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[Engineer In Charge of LHC]
Seminar at the IFT Xmas meeting 2009, Madrid

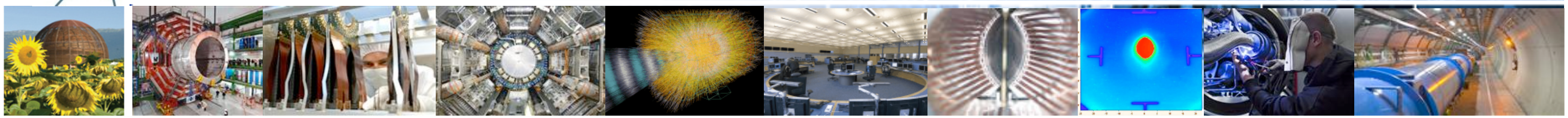
LHC & beam commissioning 2009

Contents:

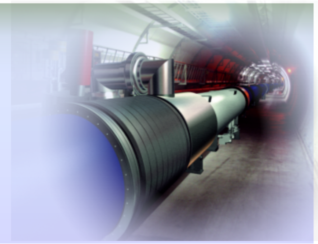
I. The machine: energy stored in the magnets

II. The beam: energy stored in the beams

III. The interaction regions



I. The machine



Contents:

I. Basic layout of the machine

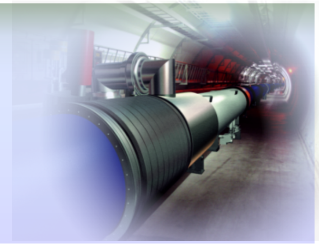
II. Energy stored in the magnets

   I. Quench protection system

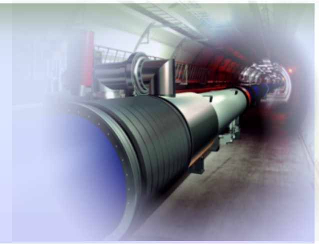
   II. Energy extraction

   III. Power interlock controller

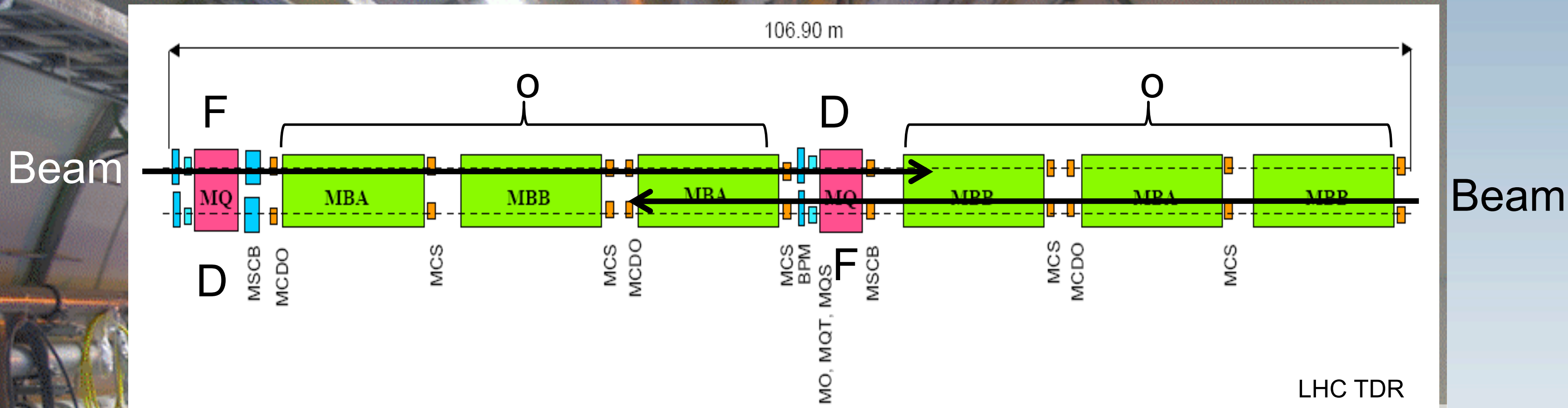
I.I Basic layout of the machine

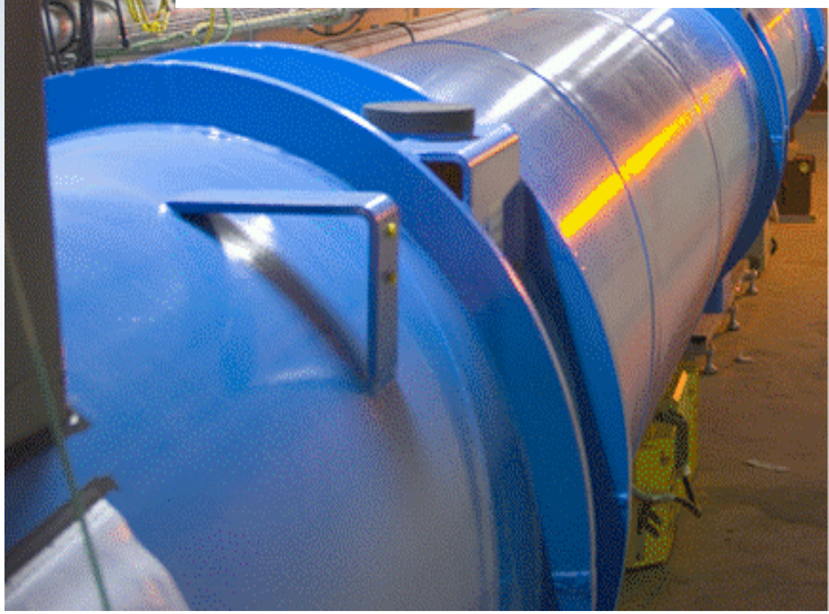


I.I. Basic layout of the machine: the arc



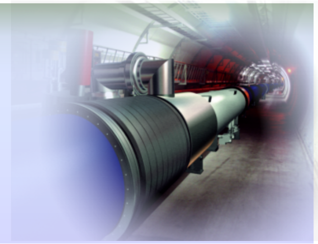
LHC arc cells = FoDo lattice* with
~ 90º phase advance per cell in the V & H plane



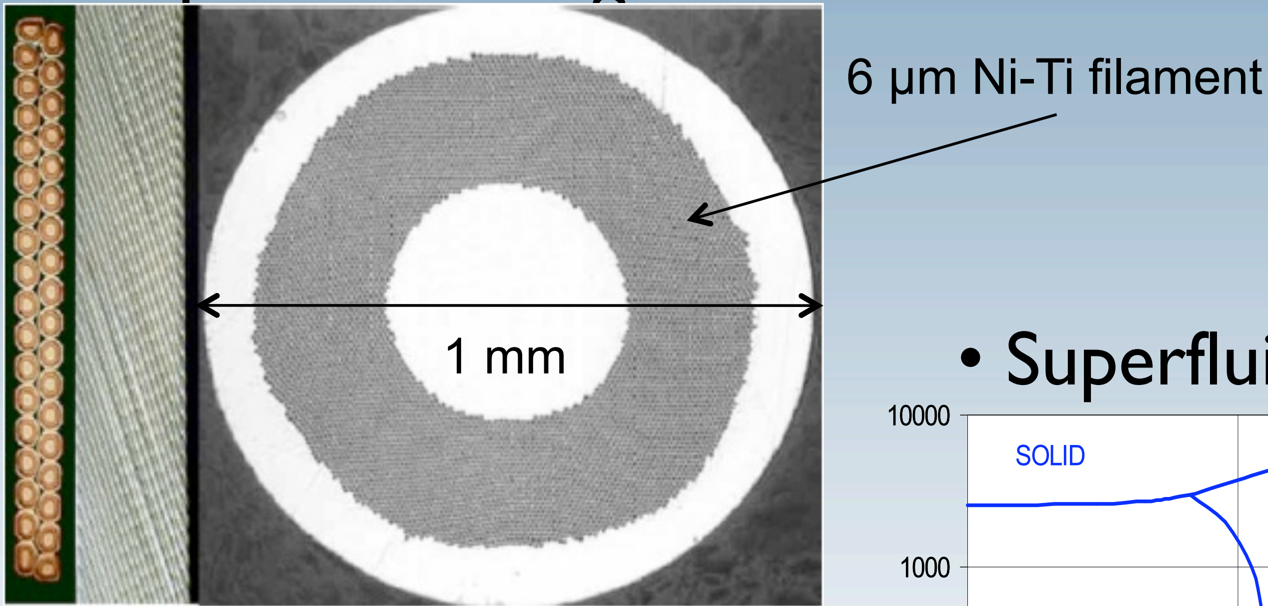


MB: main dipole
MQ: main quadrupole
MQT: Trim quadrupole
MQS: Skew trim quadrupole
MO: Lattice octupole (Landau damping)
MSCB: Skew sextupole + Orbit corrector (lattice chroma+orbit)
MCS: Spool piece sextupole
MCDO: Spool piece octupole + Decapole
BPM: Beam position monitor

I.I. Basic layout of the machine

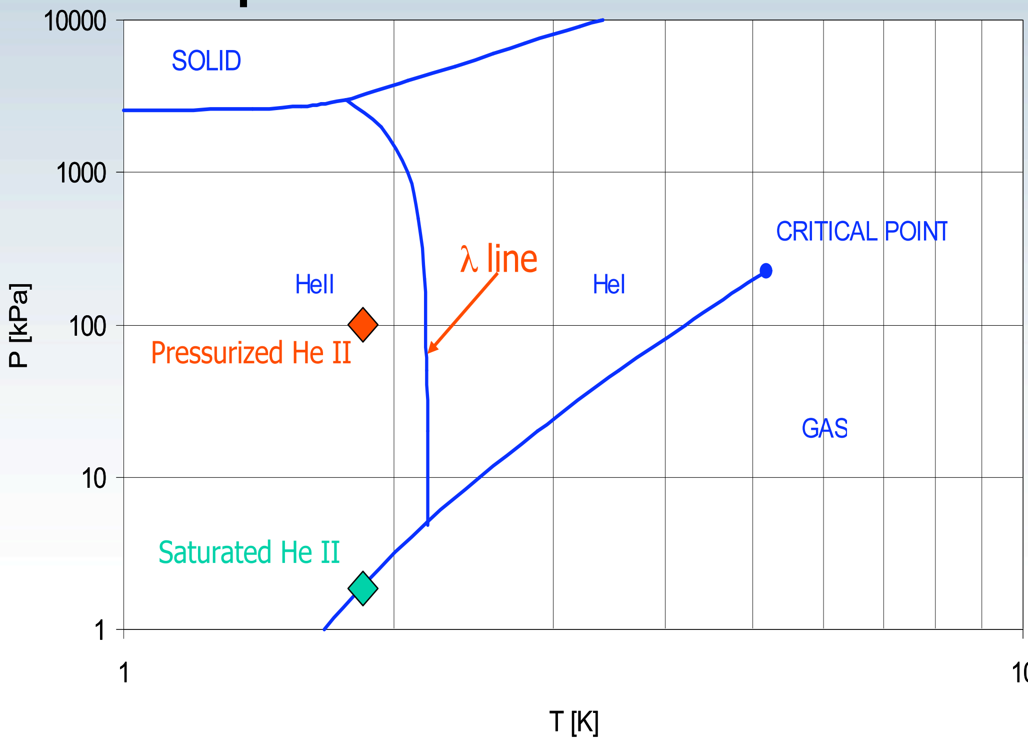


- Superconducting cables of Nb-Ti

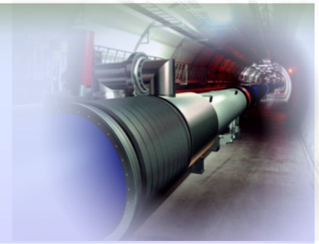


LHC ~ 27 km circumf. with 20 km of superconducting magnets operating @8.3 T. An equivalent machine with normal conducting magnets would have a circumference of 100 km and would consume 1000 MW of power ➔ we would need a dedicated nuclear power station for such a machine. LHC consumes ~ 10% nuclear power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

- Superfluid helium



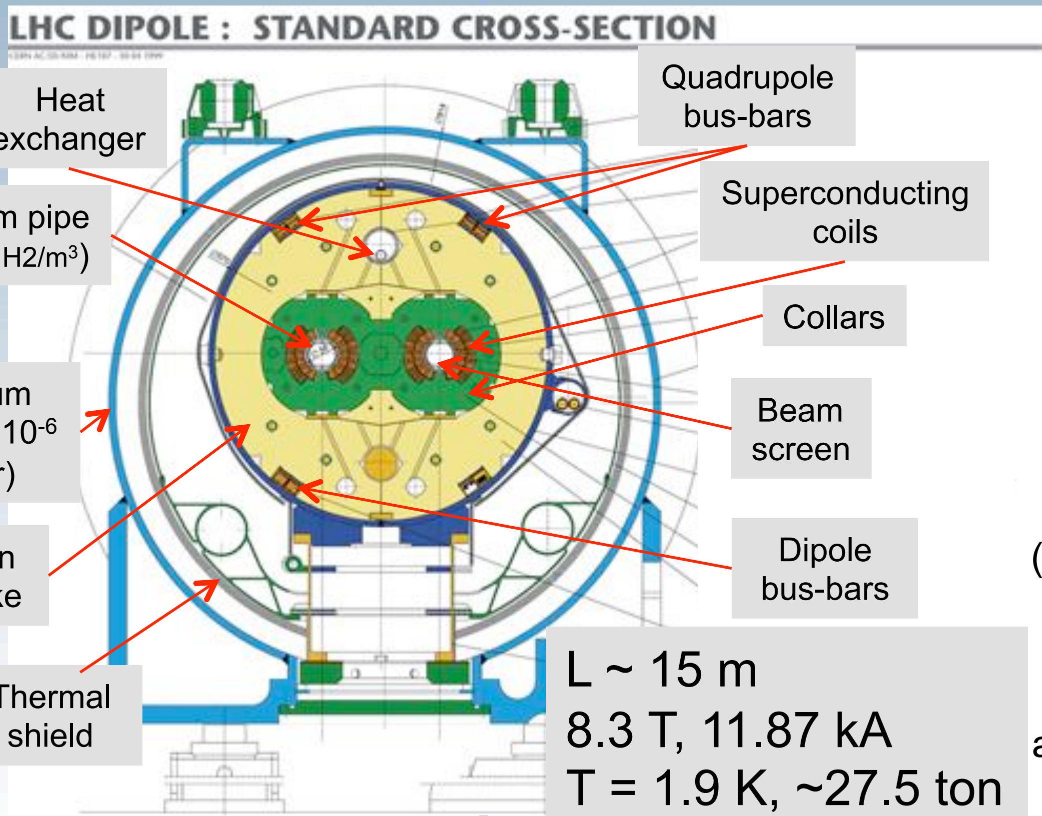
I.I. Basic layout of the machine: main dipoles



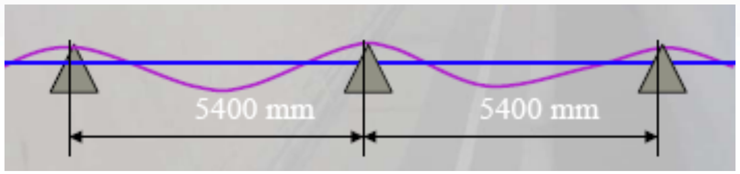
- The geometry of the main dipoles (Total of 1232 dipoles in LHC)

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

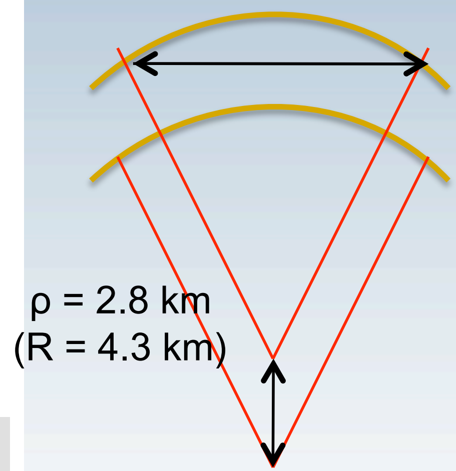


L ~ 15 m
8.3 T, 11.87 kA
T = 1.9 K, ~27.5 ton



HORIZONTAL PLANE

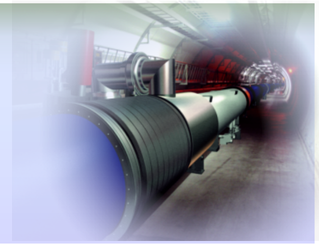
Length of the bend part =14.3 m

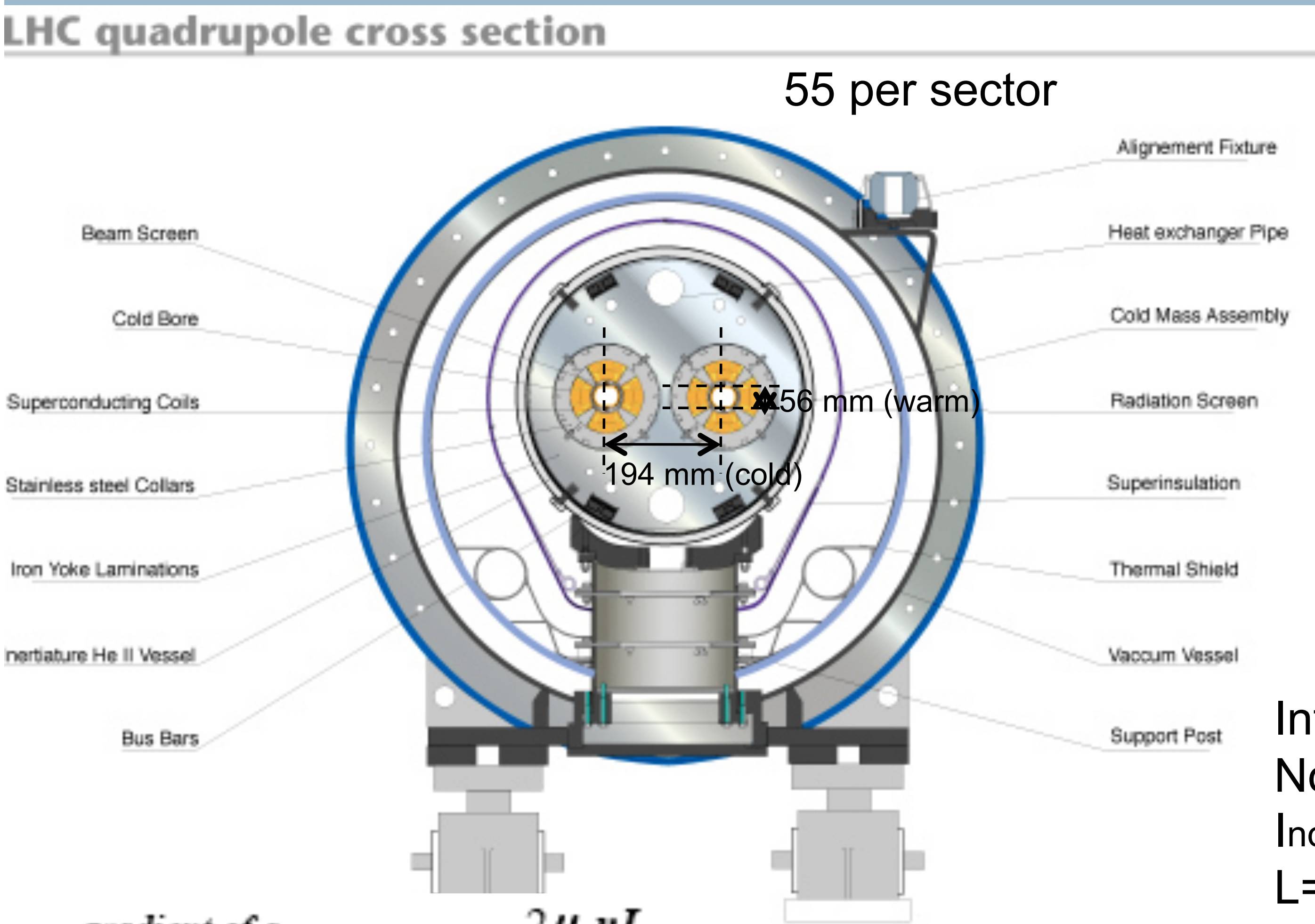


Distance between apertures = 194.5 mm

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.

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





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

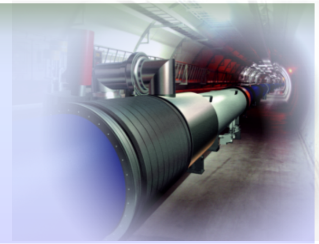
Integrated gradient = 690 T

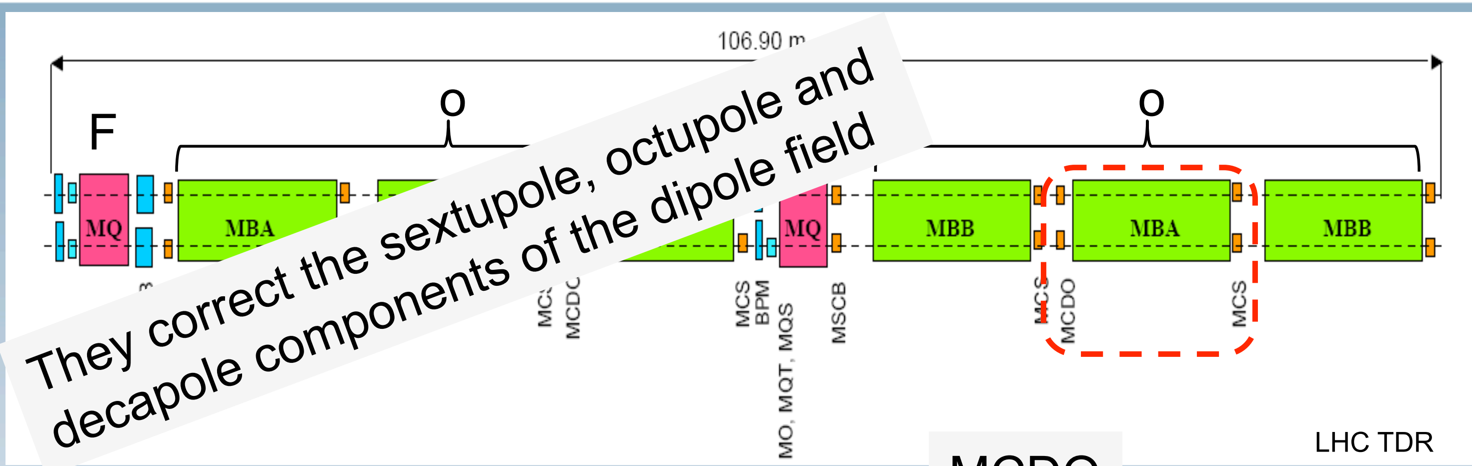
Nominal gradient = 223 T/m

$I_{nominal}$ = 11.87 kA

L=3.1 m

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

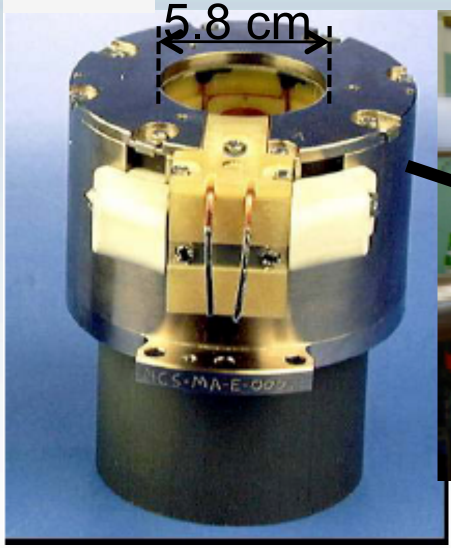


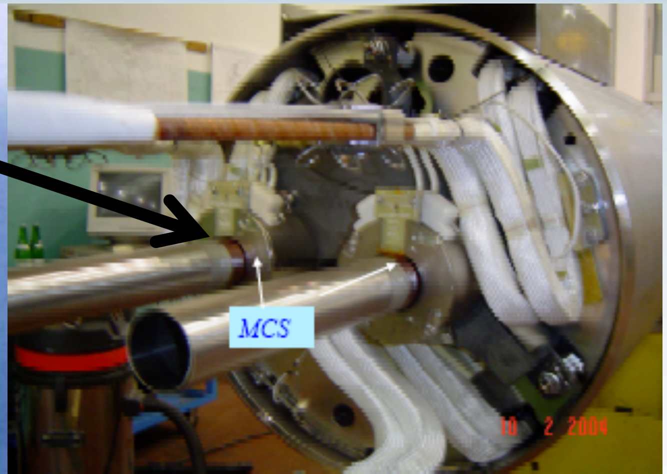


They correct the sextupole, octupole and decapole components of the dipole field

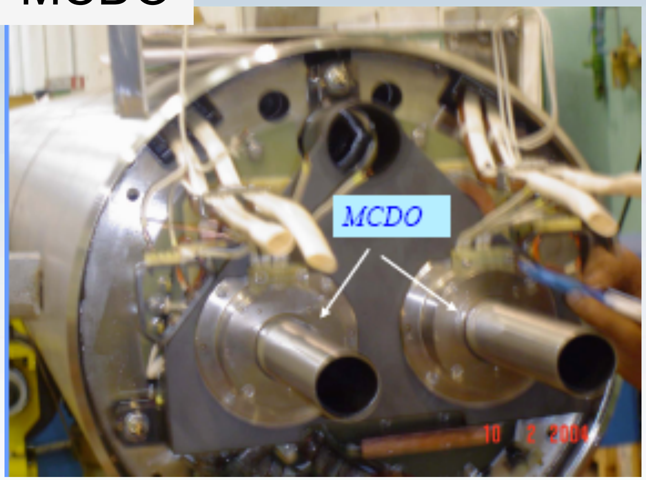
LHC TDR

MCS





MCDO

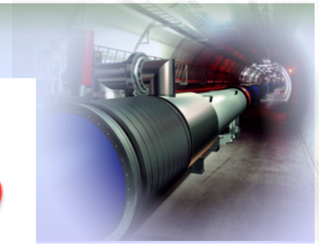


Nominal main field strength = 1630 T/m^2
Inominal = 550 A, 1.9 K,
L=15.5 cm, ~10 kg

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.I. Basic layout of the machine:



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

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

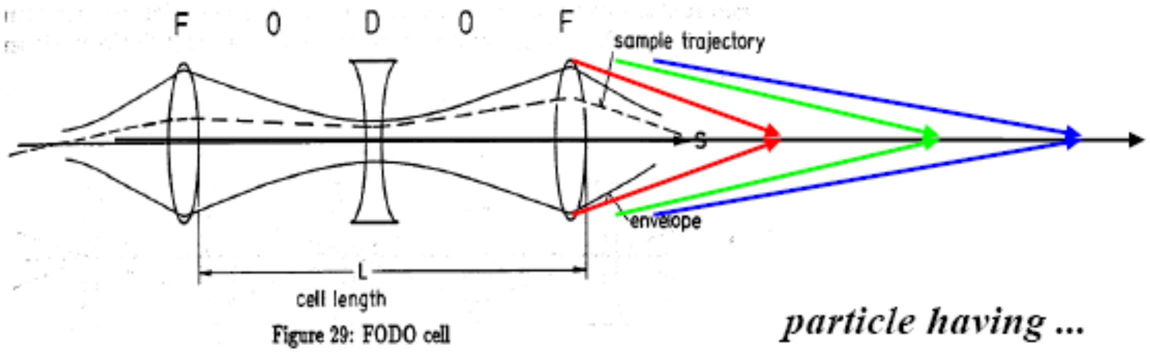
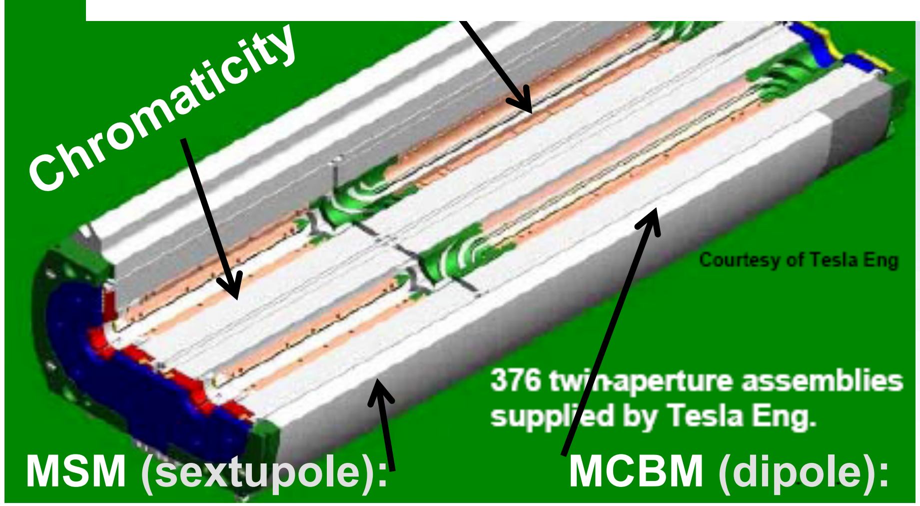


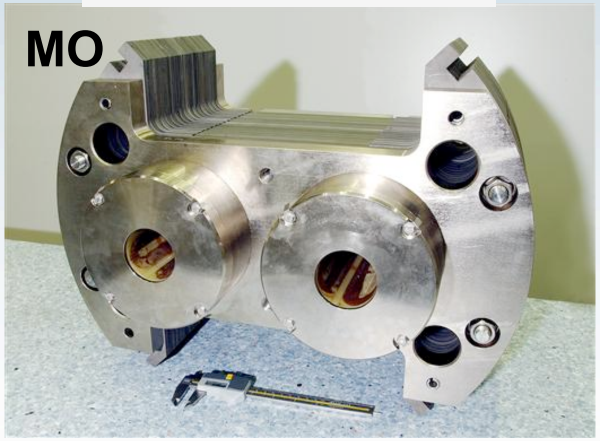
Figure 29: FODO cell

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

M

Landau damping





MQT/MQS: tune correction
Nominal main field strength = 123 T/m
Inominal = 550 A, 1.9 K
L=38 cm, ~250 kg

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

MCBM (dipole):
Nominal main field strength = 2.93 T
Inominal = 55 A, 1.9 K,
L=78.5 cm, ~143 kg

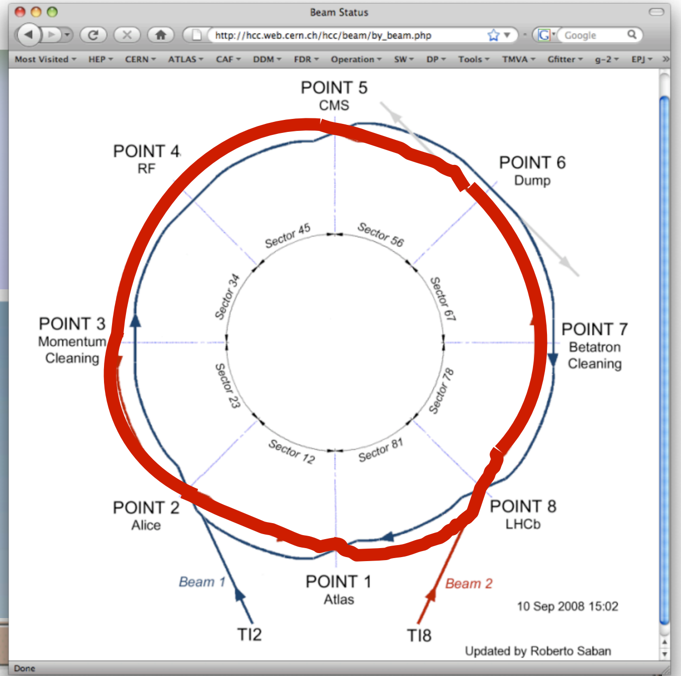
Nominal main field strength = 63100 T/m^3
Inominal = 550 A, 1.9 K
L=38 cm, ~8 kg

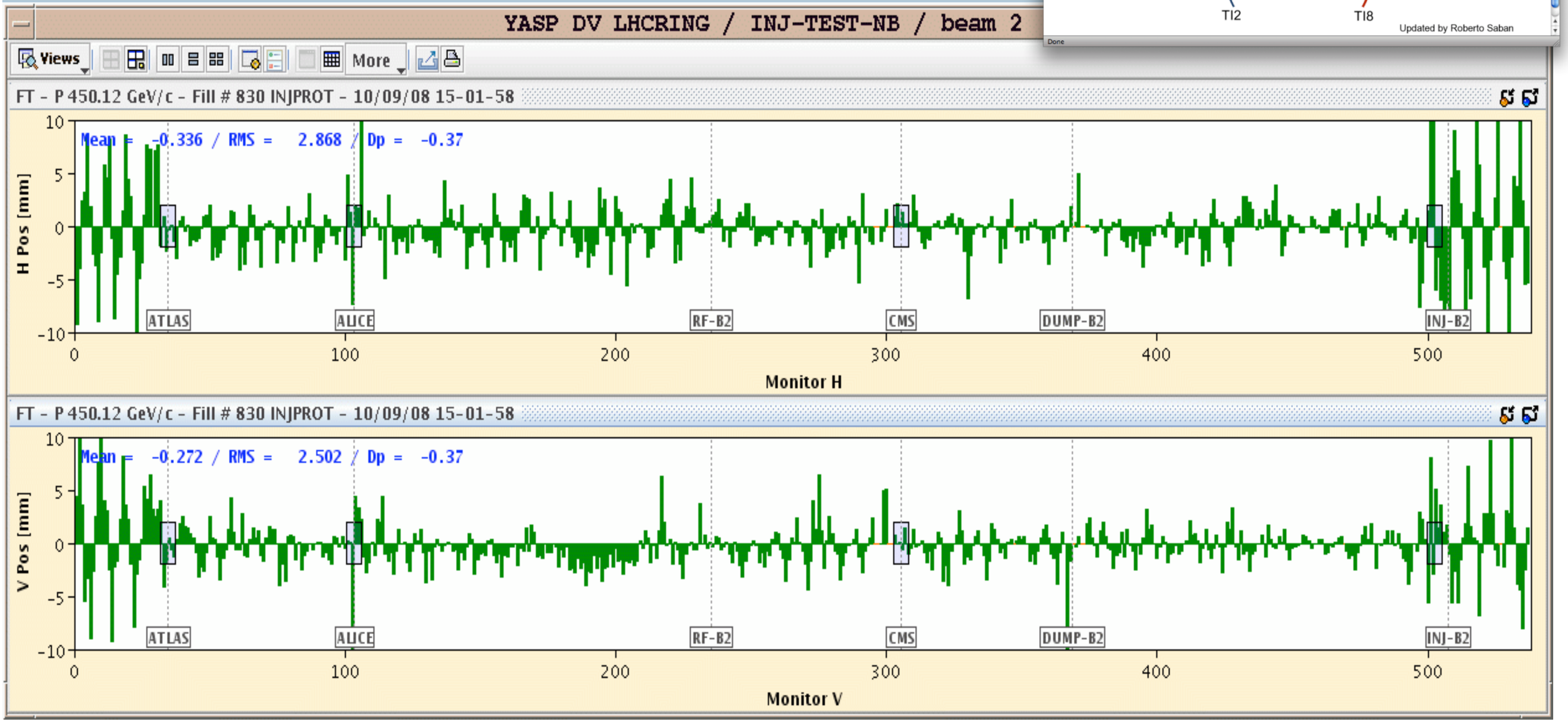
Beam threading (MCBM)

Threading by sector:

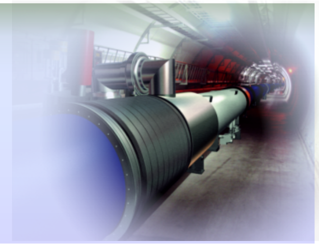
- One beam at the time
- Beam through 1 sector (1/8 ring),
  correct trajectory, open collimator and move on.

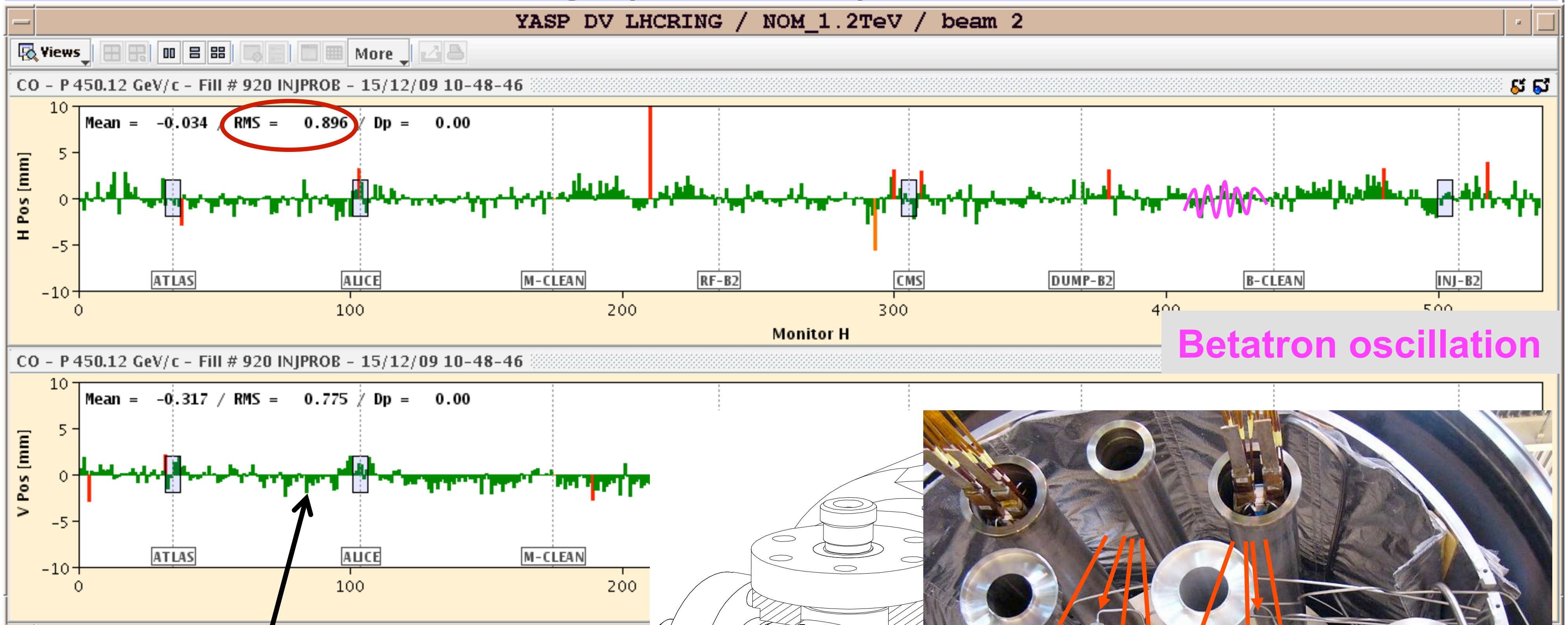
Beam 2 threading





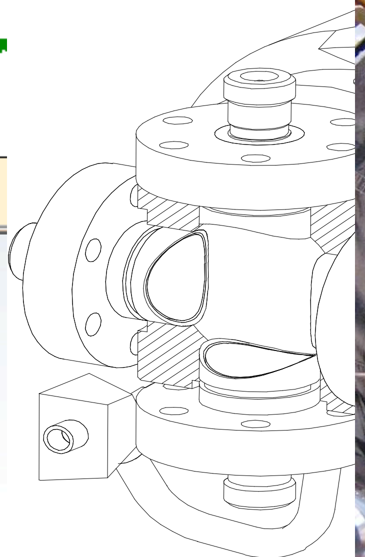
Beam threading (MCBM)

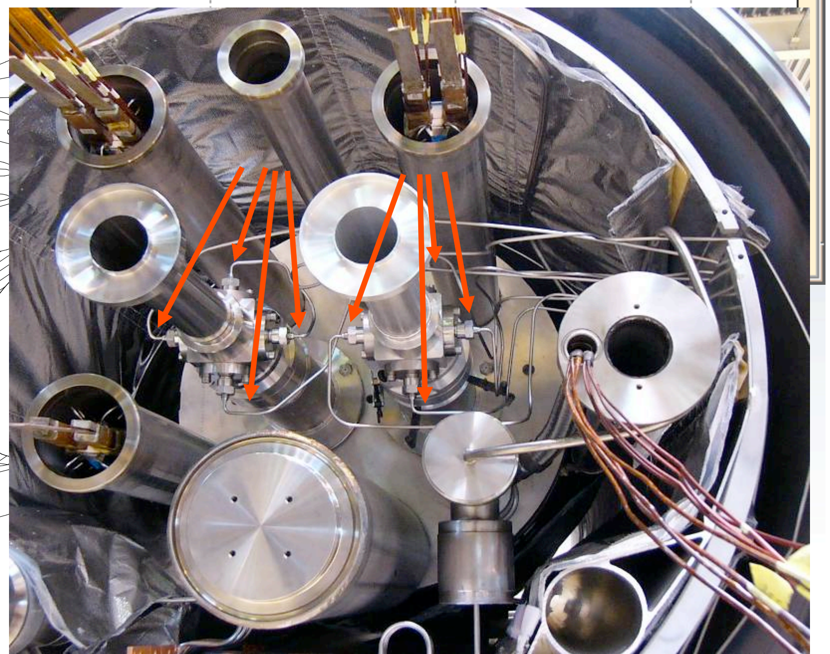




Betatron oscillation

Each point is a BPM (Beam Position Measurement)





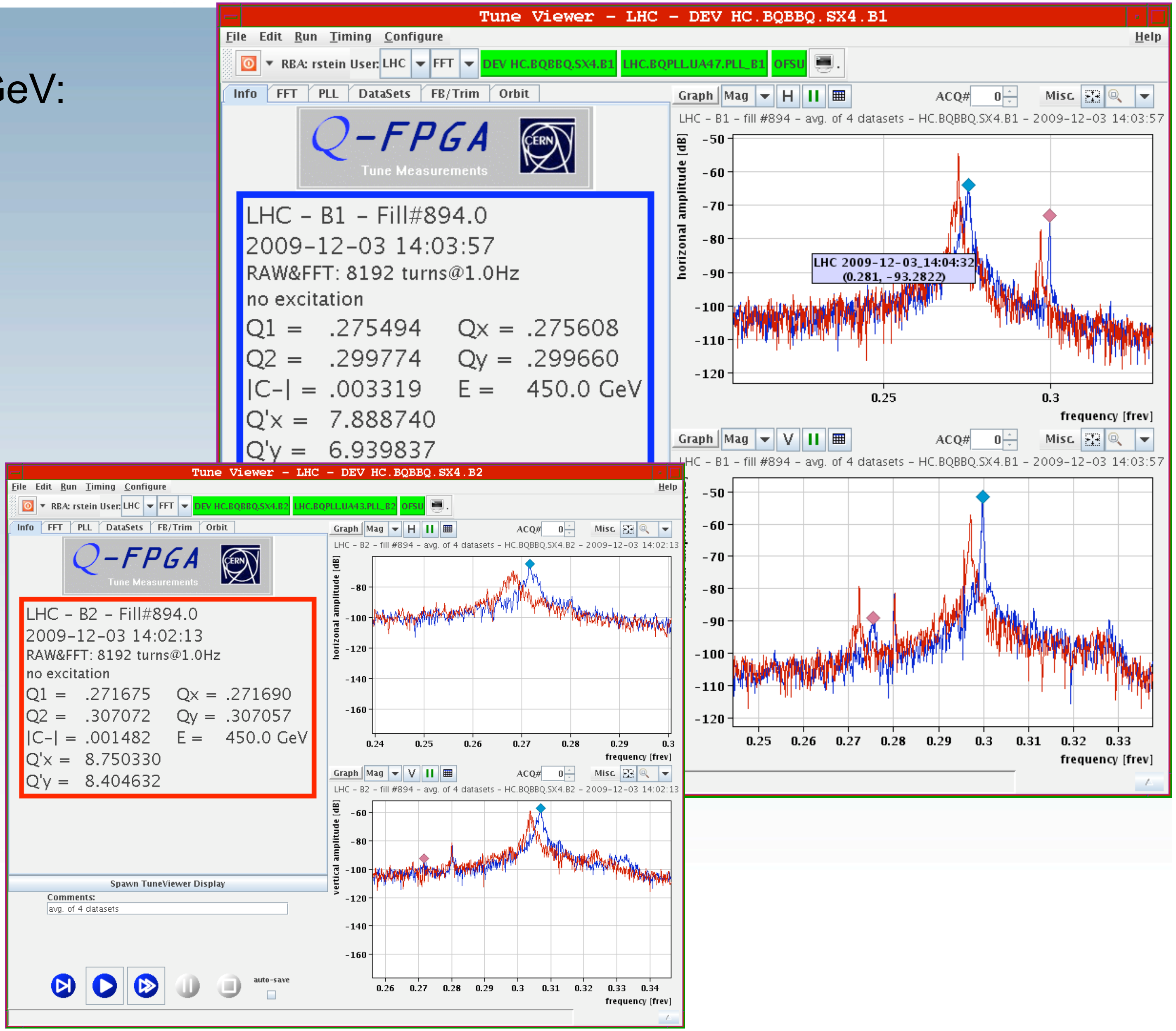
49 mm aperture

Tune (MQT)

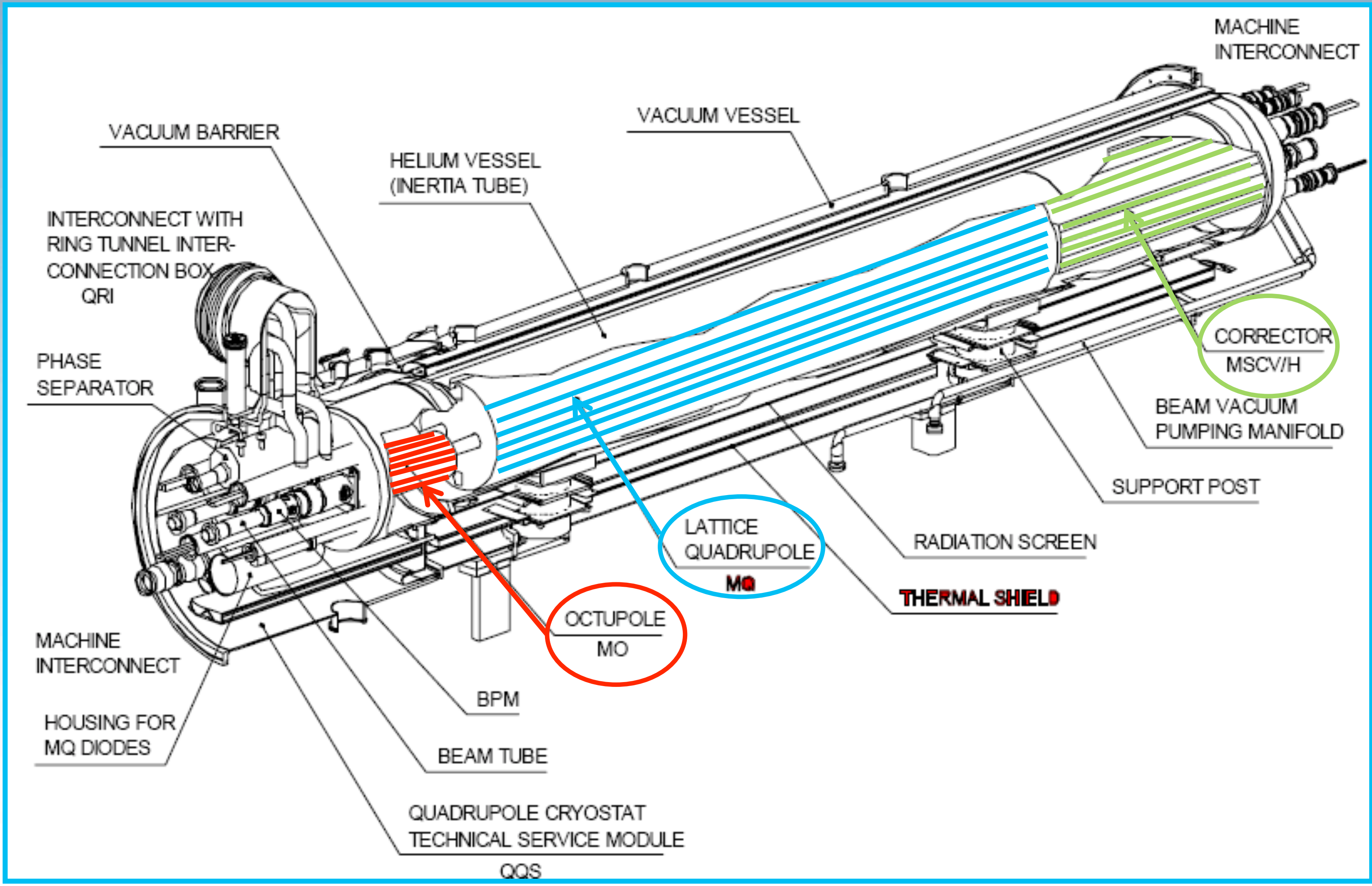
Theoretical tune @450 GeV:
Qx = 64.28
Qy = 59.31
Theoretical Chromaticity:
Q'x = 2
Q'y = 2

Integer part

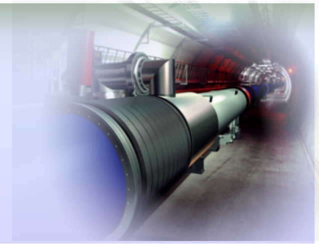
Fractional part always away from resonances, like 1/3=0.33



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

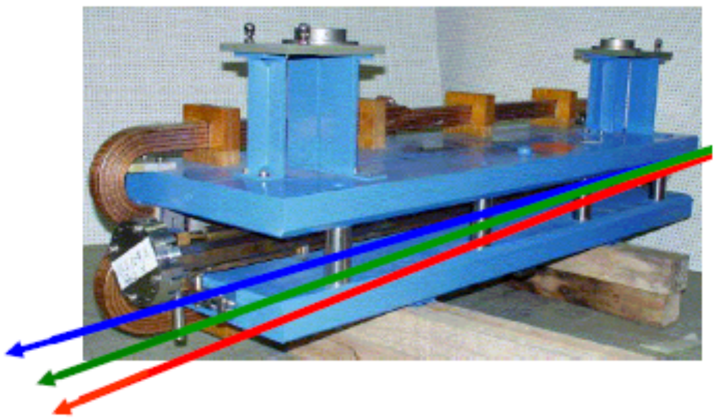


I.I. Basic layout of the machine: Dispersion suppression



dipole magnet

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



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

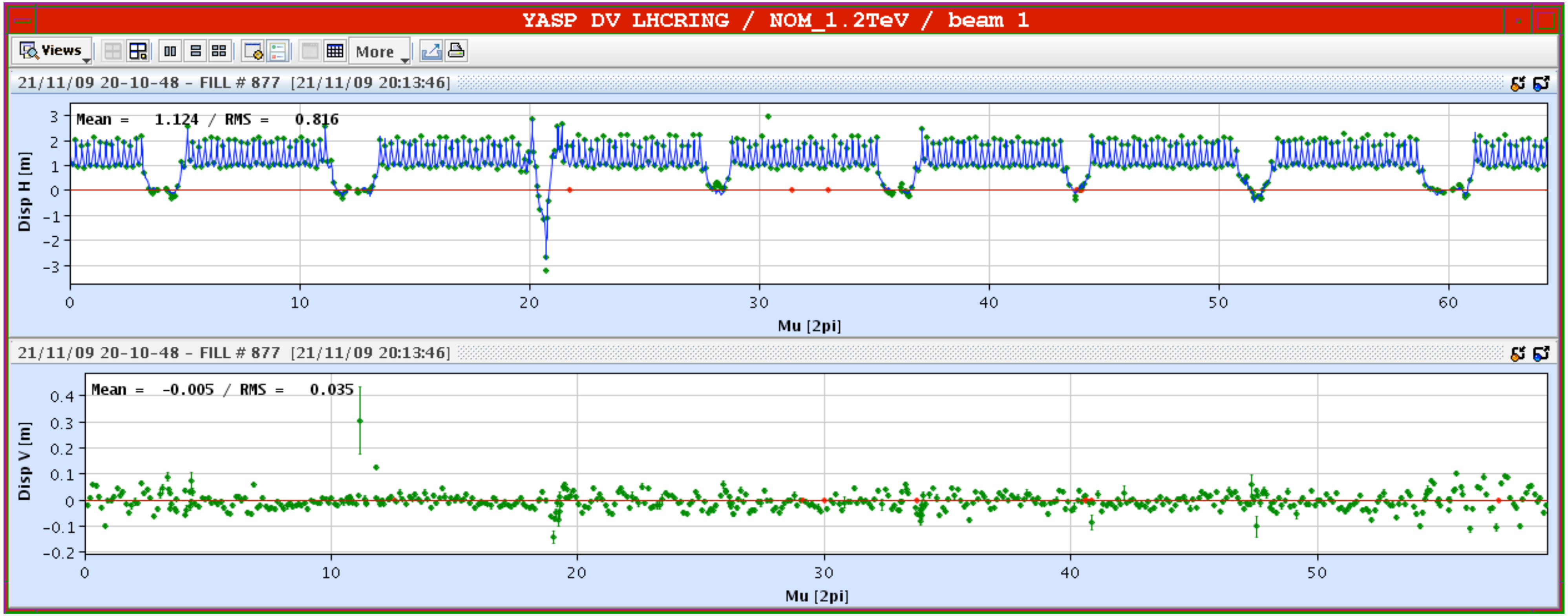
The dispersion suppression is located at the transition between the arc and the straight section. The schema above applies to all DS except the ones in IR3 and IR7.

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

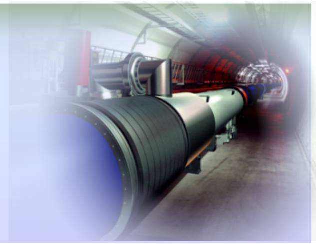
It is like an arc cell but with one missing dipole because of lack of space. If only dipoles are used they cannot fully cancel the dispersion, just by a factor 2.5. Therefore individual powered quadrupoles are required (Q8-Q11 with I ~ 6000 A).

Dispersion B1

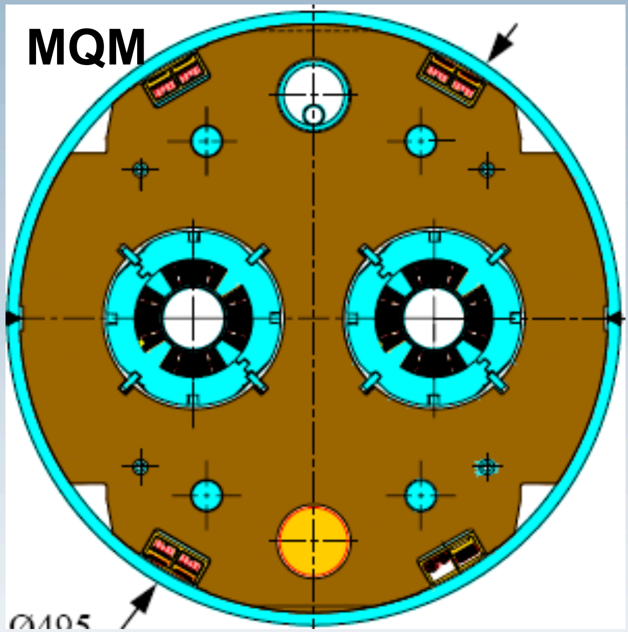


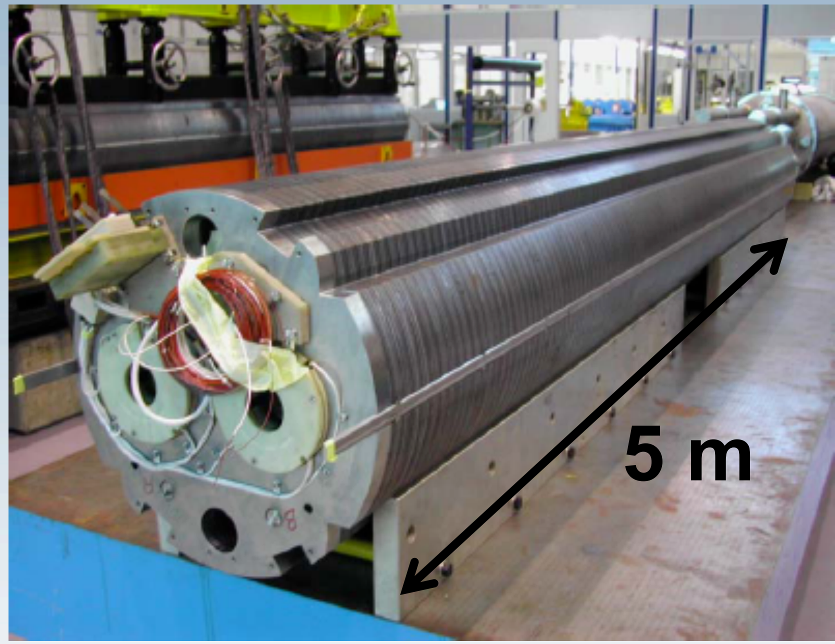
Green dots are measured: blue line calculated

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



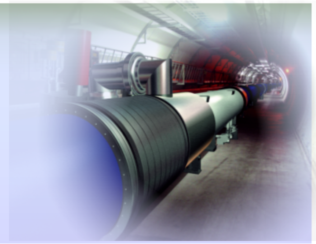
- Quadrupole types: MQ, **MQM**, MQTL





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

I. The machine



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I. Basic layout of the machine

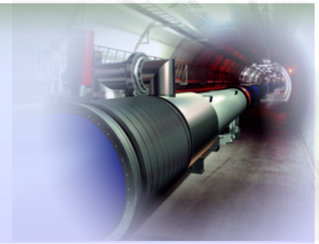
II. Energy stored in the magnets

    I. Quench protection system

    II. Energy extraction

    III. Power interlock controller

I.II. Energy stored in the magnets



~ 10 Gjoule* (only in the main dipoles) corresponds to ...

... an aircraft carrier at battle-speed of 55 km/h

The energy of ~3 Tons TNT
The energy of 370 kg dark chocolate

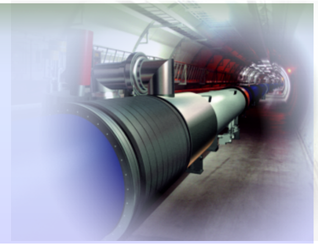
More important than the amount of energy is ...

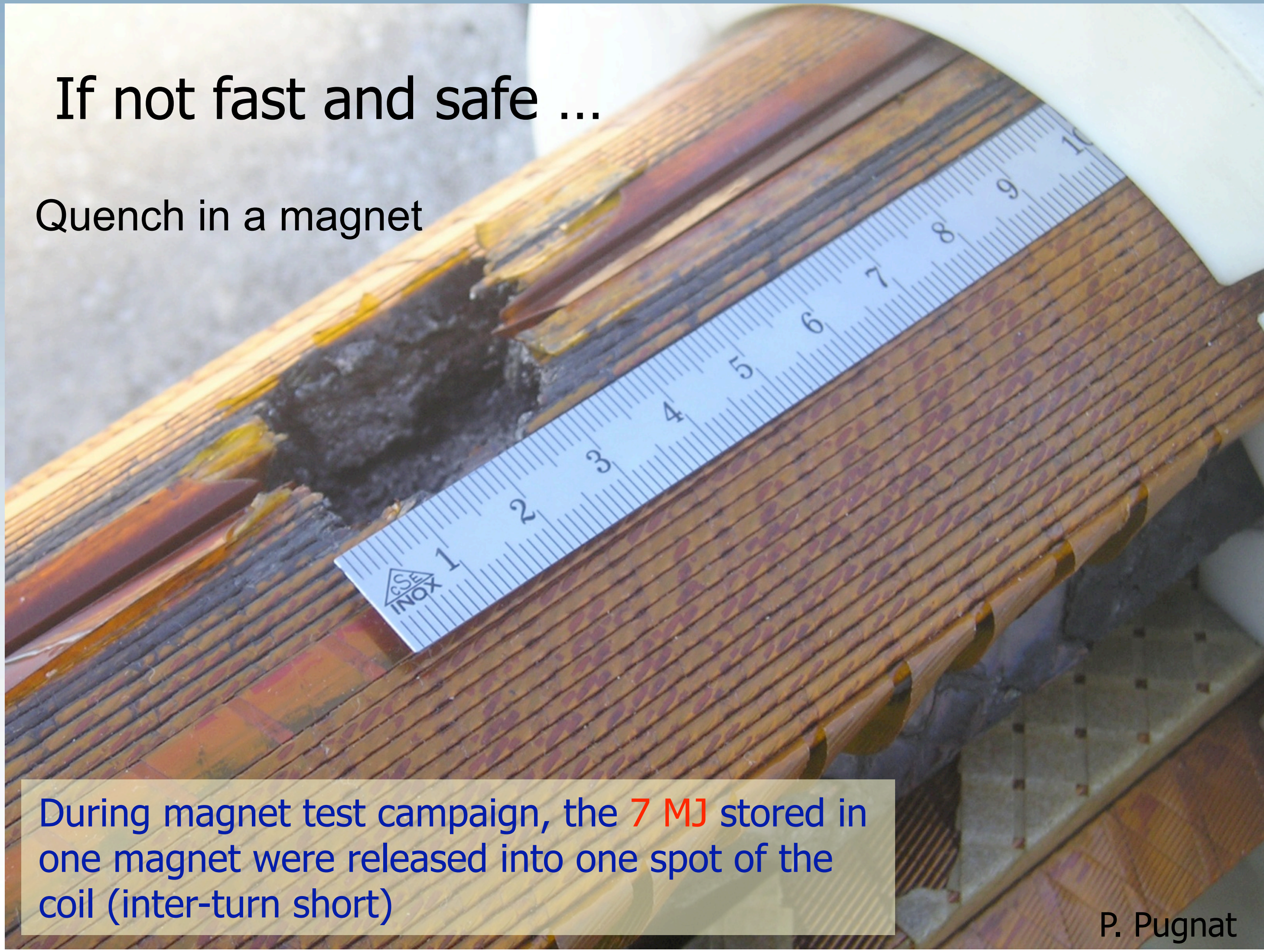
How fast (an safe) can this energy be released?

*$E=1/2LI^2$

L: inductance ~0.1 Henry for LHC dipoles

I.II. Energy stored in the magnets: quench





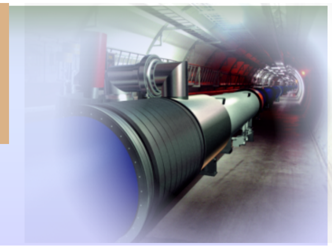
If not fast and safe …

Quench in a magnet

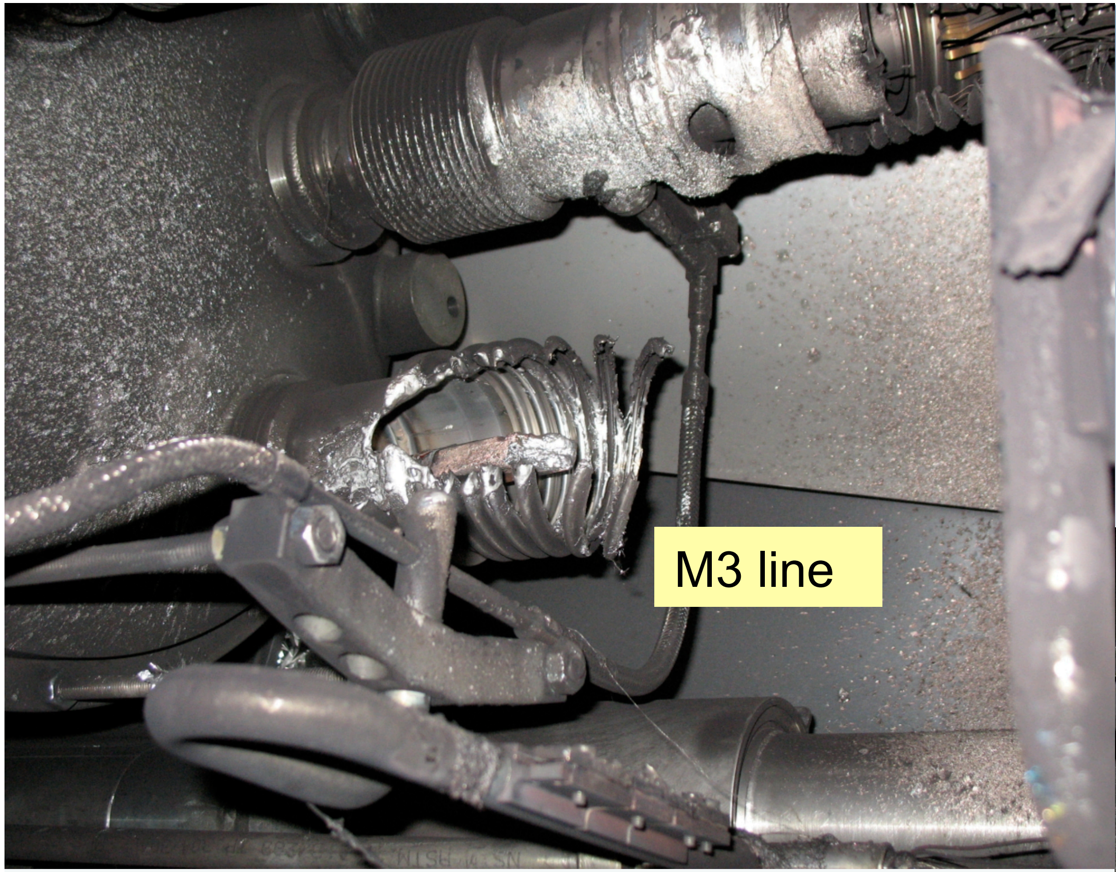
During magnet test campaign, the 7 MJ stored in one magnet were released into one spot of the coil (inter-turn short)

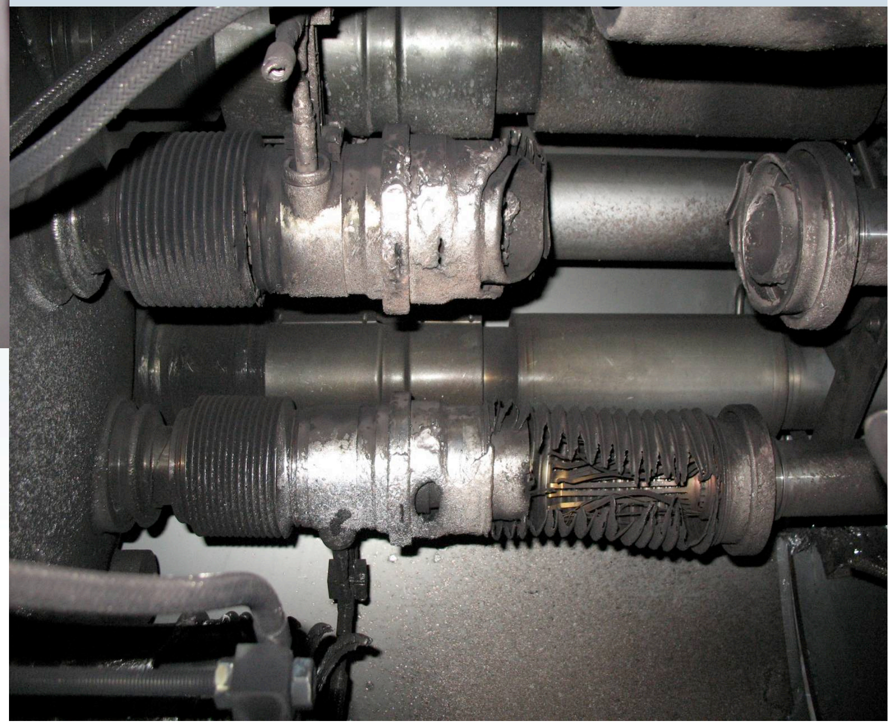
P. Pugnat

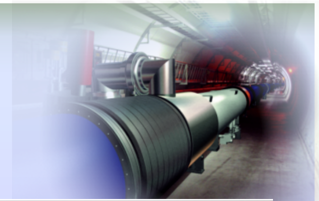
Quench in a bus bar (19 Sep 2008)

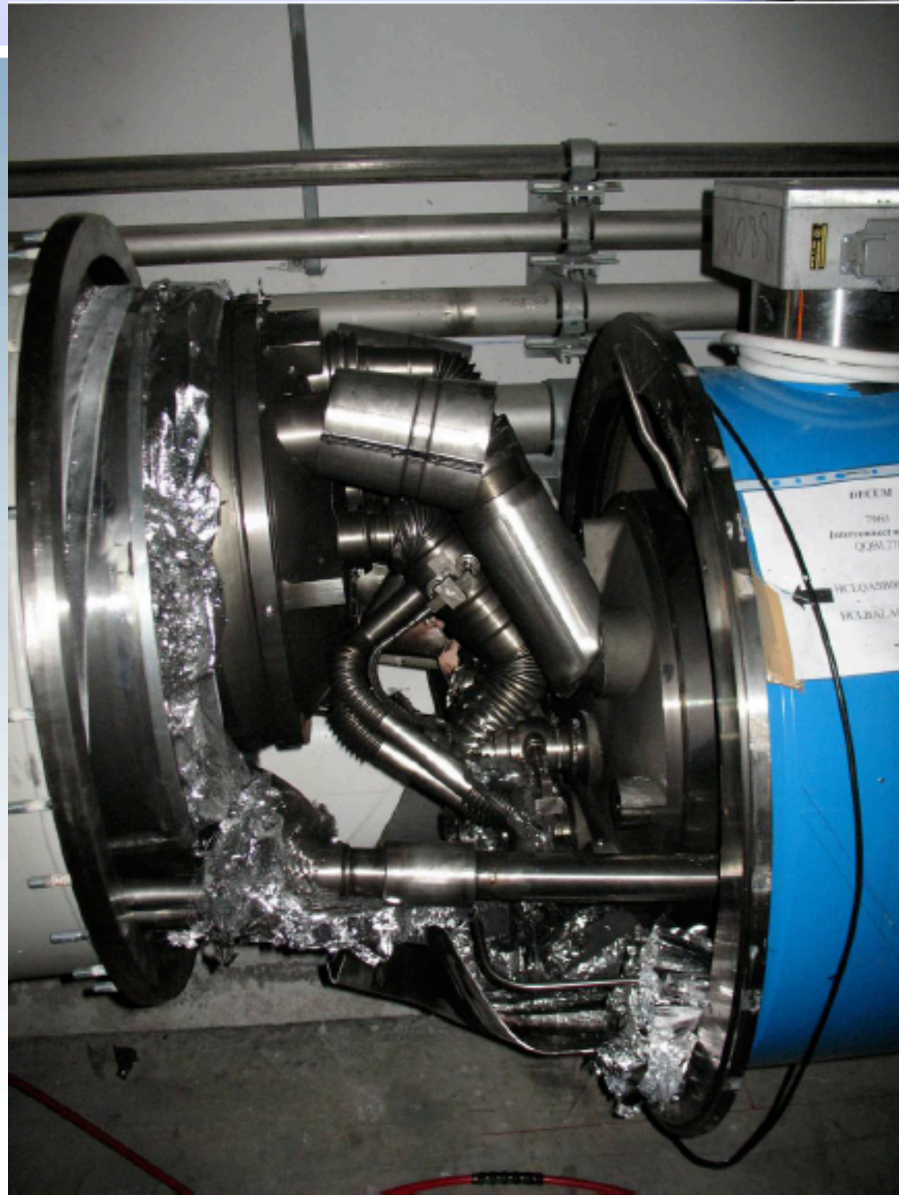


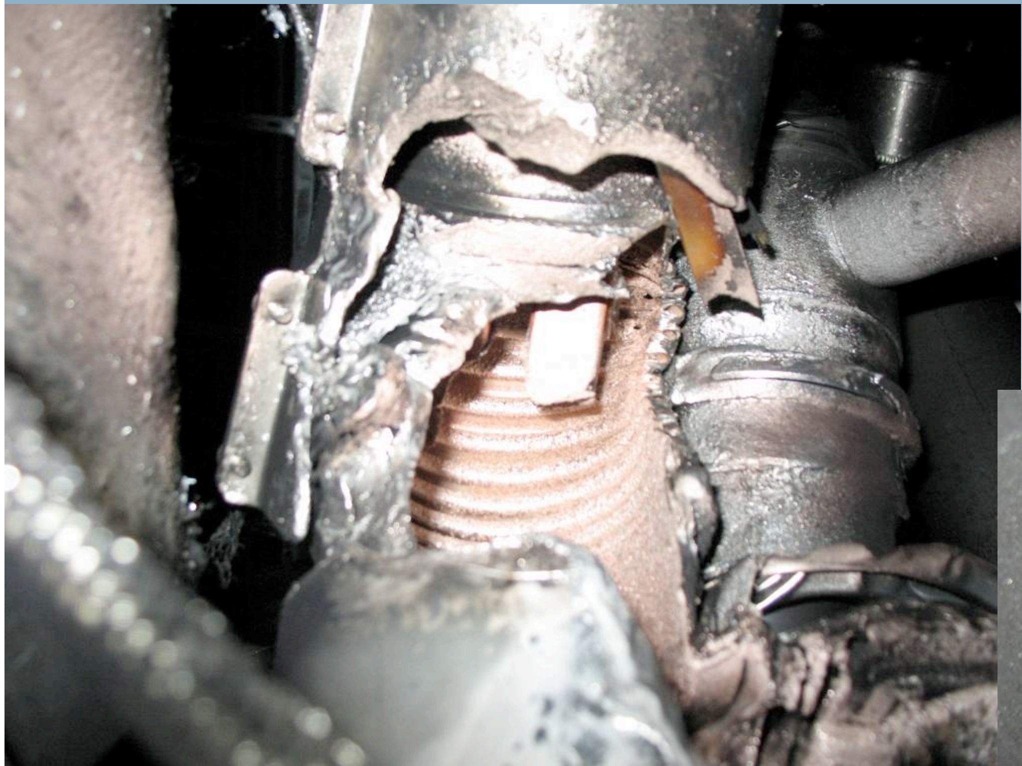
Electrical arc between C24 and Q24







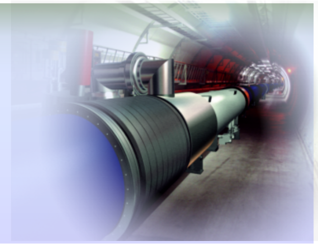




QQBI.27R3 M3 line

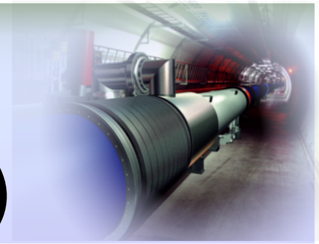
QBBI.B31R3 M3 line

I.II. Energy stored in the magnets: quench



- A quench is the phase transition of a super-conducting to a normal conducting state
- Quenches are initiated by an energy release of the order of mJ:
  - ***Movement*** of the superconductor by several μm (friction and heat dissipation)
  - ***Beam losses***:
    - @7 TeV ➔ 0.6 J/cm^3 can quench a dipole; this energy density can be generated by 10^7 protons;
    - @450 GeV (injection energy), 10^9 protons are needed
  - ***Cooling failure***

I.II. Energy stored in the magnets: Quench Protection System (QPS)



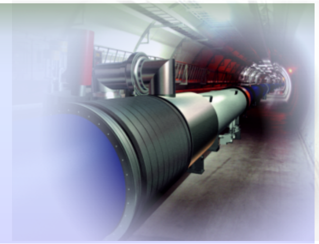
- To limit the temperature increase after a quench

Quench Protection System

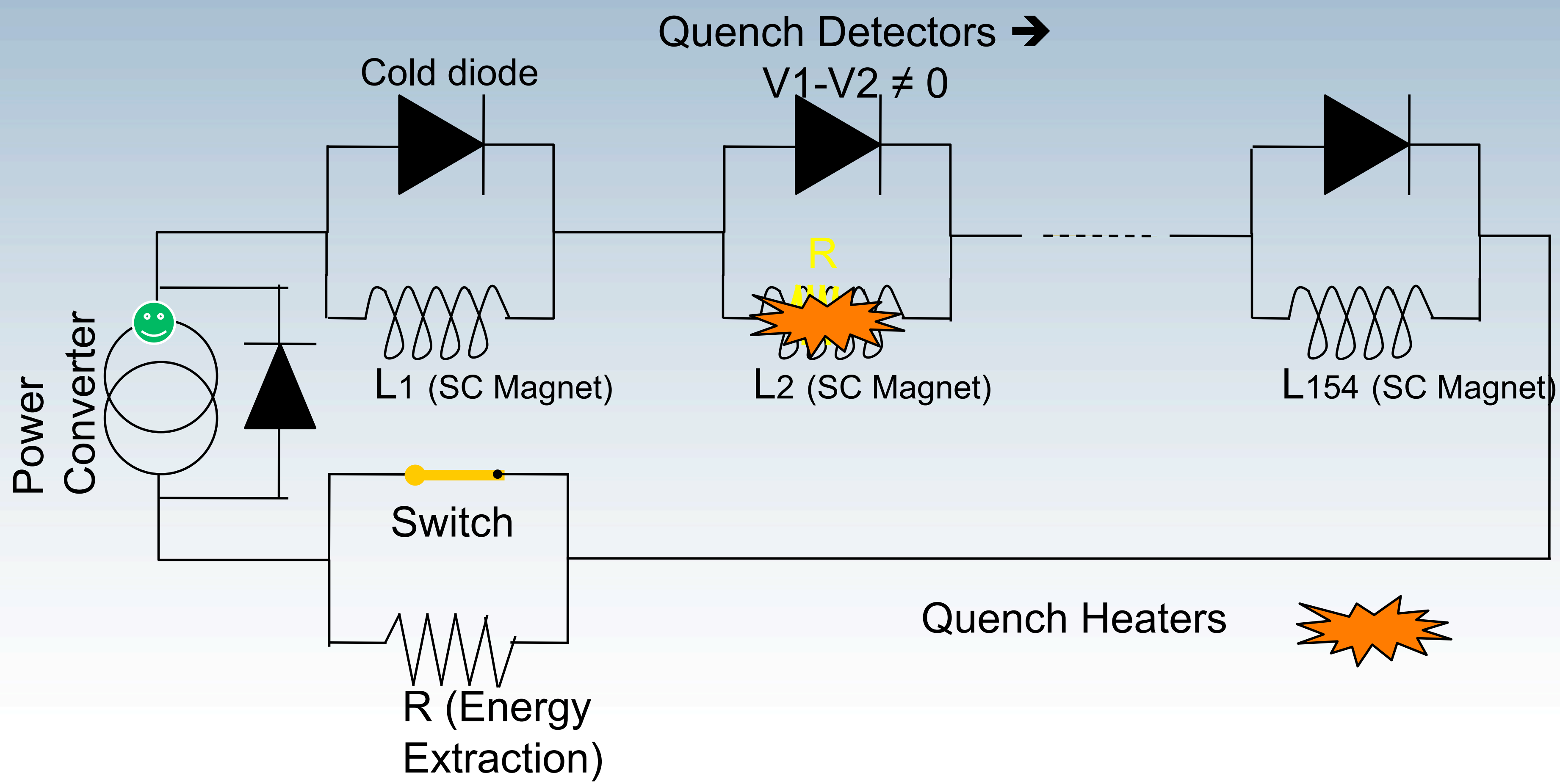
  - The quench has to be detected ➔ ***Quench Detectors****
  - The energy is distributed in the magnet by force-quenching the coils using ***Quench Heaters****
  - The stored energy is released in a controlled way ➔ ***Cold by-pass diodes**** and ***Energy Extraction System***
- Failure in the QPS system:
  - False quench detection: down time some hours 
  - Missed quench: damage of magnets, down time 30 days

*** On every SC magnet**

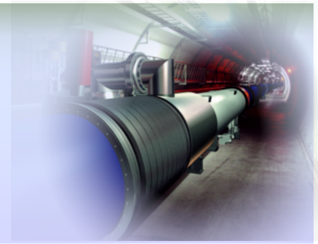
I.II. Energy stored in the magnets: Quench Protection System



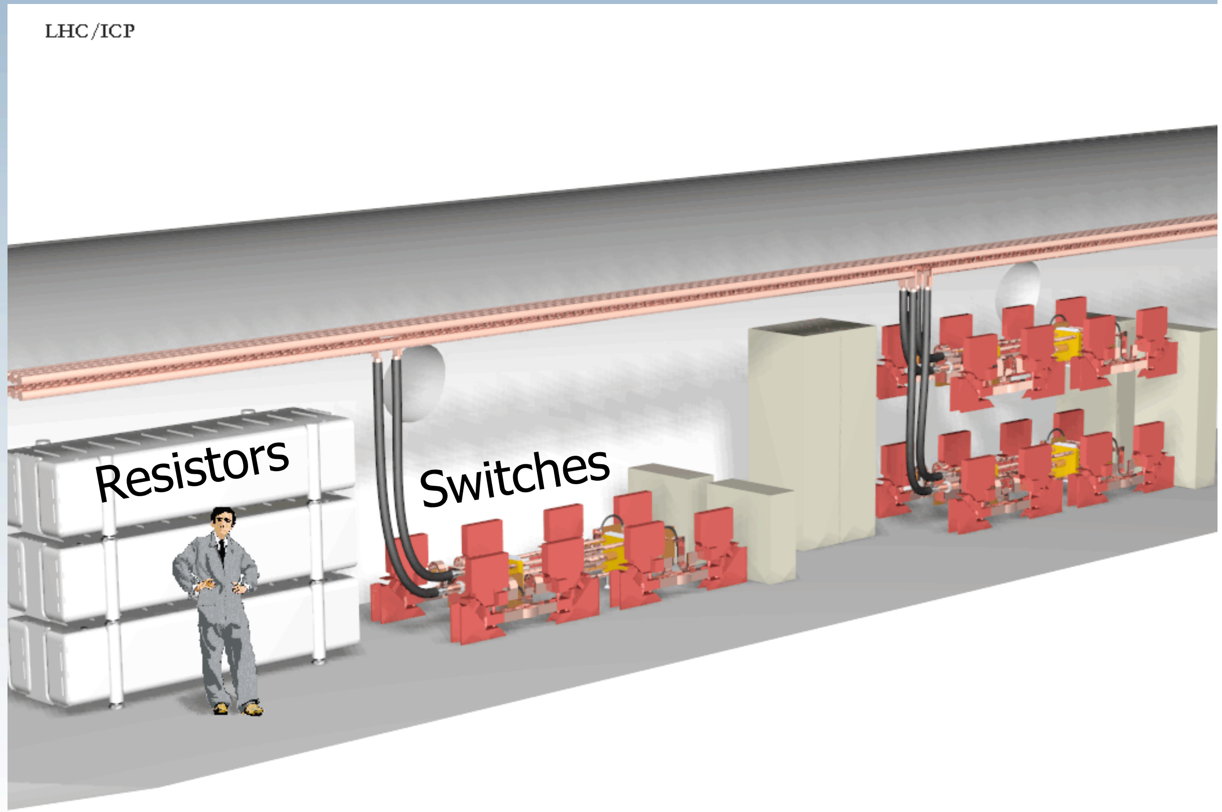
- Schematics of the QPS in the main dipoles of a sector



I.II. Energy stored in the magnets: Energy Extraction System (EES)



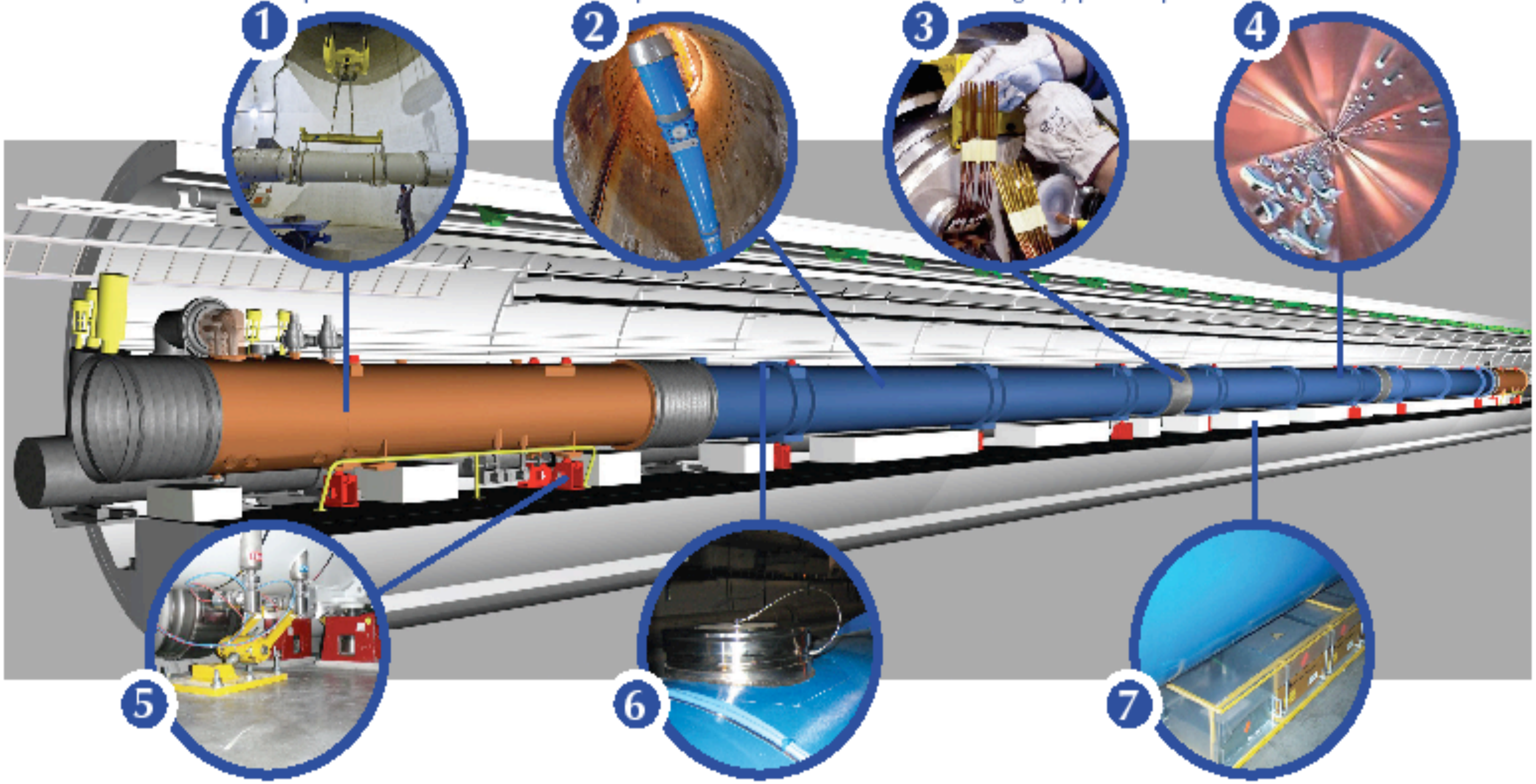
- During normal operation every ramp down of the magnets implies energy extraction, but this takes ~ 20 min ➔ too slow in case of a quench.
- A dedicated Energy Extraction System for quench protection is needed.
- There are 32 EES for the 24 13 kA main circuits (dipoles + quadrupoles) (+ the EES for the 600 A correctors).



- The EES releases the energy in 104 s for the dipoles (-125 A/s) and in 40 s for the quadrupoles (-325 A/s).

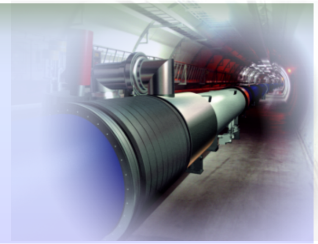
The LHC repairs in detail

After 19th Sep 08



+ cryogenics!

II. The Beam



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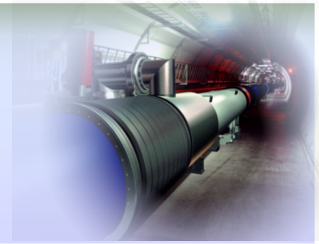
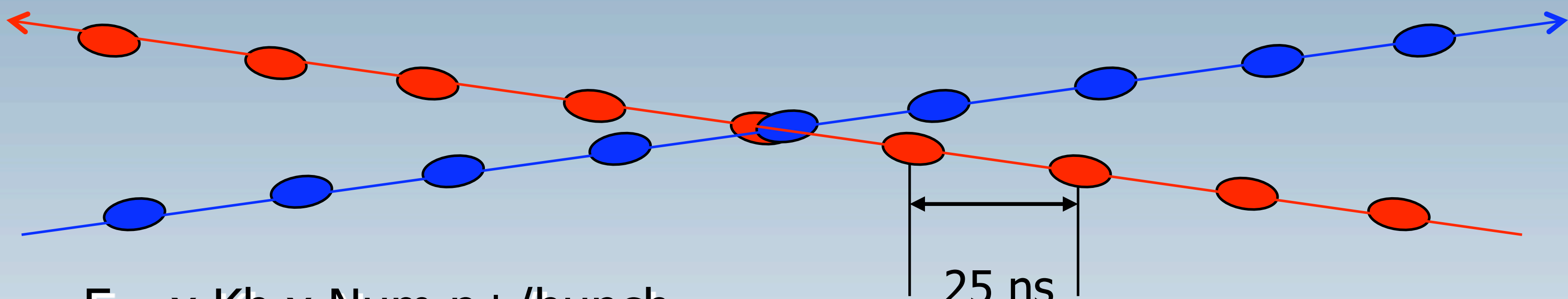
   I. Beam dump system
   II. Collimation system
II. Beam parameters
III. Overview of the Beam Interlock System

II.I. Energy stored in the beams





$E_{beam} = E_{p+} \times Kb \times \text{Num p+/bunch}$

$E_{p+} = 7$ TeV

$Kb = 2808$

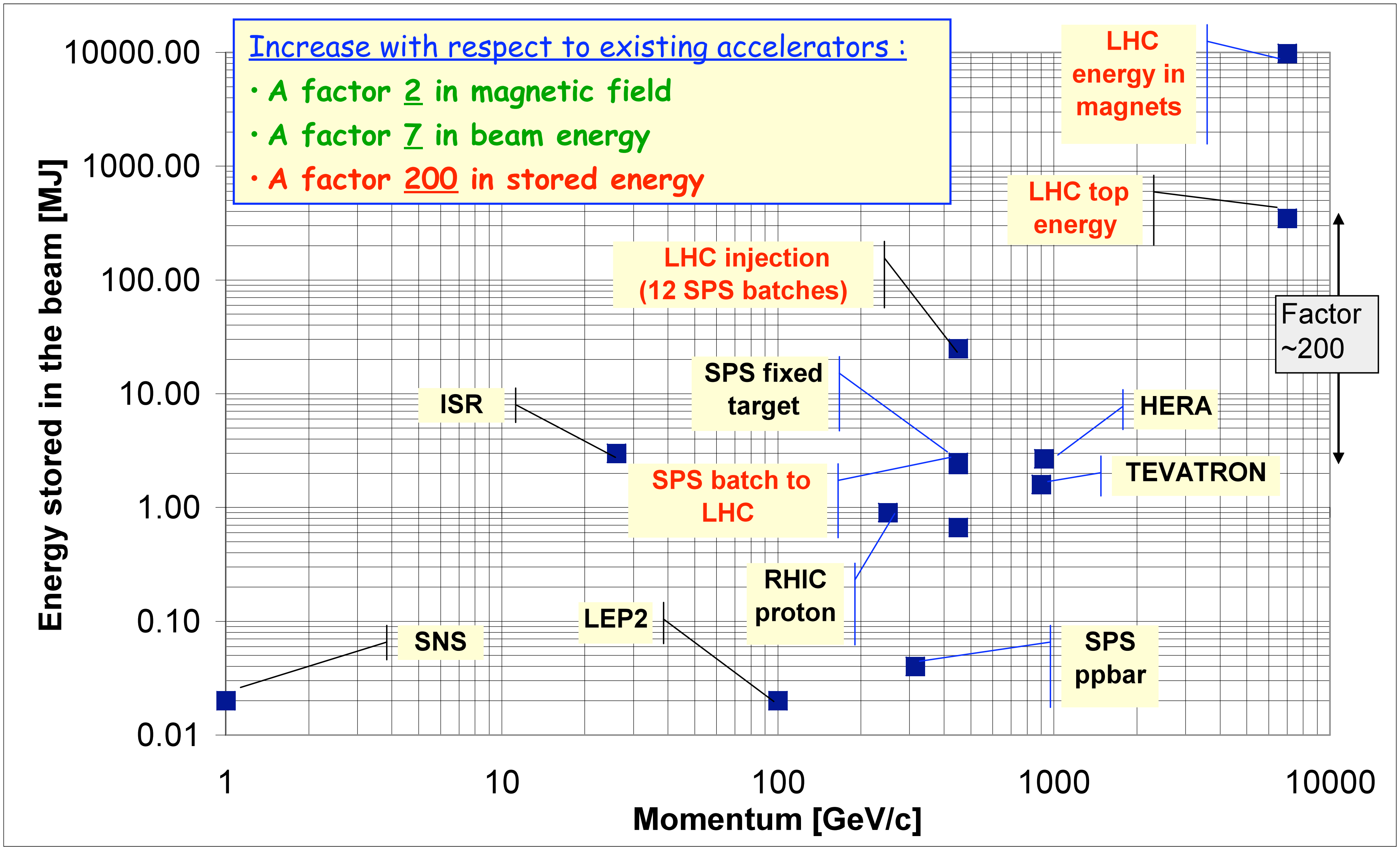
Num p+/bunch = 1.15×10^{11}

$E_{beam} = 362$ MJoules

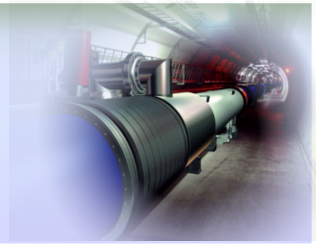
} Nominal values

Enough to melt 500 kg of copper

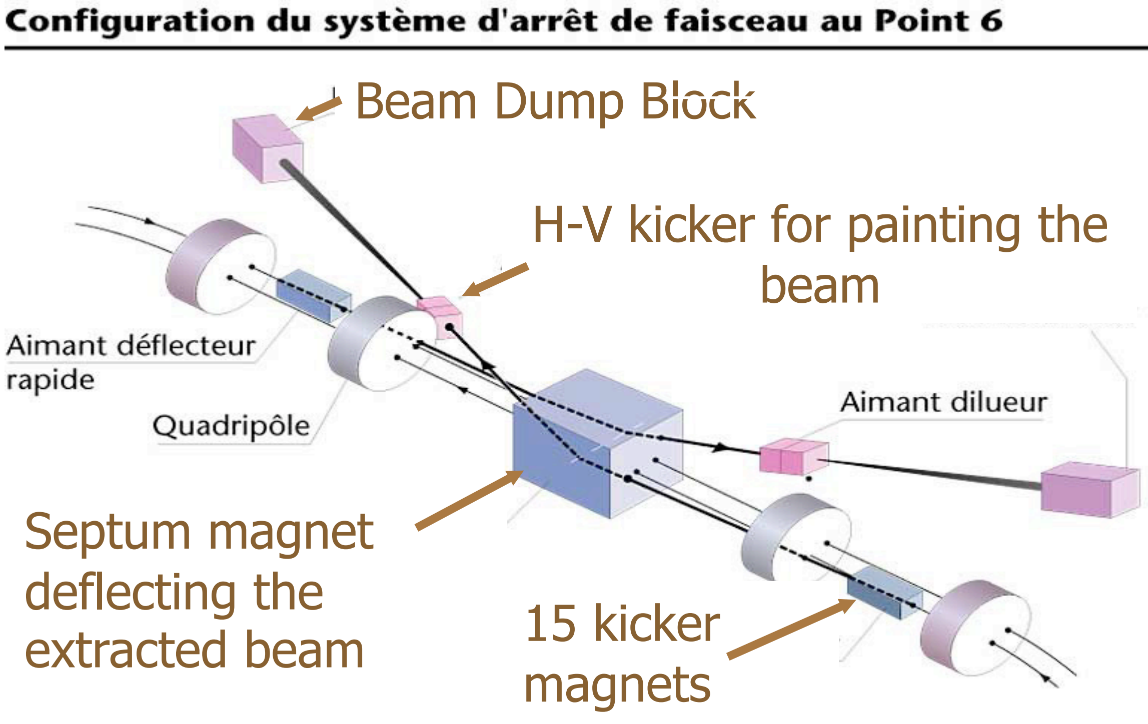
II.I. Energy stored in the beams

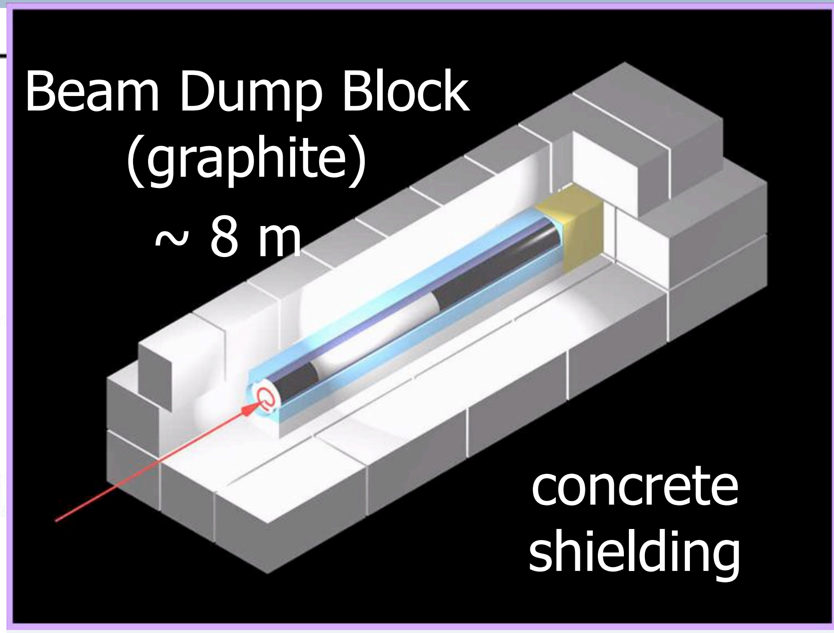


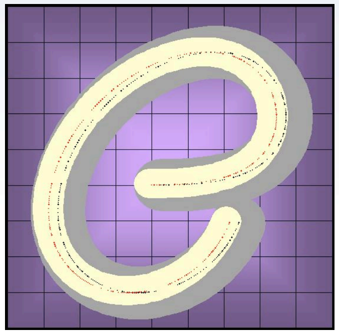
II.I. Energy stored in the beams: Beam Dump System (LBDS)



Is the only system in LHC able to absorb the full nominal beam







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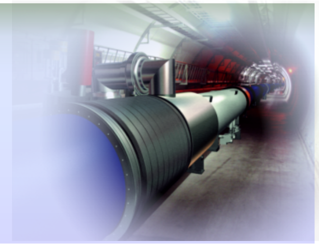
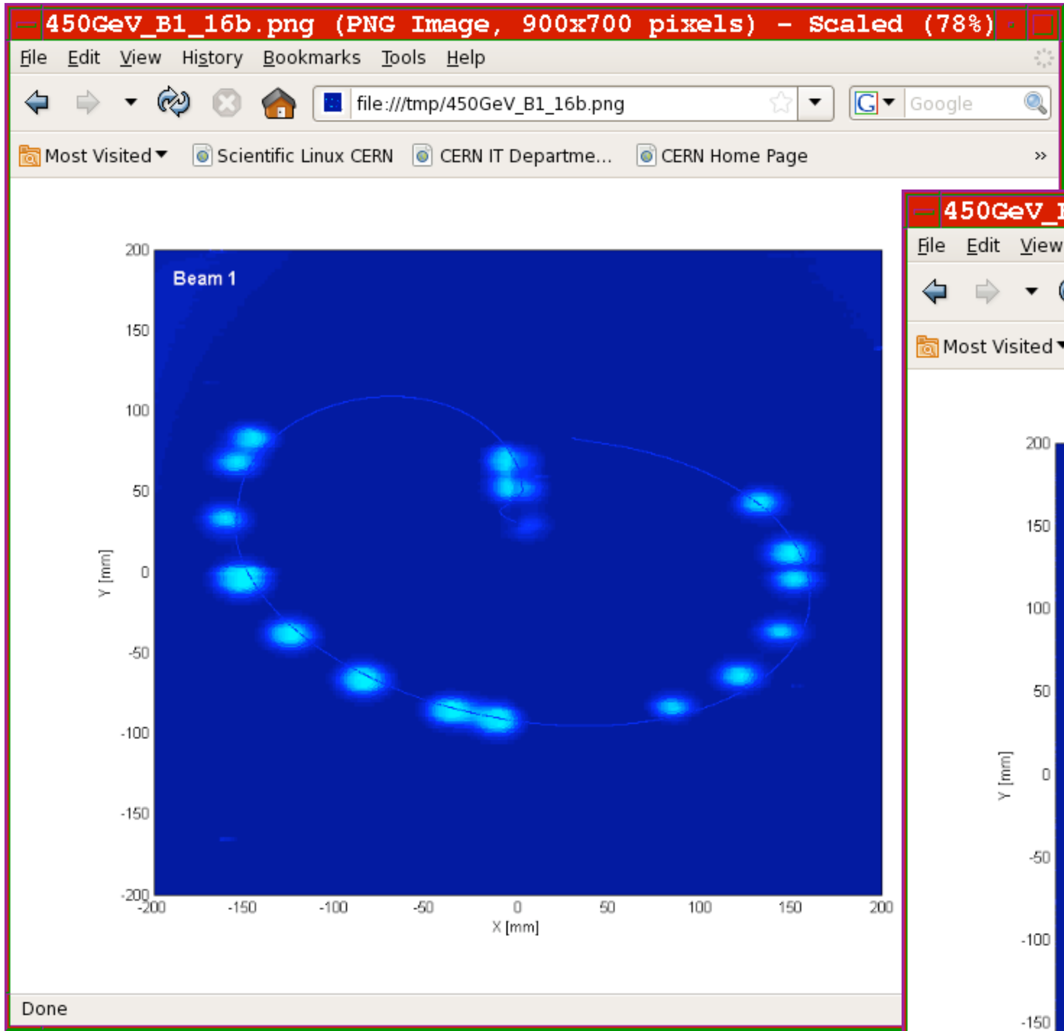
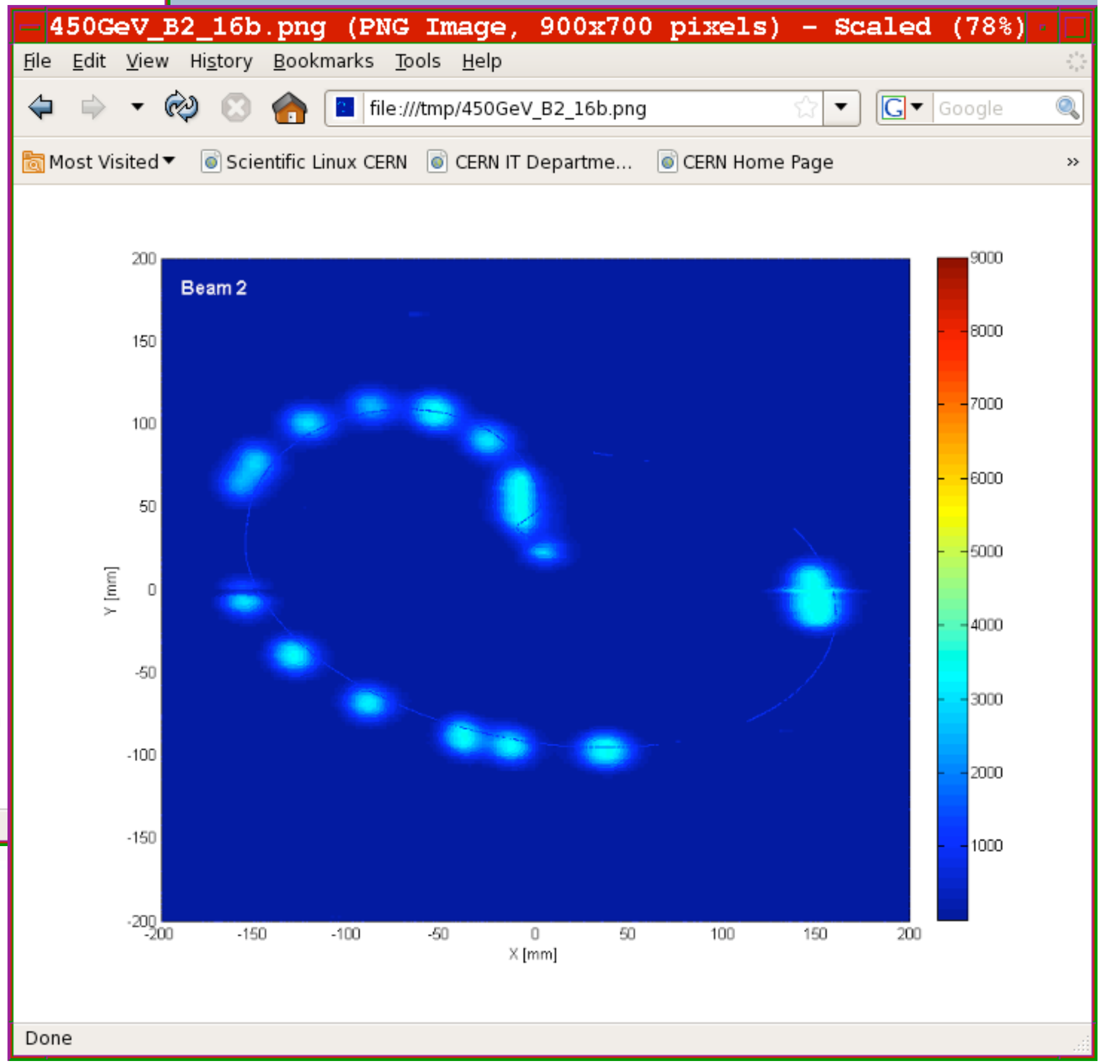
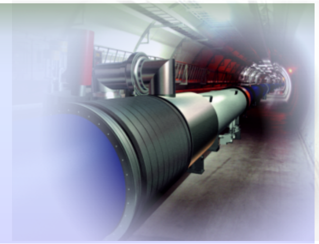


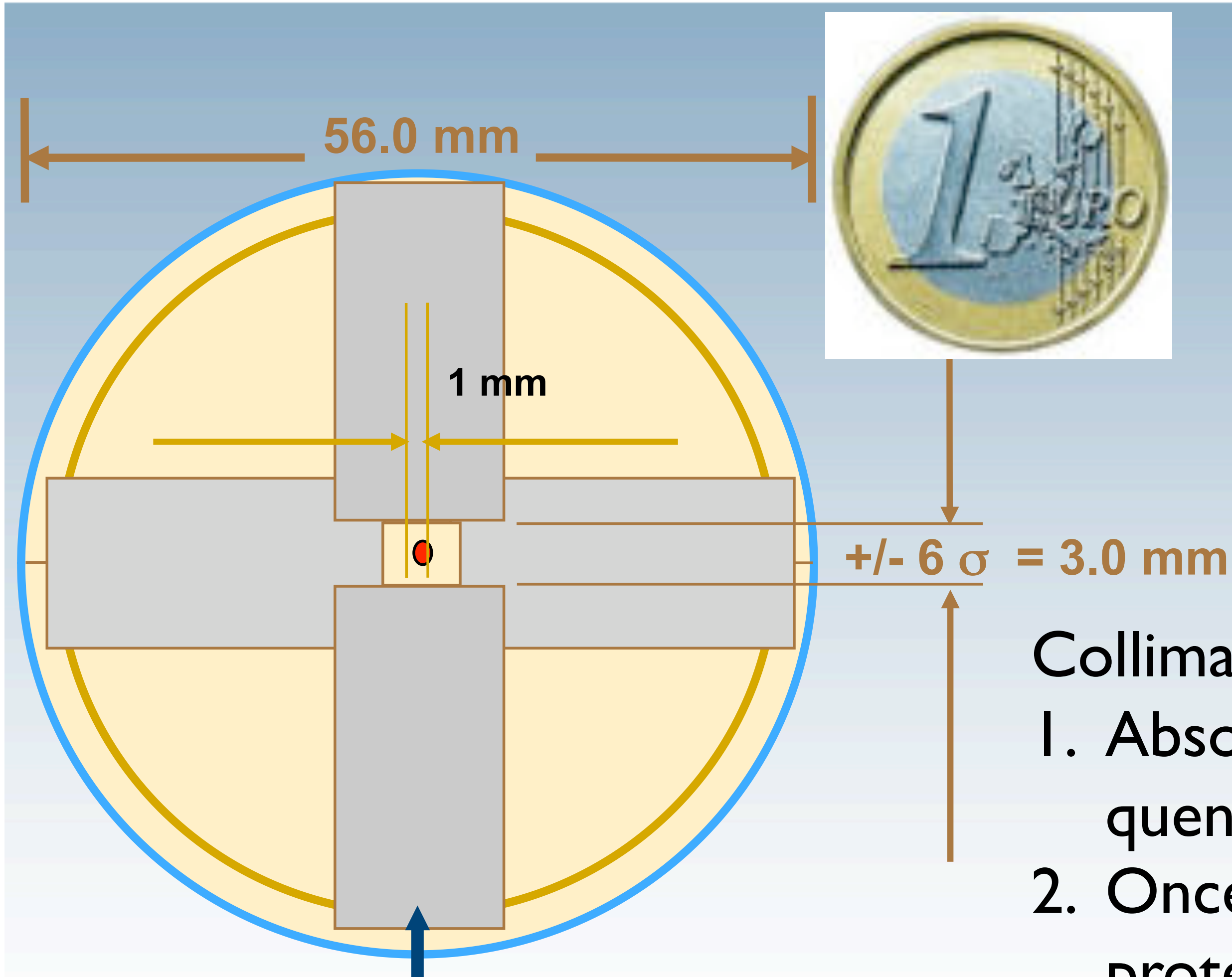
14th Dec 09

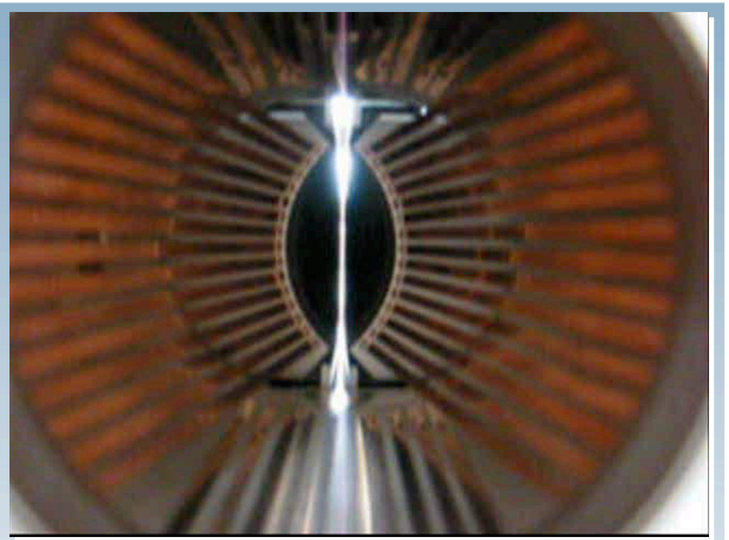




II.I. Energy stored in the beams: Collimation System







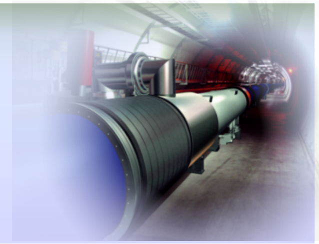
E.g. Settings of collimators @7 TeV with luminosity optics

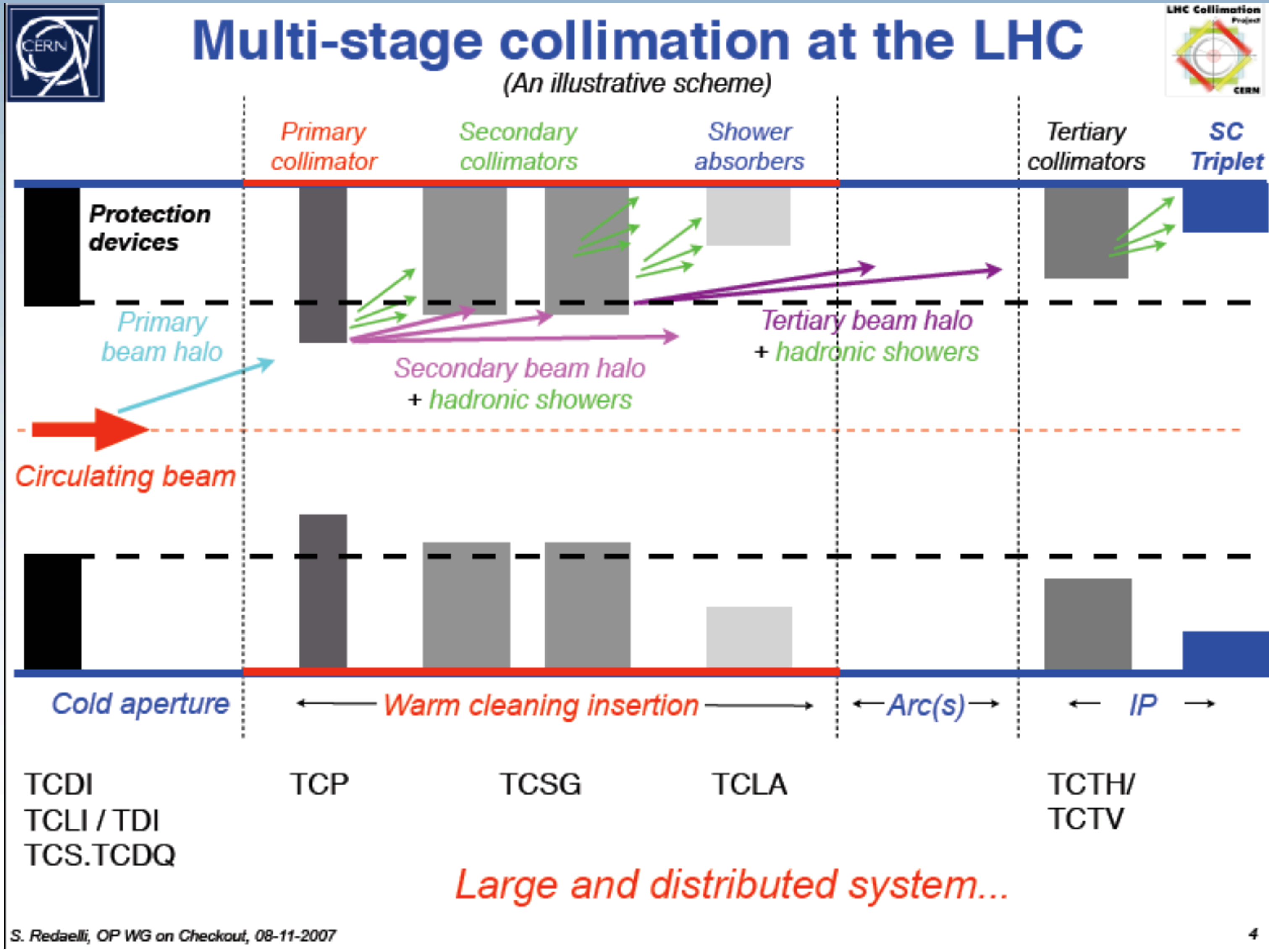
Very tight settings ➔ orbit feedback!!

Collimation system functionality:

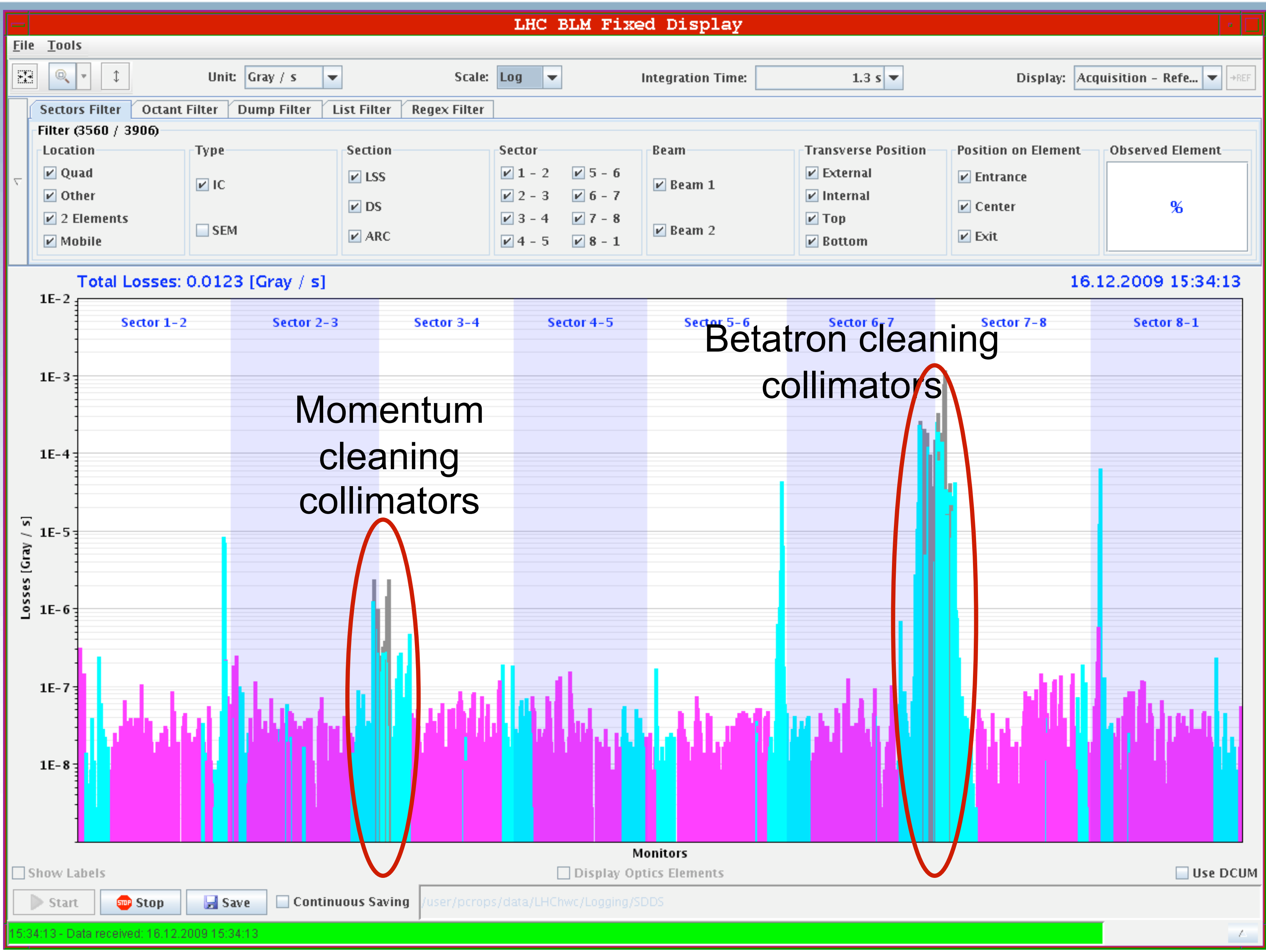
1. Absorb beam halo to avoid quenches
2. Once beam losses appear, they protect the equipment and the experiments. If BLM > threshold ➔ Beam Interlock ➔ Beam Dump System

II.I. Energy Stored in the Beams: Collimation System

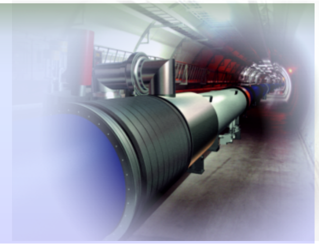




II.I. Energy Stored in the Beams: BLM losses



II. The Beam



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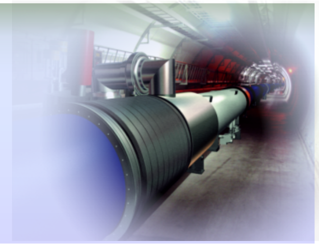
  II. Collimation system

II. Beam Parameters

III. Overview of the Beam Interlock System

II.II Beam parameters (nominal)

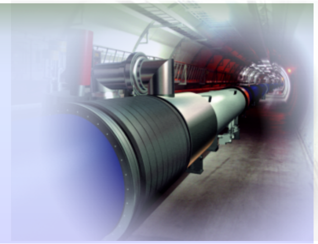


		Injection	Collision
Proton energy	GeV	450	7000
Particles/bunch		1.15×10^{11}	
Num. bunches		2808	
Longitudinal emittance (4σ)	eVs	1.0	2.5
Transverse normalized emittance	µm rad	3.5	3.75
Beam current	A	0.582	
Stored energy/beam	MJ	23.3	362
		Peak luminosity related data	
RMS bunch length	cm	11.24	7.55
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}

β = 10 m
ε = 0.5 nm rad

β = 0.55 m
ε = 0.5 nm rad

II. The Beam



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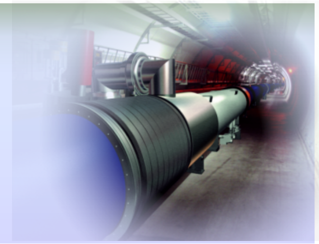
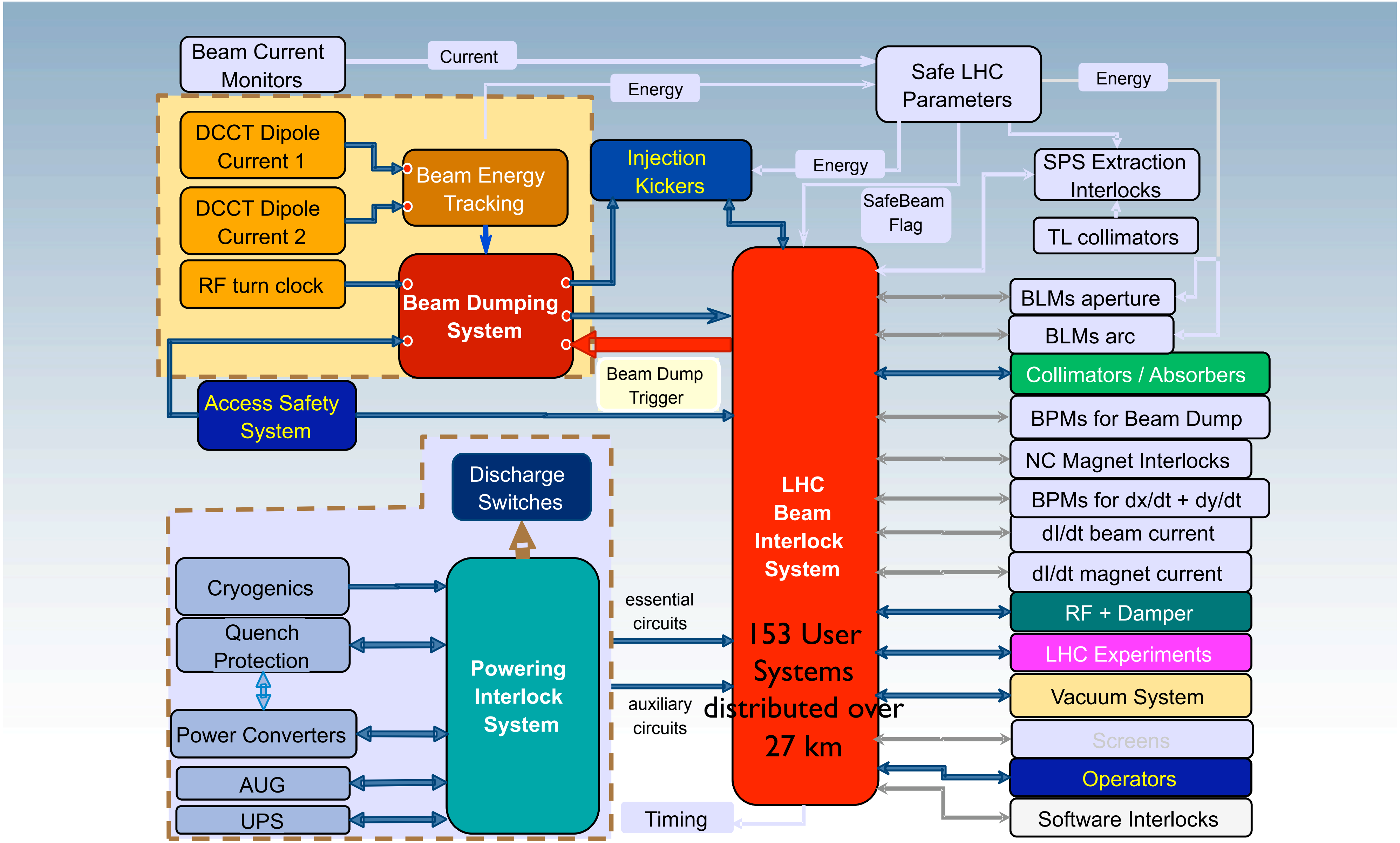
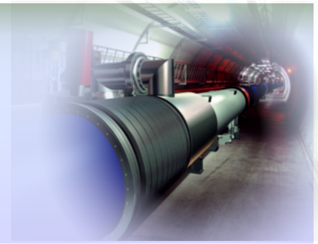
II.III. Beam Interlock System Overview





III. The Interaction Regions



Contents:

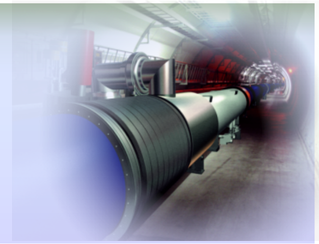
I. High luminosity insertions

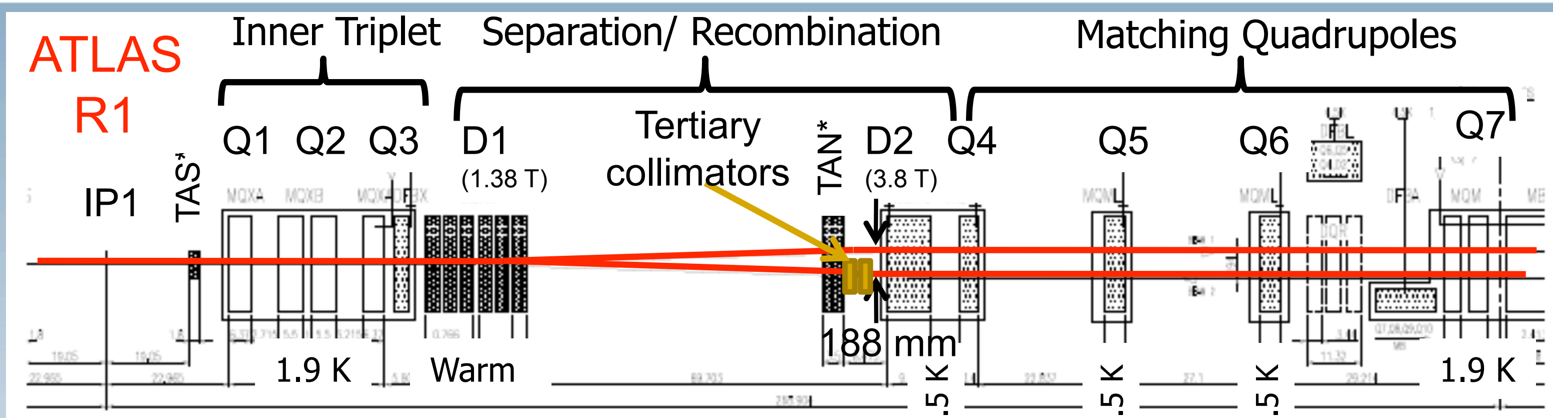
II. Low luminosity insertions

III. Squeeze

IV. Colliding with crossing angle

III.I. The experiments: High luminosity insertions





6.45 kA 10.63 kA

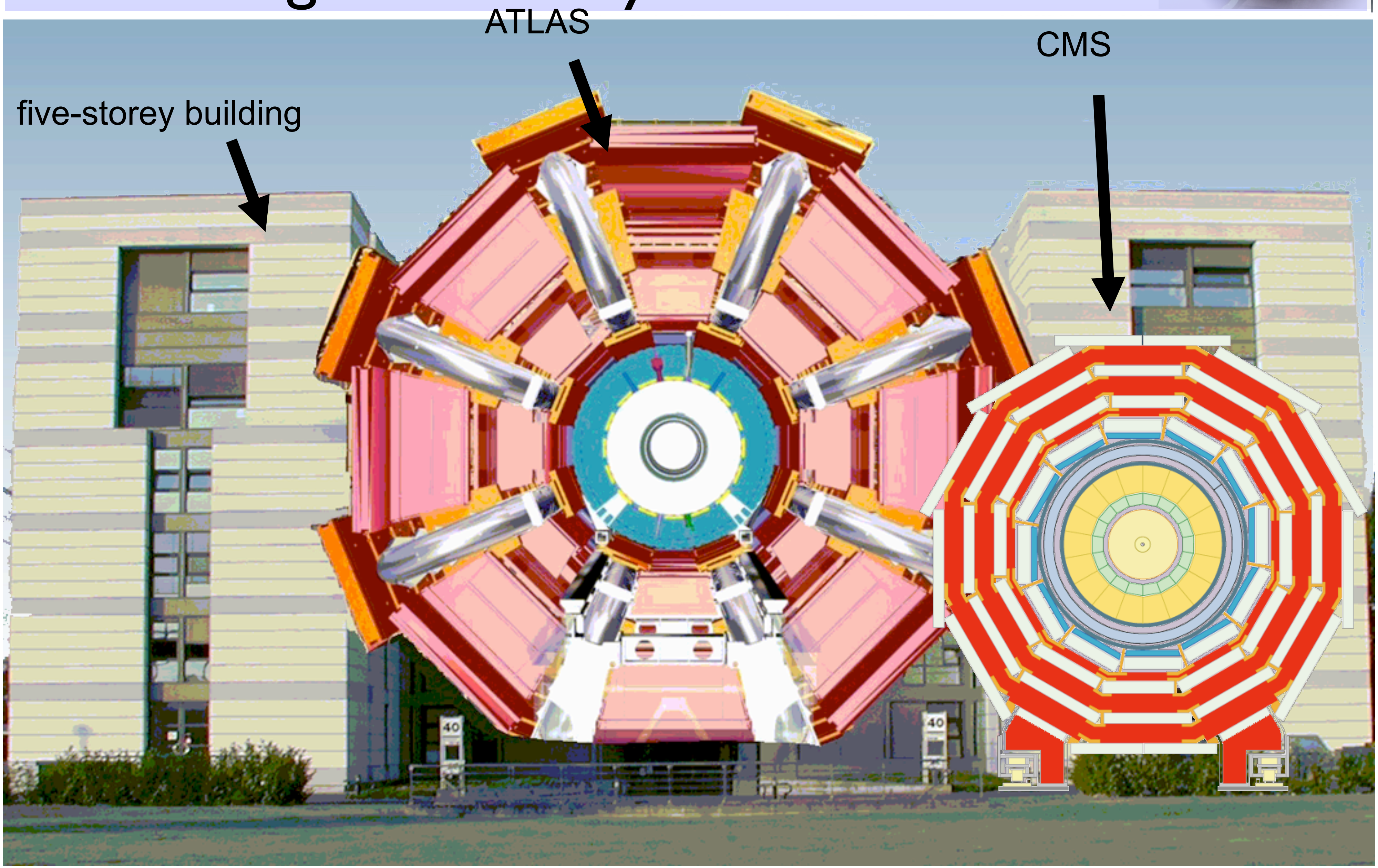
	LSS						
	low-β triplet			MS			
Magnet	Q1	Q2	Q3	Q4	Q5	Q6	Q7
#	1	2	1	1	1	1	2
Type: MQ-	XL	X	XL	Y	ML		M
L [m]	6.3	5.5	6.3	3.4	4.8	4.8	3.4
T [K]	1.9			4.5			1.9
G [T/m]	200/205			160			200
r [mm]	23.85 18.95	28.95 24.05		29.0 24.0	22.5 17.6		22.2 17.3

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

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

III.I. The experiments: High luminosity insertions



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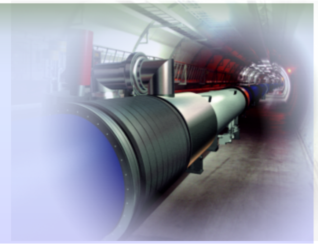

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III. Squeeze

IV. Colliding with crossing angle

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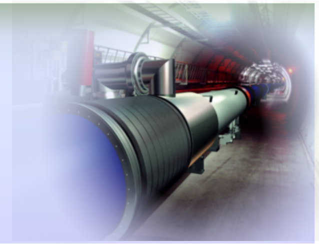
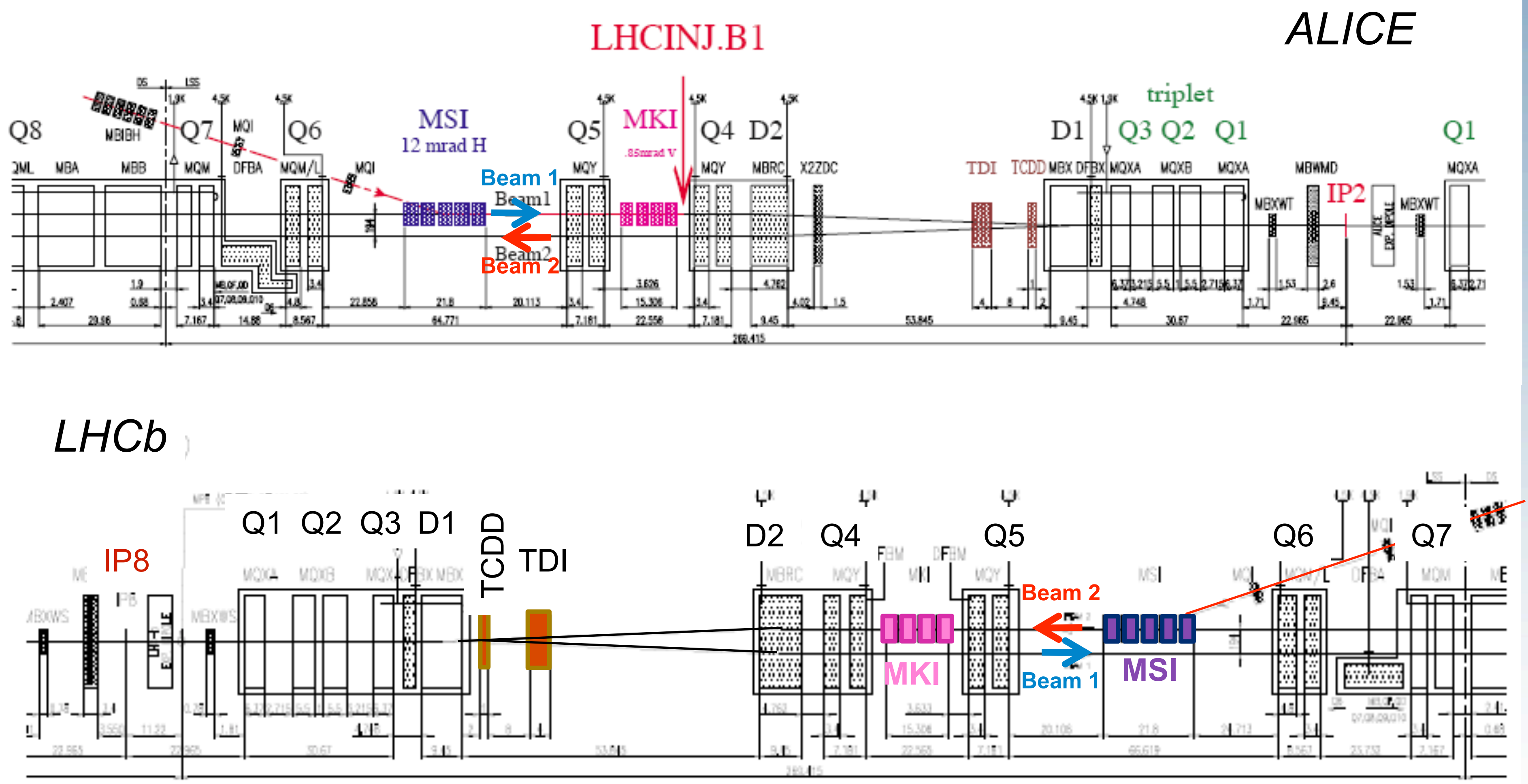
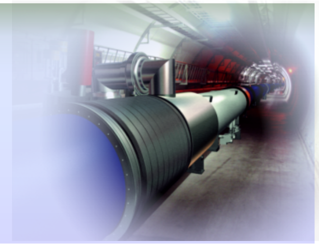
Low luminosity insertions

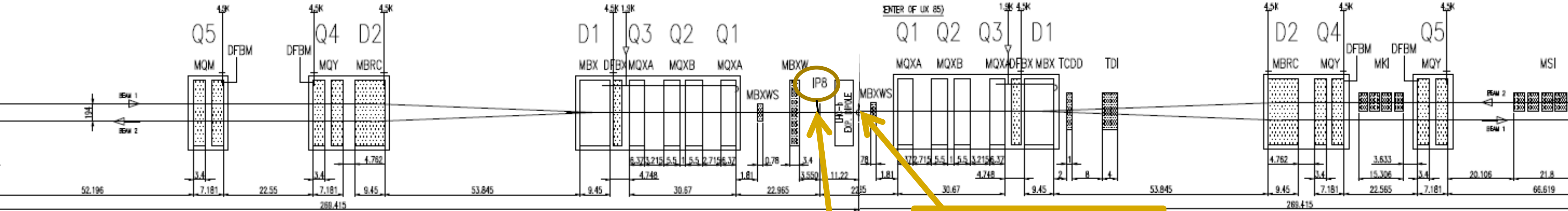


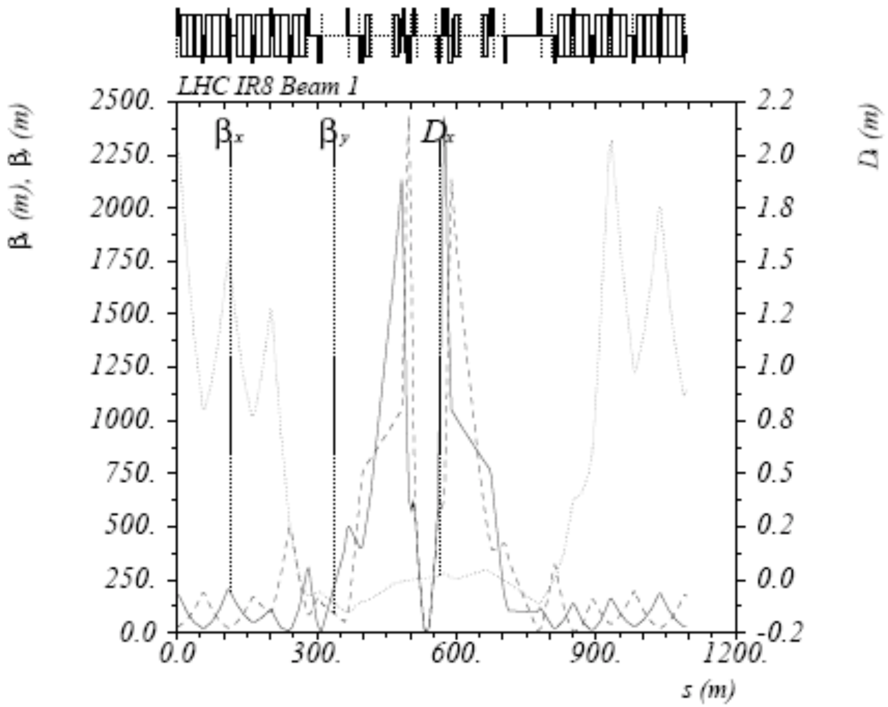


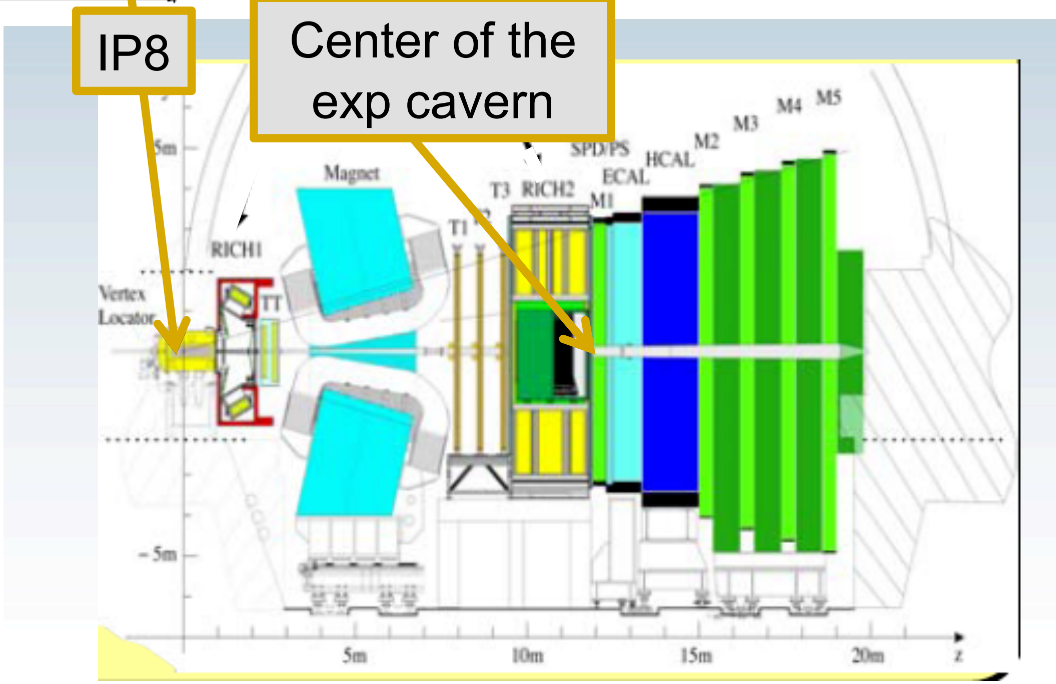
LHCb experiment



LHCb

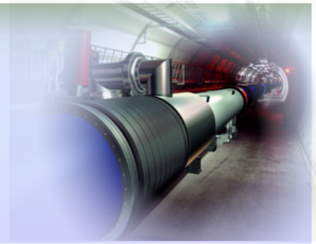






(c) Beam 1, collision optics

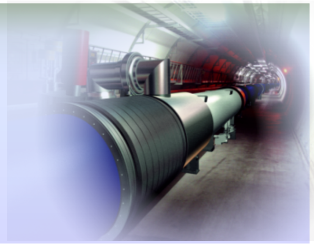
III.II. The experiments: Low luminosity insertions



ALICE

LHCb

III. The Interaction Regions



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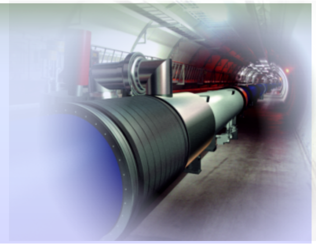
III. Squeeze

IV. Colliding with crossing angle

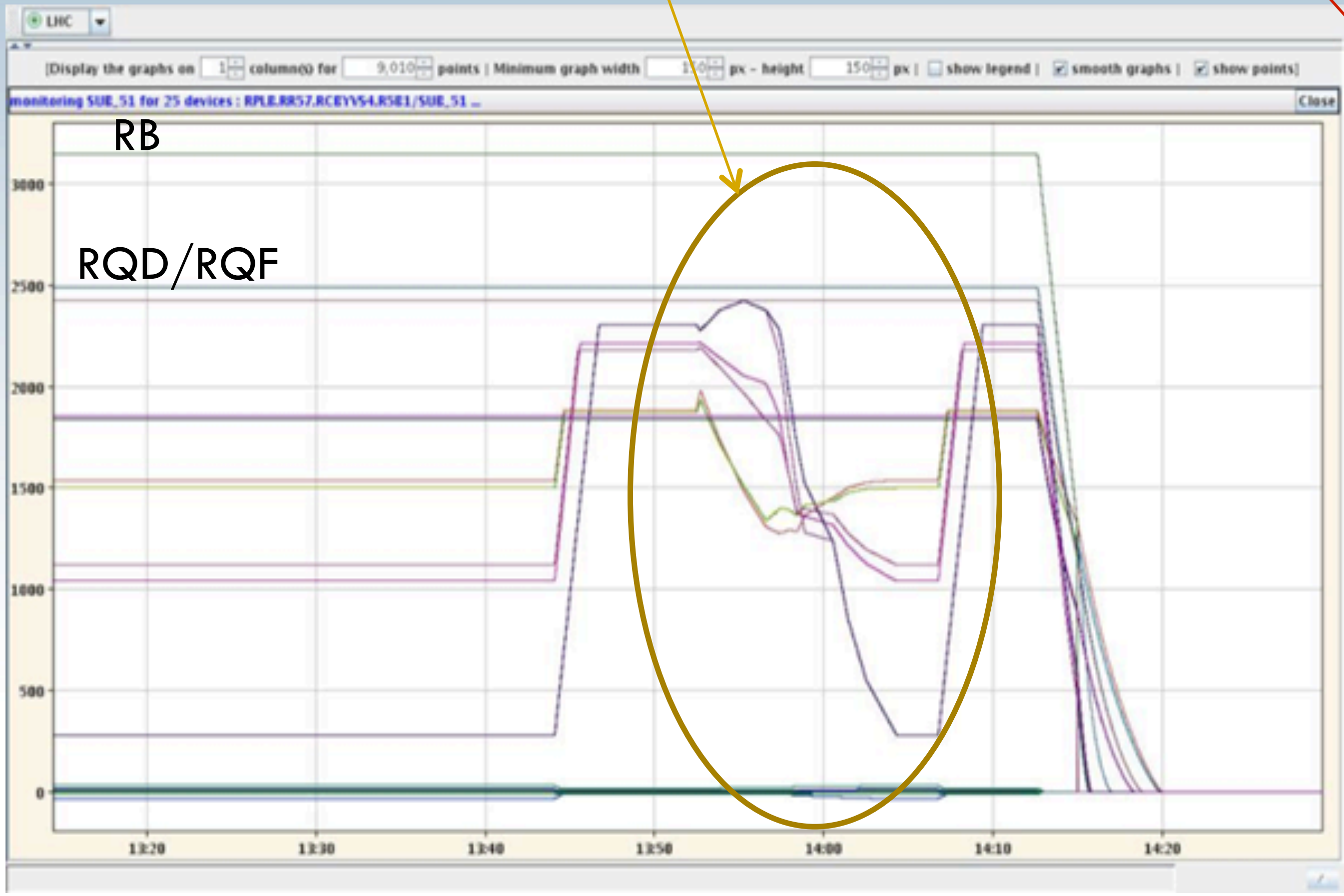
III.III. Squeeze



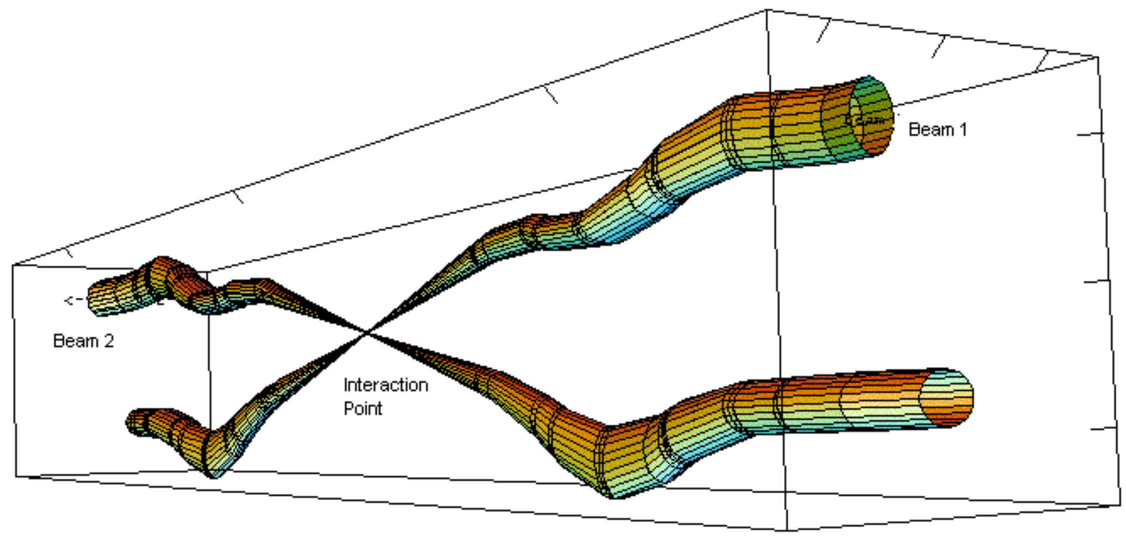
- Squeeze: change quadrupole currents (magnet strength) in a way that the beta function (β) at the interaction point is very small ➔ to increase luminosity
- Magnets: matching quadrupoles

$$L = \frac{N_1 N_2 f_{rev} N_b}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} F \cdot W \cdot e^{\frac{B^2}{A}}$$

$\sigma = \sqrt{(\beta\varepsilon)}$

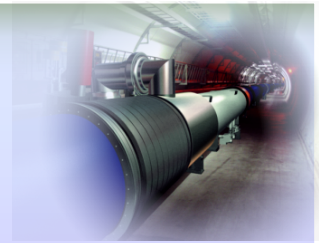


III.III. Squeeze



Relative beam sizes around IP1 (Atlas) in collision

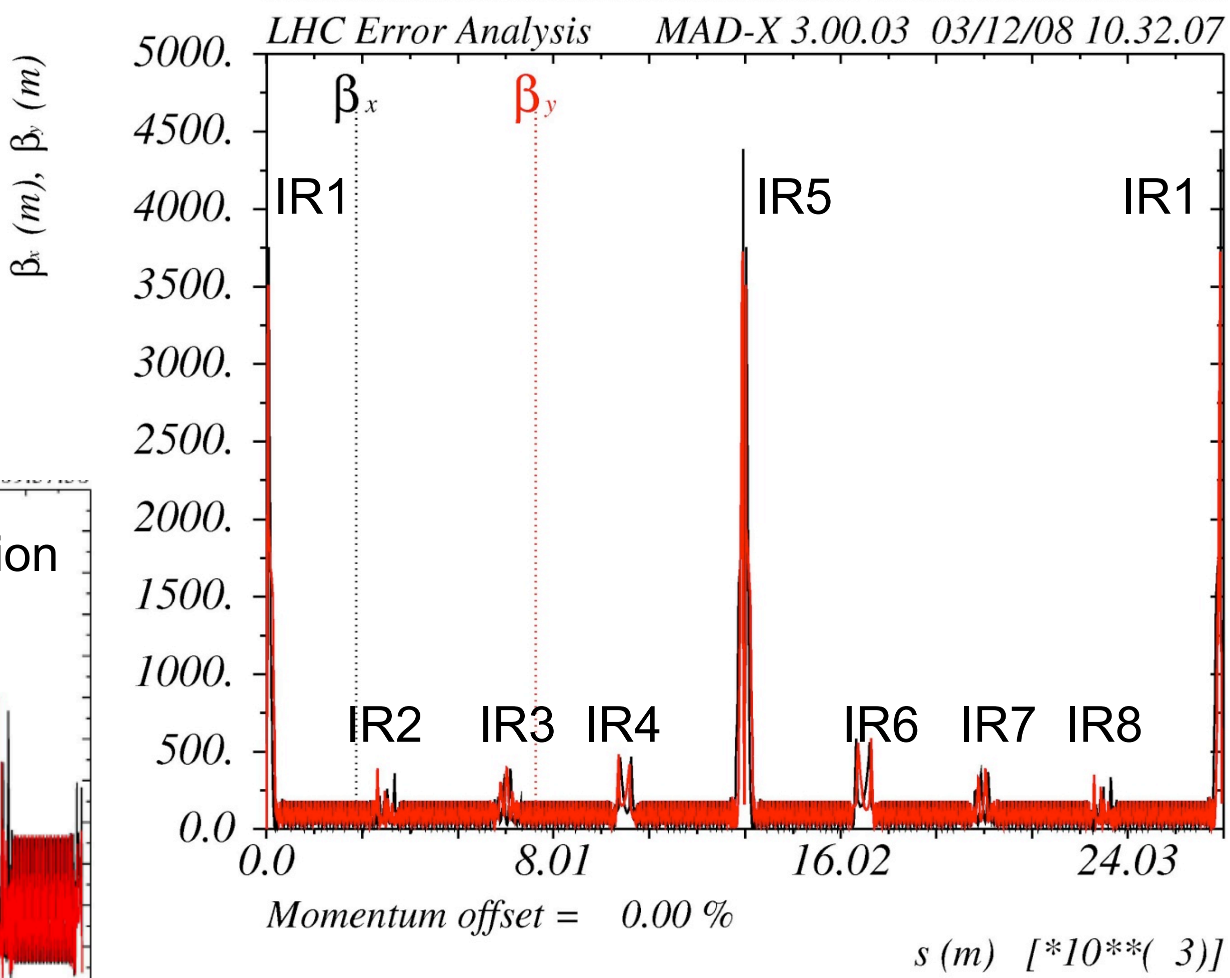
Squeeze the beam size down as much as possible at the collision point to increase the chances of a collision

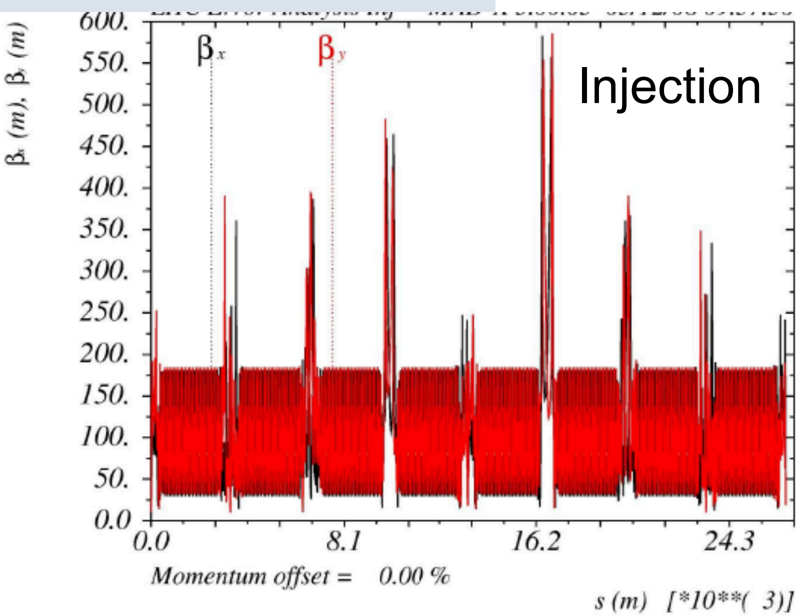


- So even though we squeeze our 100,000 million protons per bunch down to 16 microns (1/5 the width of a human hair) at the interaction point. We get only around 20 collisions per crossing with nominal beam currents.
- The bunches cross (every 25 ns) so often we end up with around 600 million collisions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

Beta function at top energy and after squeeze





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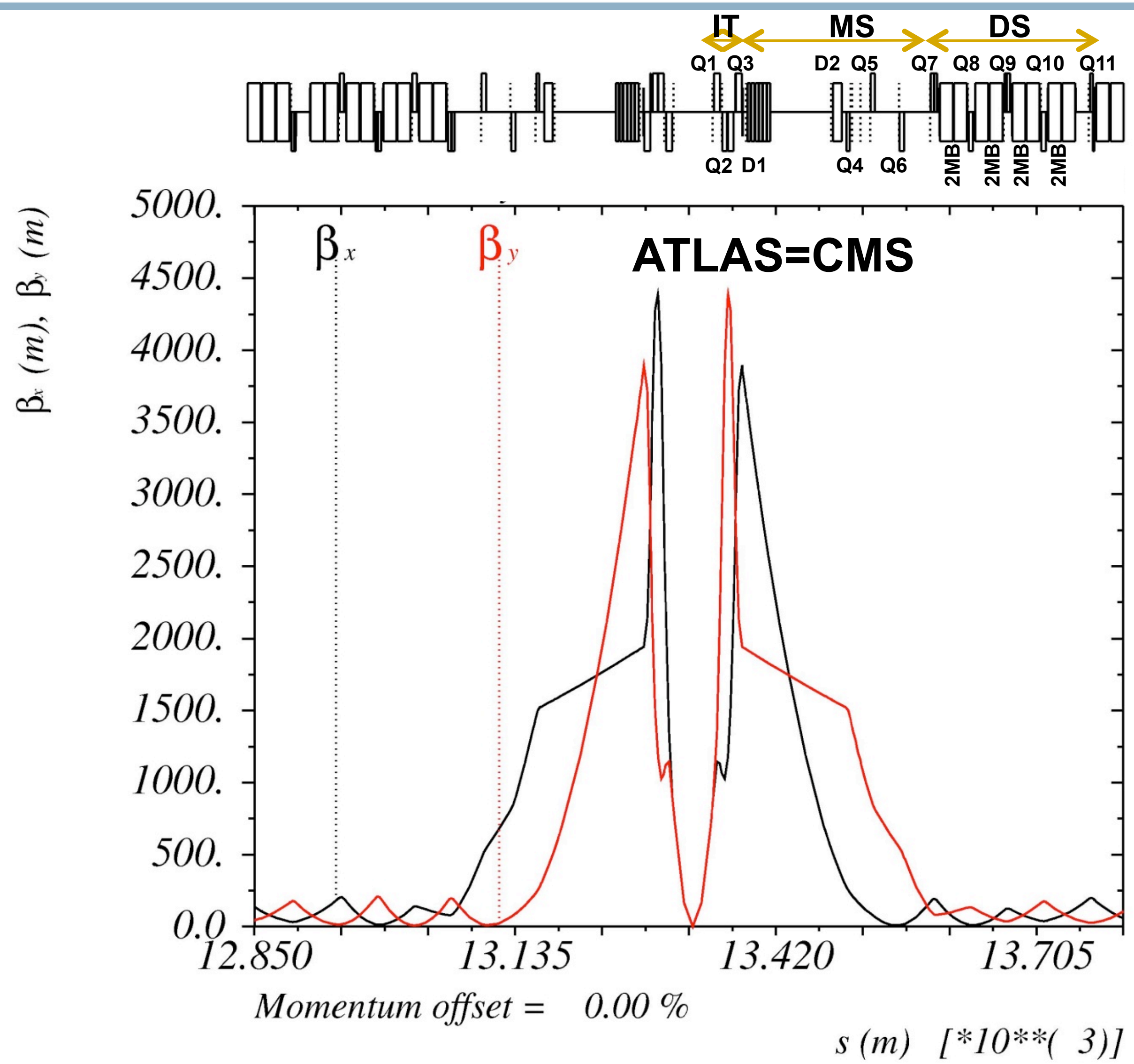

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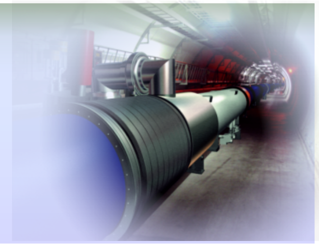

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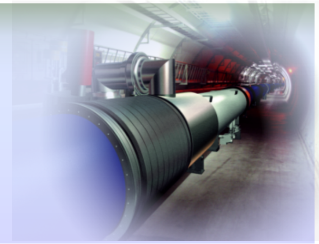
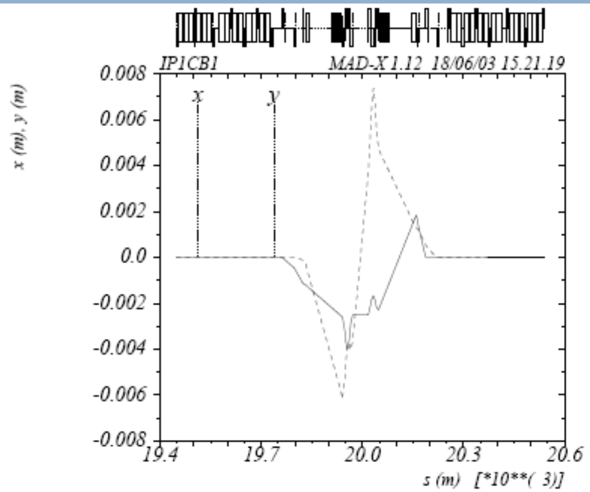
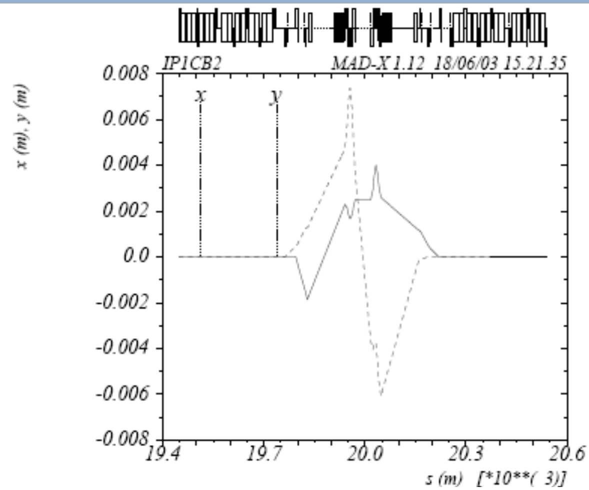


III.IV Colliding with a Xangle

Why? ➔ to minimize beam-beam interaction effects

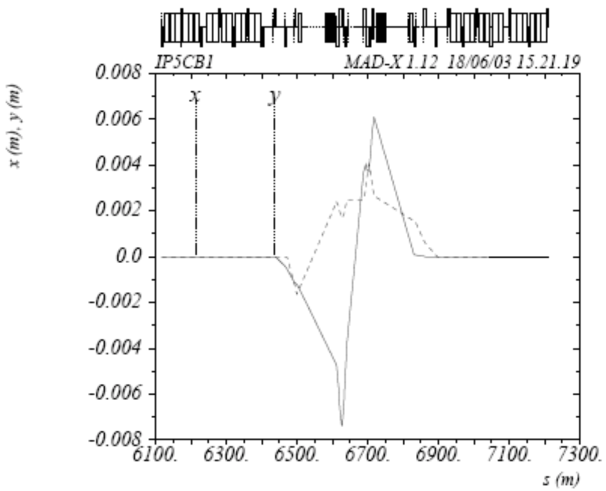


(a) Beam 1 in IR1

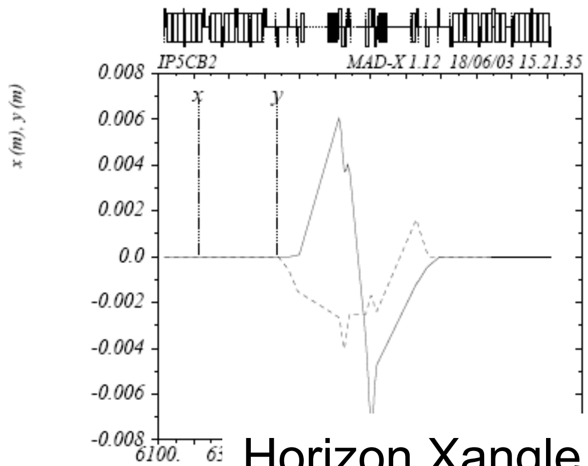


(b) Beam 2 in IR1

Vertical Xangle (160 μrad @ injection, 142.5 μrad @collis)



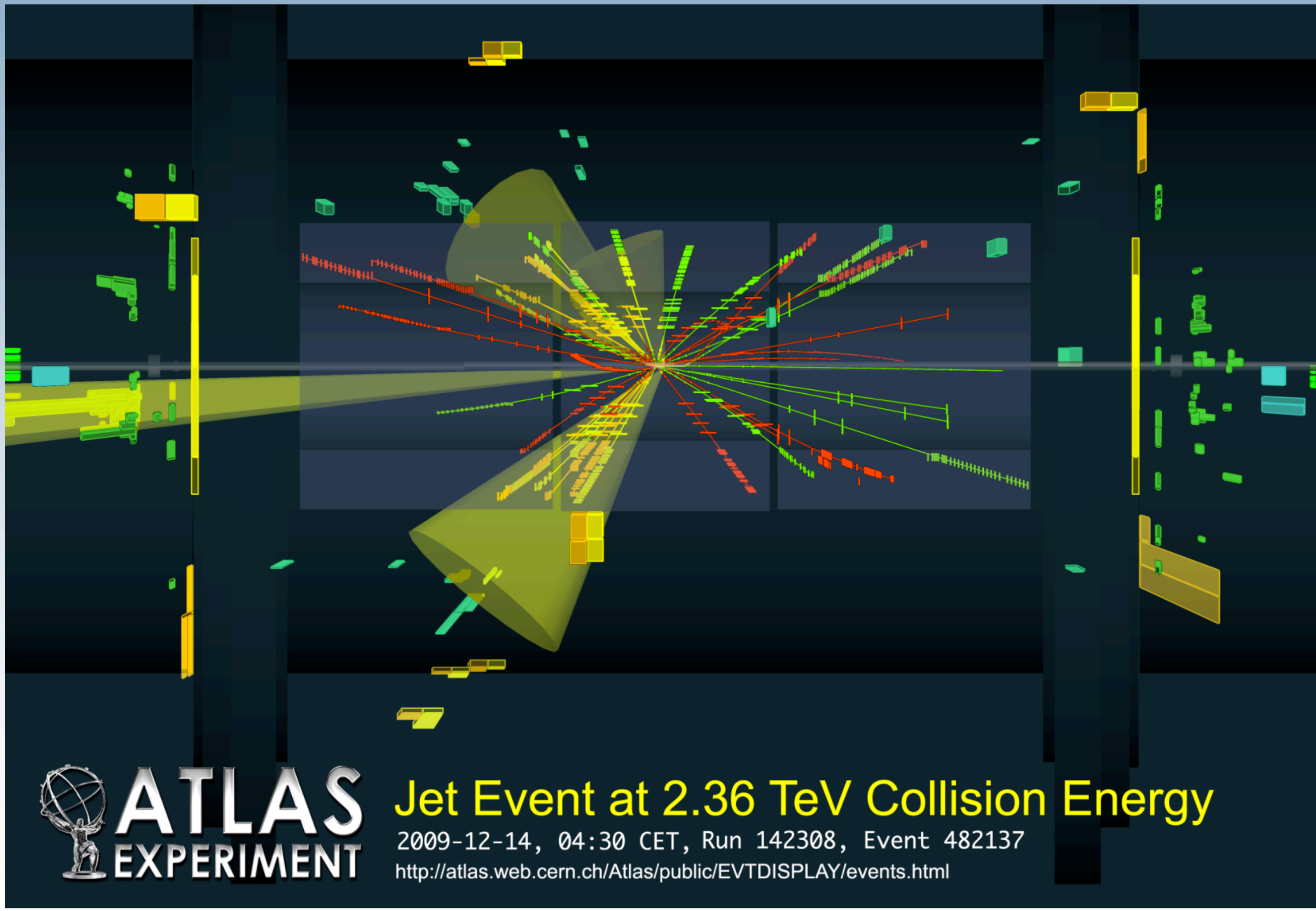
(c) Beam 1 in IR5



(d) Beam 2 in IR5

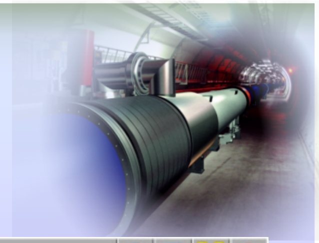
Horizon Xangle (160 μrad @ injection, 142.5 μrad @collis)

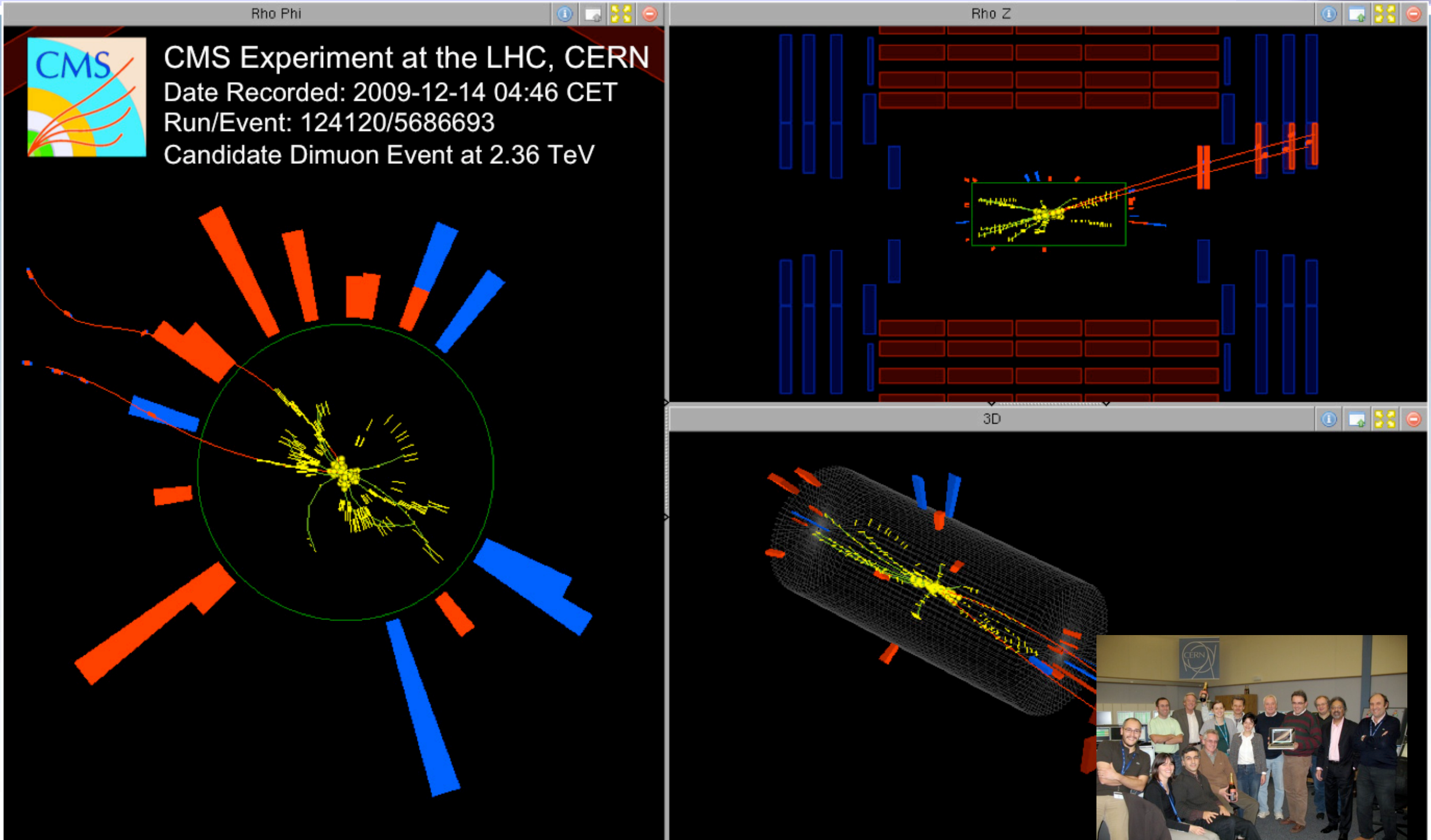
All this effort for … ATLAS EVENT AT 2.36 GeV



and this

CMS EVENT AT 2.36 GeV

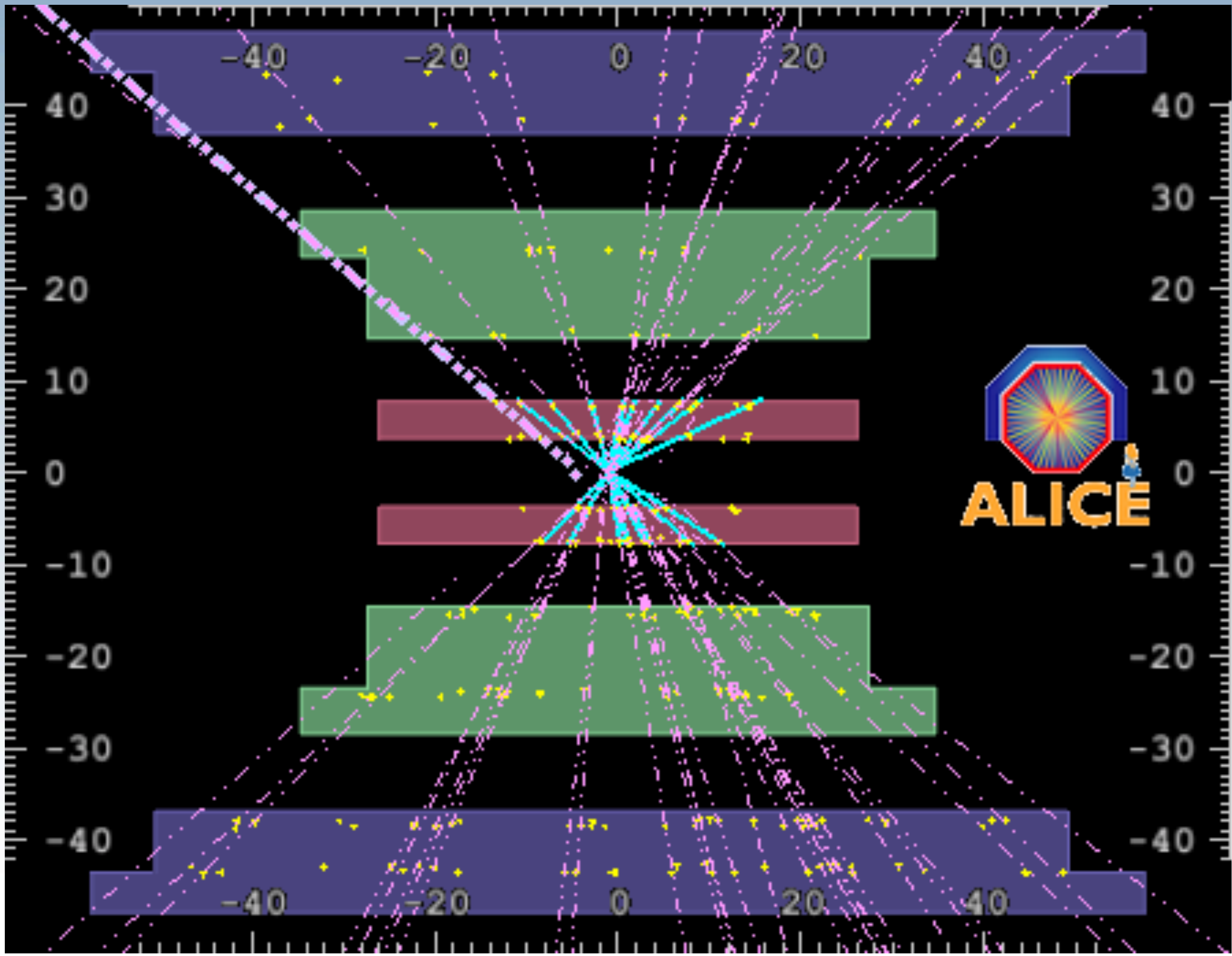




$p_T(\mu_1)$ = 3.6 GeV, $p_T(\mu_2)$ = 2.6 GeV, $m(\mu\mu)$= 3.03 GeV

and this

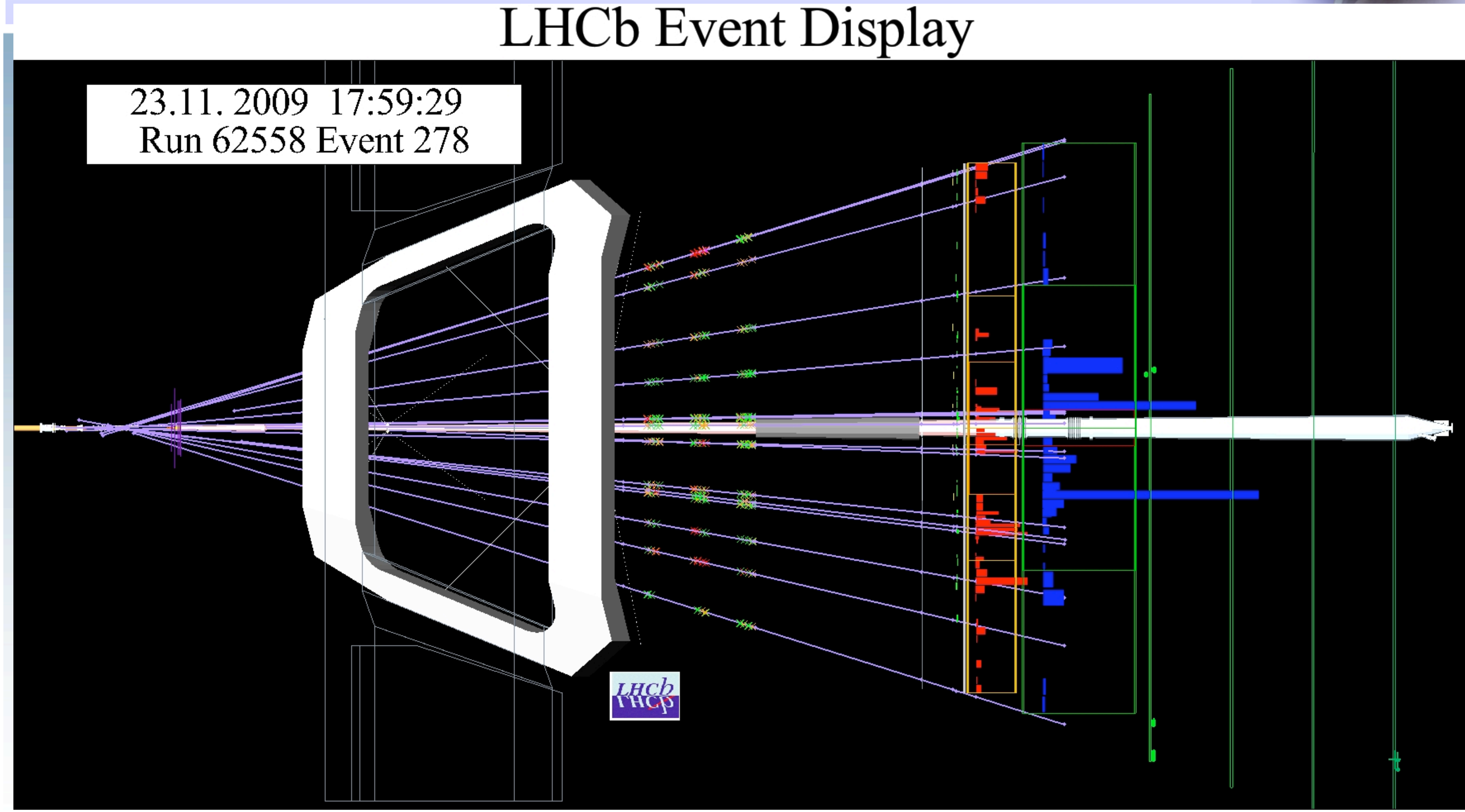
ALICE EVENT AT 900 GeV



Monday 23, Nov

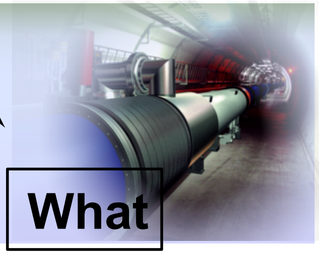
and this

LHCb EVENT AT 900 GeV



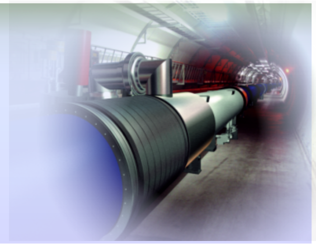
Monday 23, Nov

Plans



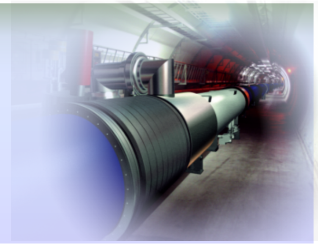
		When	What
• **Train magnets** • Should be easy to get to 6TeV • 6.5 TeV and 7 TeV will take time	7 TeV	2014 ?	Training
• **Fix stabilizers for 12kA** • Machine wide • Do it in 2 shutdowns ?	6 TeV	2012 ?	Stabilizers
• **Commission circuits to 9kA** • Based on experience gained • Not at all guaranteed !	5 TeV 9 kA	Summer 2010	
• **Fix connectors and commission circuits to 6kA**	3.5 TeV 6 kA	January and February 2010	nQPS

and many more that will come



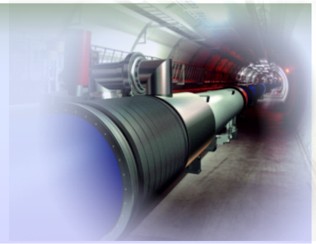
Feliz Navidad

III. The Interaction Regions



Contents:

III.IV Luminosity optimization



- Luminosity formulae:

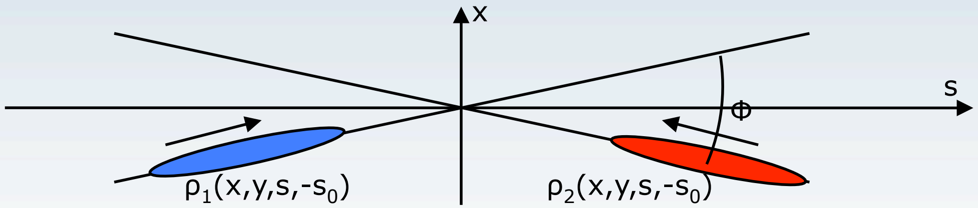
$$L = \frac{N_1 N_2 f_{rev} N_b}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} F \cdot W \cdot e^{\frac{B^2}{A}}$$

N_i = number of protons/bunch
N_b = number of bunches
f_{rev} = revolution frequency
σ_{ix} = beam size along x for beam i
σ_{iy} = beam size along y for beam i
Assume Gaussian distributions for the beam distribution functions and equal bunch length.

F is a pure **crossing angle (Φ) contribution**, which for a crossing angle in the horizontal plane (XS, with S the direction of movement) takes the form:

$$F = \frac{1}{\sqrt{1 + 2\frac{\sigma_s^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\tan^2\frac{\phi}{2}}}$$

F_{LHC} = 0.836



W is a **pure beam offset contribution**. If the offset is in the horizontal plane beam 1 is displaced by d_1 and beam 2 is displaced by d_2 with respect to their reference orbits, thus *W* takes the form:

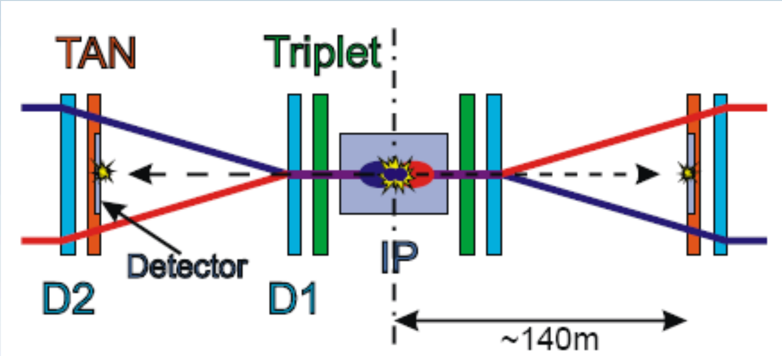
$$W = e^{-\frac{(d_2 - d_1)^2}{2(\sigma_{x1}^2 + \sigma_{x2}^2)}}$$

III.IV Luminosity optimization

exp(B²/A) is a term that appears when beams collide with a crossing angle and an offset at the same time. For a crossing angle and an offset in the x direction:

$$A = \frac{2\sin^2\frac{\phi}{2}}{\sigma_{1x}^2 + \sigma_{2x}^2} + \frac{\cos^2\frac{\phi}{2}}{\sigma_s^2} \qquad B = \frac{(d_2 - d_1)\sin\frac{\phi}{2}}{\sigma_{1x}^2 + \sigma_{2x}^2}$$

Luminosity monitors in the machine ➔ BRAN detectors:



Luminosity scans:

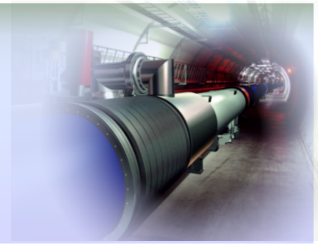
1: Get the beams into collision (the first days of beam commissioning);

2: Optimize luminosity ➔ **every fill**

3: Calibrate luminosity based on machine parameters ➔ **dedicated runs**

Each of these is of course applicable at each of the four LHC interaction points.

The RF system: functionality and beam parameters



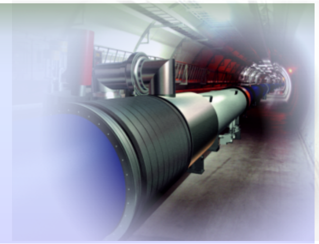
Functionality:

- Proton machine:
  1. Injection synchronization
  2. Capture bunches
  3. Accelerate/decelerate
  4. Beam measurements
- Lepton machine:
  1. Accelerate
  2. Compensate for synchrotron radiation losses

Main beam and RF parameters directly relevant to the design of the RF:

	Unit	Injection	Collision
Bunch area (2σ)	eVs	1.0	2.5
Bunch length (4σ)	ns	1.71	1.06
Energy spread (2σ)	10^{-3}	0.88	0.22
Protons/bunch	10^{11}	1.15	
Num. bunches		2808	
Transverse normalized emittance (H/V)	µm rad	3.5	3.75
Ibeam	A	0.582	
Synchrotron radiat. loss/turn	keV		7
Longitudinal damping time	h		13
Intra beam scattering growth time H	h	38	80
Intra beam scattering growth time V	h	30	61
RF frequency	MHz	400.789	400.790
Harmonic number		35640	
RF voltage/beam	MV	8	16
Energy gain/turn (20 min ramp)	keV	485	
RF power supply during accel./beam	kW	~275	
Synchrotron frequency	Hz	63.7	23.0
Bucket area	eVs	1.43	7.91
RF(400MHz) component of Ibeam	A	0.87	1.05

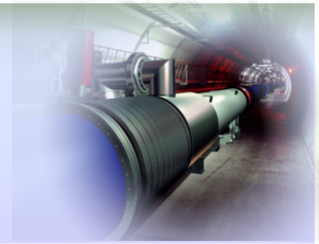
The RF system: components

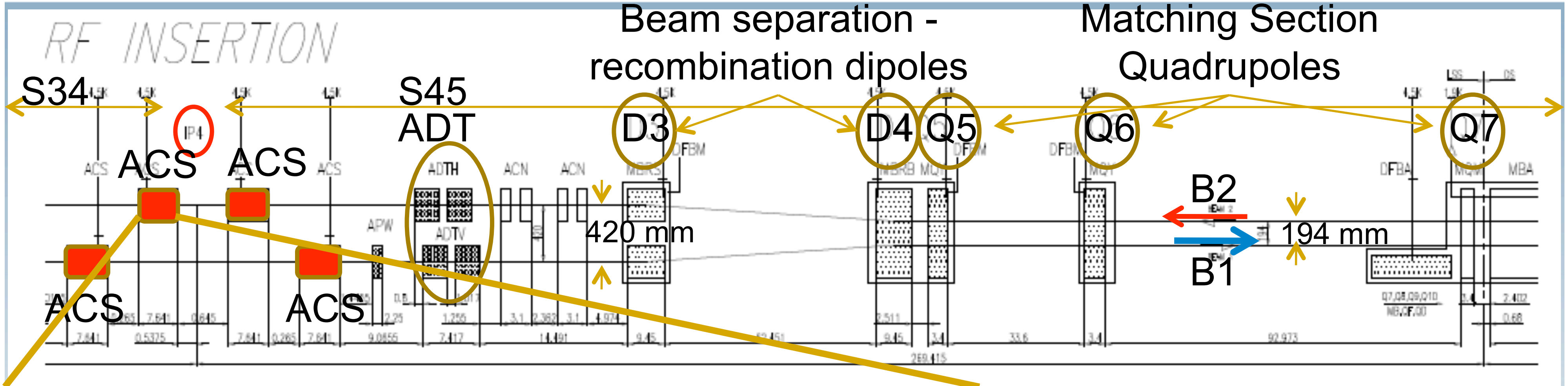


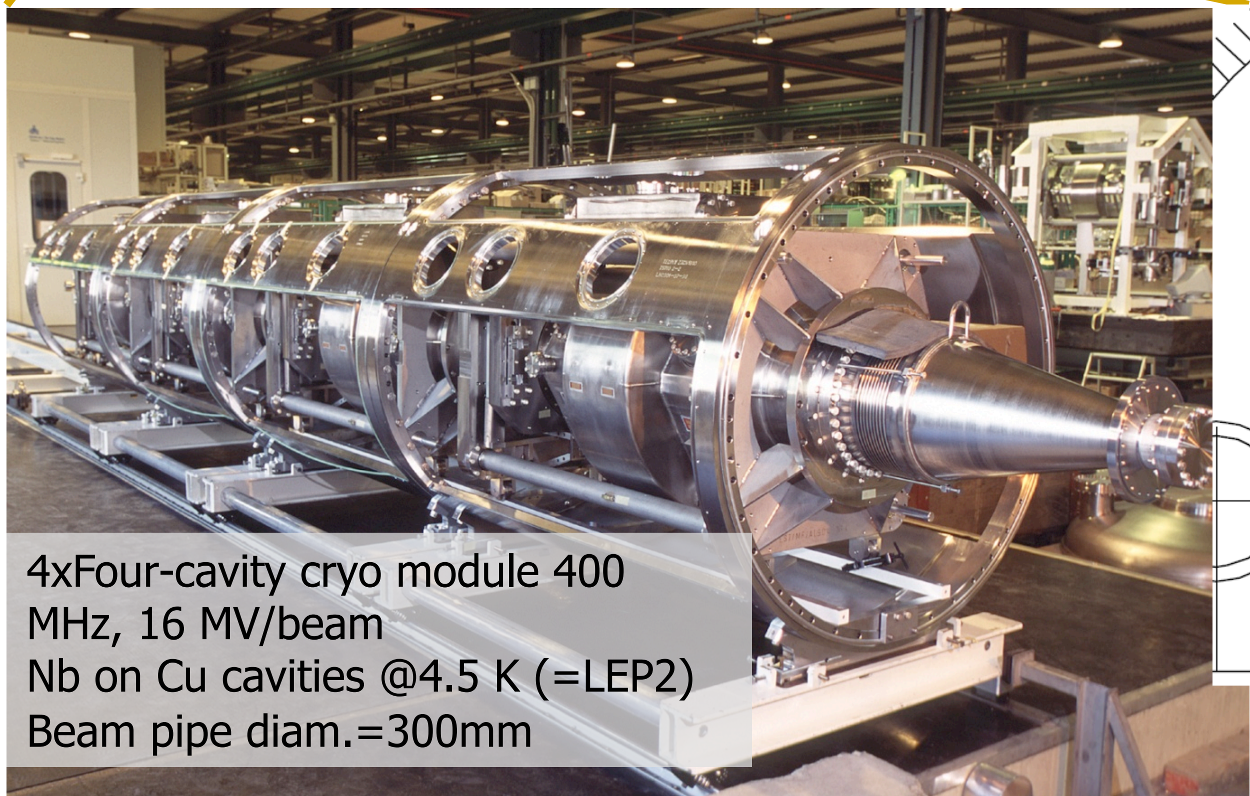
- Main 400 MHz Accelerating System (ACS)
- Transverse damping and feed-back system (ADT)
  - Functionality:
    - Dumps transverse injection oscillations
    - Prevents transverse coupled bunch instabilities (dipole modes)
    - Can excite transverse oscillations for beam measurements
- Low-level RF (part of the 400 MHz Accelerating Sys.)

Low level RF components:	
Cavity controller (RF feedback and tuning)	Beam control & RF synchronization
Fast timing distribution to kickers, dump and experiments	Longitudinal damper

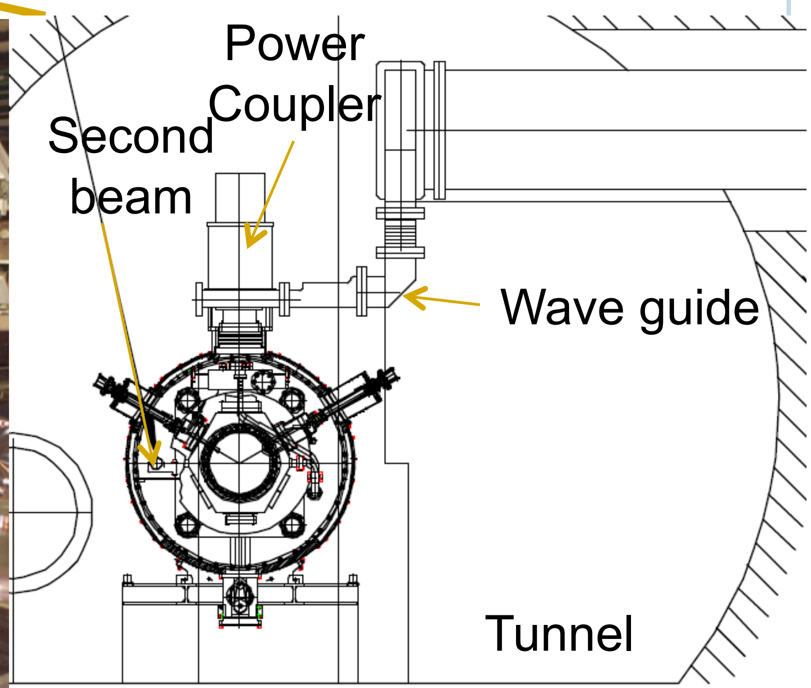
The RF system: IR4



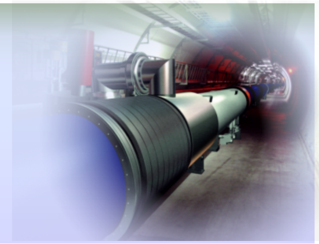


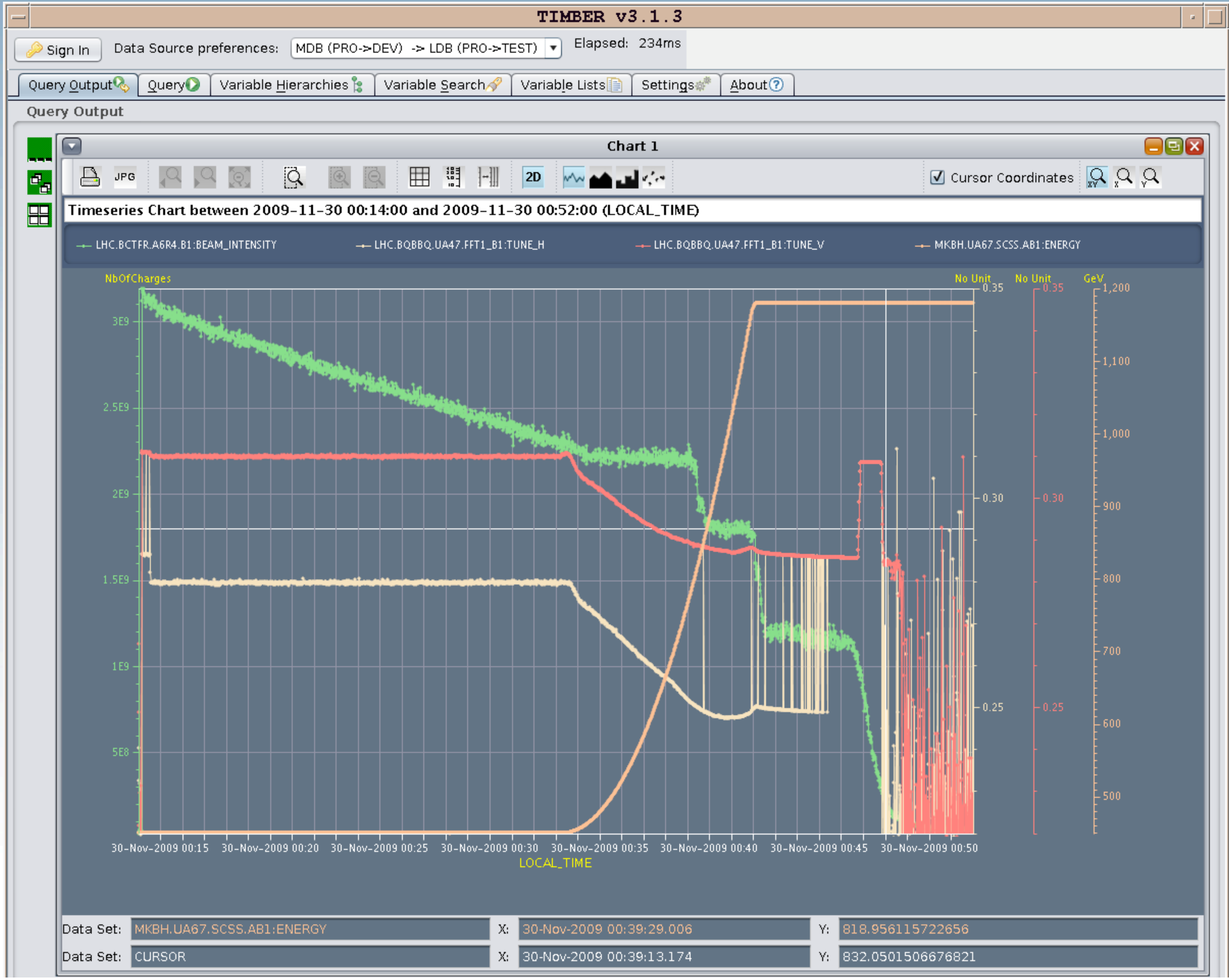


4xFour-cavity cryo module 400 MHz, 16 MV/beam
Nb on Cu cavities @4.5 K (=LEP2)
Beam pipe diam.=300mm

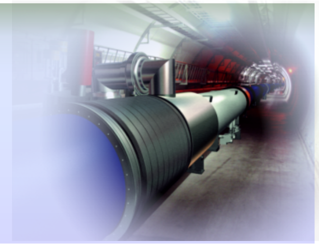


First ramp that went to 1.18 TeV



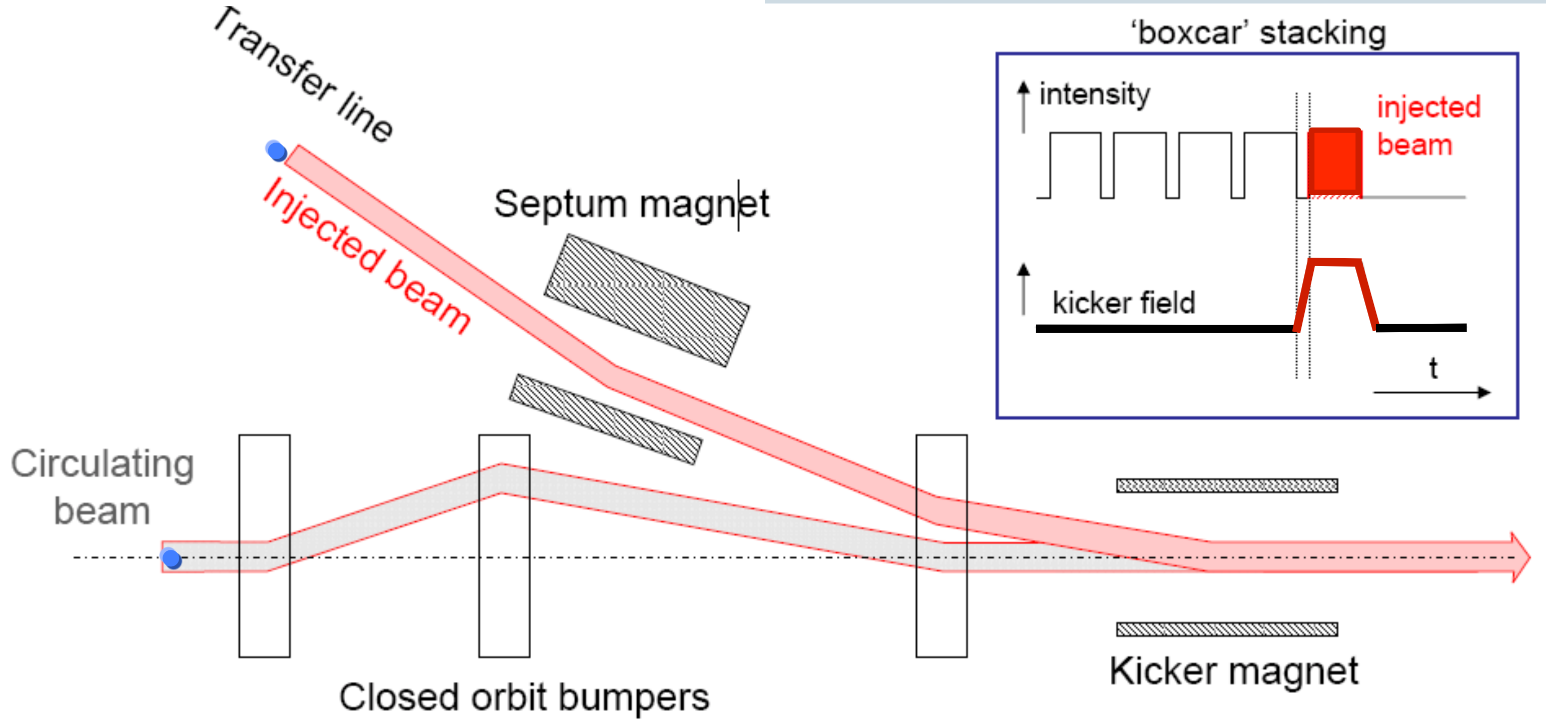


The RF system: synchronization at injection (RF low level)



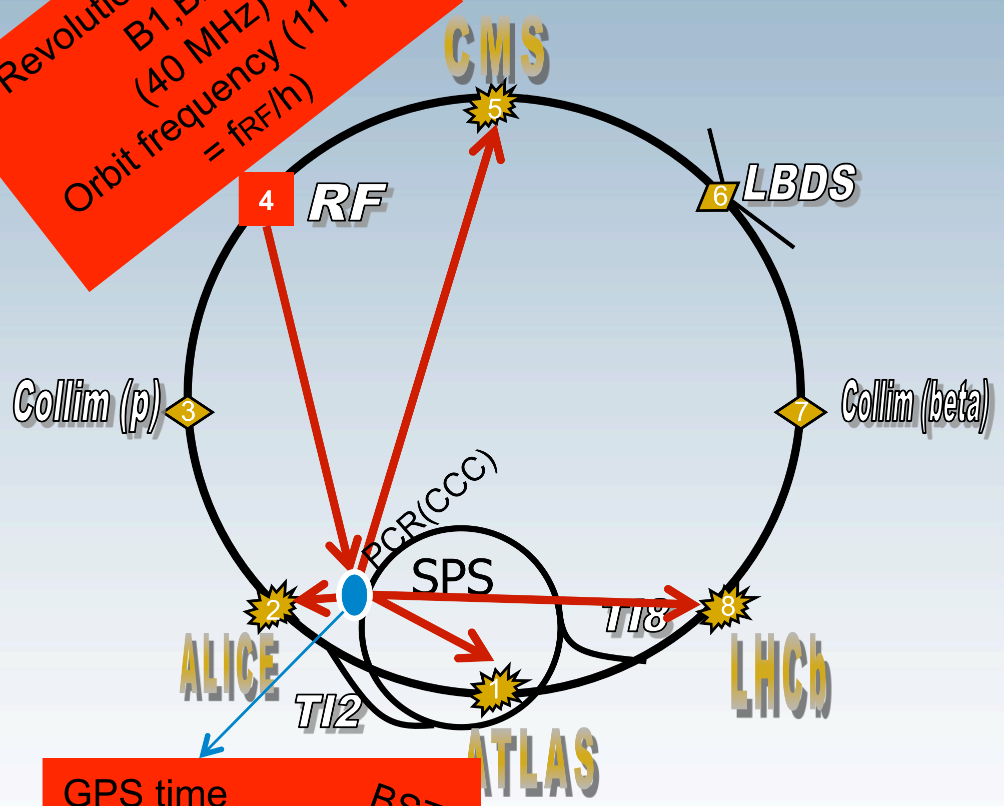
- The **synchronization** of the injection kicker timing system with the injected and circulating beam is **performed with the RF system** via the generation and distribution of the fast injection pre-pulse. This is done via a dedicated fibre optics links that connect IR4 RF with the IR2 injection kicker (inj of B1) and IR8 injection kicker (inj of B2).
- The pre-pulse is locked to the SPS/LHC common frequency.

Proton machines: single turn injection



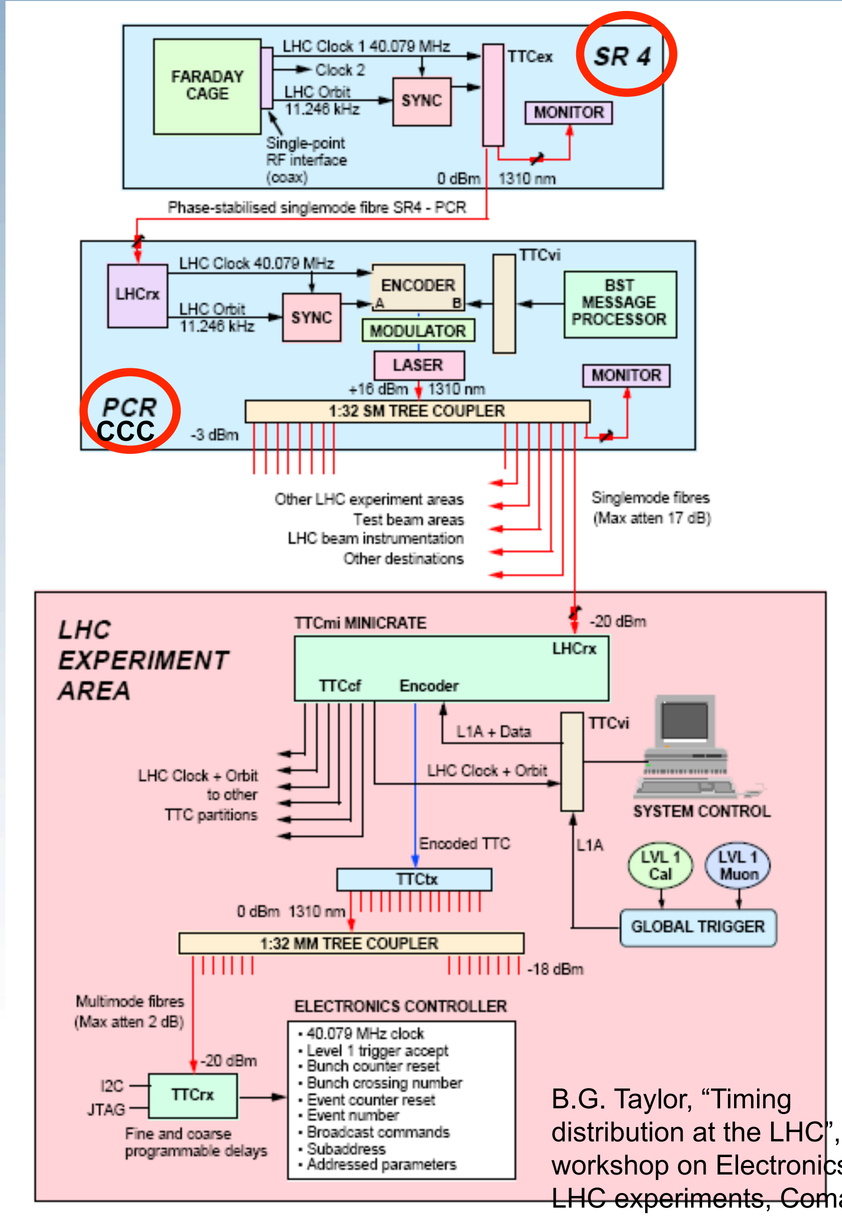
The RF system: synchronization with experiments (RF low level)

Revolution frequency B1,B2 (40 MHz)
Orbit frequency (11 kHz = fRF/h)



GPS time
Machine mode
Beam type
Beam energy
Num. Injected bunches
etc

BST msg from LHC Timing System



B.G. Taylor, “Timing distribution at the LHC”, 8th workshop on Electronics for LHC experiments, Colmar 2002