Status of the LHC and commissioning plans

by Helmut Burkhardt / CERN for the LHC team

- **Short introduction - main challenges**
- **LHC status,** 1st experience with beams and status following the incident
- **Commissioning steps and expected beam parameters**

Acknowledgements : LHC team, mentioning in particular
Lyn Evans, the former LHC and current sLHC project leader, and Steve Myers director for accelerators
K-H.Mess and R. Schmidt for advice, in particular on the issue of magnet interconnects and quench protection,
O. Brüning & M. Giovannozzi on optics and commis, M. Ferro-Luzzi on physics program, R. Bailey on commis.

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

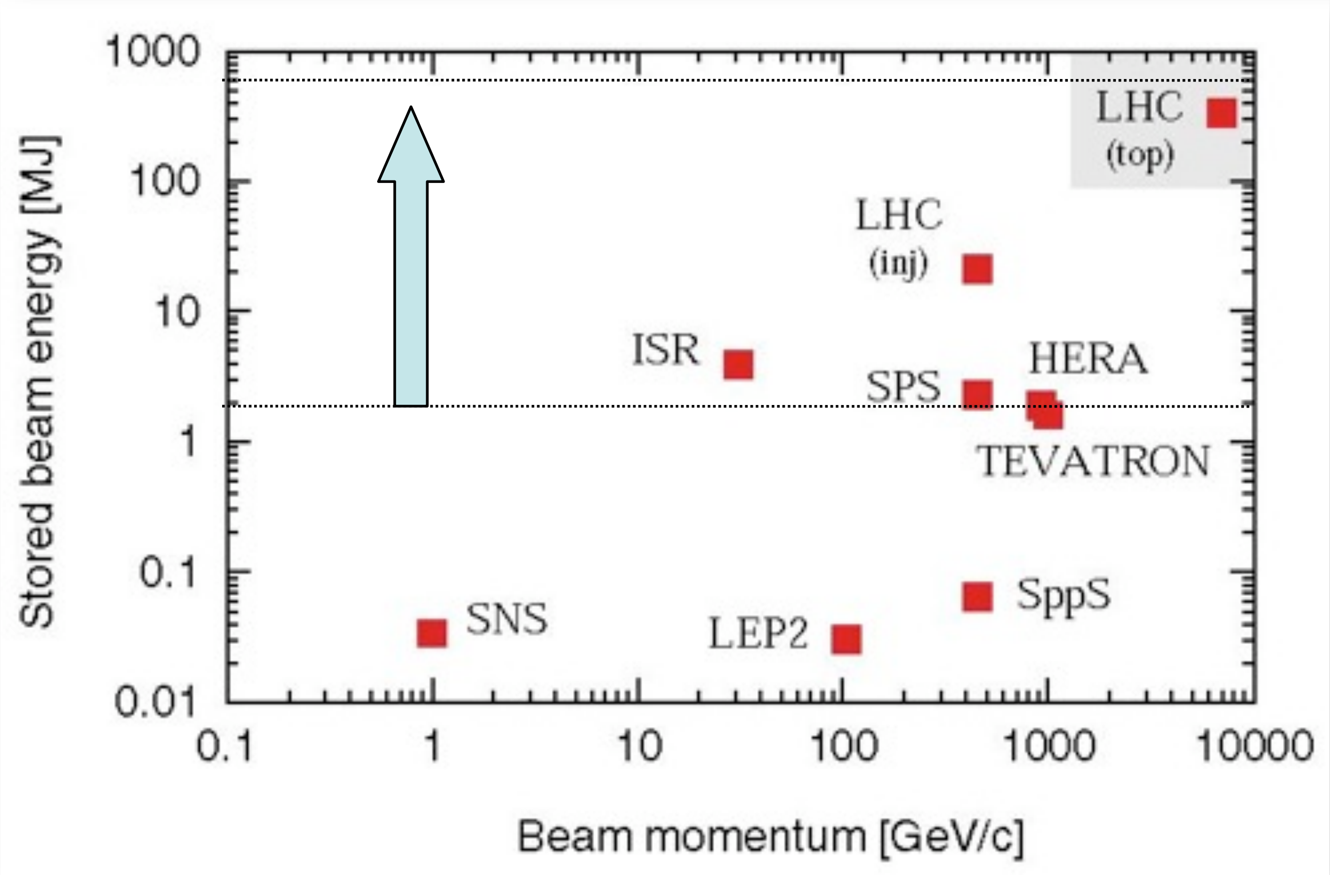
Complexity and Reliability

- 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



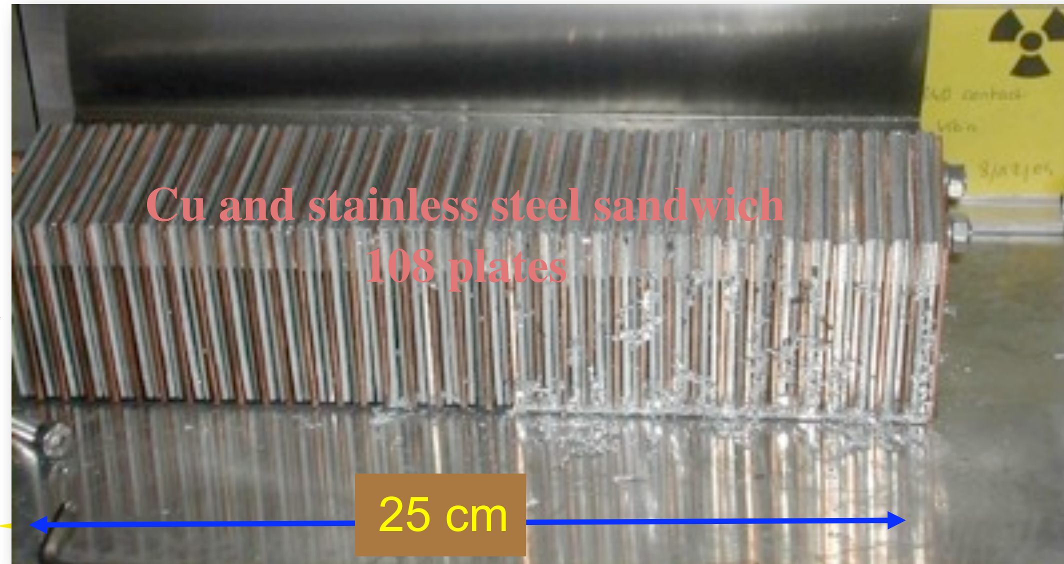
LHC: > 100 × higher stored energy and small beam size: ~ 3 orders of magnitude in energy density and damage potential. Active protection (beam loss monitors, interlocks) and collimation for machine and experiments essential.
Only the specially designed beam dump can safely absorb this energy.

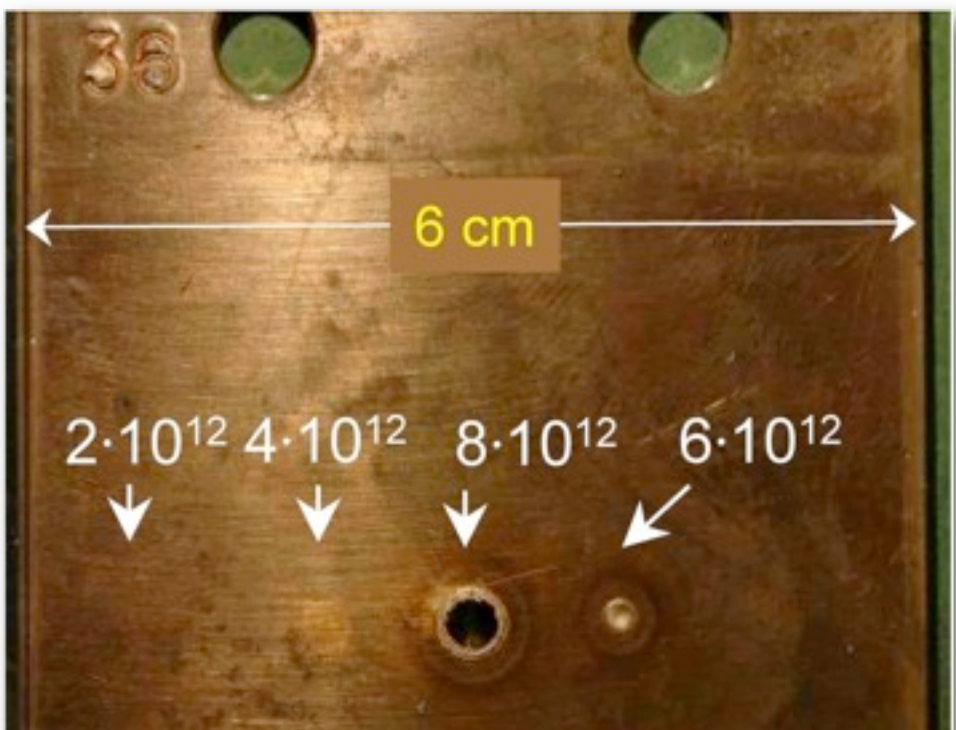
Damage potential : confirmed in controlled SPS experiment

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

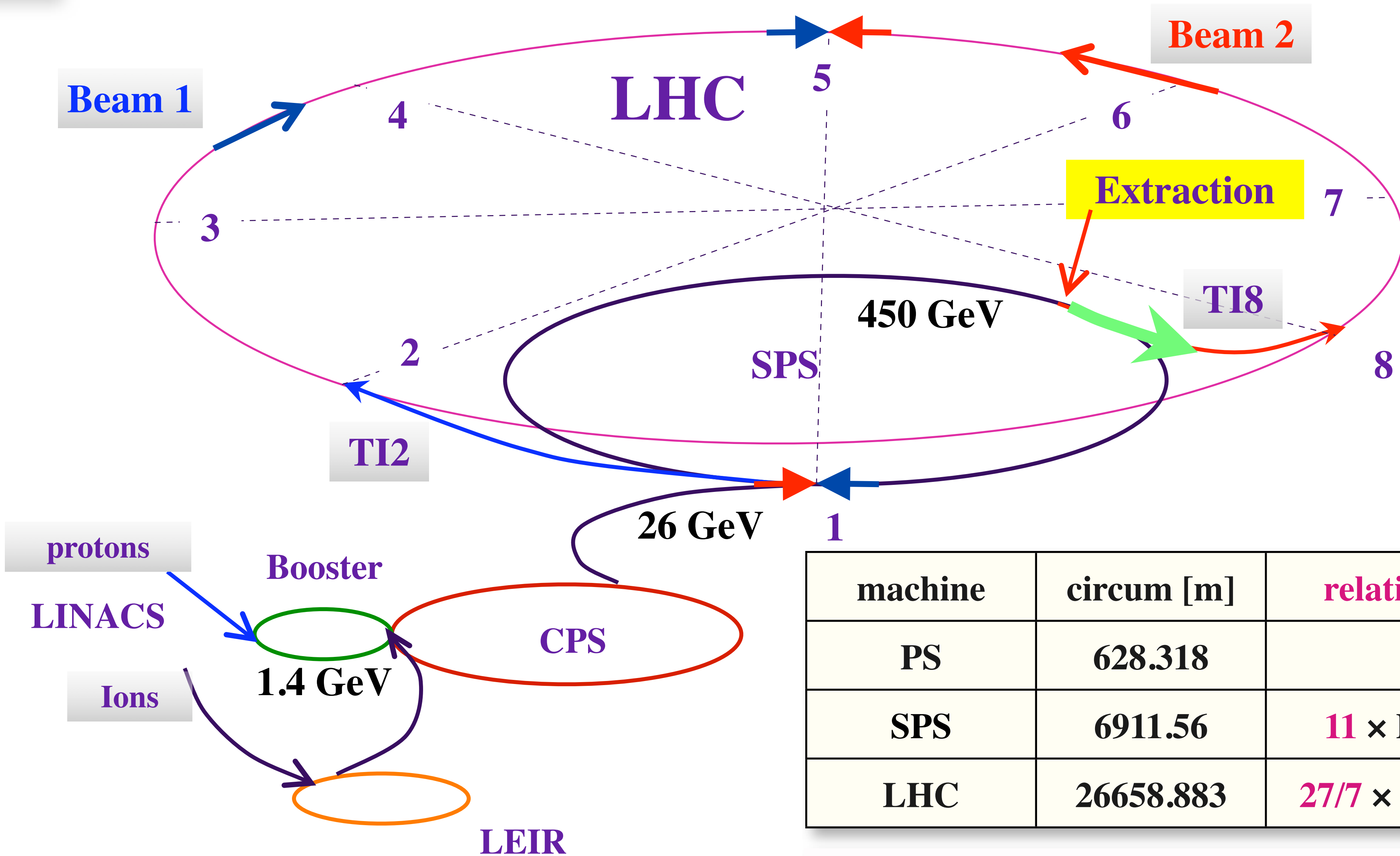
Beam parameters, LHC compared to LEP

	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

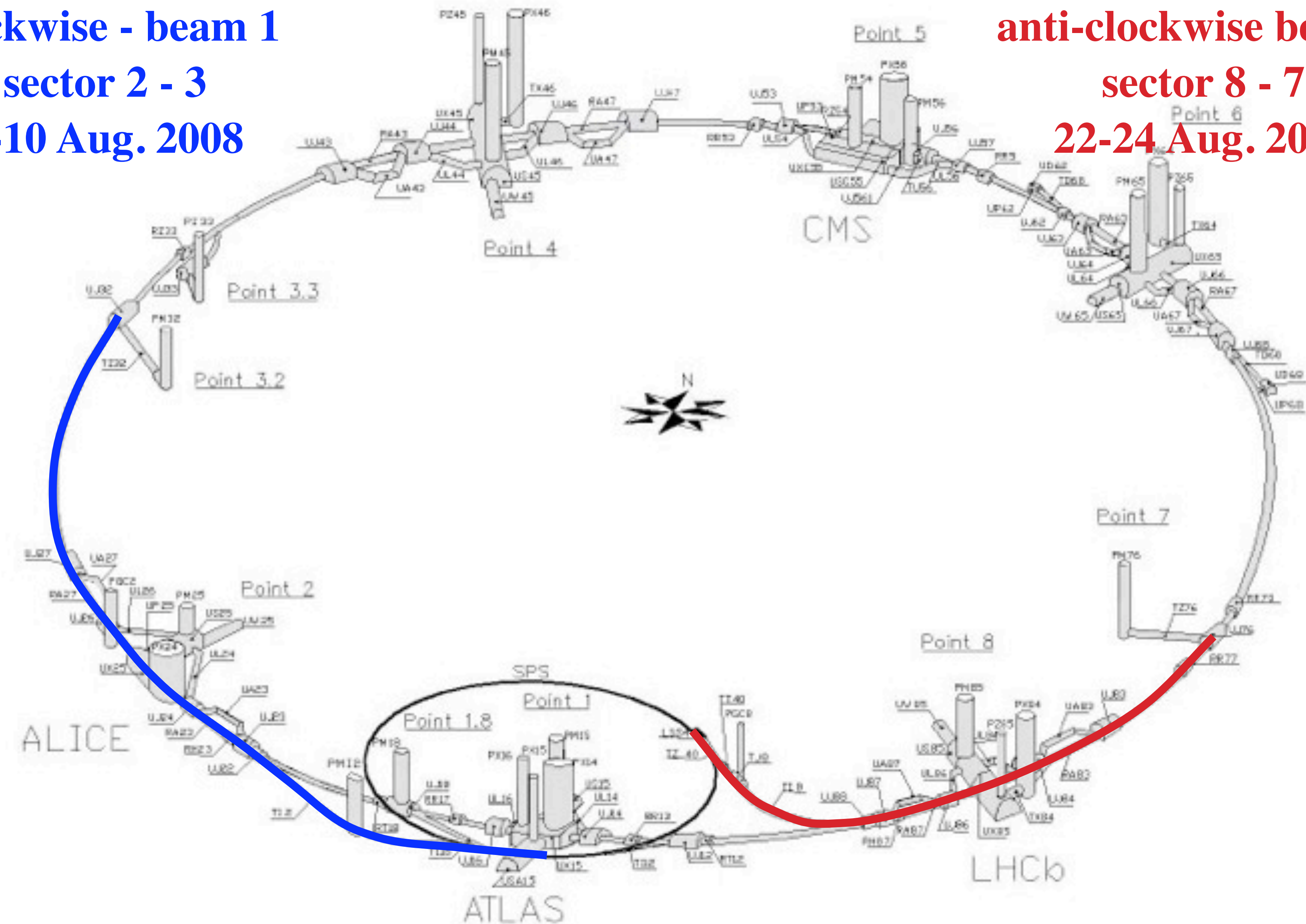
Beam size of protons decreases with energy : area $\sigma^2 \propto 1 / E$

Beam size largest at injection, using the full aperture

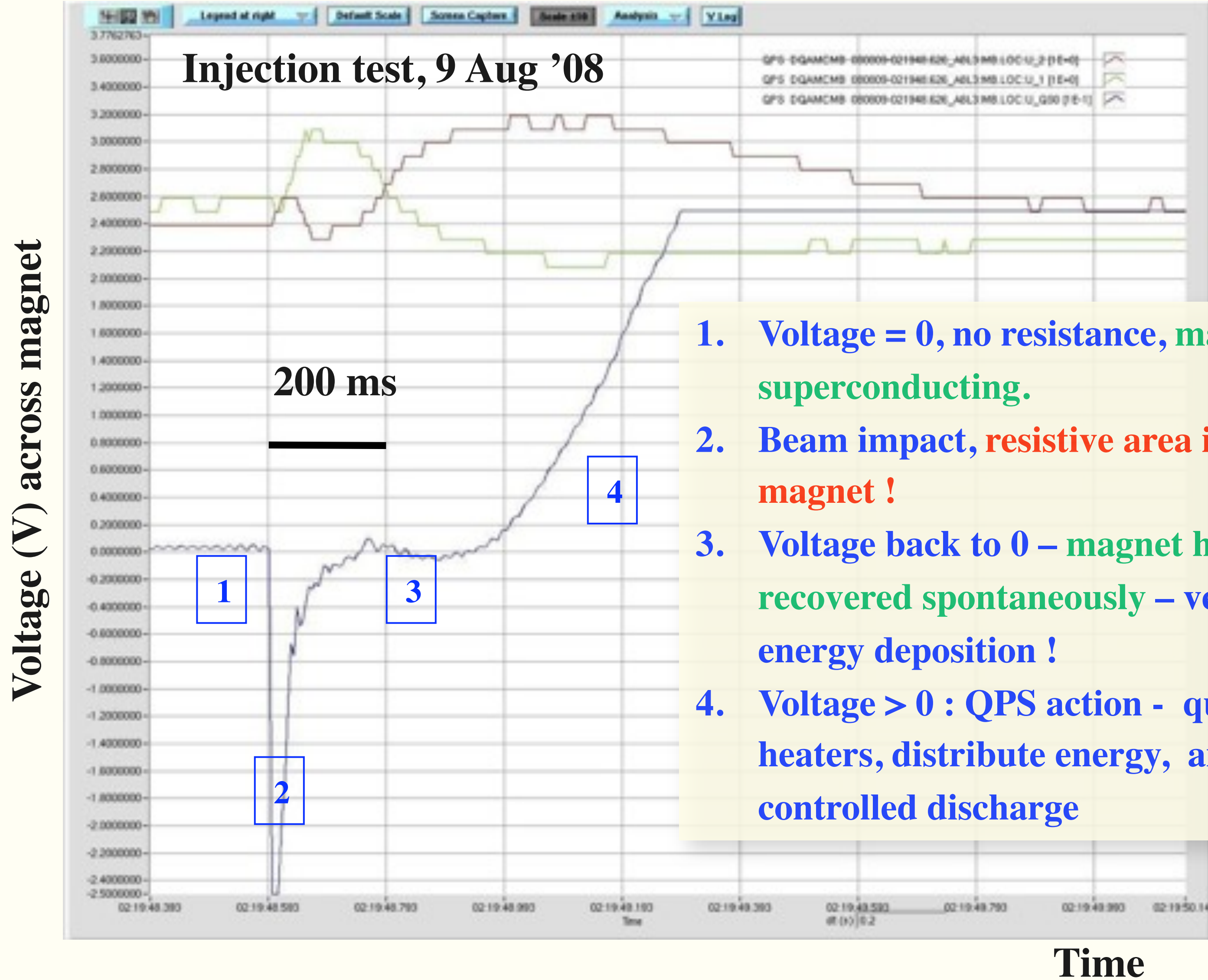
LHC Commissioning : injection tests in August'08

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



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 ~2×10⁹ protons @ 450 GeV and calibration of BeamLossMon system

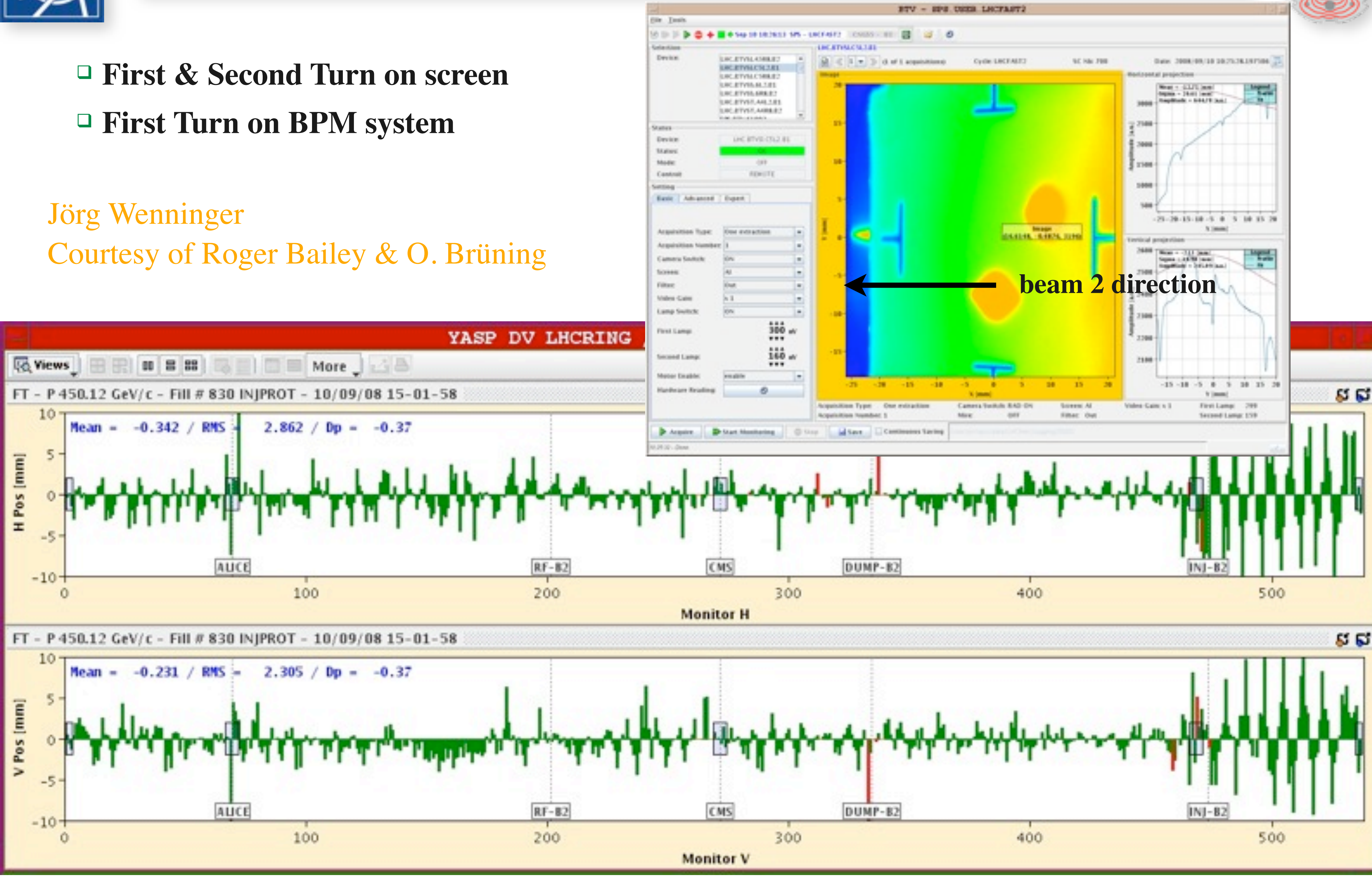
10 September 2008

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

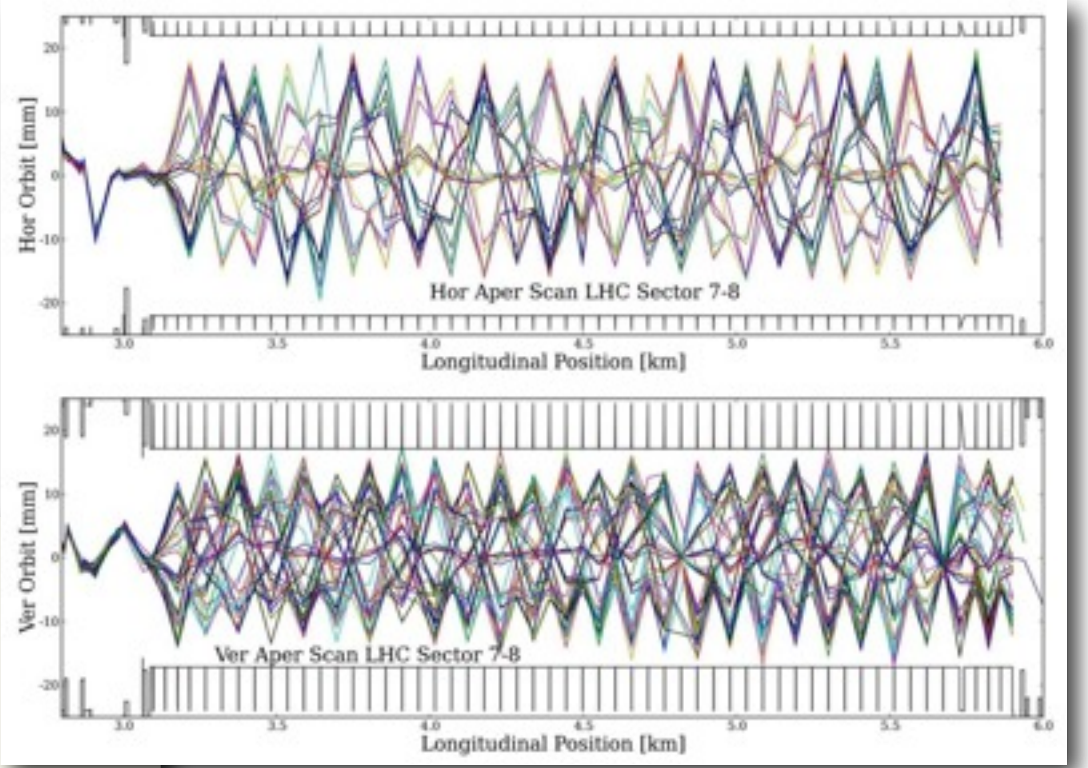


longitudinal position around the ring, *s* [m], here by monitor number

Examples of detailed aperture and optics measurements

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

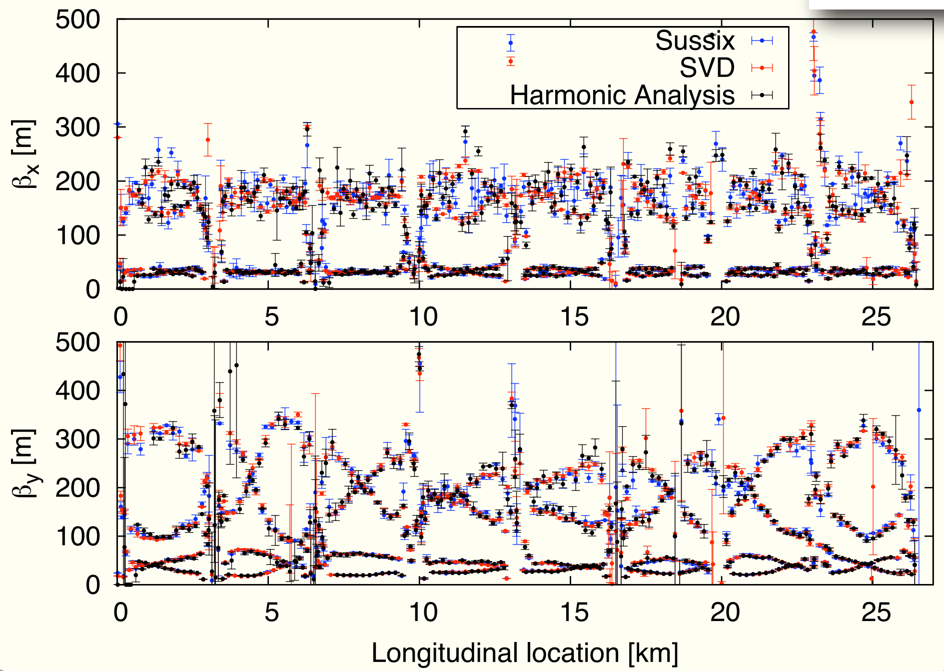
LHC Perf. Note 1 Sep.2008



β-measurements and analysis

LHC Perf. Note 8 Jan 2009

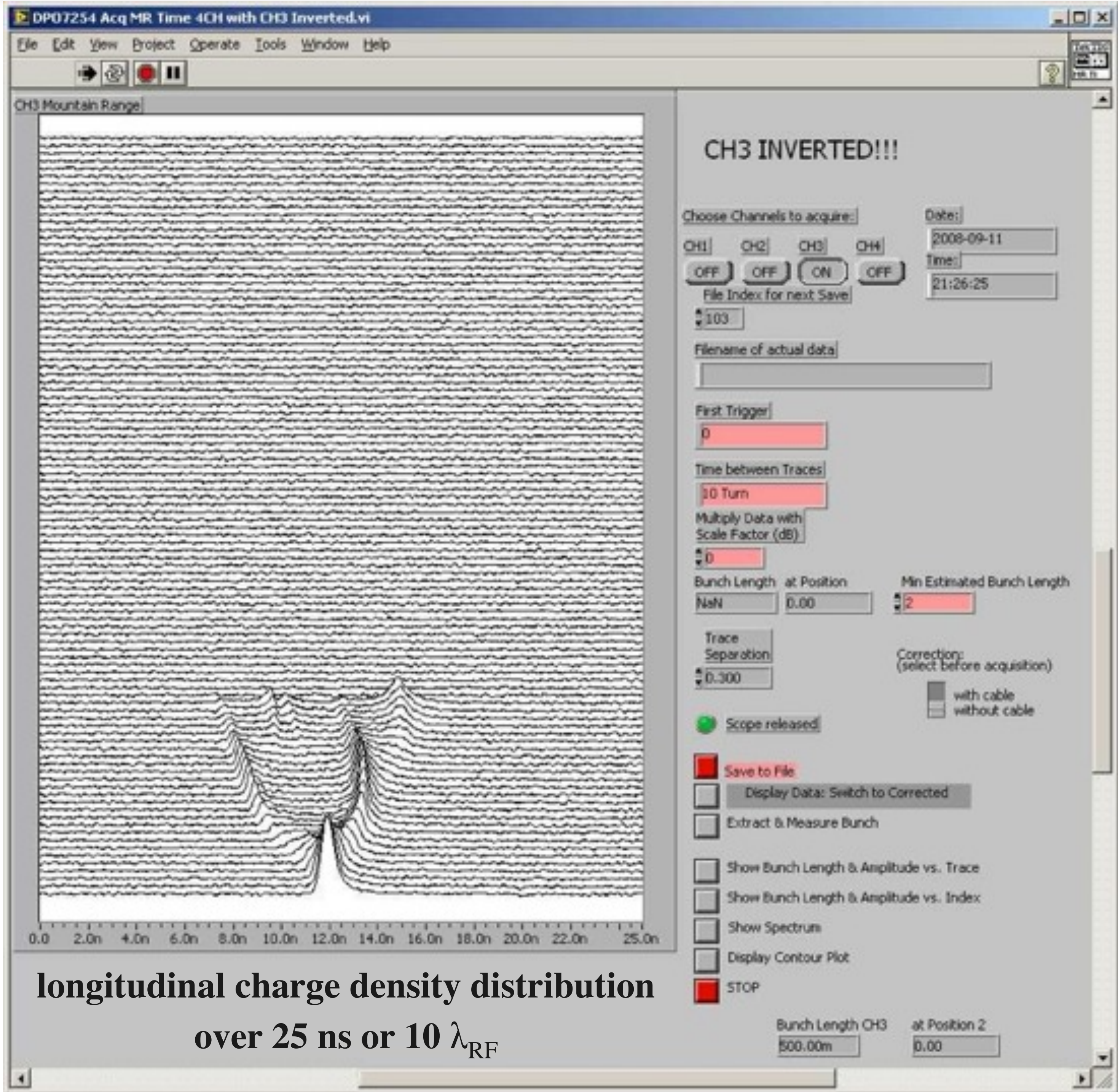
ABP and OP group



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.

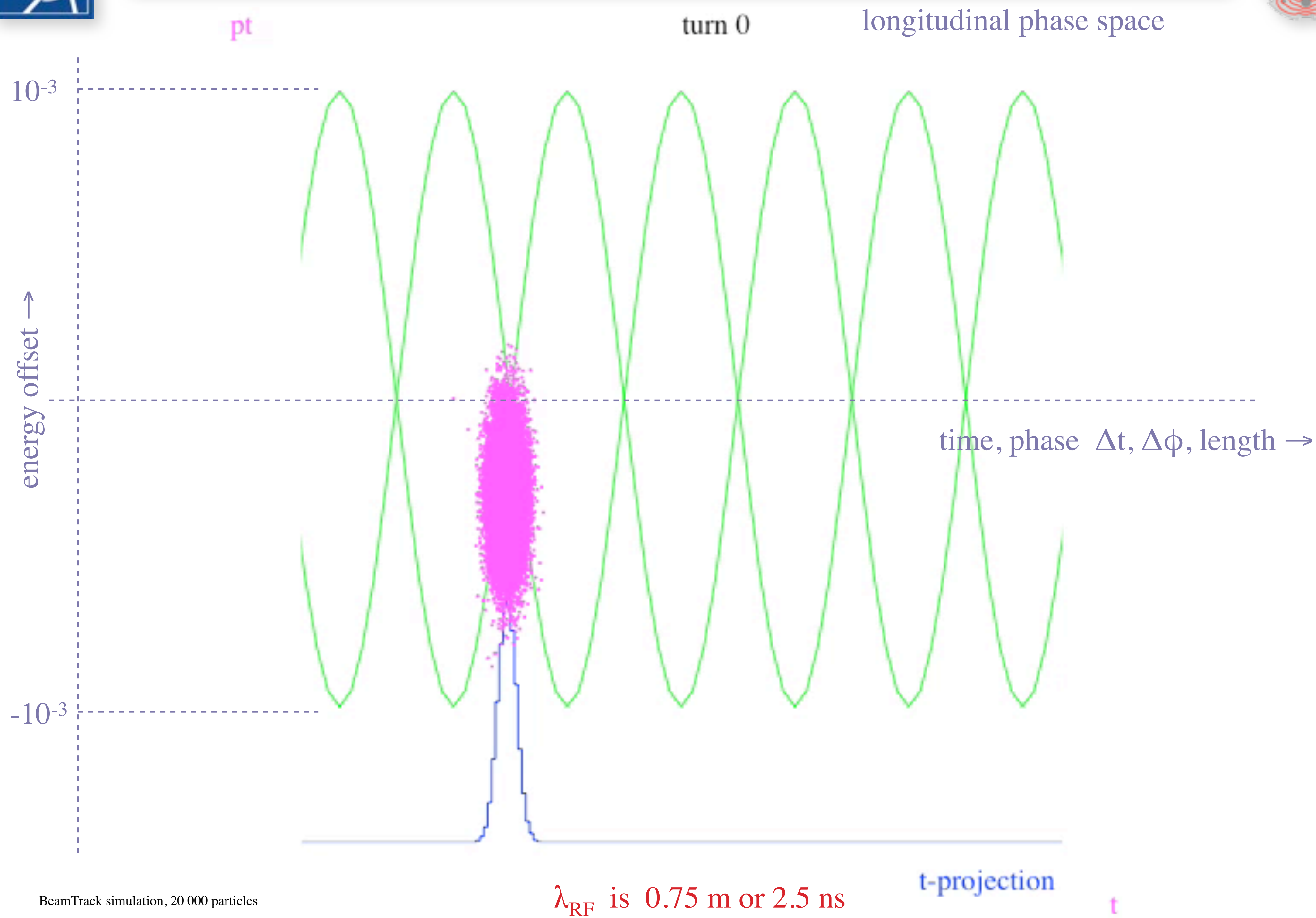
Textbook example : from first attempt to RF capture

one trace every 10 turns



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

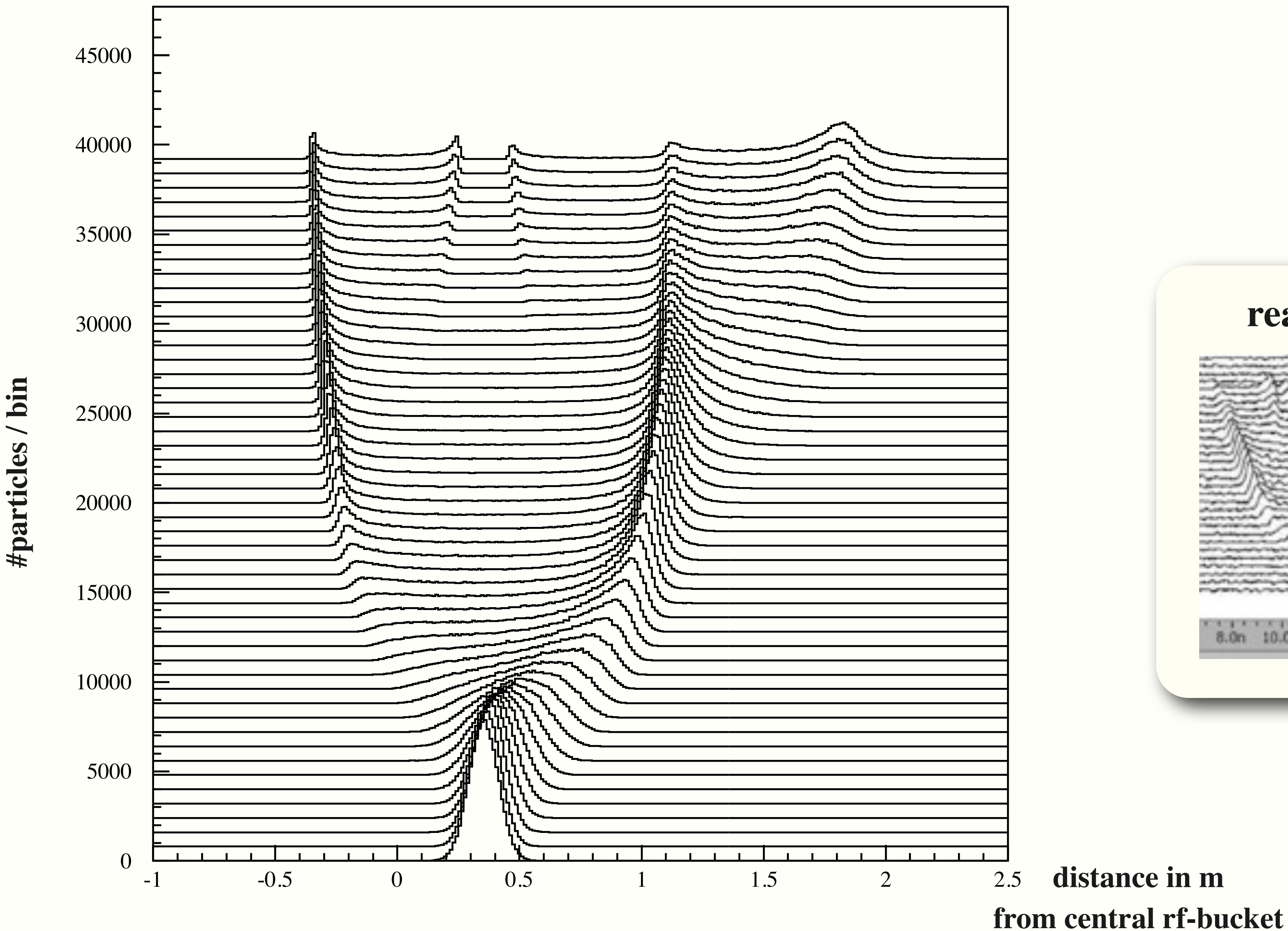
Simulation of injection with 170° injection phase offset



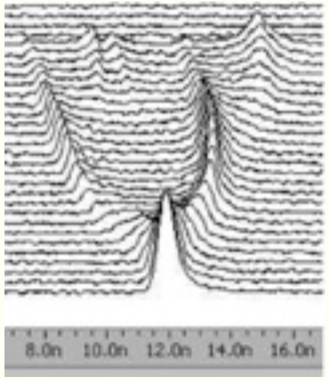
BeamTrack simulation, 20 000 particles

λ_{RF} is 0.75 m or 2.5 ns

Simulation of injection with 170° injection phase offset



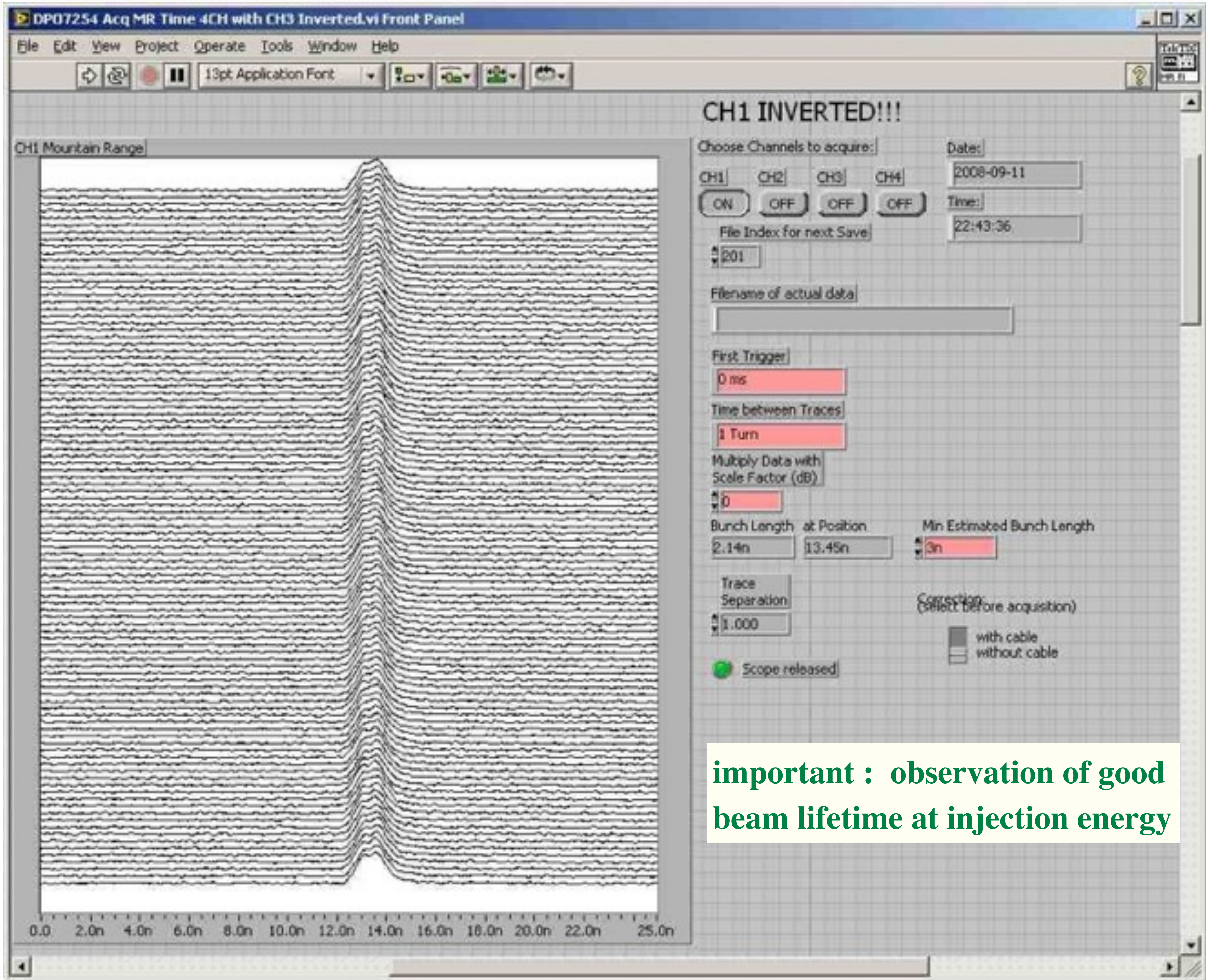
real LHC



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

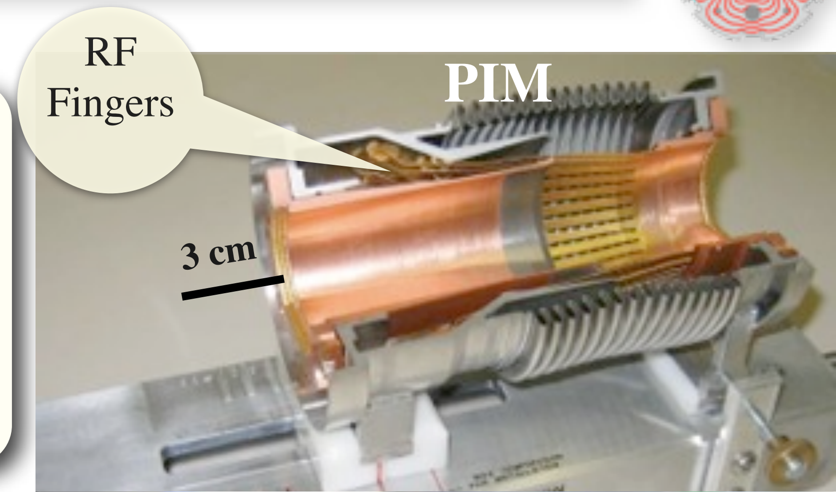
Critical Issues

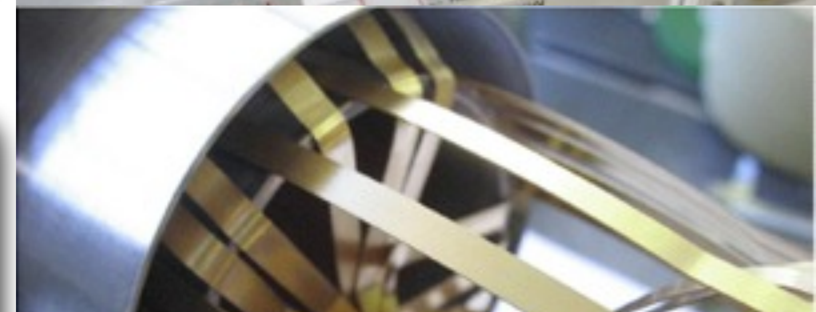
Past

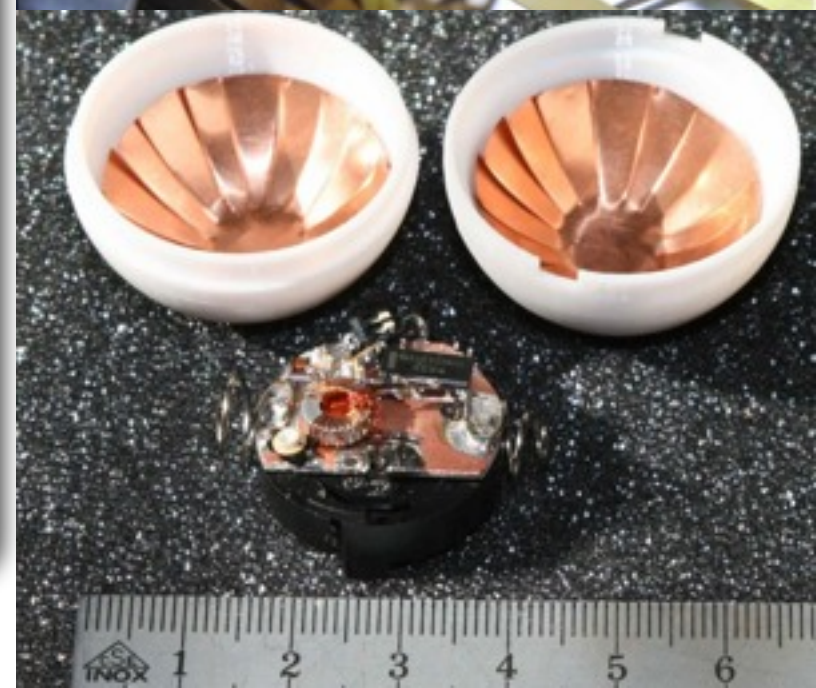
- QRL   cryo-line (He supply)
- DFB   power connections, warm to cold transition
- Triplet quadrupoles - differential pressure

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** ⇨



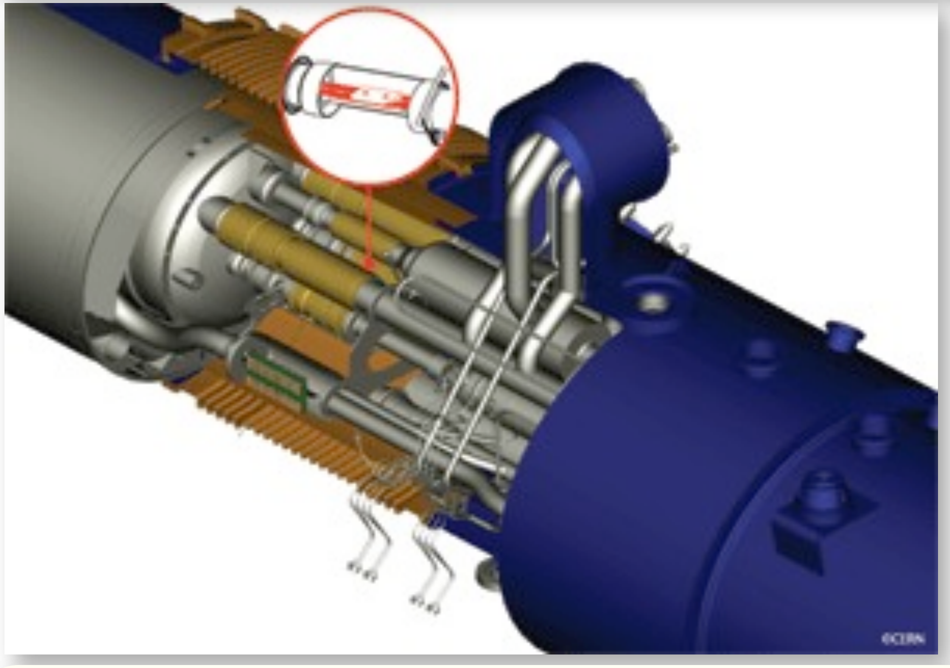




After 3 days of excellent progress with beams

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 :

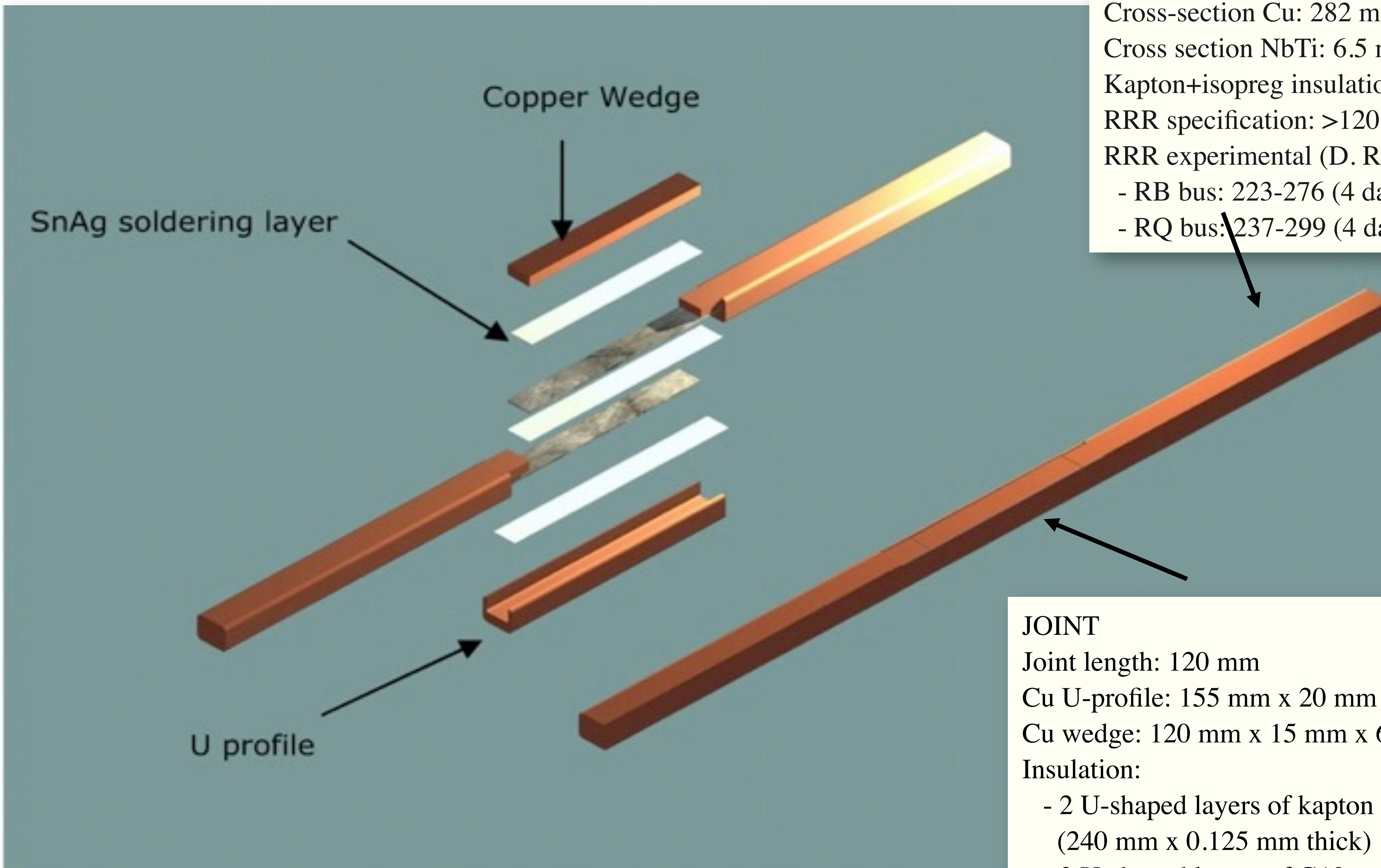
good splice ~ 0.3 nΩ, I = 12 kA, U = R I = 3.6 μV (now) possible to check

$P = R I^2 = 0.043$ 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

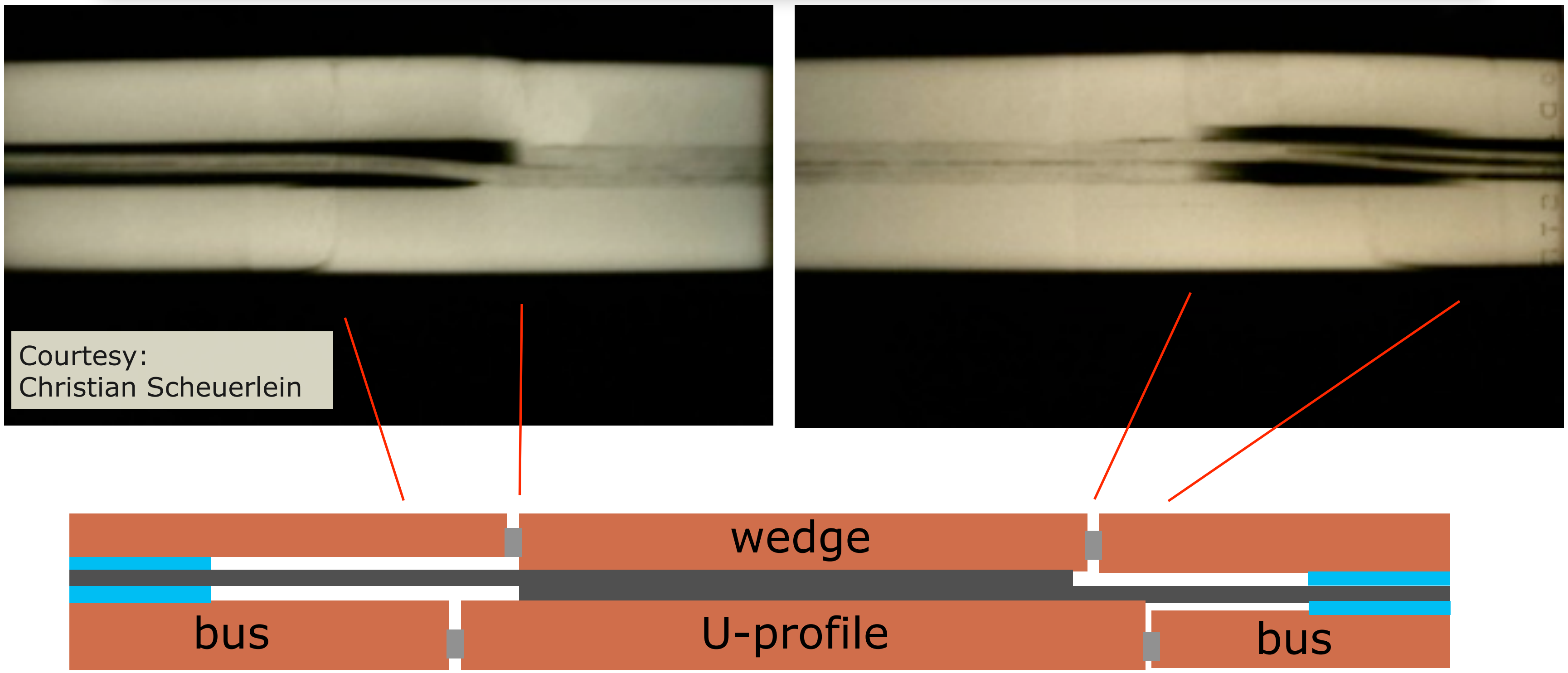


BUS
Cross-section Cu: 282 mm^2
Cross section NbTi: 6.5 mm^2
Kapton+isopreg insulation
RRR specification: >120
RRR experimental (D. Richter)
- RB bus: 223-276 (4 data)
- RQ bus: 237-299 (4 data)

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

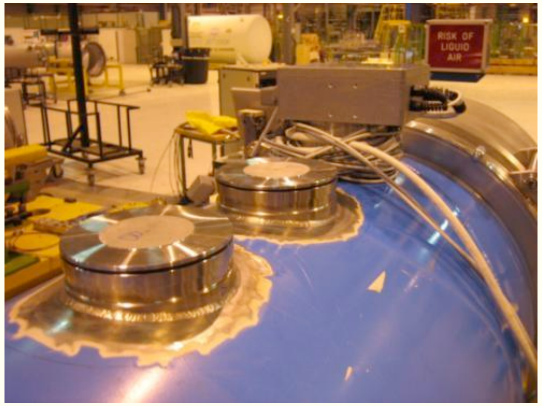
Current status - August 2009

damage repair

- **39 dipoles and 14 quadrupoles removed - and re-installed. Last magnet back in tunnel on 30/04/2009, electrical connections finished 2nd June**

avoid reoccurrence

- **Improved diagnostics, measurements of magnet interconnects - splice resistance**
- **> 50 % of machine (sectors, 1-2, 3-4, 5-6, 6-7, all standalone magnets) with fast pressure release valves**



- **Improved anchoring on vacuum barriers around the ring**
- **Enhanced Quench Protection System**
  - aperture symmetric quenches and joints in magnets
  - 2 × faster discharge
- **Remaining risks minimized by keeping maximum beam energy limited to 3.5 - 5 TeV for the first run**

Major amount of work - much of the hardware work is finished

Time also used to further improve crucial systems like BLM, complete collimator installation ..

Restart LHC with beam by mid-November 2009

Strategy for the first LHC physics run

Main strategy in commissioning :
establish circulating beams and good lifetime at the injection energy. ✔ **Sept. 2008**

Chamonix 2/2009 baseline
1 month commissioning
10 month proton physics
1 month lead ions

August '09 : Detailed discussion of the knowledge from the 5 sectors measured at warm and the 3 sectors measured at 80 K
All put together and discussed in special LMC meeting on 5 Aug. 2009.
Decision by management - 6 Aug. 2009.

Go in three steps

1. **collisions at injection energy 2×0.45 TeV = 0.9 TeV**
2. **physics run at 2×3.5 TeV = 7 TeV**
3. **physics run at increased energy, max. 2×5 TeV = 10 TeV**

Towards the end of 2010 before the winter shutdown : 1st run with heavy ions, lead - lead.

Next steps in commissioning with beam

- complete the BPM checks (70% H, 30% V done)
- adjust and capture beam 1
- beam 1 & beam 2 timing
- experiments magnets : turn on solenoids and toroids
- possible to allow for first collisions at 2×450 GeV
- turn on IP2 / 8 spectrometers - verify perfect bump closure
- start to use collimators, increase intensity
- check out the beginning of the ramp, $\sim$450 GeV to 1 TeV
- QPS commissioning
- beam dump commissioning
- full ramp commissioning to initial physics energy of 3.5 TeV
- first collisions at physics energy of 2×3.5 TeV
- increase intensity and partial squeeze

Maximum beam intensity LHC year 1

design LHC intensity : 3.23×10^{14} protons / beam

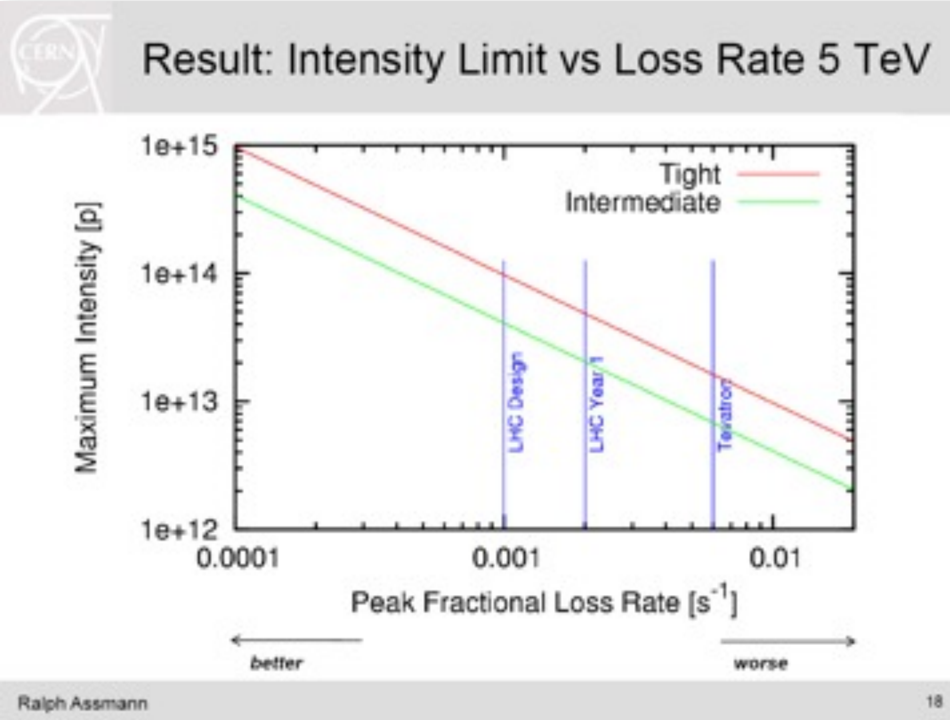
1st years, limited by magnet quench / collimation

maximum beam loss rate ~ 10^{-3} /s fraction or ~4×10^{11} p/s

Examples for 0.001/s Loss Rate

- It is really the loss rate that matters above a few ms. So what counts is the ratio of loss amount over loss duration (short loss spikes are very dangerous). We get the peak loss rate 0.001/s from:
  - 1% of beam lost in 10 s.
  - 0.1% of beam lost in 1 s.
  - 0.01% of beam lost in 100 ms.
  - 0.001% of beam lost in 10 ms.
- Stick with the official loss rate 0.001/s from now on, adding some evolution.
- Assume 0.002/s is achieved in the first year of LHC operation at 5 TeV, as shown in following slides.

Ralph Assmann 21



 # bunches : nominal is 2808 bunches, 25 ns spacing

LHC year 1 : Important to go in small steps - minimize beam losses. Max. total intensity at 5 TeV roughly ~ 1/10 nominal.

start of physics run : $I < 2\times10^{13}$ p with intermediate coll. settings

later : $I < 5\times10^{13}$ p with tight coll. settings.

3.5 TeV intensities could be a bit higher - details remain to be worked out

Scaling of beam parameters with energy

Baseline beam parameters for E_b = 5 TeV have been worked out, discussed and agreed, LPC 7/5/09
Details for 3.5 TeV still need to be defined.

		scale factor 3.5 to 5 TeV
intensity	more critical at high E	take 1 ; conservative
emittance	E^{-1}	1.43
β*	~ E^{-1} triplet aperture	1.43
Luminosity	~ E^{-2}	2
beam-beam tune shift	constant	1

Luminosity estimates : roughly 2× less at 3.5 TeV compared to 5 TeV
this should be conservative and does not take into account that lower energies are less critical for protection, shorter ramp time and faster turnaround.

Beam-beam tune shift parameter ξ
for head-on collisions depends
only on intensity (not energy, β*)

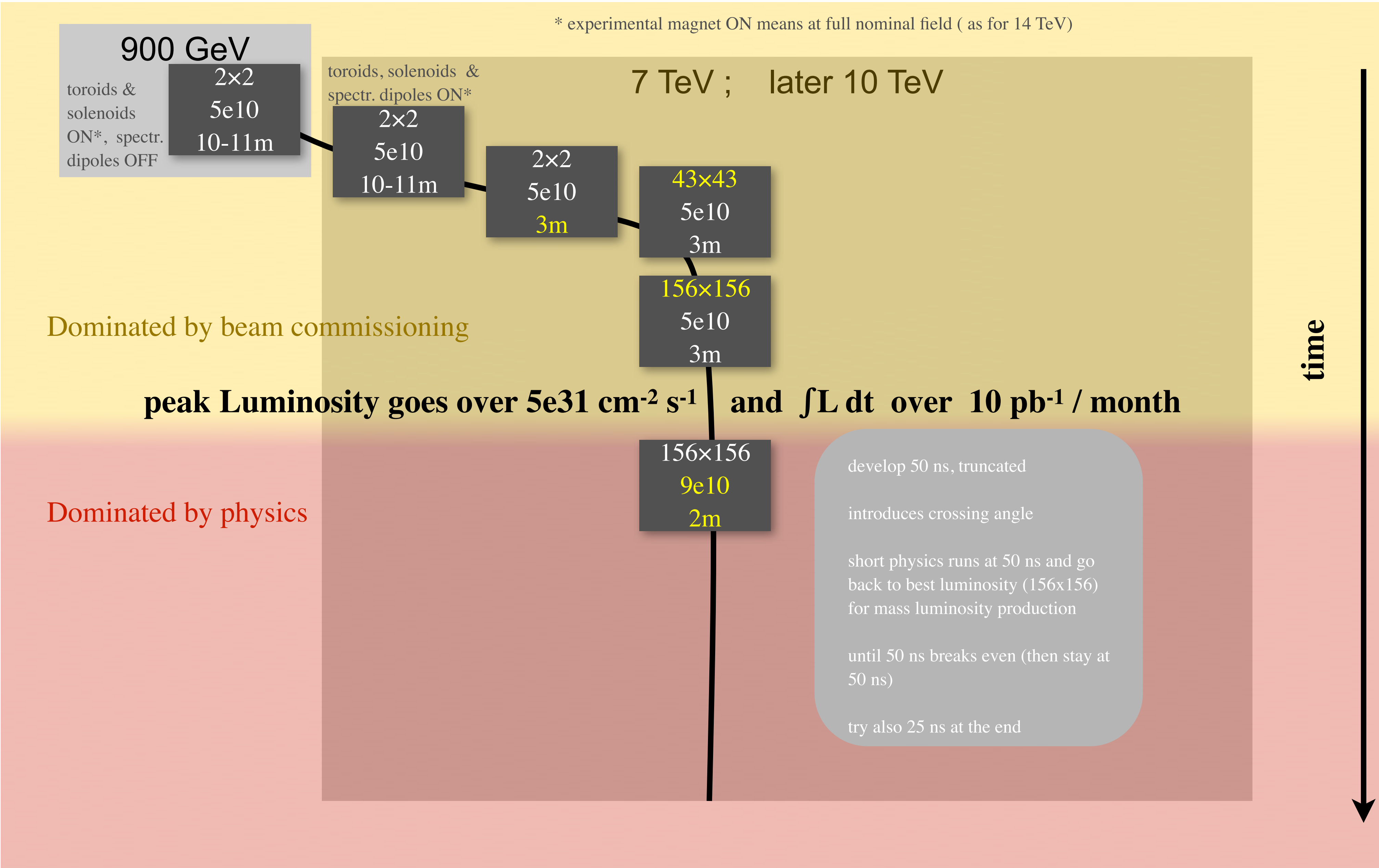
$$\xi = \frac{r_c N}{4\pi \epsilon_N}$$

nominal LHC : round beams and const ε_N $\sigma_{x,y} = \sqrt{\beta_{x,y}\, \epsilon_N / \gamma}$

N	ξ
5×10^9	0.000163
4×10^{10}	0.00130
1.15×10^{11}	0.00374

at the design emittance

Physics run modes for the 1st year



Based on Massimiliano Ferro-Luzzi, LPC 7-May 2009. Scaled to 2×3.5 TeV

Parameter space

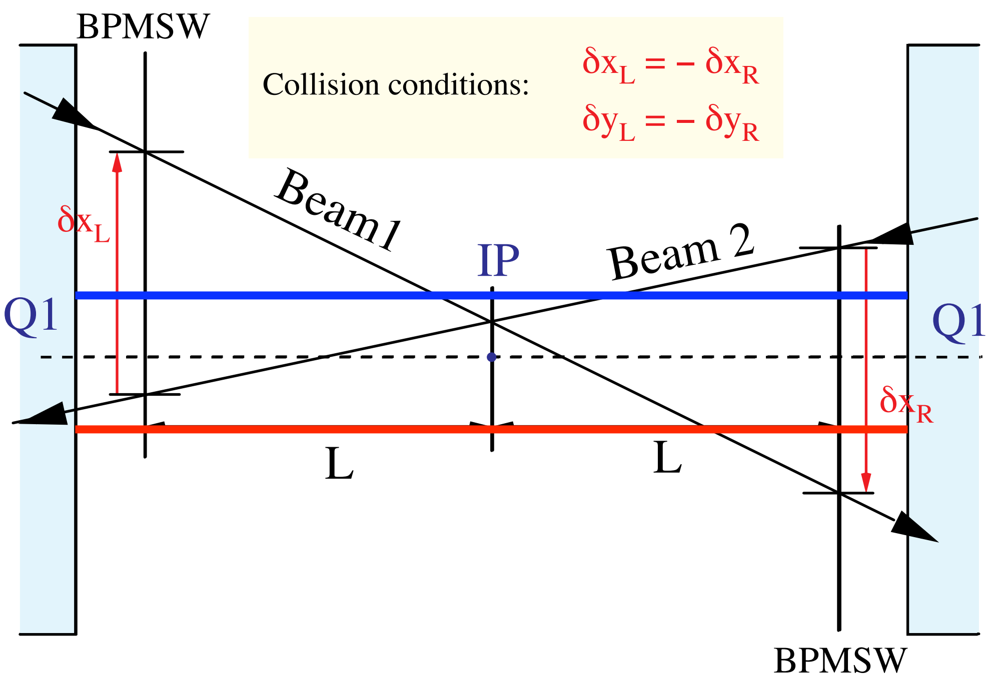
		No crossing angle						Crossing angle				
Energy	TeV	0.45	0.45	3.50	3.50	3.50	3.50	3.50	3.50	4.00	5.00	7.00
Bunch intensity	1.E+10	1	4	4	4	4	9	9	9	9	9	11.5
Bunches		4	43	43	43	156	156	702	1404	2808	156	2808
Emittance	μm	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
β*	m	11	11	11	2	2	2	3	3	3	2	1
Luminosity	$cm^{-2} s^{-1}$	4.2E+26	7.2E+28	5.6E+29	3.1E+30	1.1E+31	5.6E+31	1.7E+32	3.3E+32	7.7E+32	8.0E+31	1.0E+34
Protons		4.0E+10	1.7E+12	1.7E+12	1.7E+12	6.2E+12	1.4E+13	6.3E+13	1.3E+14	2.5E+14	1.4E+13	3.2E+14
% nominal		0.0	0.5	0.5	0.5	1.9	4.3	19.6	39.1	78.3	4.3	100.0
Stored energy	MJ	0.0	0.1	1.0	1.0	3.5	7.9	35.4	70.8	161.7	11.2	361.7
Monthly (0.2)	pb-1	0.00	0.04	0.29	1.59	5.76	29.16	85.84	171.67	399.85	41.65	5231.88
Physics month				1	2	3	4	?	?	?	?	
Pile-up, σ_{in} = 75 mb				0.09	0.5	0.5	2.4					

(10^6 seconds @ <L> of 10^{33} $cm^{-2} s^{-1} \rightarrow 1 fb^{-1}$)

courtesy : Roger Bailey, 7 Aug. 2009

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 $\delta_{\rm IP} = \sigma_{\rm BPM}$

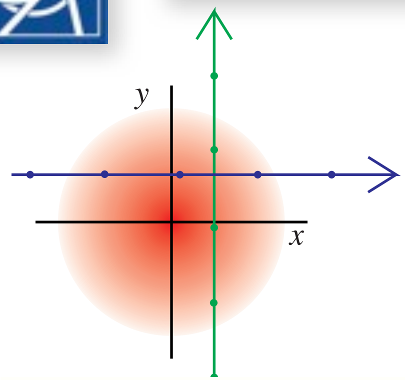
Expected resolution for small separation and 0 crossing angle ; in each plane.

~ 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

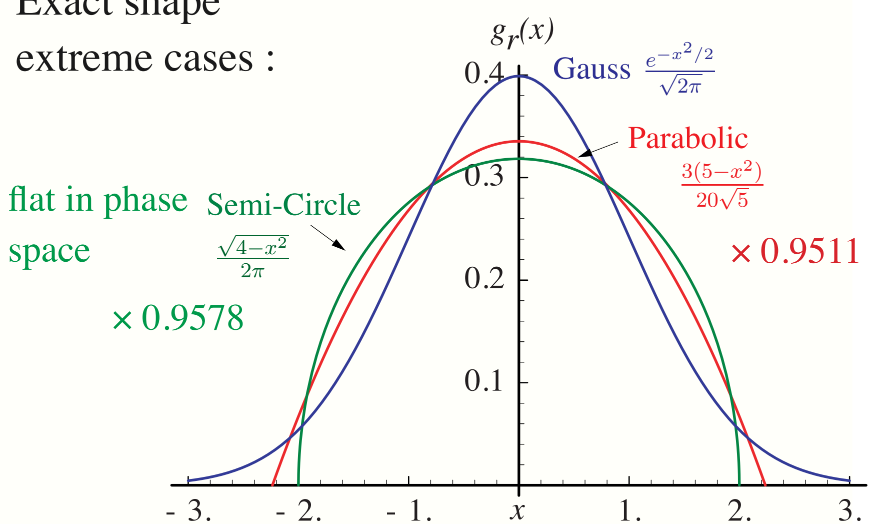
Accuracy : better than **1% at ISR**

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

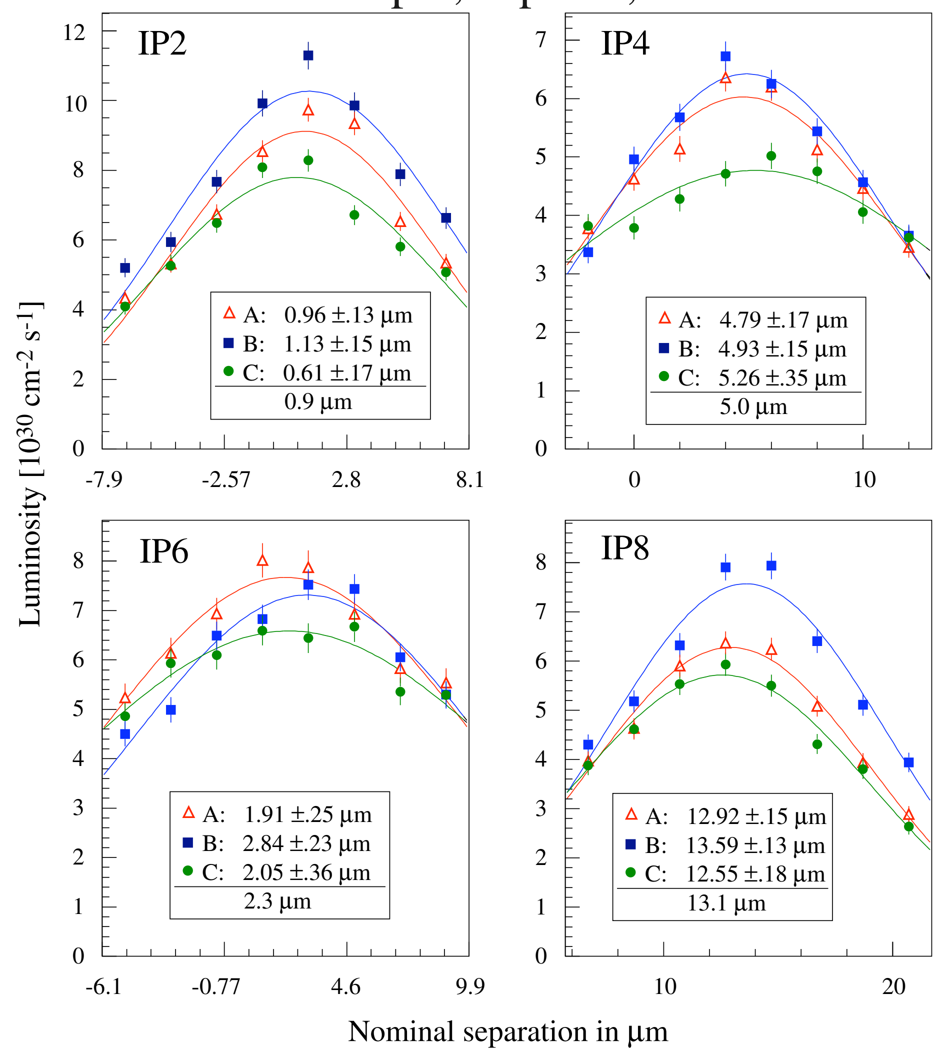
Contributions :

- 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

Experimental conditions, LBS

LBS : LHC Background Study Group.
Chaired by me, deputy D. Macina, scientific secretary A. Macpherson

In addition to background simulation, studies and optimization covering more generally experimental conditions including luminosity optimization and calibration and signal exchange between experiments and machine.

Core members include the physics coordinator & LPC chairman Massimiliano Ferro-Luzzi and contact persons from the experiments

ALICE Antonello Di Mauro, Andreas Morsch + Werner Riegler
ATLAS Witold Kozanecki, Christophe Clement, Mika Huhtinen + Siegfried Wenig
CMS Richard Hall-Wilton, Tiziano Camporesi, + Nicola Bacchetta
LHCb Gloria Corti, Richard Jacobsson + Magnus Lieng
TOTEM Mario Deile; **LHCf** Daniela Macina

Currently meeting once per month on Thu. afternoon at the CCC
Open to all interested and help most welcome.
Next meeting is on 27 August, see indico

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

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

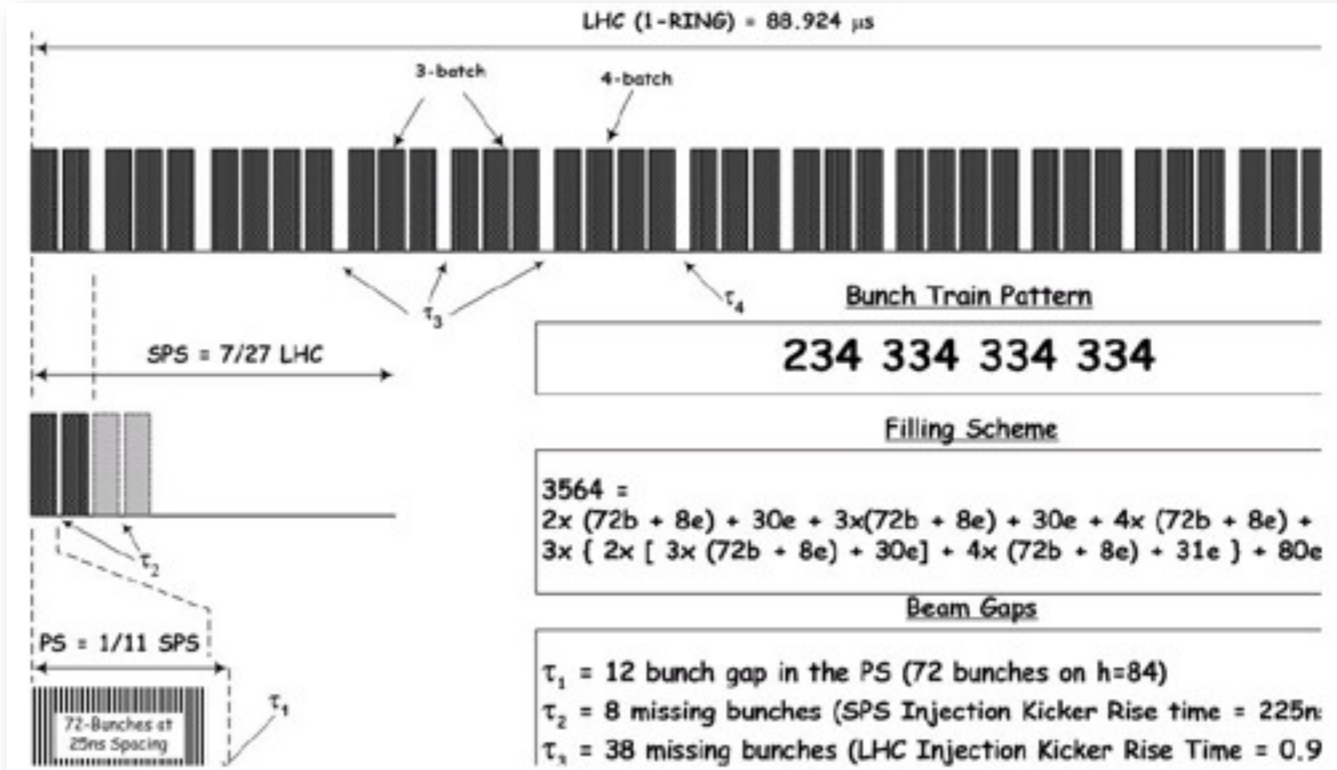
Inject batches of 2, 3 or 4 x 72 bunches

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

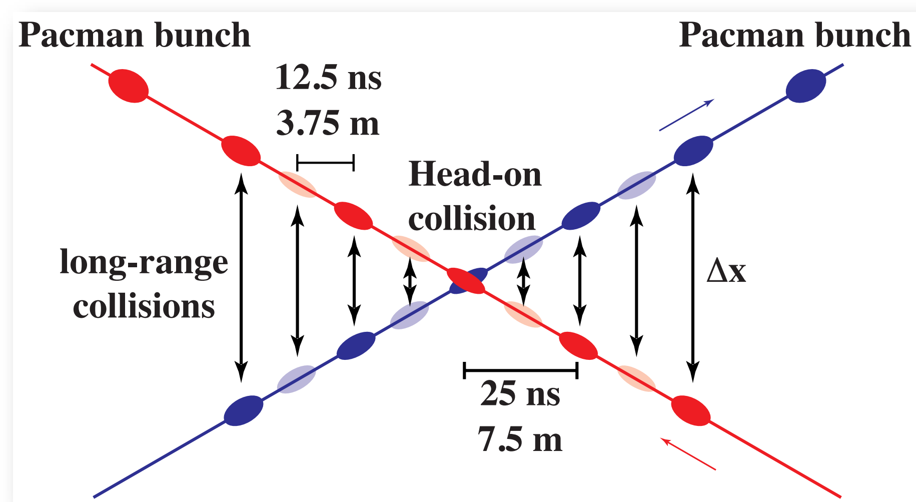


Crossing angle needed for > 156 bunches to avoid encounters closer than ~ 6 σ

Angle scales with σ or $1/\sqrt{\beta^*}$ and $1/\sqrt{E_b}$

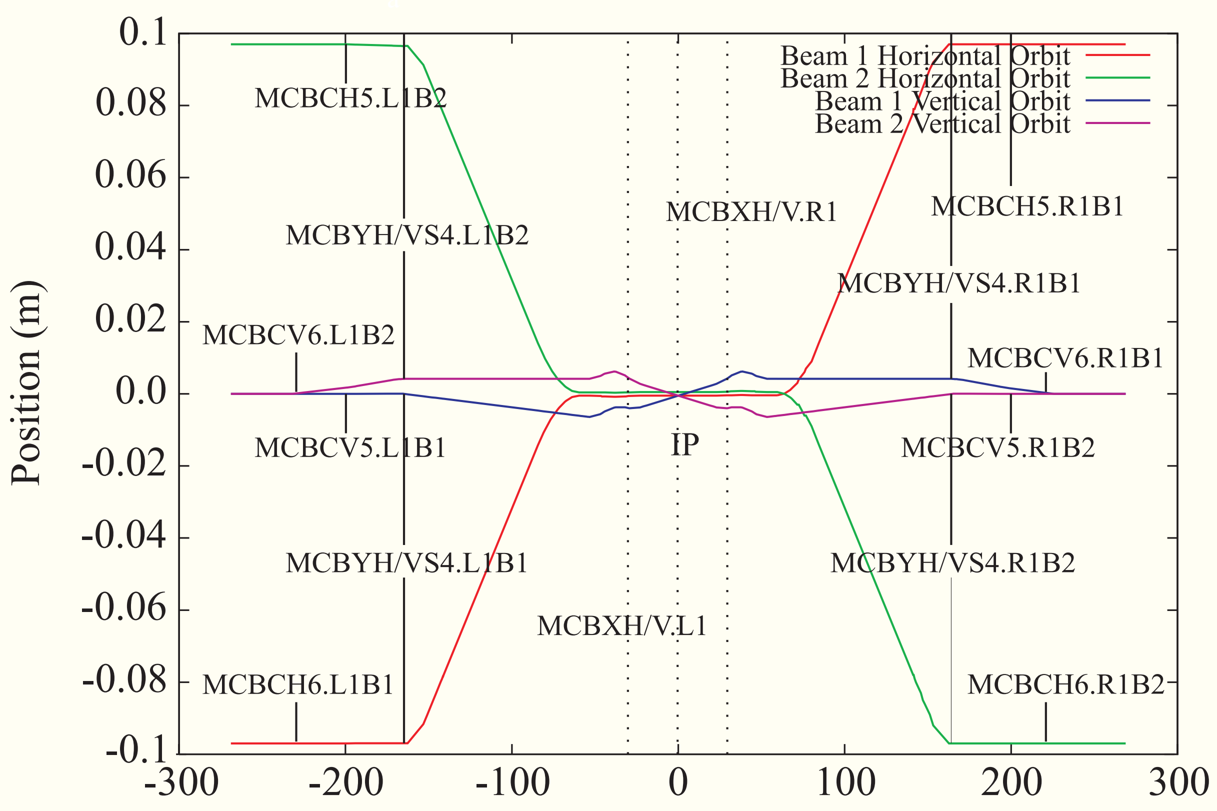
Nominal angle at 0.55 m, 7 TeV is ± 142.5 μrad

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

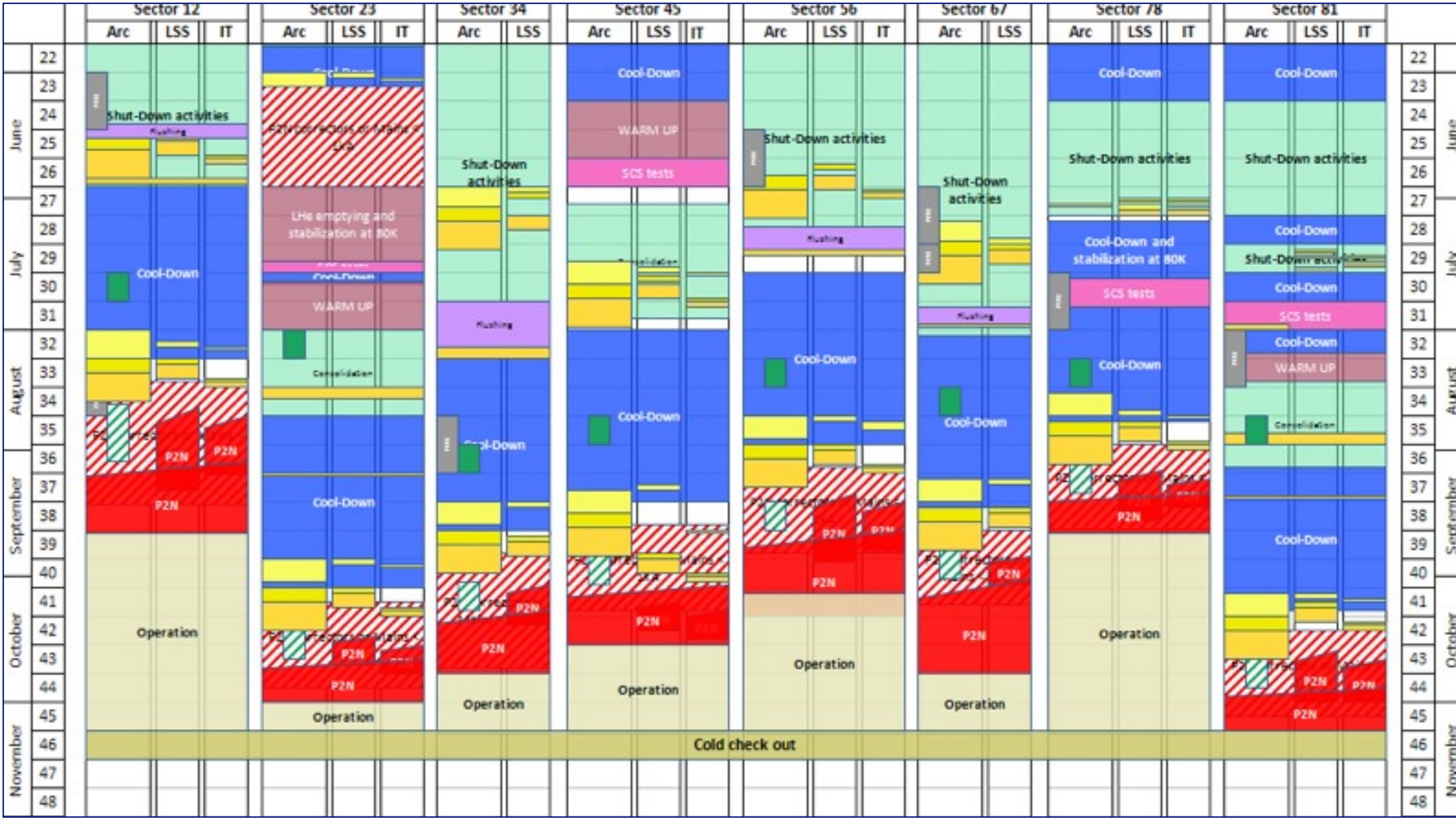
The LHC will run for the first part of the 2009-2010 run at 3.5 TeV per beam, with the energy rising later in the run. That's the conclusion that we've just arrived at in a meeting involving the experiments, the machine people and the CERN management. We've selected 3.5 TeV because it allows the LHC 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.

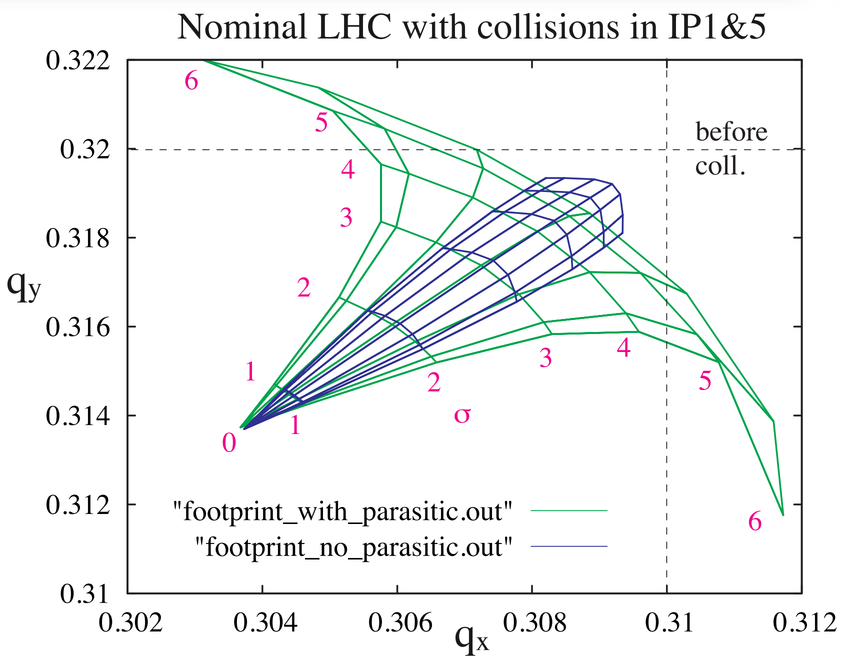
The procedure for the 2009 start-up will be to inject and capture beams in each direction, take collision data for a few shifts at the injection energy, and then commission the ramp to higher energy. The first high-energy data should be collected a few weeks after the first beam of 2009 is injected. 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.

Schedule July 22 (LMC23)

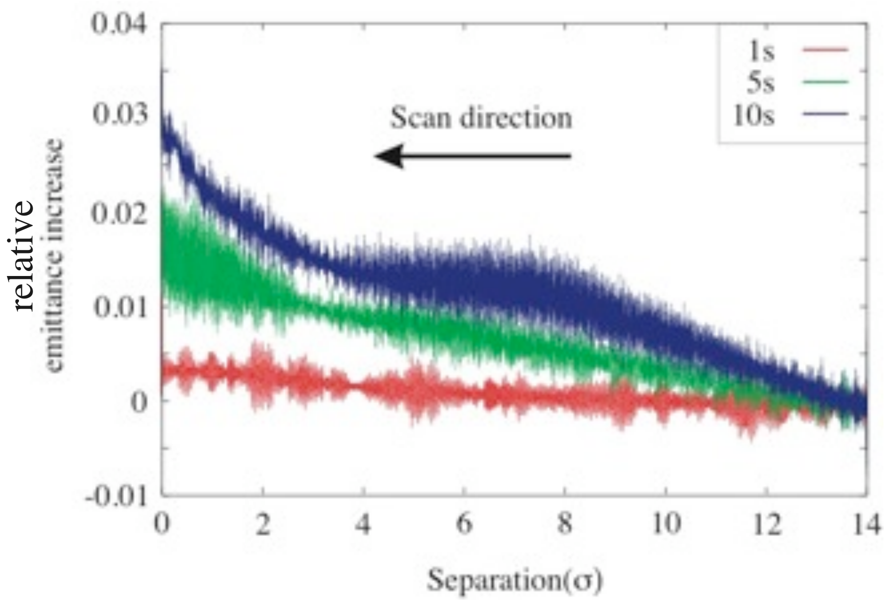


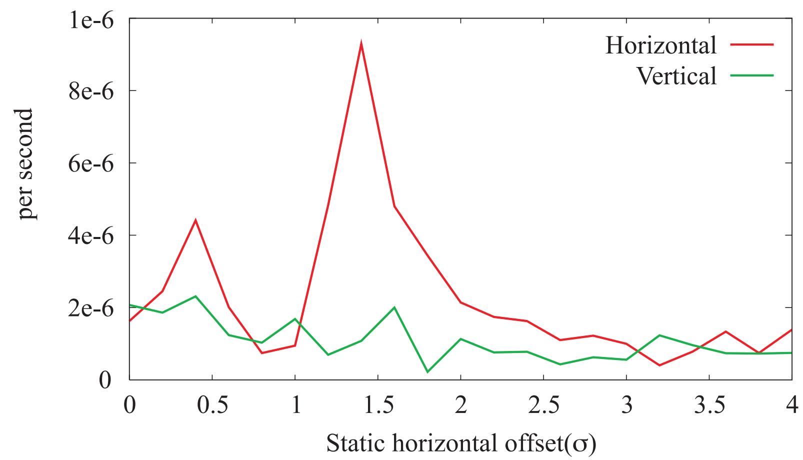
Crossing angle and parasitic beam-beam

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



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

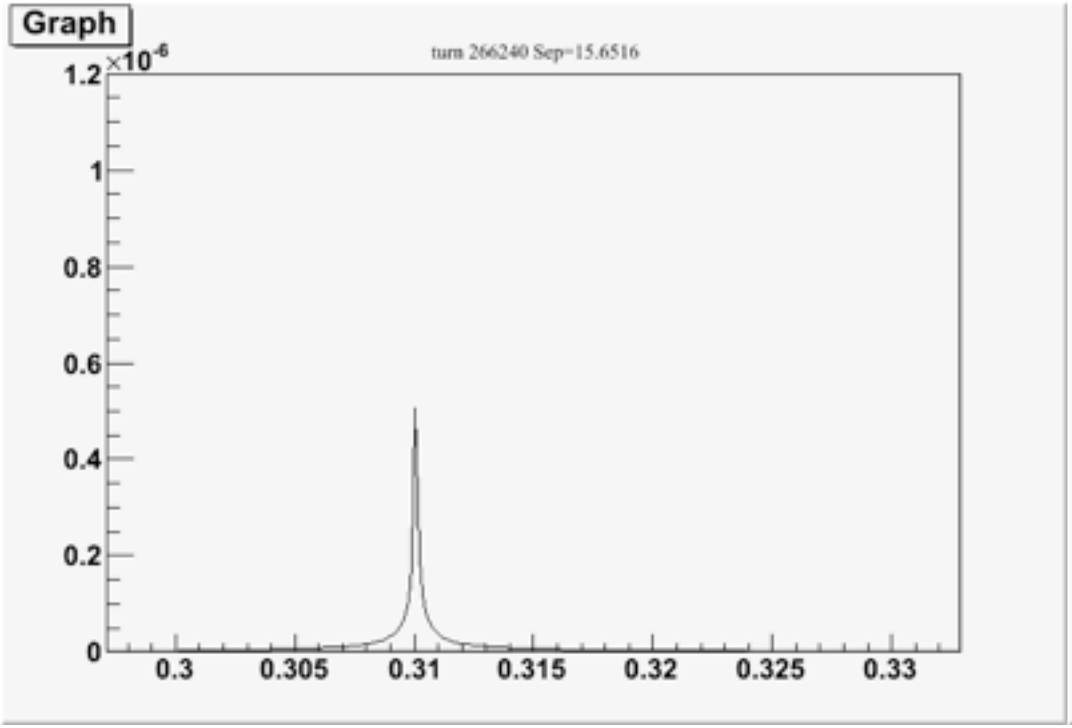
Some ref.

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

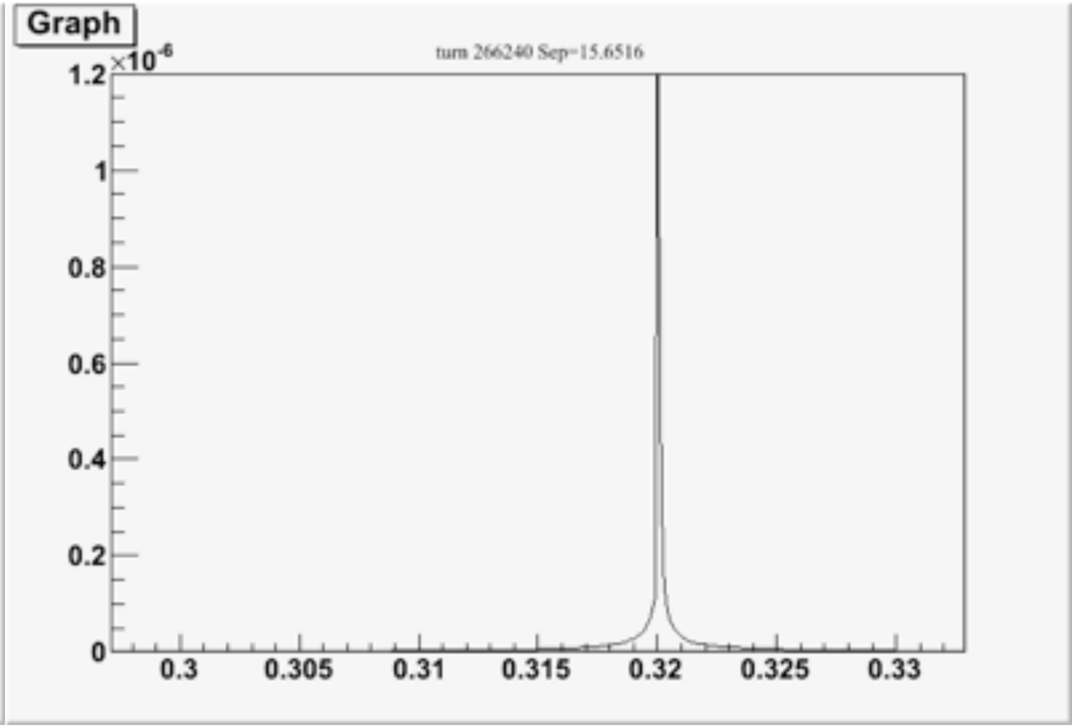
Figures above from S. M. White, H. Burkhardt, S. Fartoukh, T. Pieloni, *Optimization of the LHC Separation Bumps Including Beam-Beam Effects WE6PFP018*, PAC'09

Colliding beams in horizontal plane. Tune signal

Horizontal Tune



Vertical Tune



BeamTrack simulation for head-on collisions

Beam parameters, LHC year 1

Steps for luminosity increase during the 2009-2010 LHC pp run

	900 GeV	first high-energy coll.		Pilot physics run							
				no external crossing angle			with external crossing angle				
step	1	2	3	4	5	6	7	8	9	...	units
fill scheme	2x2	=	=	43x43	156x156	156x156	50ns@144	50ns@288	50ns@432	...	
E	**0.45**	**5**	=	=	=	=	=	=	=	...	TeV
k_b	2	=	=	**43**	**156**	=	**144+12**	**288+12**	**432+12**	...	bunches
N	5	=	=	=	=	9	=	=	=	...	10^{10} p/bunch
N_{Alice}	5	=	=	=	=	=	1	=	=	...	10^{10} p/bunch
β^*(IP1,5)	11	=	2	=	=	1	3	=	=	...	m
β^*(IP2)	10	=	=	=	=	=	3	=	=	...	m
β^*(IP8)	10	=	2	=	=	3	4	=	=	...	m
I/I_{nom}	0.031	=	=	0.67	2.42	4.3	4.05	8.1	12.1	...	%
E_{stored}	0.0072	0.08	=	1.72	6.24	11.1	10.5	20.8	31.2	...	MJ
α_{net}(IP1,5)	0	0	=	=	=	=	300	=	=	...	μrad
α_{net}(IP2)	0	200	=	=	=	=	300	=	=	...	μrad
α_{net}(IP8)	0	380	=	=	=	=	620	=	=	...	μrad
n_{bb}(IP1,5)	1	=	=	43	156	156	144	288	432	...	colliding pairs
n_{bb}(IP2)	1	=	=	4	=	=	12	=	=	...	colliding pairs
n_{bb}(IP8)	1	=	=	19	72	=	138	276	414	...	colliding pairs
L(IP1,5)	0.0026	0.029	0.16	6.9	24.9	161.5	48.3	96.5	145	...	10^{30} cm^{-2}s^{-1}
L(IP2)	0.0029	0.032	=	0.13	=	=	0.05	=	=	...	10^{30} cm^{-2}s^{-1}
L(IP8)	0.0029	0.032	0.15	2.8	10.8	23.7	32.7	65.4	98.1	...	10^{30} cm^{-2}s^{-1}
μ(IP1,5)	0.012	0.19	1.07	=	=	6.9	2.24	=	=	...	
μ(IP2)	0.013	0.21	=	=	=	=	0.028	=	=	...	
μ(IP8)	0.013	0.21	1.0	=	=	2.3	1.58	=	=	...	
Time for physics	~shifts	~days		~weeks		~months					

Definitions: μ = average number of inelastic interactions per crossing
n_{bb} = number of colliding pairs at given IP
α_{net} = net crossing angle

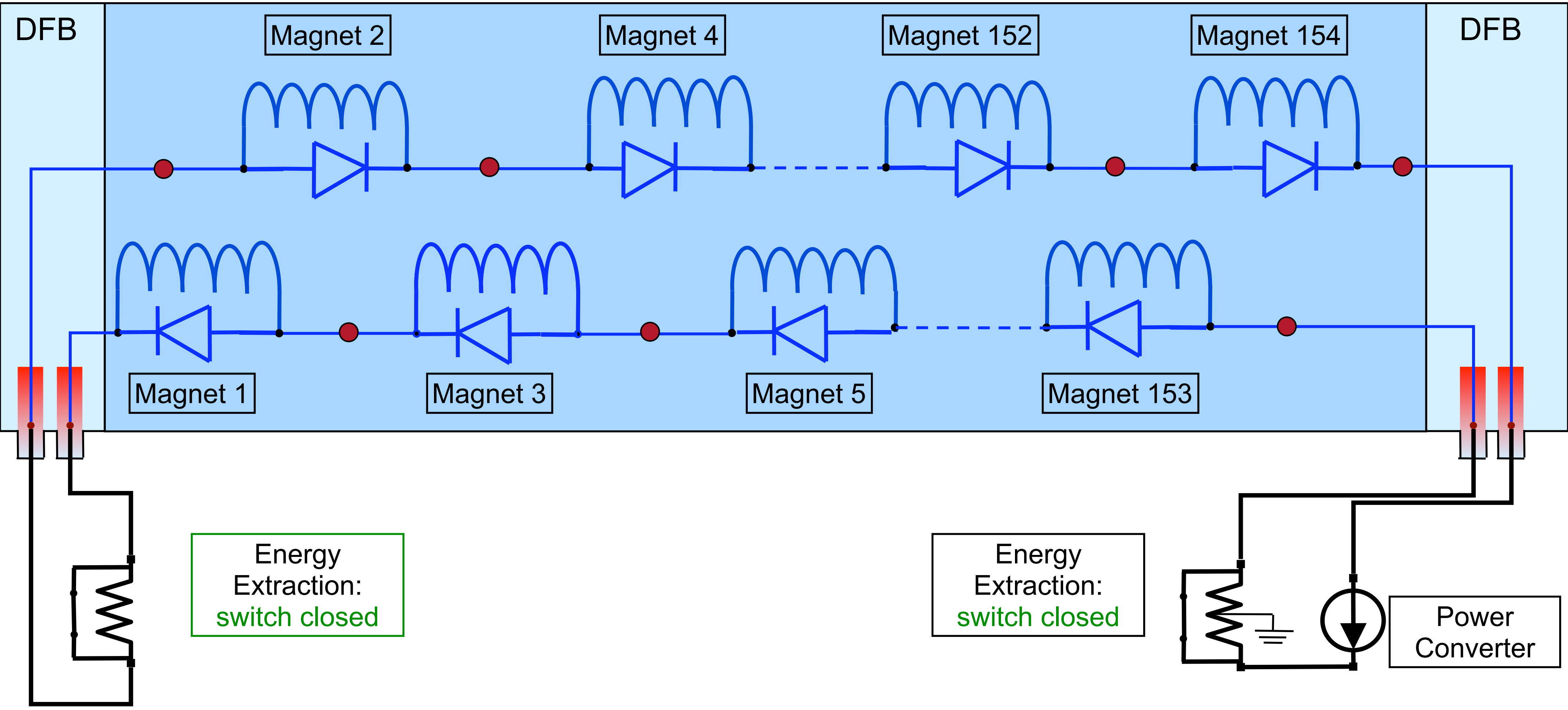
Assumptions: Longitudinal emittance $\epsilon = 0.5$ nm $\cdot$ 7 TeV$/E$
Inelastic cross section: $\sigma_{\text{inel}} = 52$ and 75 mb for $\sqrt{s} = 0.9$ and 10 TeV

Estimates: Beam commissioning time* for reaching step 6 $\approx$ six weeks
Beam commissioning time* to go from step 6 to step 7 $\approx$ two weeks
Total expected physics running time: of the order of $5 \cdot 10^6$ s

* with machine available

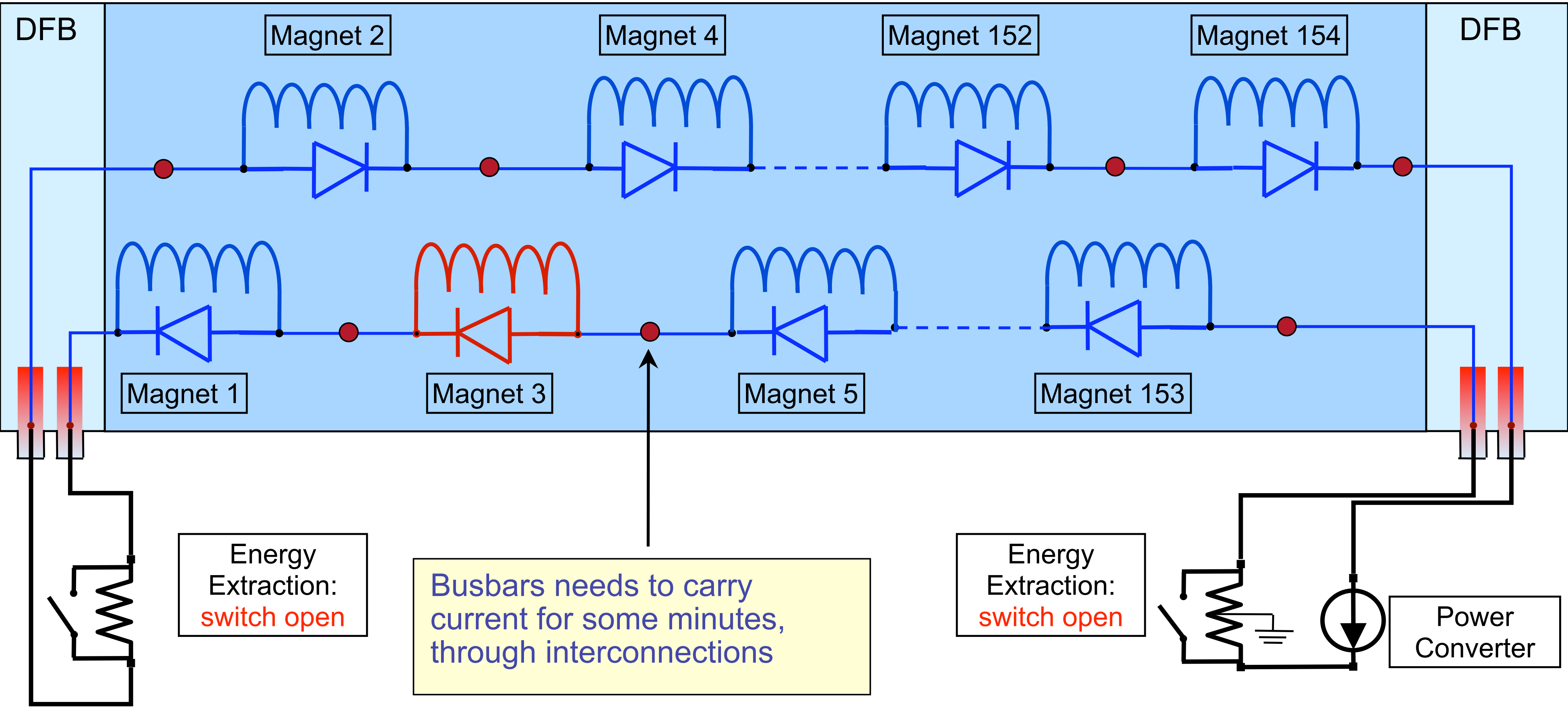
Main dipoles in arc cryostat

- Time for the energy **ramp** is about **20-30 min** (Energy from the grid)
- Time for regular discharge is about **the same** (Energy back to the grid)



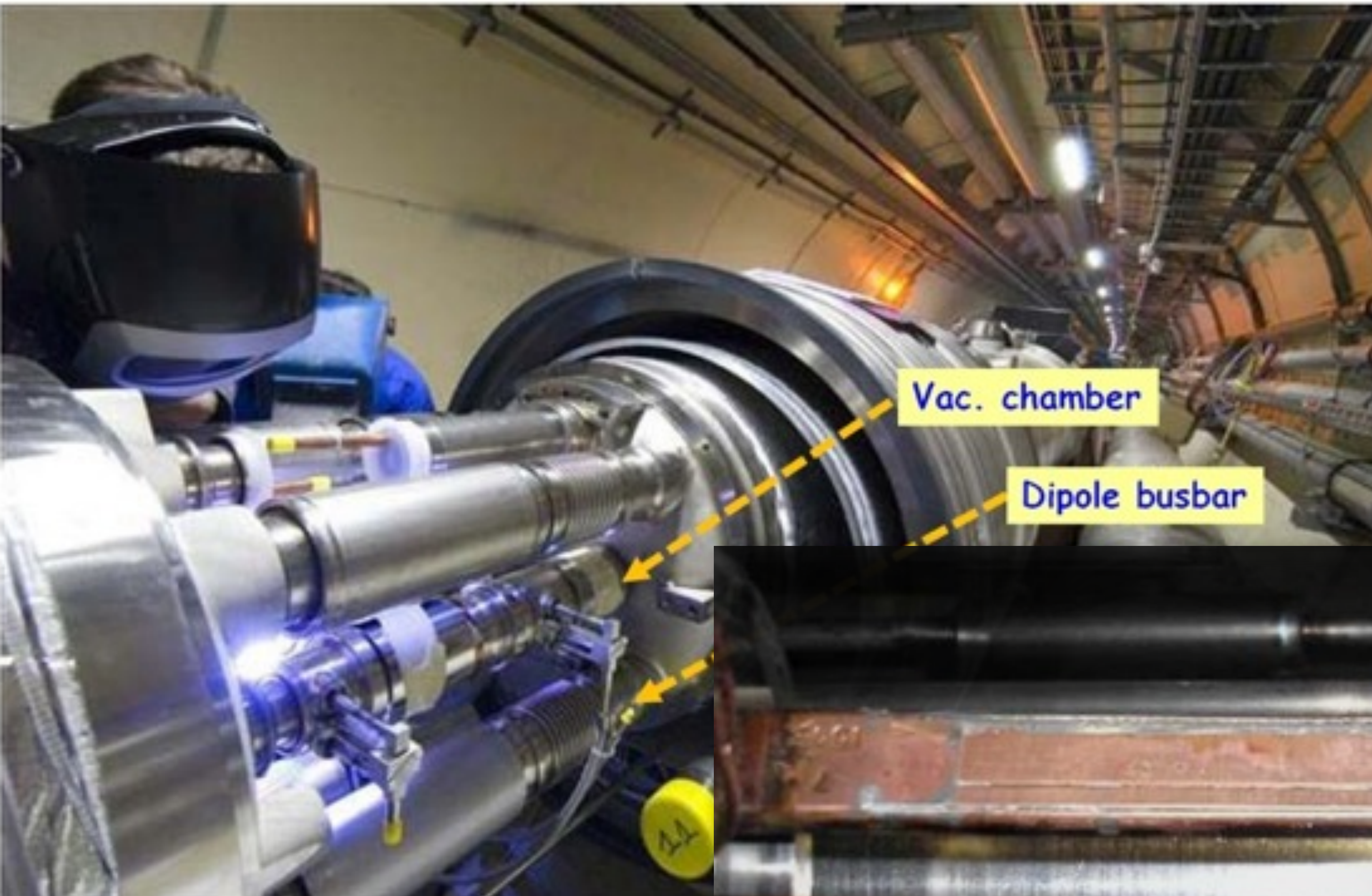
Main dipoles: magnet protection

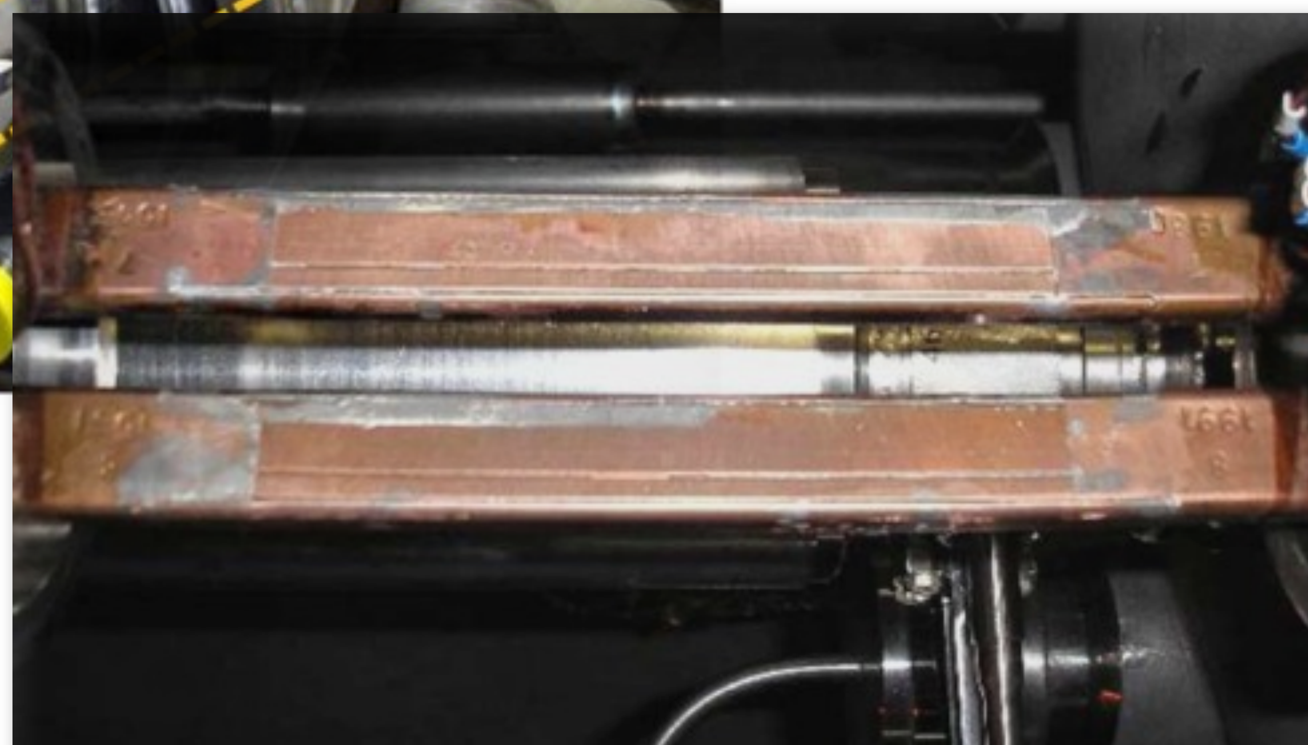
- Quench detected: energy stored in magnet dissipated inside the magnet (time constant of 200 ms)
- Diode in parallel becomes conducting: current of other magnets through diode
- Resistance is switched into the circuit: energy of 153 magnets is dissipated into the resistance (**time constant of 100 s for main dipole magnets**)



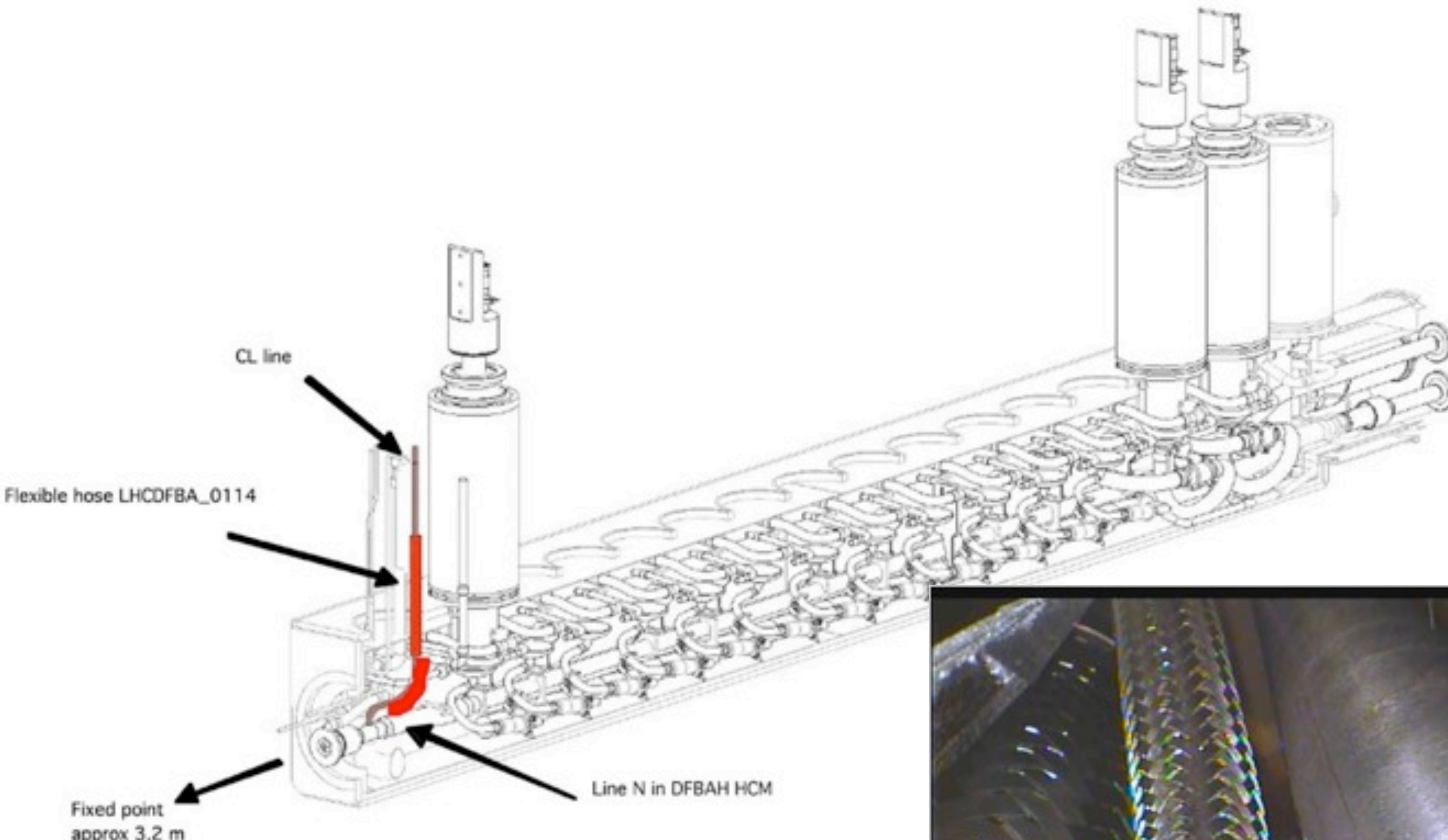
September 2008 incident

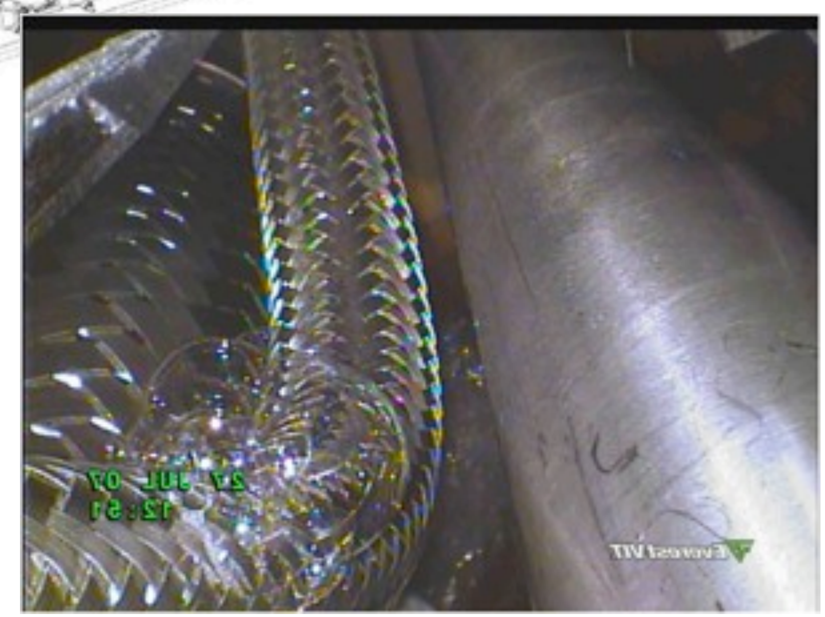
Electrical connection at interconnects:



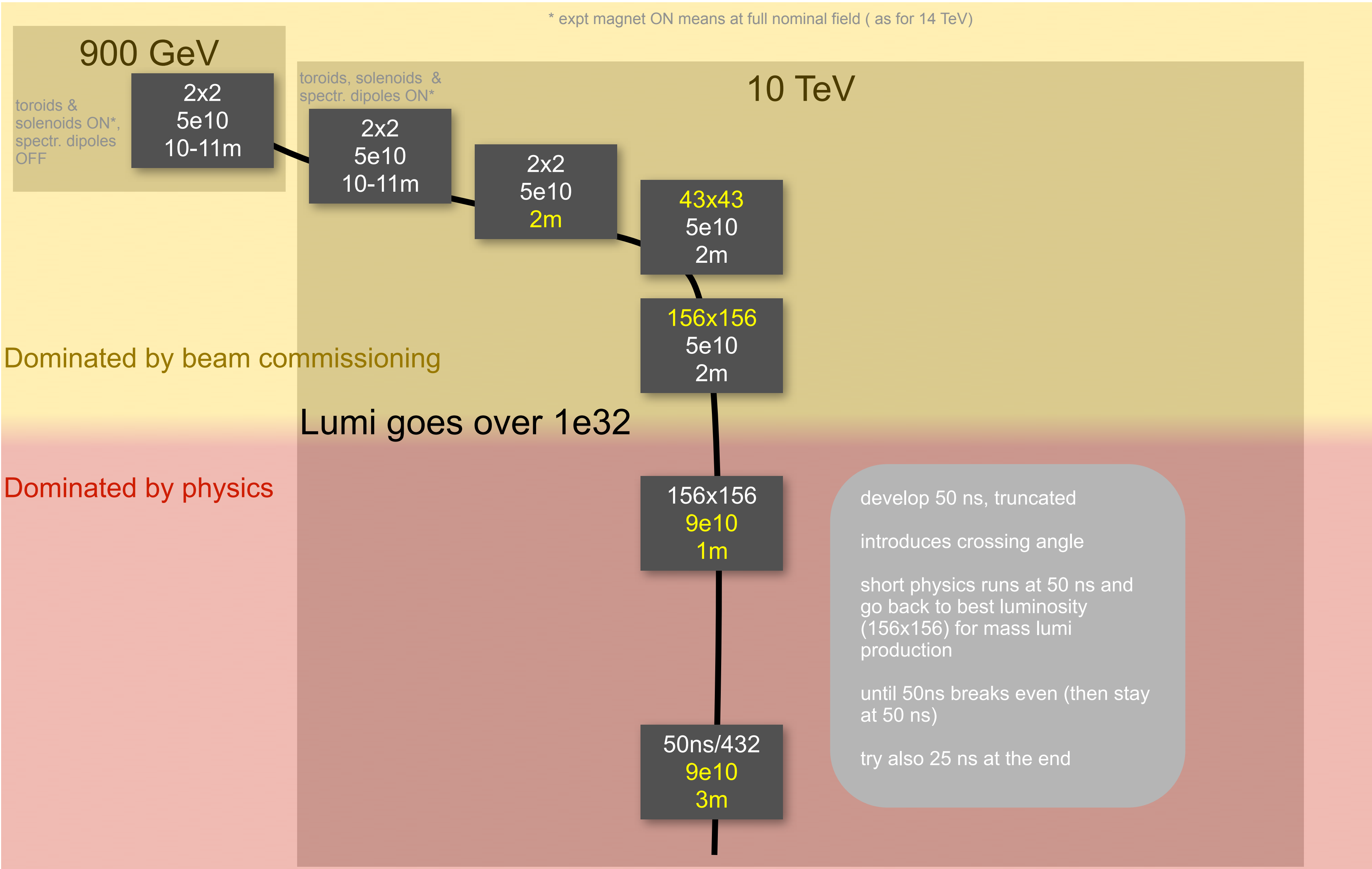


Recent vacuum issue

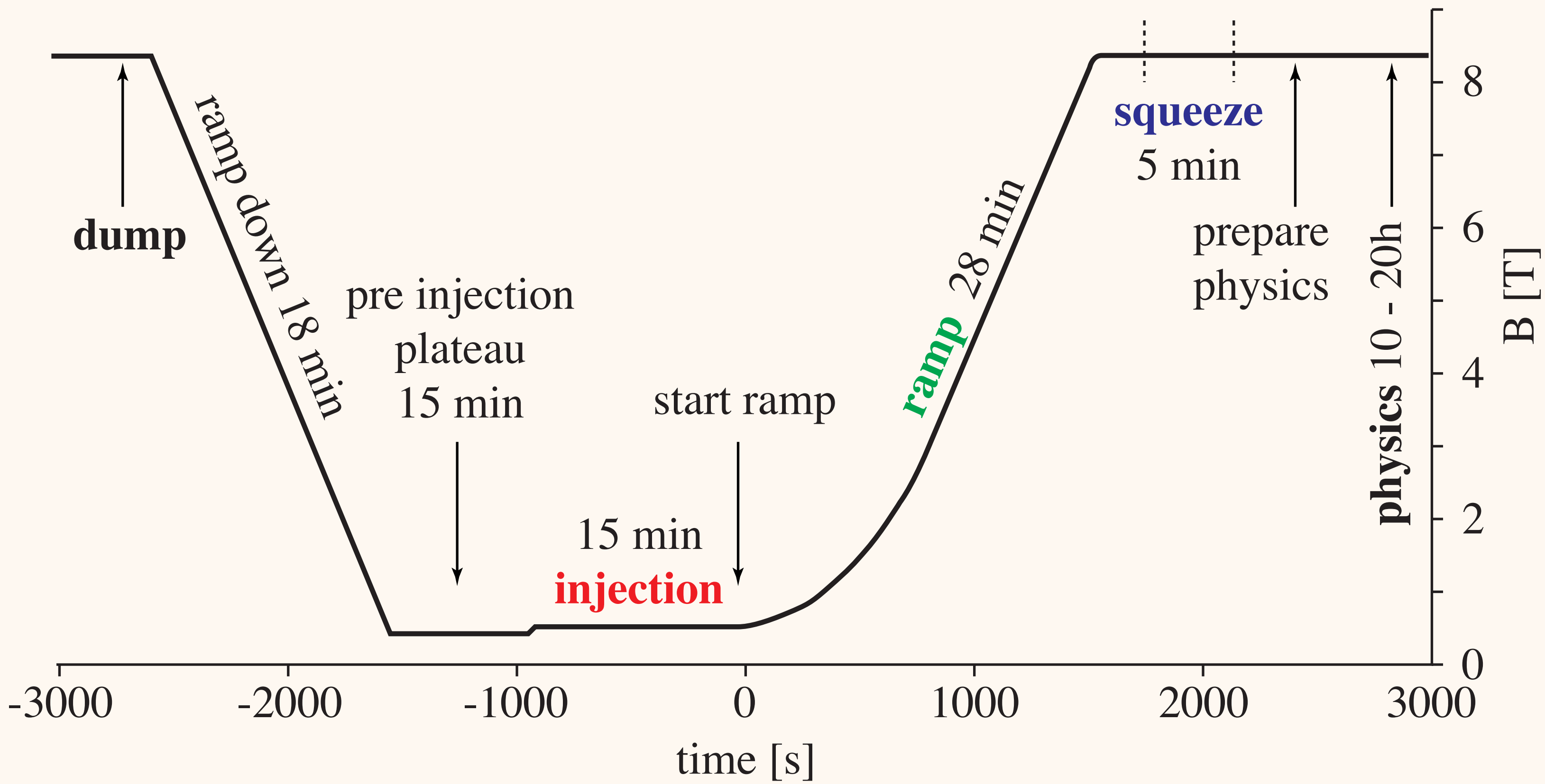




Physics run modes



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

Some beam parameters

Beam sizes and initial separation at the IP @ 5 TeV

β* [m]	σ* [μm]	n_σ
11	**88.0**	**11.4**
3	**45.9**	**21.8**
1	**26.5**	**37.7**

For a separation of $d = \pm 0.5$ mm
$\mathbf{n_\sigma} = 2\,d\,/\,\boldsymbol{\sigma^*}$ full separation in units of σ

5 TeV. Lumi reduction by ±142.5μrad crossing angle

β* [m]	L_0 / L
11	**1.0075**
3	**1.027**
1	**1.079**

L / L_0 by the Hourglass effect
$H(r)$, $r = \beta^*/\sigma_z$
for nominal $\sigma_z = 7.55$ cm

β^*	r	$H(r)$
10.	132.	0.999972
2.	26.5	0.999289
1.	13.2	0.997174
0.55	7.28	0.990833