The LHC Accelerator

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Outline

- **Introduction & Motivation : high Energy and Luminosity**
- **Looking at the machine**
- **Major challenges, high stored energy**
- **Pre-accelerators and injection**
- **LHC commissioning**
- **Experience from first beams in the LHC**

  incl. Fri 20/9 Sector 3-4 incident and current scheduling
- **Outlook into the longer term future**

LHC at the Energy Frontier

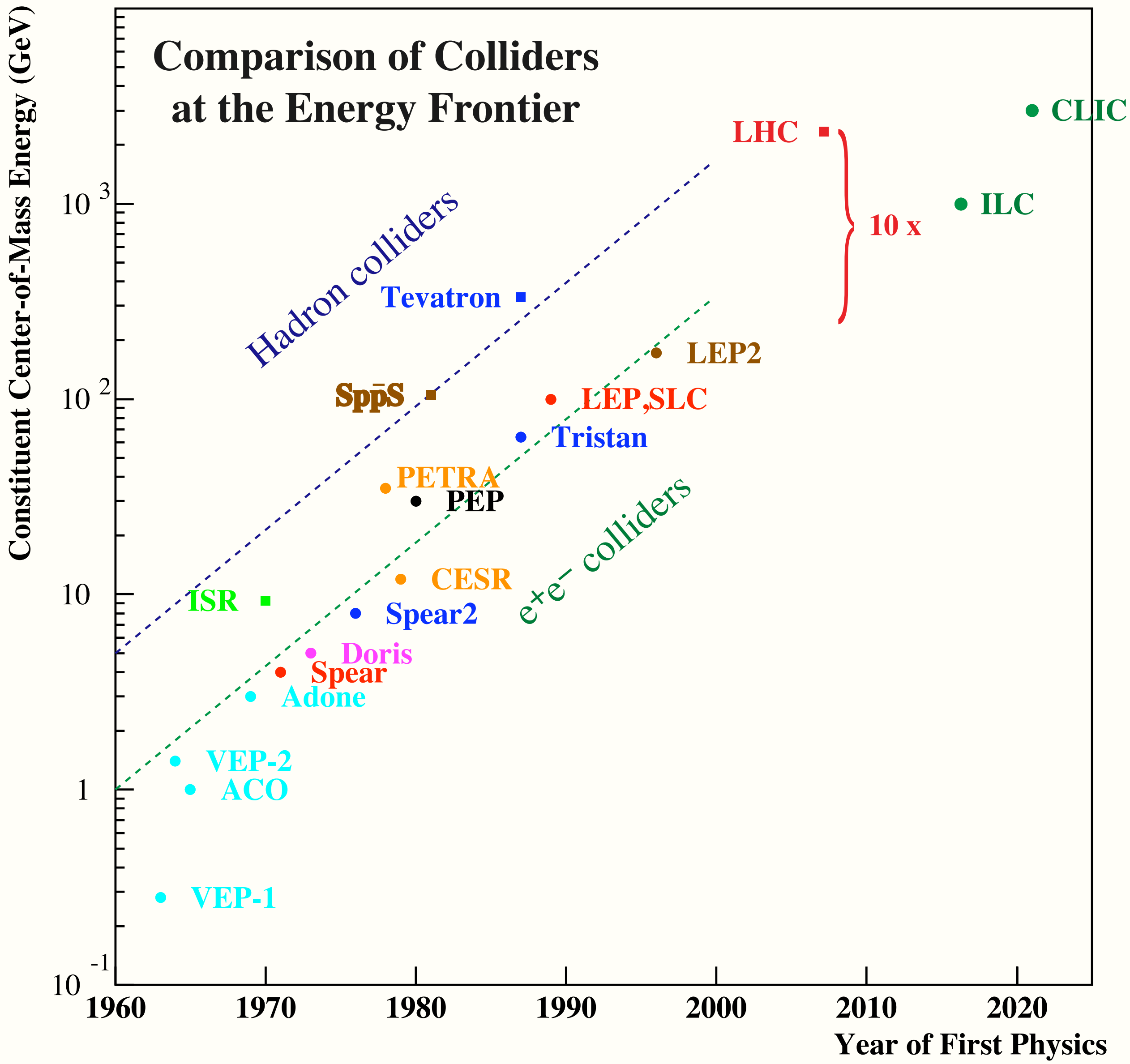
Livingston plot

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



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

both required

The LHC is a big step forward with excellent potential for major discoveries

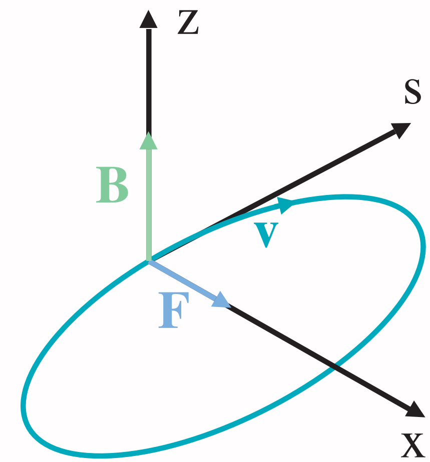
Basic machine parameters, Lorentz Force

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

charge q, normally $q = e$; $q = Z\,e$ for ions

- Electric field **E** provides the acceleration or rather energy gain
- The magnetic field **B** keeps the particles on their path

Circular motion for
$\mathbf{E} = 0$
$\mathbf{v} \perp \mathbf{B}$



ρ is the radius of curvature for motion perpendicular to the static magnetic field. Often called
- gyromagnetic or Larmor radius in astroparticle physics
- bending radius for accelerators

Bρ known as magnetic rigidity, units Tm

$$B = \frac{p}{q\,\rho}$$

for $q = e$ numerically

$B\,[\mathrm{T}] = p\,[\mathrm{GeV/c}]\quad 3.336\ \mathrm{m} / \rho$

high energy, $v = c$ "p = E"

$E < E_H = q\,B\,\rho$ Hillas criterion

LHC

- **Momentum $p = 7$ TeV/c**
- **LHC bending radius $\rho = 2804$ m**
- **Bending field B = 8.33 Tesla**
- **magnets at 1.9 K, super-fluid He**

Astroparticle

units $10^{-4}\mathrm{T} = 1\mathrm{Gauss}$; a.u. $= 1.5\times10^{11}$m

Solar system $B = 10\,\mu\mathrm{G}$ $E = 5$ TeV $\rho = 11$ a.u.

Intergalactic $B = 1\,\mathrm{nG}$ $E = 5$ PeV (knee)

$\rho = 1.7\times10^{19}$m (4 % of galaxy-radius)

Energy and Luminosity

- **High energy** : to be able to directly produce new particles (Higgs, supersymmetric particles) out of reach of previously existing machines. The LHC will provide 14 TeV from 7 TeV protons on 7 TeV protons.

- The expected cross sections for new particle production are small (fb = 10^{-39} cm^{2})
  High luminosity $\mathcal{L} \sim 10^{34}$ [cm^{-2}s^{-1}] is important to obtain sufficient event numbers and allow to observe rare events.

Event rate: $$\dot{N} = \mathcal{L}\,\sigma$$

Tevatron $p\bar{p}$ 1.96 TeV, $\mathcal{L} \approx 3\times10^{32}$ [cm^{-2}s^{-1}]

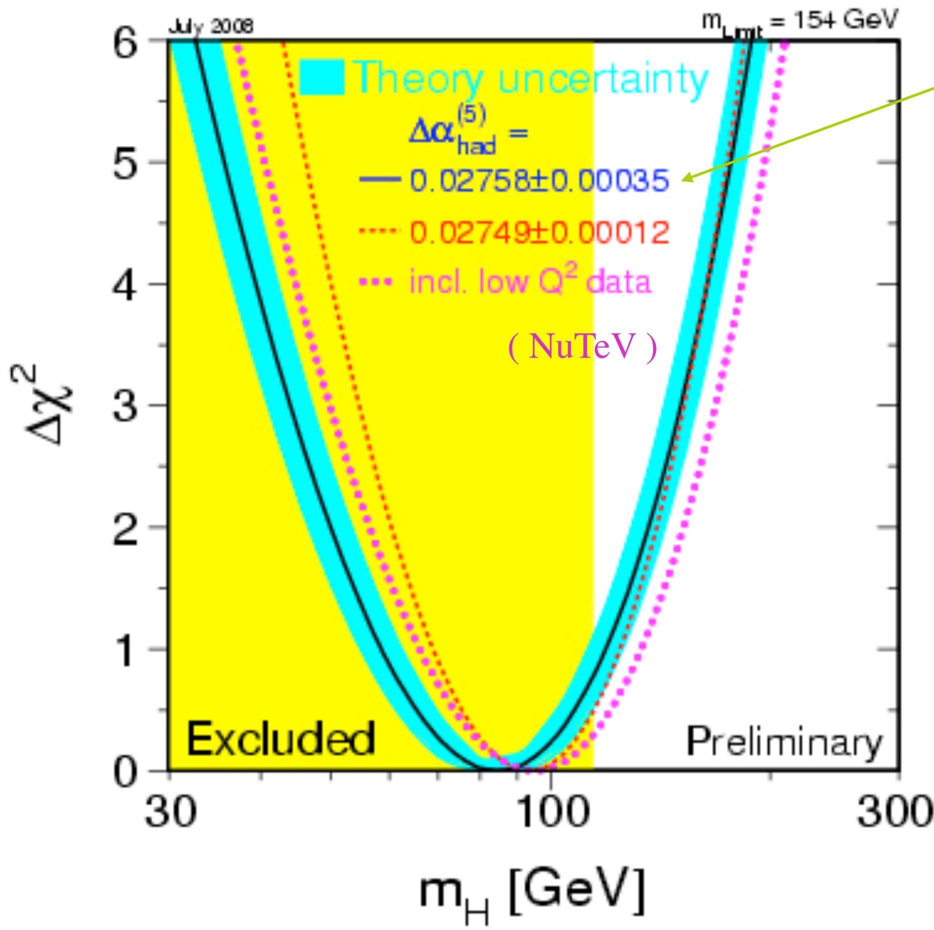
LEP2 e^+e^- 0.209 TeV, $\mathcal{L} \approx 10^{32}$ [cm^{-2}s^{-1}]

~ 1 order of magnitude in E_{cms}

~ 1-2 orders of magnitude in Luminosity at the energy frontier !

LHC : Excellent potential for major discoveries

The Standard Model Higgs is expected well below 1 TeV :



Hadronic contribution to the running of the QED fine structure constant at m_Z,
Burkhardt, Pietrzyk,
Phys. Rev. D72 : 057501, 2005

Current limits from e.w. group
lepewwg.web.cern.ch/LEPEWWG/

LEP direct search $M_{Higgs} >$ 114 GeV

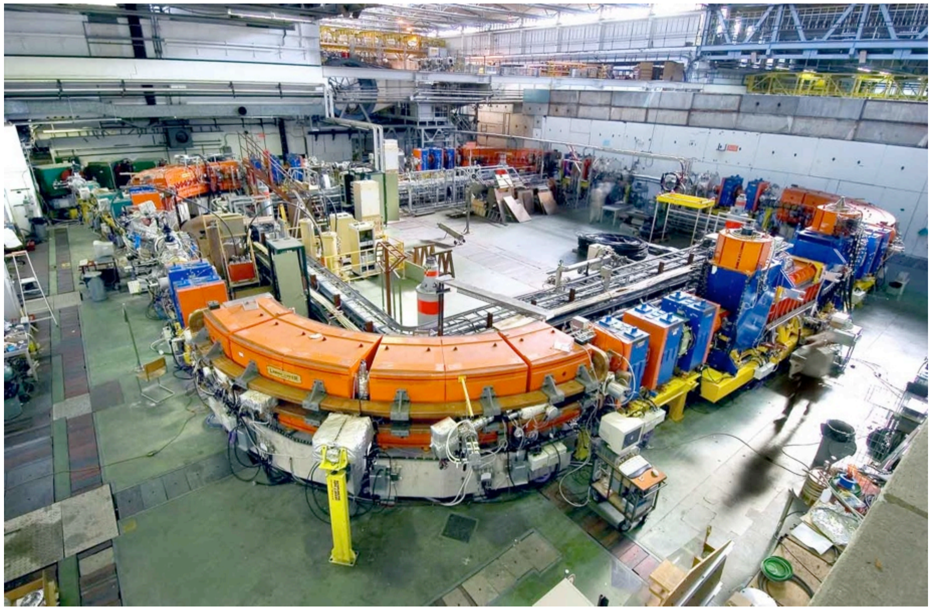
$M_{Higgs} <$ 185 GeV @ 95% CL
from e.w. fits + LEP direct search

LHC must discover Higgs or new Physics below TeV
or else unitarity is violated

G.F. Giudice at open Symposium, Orsay 30/1/06

Short remark on : Heavy Ion collisions and High β*

In addition to being designed for pp collisions at top energy and luminosity the LHC is also designed as Heavy Ion Collider



The new Low Energy ion Accumulator Ring LEAR was successfully commissioned in 2006

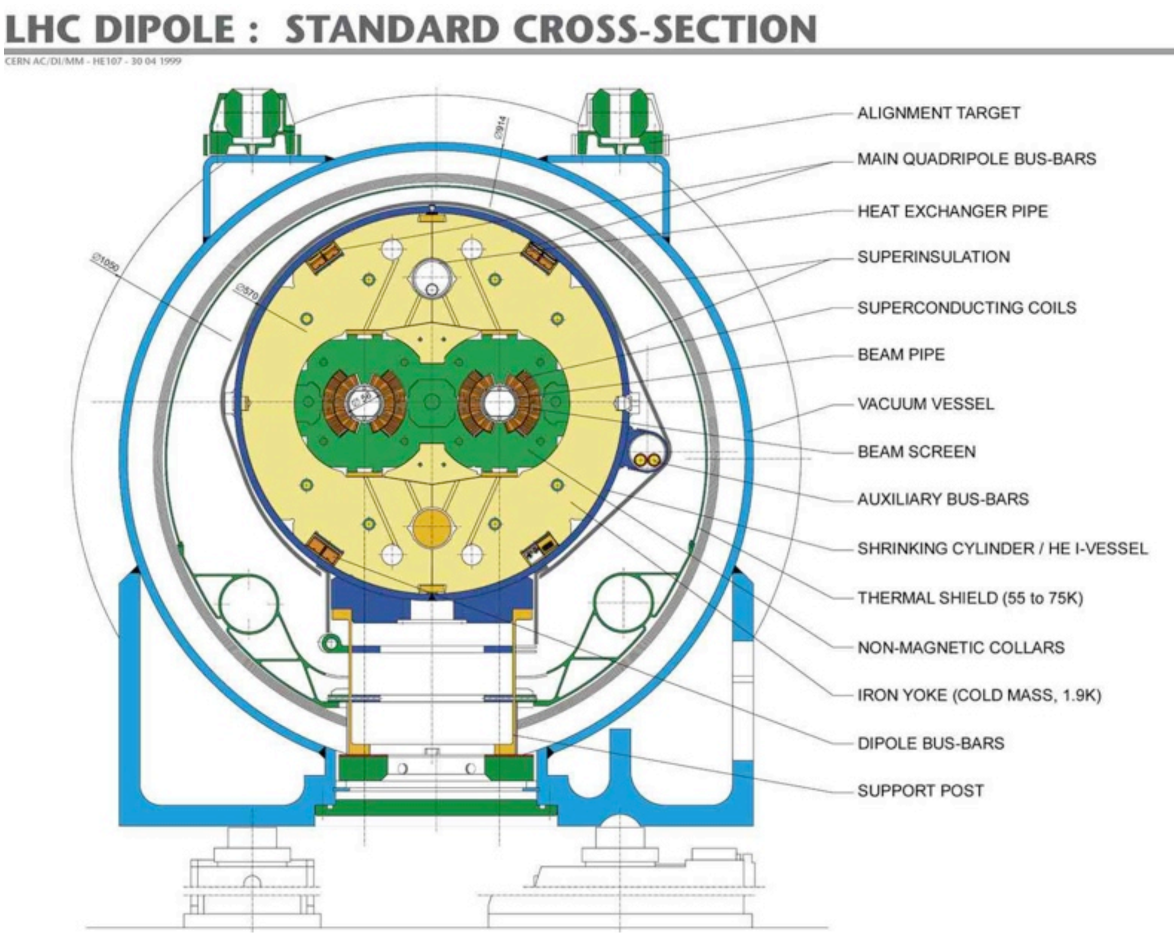
Commissioning of ions in the PS - SPS was successfully done end of 2007
Ions will be available for the LHC – in principle from the beginning.

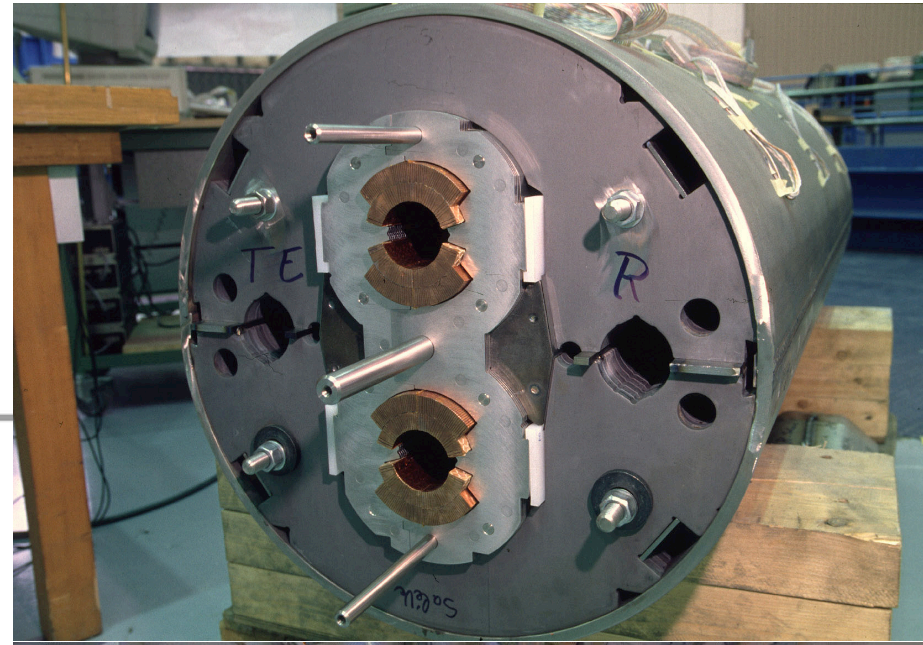
There are further (non pp high luminosity) running options :
Low angular divergence (high-β) collisions for very forward pp scattering measured with *roman-pots* in Totem/CMS and Atlas ALFA – total pp cross section and diffractive physics

Extra options need commissioning time in the LHC - how much is at present hard to predict – will know much more after the first year of running.
Mostly a question of scheduling and priorities.

LHC dipole magnet

2-in-1 dipole magnet
8.33 T field, 15 m long
mass 30 ton





LHC: From first ideas to realisation

26 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

7 y

2007 : Installation complete, starting cooldown

2008 : Start of commissioning with beam

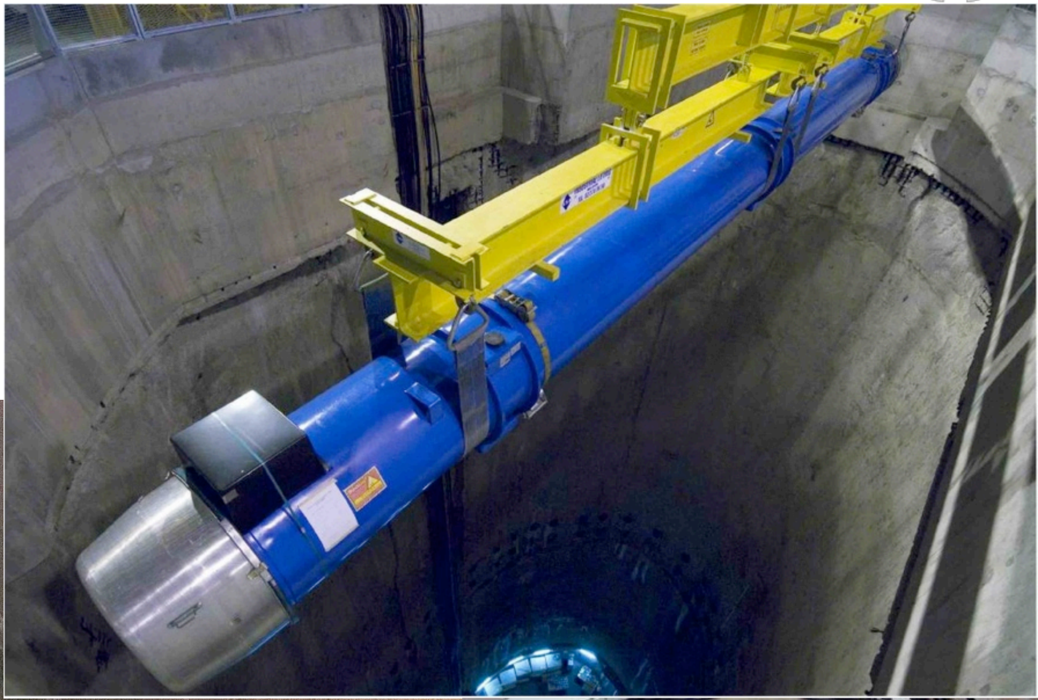
14 y

Dipole lowered to LHC tunnel level

First Dipole #1 : 7 March 2005

Last Dipole #1232 : 26 April 2007

all magnets there, 474 SC quads..



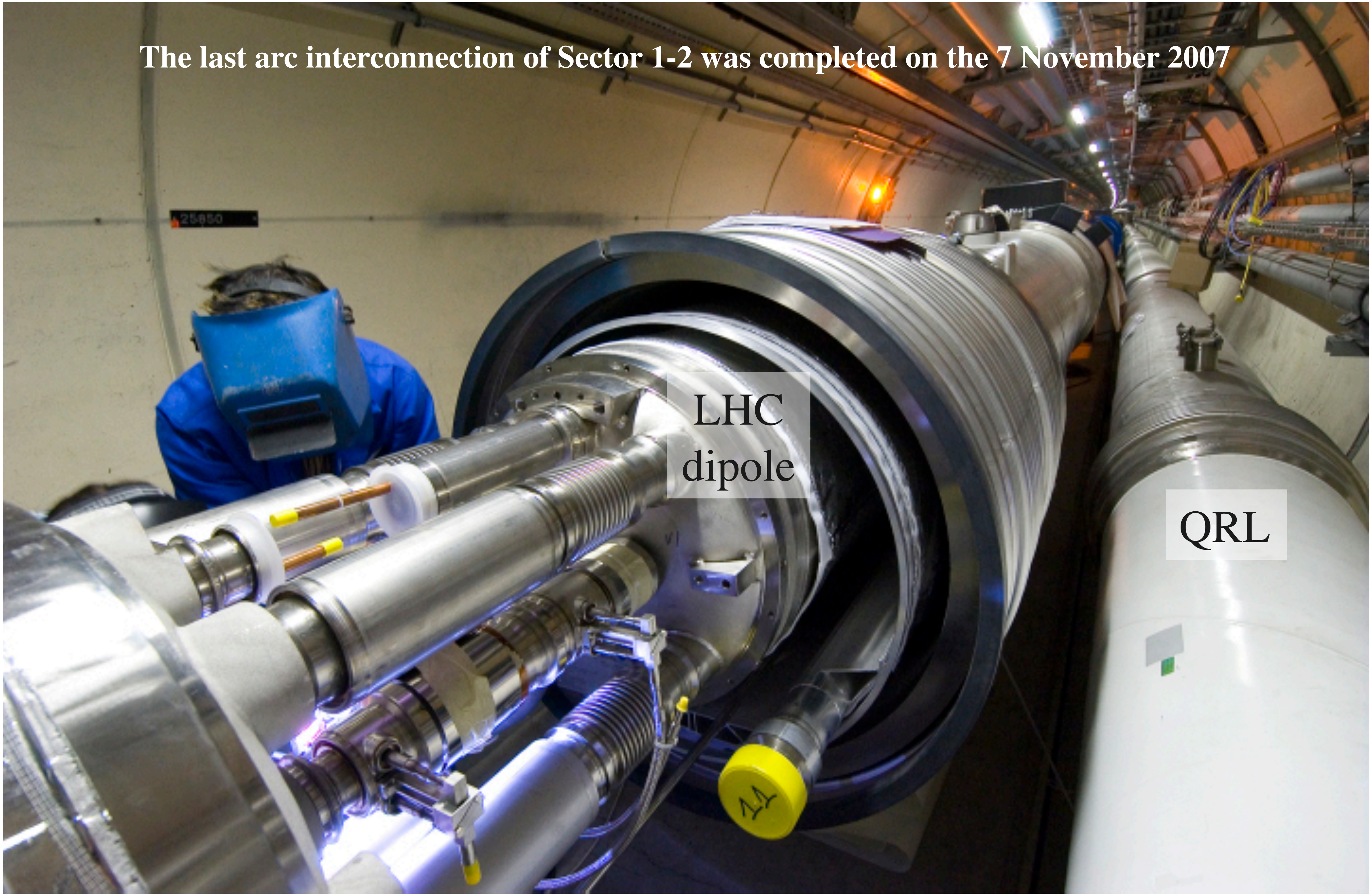
Tunnel between 50 m (this Photo) and 150 m underground

Getting the magnets in place

1600 magnets transported over ~ 15 km

Transfer on jacks

LHC magnet interconnect in the tunnel



Acceleration System pt. 4

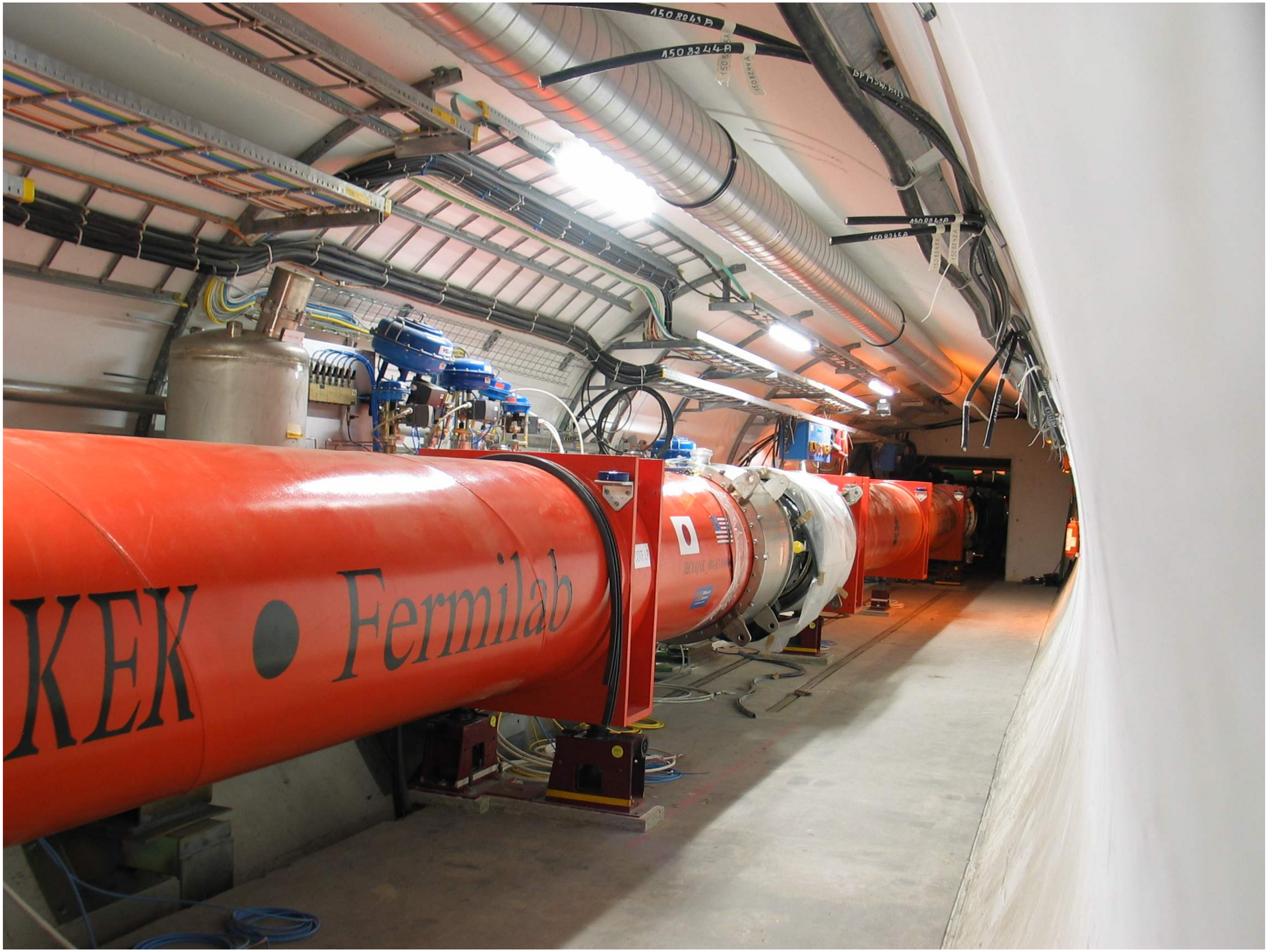
400 MHz superconducting accelerating cavities - 16 cavities in 4 modules, 2 per beam.

Transverse damping kickers - 16 electrostatic deflectors, 8 per beam - Longitudinal monitors – 6 wideband coaxial line monitors

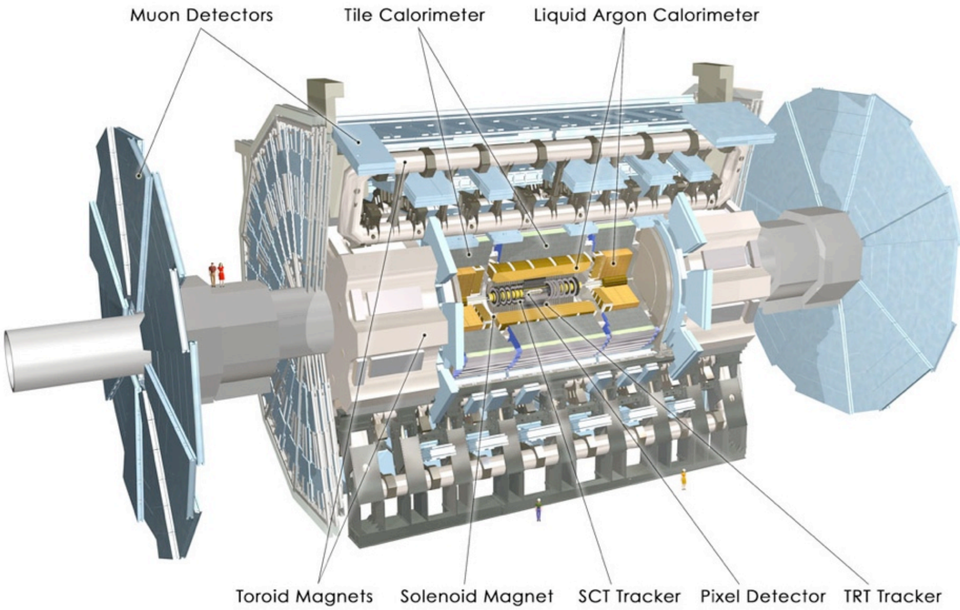
Power amplifiers for dampers

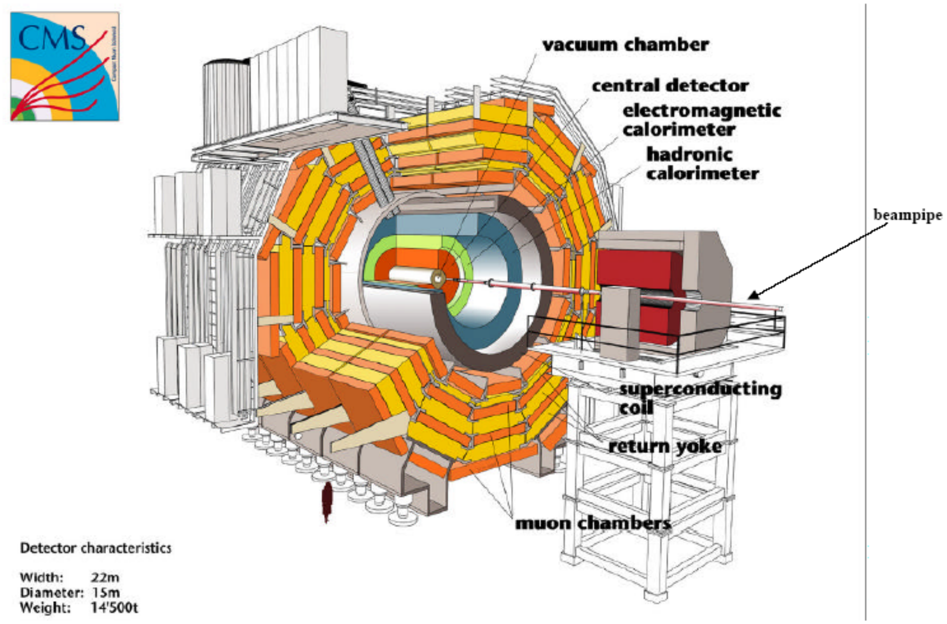
All installed and largely tested

Inner triplet Quads at Point 5



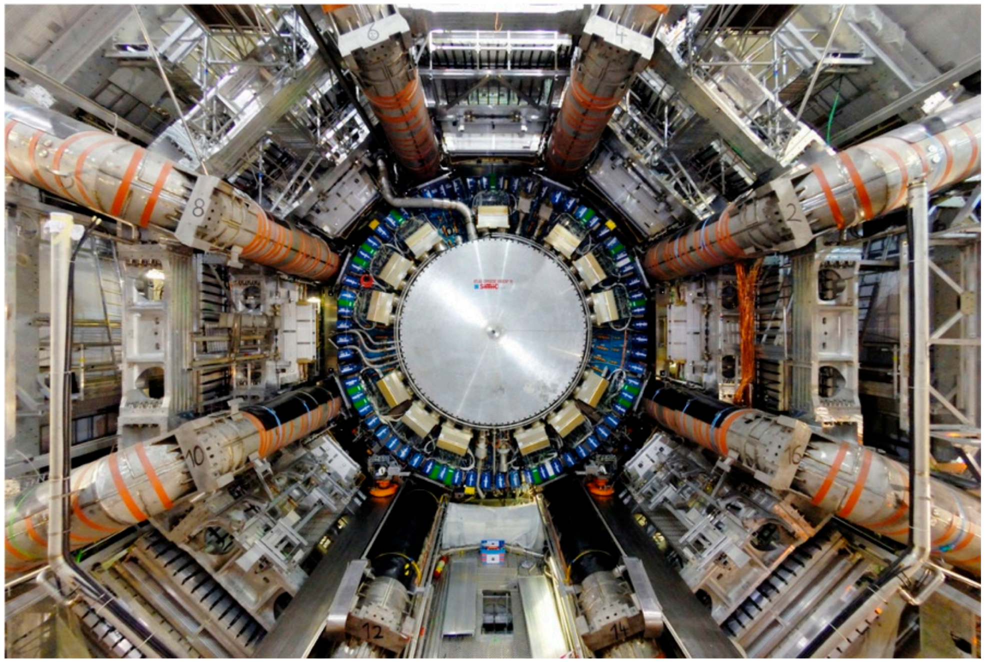
High Luminosity IR1, IR5 for the Large Multipurpose Detectors

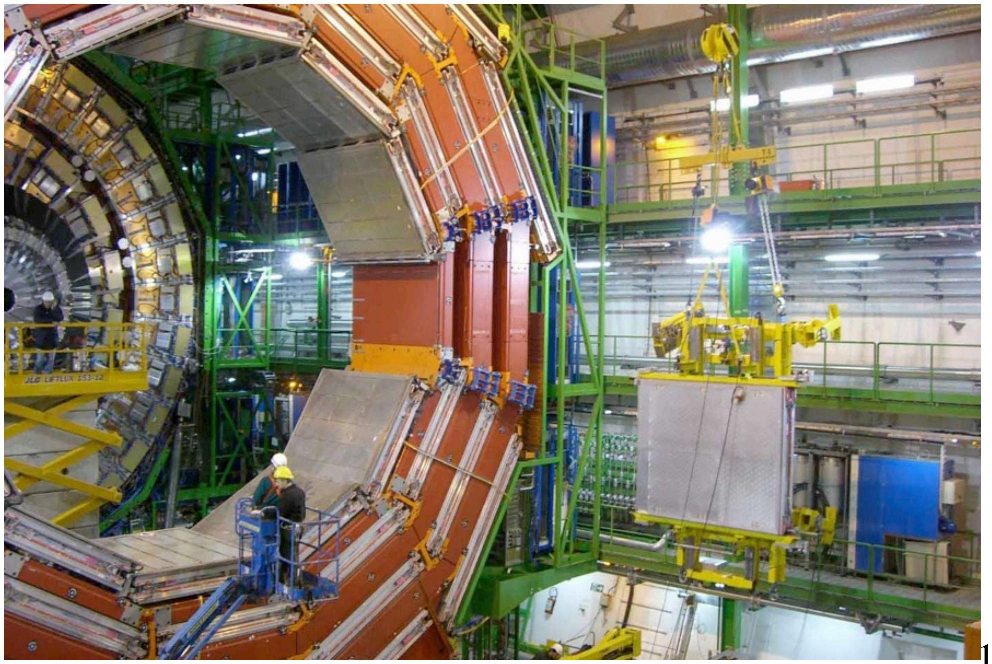




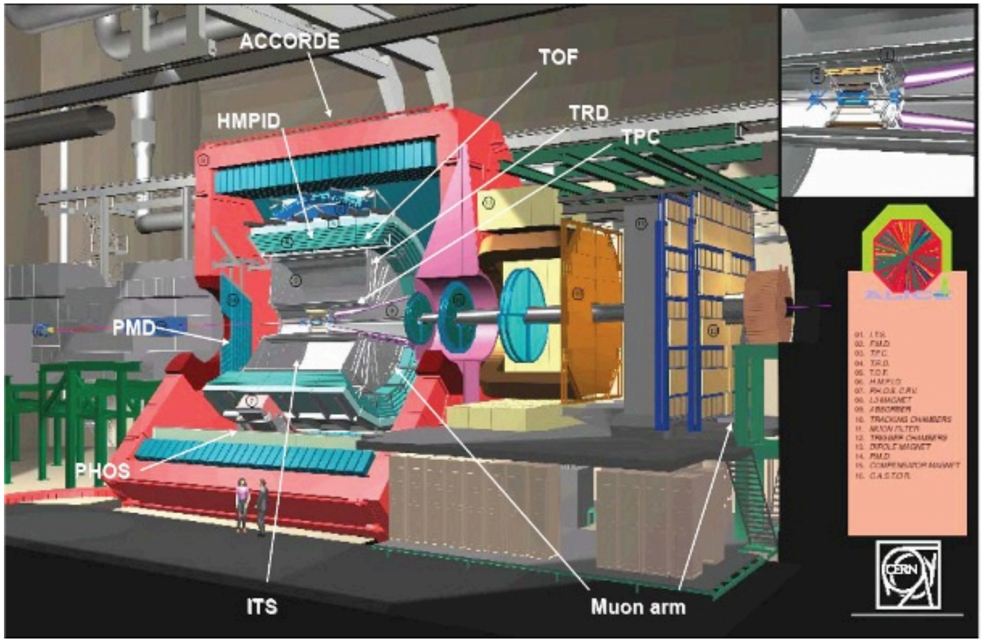
IR1 : ATLAS

IR5 : CMS

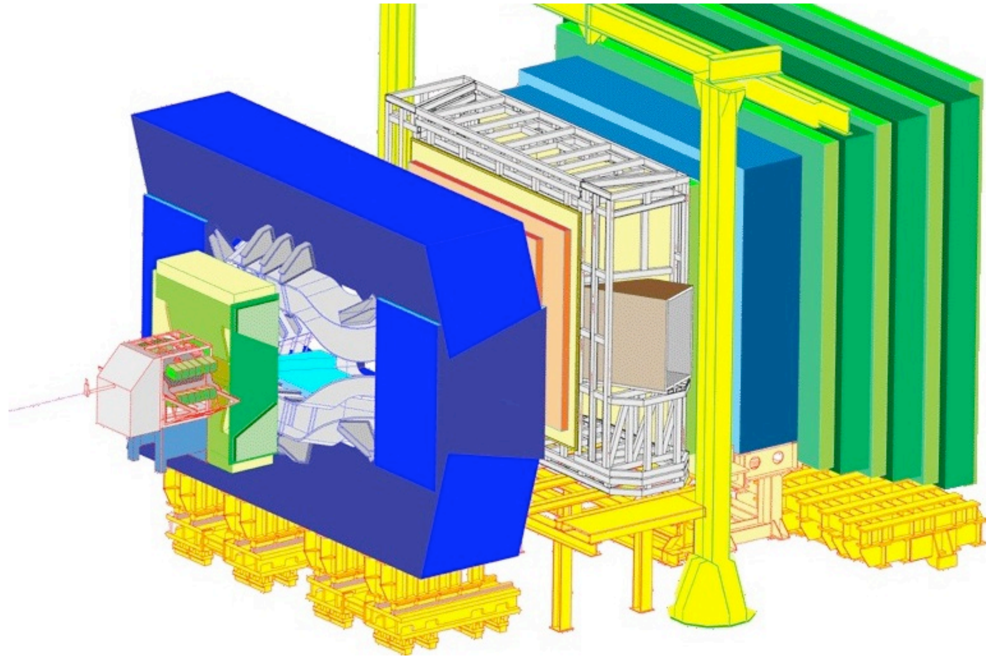




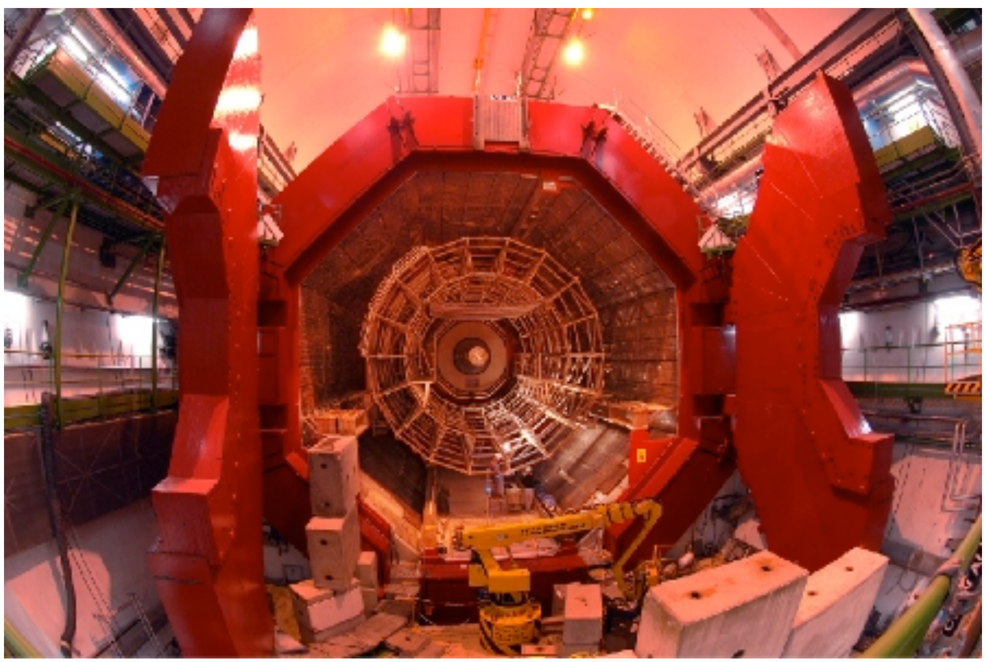
IR2, IR8 for $\mathcal{L} \sim 10^{30} - 10^{32}$ cm^{-2} s^{-1} with the more specialized Detectors

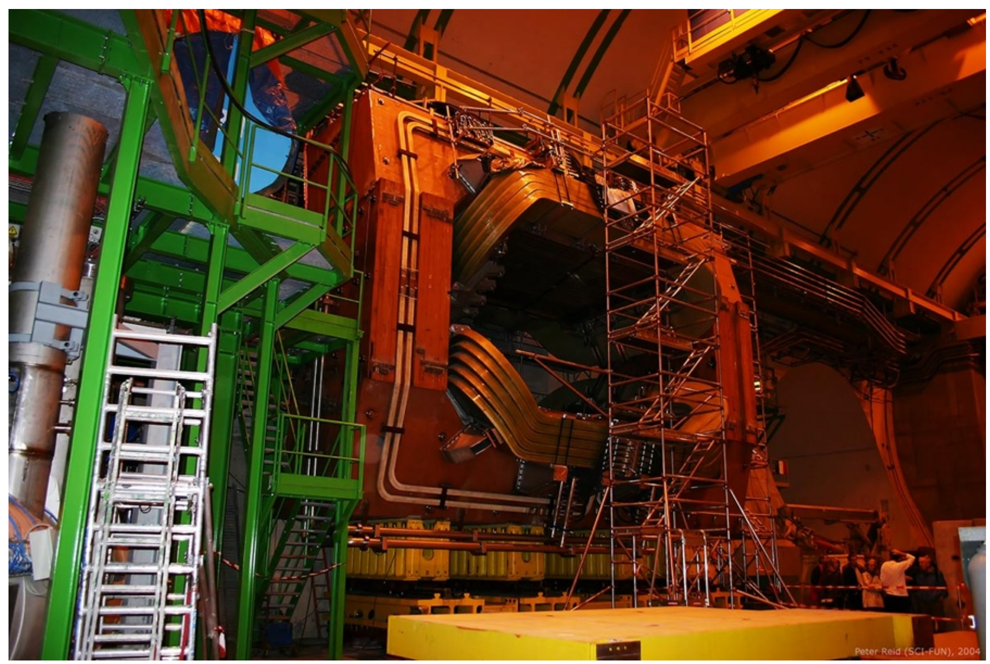


IR2 : Alice – Heavy Ion - Φ



IR8 : LHCb – B - Φ





Major LHC challenges

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
- "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

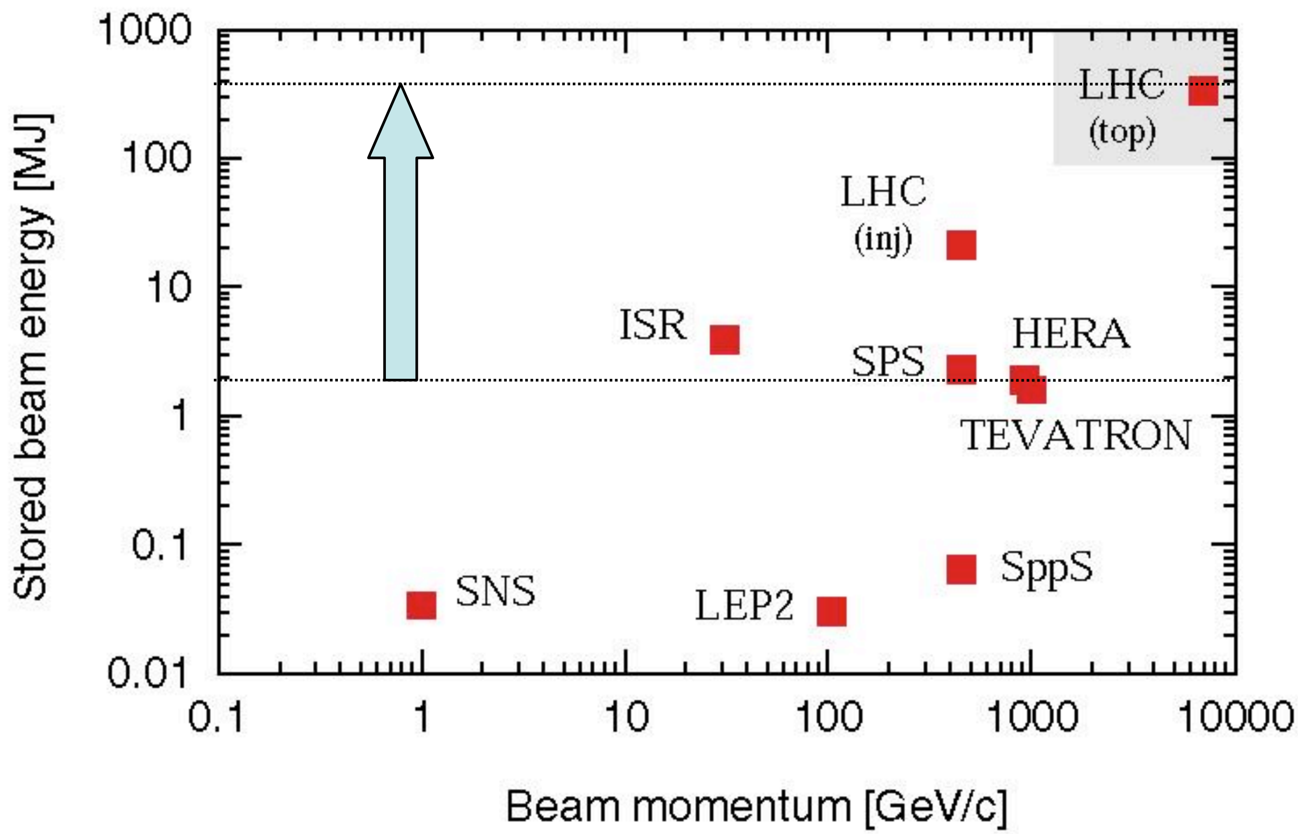
Complexity and Reliability

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

- Emittance conservation $\varepsilon_N = \beta \gamma \varepsilon$ 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)

The total stored energy of the LHC beams

Nominal LHC design: 3 x 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.

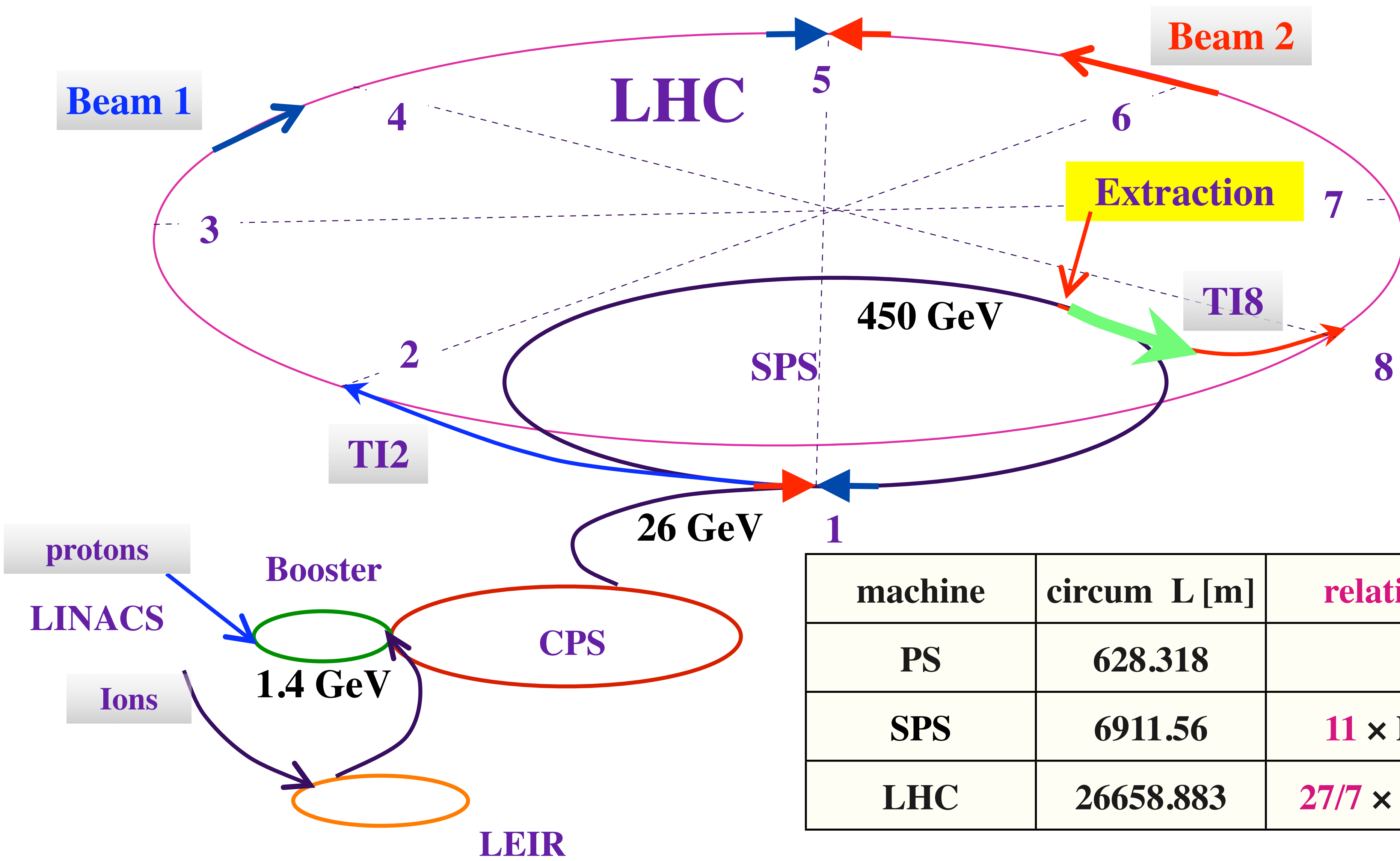
Beam parameters, LHC compared to LEP

	LHC	LEP2
Momentum at collision, TeV/c	7	0.1
Nominal design Luminosity, $cm^{-2}s^{-1}$	1.00E+34	1.00E+32
Dipole field at top energy, T	1	1
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 560t at 700 km/h
- **Energy stored in one (of 8) dipole circuits: 1.1 GJ**
- **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



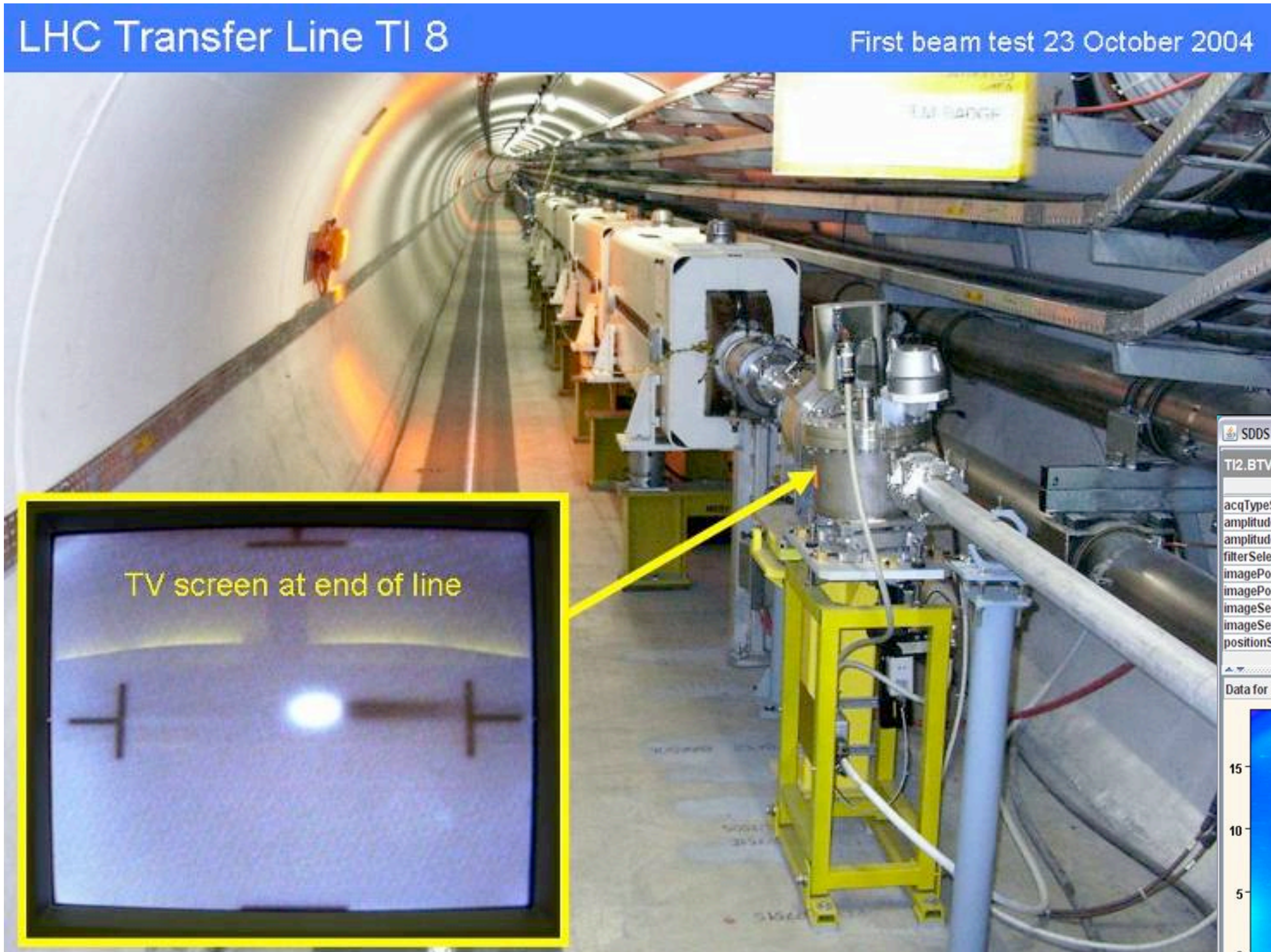
machine	circum L [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

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

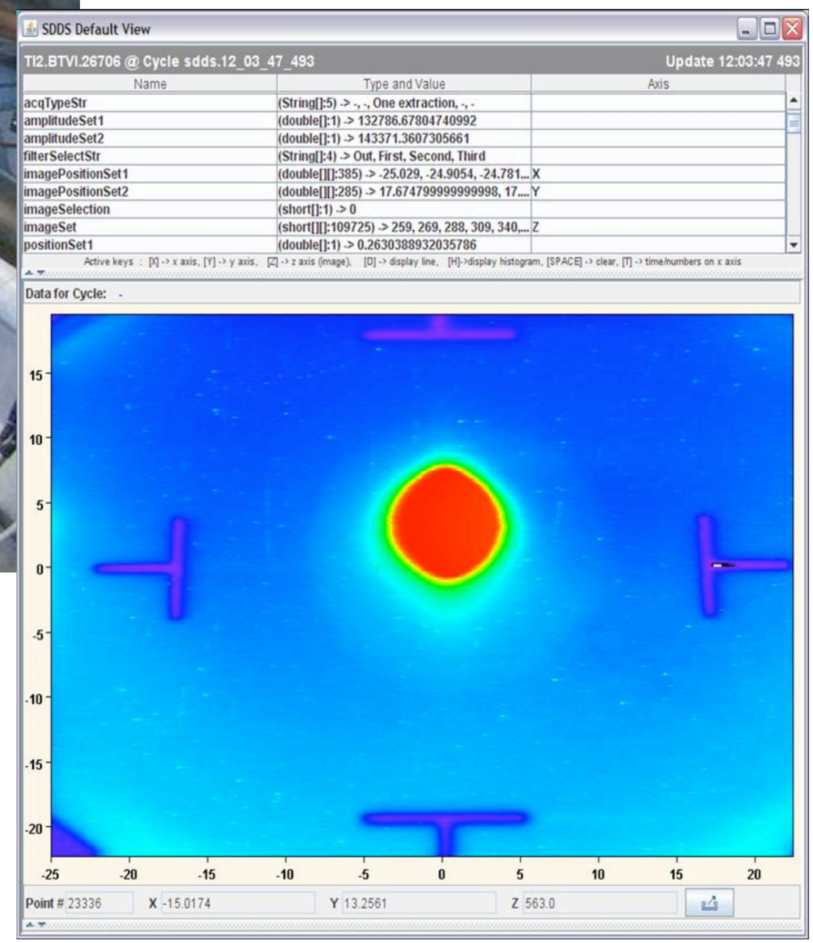
Beam size of protons decreases with energy : area $\sigma^2 = 1 / E$

Beam size largest at injection, using the full aperture

Commissioning of the LHC injectors : Transfer lines to LHC



new tunnels and completely new, normal conducting, pulsed 2.7 km and 2.9 km long tunnels and beam lines



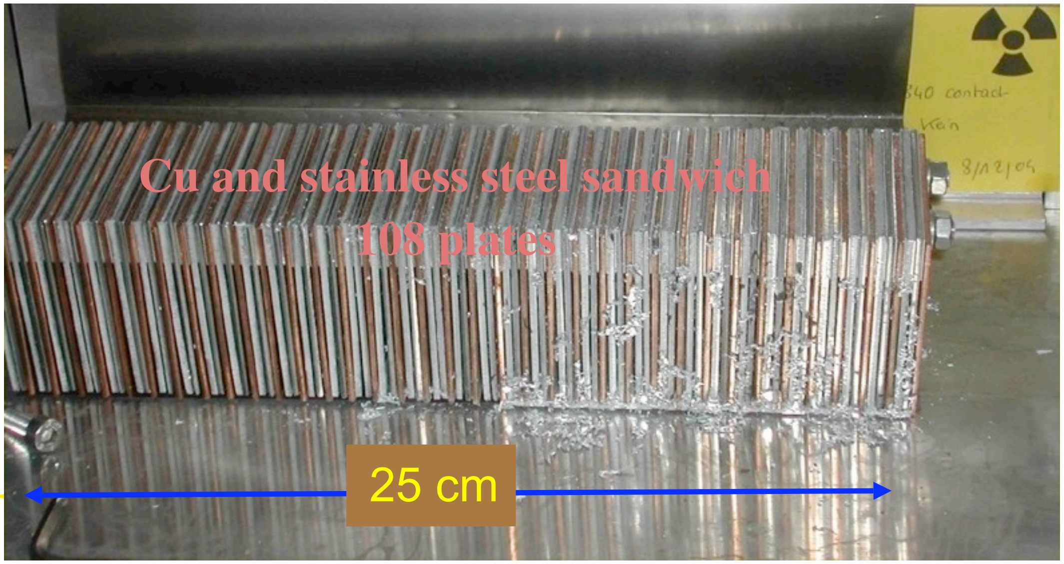
Last October weekend 2007 : beam going through TI 2 until the beam stopper 50 m before the end of the line on the first shot ! Tested again in June 08 - tripped ALICE !

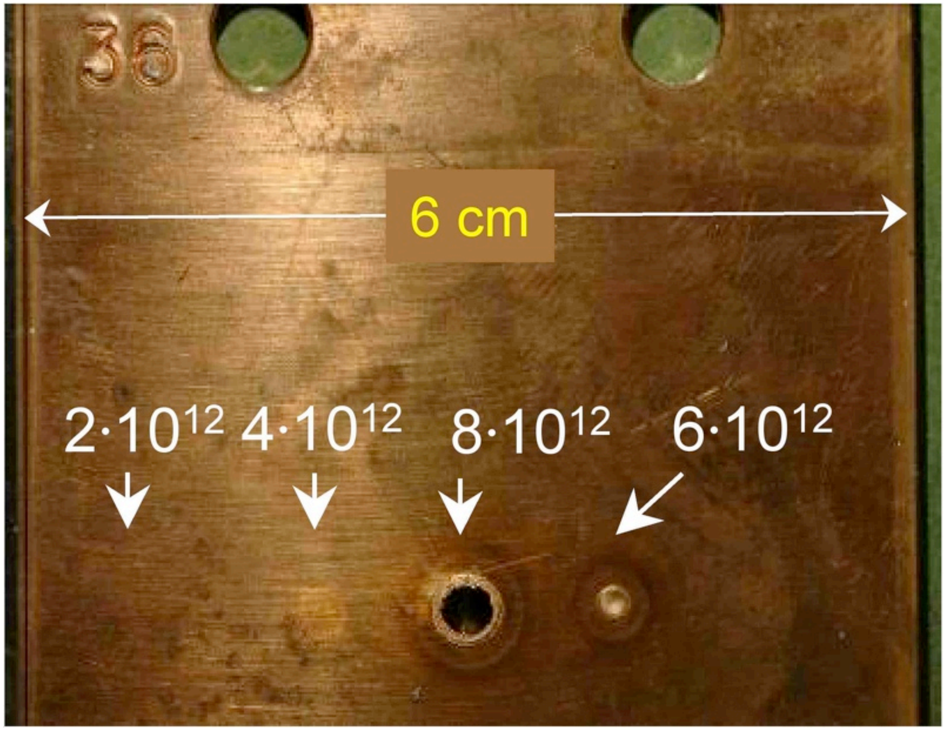
Damage potential : confirmed in controlled SPS experiment

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

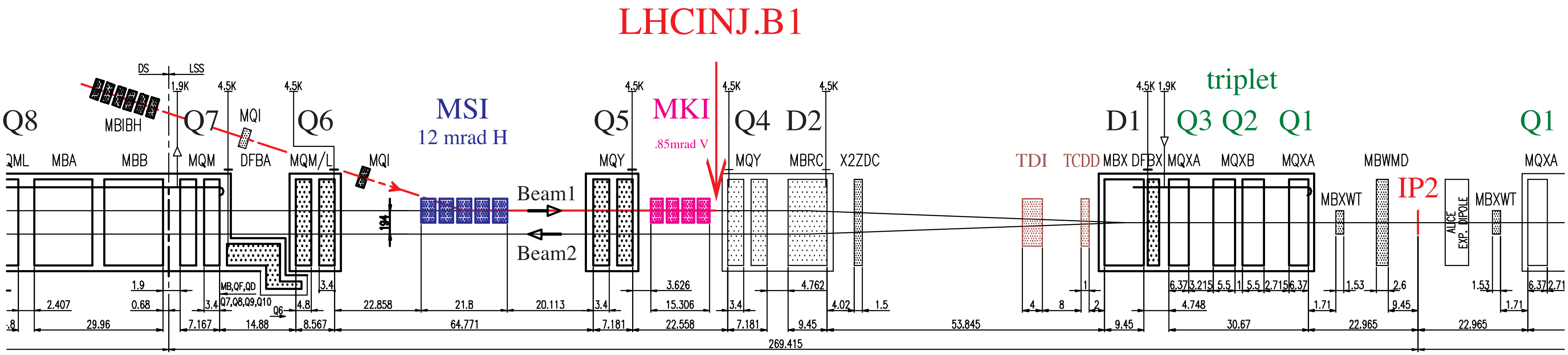
2×10^{12} below damage limit

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

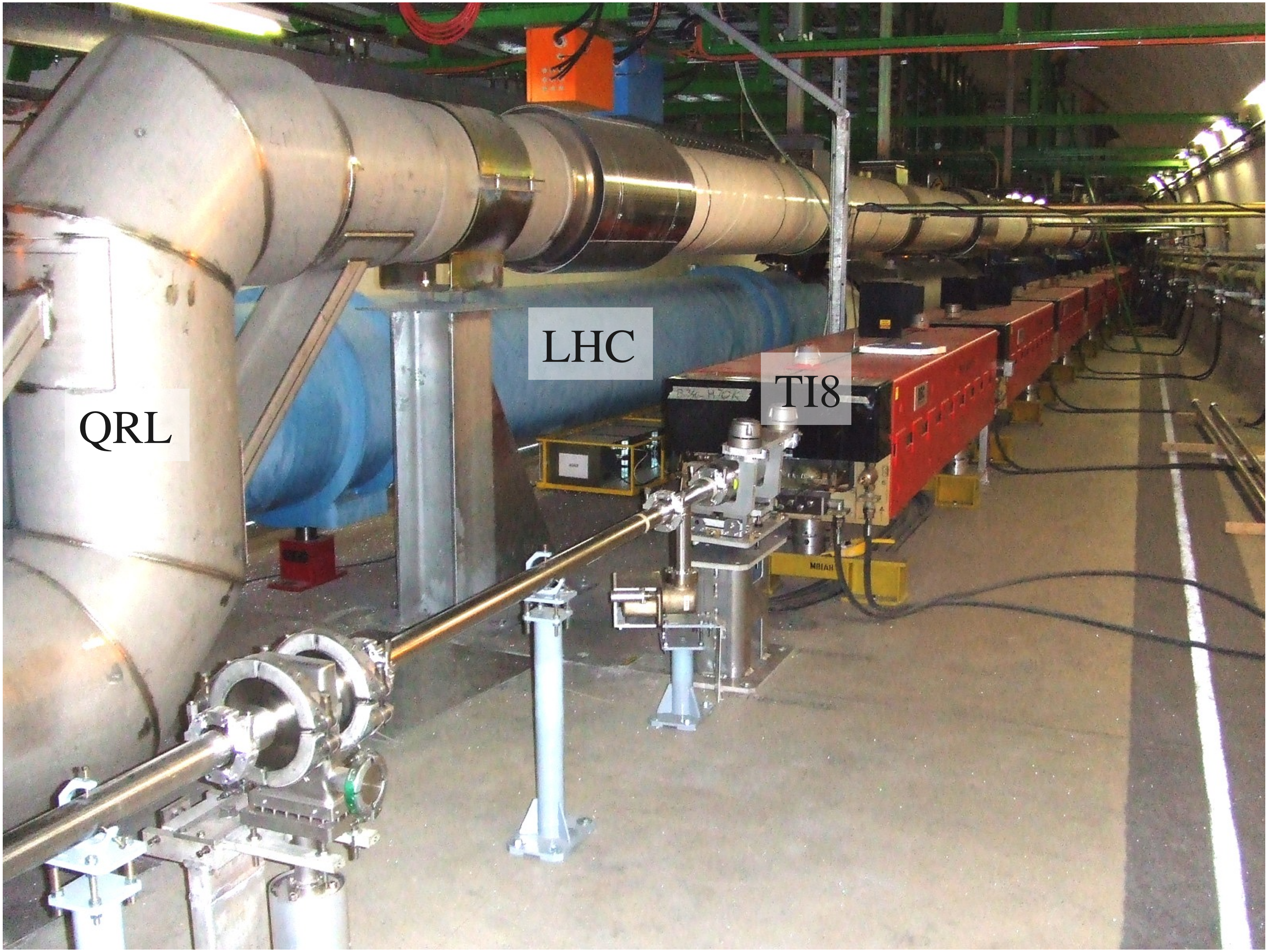
LHC injection tests

now tested and adjusted with beam in both directions :
end of transfer lines TI2/TI8 - septum MSI, kicker MKI - with timing
optics and aperture of a complete LHC sector - for each beam 1 and beam 2



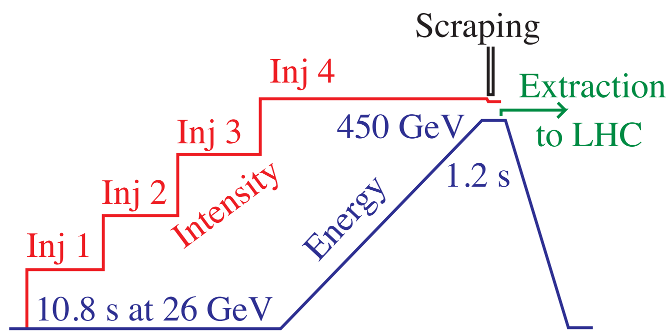
elements in LHC injection region

Injection region with TI8 & LHC



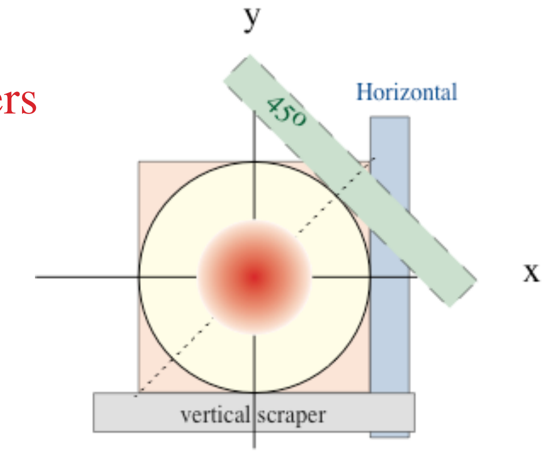
Injection with scraping and collimation

Nominal injection intensities will be ~ 20 times above damage and ~ 10^4 times above quench level : major challenge: clean injection into tight aperture, little margin for jitter and mismatch.



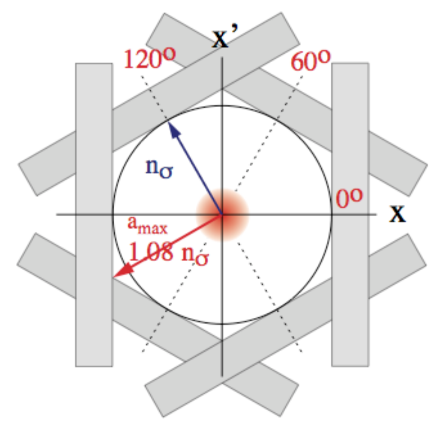
pilot and 1 batch cycles can be shorter, but always > 7 s

Scrapers SPS



Real space Hor/Vert
x and y

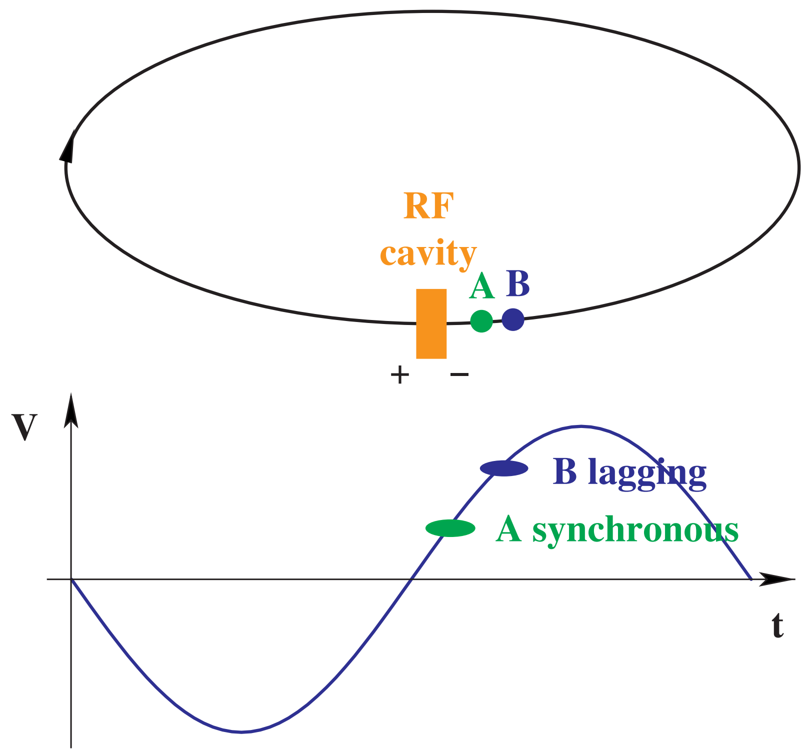
1. LHC collimation at injection starts with H/V/45° scraping in the SPS ; to avoid quenches in the LHC. Set (nominally) at approx. 3.5 σ ; Master thesis Paul Letnes, CERN+Trondheim July 2008
2. The two warm, pulsed transfer lines TI2, TI8 are equipped each with 7 TCDI collimators (Δp, 2× 0, 60, 120°) to protect against damage at injection in case of (rare) failures, at approx. 4.8 σ
3. LHC injection protection, main purpose is protection against injection kicker failures with TDI, TCDI.
4. LHC cleaning sections ; reached after ~1/2 turn; primary collimators set at approx. 5.8 σ

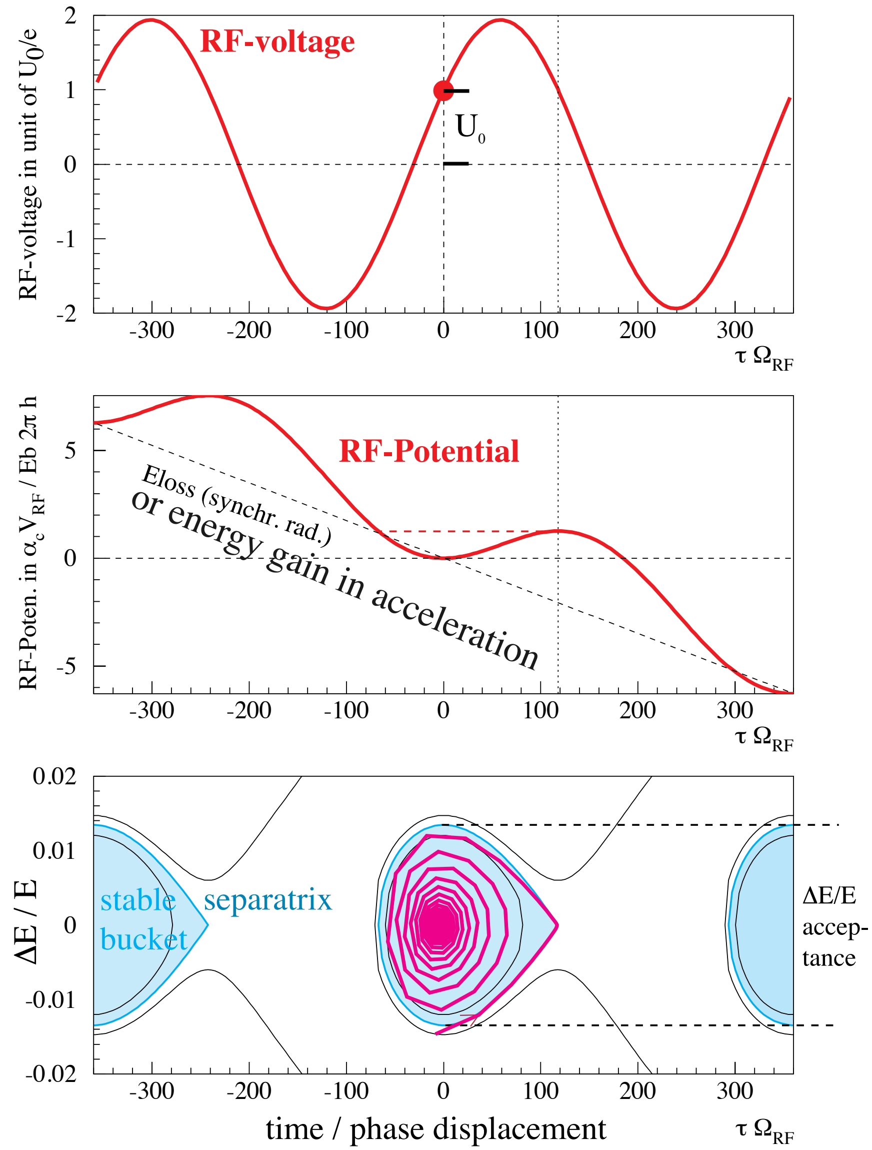


Transfer line TCDIs
in phase space

LHC cold ring aperture is about 7.5 σ incl. tolerances

RF voltage and phase stability





LHC

Revolution frequency $f_{rev} = h\, f_{rf}$ $h = 35\,640$ $f_{rf} = 400.7896$ MHz $L = 26658.864$ m

Circumference $L = v / f_{rev} = \beta\, c / f_{rev}$ $f_{rev} = 11.2455$ kHz 1 turn in 8.892446 μs

Filling and Ramping ; off-energy particles (with movie)

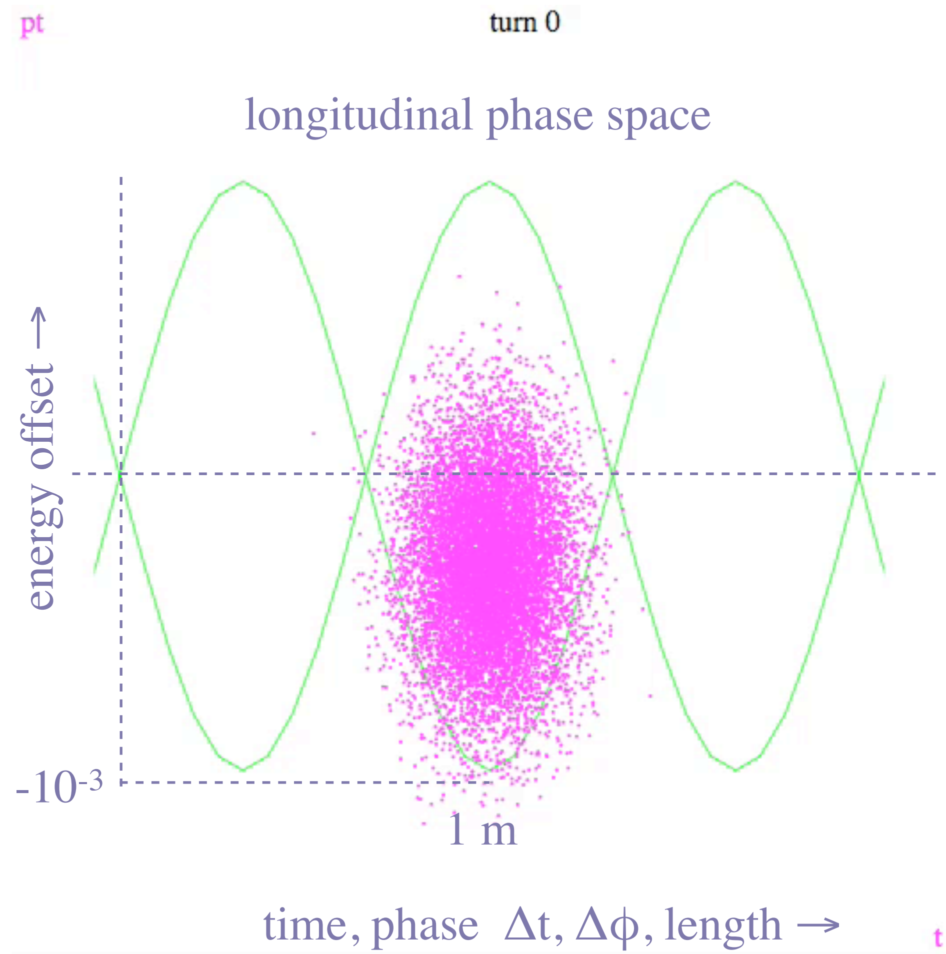
Filling: > 9 min (2 x 12 inj. × 21.6 sec.)

Filling, at 450 GeV
RF HV = 8 MV Qs = 0.005834 (171 turns)
RF-acceptance (bucket- 1/2 height) ~ 10^{-3}

Energy acceptance, limited by IR3 momentum collimation to ~ 3 × 10^{-3}

1 - 3 × 10^{-3} off-energy particles remain in the machine, migrate around the whole circumference, through the gaps reserved for injection and dump kicker rise times.

The debunching speed is about λ_{rf} / synchrotron period ≈ 50 m/s or ~ 9 minutes for one turn at injection energy, comparable to the nominal filllling time



Shown here: simulation of injection with 3×10^{-4} energy offset over 100 turns or 8.9 ms

Simulation details 6 dim phase space program BeamTrack written in C++ by H.Burkhardt 8/2003 - 2008
here 10000 particles, 100 turns. few sec on Mac Pro

Ramping and LHC cycle

stop injection : injection kickers (timing) off, synchr. with injectors can be stopped

provide enough rf-voltage

LHC nominal is 8 MV at inj. and 16 MV at top energy (shorter bunches for higher lumi with x-angle)

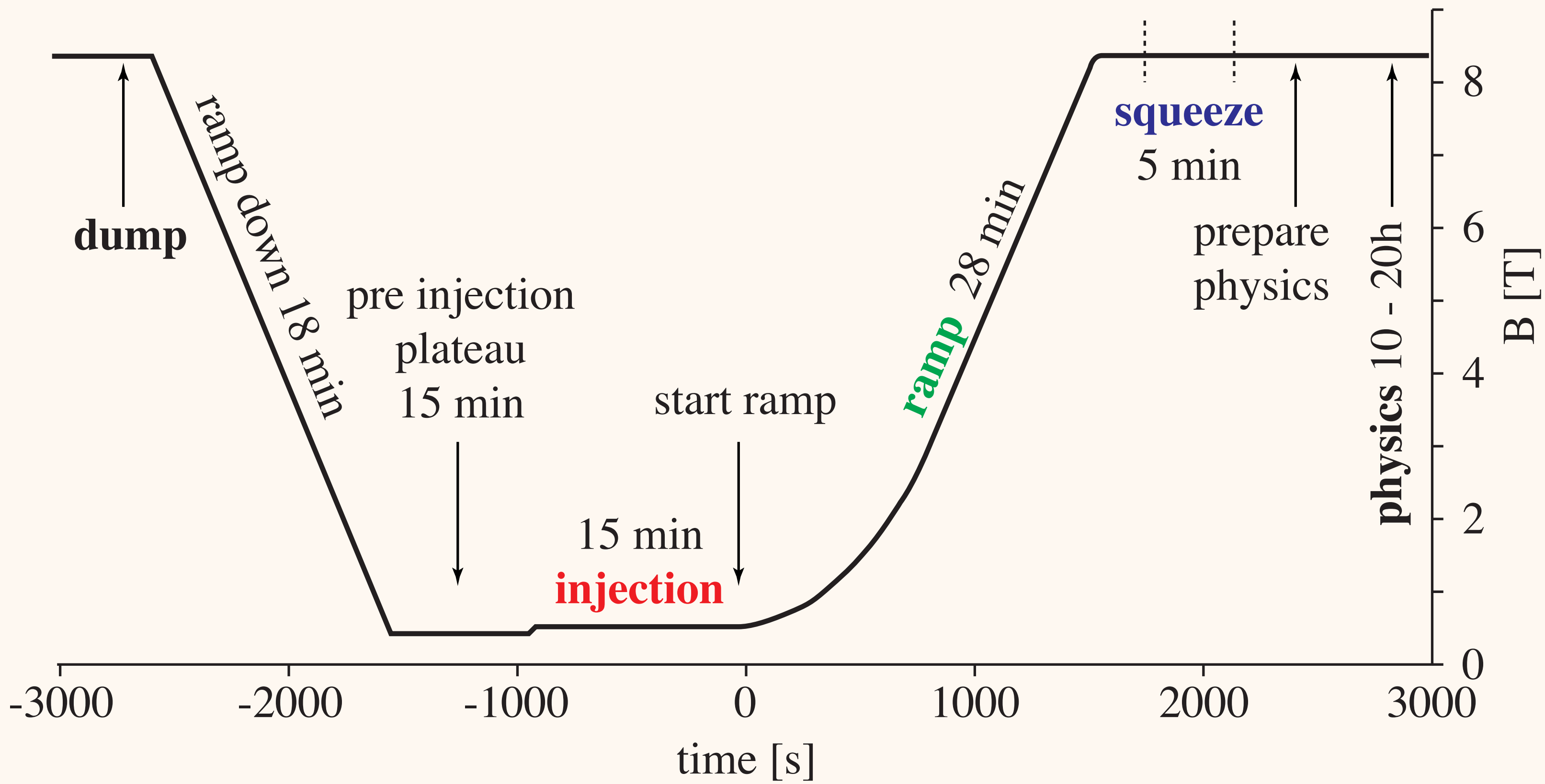
provide 700 MJ over 30 min = 1800 s $\Rightarrow$ P_{RF} = 390 kW (LEP2 was 20 MW)

per particle 6550 GeV / 1800 s = 3.64 GeV/s = 0.324 MeV / turn

program power convertors which drive all magnets with ramp functions

LHC - both rings, bends, quads, sextupoles, correctors - all ramped together

- **send start ramp signal to power convertors**



Filling pattern - bunches, buckets, …

f_{RF} = 400 MHz

λ_{RF} = 0.75 m or 2.5 ns

35 640 RF buckets

Bunches spaced by 25 ns or 10 buckets

Inject batches of

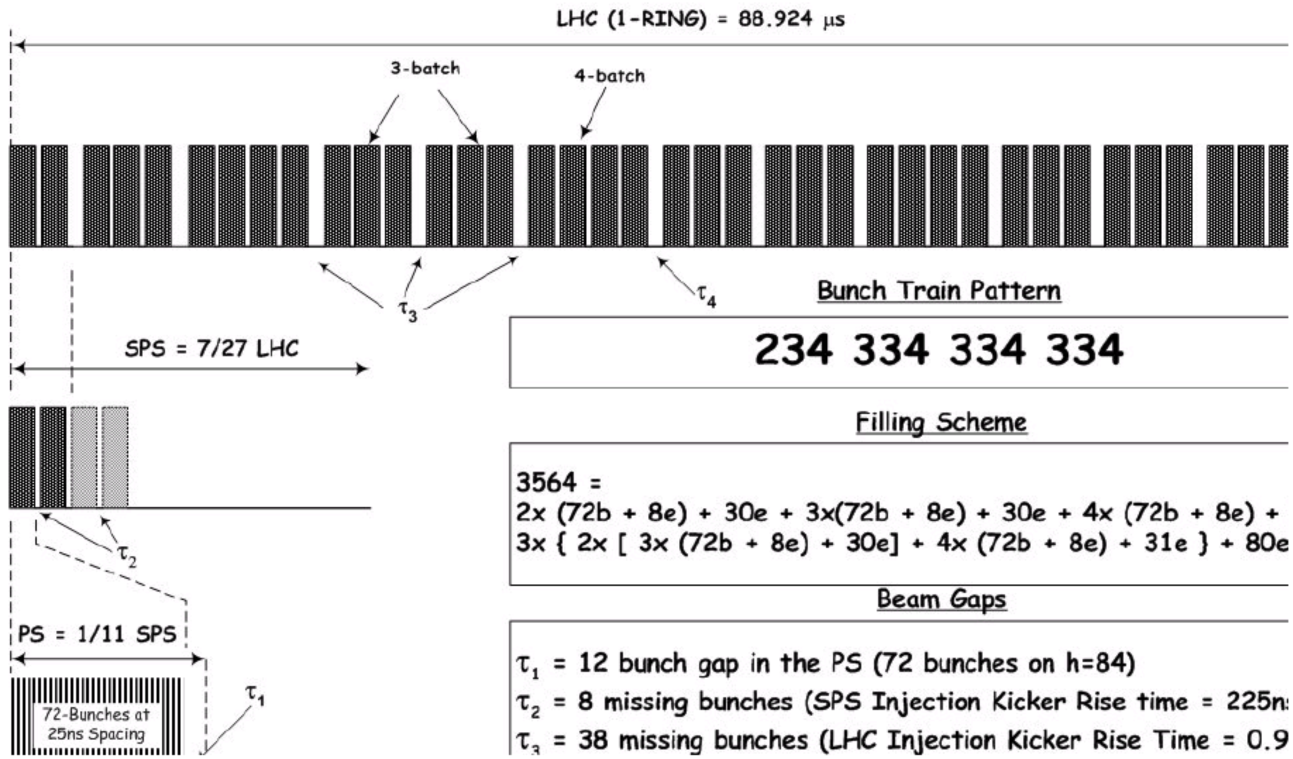
2, 3 or 4 x 72 bunches

1 batch = 72 bunches

total 39×72 = 2808 bunches

Leave a 119 bunch abort gap free ~ 3 μs

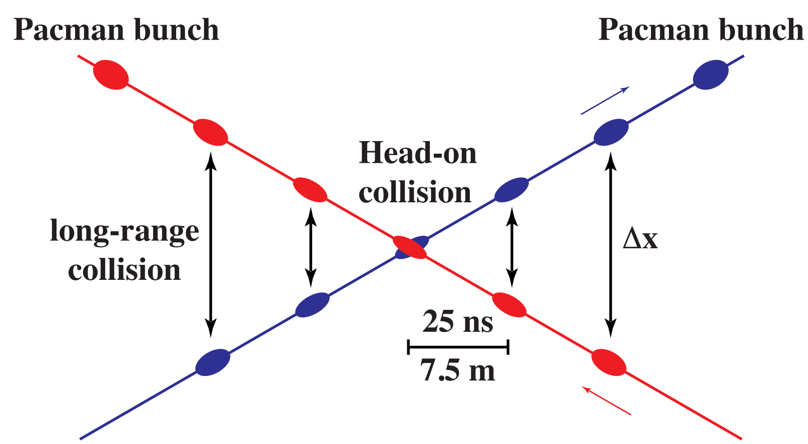
A full LHC turn is 88.9 μs



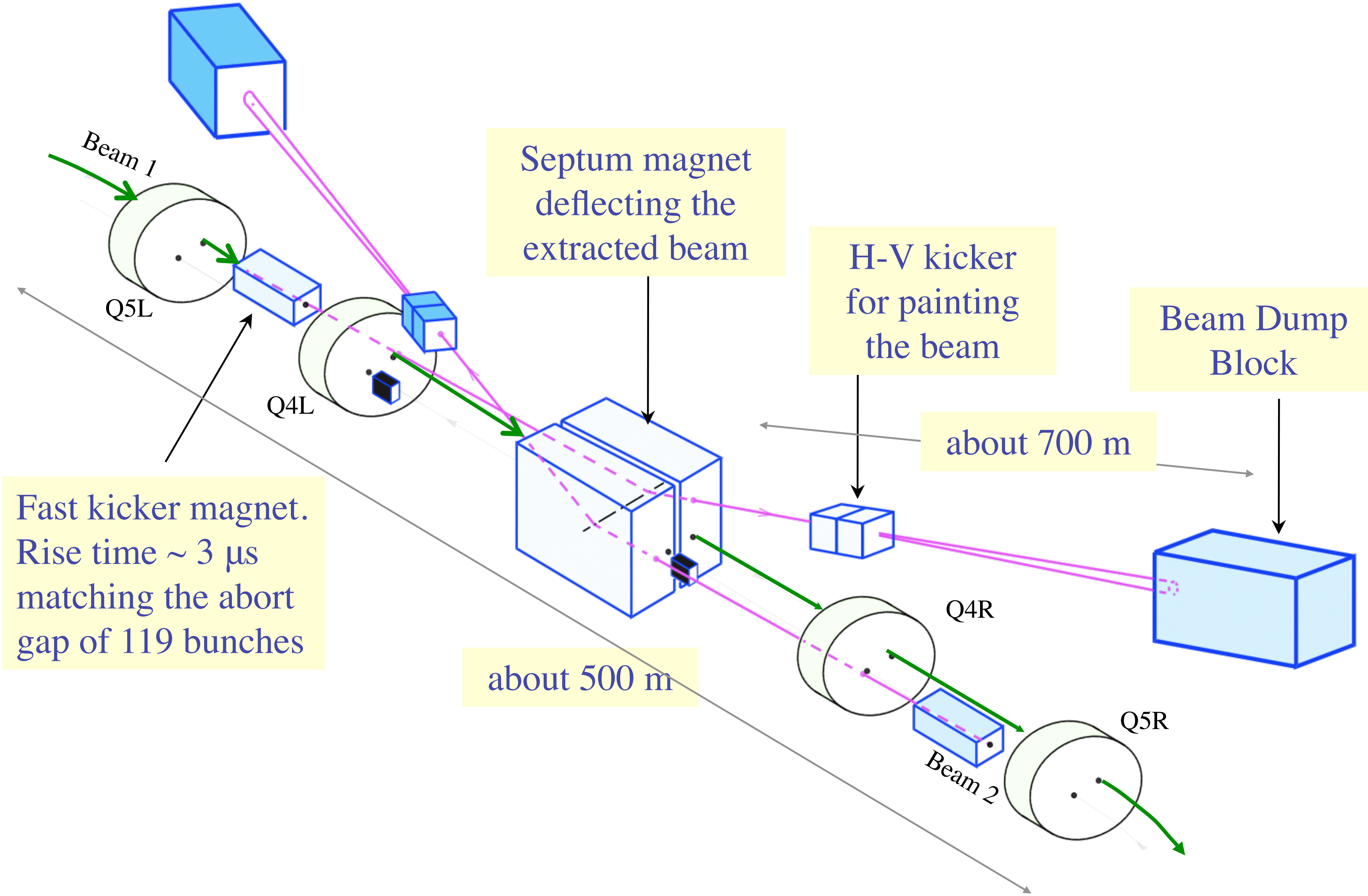
Crossing angle needed for > 156 bunches to avoid encounters closer than ~ 6 σ

Angle needed depends on β*

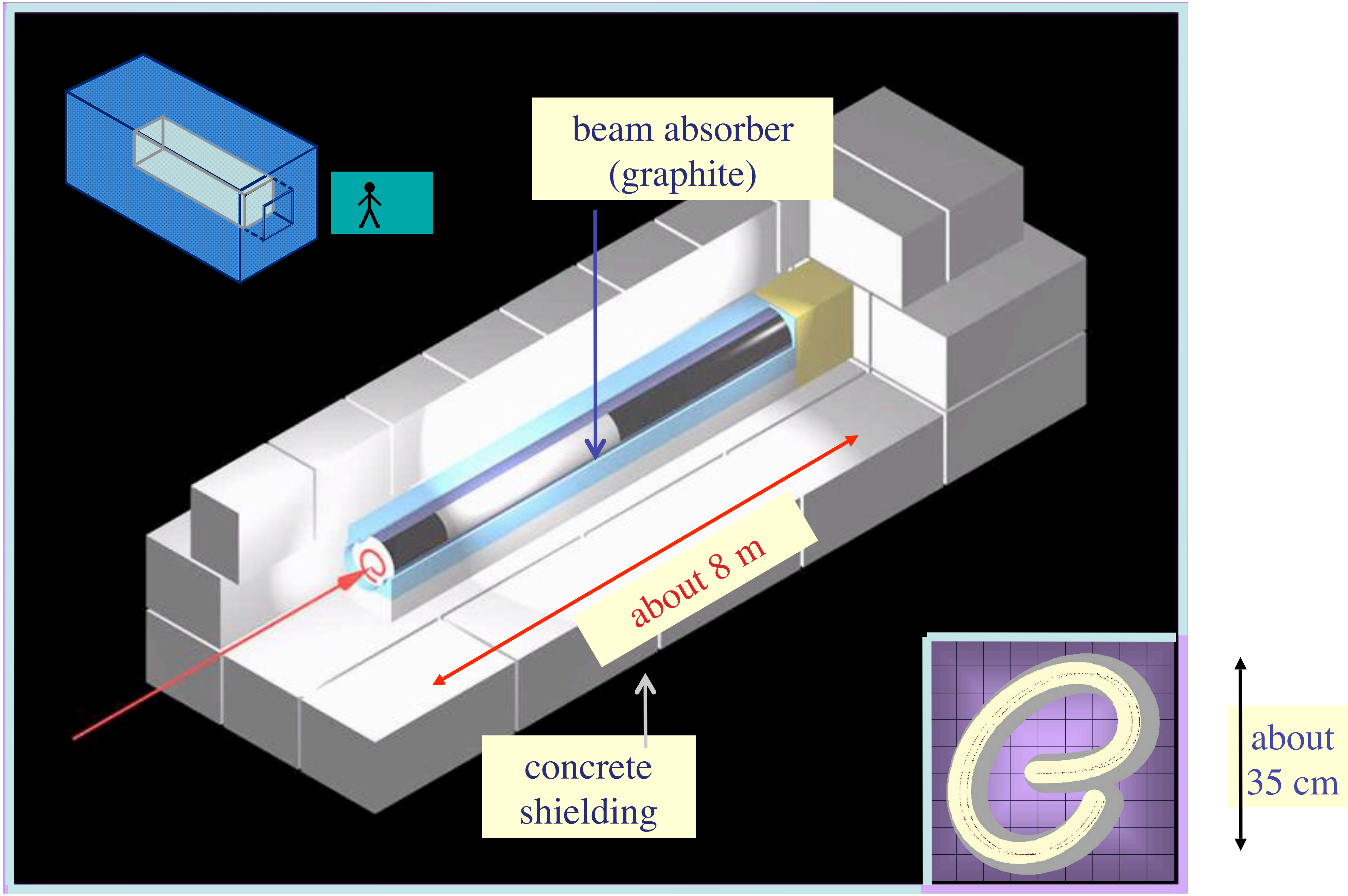
Nominal angle ± 142.5 μrad



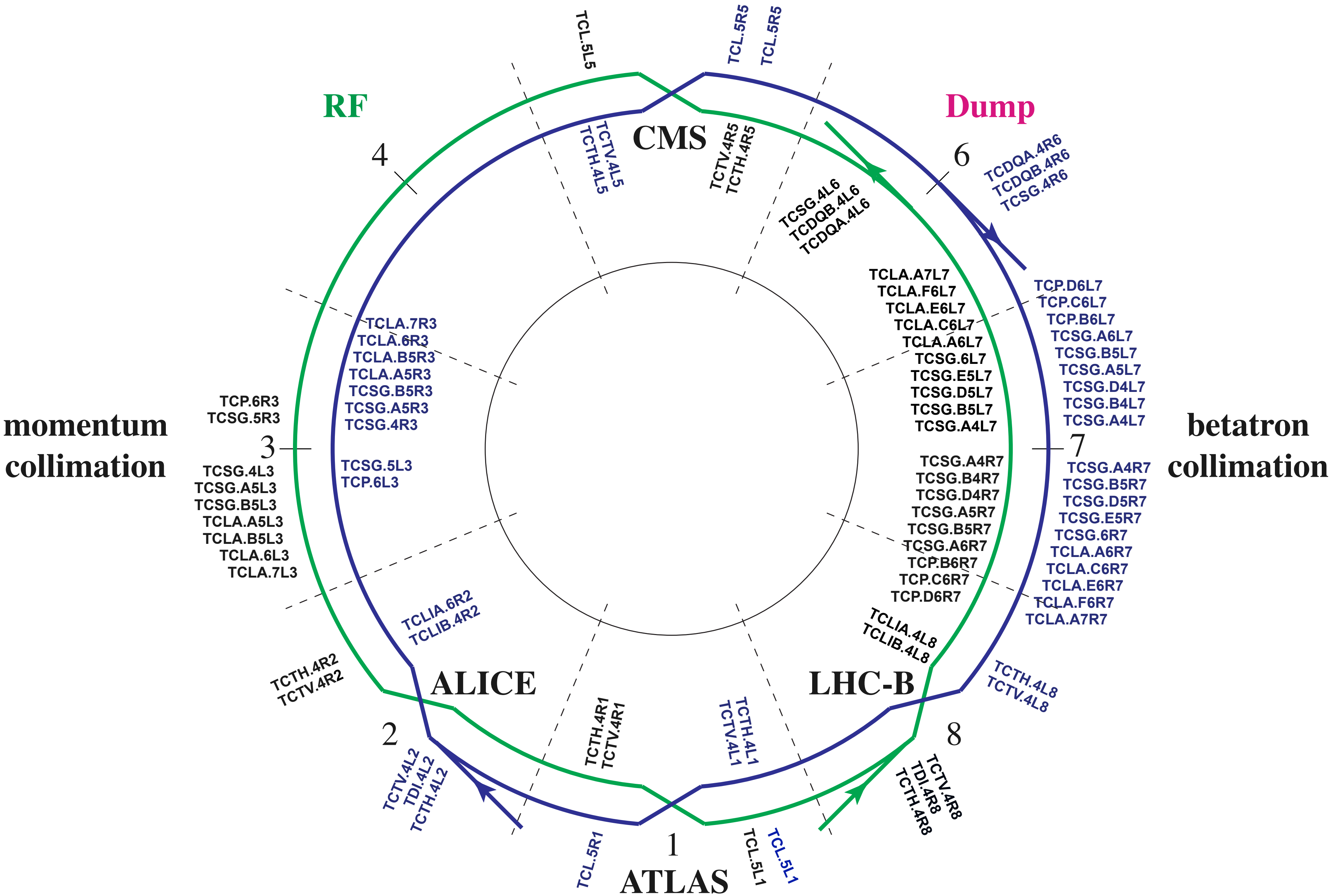
Schematic layout of beam dump system in IR6



Dumping the LHC beam



Layout of the LHC with collimation



94 collimators (phase 1)

Nominal LHC parameters at top energy

Proton energy 7 TeV	7 TeV
# protons / bunch	1.15×10^{11}
# bunches in each of the 2 beams	2808
# protons / beam	3.23×10^{14}
total energy stored in one beam	362 MJ

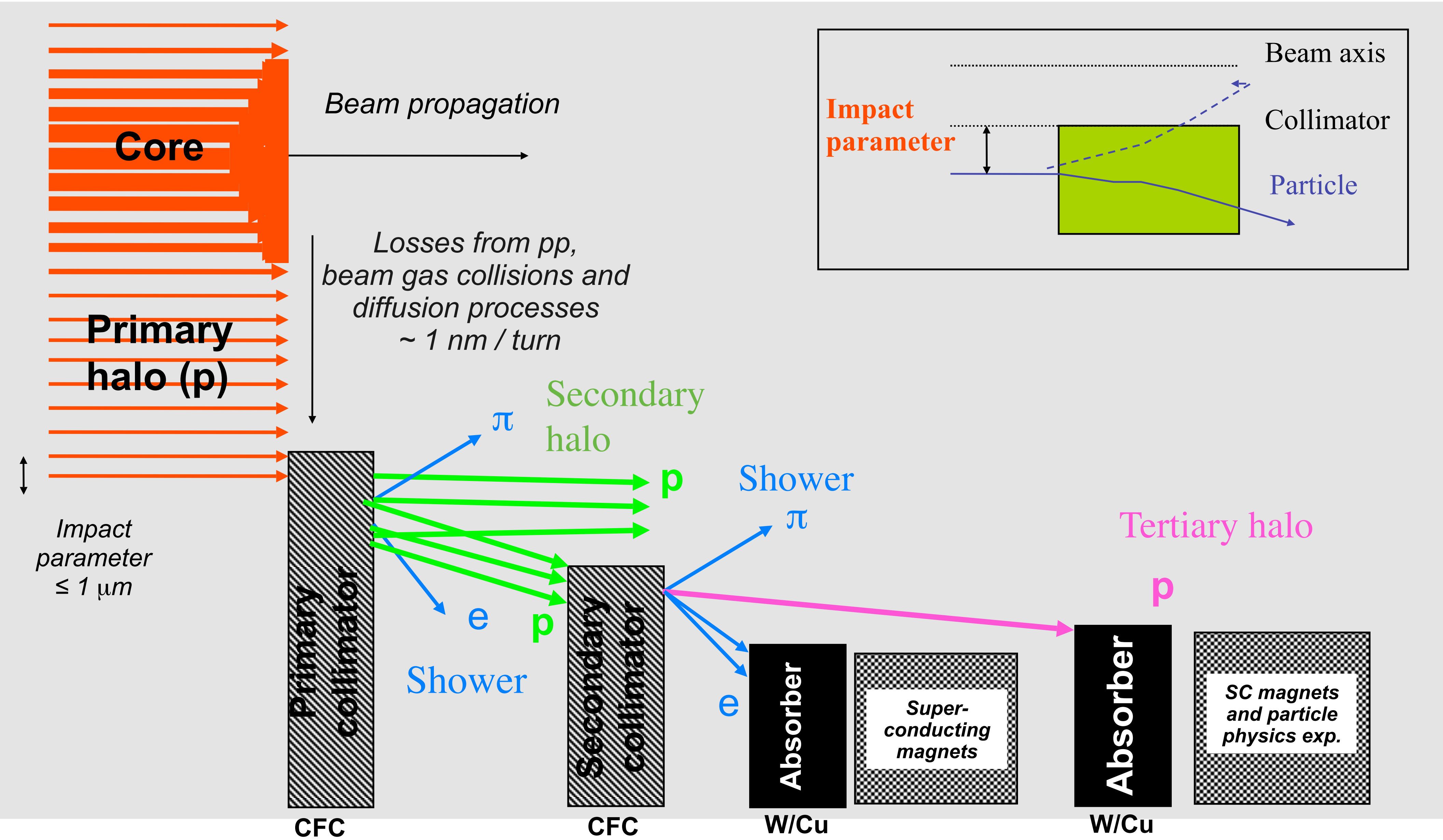
Collimation design

max loss rate (fraction at full intensity)	4.3×10^{11} / s (1.3×10^{-3}/s)
corresponding lifetime at full intensity	0.2 h
power at max loss rate P_{loss}	487 kW
quench limit q_{lim}	8.5 W/m
collimation (in)efficieny $\eta_c = q_{lim} / P_{loss}$	2×10^{-5} /m

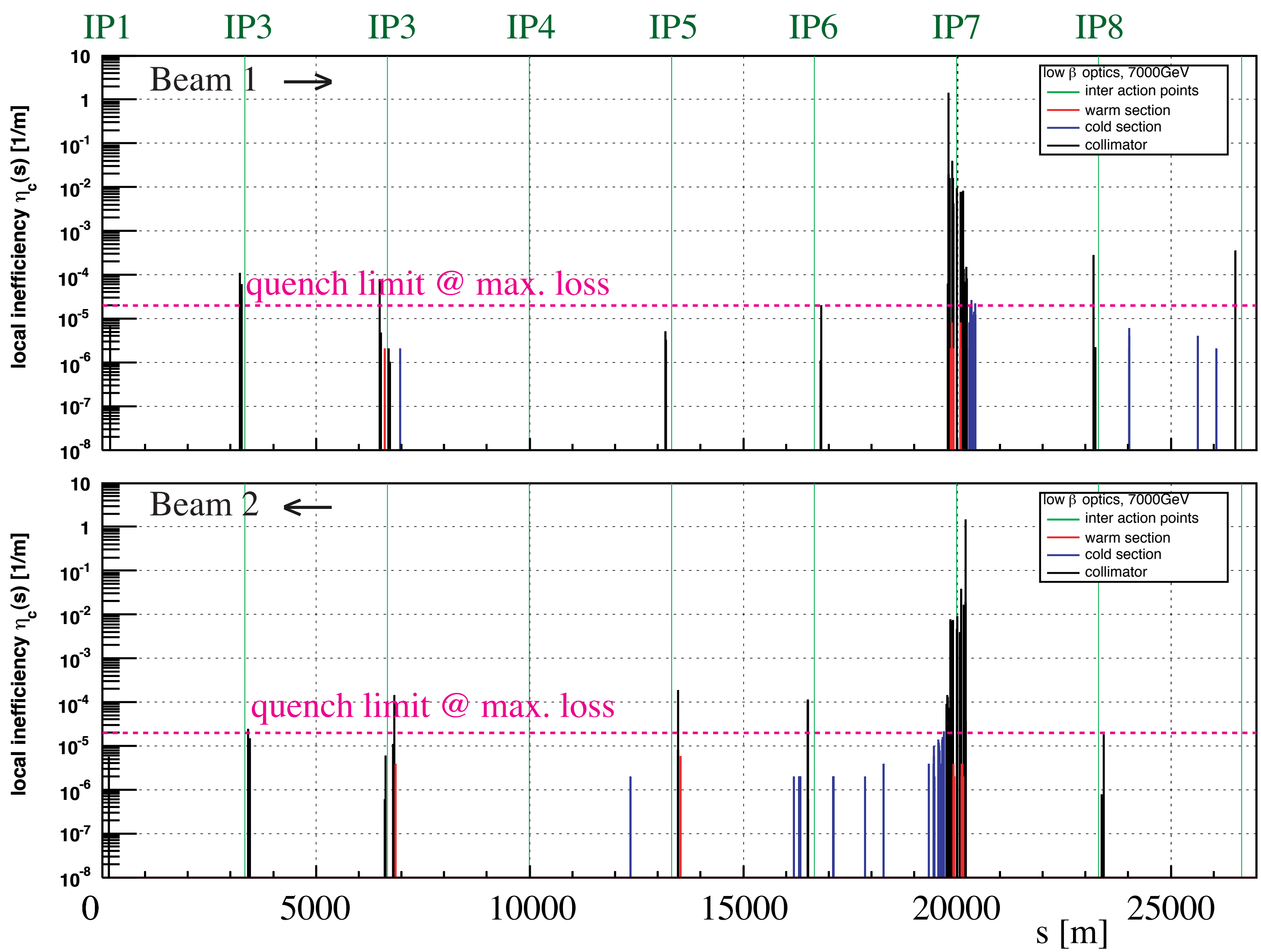
LHC Design Report 2004-003

Multiple Stage Collimation System

collimation team R. Assmann et al.



Horizontal loss map, nominal 7 TeV collision optics



Standard settings; ideal machine. All losses in cold sections below quench limit for max. tolerated loss rate of 4.3×10^{11} prot. / s (0.2h at nom. intensity)

Figure from T. Weiler, collimation team

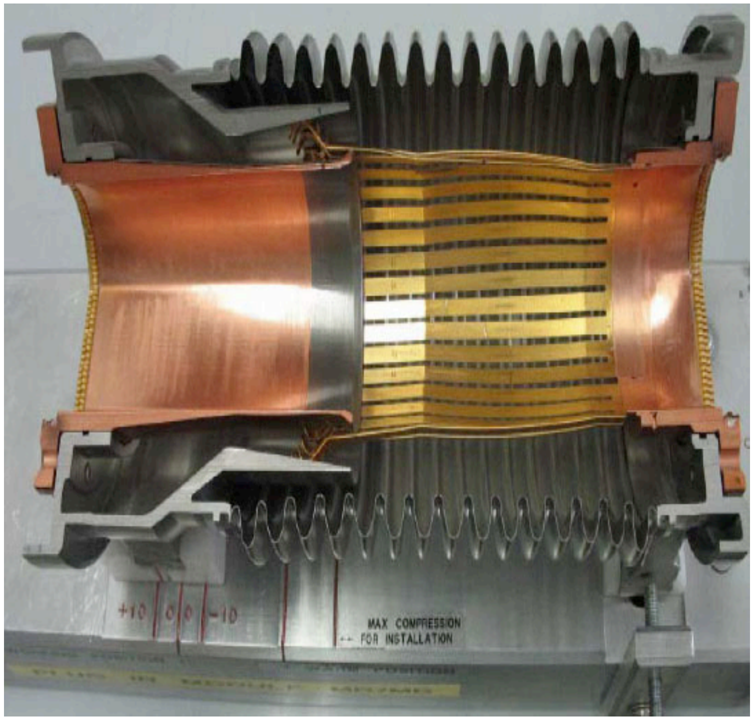
Critical Issues

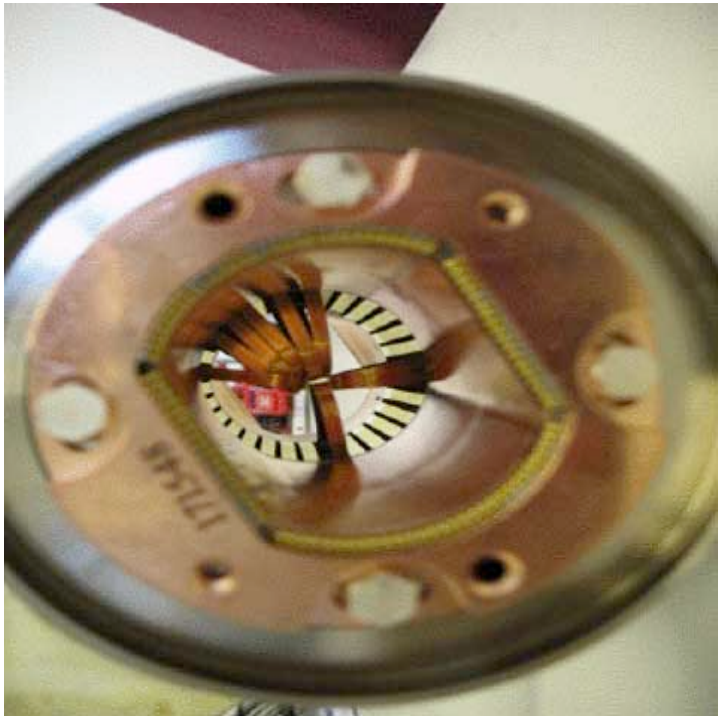
Past

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

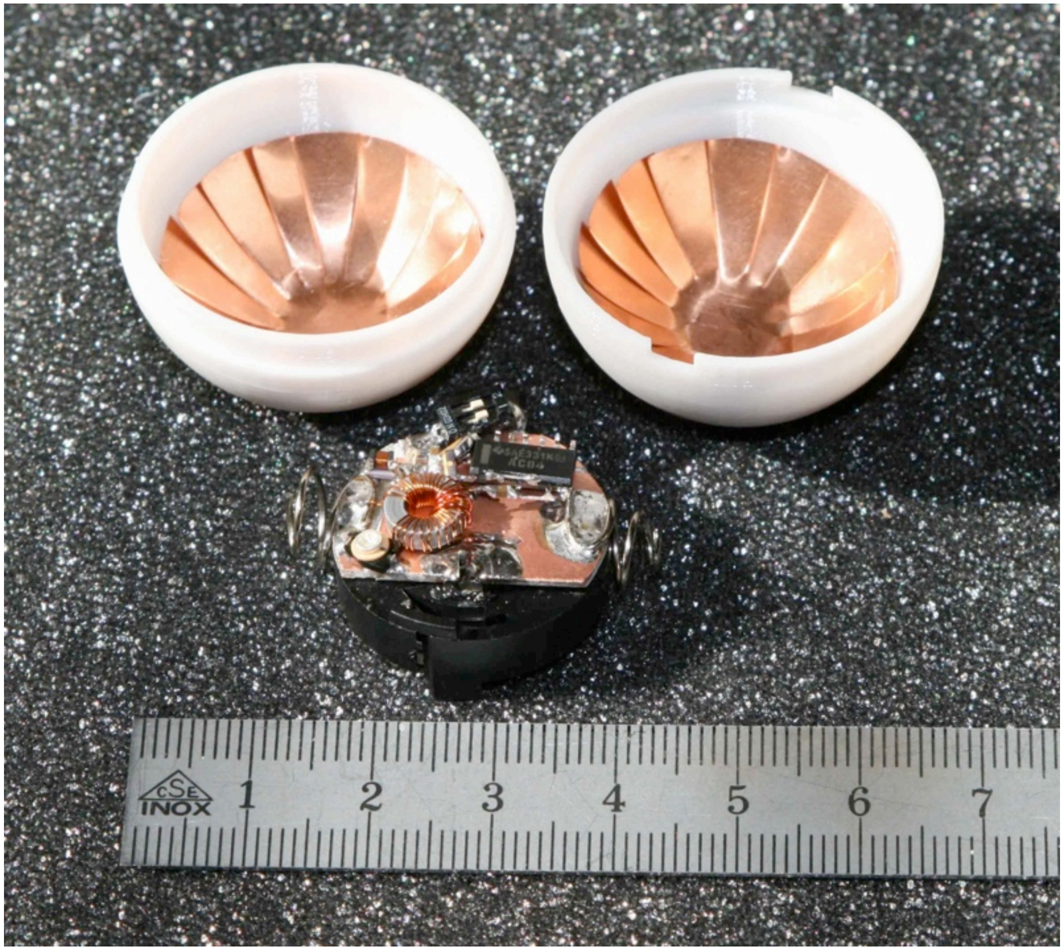
Recent

- 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





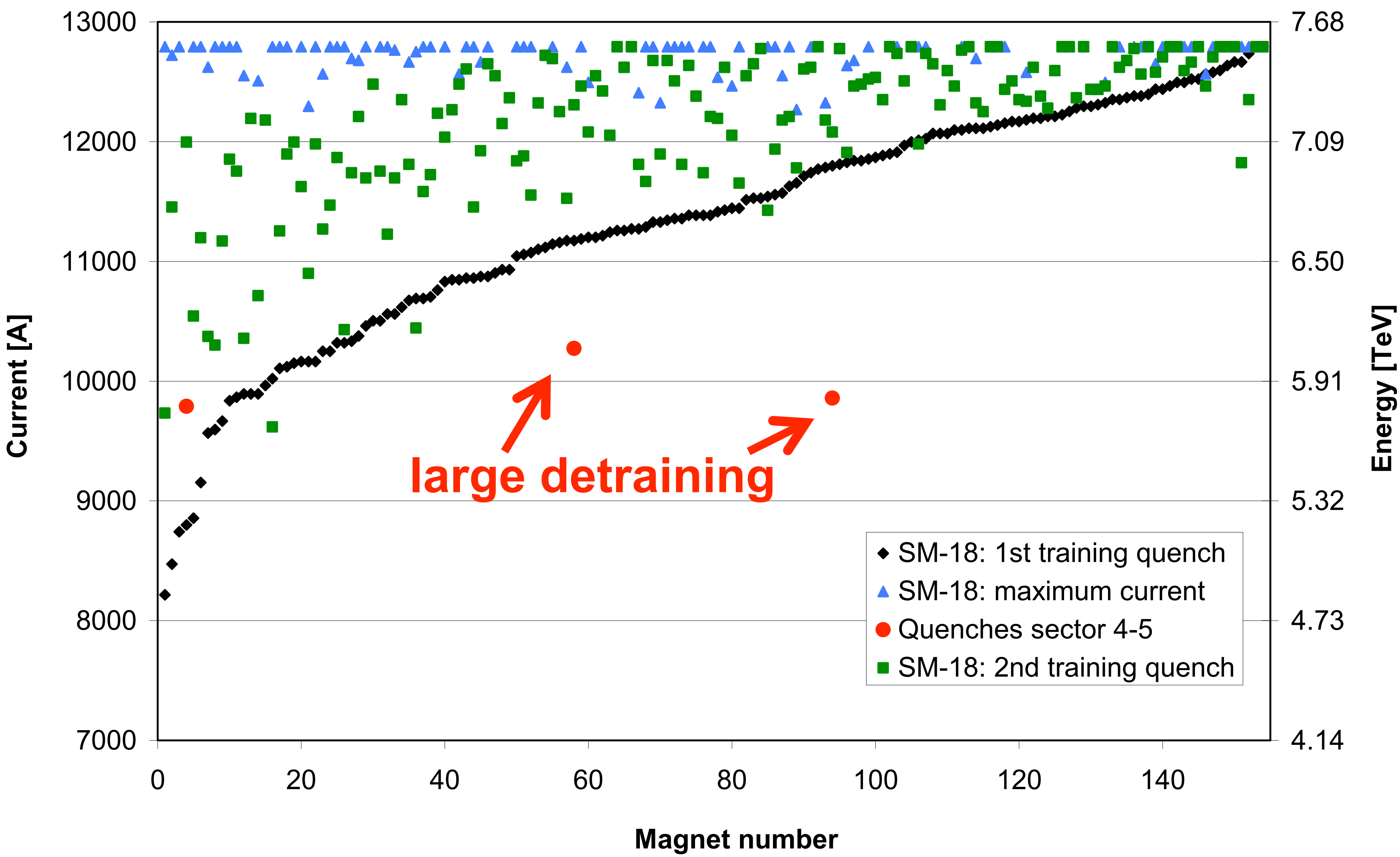
Beam vacuum ring aperture check with RF - ping-pong ball



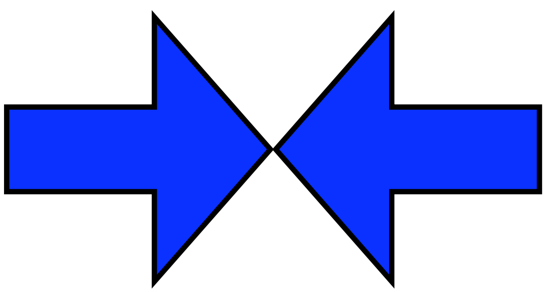
Polycarbonate shell
∅ 34 mm, 15 g
2h battery powered
40 MHz emitter
signals recorded by LHC BPM

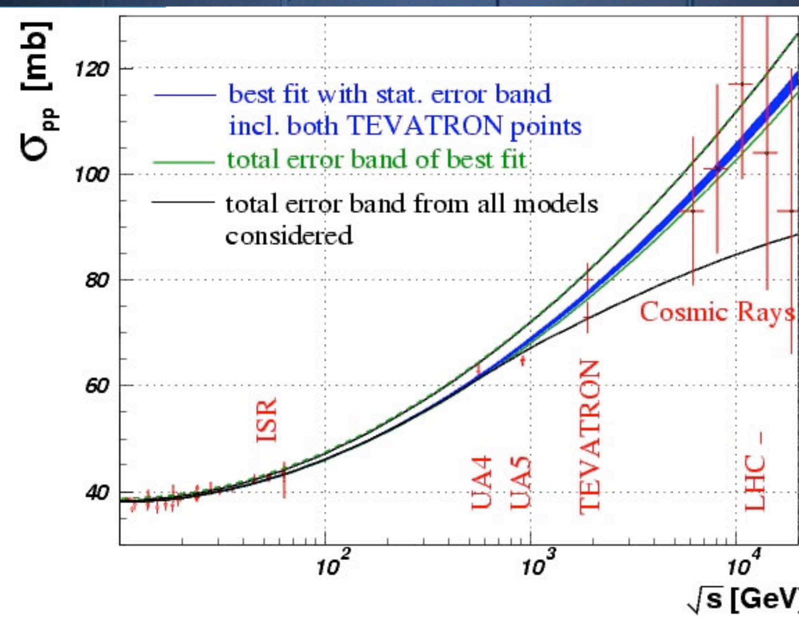
PIM issue only relevant after warm-up
localize with RF-ball - fix locally

HW commissioning, powering towards nominal in 4-5



LHC Commissioning with Beam





Organisation

preparation
&
follow up

LHC Commissioning Working Group - LHCCWG

chaired by R. Bailey ; 51 meetings ; http://lhccwg.web.cern.ch/

documented detailed commissioning procedures

continued now as

LHC Performance Committee (LHC-PerC)

chaired by S. Myers / R. Bailey

run

3 Machine Coordinators - weekly

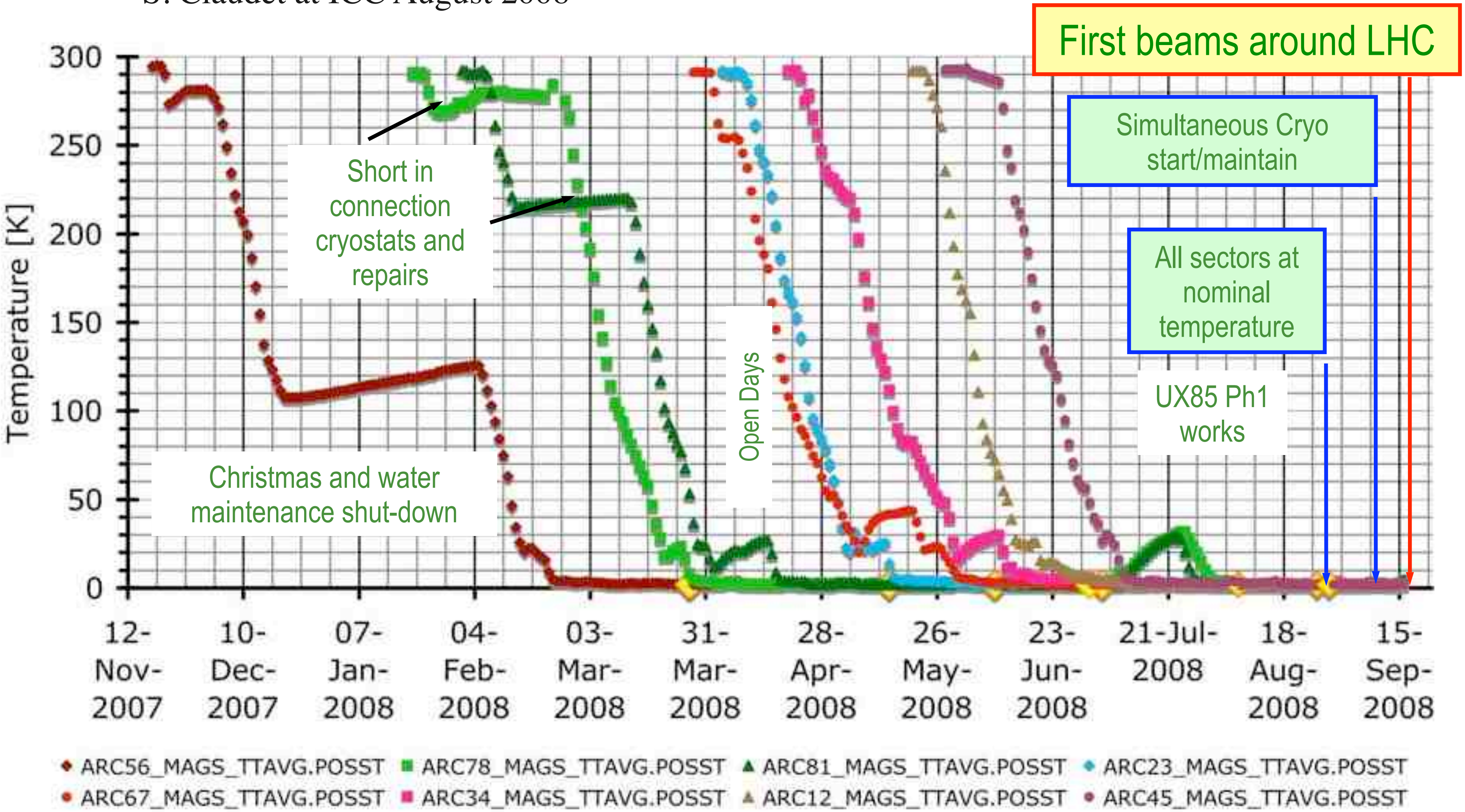
7 EICs Engineer In Charge **working in 8 hour shifts**

11 Experts with responsibility for groups of tasks including

- 450 GeV machine
- Energy Ramp
- Collimation
- Machine protection
- Collisions and Experimental Conditions (H.B.)

First cool-down of LHC sectors

S. Claudet at ICC August 2008

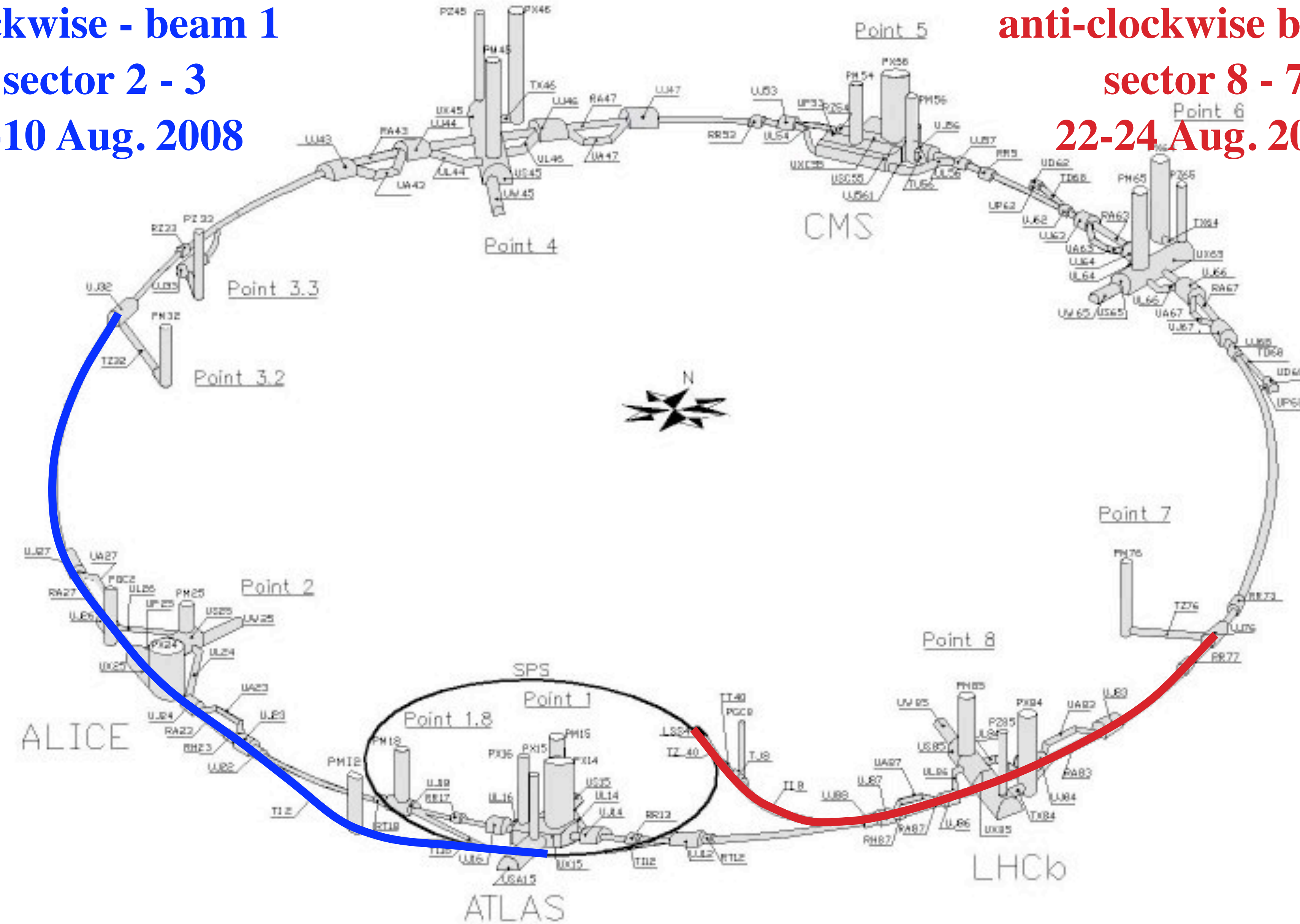


Cooling sectors + Cryo tuning + Powering activities

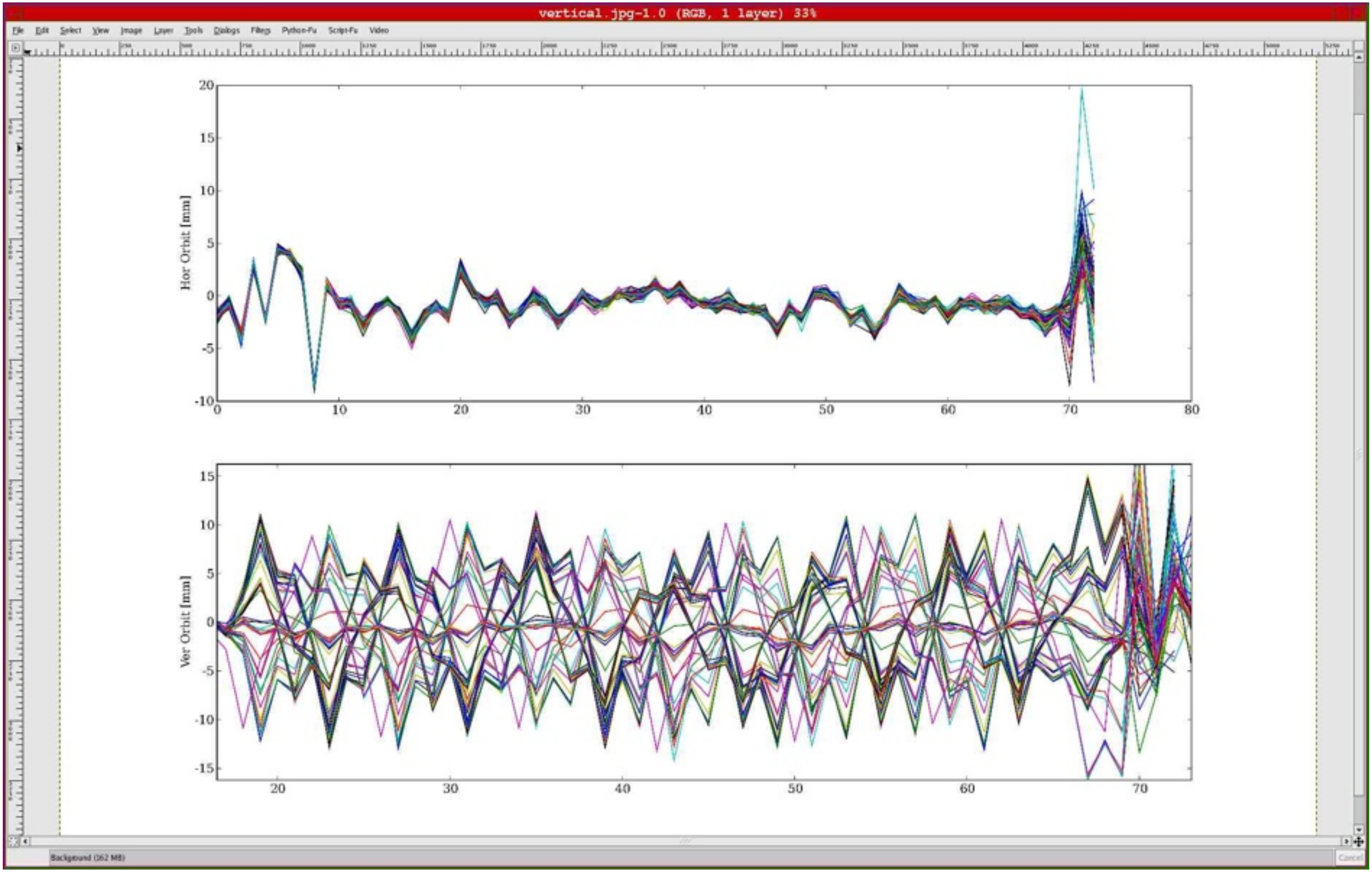
LHC commissioning with beam ; Tests in August

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

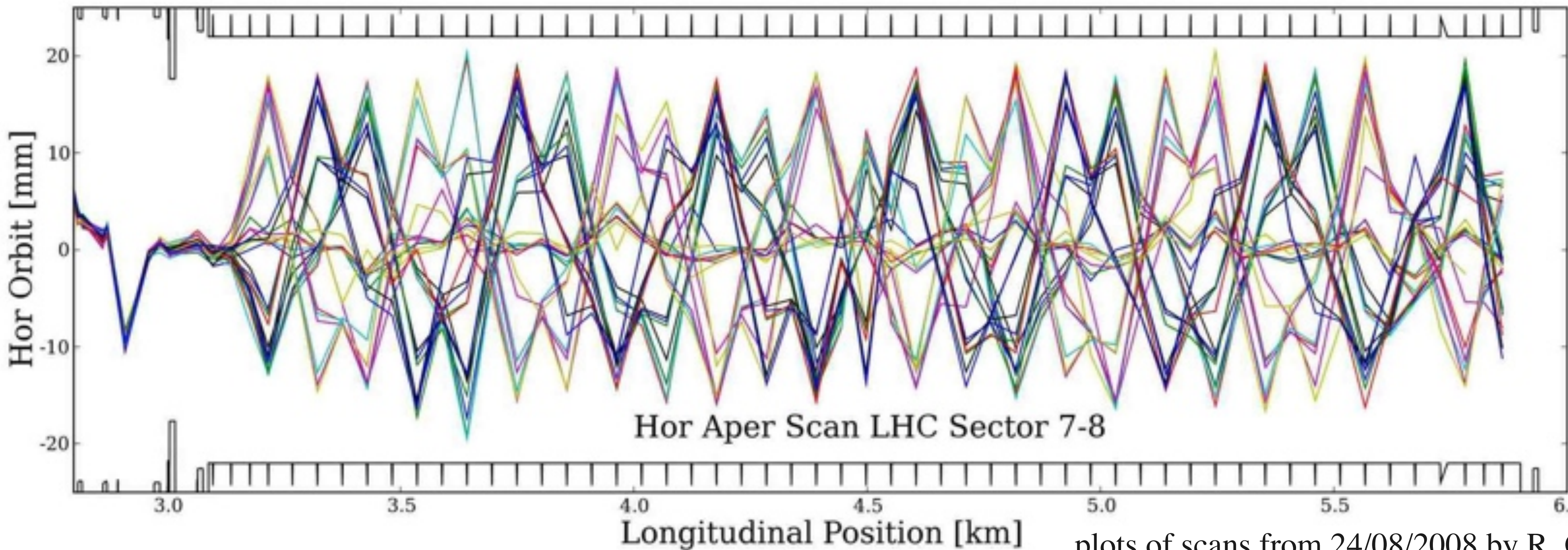
2nd Injection
anti-clockwise beam 2
sector 8 - 7
22-24 Aug. 2008



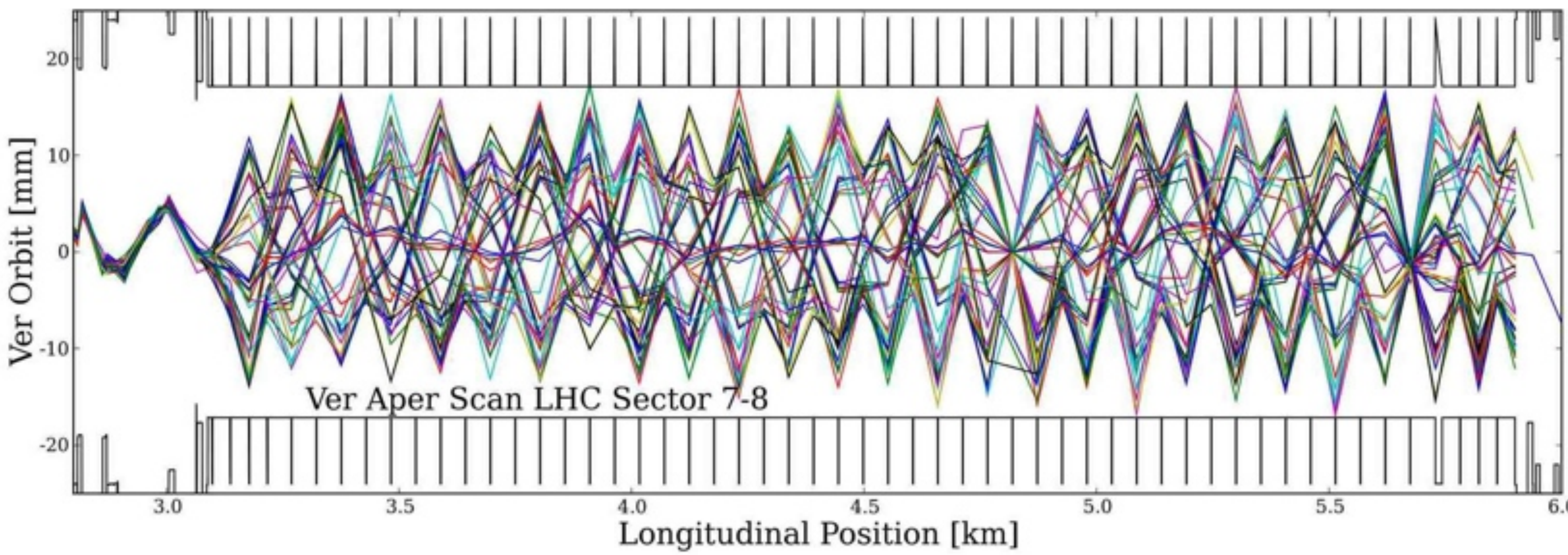
LHC sector 2-3 : 1st vertical aperture scan with beam 1



LHC sector 8-7 : aperture scan with beam 2

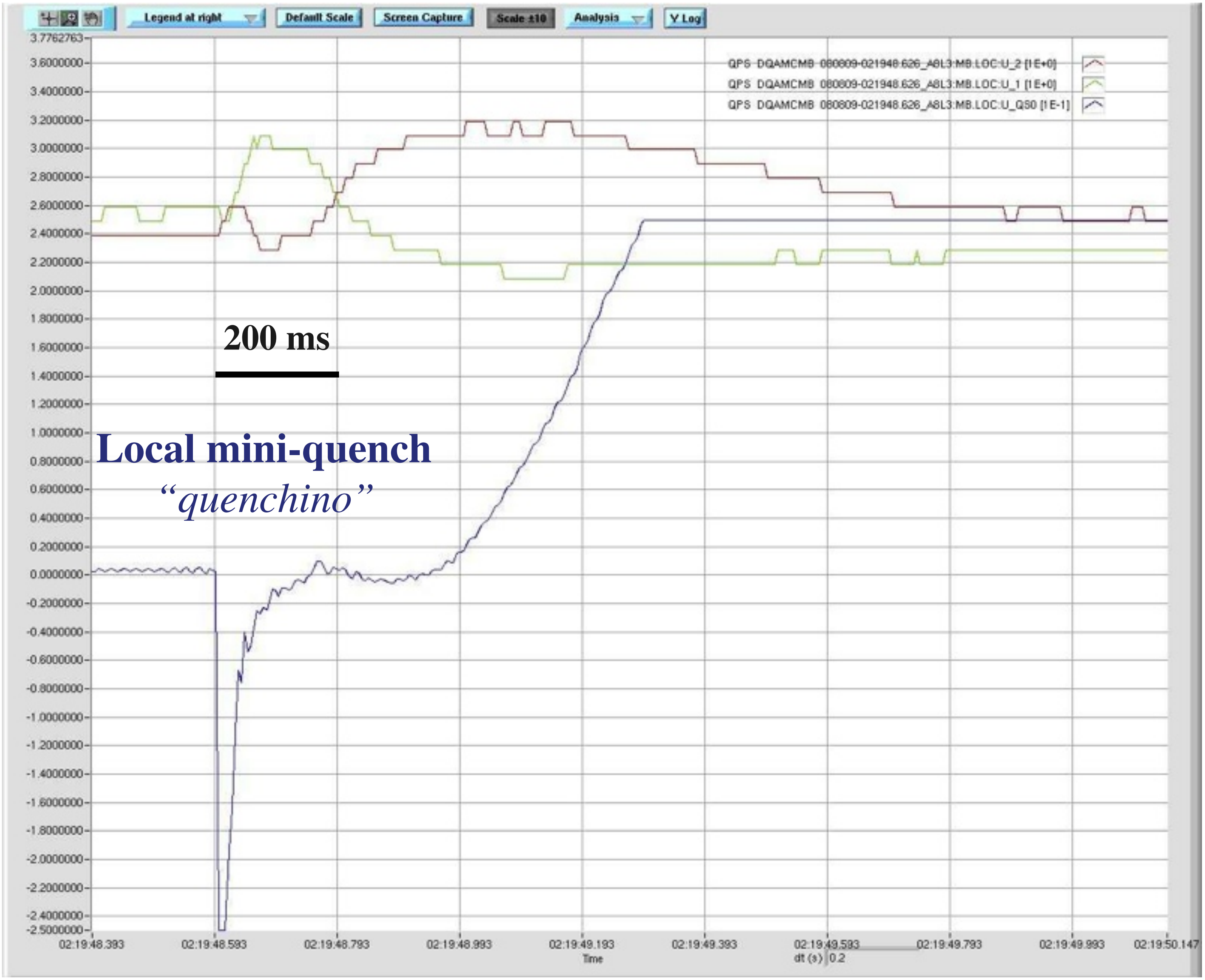


plots of scans from 24/08/2008 by R. Calaga



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

LHC first beam induced quench, 9 Aug 2008



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

Protons make first turns, Wednesday 10 September 2008

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

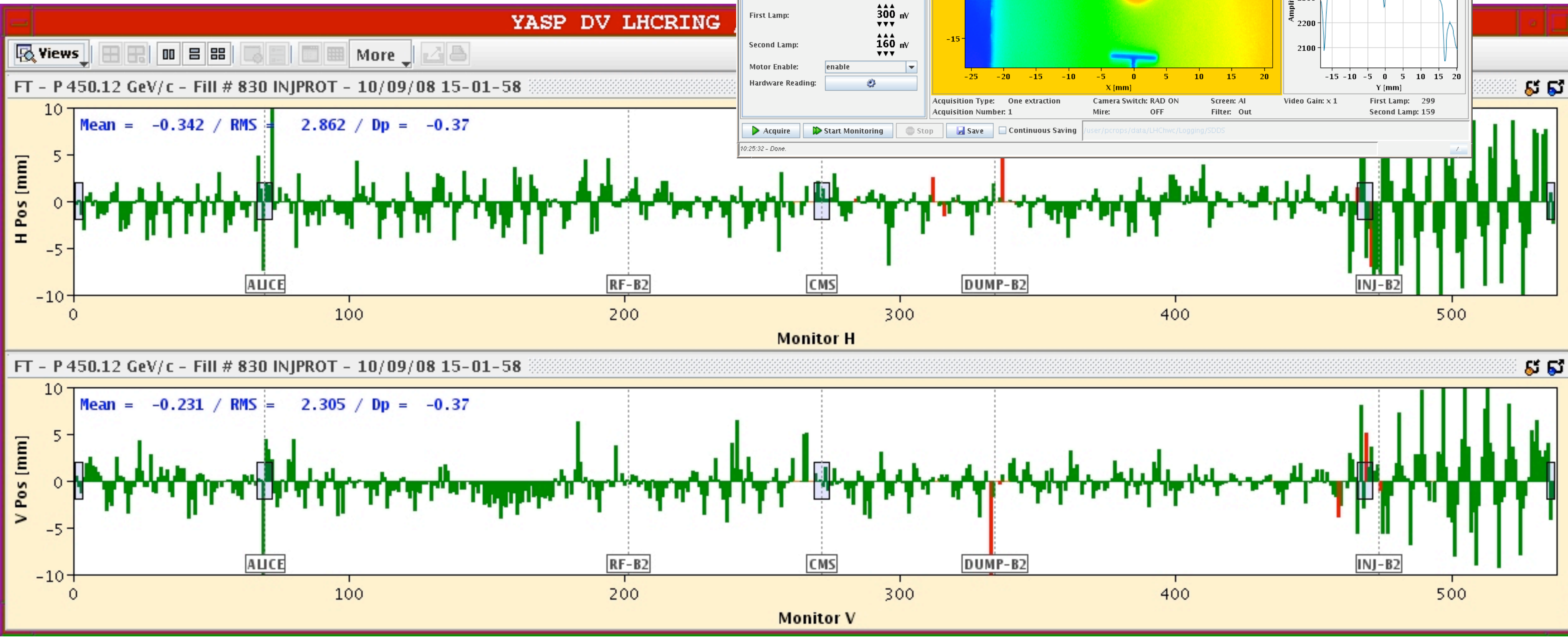
https://lhc-commissioning.web.cern.ch/lhc-commissioning/dailynews/week37.htm

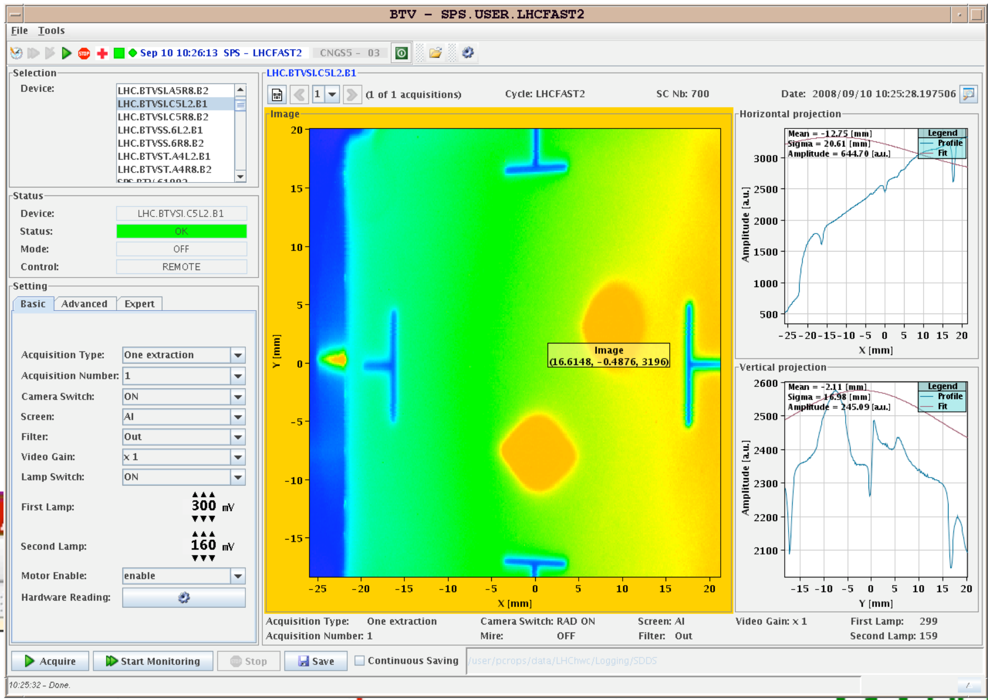
Day	Beam 1 progress	Beam 2 progress	Images
Mon 08			
Tue 09	Tests from 22h to 24h	Tests from 23h to 24h	
Wed 10	First turn 9.30 to 10.30 Makes 2 to 3 turns	First turn 13.30 to 15.00 Inject and dump working Few hundred turns BPM working multiple turns Measure Q working Fast BC working Systematic polarity 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

First turn. 10 September 2008

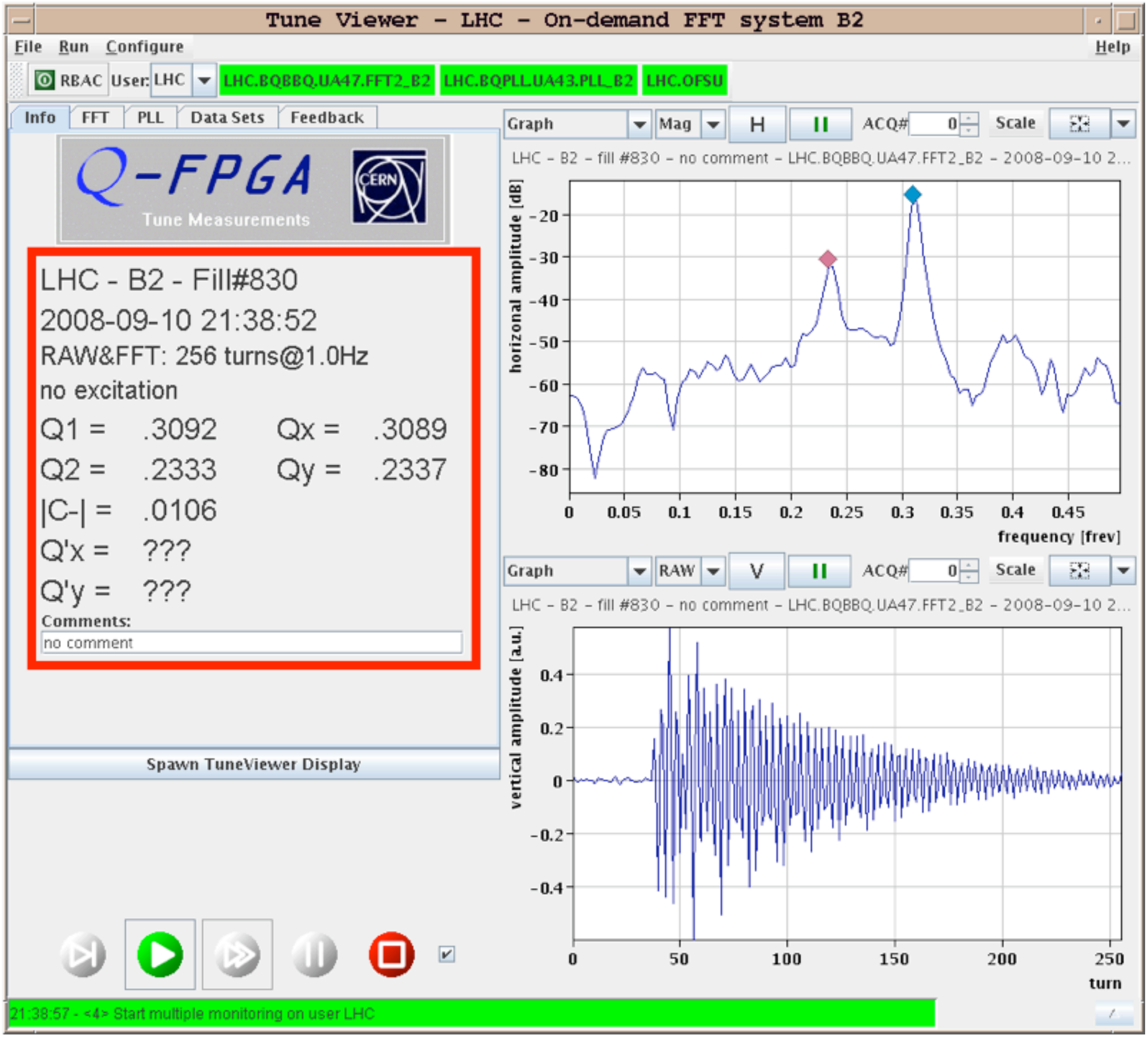
- First & Second Turn on screen
- First Turn on BPM system

Jörg Wenninger
Courtesy of Roger Bailey & O. Brüning





Tune measurement

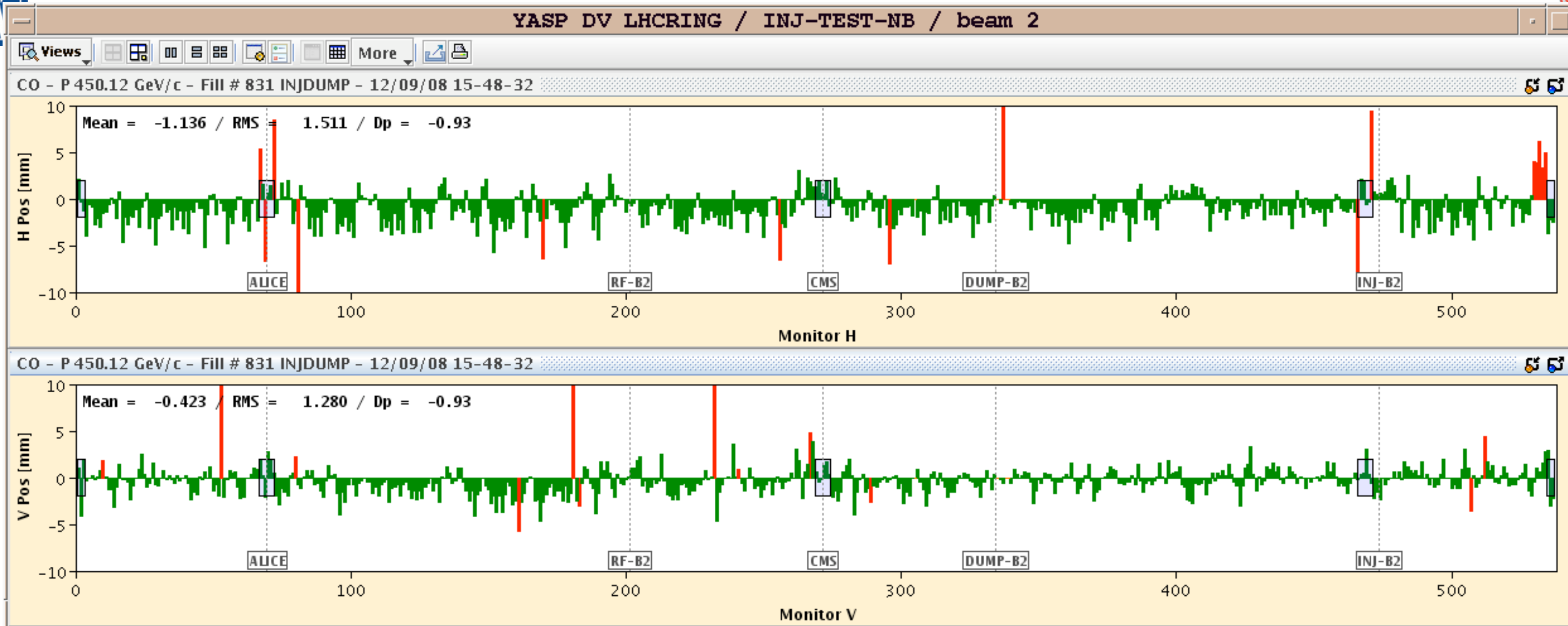


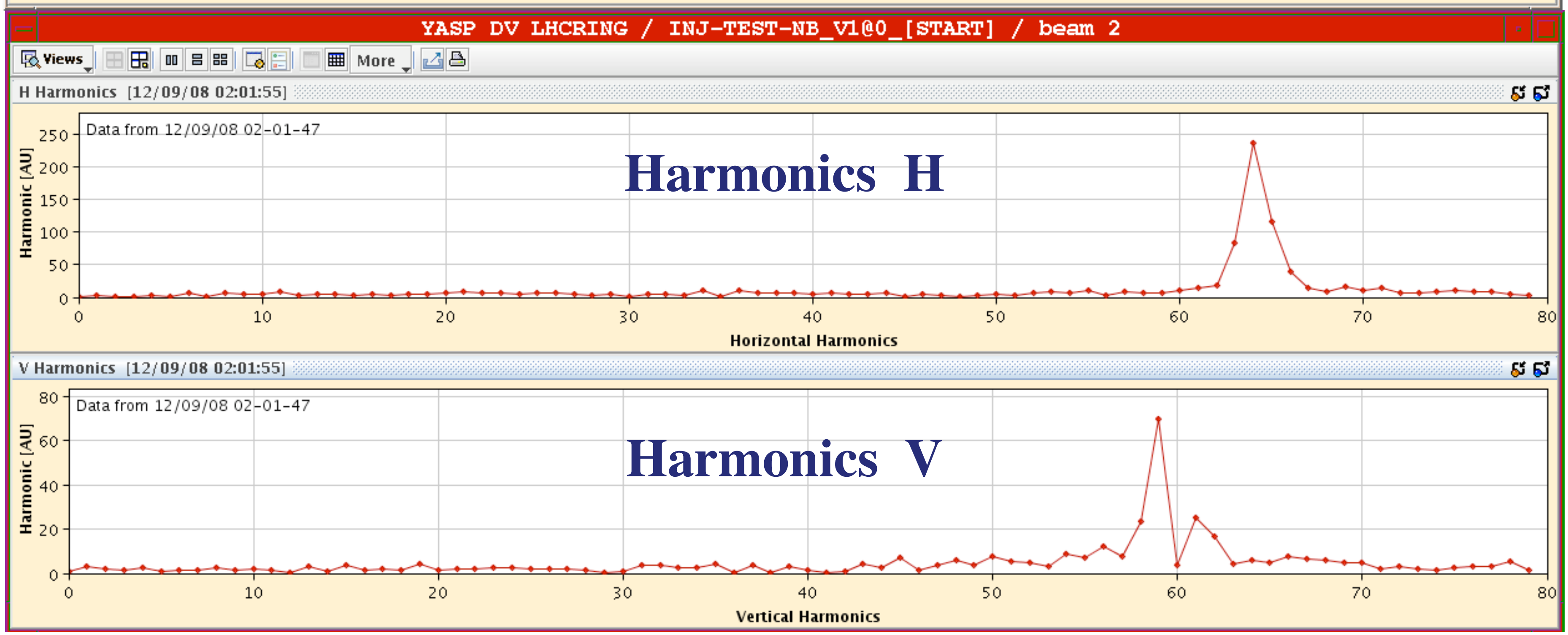
LHC nominal tunes are

Injection
$Q_x = 64.28$
$Q_y = 59.31$

Physics
$Q_x = 64.31$
$Q_y = 59.32$

LHC orbit and integer tunes from harmonic analysis





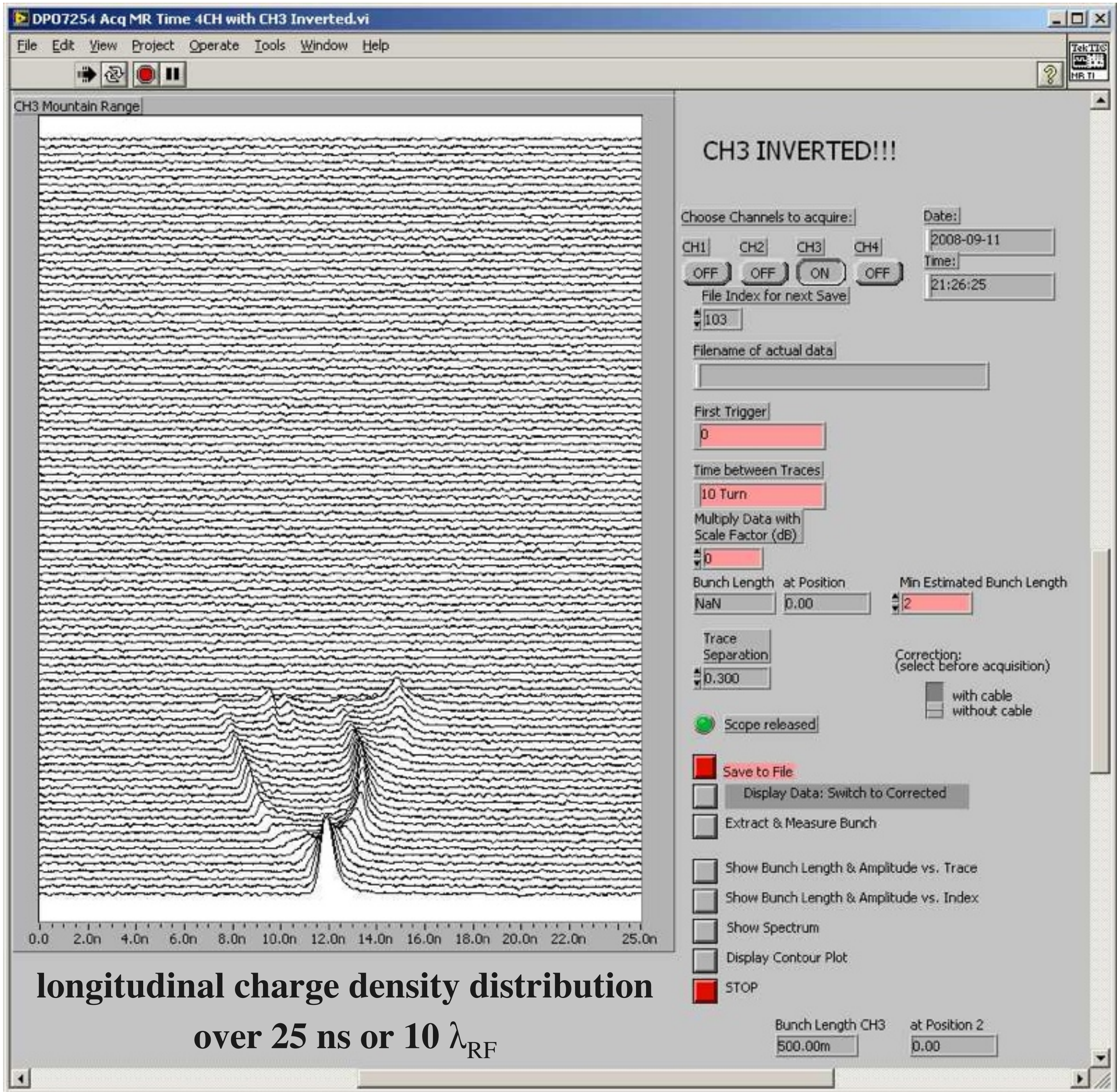
Nom:

Qx = 64.28

Qy = 59.31

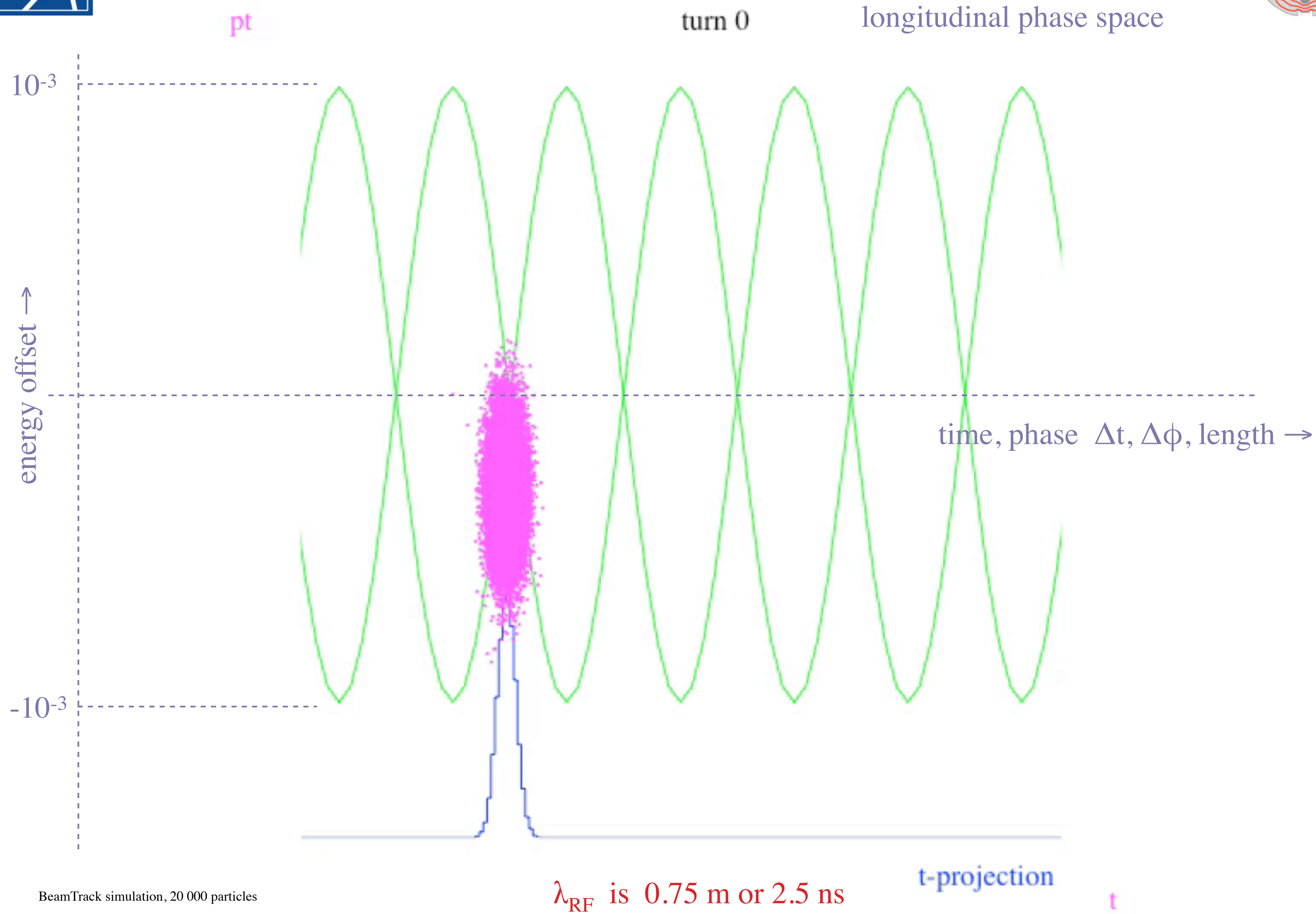
First attempt at RF capture

one trace every 10 turns



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

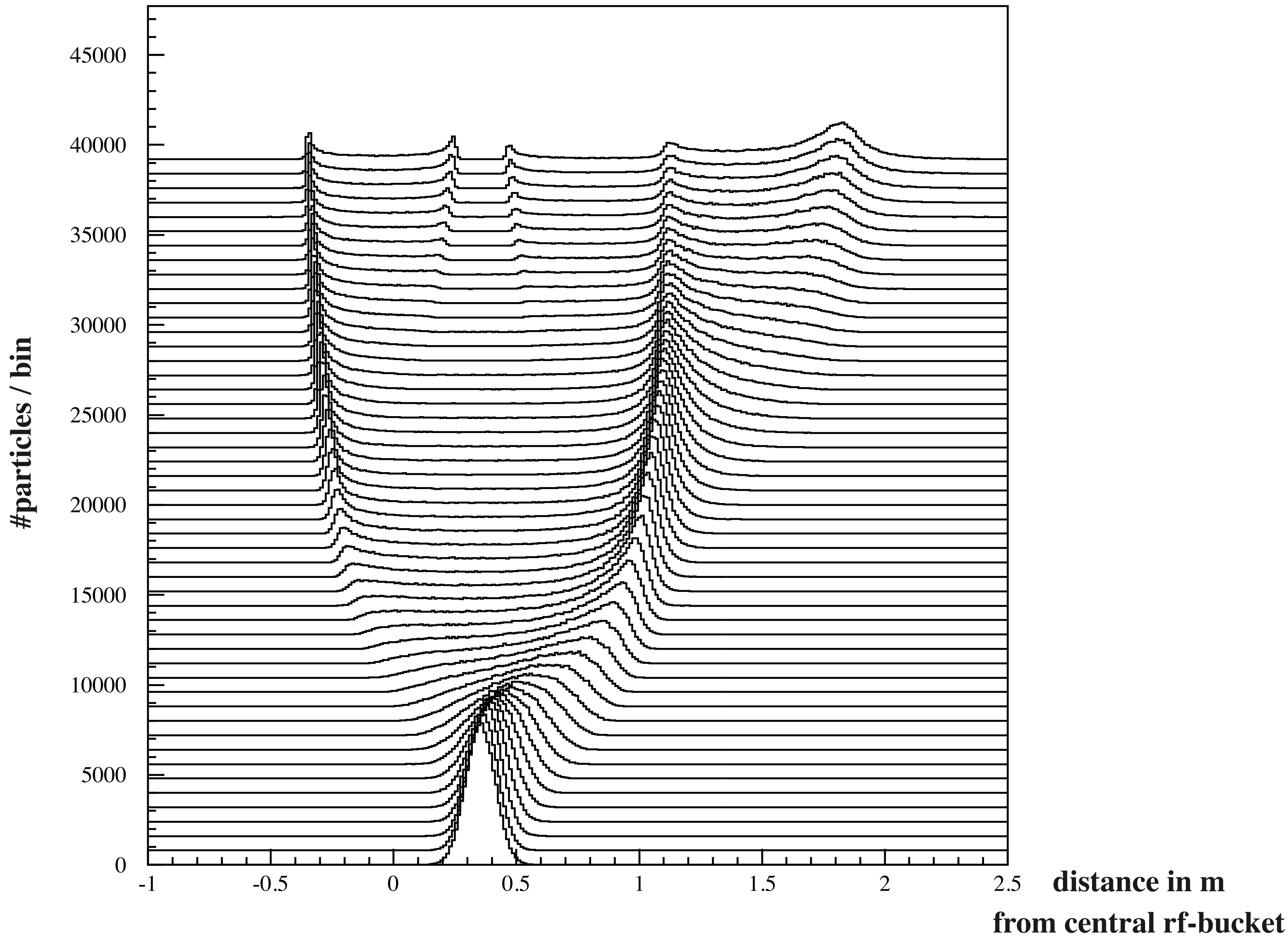
Simulation of injection with 170º injection phase offset



BeamTrack simulation, 20 000 particles

λ_{RF} is 0.75 m or 2.5 ns

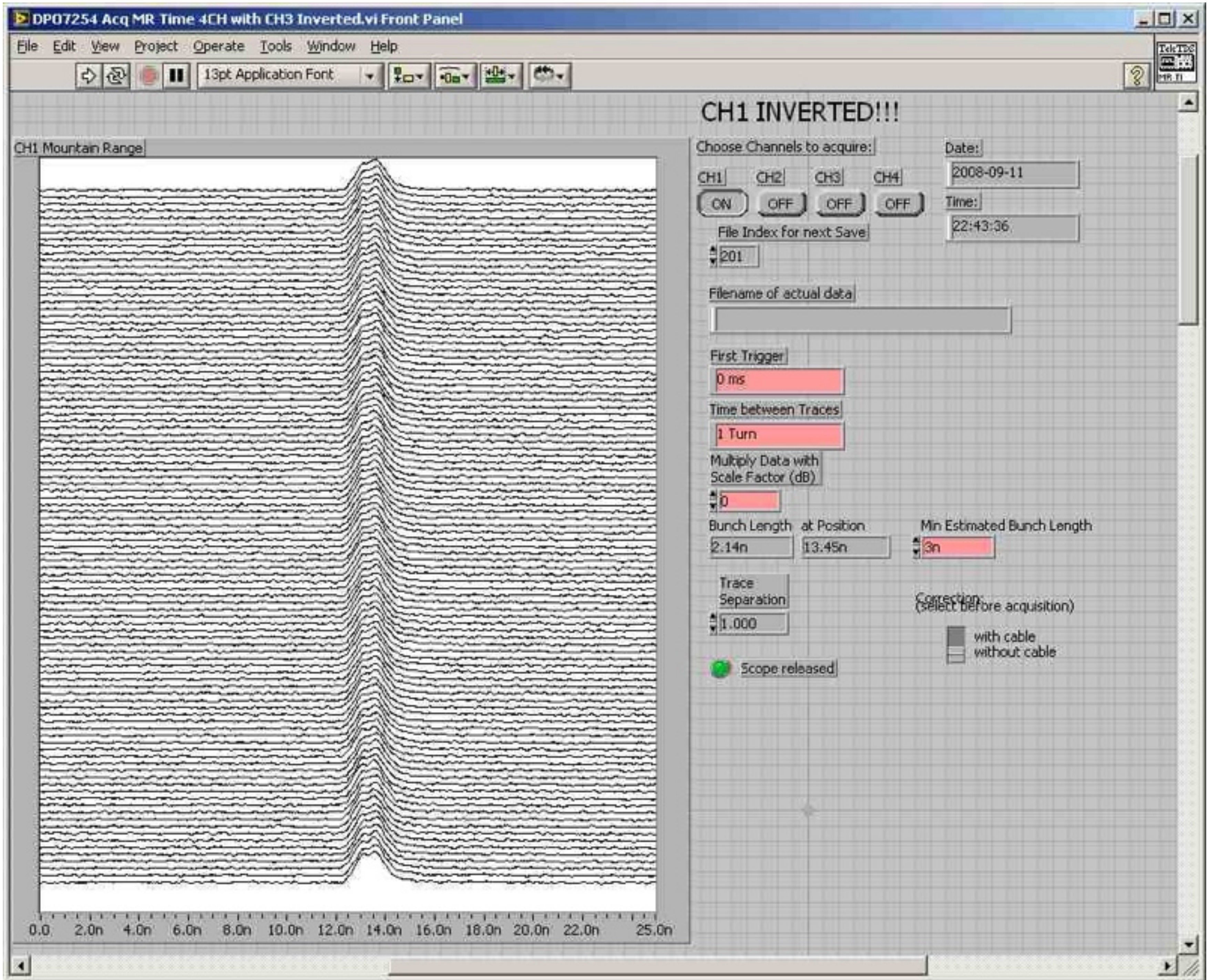
Simulation of injection with 170° injection phase offset



projection of previous plot : longitudinal charge density distribution

BeamTrack simulation, 100 000 particles

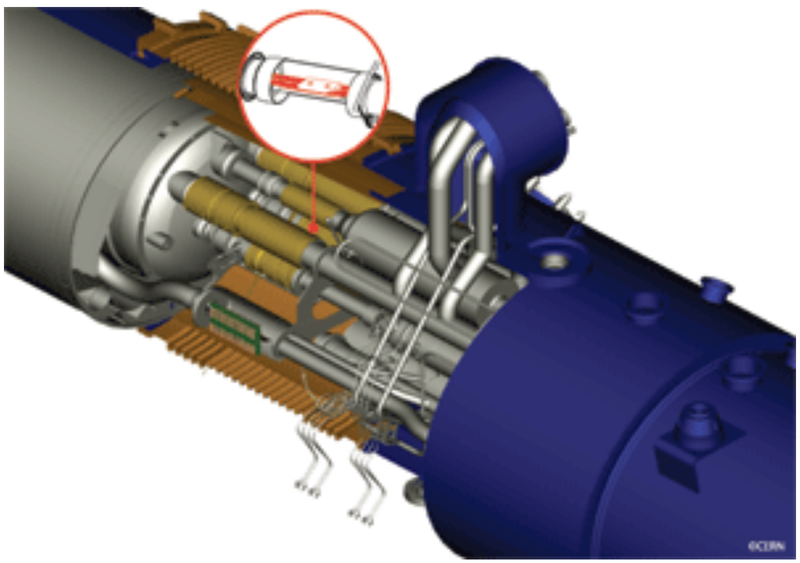
LHC beam 2 with well adjusted RF capture



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, at 9.3 kA or ~ 5.3 TeV,**



press release & interim report of task force, 16 Oct.

likely cause : bad splice at electrical connection between dipole and quad Q23
6t He or 1/2 of arc lost
pressure built up in adjacent each 107 m long, vacuum subsectors
~ 36 dipoles and 5 quads affected, inspect - repair

impact according to (my) current knowledge :
LHC operation stopped 3 month before planned operation stop
General shutdown advanced by 2 month
Aim to start-up 1. May instead of 1. June 2009 - if ✔ loss by incident ~ 2 month
Sector 34 (Roberto Saban) is on the agenda of today's LHC-PerC

Next steps in commissioning with beam

LHC commissioning with beam had 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 5 TeV
- first collisions at top energy ... physics run at 5 + 5 TeV
- increase intensity and partial squeeze

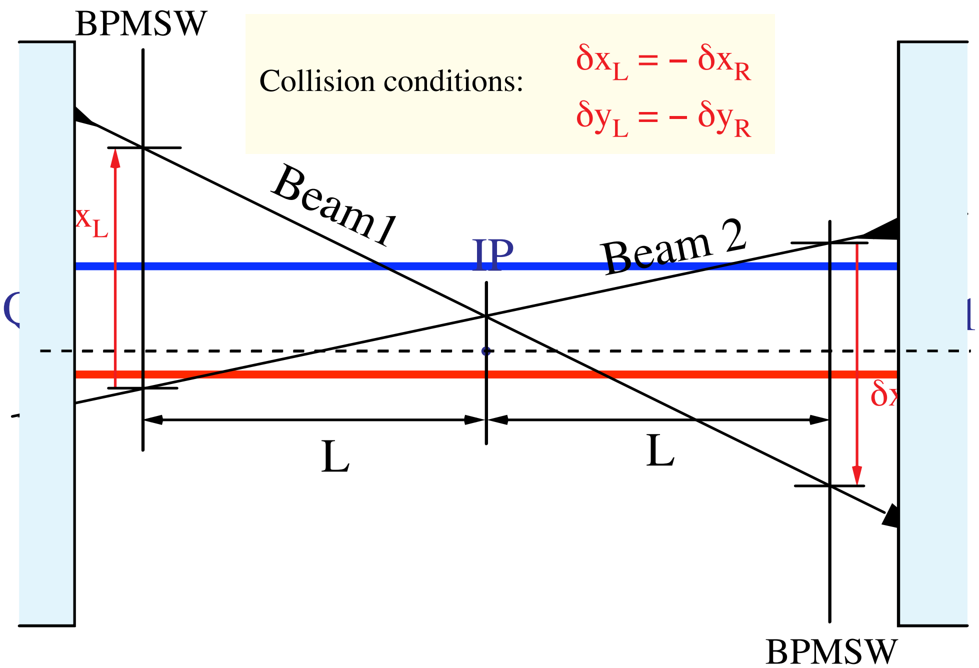
Get LHC beams colliding : BPM resolution

measured with special (beam-) directional stripline couplers BPMSW

at about 21 m L/R from IP in front of Q1,   2 each in IR

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



Expected beam sizes

Eb, TeV	β*	σ*
TeV	m	µm
0.45	11	293
5	11	88.0
7	11	74.4
7	2	31.7
7	0.55	16.6

Resolution each plane

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

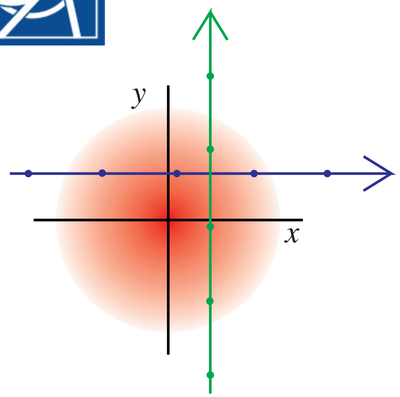
Expected resolution for small separation and 0 crossing angle ; in each plane.

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

~ 10 µm with extra button pickups for large bunch spacing, using identical electronics for b1 and b2 (planned, shutdown 2008 / 2009)

Luminosity scans and absolute luminosity

(pioneered by Van der Meer @ ISR)



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

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

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

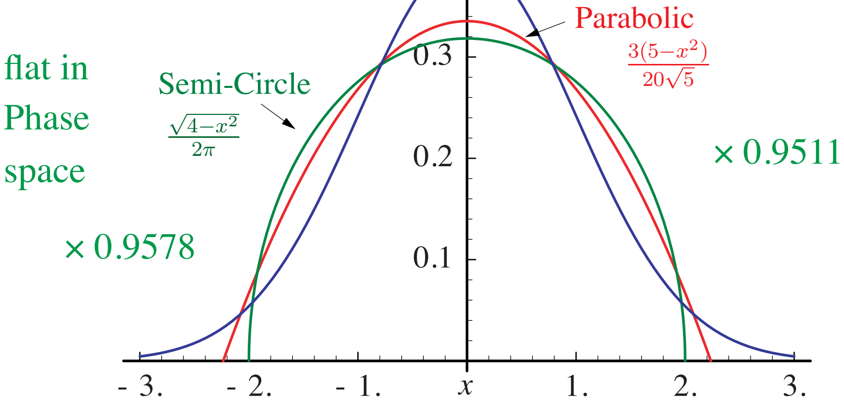
Accuracy : better than **1% at ISR**

Aim for **early LHC ~ 10 %**

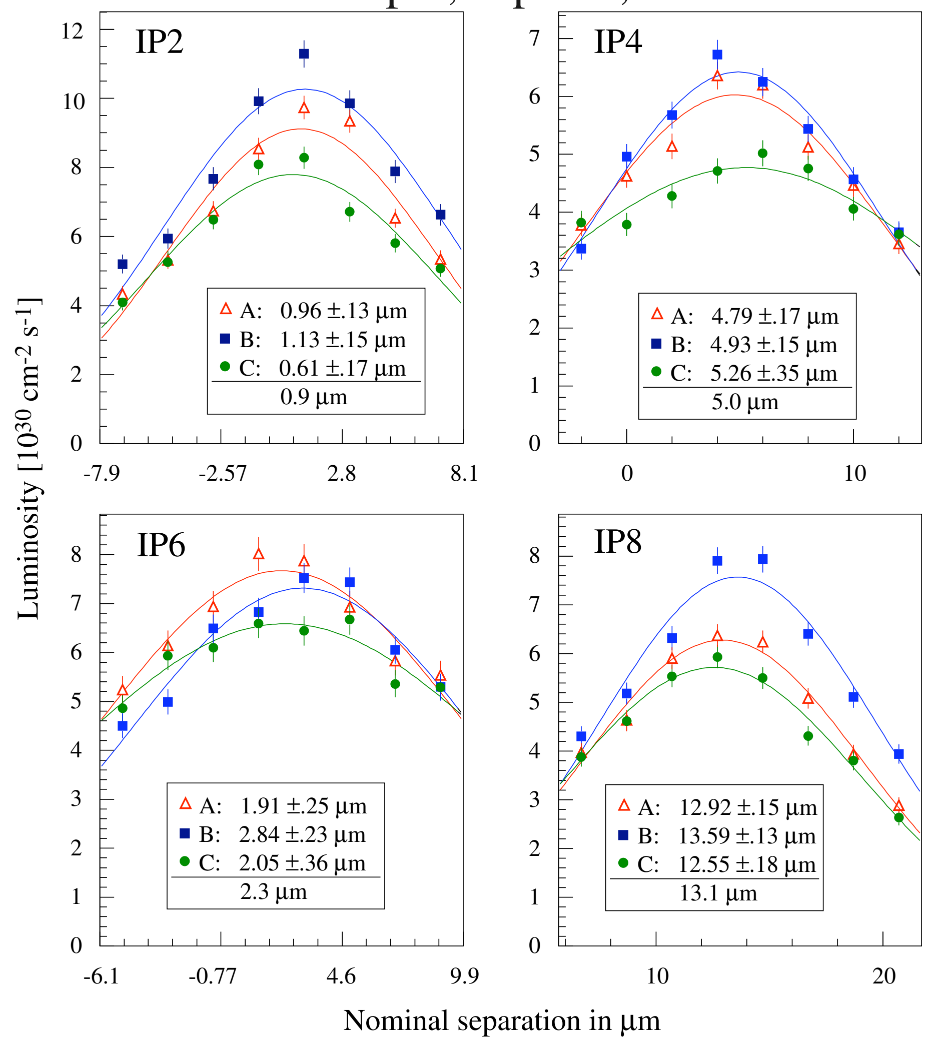
Contributions :

- 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

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

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

was our plan for 2008 - now for summer 2009

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

Parameter evolution and rates - 2009 ...

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

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

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

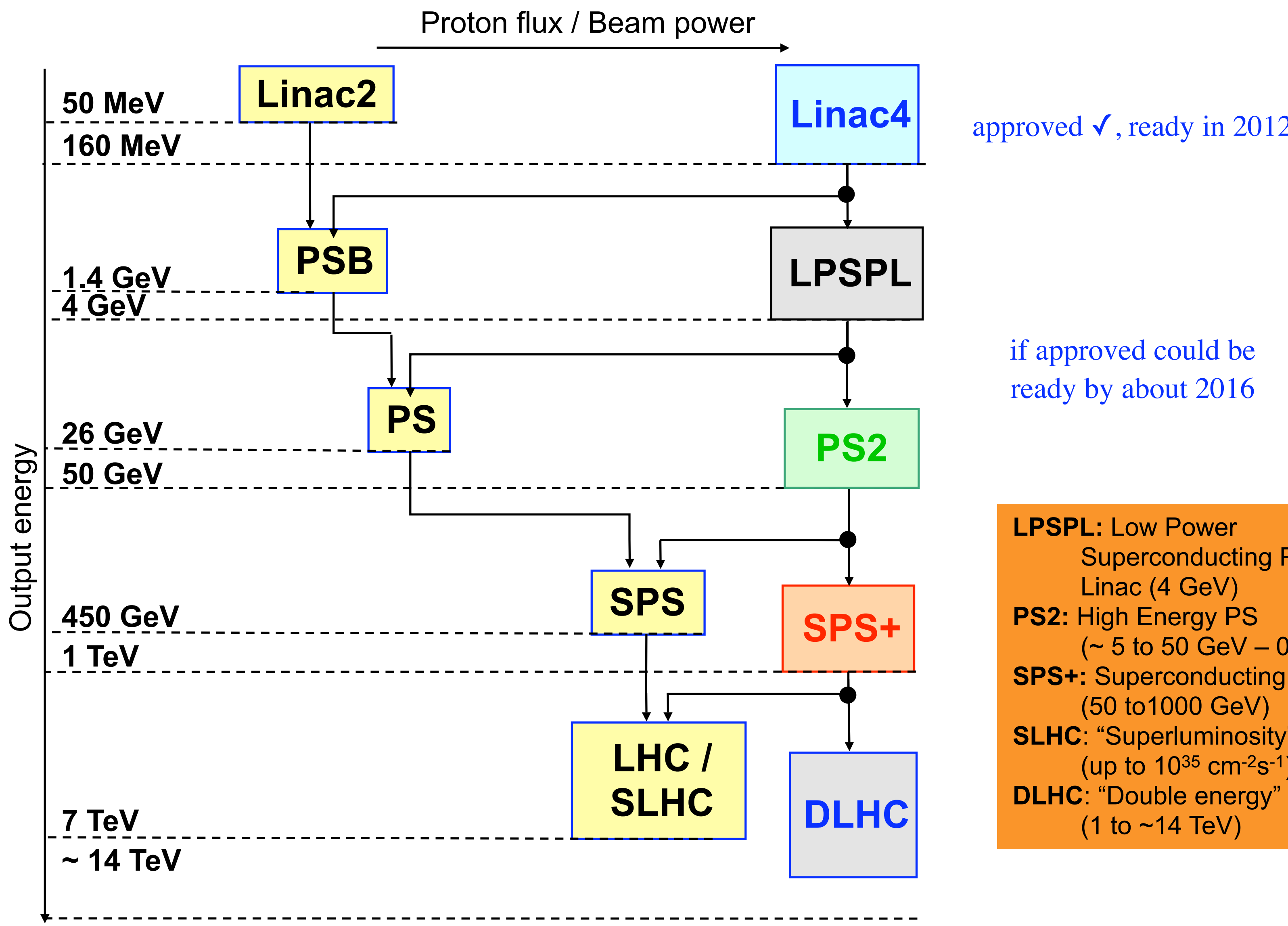
All values for 936 or 2808 bunches colliding in 2 and 8 (not quite right)

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

Outlook into the longer term future

http://cern.ch/SLHC-PP/

Upgrade Options, Injectors + LHC



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)

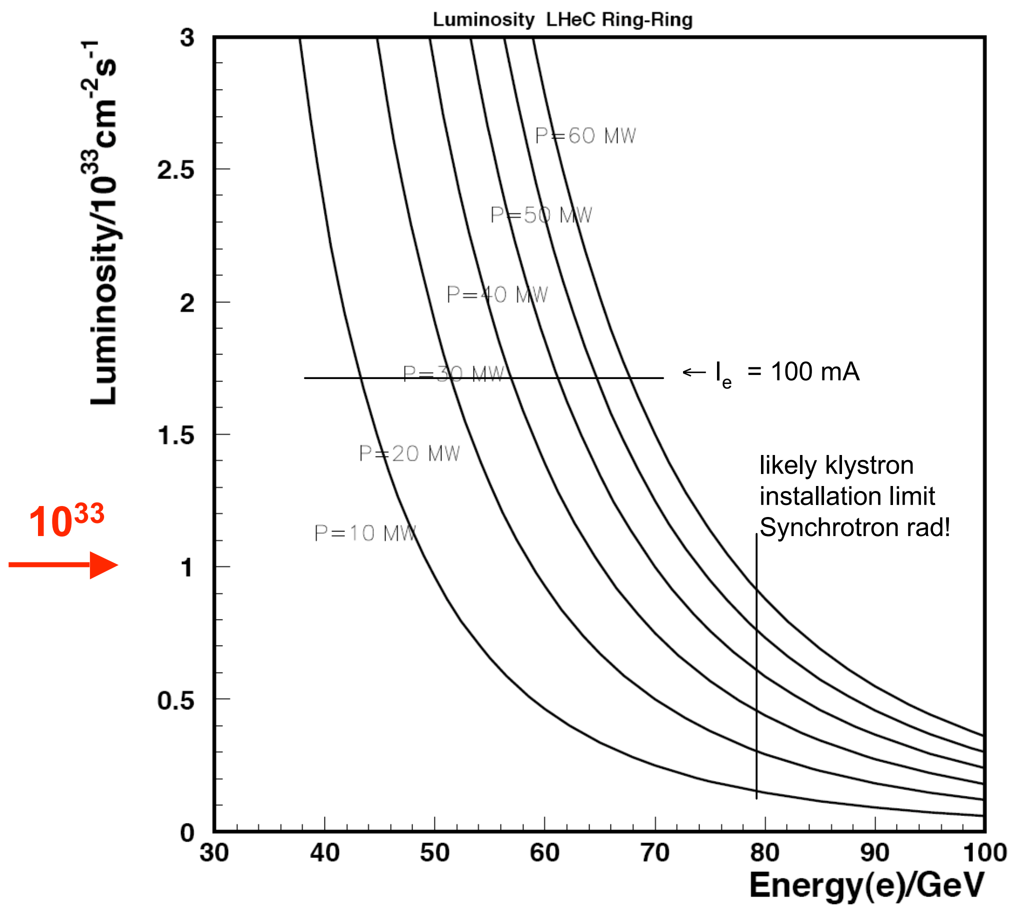
SLHC 1st step : replace current triplet by new larger aperture triplet, by ~ 2013

ep and eIon option LHeC

original idea : built the LHC on top of the existing LEP   with ep option "*for free*"
more recently (HERA stopped)   renewed proposal   J. B. Dainton, M.Klein, P. Newman, E.Perez, and F. Willeke, [hep-ex/0603016](hep-ex/0603016) 11/2006 ; **ECFA presentation** CERN 30.11.2007 **; recommended for approval , CDR in 2 y ;   Workshop in 1-3/9/2008**

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3 10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

$$\sigma_{p(x,y)} = \sigma_{e(x,y)}$$
$$\beta_{px} = 1.8m$$
$$\beta_{py} = 0.5m$$



$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$

10^{33} can be reached in RR
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-4 10^{31} cm^{-2} s^{-1}
huge gain with SLHC p beam

F.Willeke in hep-ex/0603016:
Design of interaction region
for 10^{33} : 50 MW, 70 GeV

May reach 10^{34} with ERL in
bypasses, or/and reduce power.
R&D performed at BNL/eRHIC

Concluding with two citations

- **The LHC is a global project with the world-wide high-energy physics community devoted to its progress and results**
- **As a project, it is much more complex and diversified than the SPS or LEP or any other large accelerator project constructed to date**

International Machine Advisory Committee, chaired by Prof. M. Tigner

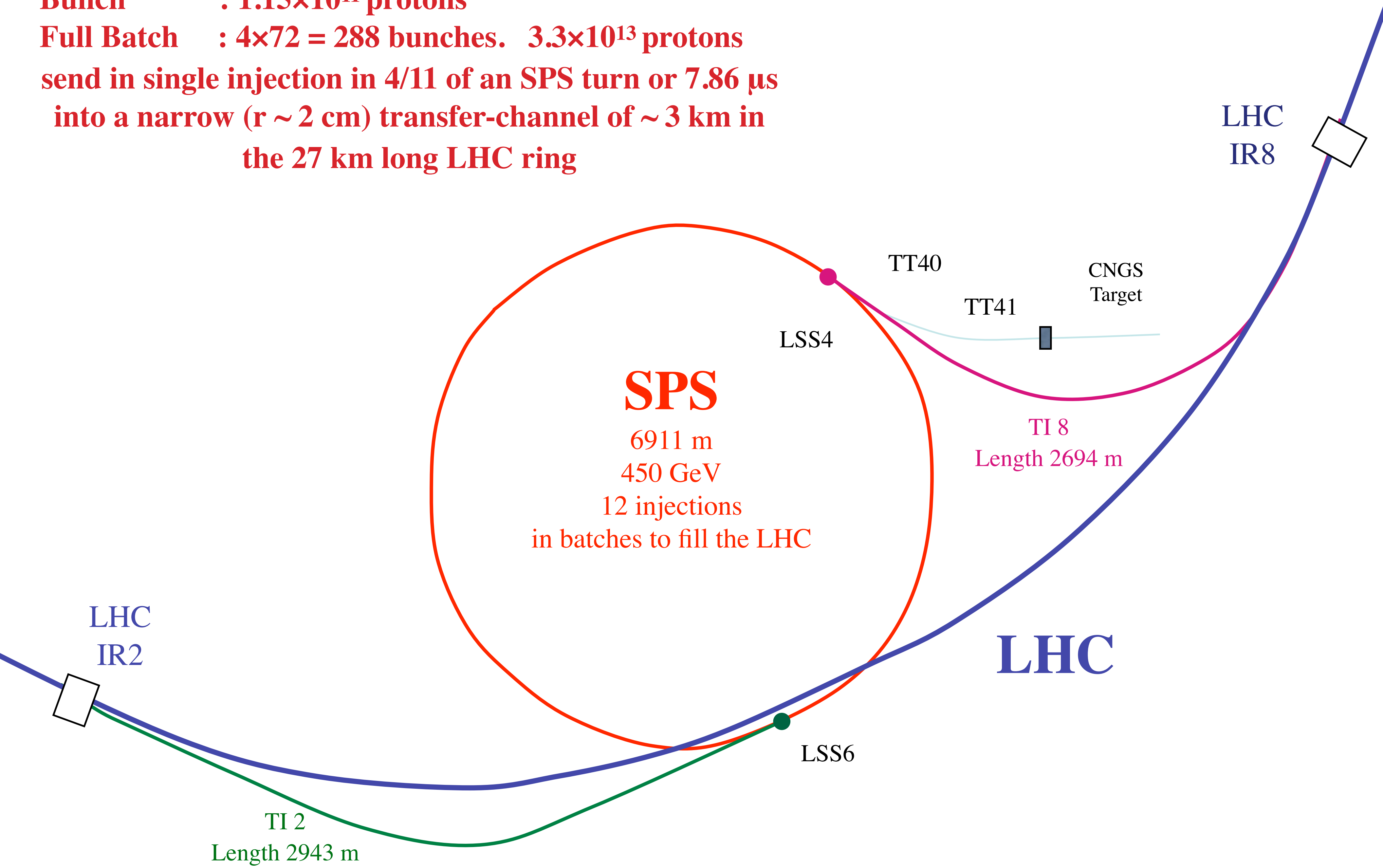
- **No one has any doubt that it will be a great challenge for both machine to reach design luminosity and for the detectors to swallow it.**
- **However, we have a competent and experienced team, and 30 years of accumulated knowledge from previous CERN projects has been put into the LHC design**

L. Evans, LHC Project Leader

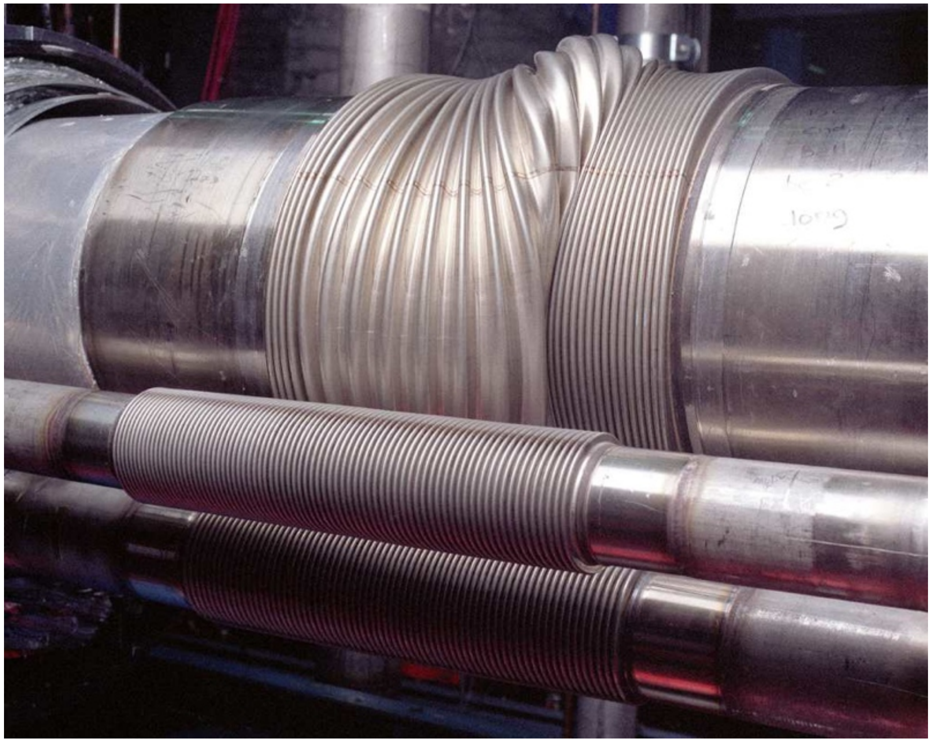
Backup Slides

Transfer and injection: SPS and transfer lines to LHC

Bunch : 1.15×10^{11} protons
Full Batch : $4\times72 = 288$ bunches. 3.3×10^{13} protons
send in single injection in 4/11 of an SPS turn or 7.86 µs into a narrow (r ~ 2 cm) transfer-channel of ~ 3 km in the 27 km long LHC ring



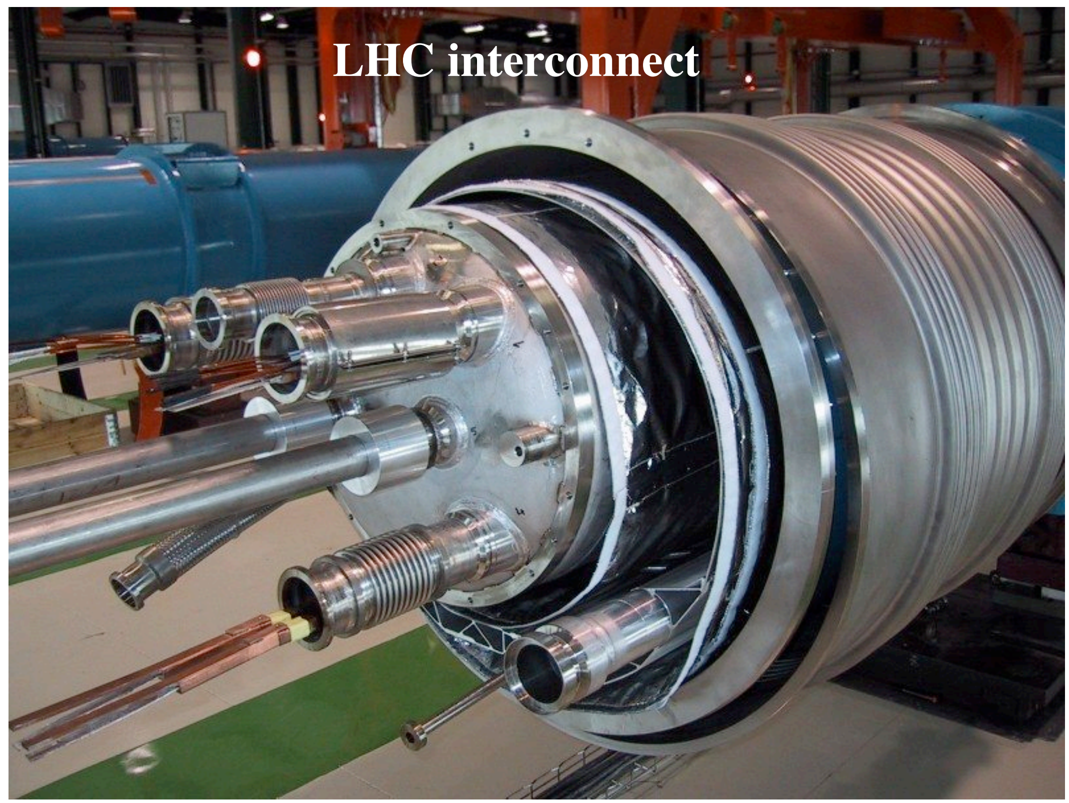
cold magnet interconnects



From *Thomas H. Nicol / Fermilab,*
ASC 2002 short course presentation
"Packaging of Superconducting
Accelerator Magnet Systems"

SSC dipole interconnect (never assume you know all the answers..!)

T. Nicol, FNAL 2002



Abort gap cleaning

Abort gap monitoring and active gap cleaning is foreseen.

Cleaning will be done using the transverse damper, W. Höfle et al., RF-group

i.e. with the device that can act on bunches and damp or in this case excite transverse oscillations to amplitudes where they are removed by the cleaning collimators.

Was tested in the SPS (in 2002 and again this year, reported in LHCMAC 21)

Off energy particles are lost in ramping.

The smaller beam sizes at 7 TeV allow for momentum collimation at ~10^{-3}
the rf acceptance is also reduced to ~ 3.5×10^{-4}
The energy loss in synchrotron radiation $\Delta E_{sync.rad} / E \approx 10^{-3}$ / min and results in natural cleaning on the timescale of 1 min.

details : E. Shaposhnikova et al. Chamonix 2003 and EPAC 2004

Get beams colliding : longitudinal position

The two beams could still miss each other in presence of both a crossing angle and longitudinal offset.

To exclude this, a new electronic card was developed. It uses the BPMs around the IP and existing infrastructure and allows to measure the relative beam arrival times with sub ns resolution.

Rhodri Jones, AB/BI

LHC Optics and Parameters

Optics : currently finalizing V6.503 - compared to since design report from 2003 larger re-optimization (aperture at injection) and hardware as built - collimators as installed

Nominal parameters : <u>weblink</u> no change from design report

Target tunes H/V : injection 64.28 / 59.31 collision 64.31 / 59.32

1.15e11 protons per bunch, 2808 bunches, 0.582 A current / beam

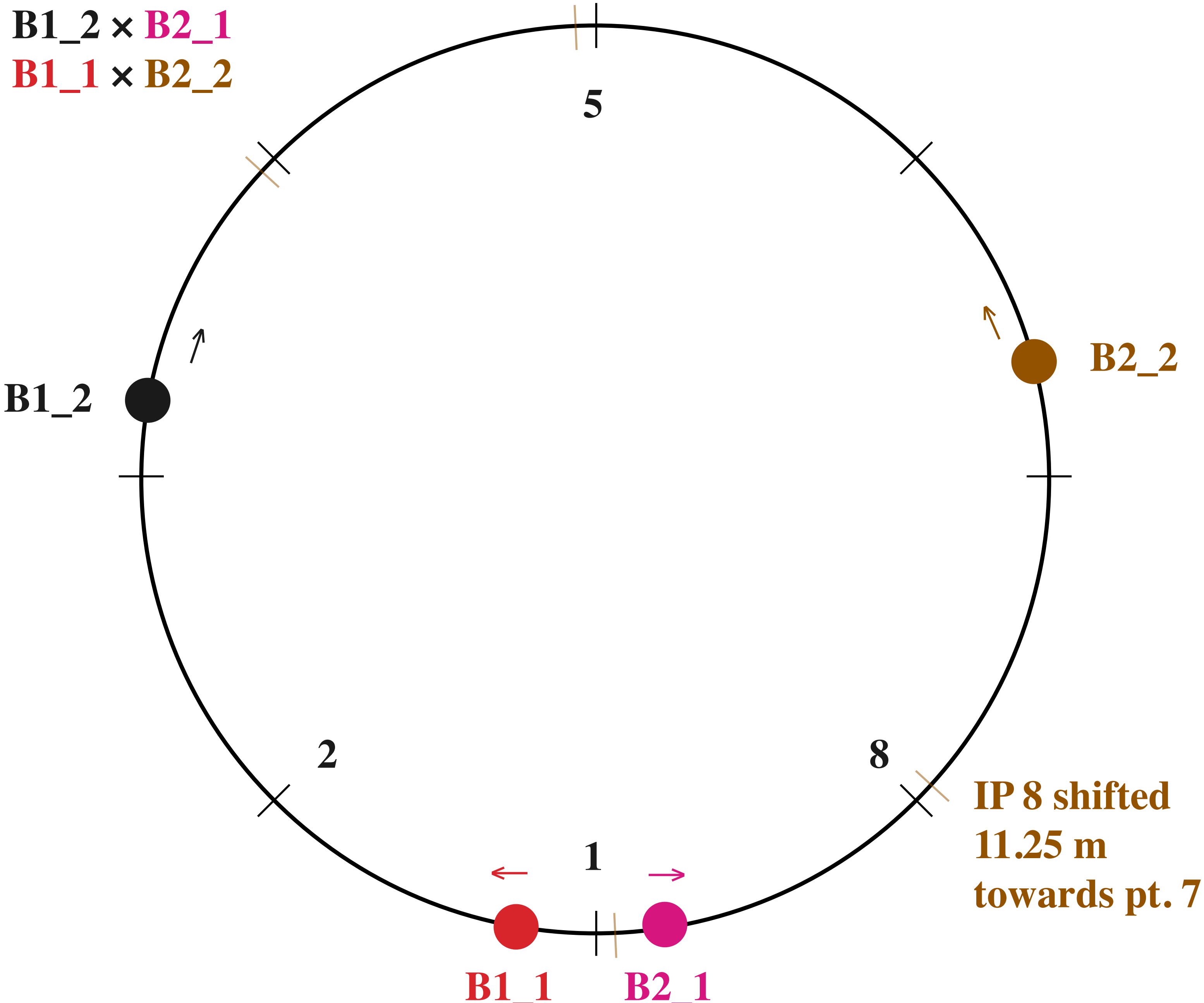
normalized emittance 3.75 um - round beams
β^* = 0.55 m L = 1.0e34 cm^-2s^-1
b.b. tune shift parameter both planes 0.0037

Collision schedule, example with 2 × 2 bunch collisions

IP1 & 5 : B1_1 × B2_1 + B1_2 × B2_2 (offset)

IP2 : B1_2 × B2_1

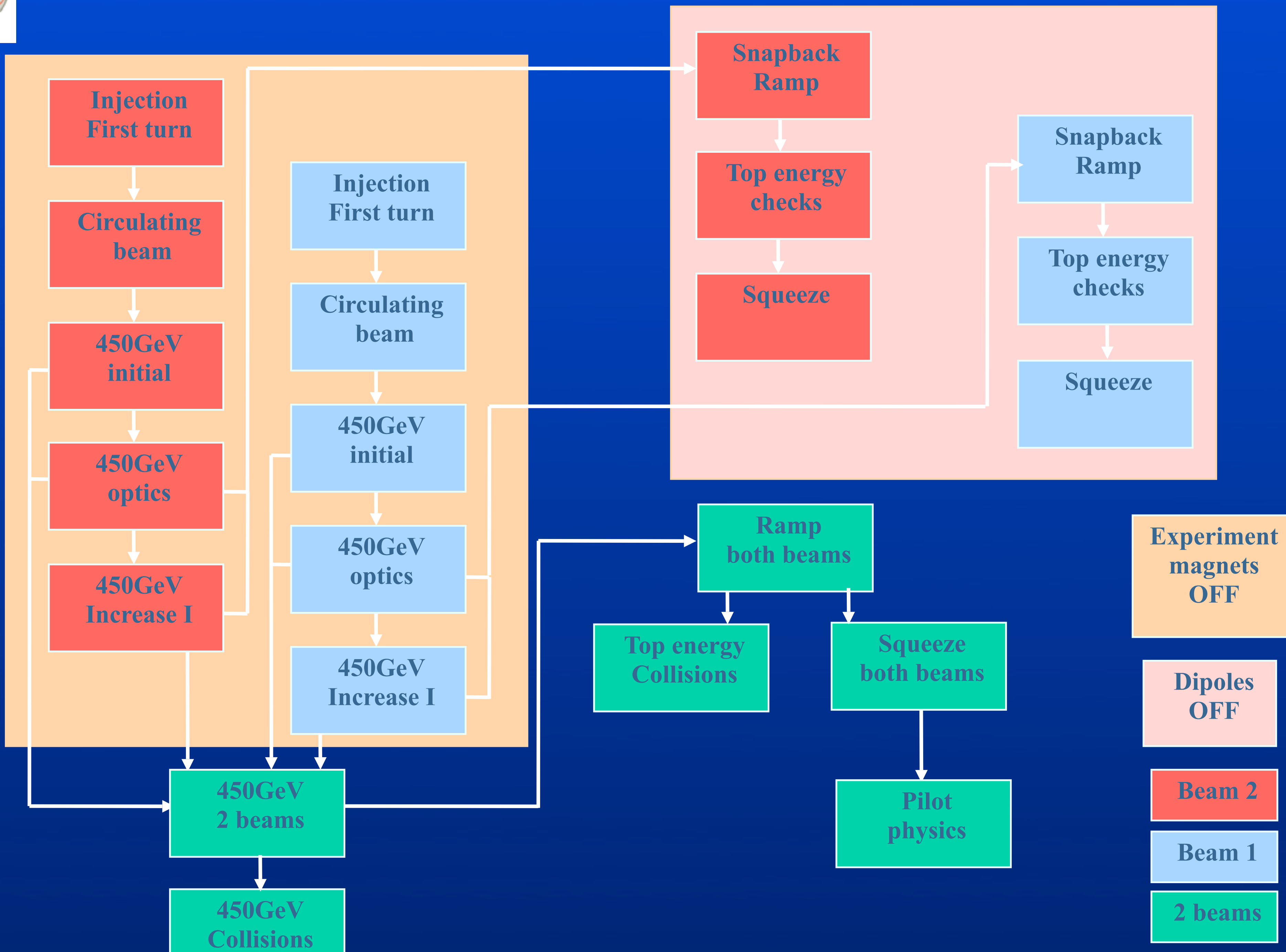
IP8 : B1_1 × B2_2



Cooling a sector

- **From room temp. to 80K precooling with liquid N2. 1200 tons of LN2 (64 trucks of 20 tons). About three weeks.**
- **From 80K to 4.5K. Cooldown with refrigerator. 4700 tons of material to be cooled. About 3 weeks**
- **From 4.5K to 1.9K. Cold compressors at 15 mbar. Four days for the first sector**

Stage A: routes through the commissioning phases



R.Bailey, 2008

Accelerator System or activity	Commissioner
Machine checkout	**G.Arduini**
Transfer lines **LHC injection and protection**	**J.Uythoven**
Threading **First turn** **Closed orbit**	**J.Wenninger**
RF **Capture** **Energy matching**	**G.Arduini**
LBDS and protection	**B.Goddard**
BI systems	**R.Jones**
450GeV machine **Q, Q', coupling** **Beating and dispersion** **Aperture**	**M.Giovannozzi**
Collimation	**R.Assmann**
Machine protection	**R.Schmidt**
Ramp	**M.Lamont**
Top energy machine **Q, Q', coupling** **Beating and dispersion** **Aperture**	**F.Zimmermann**
Collisions **Experimental conditions**	**H.Burkhardt**
Squeeze **Q, Q', coupling** **Beating and dispersion** **Aperture**	**S.Fartoukh**

How to estimate physics time/integrated luminosity

LEP1 statistics		1990	1991	1992	1993	1994	1995
scheduled for physics	h	2504	2762	3439	2943	3175	3070
beam in coast	h	1048	1242	1742	1619	1871	1414
number of coasts		143	154	199	168	197	194
Coasts per day		1.37	1.34	1.39	1.37	1.49	1.52
average coast length	h	7.33	8.06	8.75	9.64	9.50	7.29
efficiency for physics (in coast/scheduled)	%	41.85	44.97	50.65	55.01	58.93	46.06
Peak initial luminosity	1030	11.0	10.0	11.0	15.5	22.4	24.9
Integrated luminosity	nb^{-1}	12100	18900	28600	40000	64500	46100
Overall efficiency factor (integrated/scheduled*peak)		0.12	0.19	0.21	0.24	0.25	0.17

- Expect to spend as much time out of physics as in
  - Rampdown, injection, ramp, squeeze, prepare
  - Faults, access, other problems
  - If we average a 10h fill per day in 2009 we'll be doing well (40% efficiency for physics)
- Overall efficiency factor
  - Measure of how much physics we get from scheduled time with a given peak luminosity
  - Includes all the time not in physics (as above) AND luminosity decay in coast
  - If we get this up to 0.2 in 2009 we'll be doing well

Applying this to 2008 and 2009

Month	Phase	Days physics	Efficiency factor	Peak luminosity	Delivered luminosity
Jan	Cooldown and Hardware Commissioning and Machine checkout				
Feb					
Mar					
Apr					
May					
June					
Jul					
Aug	Beam Commissioning				
Sep					
Oct	Physics run				
Nov		40	0.1	$5\ 10^{31}$	$20\ pb^{-1}$
Dec	Shutdown				
Jan					
Feb					
Mar	Machine checkout				
Apr	75ns Commissioning				
May	Physics run	150	0.2	1033	$2.5\ fb^{-1}$
June					
Jul					
Aug					
Sep					
Oct					
Nov					
Dec					

Aims for 2008

- Commission machine to 5TeV
  - Multiple bunches circulating in each ring (43)
  - Moderate intensities (few $10^{10)}$
  - Single beam lifetimes ~ 30h
  - Injection optics (β*= 11 m in IR 1 & 5, β*= 10 m in IR 2 & 8)
  - No squeeze
  - No crossing angle
  - Collisions
- Secondary aims
  - Commission squeeze in 1 and 5 to 3m
  - Commission squeeze in 8 to 6m
  - Push intensities (156 bunches, high 10^{10})
- Tertiary aims
  - Commission crossing angle
  - Commission 75ns beams

Realistically (1 and 5)

50 days of physics
Peak luminosity a few 10^{31} cm^{-2} s^{-1}
Integrated luminosity ~ 10th of pb^{-1}

Aims for 2009

- Commission high energy operation
  - Aim for 7TeV (magnets will decide)
  - 43 /156 bunch running to start (brief)
  - 75ns running
  - 25ns running
  - High 10^{32} cm^{-2} s^{-1} is in reach

- 150 days for proton physics
- Efficiency for physics 40%
- Overall efficiency factor 0.2

- Ion run ?

Realistically (1 and 5)

140 days of physics
Peak luminosity 10^{33} cm^{-2} s^{-1}
Integrated luminosity ~ fb^{-1}

LHC nominal and *ultimate* parameters

Parameters	nominal	'Ultimate'	
# bunches	2808	2808	
N / bunch	$1.15 * 10^{11}$	$1.7*10^{11}$	beam-beam
β^*	0.55m	0.5m	impedance
ε_n	3.75 μm	3.75 μm	
σ^*	16.6 μm	15.9 μm	
σ_L	7.55 cm	7.55 cm	
full crossing angle	285μrad	> 315μrad	triplet aperture
events / crossing	19.2	44.2	detector efficiency?
peak luminosity	$1.0*10^{34}cm^{-2}sec^{-1}$	$2.4*10^{34}cm^{-2}sec^{-1}$	
L lifetime	15h	10h	1 physics run per day
E[TeV]	7	7 -> 7.45	
E[MJ]	366	541	quench & damage risk

from Oliver Brüning HEPP-EPS conf. 2007

Nominal, *ultimate* and upgrade parameters considered

parameter	nominal	ultimate	ES (25ns)	LPA (50ns)
Protons per bunch	1.15×10^{11}	1.7×10^{11}	1.7×10^{11}	$4.9\ 10^{11}$
Total beam current	0.58 A	0.86 A	0.86 A	1.22 A
Longitudinal bunch profile	Gauss	Gauss	Gauss	Flat
β^* at the IPs	0.55m	0.5m	8 cm (➔14 cm)	25 cm
Full crossing angle at the IPs	285 μrad	315 μrad	0 μrad	381 μrad
Peak luminosity [$cm^{-2}\ sec^{-1}$]	1×10^{34}	2.3×10^{34}	15.5×10^{34}	10.7×10^{34}
Peak events per crossing	19	44	294	403
Initial luminosity lifetime	25h	14h	2.2h (w.o. leveling)	4.5h (w.o. leveling)
Stored beam energy	370MJ	550MJ	550MJ	780MJ
Additional requirements	-	-	Large aperture triplet magnets	Large aperture triplet magnets
			Efficient absorbers / radiation hard	Efficient absorbers / radiation hard
			(wire compensators)	(wire compensators)
			D0	
			Crab cavities	
			luminosity levelling	flat beam operation
			Cryoplant upgrade	Cryoplant upgrade

ES : early separation LPA : large Piwinski angle

from Oliver Brüning, RD50 meeting at CERN; November 2007 ; mostly based on LUMI'06

Scenarios studied for L = 10^{35} cm^{-2} sec^{-1} peak

parameter	symbol	ultimate	25 ns, small β*	50 ns, long
protons per bunch	N_b [10^{11}]	1.7	1.7	4.9
bunch spacing	Δt [ns]	25	25	50
beam current	I [A]	0.86	0.86	1.22
longitudinal profile		Gauss	Gauss	Flat
rms bunch length	σ_z [cm]	7.55	7.55	11.8
beta* at IP1&5	β* [m]	0.5	0.08	0.25
full crossing angle	θ_c [μrad]	315	0	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.75	0	2.0
Luminosity reduction		0.8	0.86	0.45
peak luminosity	L [10^{34} $cm^{-2}s^{-1}$]	2.3	15.5	10.7
peak events per crossing		44	294	403
initial lumi lifetime	τ_L [h]	14	2.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} $cm^{-2}s^{-1}$]	0.91	2.4	2.5
	$T_{run,opt}$ [h]	17.0	6.6	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} $cm^{-2}s^{-1}$]	1.15	3.6	3.5
	$T_{run,opt}$ [h]	12.0	4.6 / 2.6	6.7 / 2.9
extent luminous region	σ_l [cm]	4.3	3.7	5.3
comment			D0 + crab (+ Q0)	wire comp.

from Oliver Brüning HEPP-EPS conf. 2007 based und Lumi'06

Layout of the new injectors