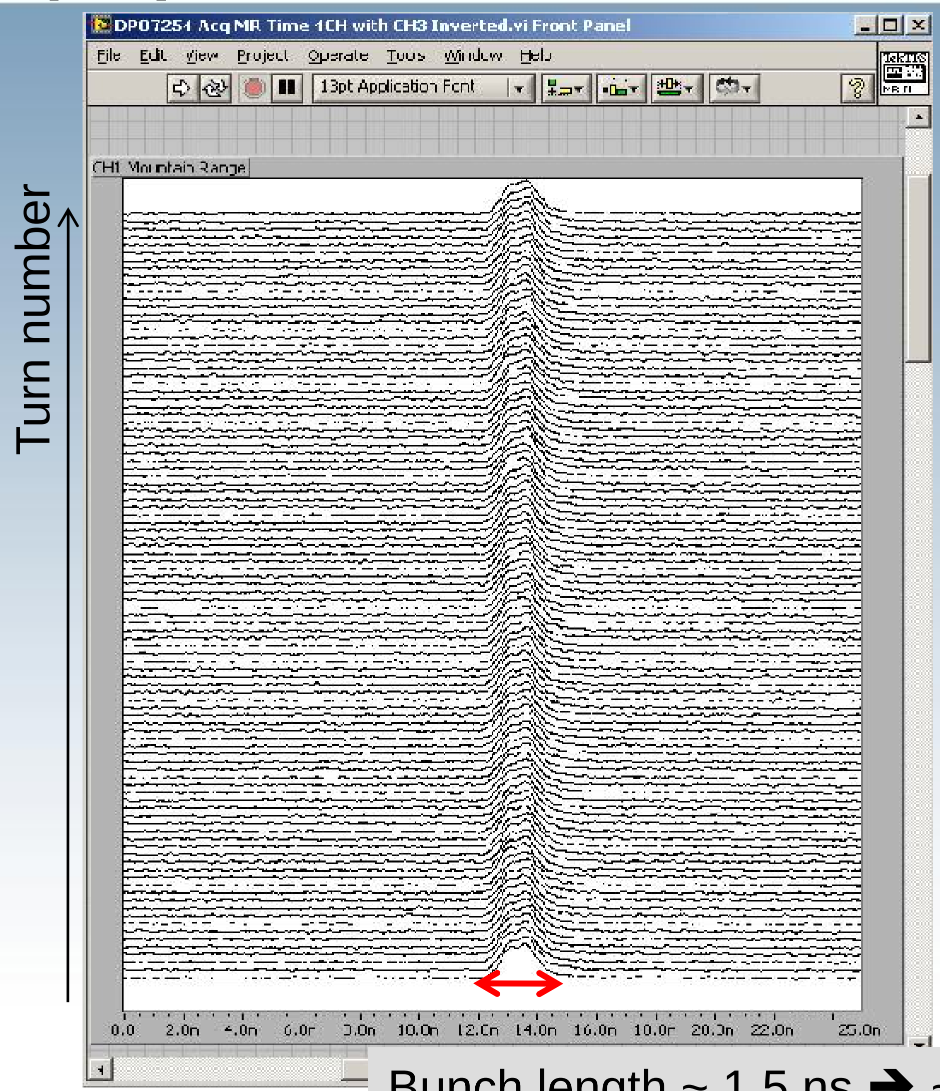
BPM pos ➔ FFT ➔ tune



XIII. Fast BCT (Beam Current Transformer)



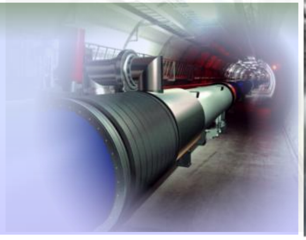
XIV. Beam captured – mountain range display



Bunch length ~ 1.5 ns ➔ ~ 45 cm

Now RF ON

Beam parameters (nominal)



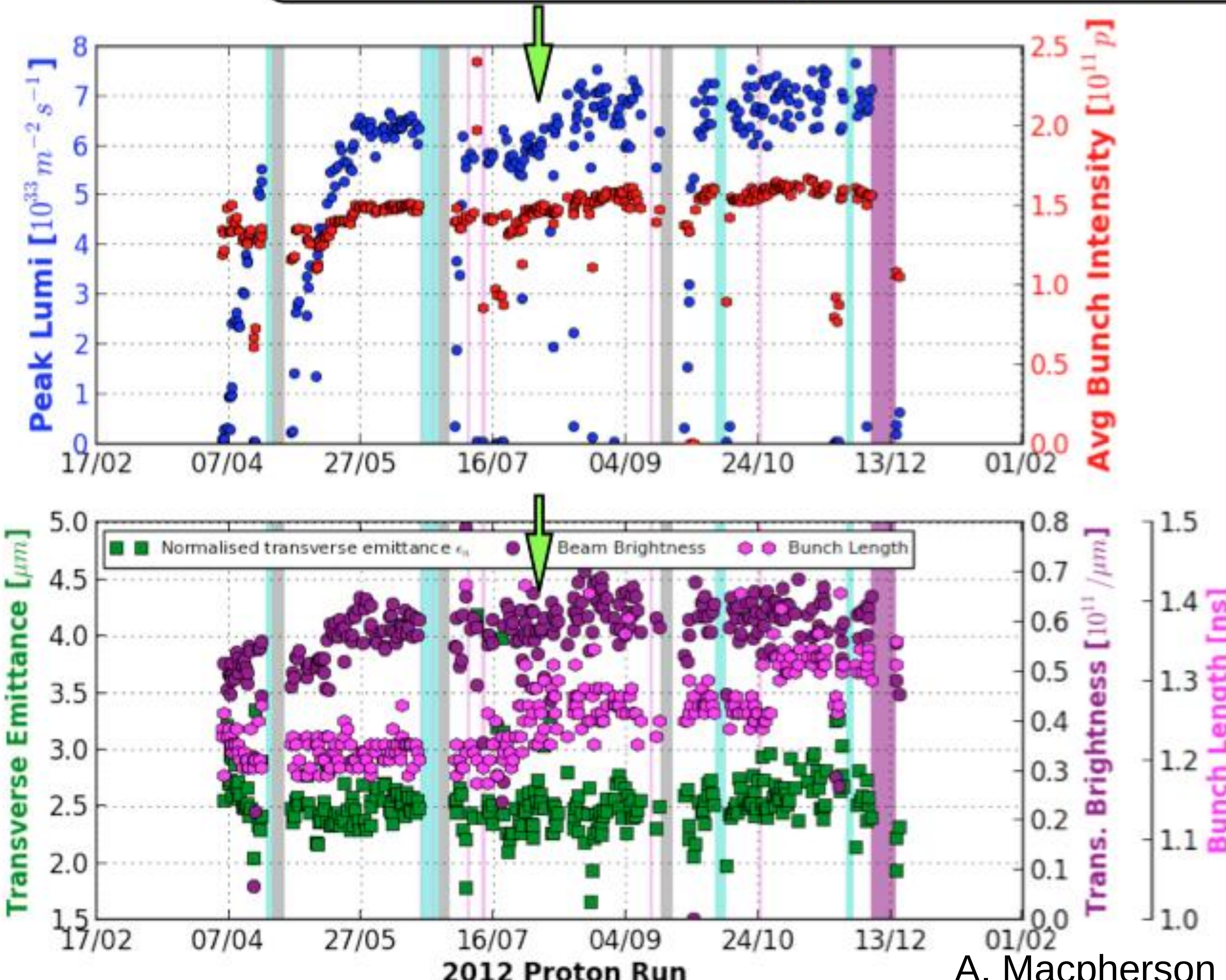
		Injection	Collision	2012
Proton energy	GeV	450	7000	4000
Particles/bunch		1.15×10^{11}		**1.6** $\times 10^{11}$
Num. bunches		2808		1380
Longitudinal emittance (4σ)	eVs	1.0	2.5	
Transverse normalized emittance	µm rad	3.5	3.75	
Beam current	A	0.582		
Stored energy/beam	MJ	23.3	362	
		Peak luminosity 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

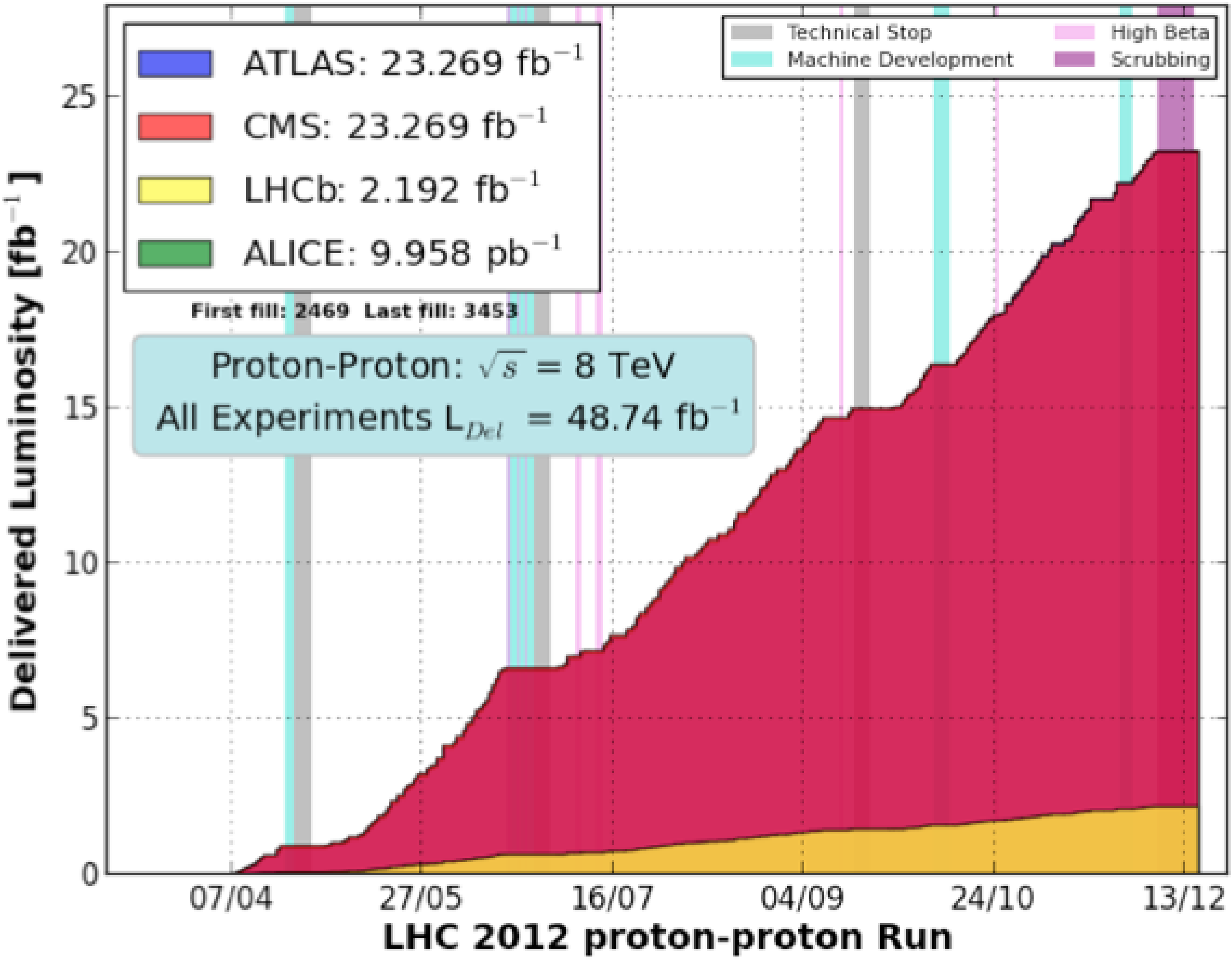
2012 Performance evolution - in one slide

Peak lumi increases with brightness and mean bunch length



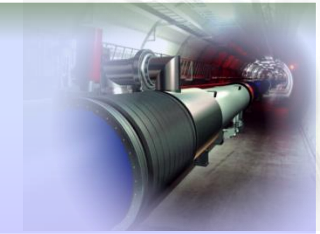
A. Macpherson Evian 2012

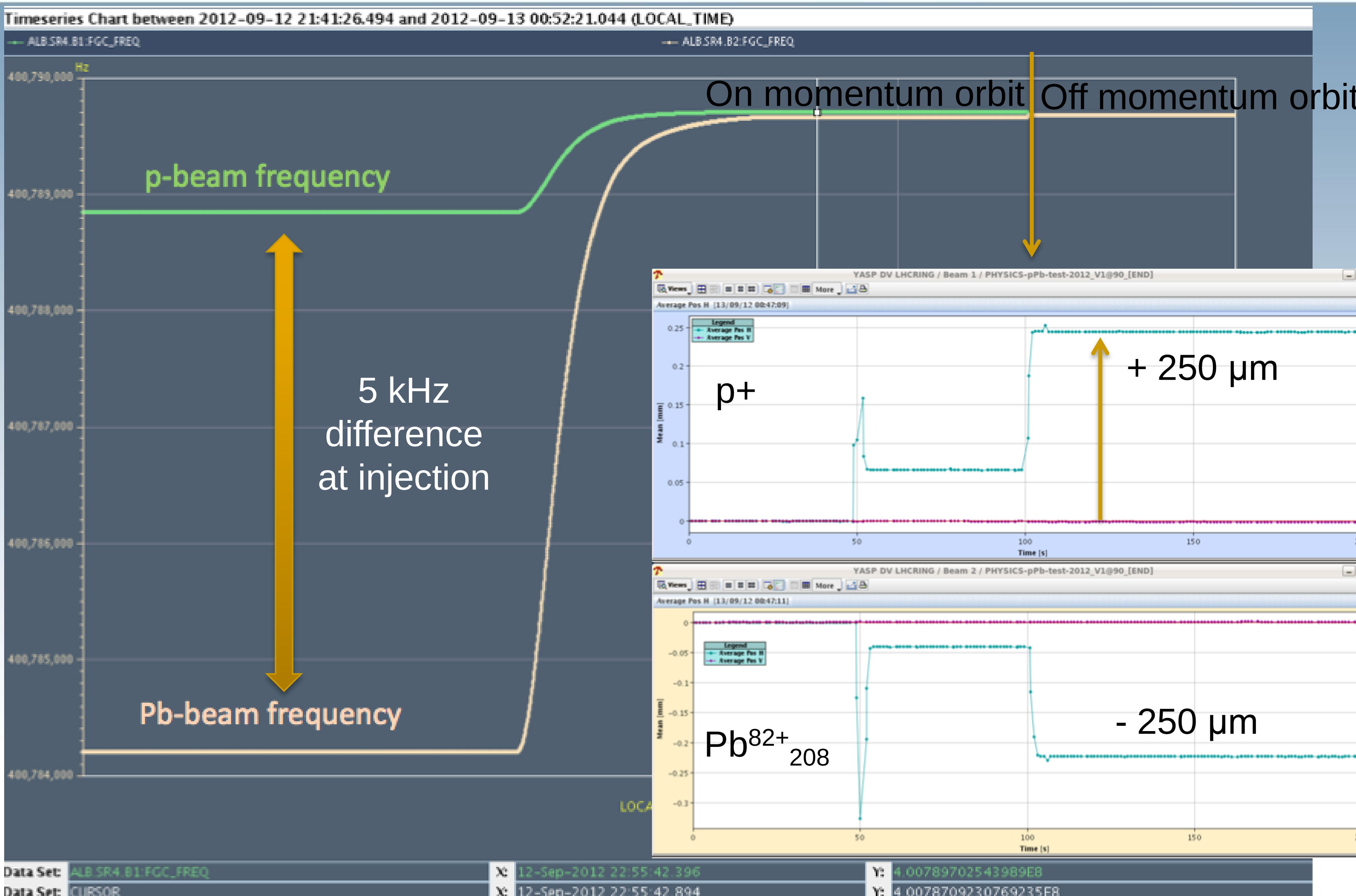
2012 - Luminosity Delivered

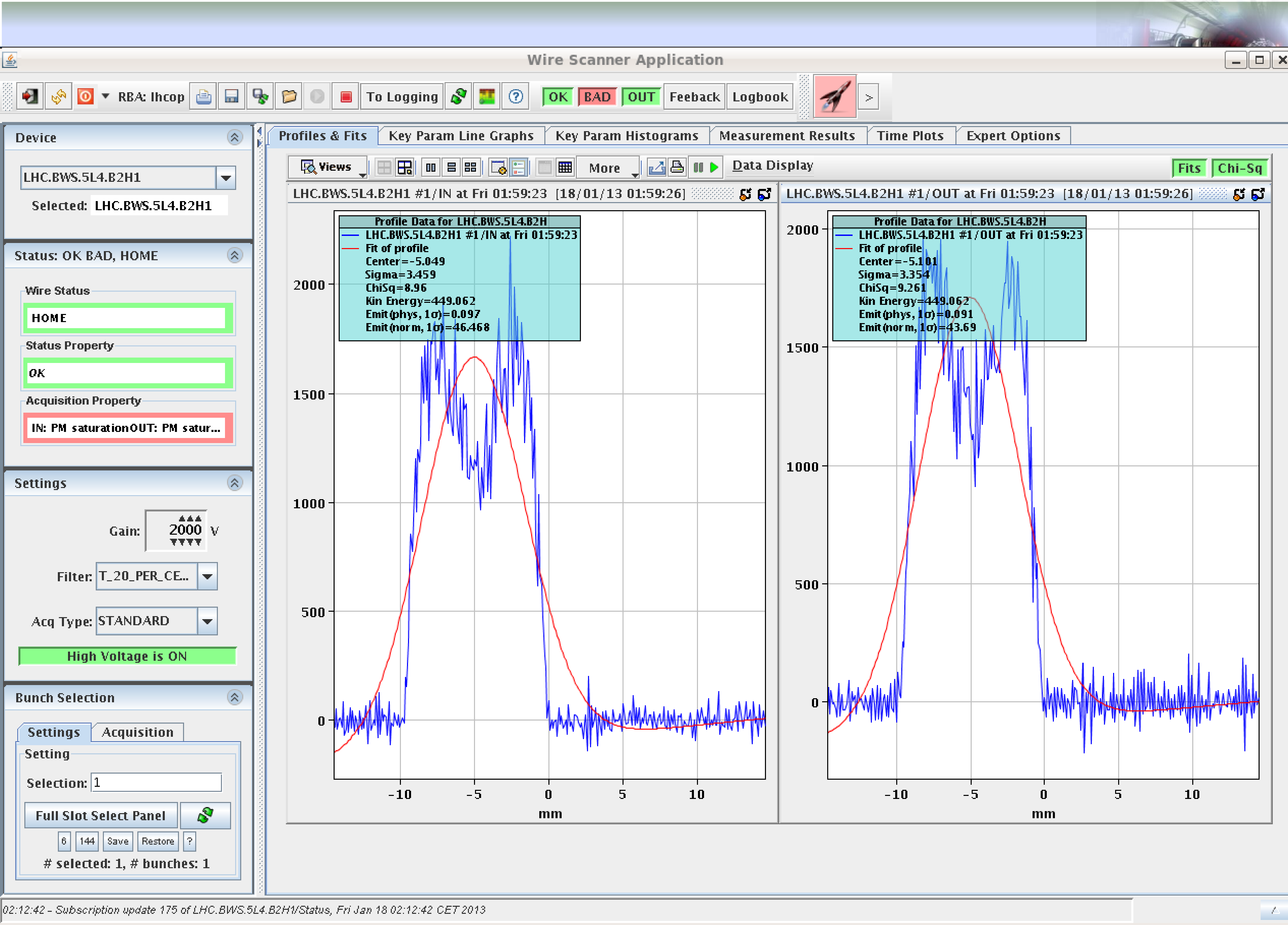


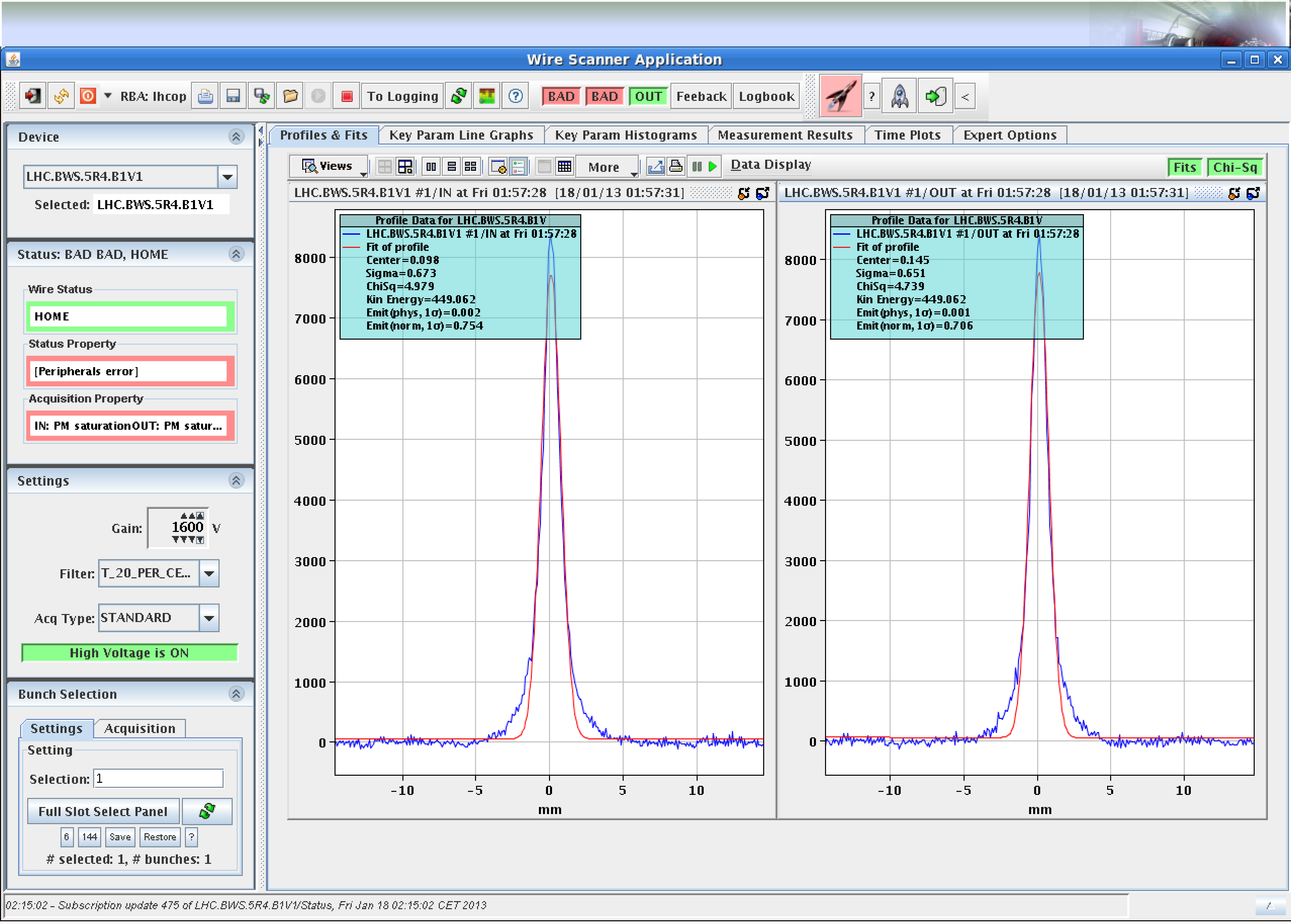
A. Macpherson Evian 2012

pPb physics during 2013






Wire Scanner Application
RBA: lhcop
To Logging
OK
BAD
OUT
Feeback
Logbook
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
Settings
Acquisition
Setting
Selection: 1
Full Slot Select Panel
6
144
Save
Restore
?
selected: 1, # bunches: 1
Profiles & Fits
Key Param Line Graphs
Key Param Histograms
Measurement Results
Time Plots
Expert Options
Views
More
Data Display
Fits
Chi-Sq
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
mm
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
mm
02:12:42 - Subscription update 175 of LHC.BWS.5L4.B2H1/Status, Fri Jan 18 02:12:42 CET 2013



Wire Scanner Application
RBA: lhcop
To Logging
BAD
BAD
OUT
Feeback
Logbook
Device
LHC.BWS.5R4.B1V1
Selected: LHC.BWS.5R4.B1V1
Status: BAD BAD, HOME
Wire Status
HOME
Status Property
[Peripherals error]
Acquisition Property
IN: PM saturationOUT: PM satur...
Settings
Gain: 1600 V
Filter: T_20_PER_CE...
Acq Type: STANDARD
High Voltage is ON
Bunch Selection
Settings
Acquisition
Setting
Selection: 1
Full Slot Select Panel
6
144
Save
Restore
?
selected: 1, # bunches: 1
Profiles & Fits
Key Param Line Graphs
Key Param Histograms
Measurement Results
Time Plots
Expert Options
Views
More
Data Display
Fits
Chi-Sq
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
mm
mm
02:15:02 - Subscription update 475 of LHC.BWS.5R4.B1V1/Status, Fri Jan 18 02:15:02 CET 2013