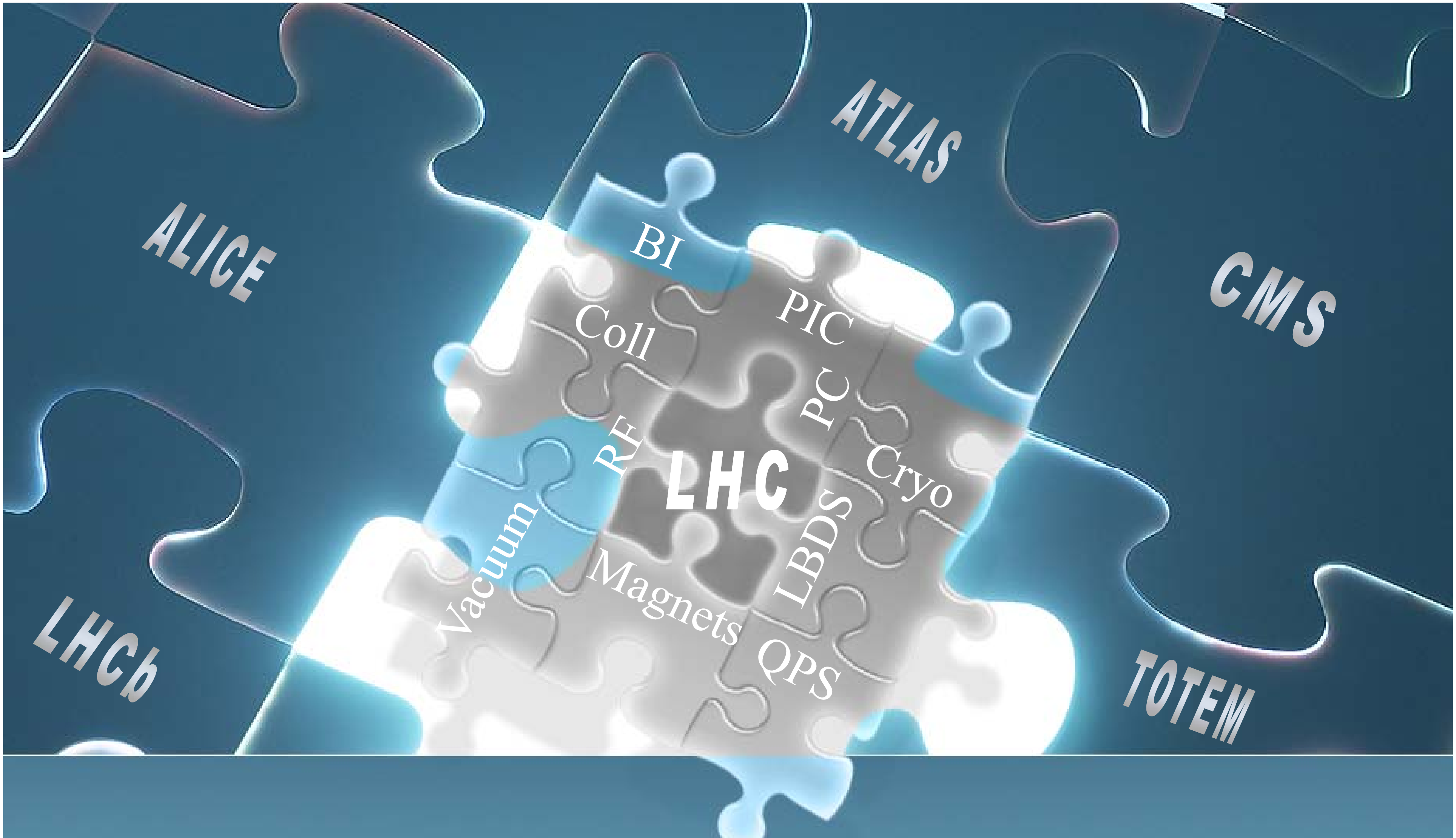

LHC Status & Commissioning

R. Alemany (CERN AB/OP)

UCLs Seminar 21.05.2008

Content

1. Accelerator complex
2. Energy Stored in the Magnets
   - Quench Protection System
   - Power Interlock System
   - Energy Extraction
3. Energy Stored in the Beams
   - Beam Dump System
   - Collimation System
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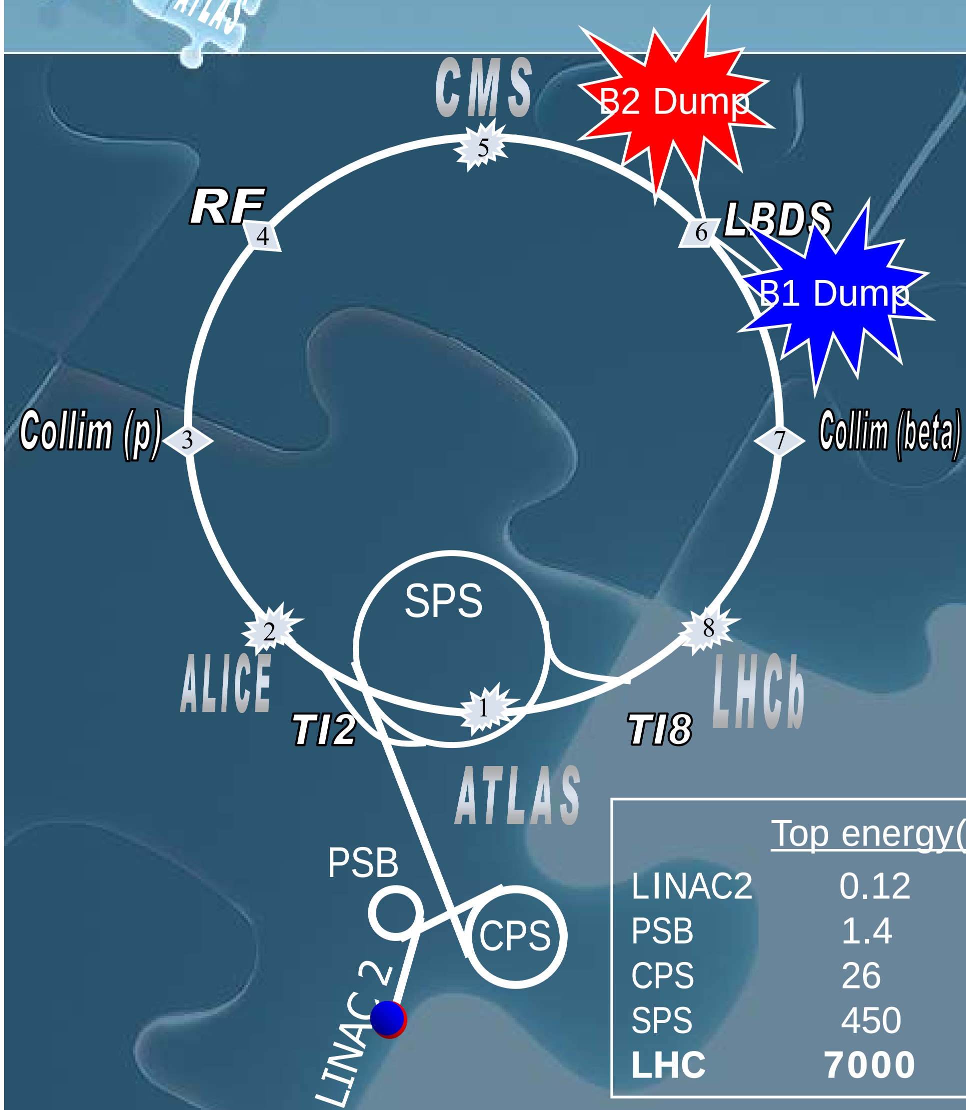
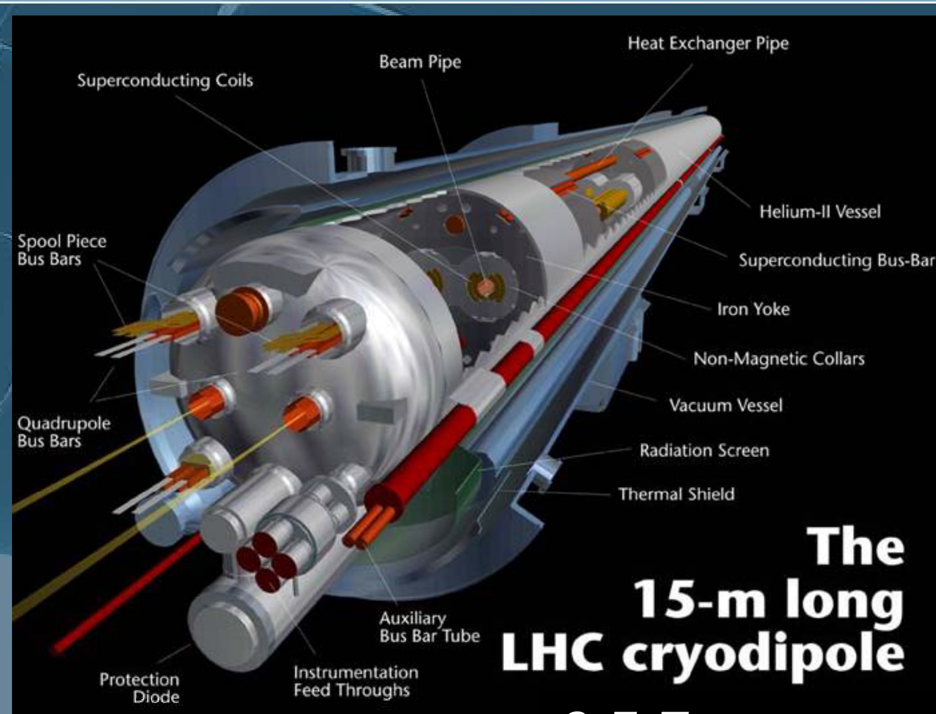
Accelerator complex for p



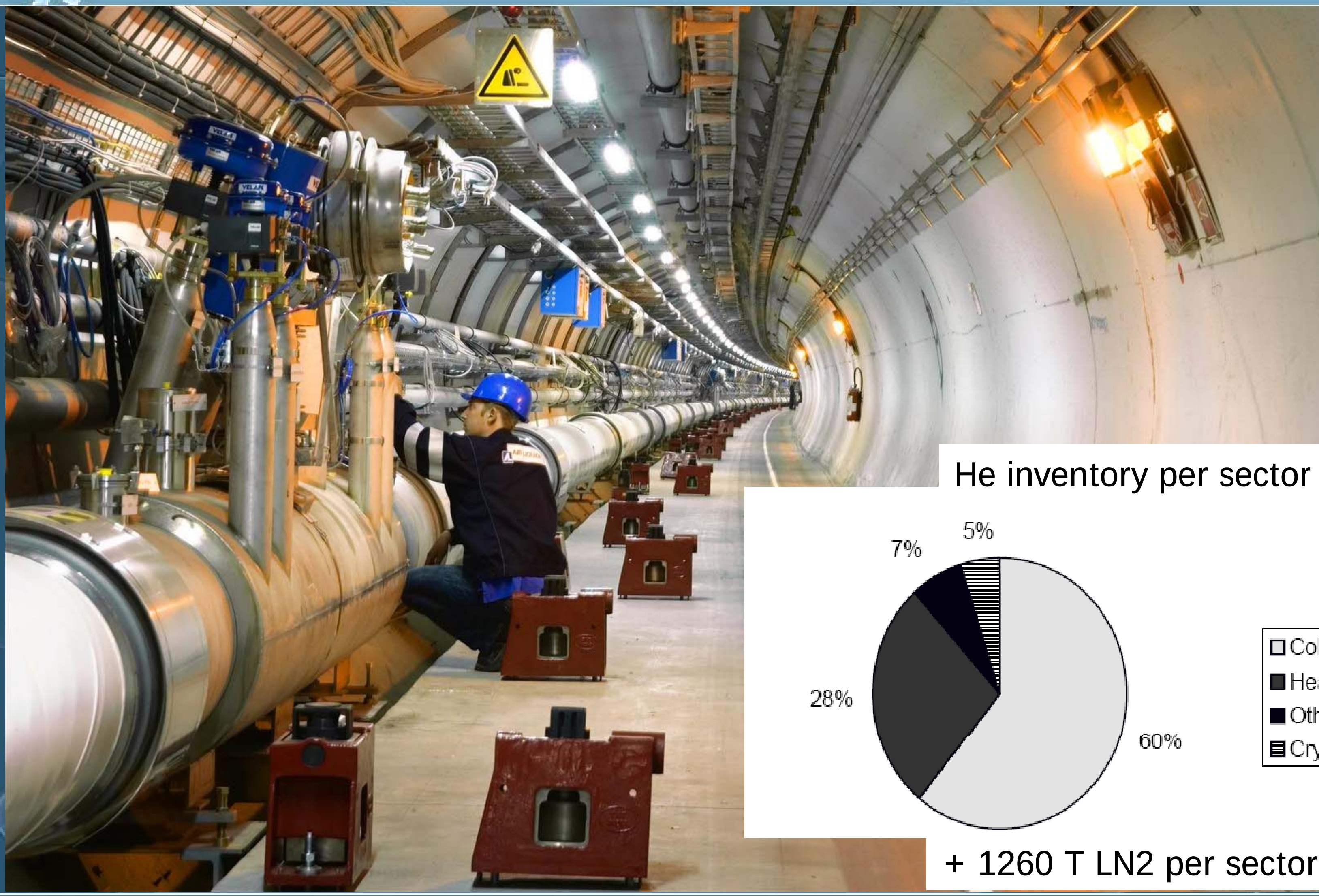


8.7 T
11.8 kA / 7 MJ
1.9 K

1232 cryodip.

	Top energy(GeV)	Circumference(m)
LINAC2	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6911 = 11 x PS
LHC	**7000**	**26657 = 27/7xSPS**

QRL (Cryogenic Line Installation)

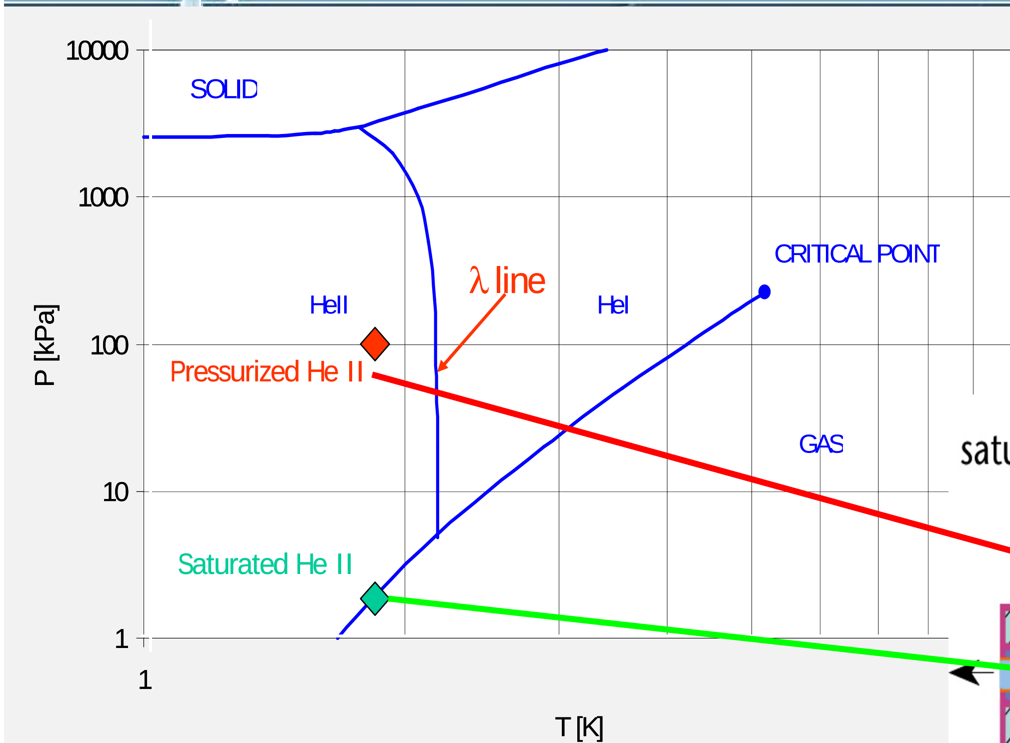


He inventory per sector

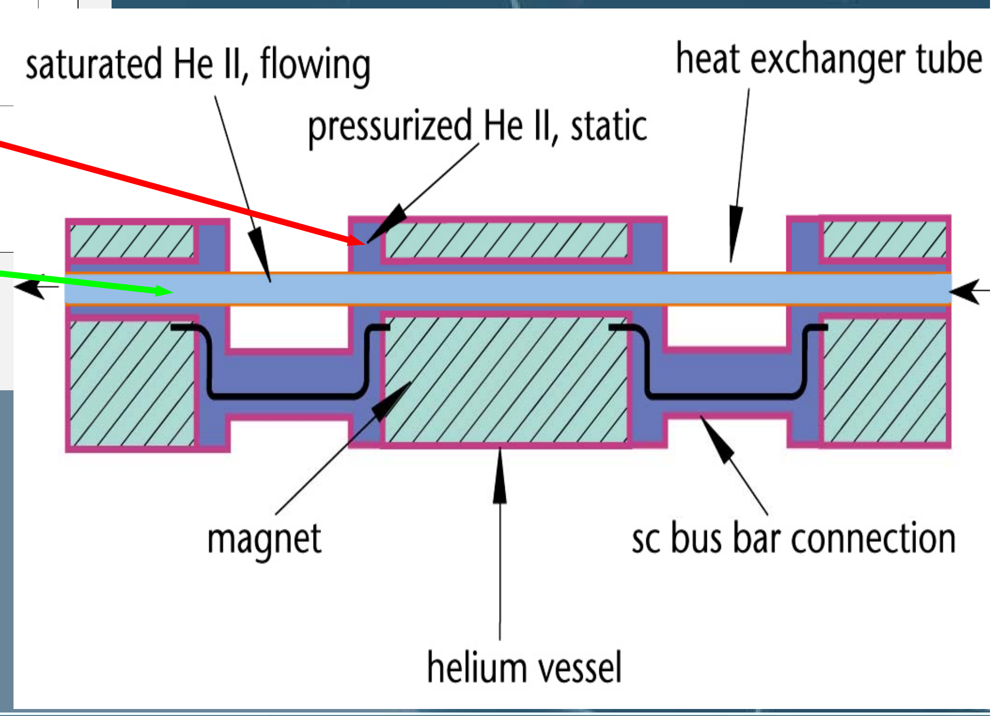
LHC TDR

+ 1260 T LN2 per sector

LHC Cryogenics



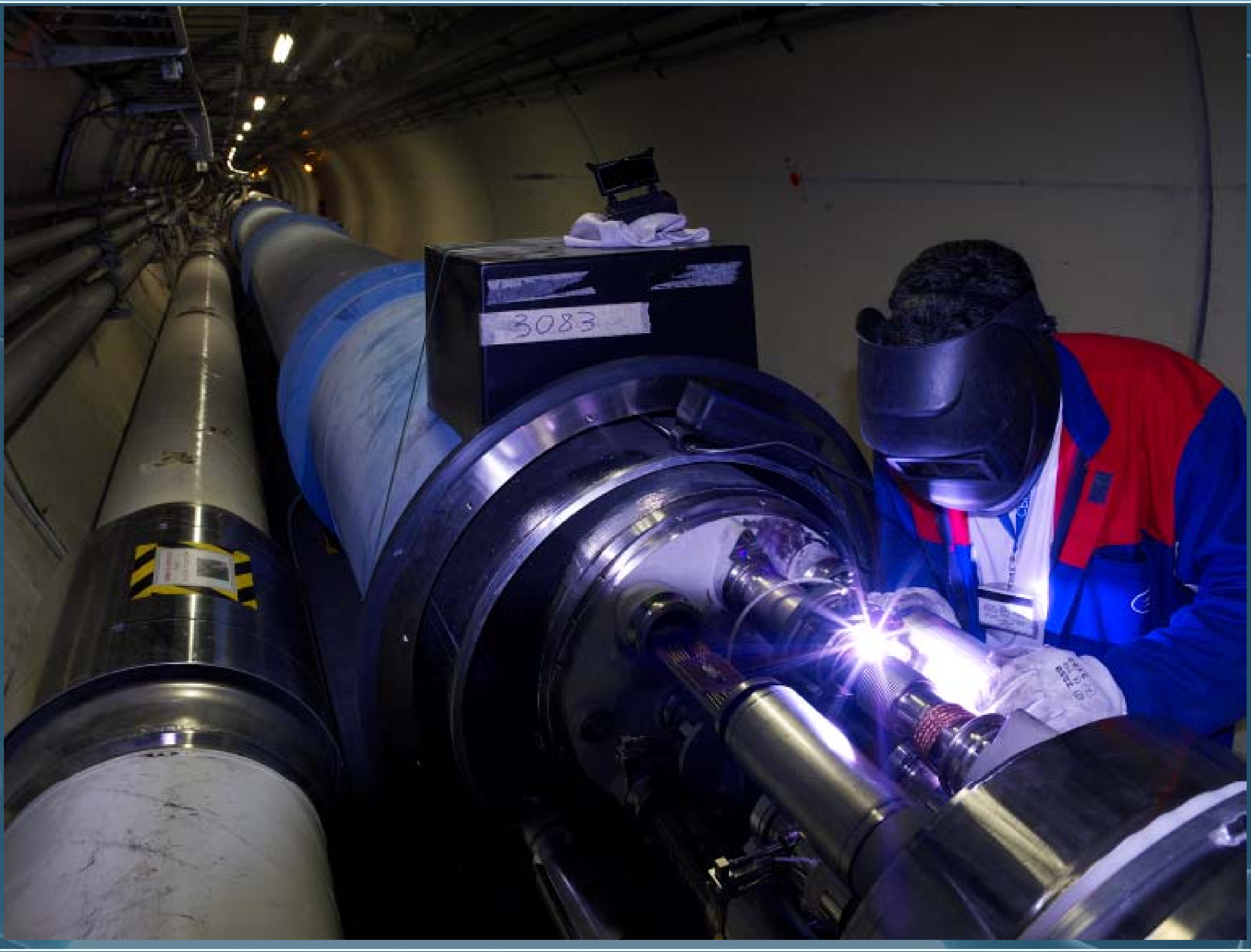
- **From RT to 80K**: Precooling with LN2 1200 tons of LN2 (64 trucks of 20 tons) ➔ [Three weeks]
- **From 80K to 4.5K**: Cooldown with He turbines 4700 tons of material to be cooled ➔ [Two weeks]



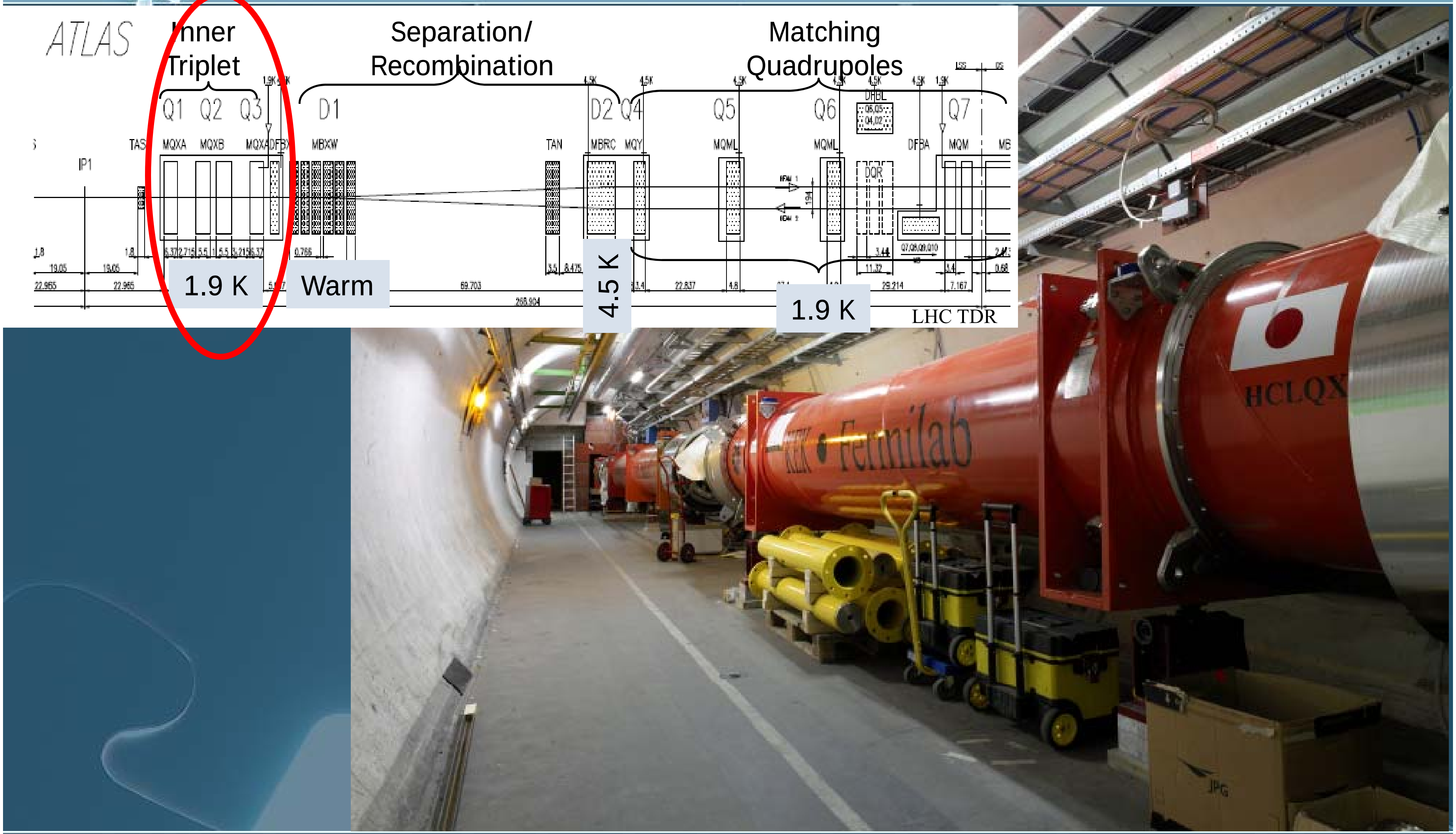
- **From 4.5K to 1.9K**: Cold compressors (15 mbar) More than 15 tons of helium inventory [One week]
- **Tuning before powering**: Instrumentation, Electrical feed-boxes (DFB's), global process [One week]

LHC Dipoles Installation

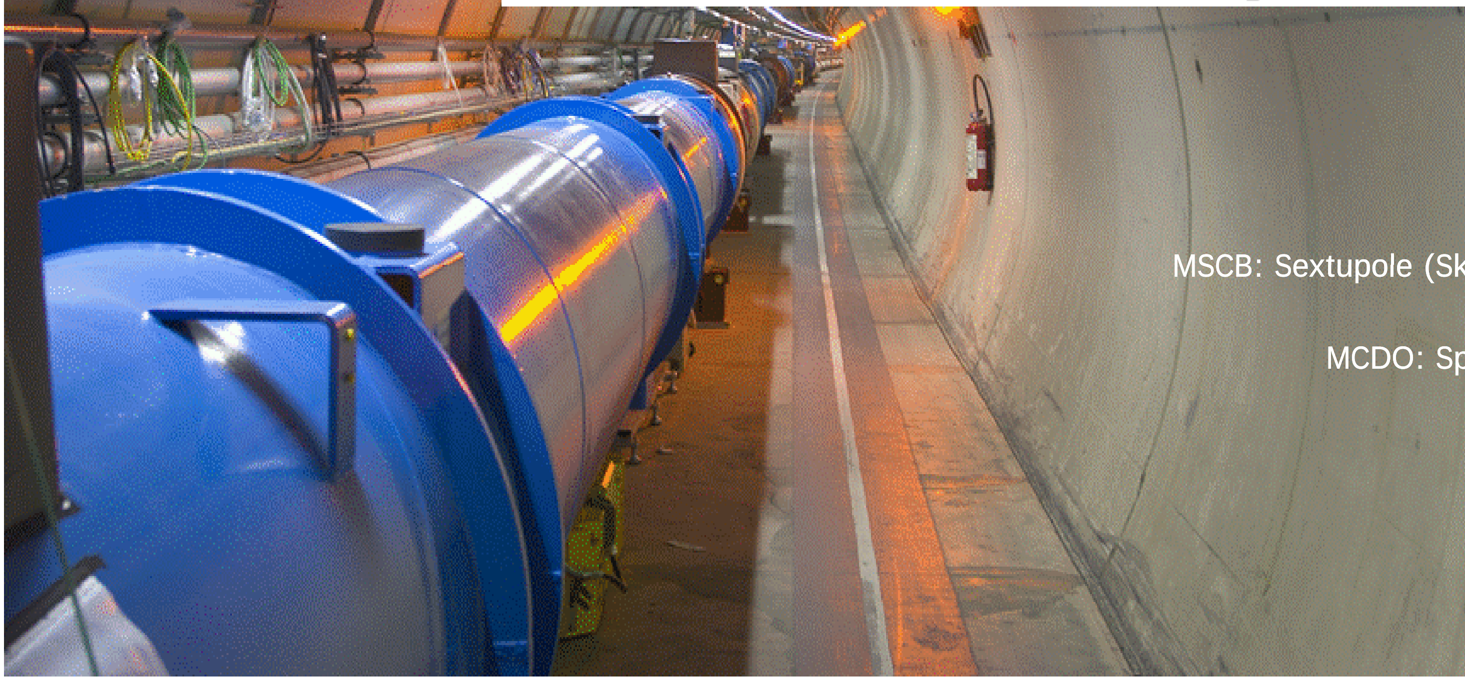
Interconnection

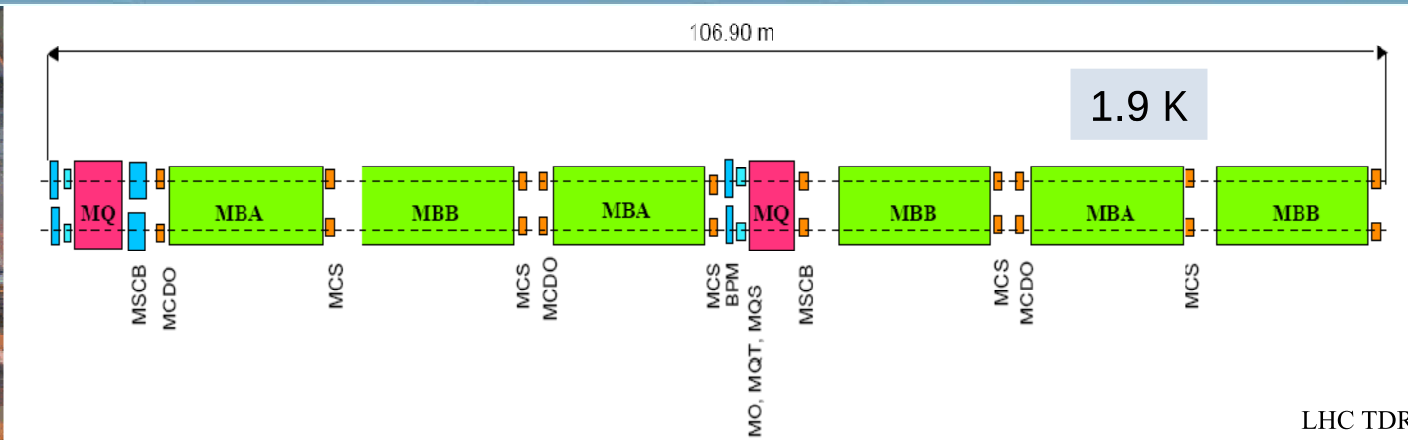


Inner Triplet



LHC Arc





LHC TDR

MBB: Main Dipole
MQ: Main Quadrupole
MQT: Trim Quadrupole
MQS: Skew Trim Quadrupole
MO: Lattice Octupole
MSCB: Sextupole (Skew Sextupole)+Orbit Corrector
MCS: Spool Piece Sextupole
MCDO: Spool Piece Octupole + Decapole
(BPM: Beam Position Monitor)

LHC Magnet Inventory

Magnet Type	Order	Description	Number of Magnets
MB	1	Main Dipole Coldmass	1232
MBAW	1	Alice Spectrometer (Muon Dipole)	1
MBLW	1	LHC-b Spectrometer	1
MBRB	1	Twin Aperture Separation Dipole (194 mm) D4	2
MBRC	1	Twin Aperture Separation Dipole (188 mm) D2	8
MBRS	1	Single Aperture Separation Dipole D3	4
MBW	1	Twin Aperture Warm Dipole Module D3 and D4 in IR3 and IR7	20
MBWMD	1	Single Aperture Warm Dipole Module Compensating Alice Spectrometer	1
MBX	1	Single Aperture Separation Dipole D1	4
MBXW	1	Single Aperture Warm Dipole Module D1 in IR1 and IR5	24
MBXWH	1	Single Aperture Warm Horizontal Dipole Module Compensating LHC-b Spectrometer	1
MBXWS	1	Single Aperture Warm Horizontal Dipole Short Module	2
MBXWT	1	Single aperture warm compensator for ALICE	2
MCBCH	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBCV	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBH	1	Arc Orbit Corrector in MSCBA(B,C,D), Horizontal	376
MCBV	1	Arc Orbit Corrector in MSCBA(B,C,D), Vertical	376
MCBWH	1	Single Aperture Warm Orbit Horizontal Corrector	8
MCBWV	1	Single Aperture Warm Orbit Verticall Corrector	8
MCBXH	1	Horizontal Orbit Corrector in MCBX(A)	24
MCBXV	1	Vertical Orbit Corrector in MCBX(A)	24
MCBYH	1	Orbit Corrector in MCBYA(B)	44
MCBYV	1	Orbit Corrector in MCBYA(B)	44
MCD	5	Decapole Corrector in MCDO, (Spool Piece Corrector)	1232
MCO	4	Octupole Corrector in MCDO, (Spool Piece Corrector)	1232
MCOSX	3	Skew Octupole Spool-Piece Associated to MQSX in MQSXA	8
MCOX	4	Octupole Spool-Piece Associated to MQSXA	8
MCS	3	Sextupole Corrector, (Spool Piece Corrector)	2464
MCSSX	3	Skew Sextupole Spool-Piece Associated to MQSX in MQSXA	8
MCSX	3	Sextupole Spool-Piece Associated to MCBXA	8
MCTX	6	Dodecapole Spool-Piece Associated to MCBXA	8
MKA	1	Tune kicker	2
MKD	1	Ejection dump kicker	30
MKI	1	Injection kicker	8
MKQ	1	Kicker For Q And Aperture Measurement	2

Magnet Type	Order	Description	Number of Magnets
MO	4	Octupole Lattice Corrector in Arc Short Straight Section	336
MQ	2	Lattice Quadrupole in the Arc	392
MQM	2	Insertion Region Quadrupole 3.4 m	38
MQMC	2	Insertion Region Quadrupole 2.4m	12
MQML	2	Insertion Region Quadrupole 4.8 m	36
MQS	2	Skew Quadrupole Lattice Corrector in Arc Short Straight Section	64
MQSX	2	Skew Quadrupole Q3	8
MQT	2	Tuning Quadrupole Corrector in Arc Short Straight Section	320
MQTLH	2	(MQTL Half Shell Type)	48
MQTLI	2	(MQTL Inertia Tube Type)	72
MQWA	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Asymmetrical FD or DF	40
MQWB	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Symmetrical FF or DD	8
MQXA	2	Single Aperture Triplet Quadrupole (Q1, Q3)	16
MQXB	2	Single Aperture Triplet Quadrupole (Q2)	16
MQY	2	Insertion Region Wide Aperture Quadrupole 3.4 m.	24
MS	3	Arc Sextupole Lattice Corrector Associated to MCBH or MCBV in MSCBA, MSCBB, MSCBC and MSCBD	688
MSDA	1	Ejection dump septum, Module A	10
MSDB	1	Ejection dump septum, Module B	10
MSDC	1	Ejection dump septum, Module C	10
MSIA	1	Injection septum, Module A	4
MSIB	1	Injection septum, Module B	6
MSS	2	Arc skew Sextupole Corrector Associated to MCBH in MSCBC and MSCBD	64

~ 9000 magnets powered with ~1700 power converters

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Energy Stored in the Magnets

~ 11 GJoule (only in the main dipoles*) corresponds to ...

... an aircraft carrier at battle-speed of 55 km/h

the energy of ~3 Tons TNT
the energy of 370 kg dark chocolate

More important than the amount of energy is ...

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

* 400 MJ in the main quadrupoles

Energy Stored in the Magnets

Energy Stored in the Magnets:
Quench & Quench Protection System

- **A Quench is the phase transition of a super-conducting to a normal conducting state**
- **Quenches are initiated by an energy release of the order of mJ:**
  - **Movement of the superconductor by several μm (friction and heat dissipation)**
  - **Beam losses:**
    - **@7 TeV 0.6 J/cm³ can quench a dipole; this energy density can be generated by 10^7 protons**
    - **@450 GeV (injection energy), 10^9 protons are needed**
  - **Failure in cooling**

Energy Stored in the Magnets:
Quench & Quench Protection System

Quench Protection System

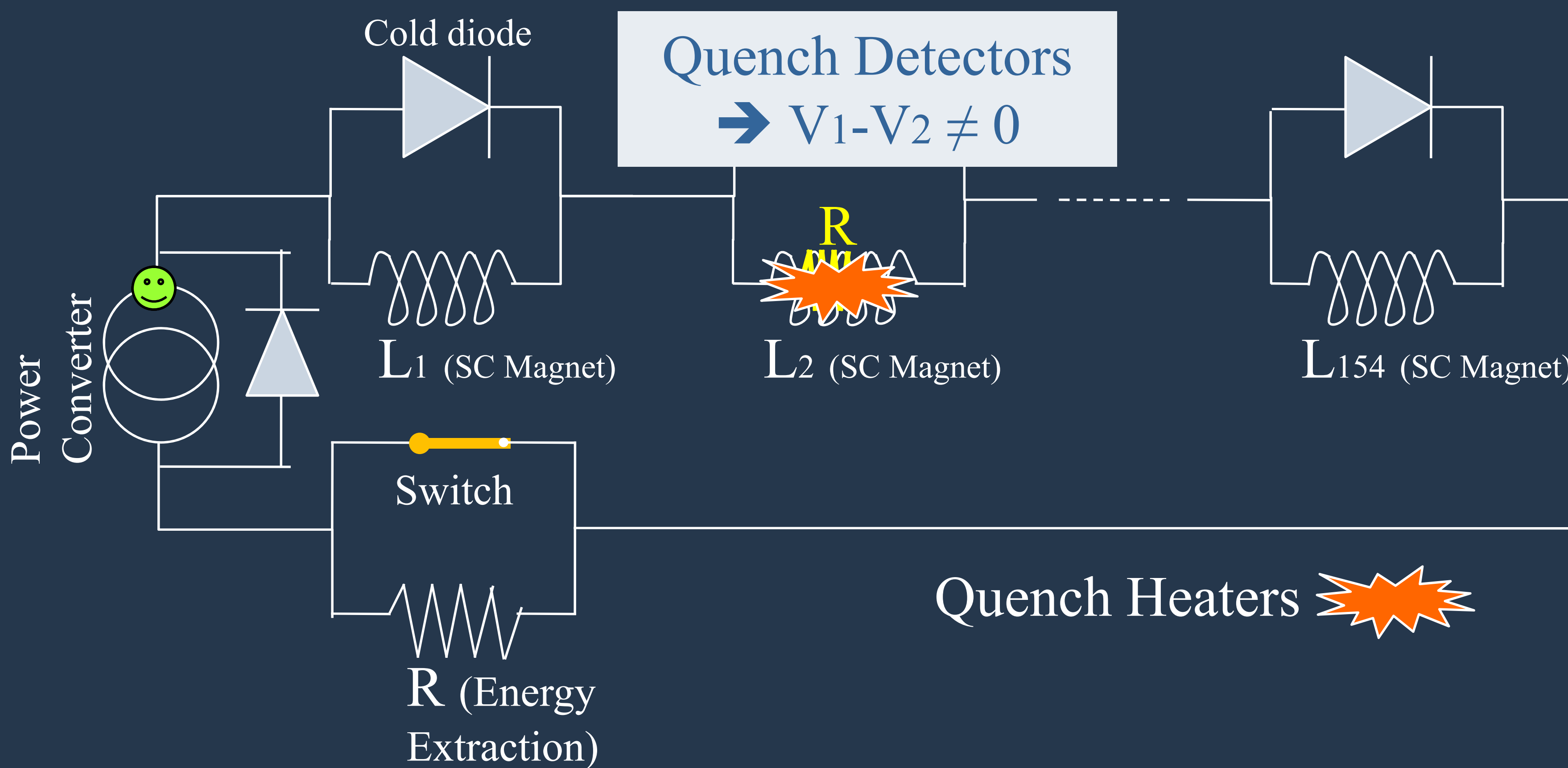
- To limit the temperature increase after a quench
  - The quench has to be detected ➔ Quench Detectors*
  - The energy is distributed in the magnet by force-quenching the coils using Quench Heaters*
  - The stored energy is released in a controlled way ➔ Cold by-pass diodes* & Energy Extraction System
  - The magnet current is switched off within << 1 second ➔ Power Interlock System

- Failure in QPS:
  - False quench detection: down time of some hours
  - Missed quench: damage of magnet, down time 30 days

* On every SC magnet

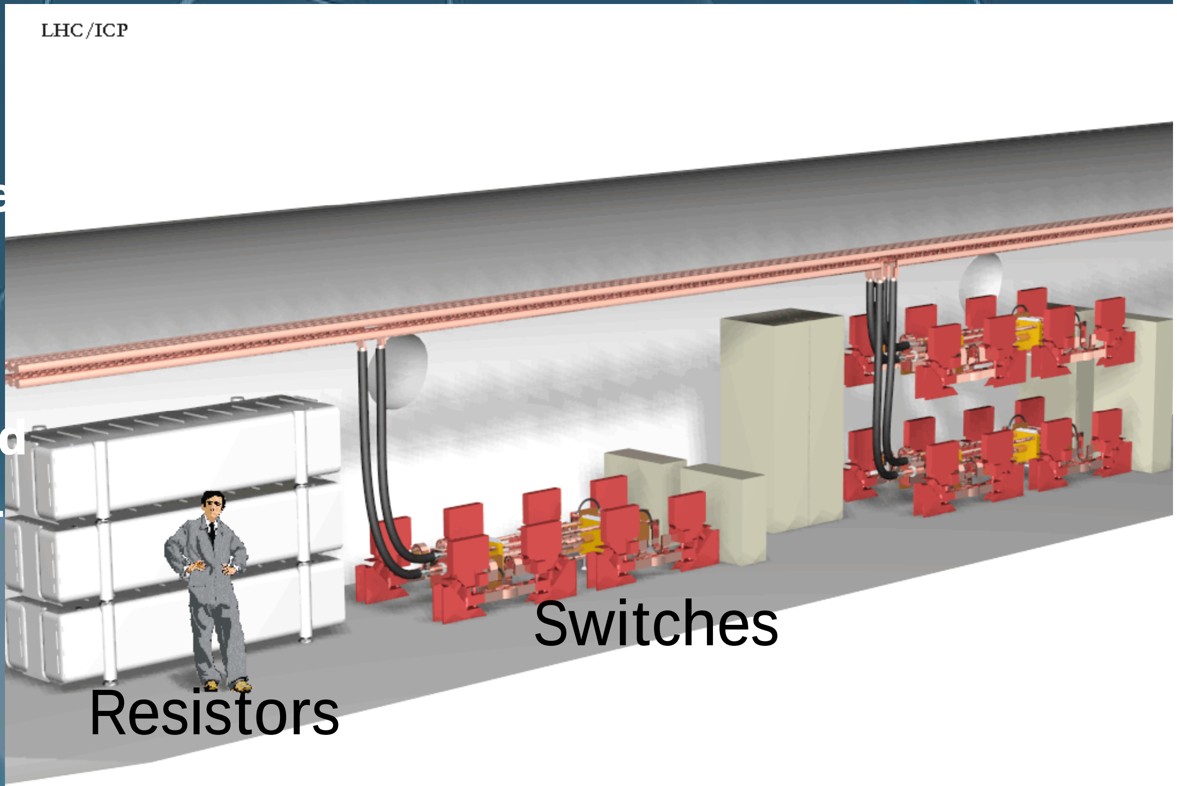
Energy Stored in the Magnets:
Quench & Quench Protection System

LHC Main Dipole System in one sector



Magnet Energy: Energy Extraction System

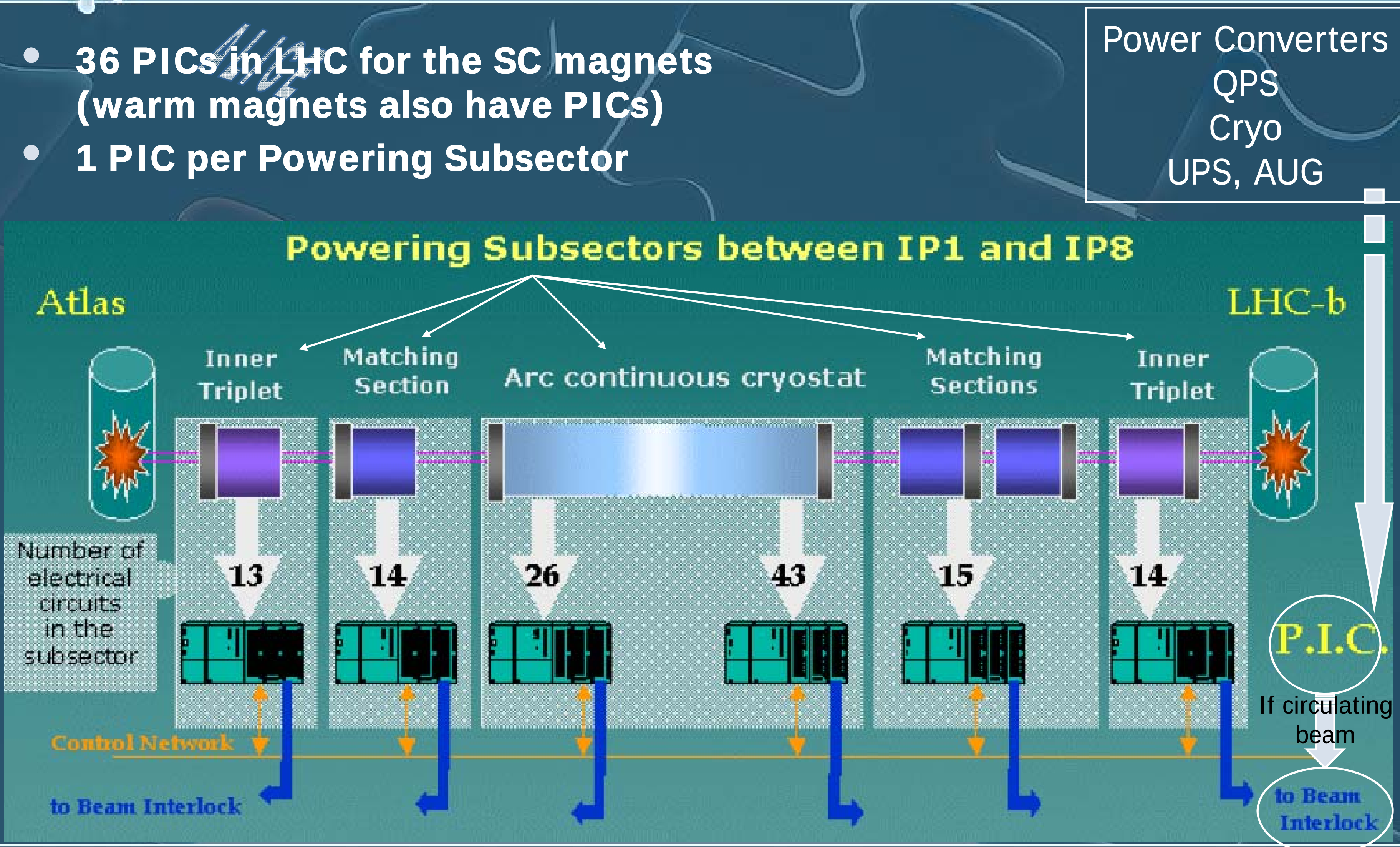
- During normal operation every ramp down of the magnets implies energy extraction, but this takes ~20 min ➔ too slow in case of a quench
- A dedicated Energy Extraction System for quench protection is needed
- There are 32 EES for the 24 13kA main circuits (dipoles & quadrupoles) (+ the EES for the 600 A correctors)
- This system releases the energy in 104 s for the dipoles (-125 A/s) and in 40 s for the quadrupoles (-325 A/s)



13kA Energy Extraction Facilities in the UA's
for LHC Main Dipole and QF/QD circuits

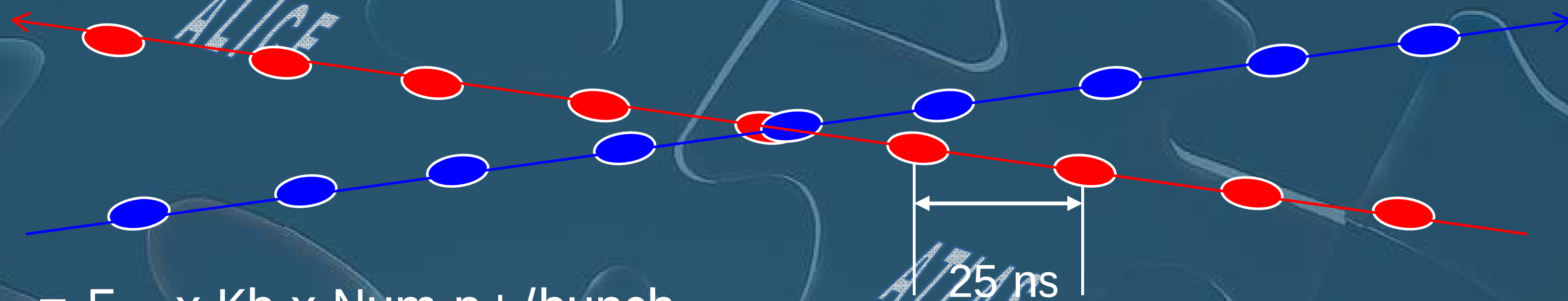
Magnet Energy: Power Interlock Controller

- **36 PICs in LHC for the SC magnets (warm magnets also have PICs)**
- **1 PIC per Powering Subsector**



Contents

Energy Stored in the Beams



$E_{beam} = E_{p+} \times Kb \times Num\ p+/bunch$

$E_{p+} = 7$ TeV

$Kb = 2808$

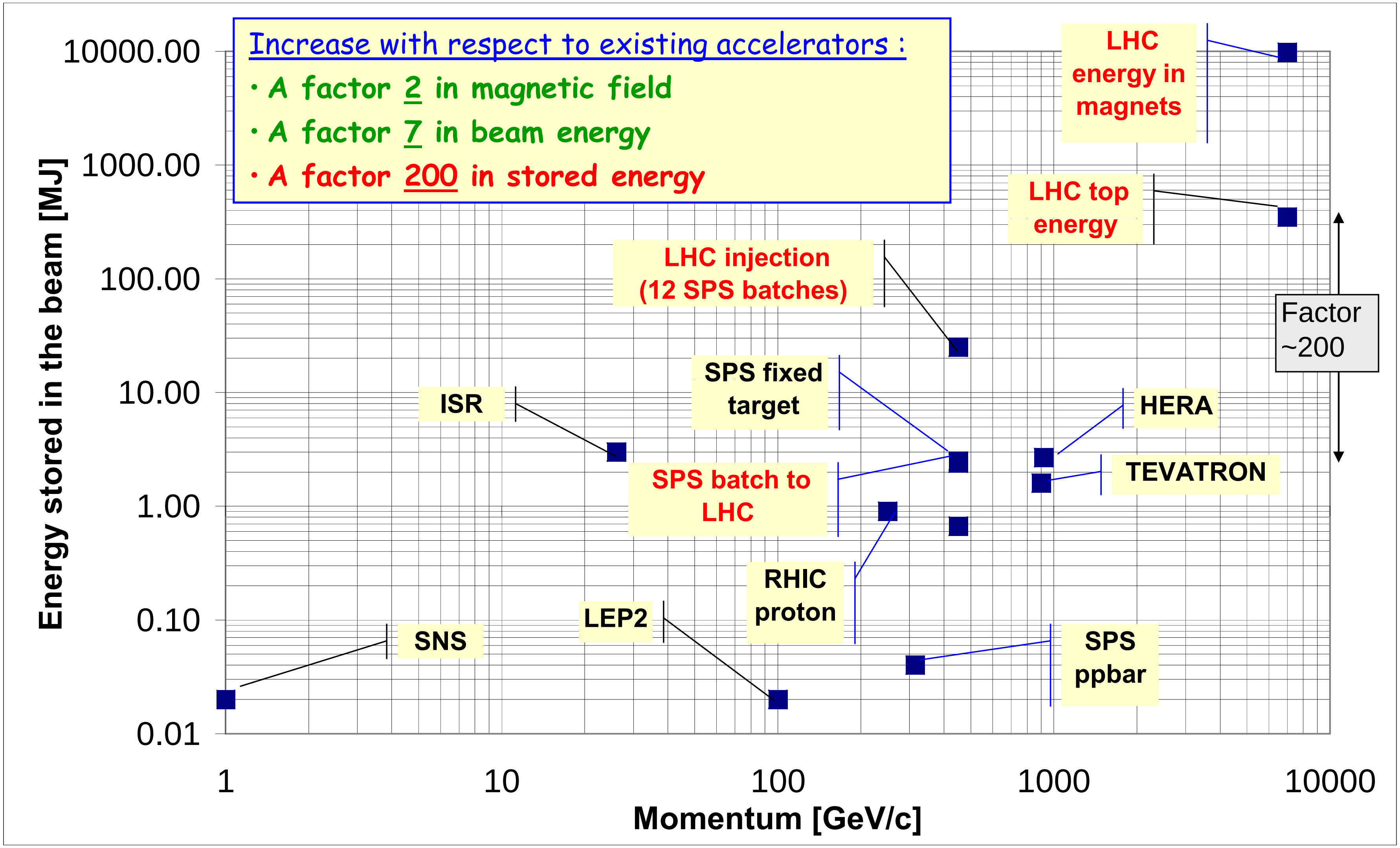
Num p+/bunch = 1.15×10^{11}

Nominal values

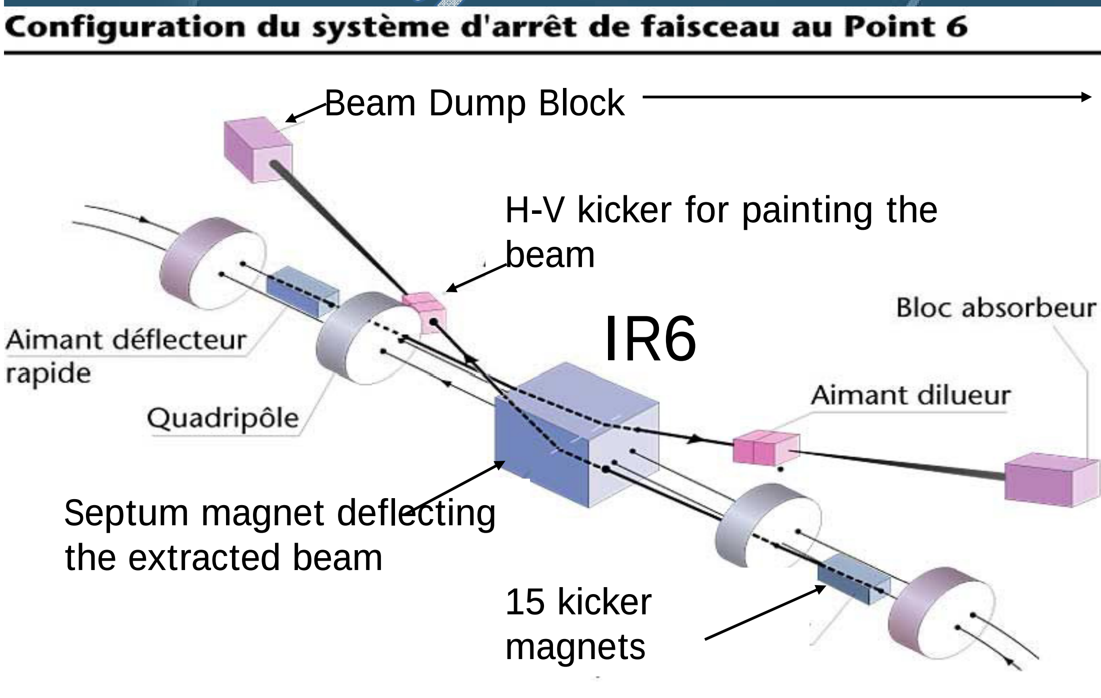
$E_{beam} = 362$ MJules

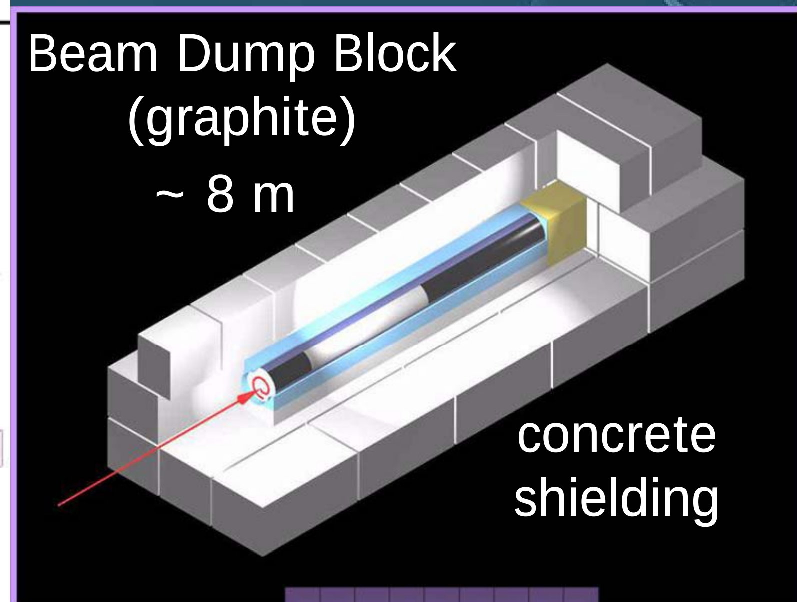
Enough to melt 500 kg of copper

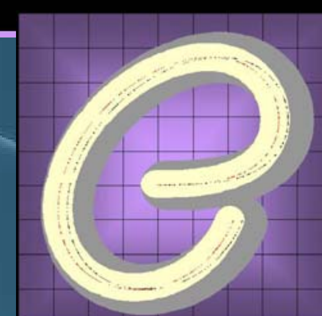
Energy Stored in the Beams



Energy Stored in the Beams: Beam Dump System

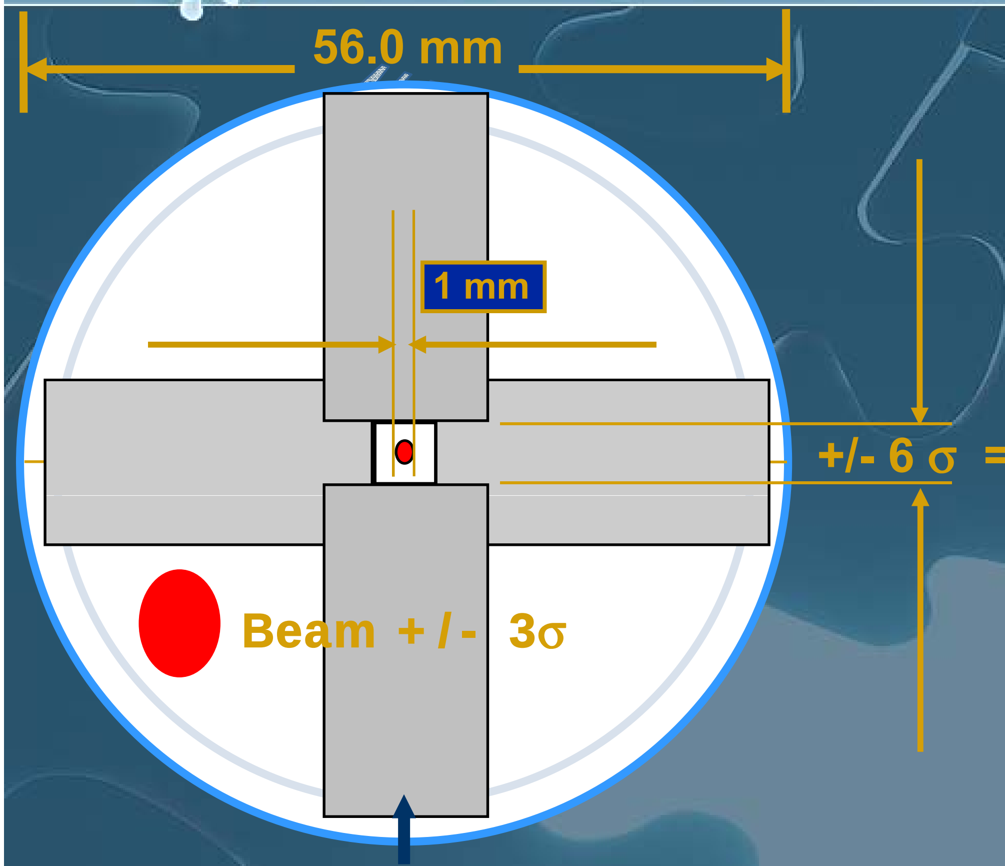






Is the only system in LHC able to absorb the full nominal beam

Energy Stored in the Beams: Collimation System



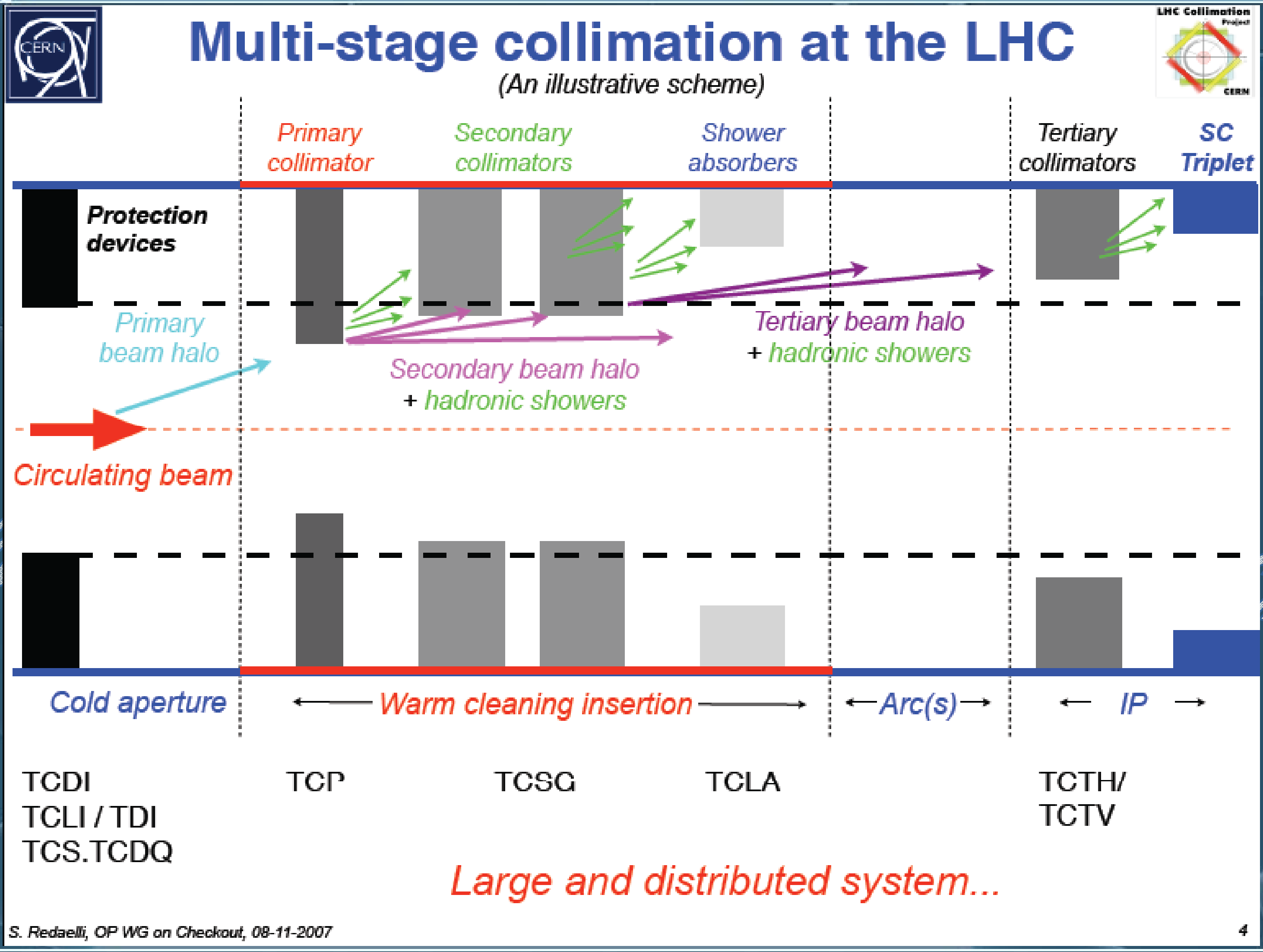
E.g. Settings of collimators @7 TeV with luminosity optics

Very tight settings ➔ orbit feedback!!

Collimation System Functionality:

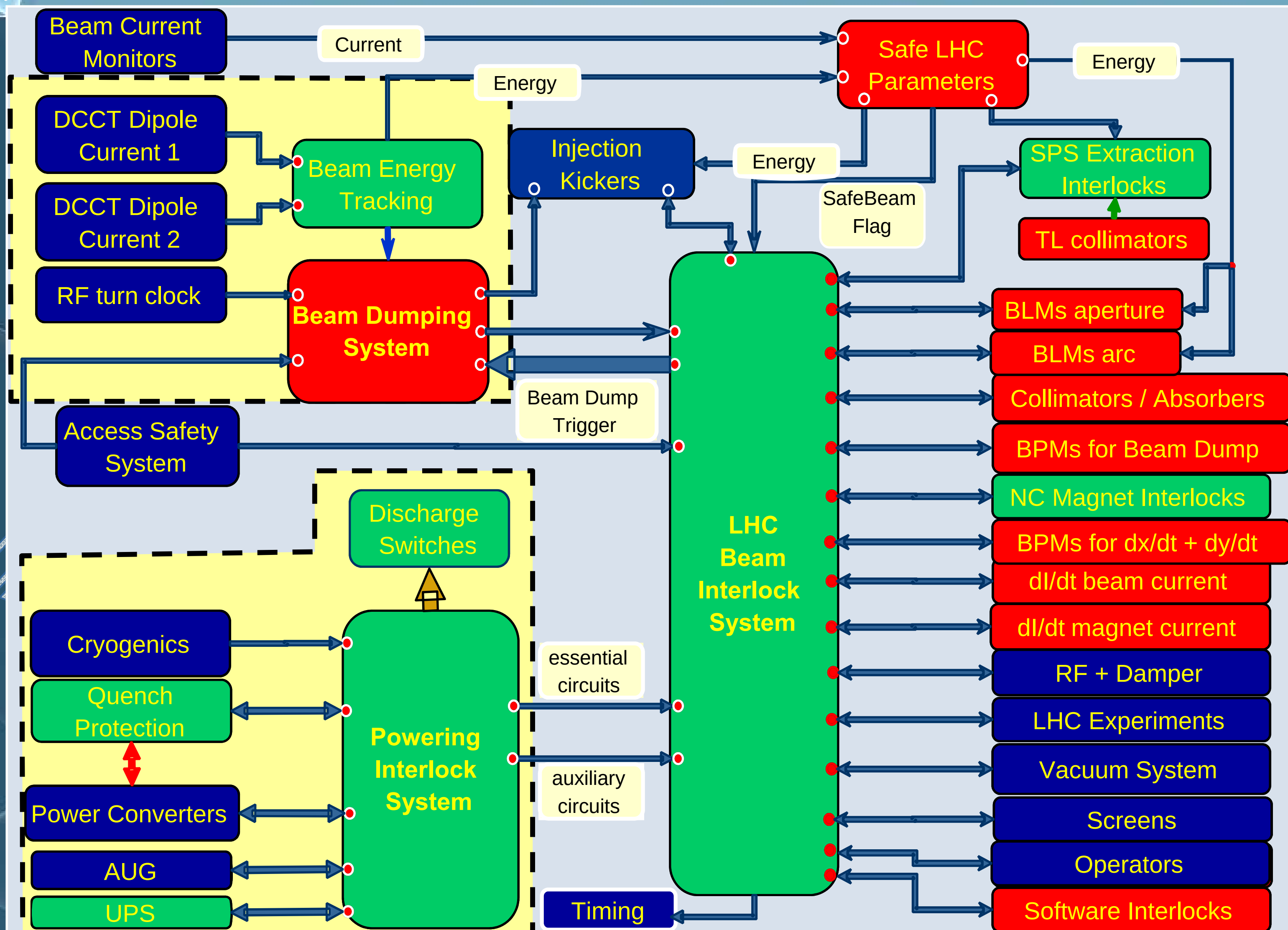
1. Absorb beam halo to avoid quenches
2. Once beam losses appear they protect the equipment and experiments. If BLMCs > Threshold ➔ Beam Interlock ➔ Beam Dump

Energy Stored in the Beams: Collimation System



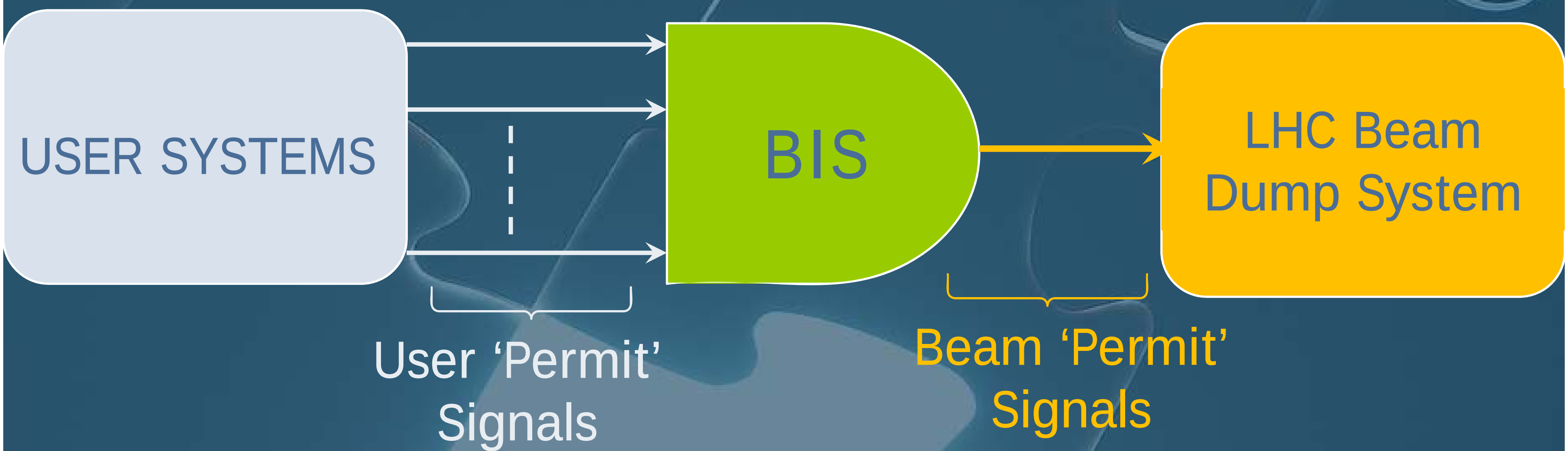
Contents

Machine Protection System



Green = ready before first beam

Machine Protection System: Beam Interlock



153 User Systems distributed over 27 km

Contents

Overall Strategy for Commissioning

	Stage A	B	C		D
Hardware commissioning Machine checkout	Pilot Physics Run	75ns ops	25ns ops I	Install Coll Phase II and MKB	25ns ops II
No beam	Beam				

Hardware Commissioning

Thorough commission of technical systems:

- Magnets, vacuum, cryo, PC, quench detection, energy extraction, RF, beam instrumentation, kickers, septa, collimators, absorbers, etc.
- Services: AC distribution, water-cooling, ventilation, access control, safety, etc.

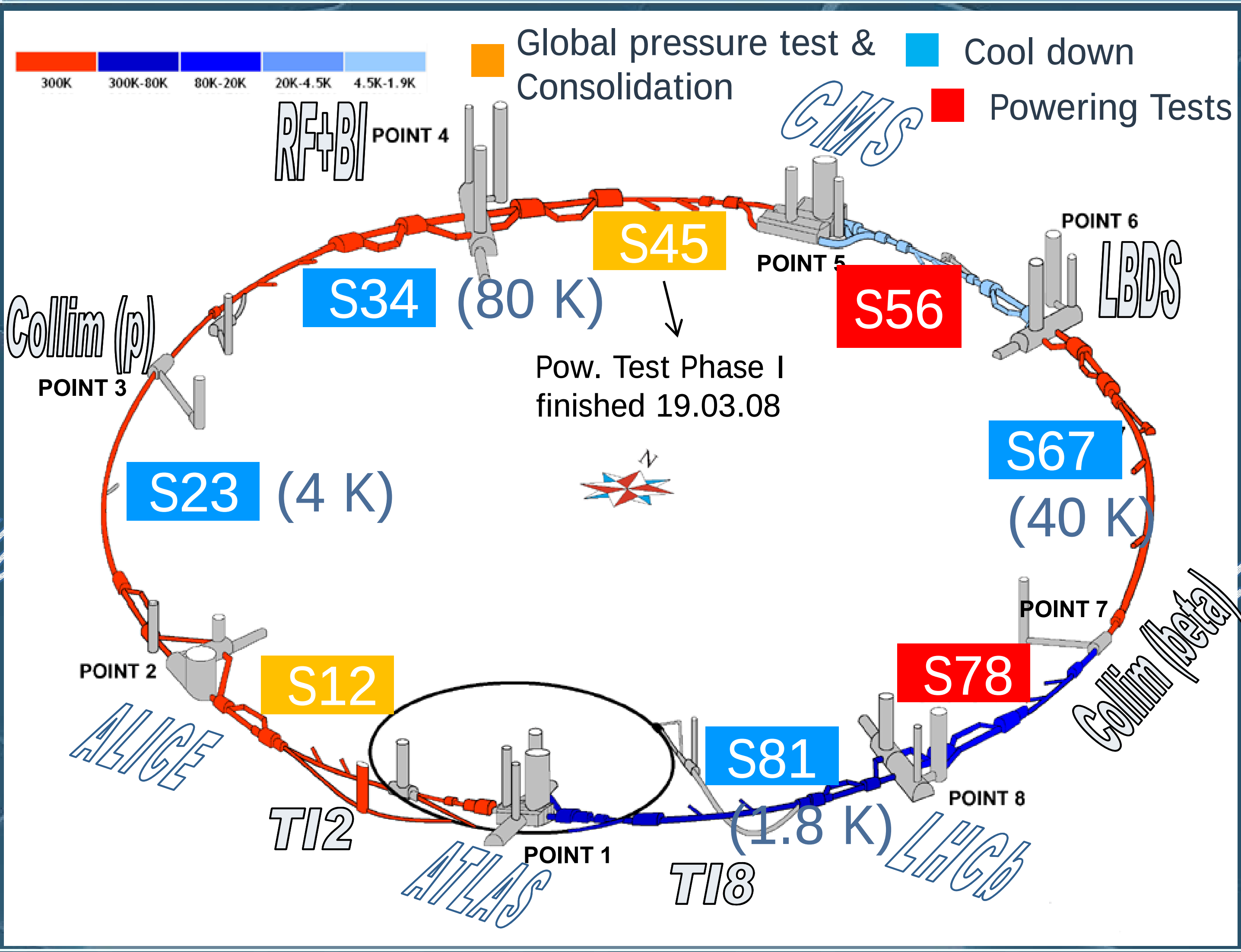
Stages:

1. Individual system test
2. Global system test

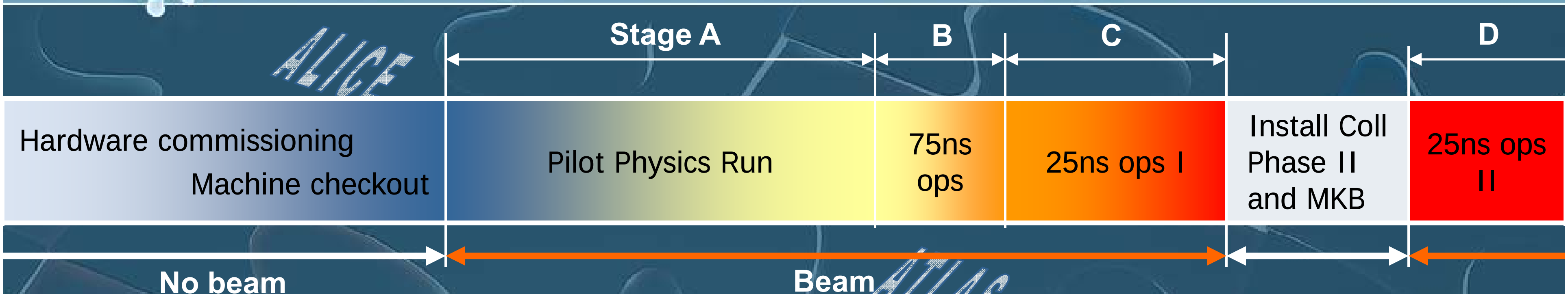
Commissioned energy:

1. 2008 ➔ Eb = 5.5 TeV (no training quenches)
2. 2009 ➔ Eb = 7 TeV (magnet training required)

Hardware Commissioning Status



Overall Strategy for Commissioning



Machine Checkout

- Drive all systems through the standard operational sequence (synchronized)
- Check Control System functionality from CCC high-level software applications
- Check beam instrumentation acquisition chain
- Check timing synchronization
- Check all equipment control functionality
- Check machine protection and interlock system

Stages:

1. Individual system test. First integration into the OP group
2. Multi-system test, e.g. Machine Protection (BLM, BIS, LBDS)
3. Dry run: drive the whole machine through the nominal sequence.

Overall Strategy for Commissioning

No beam	Stage A (Beam)	B (Beam)	C (Beam)	No beam	D (Beam)
Hardware commissioning Machine checkout	Pilot Physics Run	75ns ops	25ns ops I	Install Coll Phase II and MKB	25ns ops II

Beam Commissioning

Stage A: Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance
- Performance limit 10^{32} $cm^{-2}s^{-1}$ (event pileup)

Stage B: 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} $cm^{-2}s^{-1}$ (evt pileup)

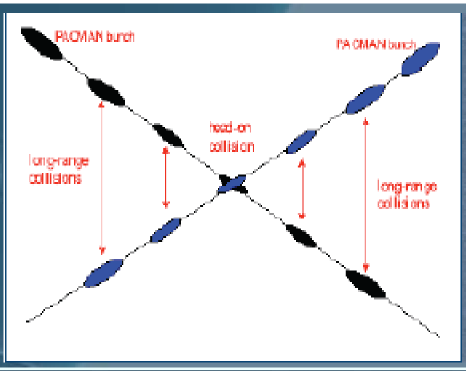
Stage C: 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} $cm^{-2}s^{-1}$

Stage D: 25ns operation II
- Push towards nominal performance
- Requires hardware updates: collimators and beam dump system
- Performance goal: 10^{34} $cm^{-2}s^{-1}$

Beam Commissioning with p^+

- LHC Design Parameters:

Design Parameters	
Lumi IP 1,5 ($cm^{-2} s^{-1}$)	10^{34}
Lumi IP 2,8 ($cm^{-2} s^{-1}$)	$5\ 10^{32}$
σ_{xy} IP 1,5 (μm)	16.7
σ_{xy} IP 2,8 (μm)	70.9
Crossing angle (μrad)	285



Nominal Settings	
E_{beam} (TeV)	7
# p^+/bunch	$1.15\ 10^{11}$
# bunches/beam	2808
E_{beam} Stored (MJ)	362
ε_n^{xy} (μm rad)	3.75
Bunch length (cm)	7.5
β^* (IP: 1,2,5,8) (m)	0.55, 0.55, 10, 10

R1

Beam Commissioning with p^+ Stage A

- Start as simple as possible
- Change 1 parameter (kb, N, β*) at a time
- All values for:
  - nominal emittance
  - 7 TeV
  - 2 m β* (IP: 1&5)

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

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

Protons/beam $\lesssim 10^{13}$
(LEP beam currents)

Stored energy/beam $\lesssim$ 10MJ
(SPS fixed target beam)

Parameters			Beam levels		Rates in 1 and 5		Rates in 2	
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
1	10^{10}	11	$1\ 10^{10}$	10^{-2}	$1.6\ 10^{27}$	<< 1	$1.8\ 10^{27}$	<< 1
43	10^{10}	11	$4.3\ 10^{11}$	0.5	$7.0\ 10^{28}$	<< 1	$7.7\ 10^{28}$	<< 1
43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	2	$1.1\ 10^{30}$	<< 1	$1.2\ 10^{30}$	0.15
43	$4\ 10^{10}$	2	$1.7\ 10^{12}$	2	$6.1\ 10^{30}$	0.76	$1.2\ 10^{30}$	0.15
156	$4\ 10^{10}$	2	$6.2\ 10^{12}$	7	$2.2\ 10^{31}$	0.76	$4.4\ 10^{30}$	0.15
156	$9\ 10^{10}$	2	$1.4\ 10^{13}$	16	$1.1\ 10^{32}$	3.9	$2.2\ 10^{31}$	0.77

Slide 34

R1

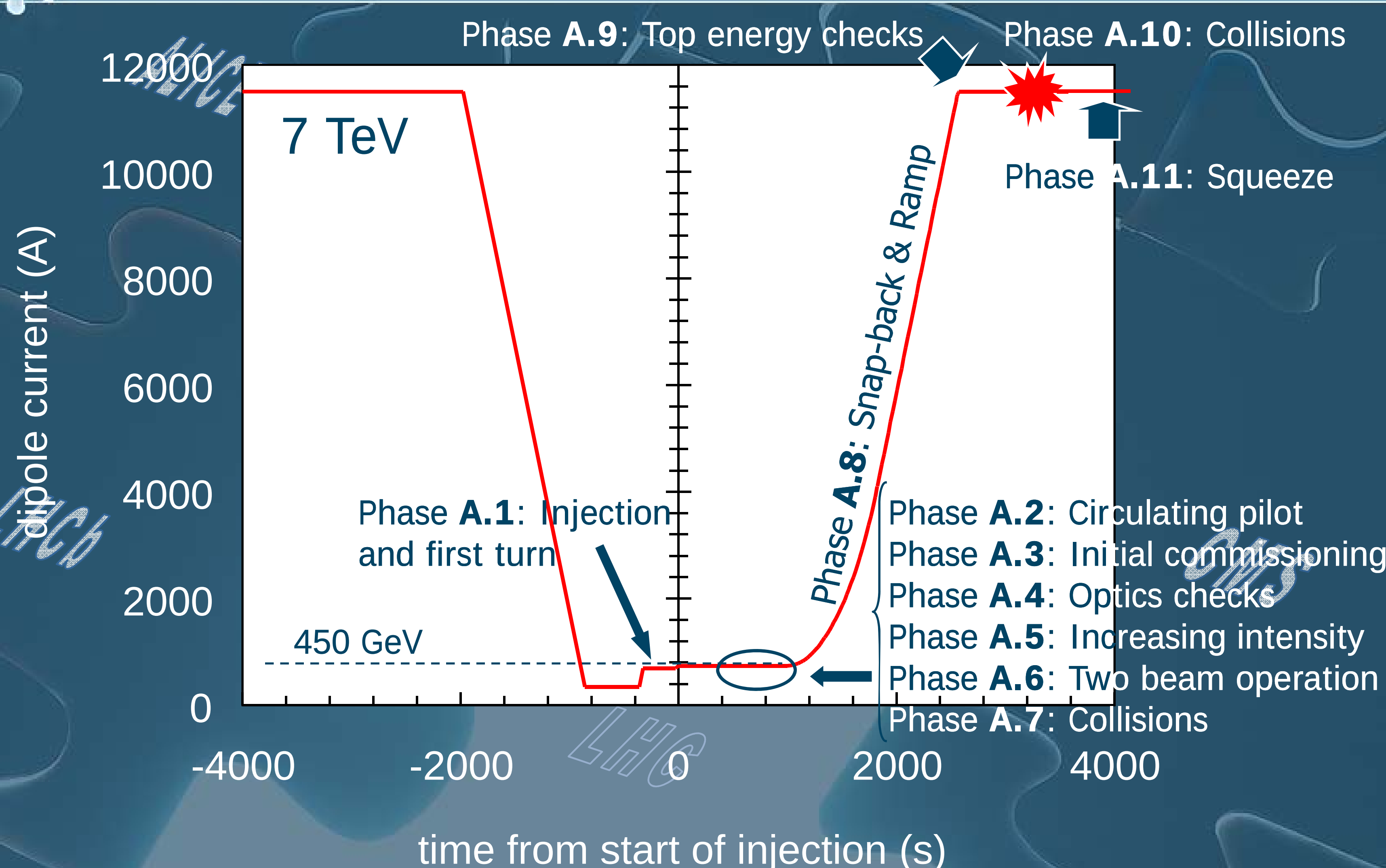
Find a balance between robust operation and satisfying the experiments
Maximize integrated luminosity
Minimize event pile-up (to event + 2)
Avoid quenches (and damage)
Higher b* to avoid problems in the (later part of) the squeeze
Reduce total current to reduce stored beam energy
Lower ib
Fewer bunches
Reduce energy to get more margin ?
Against transient beam losses
Against magnet operating close to training limit
Hardware commissioning will tell us more

With lower currents in mind, two machine systems will be staged
Only 8 of 20 beam dump dilution kickers initially installed
Total beam intensity < 50% nominal
Install the rest when needed

Collimators (robustness, impedance and other issues)
Phased approach
Run at the impedance limit during phase I
Lower currents
Higher b*

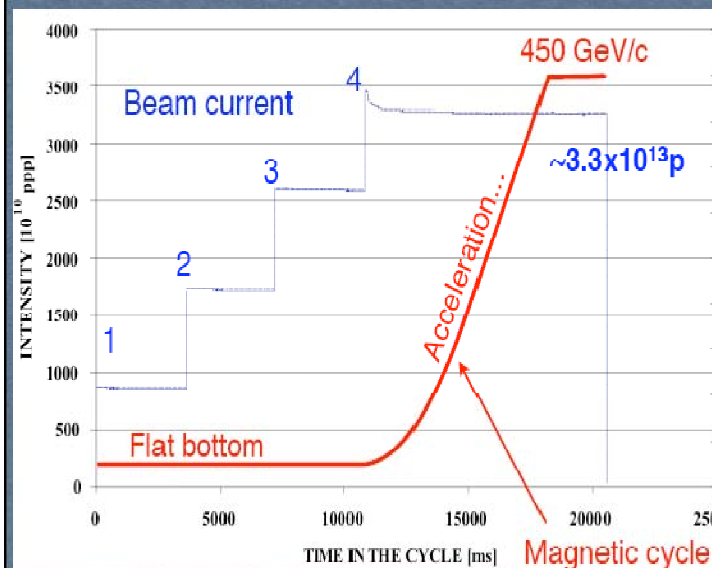
Reyes, 3/25/2008

Beam Commissioning with p+ Stage A

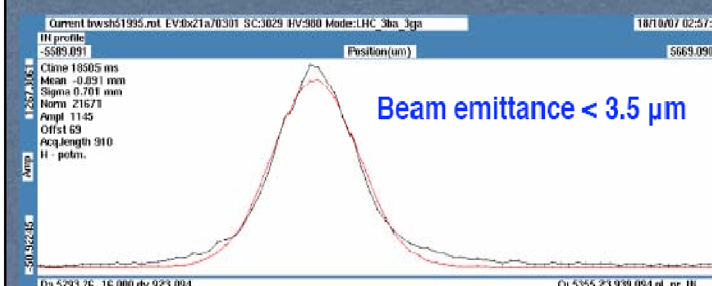


Beam Commissioning in the Injectors

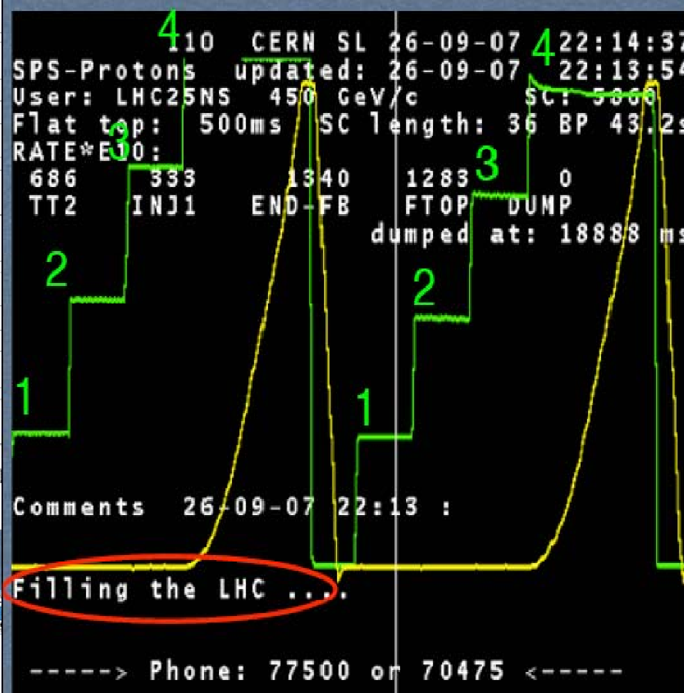
LHC beams at t



SPS 2004 run. Courtesy of G. Arduini, E. Métral



SPS: interleaved B1/B2 extractions



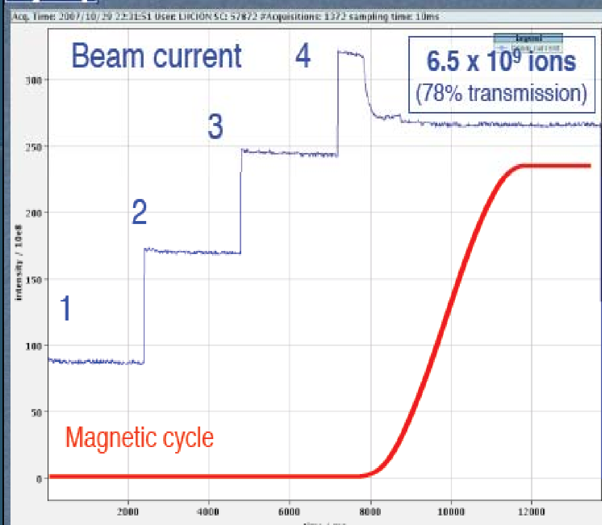
***SPS 2007 run**. Courtesy of J. Wenninger*
Beam intensity lower than nominal (no dedicated studies for beam optimization)

Cycle for interleaved extractions of Beam1 and Beam2 successfully set-up in 2007!
"Page 1" could announce that we were ready for "Filling the LHC...."

Shorter cycles also available for lower beam intensities: faster and more flexible operation for commissioning scenarios

Beam Commissioning in the Injectors

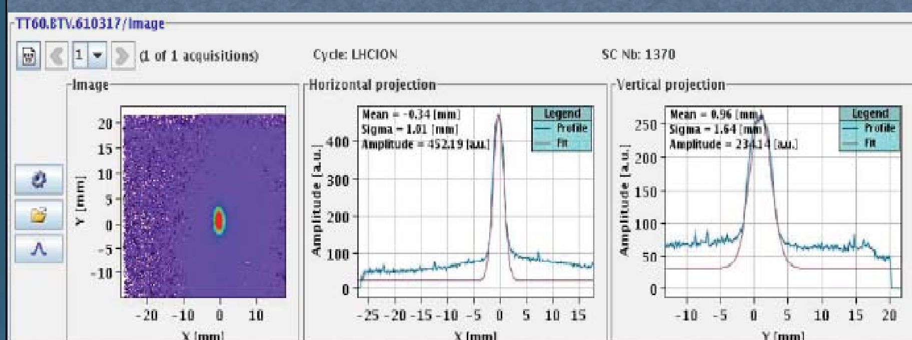
The “early” LHC ion beam is also ready



Summary table of main achievements

	expected	obtained				
		Bunch				
		1	2	3	4	
transmission	75%					78%
N_Q	7.4×10^9					6.5×10^9
ϵ/A (eVs)	0.28	0.068	0.076	0.083	0.12	
τ (ns)	1.8	0.90	0.94	1.0	1.2	
$\Delta p/p$ (10^{-4})	6.3	2.7	2.9	3.1	3.6	

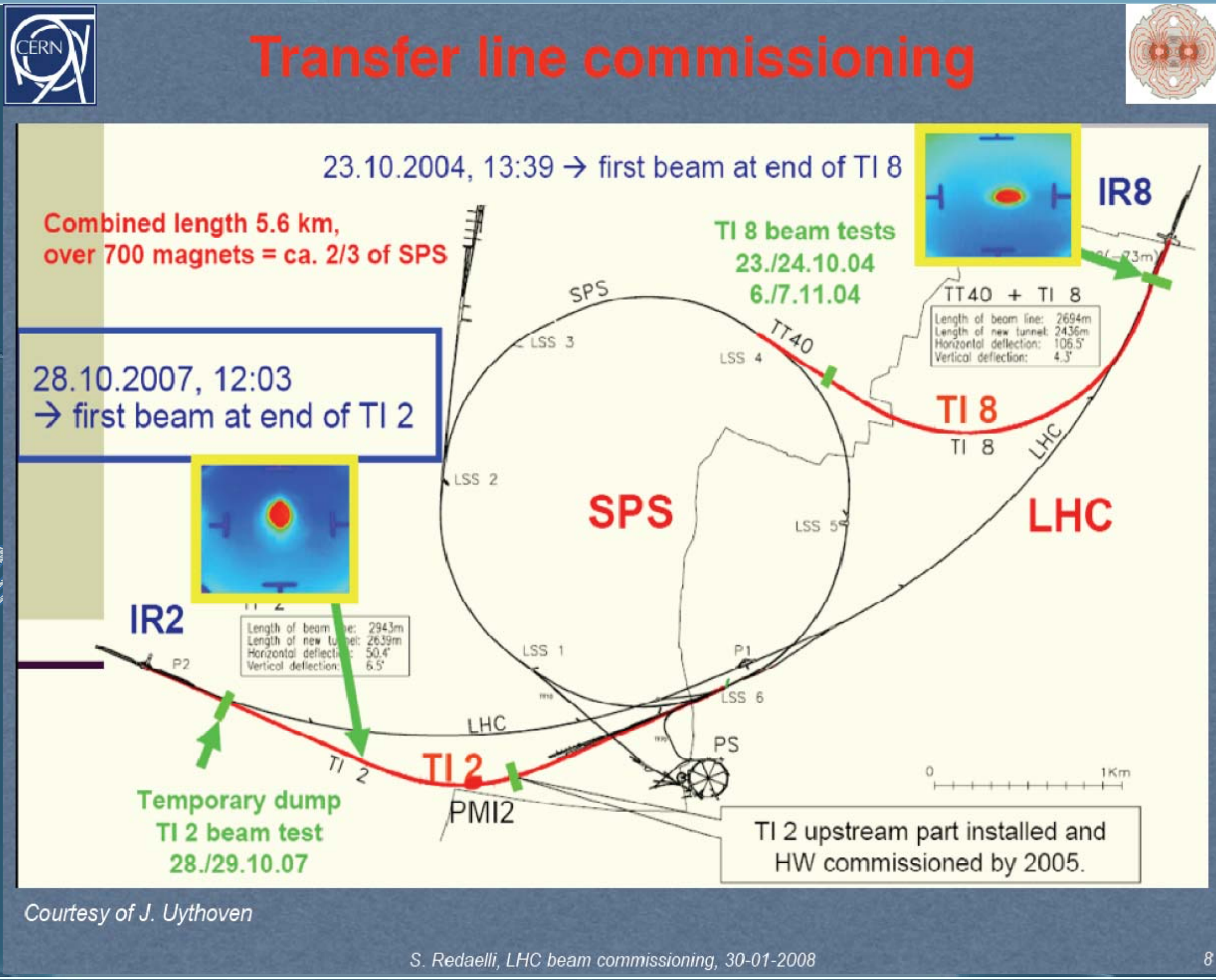
Courtesy of T. Bohl



Extracted Lead ion beam in TT60!

SPS 2007 run. Courtesy of D. Manglunki.

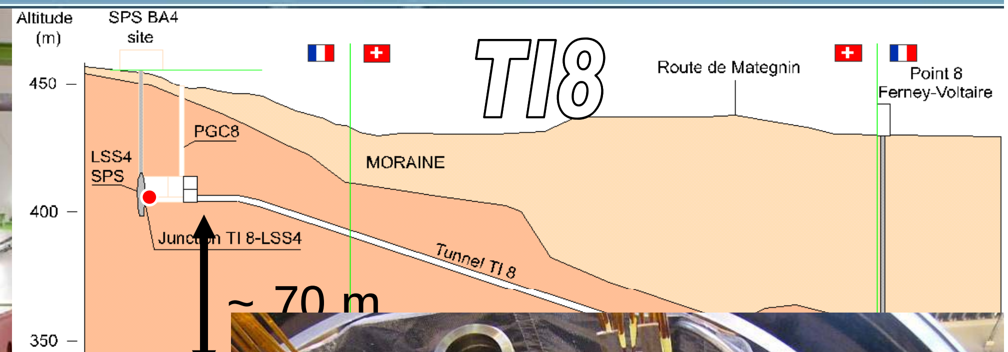
Beam Commissioning in the Transfer Lines

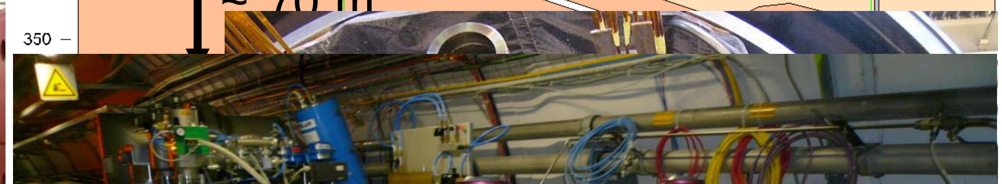


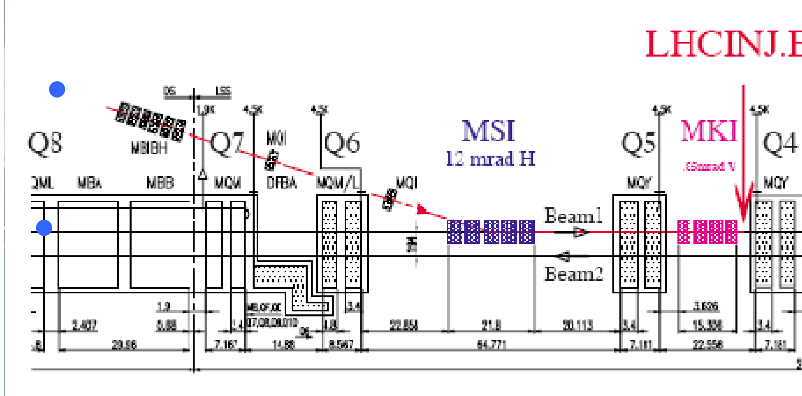
Phase A.1: Injection and first turn

Objectives:

- Commissioning of the last 100 m of the transfer line and the injection
- First commissioning of key beam instrumentation: BPM, BLM, BTV and FBCT
- Commissioning of the trajectory acquisition and correction
- Threading the beam around the two rings (first turn)
- Closing the orbit to be ready for phase A.2 (establishing circulating beam)

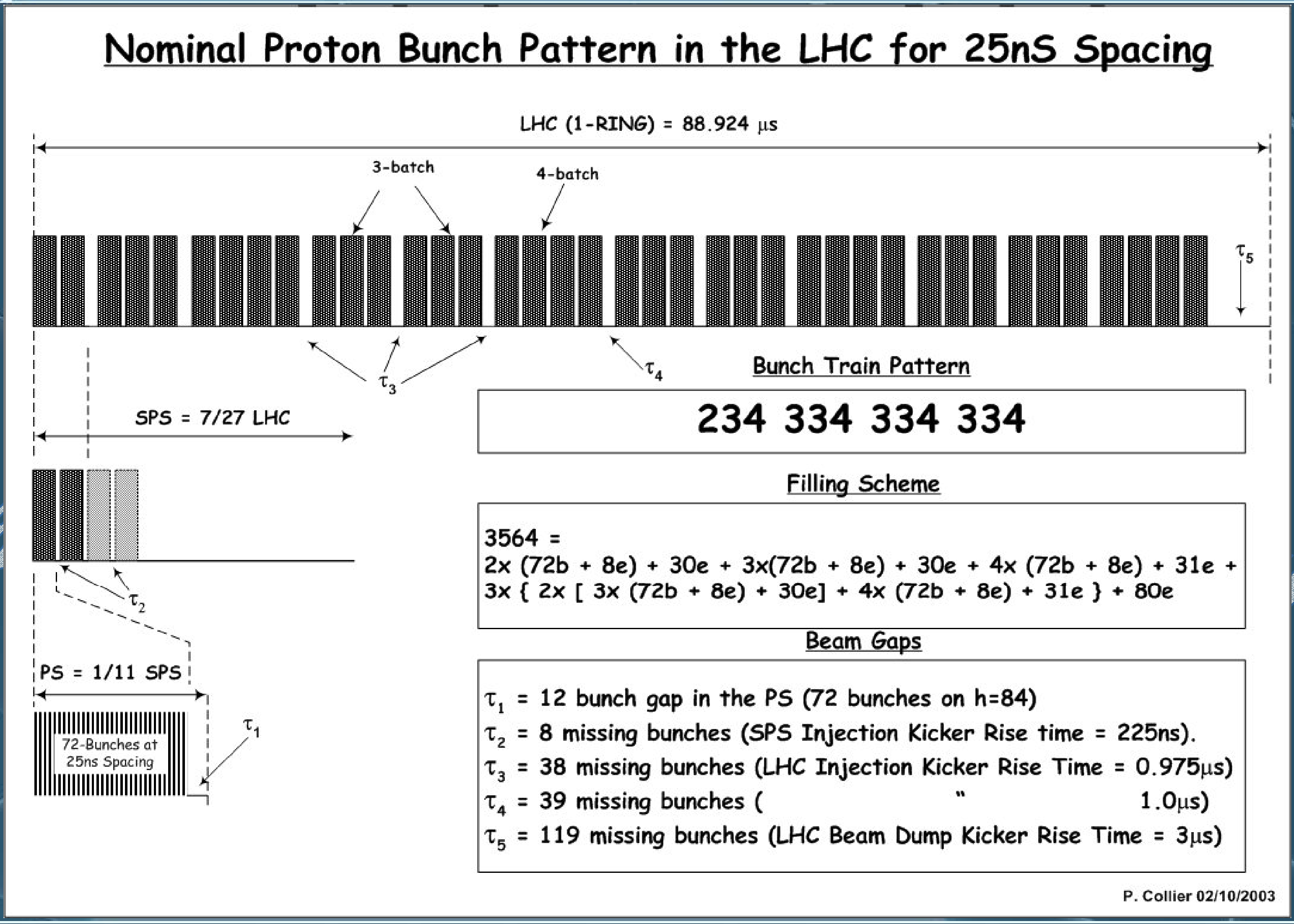






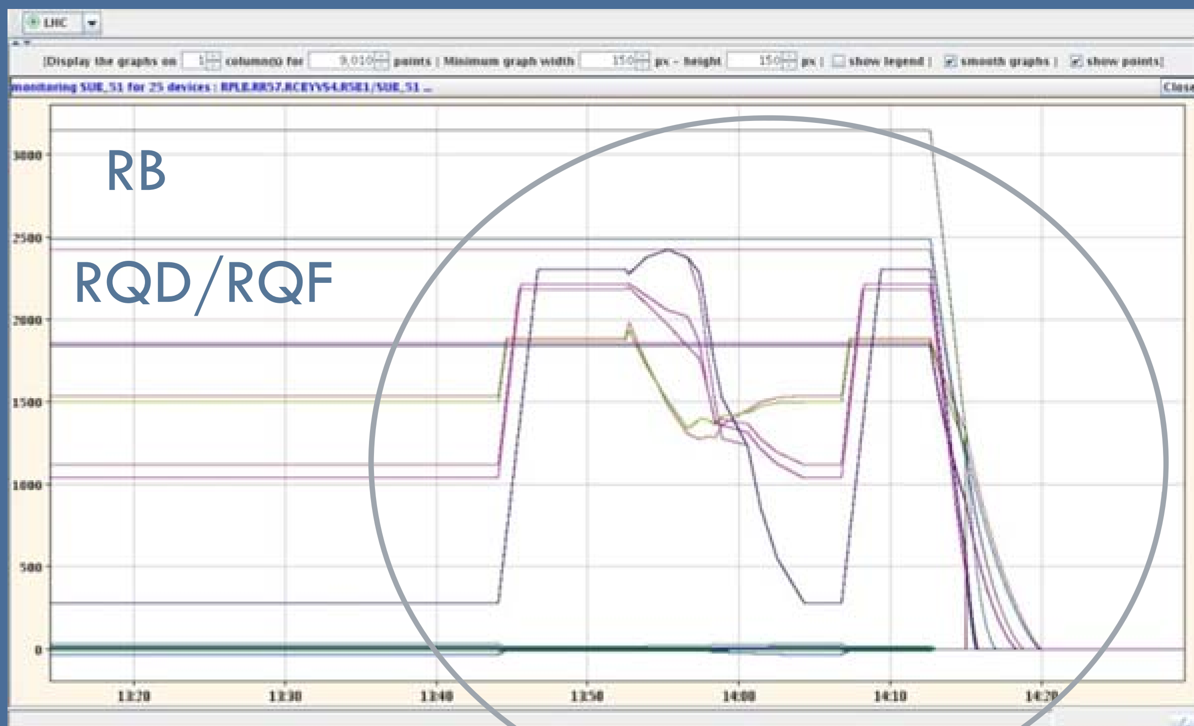
FBCT

Phase A.1: Injection and first turn
Nominal Injection Schema



Phase A.10: Top energy collisions
Phase A.11: Top energy squeeze

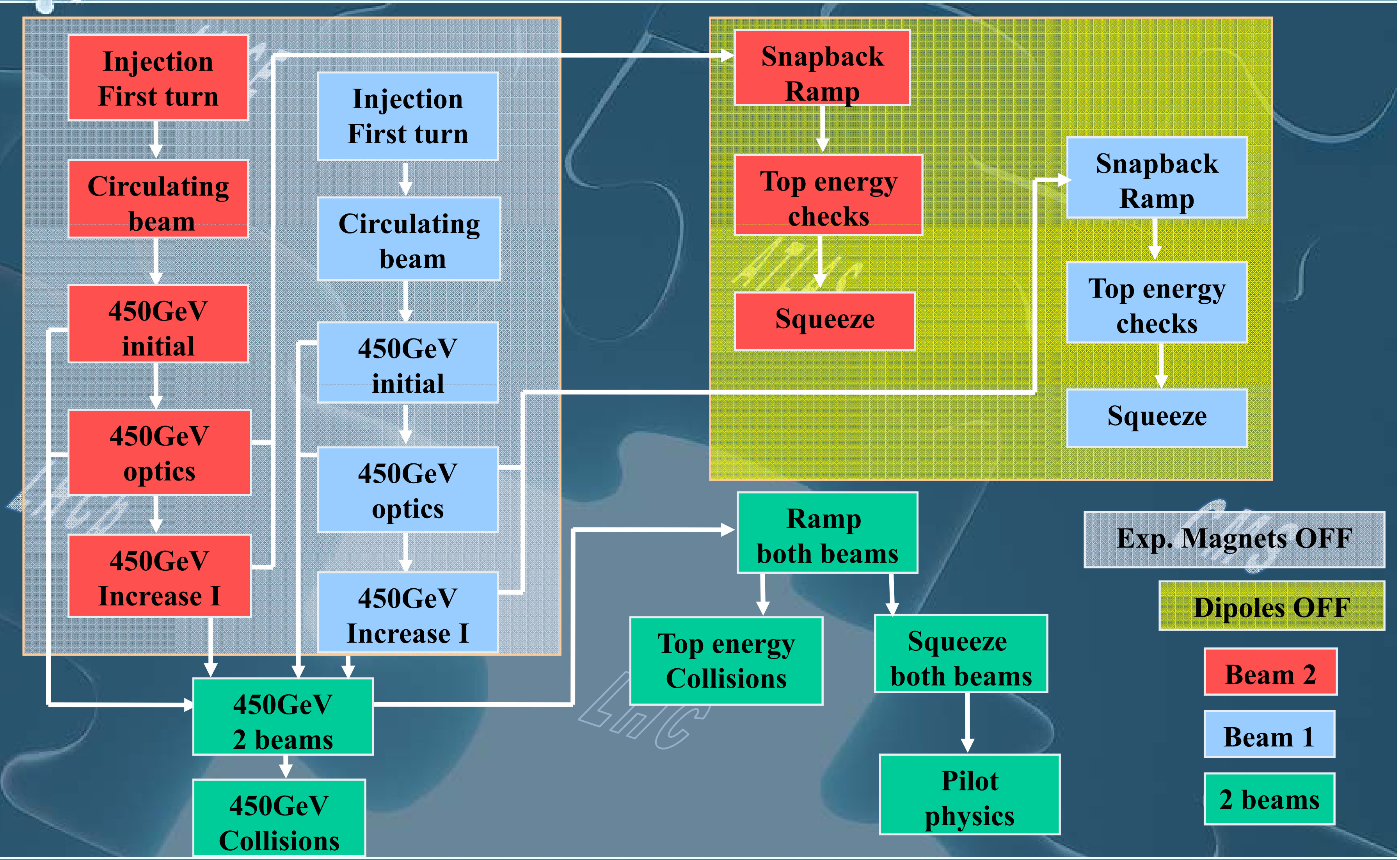
ARC+ML6+LR5 (156 PCs) @ 5 TeV



SQUEEZE

Beam Commissioning with p+

Phase A: commissioning plans



Beam Commissioning with p+ Stage B: Intermediate physics run

$$F = 1/\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

- Relaxed crossing angle (250 μrad)
- Start un-squeezed
- Then go to where we were in stage A
- All values for
  - nominal emittance
  - 7 TeV
  - 10 m β* in points 2 and 8

Protons/beam ≈ few 10^{13}

Stored energy/beam ≤ 100 MJ

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
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

Beam Commissioning with p+ Stage C&D: 25 ns Operation

- Nominal crossing angle (285 μrad)
- Start un-squeezed
- Then go to where we were in stage B
- All values for
  - nominal emittance
  - 7 TeV
  - 10m β* in points 2 and 8

Protons/beam ≈ 10^{14}

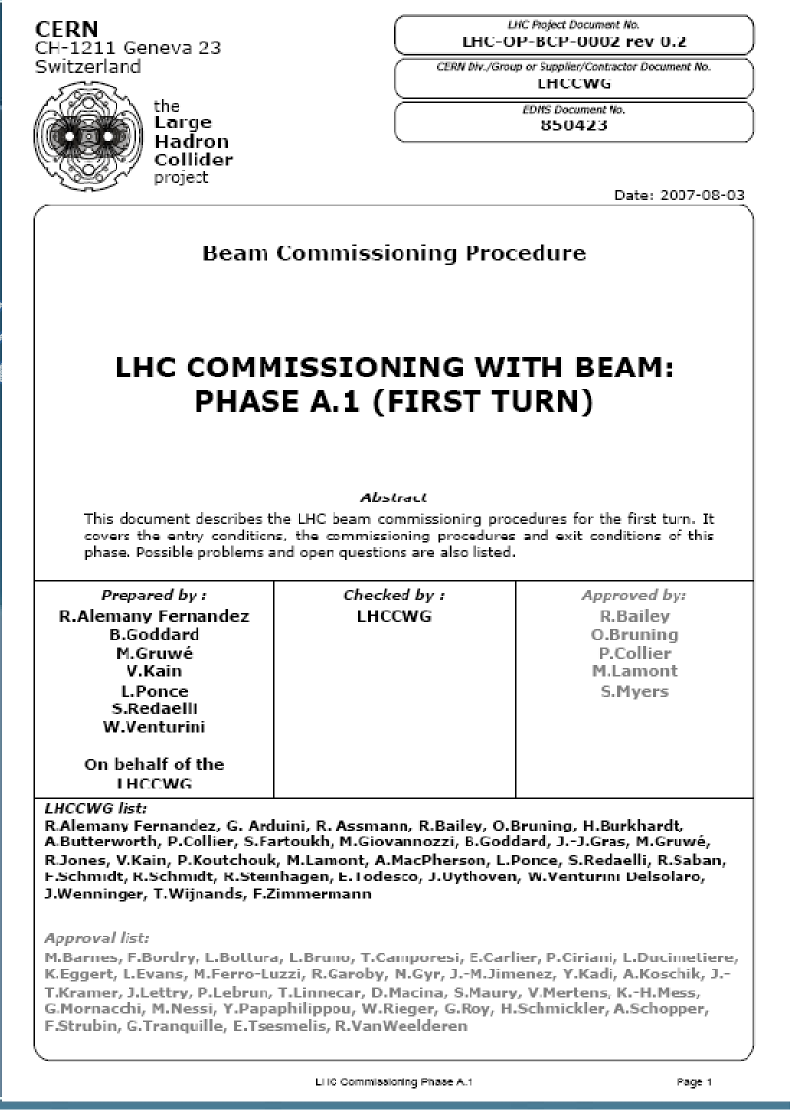
Stored energy/beam ≥ 100 MJ

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
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	$5\ 10^{10}$	2	$1.4\ 10^{14}$	157	$5.9\ 10^{32}$	1.1	$1.2\ 10^{32}$	0.24
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
Nominal			$3.2\ 10^{14}$	362	10^{34}	19	$6.5\ 10^{32}$	1.2

Contents

Documentation

- Hardware Commissioning Coordination
  - http://hcc.web.cern.ch/hcc/
- Machine Checkout
  - http://wikis/display/LHCOP/LHC+Machine+Checkout
- LHC Commissioning Procedures
  - http://lhccwg.web.cern.ch/lhccwg/overview_index.htm



CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No.
LHC-OP-BCP-0002 rev 0.2

CERN Div./Group or Supplier/Contractor Document No.
LHCCWG

EDMS Document No.
850423

Date: 2007-08-03

Beam Commissioning Procedure

LHC COMMISSIONING WITH BEAM: PHASE A.1 (FIRST TURN)

Abstract

This document describes the LHC beam commissioning procedures for the first turn. It covers the entry conditions, the commissioning procedures and exit conditions of this phase. Possible problems and open questions are also listed.

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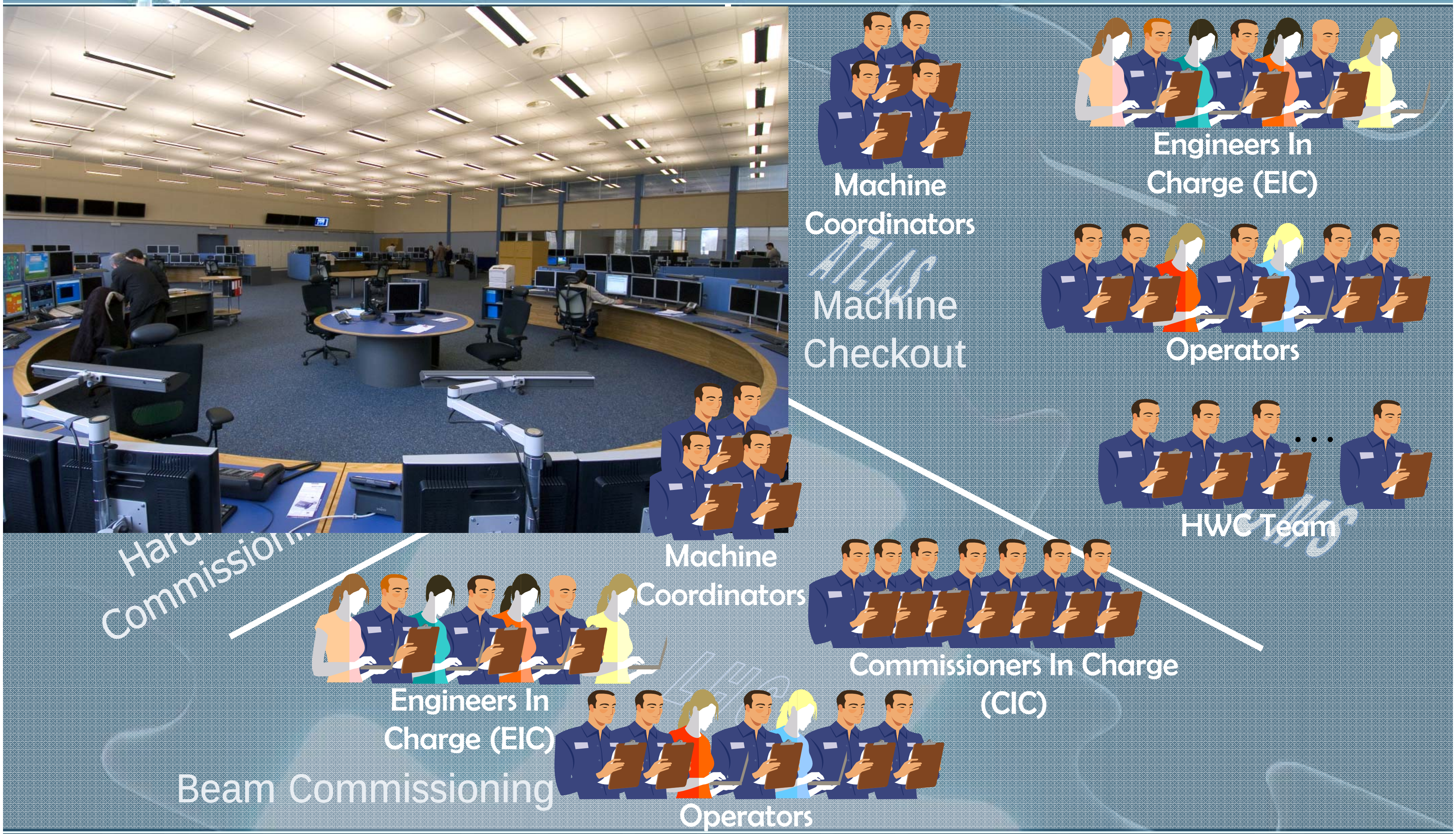
Human Resources



Summary

- To fully commission LHC three steps are envisaged:
  - Hardware Commissioning
  - Machine Checkout
  - Beam Commissioning
- To tackle the machine unprecedent complexity and potential danger (energy stored in the magnets and in the beam), each step is divided in well defined phases
- The success of the commissioning relies, among other things, upon:
  - Carefull elaboration of procedures (Documentation)
  - Perfect matching between the exit conditions of one step or phase with the entry conditions of the next one
  - Have always a « plan B » prepared

Acknowledges

The content of this presentation has been elaborated from material coming from the

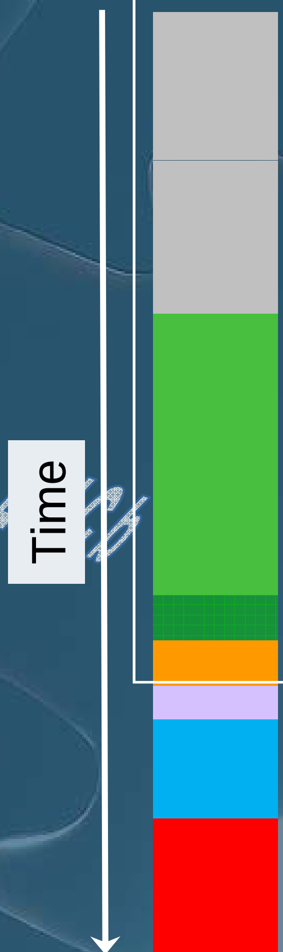
LHC Commissioning Working Group

and

Hardware Commissioning Coordination Group

Hardware Commissioning Status

Life cycle of a sector (after installation, before beam)



Done in all sectors

- Installation
- Interconnection of the continuous cryostat
- Leak tests of the last sub-sectors
- Global pressure test & Consolidation
- Flushing
- Cool down
- Powering Tests

Extra Slides

The Phase I LHC collimation system

Multi-stage halo cleaning

Two warm cleaning insertions

IR3: Momentum cleaning
- **1 primary (H) → TCP [C]**
- **4 secondary (H,S) → TCS [C]**
- **4 shower abs. (H,V) → TCLA [W]**

IR7: Betatron cleaning
- **3 primary (H,V,S)**
- **11 secondary (H,V,S)**
- **5 shower abs. (H,V)**
- **3 beam scrapers (H,V,S)**

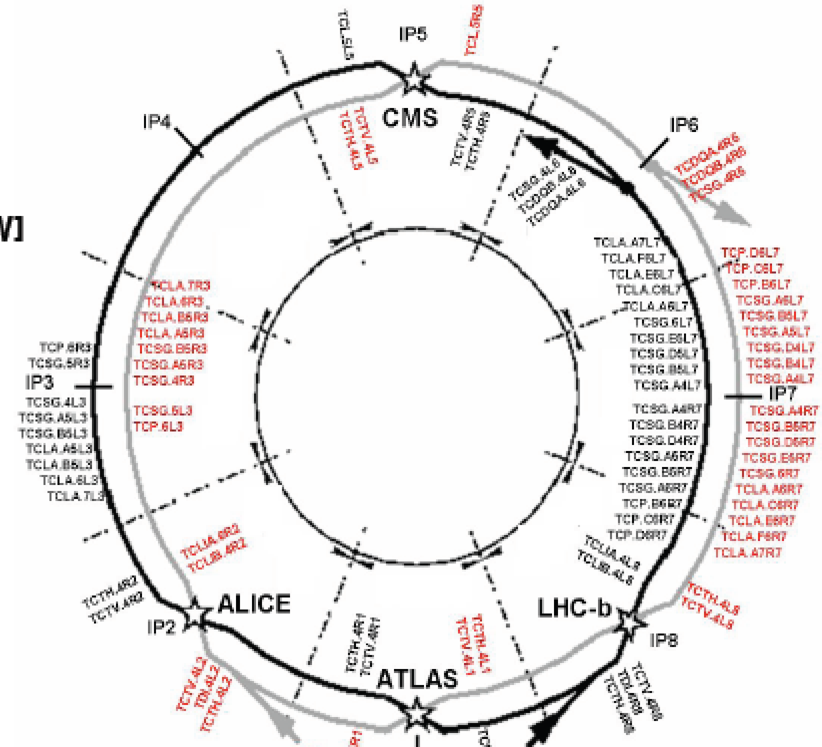
Local cleaning at triplets
- **8 tertiary (2 per IP)→ TCT [W]**

Physics debris absorbers [Cu]
- 2 TCLP's (IP1/IP5)

Protection (injection/dump)
- 10 elements →TCLI/TCDQ [C]

Transfer lines
- 13 collimators → TCDI [C]

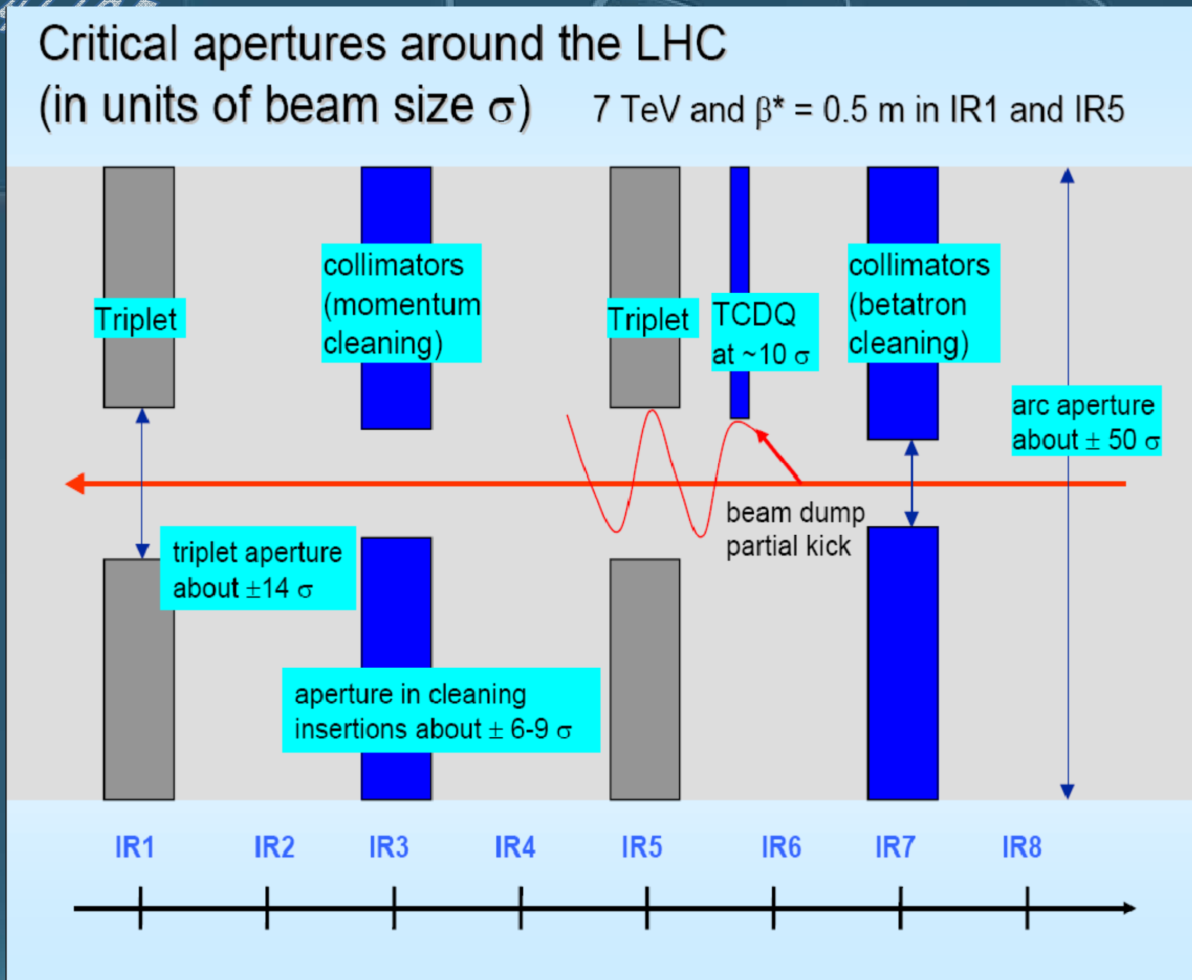
Passive absorbers for warm magnets



Picture by C. Bracco

*41 movable **ring** collimators per beam!*

Energy Stored in the Beams: Collimation System



Machine Protection System: Beam Interlock

4 fibre-optic channels from IP6
1 clockwise & 1 anticlockwise for **each** Beam

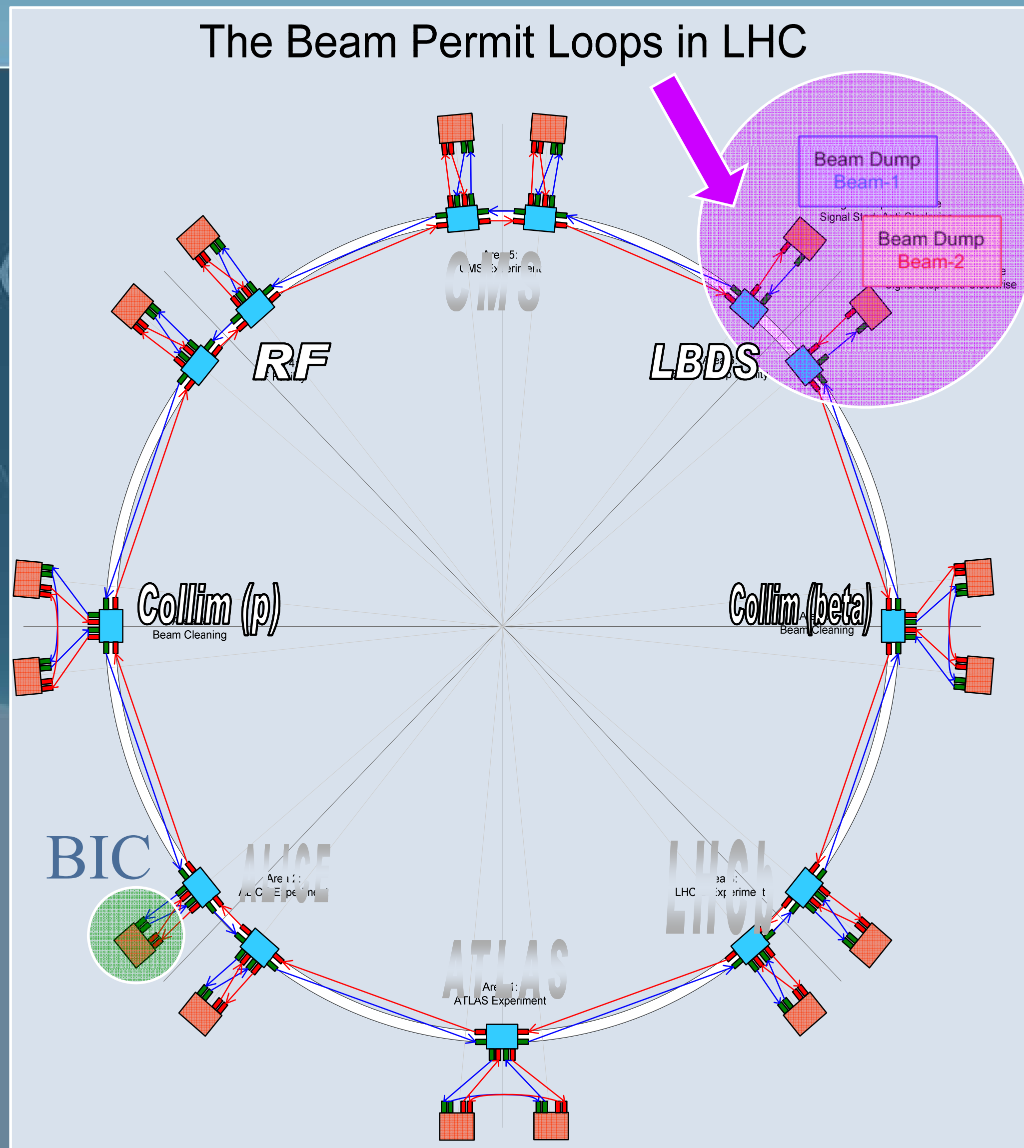
10MHz Square wave generated at IP6
-Signal can be cut by any Controller

When any of the four 10MHz signals are absent at IP6
➔BEAM DUMP!

B1 / B2 are Independent!

16 BICs per beam
- Two at each Insertion Point

Up to 20 User Systems/BIC

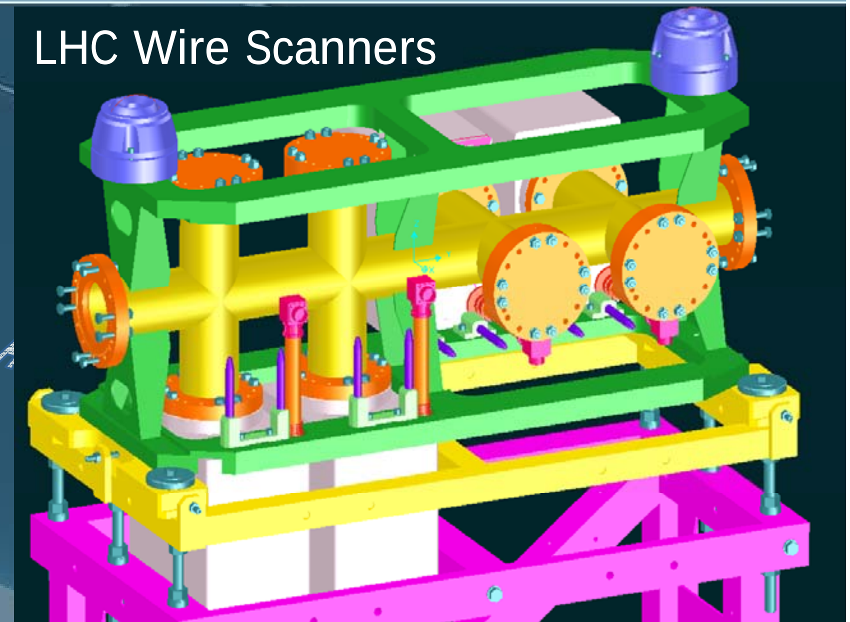


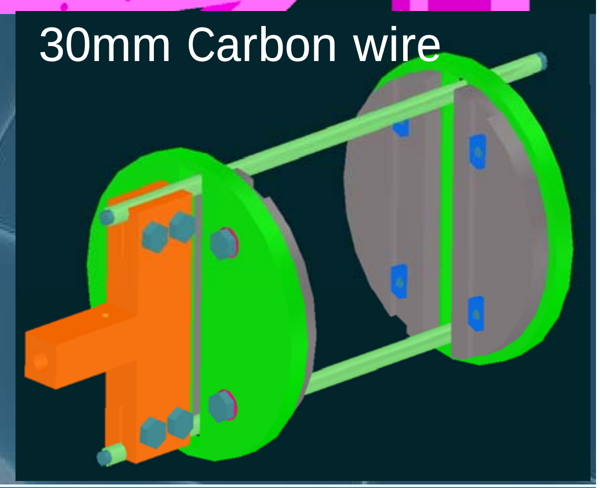
Phase A.2: Circulating pilot

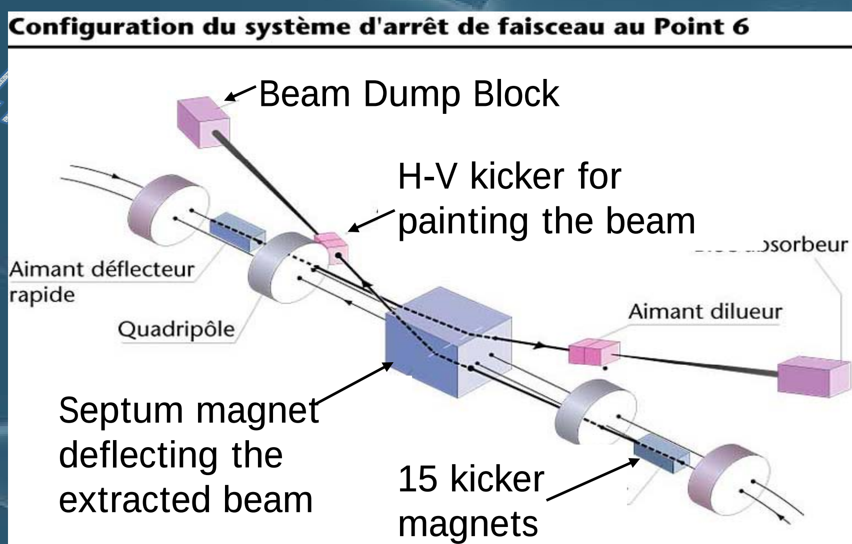
- Objectives:
  - Establish closed orbit
  - Commissioning of additional instrumentation: BPM intensity acquisition
  - Preliminary orbit, tune, coupling and chromaticity adjustments
  - Obtaining circulating beam (few hundred turns at least)
  - SPS-LHC energy matching
  - Commissioning of RF capture

Phase A.3: 450 GeV initial commissioning

- Objectives:
  - Commissioning of BI (BWS, BSRT, BCT, BGI, Q, Q’, BLM, BPM)
  - Improving lifetime
  - First optics checks
  - First commissioning of the Dump System





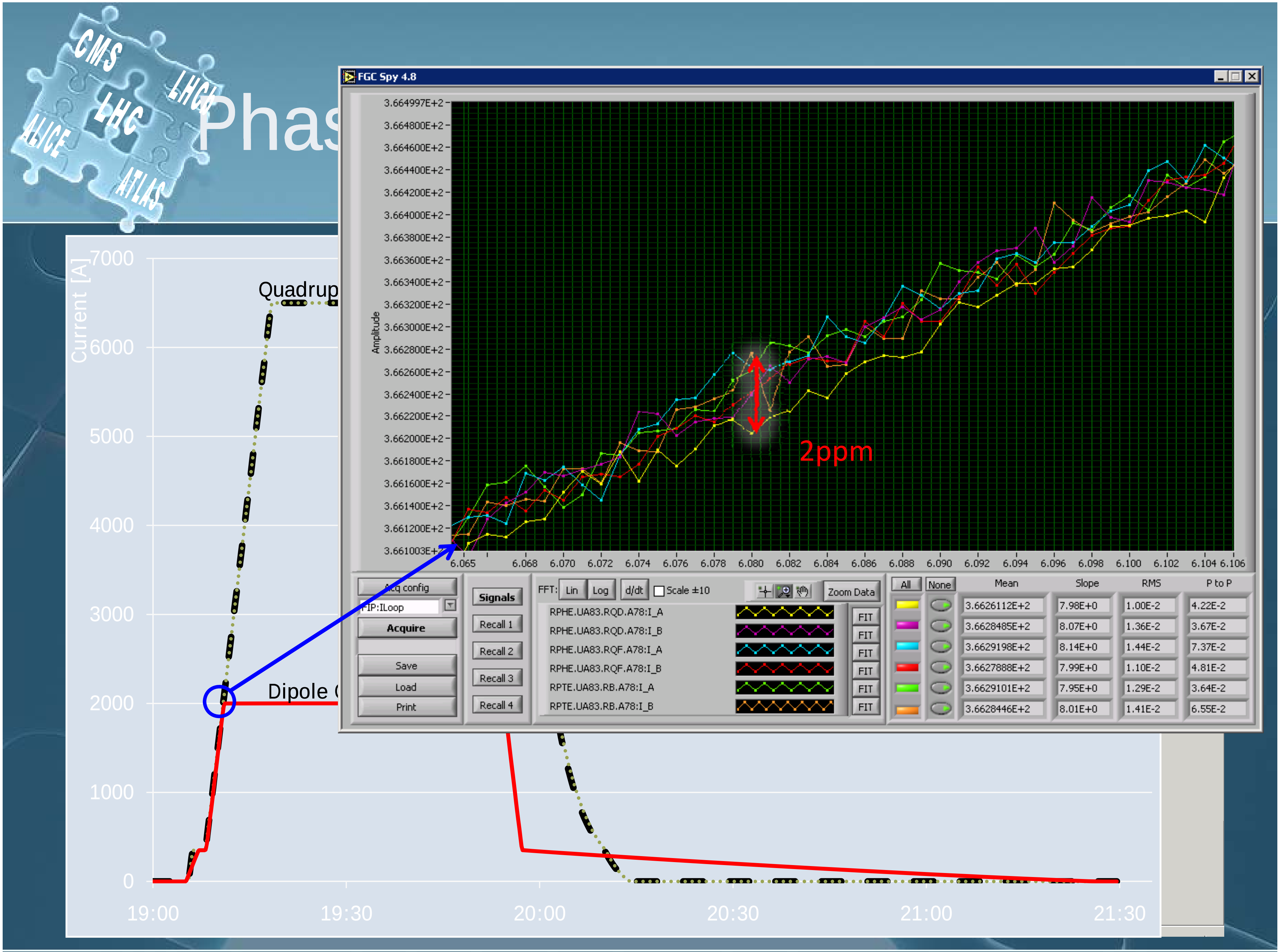


Phase A.5: 450 GeV increasing intensity

- Objectives:
  - Safe machine operation with up to 1.4 10^{13} p+ at 450 GeV
  - Multi-bunch injection commissioned up to 16 x 9 10^{10} p+ and well tuned, including cleaning and protection
  - LHC BIS fully commissioned
  - Commissioning of the Beam Dump System up to 1.4 10^{13} p+ at injection energy
  - Collimators set-up for operation up to 1.4 10^{13} p+ at injection energy, in particular, BLM loss pattern established
  - Improved definition of thresholds for the BLMs
  - Beam instrumentation operational with up to 156 bunches and total intensity of up to 1.4 10^{13} p+
  - RF adjusted for injection and circulating multi bunch operation

Phase A.6: Two beam operation

- Objectives:
  - Establish two safely circulating (unsafe) beams with a lifetime of 5 to 10 hours. Separation bumps fully commissioned
  - Aperture in triplet and IR verified for both beams
  - Interleaved injection working
  - Two beam collimation commissioned


CMS
LHCb
LHC
ALICE
ATLAS
Phas
Current [A]
7000
6000
5000
4000
3000
2000
1000
0
19:00
19:30
20:00
20:30
21:00
21:30
Quadrup
Dipole (
FGC Spy 4.8
Amplitude
3.664997E+2
3.664800E+2
3.664600E+2
3.664400E+2
3.664200E+2
3.664000E+2
3.663800E+2
3.663600E+2
3.663400E+2
3.663200E+2
3.663000E+2
3.662800E+2
3.662600E+2
3.662400E+2
3.662200E+2
3.662000E+2
3.661800E+2
3.661600E+2
3.661400E+2
3.661200E+2
3.661003E+2
6.065
6.068
6.070
6.072
6.074
6.076
6.078
6.080
6.082
6.084
6.086
6.088
6.090
6.092
6.094
6.096
6.098
6.100
6.102
6.104
6.106
2ppm
Acq config
FIP:ILoop
Acquire
Save
Load
Print
Signals
Recall 1
Recall 2
Recall 3
Recall 4
FFT: Lin Log d/dt Scale ±10
Zoom Data
RPHE.UA83.RQD.A78:I_A
RPHE.UA83.RQD.A78:I_B
RPHE.UA83.RQF.A78:I_A
RPHE.UA83.RQF.A78:I_B
RPTE.UA83.RB.A78:I_A
RPTE.UA83.RB.A78:I_B
FIT
All
None
Mean
Slope
RMS
P to P
3.6626112E+2 7.98E+0 1.00E-2 4.22E-2
3.6628485E+2 8.07E+0 1.36E-2 3.67E-2
3.6629198E+2 8.14E+0 1.44E-2 7.37E-2
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3.6629101E+2 7.95E+0 1.29E-2 3.64E-2
3.6628446E+2 8.01E+0 1.41E-2 6.55E-2

Phase A.8: Snap-back & Ramp

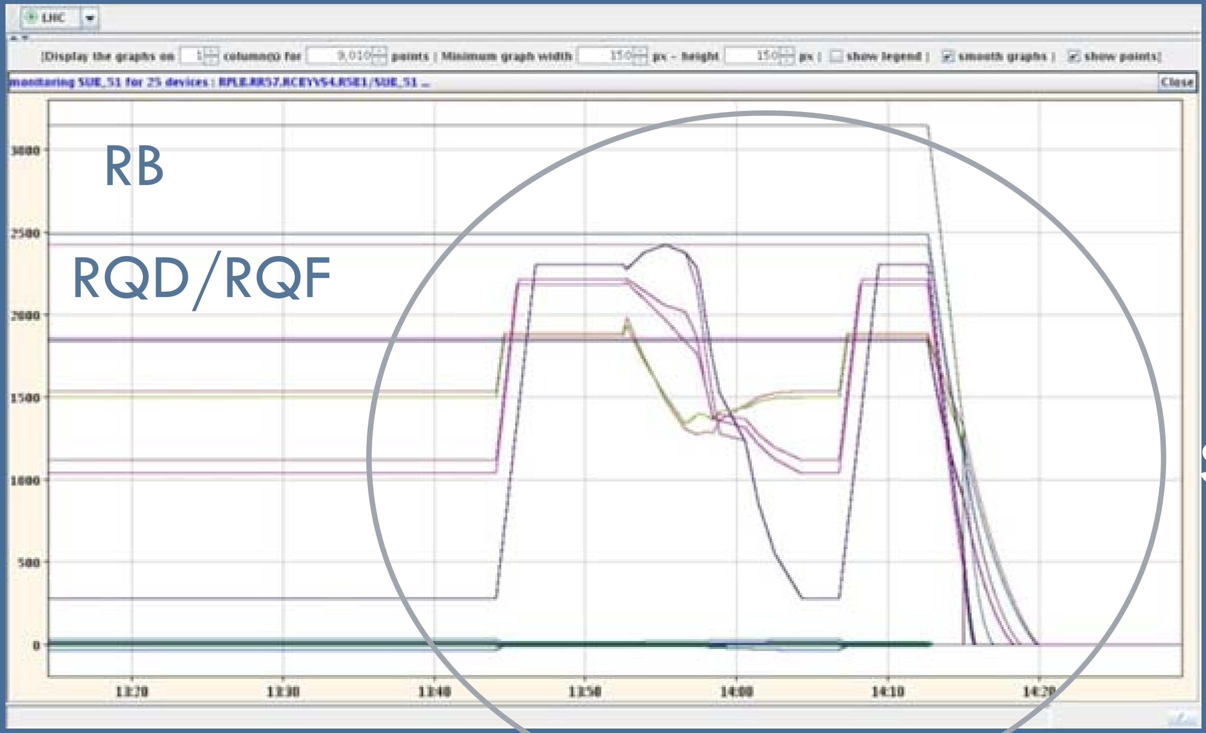
- The magnetic field (the current) in a magnet decays when the current is kept constant, like for example during the injection phase in LHC.
- The decay of the current gets manifested as a:
  - DECAY of the multiple errors seen by the beam at constant current;
  - Fast recovery (SNAP-BACK) when the current is varied again.
- The source of this effect is mainly the Eddy currents flowing in the superconducting cables.

Phase A.9: Top energy checks

- Objectives:
  - Measure and correct the optics at 7 TeV before colliding/squeezing beams: orbit, tunes, coupling, chromaticity and beta beat
  - Transition from injection optics to un-squeezed collision optics
  - Aperture measurements at 7 TeV
  - Disentangling of triplet alignment errors and D1/D2 transfer function errors; set good conditions for squeeze
  - Optimization of beam lifetime
  - Optimization of the Beam Dump System before we start collisions or squeeze, and before we increase intensity

Phase A.10: Top energy collisions
Phase A.11: Top energy squeeze

ARC+ML6+LR5 (156 PCs) @ 5 TeV



SQUEEZE