Status of the LHC Machine

Helmut Burkhardt, CERN

RADCOR'09, 26 Oct. 2009, Ascona Switzerland

Accelerators at the Energy Frontier

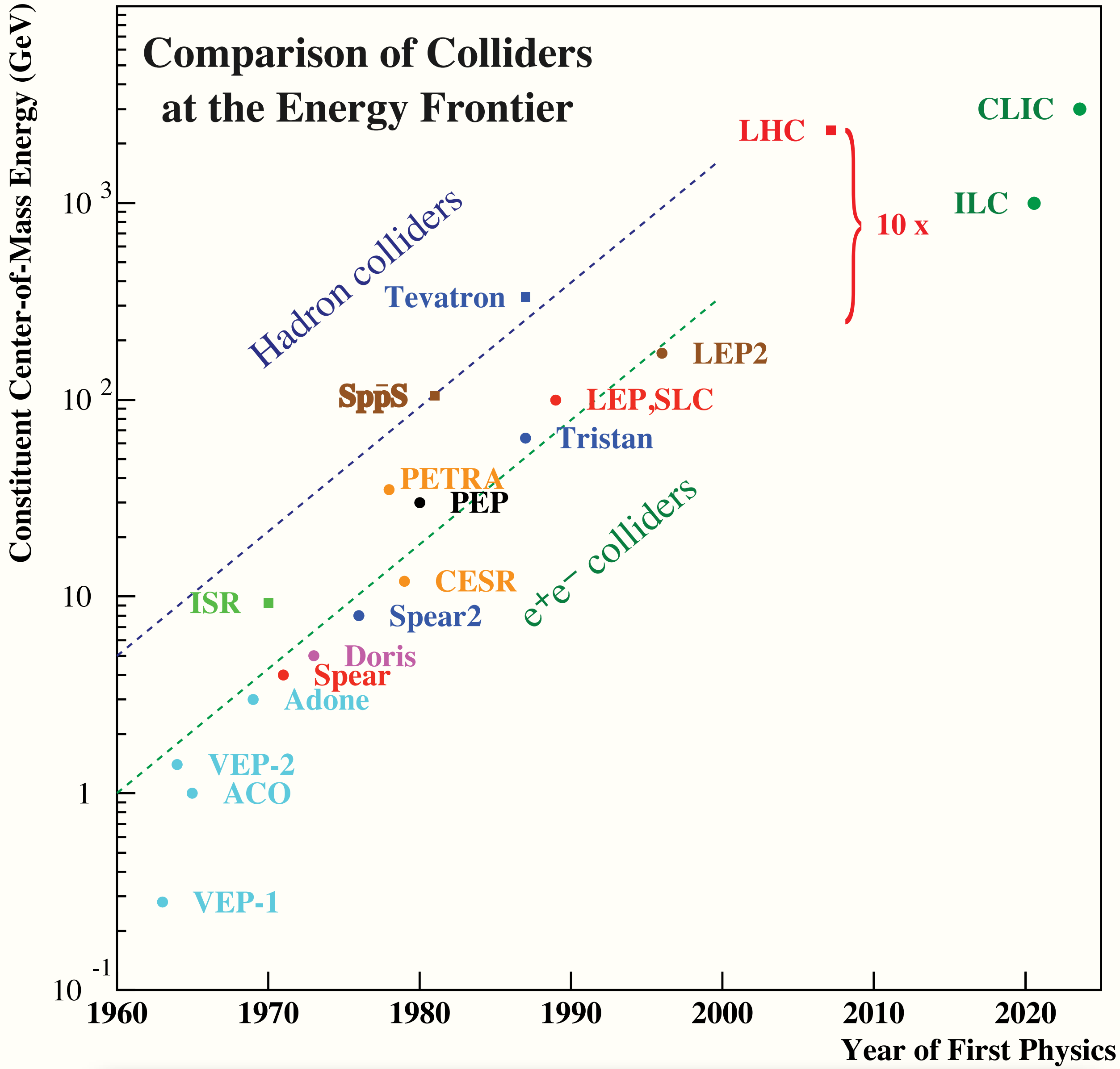
Livingston plot

Exponential growth of E_{cms} in time

Starting in 60's with e^+e^- at about 1GeV

Factor 4 every 10 y

pp, $p\bar{p}$: E_{cms} / 6 still 5 × above e^+e^- at same time



The LHC is a big step forward; Excellent potential for major discoveries; according to RADCOR Higgs well within range

pp, $p\bar{p}$: discovery
e^+e^- : precision machines
both required

LHC: From first ideas to realisation

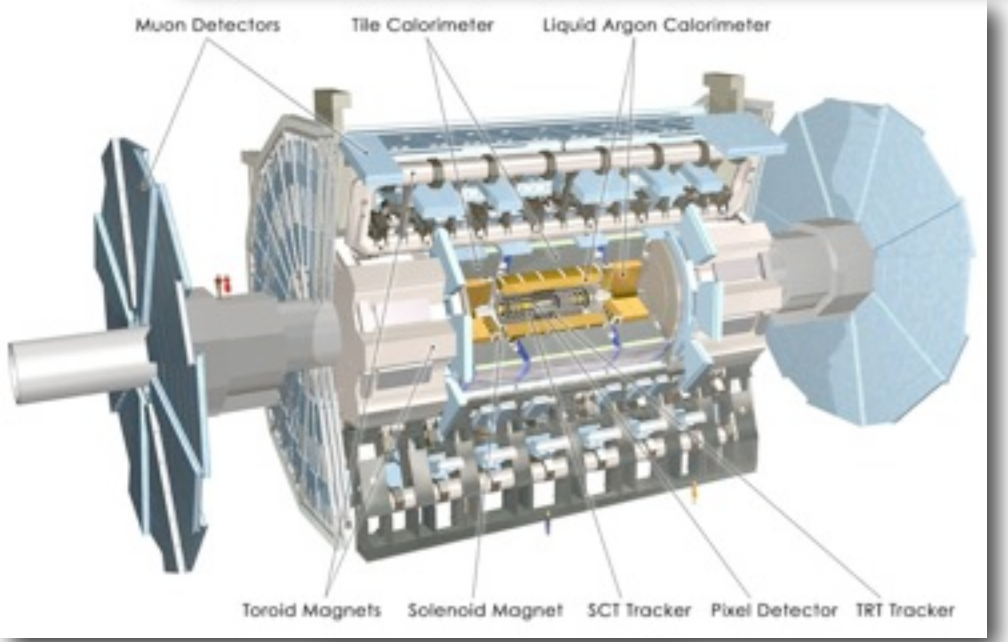
28 y

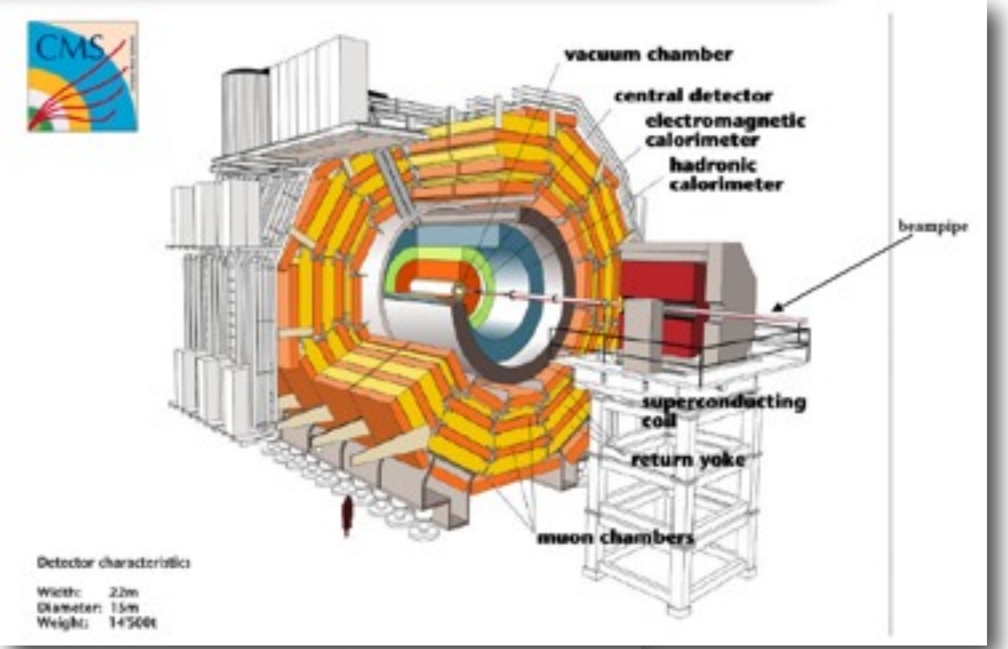
1982 : First studies for the LHC project
1983 : Z discovered at SPS proton antiproton collider
1989 : Start of LEP operation ~ 92 GeV, Z-factory
1994 : Approval of the LHC by the CERN Council
1996 : Final decision to start the LHC construction
1996 : LEP2 operation towards ~ 200 GeV, W^+W^-
2000 : End of LEP operation
2002 : LEP equipment removed
2003 : Start of the LHC installation - infrastructure
2005 : Start of Magnet installation in LHC tunnel
2007 : Installation complete, starting cooldown
2008 : Start of commissioning with beam
2010 : First physics results (?)

9 y

16 y

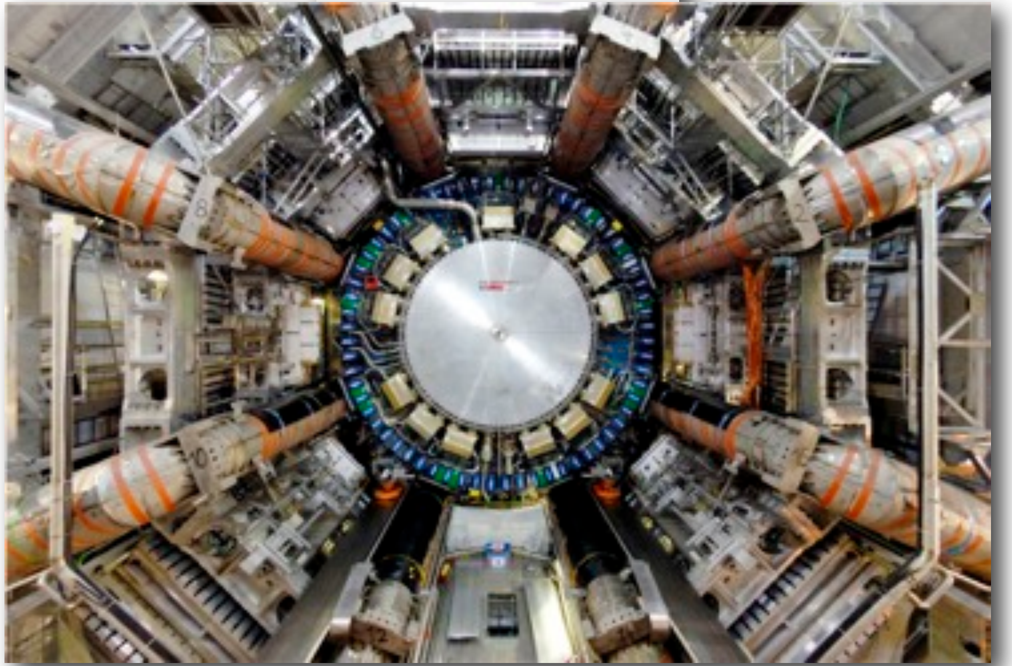
High Luminosity IR1, IR5 for the Large Multipurpose Detectors

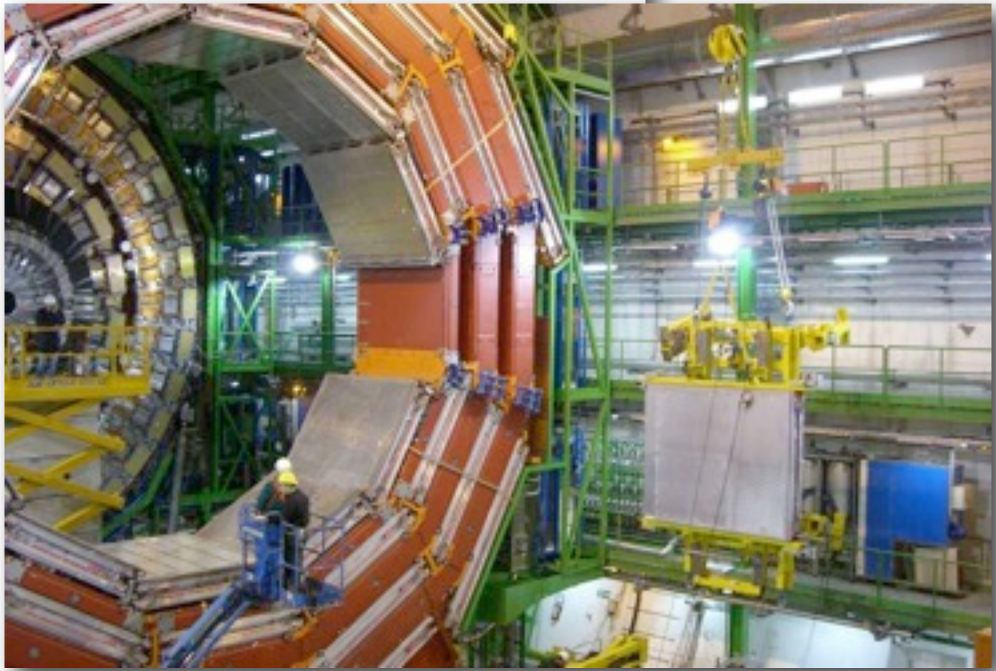




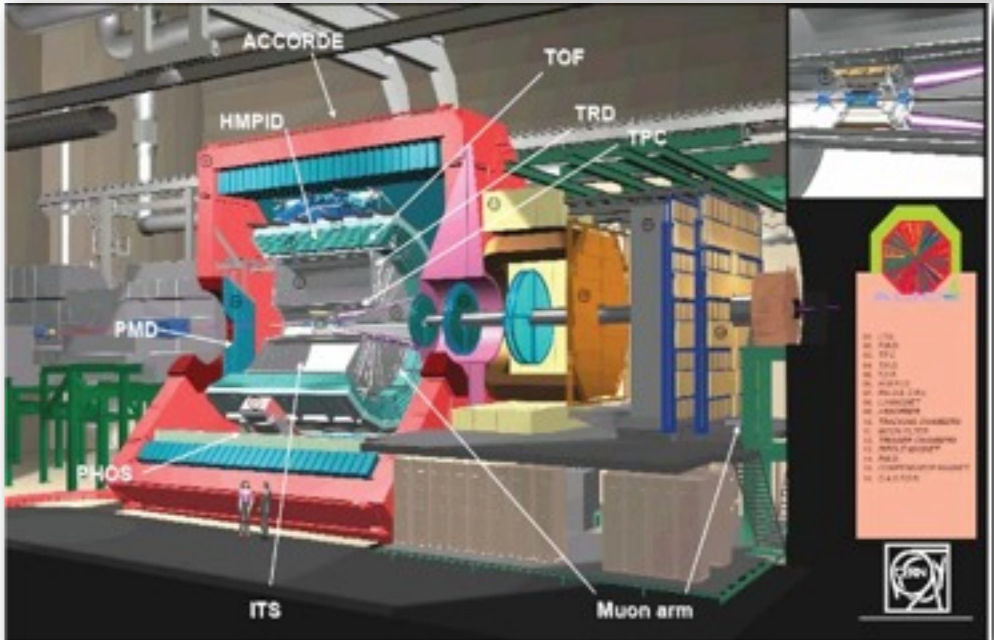
IR1 : ATLAS

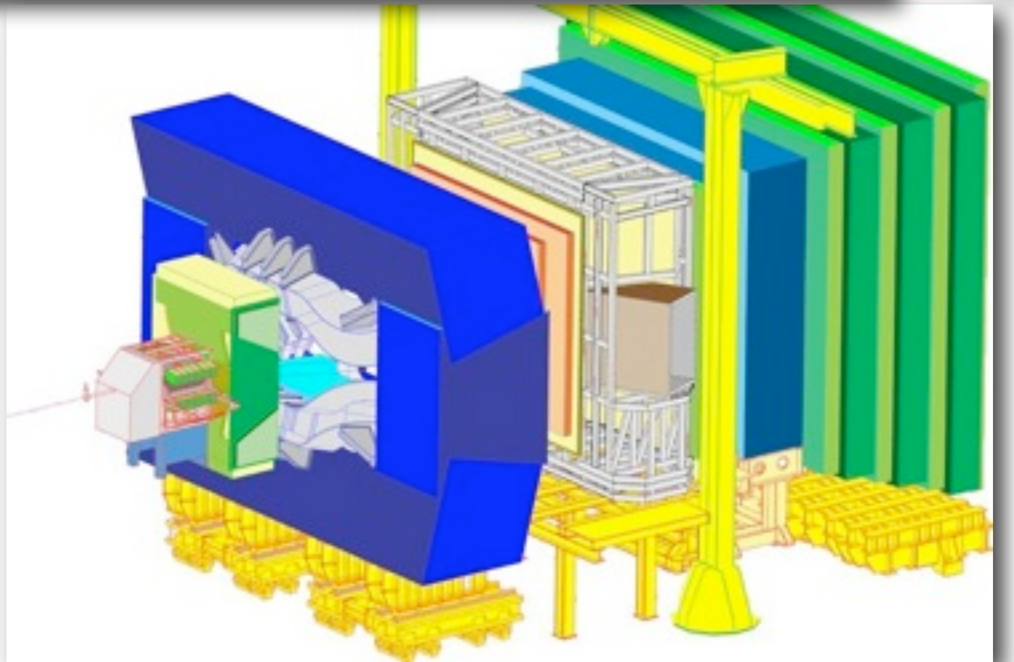
IR5 : CMS





IR2, IR8 for $\mathcal{L} \sim 10^{30} - 10^{32}$ cm^{-2} s^{-1} with the more specialized Detectors





IR2 : Alice – Heavy Ion - Φ

IR8 : LHCb – B - Φ

Major LHC challenges

High design Centre-of-mass energy of 14 TeV in given (ex LEP) tunnel

- Magnetic field of 8.33 T with superconducting magnets
- Helium cooling at 1.9 K
- Large amount of energy stored in magnets
- "Two accelerators" in one tunnel with opposite magnetic dipole field and ambitious beam parameters pushed for very high of luminosity of 10^{34} cm^{-2} s^{-1}
- Many bunches with large amount of energy stored in beams

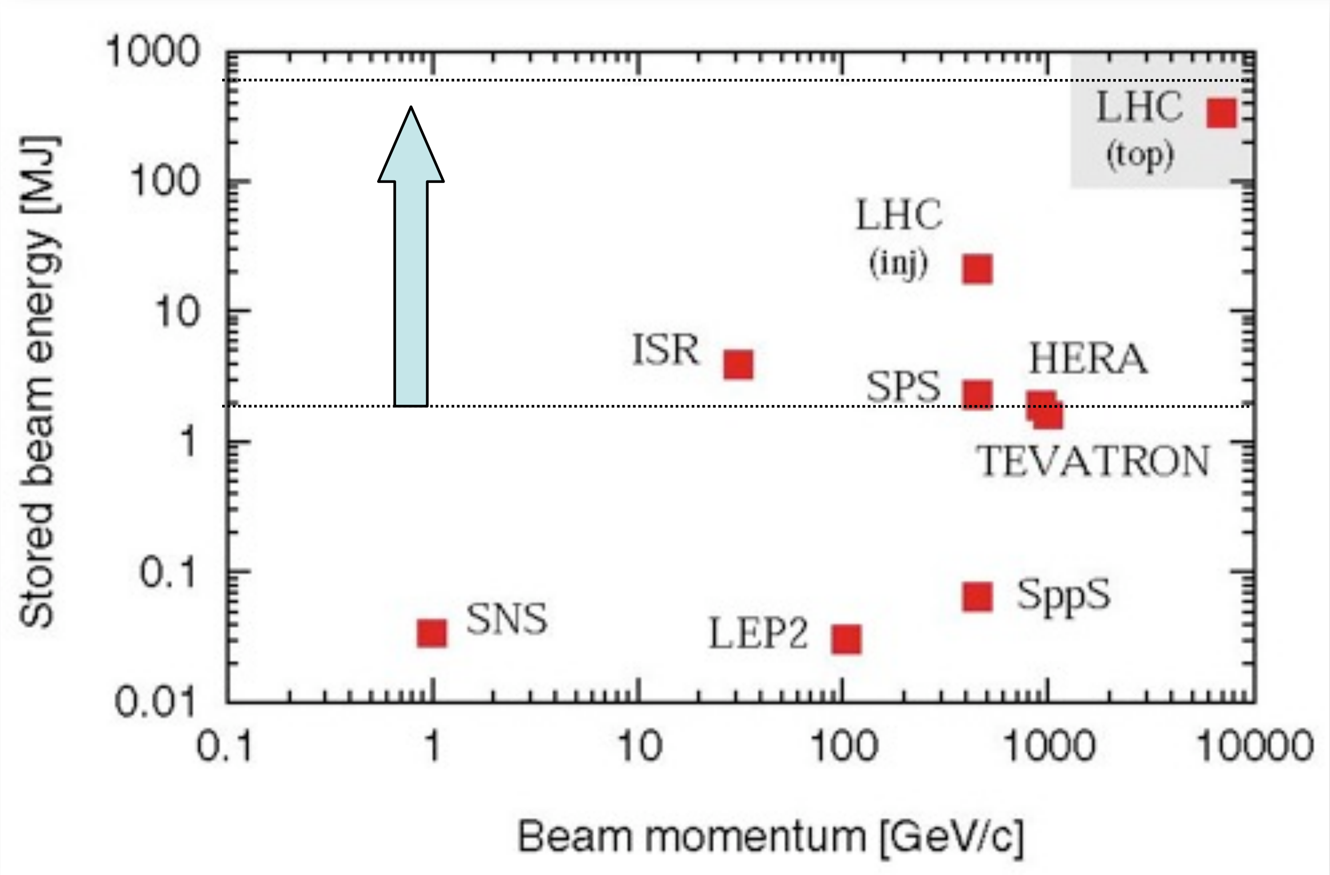
Complexity and Reliability

- Unprecedented complexity with 10000 magnets powered in 1700 electrical circuits, complex active and passive protection systems, ….

- **Emittance conservation** $\varepsilon_N = \beta \gamma \varepsilon$, related to phase space density conservation, Liouville constant "intrinsic" normalized emittance ε_N, real space emittance ε decreases with energy
- in absence of major energy exchange in synchrotron radiation / rf damping
- clean, perfectly matched injection, ramp, squeeze, minimize any blow up from: rf,
- kicking beam, frequent orbit changes, vibration, feedback, noise,..
- dynamic effects - persistent current decay and snapback
- non-linear fields (resonances, diffusion, dynamic aperture, non-linear dynamics)

The total stored energy of the LHC beams

Nominal LHC design: 3.2×10^{14} protons accelerated to 7 TeV circulating at 11 kHz in a SC ring



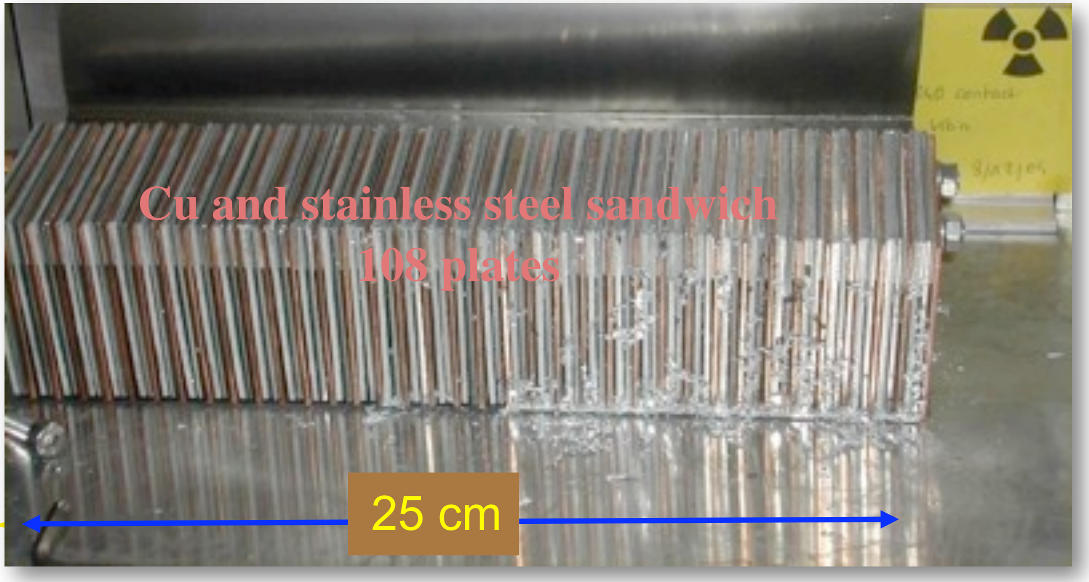
LHC: > 100 × higher stored energy and small beam size: ~ 3 orders of magnitude in energy density and damage potential. Active protection (beam loss monitors, interlocks) and collimation for machine and experiments essential.
Only the specially designed beam dump can safely absorb this energy.

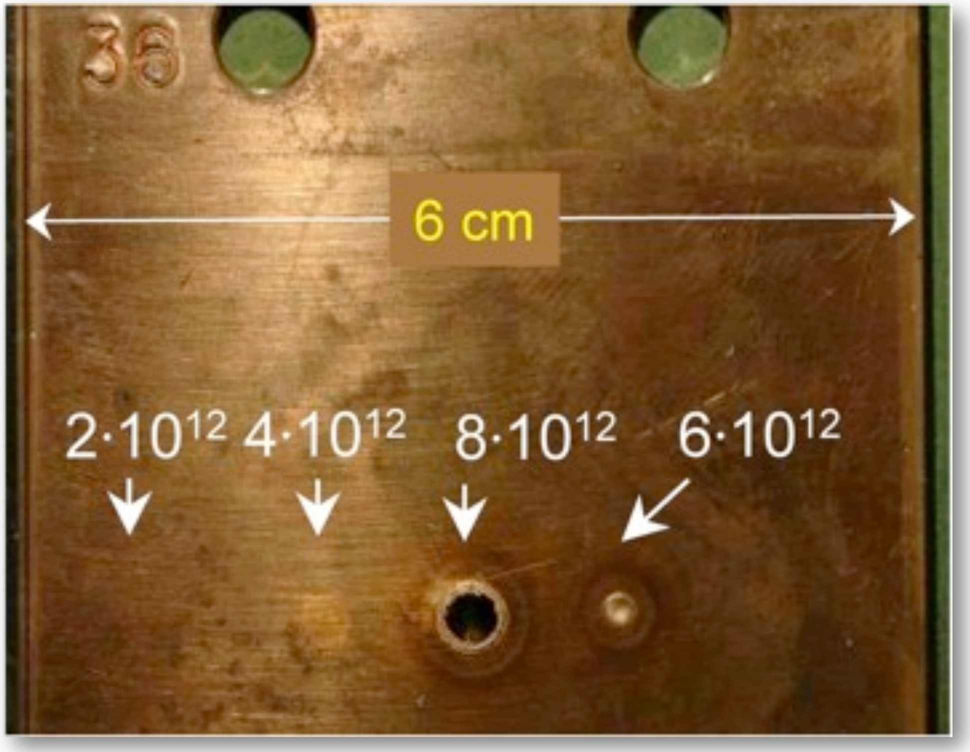
Damage potential : confirmed in controlled SPS experiment

controlled experiment with beam extracted from SPS at 450 GeV in a single turn, with perpendicular impact on Cu + stainless steel target

450 GeV protons →

r.m.s. beam sizes $\sigma_{x/y} \approx 1$ mm





SPS results confirmed :

8×10^{12} clear damage

2×10^{12} below damage limit

for details see V. Kain et al., PAC 2005 RPPE018

For comparison, the LHC nominal at 7 TeV :
$2808 \times 1.15 \times 10^{11} = 3.2 \times 10^{14}$ p/beam
at $< \sigma_{x/y} > \approx 0.2$ mm
over 3 orders of magnitude above damage level for perpendicular impact

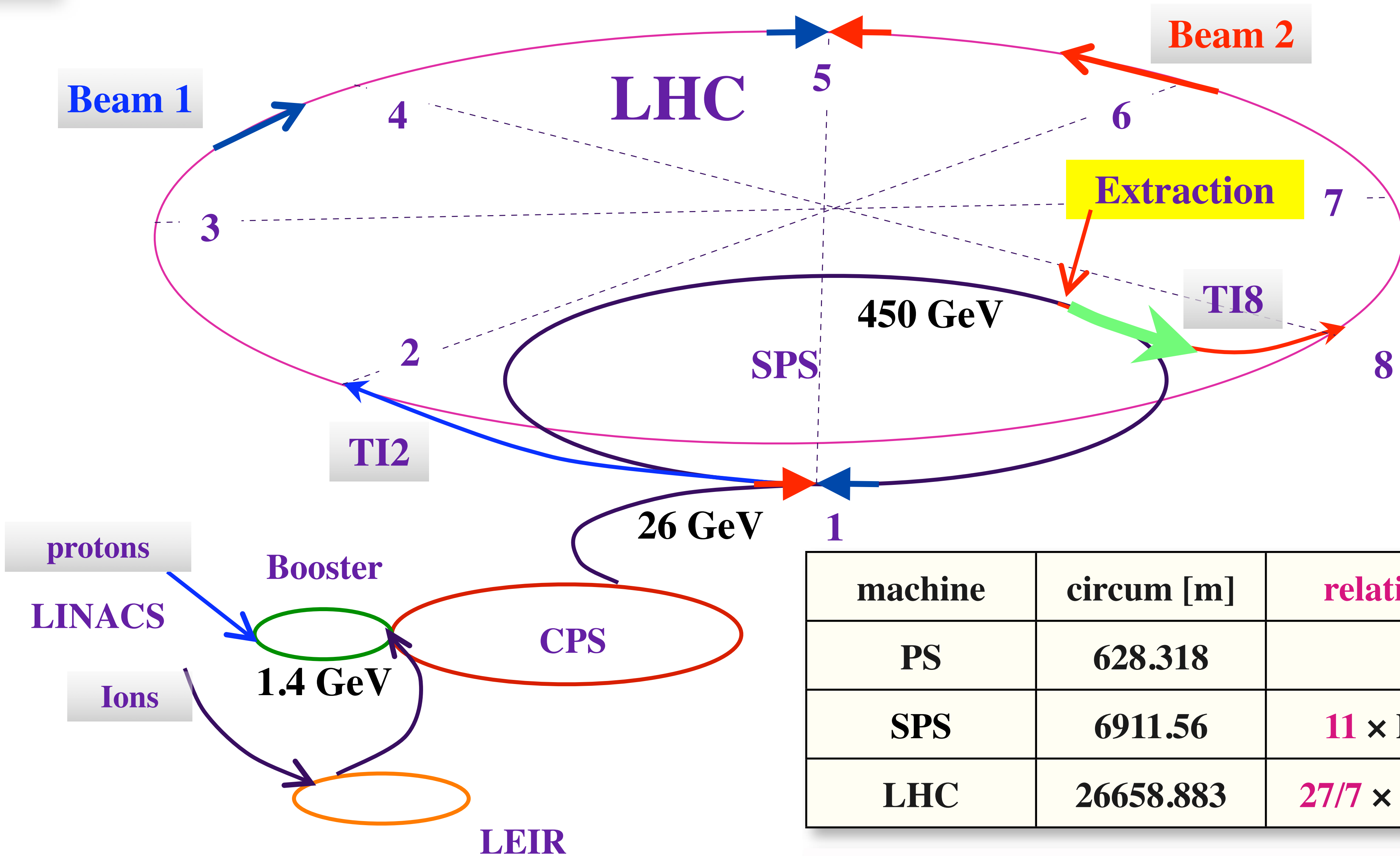
Beam parameters, LHC compared to LEP

	LHC	LEP2
Momentum at collision, TeV/c	7	0.1
Nominal design Luminosity, $cm^{-2}s^{-1}$	1.0E+34	1.0E+32
Dipole field at top energy, T	8.33	0.11
Number of bunches, each beam	2808	4
Particles / bunch	1.15E+11	4.20E+11
Typical beam size in ring, µm	200 – 300	1800/140 (H/V)
Beam size at IP, µm	16	200/3 (H/V)

- **Energy stored in the magnet system:** **10 GJoule** — Airbus A380, 560 t at 700 km/h
- **Energy stored in one (of 8) dipole circuits:** **1.1 GJ (sector)**
- **Energy stored in one beam:** **362 MJ** — 20 t plane
- **Energy to heat and melt one kg of copper:** **0.7 MJ**

the LEP2 total stored beam energy was about 0.03 MJ

The CERN accelerator complex : injectors and transfer



machine	circum [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

simple rational fractions for synchronization based on a single frequency generator at injection

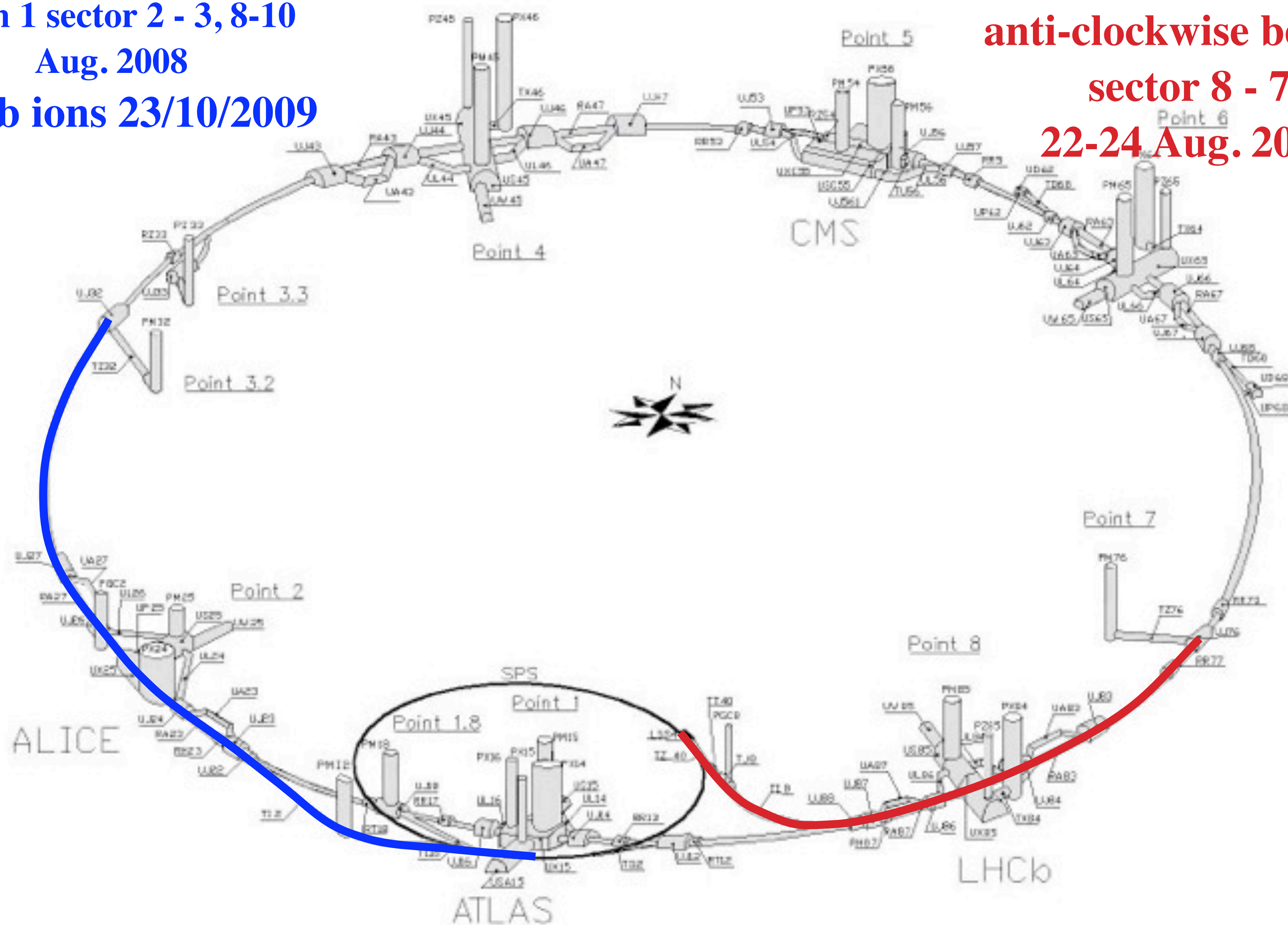
Beam size of protons decreases with energy : area $\sigma^2 \propto 1 / E$
Beam size largest at injection, using the full aperture

LHC Commissioning : injection tests in Aug'08 + Oct'09

1st Injection clockwise - beam 1 sector 2 - 3, 8-10 Aug. 2008

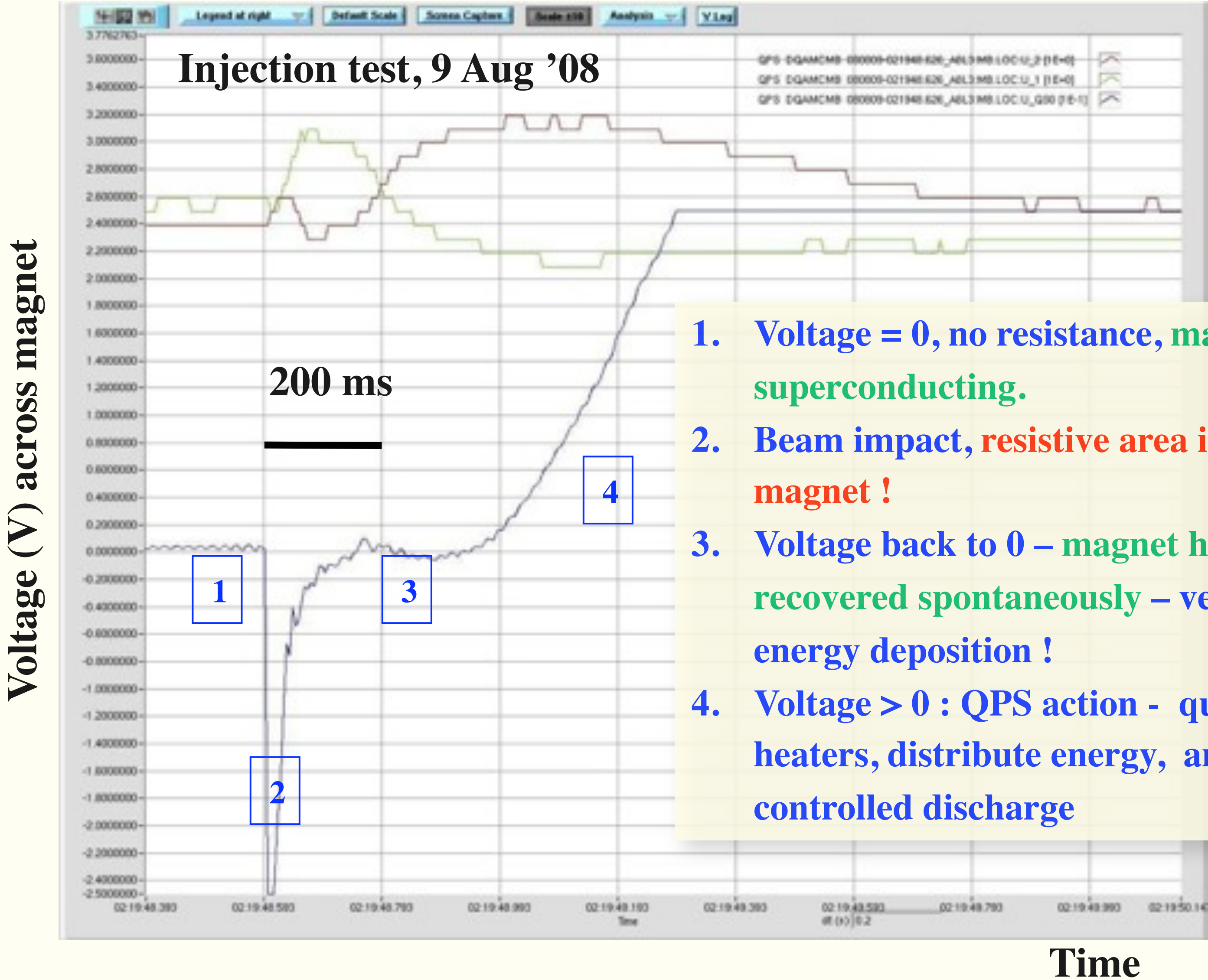
1st Pb ions 23/10/2009

2nd Injection anti-clockwise beam 2 sector 8 - 7 22-24 Aug. 2008



again over week-end 24-25 Oct 2009, with LHCb spectrometer compensation

Experience with beam : first beam induced quench



1. Voltage = 0, no resistance, magnet is superconducting.
2. Beam impact, resistive area in the magnet !
3. Voltage back to 0 – magnet has recovered spontaneously – very little energy deposition !
4. Voltage > 0 : QPS action - quench heaters, distribute energy, and controlled discharge

Local mini-quench
"quenchino"

verification of quench limit in magnets ~2×10^9 protons @ 450 GeV and calibration of BeamLossMon system

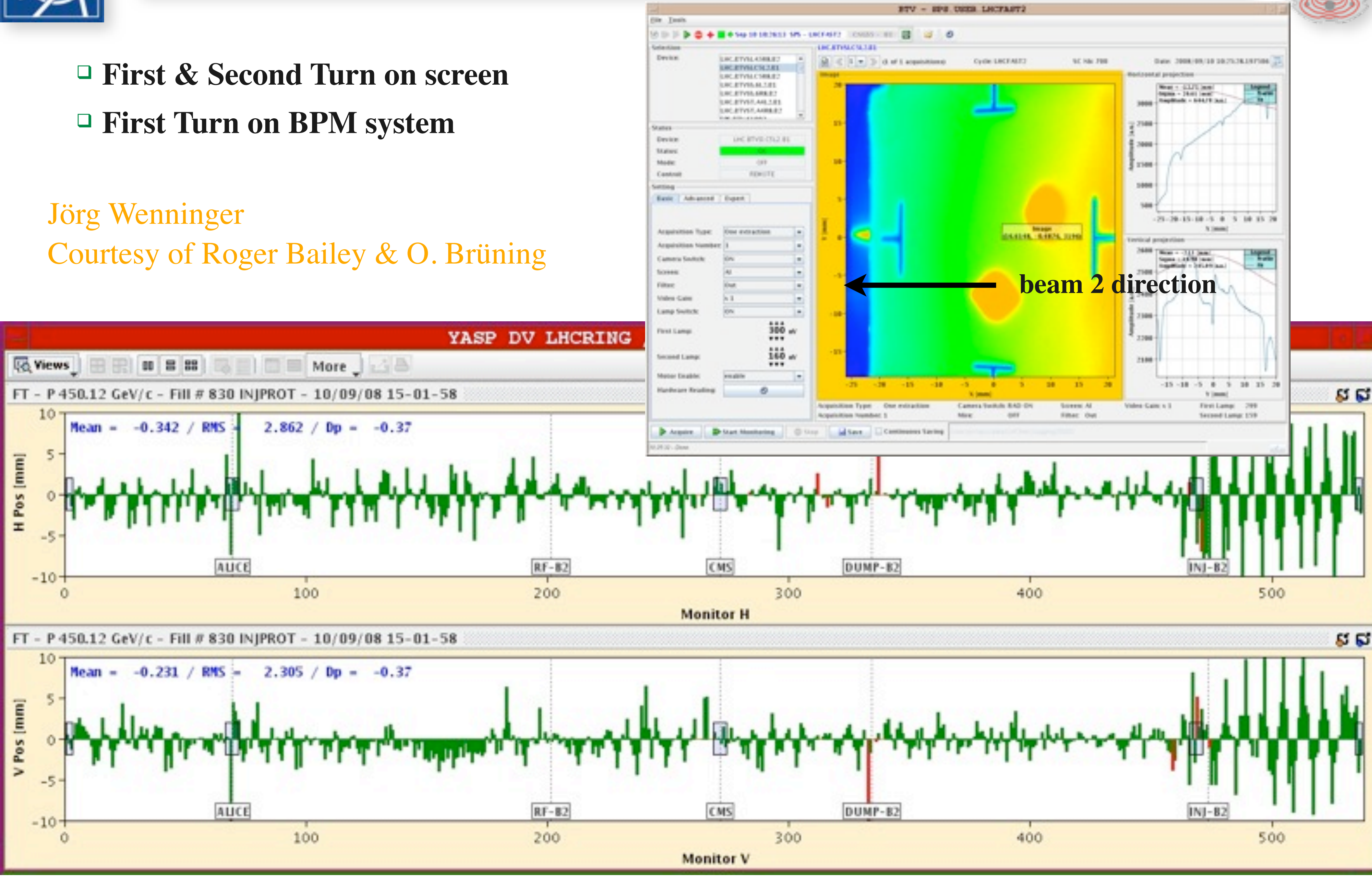
10 September 2008

10:30	beam 1	3 turns
15:00	beam 2	3 turns
22:00	beam 2	several 100 turns

First turn. 10 September 2008

- First & Second Turn on screen
- First Turn on BPM system

Jörg Wenninger
Courtesy of Roger Bailey & O. Brüning

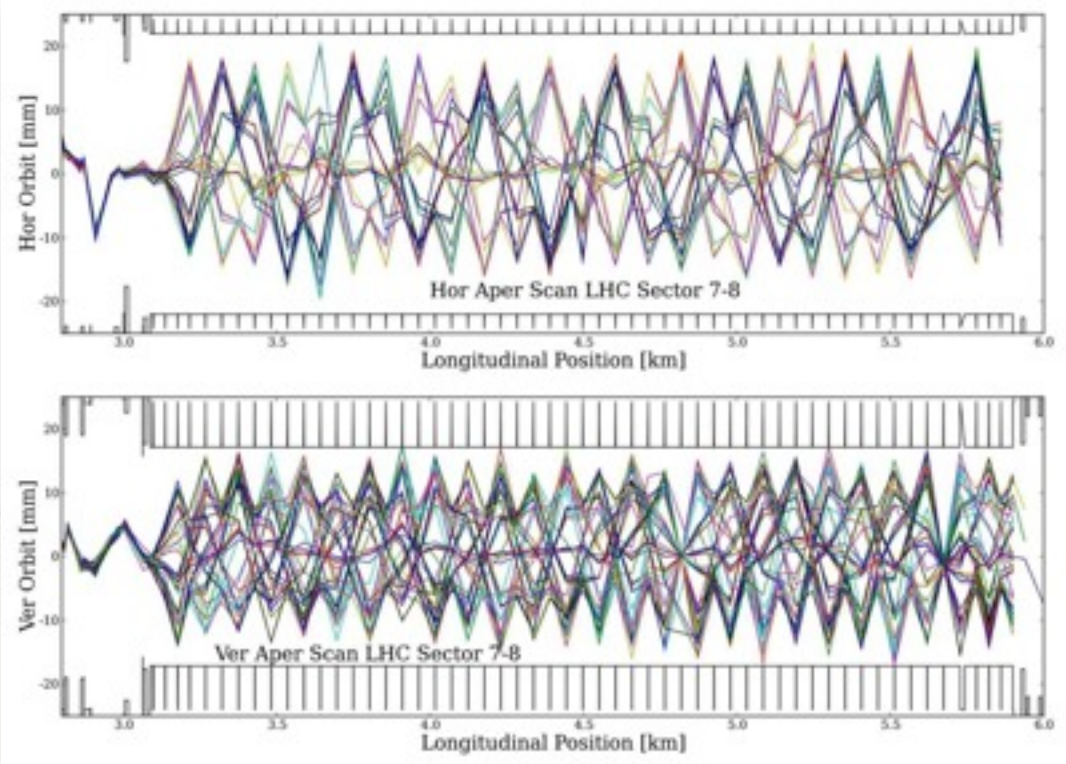


longitudinal position around the ring, *s* [m], here by monitor number

Examples of detailed aperture and optics measurements

H and V successfully scanned in the range ± 12 - 18 mm

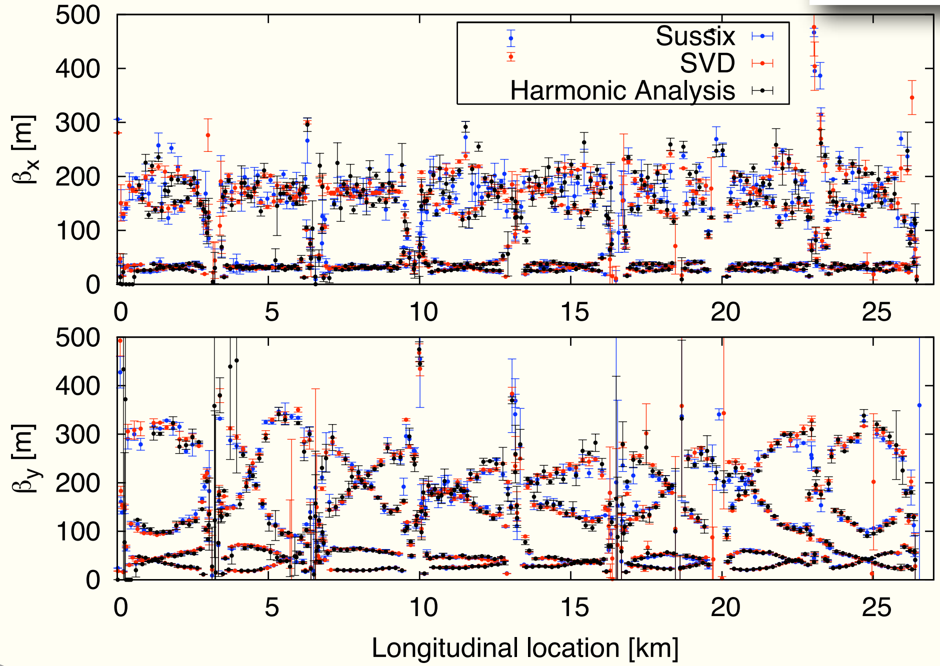
LHC Perf. Note 1 Sep.2008



β-measurements and analysis

LHC Perf. Note 8 Jan 2009

ABP and OP group

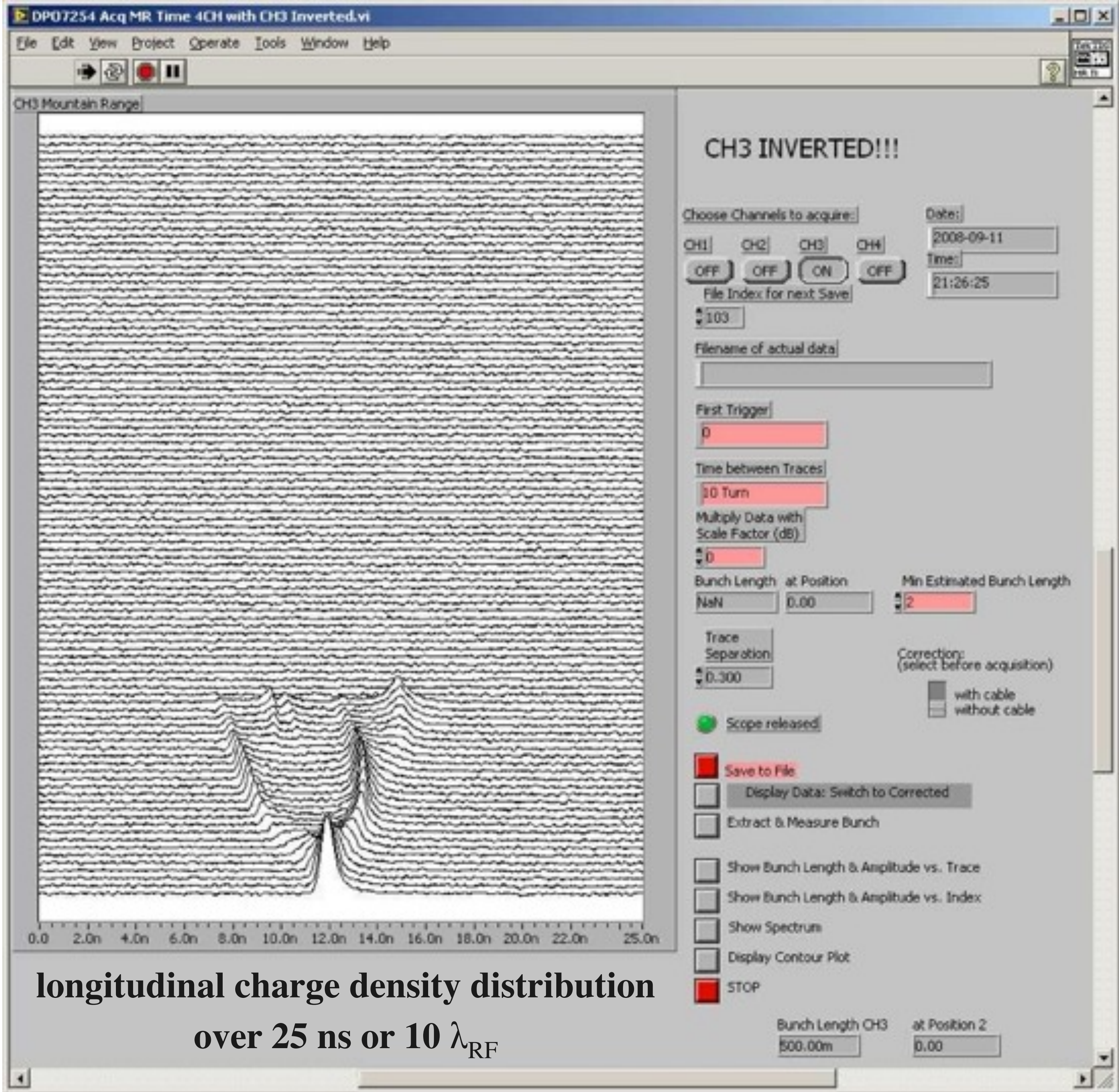


A lot was learned from the cold-checkout, injection tests and the few days with beams in the LHC in 2008. Instrumentation and software and analysis worked very well and allowed many measurements, detailed analysis and adjustments.

This also allowed to diagnose and later correct noisy channels and cabling error etc.

Textbook example : from first attempt to RF capture

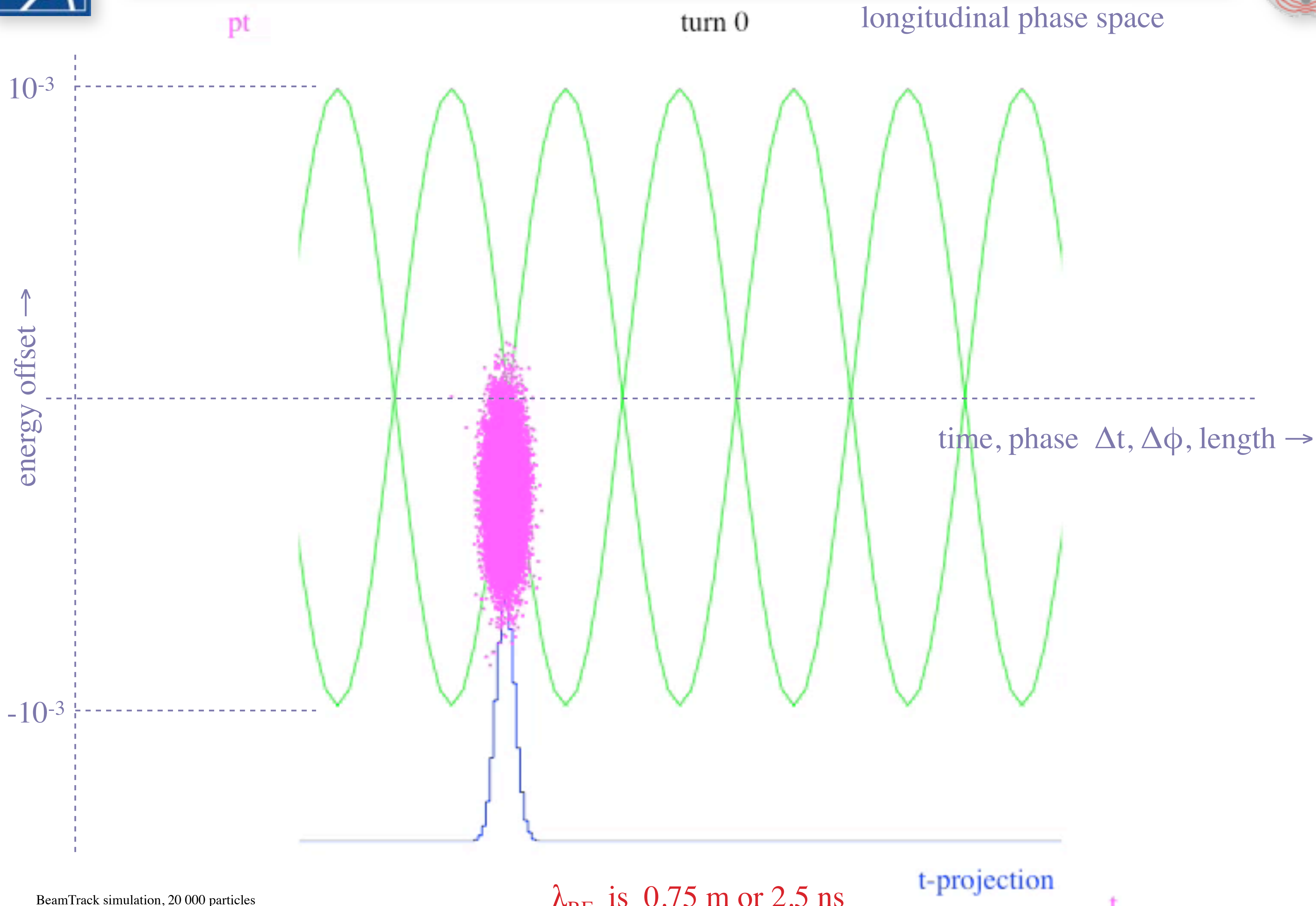
one trace every 10 turns



longitudinal charge density distribution

over 25 ns or 10 λ_{RF}

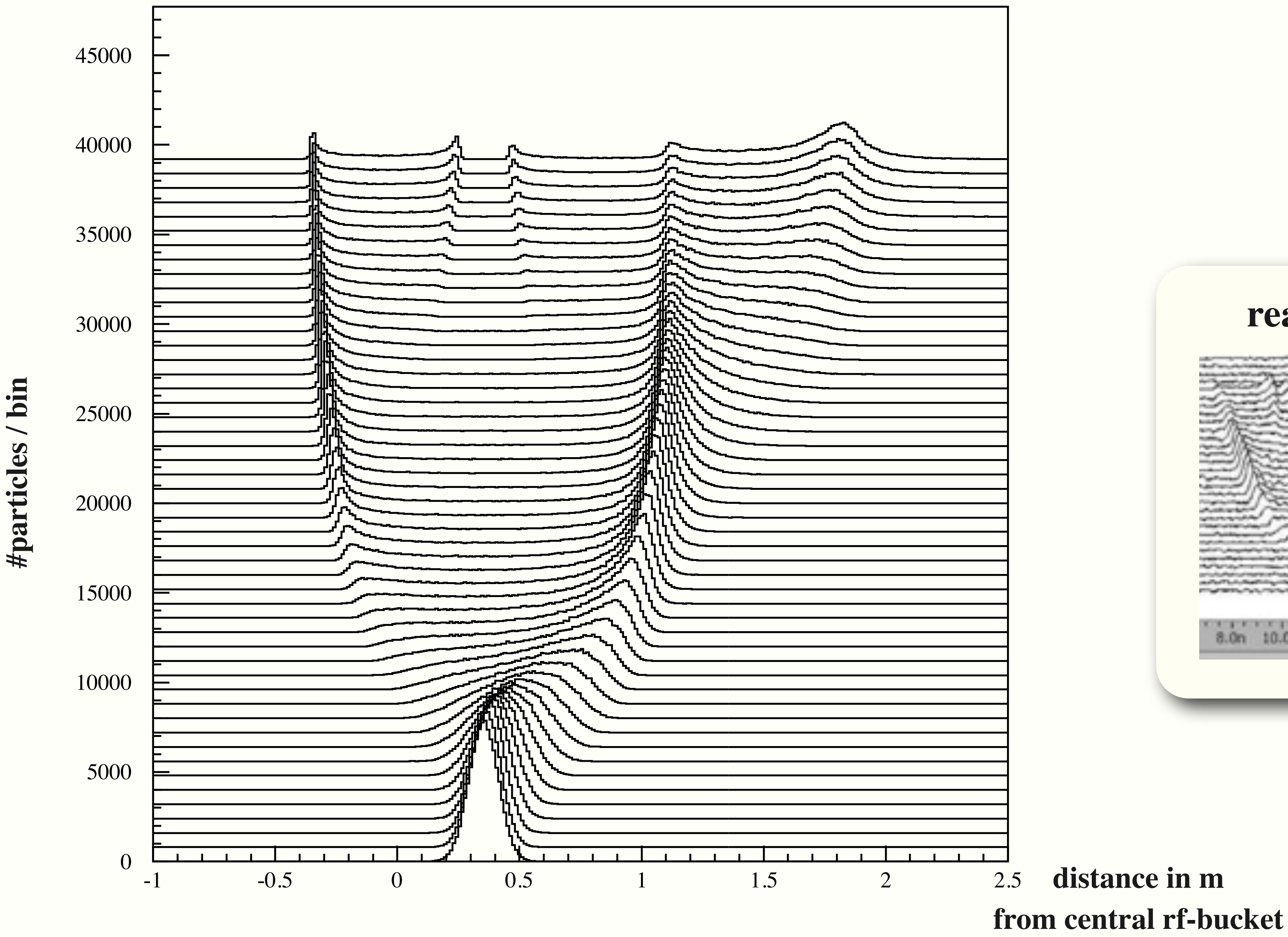
Simulation of injection with 170° injection phase offset



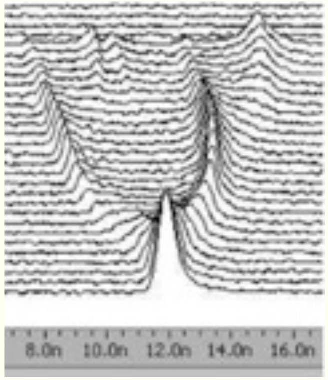
BeamTrack simulation, 20 000 particles

λ_{RF} is 0.75 m or 2.5 ns

Simulation of injection with 170° injection phase offset



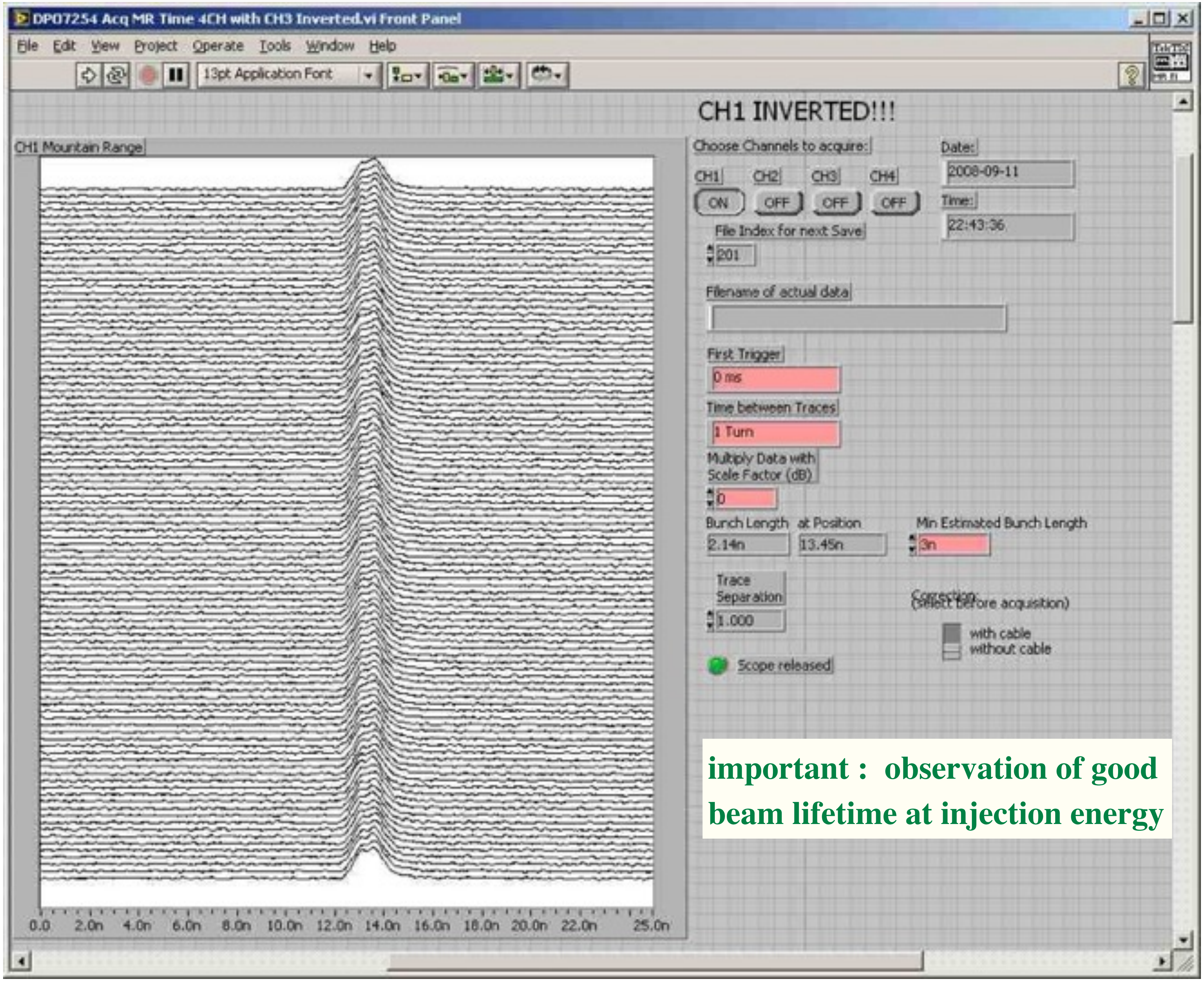
real LHC



projection of previous plot : longitudinal charge density distribution

BeamTrack simulation, 100 000 particles

LHC beam 2 with well adjusted RF capture



important : observation of good beam lifetime at injection energy

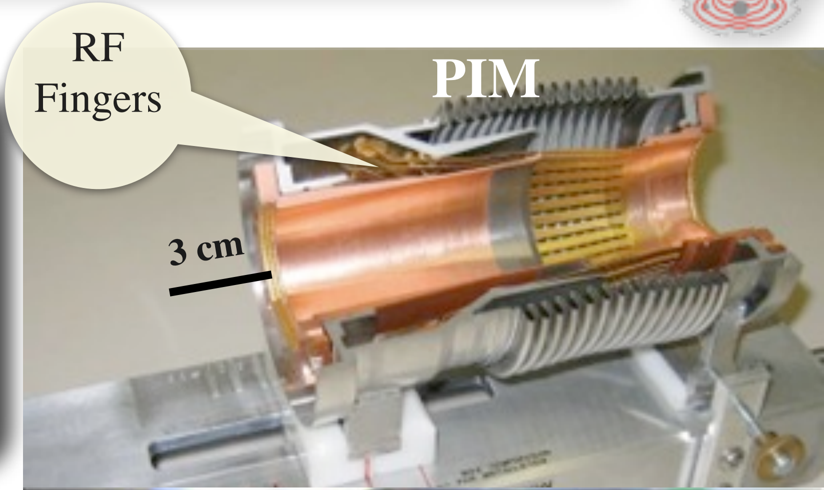
Critical Issues

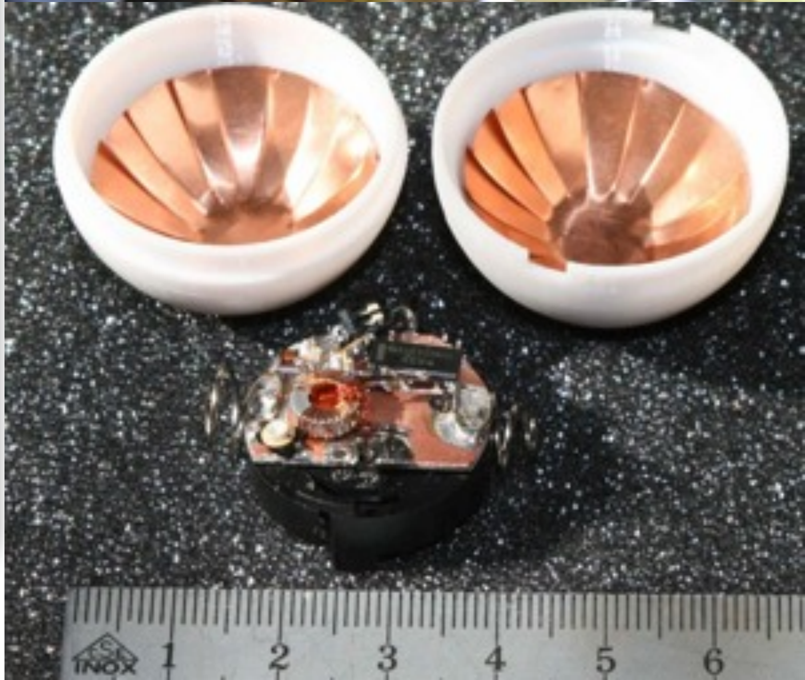
Past

- **QRL   cryo-line (He supply)**
- **DFB   power connections, warm to cold transition**
- **Triplet quadrupoles - differential pressure**

More recent

- **PIM** plug in module with bellow, systematically checked / repaired after warm up using "ping-pong" ball with RF-emitter : polycarbonate shell, ∅ 34 mm, 15 g, 2h battery powered, 40 MHz emitter, signals recorded by LHC BPM
- **Vacuum leaks, condensation - humidity sector 3/4**
- **Magnet powering**   check / correct : min/max, cabling - polarity
- **Single event upset,** radiation to electronics, shielding etc
- **Magnet re-training** magnets quenching below what was reached in SM18
- **Magnet interconnects, splices** ⇨

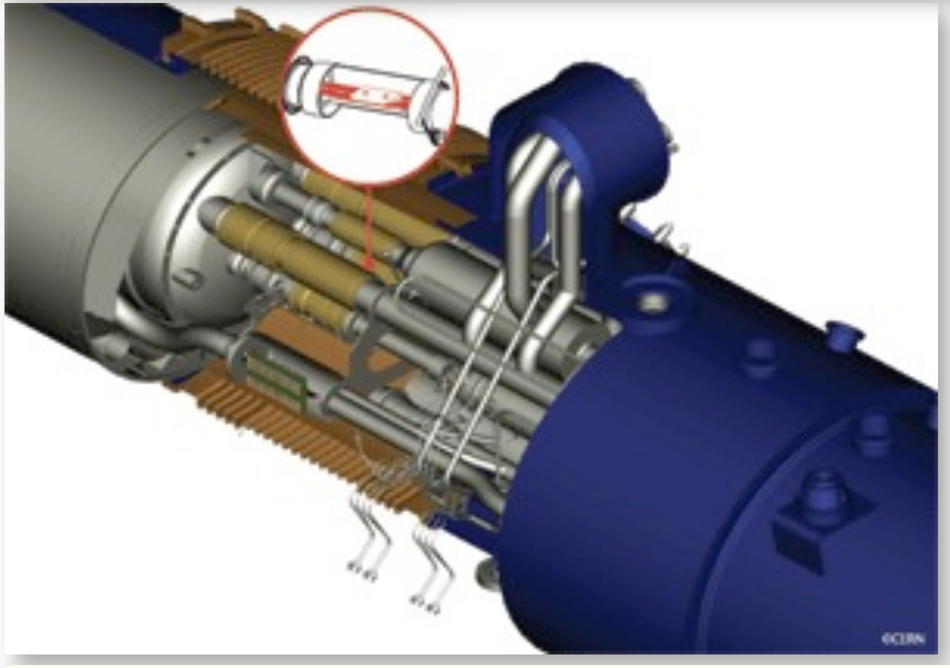




After 3 days of excellent progress with beams

Commissioning with beam interrupted by a series of hardware failures - not related to beams

- **two large transformers ; 13 - 18 September 2008 ’08**
- **19 Sept. ’08** at 11:18:36**, incident during hardware commissioning of sector 3/4 towards 5.5 TeV/ 9.3 kA, at 8.7 kA or ~ 5.2 TeV,** of the 600 MJ stored energy about 2/3 dissipated into the cold-mass 1 MJ melts 2.4 kg Cu



bad splice 220 nΩ at electrical connection between dipole and quad Q23, ~ 6 t He or 1/2 of arc lost; pressure built up in adjacent each 107 m long, vacuum sub-sectors causing significant collateral damage.

details : LHC-PROJECT-REPORT-1168 March ’09

some typical numbers and back of envelope estimates :

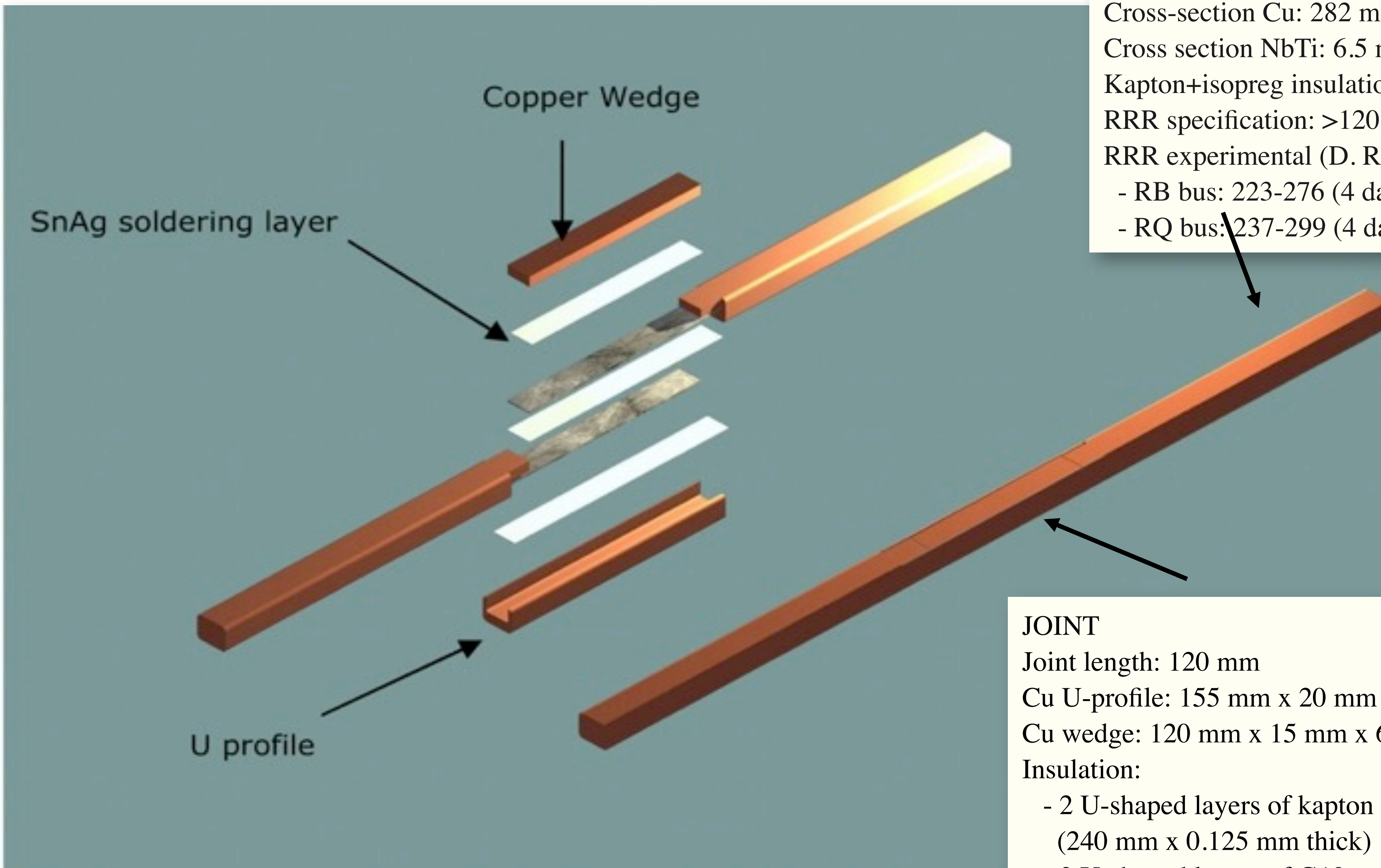
good splice ~ 0.3 nΩ, I = 12 kA, U = R I = 3.6 μV (now) possible to check

$P = R I^2 = 0.043$ W quench would need locally > 10 W - depending on position - less critical in magnet

new QPS triggers at 0.3 mV for > 10 ms

LHC dipole L = 100 mH stored energy in single dipole $I^2 L/2 = 7.2$ MJ × 154 = 1.1 GJ / sector

Busbar Splice



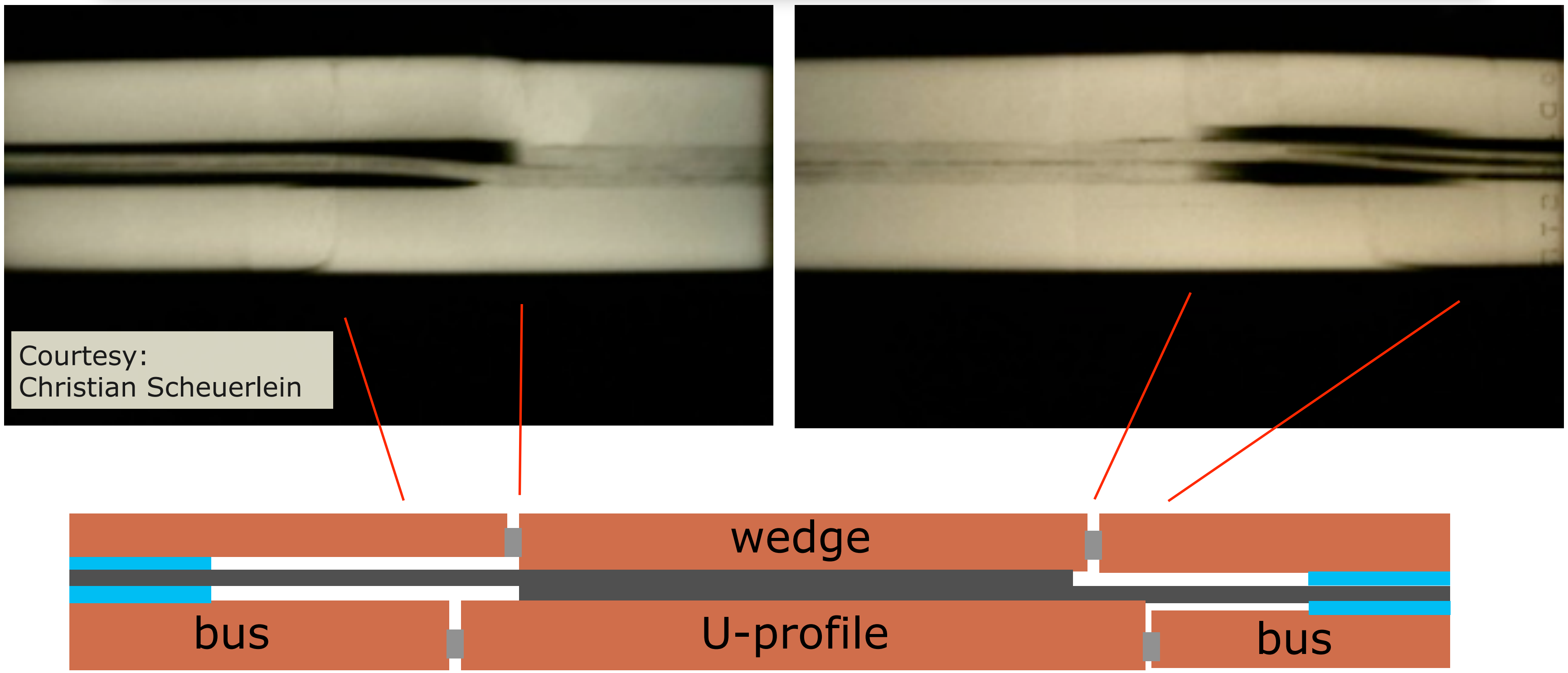
BUS
Cross-section Cu: 282 mm^2
Cross section NbTi: 6.5 mm^2
Kapton+isopreg insulation
RRR specification: >120
RRR experimental (D. Richter)
- RB bus: 223-276 (4 data)
- RQ bus: 237-299 (4 data)

JOINT
Joint length: 120 mm
Cu U-profile: 155 mm x 20 mm x 16 mm
Cu wedge: 120 mm x 15 mm x 6 mm
Insulation:
- 2 U-shaped layers of kapton (240 mm x 0.125 mm thick)
- 2 U-shaped layers of G10 (190 mm x 1 mm)

Busbar Splice

normal conducting, soldered electrical connection between SC cables

1684 units × 6 ≈ 10 000 splices at magnet interconnects; 1/3 dipole, 2/3 quads



A. Siemko et al. LMC 5/08/09

possible problems in soldering :

overheating - SnAg loss

too cold - SnAg unmelted, poor connection

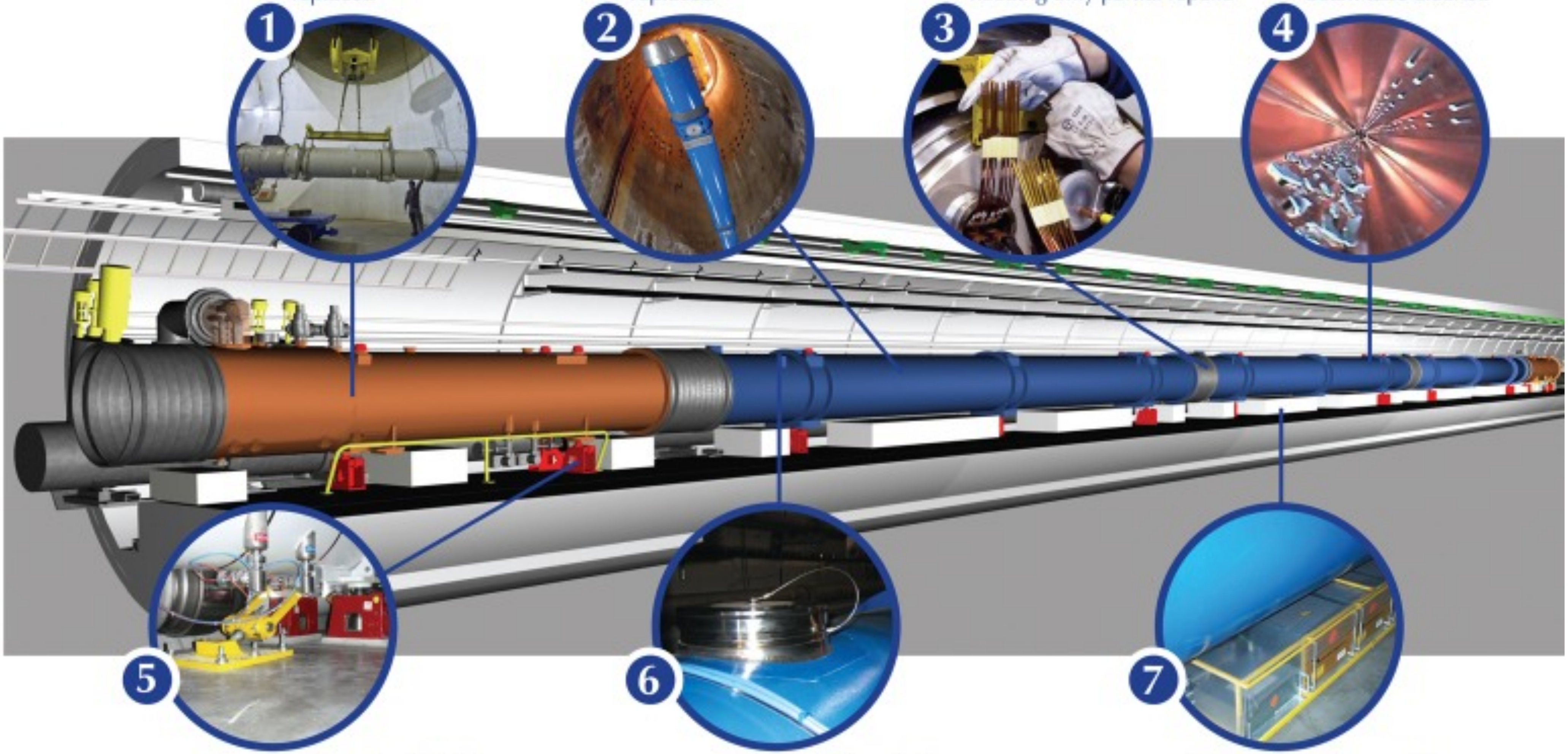
Now possible to diagnose : X-ray, ultrasound, resistance measurement.

Most reliable : resistance measured at room temperature

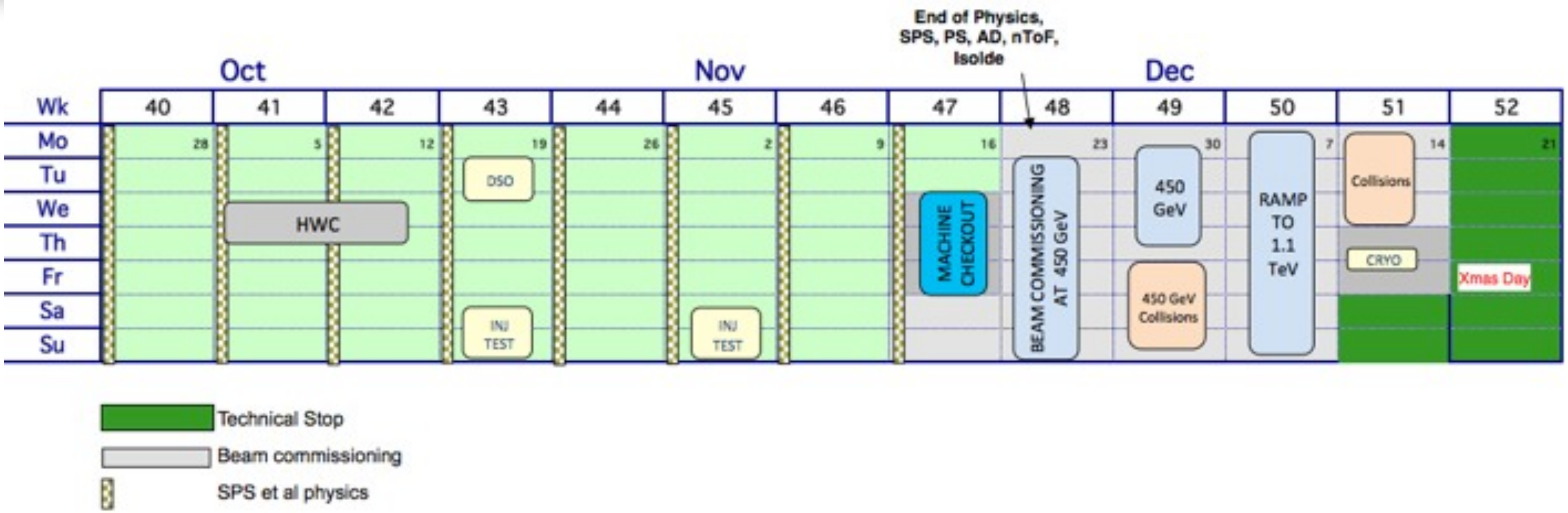
good : 10 μΩ dipole (RB) , 17 μΩ quadrupole (RQ).

Measured in 5 sectors which were warmed up. Fixed all above ~ 40 μΩ. Other sectors measured at 80 K

The LHC repairs in detail



End of year schedule



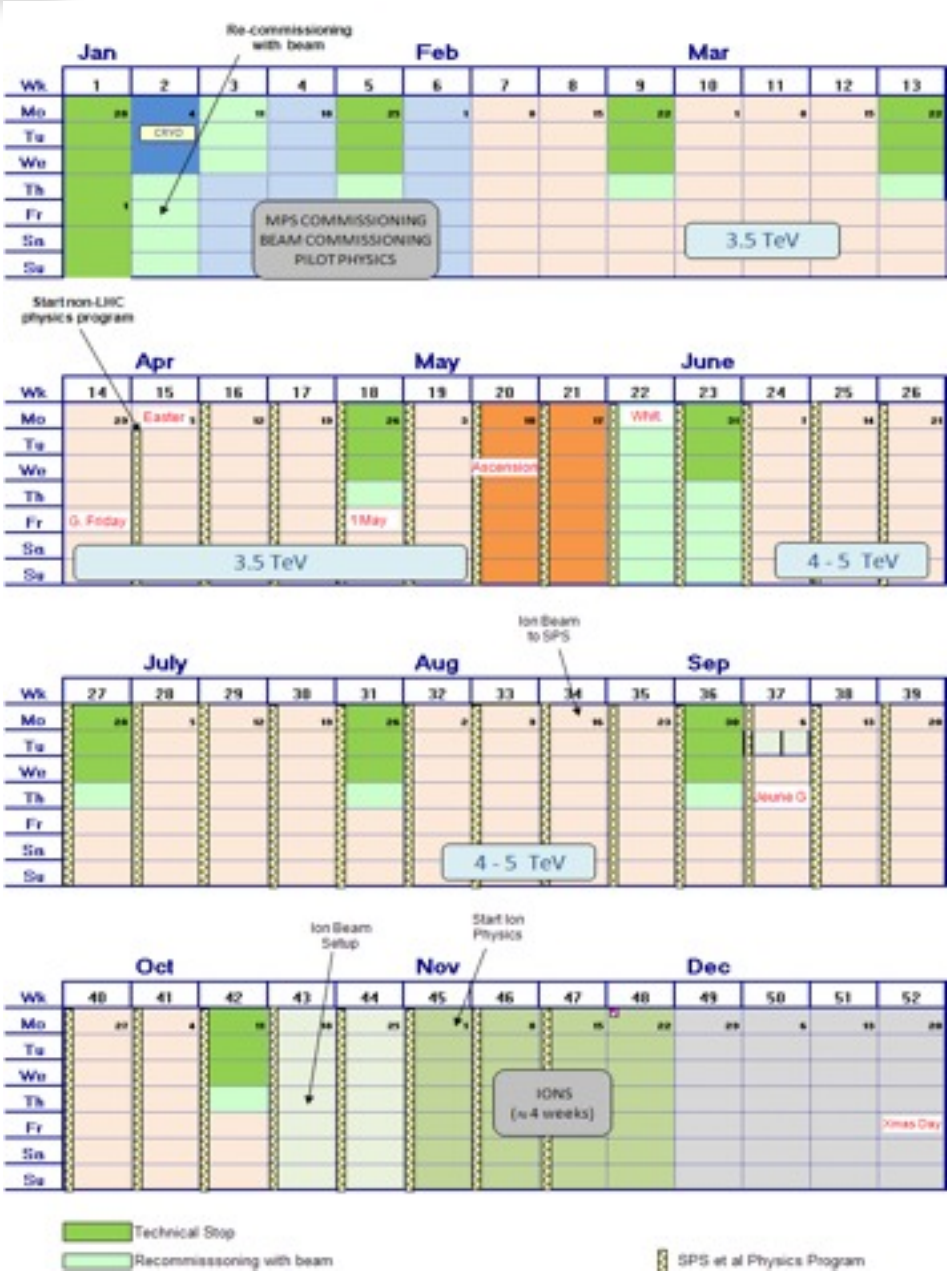
Preparation well advanced :

HW tests nearly completed, transfer lines tested ok inclusive ions !

Schedule from LPC 26-10-2009
Dipole current limited to 2kA in 2009, or just over 2 TeV E_{cm}

- All dates approximate…
- Reasonable machine availability assumed
- Stop LHC with beam ~17th December 2009, restart ~ 7th January 2010

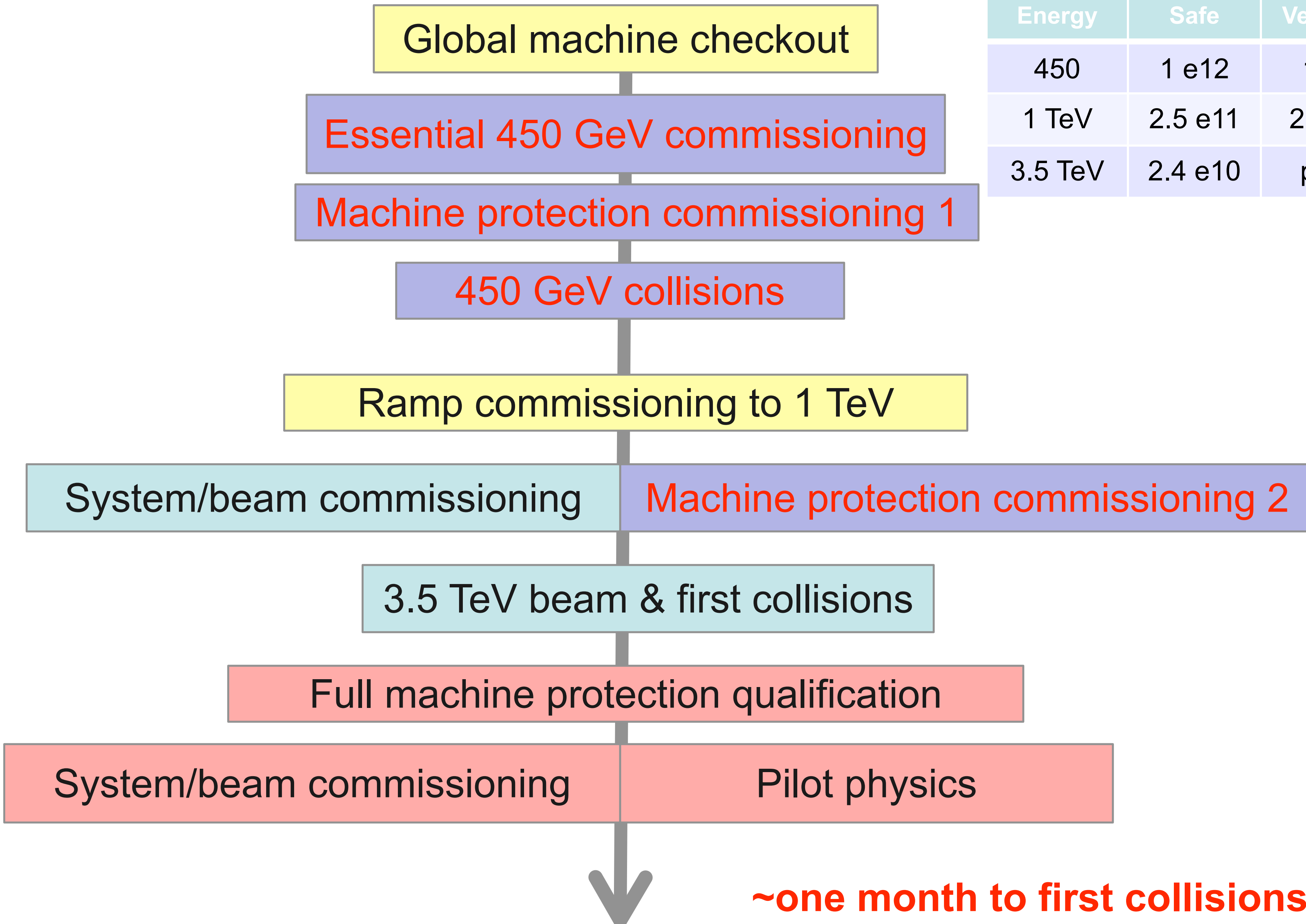
LHC 2010 schedule draft



- **2009**:
  - 1 month commissioning
- **2010**:
  - 1 month pilot & commissioning
  - 3 month 3.5 TeV
  - 1 month step-up
  - 5 month 4 - 5 TeV
  - 1 month ions

LHC beam commissioning

this and next slide : as discussed in Commis. WG + LMC and summarized by S.M. in Sept. ’09 LHCC



Energy	Safe	Very Safe
450	1 e12	1 e11
1 TeV	2.5 e11	2.5 e10
3.5 TeV	2.4 e10	probe

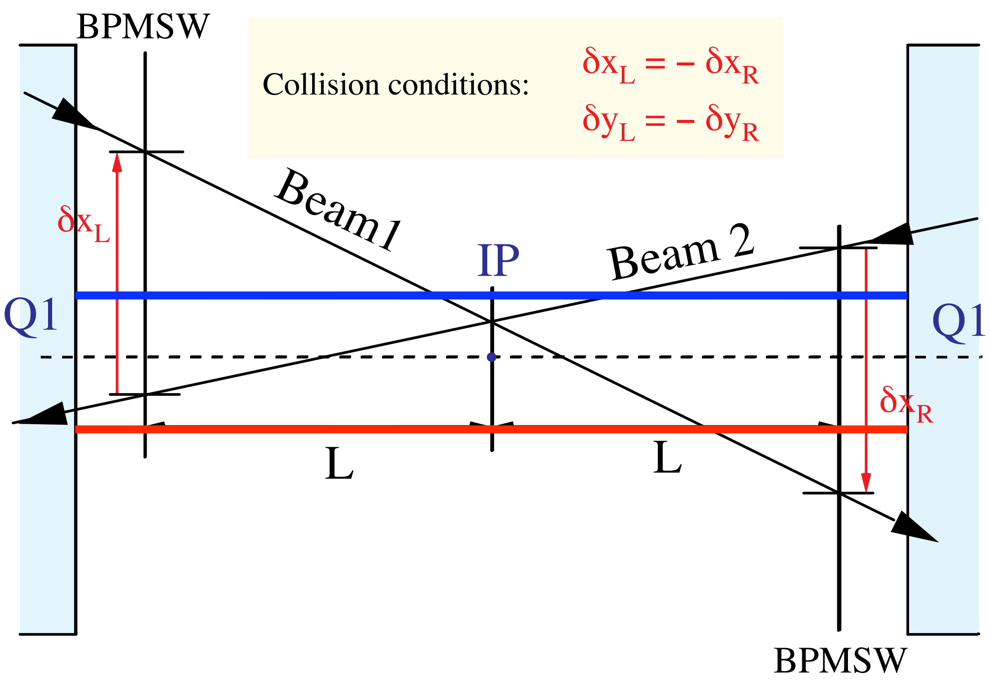
~one month to first collisions

LHC 09/10 parameters and rough luminosity estimate

Month	OP scenario	Max number bunch	Protons per bunch	Min beta*	Peak Lumi	Integrated	% nominal
1	Beam commissioning						
2	Pilot physics combined with commissioning	43	3×10^{10}	4	8.6×10^{29}	~200 nb^{-1}	
3		43	5×10^{10}	4	2.4×10^{30}	~1 pb^{-1}	
4		156	5×10^{10}	2	1.7×10^{31}	~9 pb^{-1}	2.5
5a	No crossing angle	156	7×10^{10}	2	3.4×10^{31}	~18 pb^{-1}	3.4
5b	No crossing angle – pushing bunch intensity	156	1×10^{11}	2	6.9×10^{31}	~36 pb^{-1}	4.8
6	Shift to higher energy: approx 4 weeks	Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity					
7	4 – 5 TeV (5 TeV luminosity numbers quoted)	156	7×10^{10}	2	4.9×10^{31}	~26 pb^{-1}	3.4
8	50 ns – nominal Xing angle	144	7×10^{10}	2	4.4×10^{31}	~23 pb^{-1}	3.1
9	50 ns	288	7×10^{10}	2	8.8×10^{31}	~46 pb^{-1}	6.2
10	50 ns	432	7×10^{10}	2	1.3×10^{32}	~69 pb^{-1}	9.4
11	50 ns	432	9×10^{10}	2	2.1×10^{32}	~110 pb^{-1}	12

Get LHC beams colliding : BPM resolution

adjust orbits such, that the beam 1 and 2 difference left/right of the IP is the same
beams must then collide. This is independent of mechanical offsets and crossing angles



nominal beam sizes at the IP			
	450GeV	3.5 TeV	5 TeV
β* [m]	σ* [μm]	σ* [μm]	σ* [μm]
11	293	105	88.0
3	153	54.9	45.9
2	125	44.8	37.5
1	88.4	31.7	26.5

$\frac{\delta x}{\sigma_x}$	$\frac{\delta y}{\sigma_y}$	$\mathcal{L}/\mathcal{L}_0$
0	0	1.0000
0.1	0	0.9975
0.2	0	0.9901
0.3	0	0.9778
0.4	0	0.9608
0.5	0	0.9394
0.5	0.5	0.8825
1	0	0.7788
1	1	0.6065
2	0	0.3679
2	2	0.1353

measured with special (beam-) directional strip-line couplers BPMSW, at about L = 21 m left and right of the IP in front of Q1 in each IR. Resolution each plane $\delta_{\mathrm{IP}} = \sigma_{\mathrm{BPM}}$

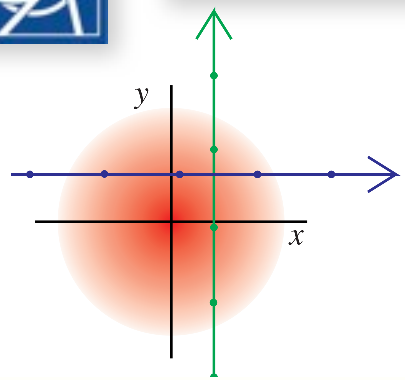
Expected resolution for small separation and 0 crossing angle ; in each plane.

~ 50 μm using selected, paired electronics ; otherwise ~ 100 - 200 μm
beam 1 and beam 2 have separate electronics

~ 10 μm with extra BPMWF button pick-ups. Installed in 1&5, for large bunch spacing, EDMS doc 976179

Luminosity scans and absolute luminosity

(pioneered by Van der Meer @ ISR)



Orthogonal x, y scans to determine $\sigma_{x,y}$*

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi\, \sigma_x\, \sigma_y}$$

$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left[-\left(\frac{\delta x}{2\sigma_x}\right)^2 - \left(\frac{\delta y}{2\sigma_y}\right)^2\right]$$ gaussian beams

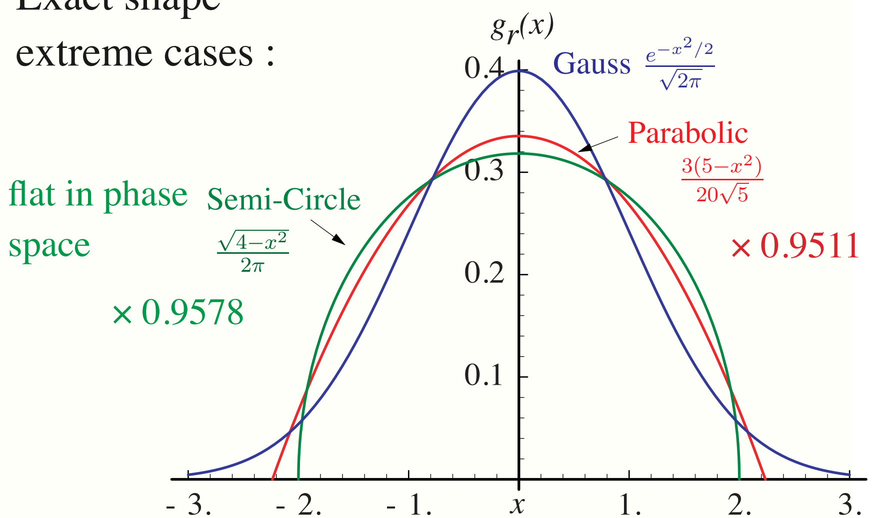
Accuracy : better than **1% at ISR**

Aim for **early LHC ~ 10 %** (done @ RHIC)

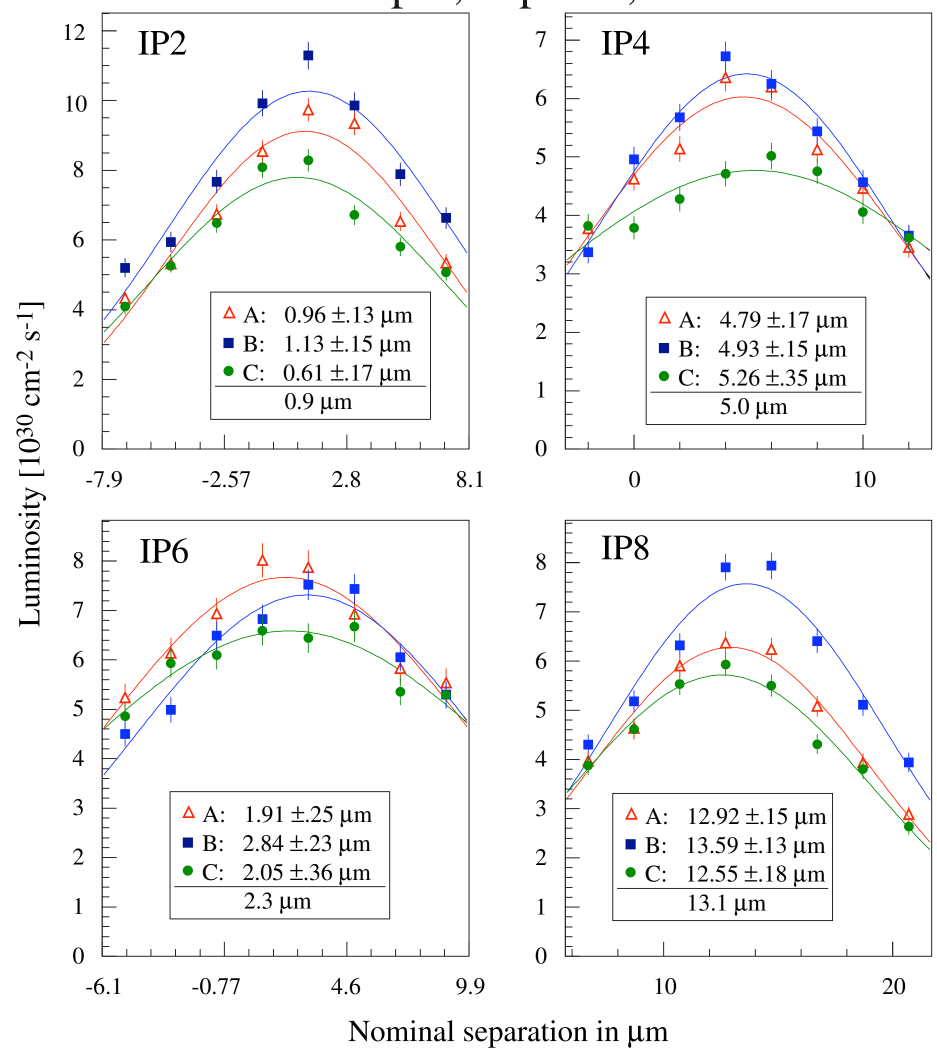
Contributions :

- Intensity $N_{1,2}$ BCT ~1%
- Length scale - from BPM, bumps optics, few %
- Particles in tails
- Exact shape

  extreme cases :



LEP example, V-plane, 3 bunches



studied by Simon White - as PhD thesis.

principle : H.B. and Per Grafstrom; LHC Report 1019 from 23 May 2007 http://cdsweb.cern.ch/record/1056691

and H.B., R. Schmidt, *Intensity and Luminosity after Beam Scraping*, CERN-AB-2004-032

Physics plans

The physics program is made by the physics community (you; not the machine)

To my knowledge the program is basically :

- always run at highest possible energy
- get the maximum integrated luminosity

with few exceptions :

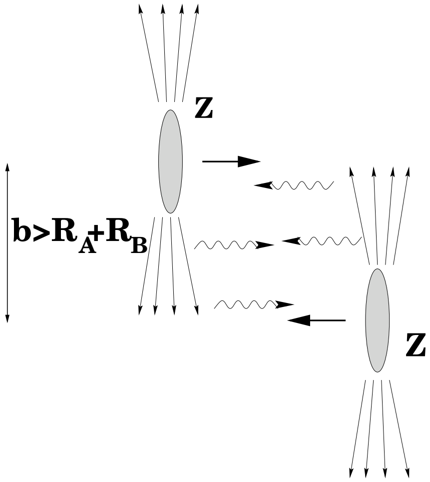
- **heavy ion runs (Pb-Pb, maybe later also other ions)**
- **high β* TOTEM and later ALFA operation - for forward (diffractive) physics, σ_{tot}**

Any other ideas and requests ?

LHC constraints : $E_{b1} = E_{b2}$, same sign of charge, no polarisation

What about

- **Precision and knowledge of beam-parameters - energy and luminosity calibration, vertex precision and stability**
- **interest in UPCs, γγ ? as discussed in pAworkshop2 and 0706.3356**



ultraperipheral p, Ion

Concluding remark

The LHC is the worlds largest and most energetic machine. We also all know that it is not an easy machine and already faced and solved many difficulties.

Interventions which require warmup / cool down of sectors imply month's without circulating beams.

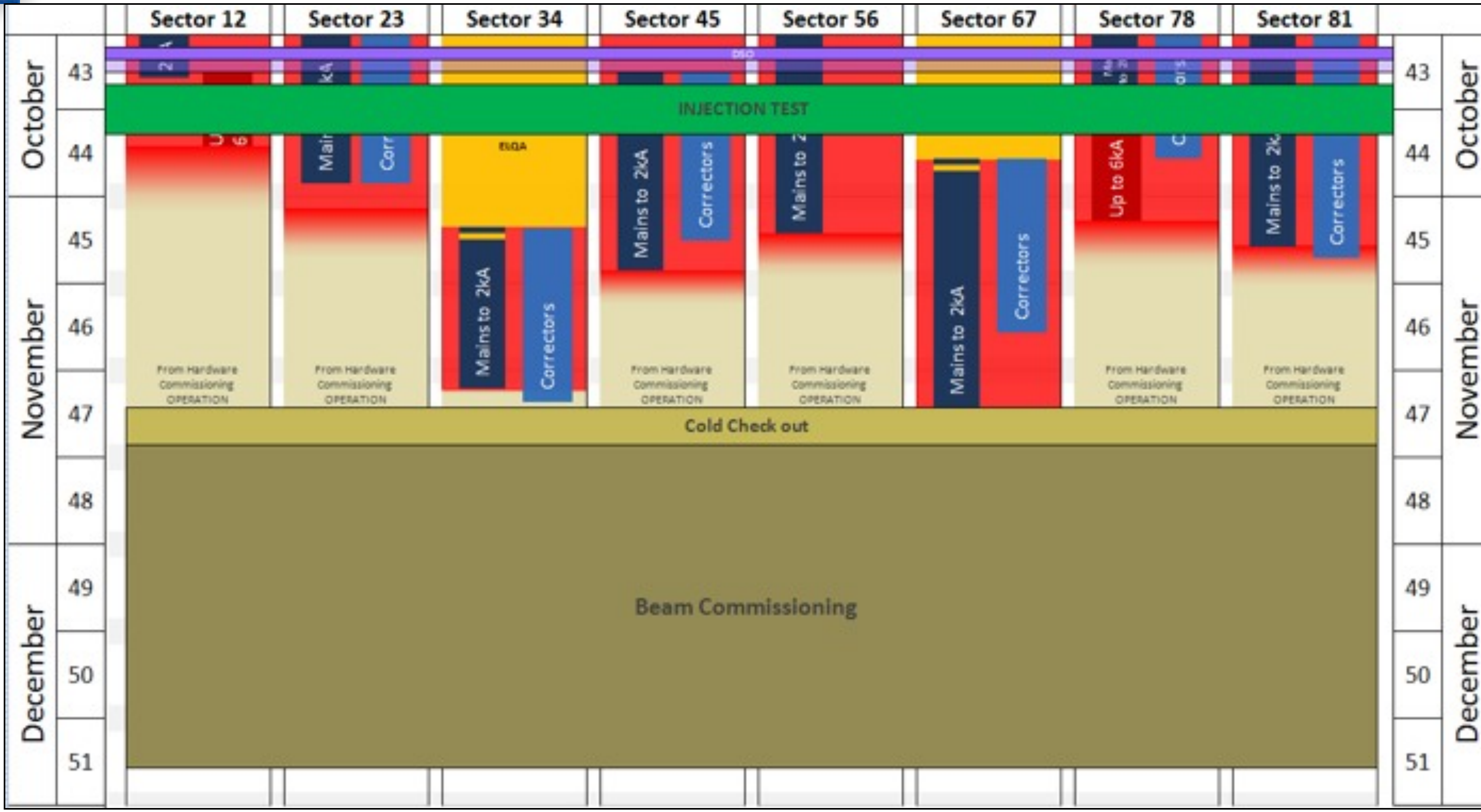
We had an excellent start of the LHC with beams in 2008 getting quickly both beams around the ring and good lifetime in only 3 days !

The current repair and shutdown is also used to further improve the preparations for beams for physics.

The LHC is scheduled to restart in mid November'09. First collisions will be at injection energy and the first high energy physics run at 3.5 TeV beam energy. During 2010 the energy will be increased towards 5 TeV. A run with lead-ions is scheduled towards the end of the run later in 2010.

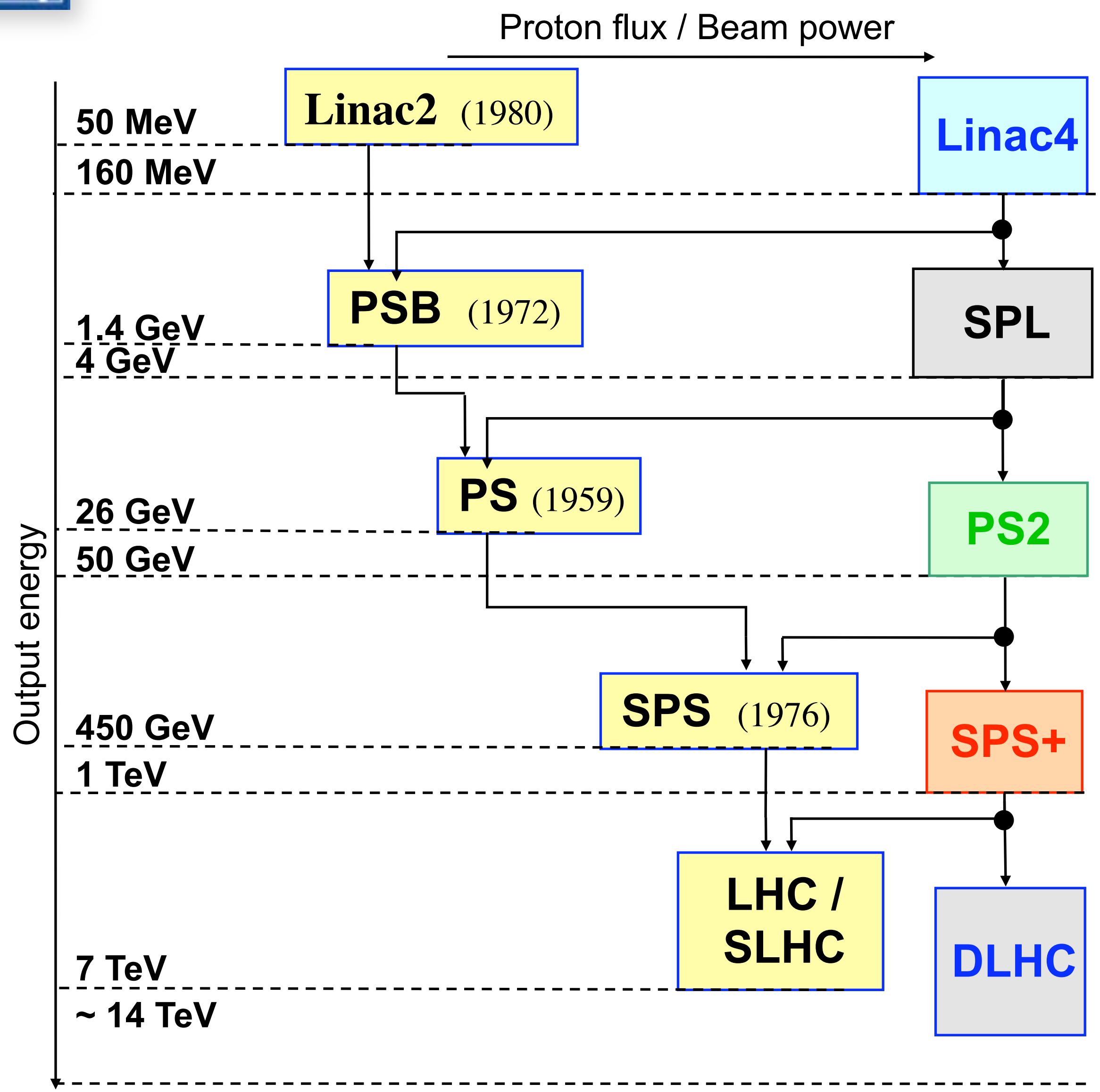
Backup Slides

Schedule 2009



by Katy Foraz, presented by M. Lamont LPC 26 Oct 2009

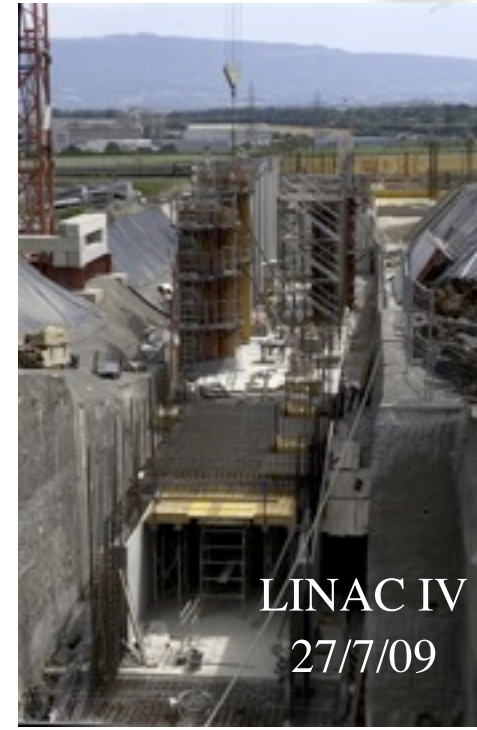
Upgrade options and future machines



started : ready in 2013-14

if approved could be ready by about 2018

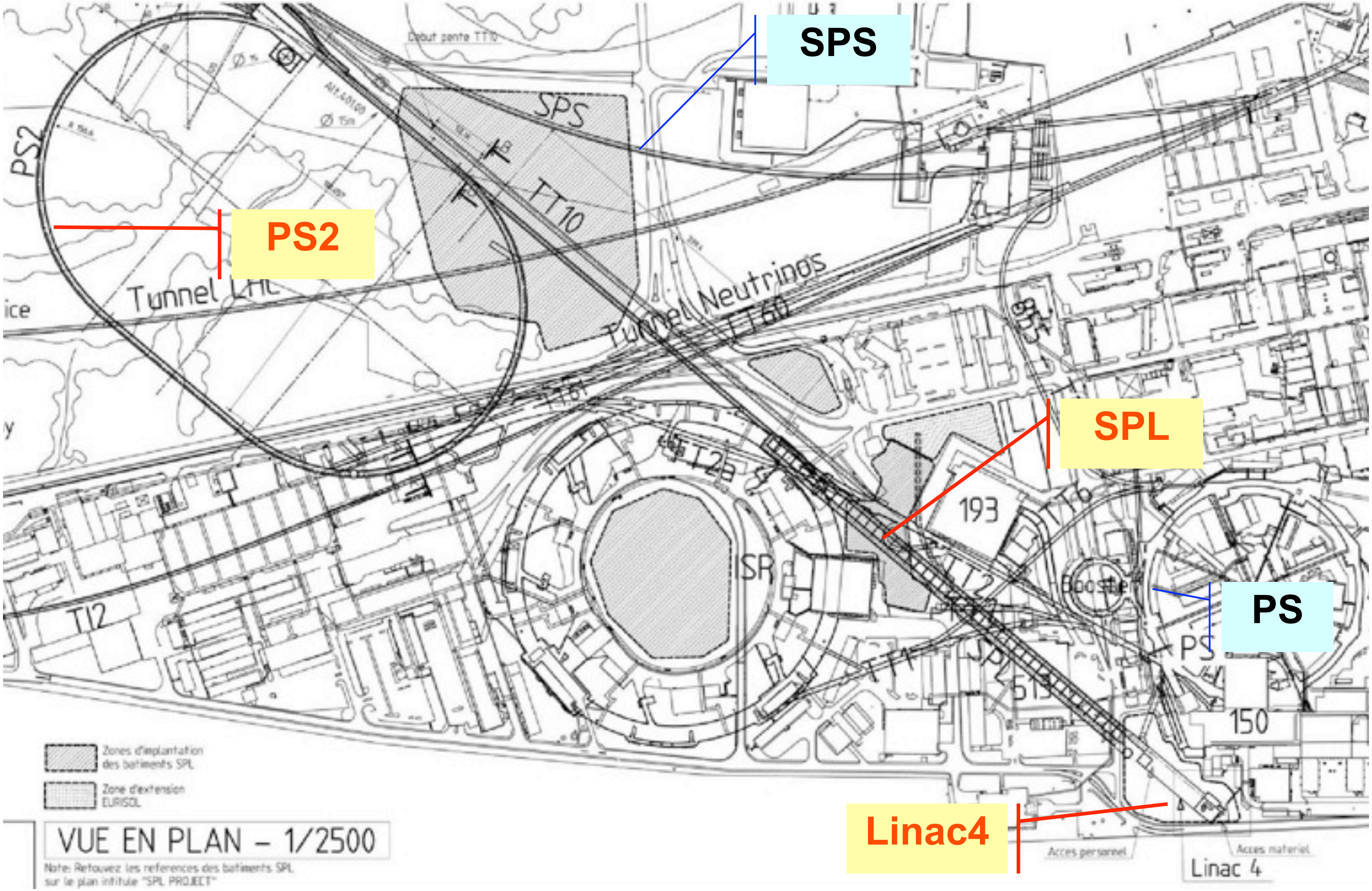
2018 ?



SPL: Superconducting Proton Linac (4 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

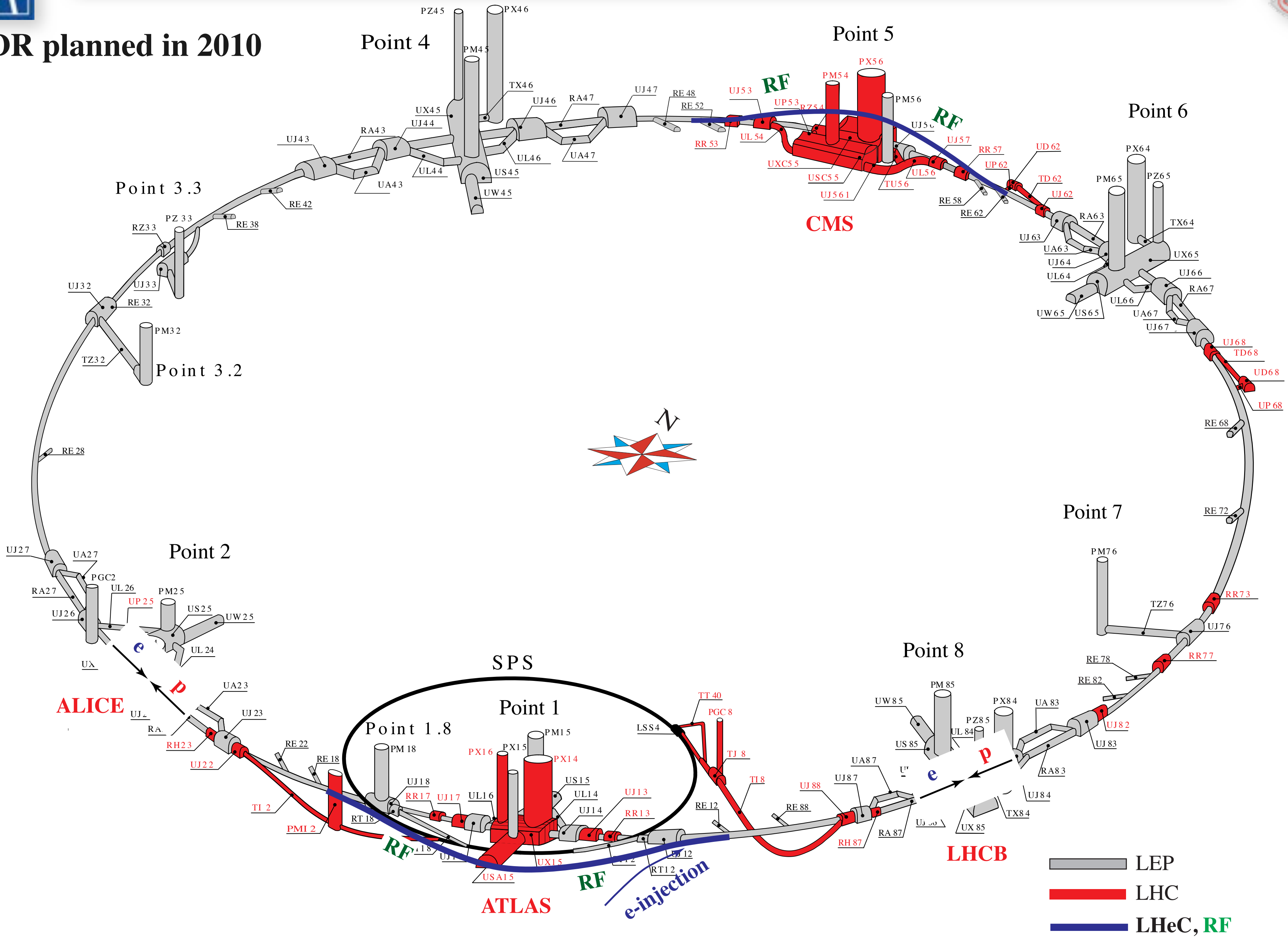
SLHC 1st step : replace current triplet by new larger aperture triplet, by ~ 2014

Layout of planned new CERN injectors



LHeC

CDR planned in 2010



Nominal filling pattern - bunches, buckets and crossing angle

f_{RF} = 400.7896 MHz

λ_{RF} = 0.748 m or 2.4951 ns

35 640 RF buckets

Bunches spaced by 25 ns or 10 buckets

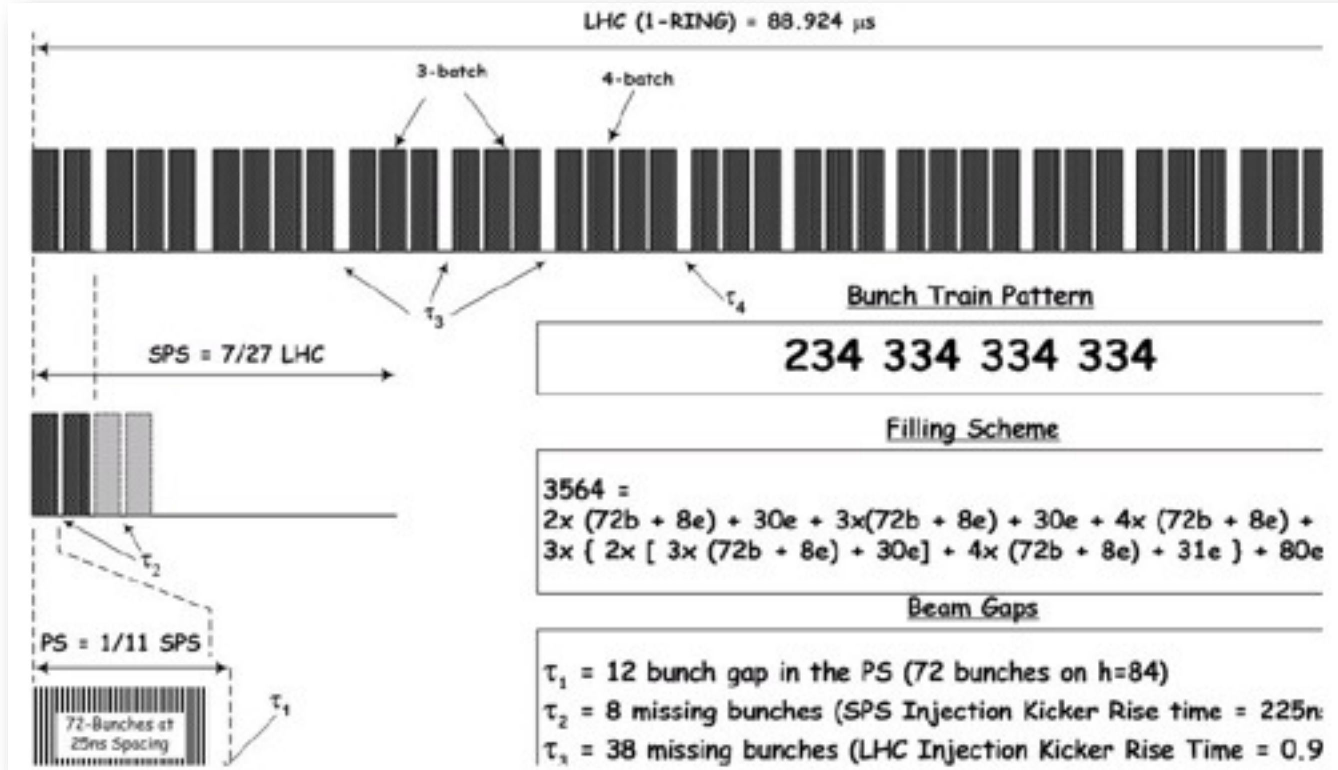
Inject batches of 2, 3 or 4 x 72 bunches

1 batch = 72 bunches

total 39×72 = 2808 bunches

Leave a 119 bunch abort gap free ~ 3 µs

A full LHC turn is 88.9244 µs

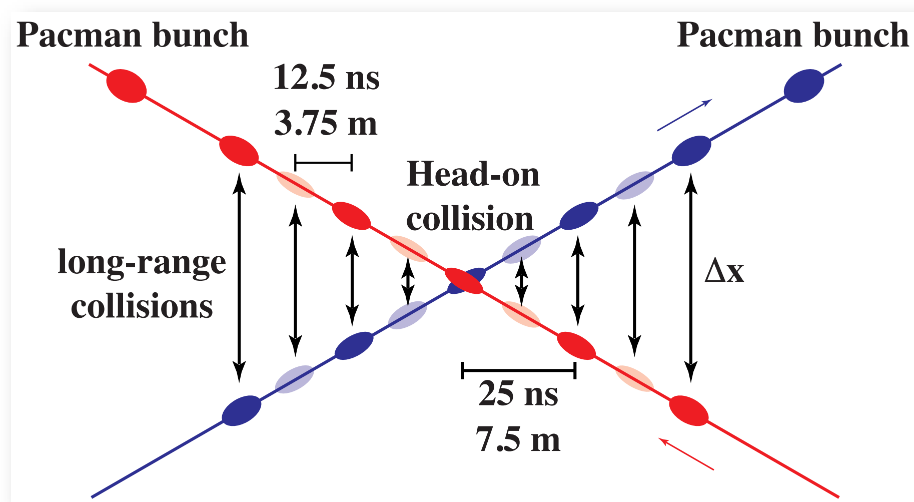


Crossing angle needed for > 156 bunches to avoid encounters closer than ~ 6 σ

Angle scales with σ or 1/√β* and 1/√E_b

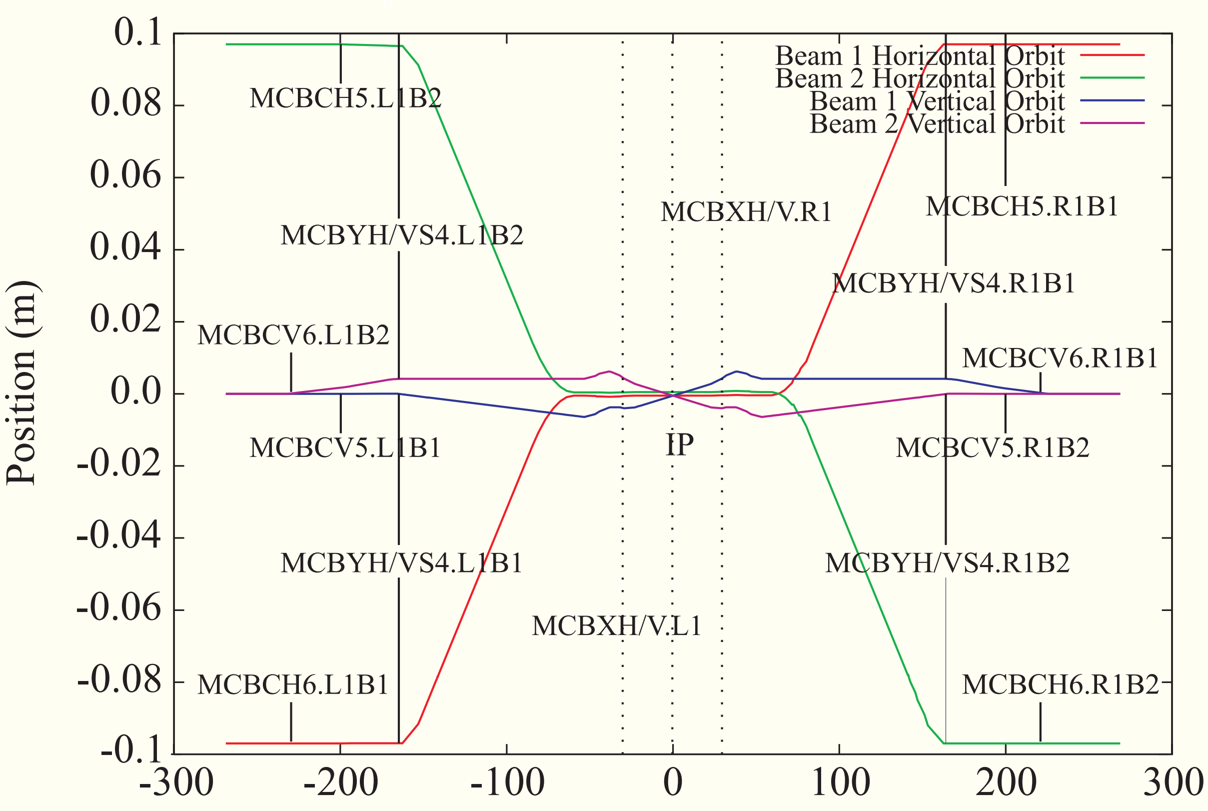
Nominal angle at 0.55 m, 7 TeV is ± 142.5 µrad

2×15 parasitic crossings ±58m from IP at 7.5 – 13 σ



IR-bump details

two types of magnetic separation bumps :
parallel separation to avoid collisions in beam preparation, off in physics
crossing angle to avoid parasitic collisions, always required for > 156 bunches
IR1 : horizontal separation and vertical crossing angle
IR5 : vertical separation and horizontal crossing angle



courtesy Simon White

orbit corrector magnets used in the IP bumps

MCBX in triplet - important for crossing angle and aperture at injection

collapse bump by combination of MCBC, MCBY and MCBX
or ramp down MCBX first

Separation scans, optimization with MCBC, MCBY on one beam

LHC news, R.Heuer DG 6/08/2009

The LHC will run for the first part of the 2009-2010 run at 3.5 TeV per beam, with the energy rising later in the run. That's the conclusion that we've just arrived at in a meeting involving the experiments, the machine people and the CERN management. We've selected 3.5 TeV because it allows the LHC operators to gain experience of running the machine safely while opening up a new discovery region for the experiments.

The developments that have allowed us to get to this point are good progress in repairing the damage in sector 3-4 and the related consolidation work, and the conclusion of testing on the 10000 high-current electrical connections last week. With that milestone, every one of the connections has been tested and we now know exactly where we stand.

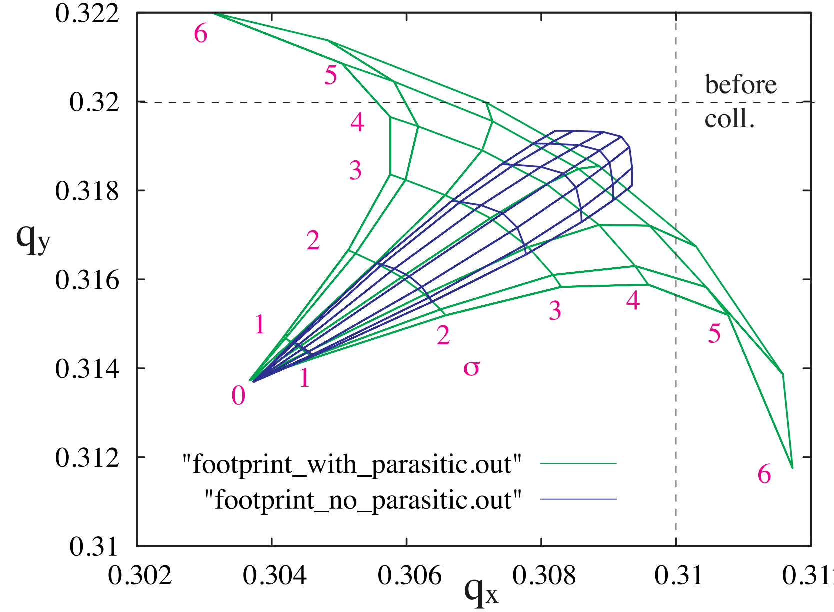
The latest tests looked at the resistance of the copper stabilizer that surrounds the superconducting cable and carries current away in case of a quench. Many copper splices showing anomalously high resistance have been repaired already, and the tests on the final two sectors revealed no more outliers. That means that no more repairs are necessary for safe running this year and next.

The procedure for the 2009 start-up will be to inject and capture beams in each direction, take collision data for a few shifts at the injection energy, and then commission the ramp to higher energy. The first high-energy data should be collected a few weeks after the first beam of 2009 is injected. The LHC will run at 3.5 TeV per beam until a significant data sample has been collected and the operations team has gained experience in running the machine. Thereafter, with the benefit of that experience, we'll take the energy up towards 5 TeV per beam. At the end of 2010, we'll run the LHC with lead-ions for the first time. After that, the LHC will shut down and we'll get to work on moving the machine towards 7 TeV per beam.

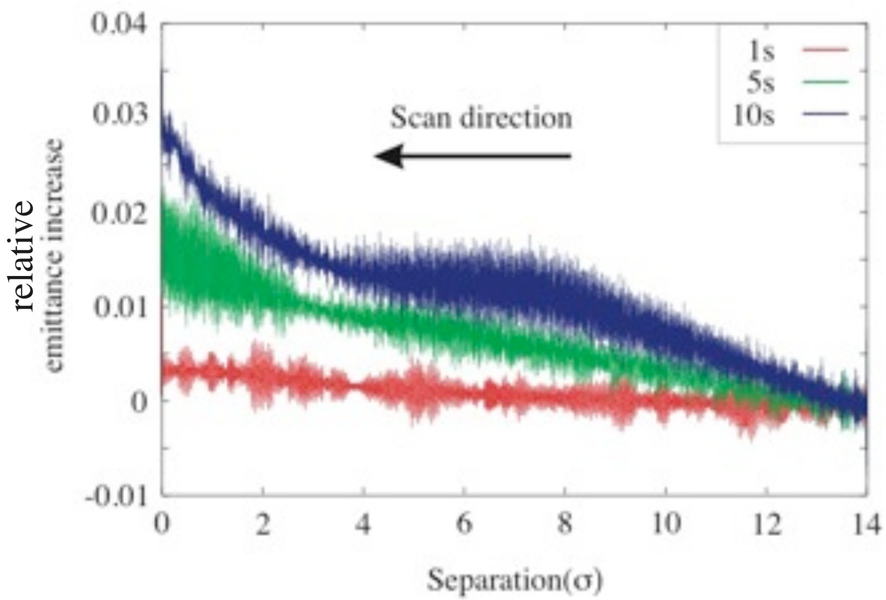
Crossing angle and parasitic beam-beam

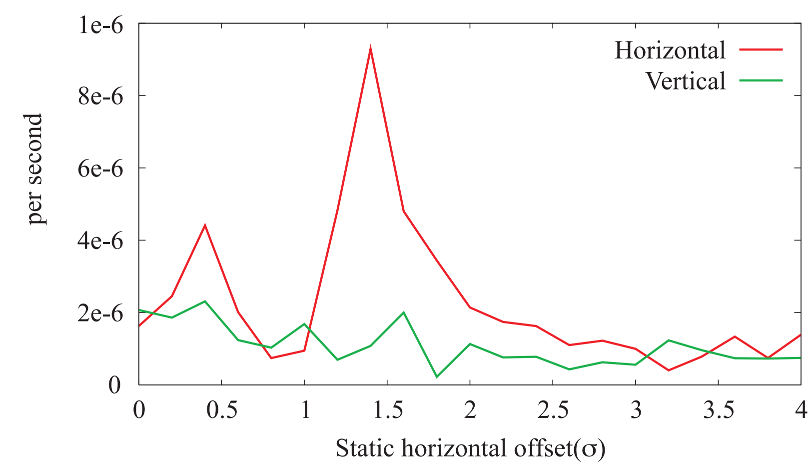
Can be completely avoided up to 156 bunches
Then gradually becoming an issue
would be good to gain first experience on this
in the 2009 / 2010 run
Nominal, IP1/5 : each 30 parasitic collisions ~ 9σ
Parasitic b.b. effects reduce with fewer bunches
or increased crossing angle

Nominal LHC with collisions in IP1&5



Simulation : IP5 colliding. IP1 going into collision
by ramping down the horizontal separation





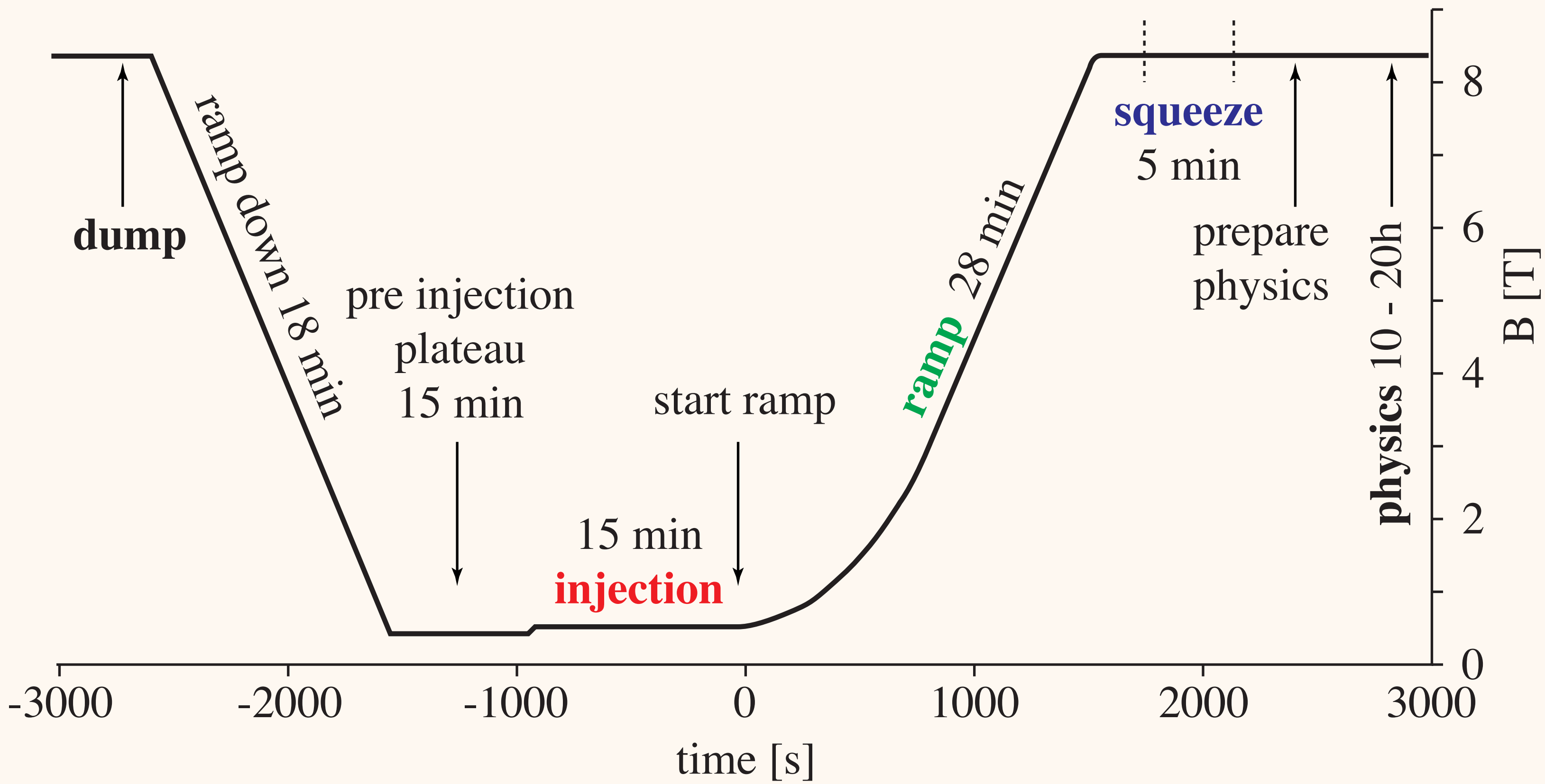
close to head on beam-beam :
peaks in blow up at 0.5 and 1.5 σ

Some ref.

W. Herr, M. Zorzano LHC Project Report 462 ; Tatiana Pieloni thesis

Figures above from S. M. White, H. Burkhardt, S. Fartoukh, T. Pieloni, *Optimization of the LHC Separation Bumps Including Beam-Beam Effects WE6PFP018*, PAC'09

LHC operation



Many machine modes

Here concentrating on STABLE BEAMS. How to get the most for physics

Optimize conditions - based on direct feedback from experiment