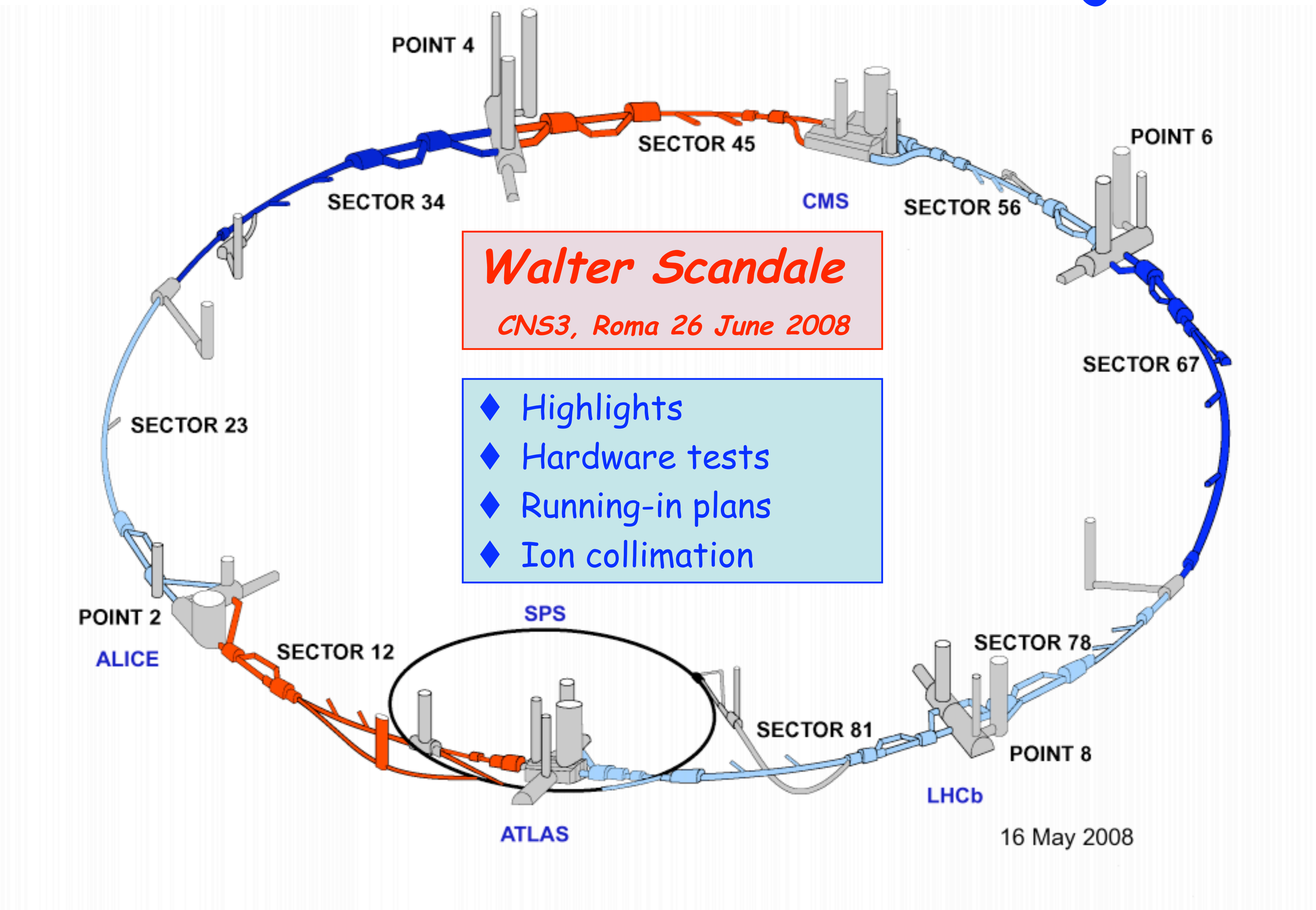
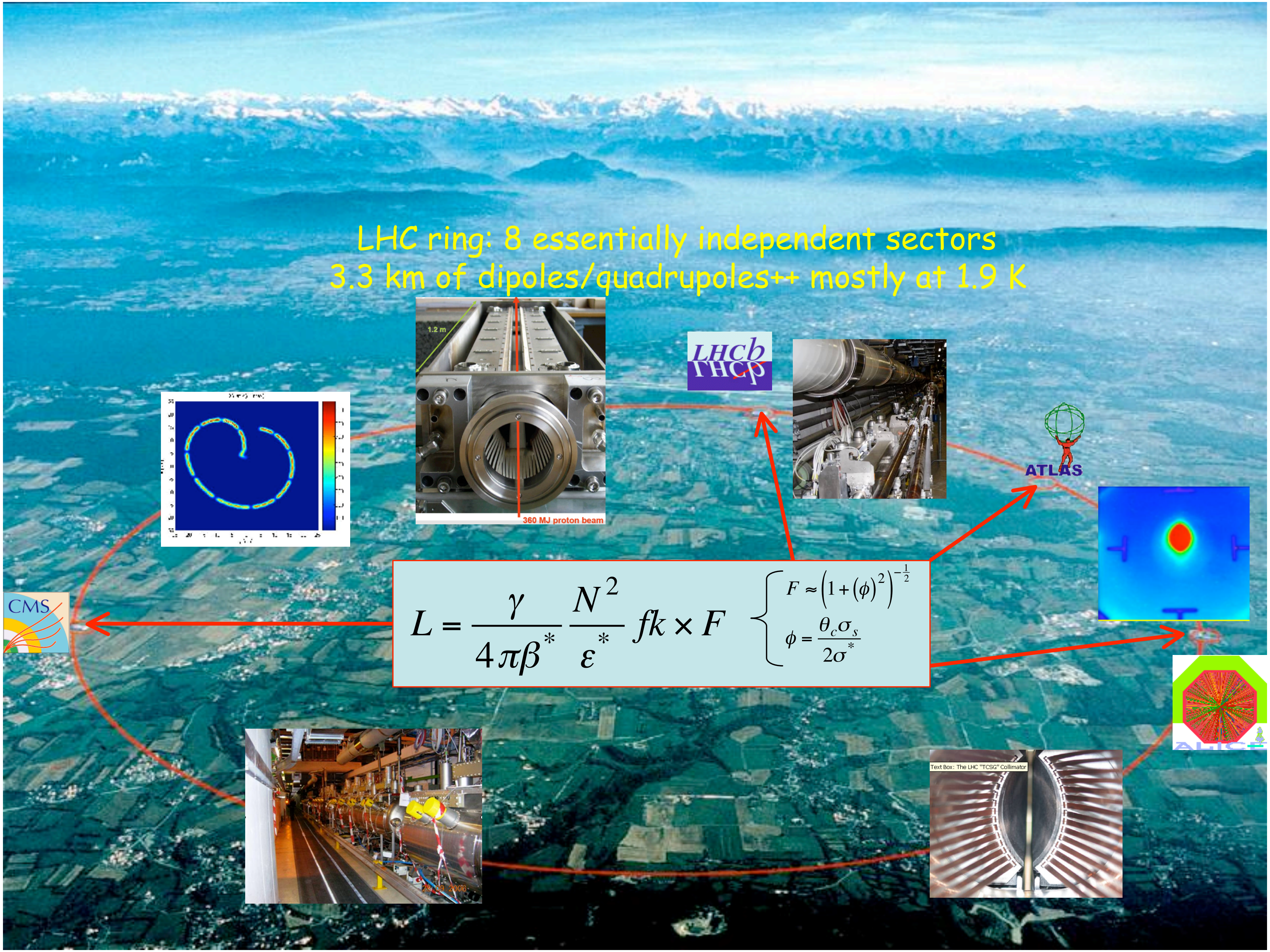
Status of the LHC Project



Walter Scandale

CNS3, Roma 26 June 2008

- Highlights
- Hardware tests
- Running-in plans
- Ion collimation


LHC ring: 8 essentially independent sectors
3.3 km of dipoles/quadrupoles++ mostly at 1.9 K
1.2 m
360 MJ proton beam
LHCb
ATLAS
CMS
Text Box: The LHC "TCSG" Collimator
$$L = \frac{\gamma}{4\pi\beta^{*}} \frac{N^{2}}{\varepsilon^{*}} fk \times F \quad \begin{cases} F \approx \left(1 + (\phi)^{2}\right)^{-\frac{1}{2}} \\ \phi = \dfrac{\theta_{c}\sigma_{s}}{2\sigma^{*}} \end{cases}$$

...towards circulating beams - summer 2008

Installation

Interconnection

Pressure tests
(vacuum leaks, design faults)

Electrical quality assurance
(earth faults, bad splices...)

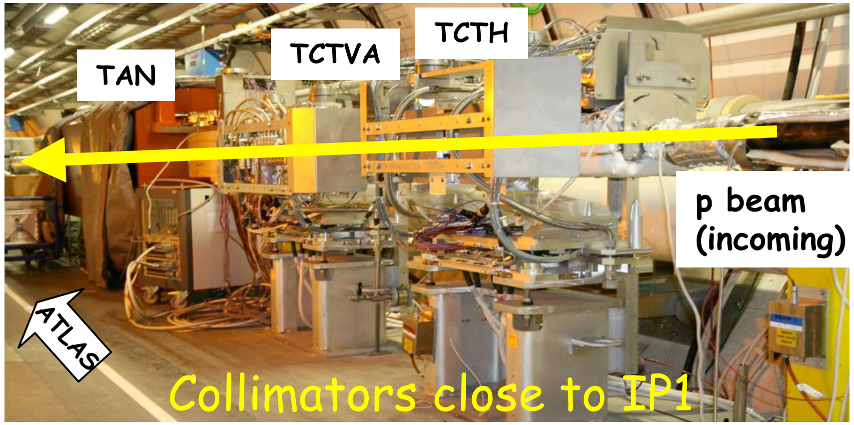
done

Cool-down
(cryogenics, vacuum leaks)

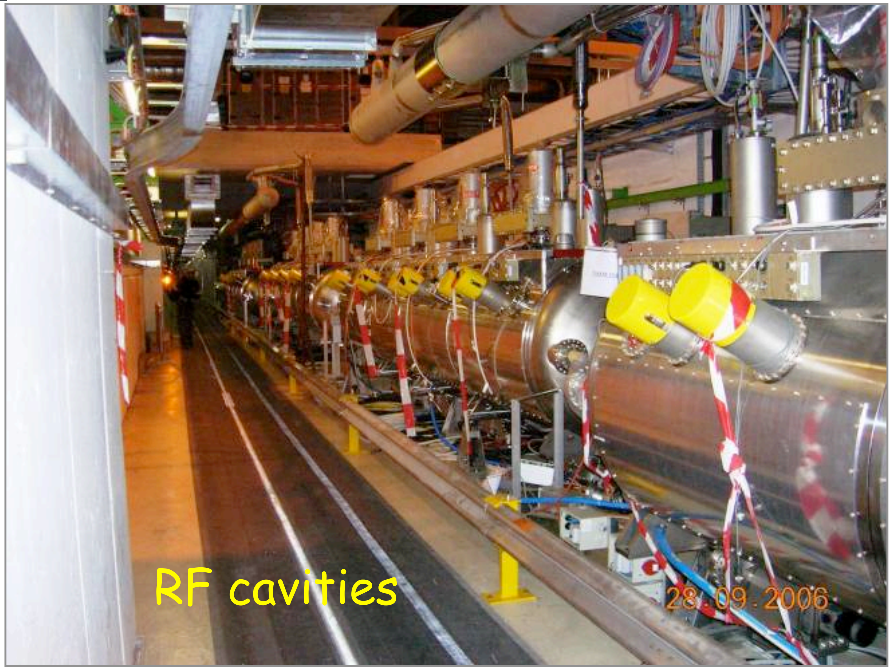
Hardware Commissioning
(Quenches, electrical problems, non-conformities)

in progress

Installation completed: not only main magnets !

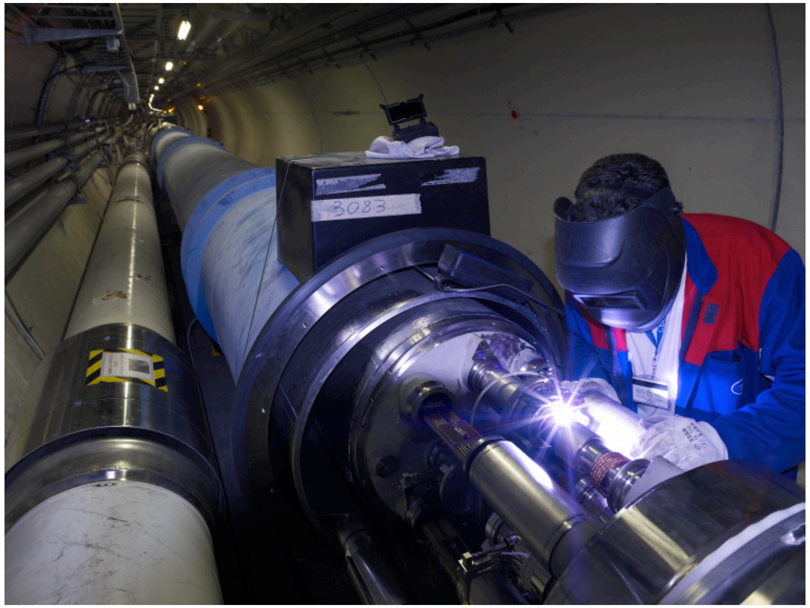


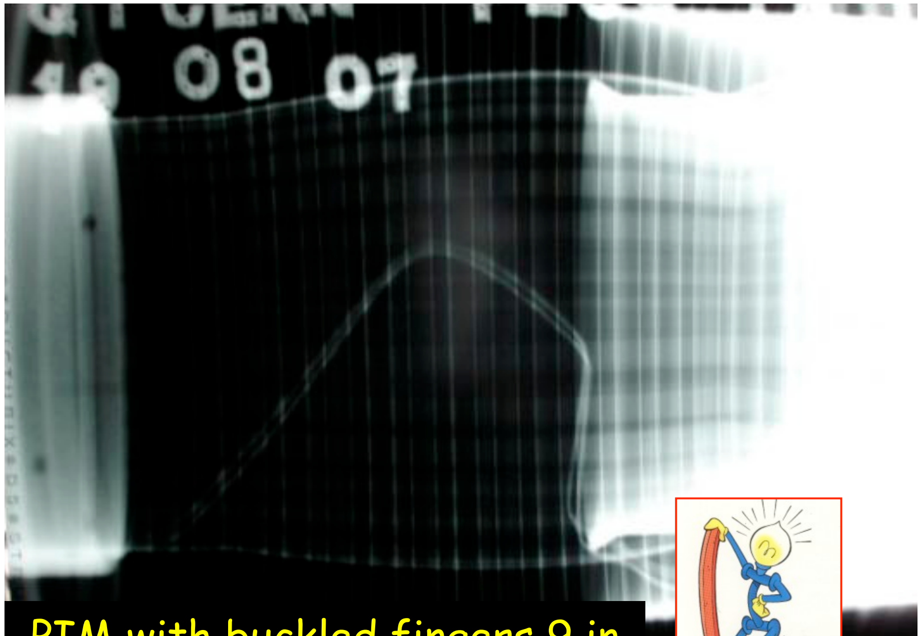
- Main magnets
- RF
- collimators,
- beam dump,
- injection hardware,
- instrumentation
- etc…



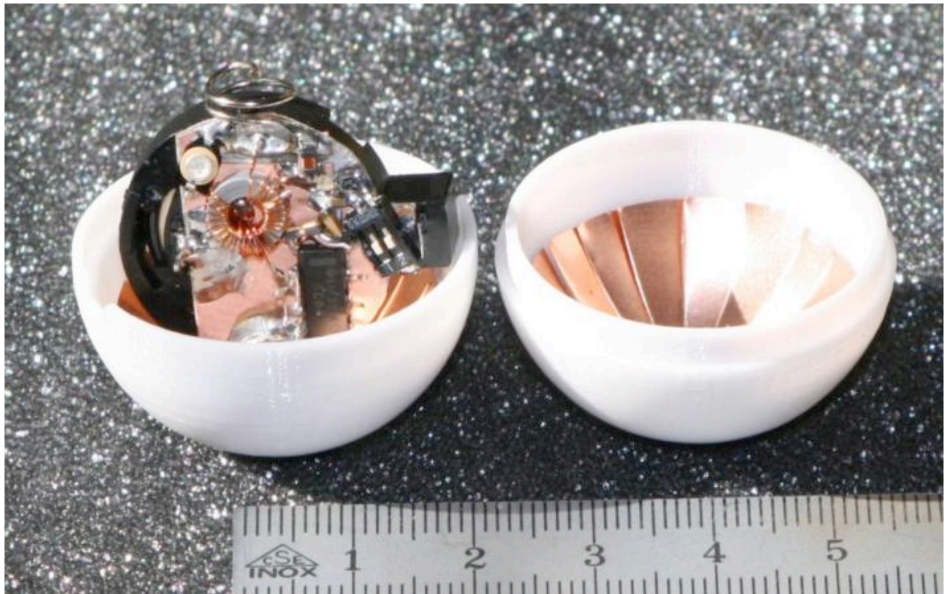
Magnet interconnections

- Vacuum, bellows, RF contacts plus leak checks
- Thermal shield, heat exchanger
- Bus bars: superconducting splices x 10,000 (induction welding)
- Corrector circuits: splices x 50,000 (ultrasonic welding)





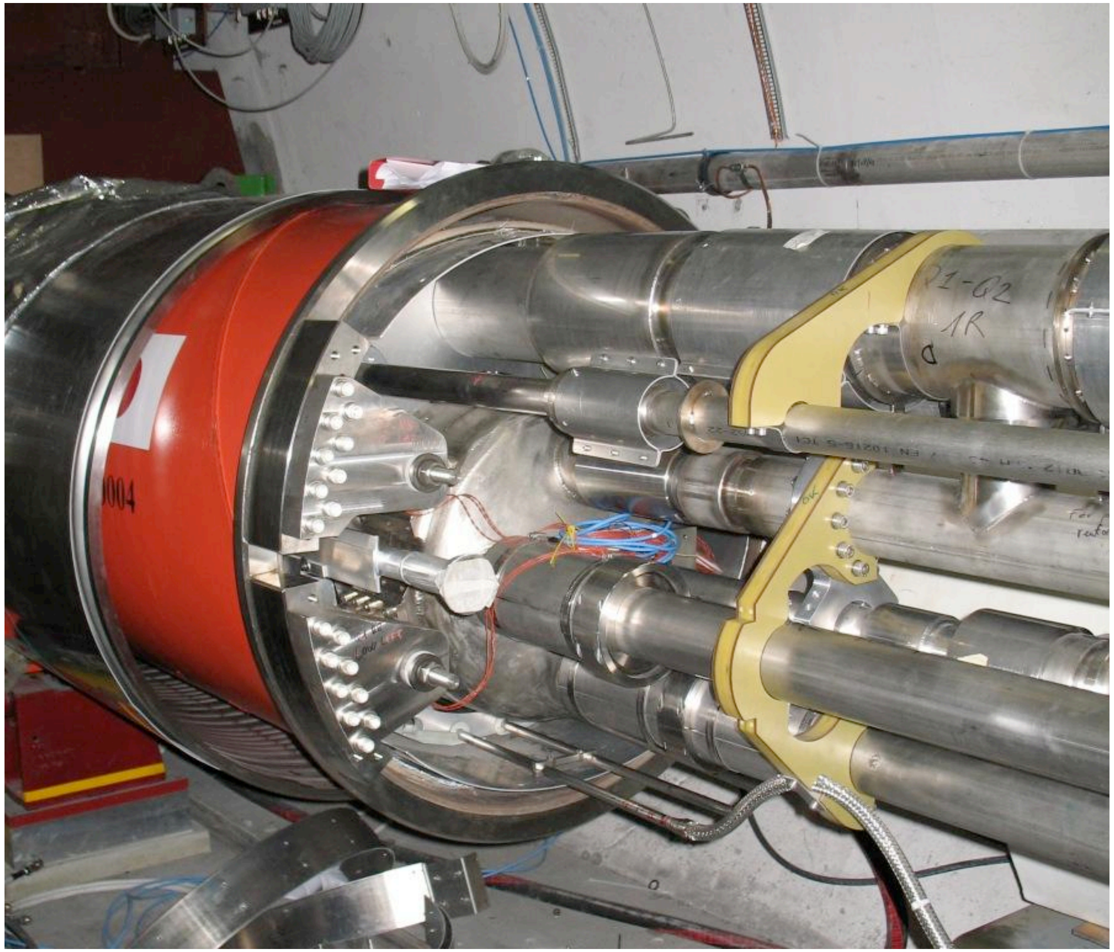
PIM with buckled fingers 9 in sector 78 and 12 in sector 45



40 MHz RF emitter to search buckled fingers
BPM detect the passage of the ball

Pressure and electrical tests

- 1695 magnet-to-magnet interconnections
- 224 magnet-to-QRL interconnections



Per interconnection

- 18 assembly actions
- 9 mechanical intervention
- 5 leak tightness checks
- 5 electrical tests
- 1 RF test

Localization of electrical faults:

- **At warm**: measure voltage drop
- **At cold**: time domain reflectometry (time of flight of em waves propagating from the fault location)

Assembly | Cool down | Powering

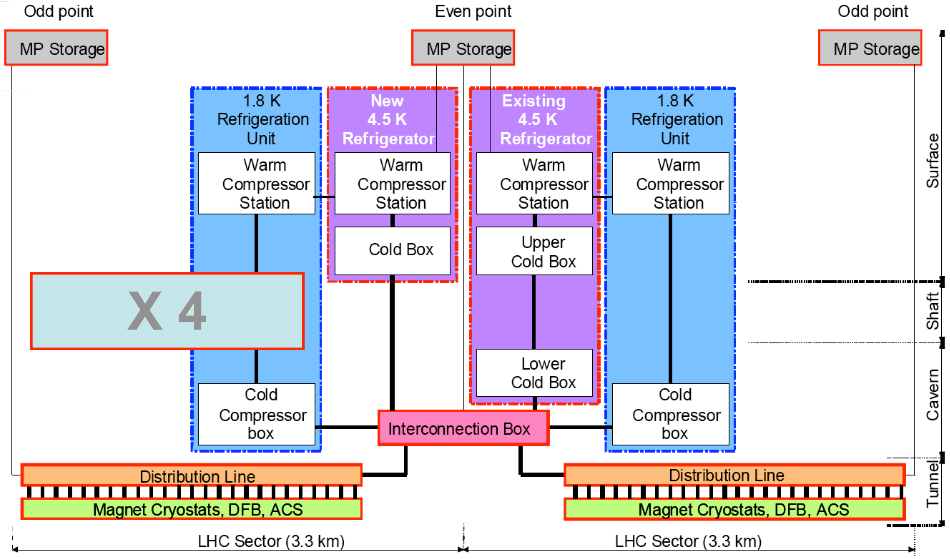
ELQA @ Warm | ELQA @ Cold

Closure of continuous cryostat - November 07

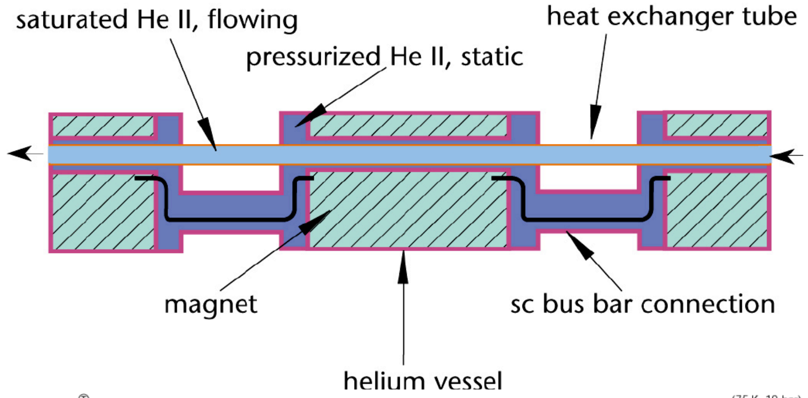
Hardware Commissioning (HWC)…in progress

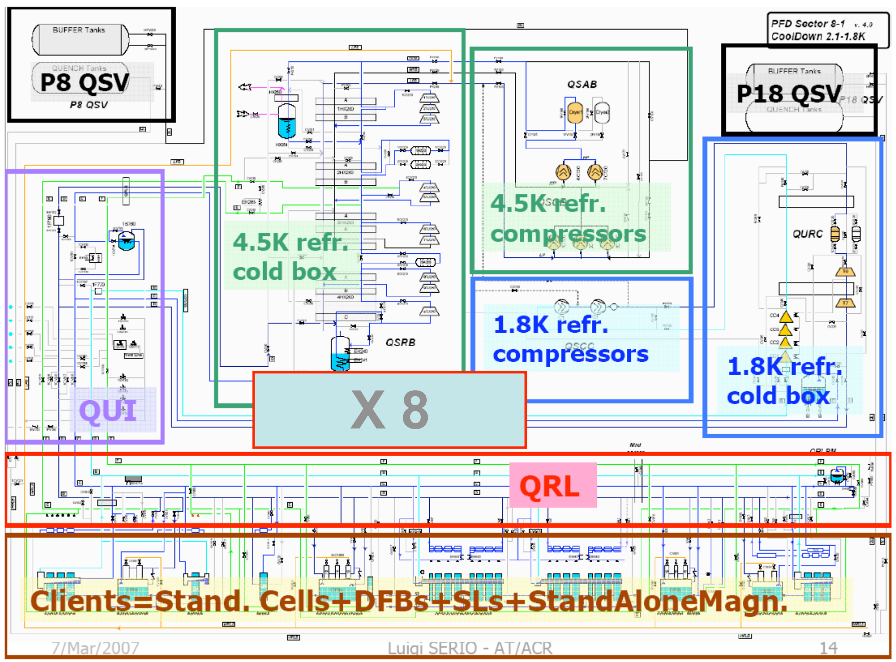
- Commissioning of continuous arc cryostat & LSS cryostats (insertion quadrupoles…, inner triplet, etc.)
  - **Cryogenics, Vacuum, QPS, PIC, Powering**:
    - Electrical Quality Assurance,
    - Tests prior to powering,
    - **Powering (QPS, PC, MPS) of all circuits one by one**,
      - Magnets, busbars, DFBs, services, UPS, AUG, controls…
    - **Powering of all the circuits of a sector together**
    - Power converters: protection, calibration, ramp tests performed
    - Interlocks, compatibility tests, protection tests

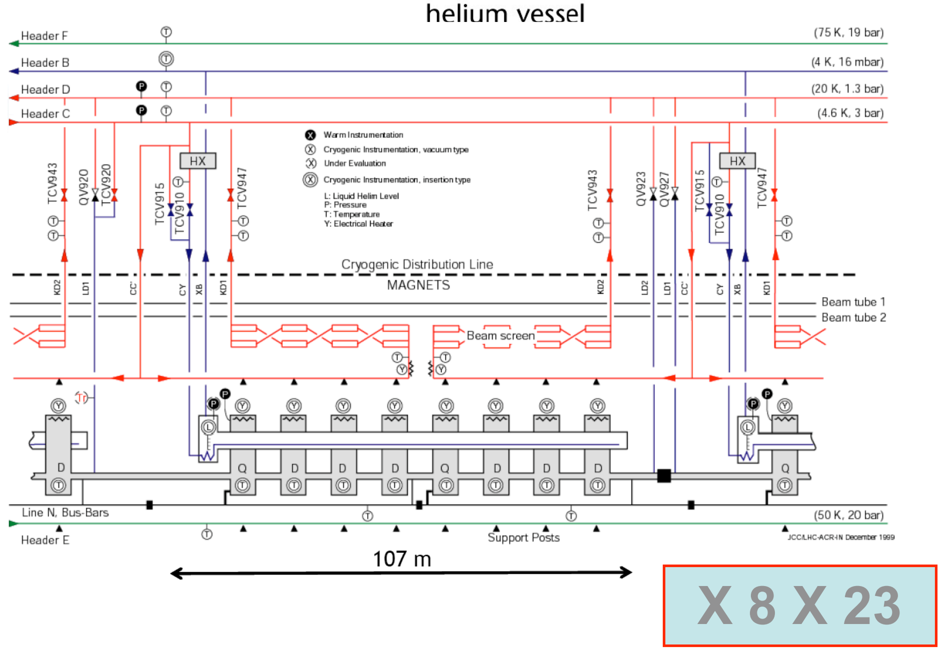
Cryogenics – a huge system



- ~120 tonnes of He
- 10,000 tonnes LN2
- Cold mass 31,000 tonnes







Towards nominal conditions

- Time for getting nominal conditions:
  - Presently 10 weeks for getting nominal conditions,
  - In routine operation, about 1 month is foreseen,

	CW1	CW2	CW3	CW4	CW5	CW6	CW7	CW8	CW9	CW10
Today for HWC	Purge & leak test	Flushing		Cool-down 300-5 K					Filling, CD 1.9 K & cryo-tuning	
Nominal after a routine shutdown	Pur-ge / Cool-down 300-5 K			Filling, CD 1.9 K & cryo-tuning						

- LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide.
- Operation for the needs of Sector HWC is now demonstrated.
- Based on experience, together with procedures and tools being put in place, availability must be improved for the next phase: The Beam Commissioning.

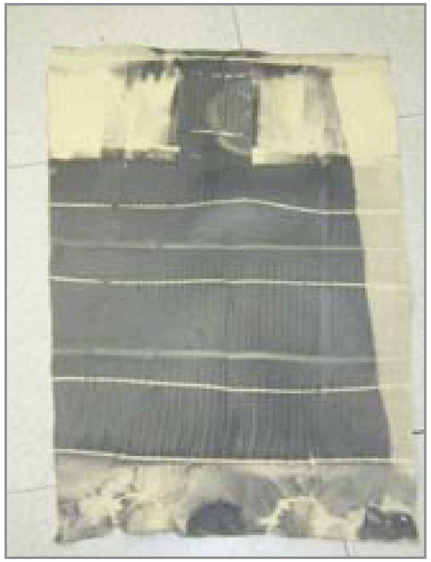
Cryogenics flushing…

QUI return line filter after 1st phase of flushing QRL81

20 h / 260g/s – C to D

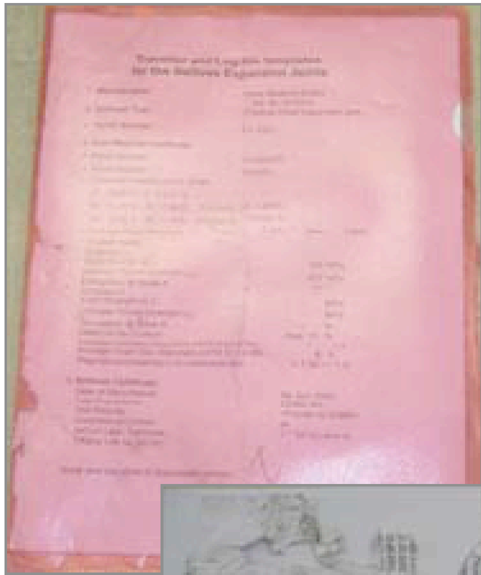
20 h / 160g/s – C to B

20h / 210g/s – E/F to D



SC - 21Sept'07

New dust since 2005!



Paper found in line E when connecting QRL81 to QUI

Paper found at end of line E, blocking valve CV994 in QRL Return Module

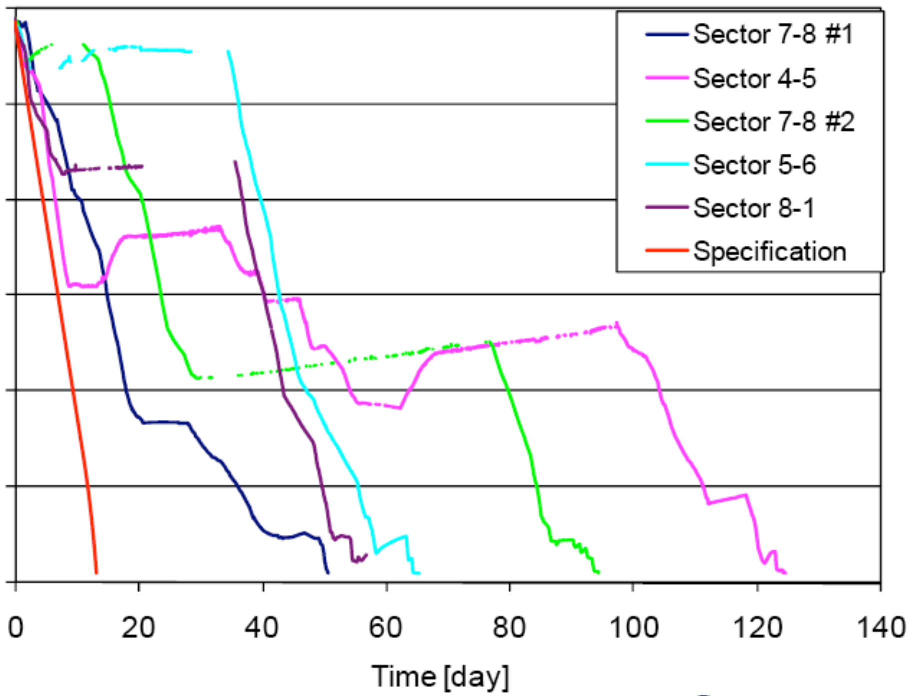
Valve in B blocked in QUI (more plastic ?)

Duration of the cool down

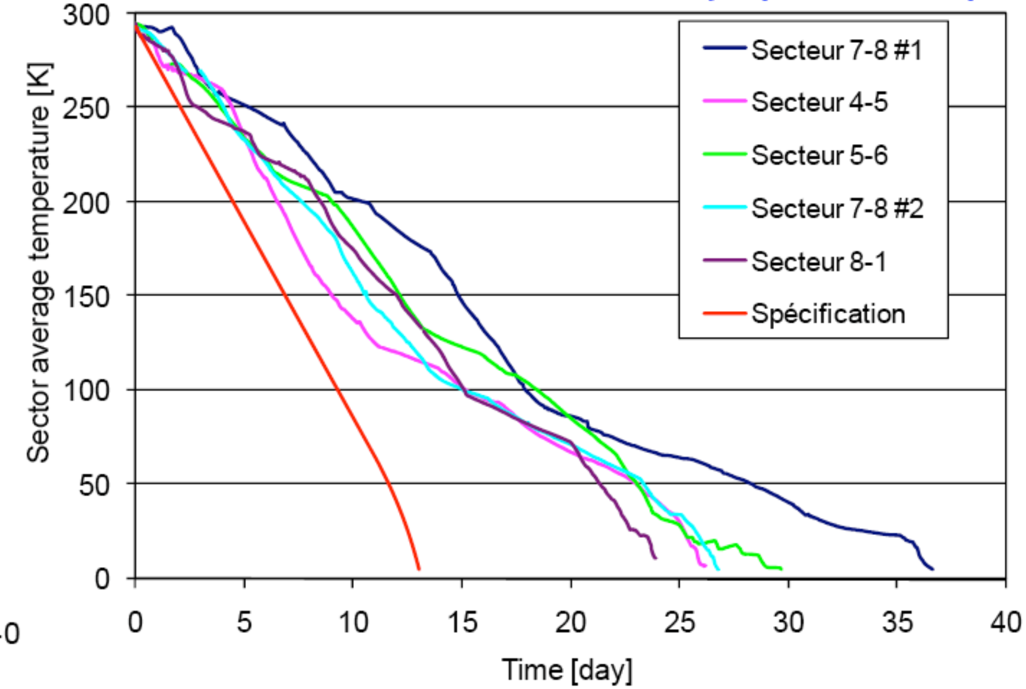
Cool-down time hampered by:

- external factors (leaks, electrical short-circuits, electrical control plateaus),
- cryogenic stops (utility loss, cryogenic problems),
- cryogen logistics management (week-ends, nights…),
- cryoplant and tunnel cooling loops tuning and limitations.

Total

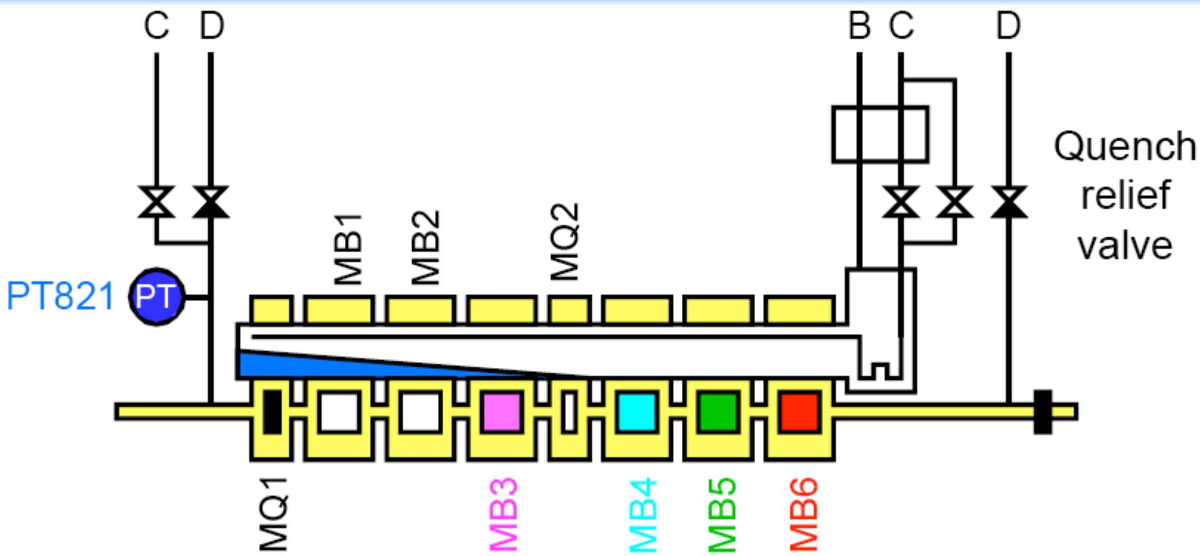


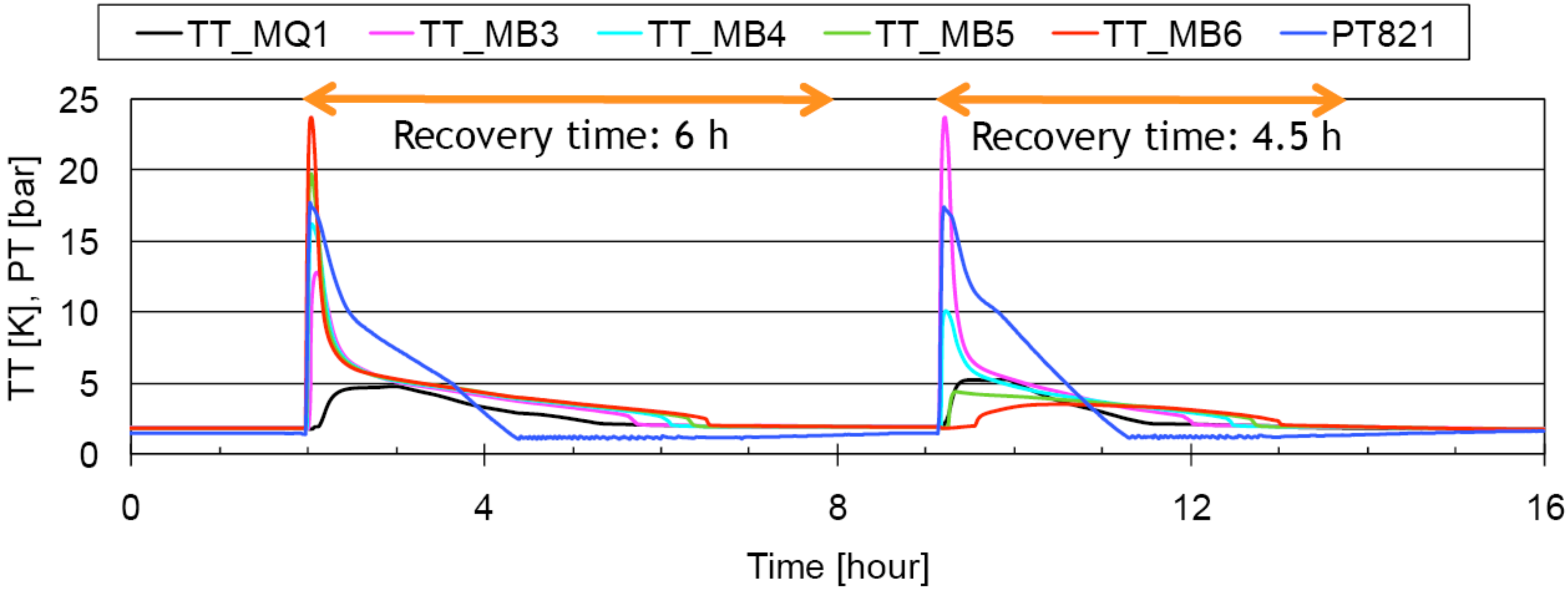
w/o external factors & cryoplant stops



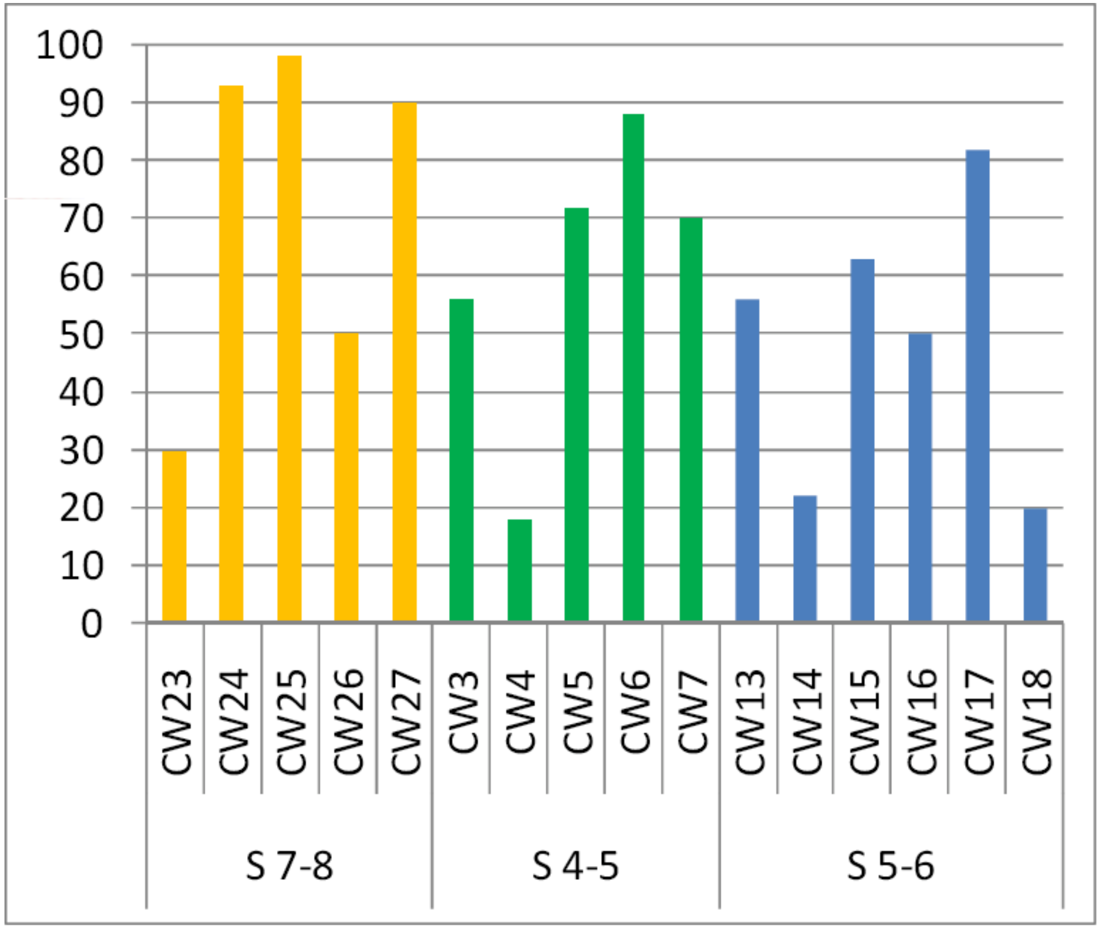
Room for improvement !

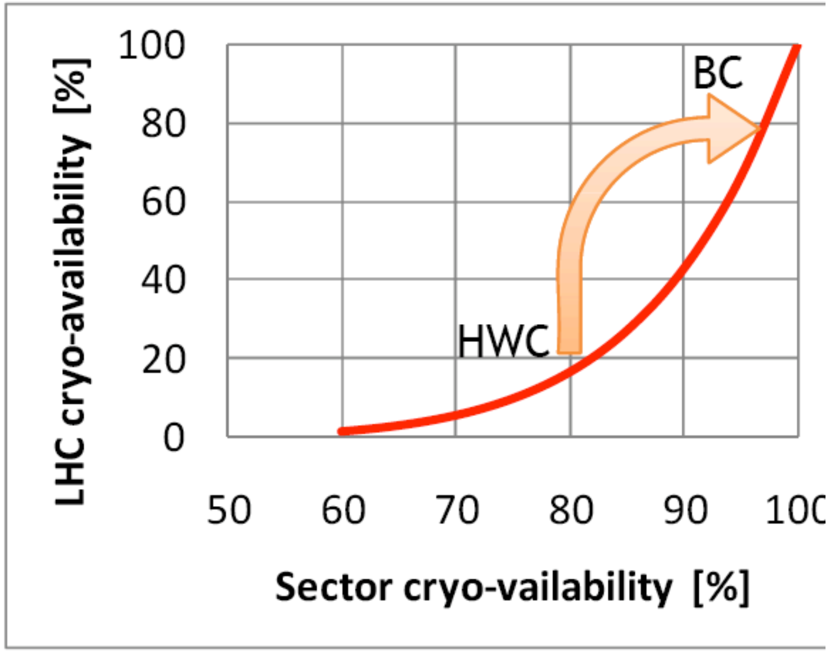
Quench recovery





Availability for power tests

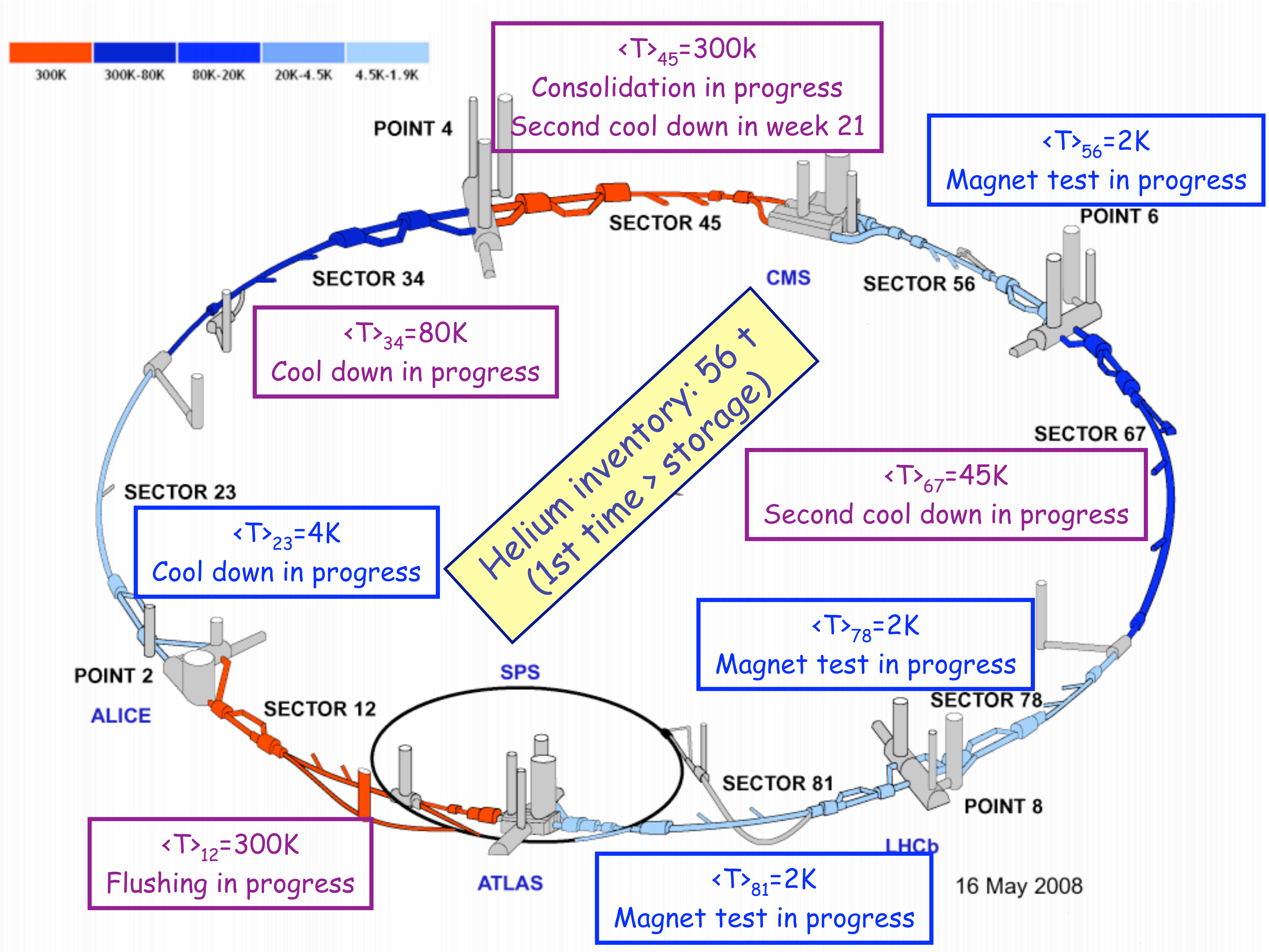




(Considering independent origins of problems)

- Availability for sector HWC : 80 % during weeks w/o resistive transition
- To be improved during beam commissioning: more than 95 % per sector
  Note : A cryogenic system takes time (hours) to recover any kind of stop !

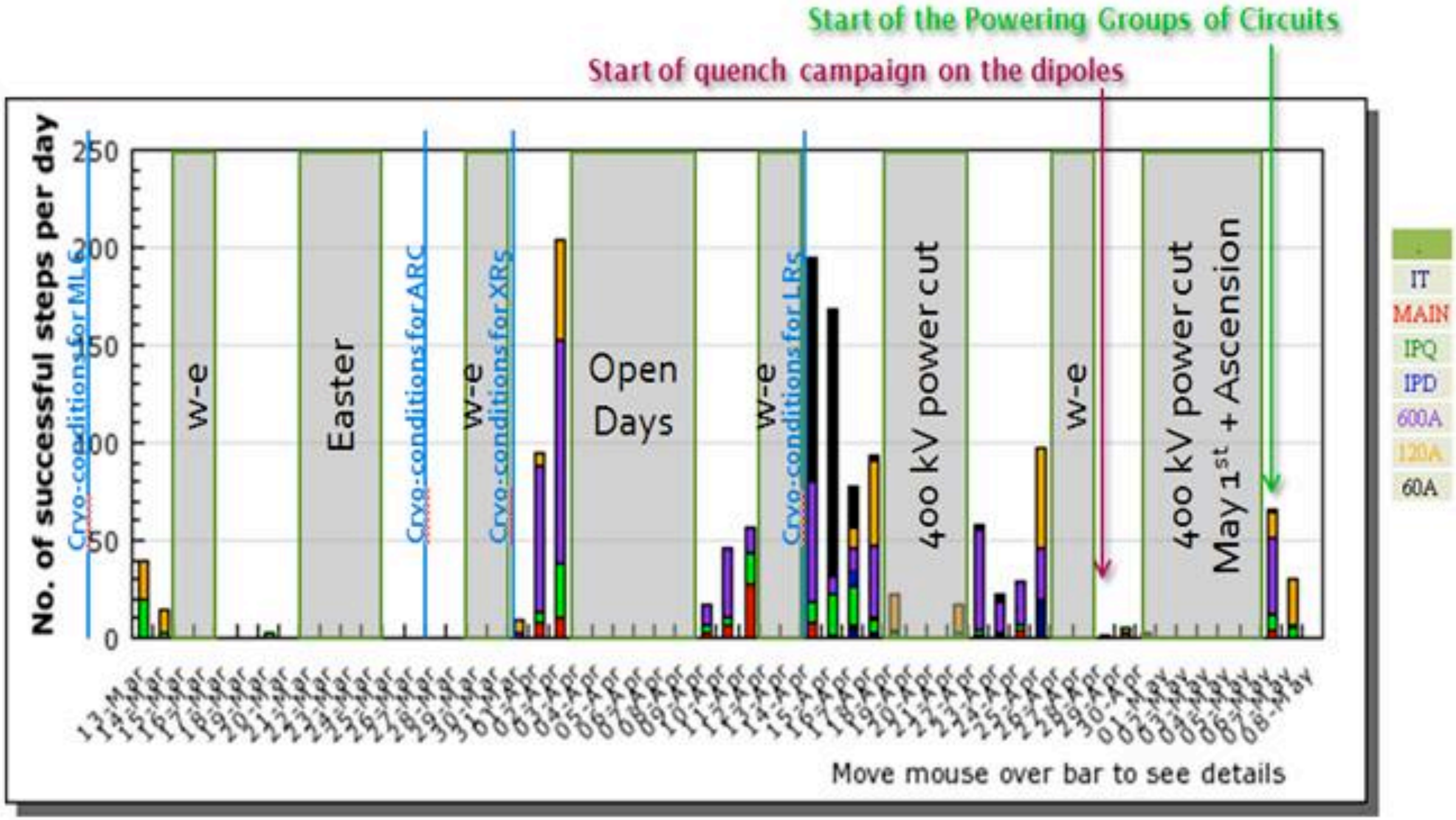
Cool-down in progress

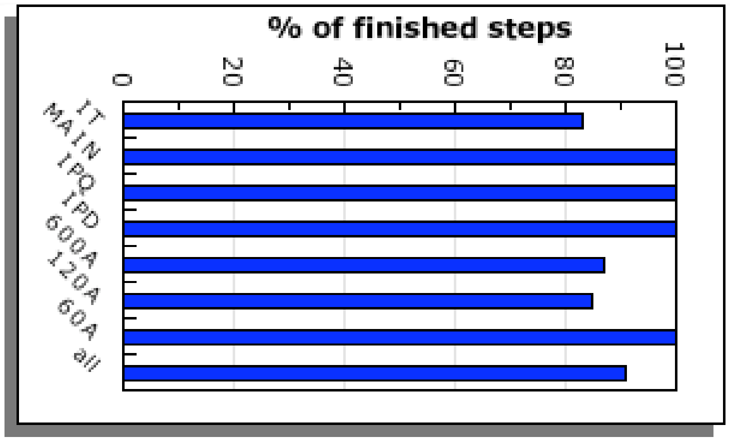


Cool-down in progress

sector	Average T [K]	status
12	300	flushing
23	4	Cool down
34	80	Cool down
45	300	Commissioning to 5 TeV (except for the triplet) Inner triplet connected Consolidation completed Second cool down starting
56	2	Fully commissioned to 5 TeV Dipoles and quadrupoles being trained to 7 TeV
67	45	Cool down
78	2	Partially tested in June 07 Inner triplet connected Powering test in progress
81	2	Powering test in progress

Powering test in Sector 56





Training campaign in Sector 56

dipoles

$I_{nominal}$=11796 A

☹ slow growth ☹

Remedy:
5 TeV beam commissioning

Current [A]	Equivalent Energy [TeV]	Magnet (Position)	Date
10004	5.91	3362 (A28L6) - 2245 (B29R5)	28/04/08
10227	6.04	3370 (A29L6)	28/04/08
10357	6.12	3372 (A23L6)	29/04/08
10546	6.23	3188 (A15R5)	30/04/08
10652	6.29	3368 (C32R5)	06/05/08
10714	6.33	3246 (A10L6) - 3387 (C16L6)	07/05/08
10751	6.35	3335 (A21R5)	09/05/08
10793	6.38	3337(B8R5)	15/05/08
10834	6.40	3357 (A20L6)	16/05/08

…and quadrupoles

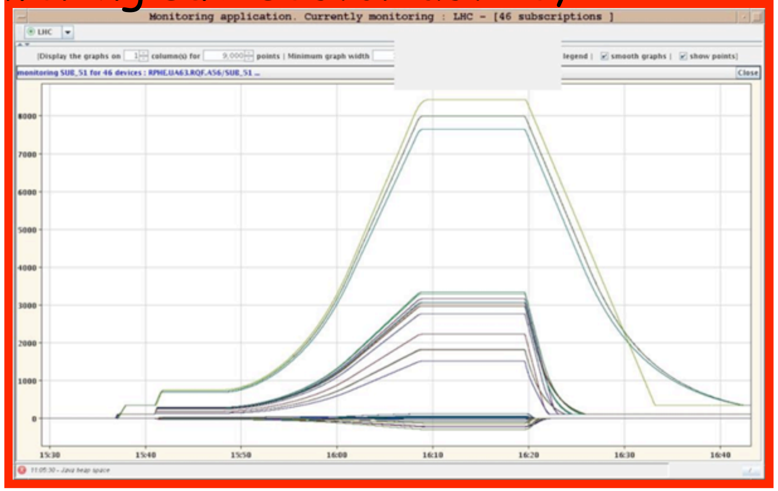
$I_{nominal}$=11870 A

Current [A]	Magnet Position	Date
11280	251(14R5)	09/05/08

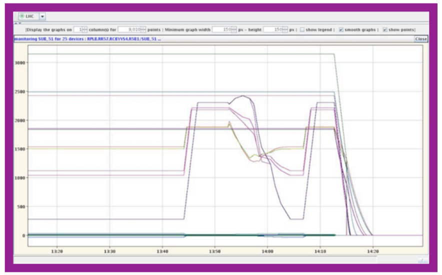
Powering tests in Sector 56

♦ Global Protection Mechanism for the ARC powering sub-sector active,

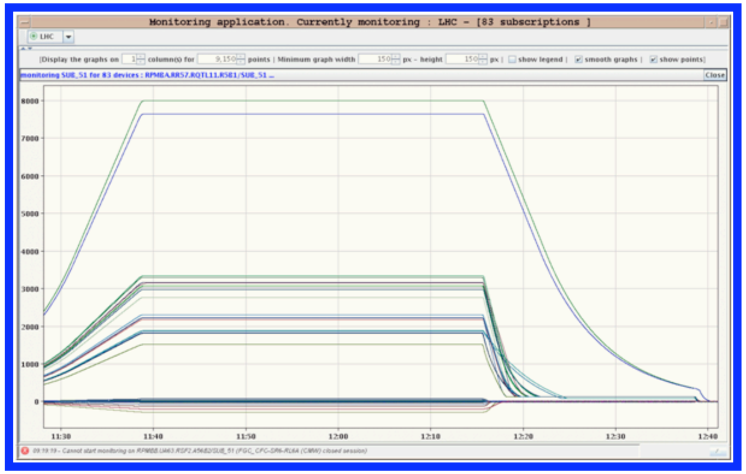
- ♦ PGC (Powering Groups of Circuits) test
  - ➢ 168 converters, in the arc
  - ➢ all circuits of the matching sections
  - ☺ up to 5 TeV equivalent current



- ♦ Powering of the two matching sections
  - ➢ 8 converters
  - ☺ up to nominal current

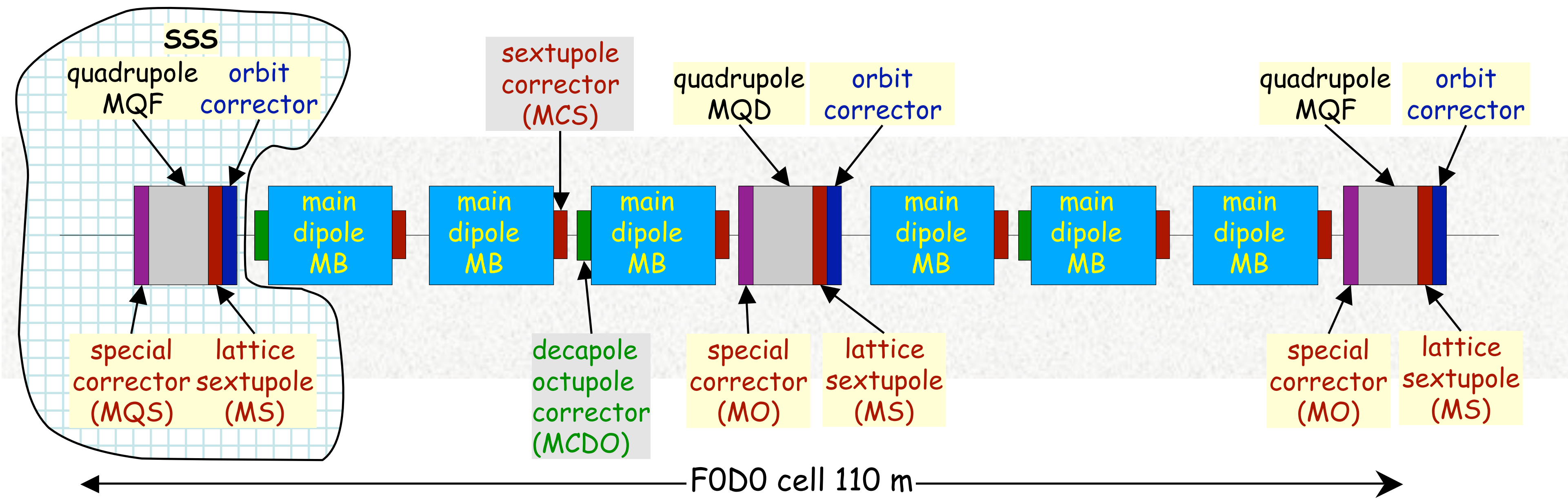


- ♦ Test of the arc + 2 matching sections
  - ➢ 176 converters, in total
  - ☺ up to 5 TeV equivalent current

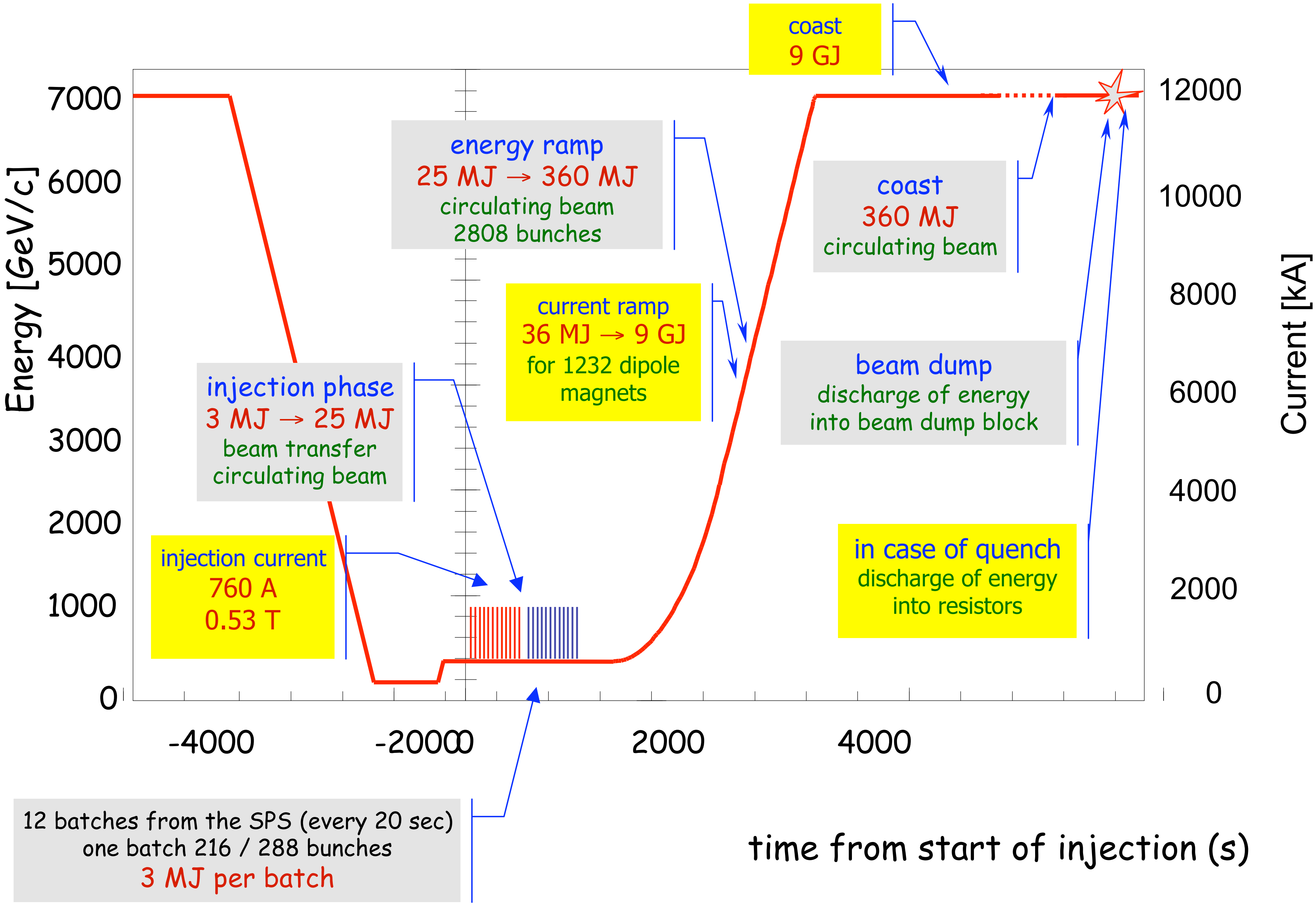


Test of electrical circuits

- Magnets can be **powered in series** or **individually**
  - Per octant 1618 electrical circuits grouped into nine "**Electrical Circuit Types**"
    - eight types for superconducting magnets (+ one for nc magnets),
      - main dipole (12 kA, 1.2 GJ)
      - lattice sextupole per octant
      - multipoles and other correctors
    - many individual circuits
      - 256 individual orbit corrector (60 A, 9 kJ)
      - and trim quadrupoles and other correctors (80 - 600 A)
- ✓ risks, magnet protection, interlocks, commissioning procedures, etc.



Beam versus em energy



Machine Protection

Dealing with em energy

- During commissioning and operation of the powering system all the SC magnets and current leads must be protected
- The magnet protection and powering interlock systems become operational during this time, long before starting beam operation
- **In case of failure, the energy of the superconducting magnets must be discharged into resistors**

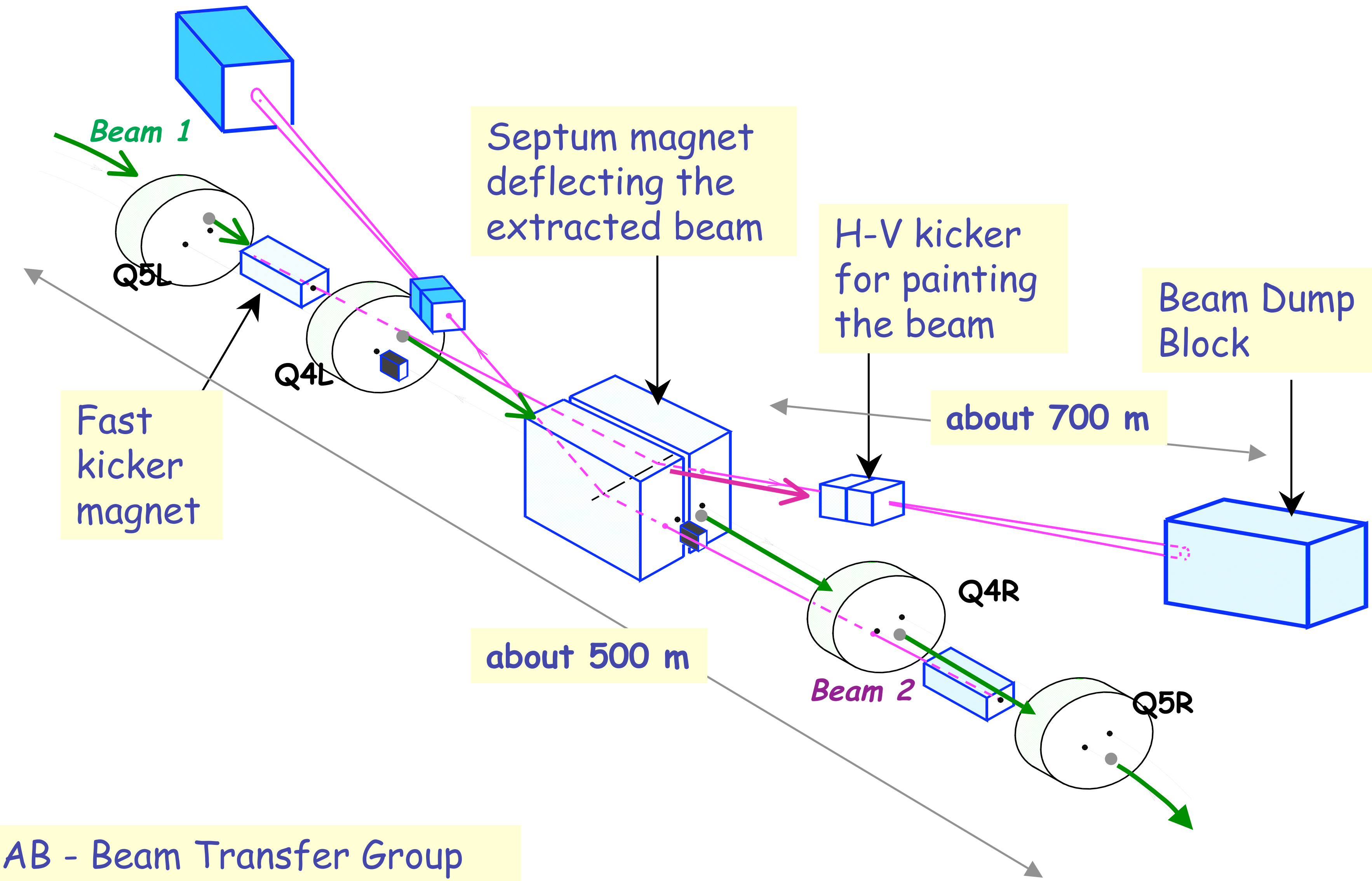
Dealing with beam energy

- During beam commissioning and operation: protection from the injection process, during the energy ramps and at 7 TeV is mandatory
- **The only component that can stand a loss of the full beam is the beam dump block - all other components would be damaged**
- The LHC beams must ALWAYS be extracted into the beam dump blocks, at the end of a fill and in case of failure

- **In general, an electrical circuit failure leads to beam extraction**

Beam dumping system in IR6

To be tested during beam commissioning



AB - Beam Transfer Group

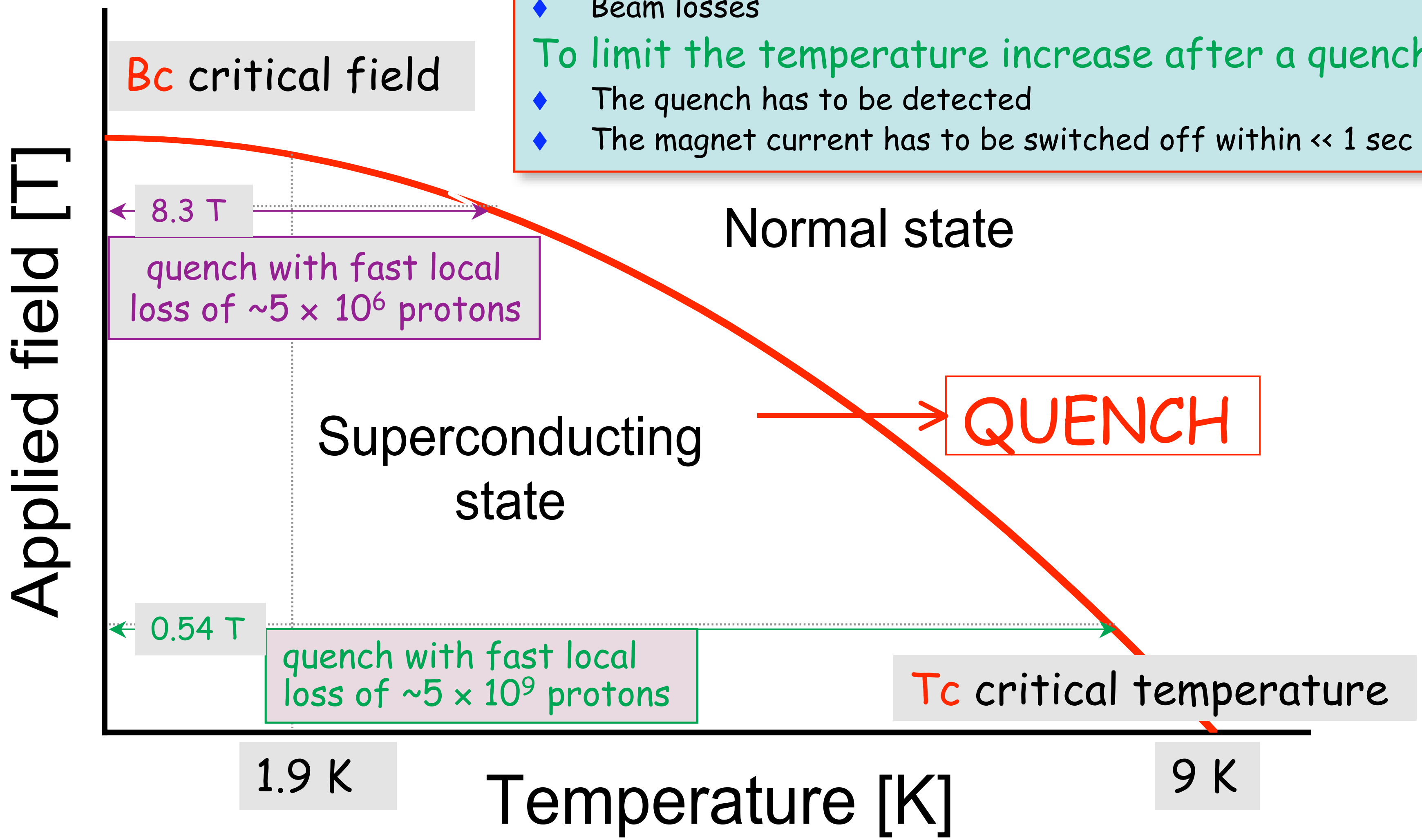
Operational margin

Quenches are initiated by a mJ energy deposit

- Movement of the superconductor by several μm (friction and heat dissipation)
- Failure in cooling
- Beam losses

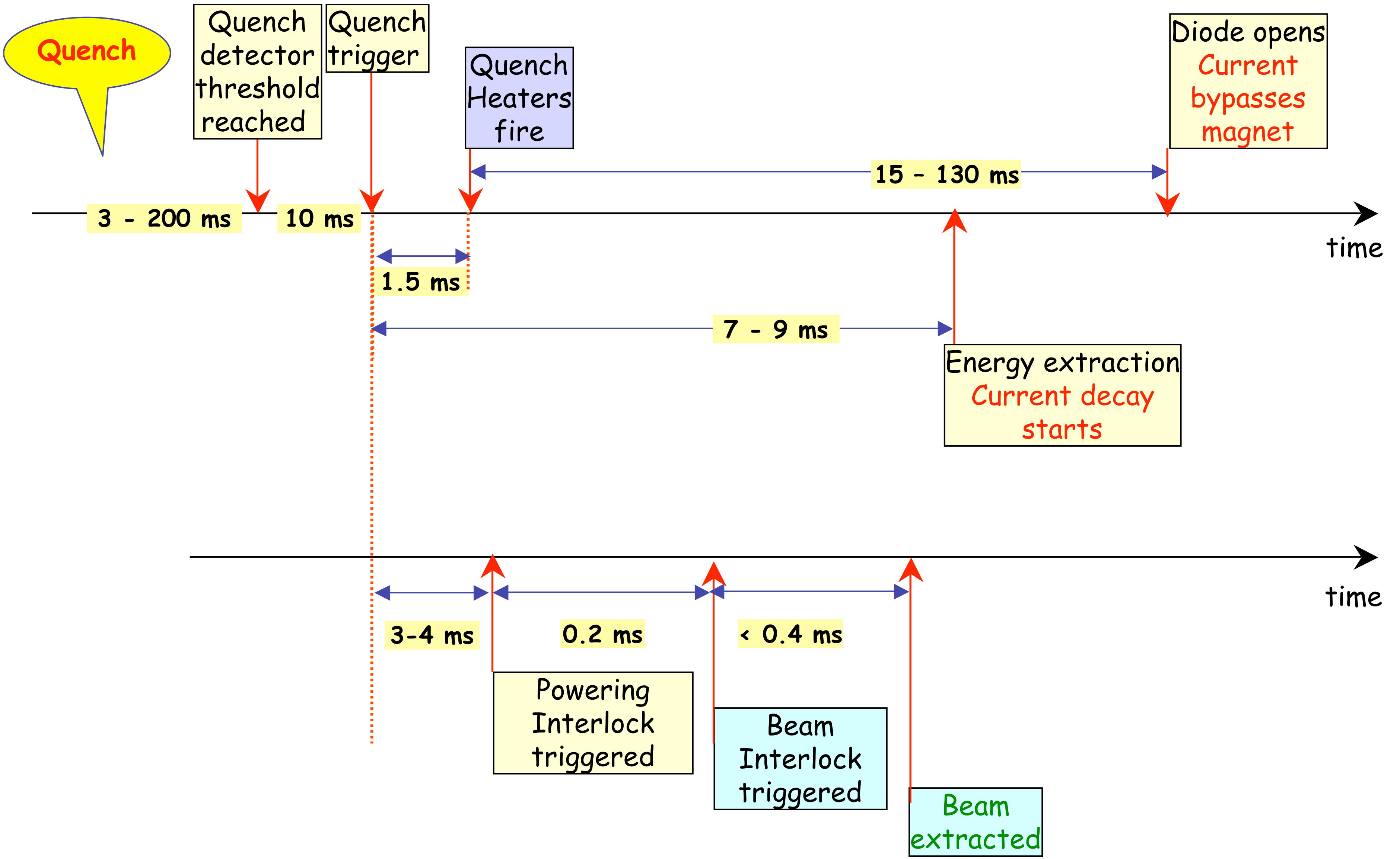
To limit the temperature increase after a quench

- The quench has to be detected
- The magnet current has to be switched off within « 1 sec

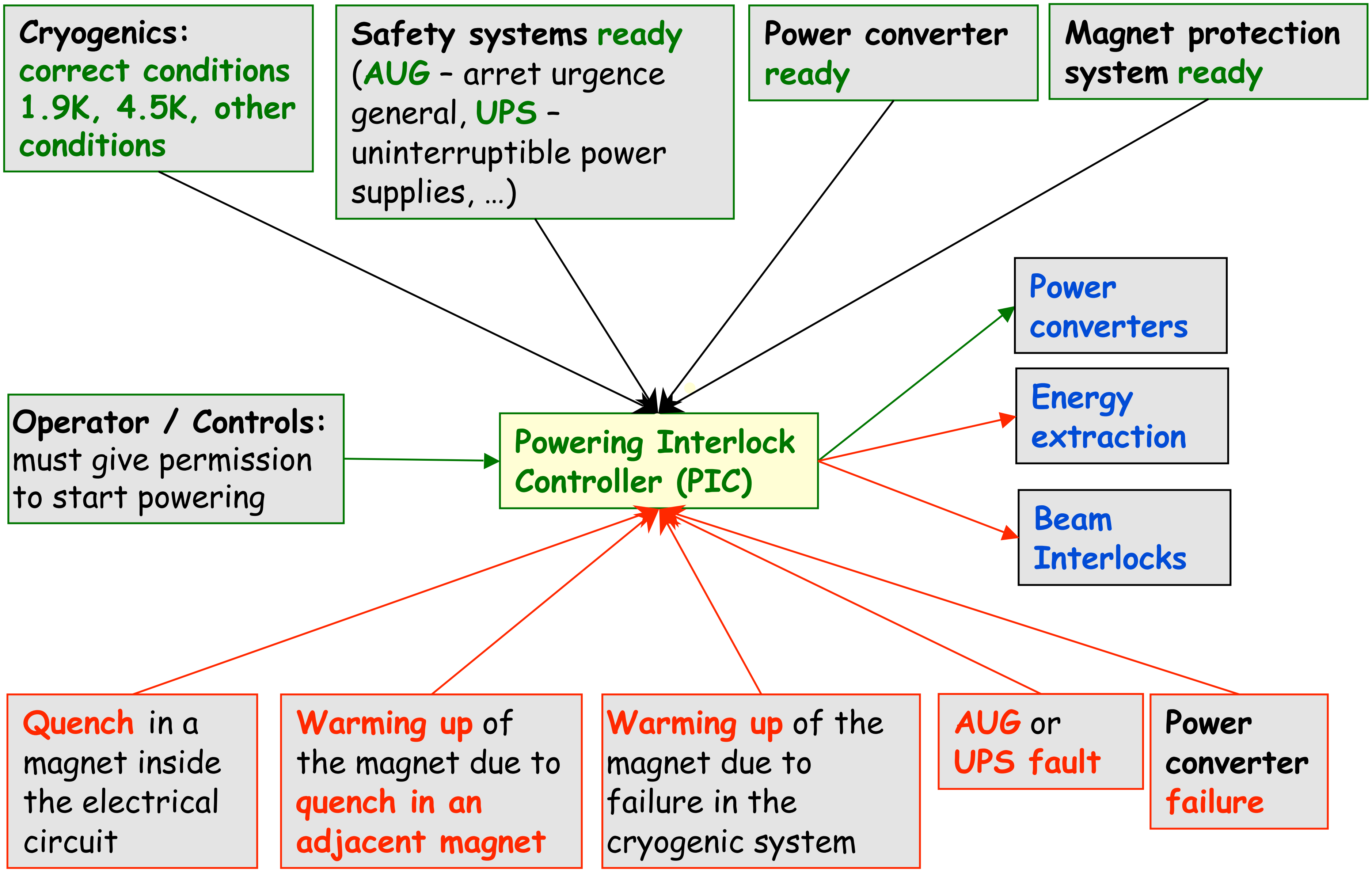


Quench detection and beam dump trigger

Test undergoing during HWC

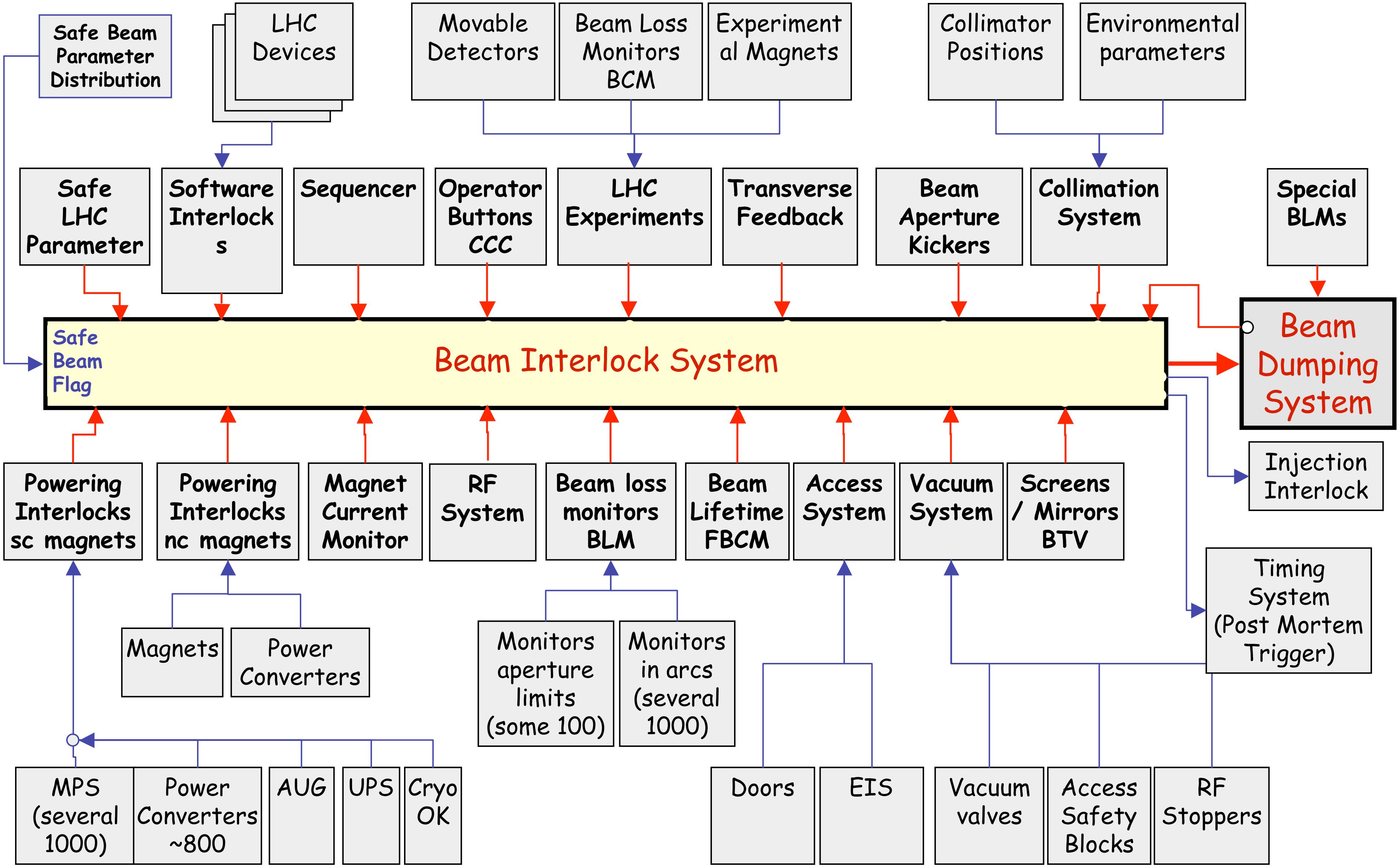


Conditions for powering



LHC Machine Interlocks

Test undergoing during HWC



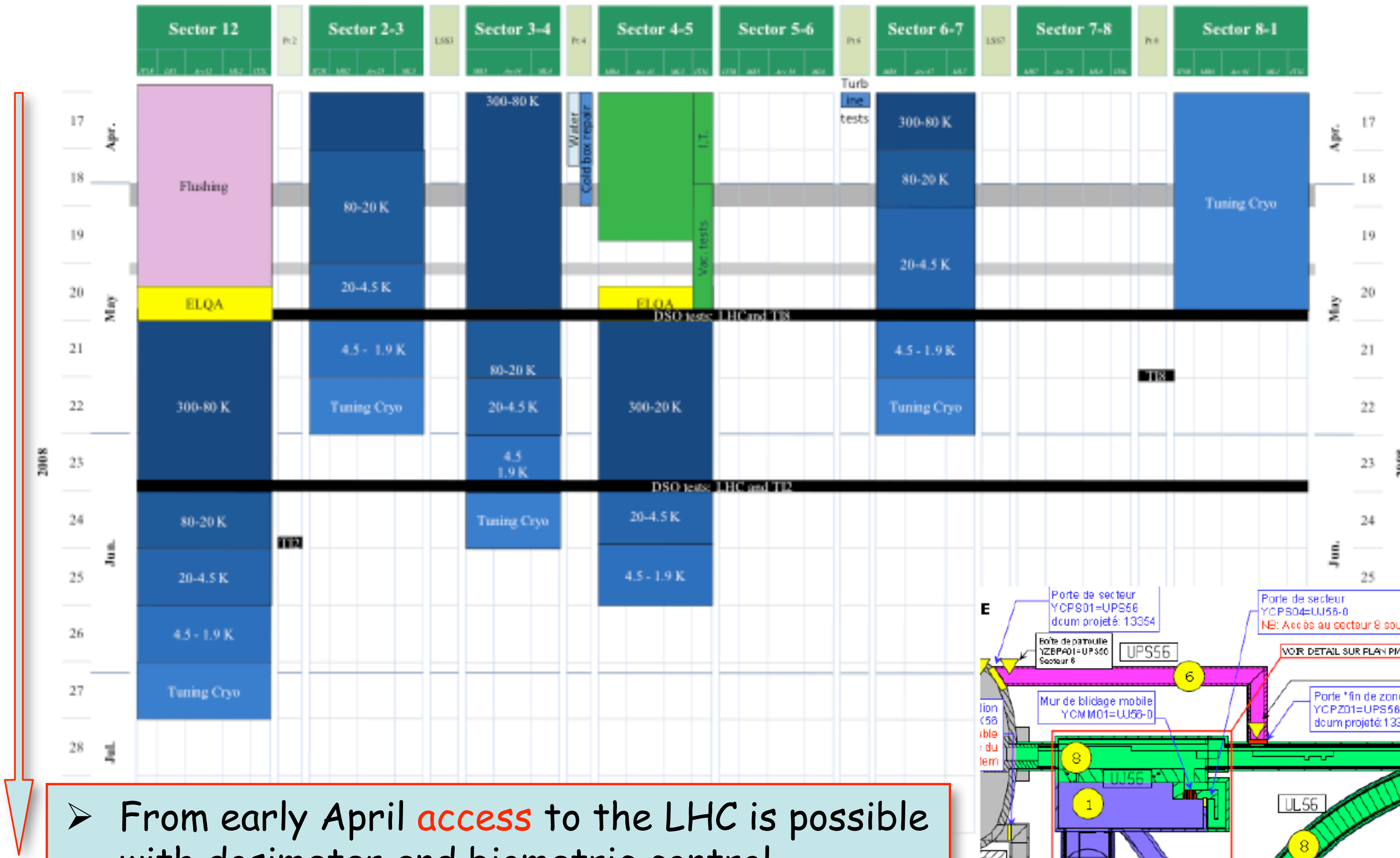
LHC status – June 2008

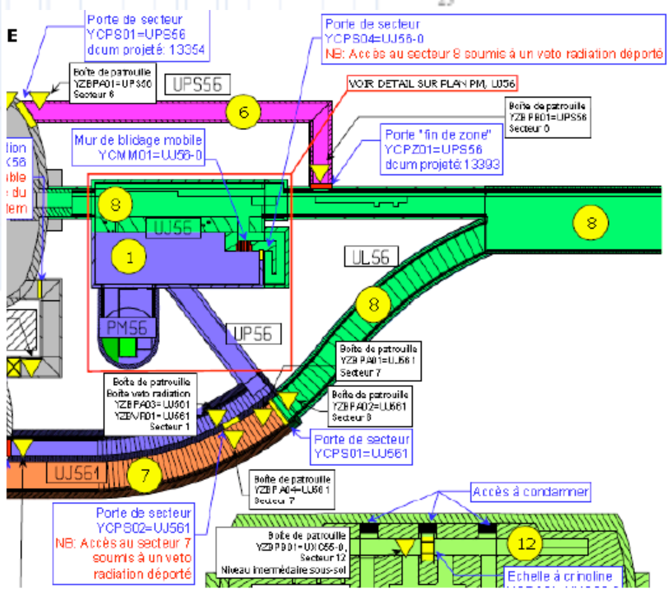
- Installation effectively complete
- Interconnection work effectively complete
- Three sectors cooled down to nominal temperature and operated with super-fluid helium
- Three sectors in cool-down
- Power tests progressing well

Priority is to have LHC

- cold
- leak tight
- electrically tested

General Coordination Schedule - wk.10 (update wk. 19)





- From early April access to the LHC is possible with dosimeter and biometric control.
- All the sectors in Hardware Commissioning today make use of the system
- *Controlled access to be soon extended to the experimental areas*

Schedule 2008

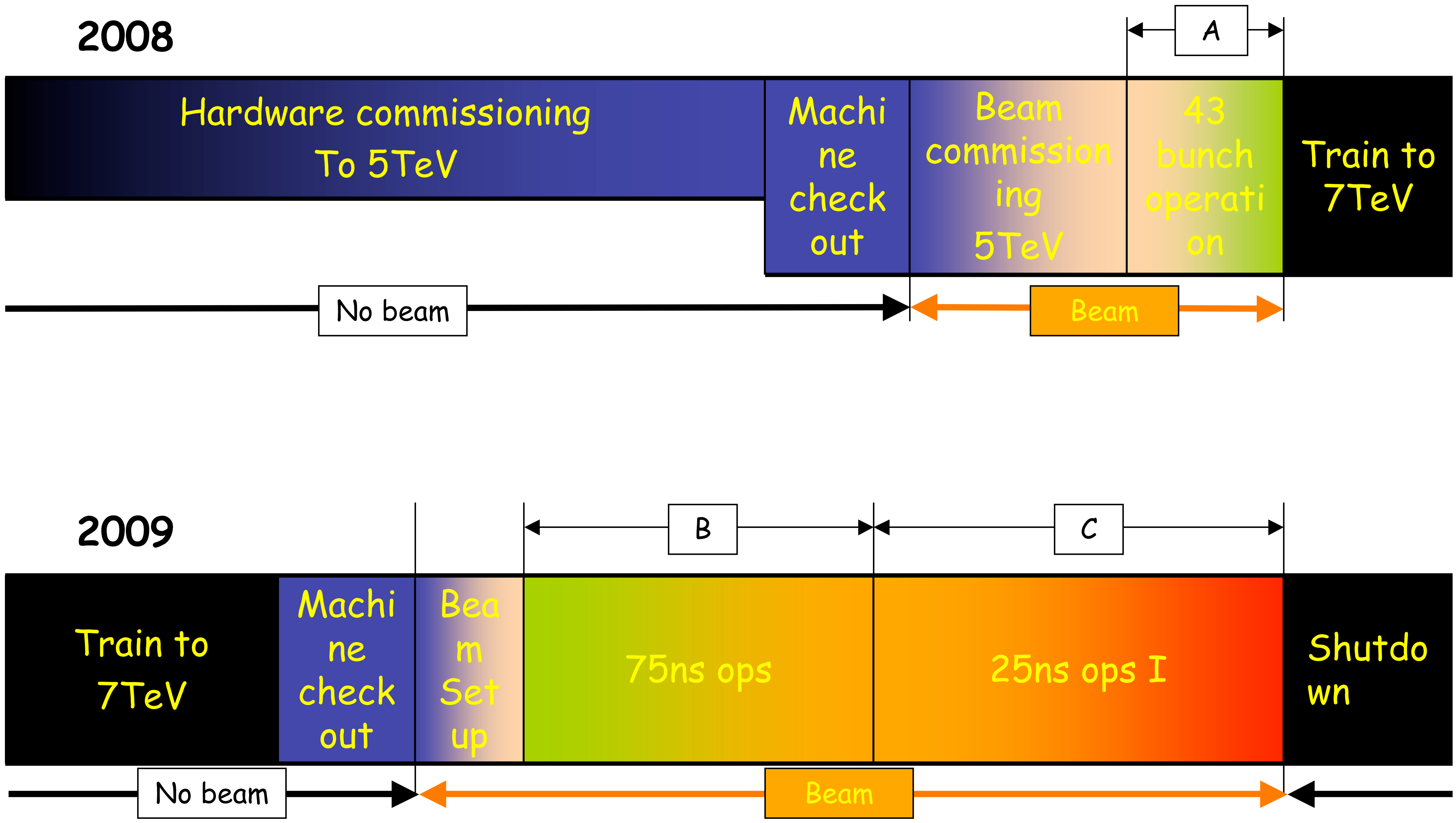
- High parallelism for cool down and power tests until the End of July

- <u>1 July</u>: LHC **cooled down at 1.9 K** and the beam pipe in the experiments backed up
- <u>15 July</u>: the experimental **caverns closed**, tunnel patrolled, controlled access fully activated
- <u>1 August</u>: **first particles injected in LHC**, and the beam commissioning starts.

☺ **about 2 months to have first collisions at 10 TeV.**

- Energy of the 2008 run will be 10 TeV.
  - → safe setting to optimize up-time of the machine until the winter shut-down (starting likely around end of November)
- In the winter shut-down commissioning and train the magnets up to full current
  - → the 2009 run will start at the full 14 TeV energy

Strategy for 2008 - 2009



Beam commissioning stages

STAGE A
INITIAL COMMISSIONING
43 x 43 -> 156 x 156 3×10^{10} per bunch
Zero to partial squeeze

STAGE B
75 ns OPERATION
3-4 x 10^{10} per bunch
Partial squeeze

STAGE C
25 ns OPERATION
3-4 x 10^{10} per bunch
Partial to near full squeeze

LONG SHUTDOWN

STAGE D
25 ns OPERATION
push to nominal per bunch
Partial to full squeeze

Safely establish colliding beams as quickly as possible

Stage A

- Initial optics:
  - β^*= 11 m in IR 1 & 5
  - β^*= 10 m in IR 2 & 8
- Crossing angles off
  - Low bunch intensity
  - 1, 12, 43, 156 bunches per beam
  - No parasitic encounters - no long range beam-beam
  - Larger aperture in IRs

5 TeV parameters

- **L** scaling factor 0.71 (=5/7)
- **Luminous region length** scaling:
  - with same longitudinal parameters, it re-scales by a factor 0.71.
  - Nominal case:

$$L(s) = \frac{N_p^2 \, f \, N_b}{4\pi\sigma^2} Erf\left(\frac{s}{\sigma_s}\right)$$

  - The final length will depend on the value of the longitudinal parameters

$$L = \frac{\gamma}{4\pi\beta^*}\frac{N^2}{\varepsilon^*} fk \times F \quad \begin{cases} F \approx \left(1+(\phi)^2\right)^{-\frac{1}{2}} \\ \phi = \dfrac{\theta_c \sigma_s}{2\sigma^*} \end{cases}$$

- for stage A physics run 43 (and 156) bunches

IP 1 & 5

Bunches	β*	I_b	Luminosity	Event rate
1 x 1	11	10^{10}	0.7×10^{27}	Low
43 x 43	11	3×10^{10}	4.3×10^{29}	0.04
43 x 43	4	3×10^{10}	1.2×10^{30}	0.15
43 x 43	2	4×10^{10}	4.3×10^{30}	0.55
156 x 156	4	4×10^{10}	0.8×10^{31}	1.1
156 x 156	4	9×10^{10}	4.0×10^{31}	1.4
156 x 156	2	9×10^{10}	0.8×10^{32}	2.8

Stage A physics run for ALICE and LHCb

- 43 equidistant bunches
- Need to do something for LHCb
  - Previously thought to displace bunches in one beam (asymmetric)
  - Can do better (symmetrically displace bunches in both beams)
  - Allows to adjust luminosity sharing between 2 and 8 while keeping maximum number of collisions in 1 and 5

displaced	0	4 (asym)	4 (sym)	11 (sym)	19 (sym)
IP1	43	39	43	43	43
IP2	42	38	34	21	4
IP5	43	39	43	43	43
IP8	0	4	4	11	19

Pilot physics – the first months

- Interleaved physics and commissioning
- Push number of bunches, intensity, squeeze…
  - 156 x 156
  - 3 x 10^{10} protons per bunch
  - $\beta^* = 2$ m.
- Peak luminosity: 0.8×10^{31}
- Integrated luminosity: few pb^{-1}

Nov 08 ?

Pushing the bunch intensities with 156x156 with reasonable operational efficiency another month would see 30-40 pb^{-1}

2009

- Training to 7 TeV
- Circuits not commissioned in 2008
- Commission and exploit 75 ns.
- Move to 25 ns
- ions

- Initial luminosity 8×10^{32} $cm^{-2}s^{-1}$ (say)
- 2808 bunches, $\beta^* = 2$ m, 6×10^{10} protons per bunch
- Luminosity lifetime: 27 hours
- Fill length: 12 hours
- Turn around time: 5 hours
- 100 days of physics
- Operational efficiency 60%

$\int Ldt$ of the order 2-3 fb^{-1}

Conclusions

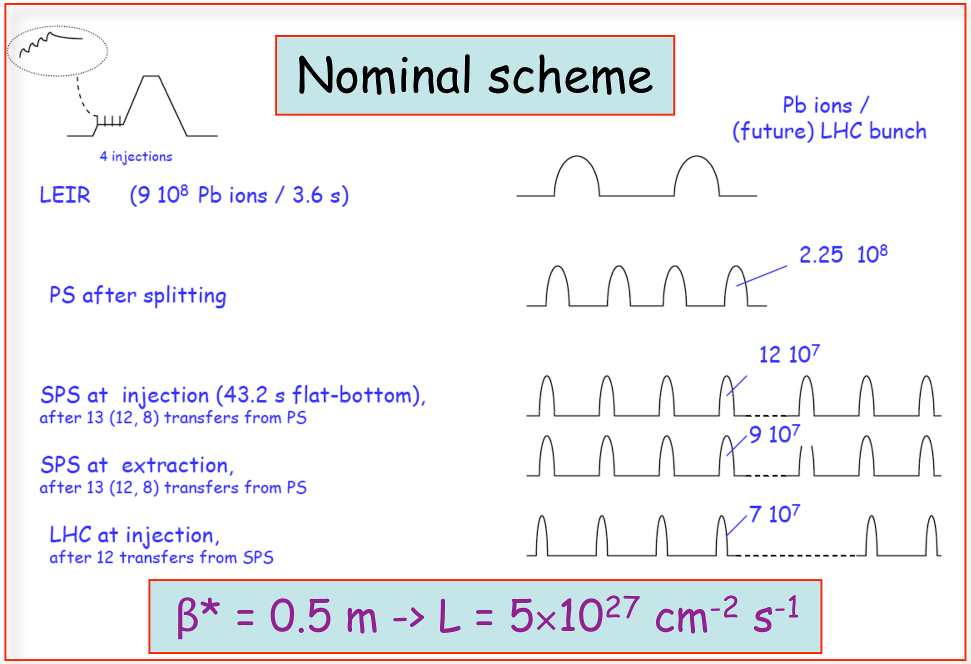
- Priority is to get the machine cold and leak tight
- Machine should be cold in June 2008
  - Caveat: problems found at cold cost ~3 months to fix
- Take beam at 450 GeV before machine ready for 5 TeV
- First 5 TeV collisions 2+ months after first taking beam

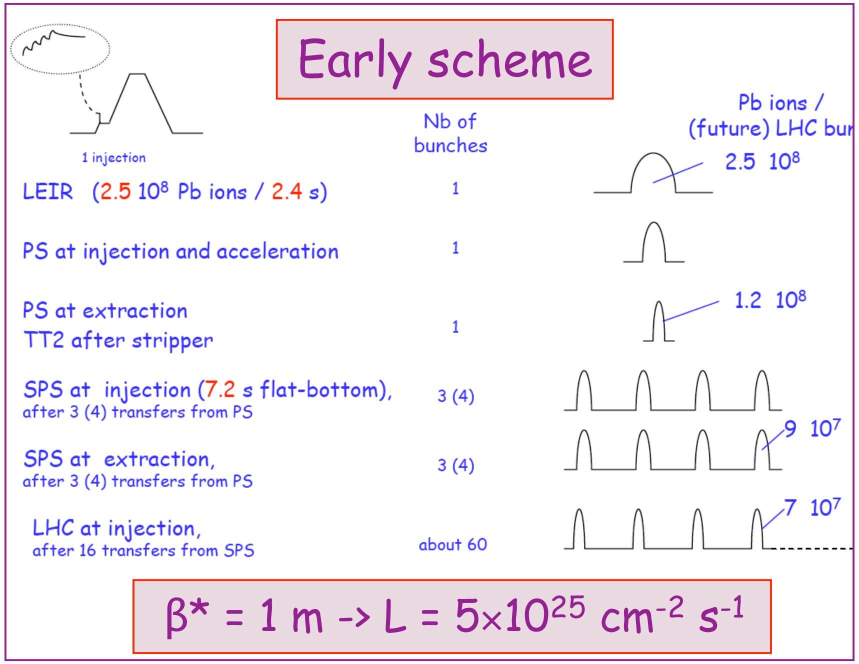
Expectation of the management!

- The LHC is a huge, complex beast.
- Progress is good
- It will work
- BUT it is going to take time

Nominal parameters for ion beam

	ECR Source	Linac 3	LEIR	PS	SPS	LHC
Output energy	2.5 KeV/u	4.2 MeV/u	72.2 MeV/u	5.9 GeV/u	177 GeV/u	2.76 TeV/u
208Pb charge state	29+	29+ ⇒54+	54+	54+ ⇒82	+ 82+	82+
Output Bρ [Tm]		2.12 ⇒1.14	4.80	86.7 ⇒57.3	1500	23350
bunches/ring			2 (1/8 of PS)	4	52	592
ions/pulse	9×10^{9}	1.15×10^{9}	9×10^{8}	4.8×10^{8}	4.7×10^{9}	4.1×10^{10}
ions/LHC bunch	**1.1×10^{10}**	**1.45×10^{9}**	**2.25×10^{8}**	**1.2×10^{8}**	**9×10^{7}**	**7×10^{7}**
bunch spacing [ns]				100	100	100
ε*(norm. rms) [μm]	0.07	0.25	0.7	1.0	1.2	1.5
ε (phys. rms) [μm]	30	2.6	1.75	0.14	0.0063	0.0005
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	~10'fill/ring





2007 achievements

- LEIR
  - Improved diagnostics
  - Reliably run from CCC
  - Progress towards nominal beam
- PS:
  - New cycle with lower intermediate plateau
  - Lots of debugging, improved transmission
  - Finalized low-beta optics; complete rematching of transfer line
  - No effort possible on nominal beam (priority to proton and early beams)
  - Vacuum leak at end of run
- SPS:
  - RF hardware late delivery; first 2 dedicated MD sessions replaced by magnet repair
  - Injection, acceleration, extraction of early beam
  - Loss maps studies at 17 and 270 Z GeV/c
  - Studies of beam behaviour on injection plateau
  - No time for slow extraction in North Area (crystal channeling)

Program for 2009 (for PS and SPS)

- PS RF:
  - Second iteration for frequency programme
  - Test new hardware (being built this shutdown) for 423-divider
  - ejection synchronization
  - RF gymnastics for nominal beam
- SPS RF: (4 weeks parallel + 4 dedicated sessions)
  - reproduction of results of 2007 with definitive hardware and software
  - synchronization with LHC at flat top
  - Reduce the longitudinal emittance blow-up
- SPS full extraction of early beam to both TI2 and TI8
- SPS Slow Extraction to North Area for crystal channeling studies

Ion collimation

- Why is heavy ion collimation for LHC a specific issue?
- For protons efficiency $\eta \approx 10^{-5}$ required
- I-LHC beam has only 1/100 of the proton beam power, so only collimation efficiency $\eta \approx 10^{-3}$ required .
- Where is the problem ?

Collider	Atomic number	Mass number	Energy / nucleon GeV/u	Circumference m	Number of Bunches	Number part. / Bunch 10^7	stored energy / beam MJ	Instantaneous beam power GW
p-LHC	1	1	7000	26659	2808	11500	362.1	4075
I-LHC	82	208	2760	26659	592	7	3.8	43
I-LHC early scheme	82	208	2760	26659	62	7	0.4	4
p-HERA	1	1	920	6336	180	7000	1.9	88
TEVATRON	1	1	980	6280	36	24000	1.4	65
I-RHIC	79	183	99	3834	60	110	0.2	14
p-RHIC	1	1	230	3834	28	17000	0.2	14

Ion-collimator interaction

Nominal ion beam has 100 times less beam power than proton beam, but particle-collimator physics very different:

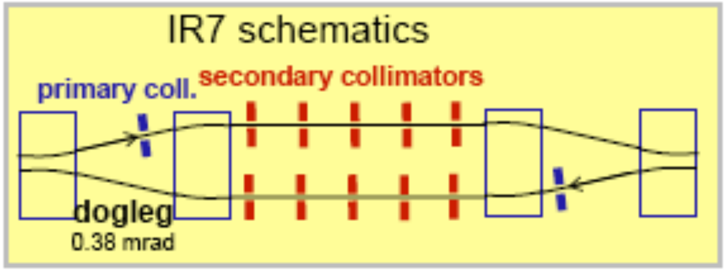
Physics process	Proton	^{208}Pb
$\frac{dE}{Edx}$ due to ionisation	-0.12 %/m -0.0088 %/m	-9.57 %/m -0.73%/m
Mult. Scattering (projected r.m.s. angle)	73.5μrad/m^{½} 4.72μrad/m^{½}	73.5μrad/m^{½} 4.72μrad/m^{½}
Nucl. Interaction length ≈fragment. length for ions	38.1cm 38.1cm	2.5cm 2.5cm
Electromagnetic dissociation length	-	33cm 19cm

High probability to undergo nuclear interactions in the primary collimator before 2-stage collimation condition is satisfied

$$L \approx L_{\text{int}} = \frac{A_{coll}}{N_A \rho (\sigma_{had} + \sigma_{emd})}$$

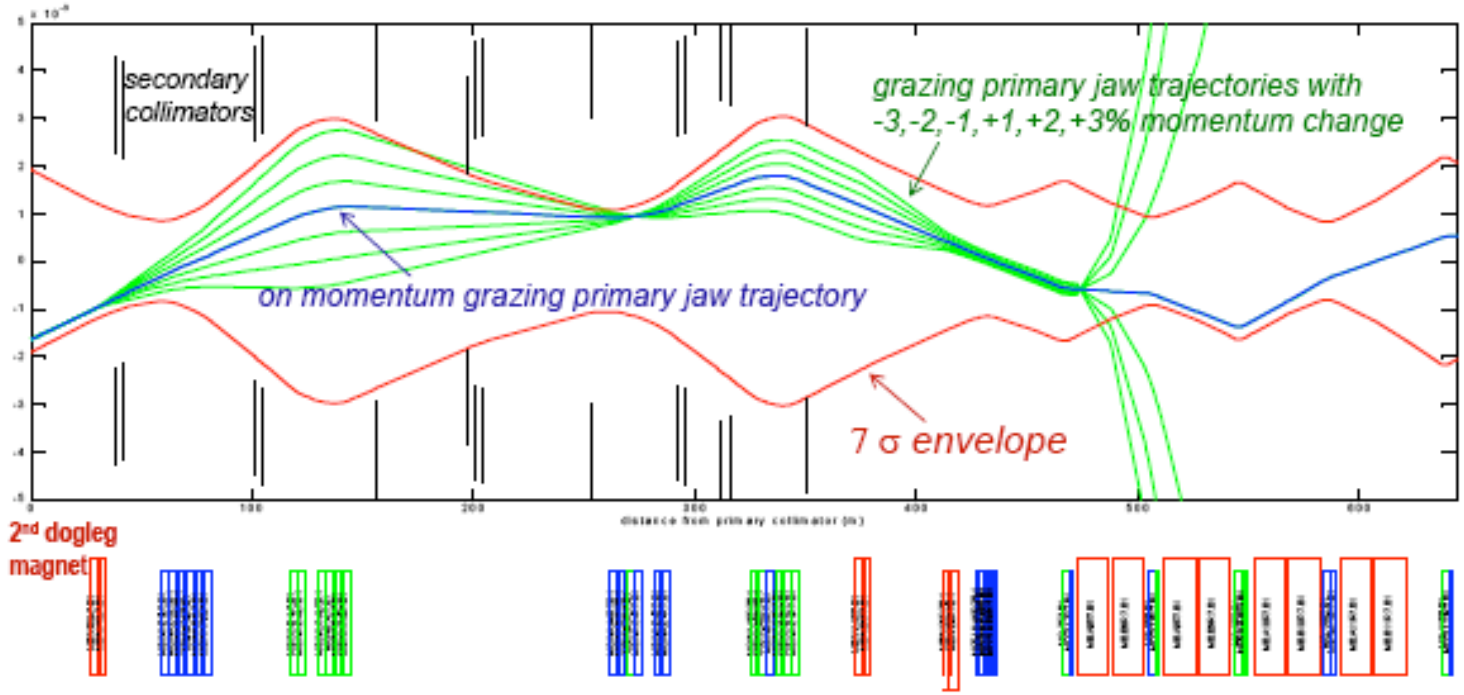
First impacts of halo ions on primary collimators is usually grazing,

- → small effective length of collimator.
- → high probability of conversion in neighboring isotopes without change of momentum vector
- → isotopes miss secondary collimator and are lost in downstream SC magnet because of wrong Bρ value



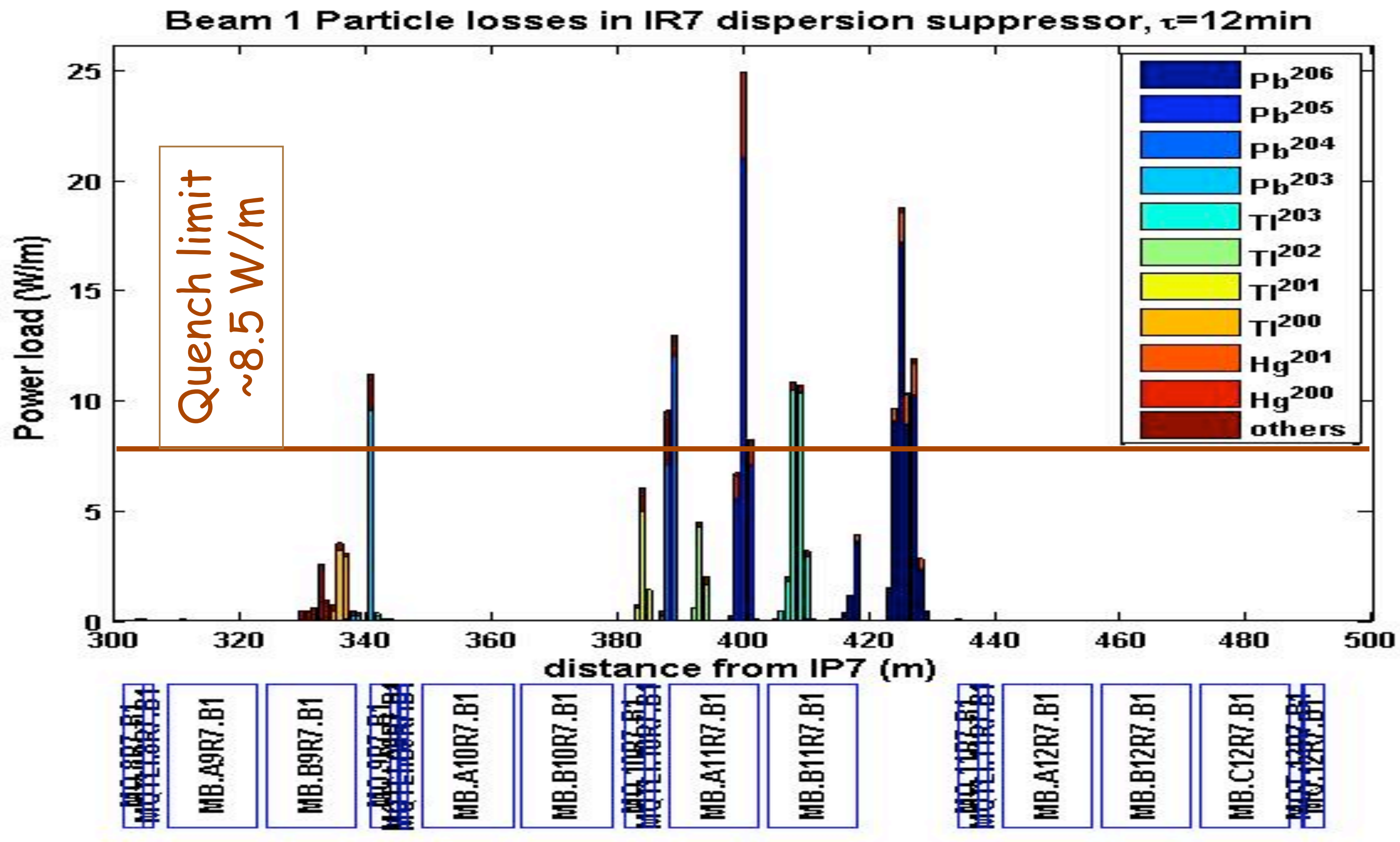
Only particles with effective ΔP/P>3% can be intercepted with secondary collimators.
Trivial (and impossible) solution:
Increase strength of dogleg magnets by factor 4

Perhaps a different IR7 optics could give some improvement. Needs further study.



Loss maps

Nominal ion beam with collision optics and standard collimator settings:



~50% current limit on nominal ^{208}Pb ion beam (due to collimation inefficiency)

Ion current limit

- Present 2 stage collimation of LHC gives insufficient protection of s.c. magnets against heavy ion fragments.
- Collimation system acts almost like a single stage system.
  ⇒ particle losses in SC magnets exceeds permissible values by a factor ~2 for nominal ion beams at collision energy.
- Early Ion scheme and losses at injection seem to be ok
- Collimator robustness sufficient for kicker accidents with ion beams
- No solution for nominal beam found yet

Ideas to be explored:

- Explore different optics for IR3/IR7 to improve specifically ion collimation
- Thin high-Z spoilers downstream of primary collimator at high β_{TWISS}
- Collimators with magnetised jaws for extra deflection (P.Bryant, 1993)
- Crystal collimators: conceivable to use them in place of primary collimators to deflect halo particles away from the beam core onto absorbers at specific downstream locations

...but almost no data available to substantiate the idea...

Crystal-based collimation: open issues

Idea

- Enhance standard collimation efficiency with the use of crystals to channel/reflect halo particles away from beam core onto special absorbers

Challenges (generic, p and ions alike):

- Efficiency: not 100%, *need to be flanked by standard collimation system* (at close to nominal settings in case of misalignments)
- Stability through operations: tight alignment tolerances (esp. for channeling, more relaxed for reflection) and energy dependence of the critical parameters (and beam divergence, in general). *Feasible to follow energy ramp with the crystal alignment during operations?*
- Absorbers: should be able to withstand full impact of deflected beam on a potentially small spot size ⇒ *robustness, cooling?*

Crystal-based collimation: open issues

- Concomitance of 3 different processes deflecting beam in opposite directions: different acceptances in principle, but allowing for alignment tolerances, ***need for multiple absorbers ?***
- Machine protection*:* non negligible chance that a wrong setup could end up displacing the beam at high $\beta \Rightarrow$ **how dangerous for machine integrity?**
- Radiation damage: how long can a crystal survive normal LHC beam operations before deteriorations kick in? ..**maintenance issues**

Ions specific concerns:

- **Much lower threshold** for radiation damage of the crystals (?)
- Si/ion interactions fairly understood for single pass channelling experiments.. what about multi-pass case? Crystal behaves like amorphous material for small impact parameters (surface effects) è **what happens to isotopes produced by nuclear interactions with the wrong rigidity?**
- What is the role played by nuclear/EM interactions in the case of **volume reflection?**

Crystal-based collimation: perspectives

The Holy Grail for ion collimation would be to find a mechanism to deflect beam halo to high β that's

1) efficient
2) clean (i.e. with suppression of NF/EM processes).

Crystals are a conceptually interesting idea but it needs

➔ substantial experimental backing to assess advantages, feasibility and optimal implementation

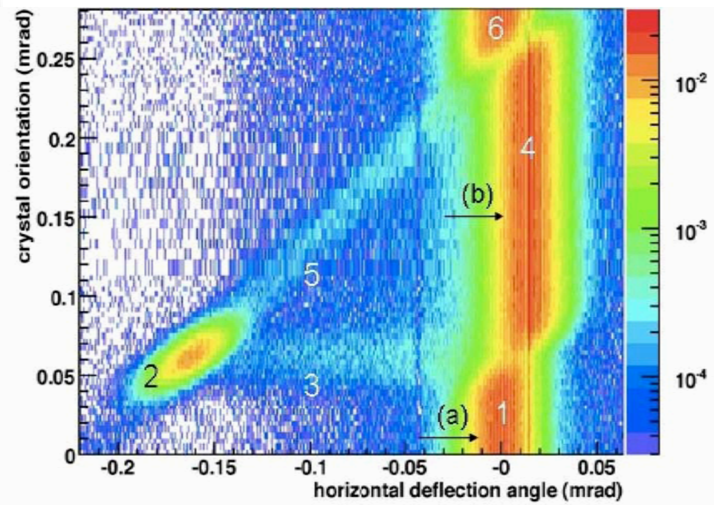
➔ deep understand of ion interactions within crystals by cross-checking experiments with simulations

Volume reflection higher efficiency and acceptance

a) for ions as well ?
b) nuclear/em interactions is it significant ? (fairly clean, single pass process)

channelling larger deflecting angle

a) proved suppression of NF interactions for channelled particles
b) EMD?
c) can we really reach efficiencies~ 50% for ions?



Roadmap of SPS experiments with ion beams

1) **External beamline** (*simpler single pass case*)

- direct type experiment
- ability to measure outgoing beam composition in terms of different ion species
- different energies

Measure efficiencies for volume reflection and channelling and study physical processes of ion/crystal interactions

..& if promising...

2) **SPS ring experiments**

-Study multipass effects

-Try different beam excitations

-Beam extraction and collimation (with setup of secondaries)

Start thinking about a tentative 2008/2009 installation?

Many thanks