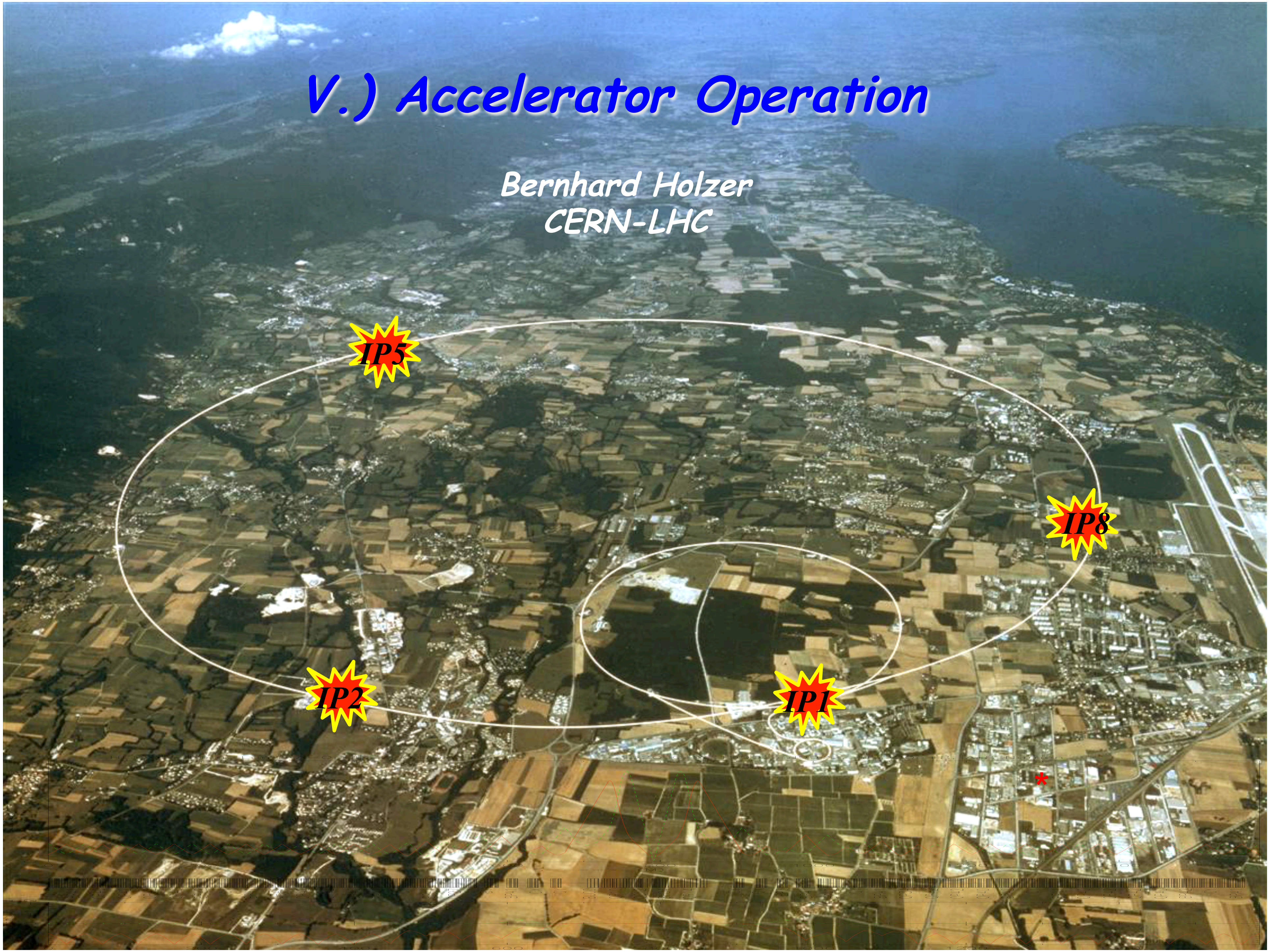
# V.) Accelerator Operation

Bernhard Holzer
CERN-LHC



***1.) How do we operate such sa huge machine ?***

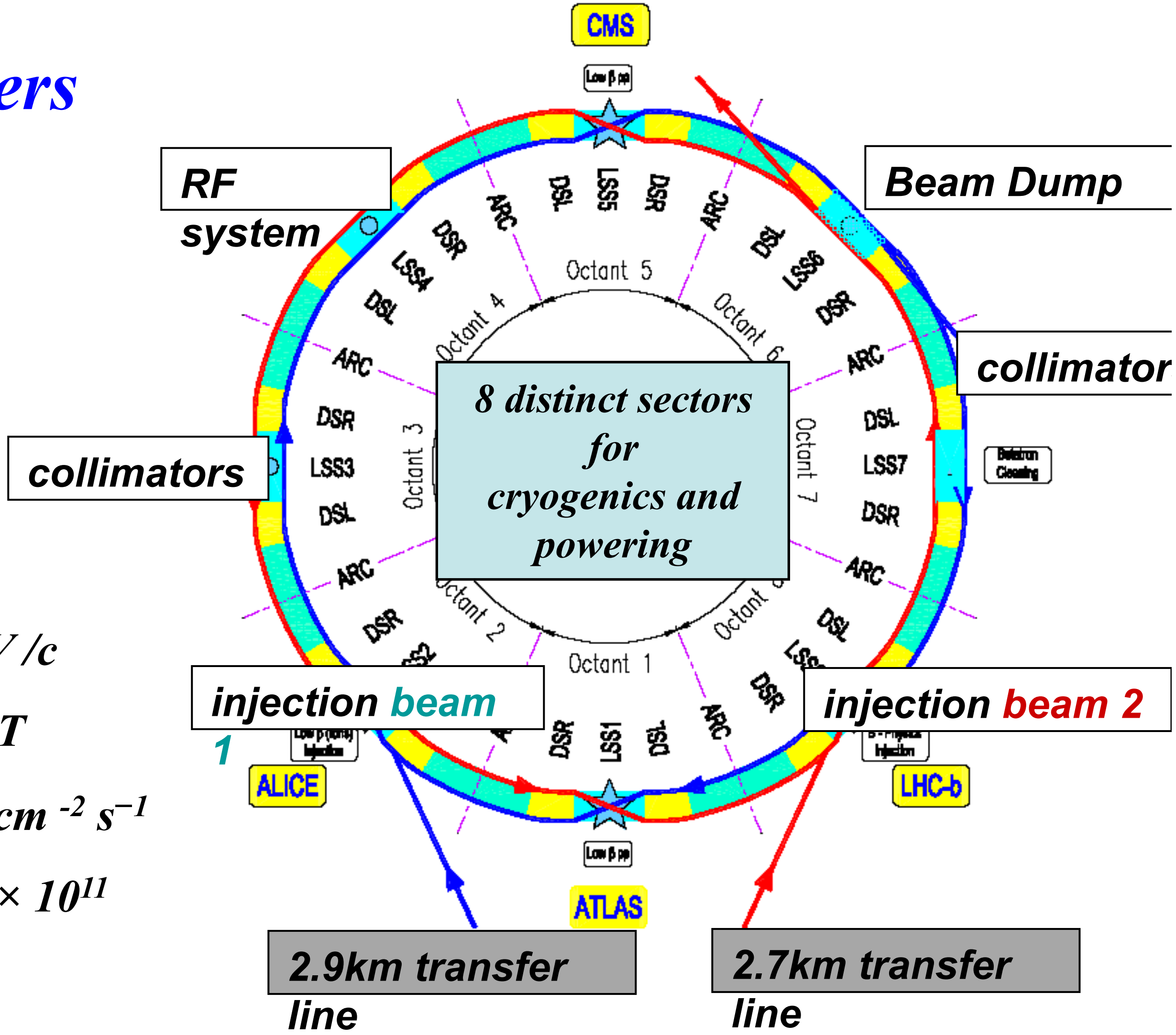
***Injection***

***Acceleration***

***Collision***

***Safety***

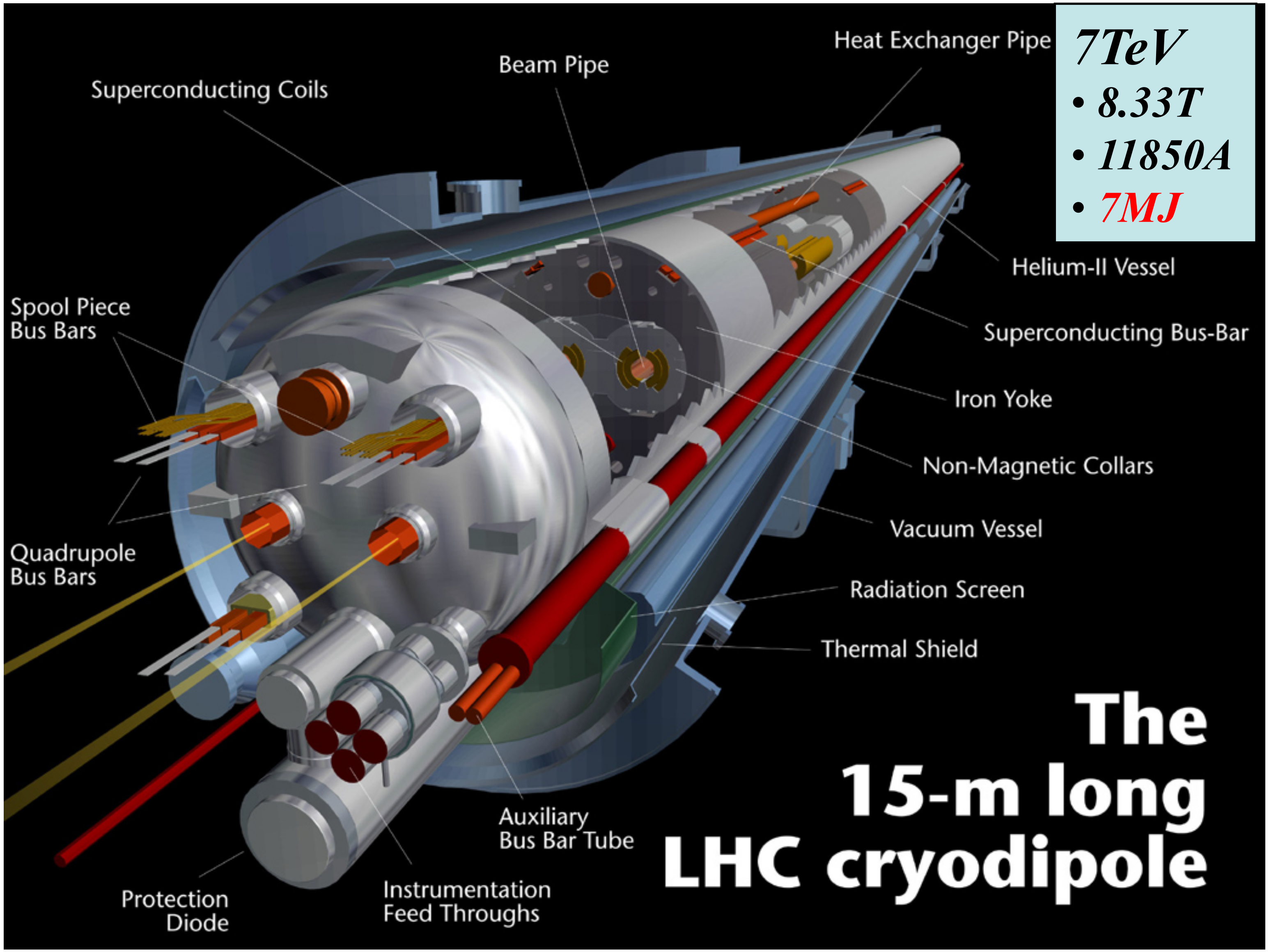
# *LHC Main Parameters*




| | |
|---|---|
| *Momentum at collision* | *7 TeV /c* |
| *Dipole field for 7 TeV* | *8.33 T* |
| *Luminosity* | $10^{34}$ *cm* $^{-2}$ *s* $^{-1}$ |
| *Protons per bunch* | $1.15 \times 10^{11}$ |
| *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* |

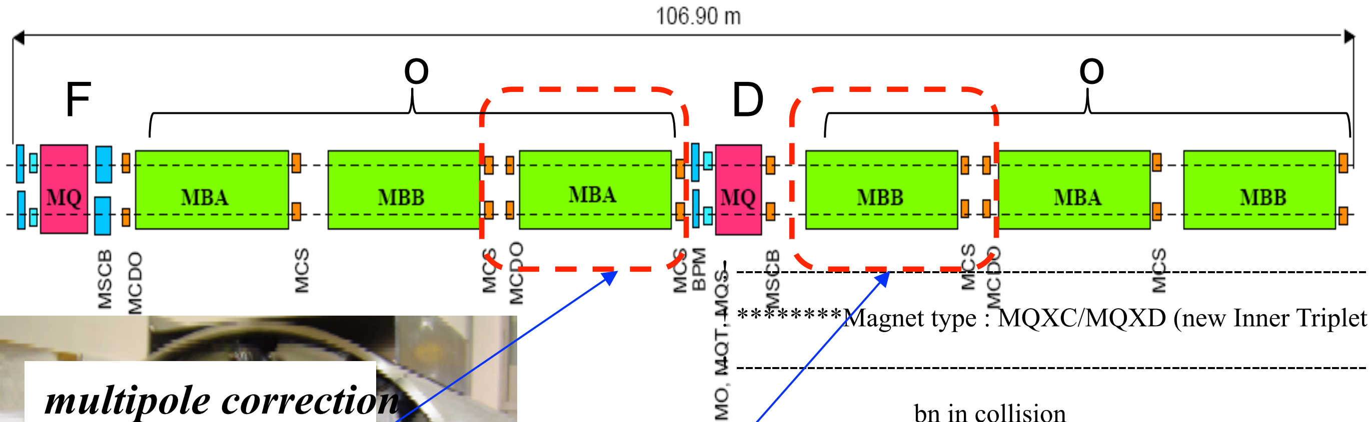
# *LHC dipoles (1232 of them)*

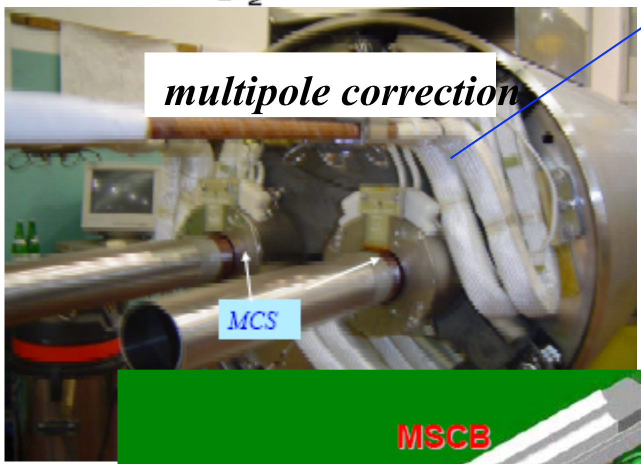
*7TeV*
- *8.33T*
- *11850A*
- *7MJ*



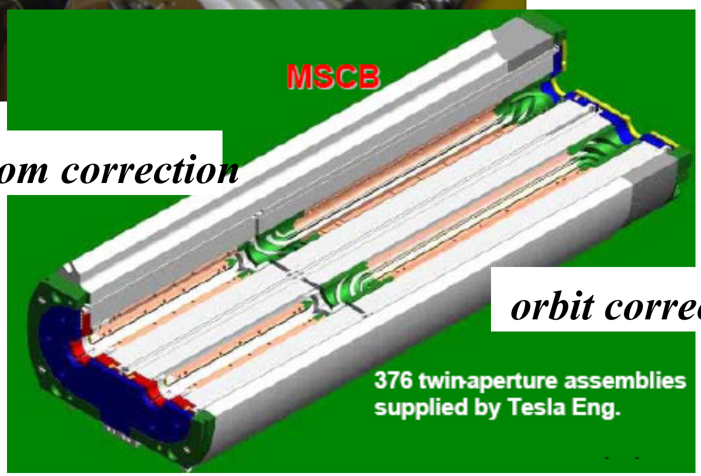
# LHC: Basic Layout of the Machine
# multipole corrector magnets

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




***multipole correction***




***chrom correction***

***orbit correction***

---------------------------------------------------------------------------

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

---------------------------------------------------------------------------

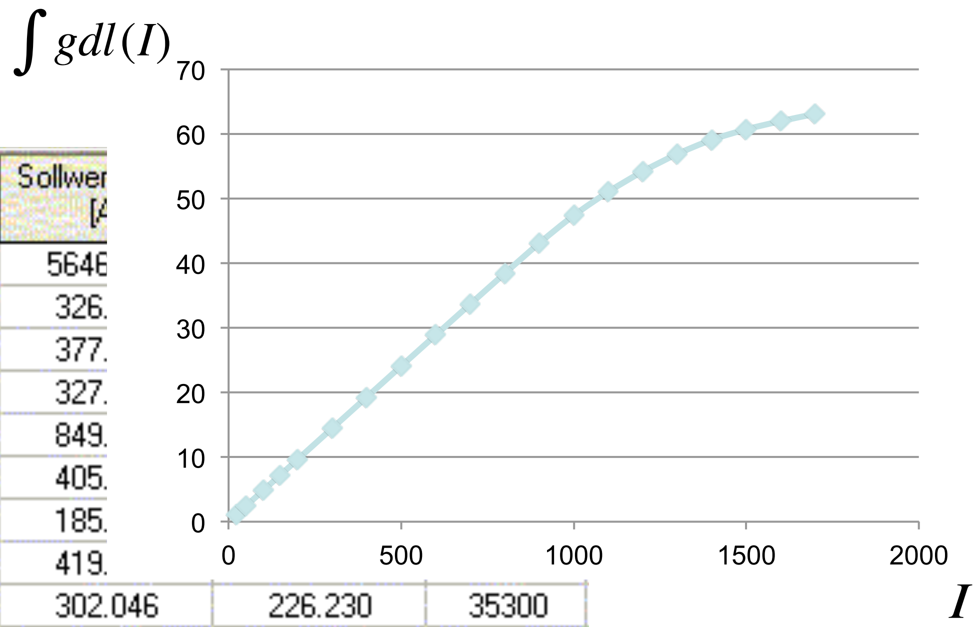
bn in collision

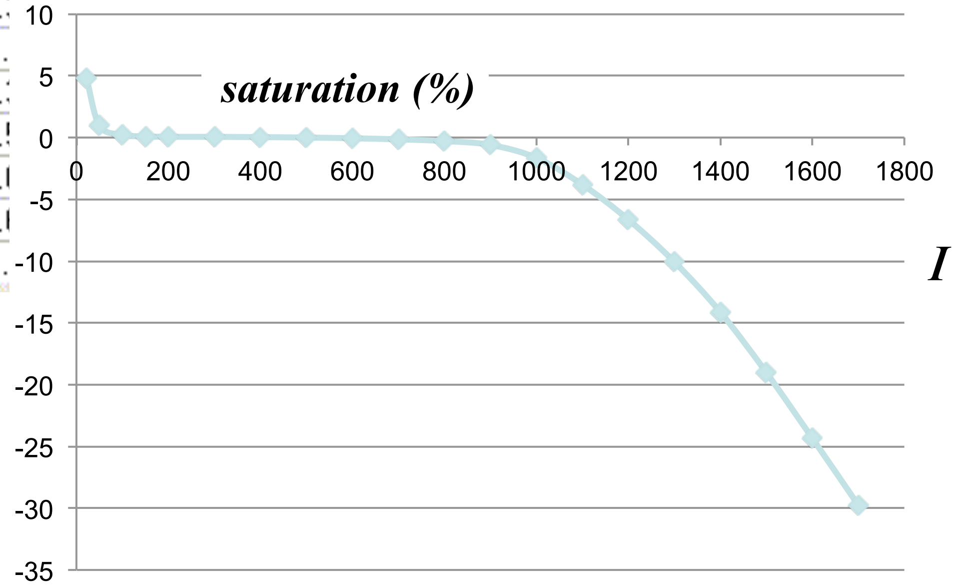
b1M_MQXCD_col := 0.0000 ; b1U_MQXCD_col := 0.0000 ; b1R_MQXCD_col := 0.0000 ;
b2M_MQXCD_col := 0.0000 ; b2U_MQXCD_col := 0.0000 ; b2R_MQXCD_col := 0.0000 ;
b3M_MQXCD_col := 0.0000 ; b3U_MQXCD_col := 0.4600 ; b3R_MQXCD_col := 0.8900 ;
b4M_MQXCD_col := 0.0000 ; b4U_MQXCD_col := 0.6400 ; b4R_MQXCD_col := 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 := 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 := 0.0000 ; 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***

# 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. | | |

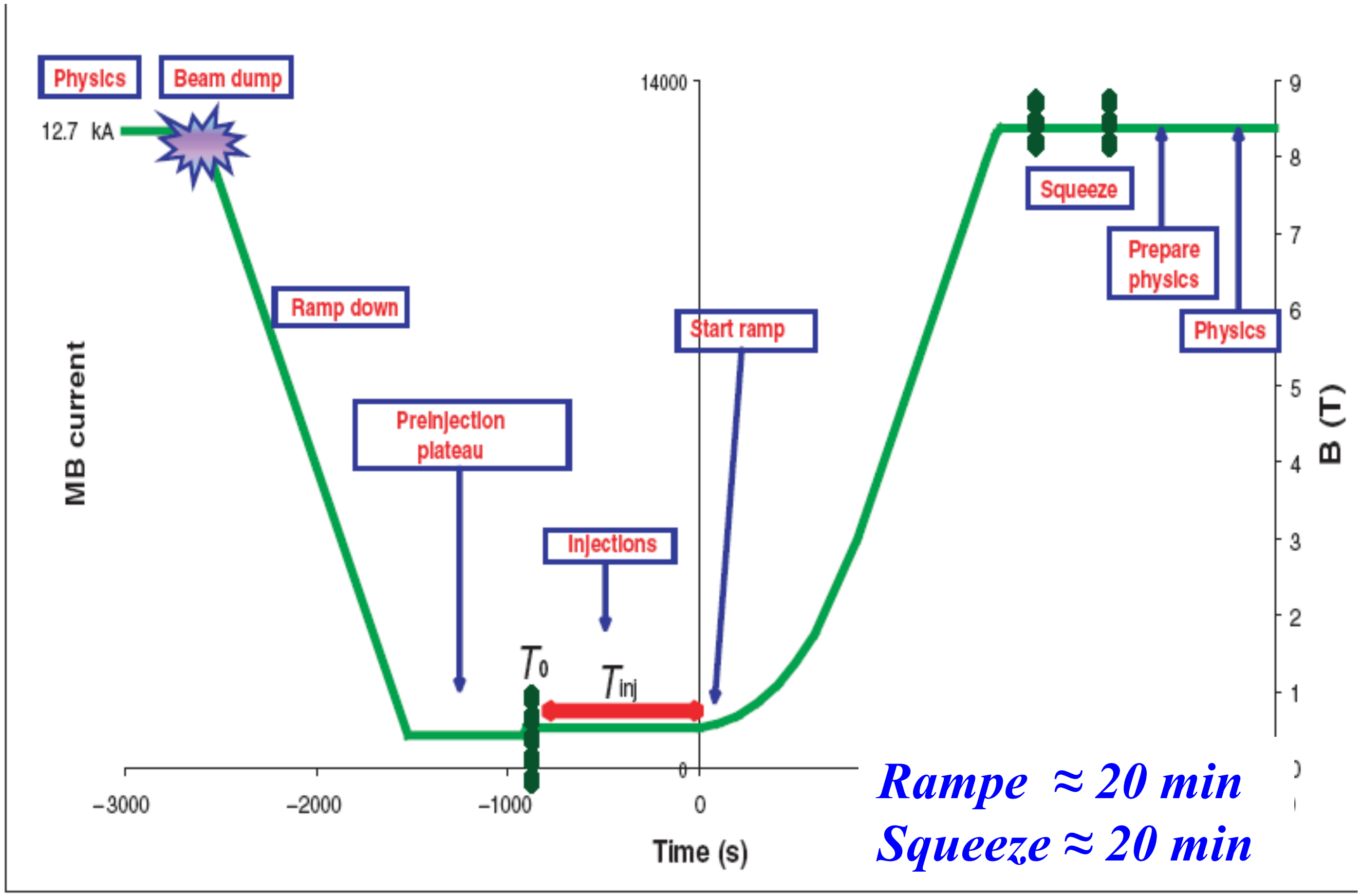


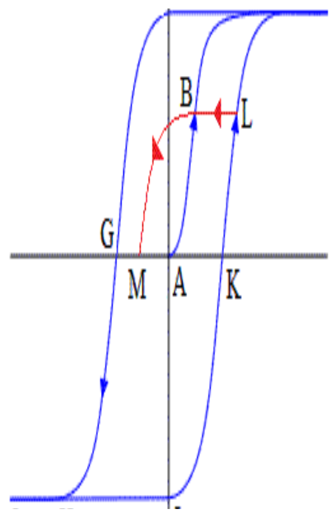

***remember: $\Delta B/B \approx 10^{-4}$***

# *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*

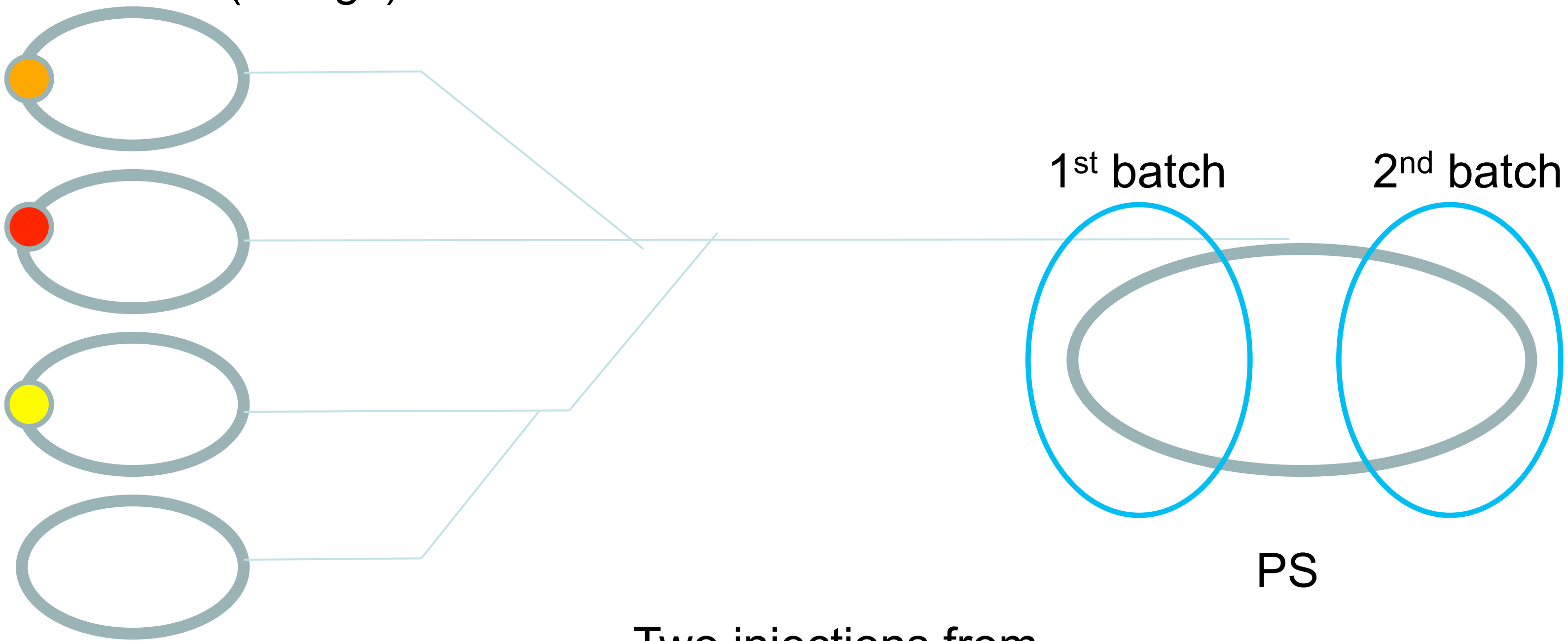



*magnet hysteresis*

# *LHC 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

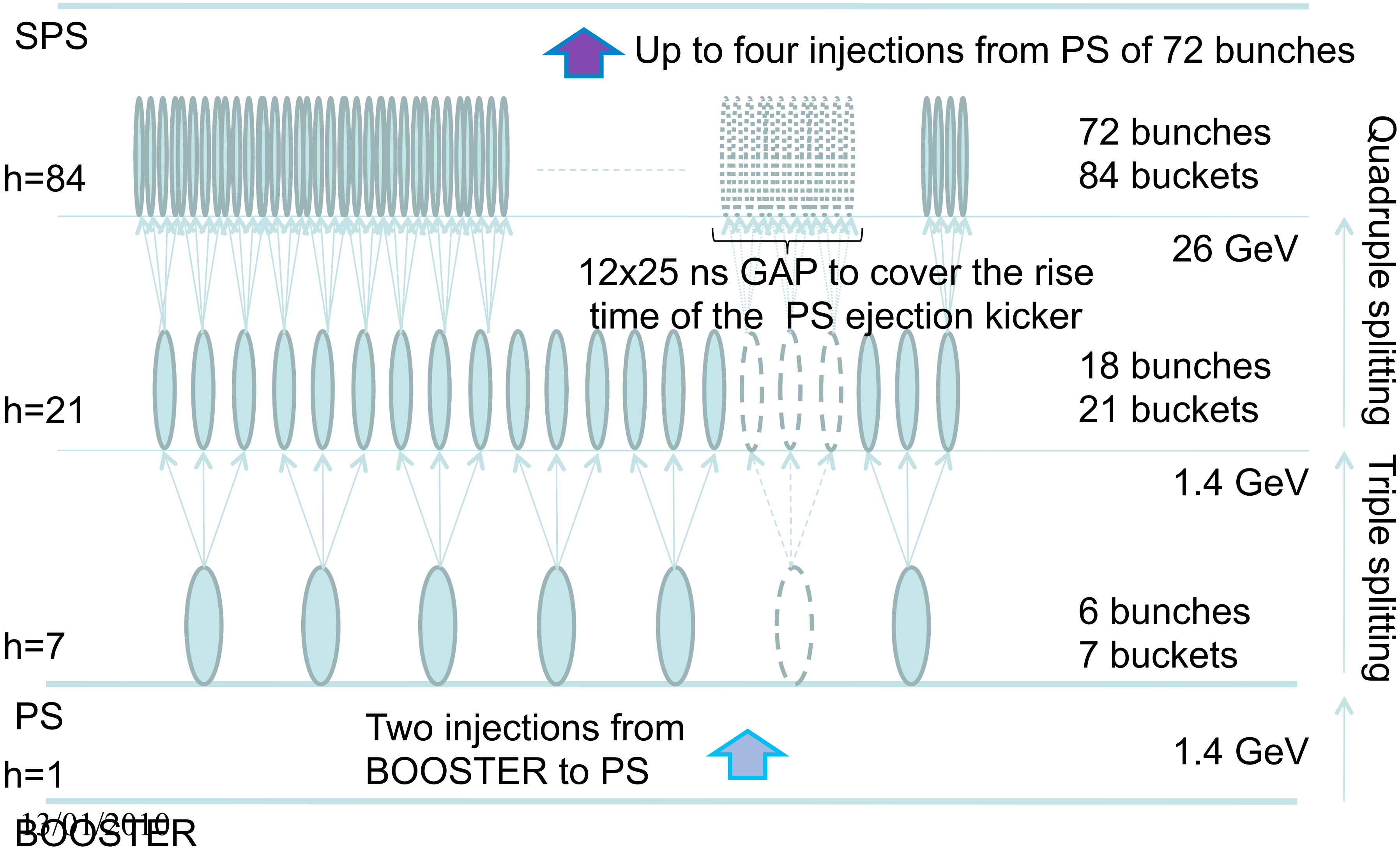
h=1

h=7 (6 buckets filled + 1 empty)



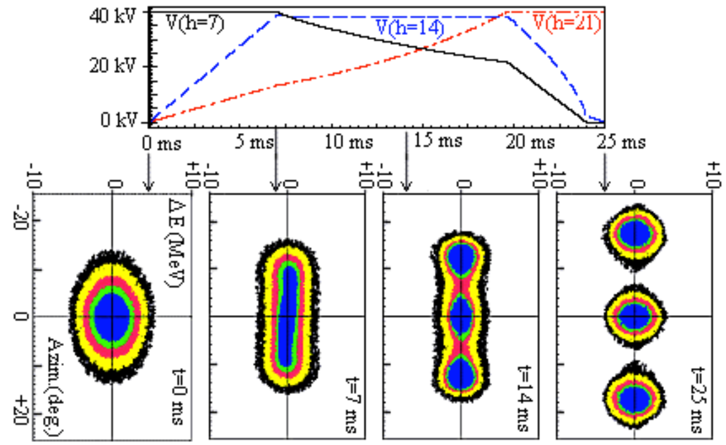
*court. R. Alemany*

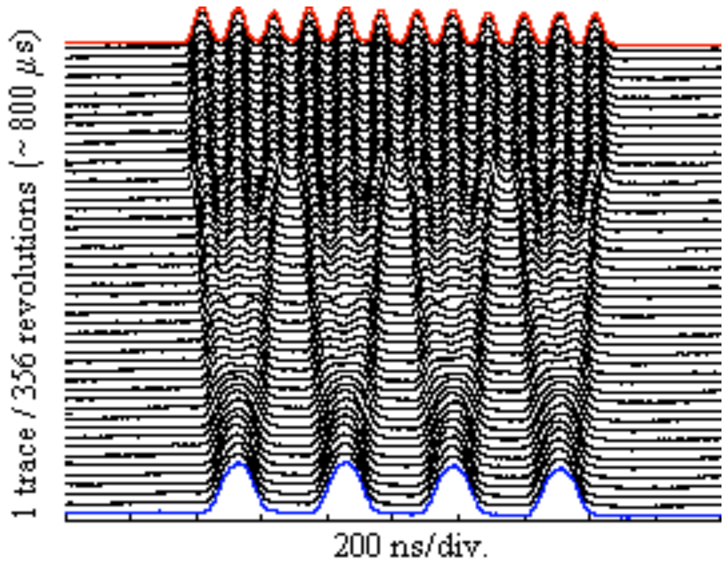
# *LHC Injection: Preparing the Bunch Trains*



# Beam Injection

***Bunch Splitting in the PS***



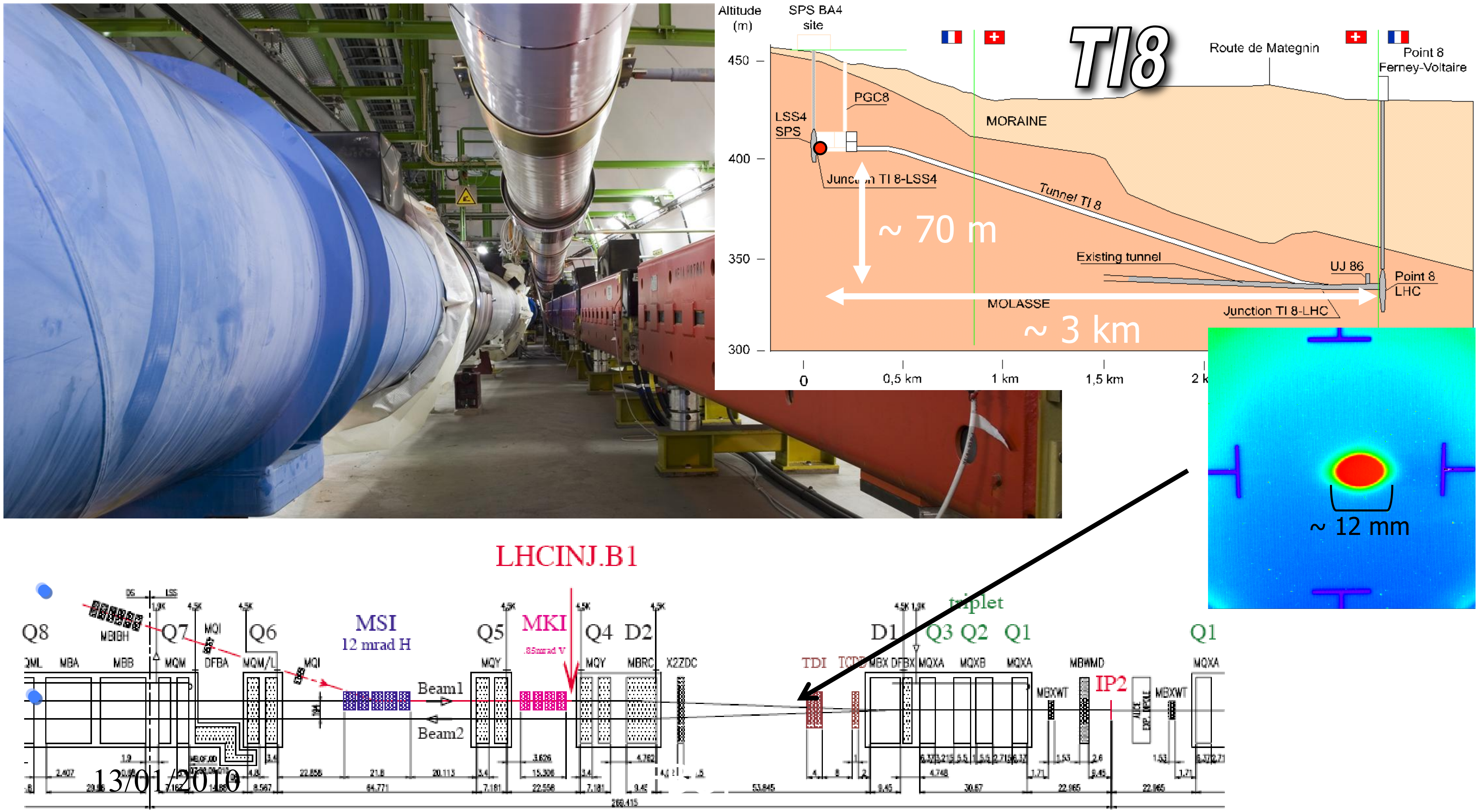

***CERN: Linac 2 injection into PSB***

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

***$\beta = 0.31$***

***$\gamma = 1.05$***

# *Injection mechanism: the transfer lines*





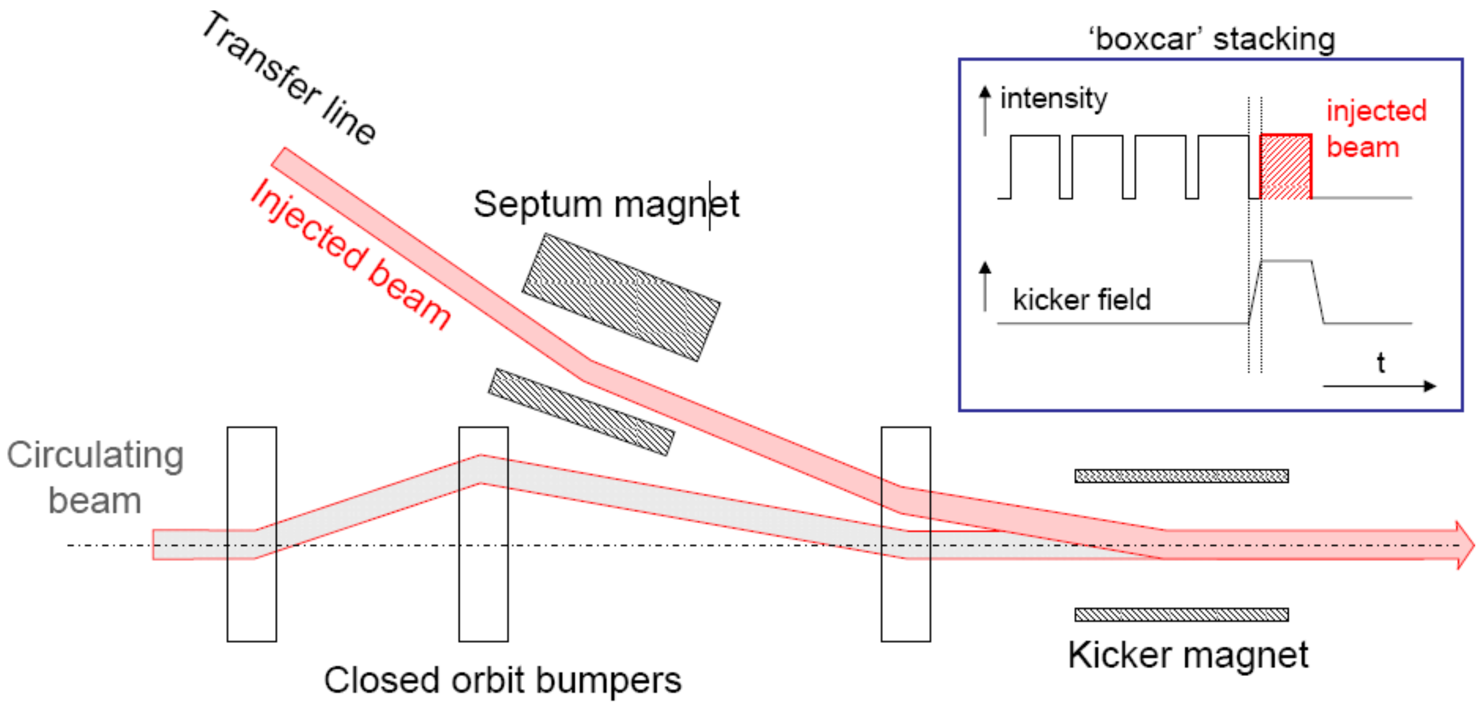

*court. R. Alemany*

# *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*

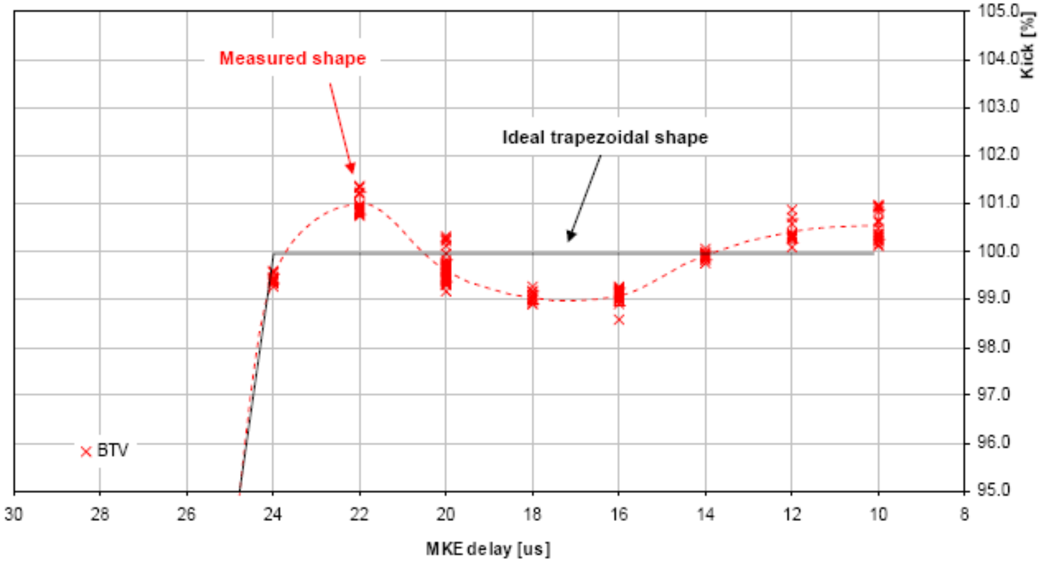
** quadrupole strengths --> "beta beat" $\Delta\beta / \beta$*
** alignment of magnets --> orbit distortion in transferline & storage ring*
** septum & kicker pulses --> orbit distortion & emittance dilution in storage ring*

***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***

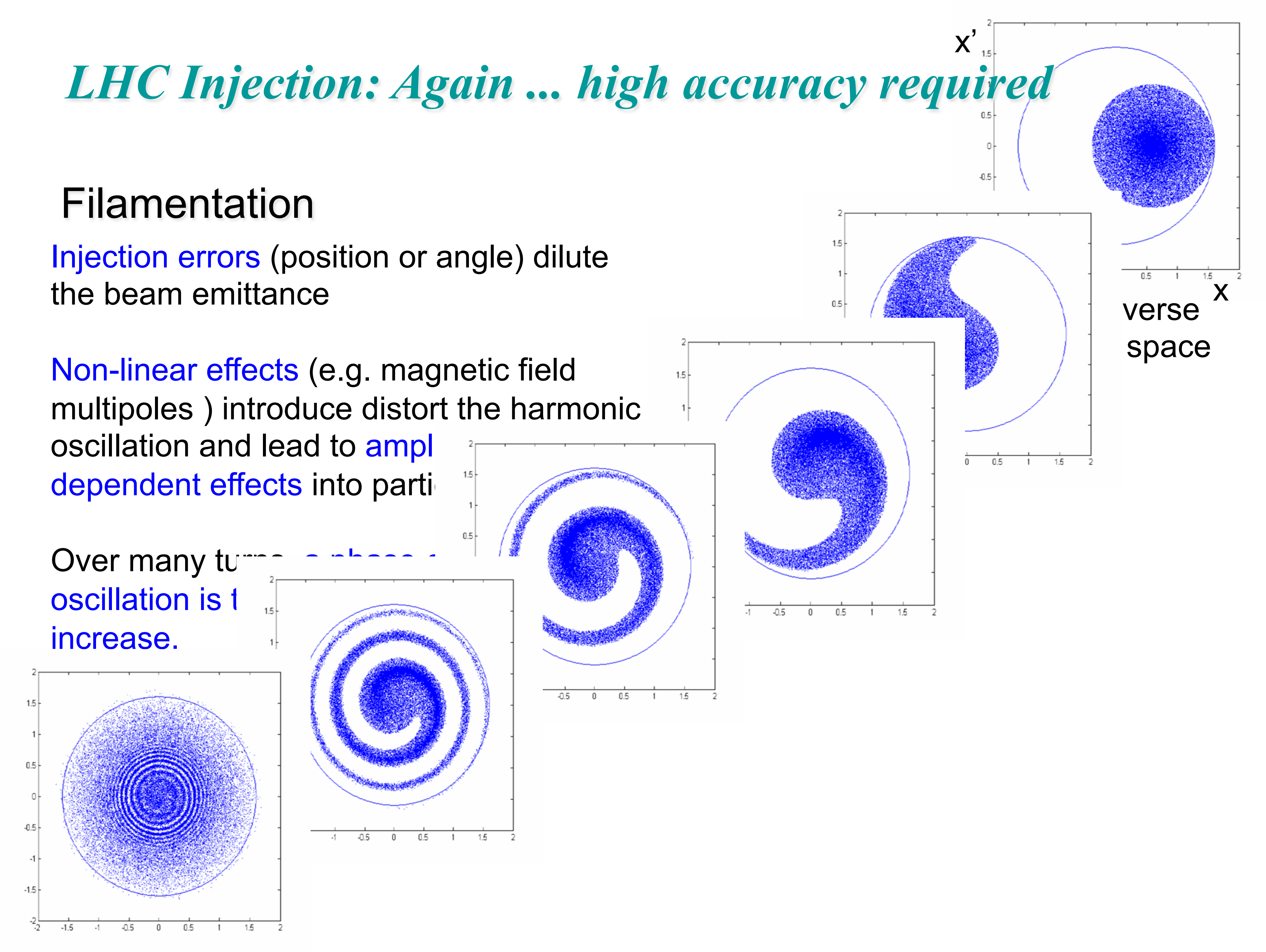
# *LHC Injection: Again ... high accuracy required*

## Filamentation

Injection errors (position or angle) dilute the beam emittance

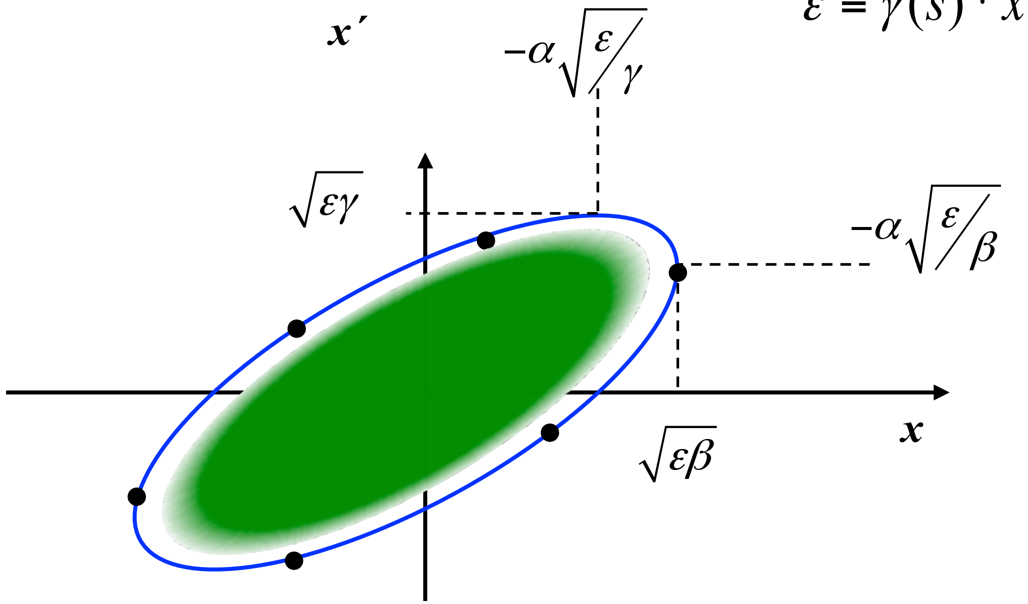
Non-linear effects (e.g. magnetic field multipoles ) introduce distort the harmonic oscillation and lead to ampl dependent effects into parti

Over many tu oscillation is t increase.

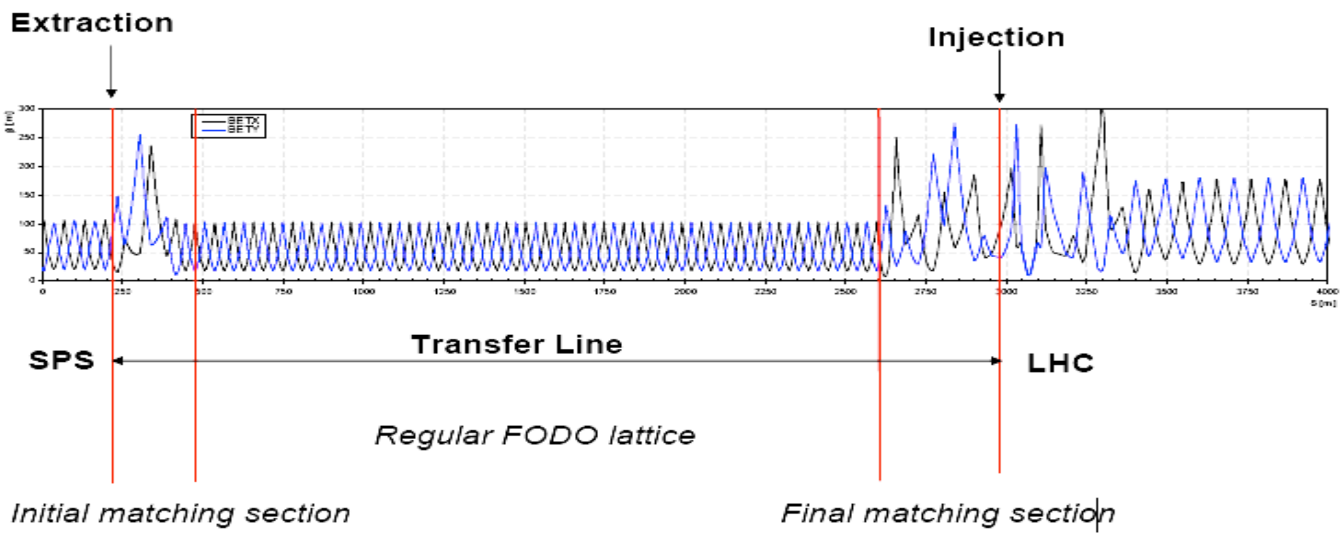


# LHC Injection: remember the phase space

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



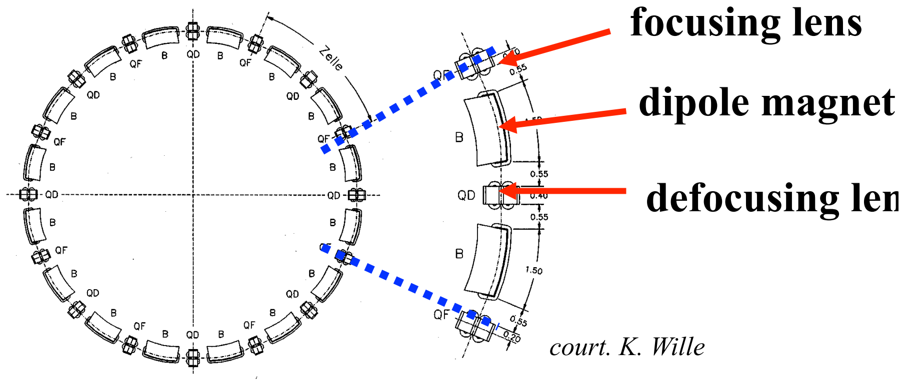

***Injected Beam has to be matched to the optics of the storage ring***



# LHC First Turn Steering

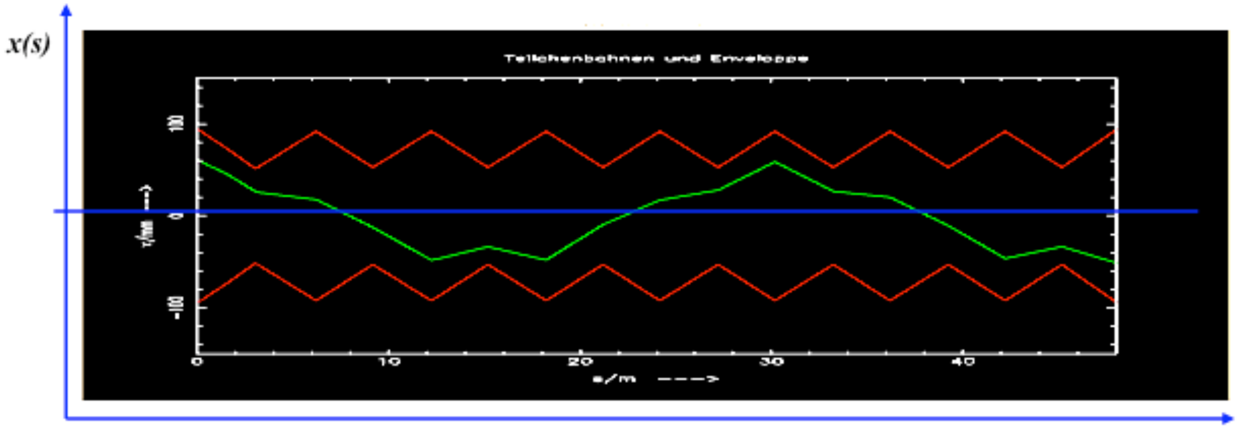
$$M_{total} = M_{QF} * M_D * M_{QD} * M_{Bend} * M_{D*.....}$$

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



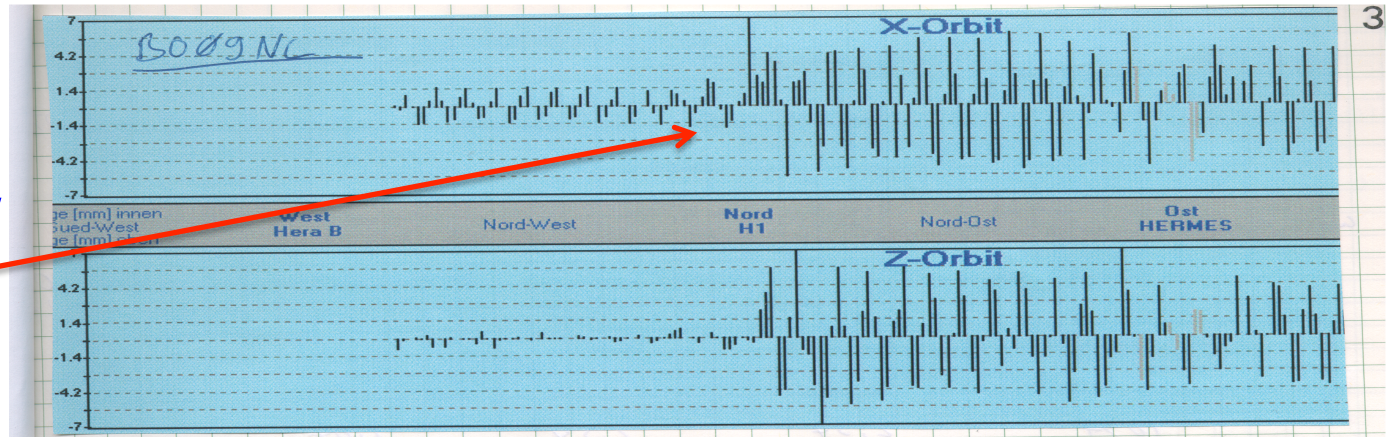

court. K. Wille

*in theory*
*nice harmonic oscillation*




*in reality:*
*effect of many localised orbit distortions*

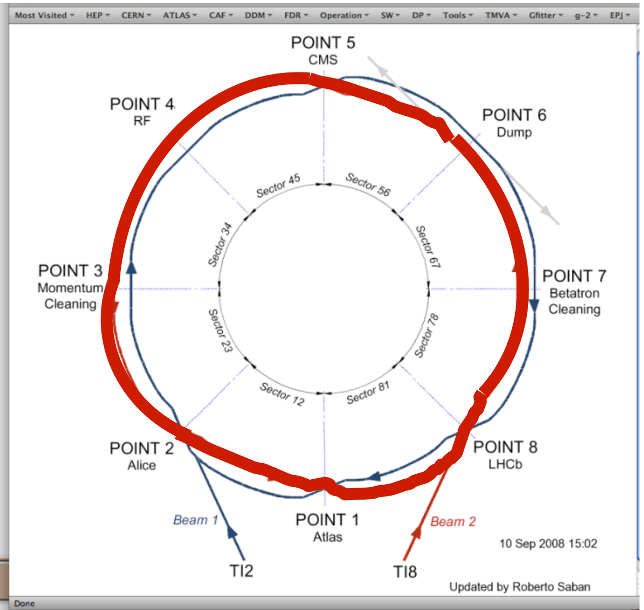
*-> correct*

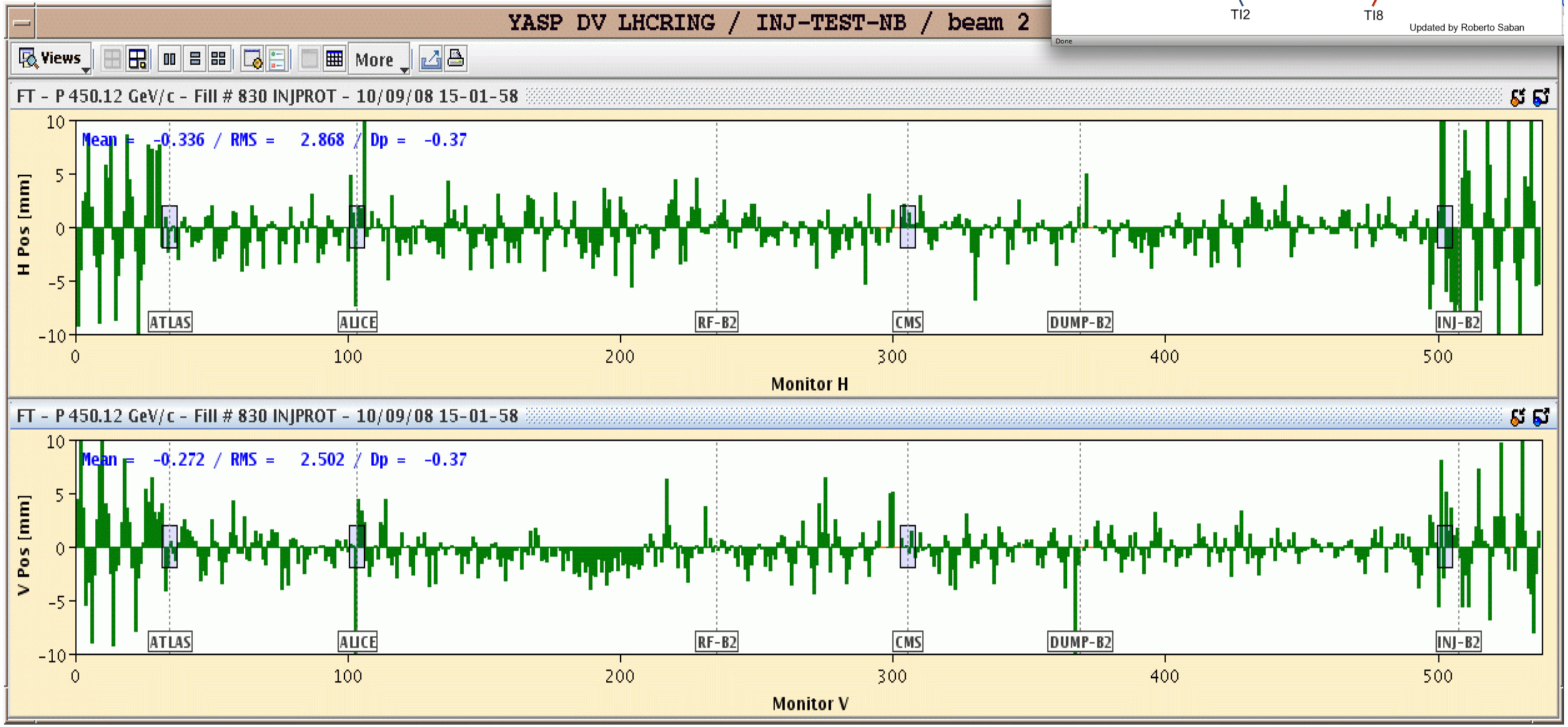


# *LHC Operation: Beam Commissioning*

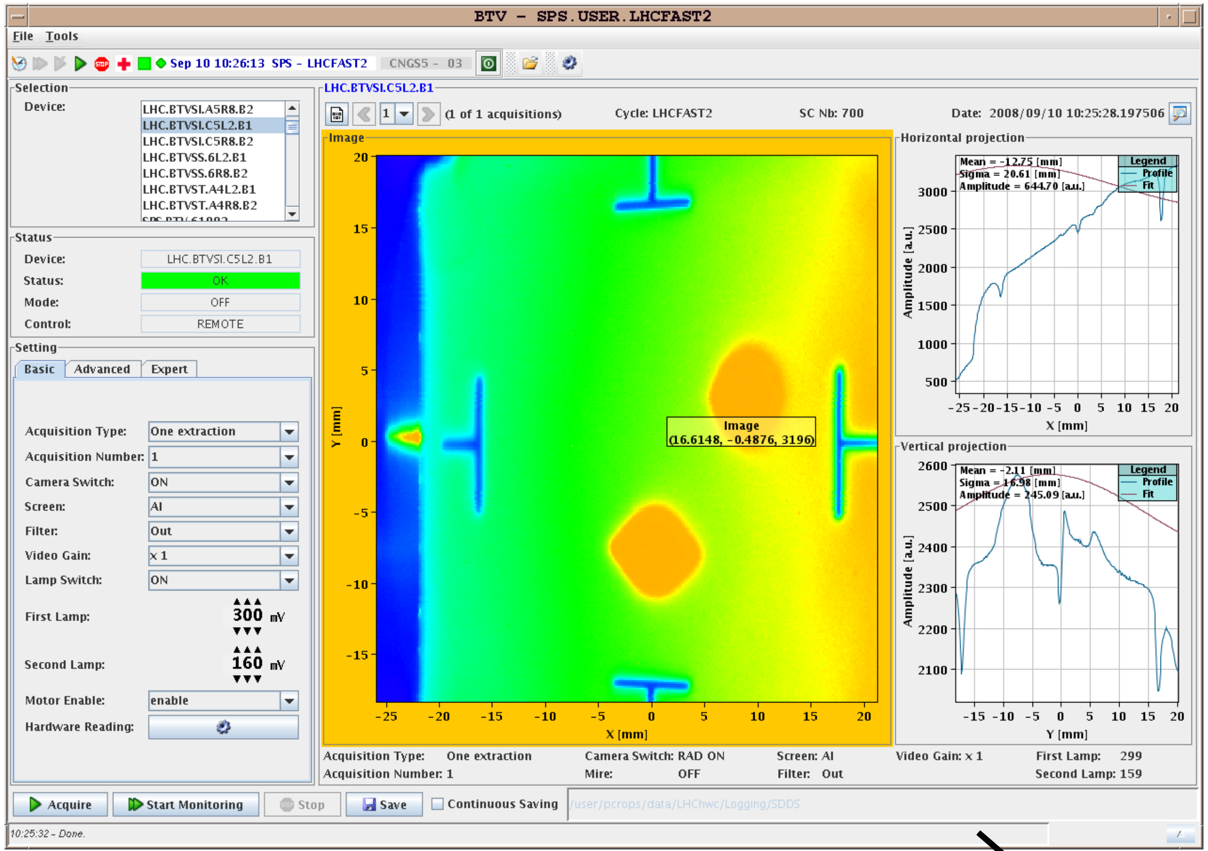
***First turn steering "by sector:"***

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



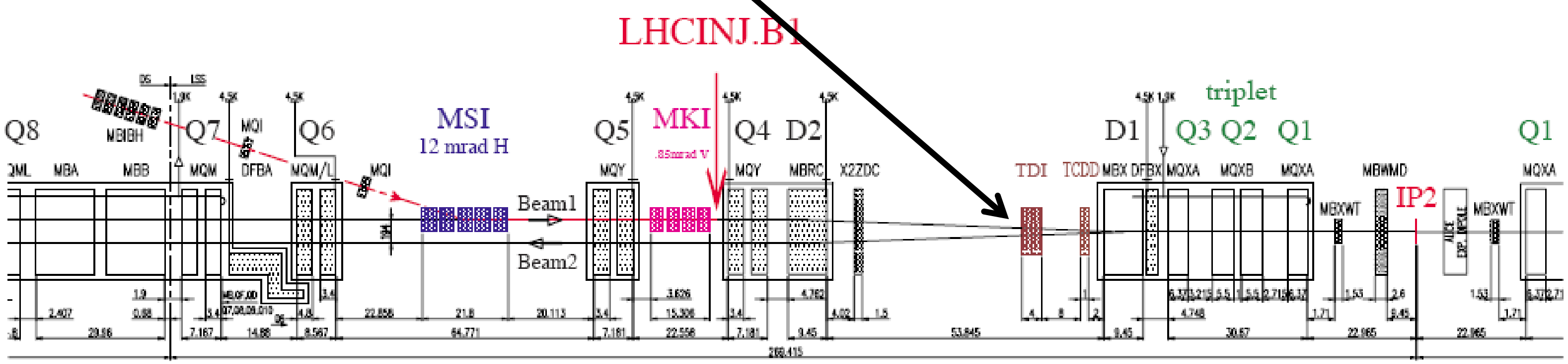



# LHC Operation: the First Turn

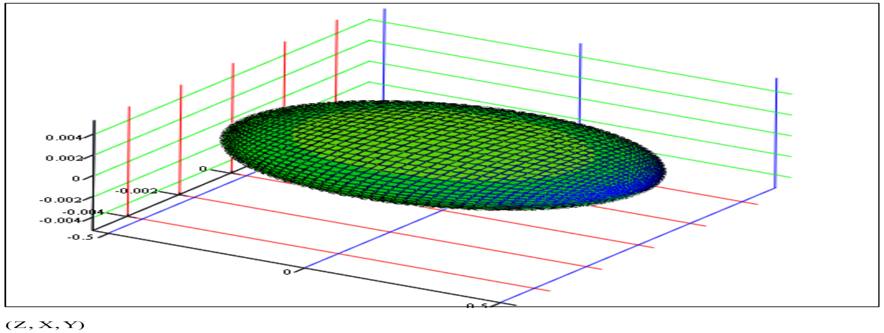



*Beam 1 on OTR screen*
*1st and 2nd turn*

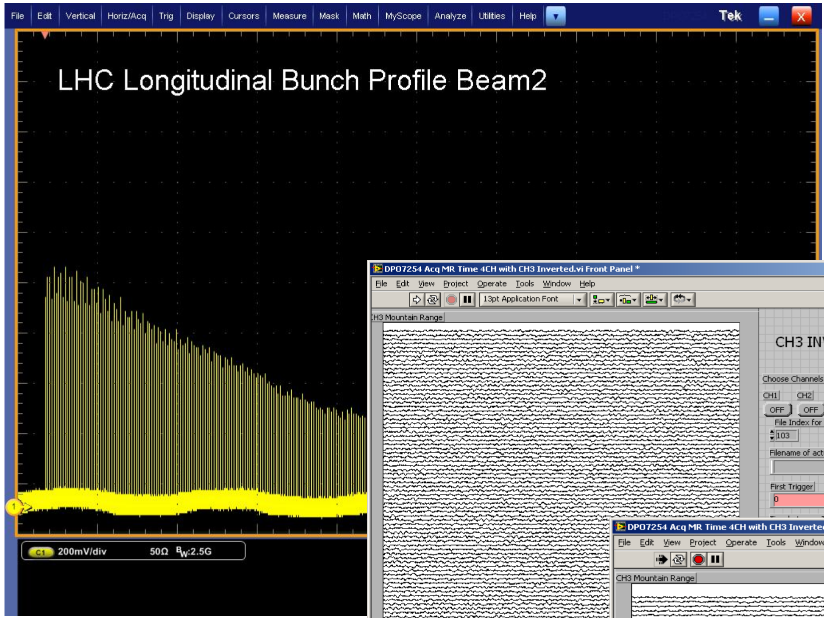
*Correct x, x’,*
*y, y’*
*to obtain the Closed Orbit*



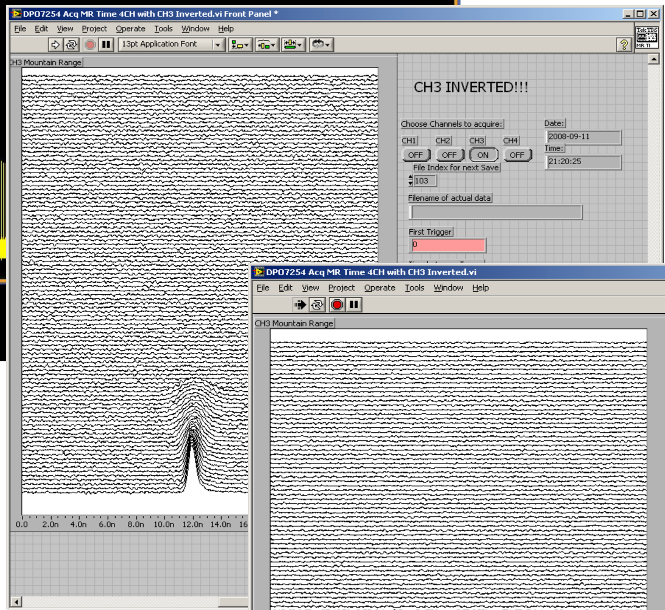
# LHC Commissioning: RF



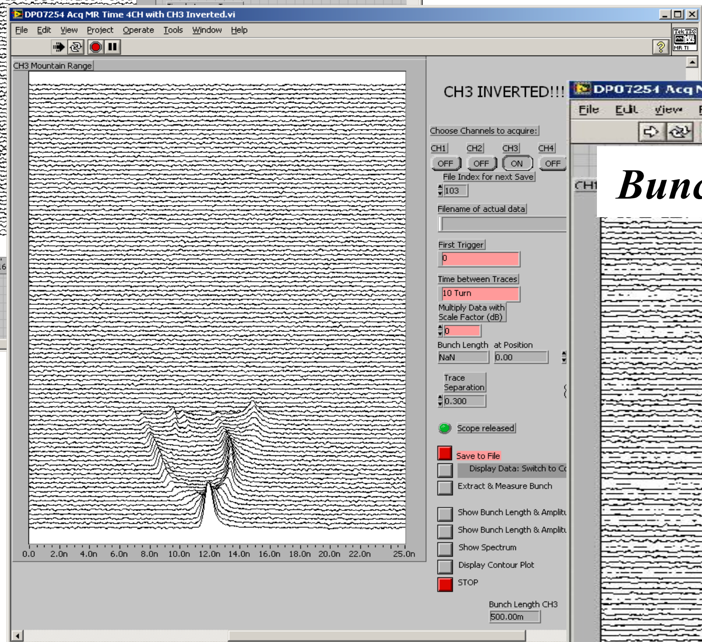

*a proton bunch: focused longitudinal by the RF field*

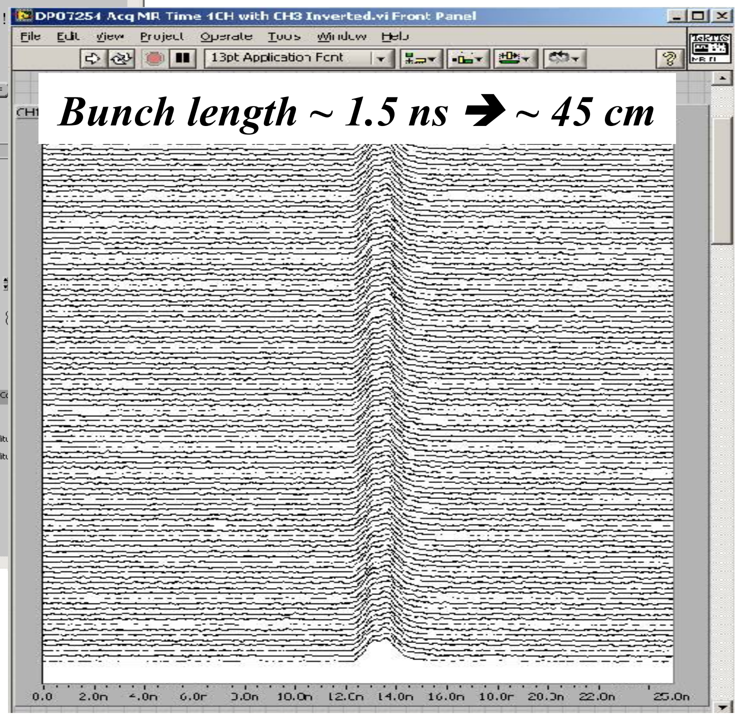



*RF off*



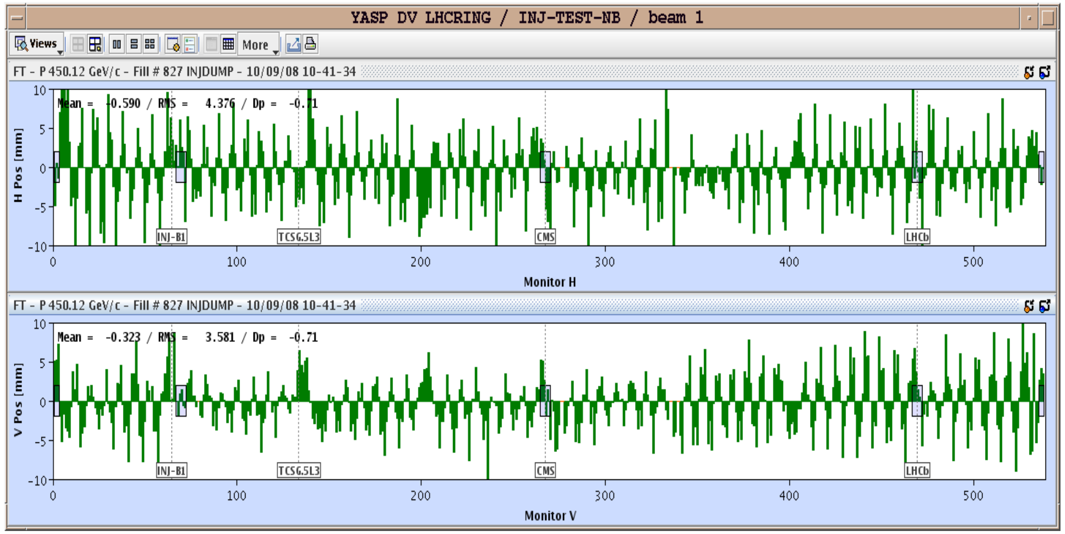

*RF on,*
*phase optimisation*




*RF on, phase adjusted,*
*beam captured*

# *Orbit & Tune:*

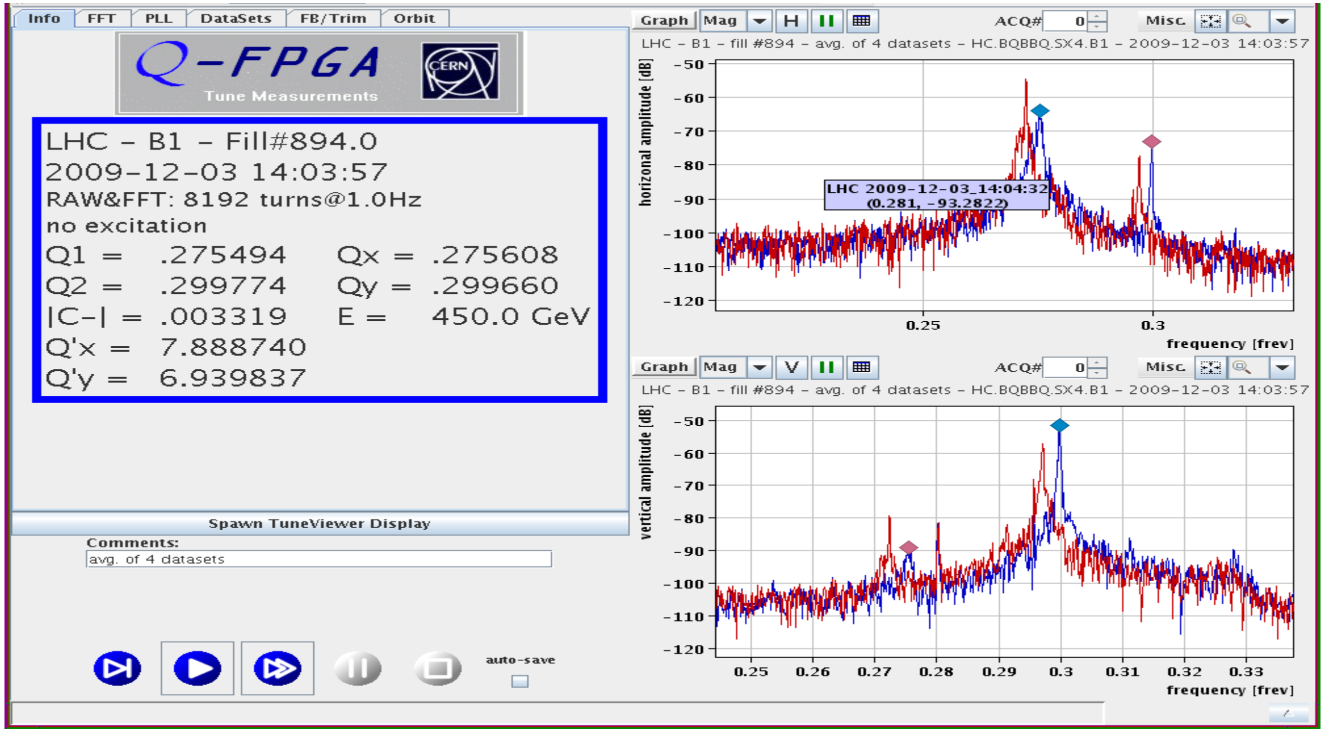



***Tune: number of oscillations per turn***

***64.31***
***59.32***

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

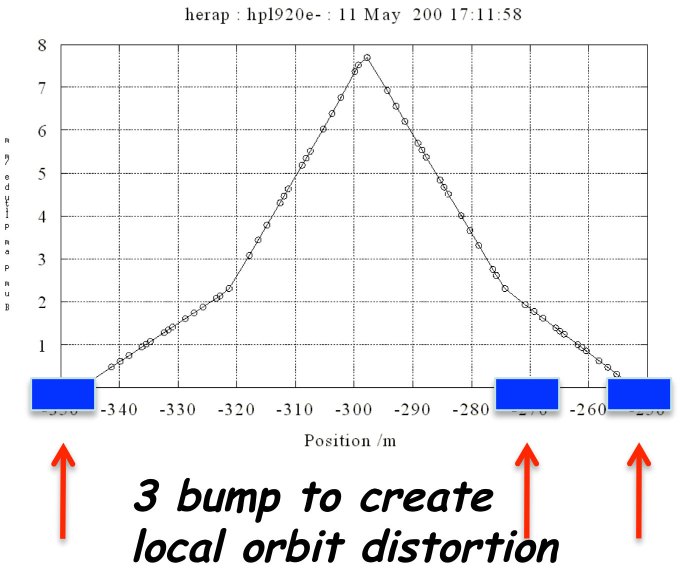
***LHC revolution frequency: 11.3 kHz***



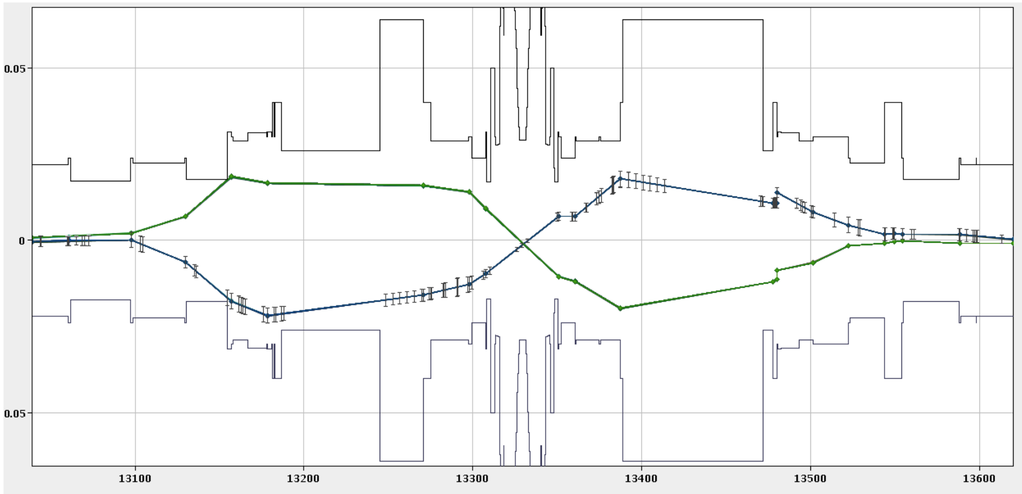

$0.31 * 11.3 = 3.5\,kHz$

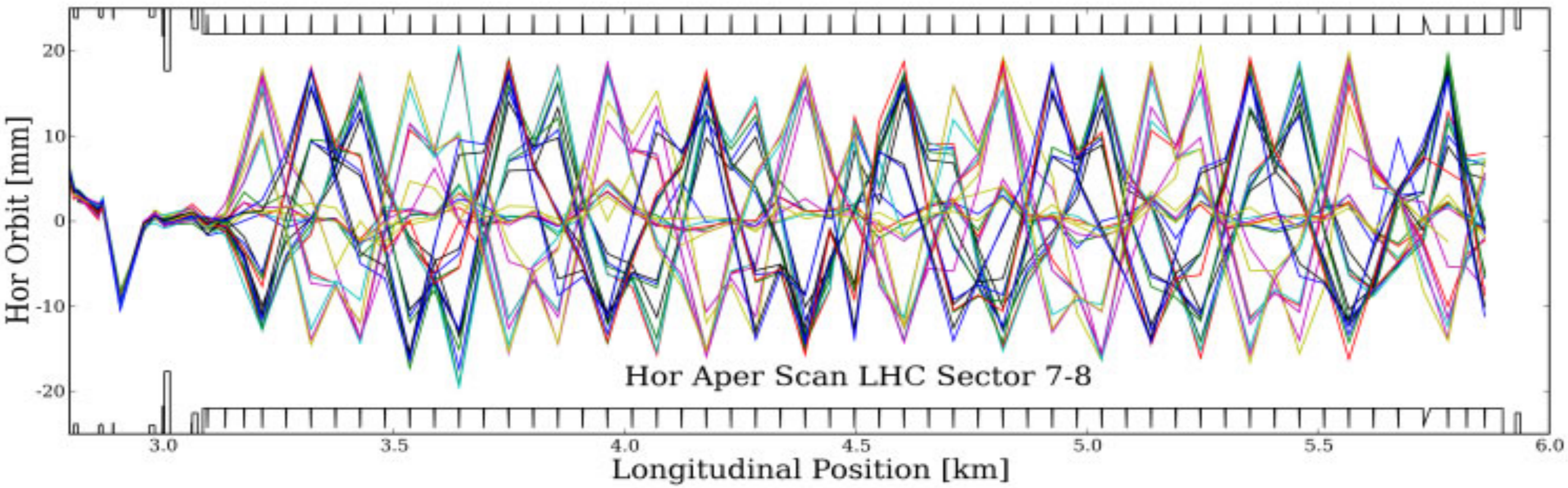
# LHC Operation: Aperture Scans

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




***3 bump to create local orbit distortion***



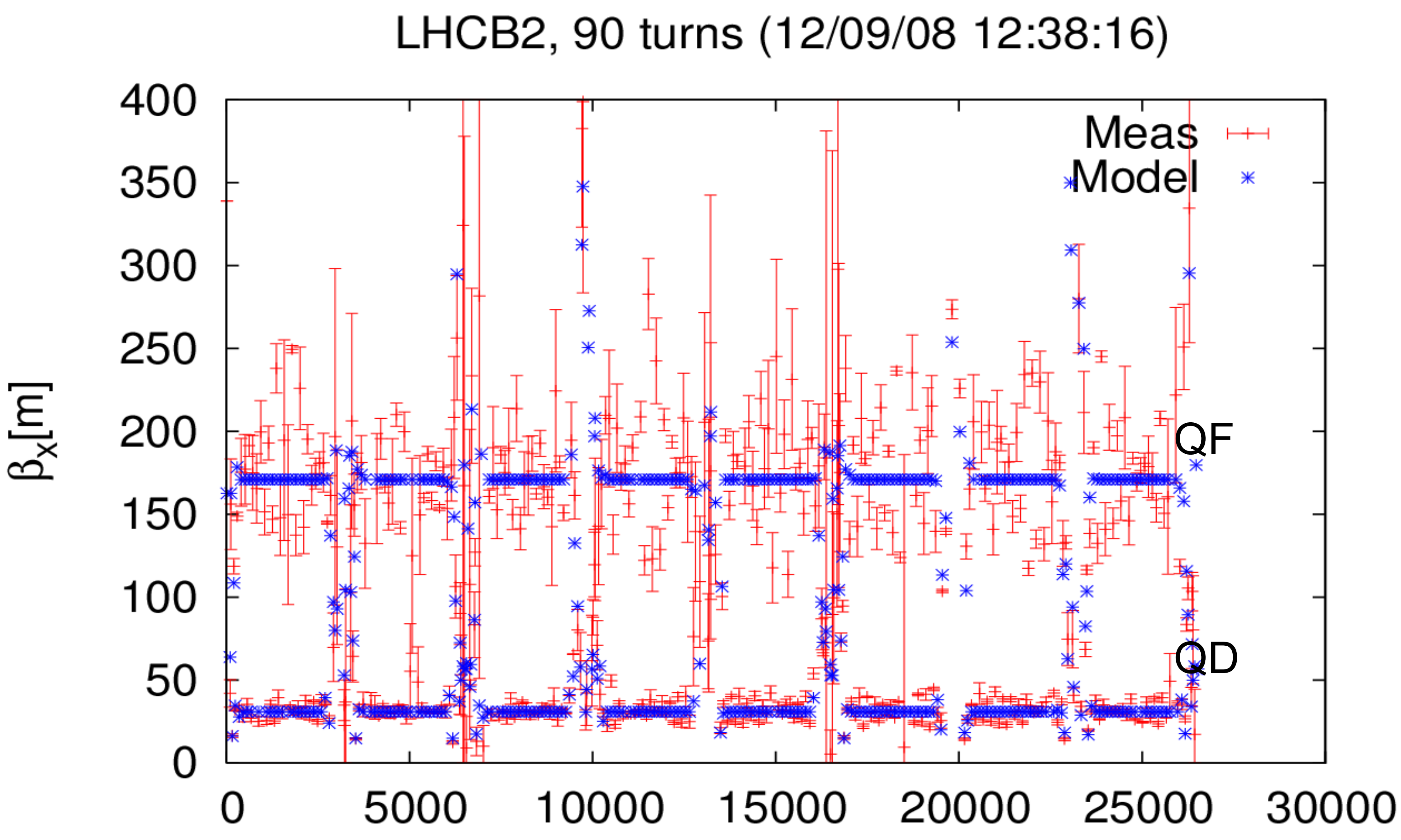



# LHC Operation: the First Beam

## Measurement of β :

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

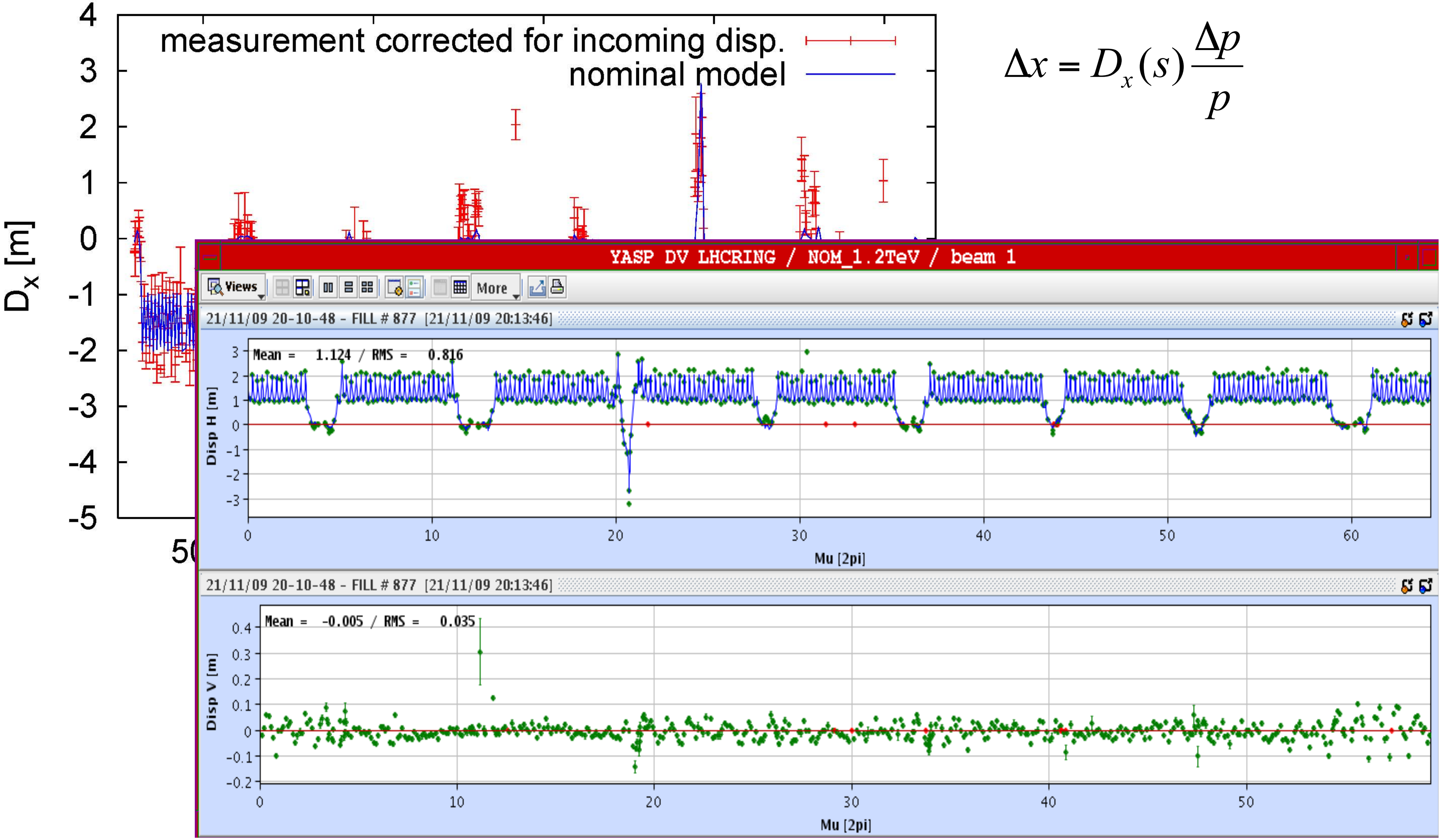
*Δβ / β = 50 %*



# LHC Operation: the First Beam

## Dispersion Measurement

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



# *Luminosity optimization*

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

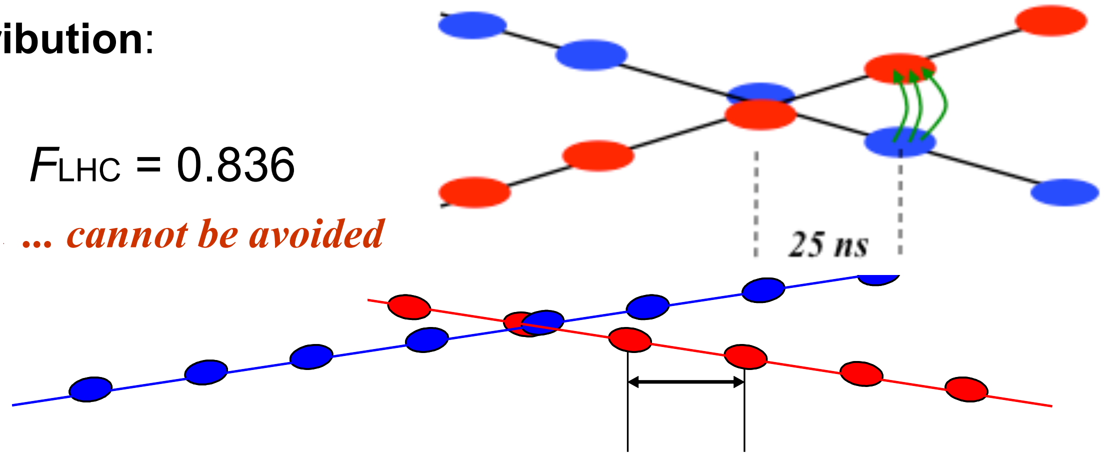
$N_i$ = number of protons/bunch
$N_b$ = number of bunches
$f_{rev}$ = revolution frequency
$\sigma_{ix}$ = beam size along x for beam i
$\sigma_{iy}$ = beam size along y for beam i

*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

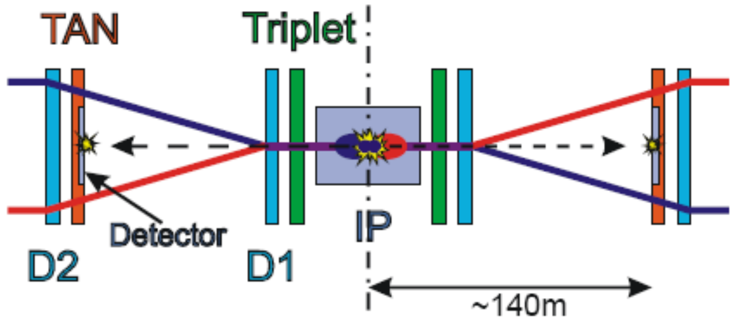
***... cannot be avoided***




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

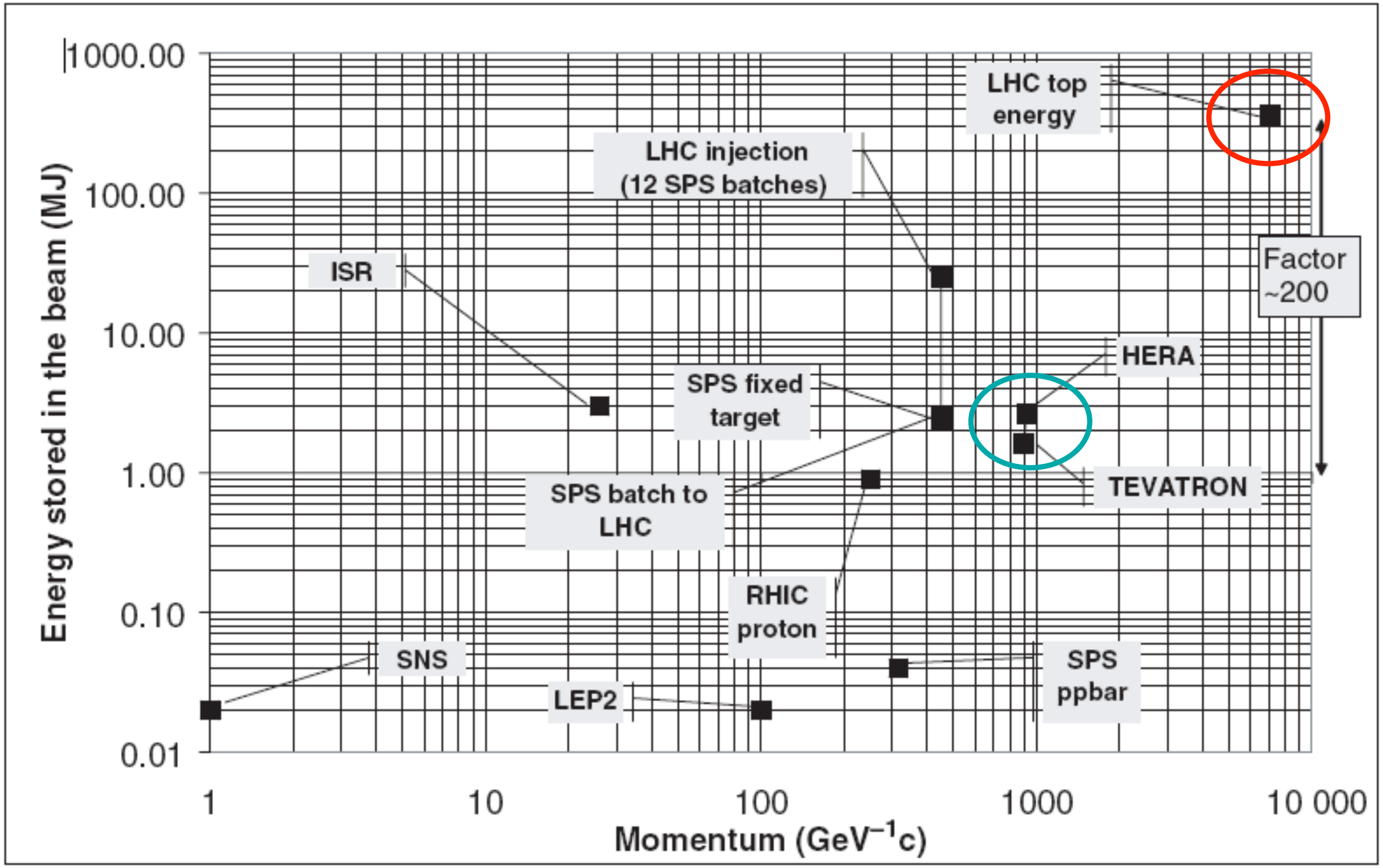
***... can be avoided by careful tuning***

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



# LHC Operation:
# Machine Protection & Safety

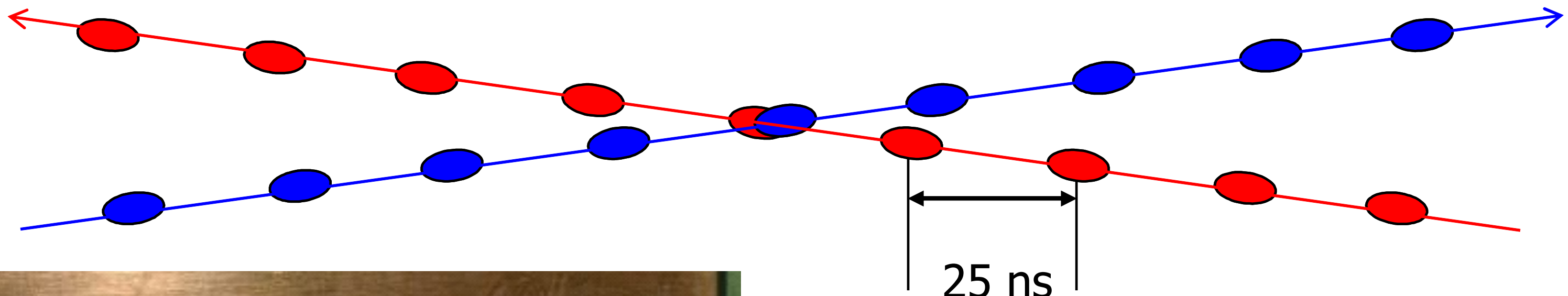
***Energy Stored in the Beam of different Storage Rings***

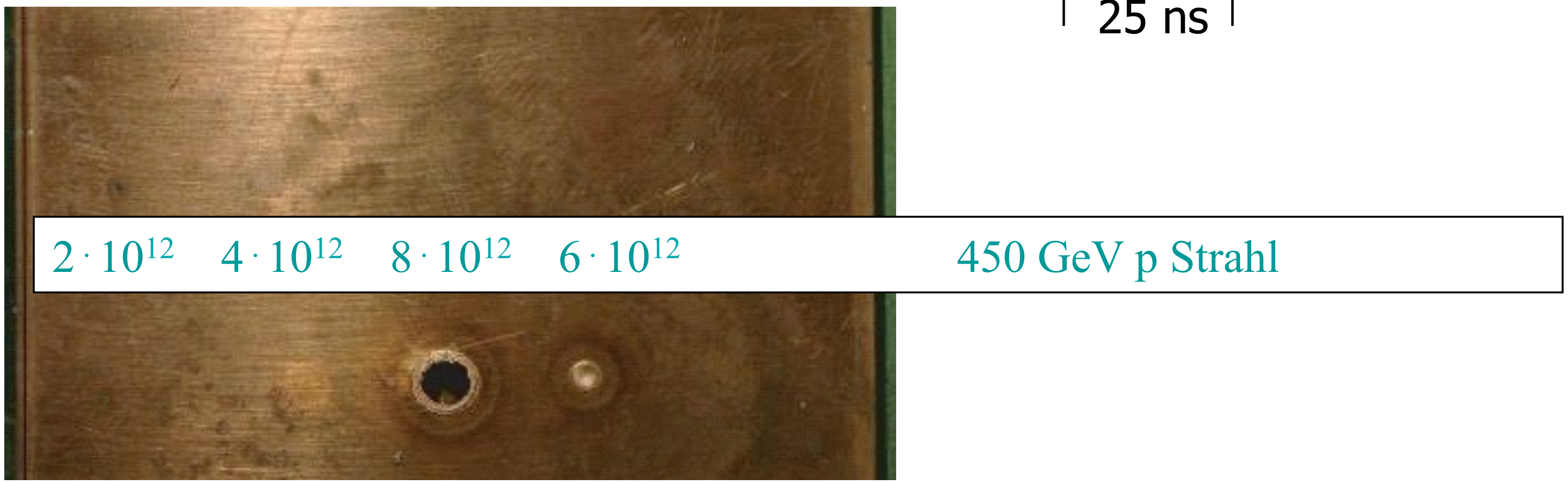


# *LHC Operation:*
# *Machine Protection & Safety*

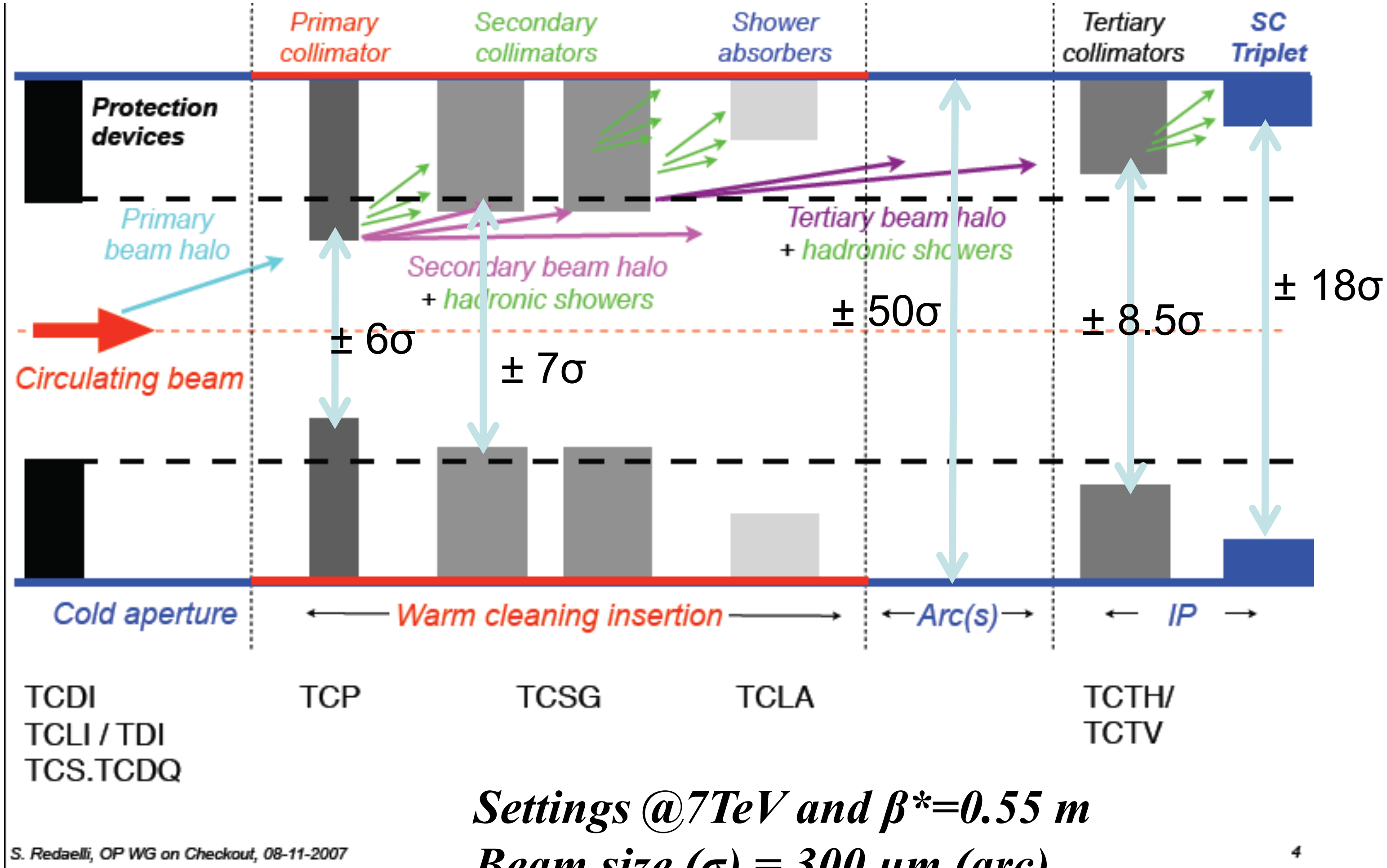
| | | |
|---|---|---|
| Energy stored in magnet system | 10 | GJ |
| Energy stored in one main dipole circuit | 1.1 | GJ |
| Energy stored in one beam | 362 | MJ |

***Enough to melt 500 kg of copper***



# LHC Aperture and Collimation



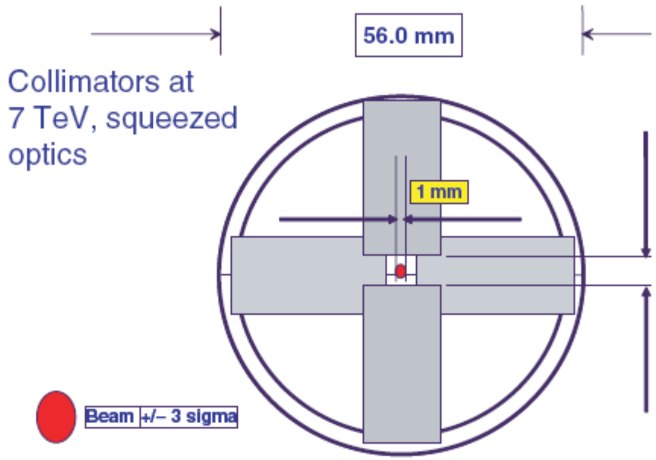

***Settings @7TeV and β*=0.55 m***

***Beam size (σ) = 300 μm (arc)***

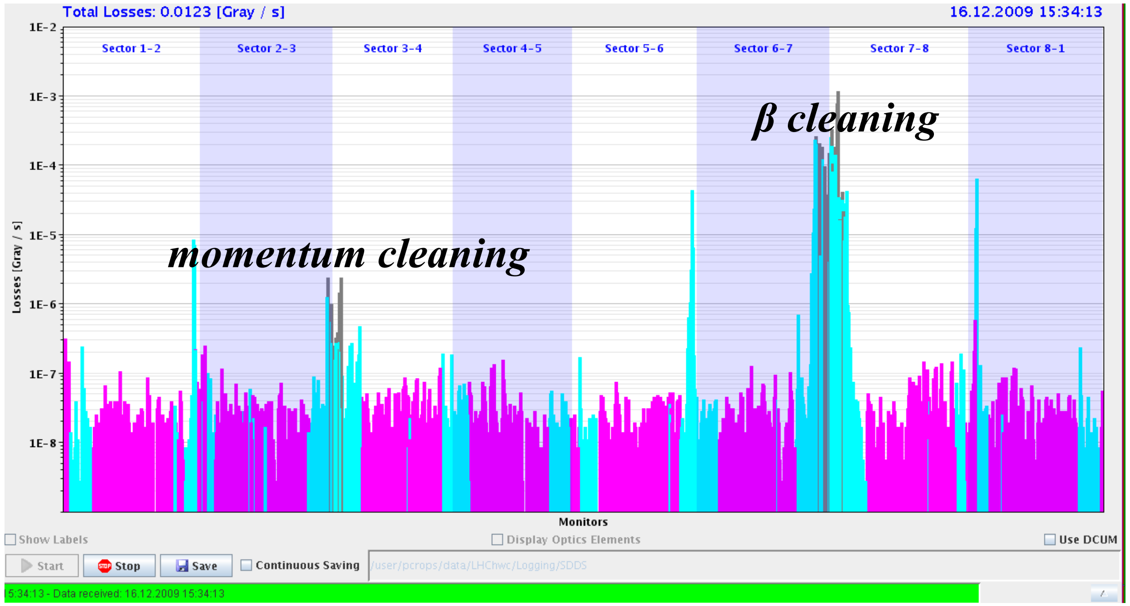
***Beam size (σ) = 17 μm (IR1, IR5)***

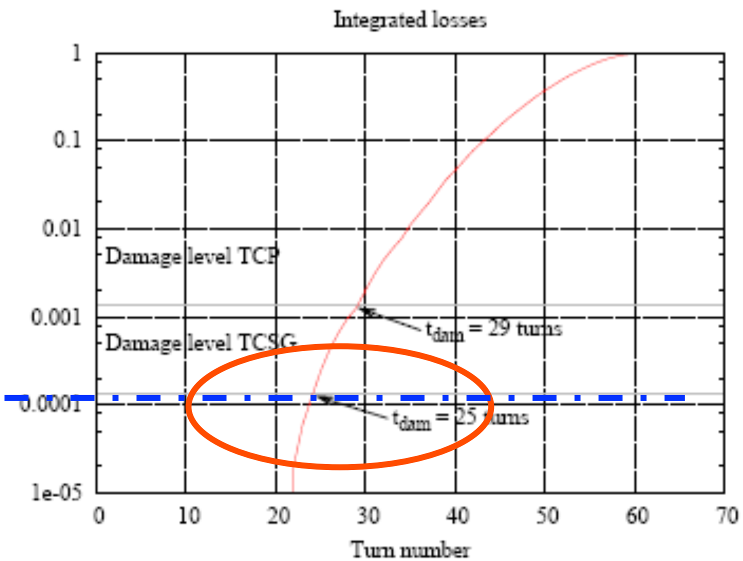
# LHC Operation:
# Machine Protection & Safety

*... Komponenten des Machine Protection Systems :*

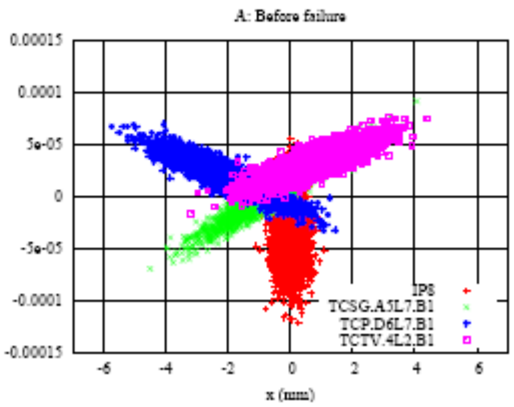


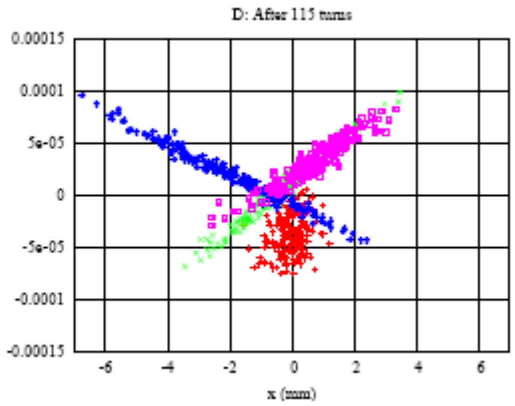

*beam loss monitors*
*QPS*
*permit server*
*orbit control*
*power supply control*
*collimators*
*online on beam check of all ( ? )*
*hardware components*
*a fast dump*
*the gaussian beam profile*



# *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:*** $\tau_{loss}$ ***=20 - 30 ms***

***BLM system reacts in time, QPS is not fast enough***

***quench in sc. arc quadrupoles:*** $\tau_{loss}$ ***=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 Gjoule* (only in the main dipoles) corresponds to …*


***More important than the amount of energy is …***

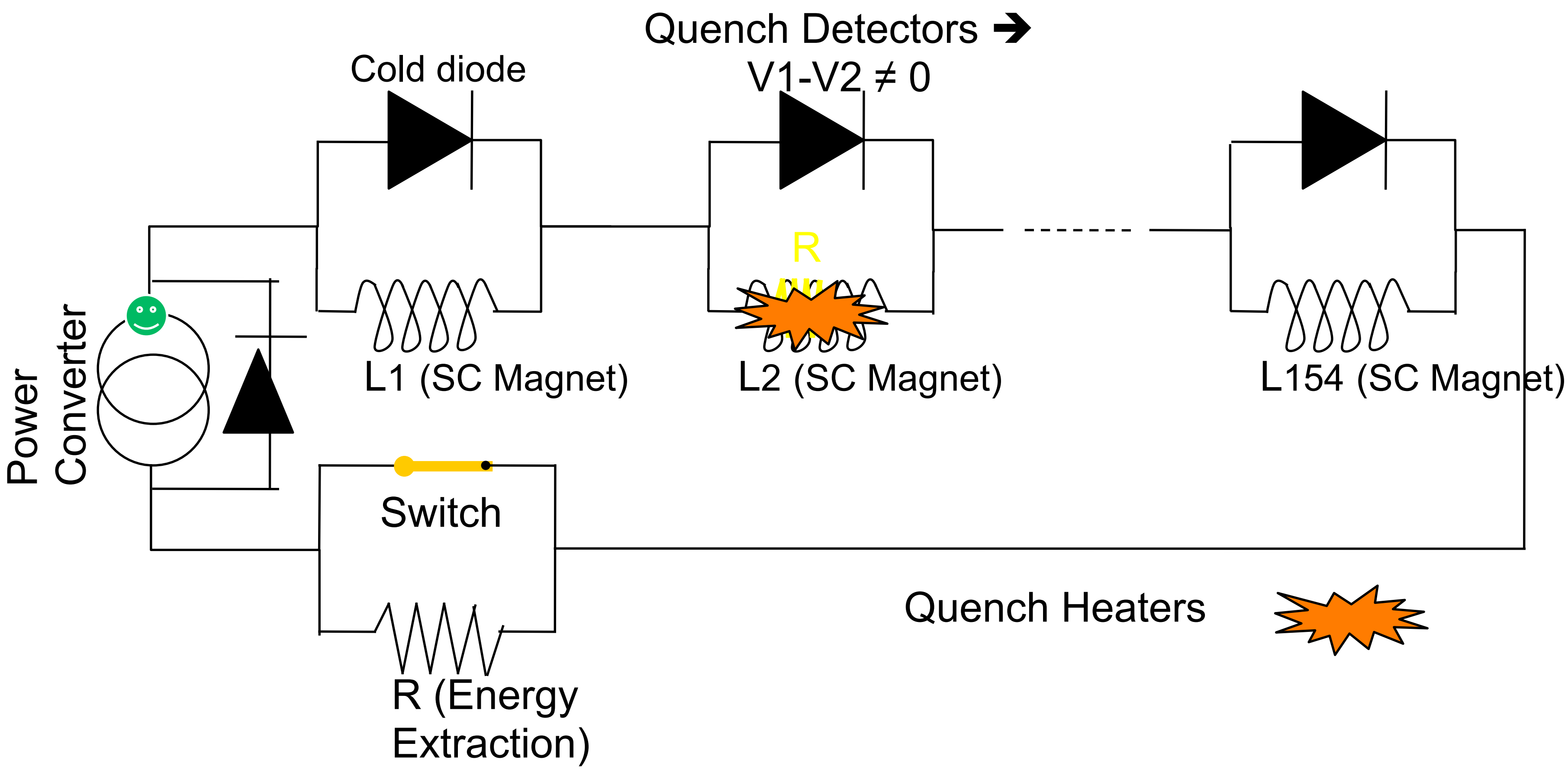
***How fast (an safe) can this energy be released?***

*$*E=1/2LI^2$*

*L: inductance ~0.1 Henry for LHC dipoles*

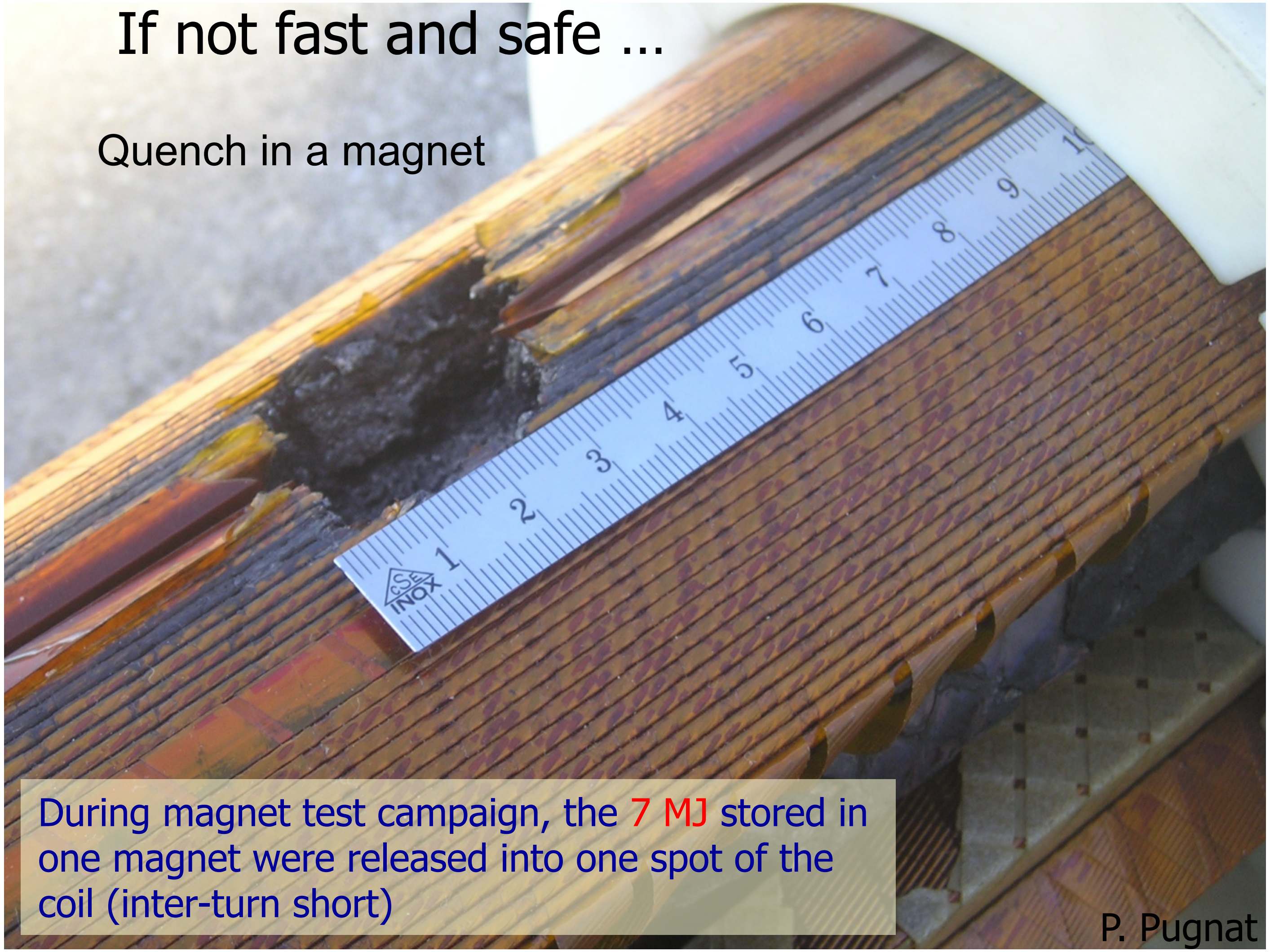
# *Energy stored in the magnets: 10 GJ*
# *Quench Protection System*

## *Schematics of the QPS in the main dipoles of a sector*

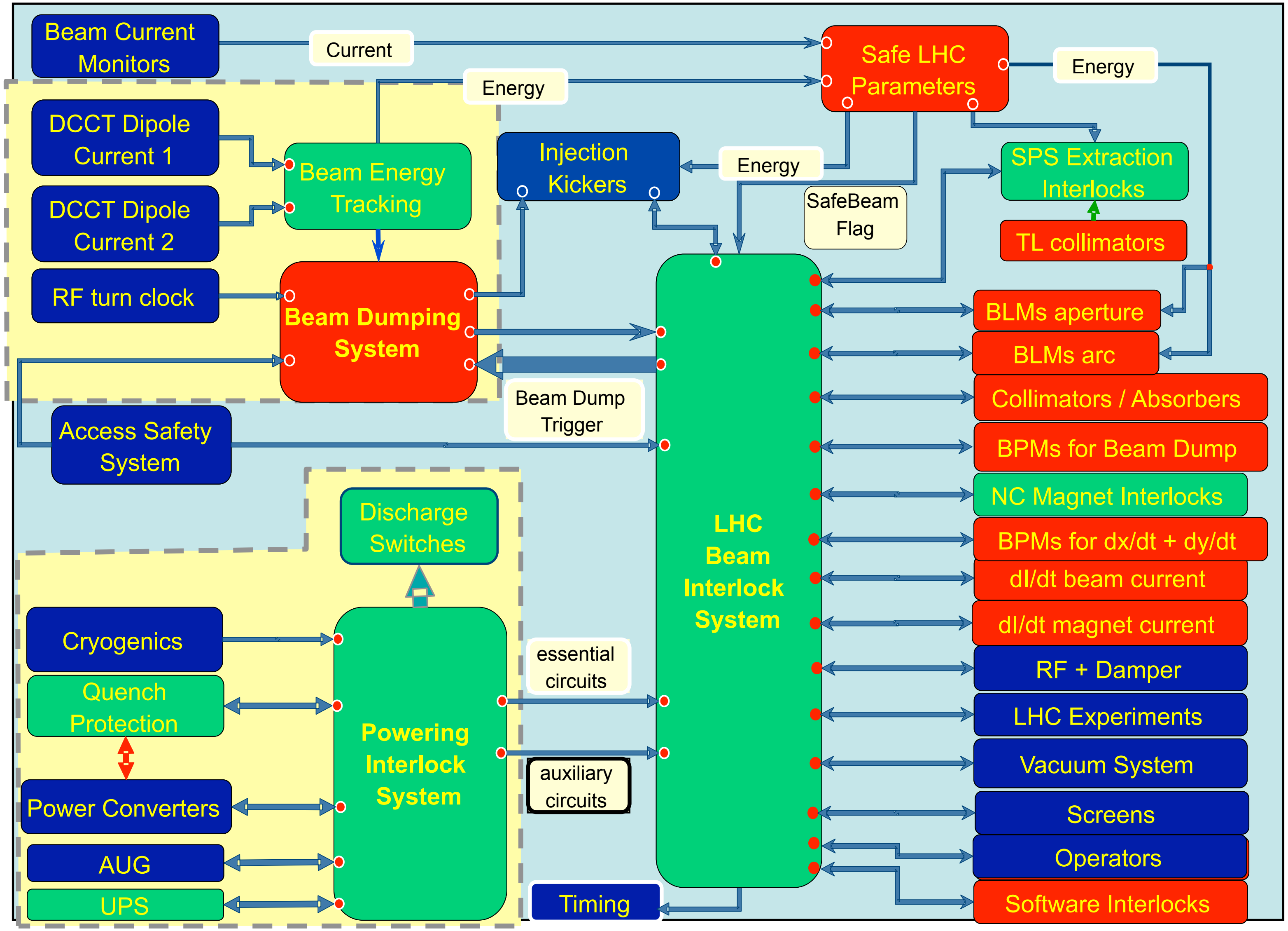



*court. R. Alemany*

# *Energy stored in the magnets: quench*

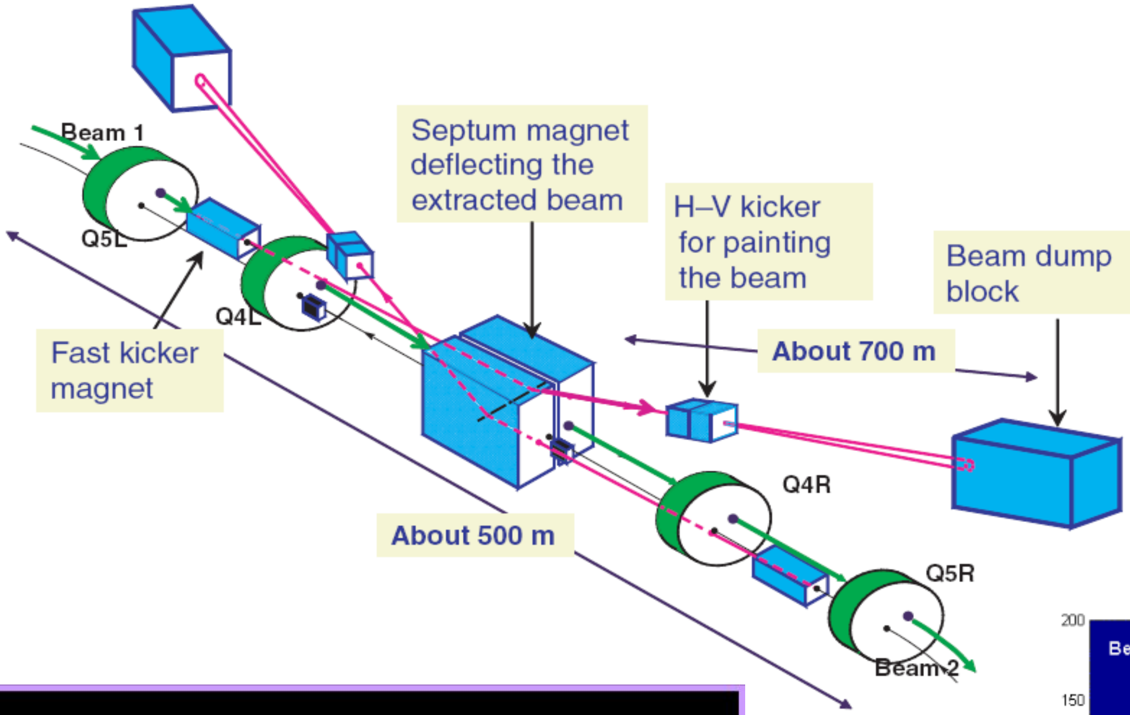


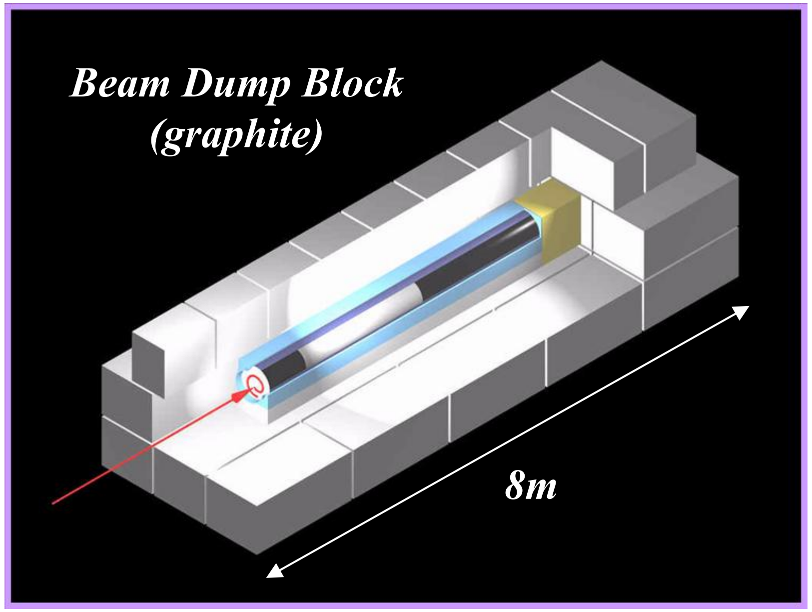
# *LHC Operation: Machine Protection & Safety*

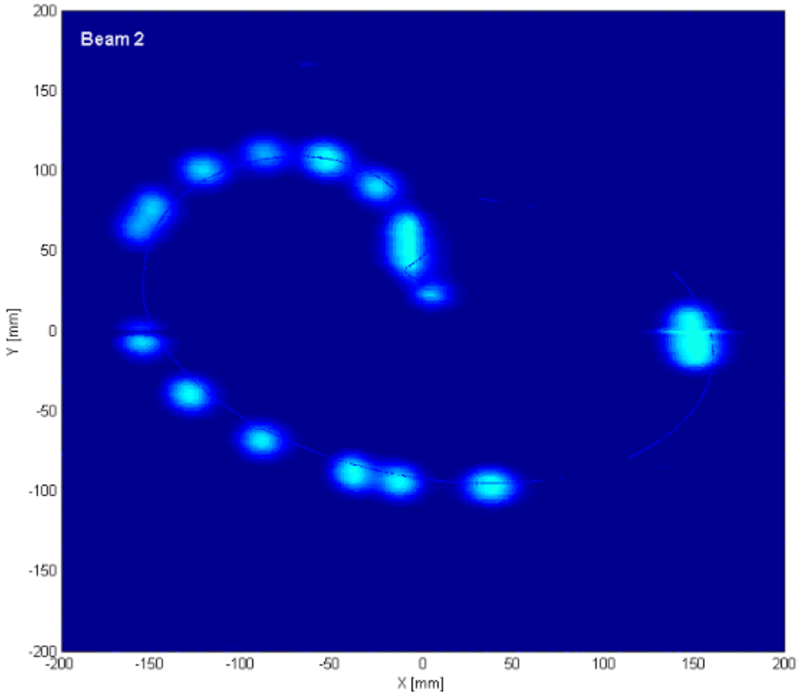



***... no comment***

# *LHC Operation: Dump System*



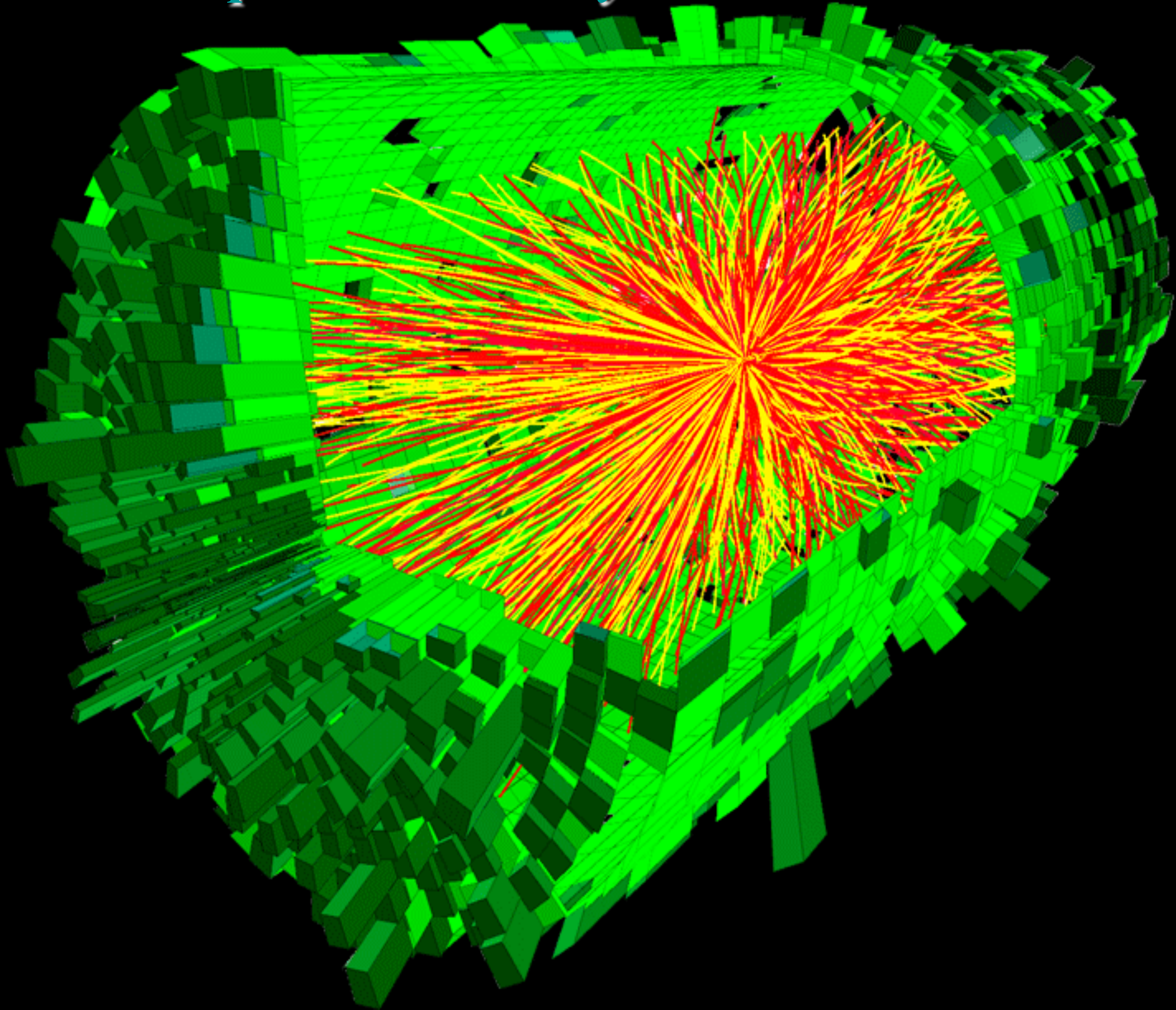



***Booooooom***

## *1.) Where are we ?*

* *Standard Model of HEP*
* *Higgs discovery*

# LHC Operation:  Heavy Ion Collisions

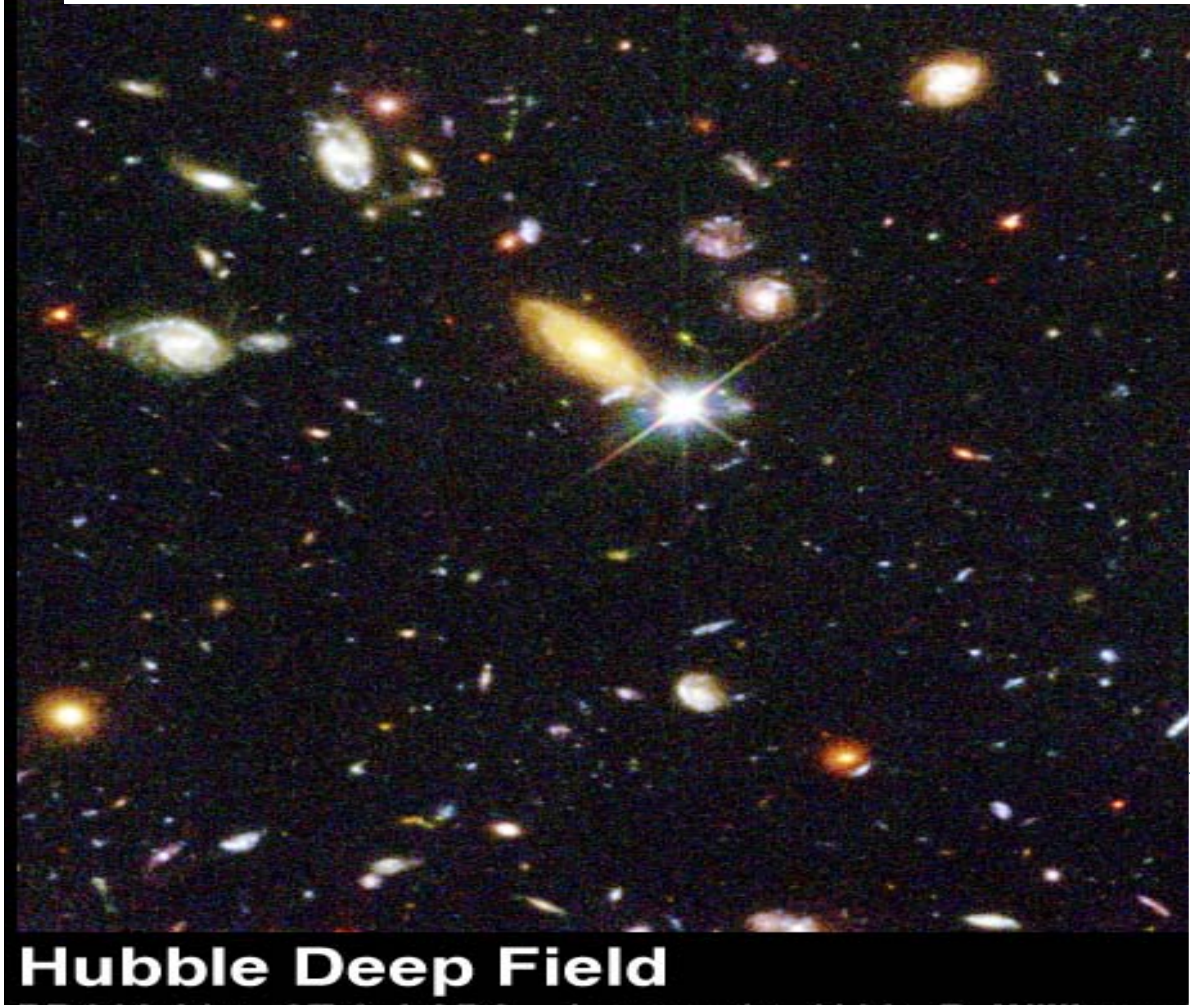


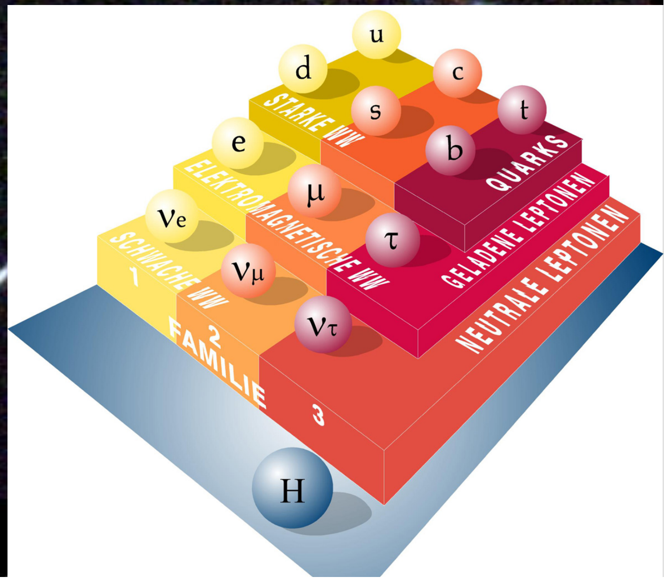
## 2.) Where do we go ?

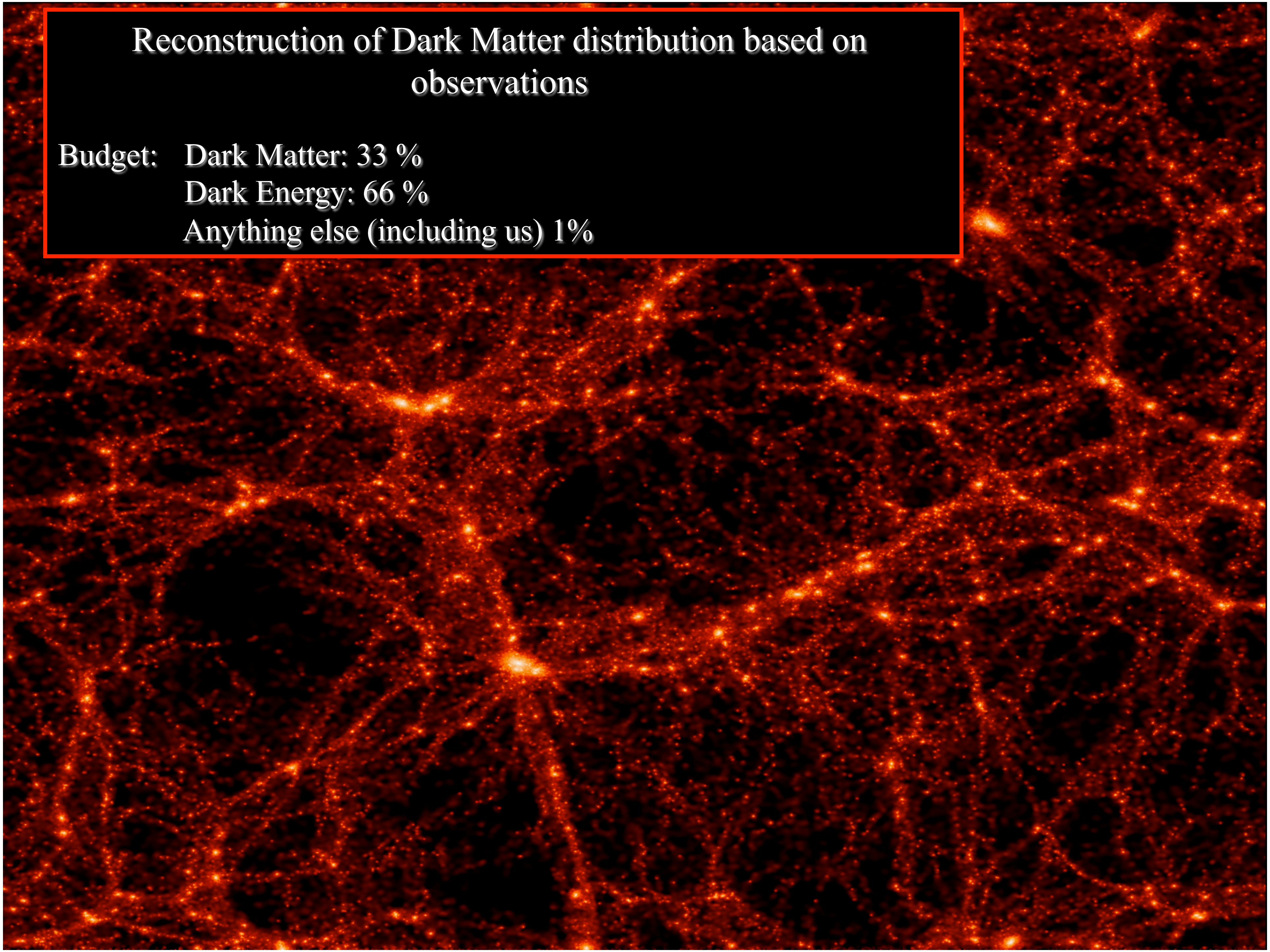
* *Physics beyond the Standard Model*
* *Dark Matter / Dark Energy*

# 10.) Storage Rings to Explain the Universe

***Precision Measurements of the Standard Model,***
***Search for Higgs, Supersymmetry, Dark Matter***
***Physics beyond the Standard Model***




Reconstruction of Dark Matter distribution based on observations
Budget: Dark Matter: 33 %
Dark Energy: 66 %
Anything else (including us) 1%

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***Schluss aus fertich***

***that's all folks ... for this time***

***eso es todo por hoy ... que aproveche***

***fin***