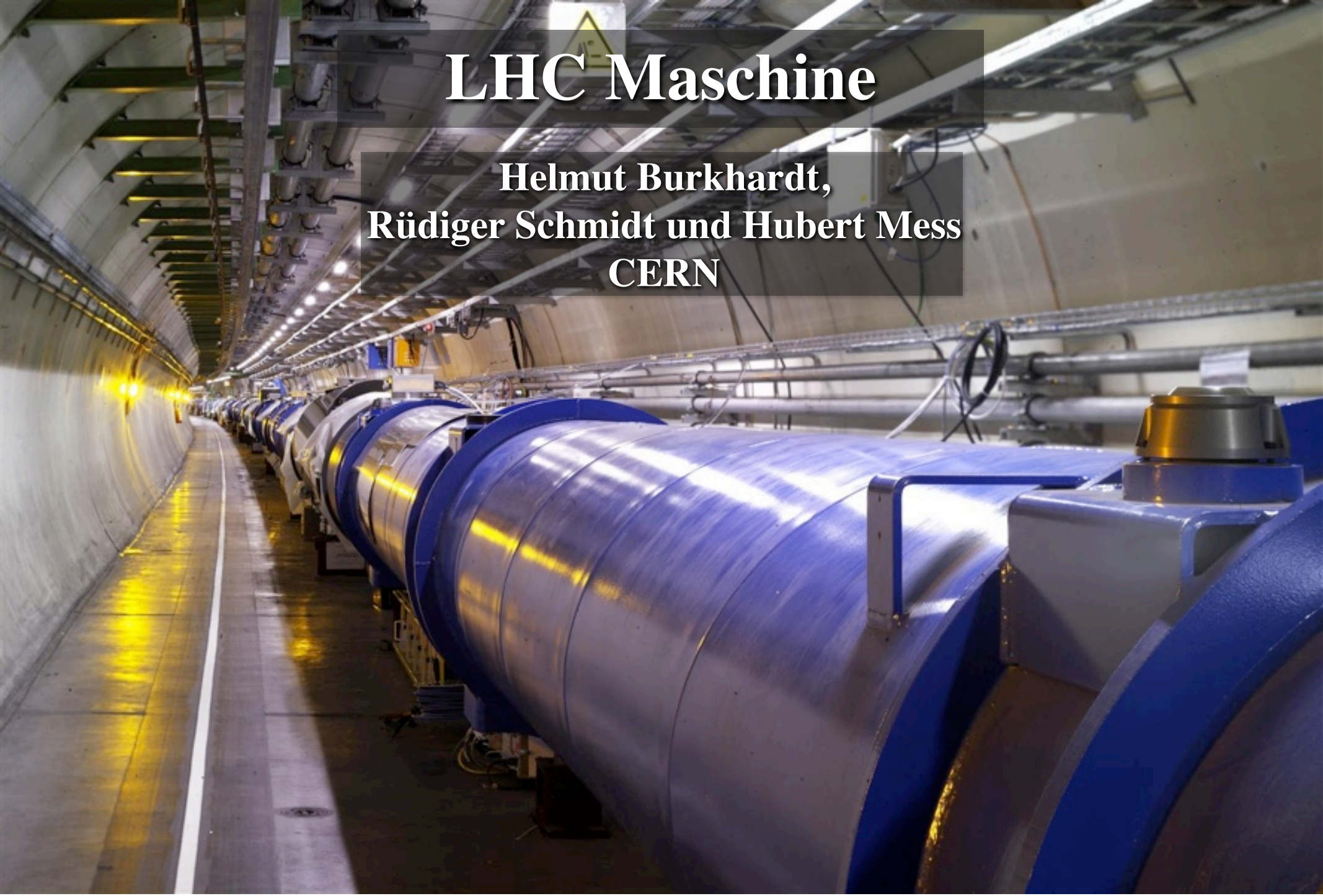
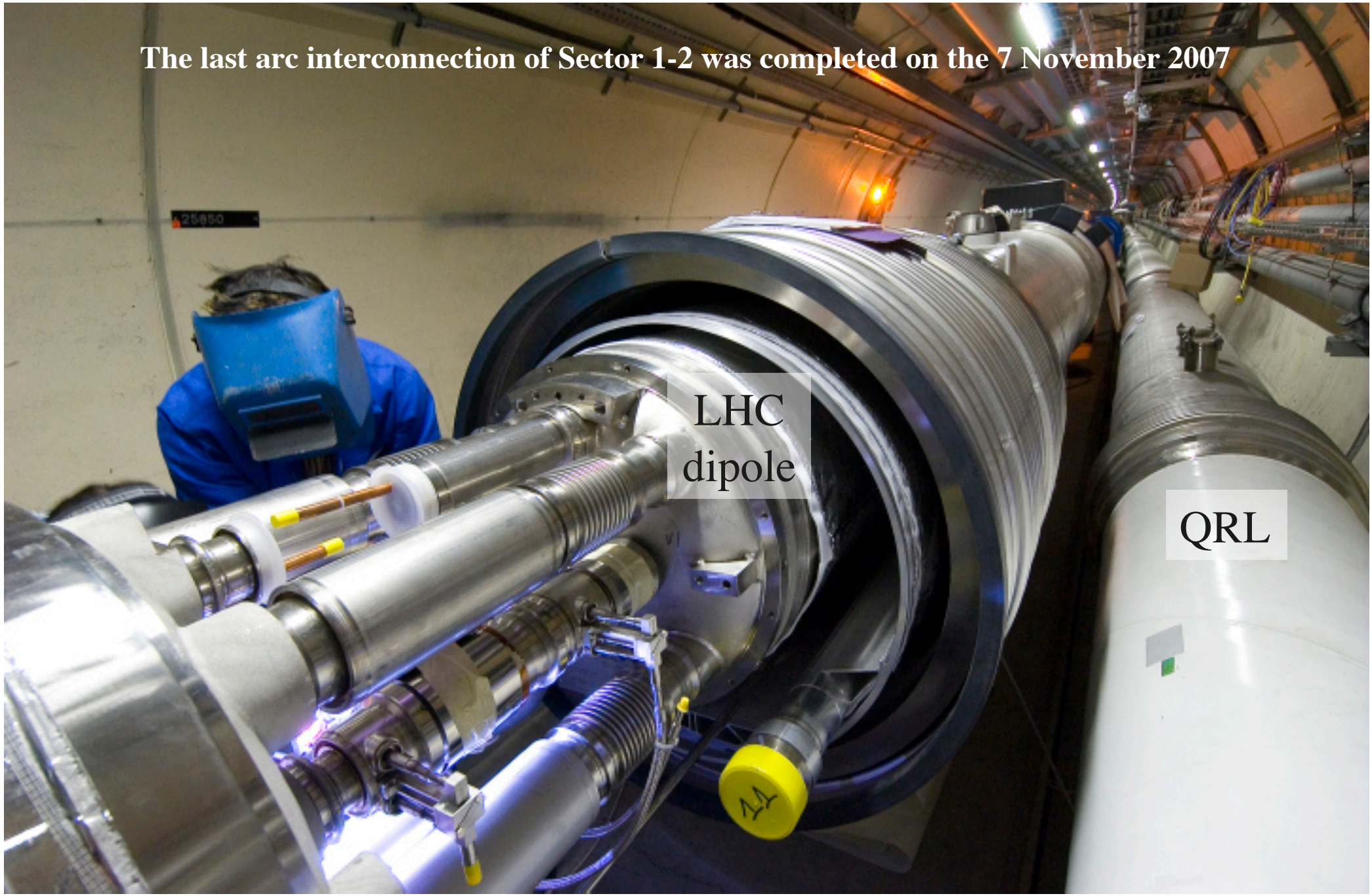


LHC Maschine

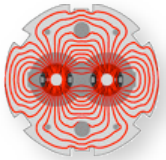
Helmut Burkhardt,
Rüdiger Schmidt und Hubert Mess
CERN

KET Jahresversammlung, Bad Honnef, Sa. 22. November 2008

LHC magnet interconnect in the tunnel



Major LHC challenges



Centre-of-mass energy of 7 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 — 10 GJoule in total
- Many bunches with large amount of energy stored in beams — 362 MJ each beam
- "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}

Complexity and Reliability

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

- Emittance conservation $\varepsilon_N = \beta\,\gamma\,\varepsilon$ const., related to phase space density conservation, Liouville
- 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)

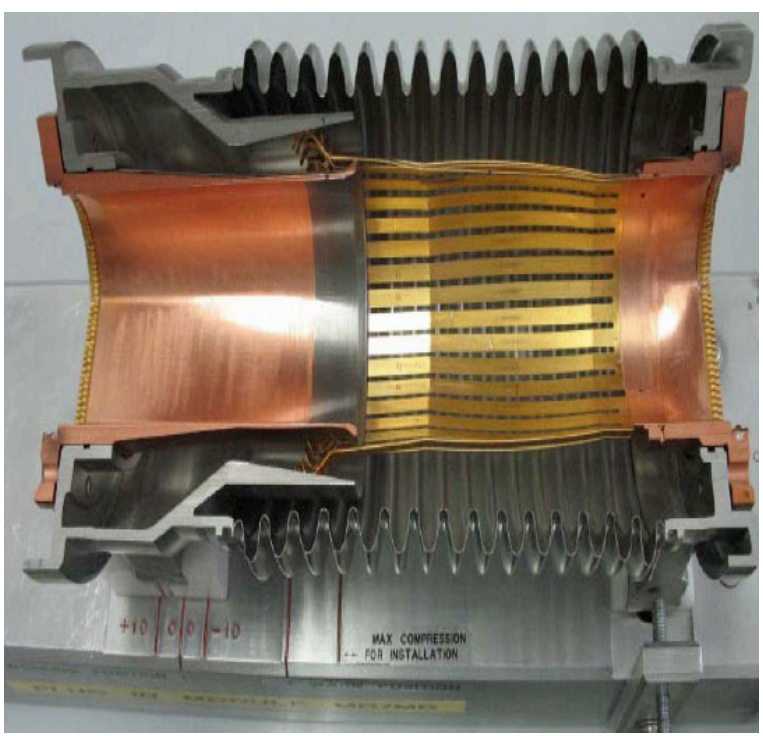
Critical Issues

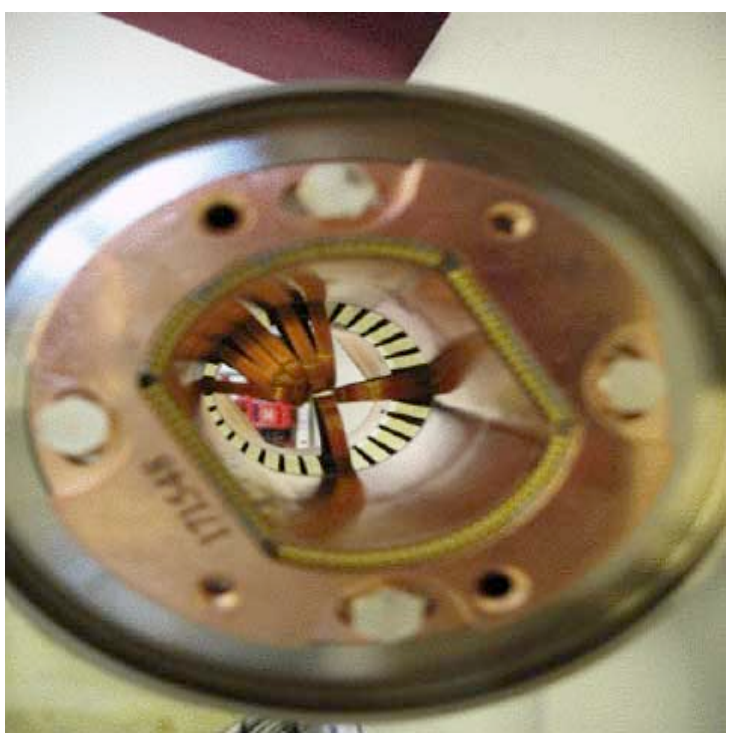
Past

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

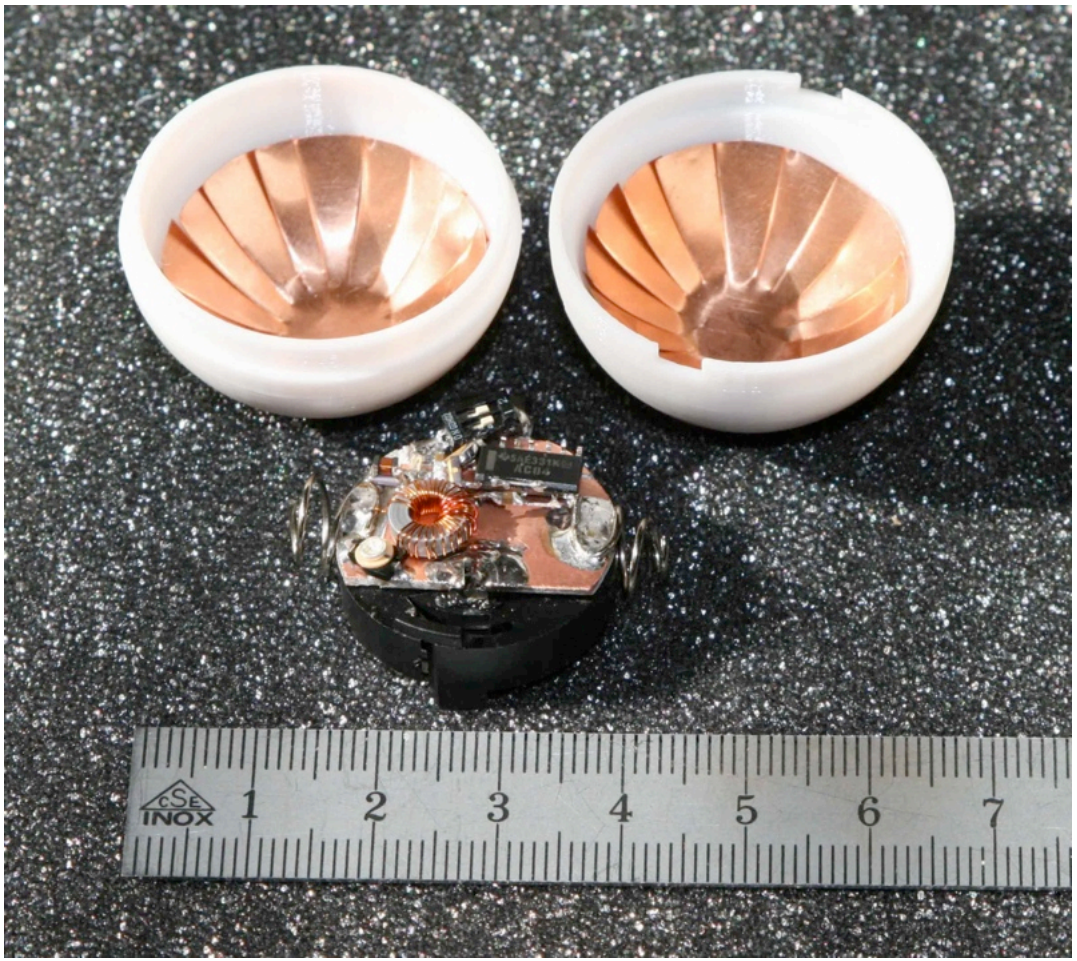
Recent

- **Vacuum leaks, condensation - humidity sector 3 - 4**
- **Magnet powering** check / correct : min/max, cabling - polarity
- **PIM** plug in module with bellow
- **Magnet re-training** few magnets quenched well below what was reached in SM18





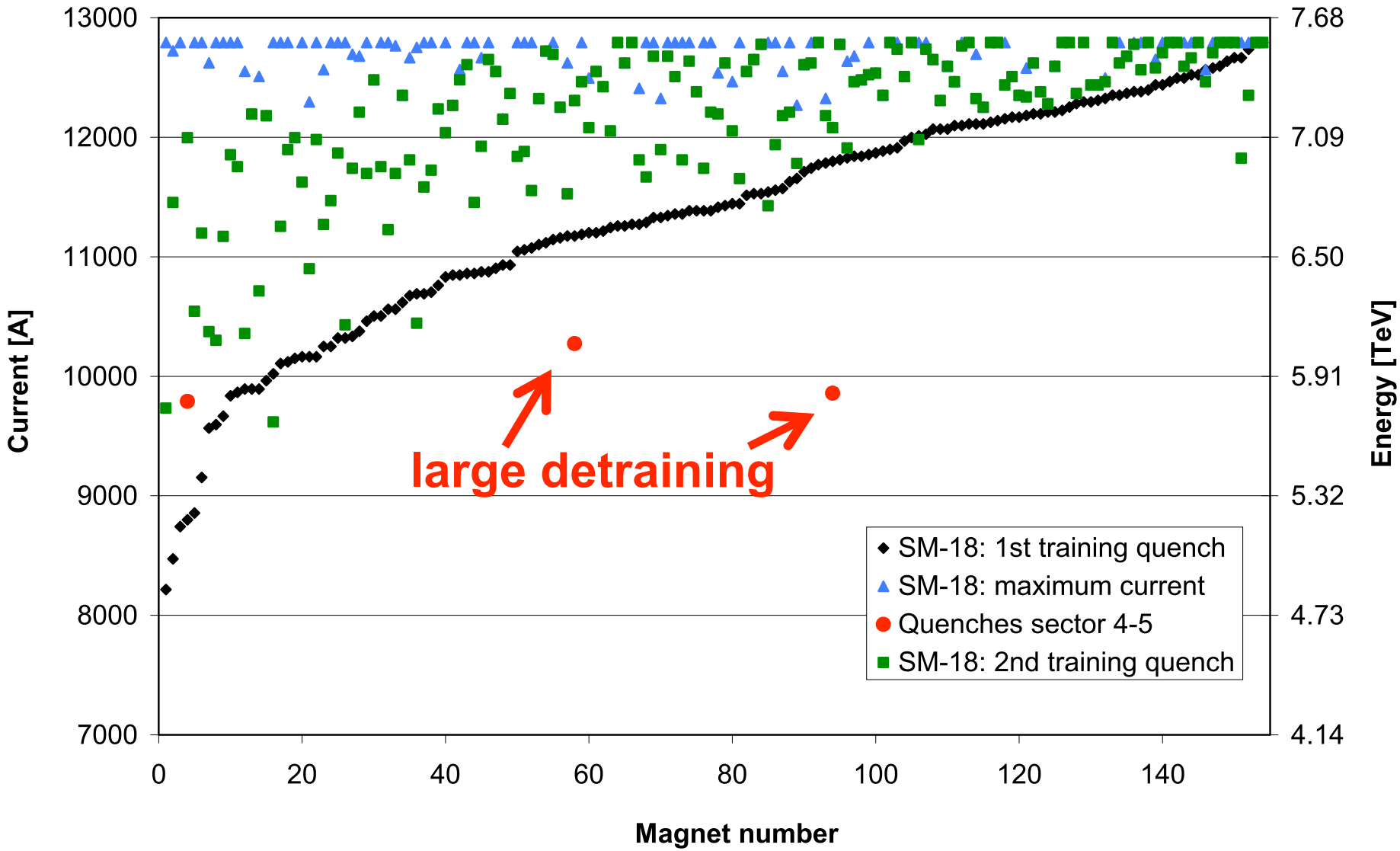
Beam vacuum ring aperture check with RF - ping-pong ball



Polycarbonate shell
∅ 34 mm, 15 g
2h battery powered
40 MHz emitter
signals recorded by LHC BPM

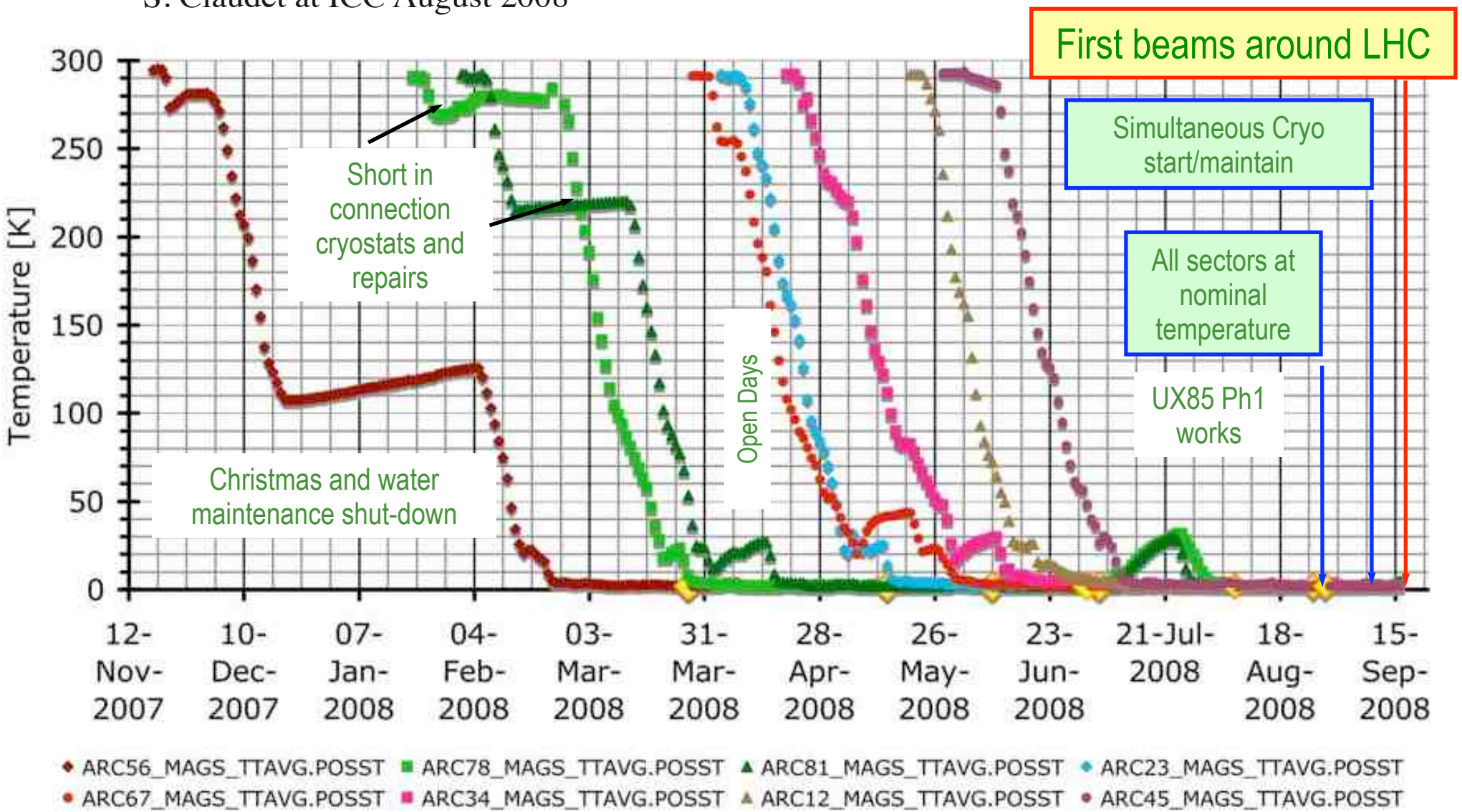
PIM issue only relevant after warm-up
localize with RF-ball - fix locally

HW commissioning, powering towards nominal in 4-5



First cool-down of LHC sectors

S. Claudet at ICC August 2008

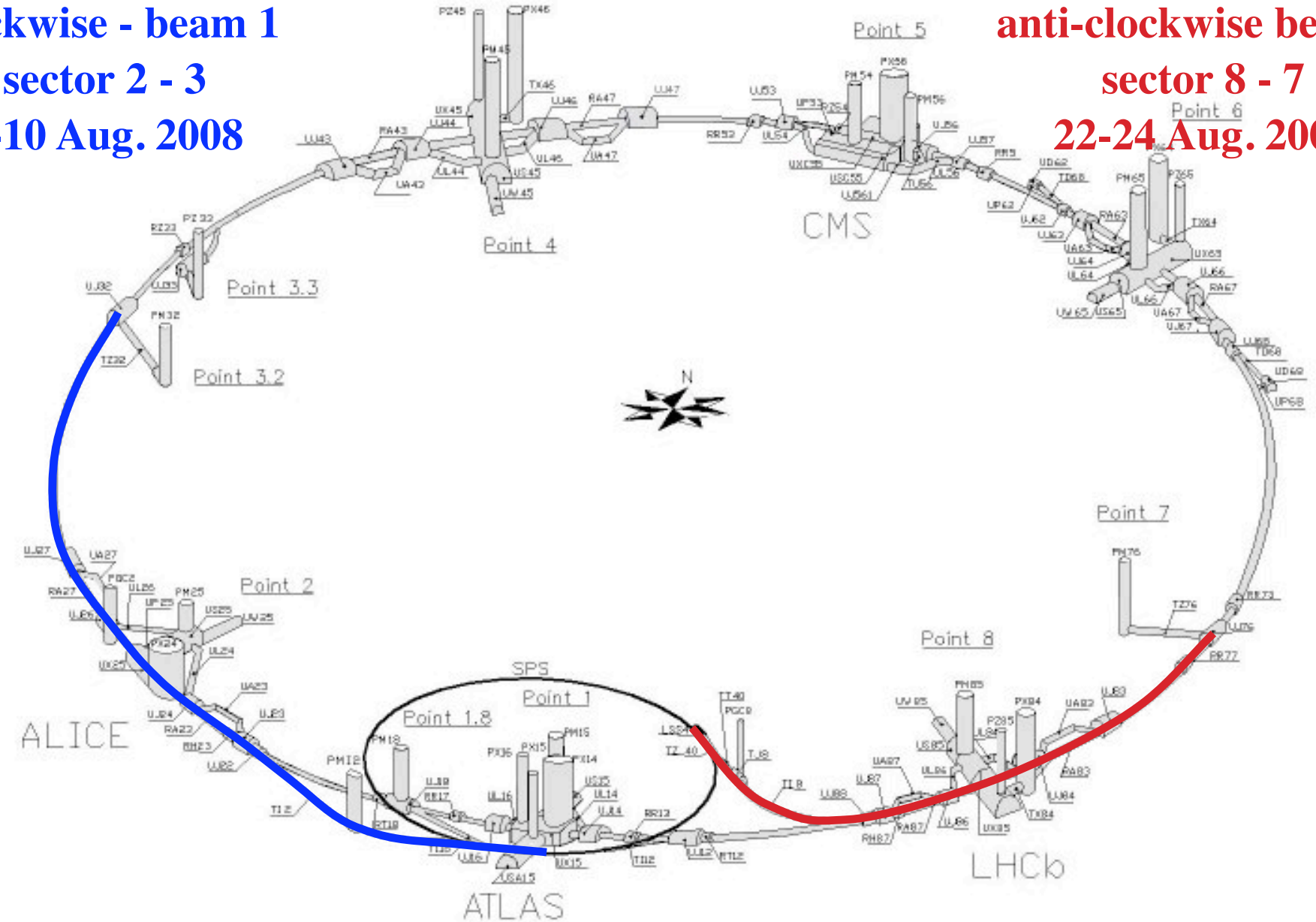


Cooling sectors + Cryo tuning + Powering activities

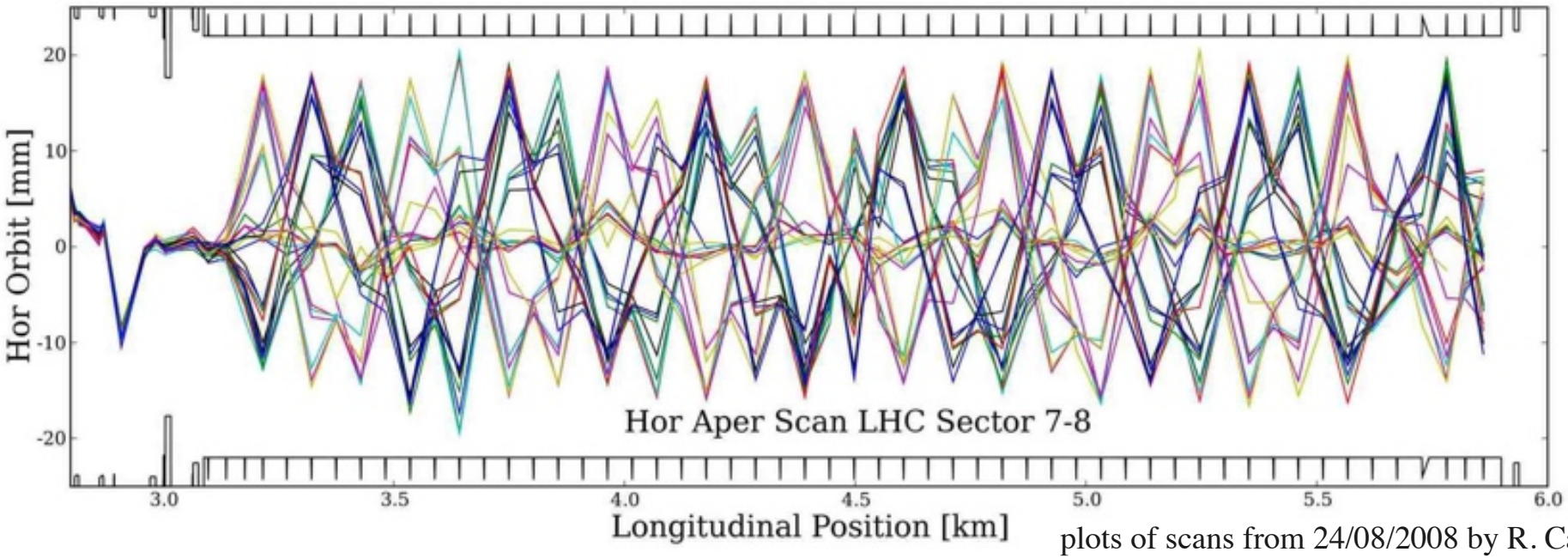
LHC commissioning with beam ; Tests in August

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

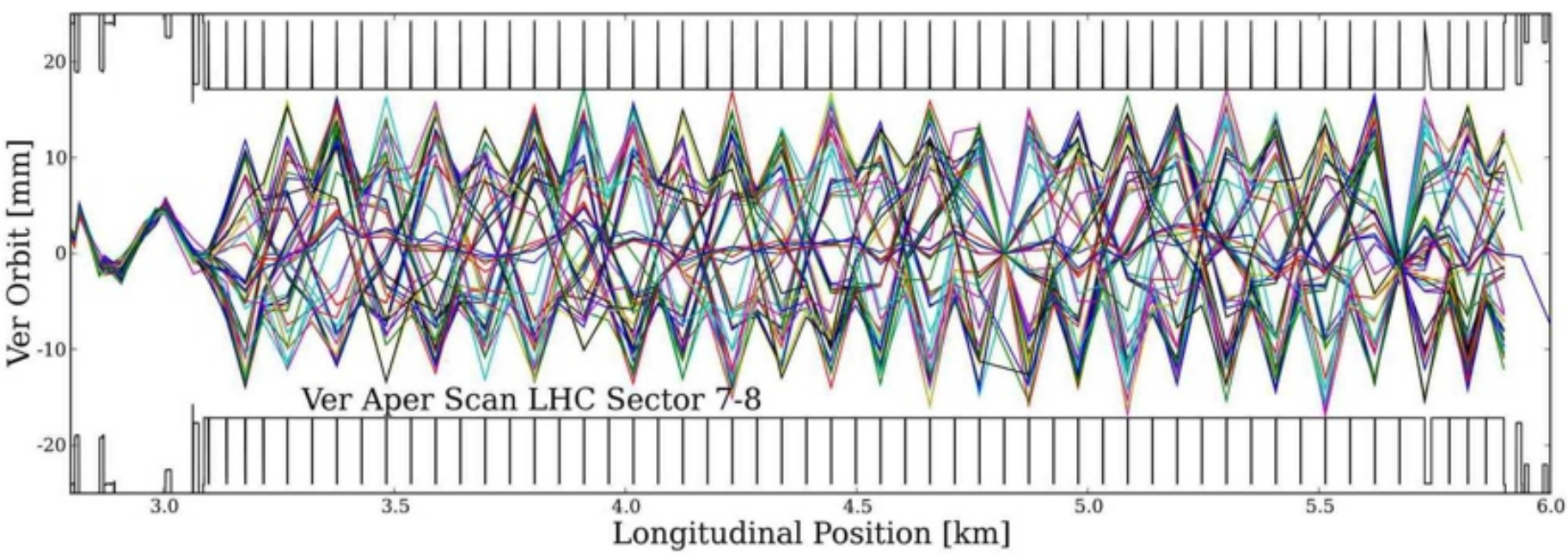
2nd Injection
anti-clockwise beam 2
sector 8 - 7
22-24 Aug. 2008



LHC sector 8-7 : aperture scan with beam 2



plots of scans from 24/08/2008 by R. Calaga



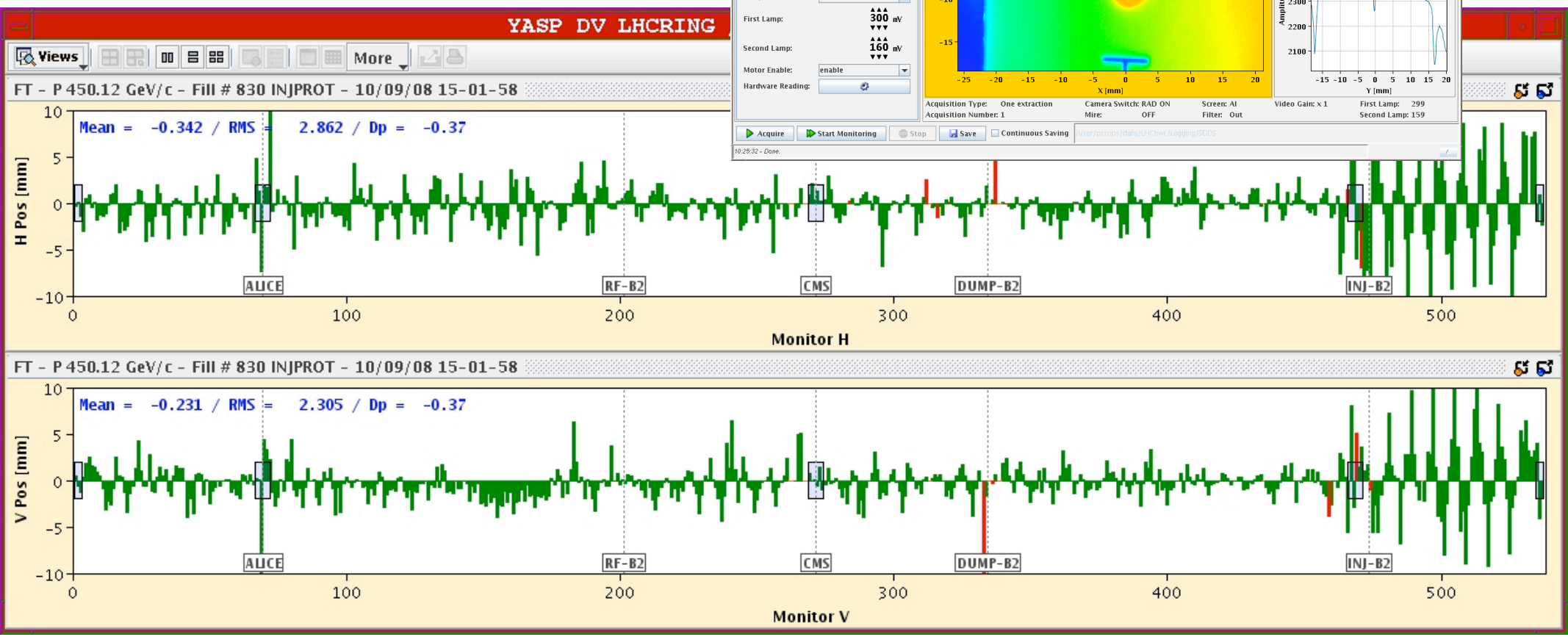
H and V successfully scanned in the range ± 12 - 18 mm

Protons make first turns, Wednesday 10 September 2008

First turn. 10 September 2008

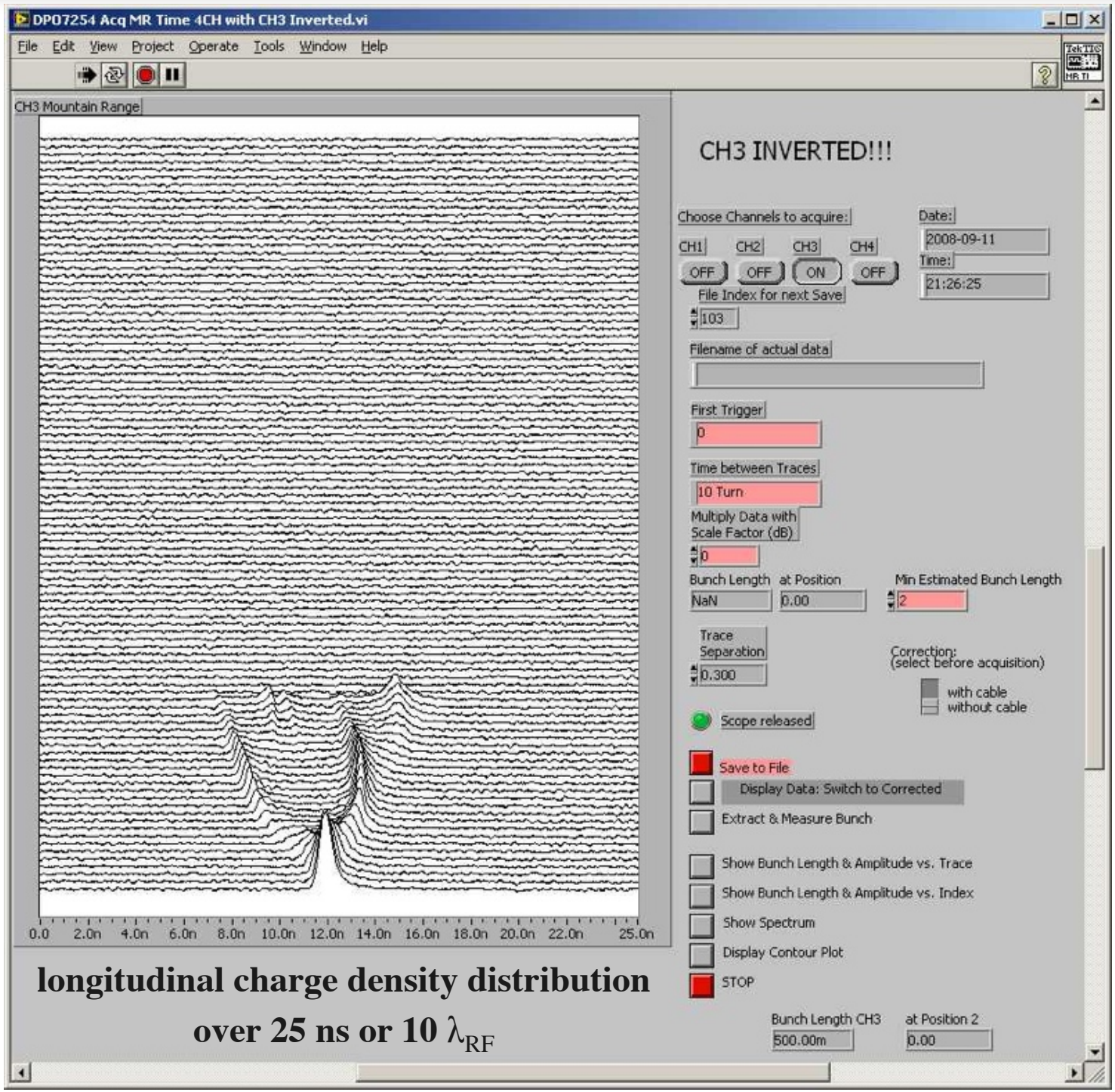
- First & Second Turn on screen
- First Turn on BPM system

Jörg Wenninger
Courtesy of Roger Bailey & O. Brüning



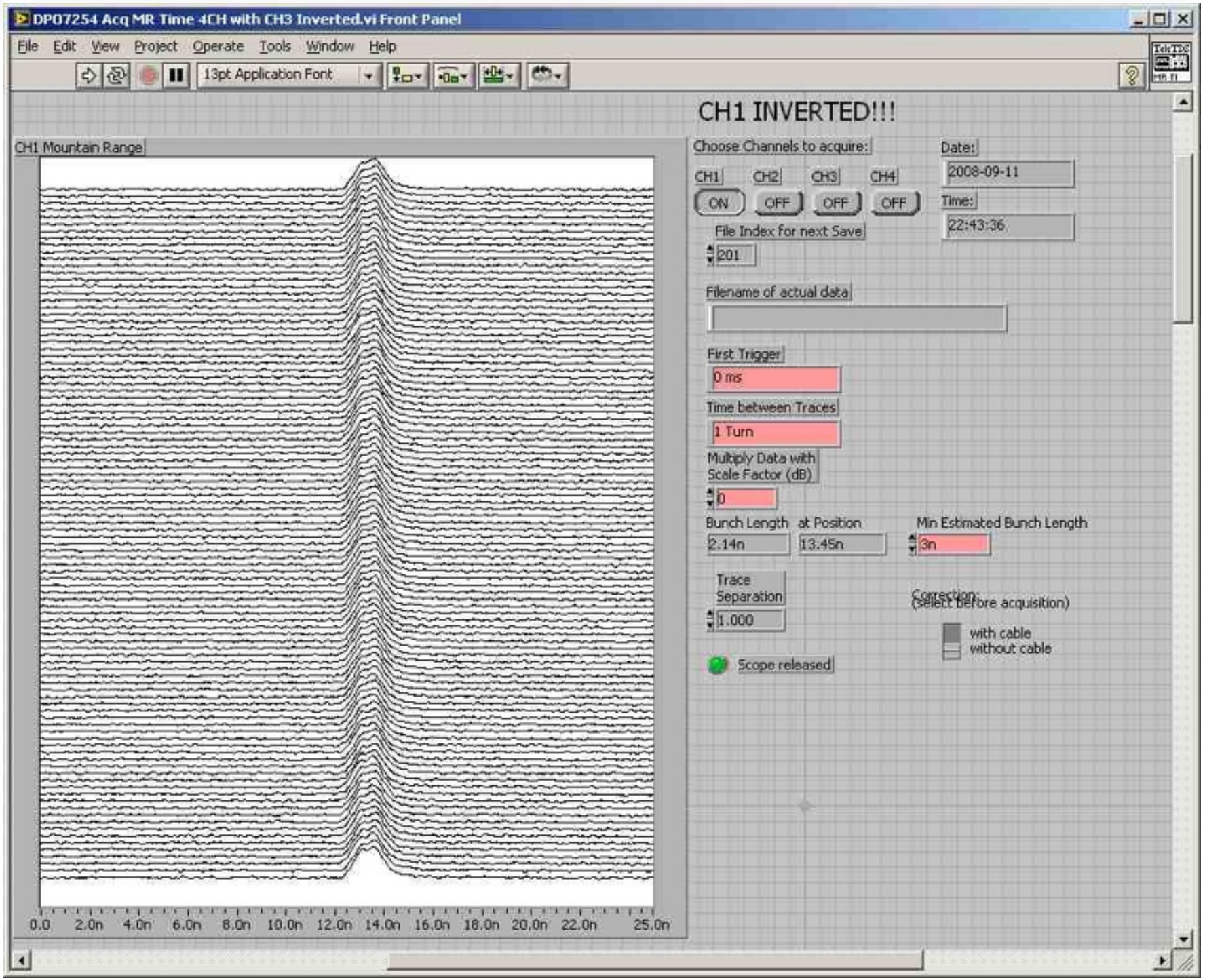
First attempt at RF capture

one trace every 10 turns



longitudinal charge density distribution over 25 ns or 10 λ_{RF}

LHC beam 2 with well adjusted RF capture

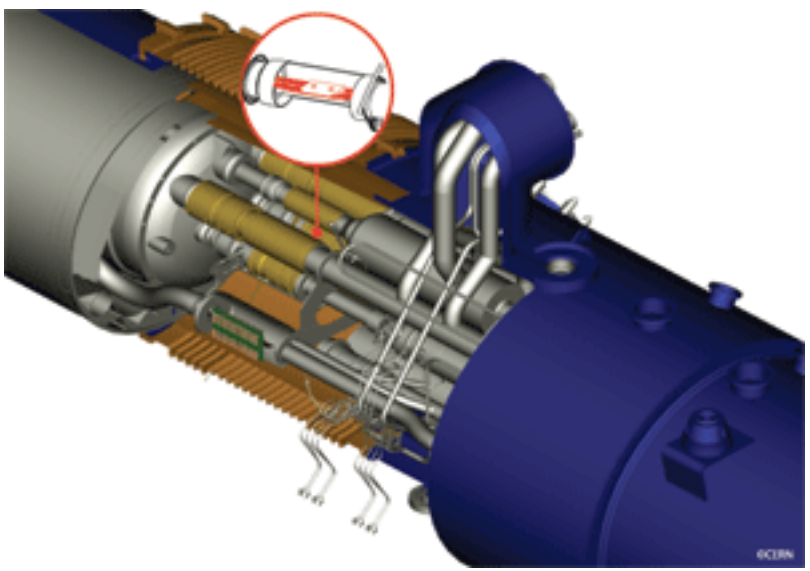


After 3 days of excellent progress with beams

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

- **two large transformers ; 13 - 18 September**
- **19 September** at 11:18:36**, incident during hardware commissioning of sector 3-4 towards**

5.5 GeV/ 9.3 kA, at 8.7 kA or ~ 5.2 TeV, of the 340 MJ stored energy about 180 MJ or 2/3 went to the dump resistors ; 1MJ melts 2.4 kg Cu



press release & interim report of task force :
likely cause : bad (~200nΩ) **splice at electrical connection between dipole C24 and quad Q24, 6t He or 1/2 of arc lost**
pressure built up in adjacent each 107 m long, vacuum subsectors
~ 45 dipoles (3.6% of LHC) and 15 quads involved : inspect and clean,
may have to repair / replace few of these

some typical numbers and back of envelope estimates :

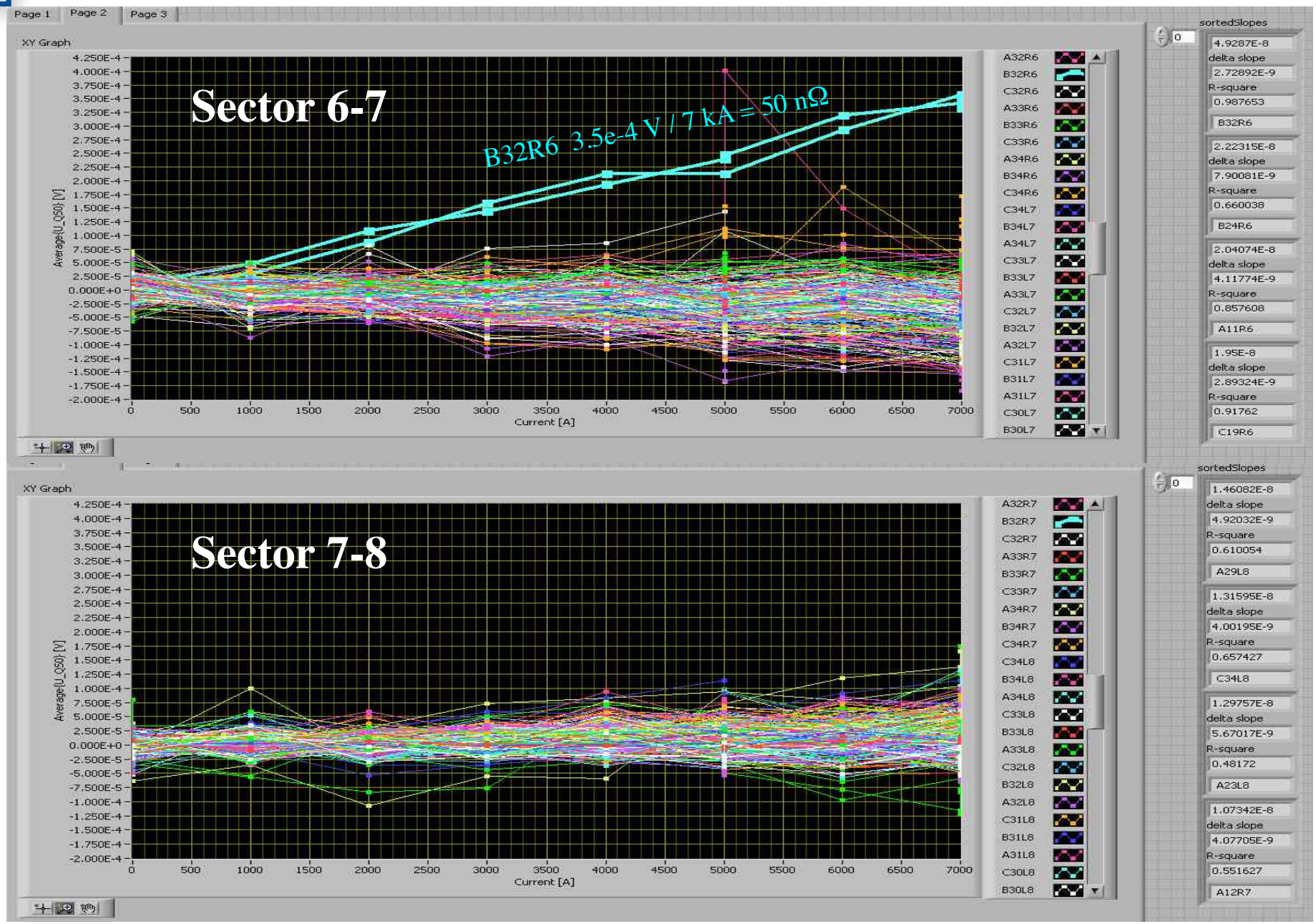
good splice ~ 0.3 nΩ, I = 13 kA, U = R I = 4 μV (now) possible to check - done for dipoles in 1/2 of LHC

$P = R I^2 = 0.05$ W quench would need locally > 10 W - depending on position - less critical in magnet

QPS triggered at 0.1 V (asym) > 10 ms ; ~ 30 - 50 ms for quench heater

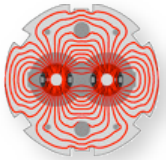
LHC dipole L = 100 mH stored energy in single dipole $I^2 L/2 = 8.45$ MJ × 1232 = 10.4 GJ

Sector 6-7, 7-8 voltage vs current



Increasing and decreasing current. Single magnet outside margin.

Possible consolidation to avoid / limit similar incidents

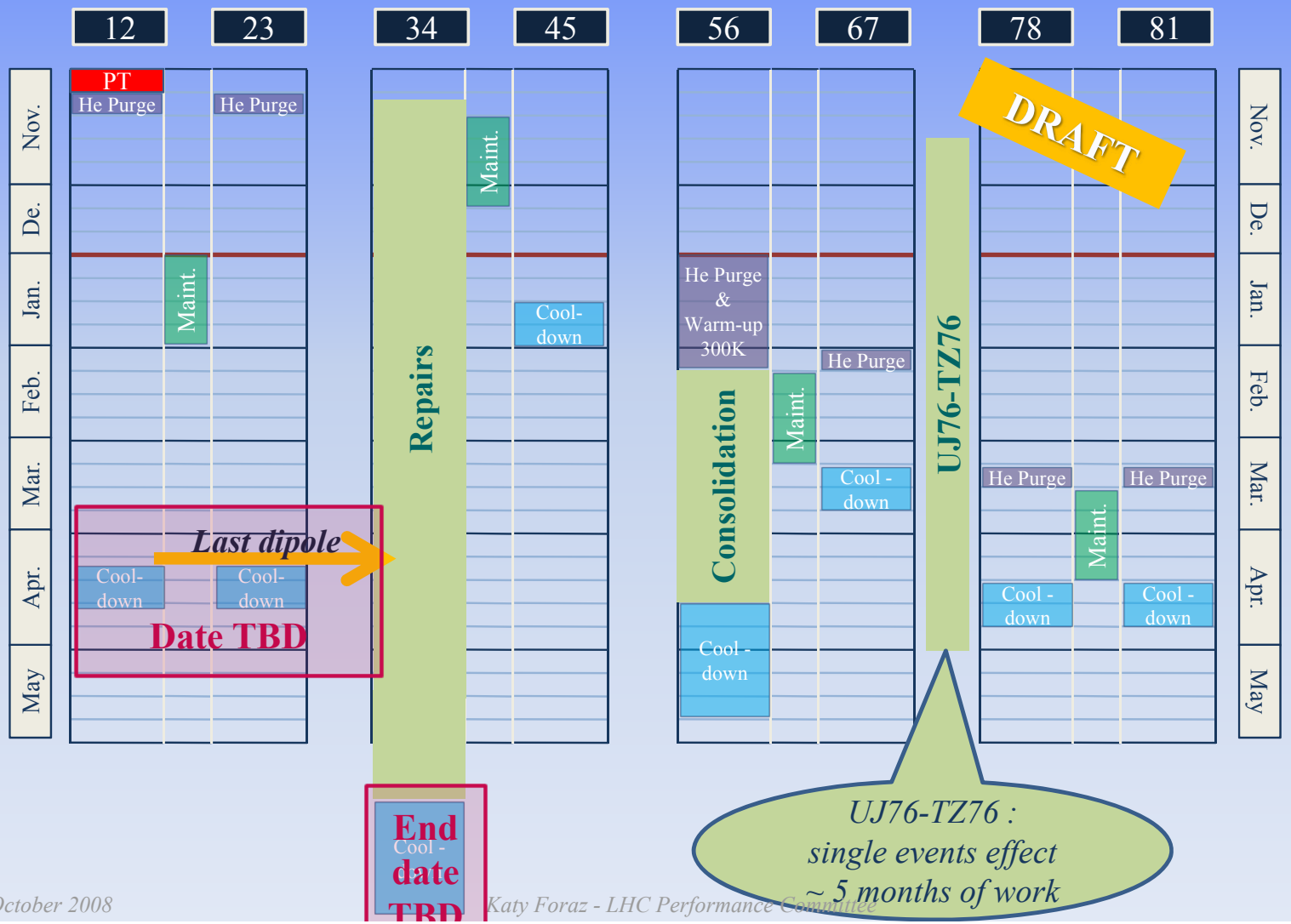


- **Upgrade QPS (quench protection system); will be done, details rather well defined**
- **Insulation vacuum overpressure release**
- **Improved anchoring of SSS with vacuum barrier to avoid displacement**

Powering tests after incident

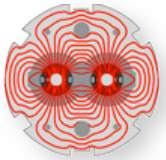
- **validate calorimetric using cryogenic system (few Watt resolution). Monitoring is performed at the level of 1mK around 1.9K**
- **demonstrated that QPS can measure 0.3 nΩ splice resistances**
- **found dipole magnet B16R1 in sector 12 (that had been powered to 13kA) with a splice resistance of 90 nΩ and B32R6 in sector 67 with ~ 50 nΩ**
- **excellent diagnostics for similar problems in the future**

LHC SD08 – Proposal for the schedule skeleton



Sectors : 3-4 is warm, warming up planned for 1-2, 6-7 to fix dipoles and 5-6 for bus bar mod. in disp. suppr.
planning very preliminary - depending on progress / cleaning - repair / QPS upgrade
critical review in LHC performance workshop, Chamonix, 1st week Feb. 2009

Next steps in commissioning with beam



LHC commissioning with beam has just started

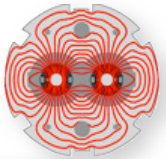
- Rapid progress when all hardware is available as Wed.-Fri. 10 - 13 Sep.
- Long time constants in case of failures affecting cryogenics / cooling 14.-17. Sep.

  month's to change cold magnets

More detailed beam commissioning needed @ injection energy 450 GeV

- complete the BPM checks (70%H, 30% V done)
- adjust and capture beam 1
- beam 1 & beam 2 timing
- start to use collimators, increase intensity
- check out the beginning of the ramp, ~450 GeV to 1 TeV
- full beam dump commissioning
- full ramp commissioning to initial physics energy, probably ~5 TeV - not yet decided
- first collisions at physics energy ... and physics run at 5 + 5 TeV or there about
- increase intensity and partial squeeze

Commissioning Stage A : 5+5 TeV collisions



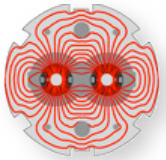
- Approx 30 days of beam to establish first collisions
- Approx 2 months elapsed
  - Given optimistic machine availability
  - Un-squeezed
  - Low intensity
- Continue commissioning thereafter
  - Increased intensity
  - Squeeze

tentative planning for initial physics

Parameters			Rates in 1 and 5	
k_b	N	β^* 1,5 (m)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
1 (2)	1010	11	$1.1\ 10^{27}$	<< 1
43	1010	11	$5.0\ 10^{28}$	<< 1
43	$4\ 10^{10}$	11	$8.0\ 10^{29}$	<< 1
43	$4\ 10^{10}$	3	$2.9\ 10^{30}$	0.36
156	$4\ 10^{10}$	3	$1.0\ 10^{31}$	0.36
156	$9\ 10^{10}$	3	$5.4\ 10^{31}$	1.8

Source : commissioning working group, R. Bailey et al.

Conclusion



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 resolved many difficulties.

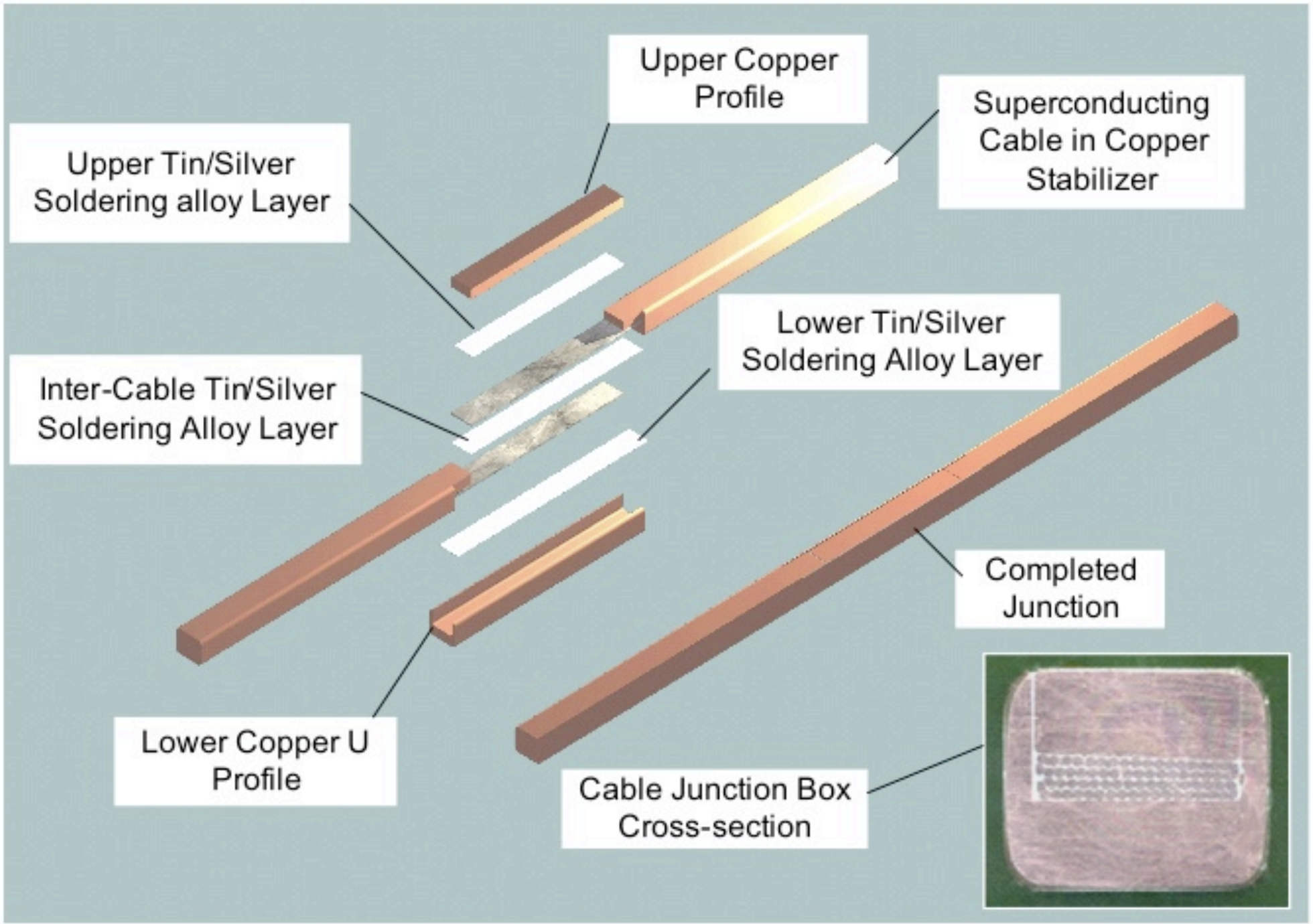
Interventions which require warmup / cooldown of sectors imply month's without circulating beams.

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

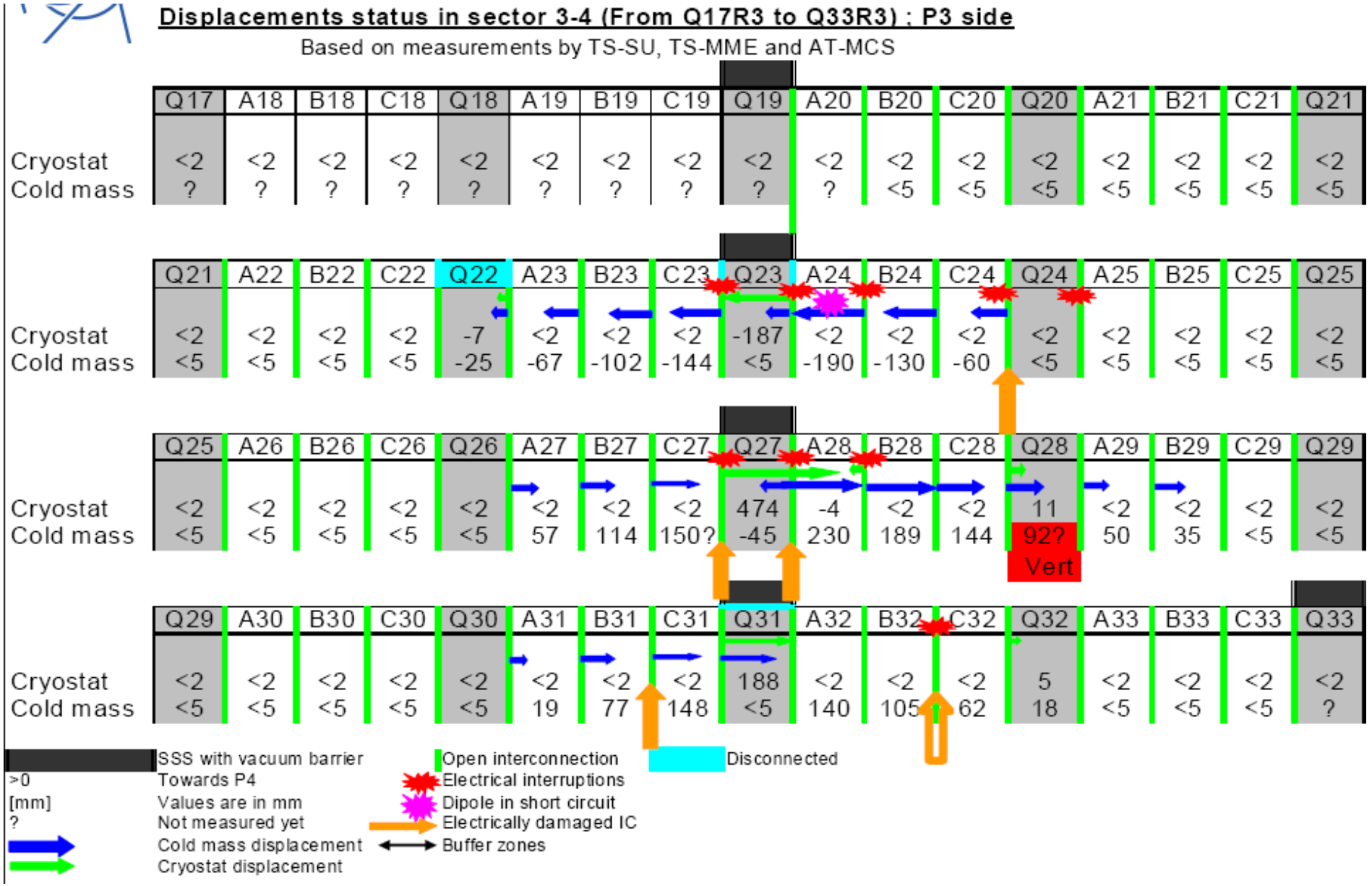
The current repair and shutdown is also used to further improve the preparations for beams for physics

Backup Slides

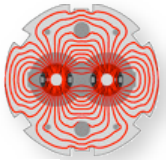
Busbar splice



Cryostat and cold masses longitudinal displacements



Beams in full LHC ring : (last) week of 10-September



https://lhc-commissioning.web.cern.ch/lhc-commissioning/dailynews/week37.htm

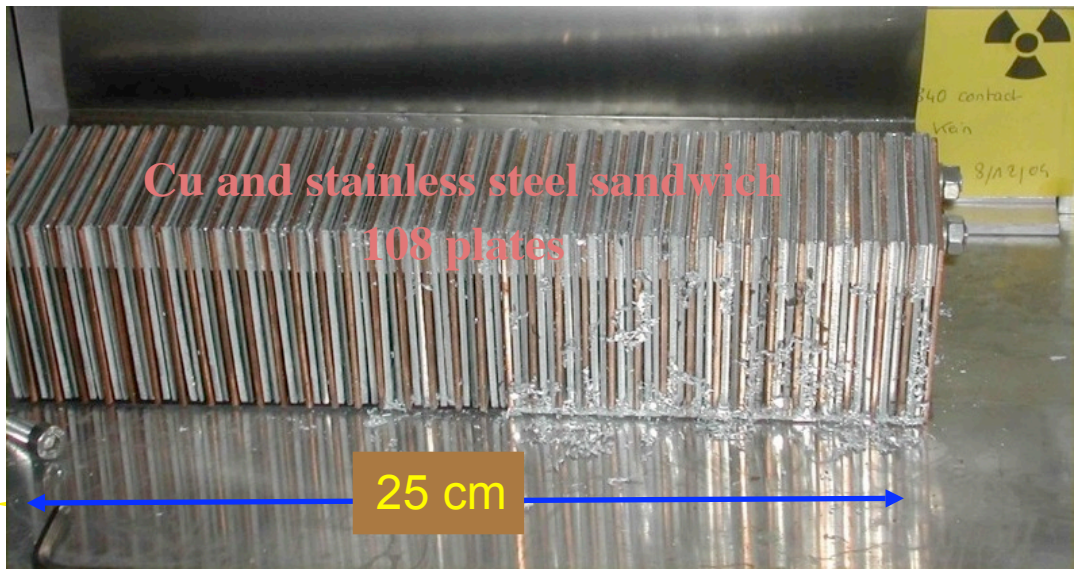
Day	Beam 1 progress	Beam 2 progress	Images
Mon 08			
Tue 09	Tests from 22h to 24h	Tests from 23h to 24h	
Wed 10	First turn 9.30 to 10.30 Makes 2 to 3 turns	First turn 13.30 to 15.00 Inject and dump working Few hundred turns BPM working multiple turns Measure Q working Fast BC working Systematic polarity checks 1	screen showing beam on and 2nd turns few 100 turns tune measurements fast BCT
Thu 11		Inject and dump Circulate and dump 50ms Circulate - dump on request RF capture working Integer tunes OK Mountain range working Systematic polarity checks 2	dump dilution sweep integer tunes mountain range
Fri 12	To TDI with Beam 2 in	Circulating beam RF capture refinement Beta-beat measurement Wire scanner H and V works	H beta-beat H wire scan

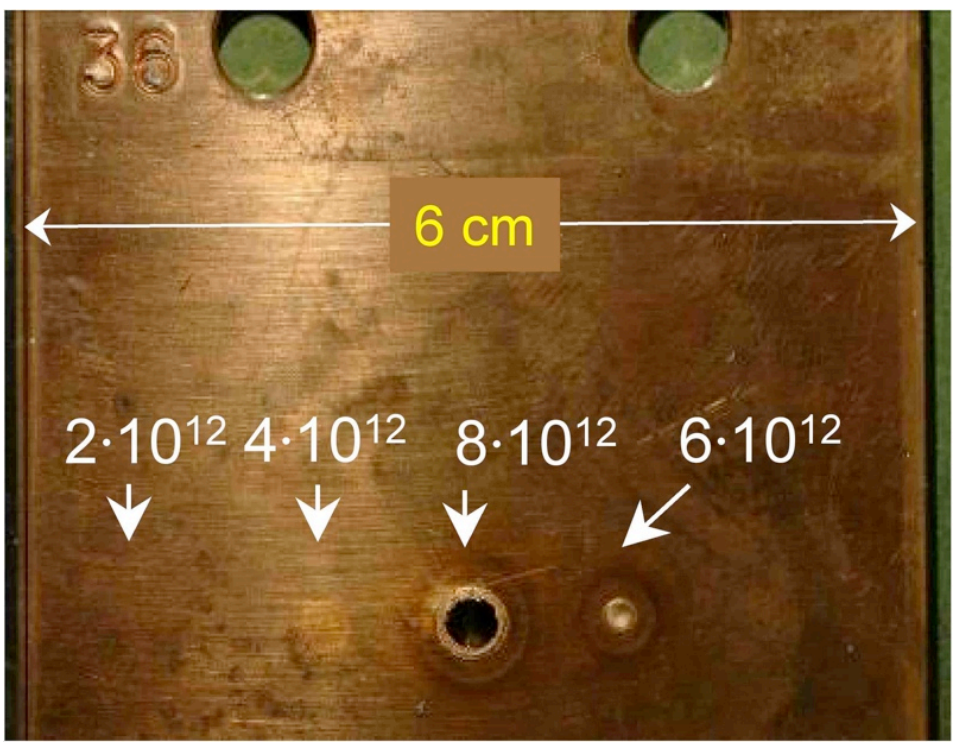
Damage potential : confirmed in controlled SPS experiment

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 :

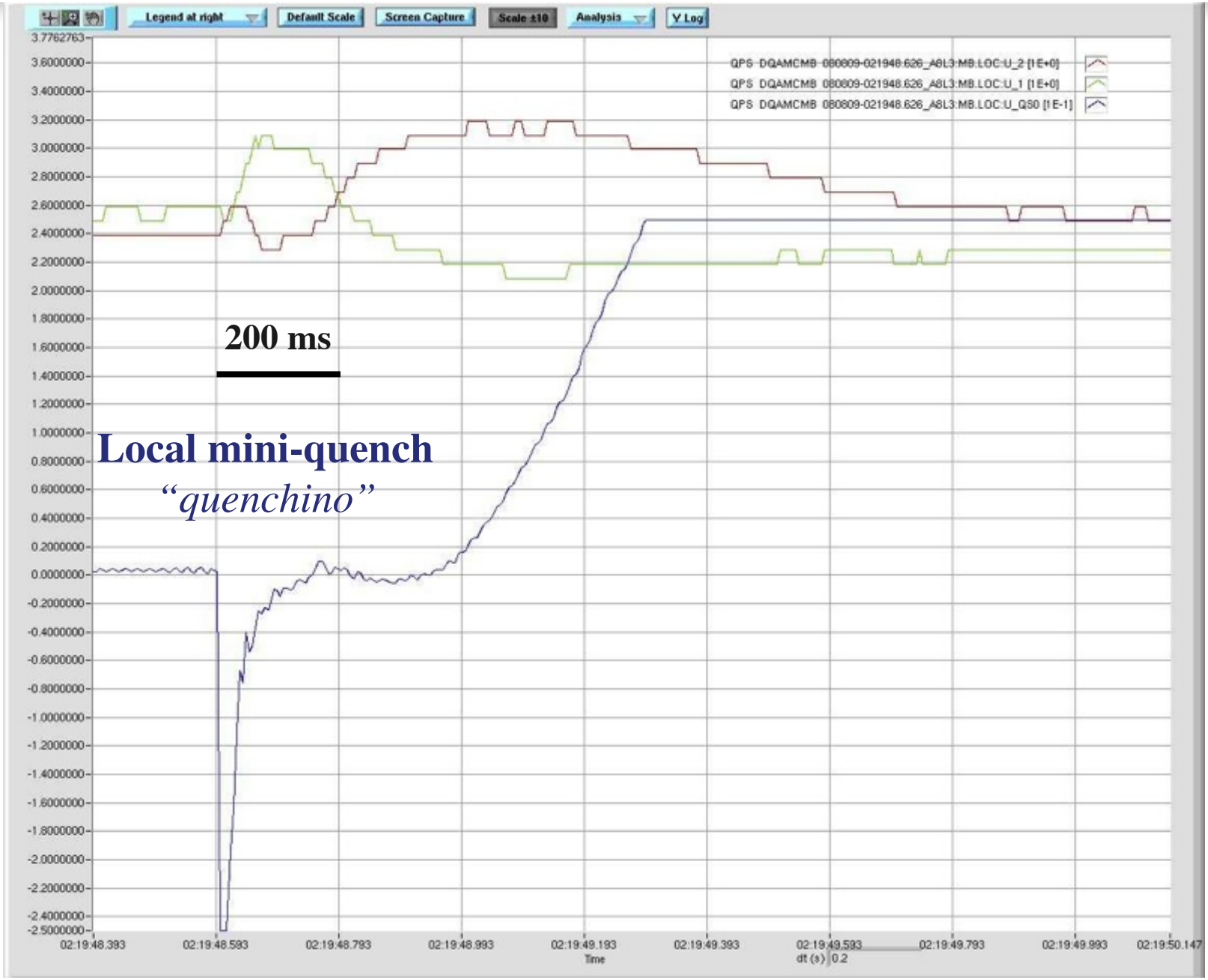
8×10^{12} clear damage

2×10^{12} below damage limit

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

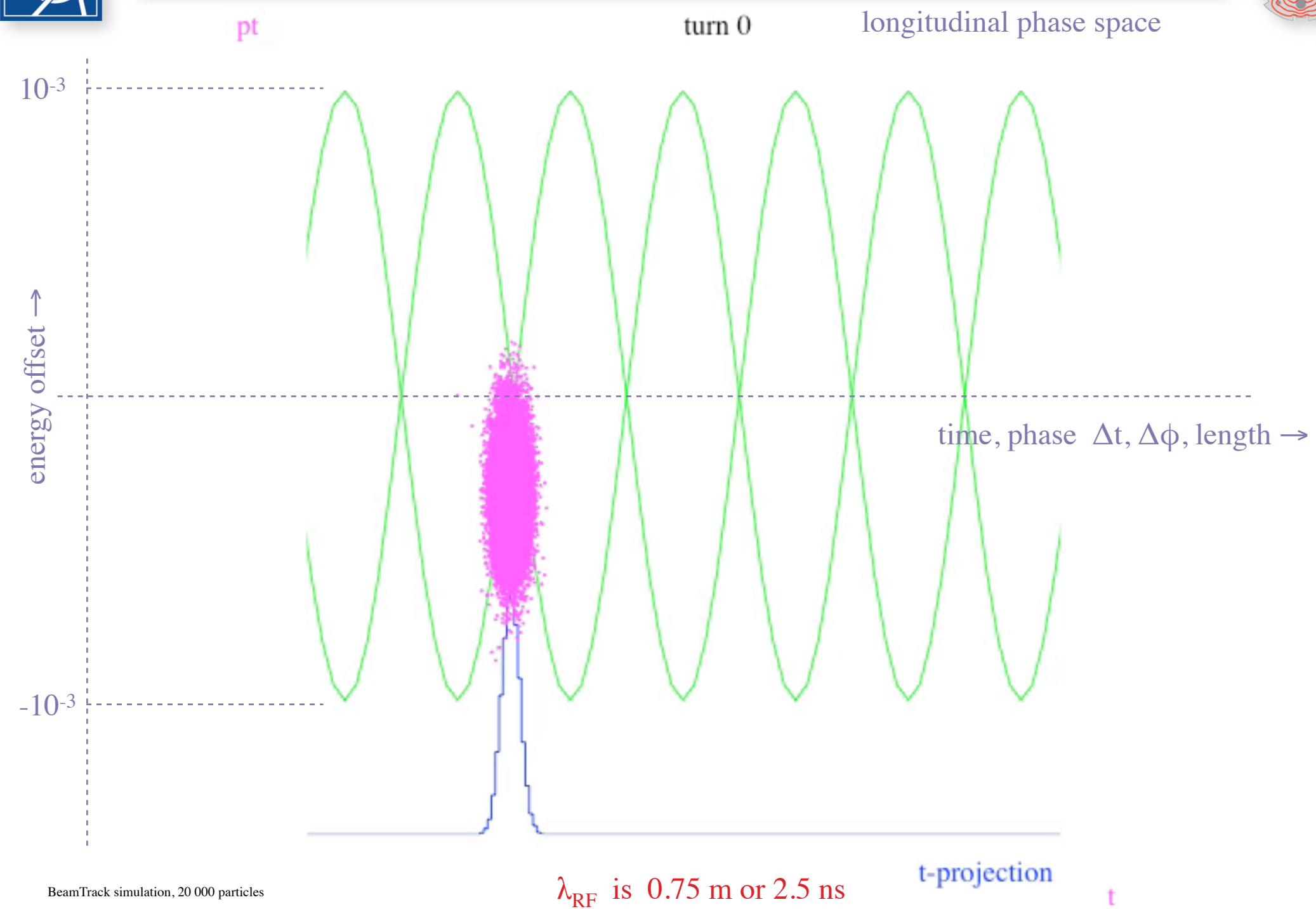
For comparison, the LHC nominal at 7 TeV :
$2808 \times 1.15\times10^{11} = 3.2\times10^{14}$ p/beam
at $< \sigma_{x/y} > \approx 0.2$ mm
over 3 orders of magnitude above damage level for perpendicular impact

LHC first beam induced quench, 9 Aug 2008



followed by : quench heaters, distribute energy, and controlled discharge

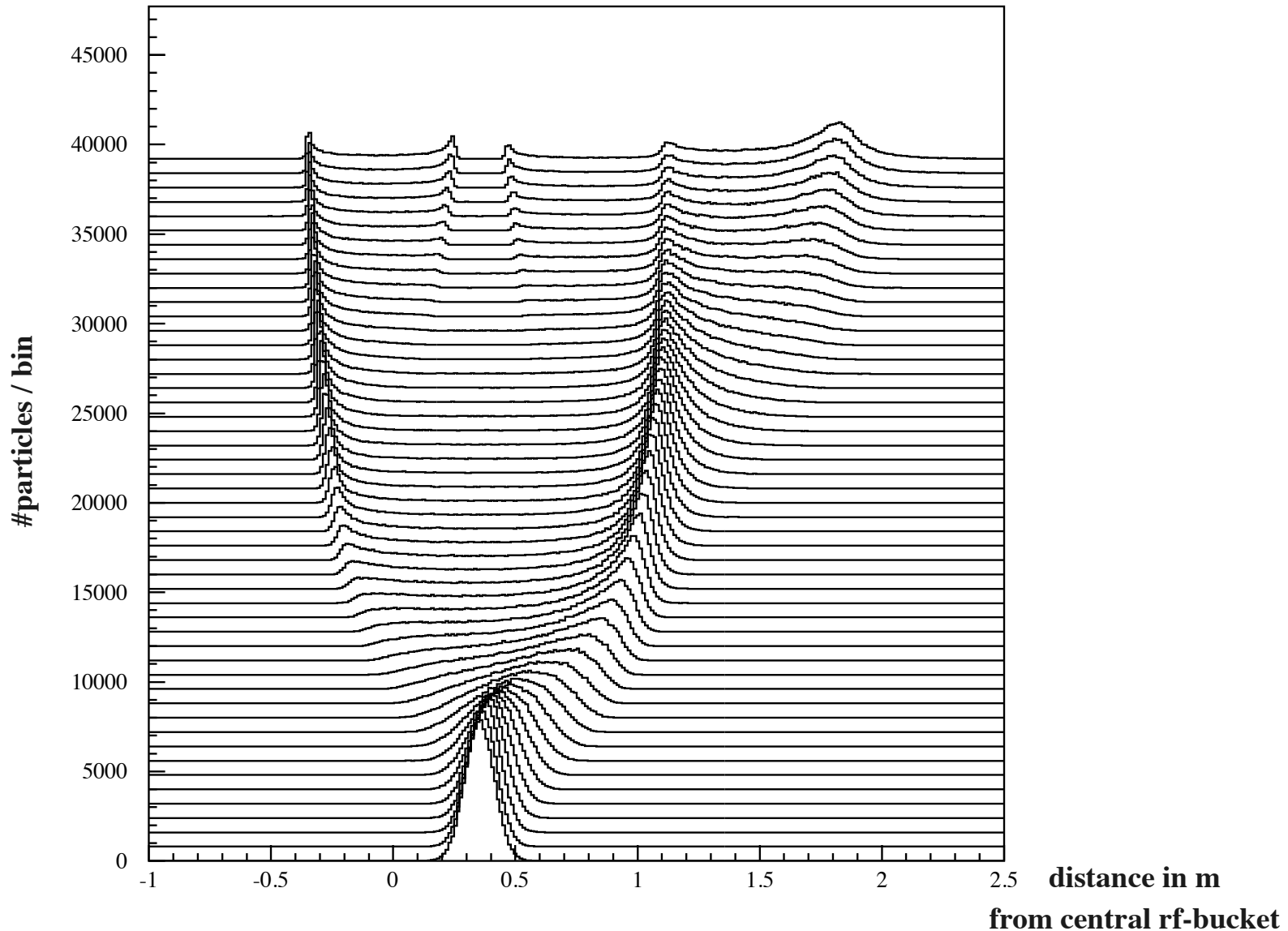
Simulation of injection with 170° injection phase offset



BeamTrack simulation, 20 000 particles

λ_{RF} is 0.75 m or 2.5 ns

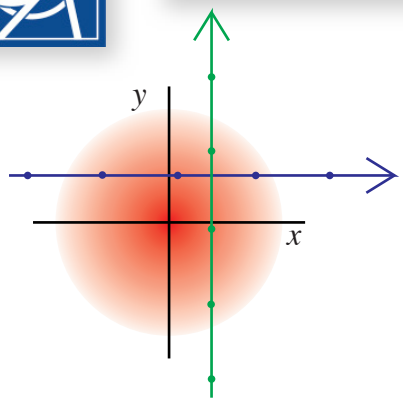
Simulation of injection with 170° injection phase offset



projection of previous plot : longitudinal charge density distribution

BeamTrack simulation, 100 000 particles

Luminosity scans and absolute luminosity



(pioneered by Van der Meer @ ISR)

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

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

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

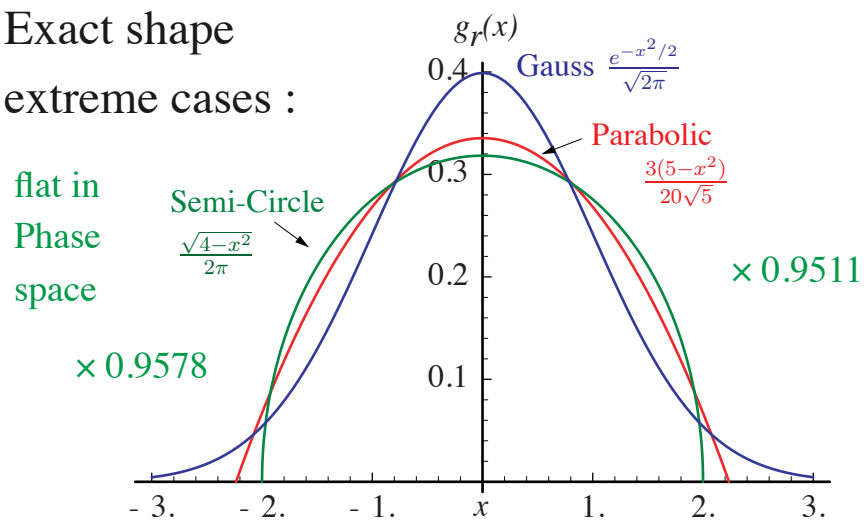
Accuracy : better than **1% at ISR**

Aim for **early LHC ~10 %**

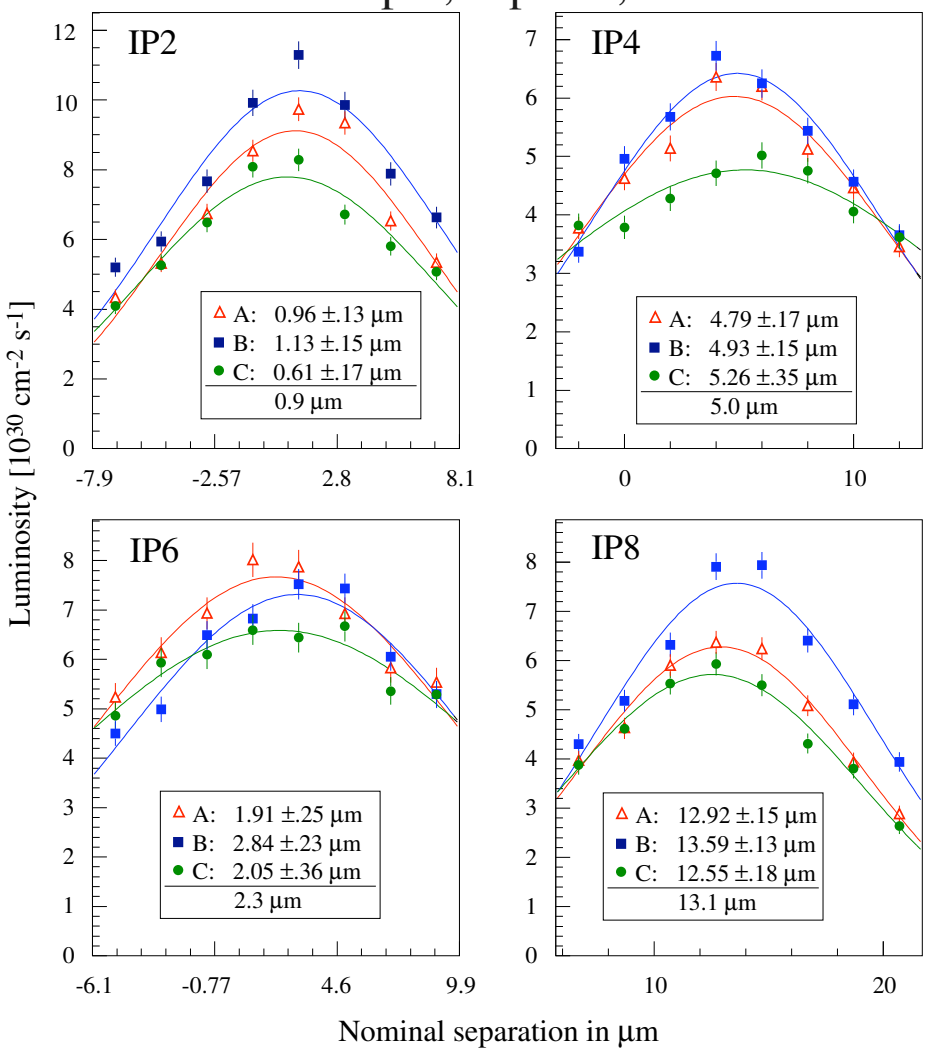
Contributions :

- 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



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

Parameter evolution and rates

$$L = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

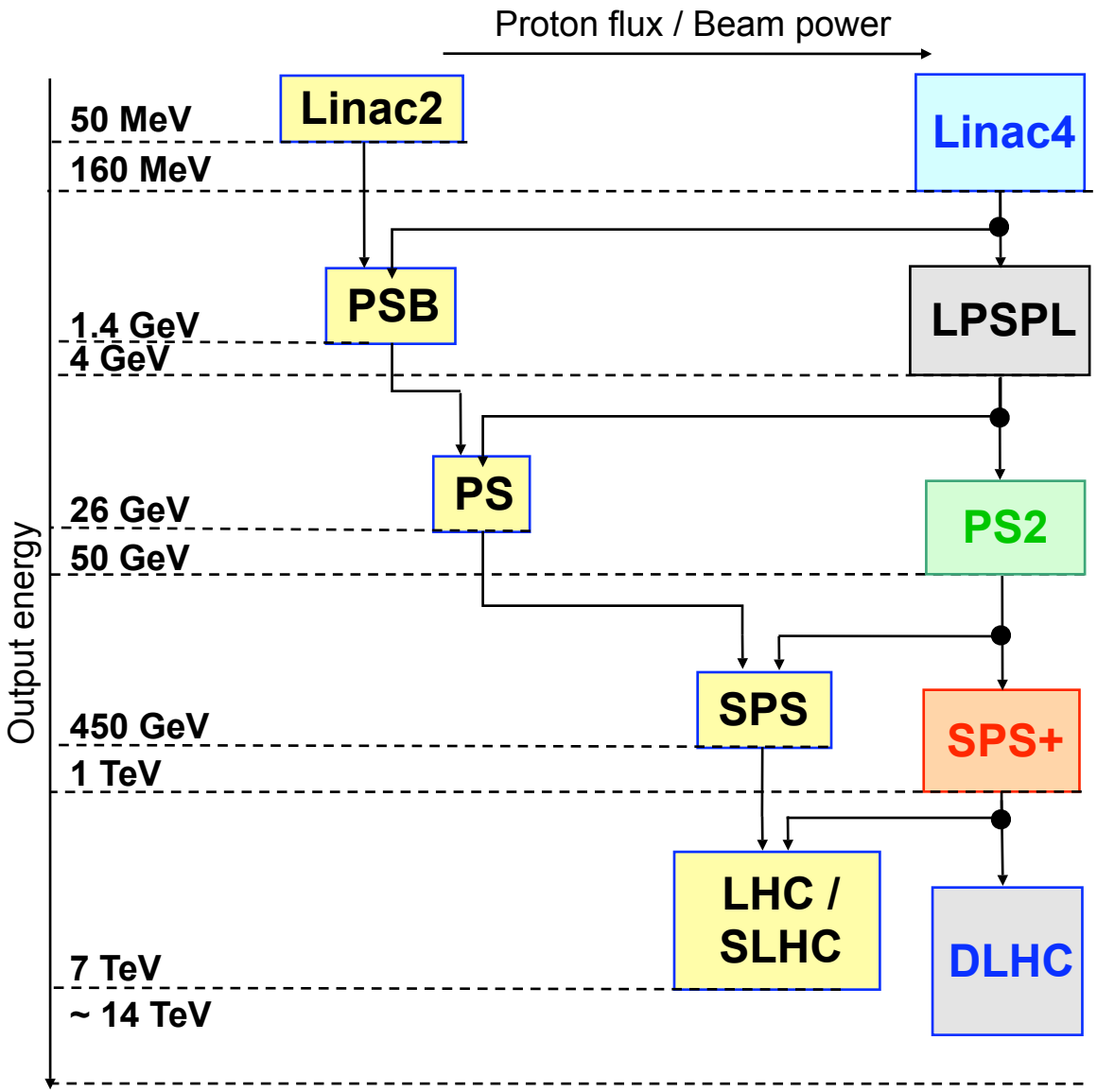
$$Eventrate/Cross = \frac{L\sigma_{TOT}}{k_b f}$$

All values for nominal emittance, 10m β* in points 2 and 8

All values for 936 or 2808 bunches colliding in 2 and 8 (not quite right)

Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	1.4	$8.0\ 10^{29}$	<< 1	Depend on the configuration of collision pattern	
43	$4\ 10^{10}$	3	$1.7\ 10^{12}$	1.4	$2.9\ 10^{30}$	0.36		
156	$4\ 10^{10}$	3	$6.2\ 10^{12}$	5	$1.0\ 10^{31}$	0.36		
156	$9\ 10^{10}$	3	$1.4\ 10^{13}$	11	$5.4\ 10^{31}$	1.8		
936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76
2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24

Upgrade Options, Injectors + LHC



approved ✓, ready in 2012

if approved could be ready by about 2016

LPSPL: Low Power 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 ~ 2013