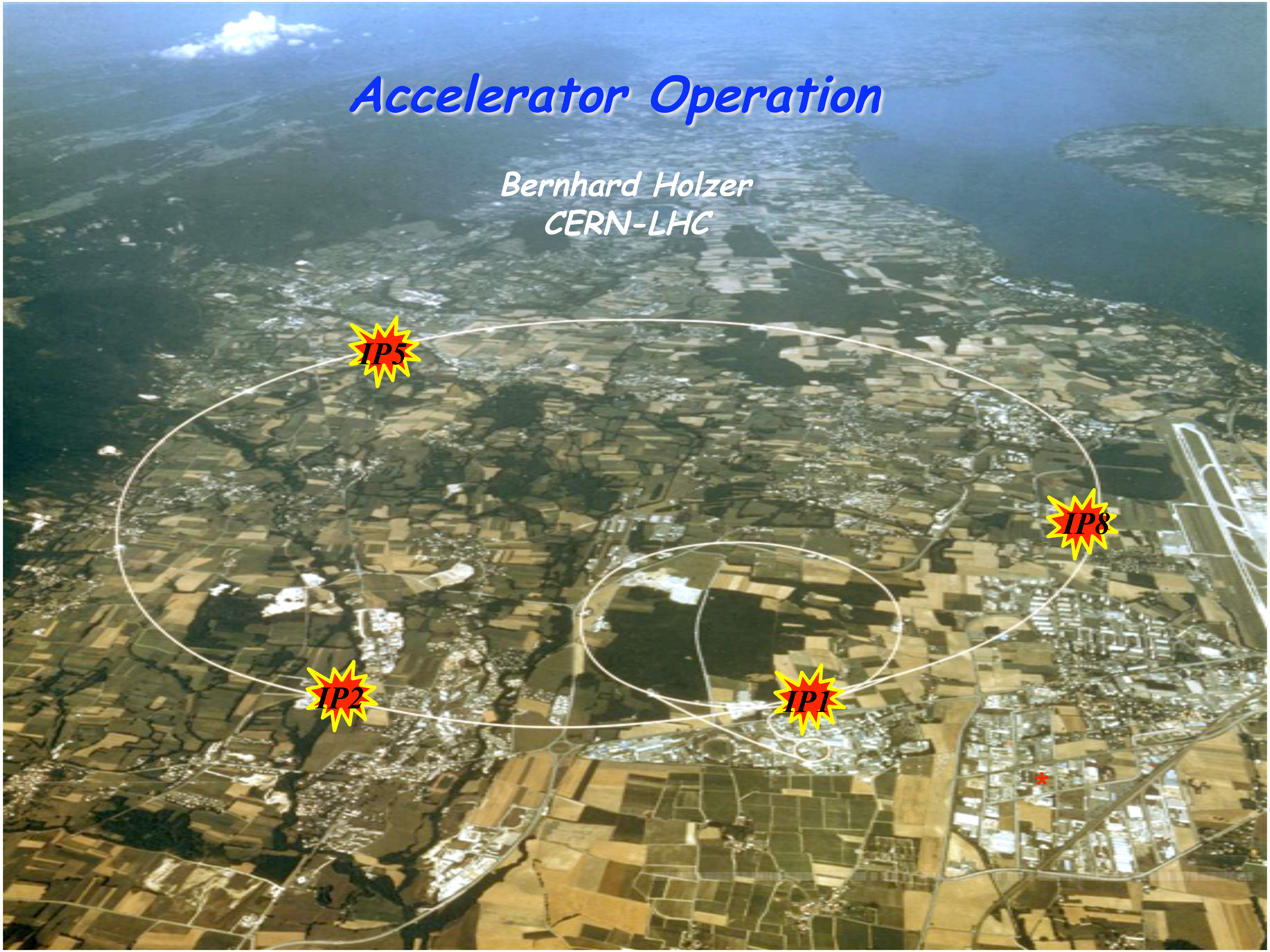
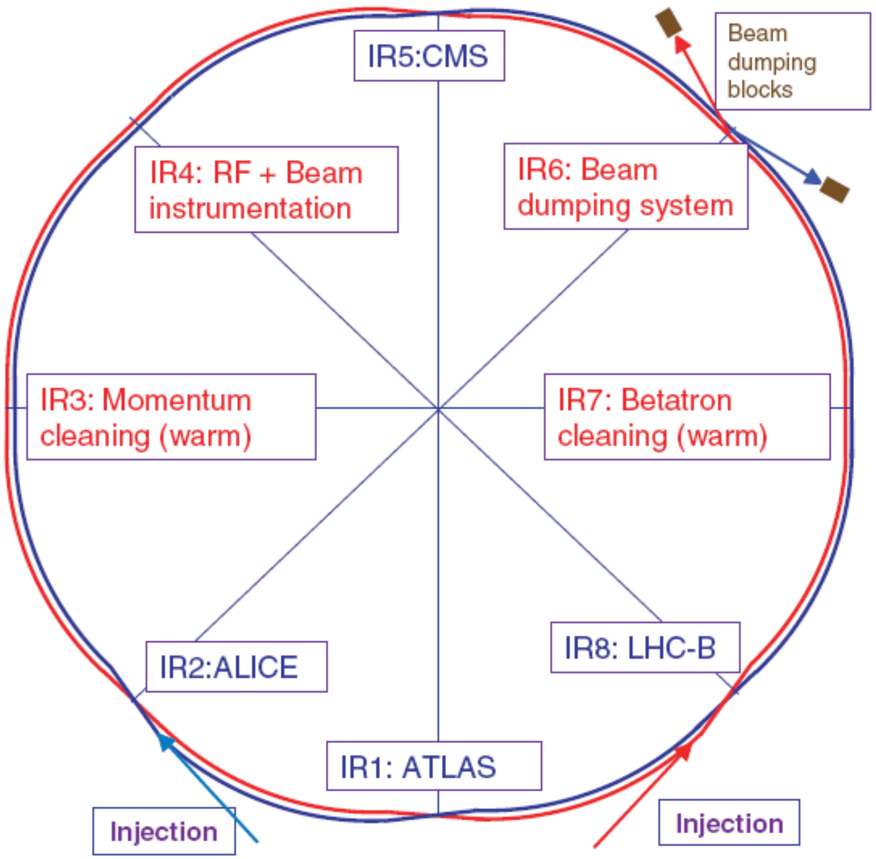
Accelerator Operation

Bernhard Holzer
CERN-LHC



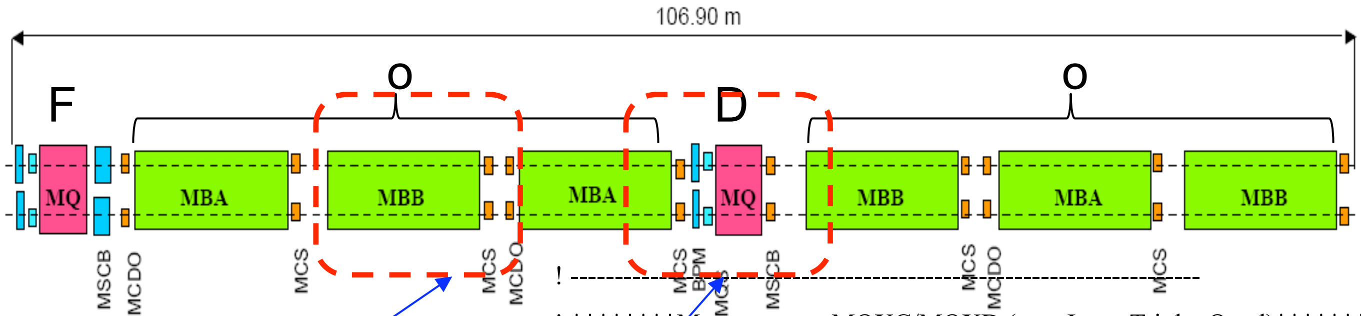
LHC Main Parameters

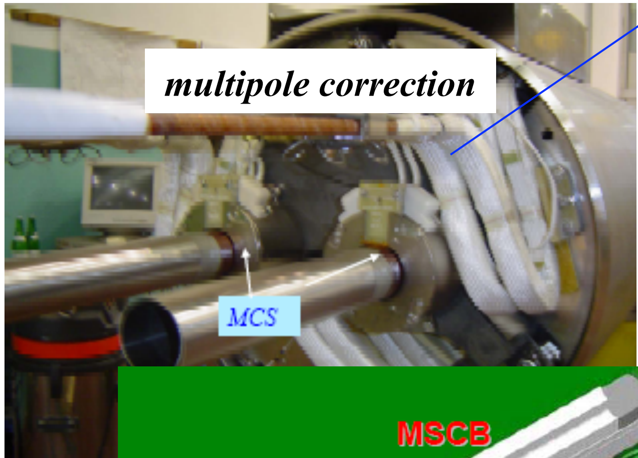
Momentum at collision	*7 TeV /c*
Dipole field for 7 TeV	*8.33 T*
Luminosity	10^{34} cm $^{-2}$ s^{-1}
Protons per bunch	1.15×10^{11}
Number of bunches/beam	*2808*
Nominal bunch spacing	*25 ns*
Normalized emittance	*3.75 µm*
rms beam size (7TeV, arc)	*300 µm*
beam pipe diameter	*56 mm*

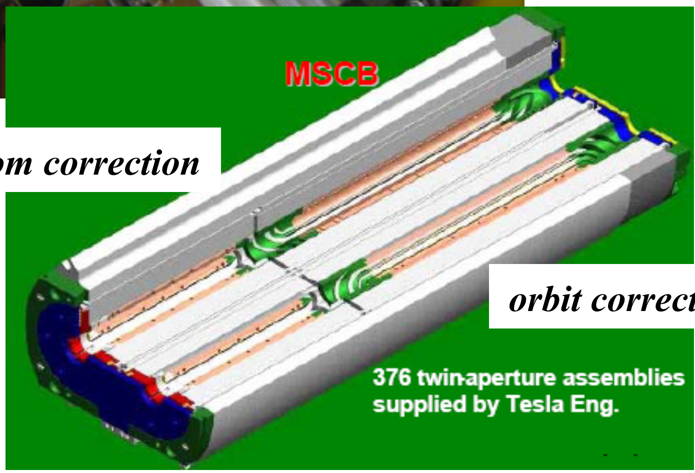


LHC: Basic Layout of the Machine multipole corrector magnets

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_M ... = 0.8900 ;

b4M_M ... = 0.6400 ;

b5M_M ... = 0.4600 ;

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

b6M_MQXCD_col := 0.0000 ; b6U_MQXCD_col := 1.7700 ; b6R_MQXCD_col := 1.2800 ;

b7M_MQXCD_col := 0.0000 ; b7U_MQXCD_col := 0.2100 ; b7R_MQXCD_col := 0.2100 ;

b8M_MQXCD_col := 0.0000 ; b8U_MQXCD_col := 0.1600 ; b8R_MQXCD_col := 0.1600 ;

b9M_MQXCD_col : ... QXCD_col := 0.0800 ;

b10M_MQXCD_col ... MQXCD_col := 0.0600 ;

...M_MQXCD_col ... MQXCD_col := 0.0300 ;

$$Q' = -\frac{1}{4\pi} \oint k(s) \beta(s)\, ds$$

M_MQXCD_col := 0.0000 ; b12U_MQXCD_col := 0.0200 ; b12R_MQXCD_col := 0.0200 ;

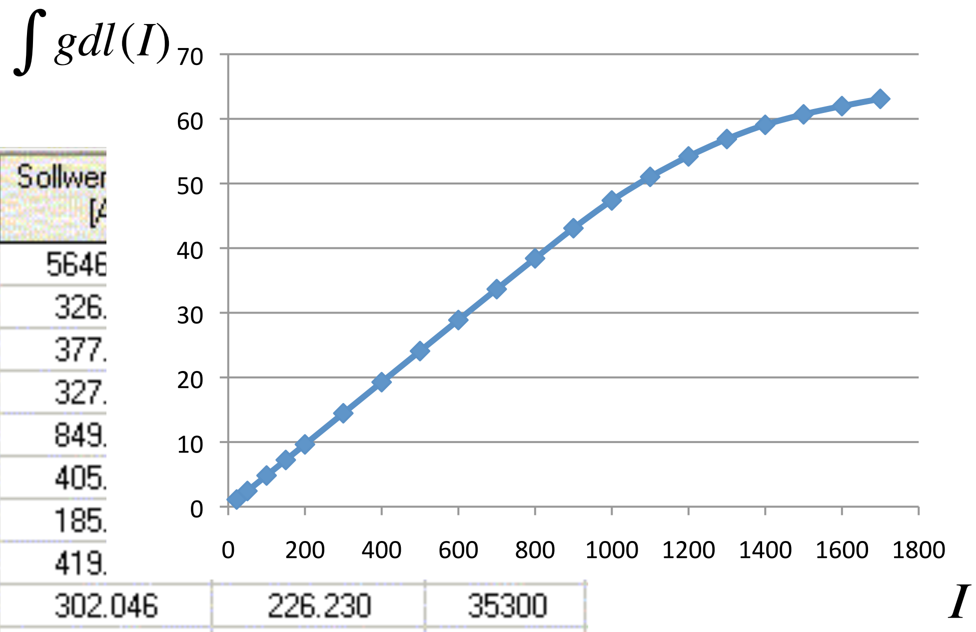
b13M_MQXCD_col := 0.0000 ; b13U_MQXCD_col := 0.0200 ; b13R_MQXCD_col := 0.0100 ;

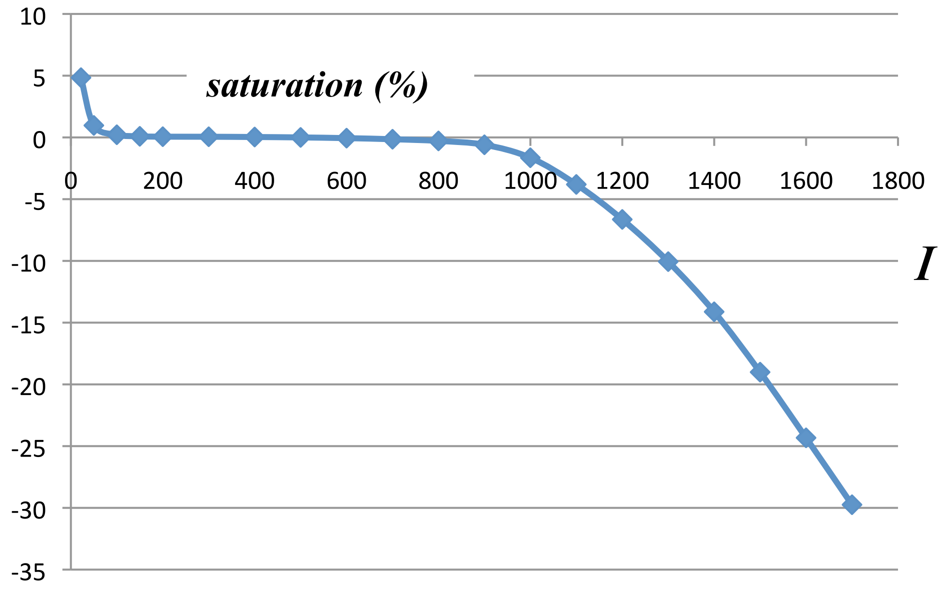
b14M_MQXCD_col := 0.0000 ; b14U_MQXCD_col := 0.0400 ; b14R_MQXCD_col := 0.0100 ;

b15M_MQXCD_col := 0.0000 ; b15U_MQXCD_col := 0.0000 ; b15R_MQXCD_col := 0.0000 ;

Magnet Currents

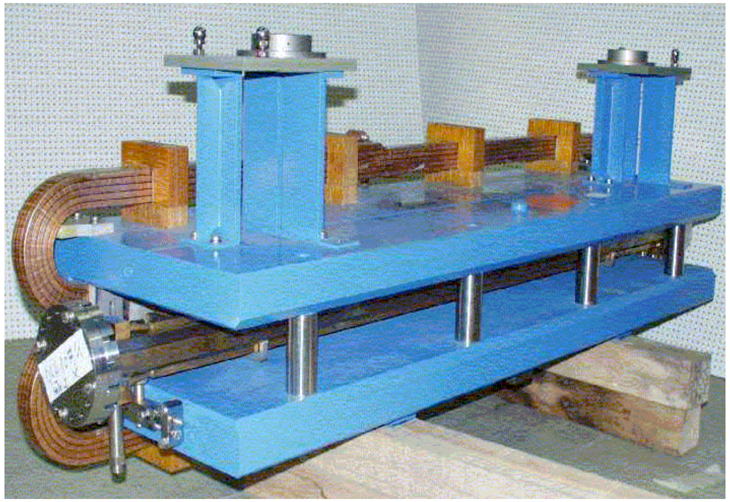
Nummer	Gruppe	Name	aktiv	Sollwerte File1 [A]	Sollwer [A		
1	HPDIPOL	BPA1	True	4138.993	5646		
2	HPMAINW	QZ51 WL	True	235.462	326.		
3	HPMAINW	QR52 WR	True	258.724	377.		
4	HPMAINW	QC53 WL	True	237.933	327.		
5	HPMAINW	QB28 WL	True	625.429	849.		
6	HPMAINW	QR54 WR	True	291.486	405.		
7	HPMAINW	QR24 WR	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.		

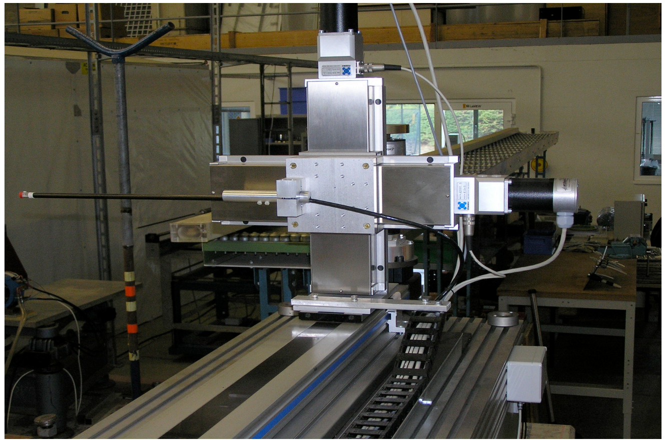




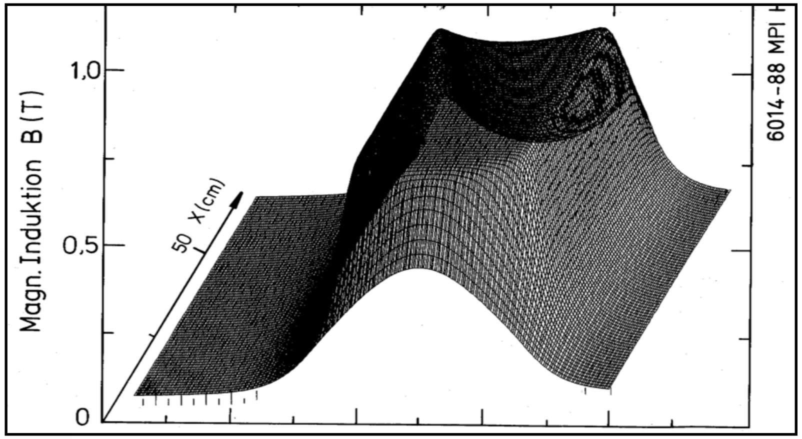
remember: $\Delta B/B \approx 10^{-4}$

Magnets: Precision Measurements

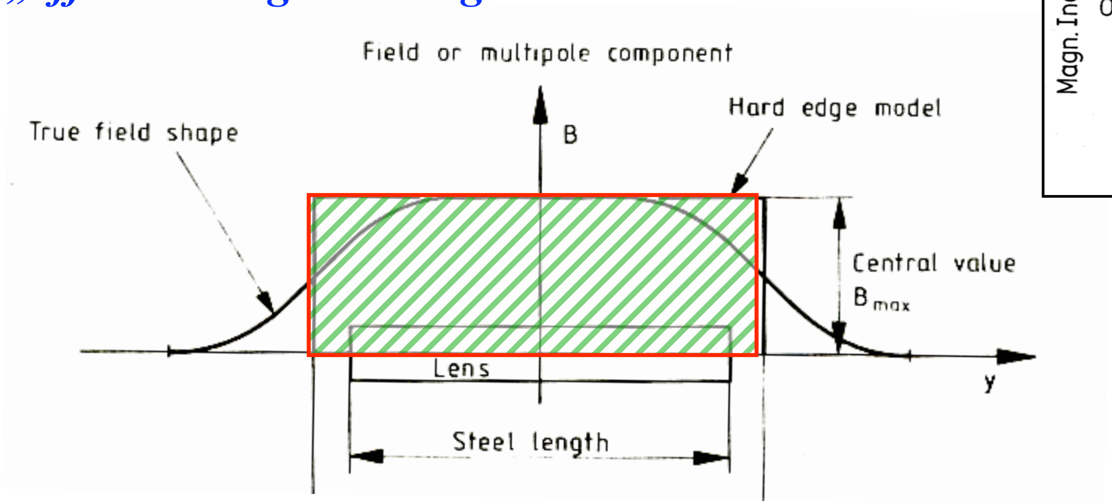




NMR, Hall probes, rotating coils etc



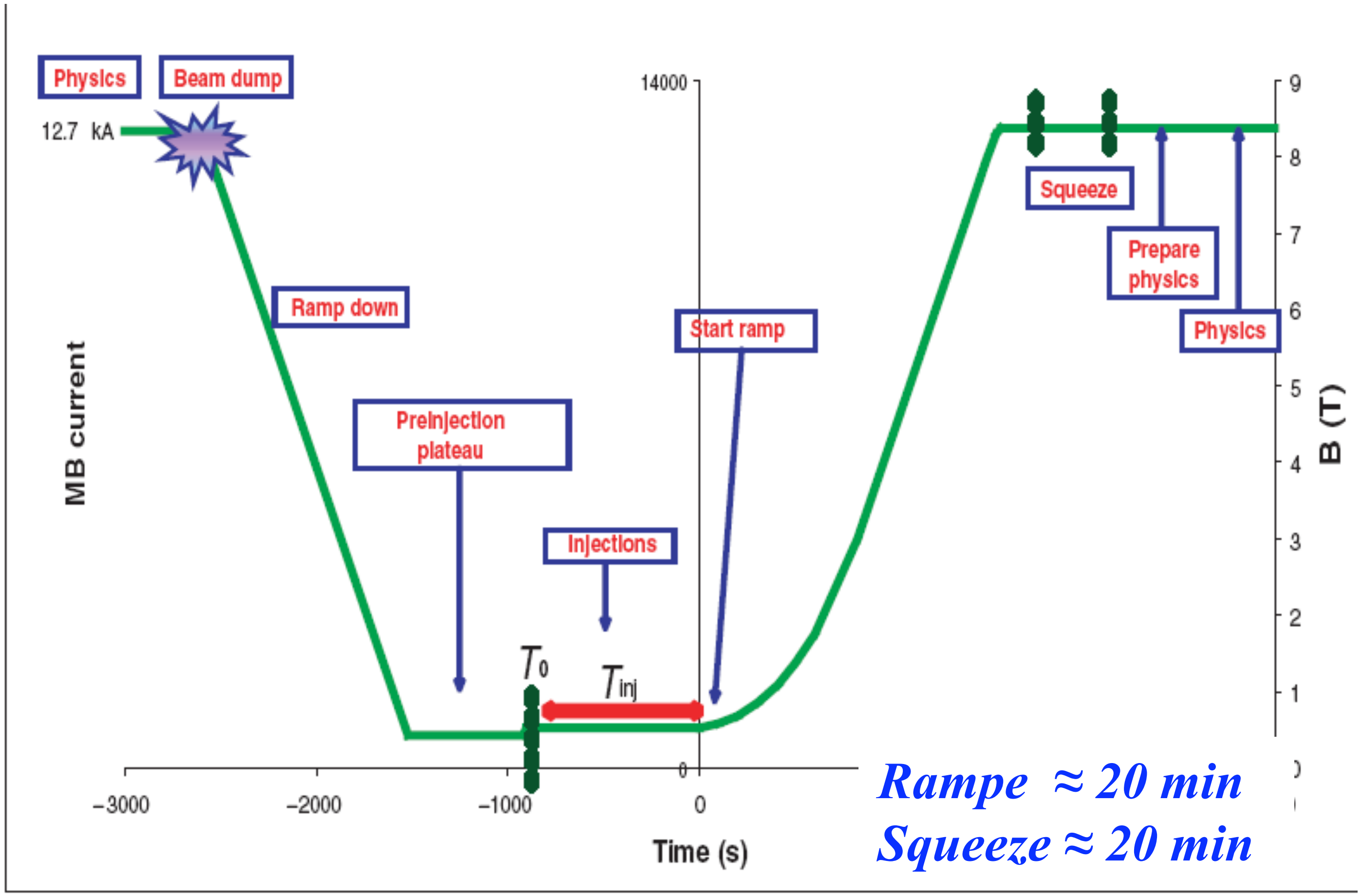
„effective magnetic length"



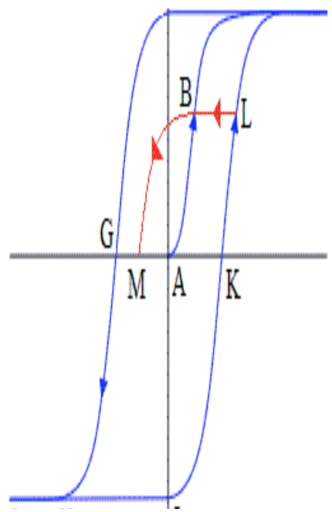
$$B * l_{eff} = \int_{0}^{l_{mag}} B ds$$

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

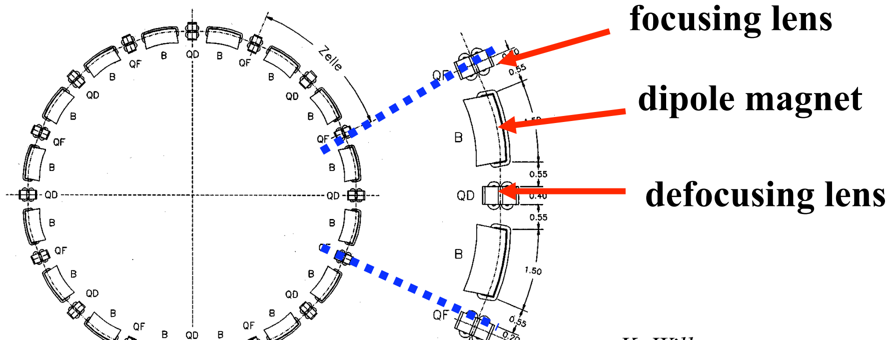


magnet hysteresis

LHC First Turn Steering

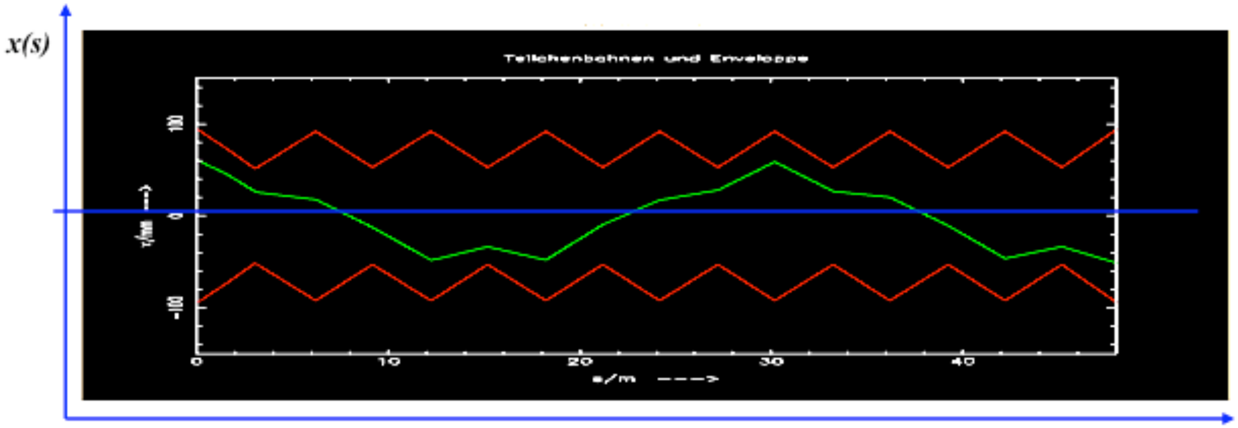
$$M_{total} = M_{QF} * M_D * M_{QD} * M_{Bend} * M_{D*.....}$$

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



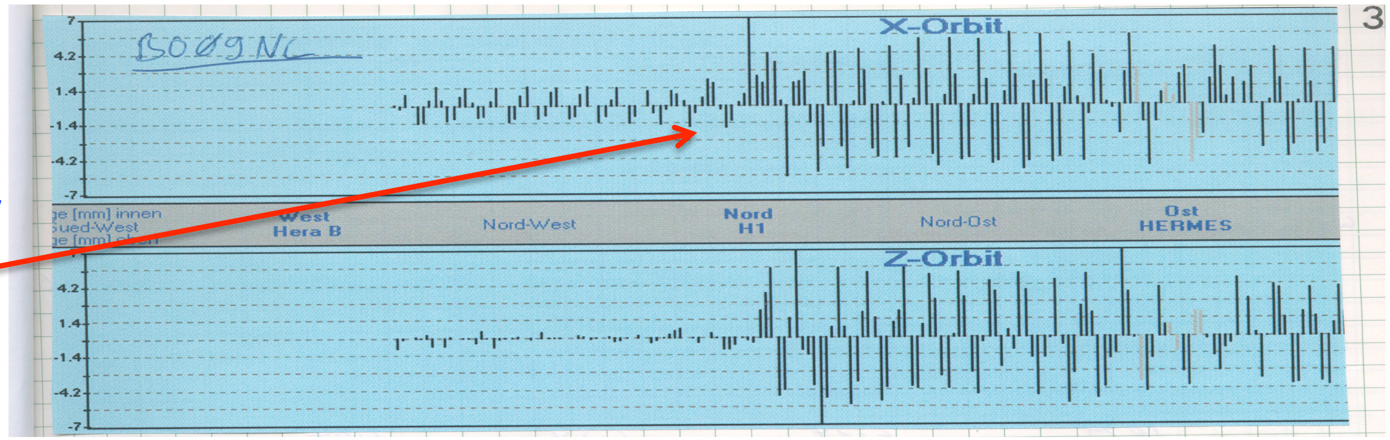
court. K. Wille

in theory
nice harmonic oscillation



in reality:
effect of many localised orbit distortions

-> correct

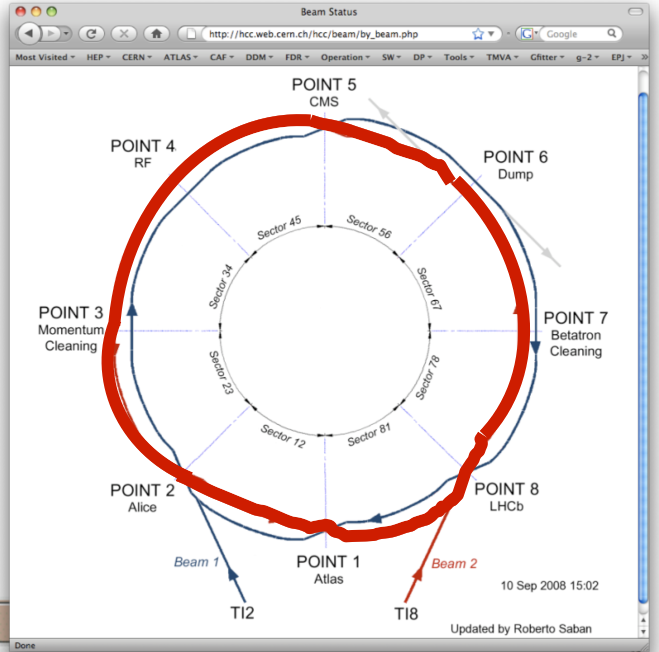


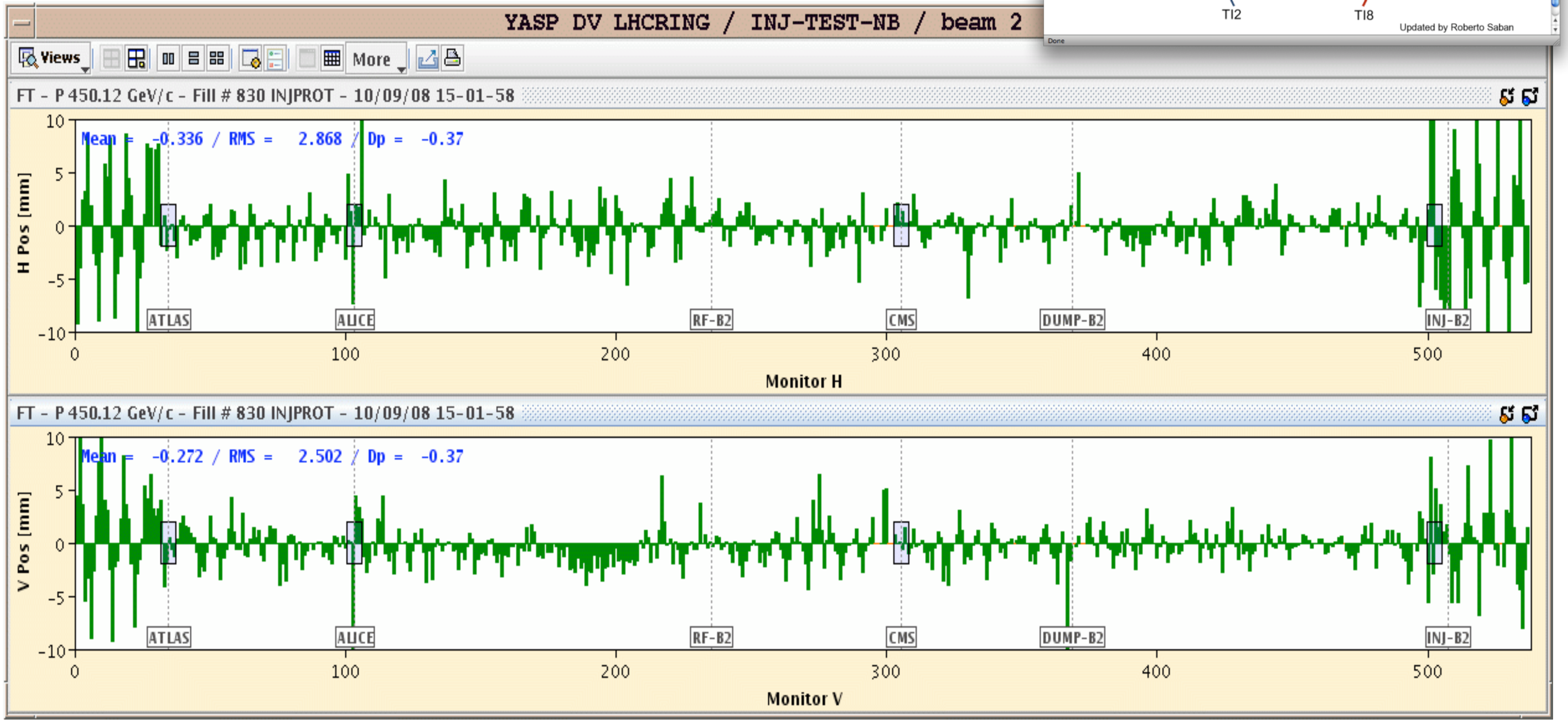
LHC Operation: Beam Commissioning

First turn steering "by sector:"

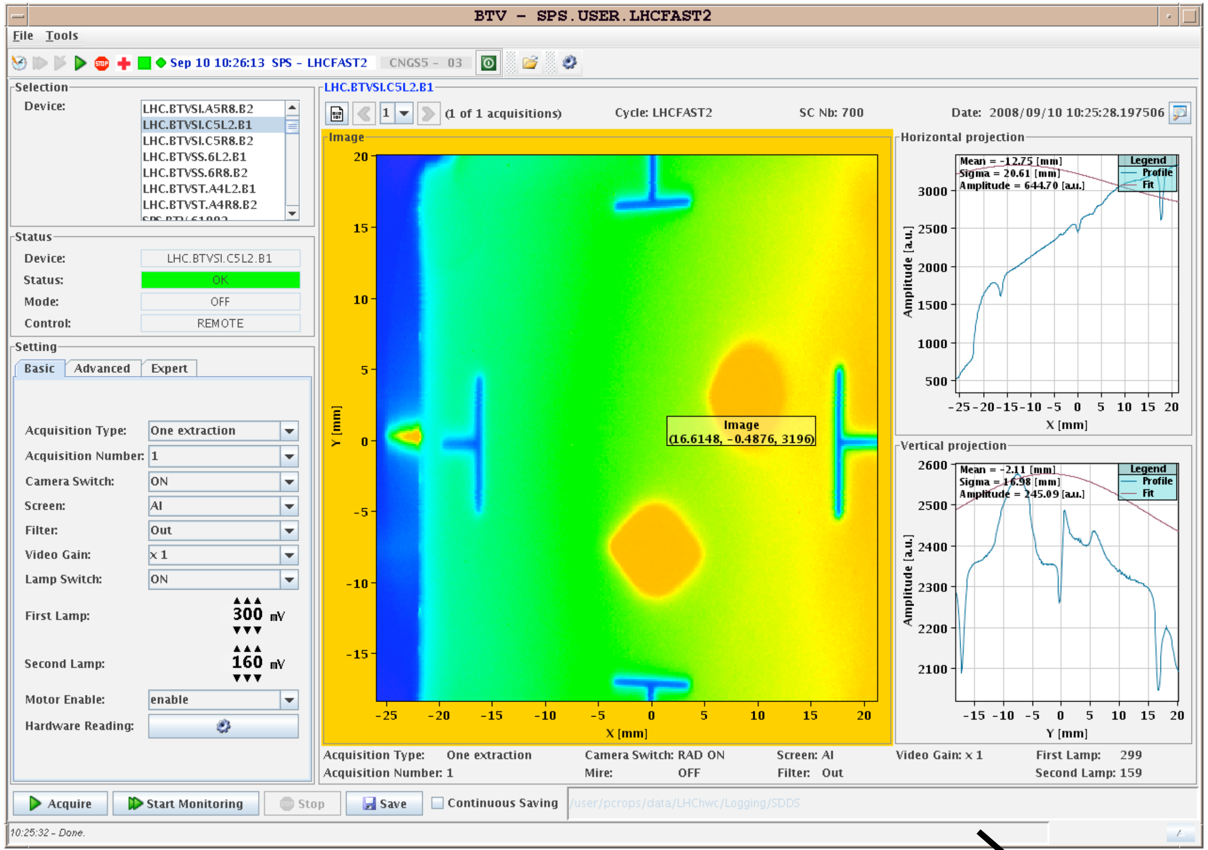
- One beam at the time
- Beam through 1 sector (1/8 ring),

correct trajectory, open collimator and move on.



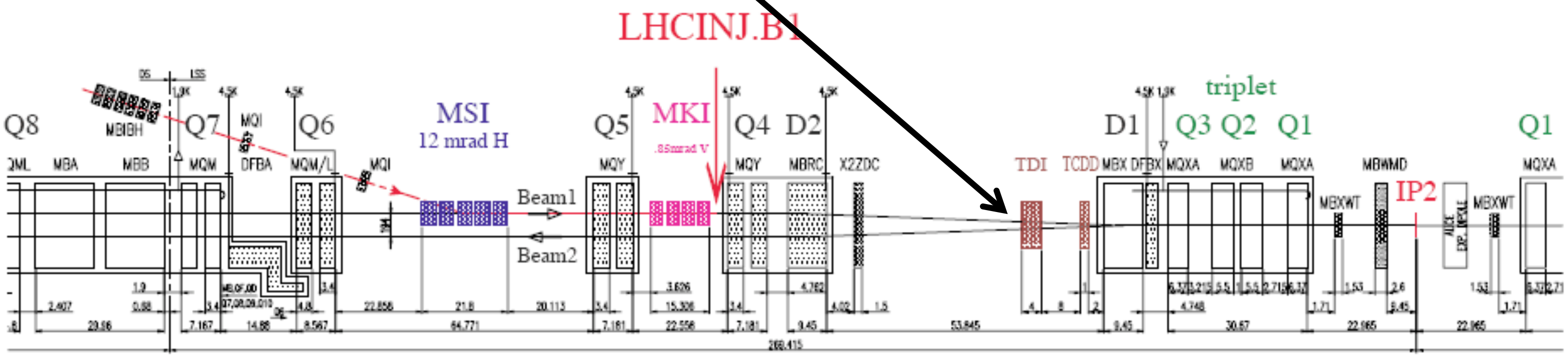


LHC Operation: the First Turn



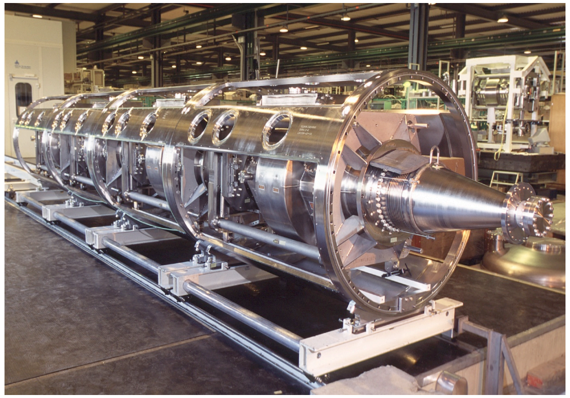
Beam 1 on OTR screen
1st and 2nd turn

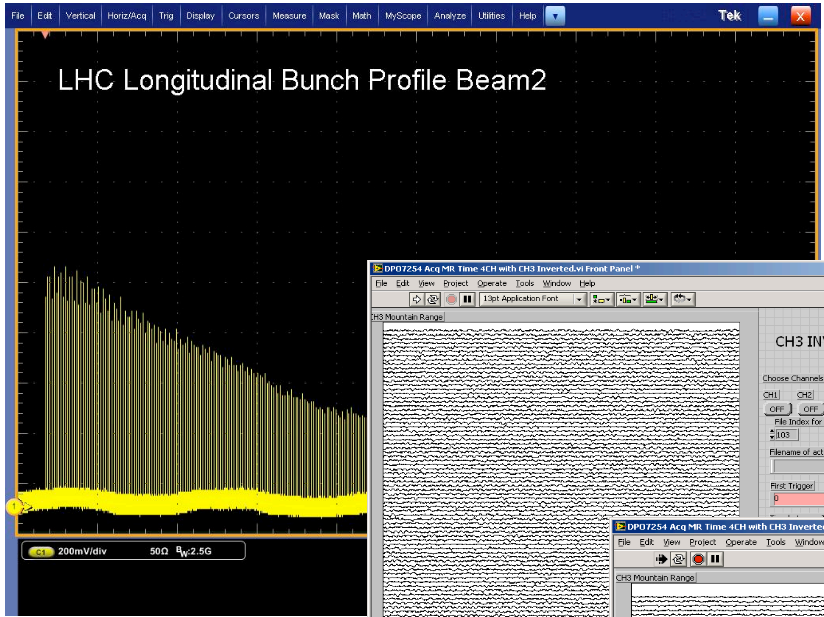
Correct x, x', y, y' to obtain the Closed Orbit



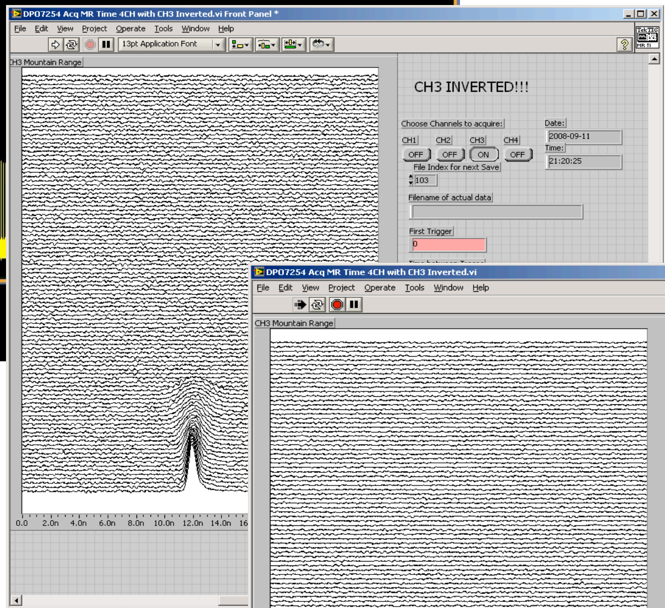
LHC Commissioning: RF

sc rf cavities:
400 MHz
16 MV/beam

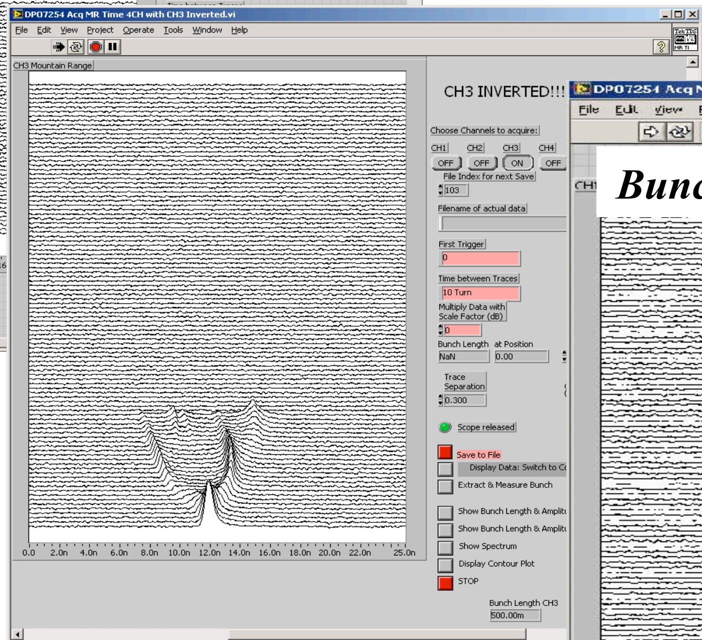


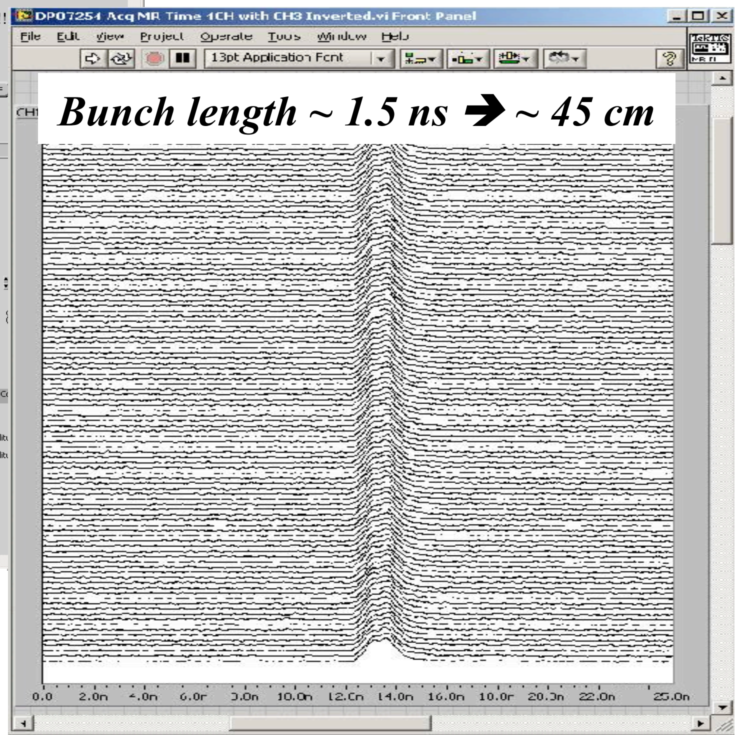


RF off



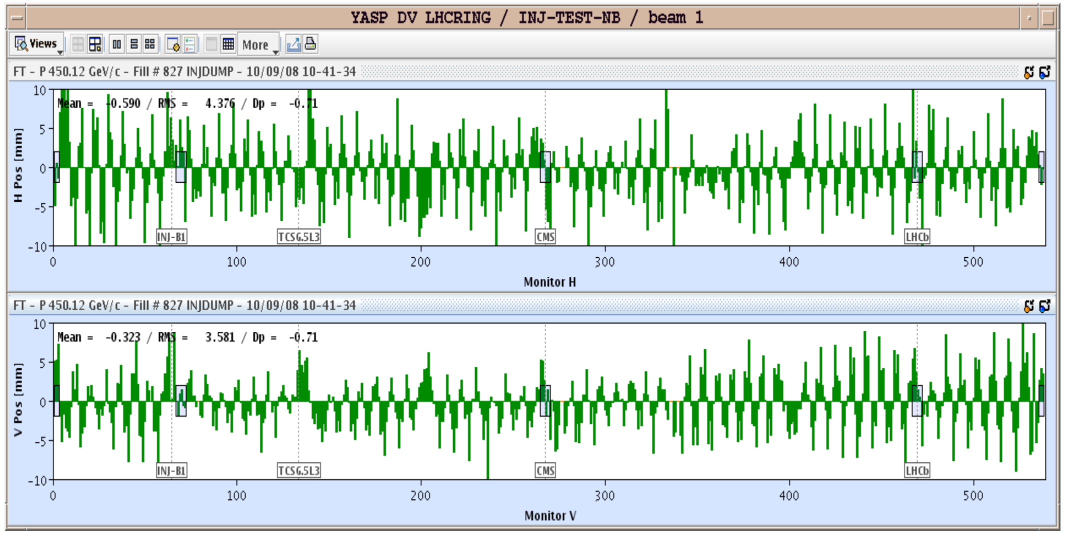
RF on,
phase optimisation





RF on, phase adjusted,
beam captured

Orbit & Tune:



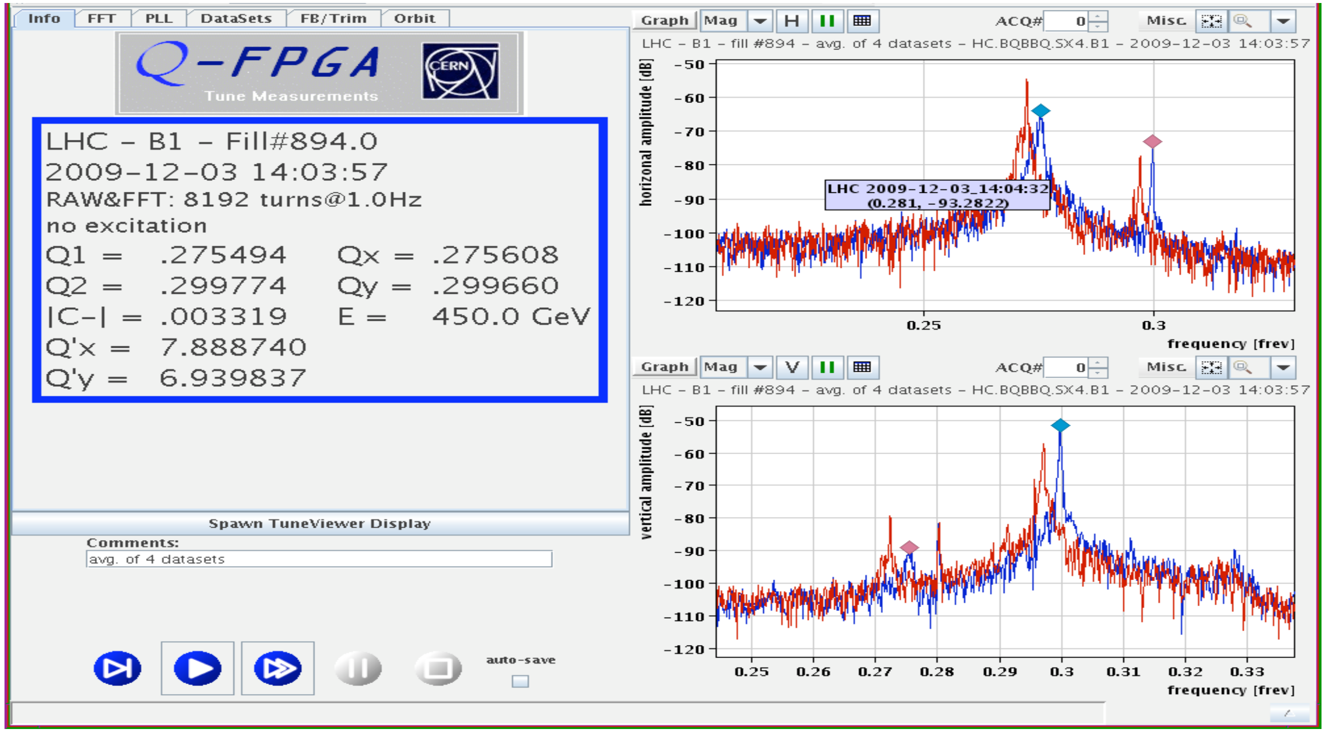
Tune: number of oscillations per turn

64.31
59.32

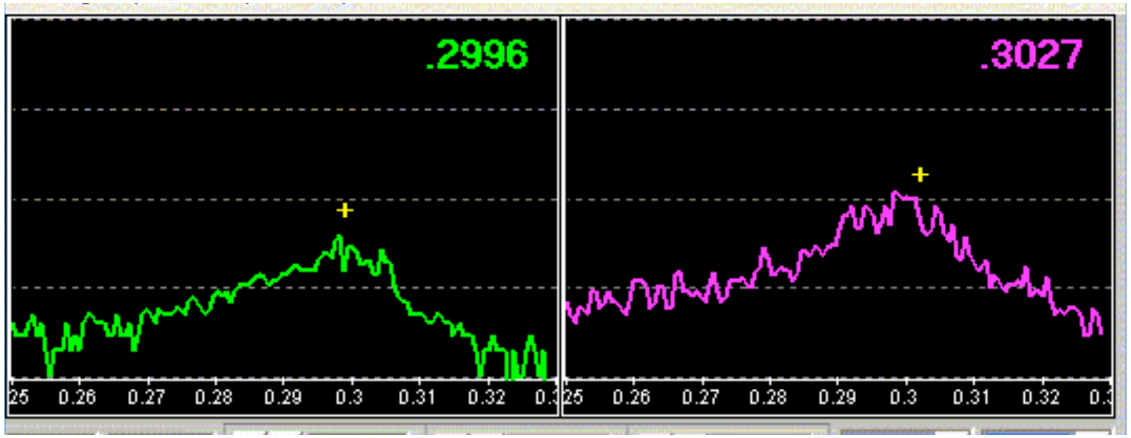
Relevant ***for beam stability:***
non integer part

LHC revolution frequency: *11.3 kHz*

$$0.31 * 11.3 = 3.5kHz$$



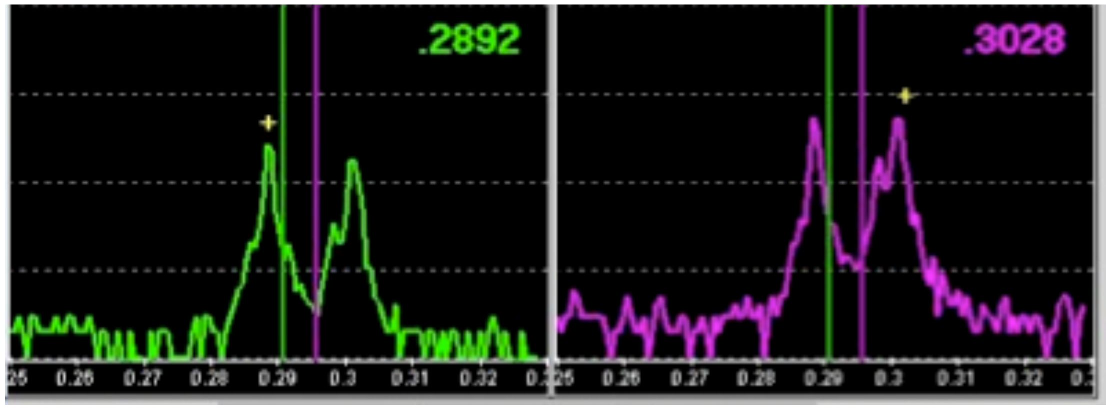
Compensate the Chromaticity

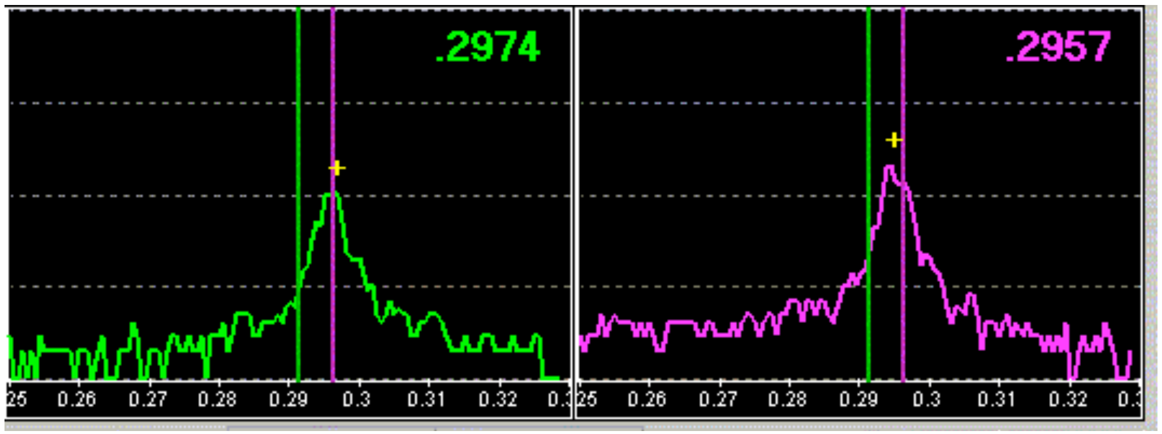


Tune signal for a nearly uncompensated cromaticity (Q' ≈ 20)

… and the Coupling

roll angle errors of quadrupoles, Solenoids of the detectors

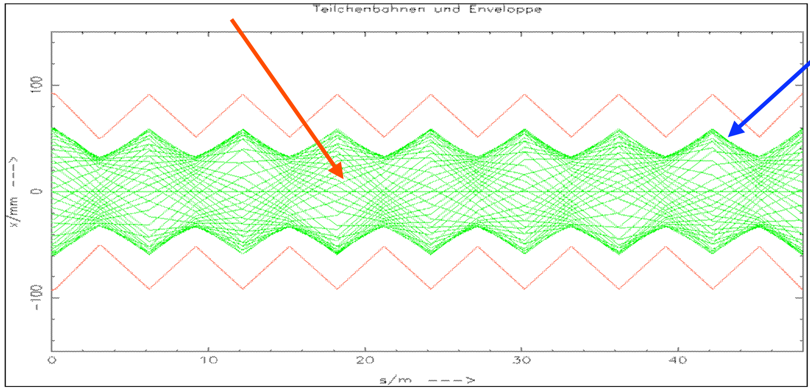




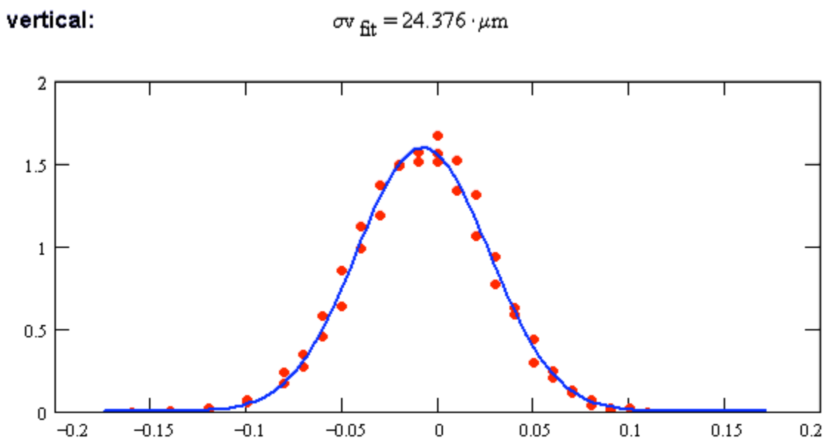
Ideal situation: cromaticity well corrected, (Q' ≈ 1) coupling compensated

Emittance of the Particle Ensemble:

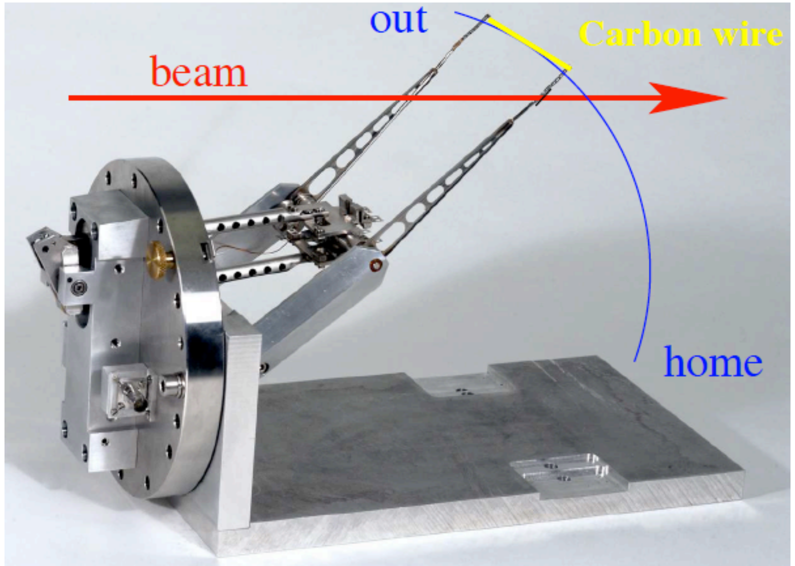
$$x(s) = \sqrt{\varepsilon}\,\sqrt{\beta(s)} \cdot \cos(\Psi(s) + \phi) \qquad \hat{x}(s) = \sqrt{\varepsilon}\,\sqrt{\beta(s)}$$



single particle trajectories, N ≈ 10 ¹¹ per bunch



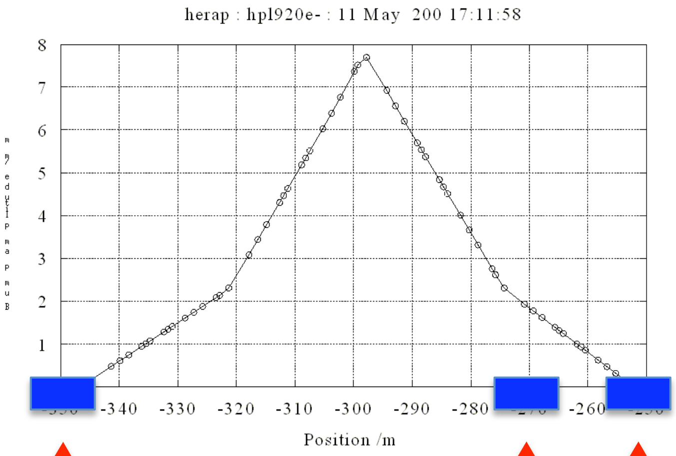
LHC Wirescanner



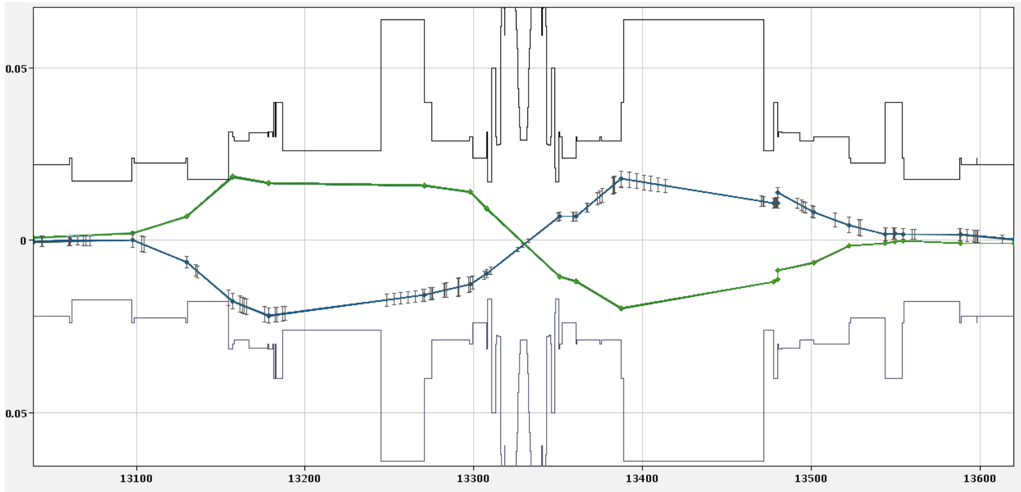
LHC: $\sigma = \sqrt{\varepsilon * \beta} = \sqrt{5*10^{-10}\,m*180\,m} = 0.3\,mm$

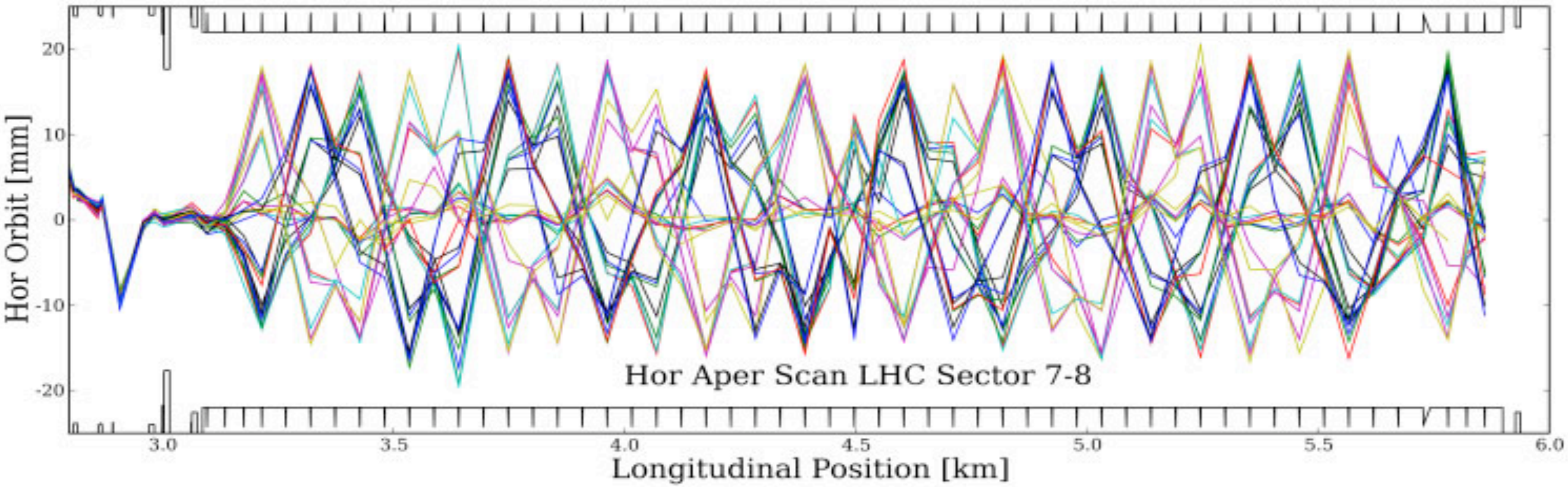
LHC Operation: Aperture Scans

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



3 bump to create local orbit distortion



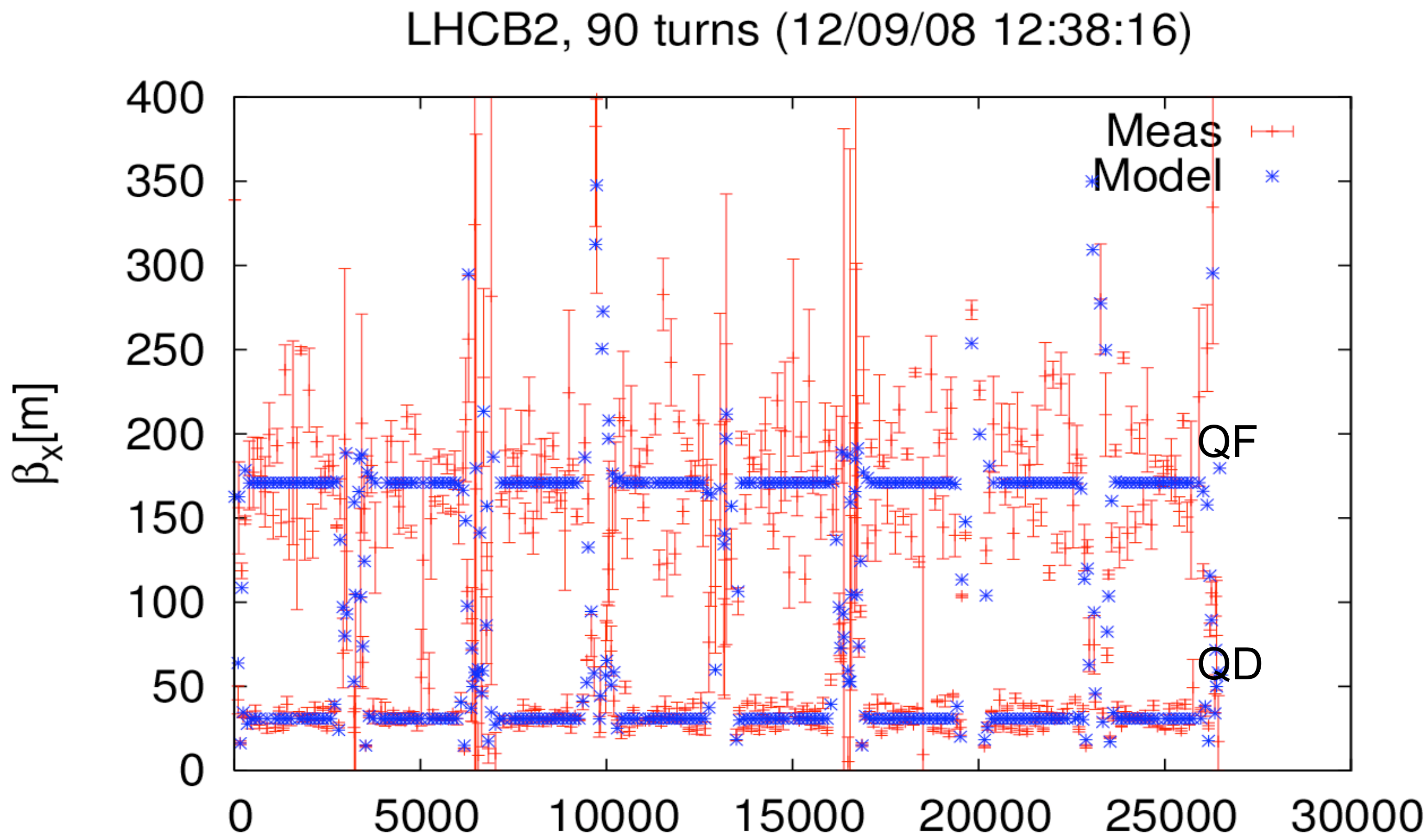


LHC Operation: the First Beam

Measurement of β :

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

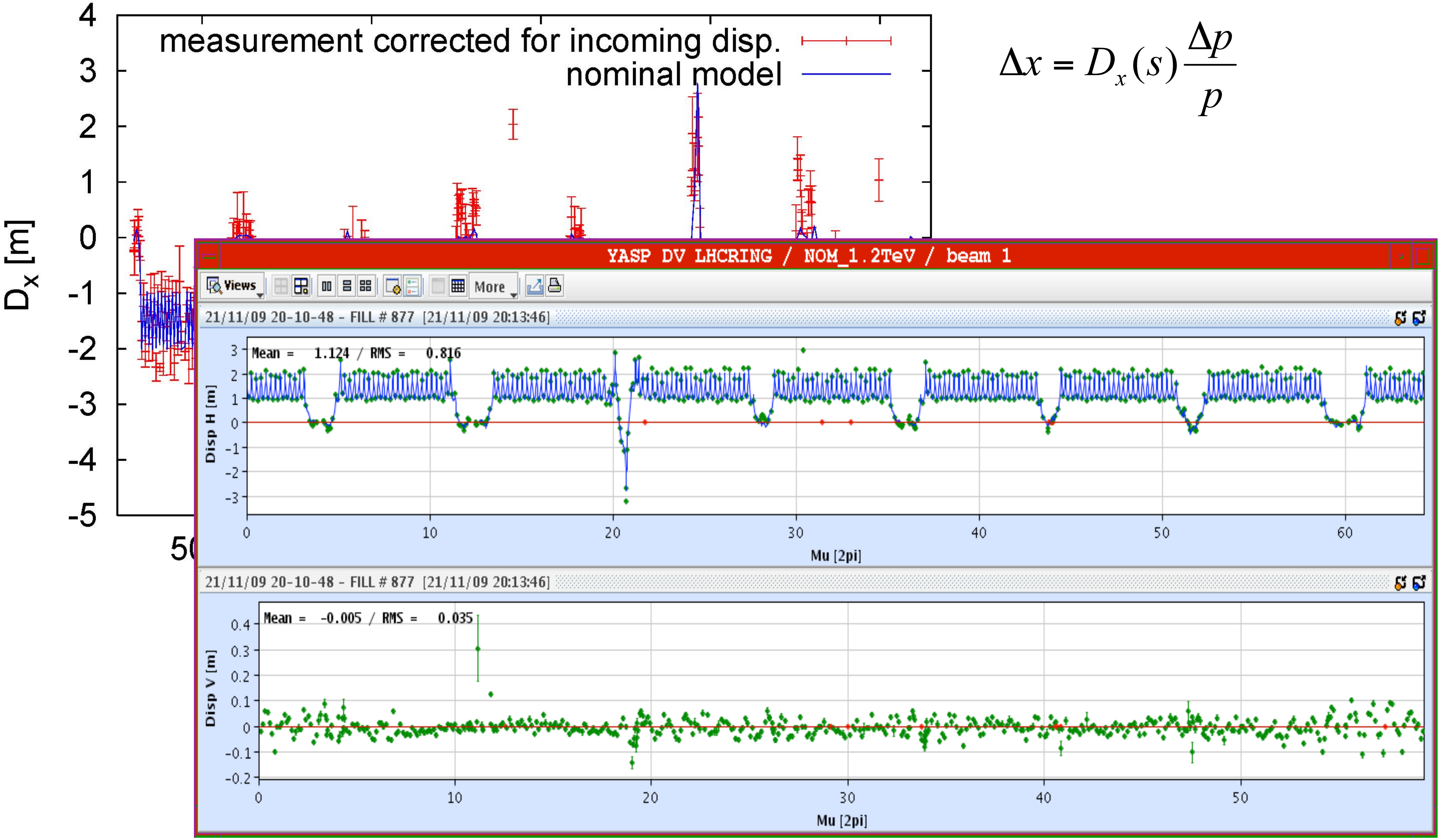
Δβ / β = 50 %



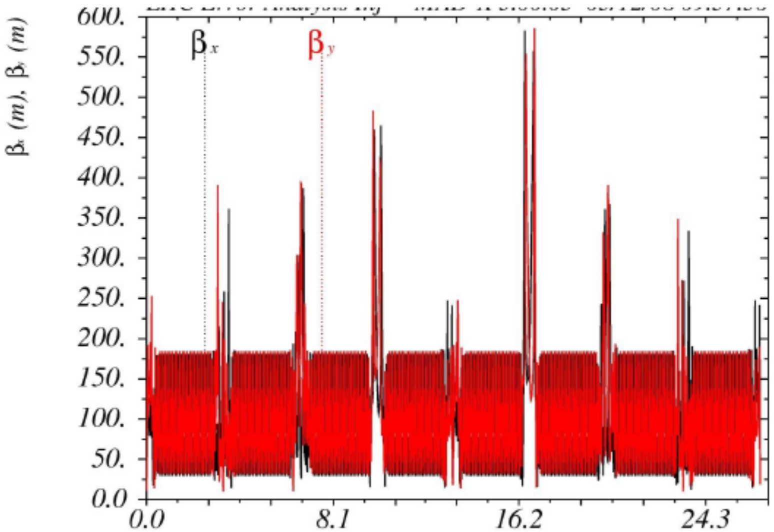
LHC Operation: the First Beam

Dispersion Measurement

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

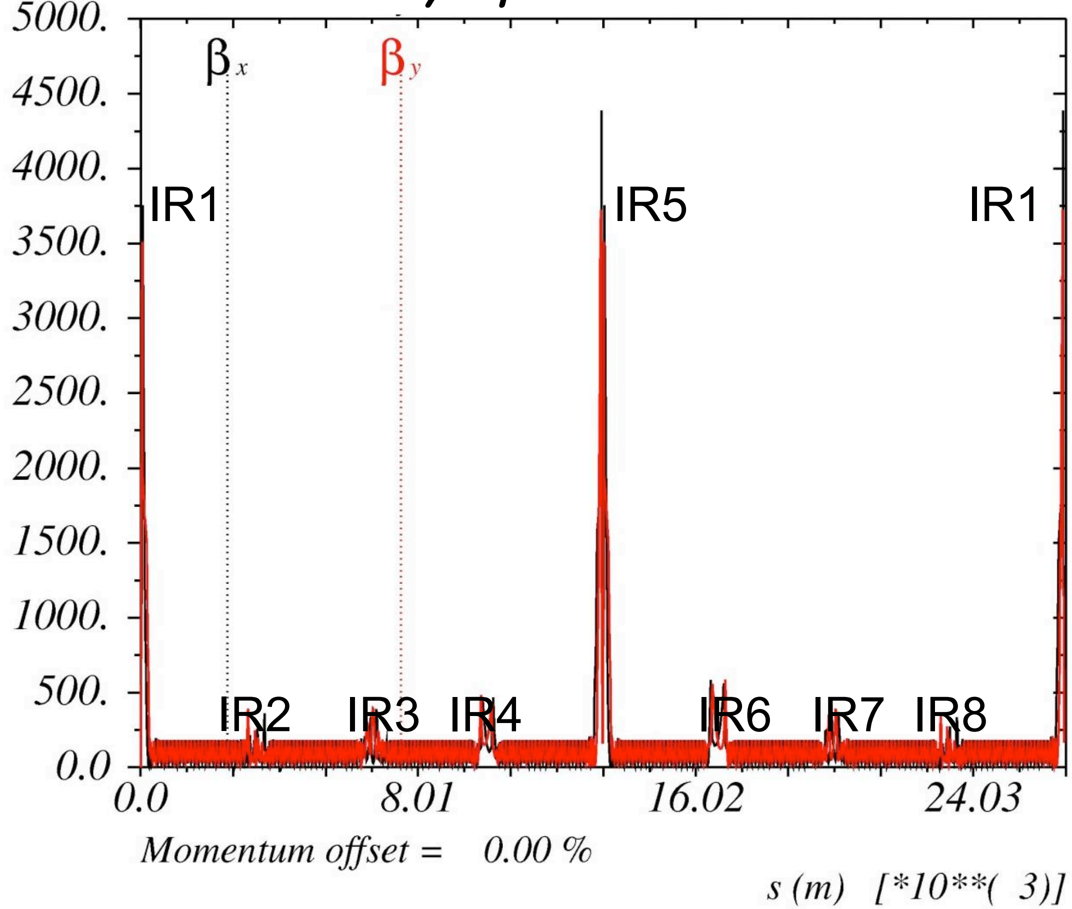


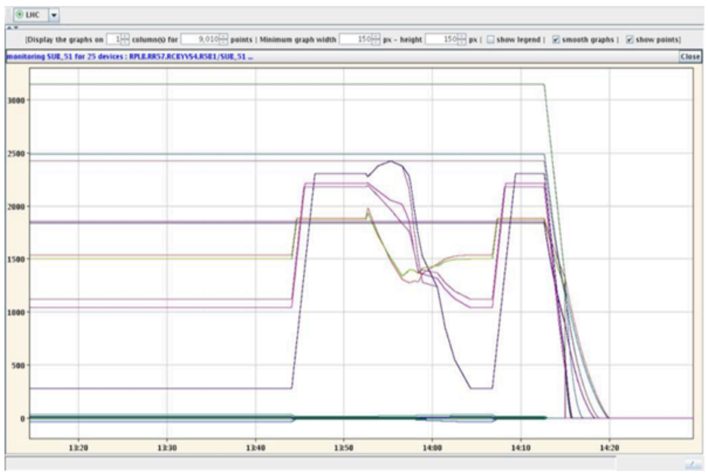
The Squeeze ... only at high energy



LHC Injection Optics

LHC Luminosity Optics





magnet currents during optics transfer

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

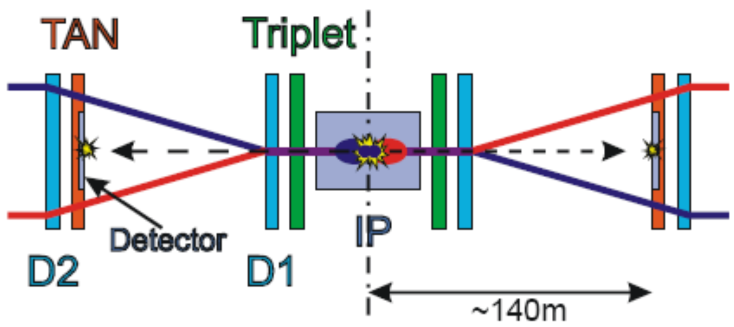
... cannot be avoided

25 ns

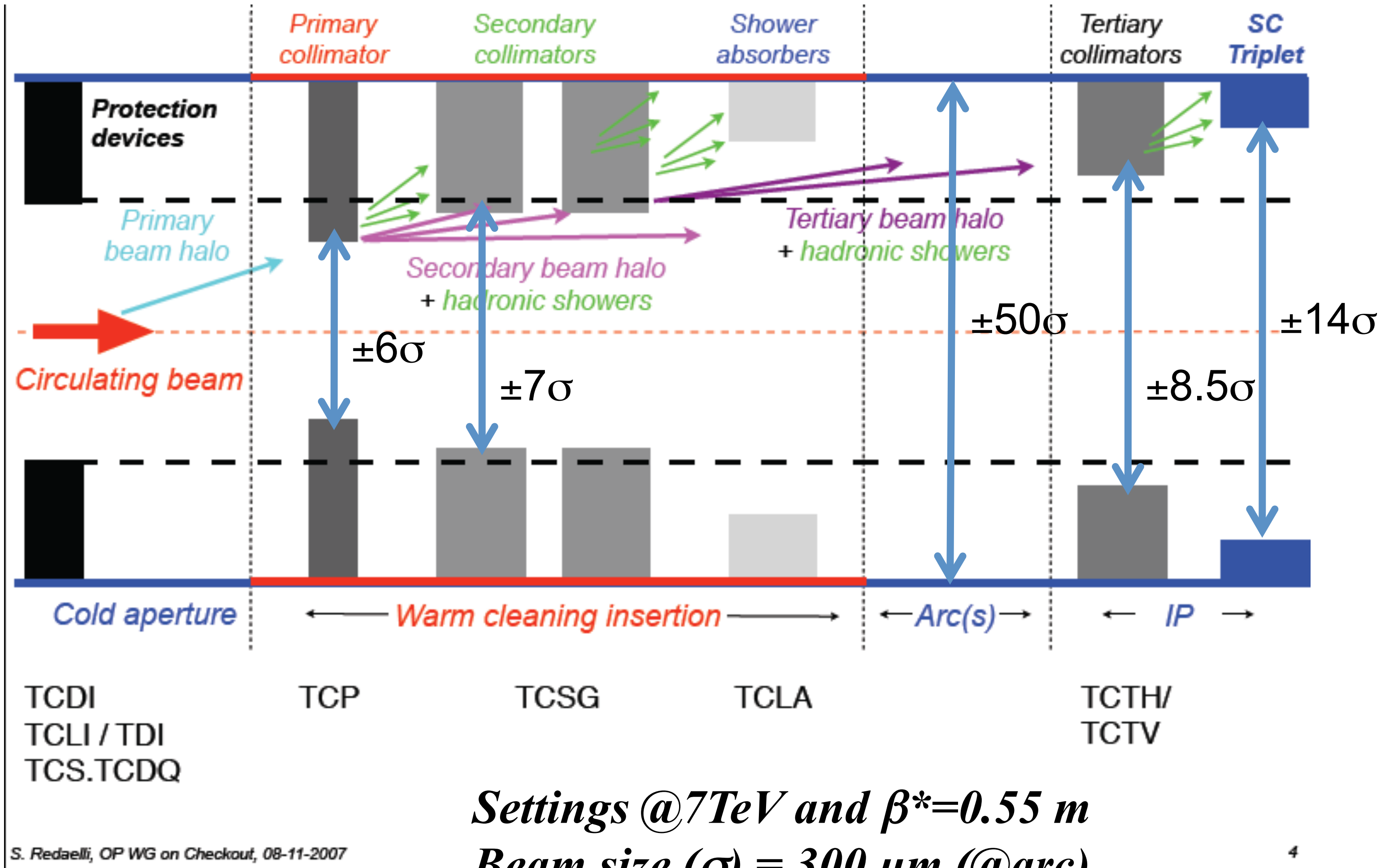
W is a **pure beam offset contribution**.

... can be avoided by careful tuning

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



LHC Aperture and Collimation



Settings @7TeV and β*=0.55 m

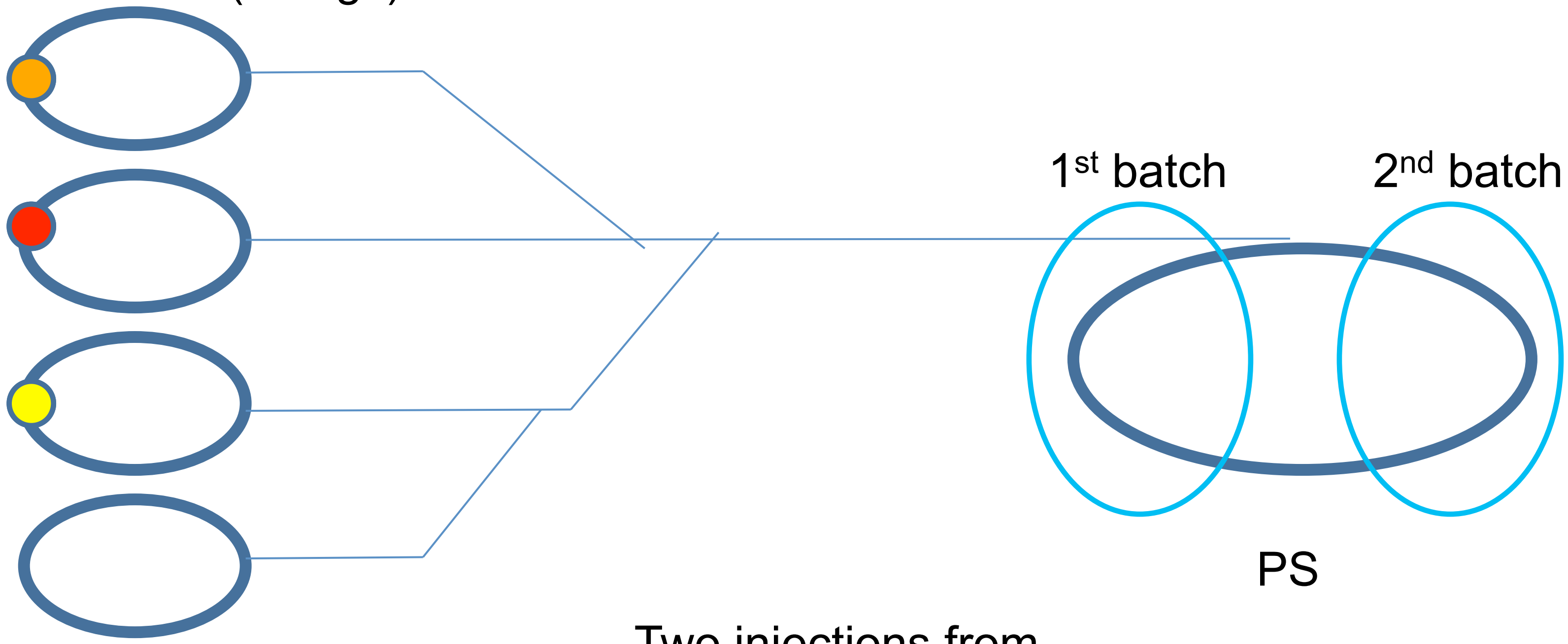
Beam size (σ) = 300 μm (@arc)

Beam size (σ) = 17 μm (@IR1, IR5)

LHC Operation: Pre-Accelerators and Injection

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

BOOSTER (4 rings)



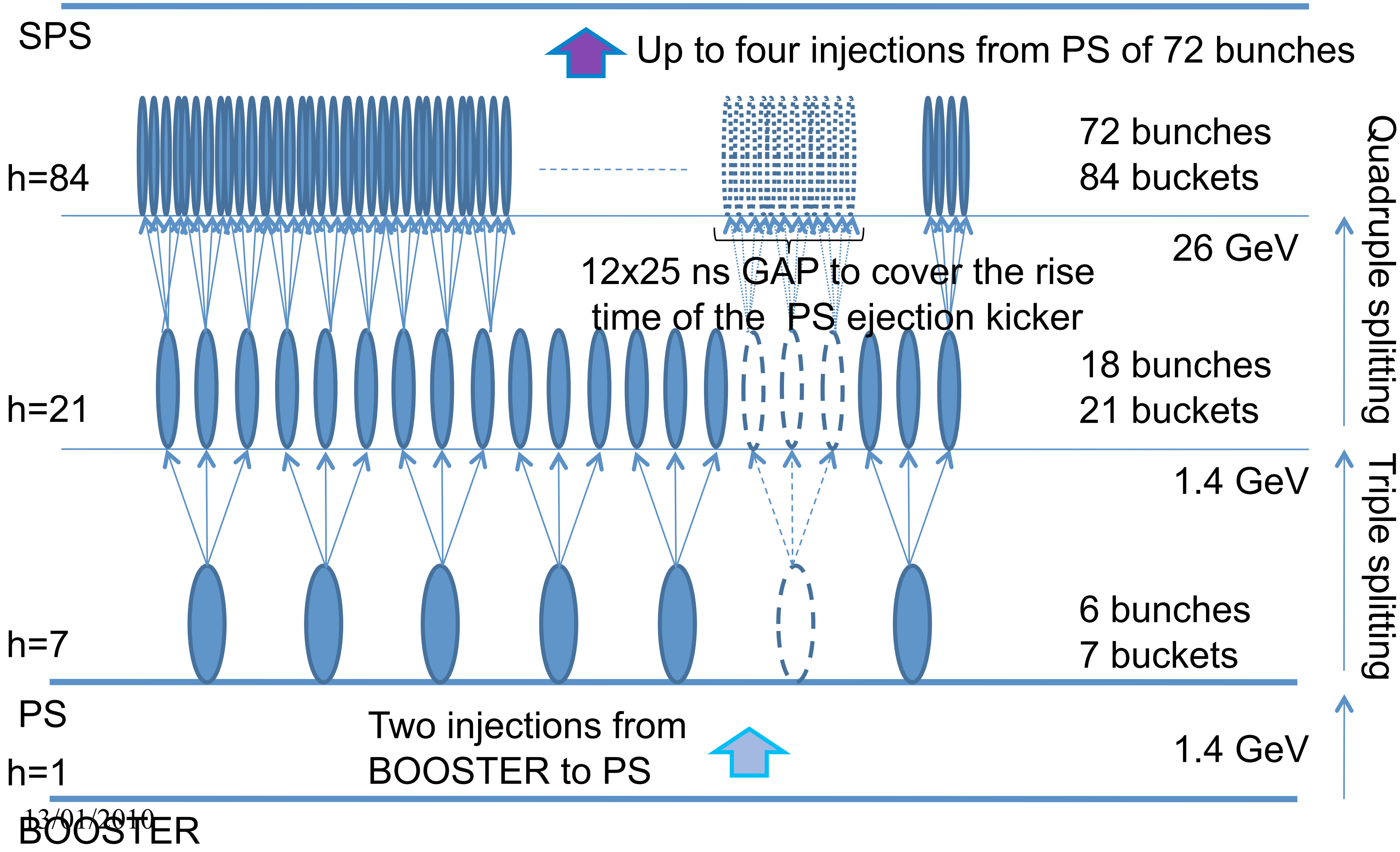
Two injections from
BOOSTER to PS

h=1

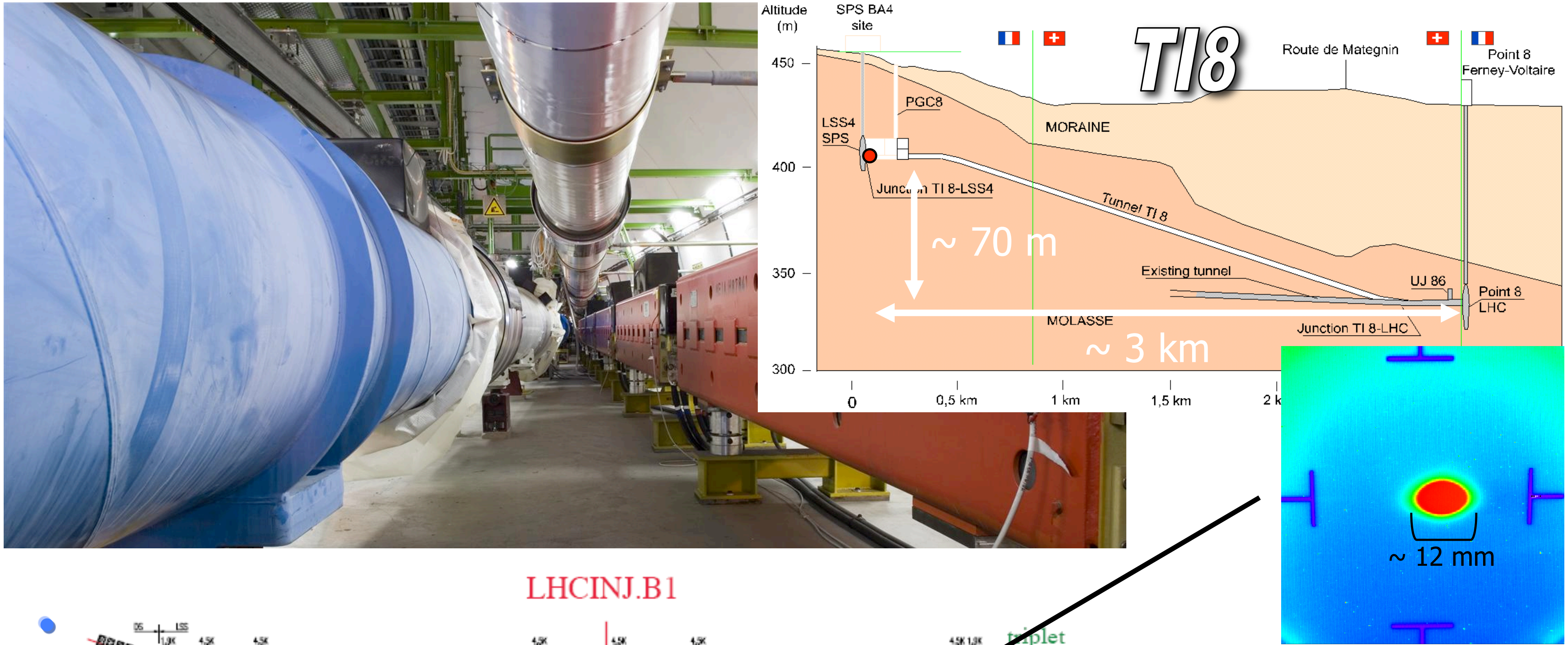
h=7 (6 buckets filled +
1 empty)

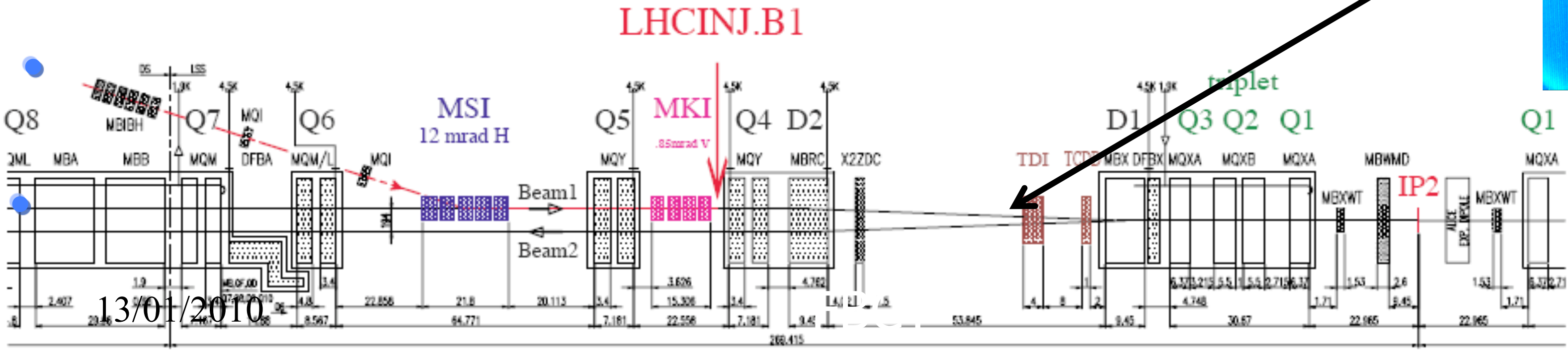
court. R. Alemany

LHC Injection: Preparing the Bunch Trains



Injection mechanism: the transfer lines

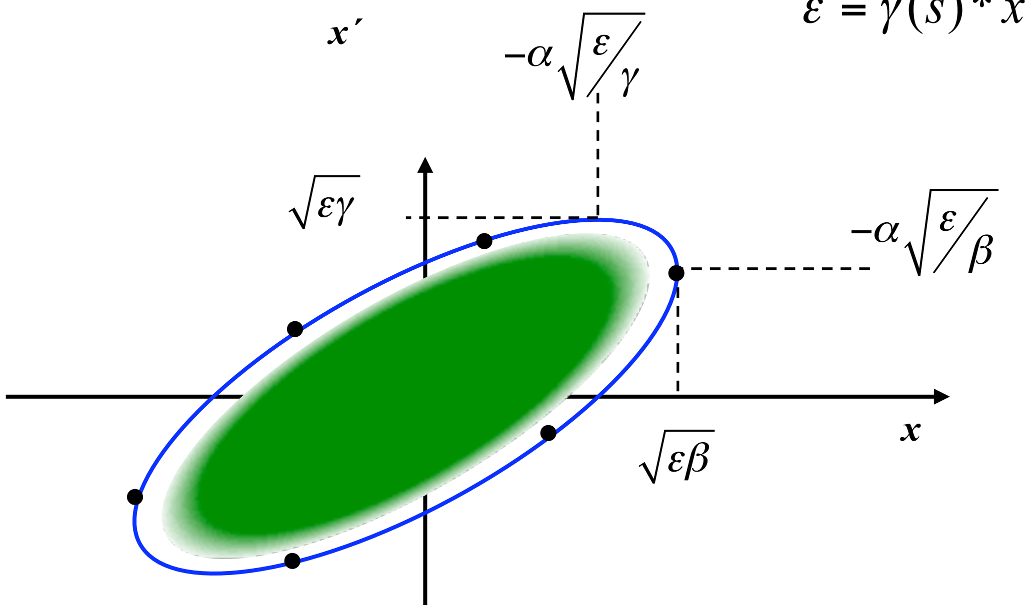




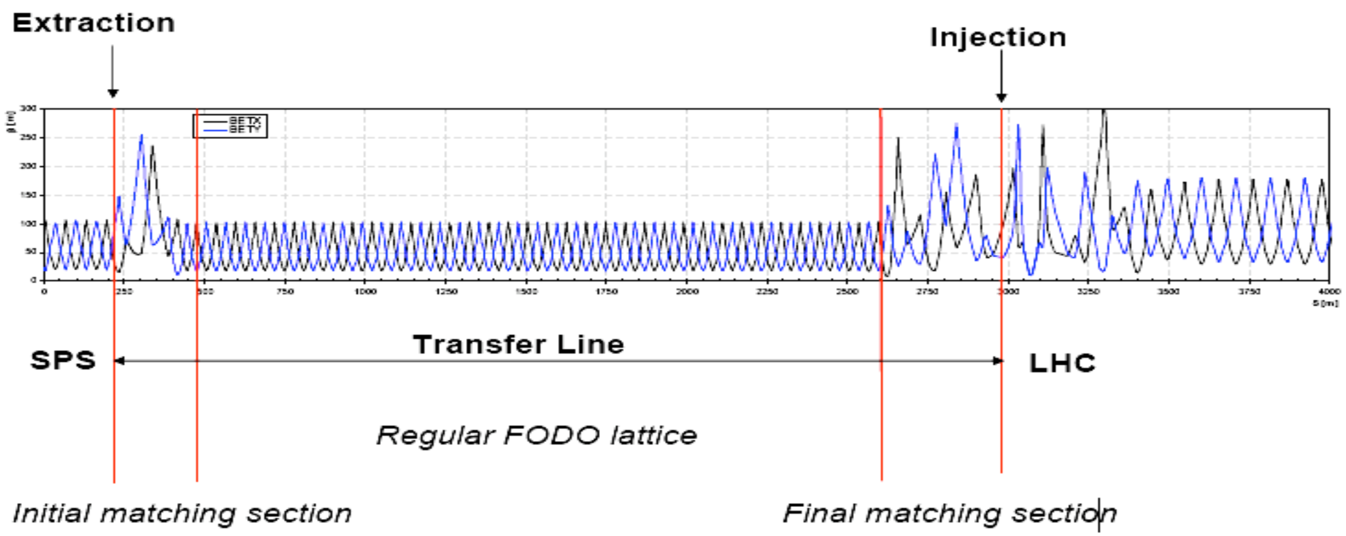
court. R. Alemany

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 Injection: Again ... high accuracy required

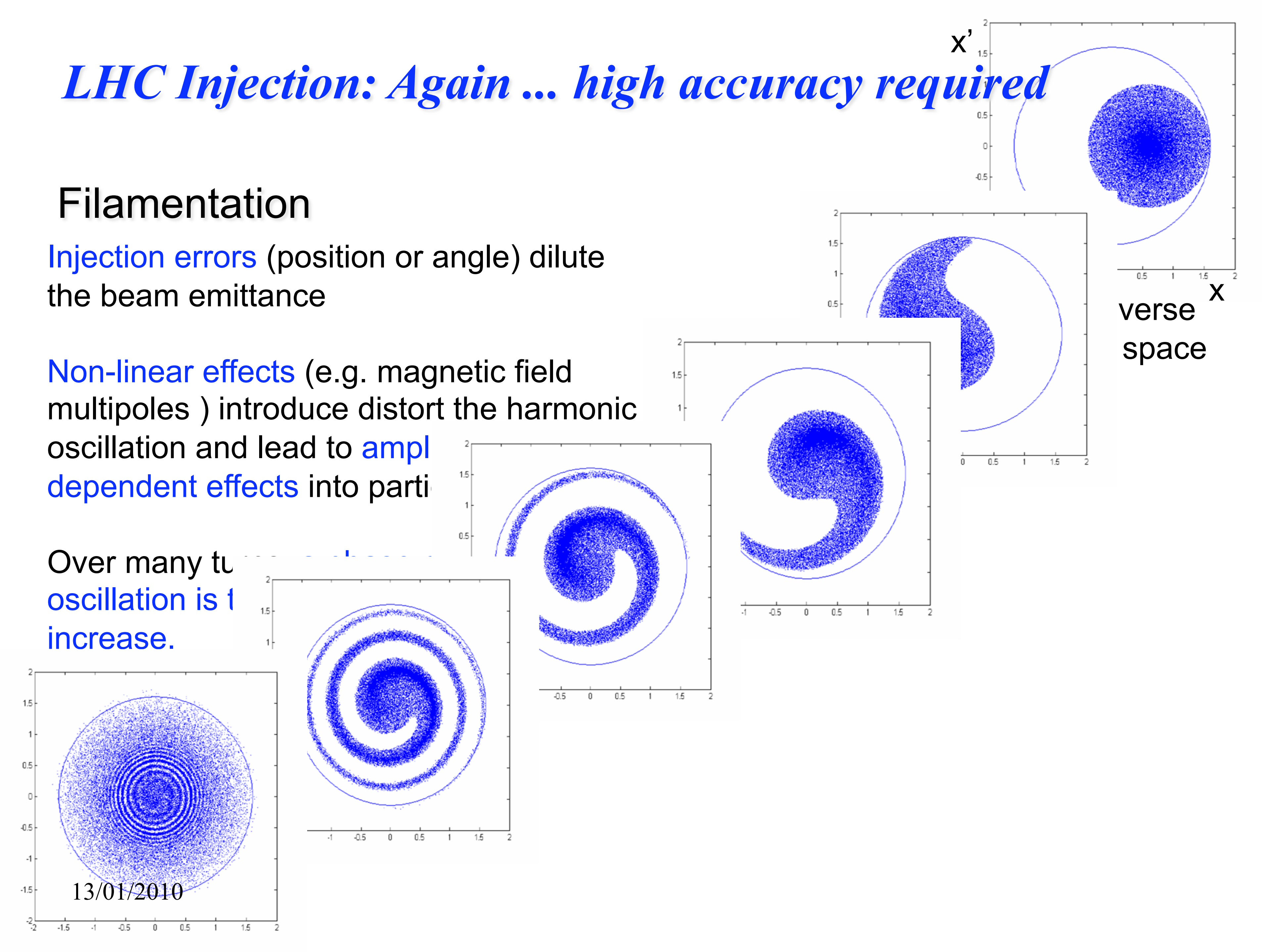
Filamentation

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

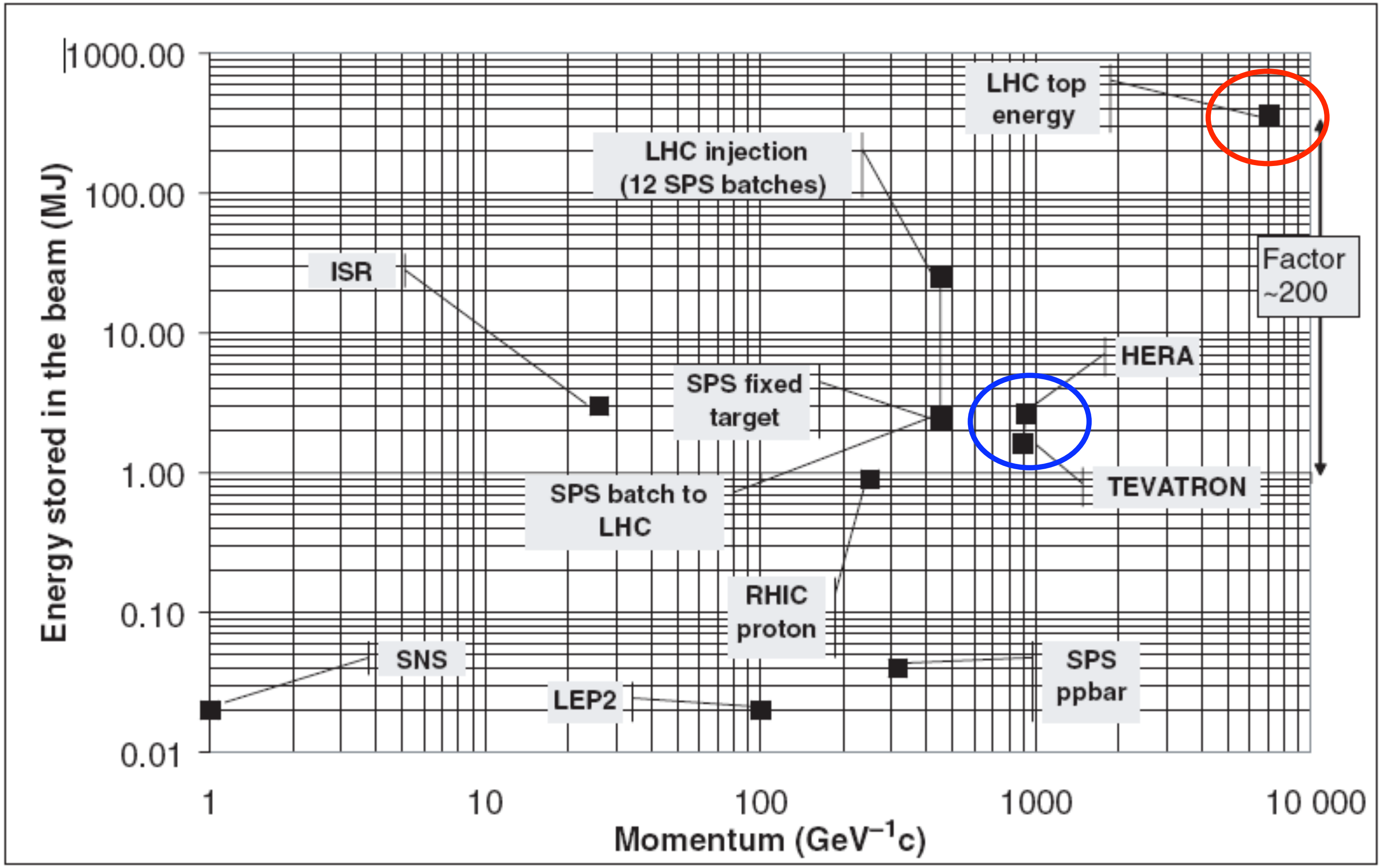
Over many tu oscillation is t increase.

verse space



LHC Operation:
Machine Protection & Safety

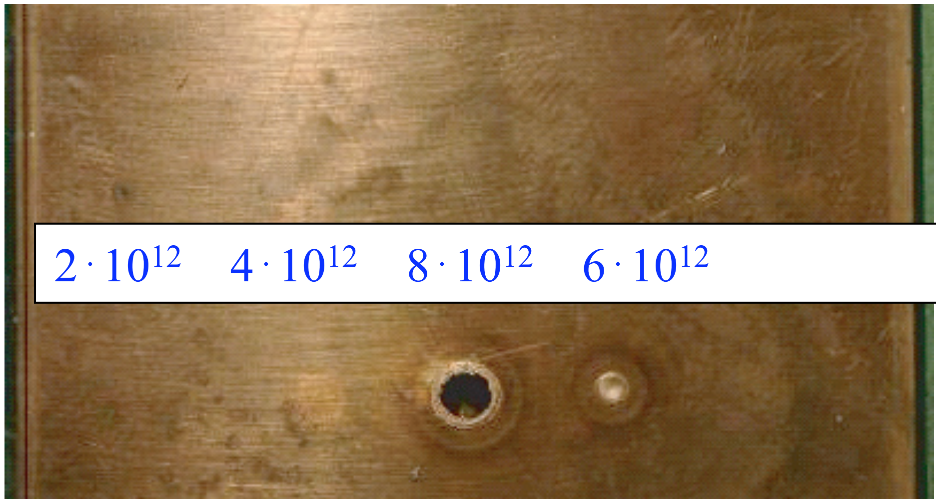
Energy Stored in the Beam of different Storage Rings



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

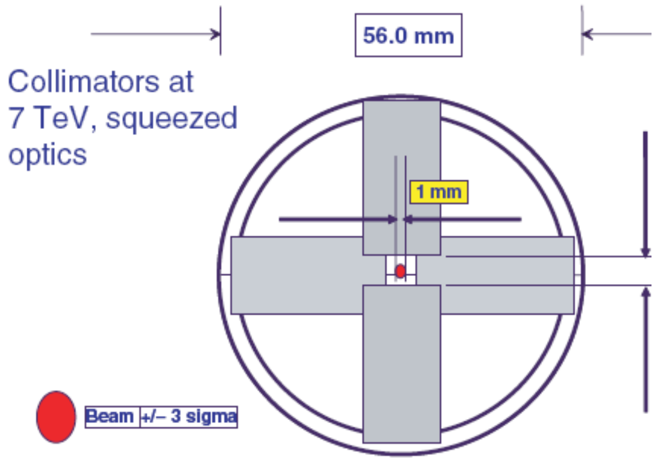
Enough to melt 500 kg of copper



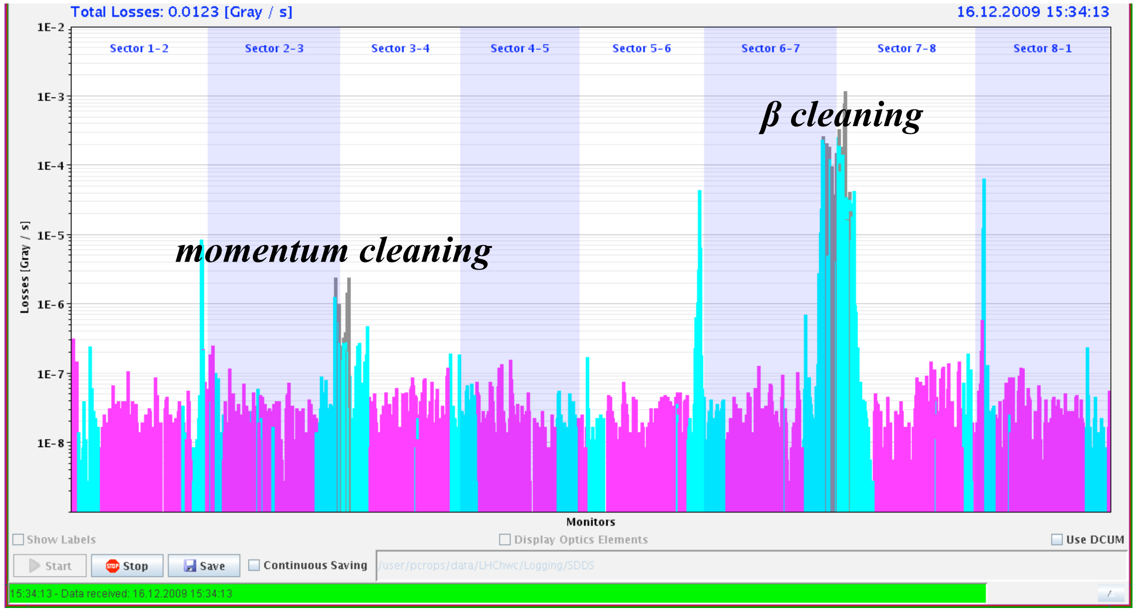
$2 \cdot 10^{12}$ $4 \cdot 10^{12}$ $8 \cdot 10^{12}$ $6 \cdot 10^{12}$ 450 GeV p Strahl

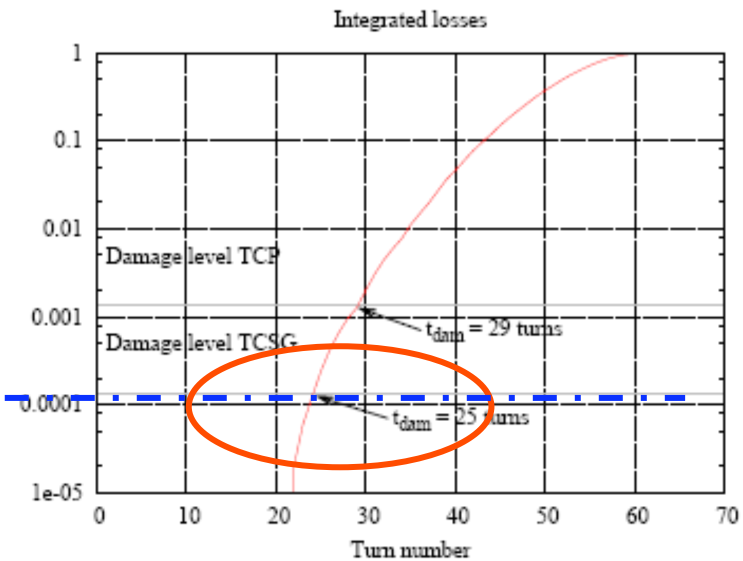
LHC Operation:
Machine Protection & Safety

... Komponenten des Machine Protection Systems :

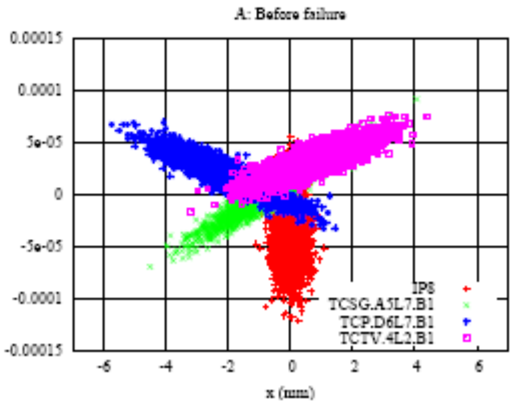


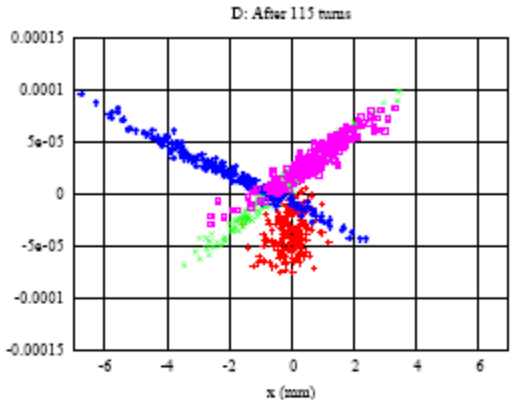
- ***beam loss monitors***
- ***QPS***
- ***permit server***
- ***orbit control***
- ***power supply control***
- ***collimators***
- ***online on beam check of all (?) hardware components***
- ***a fast dump***
- ***the gaussian beam profile***





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: τ_{det} *= 6 ms*
τ_{damage} *= 6.4 ms*

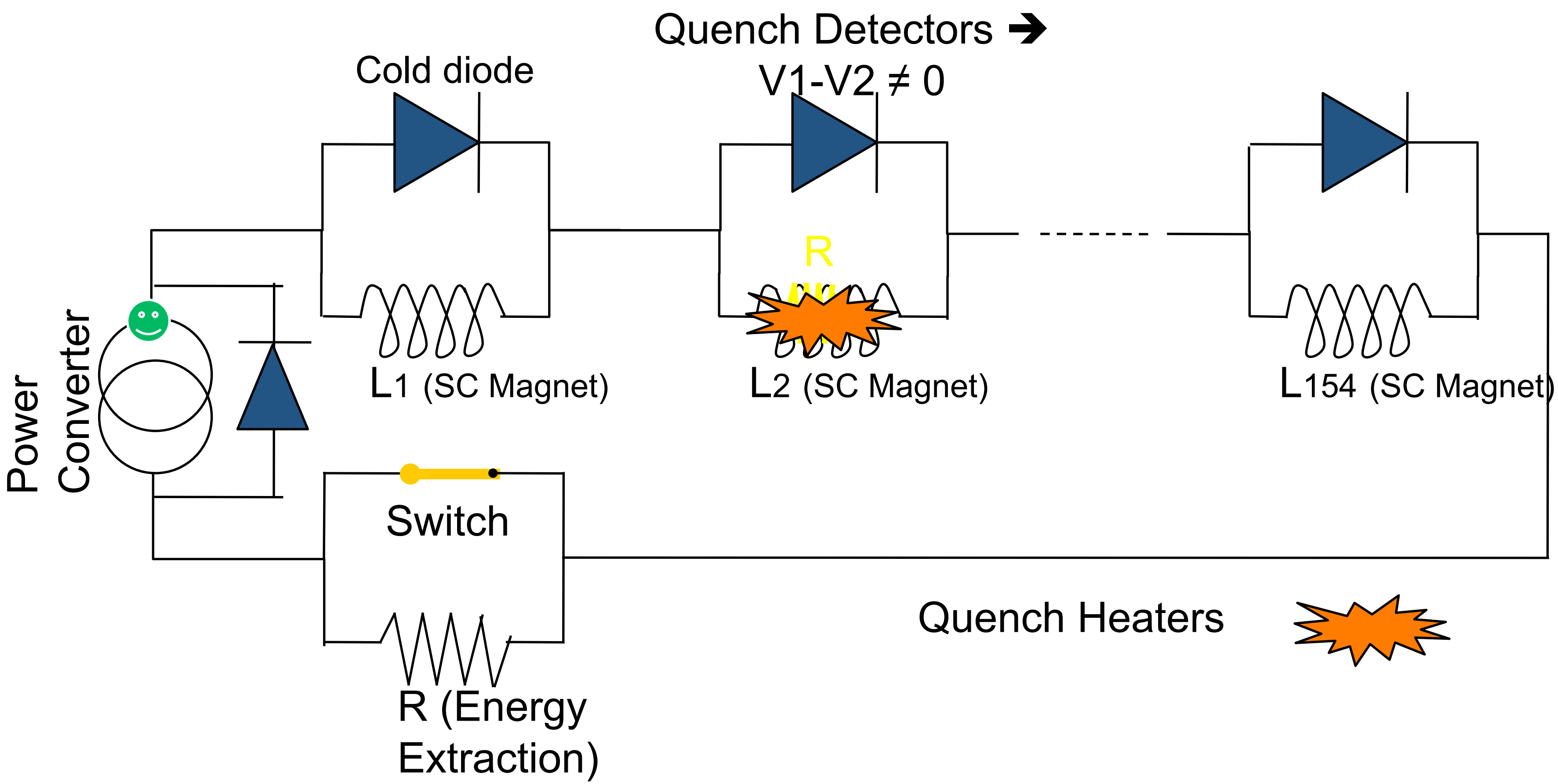
failure of nc. dipole: τ_{damage} *= 2 ms*

→ FMCM installed

Energy stored in the magnets: ***10 GJ***

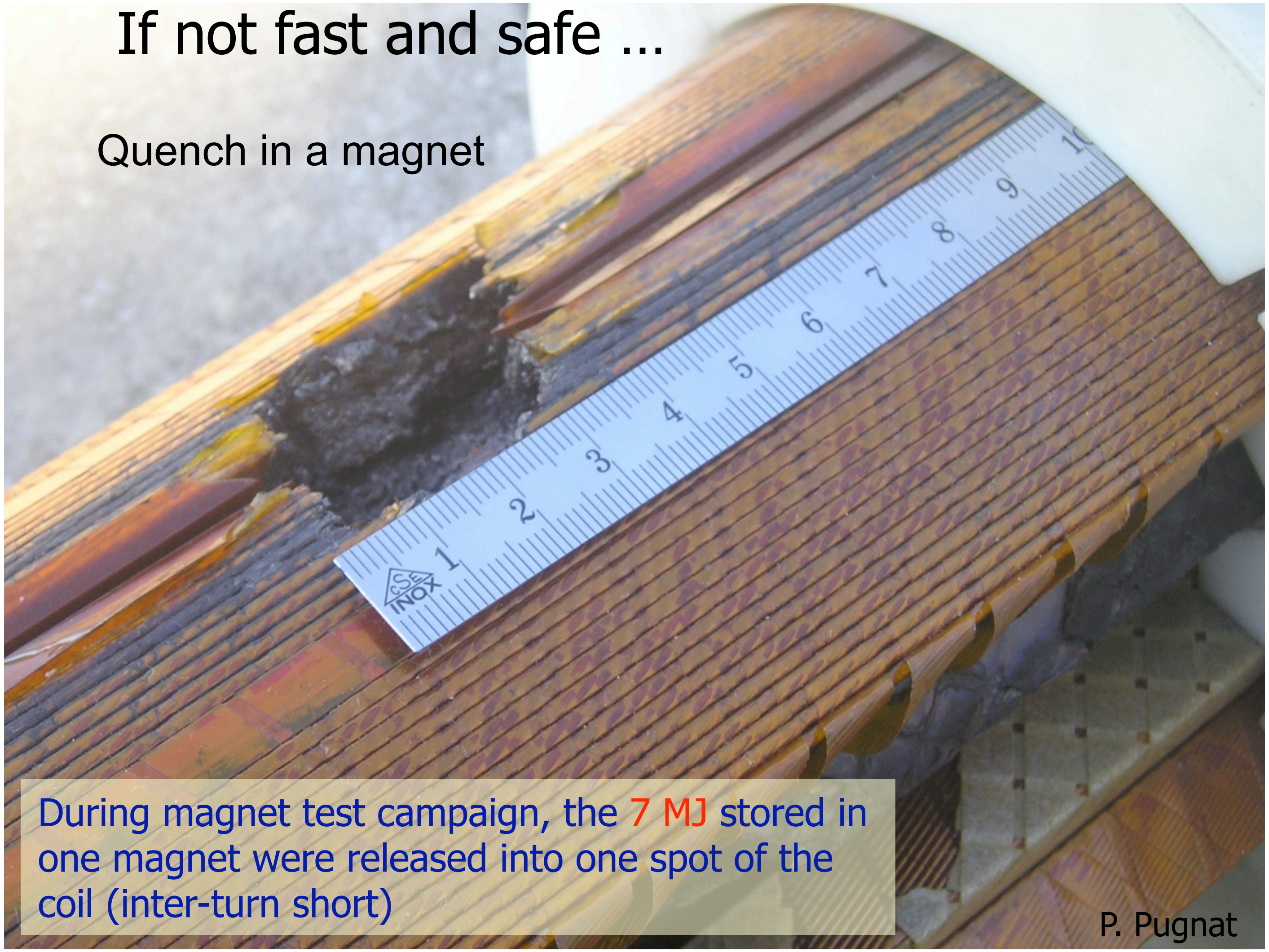
Quench Protection System

Schematics of the QPS in the main dipoles of a sector

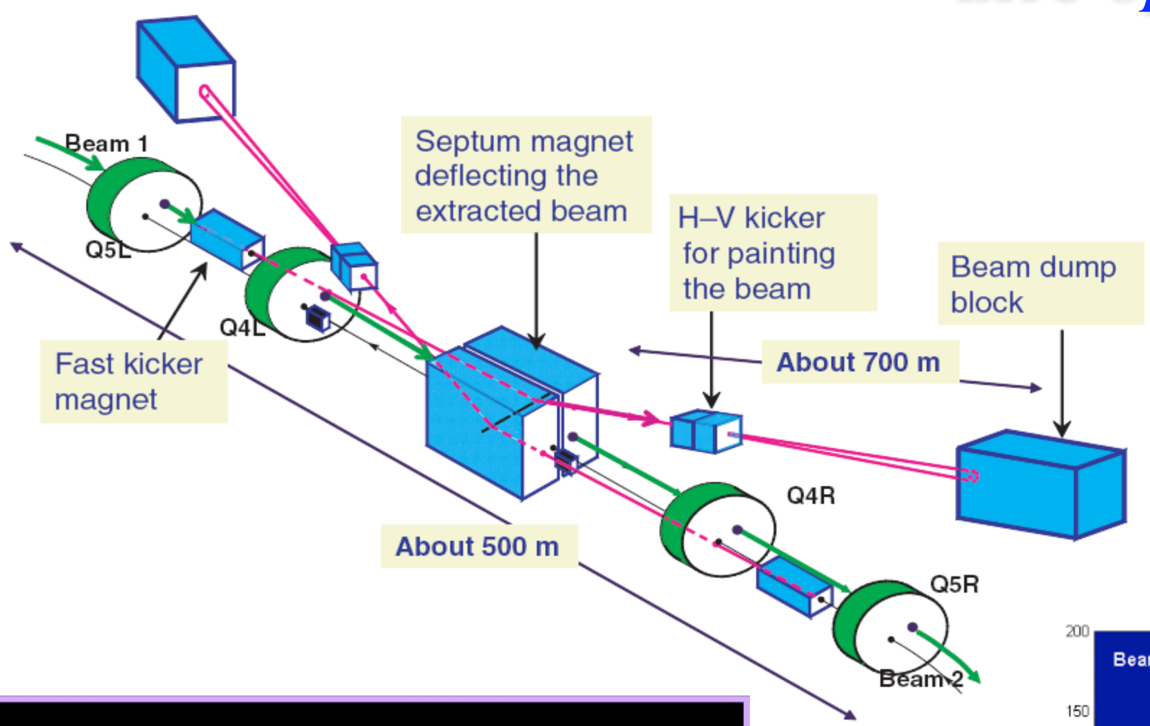


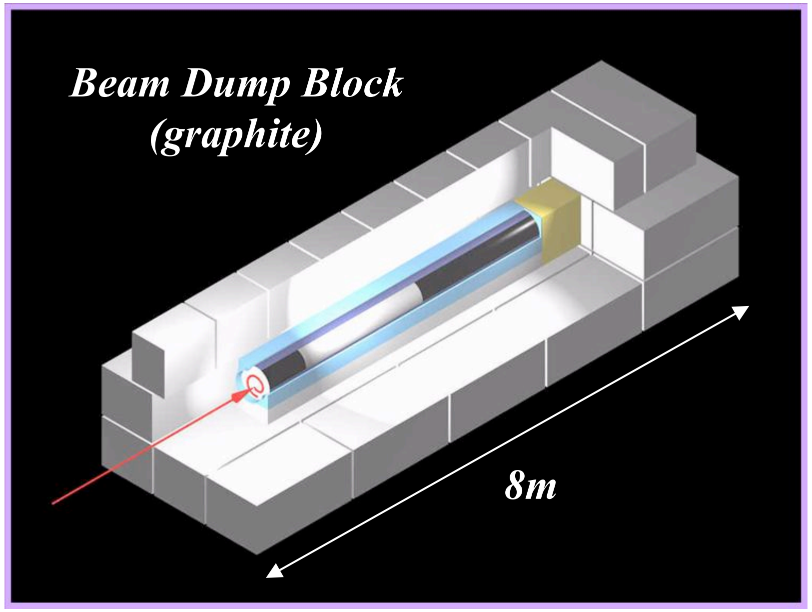
court. R. Alemany

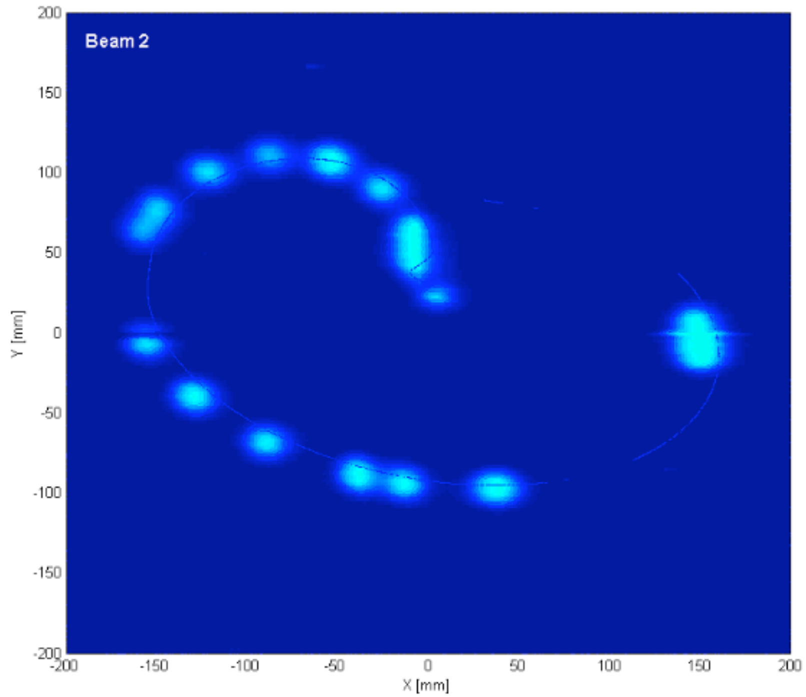
Energy stored in the magnets: quench



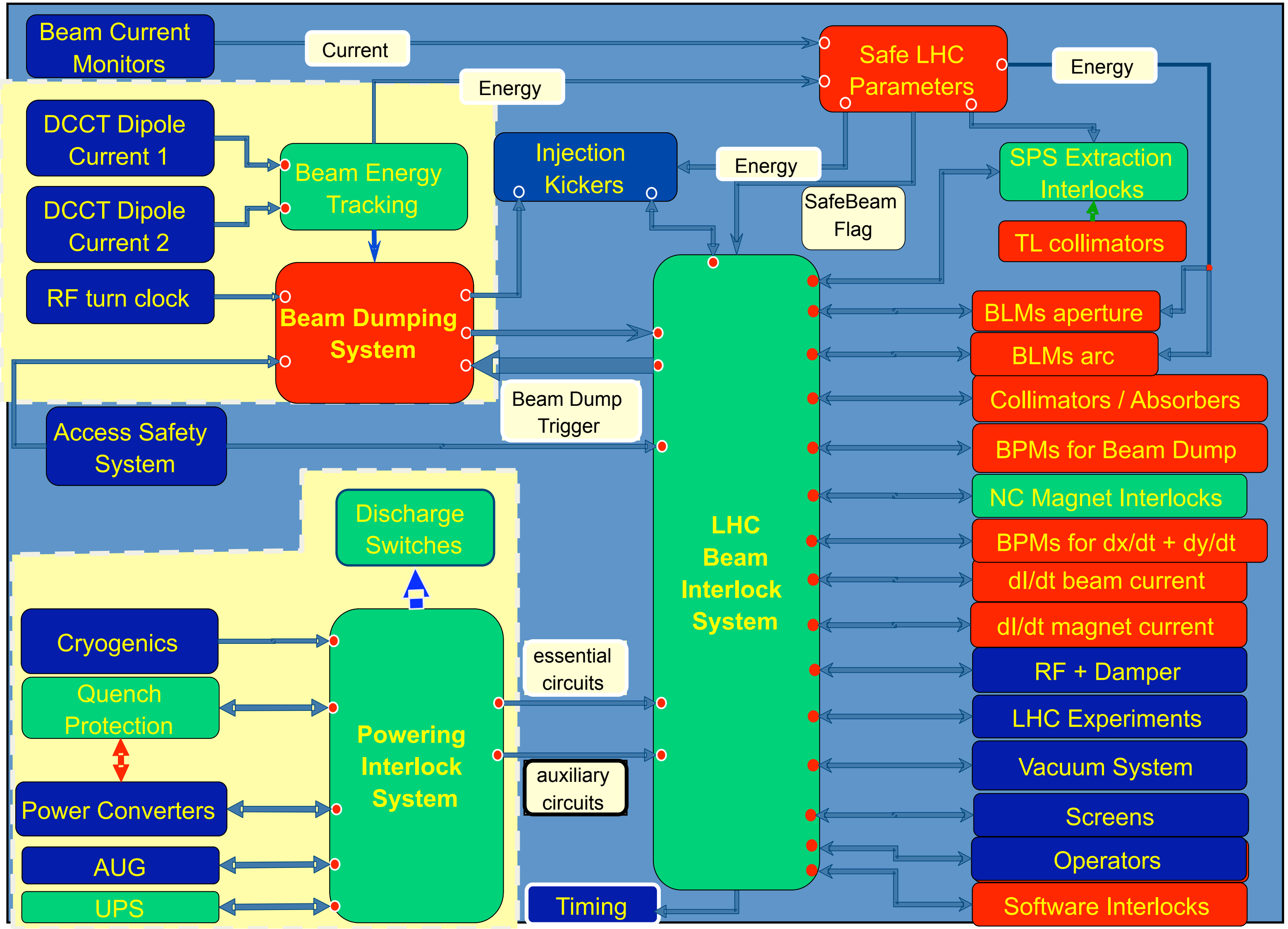
LHC Operation: Dump System





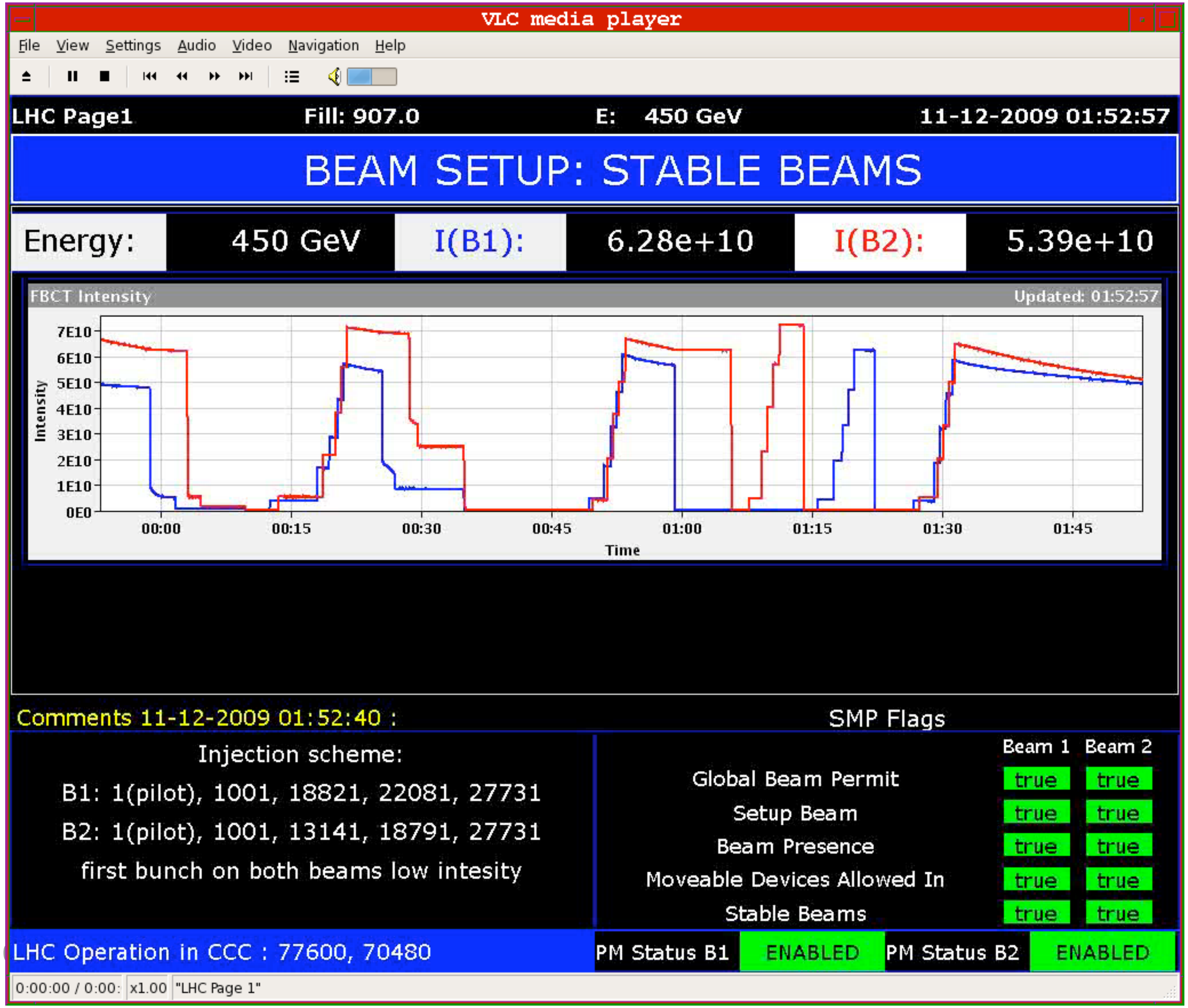


LHC Operation: Machine Protection & Safety

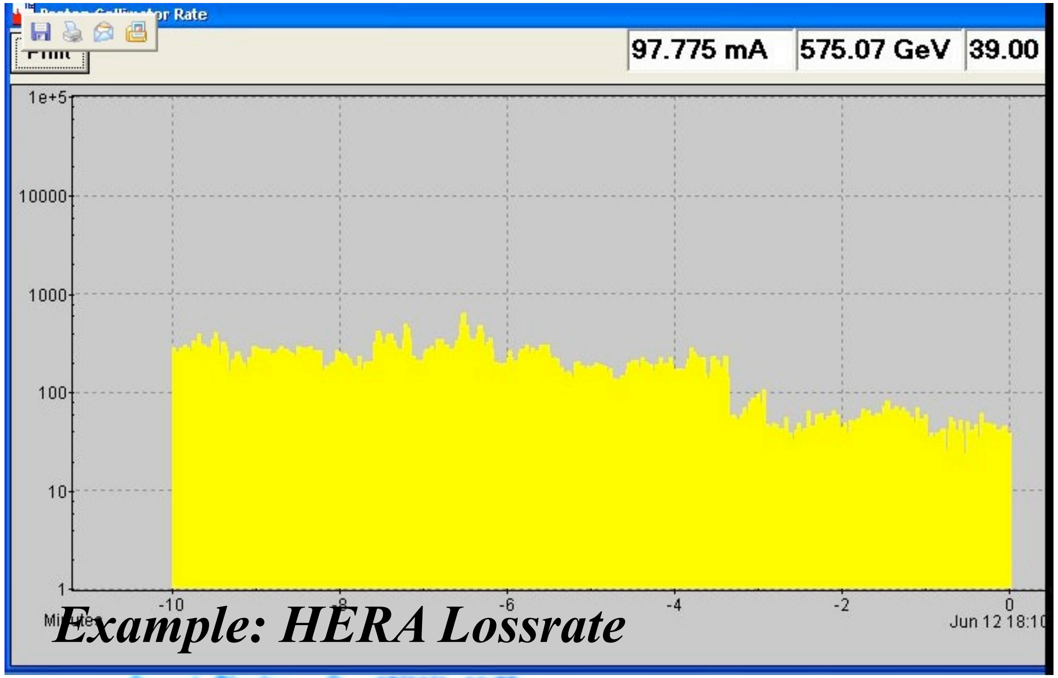


... no comment

LHC Operation: Luminosity Runs



Collider "Luminosity Run": Background Optimisation

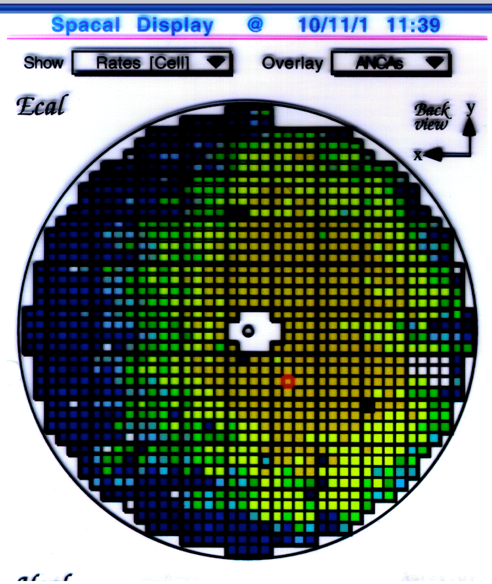


Example: HERA Lossrate

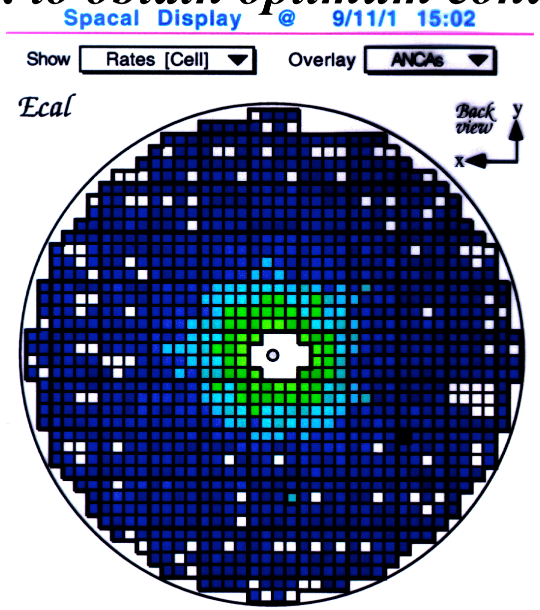
Optimise

Tune,
Orbit,
Chromaticity
Coupling,
Collision Point,
Crossing Angle,
Collimator Settings

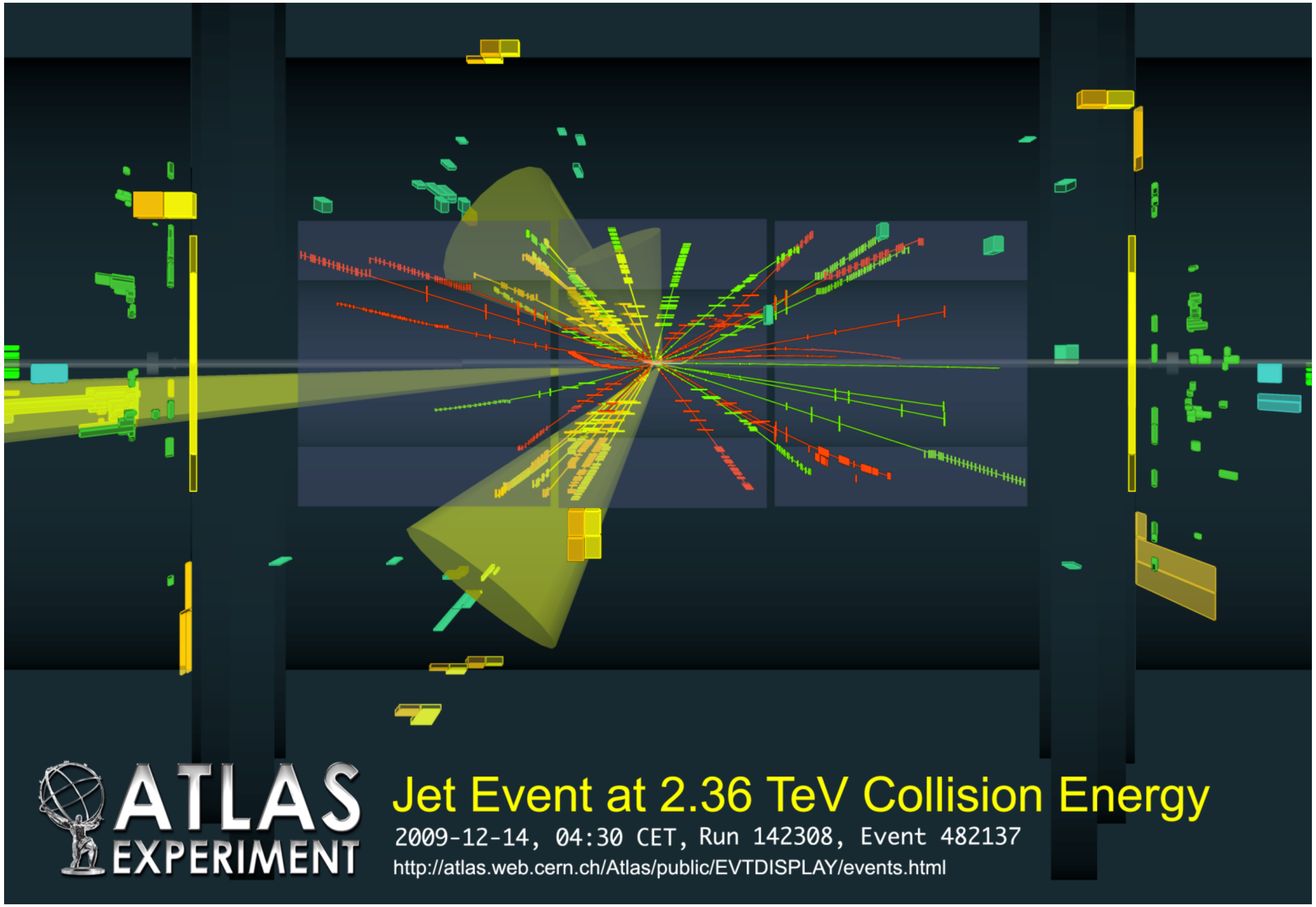
... to obtain optimum conditions



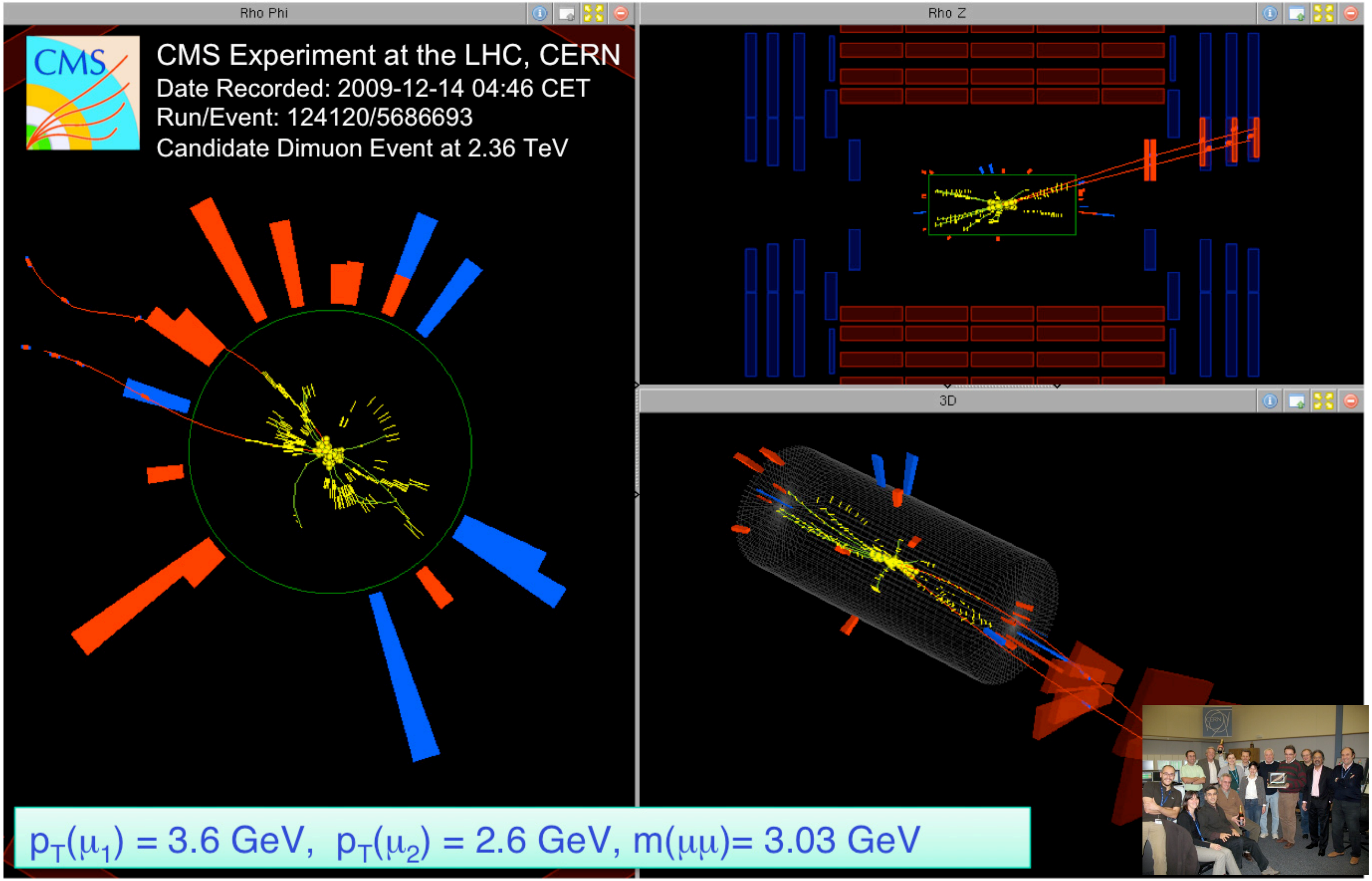
H1 Driftchamber Signals
before ... and ... after
Optimisation



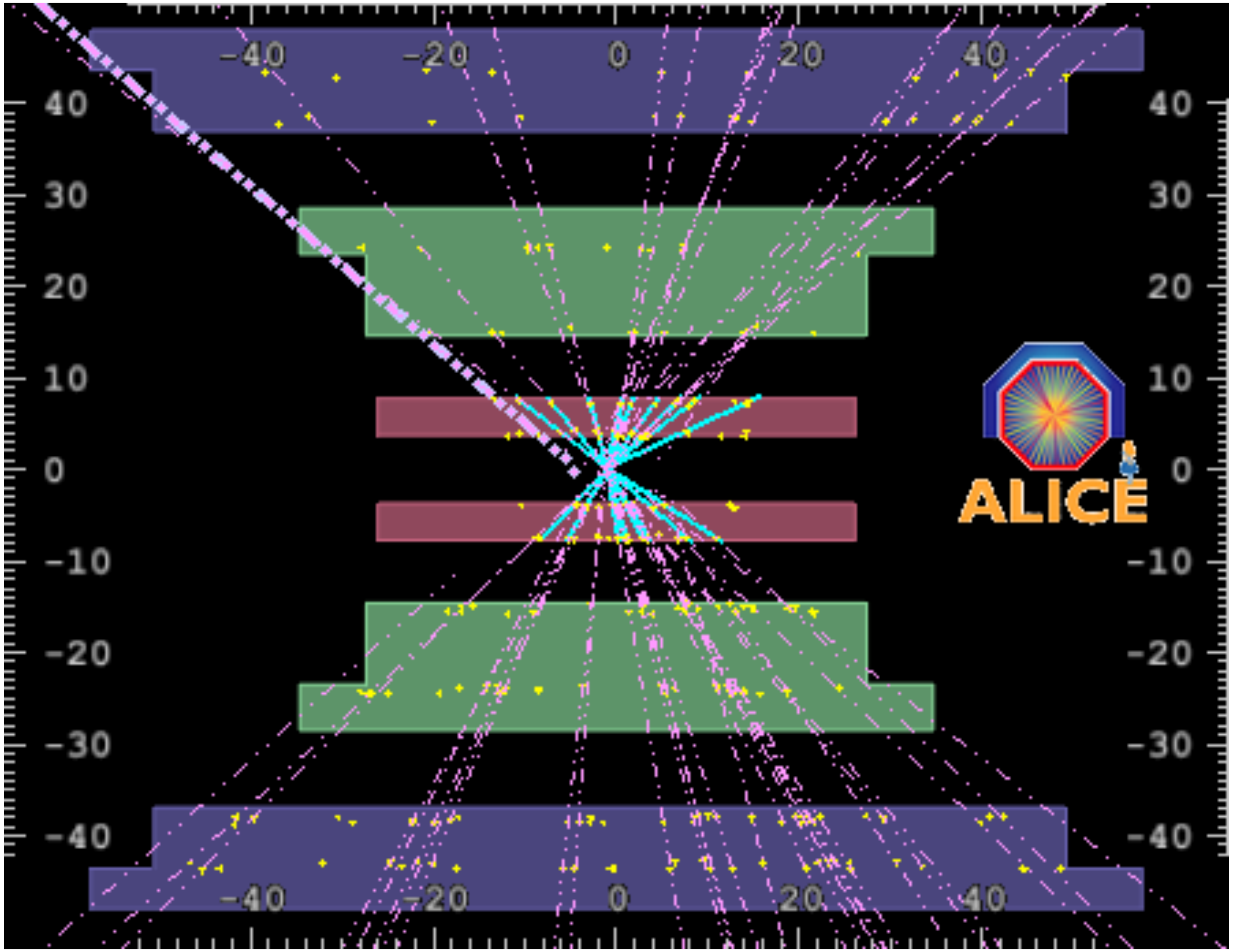
LHC Operation: the First Collisions at 2.36 TeV



LHC Operation: the First Collisions at 2.36 TeV



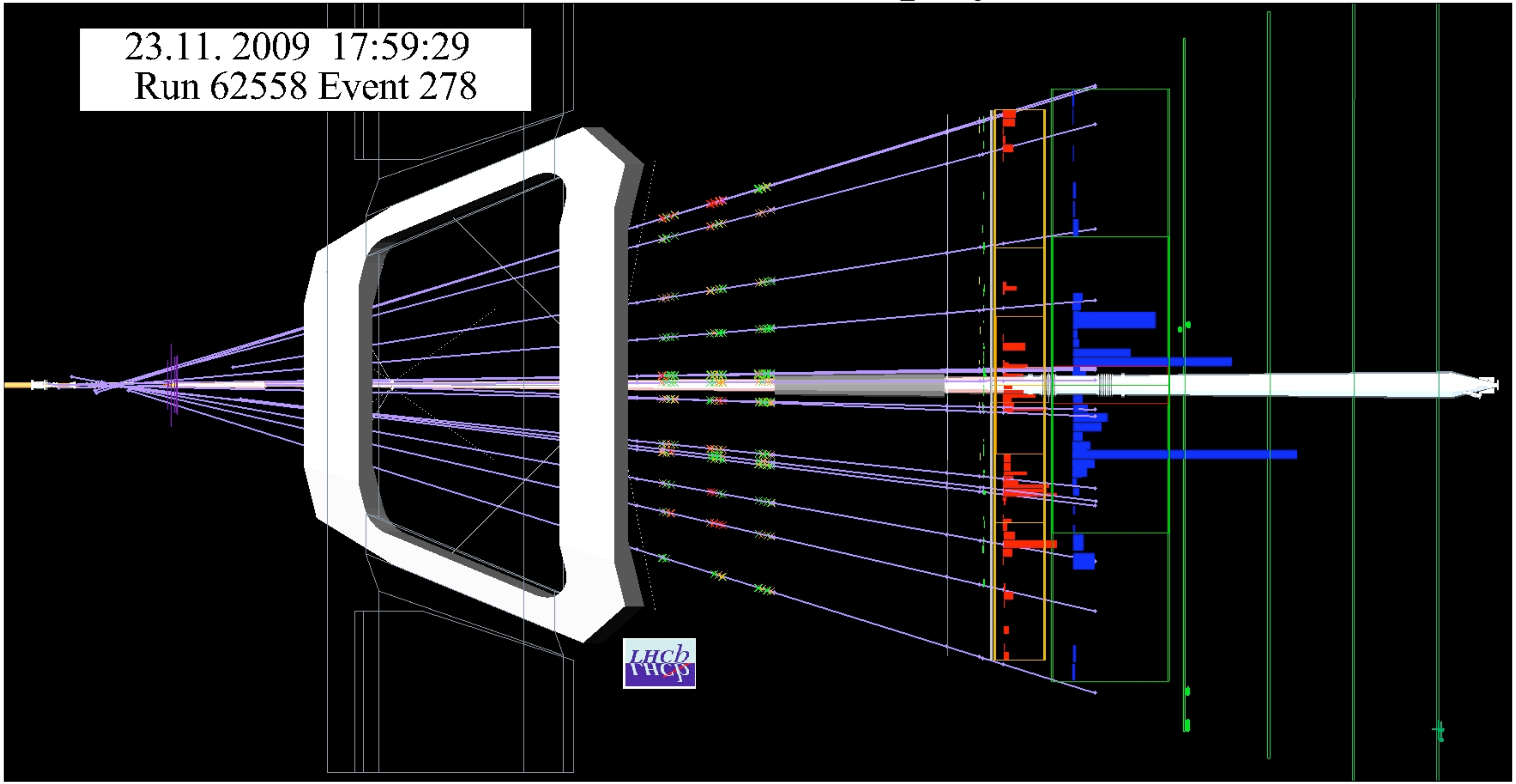
LHC Operation: the First Collisions at 900 GeV



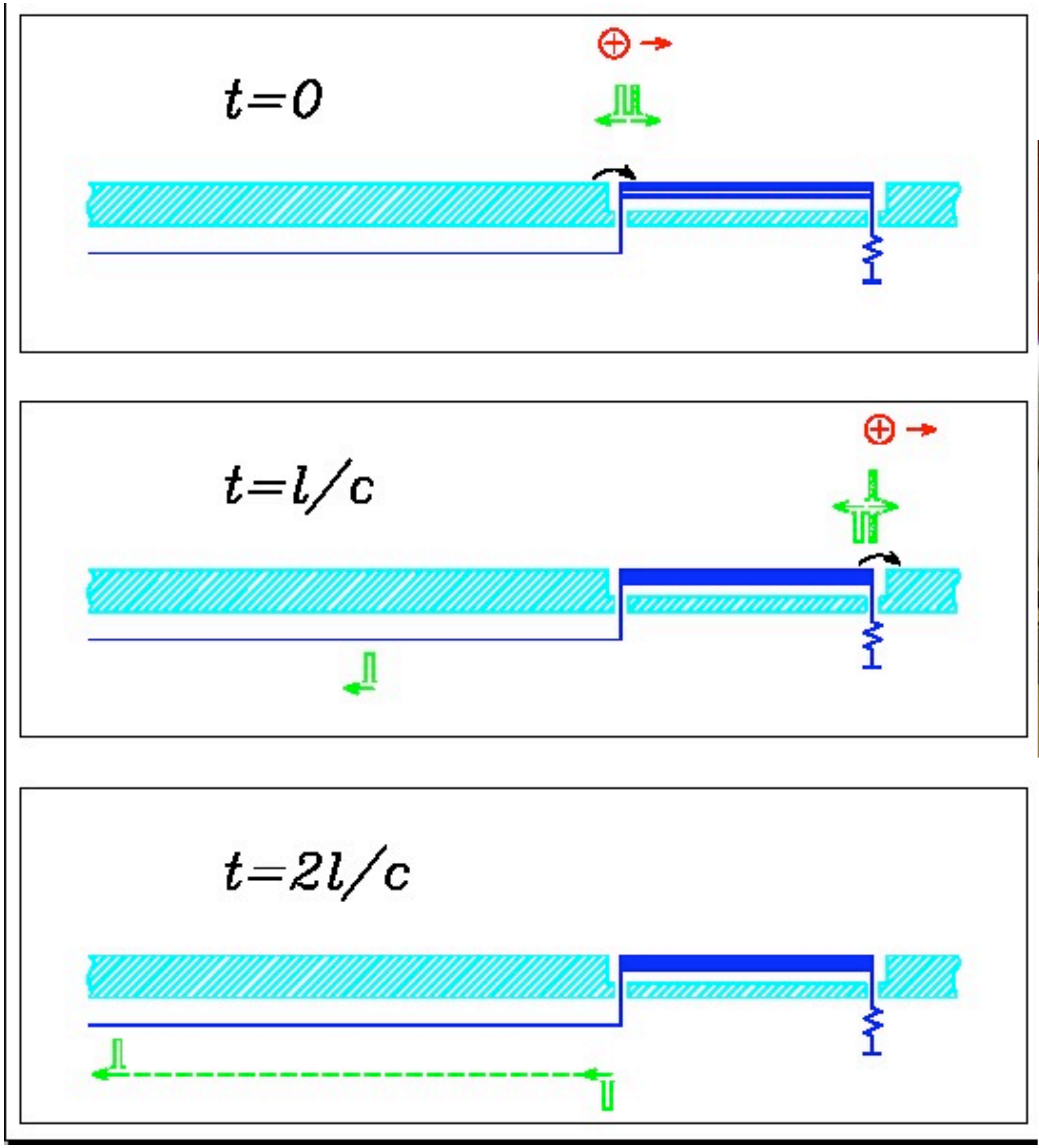
Monday 23, Nov

LHC Operation: the First Collisions at 900 GeV

LHCb Event Display



Monday 23, Nov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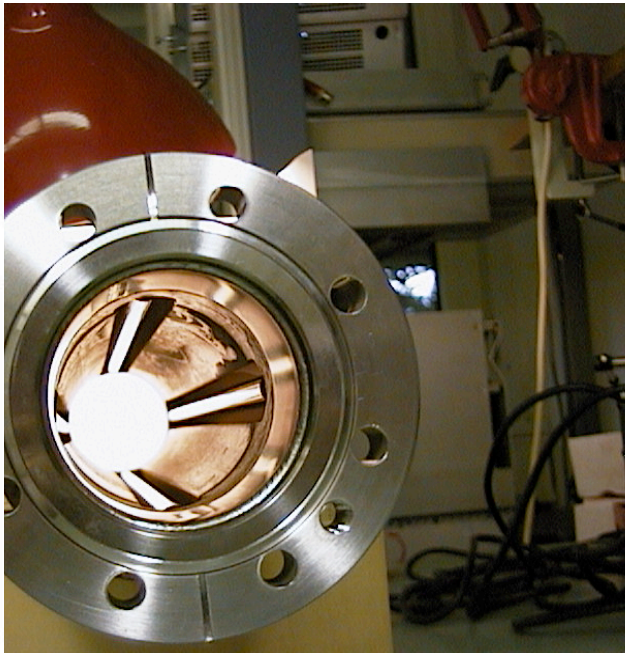
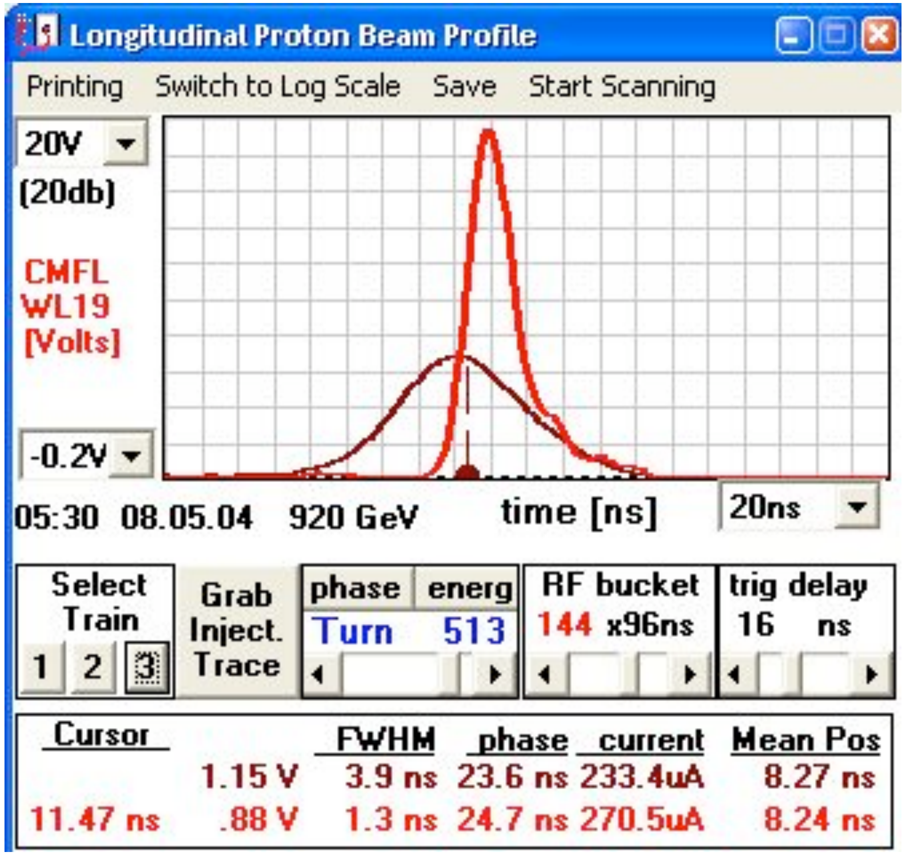
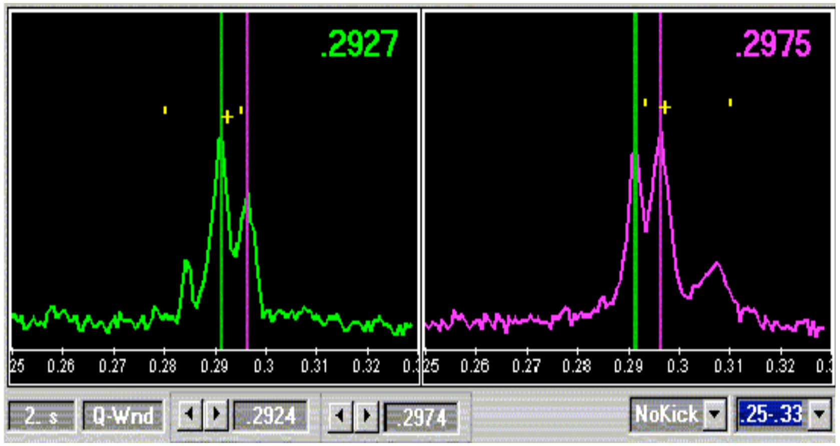
t=l/c
t=2l/c



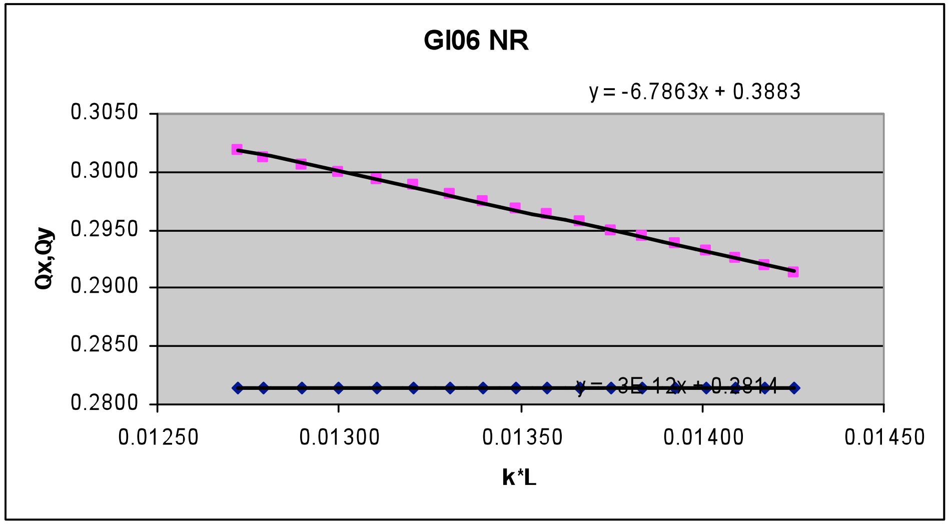

Longitudinal Proton Beam Profile
Printing
Switch to Log Scale
Save
Start Scanning
20V
(20db)
CMFL
WL19
[Volts]
-0.2V
05:30 08.05.04 920 GeV
time [ns]
20ns
Select Train
1 2 3
Grab Inject. Trace
phase energ
Turn 513
RF bucket
144 x96ns
trig delay
16 ns
Cursor
FWHM
phase
current
Mean Pos
1.15 V 3.9 ns 23.6 ns 233.4uA 8.27 ns
11.47 ns .88 V 1.3 ns 24.7 ns 270.5uA 8.24 ns

Example: deliberate change of quadrupole strength in a synchrotron:

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



tune spectrum ...

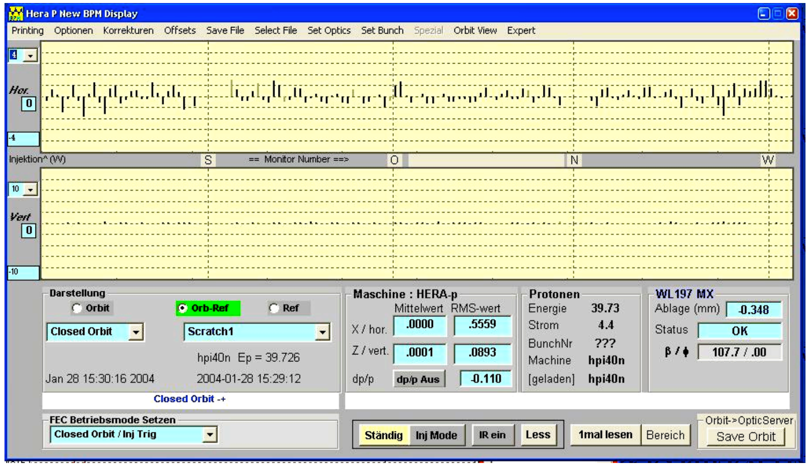


tune shift as a function of a gadient change

... for heaven's sake:

why do we get three peaks ????

Dispersion is visible



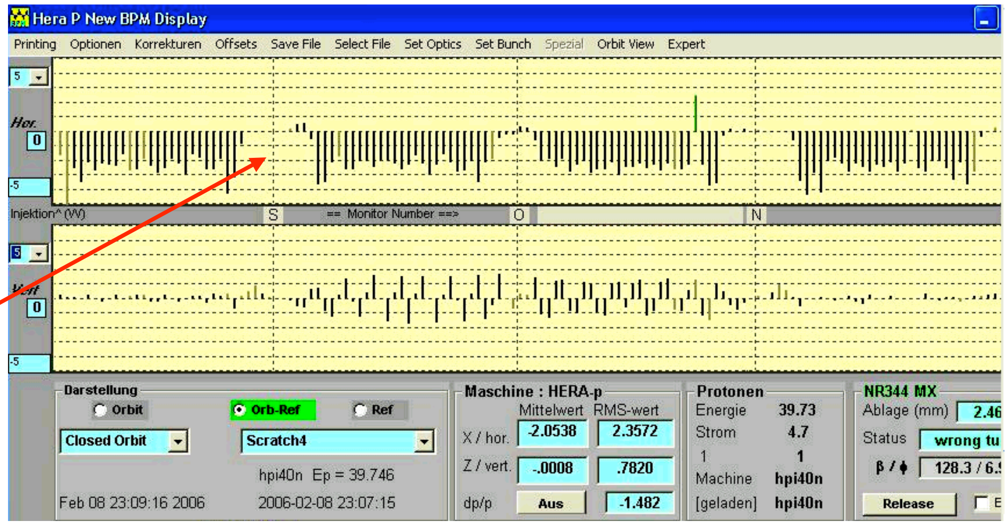
HERA Standard Orbit

HERA Dispersion Orbit

dedicated energy change of the stored beam

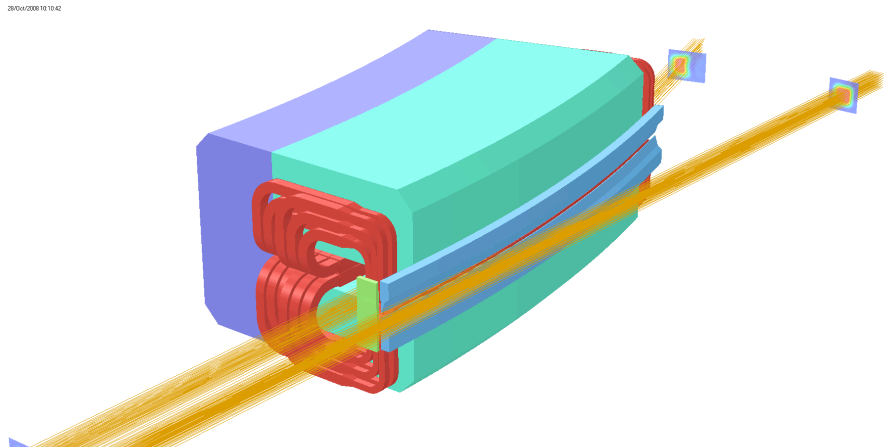
→ closed orbit is moved to a dispersions trajectory

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



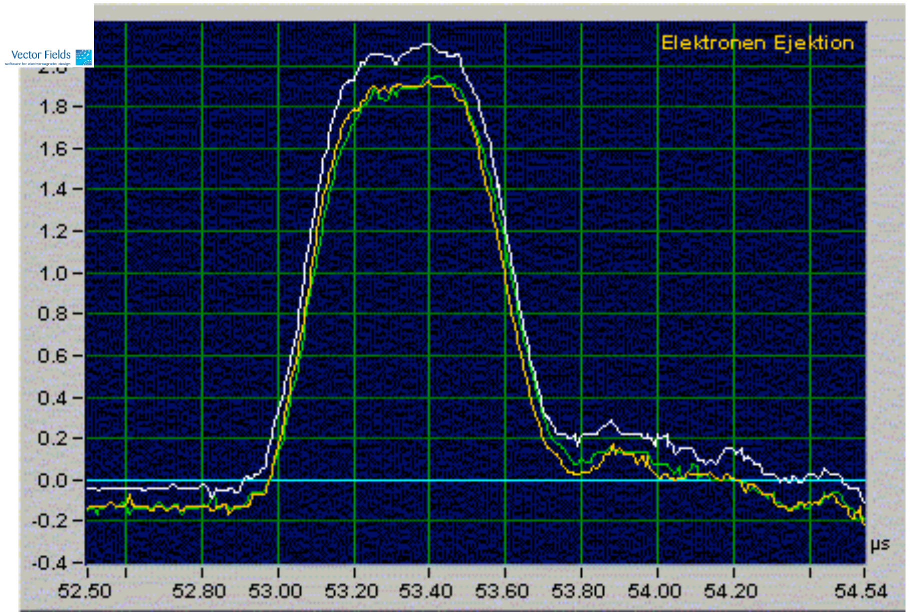
Attention: at the Interaction Points we require D=D′= 0

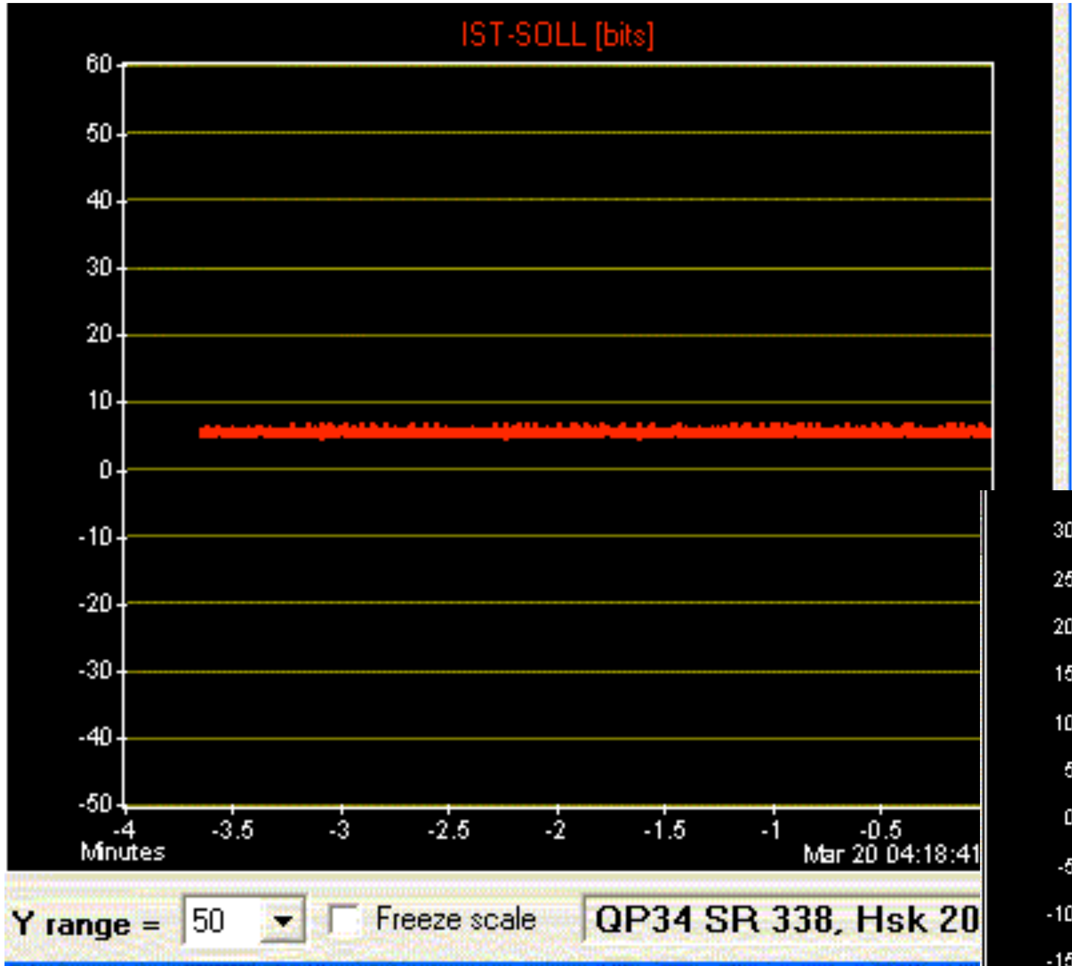
Injection: Elements
fast high precision magnets



Examples: Magnetic Septum

Kickerpulse for
Electron Injection

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-3
-2.5
-2
-1.5
-1
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Minutes
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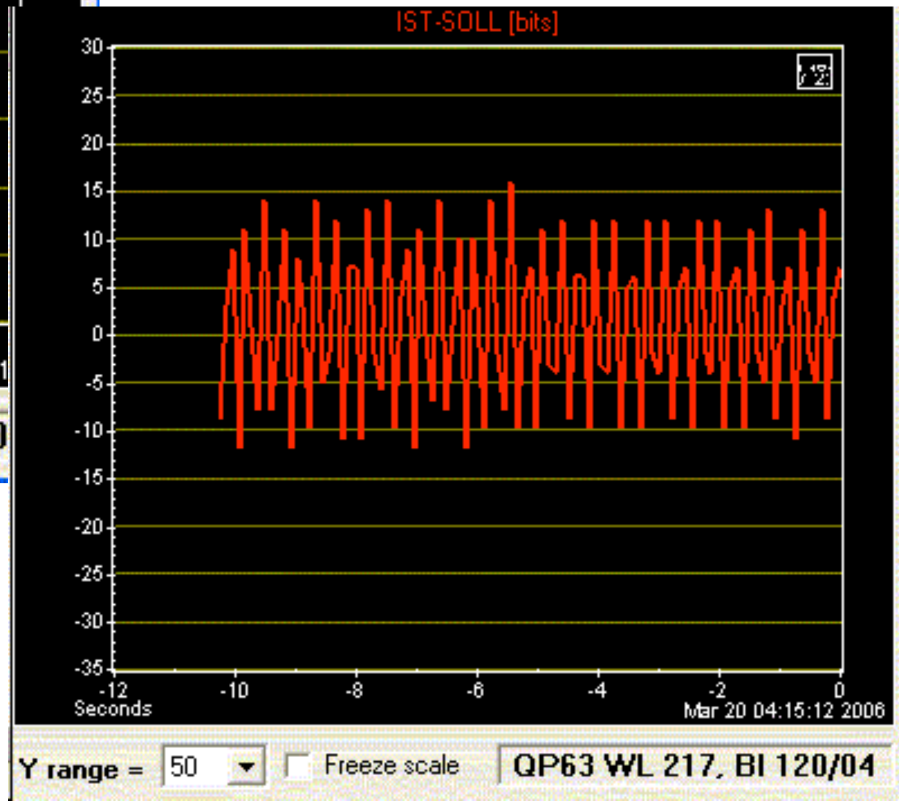
Y range =
50
Freeze scale
QP34 SR 338, Hsk 20


IST-SOLL [bits]
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25
20
15
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-12
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-4
-2
0
Seconds
Mar 20 04:15:12 2006
Y range =
50
Freeze scale
QP63 WL 217, Bl 120/04