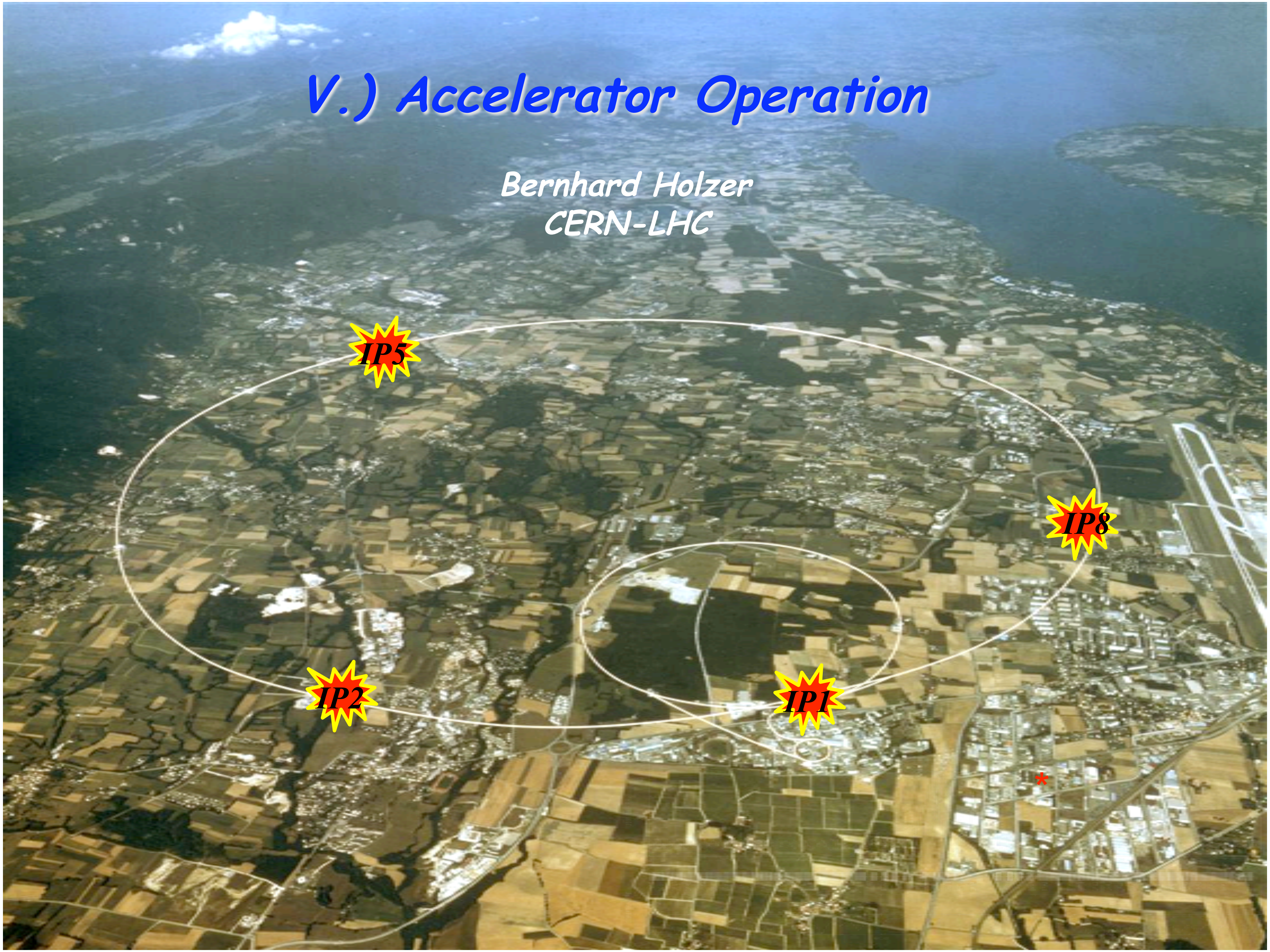
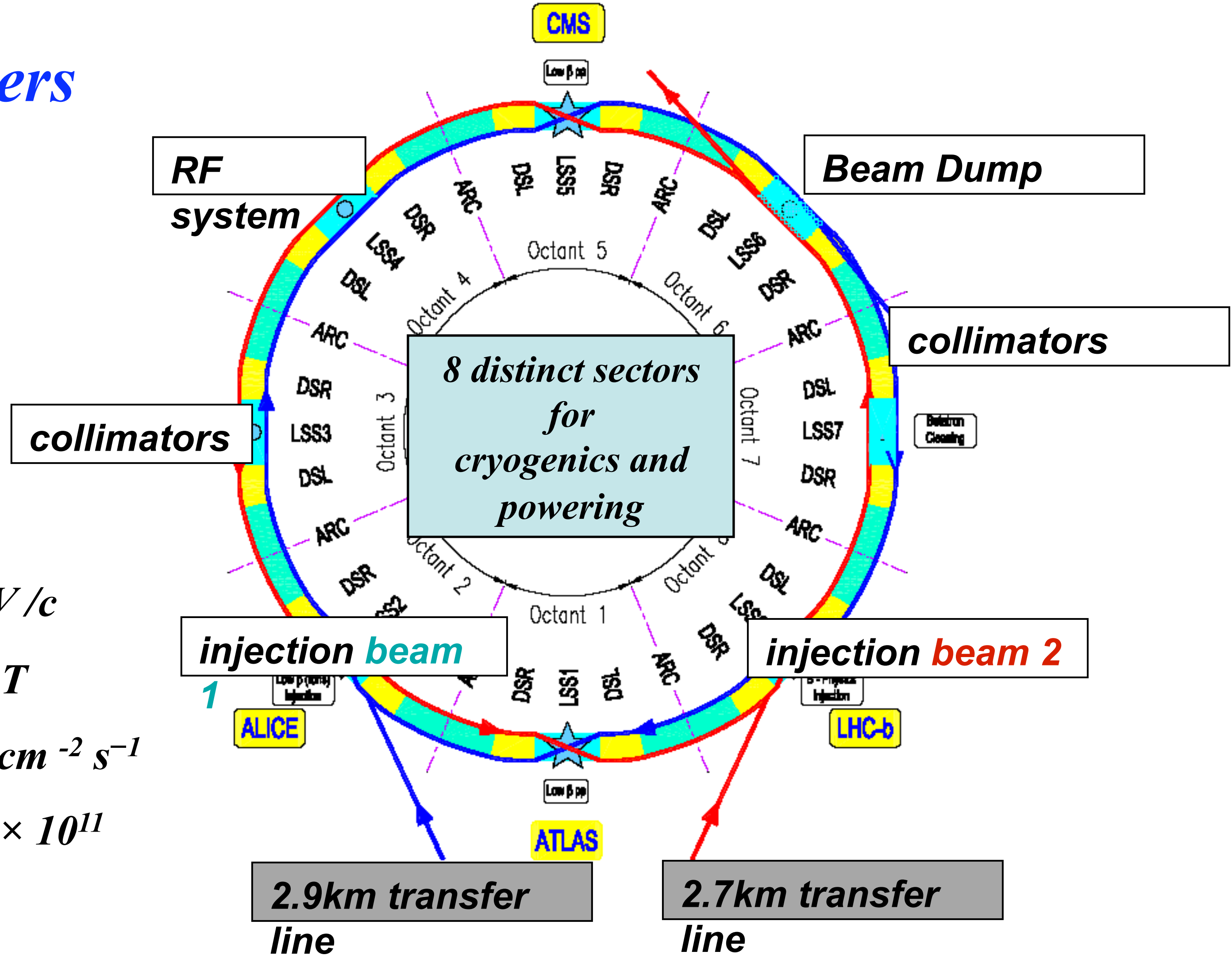
V.) Accelerator Operation

Bernhard Holzer
CERN-LHC



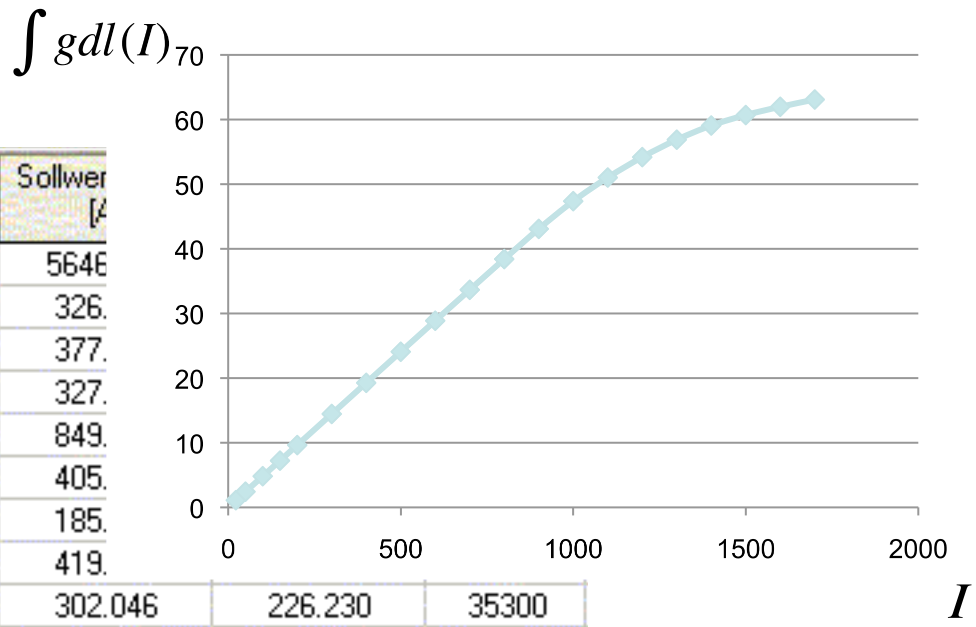
LHC Main Parameters

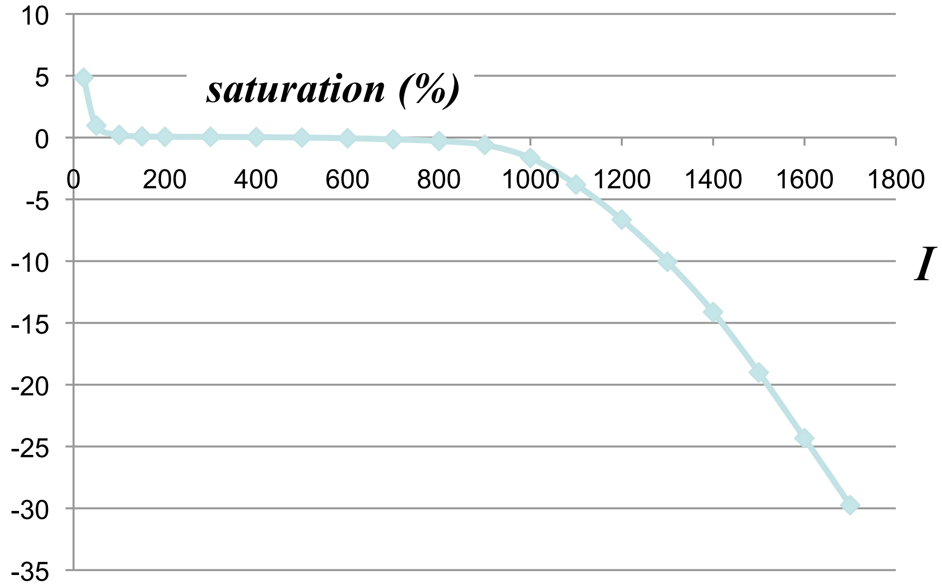


Momentum at collision	*7 TeV /c*
Dipole field for 7 TeV	*8.33 T*
Luminosity	10^{34} *cm* $^{-2}$ *s* $^{-1}$
Protons per bunch	1.15×10^{11}
Number of bunches/beam	*2808*
Nominal bunch spacing	*25 ns*
Normalized emittance	*3.75 μm*
rms beam size (7TeV, arc)	*300 μm*
beam pipe diameter	*56 mm*

Magnet Currents

Nummer	Gruppe	Name	aktiv	Sollwerte File1 [A]	Sollwer [A		
1	HPDIPOL	BPA1	True	4138.993	5646		
2	HPMAINW	QZ51 WL	True	235.462	326.		
3	HPMAINW	QR52 WR	True	258.724	377.		
4	HPMAINW	QC53 WL	True	237.933	327.		
5	HPMAINW	QB28 WL	True	625.429	849.		
6	HPMAINW	QR54 WR	True	291.486	405.		
7	HPMAINW	QR24 WR	True	139.139	185.		
8	HPMAINW	QR50 WL	True	305.348	419.		
9	HPMAINW	QC22 WR	True	75.816	302.046	226.230	35300
10	HPMAINW	QR57 WL	True	260.769	354.833	94.064	12329
11	HPMAINW	QR56 WR	True	190.123	263.722	73.599	11484
12	HPMAINW	QC20 WR	True	91.056	-13.587	-104.643	-16328
13	HPMAINW	QP58 WR	True	-5.517	19.		
14	HPMAINW	QP59 WL	True	-10.401	-11.		
15	HPMAINW	QP60 WR	True	73.600	98.		
16	HPMAINW	QP61 WL	True	69.504	90.		
17	HPMAINW	QP62 WR	True	40.163	58.		
18	HPMAINW	QP63 WL	True	47.489	63.		
19	HPMAINW	QP64 WR	True	-47.780	-71.		

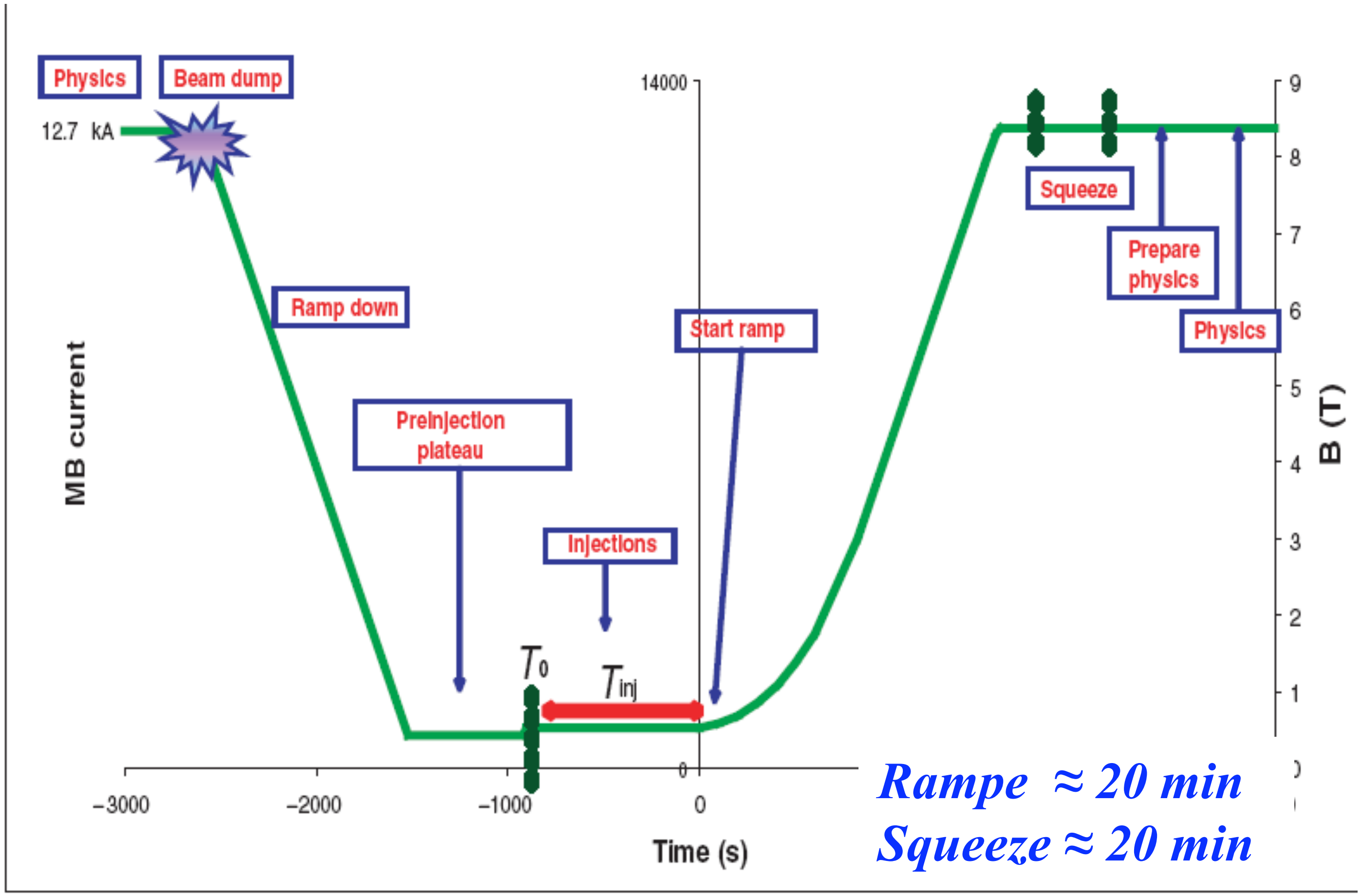




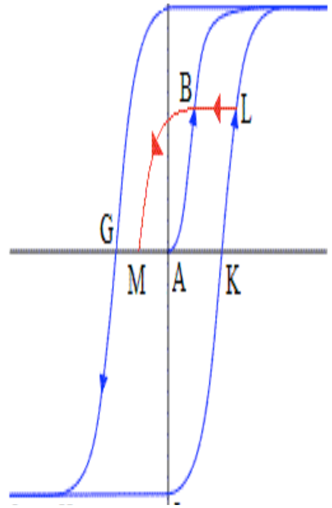
remember: $\Delta B/B \approx 10^{-4}$

LHC Operation: Magnet Preparation Cycle & Ramp

8 independent sectors, hysteresis effects, saturation & remanence in nc and sc magnets, synchronisation of the power converters, magnet model to describe the transfer functions of every element



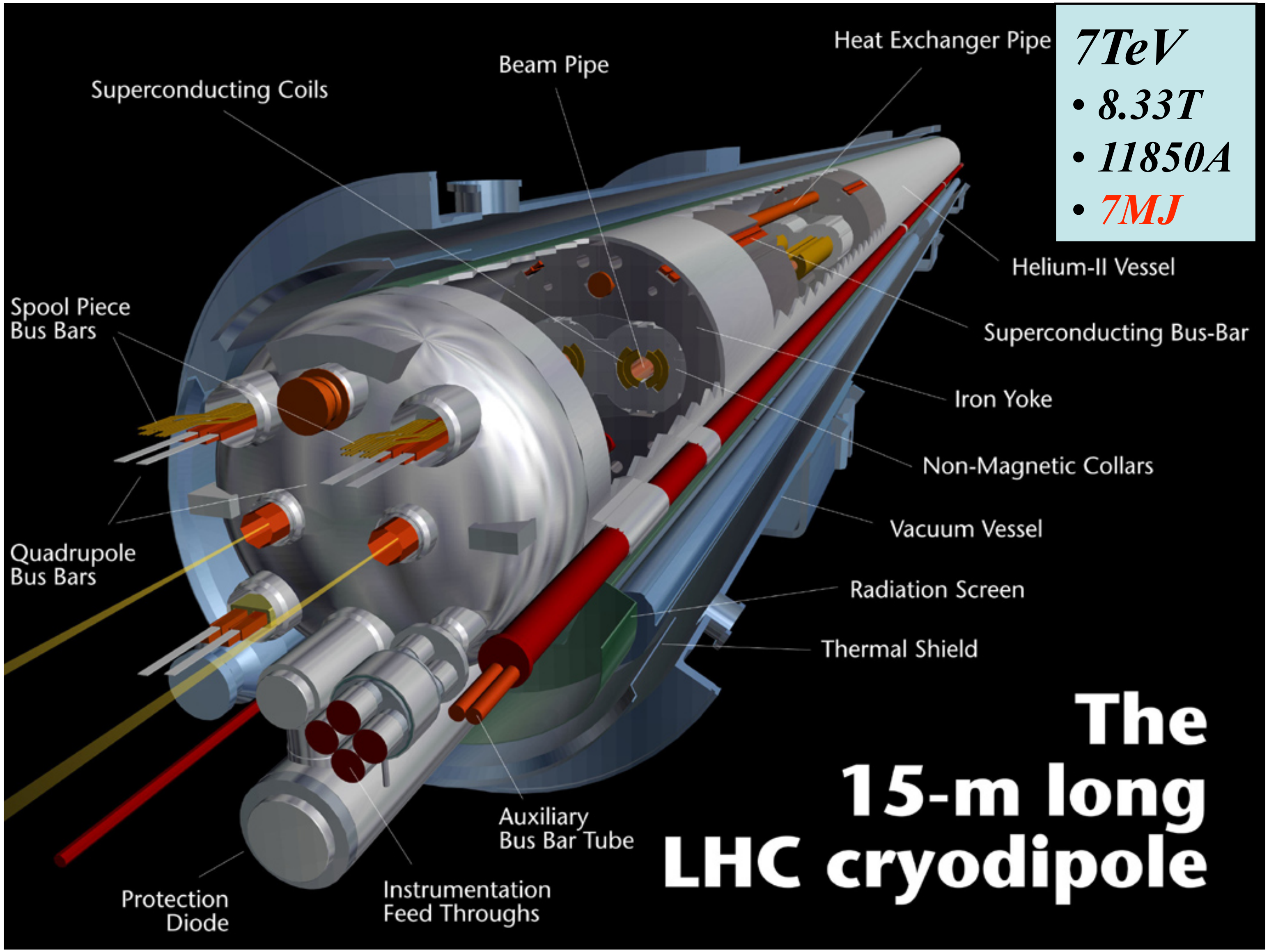
Rampe ≈ 20 min
Squeeze ≈ 20 min



magnet hysteresis

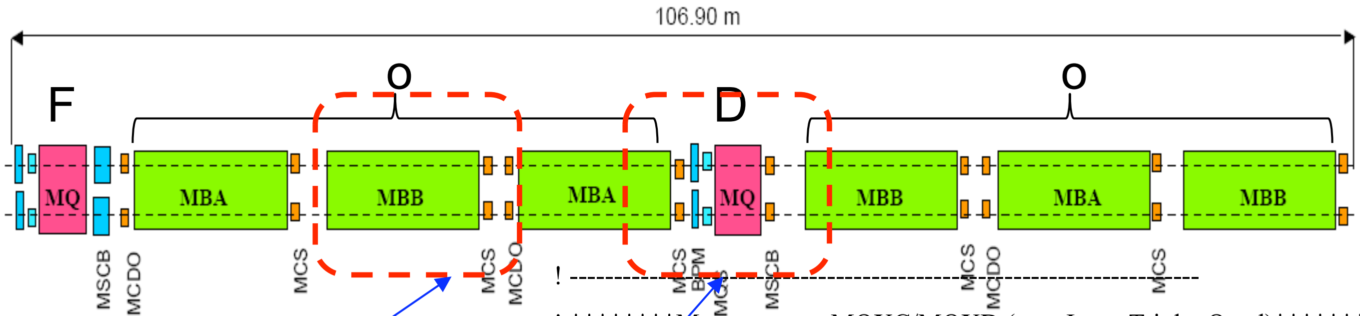
LHC dipoles (1232 of them)

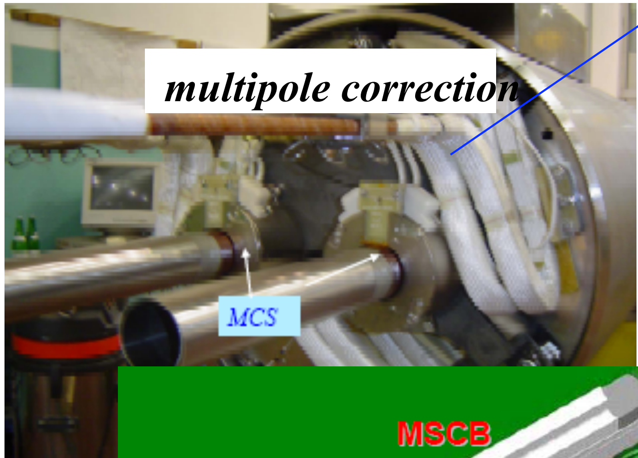
7TeV
- *8.33T*
- *11850A*
- *7MJ*

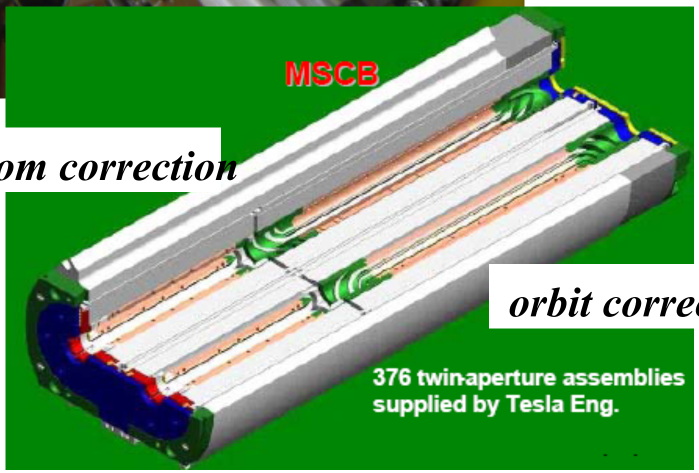


LHC: Basic Layout of the Machine multipole corrector magnets

2, 6, 8, 10, 12 pol
skew & trim quad, chroma 6pol
landau 8 pole







! ---

! ********Magnet type : MQXC/MQXD (new Inner Triplet Quad)***************

! ---

bn in collision

LHC TDR

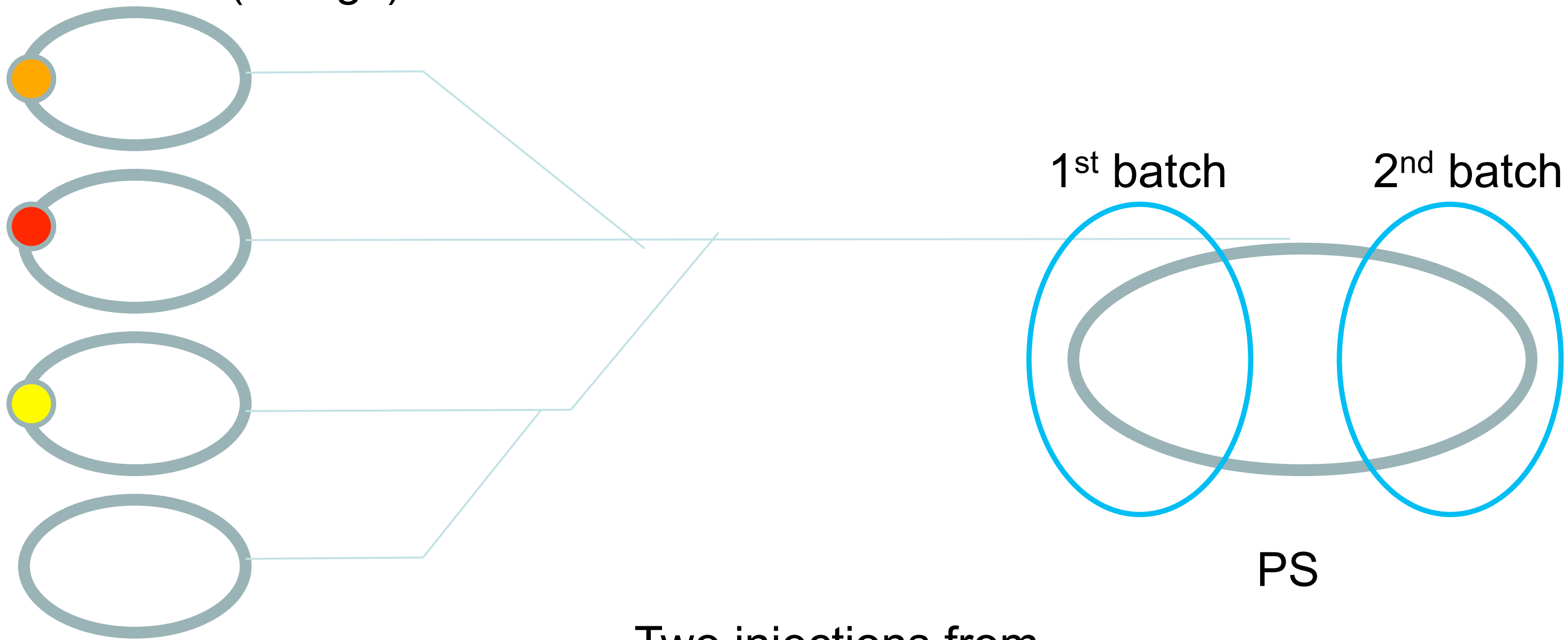
b1M_MQXCD_col := 0.0000 ; b1U_MQXCD_col := 0.0000 ; b1R_MQXCD_col := 0.0000 ;
b2M_MQXCD_col := 0.0000 ; b2U_MQXCD_col := 0.0000 ; b2R_MQXCD_col := 0.0000 ;
b3M_MQXCD_col := 0.0000 ; b3U_MQXCD_col := 0.4600 ; b3R_MQXCD_col := 0.8900 ;
b4M_MQXCD_col := 0.0000 ; b4U_MQXCD_col := 0.6400 ; b4R_MQXCD_col := 0.6400 ;
b5M_MQXCD_col := 0.0000 ; b5U_MQXCD_col := 0.4600 ; b5R_MQXCD_col := 0.4600 ;
b6M_MQXCD_col := 0.0000 ; b6U_MQXCD_col := 1.7700 ; b6R_MQXCD_col := 1.2800 ;
b7M_MQXCD_col := 0.0000 ; b7U_MQXCD_col := [illegible]100 ; b7R_MQXCD_col := 0.2100 ;
b8M_MQXC[illegible] ; b8U_MQXCD_col := [illegible] ; b8R_MQXCD_col := 0.1600 ;
b9M_MQXCD[illegible] ; b9U_MQXCD_col := [illegible] ; b9R_MQXCD_col := 0.0800 ;
b10M_MQXCD_col := 0.0000 ; b10U_MQXCD_col := 0.2000 ; b10R_MQXCD_col := 0.0600 ;
b11M_MQXCD_col := 0.0000 ; b11U_MQXCD_col := 0.0300 ; b11R_MQXCD_col := 0.0300 ;
b12M_MQXCD_col := 0.0000 ; b12U_MQXCD_col := 0.0200 ; b12R_MQXCD_col := 0.0200 ;
b13M_MQXCD_col := 0.0000 ; b13U_MQXCD_col := 0.0200 ; b13R_MQXCD_col := 0.0100 ;
b14M_MQXCD_col := 0.0000 ; b14U_MQXCD_col := 0.0400 ; b14R_MQXCD_col := 0.0100 ;
b15M_MQXCD_col := 0.0000 ; b15U_MQXCD_col := 0.0000 ; b15R_MQXCD_col := 0.0000 ;

MB: main dipole
MQ: main quadrupole
MQT: Trim quadrupole
MQS: Skew trim quadrupole
MO: Lattice octupole (Landau damping)
MSCB: Normal & Skew sextupole
Orbit corrector dipoles
MCS: Spool piece sextupole
MCDO: Spool piece 8 / 10 pole
BPM: Beam position monitor + diagnostics

LHC Operation: Pre-Accelerators and Injection

BOOSTER (1.4 GeV) ➔ PS (26 GeV) ➔ SPS (450 GeV) ➔ LHC

BOOSTER (4 rings)



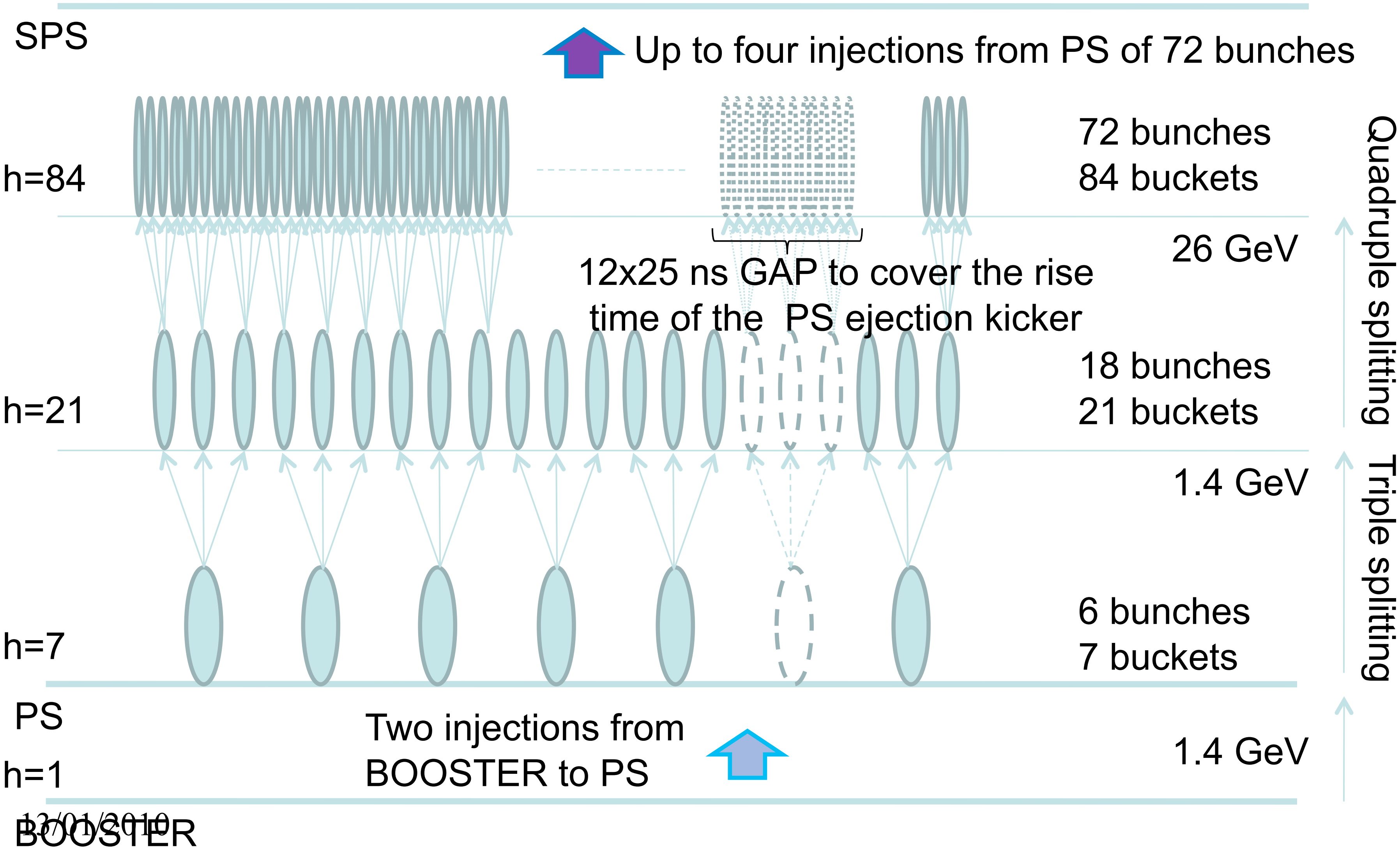
Two injections from BOOSTER to PS

h=1

h=7 (6 buckets filled + 1 empty)

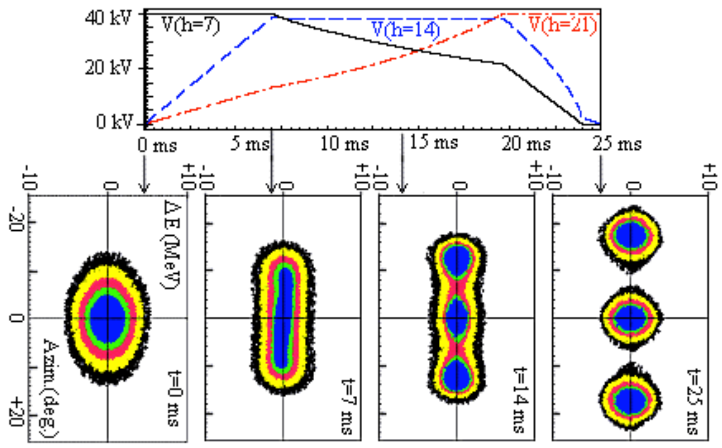
court. R. Alemany

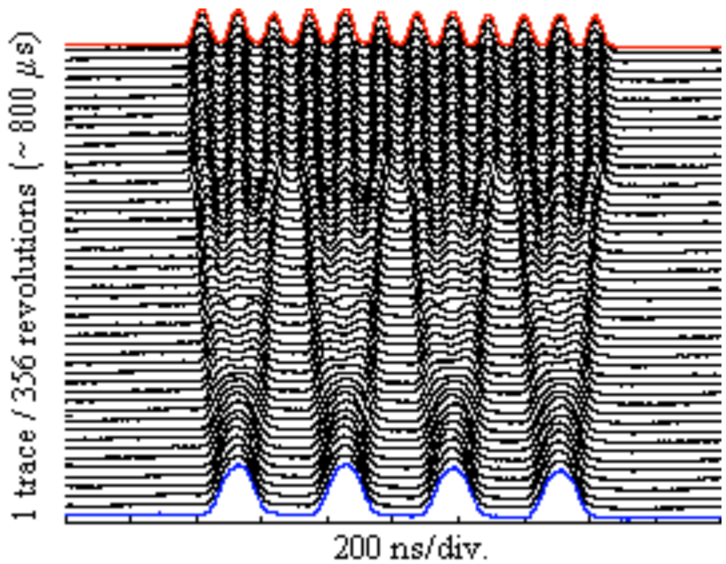
LHC Injection: Preparing the Bunch Trains



Beam Injection

Bunch Splitting in the PS





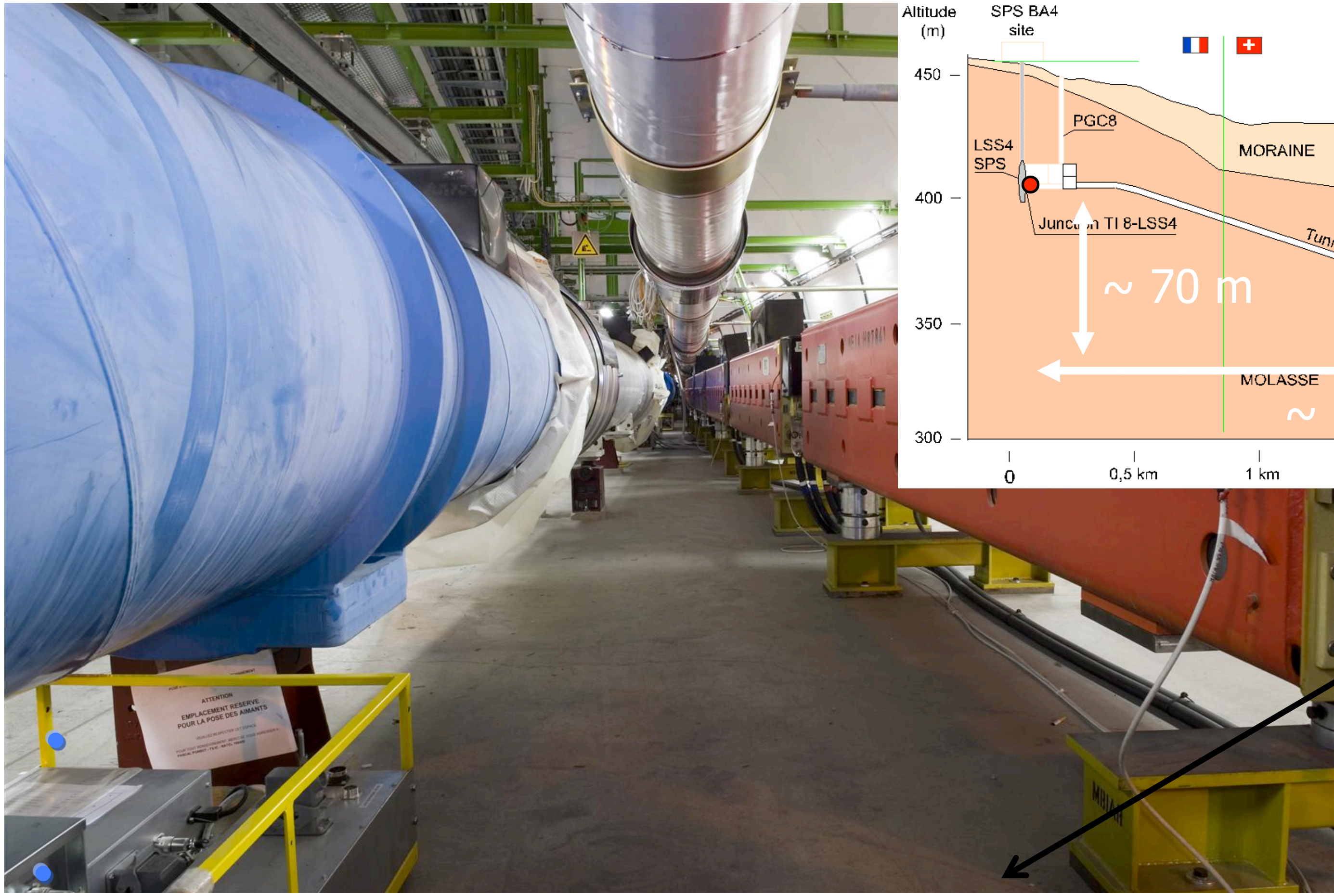
CERN: Linac 2 injection into PSB

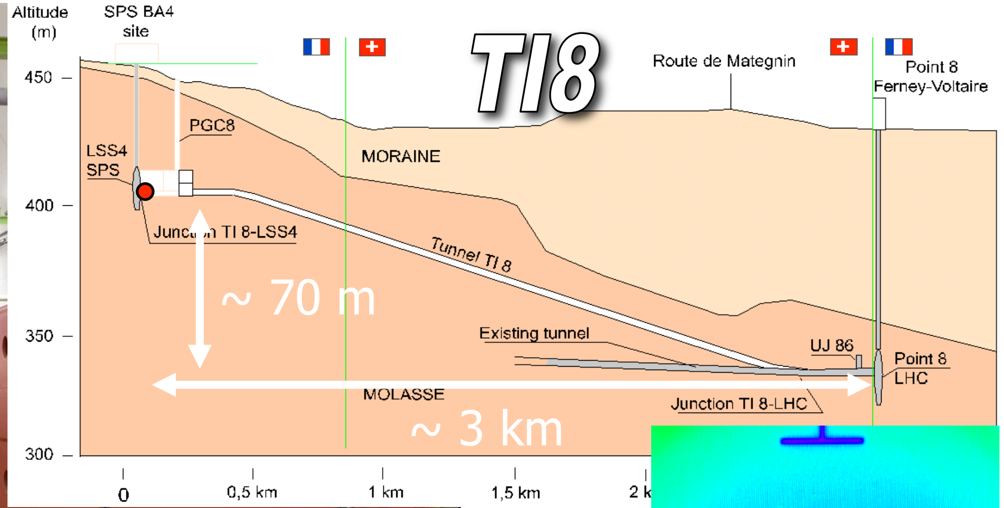
$N_p \approx 1.5 \cdot 10^{13}$ protons per bunch, ***$E_{inj} = 50$ MeV***

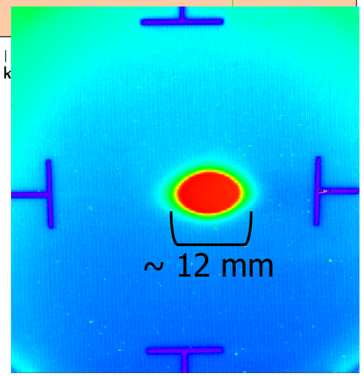
$\beta = 0.31$

$\gamma = 1.05$

Injection mechanism: the transfer lines







13/01/2010

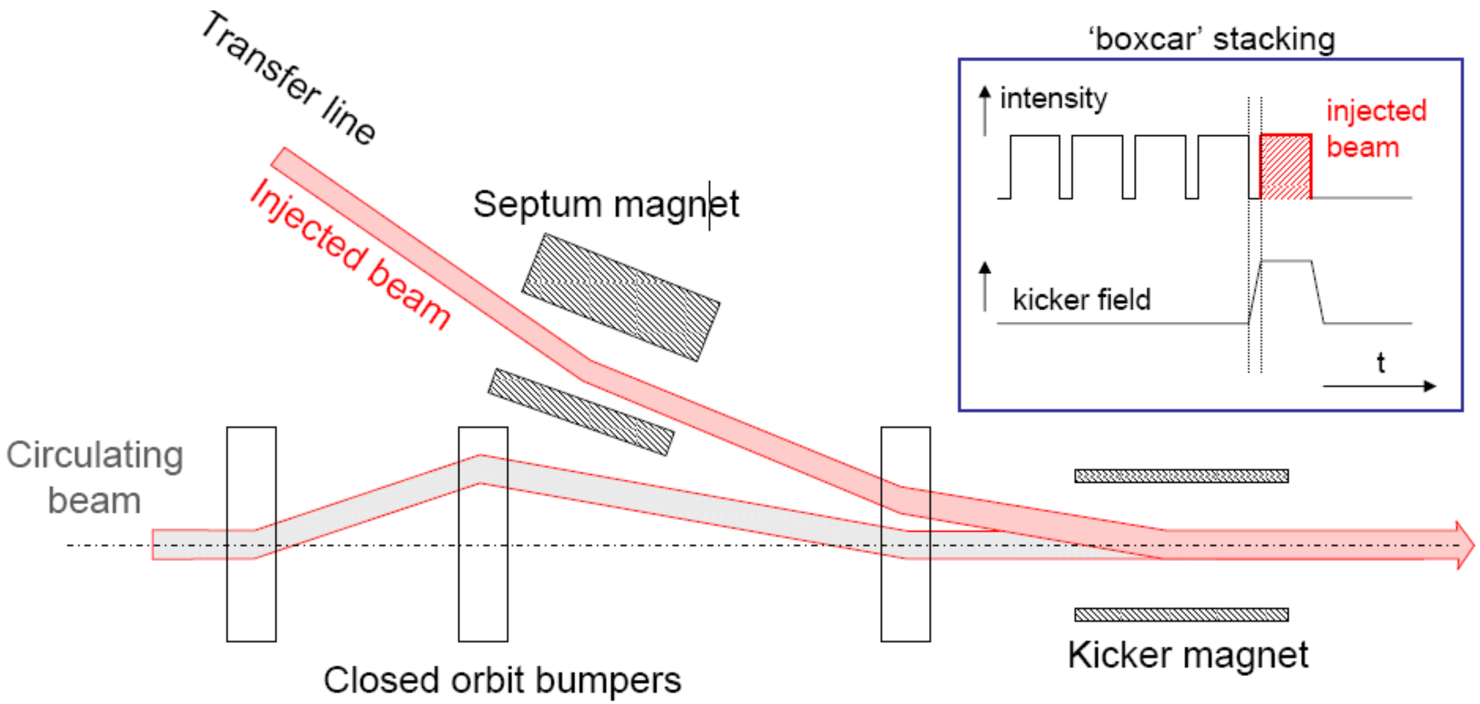
court. R. Alemany

Injection schemes:

Standard Proton Beam ... single turn Injection
Electron Beam .... "off axis" Injection
Ion Beam .... "multi turn" injection

Single Turn Injection

Example: LHC, HERA-P



Transferlines & Injection: Errors & Tolerances

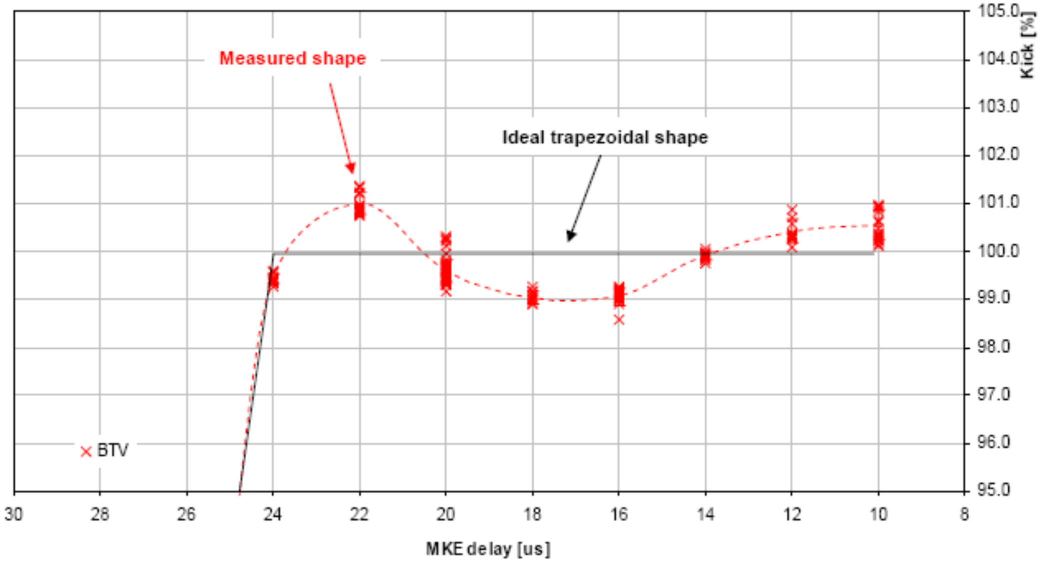
** quadrupole strengths --> "beta beat" Δβ / β*
** alignment of magnets --> orbit distortion in transferline & storage ring*
** septum & kicker pulses --> orbit distortion & emittance dilution in storage ring*

Example: Error in position Δa:

$$\varepsilon_{new} = \varepsilon_0 * (1 + \frac{\Delta a^2}{2})$$

Δa =0.5 σ

$$\rightarrow \quad \varepsilon_{new} = 1.125 * \varepsilon_0$$



Kicker "plateau" at the end of the PS - SPS transferline measured via injection - oscillations

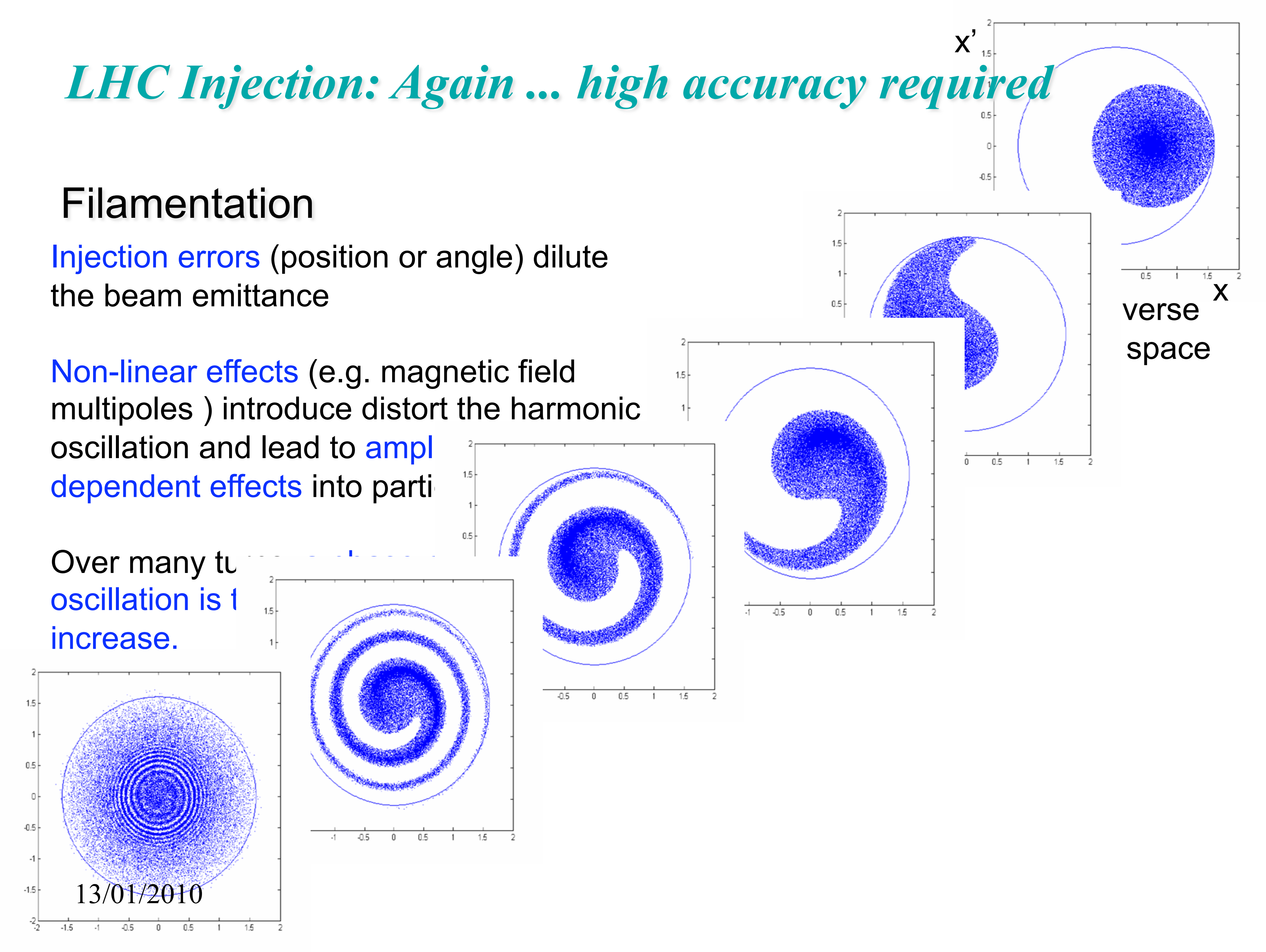
LHC Injection: Again ... high accuracy required

Filamentation

Injection errors (position or angle) dilute the beam emittance

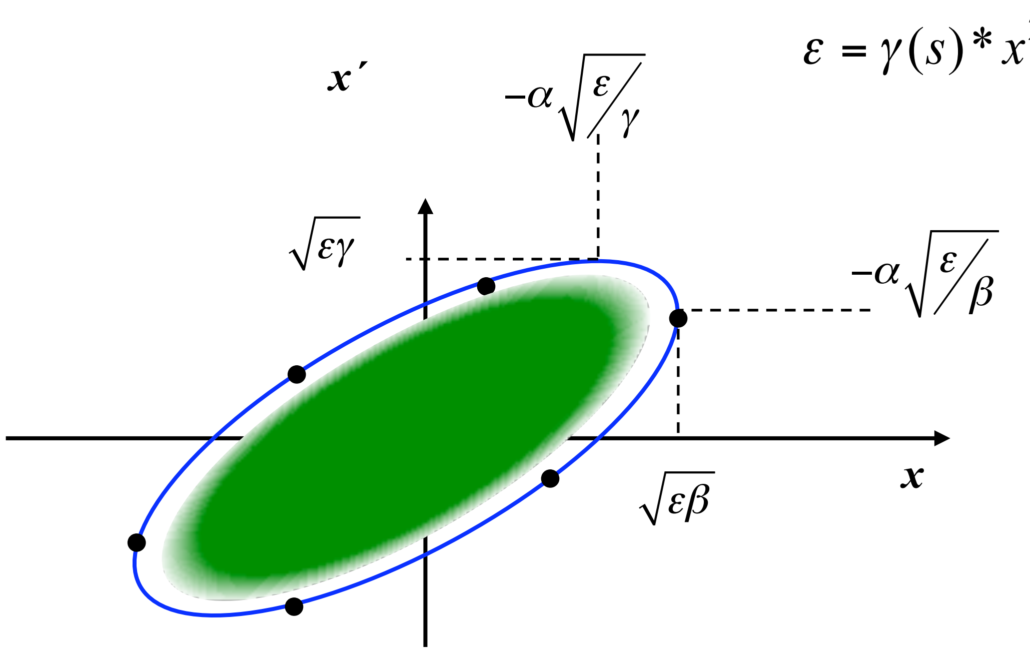
Non-linear effects (e.g. magnetic field multipoles) introduce distort the harmonic oscillation and lead to ampl dependent effects into parti

Over many tu
oscillation is t
increase.

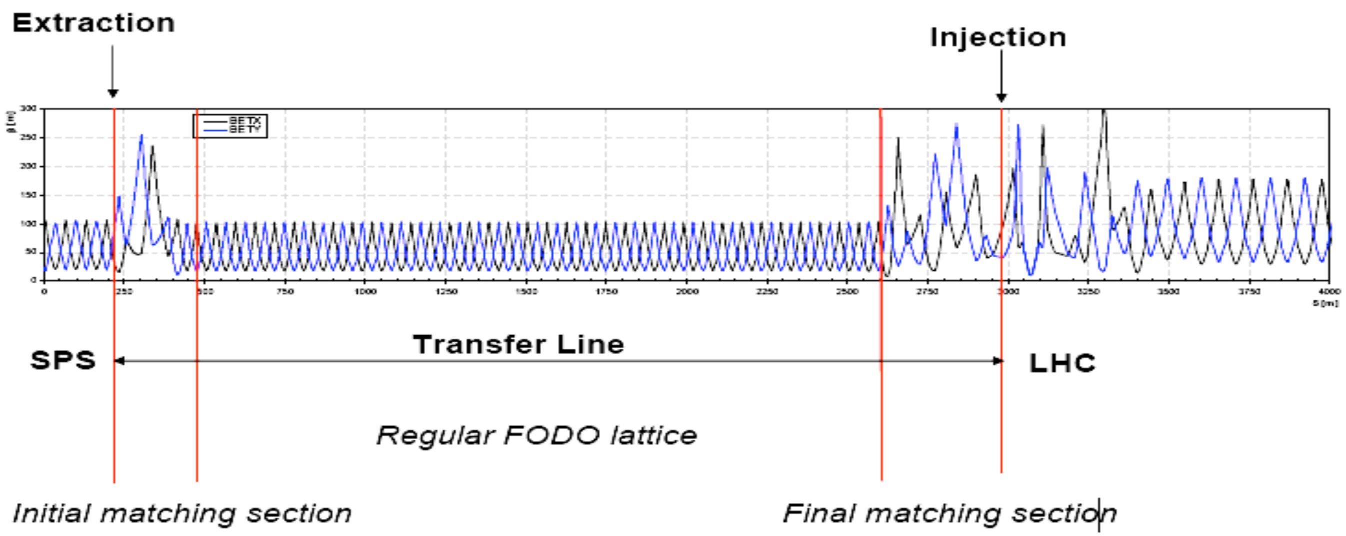


LHC Injection: remember the phase space

$$\varepsilon = \gamma(s) * x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'(s)^2$$



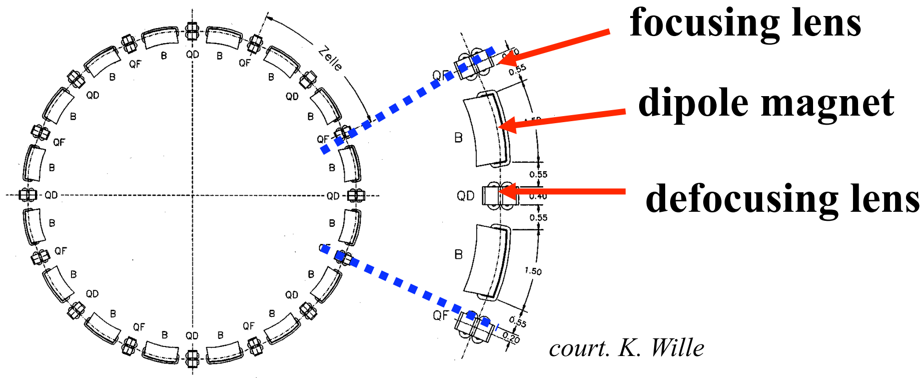
Injected Beam has to be matched to the optics of the storage ring



LHC First Turn Steering

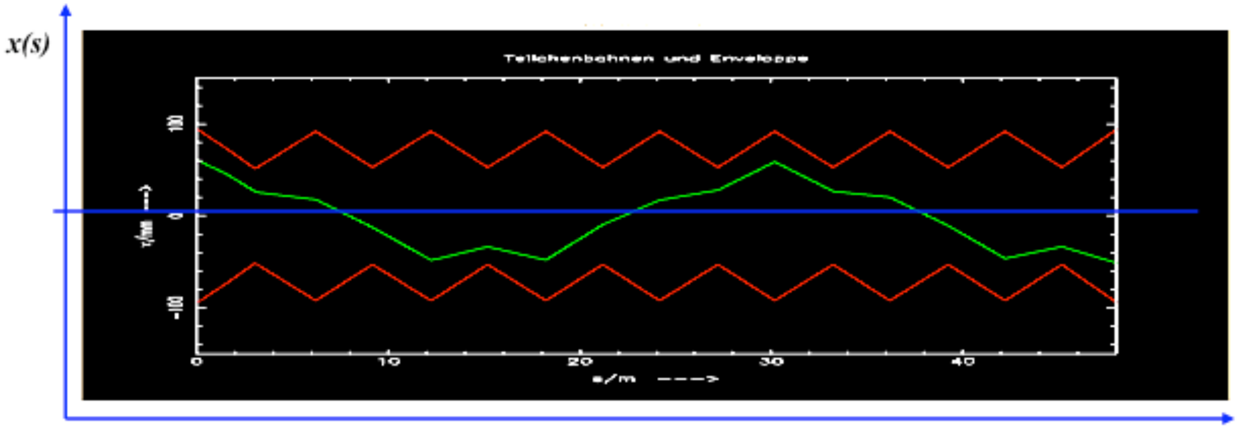
$$M_{total} = M_{QF} * M_D * M_{QD} * M_{Bend} * M_{D*.....}$$

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s2} = M(s_2, s_1) * \begin{pmatrix} x \\ x' \end{pmatrix}_{s1}$$



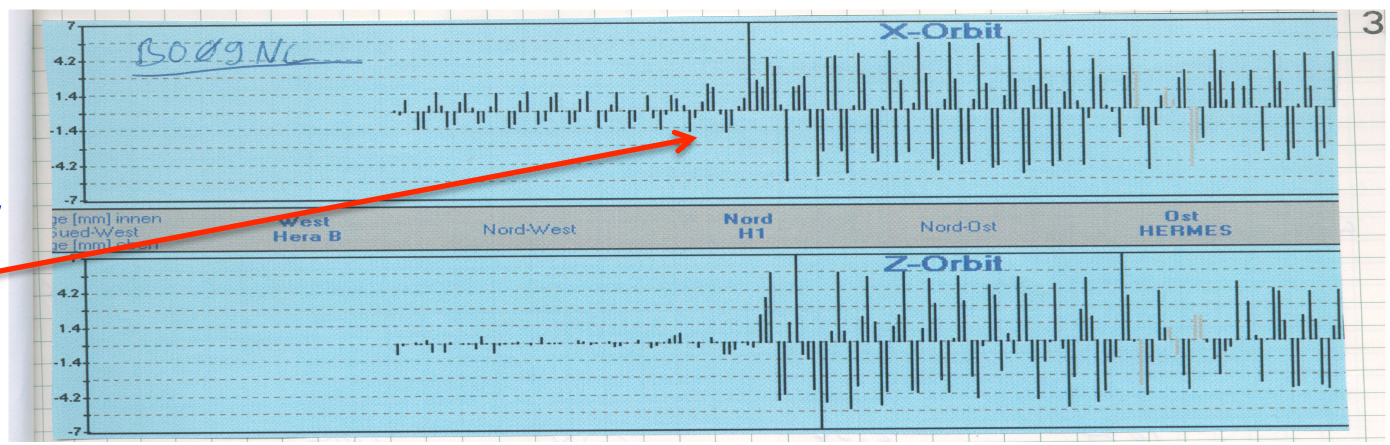
court. K. Wille

in theory
nice harmonic oscillation



in reality:
effect of many localised orbit distortions

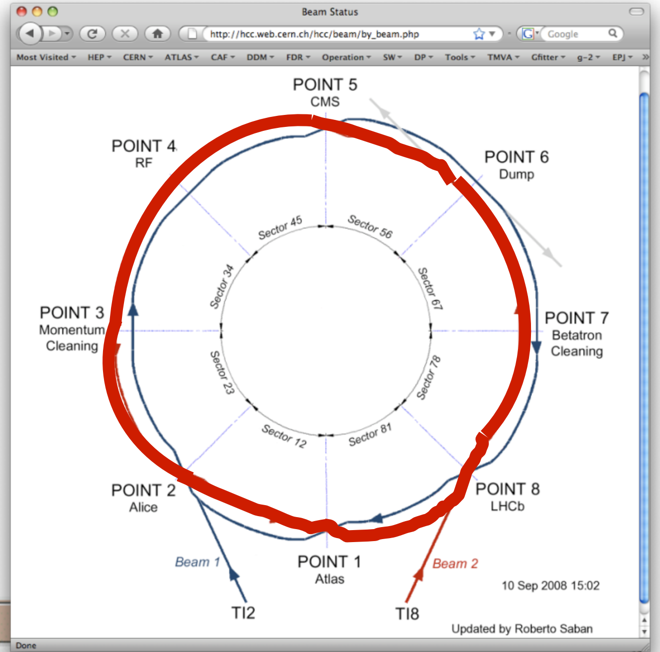
-> correct

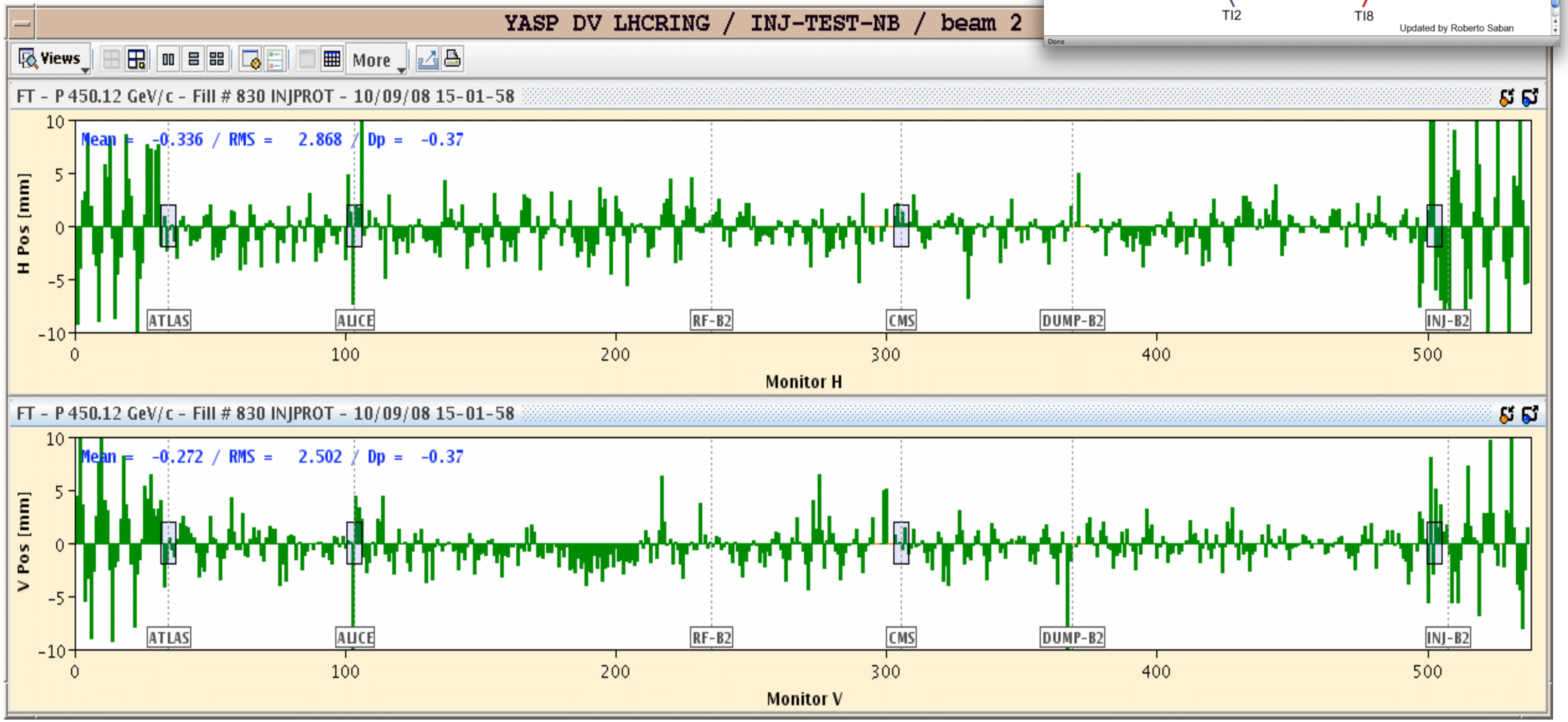


LHC Operation: Beam Commissioning

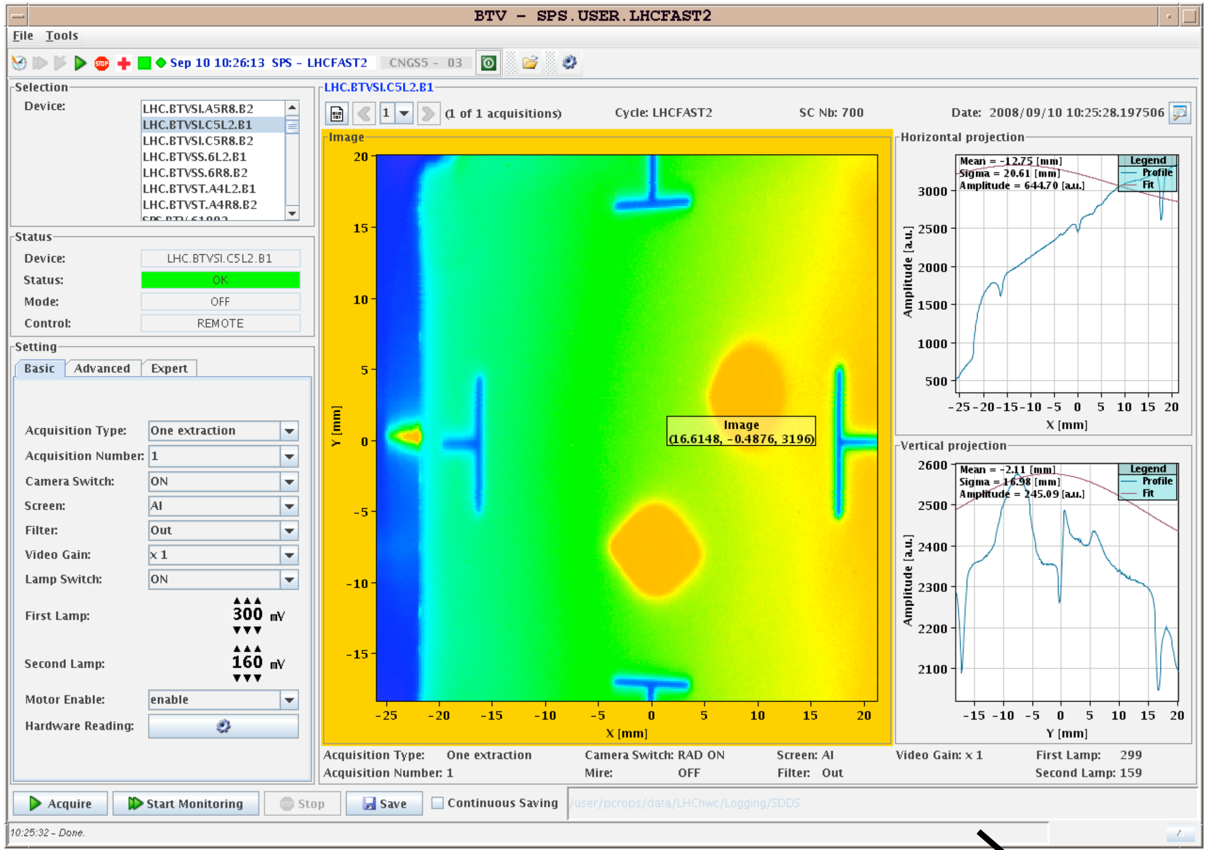
First turn steering "by sector:"

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





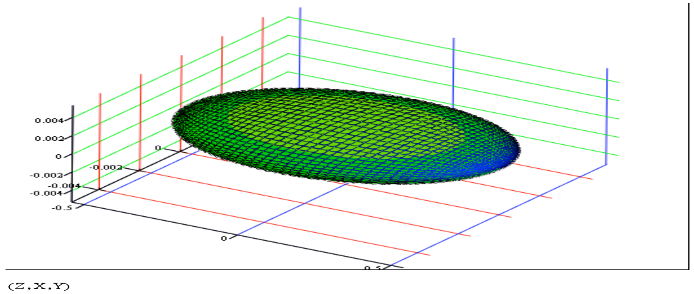
LHC Operation: the First Turn



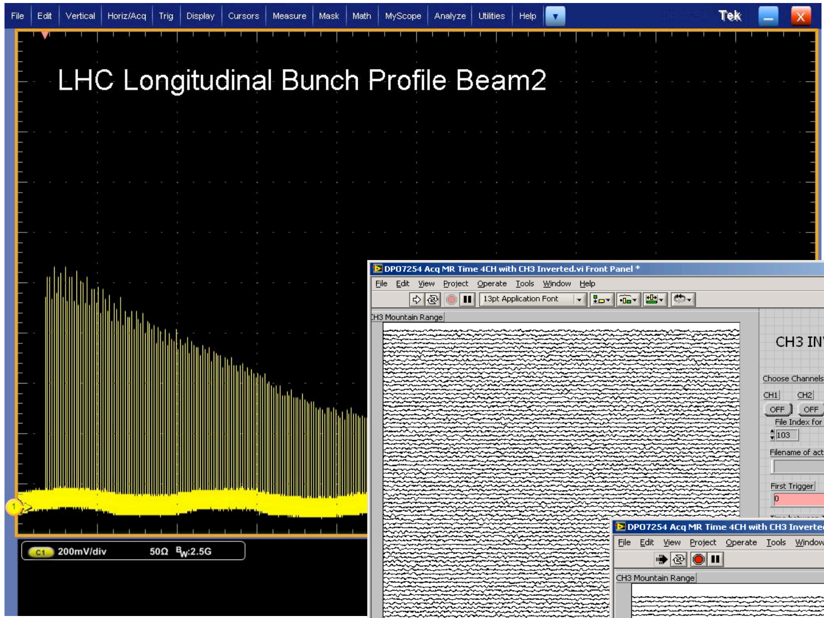
Beam 1 on OTR screen
1st and 2nd turn

Correct x, x', y, y' to obtain the Closed Orbit

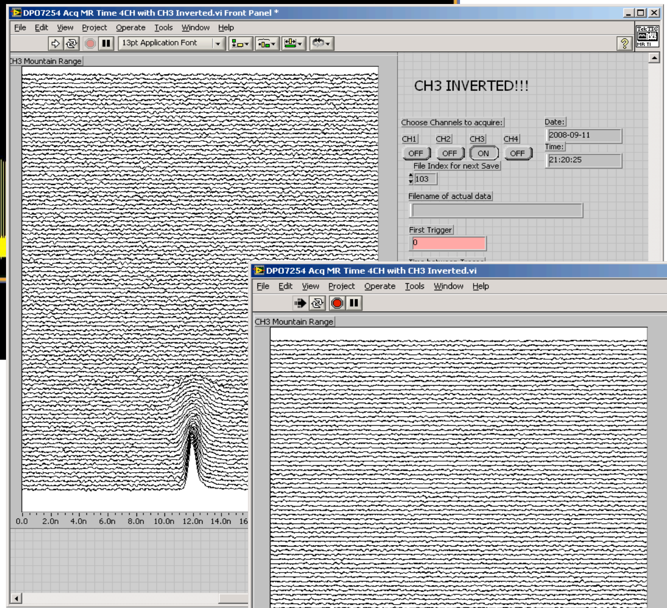
LHC Commissioning: RF



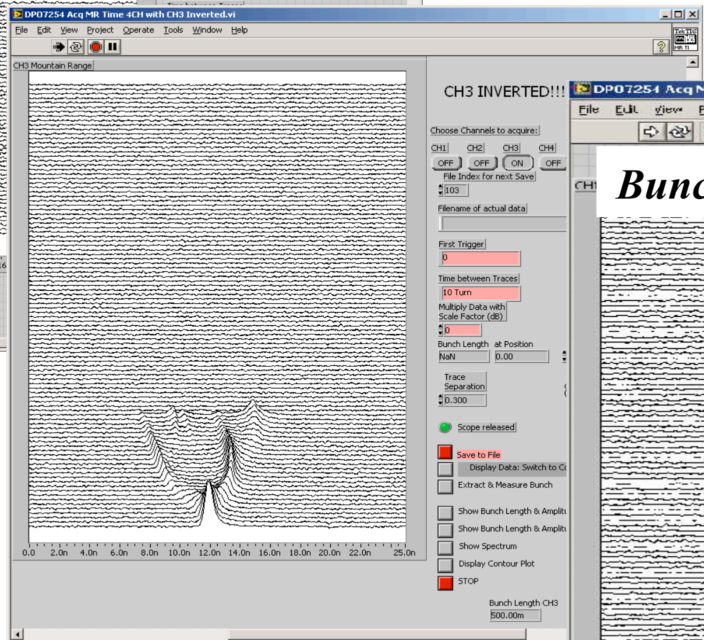
a proton bunch: focused longitudinal by the RF field

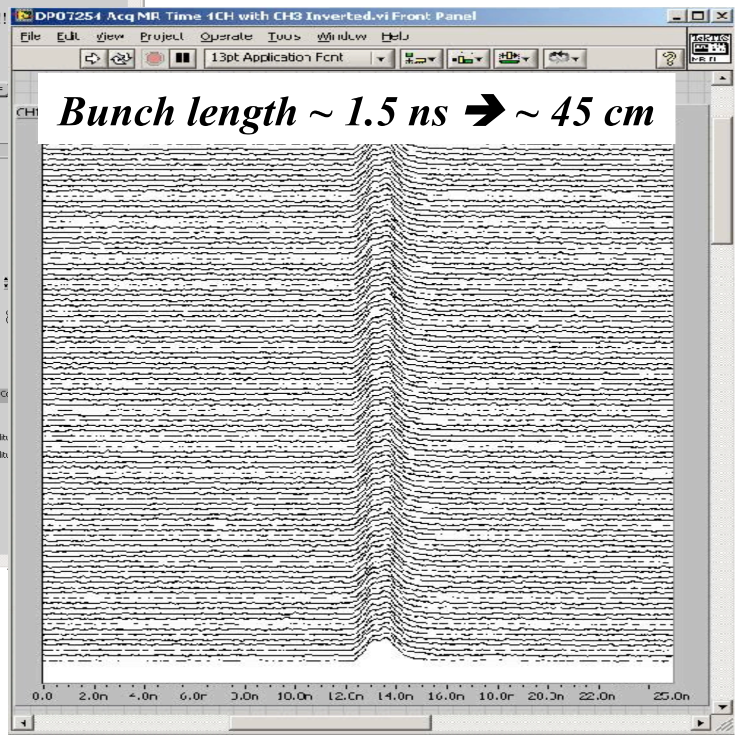


RF off



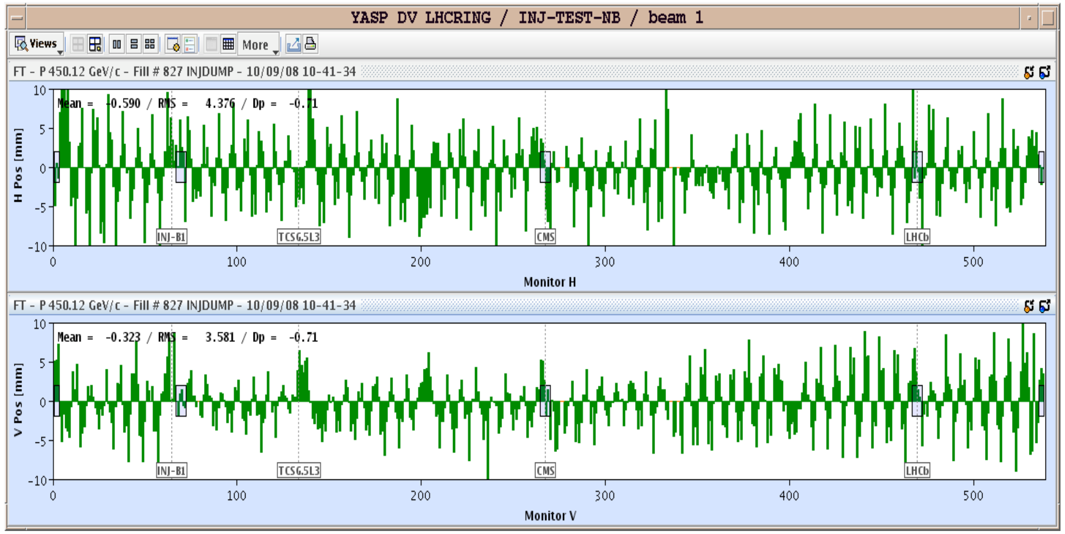
RF on,
phase optimisation





RF on, phase adjusted,
beam captured

Orbit & Tune:



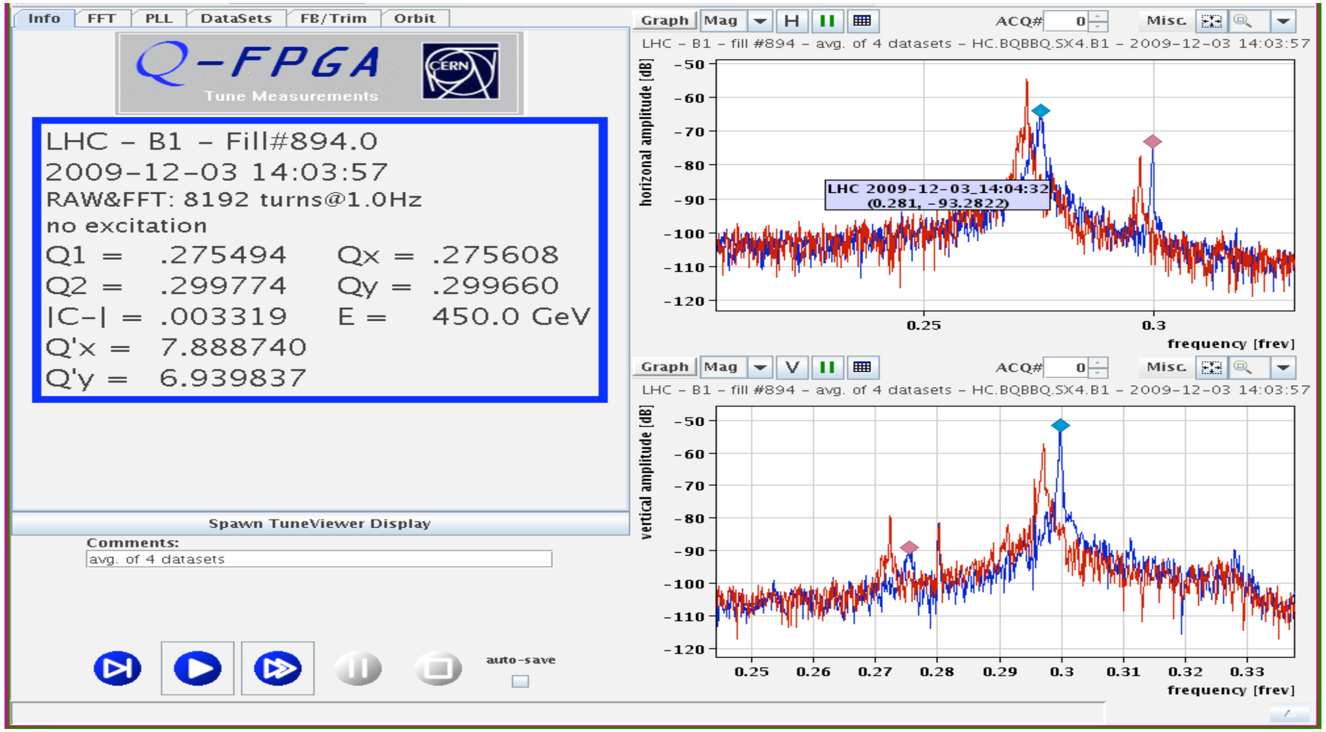
Tune: number of oscillations per turn

64.31
59.32

Relevant for beam stability:
non integer part

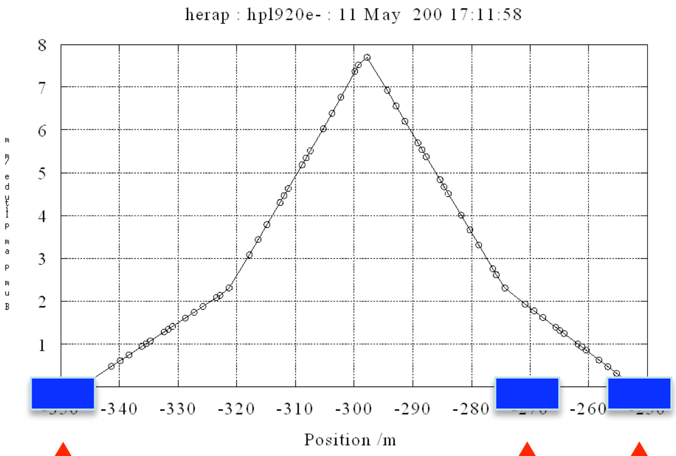
LHC revolution frequency: 11.3 kHz

$$0.31*11.3 = 3.5kHz$$

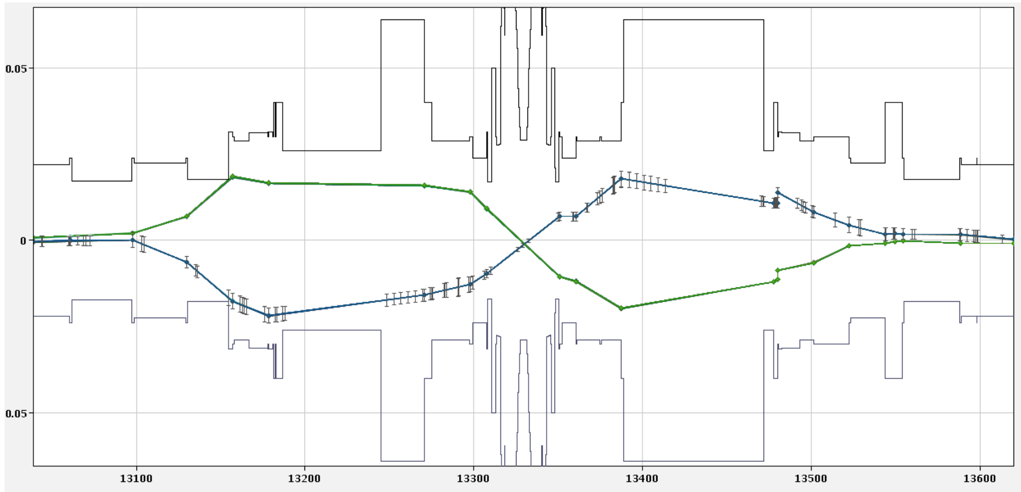


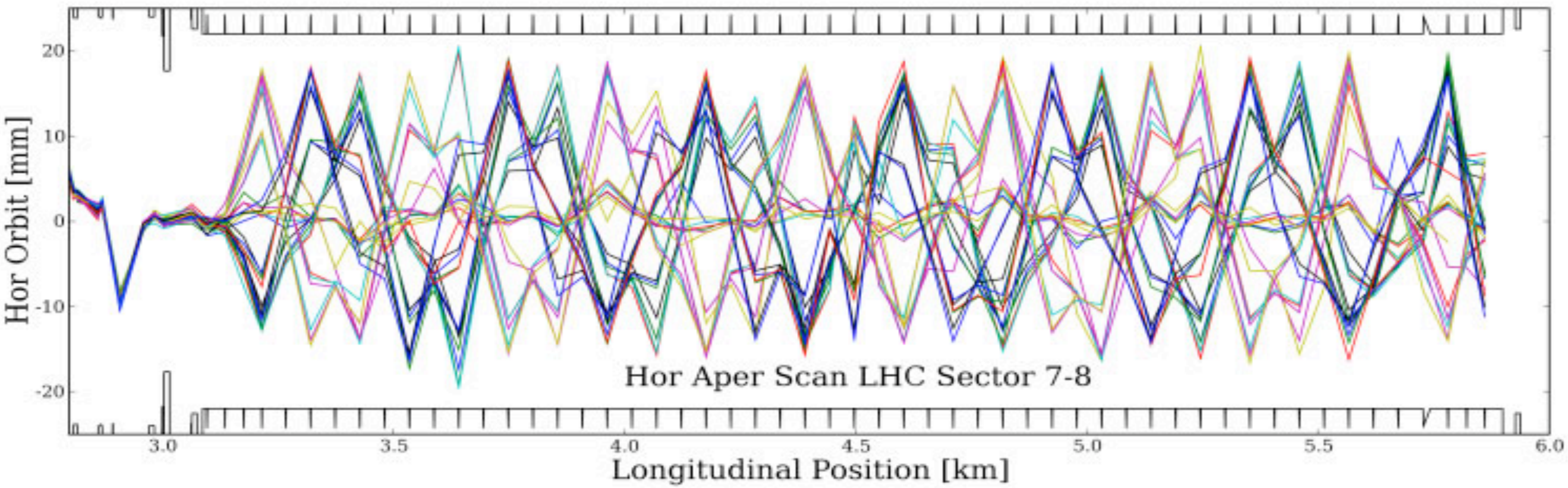
LHC Operation: Aperture Scans

Apply closed orbit bumps until losses indicate the aperture limit
... what about the beam size ?



3 bump to create local orbit distortion



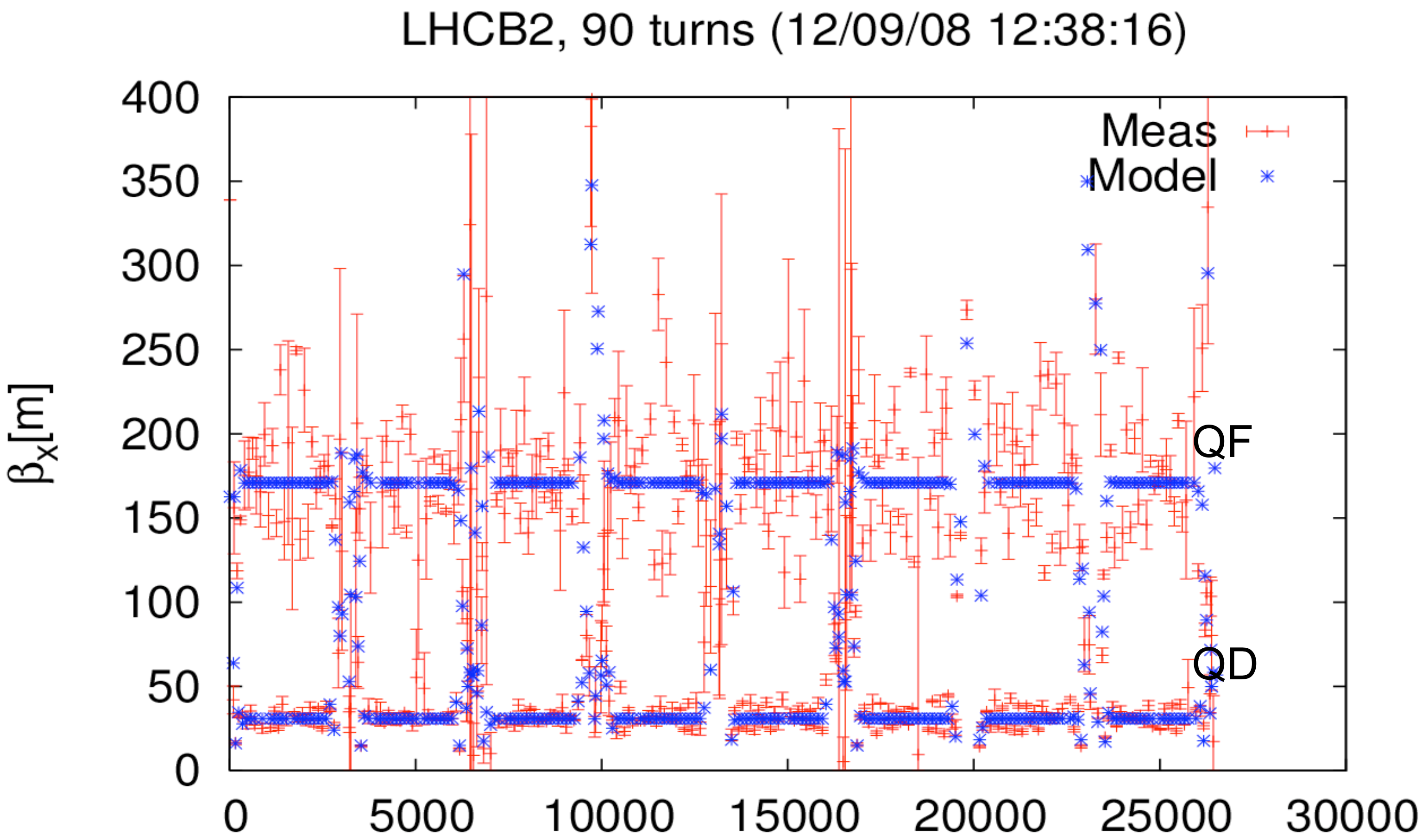


LHC Operation: the First Beam

Measurement of β :

$$\Delta\beta(s_0) = \frac{\beta_0}{2\sin 2\pi \boldsymbol{Q}} \int_{s1}^{s1+l} \beta(s_1)\Delta \boldsymbol{K} \cos\left(2\left|\psi_{s1} - \psi_{s0}\right| - 2\pi \boldsymbol{Q}\right) \boldsymbol{ds}$$

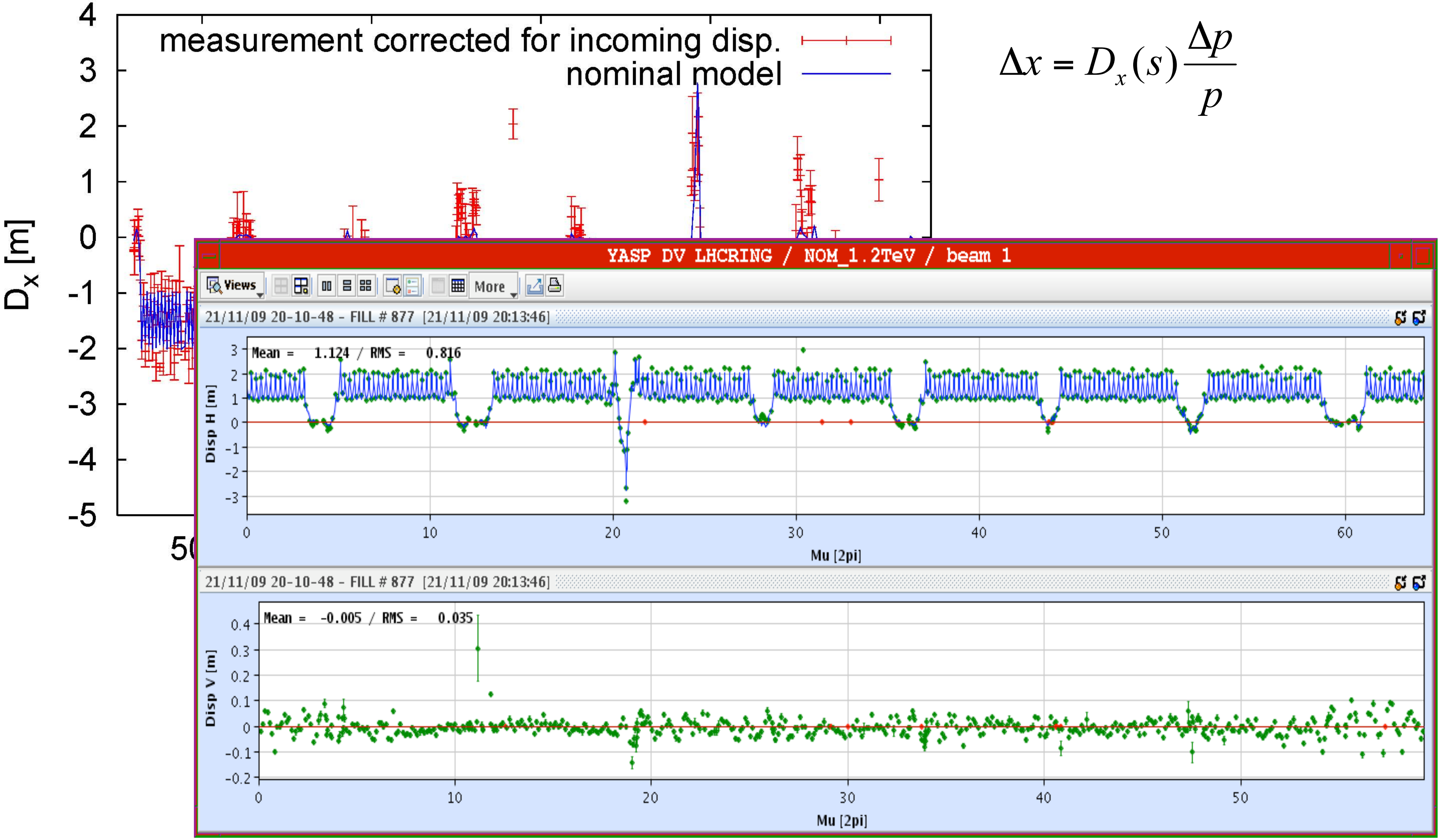
Δβ / β = 50 %



LHC Operation: the First Beam

Dispersion Measurement

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



Luminosity optimization

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

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

F is a pure **crossing angle (*Φ*) contribution**:

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

F_{LHC} = 0.836

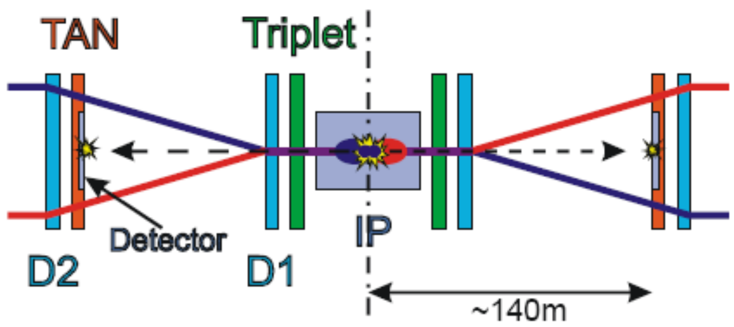
... cannot be avoided

25 ns

W is a **pure beam offset contribution**.

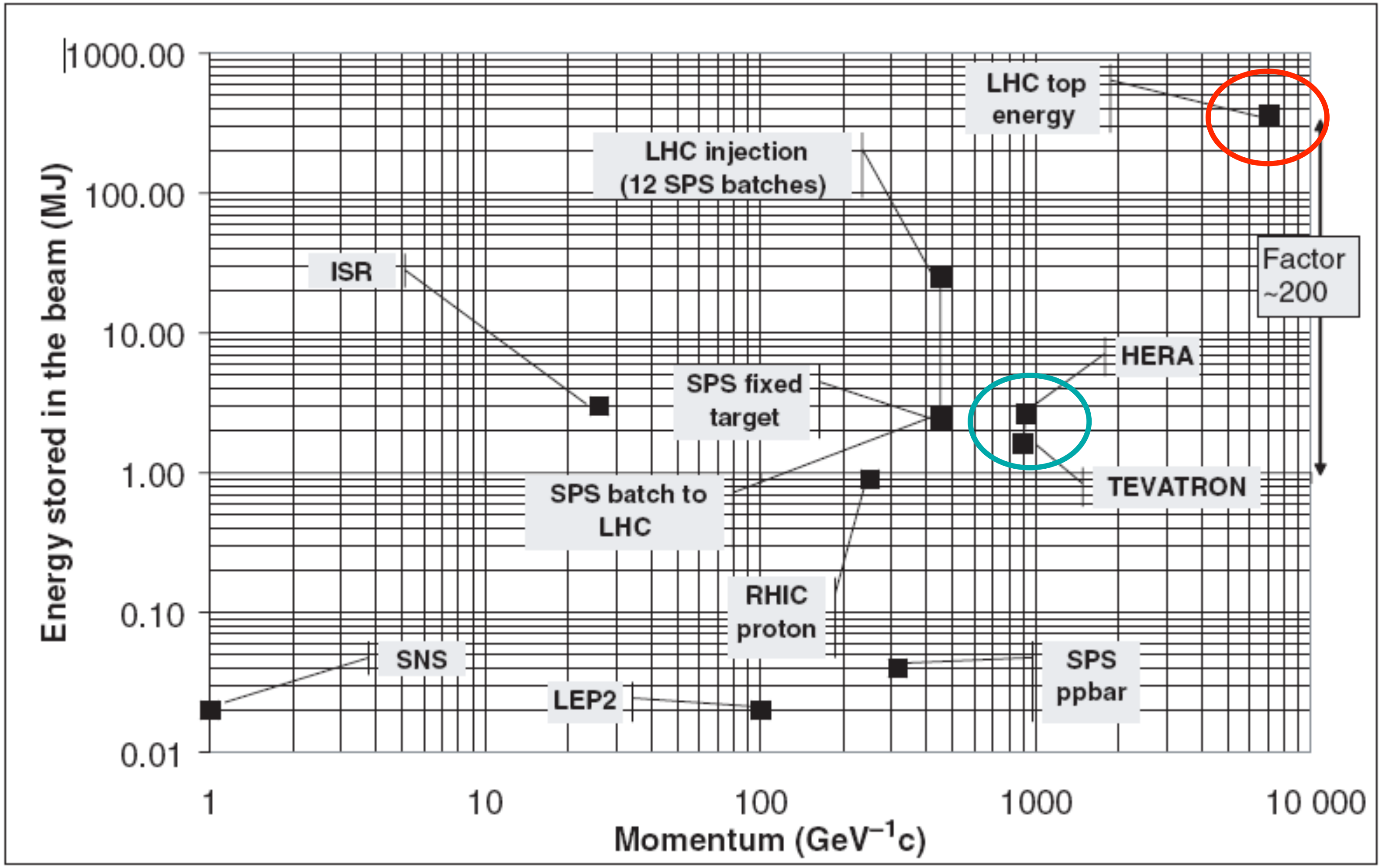
... can be avoided by careful tuning

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



LHC Operation:
Machine Protection & Safety

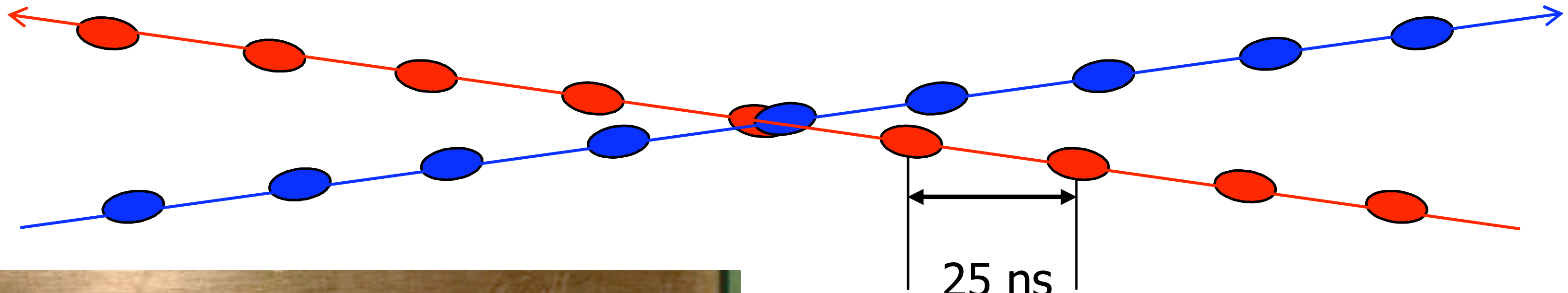
Energy Stored in the Beam of different Storage Rings

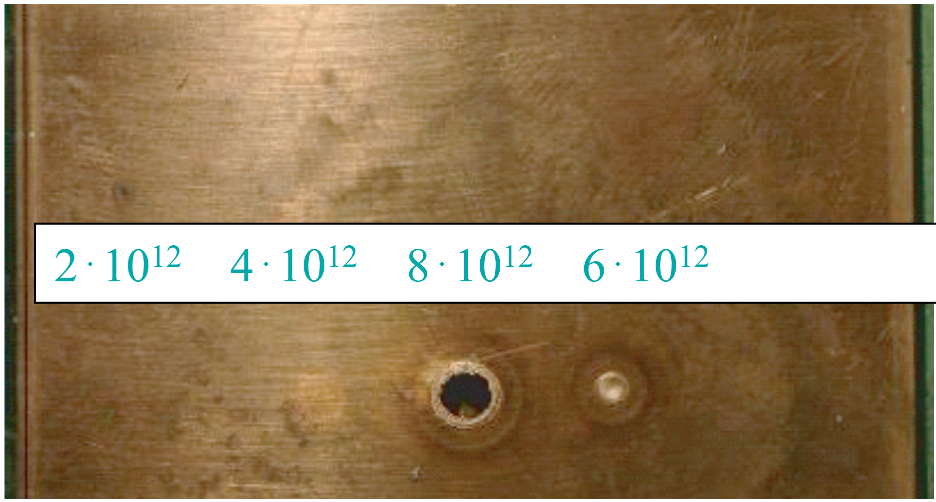


LHC Operation: Machine Protection & Safety

Energy stored in magnet system	10	GJ
Energy stored in one main dipole circuit	1.1	GJ
Energy stored in one beam	362	MJ

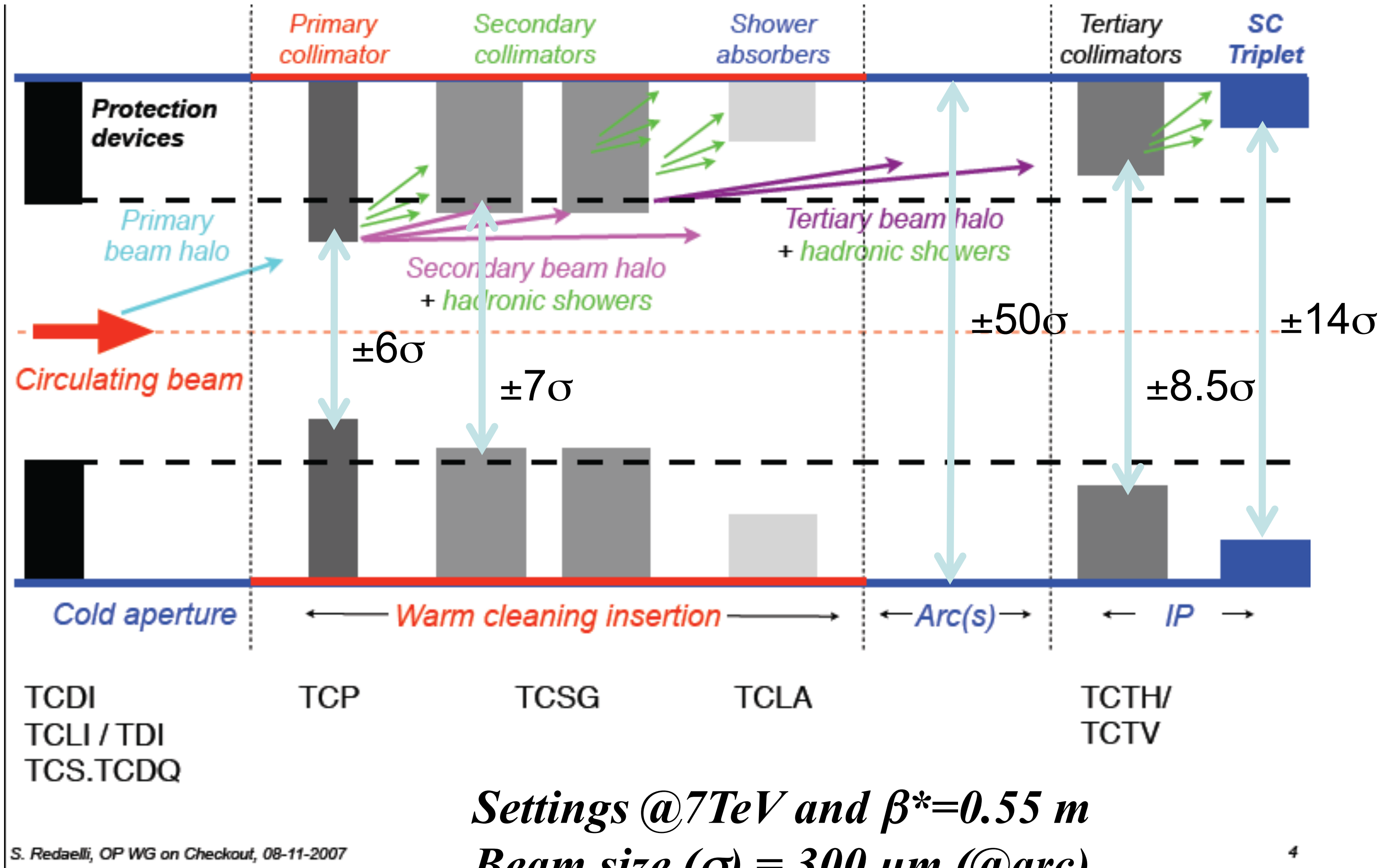
Enough to melt 500 kg of copper





$2 \cdot 10^{12}$ $4 \cdot 10^{12}$ $8 \cdot 10^{12}$ $6 \cdot 10^{12}$ 450 GeV p Strahl

LHC Aperture and Collimation



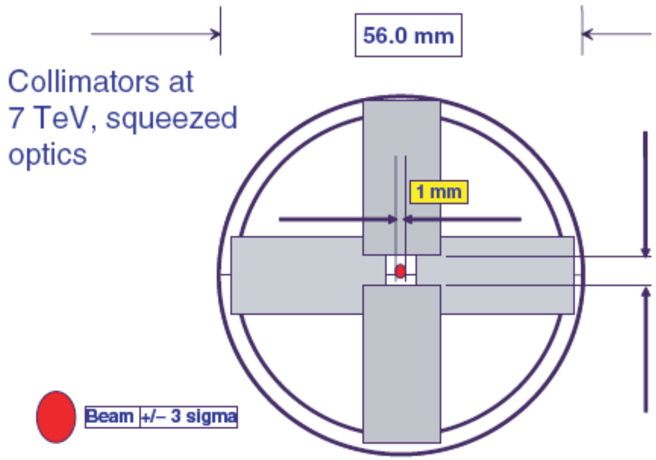
Settings @7TeV and β*=0.55 m

Beam size (σ) = 300 μm (@arc)

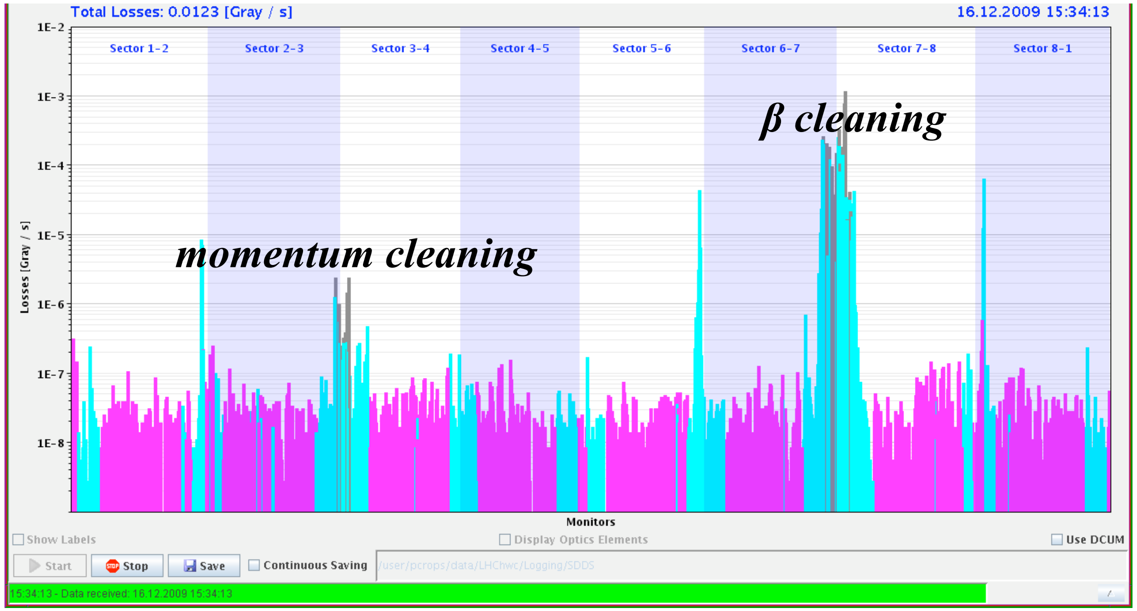
Beam size (σ) = 17 μm (@IR1, IR5)

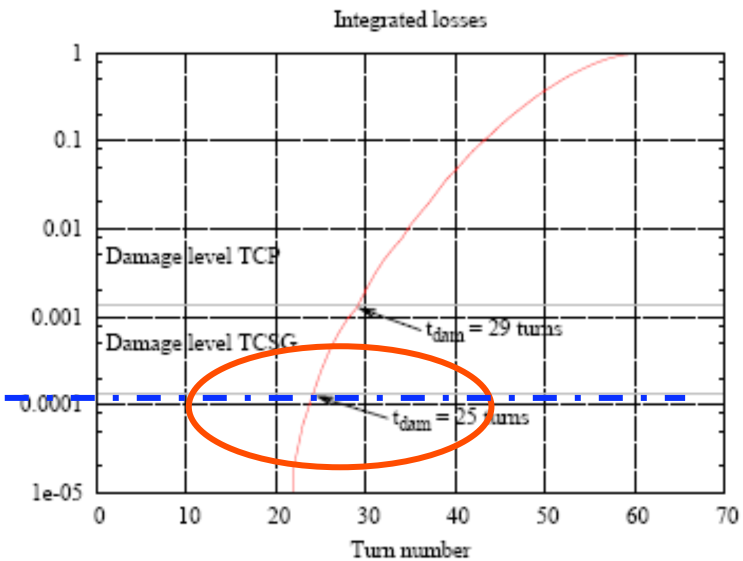
LHC Operation:
Machine Protection & Safety

... Komponenten des Machine Protection Systems :

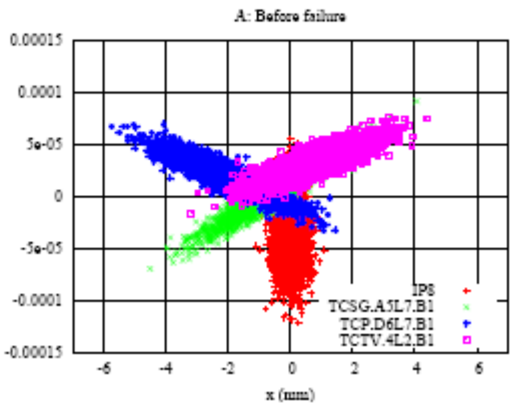


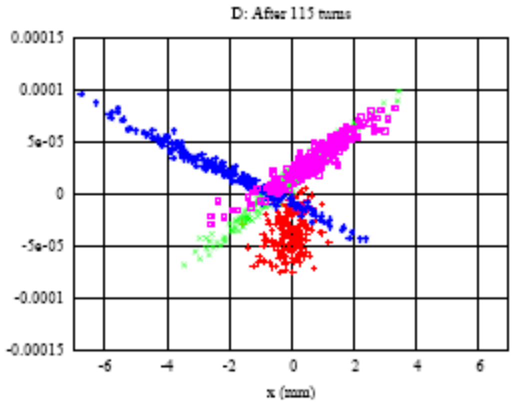
beam loss monitors
QPS
permit server
orbit control
power supply control
collimators
online on beam check of all (?)
hardware components
a fast dump
the gaussian beam profile





LHC Operation: Machine Protection & Safety





What will happen in case of Hardware Failure

Phase space deformation in case of failure of RQ4.LR7 (A. Gómez)

Short Summary of the studies:

quench in sc. arc dipoles: τ_{loss} ***=20 - 30 ms***
BLM system reacts in time, QPS is not fast enough

quench in sc. arc quadrupoles: τ_{loss} ***=200 ms***
BLM & QPS react in time

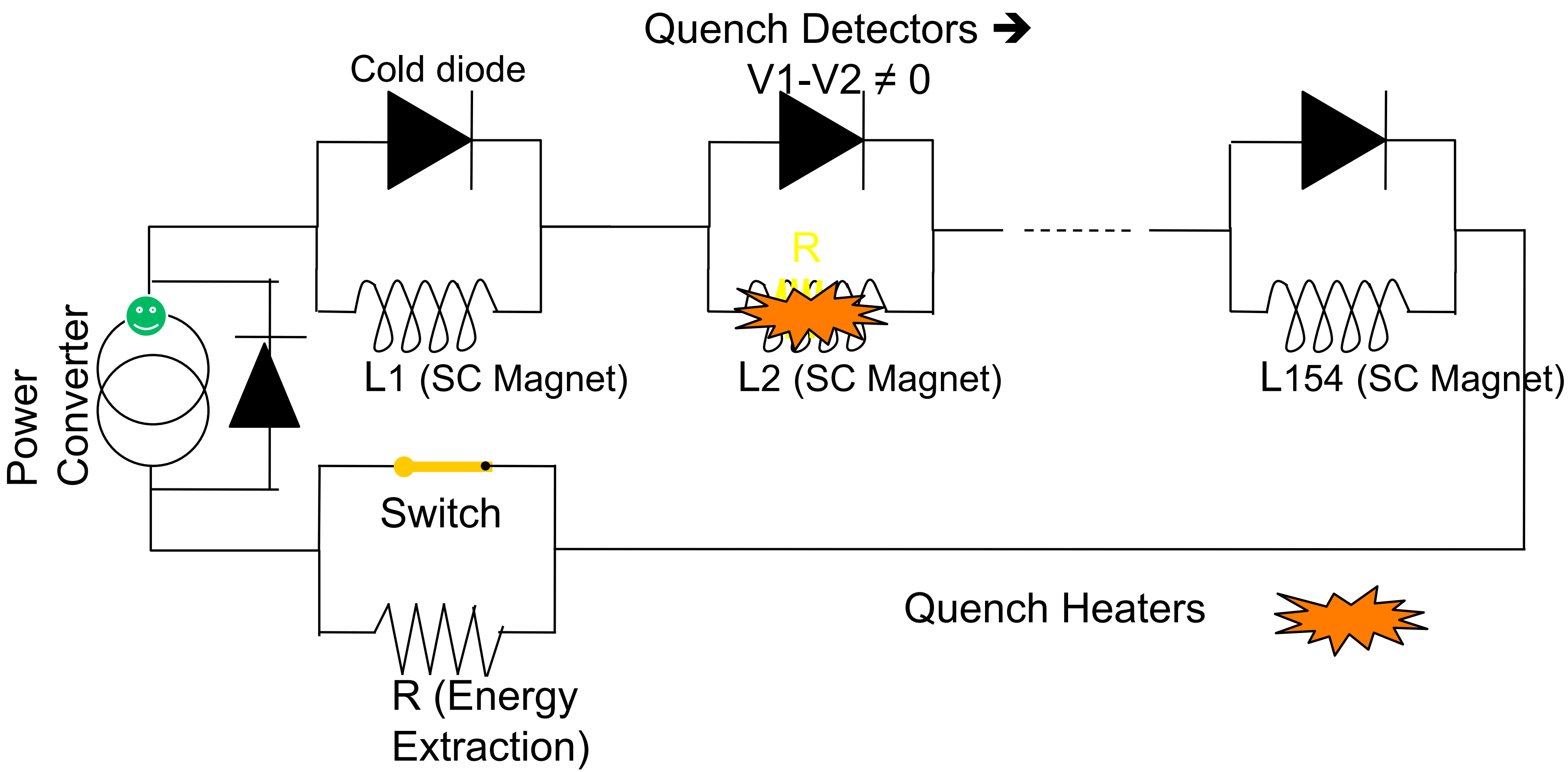
failure of nc. quadrupoles: $\tau_{det} = 6$ ***ms***
$\tau_{damage} = 6.4$ ***ms***

failure of nc. dipole: $\tau_{damage} = 2$ ***ms***

→ FMCM installed

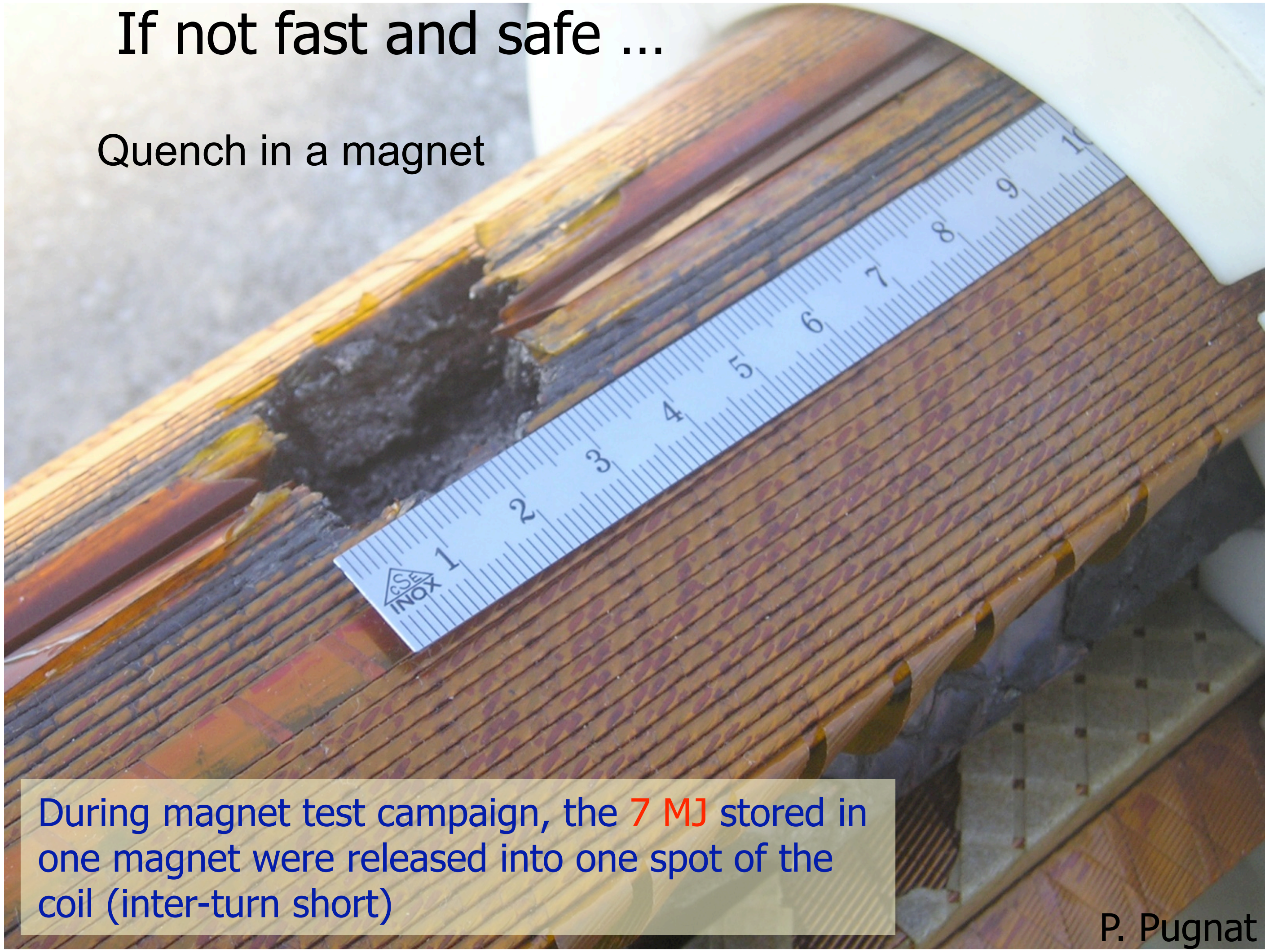
Energy stored in the magnets: ***10 GJ***
Quench Protection System

Schematics of the QPS in the main dipoles of a sector

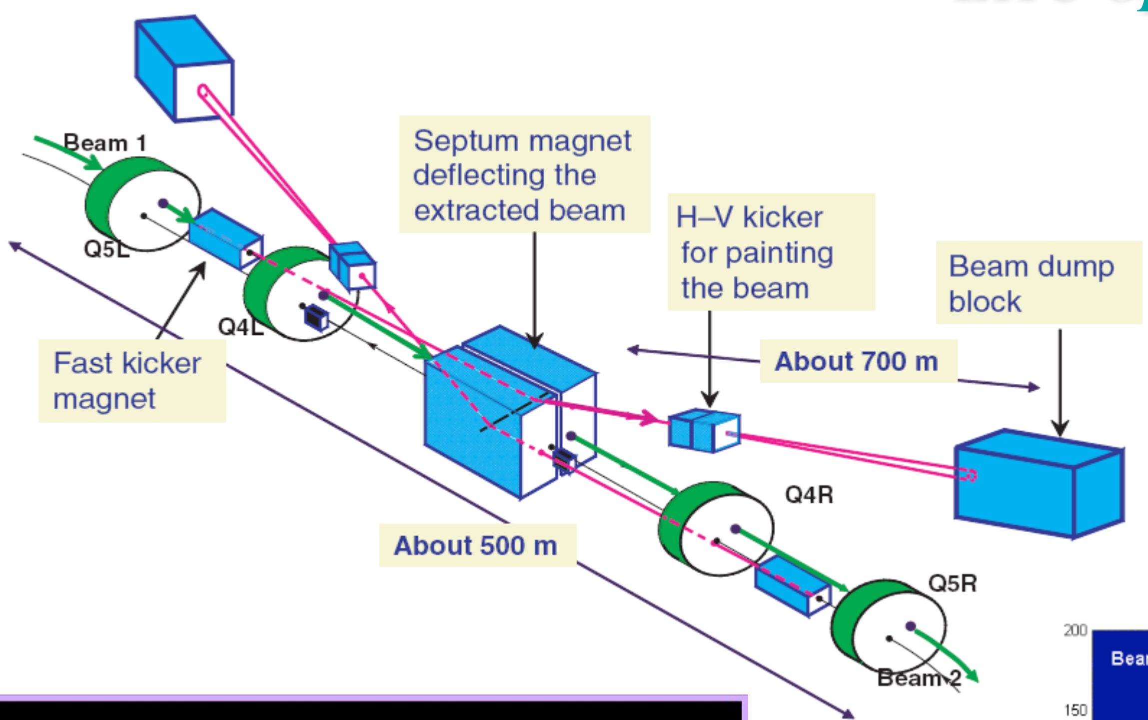


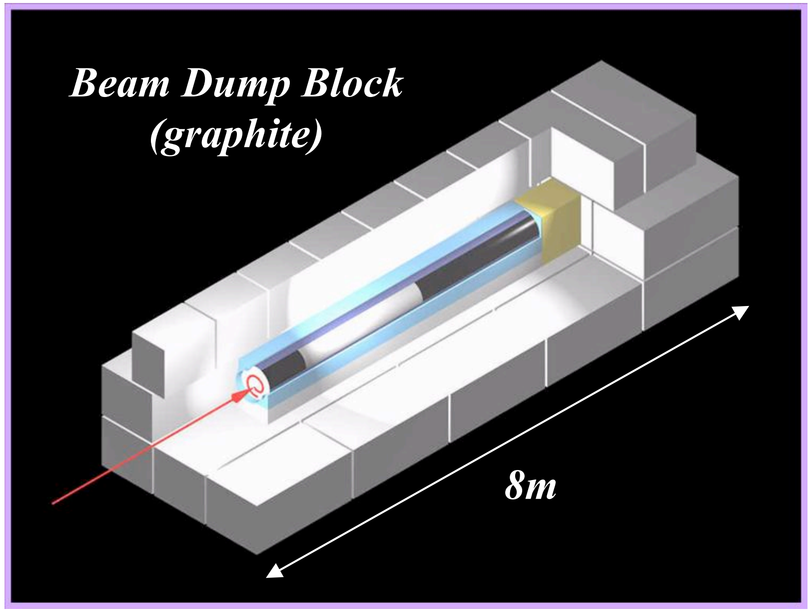
court. R. Alemany

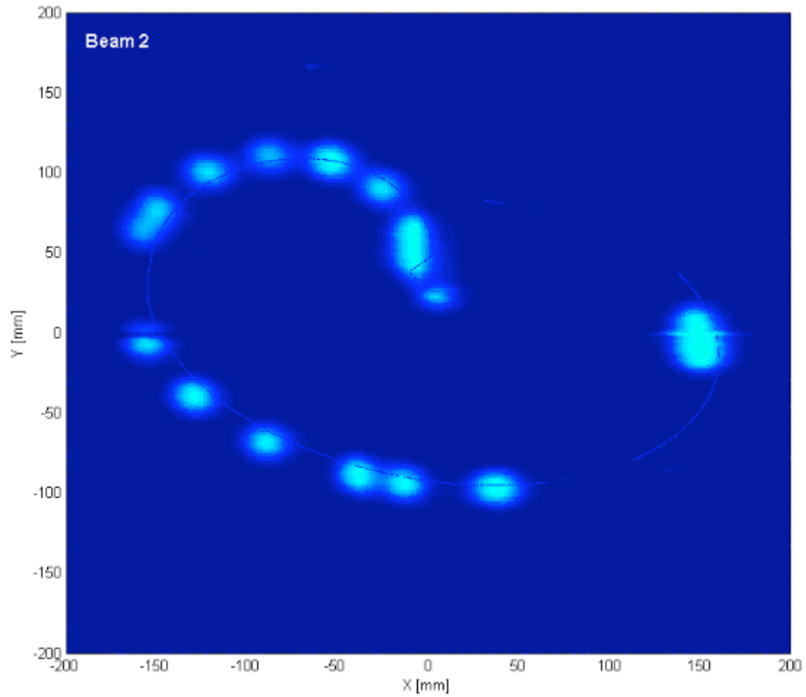
Energy stored in the magnets: quench



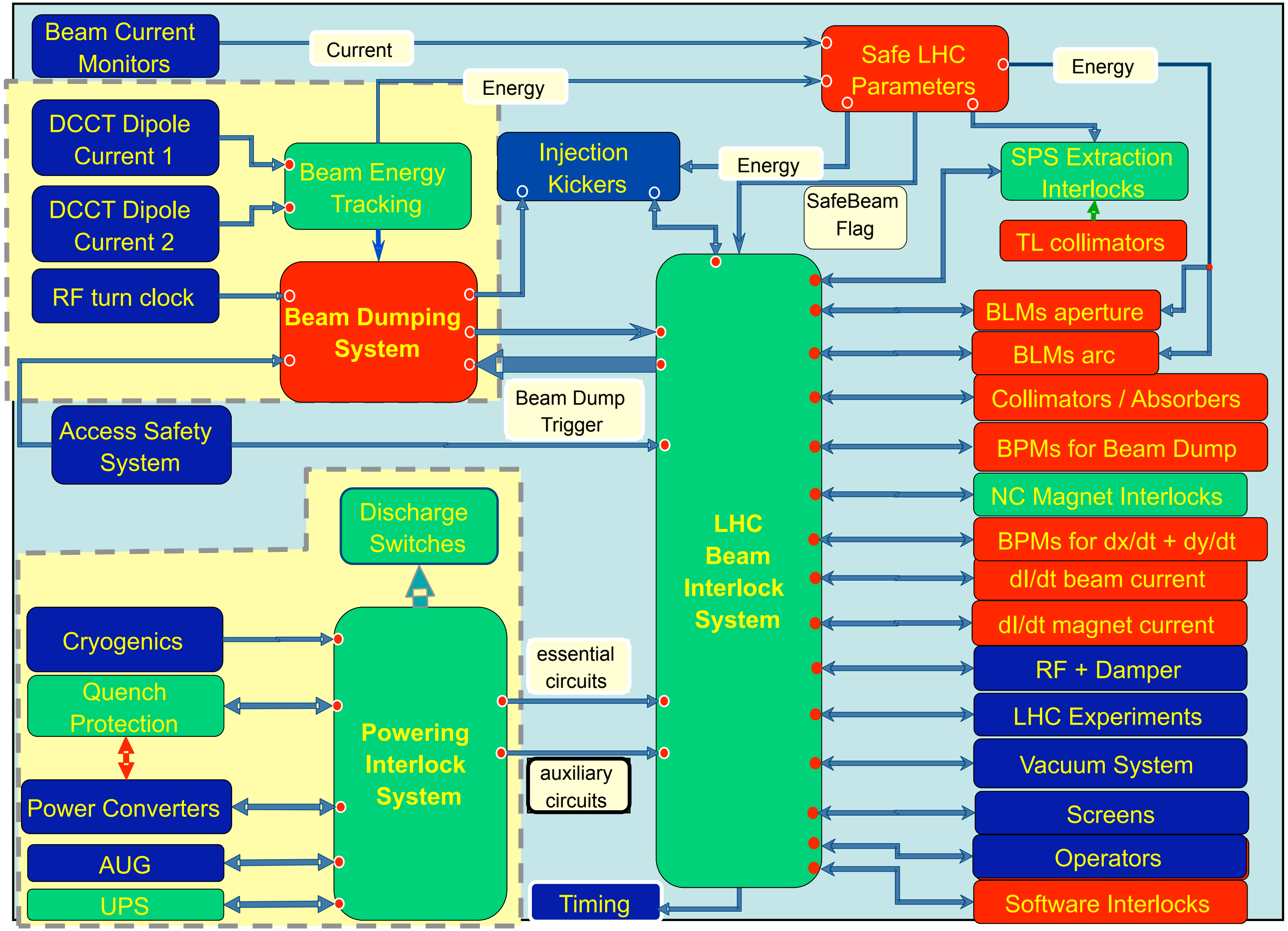
LHC Operation: Dump System







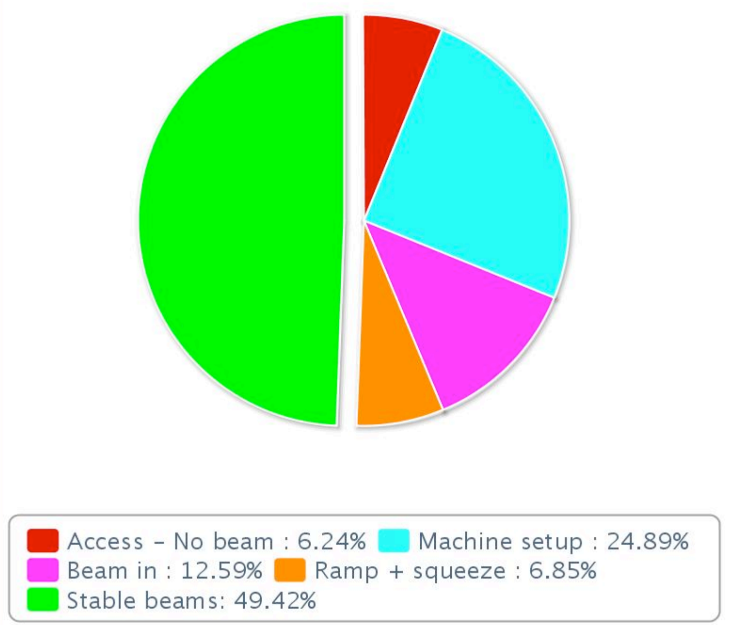
LHC Operation: Machine Protection & Safety

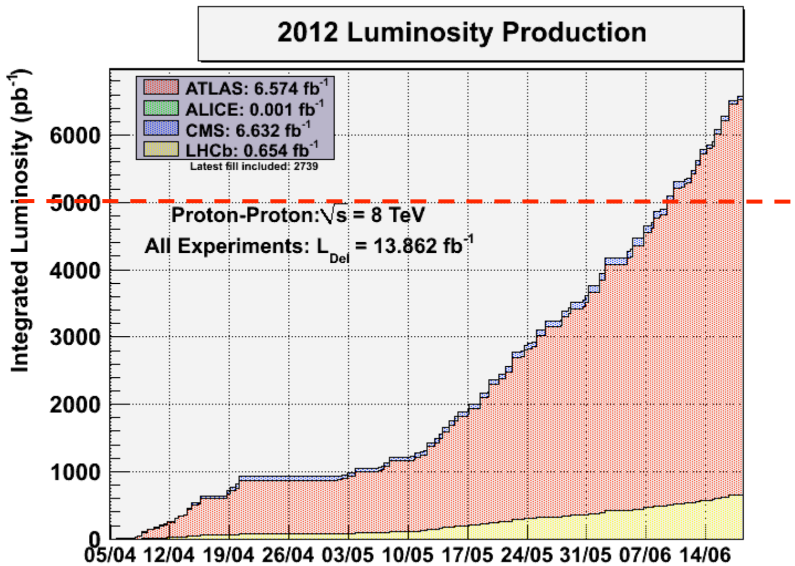


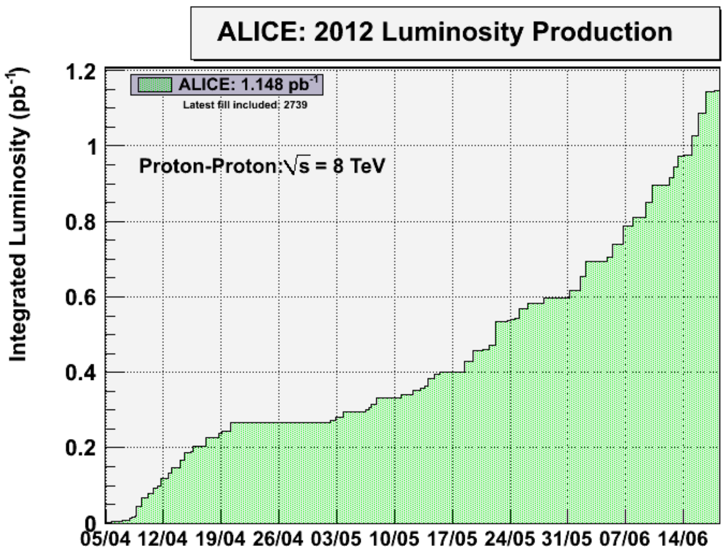
... no comment

LHC Operation where are we ?

Luminosity Efficiency:
time spent in collisions / overall time

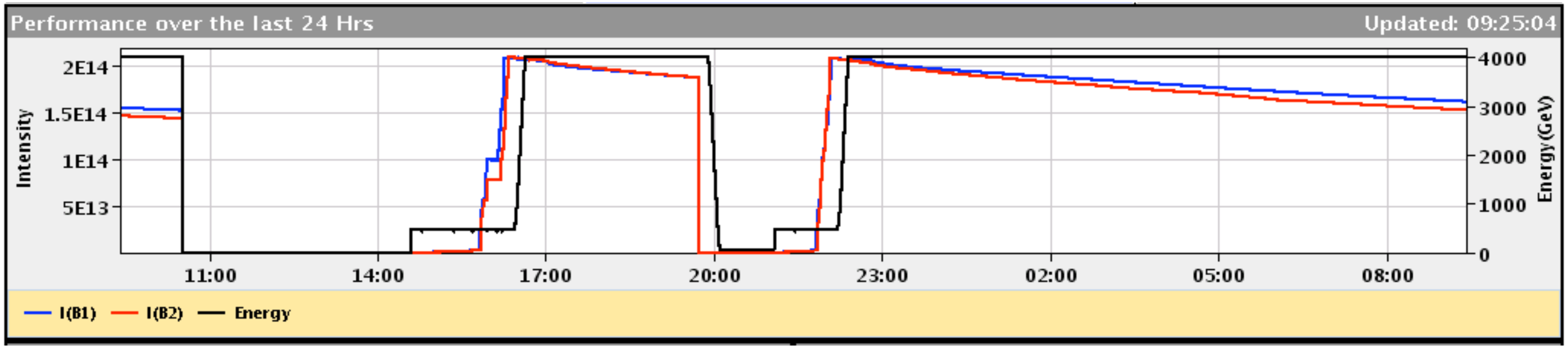




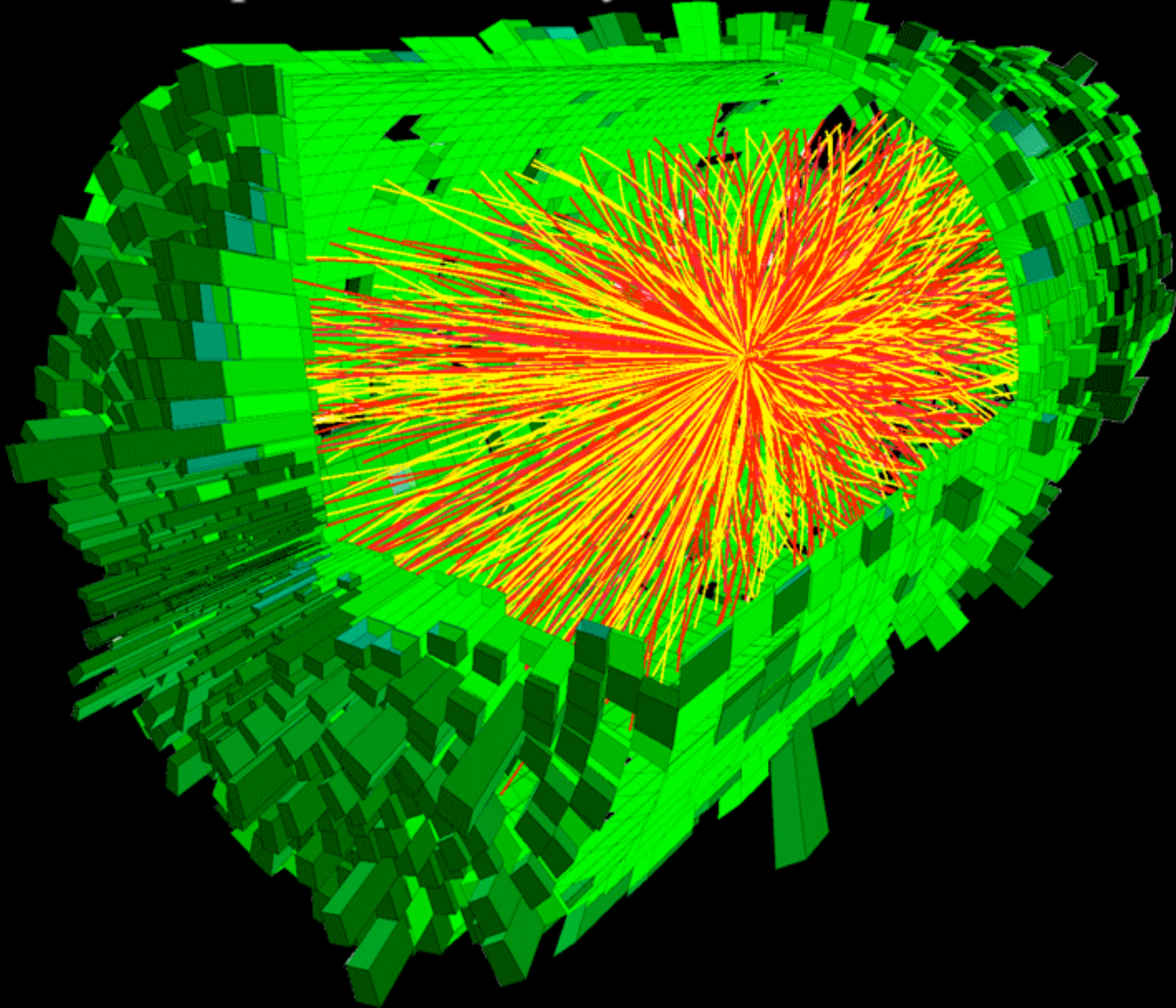


LHC Operation
where are we ?

	LHC Design	LHC 2012
Momentum at collision	7 TeV /c	3.5 TeV
Dipole field	8.33 T	4.16 T
Protons per bunch	1.15×10^{11}	1.5×10^{11}
Number of bunches/beam	2808	1380
Nominal bunch spacing	25 ns	50 ns
Normalized emittance	3.75 μm	2.2 μm
Absolute Emittance	5×10^{-10}	6.7×10^{-10}
Beta Function	0.5 m	0.6 m
rms beam size (IP)	16 μm	18 μm
Luminosity	1.0×10^{34}	6.7×10^{33}



LHC Operation: Heavy Ion Collisions



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