Progress in LHC commissioning

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CERN, Geneva, Switzerland

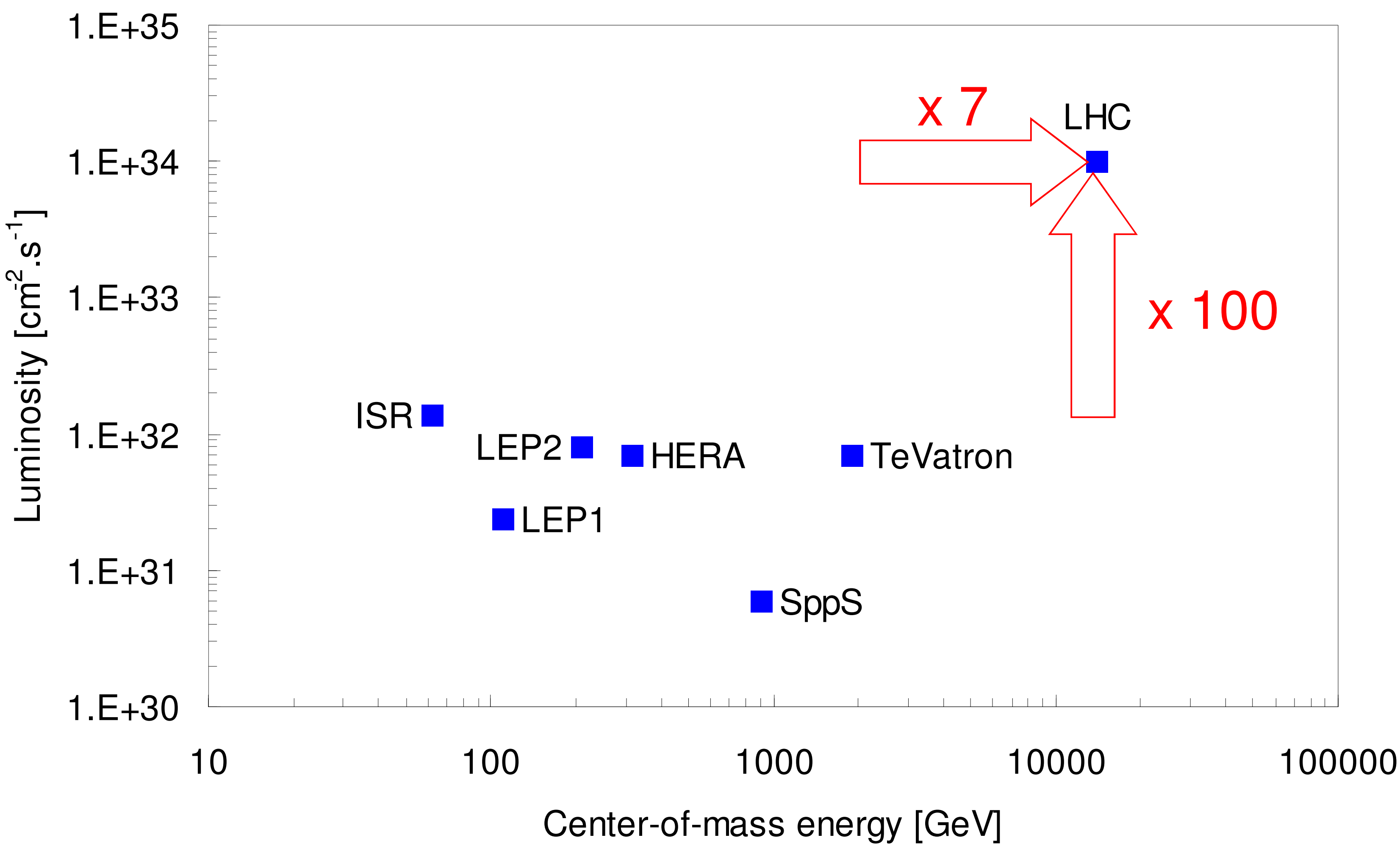
2009 Linear Collider Workshop of the Americas
29 September – 3 October 2009
Albuquerque, New Mexico

The largest scientific instrument in the world

Advanced technology at work

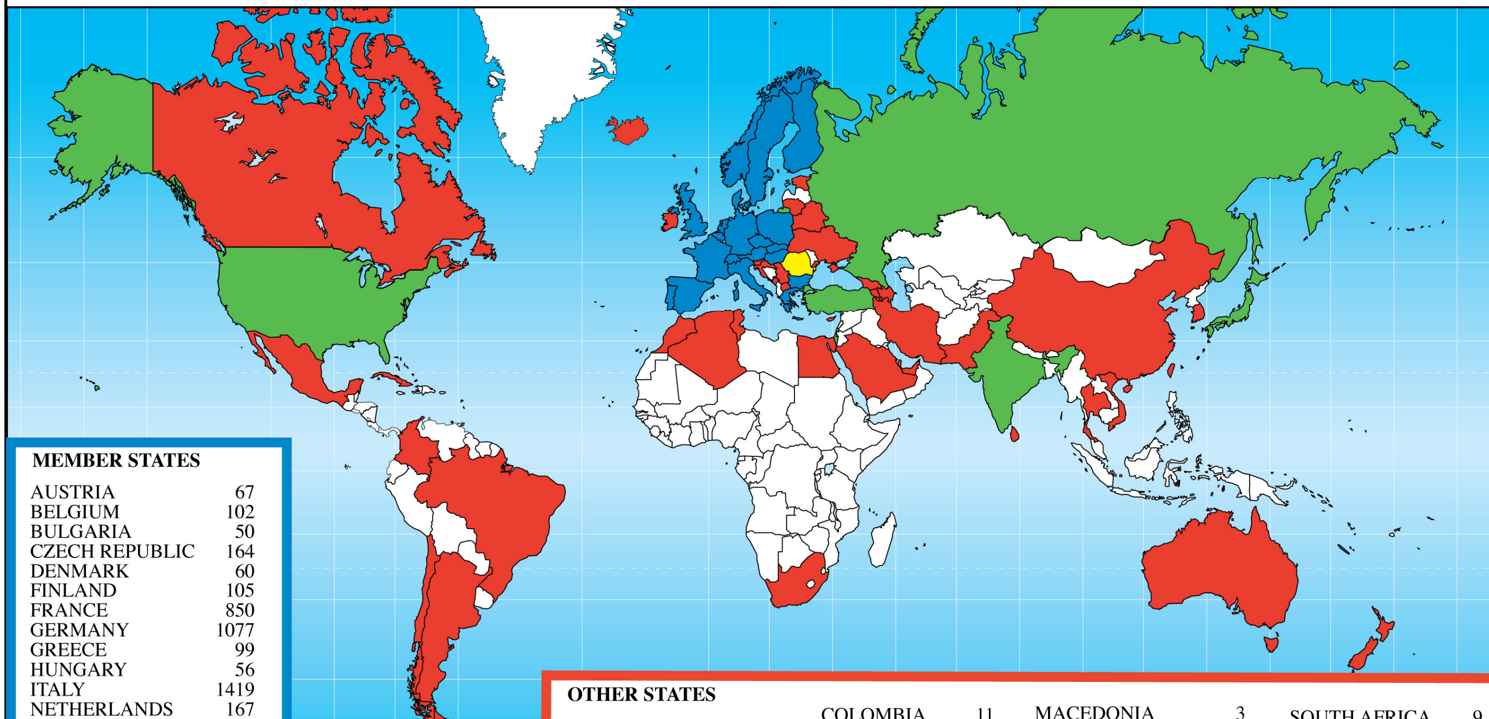
23 km of superconducting magnets cooled in superfluid helium at 1.9 K

A new territory in energy and luminosity



A research tool serving the world community of particle physicists

Distribution of All CERN Users by Nation of Institute on 2 July 2009



MEMBER STATES

AUSTRIA	67
BELGIUM	102
BULGARIA	50
CZECH REPUBLIC	164
DENMARK	60
FINLAND	105
FRANCE	850
GERMANY	1077
GREECE	99
HUNGARY	56
ITALY	1419
NETHERLANDS	167
NORWAY	78
POLAND	171
PORTUGAL	117
SLOVAKIA	54
SPAIN	286
SWEDEN	71
SWITZERLAND	336
UNITED KINGDOM	731

6060

OBSERVER STATES

INDIA	110
ISRAEL	53
JAPAN	175
RUSSIA	877
TURKEY	62
USA	1620

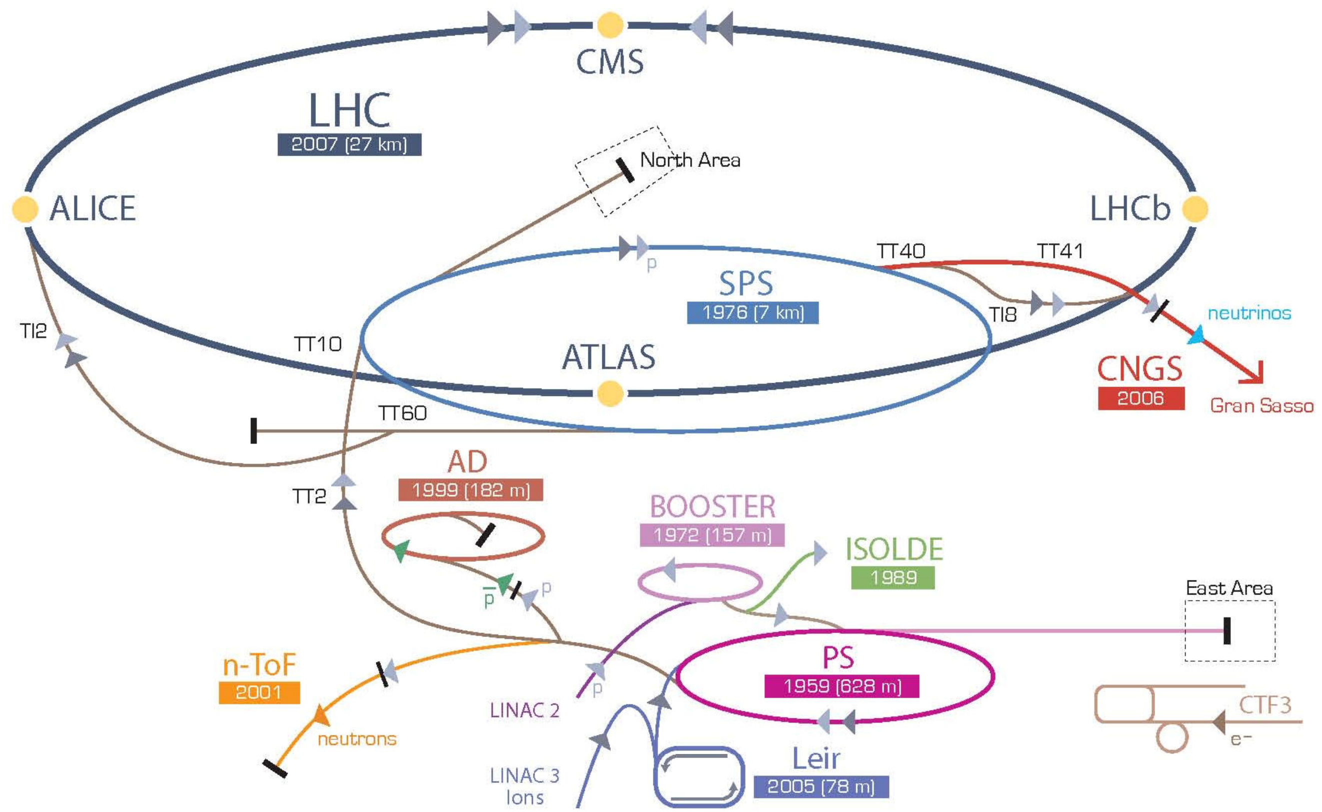
2897

OTHER STATES

ALGERIA	1
ARGENTINA	8
ARMENIA	15
AUSTRALIA	16
AZERBAIJAN	1
BELARUS	20
BRAZIL	69
CANADA	146
CHILE	2
CHINA	72
CHINA (TAIPEI)	49
COLOMBIA	11
CROATIA	21
CUBA	3
CYPRUS	8
EGYPT	1
ESTONIA	12
GEORGIA	11
ICELAND	1
IRAN	11
IRELAND	13
KOREA	56
LITHUANIA	15
MACEDONIA	3
MALTA	3
MEXICO	29
MONTENEGRO	1
MOROCCO	5
NEW ZEALAND	7
PAKISTAN	21
QATAR	1
ROMANIA	56
SAUDI ARABIA	2
SERBIA	18
SLOVENIA	16
SOUTH AFRICA	9
SRI LANKA	1
THAILAND	1
TUNISIA	1
UKRAINE	17
U.A.E.	1
VIETNAM	1

756

Optimizing ROI in CERN's infrastructure



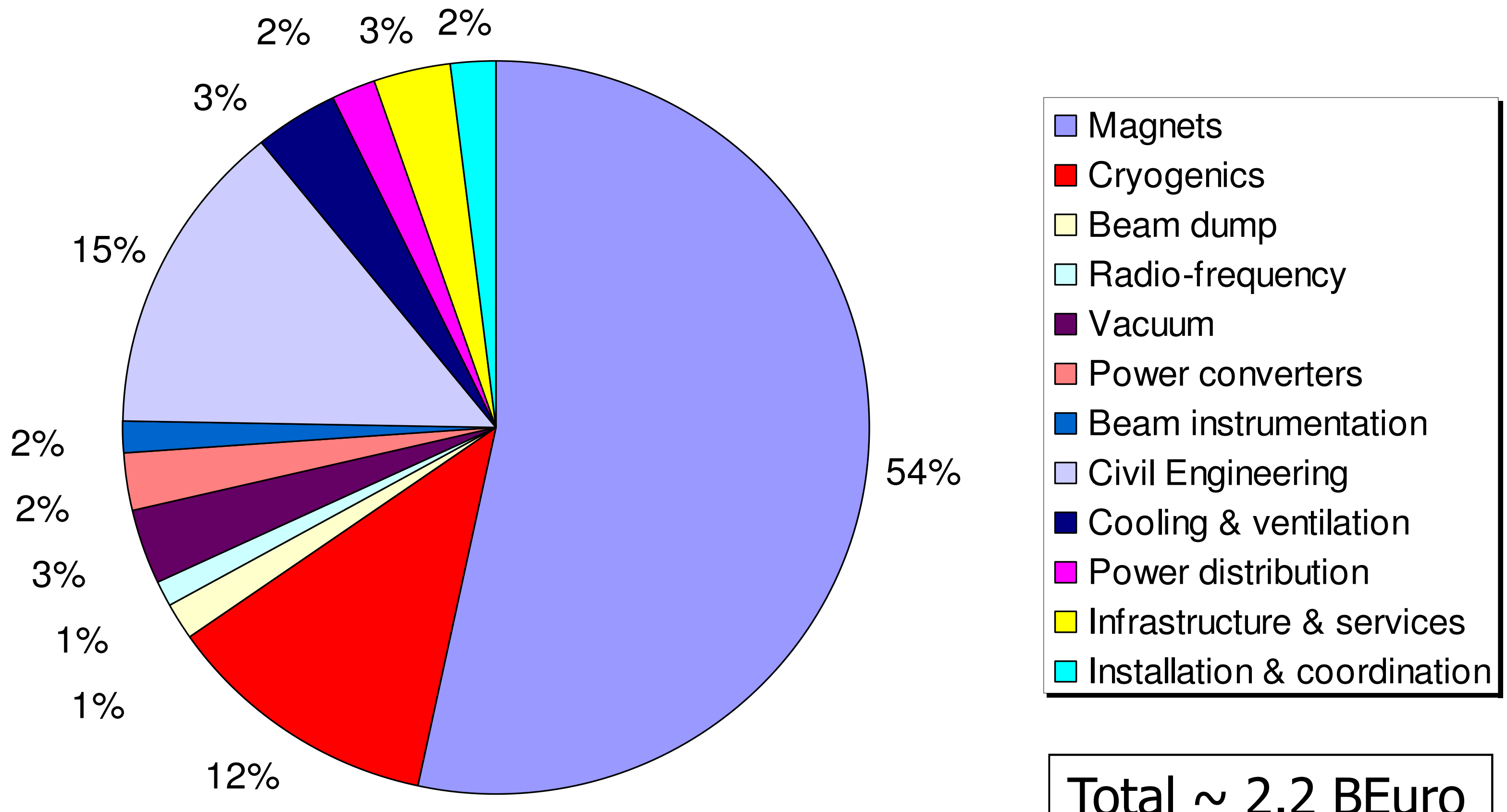
p (proton) · ion · neutrons · p̄ (antiproton) · proton/antiproton conversion · neutrinos · electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

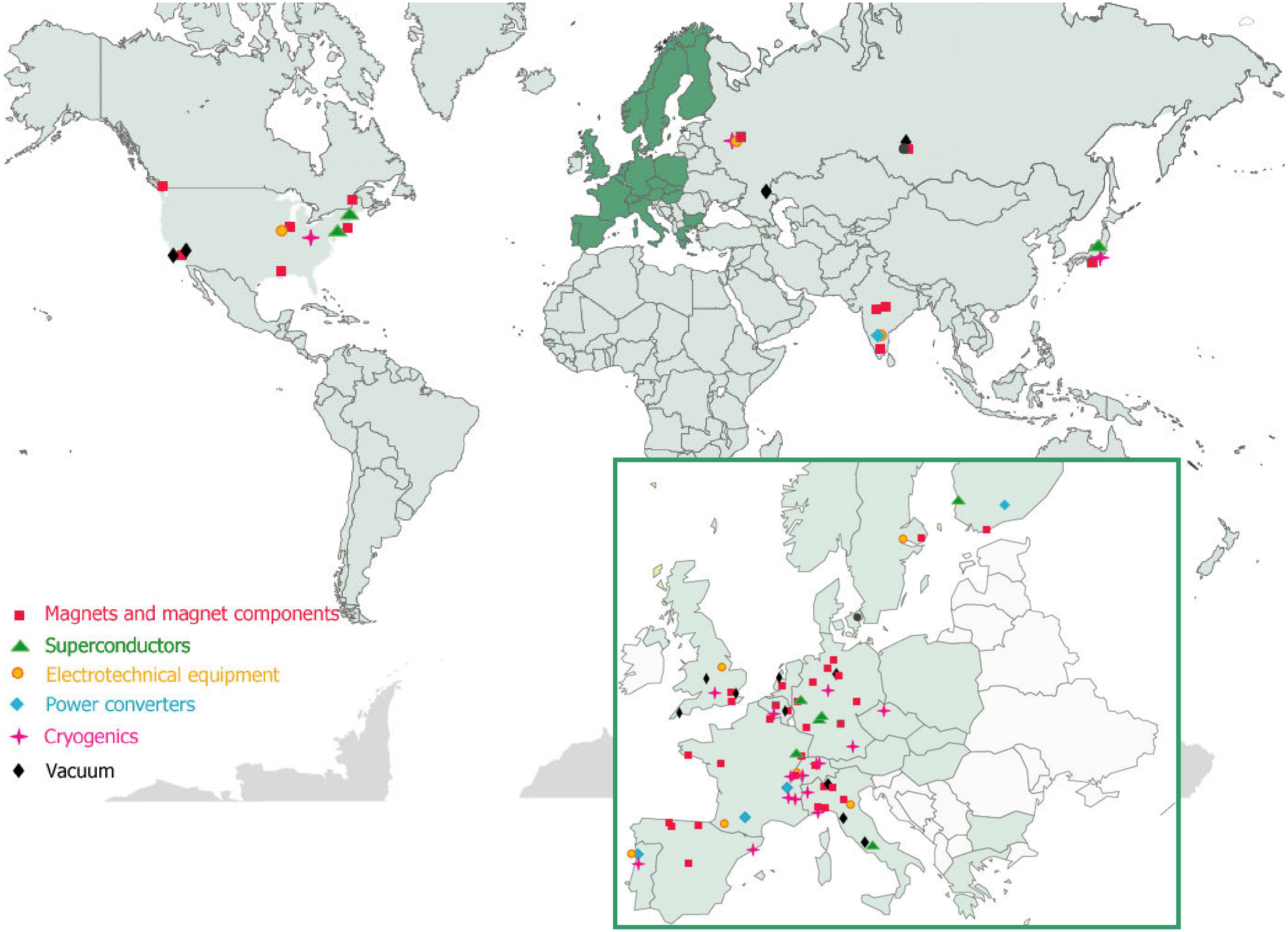
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

Cost structure of the LHC accelerator
Personnel costs not included

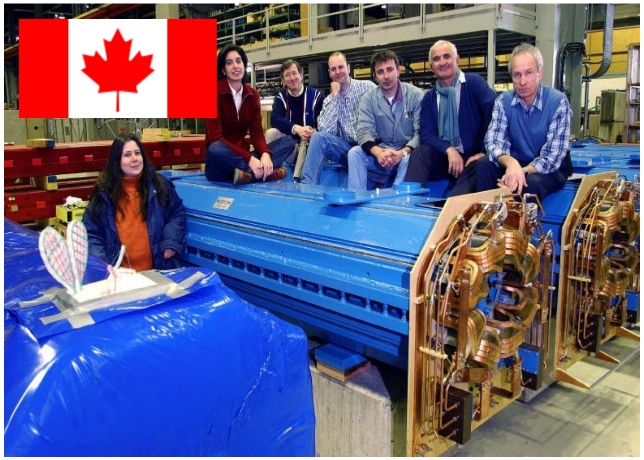


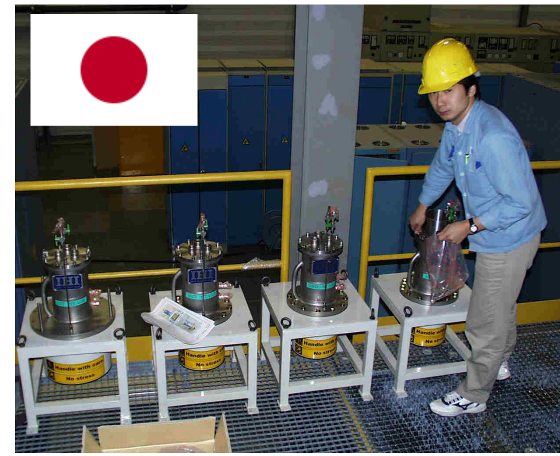
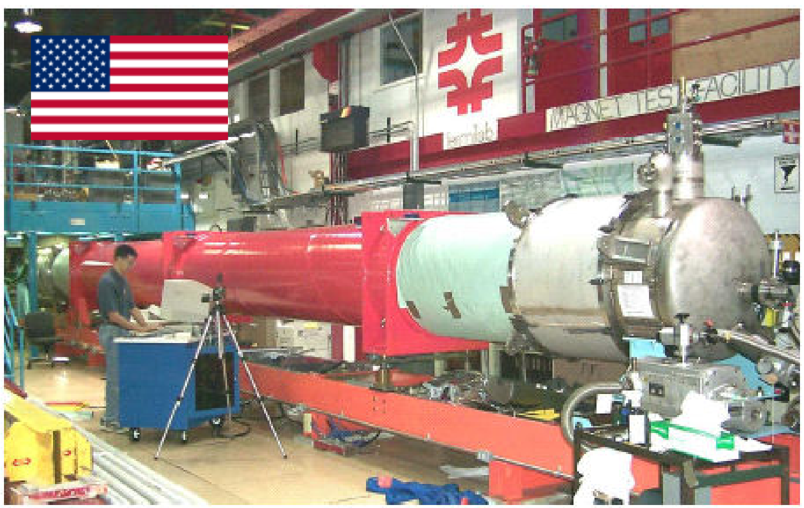
Total ~ 2.2 BEuro

90 main industrial contracts in the world



A global project spanning space…

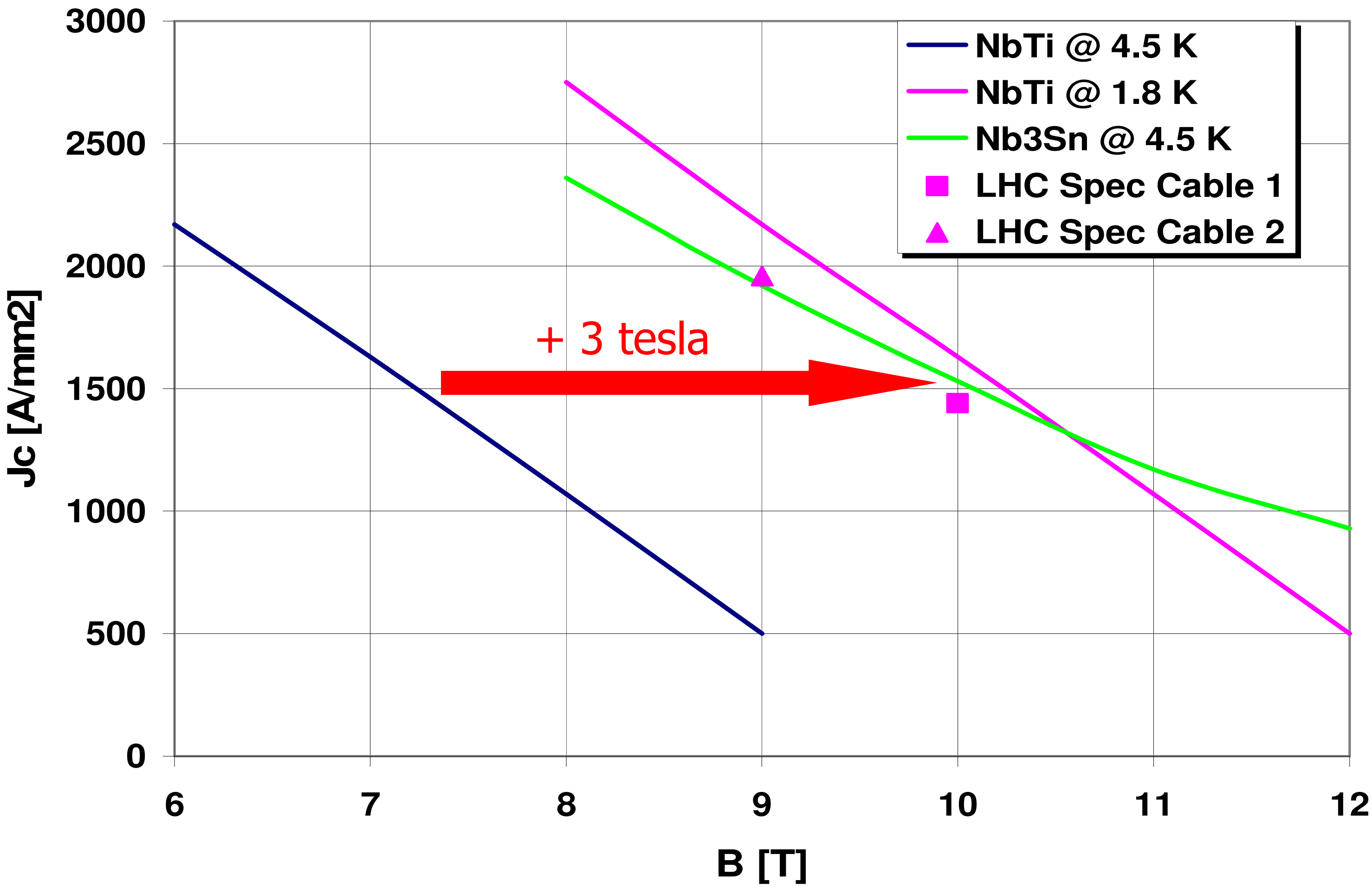


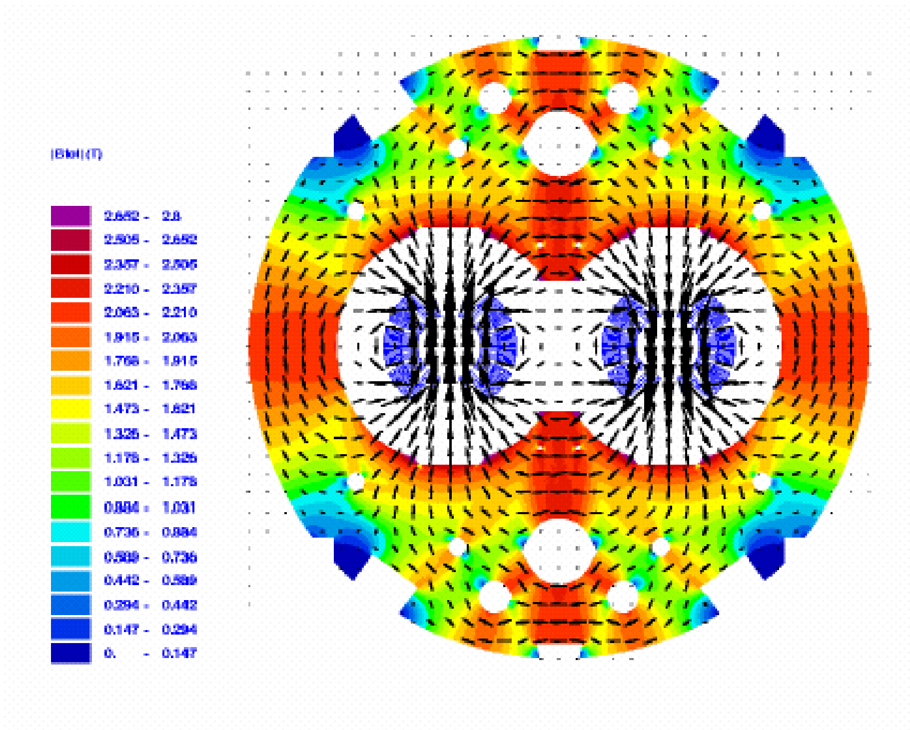
…and time

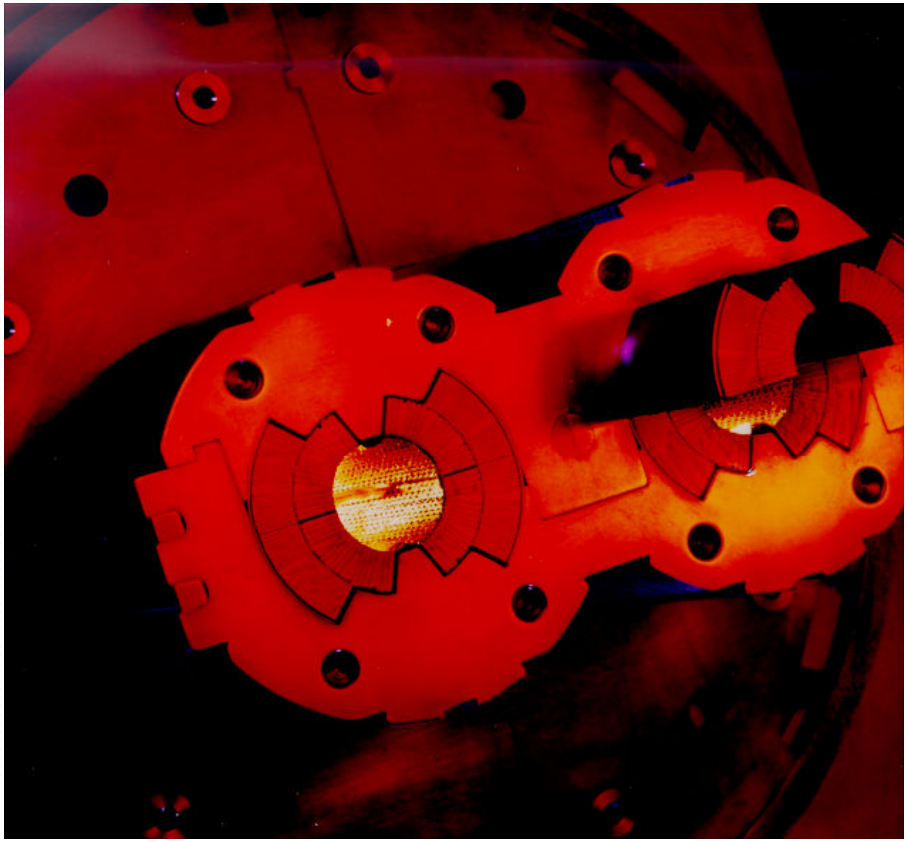
Preliminary conceptual studies	1984
First magnet models	1988
Start structured R&D program	1990
Approval by CERN Council	1994
Industrialization of series production	1996-1999
DUP & start civil works	1998
Adjudication of main procurement contracts	1998-2001
Start installation in tunnel	2003
Cryomagnet installation in tunnel	2005-2007
Functional test of first sector	2007
Commissioning with beam	2008
Operation for physics	2009-2030?

Superfluid helium cooling enhances performance of Nb-Ti superconductor



1232 twin-aperture dipole magnets



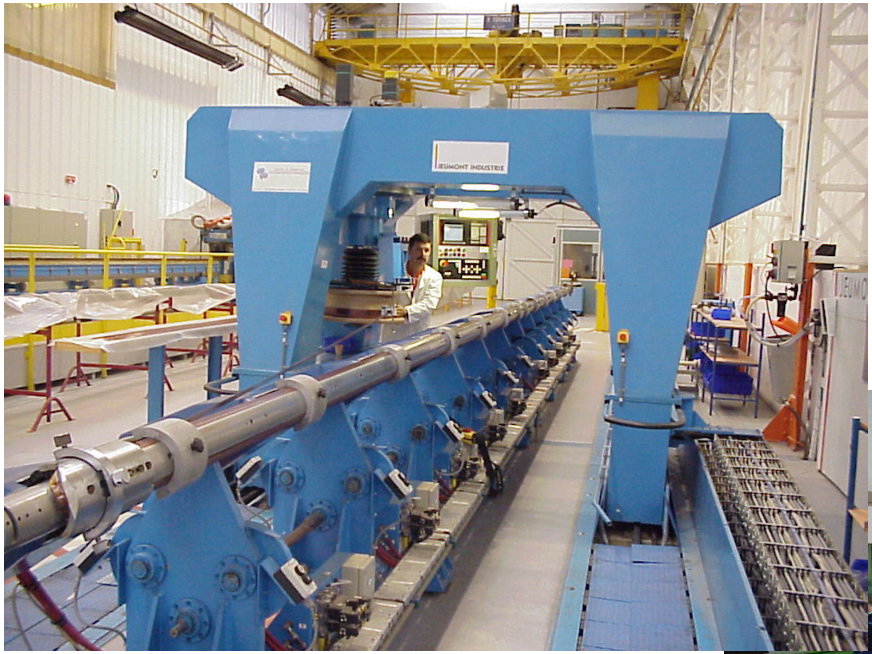


Field reproducibility/precision ~ 10^{-3}

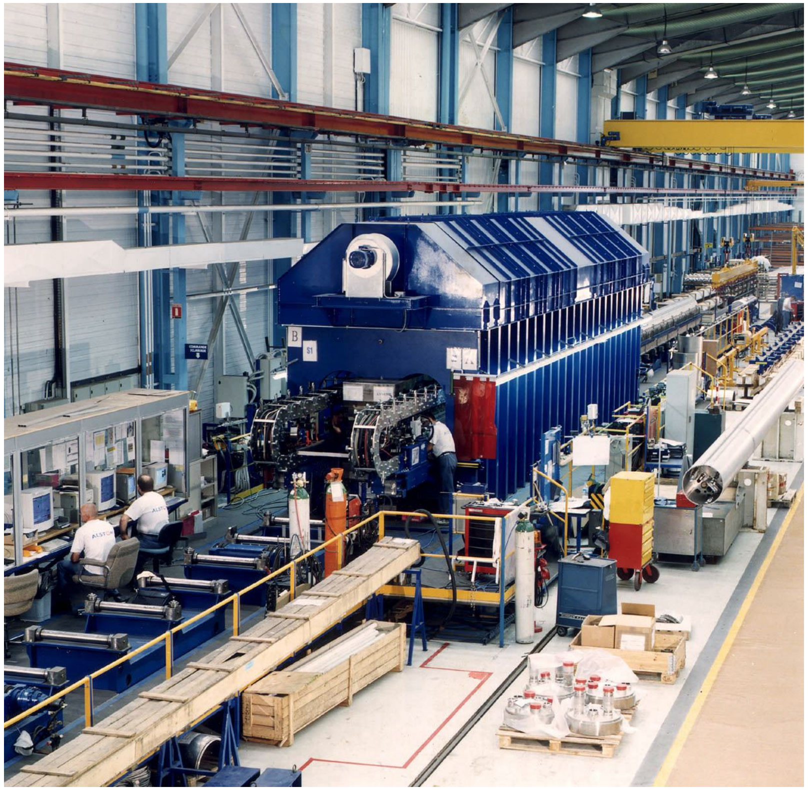
Field homogeneity ~ 10^{-4}

$\Rightarrow$ Winding precision < 0.05 mm

Manufacturing of superconducting coils



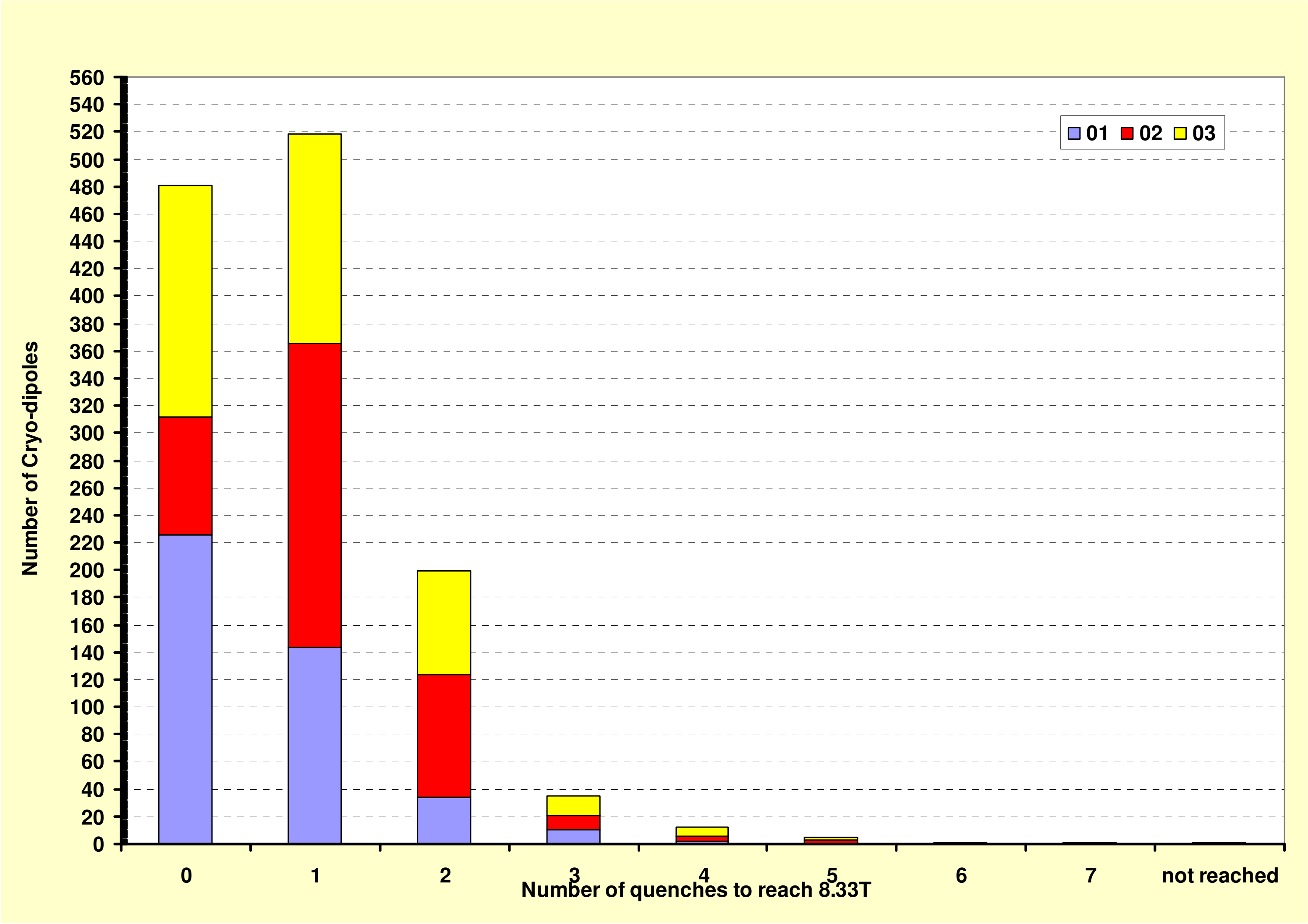
Assembly of dipole cold masses



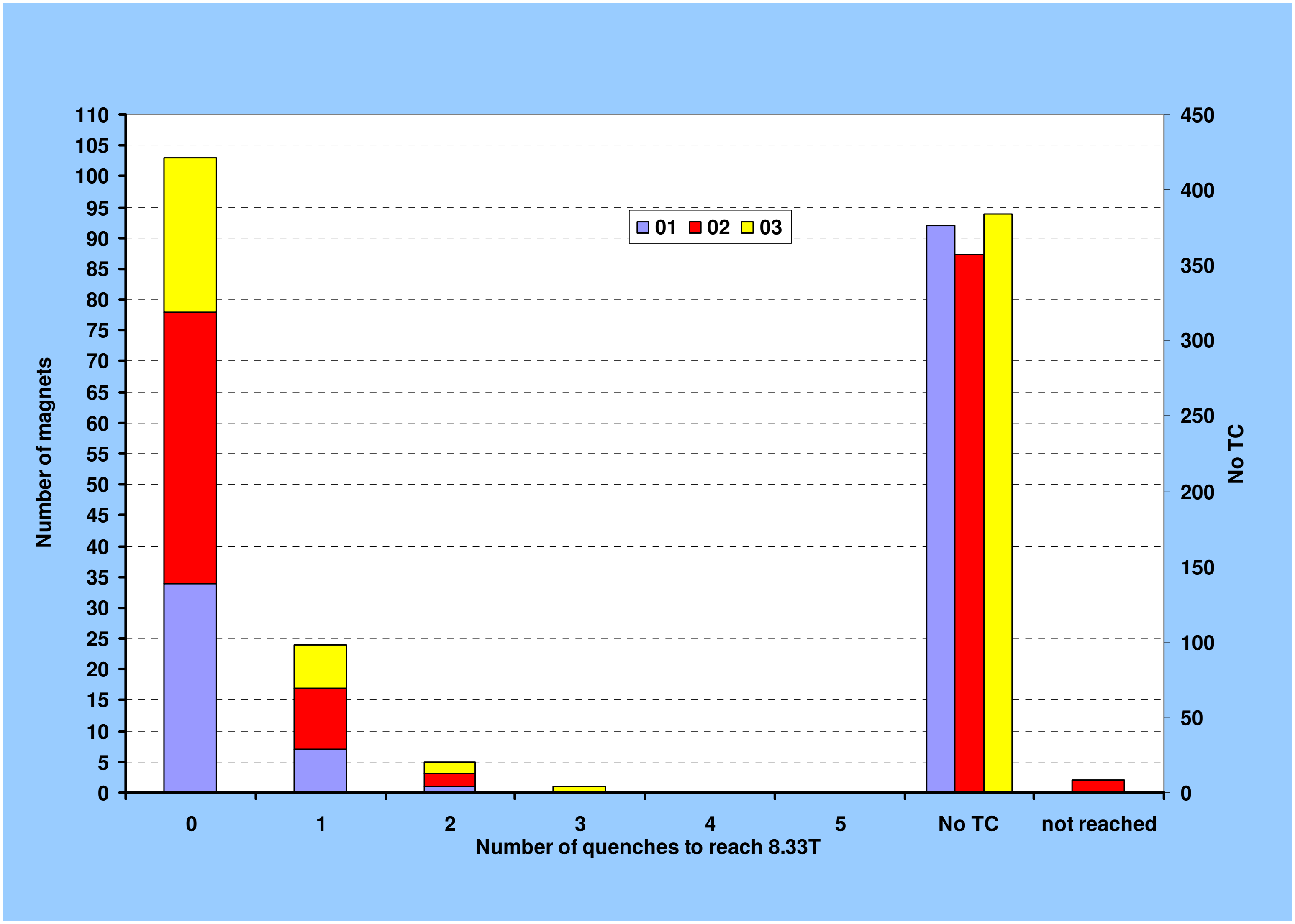
Final assembly of cryomagnets at CERN

Cryogenic tests of magnets

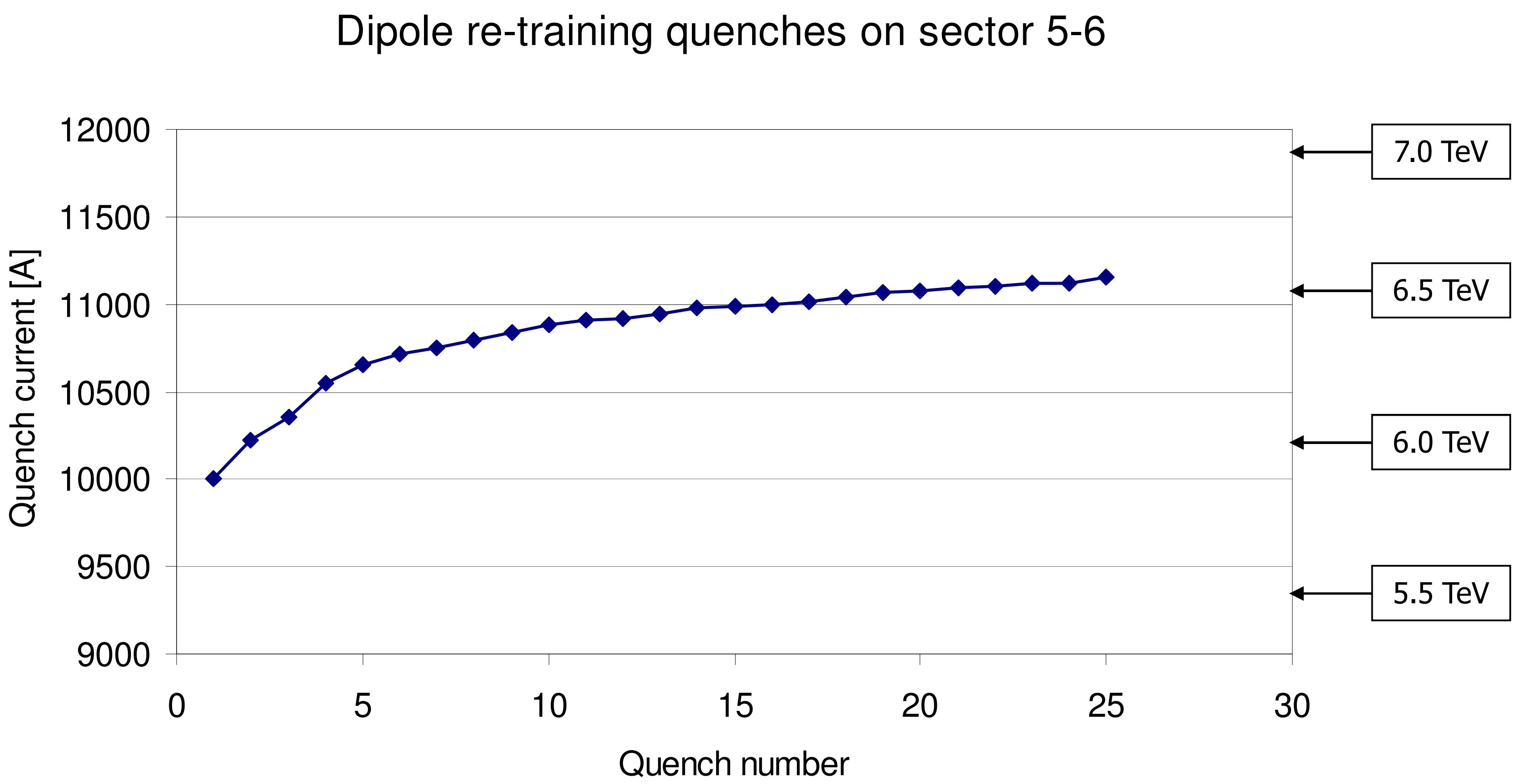
Quenches to reach 8.33 T on virgin dipoles



Quenches to reach 8.33 T after thermal cycle

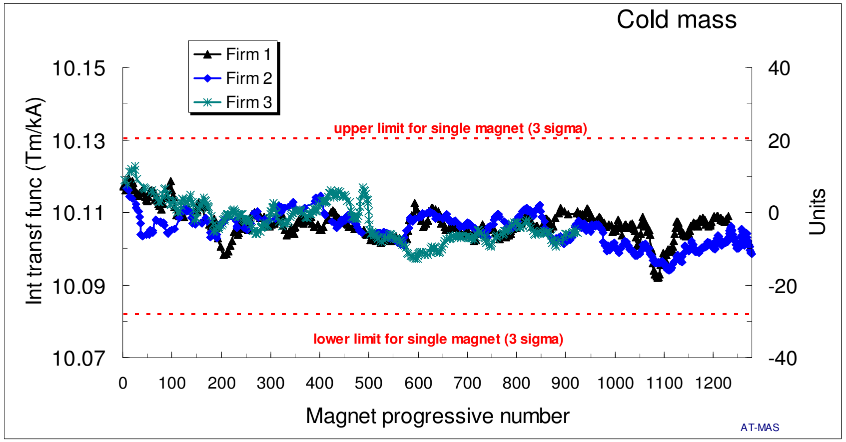


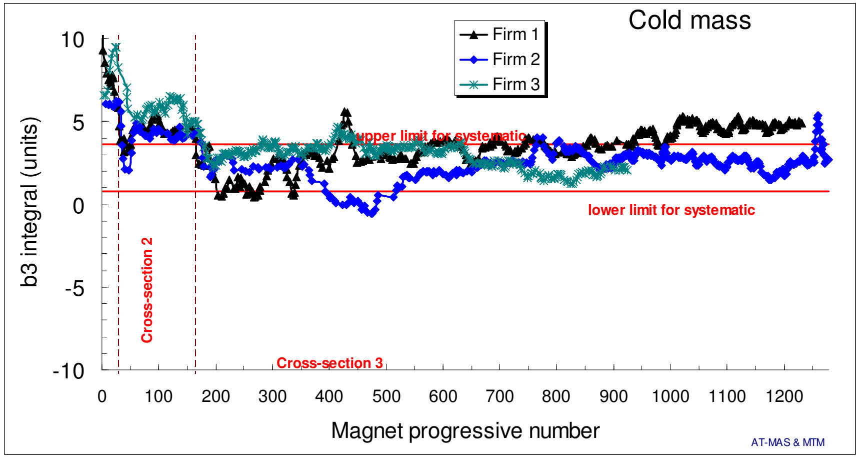
Retraining of dipoles needed on sectors

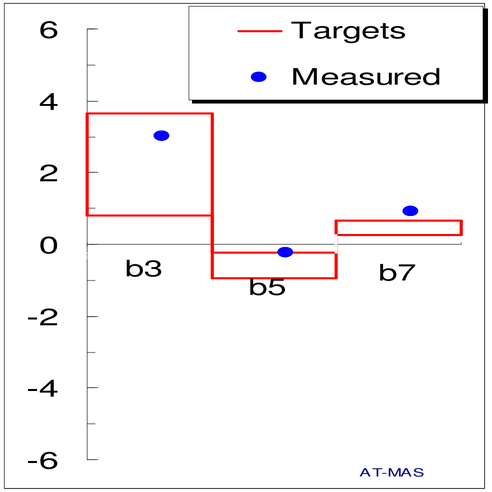


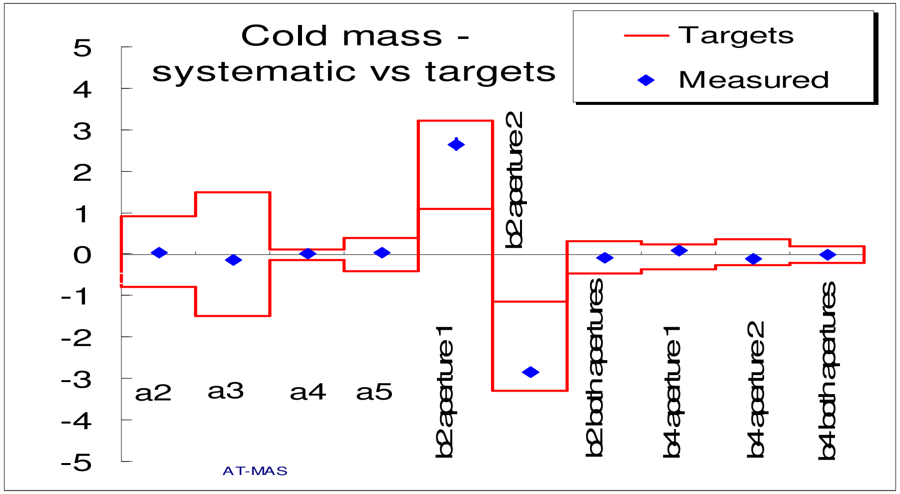
After long-term storage and installation in tunnel, re-training of some magnets needed to operate at 7 TeV ⇒ first commissioning limited to 5.5 TeV (no retraining) to operate reliably up to 5 TeV in the first year

Dipole field quality in series production

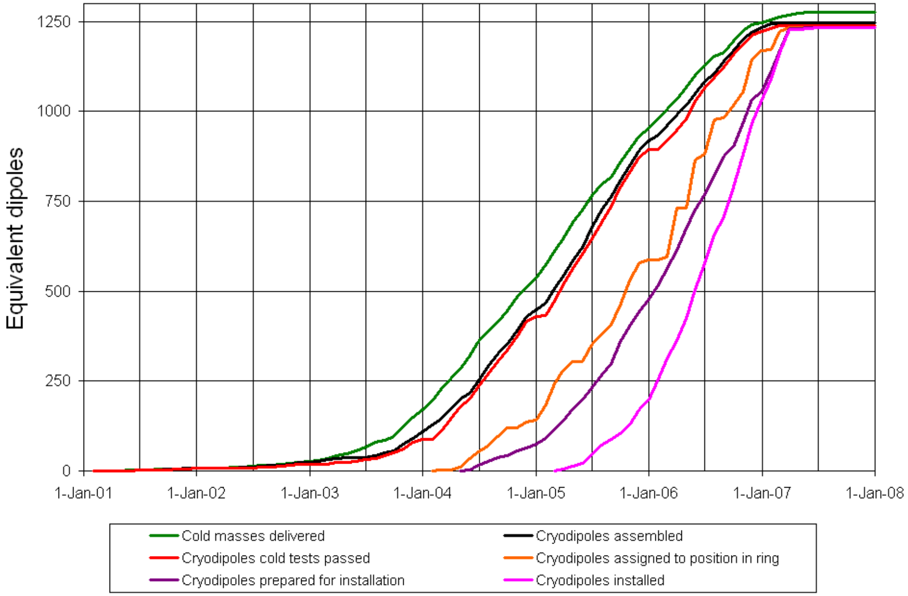


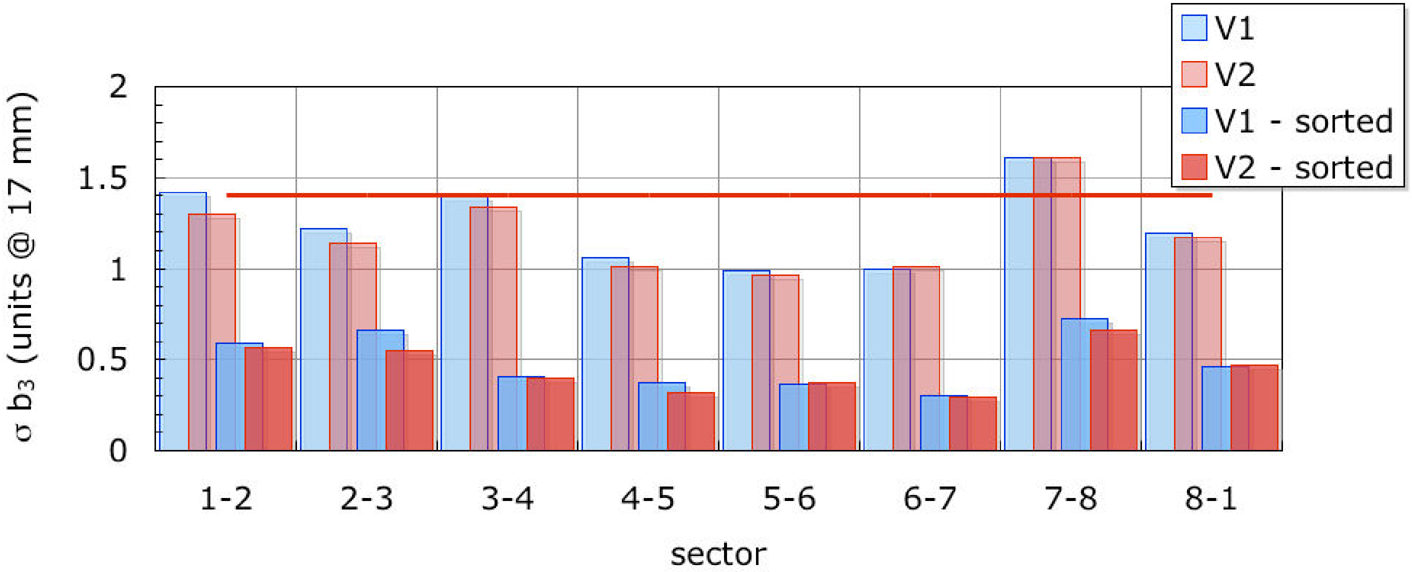






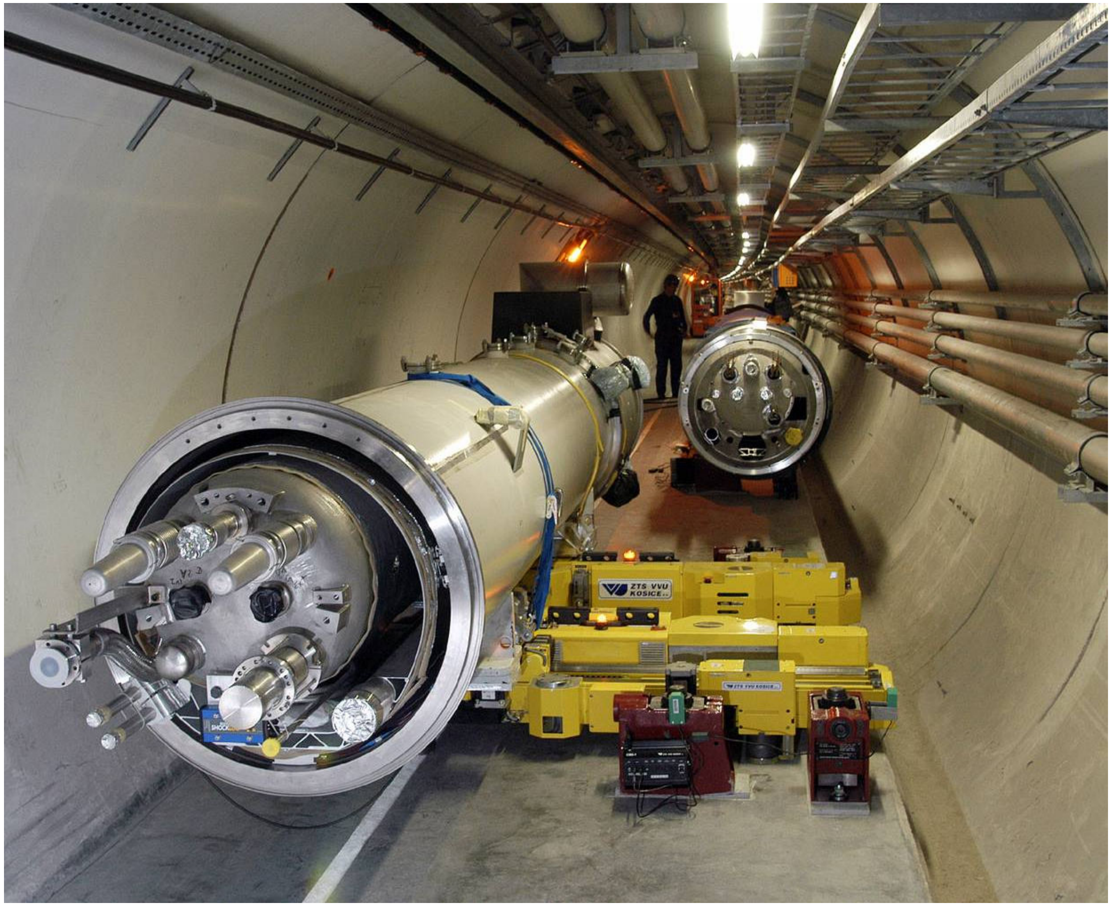
Buffer storage allows sorting and reduces dispersion





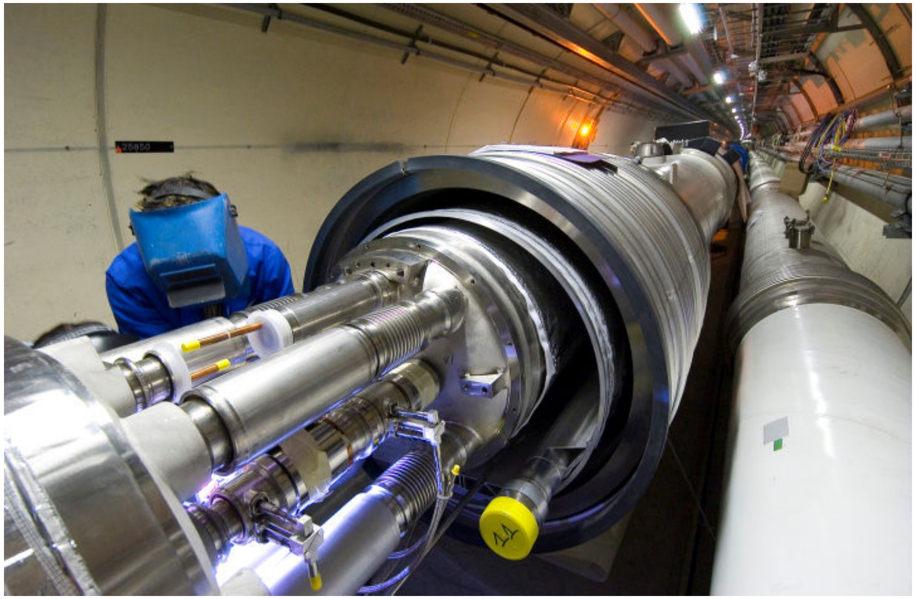
American Linear Collider Physics Group

Lowering and installation of magnets in tunnel

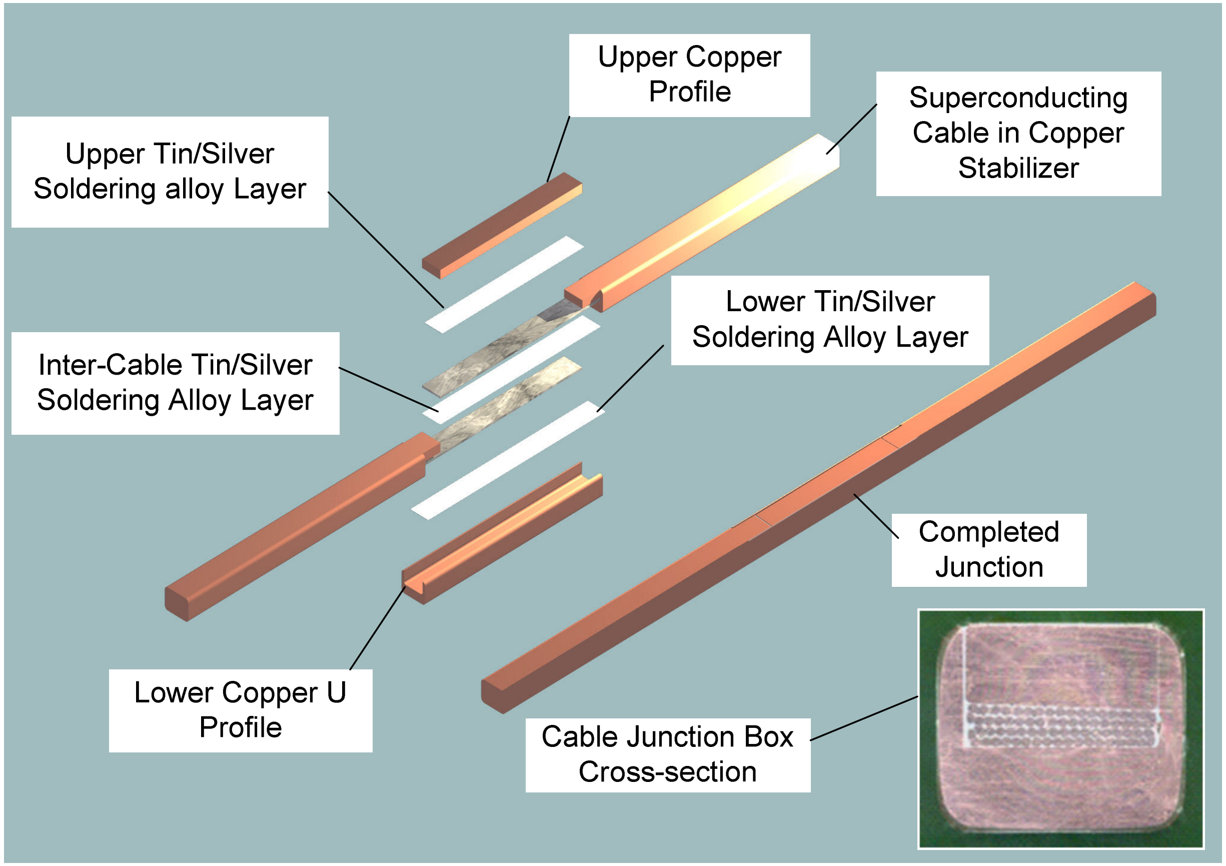


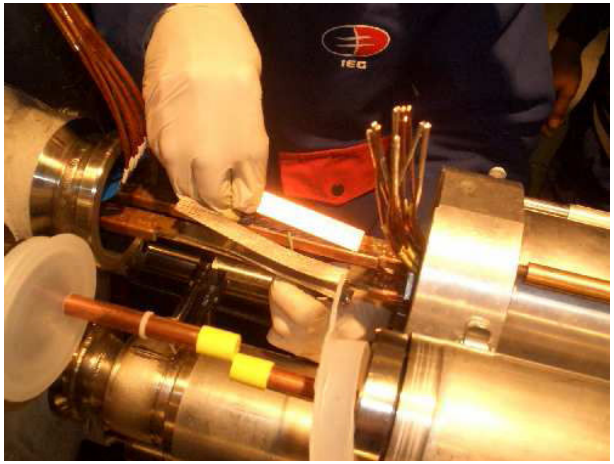
Interconnections in tunnel

65'000 electrical joints	40'000 cryogenic junctions
Induction-heated soldering	Orbital TIG welding
Ultrasonic welding	
Very low residual resistance	*Weld quality*
HV electrical insulation	*Helium leaktightness*

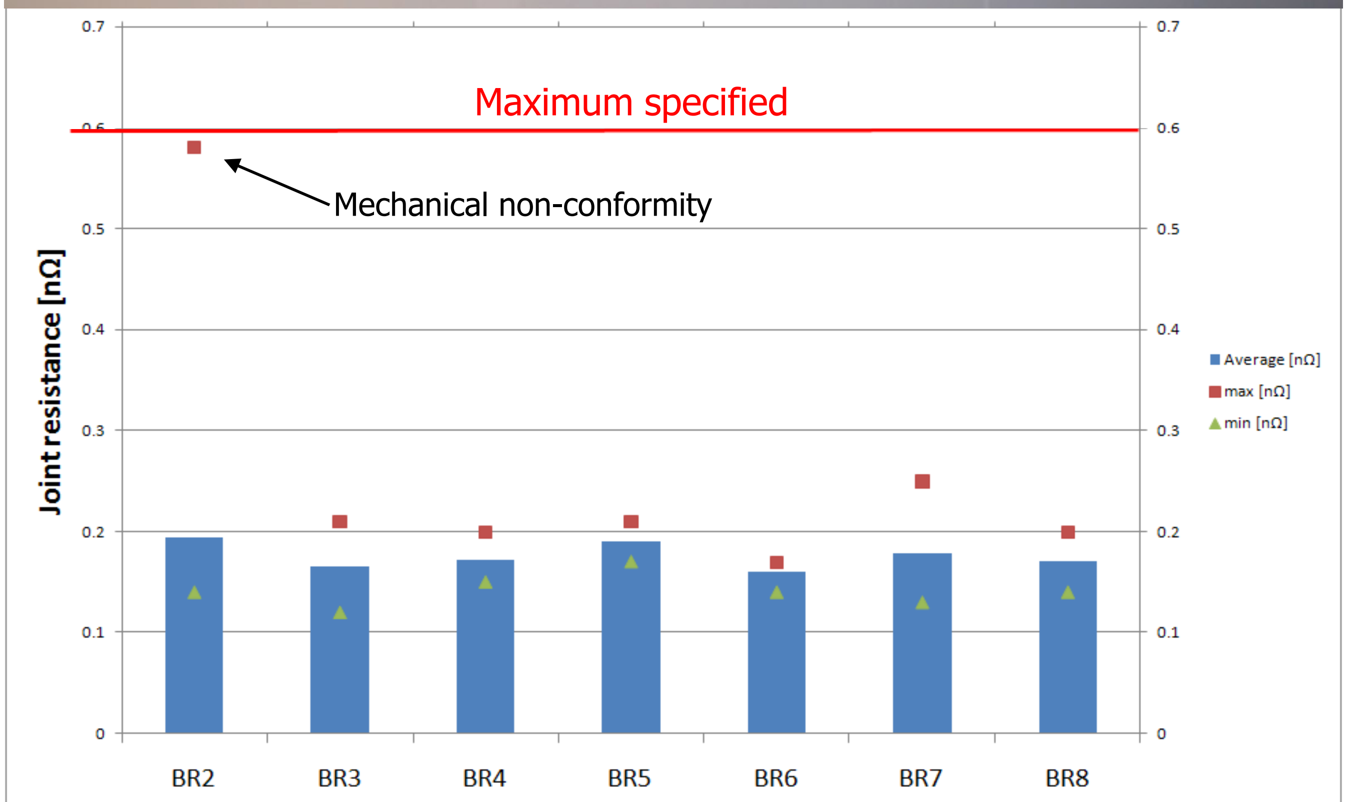


Joint in 12 kA bus bar





QA of electrical joints: witness samples



Current leads using HT superconductor

	Resistive (WFL)	HTS (4 to 50 K) Resistive (> 50 K)
Heat inleak to liquid helium	1.1 W/kA	0.1 W/kA
Exergy loss	430 W/kA	150 W/kA
Electrical power of refrigerator	1430 W/kA	500 W/kA

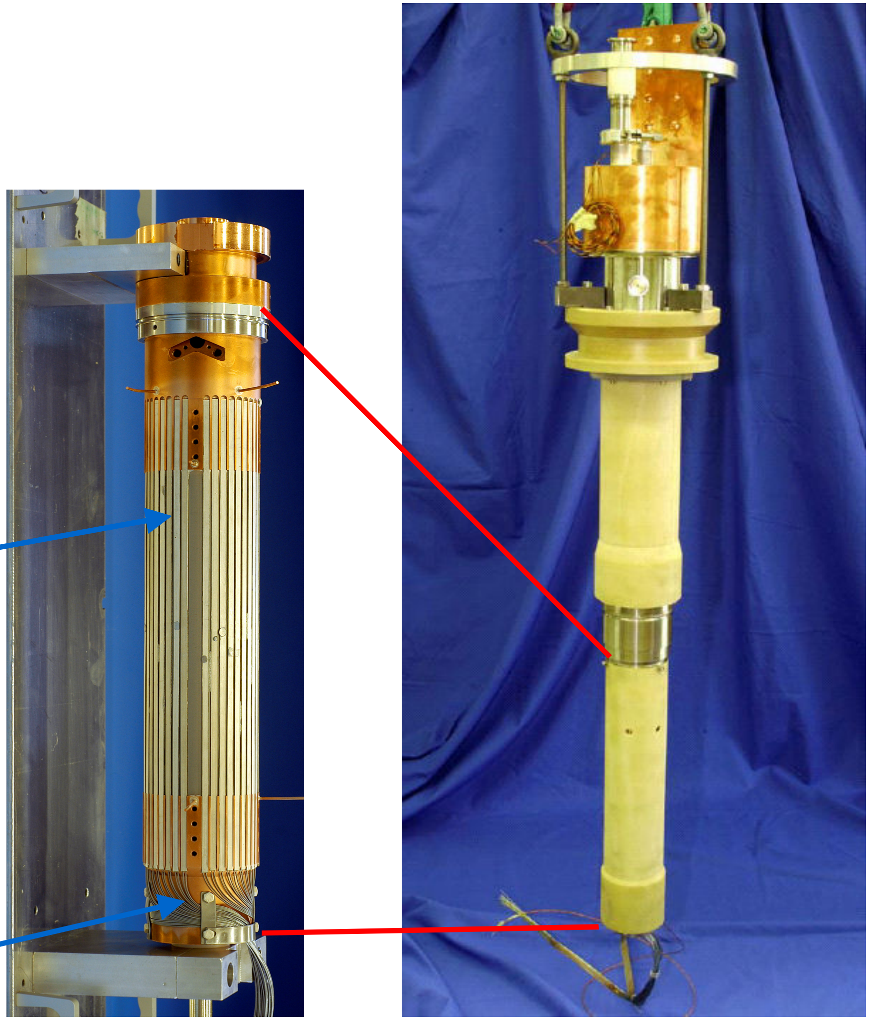
Sum of currents into LHC ~ 1.7 MA, i.e. need current leads for 3.4 MA total rating (in and out)

Economy ~ 3400 W in liquid helium ~ 5000 l/h liquid helium

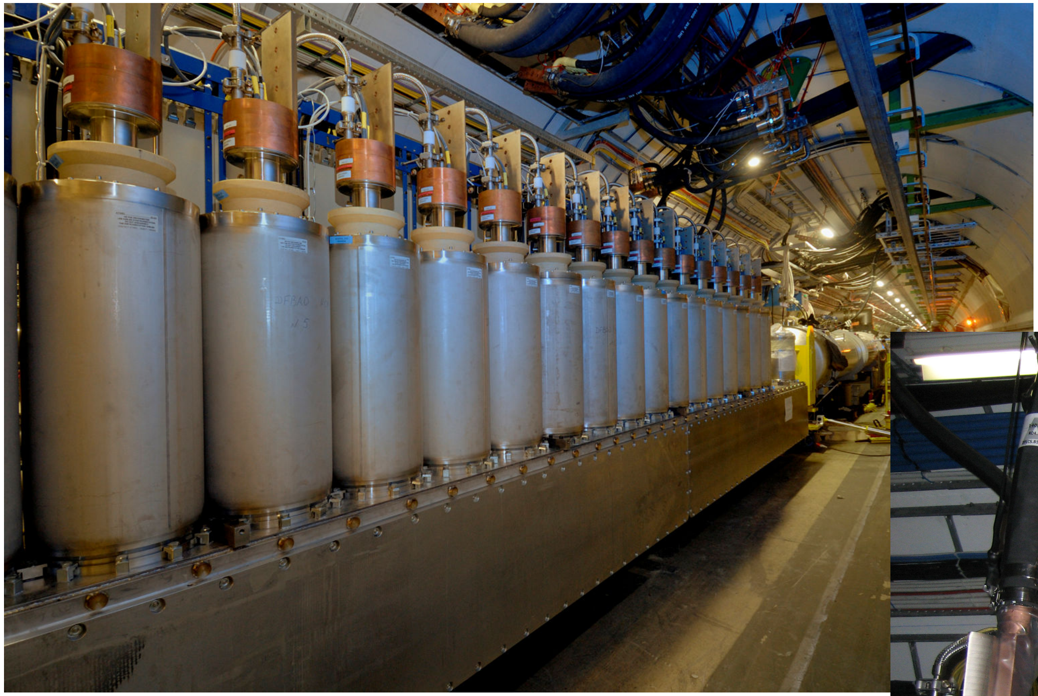
⇒ capital: save extra cryoplant

⇒ operation: save ~ 3.2 MW

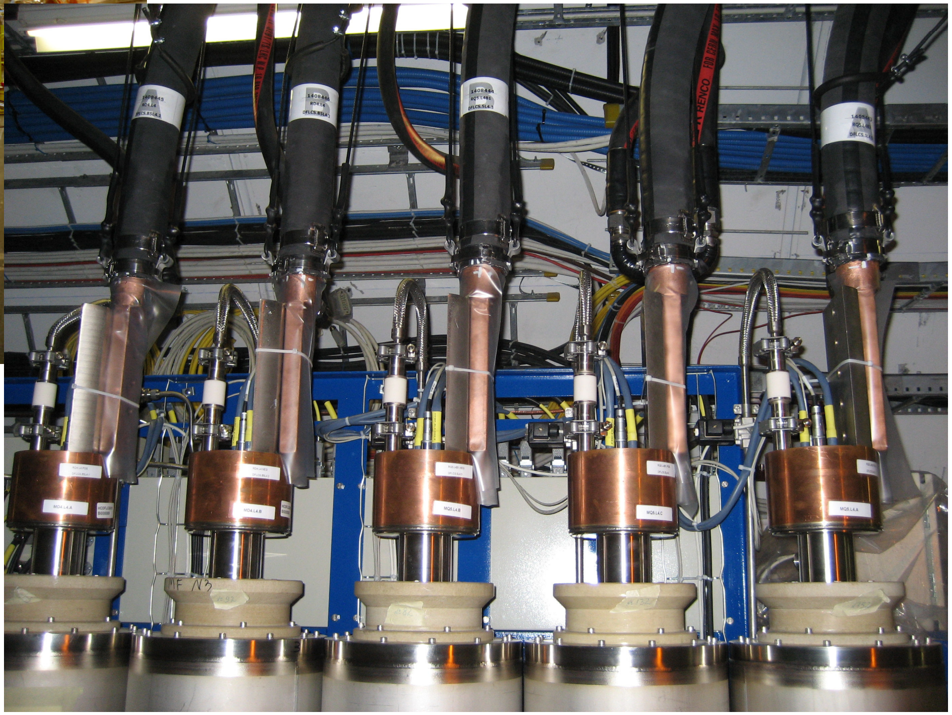
13 kA HTS current lead for LHC



HTS current leads in the LHC tunnel



6 & 13 kA leads on electrical feed-box

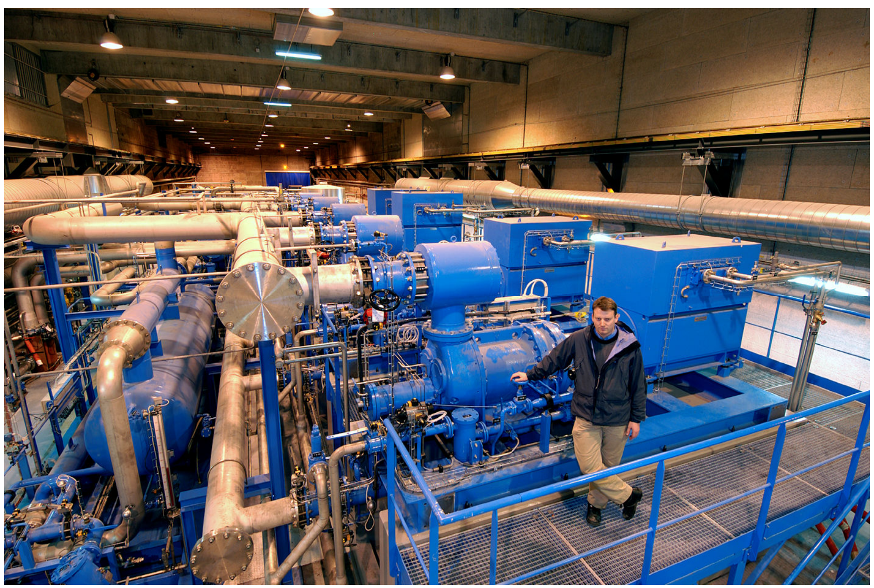


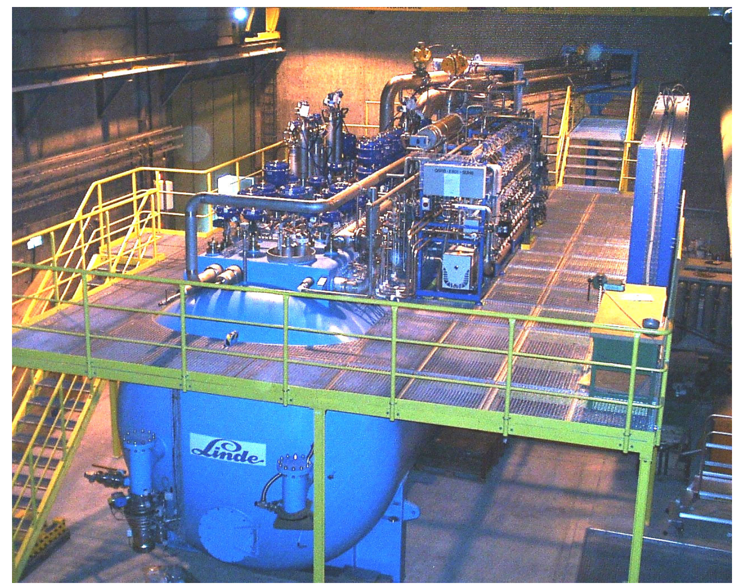
Water-cooled cables on current lead lugs

Eight 18 kW @ 4.5 K helium refrigerators

33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction

4 MW compressor power
High-efficiency ~ 220 W/W

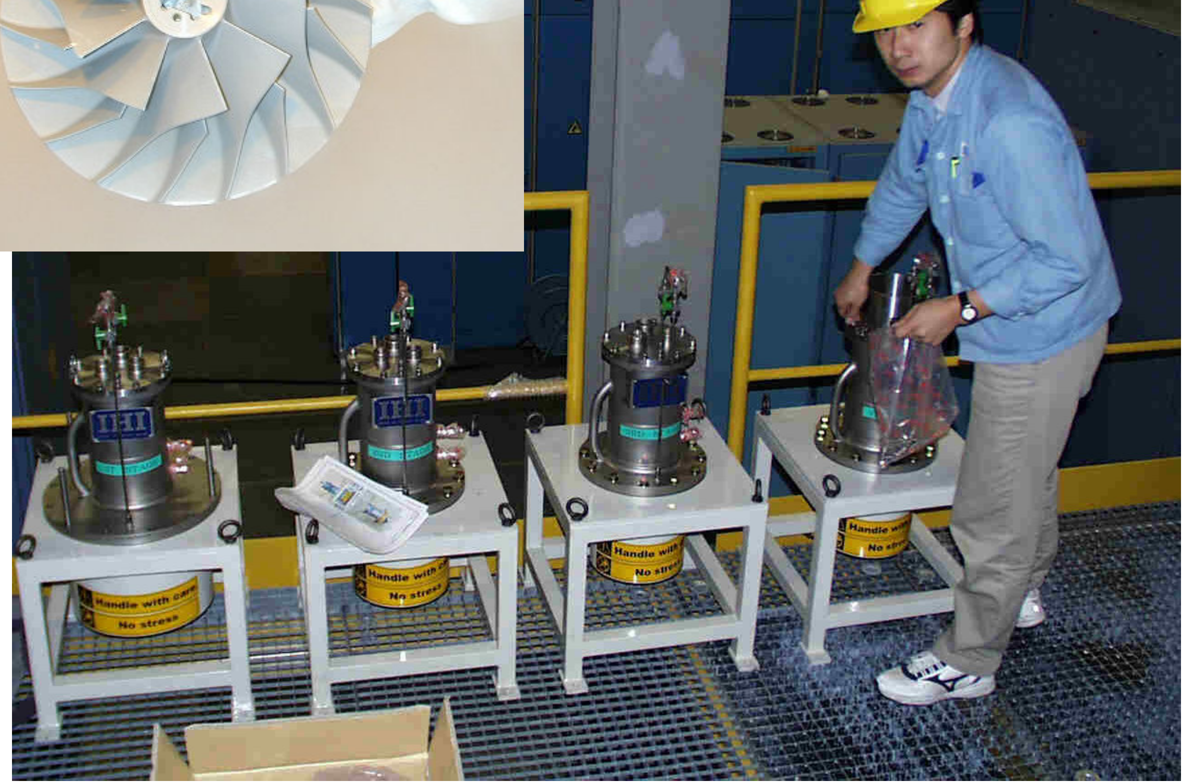




Cold compressors for 1.8 K refrigeration

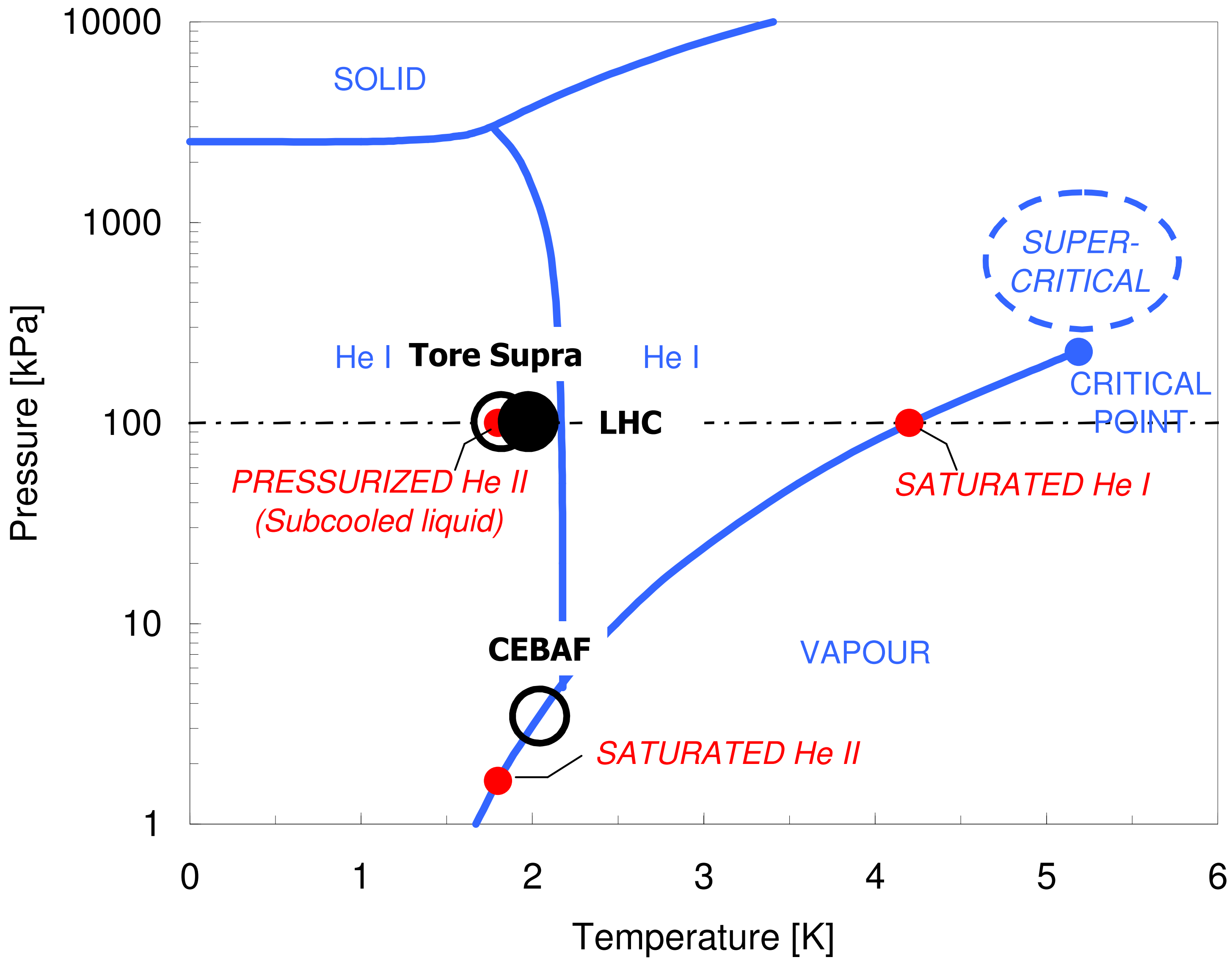
Axial-centrifugal impeller

Cartridge 1st stage



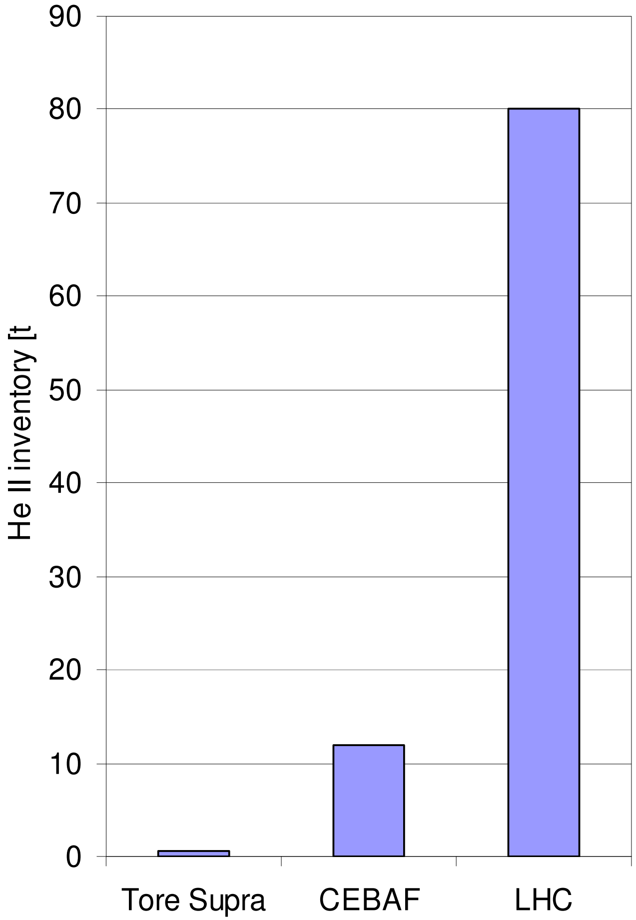
4 cold compressor stages

Superfluid helium cooling

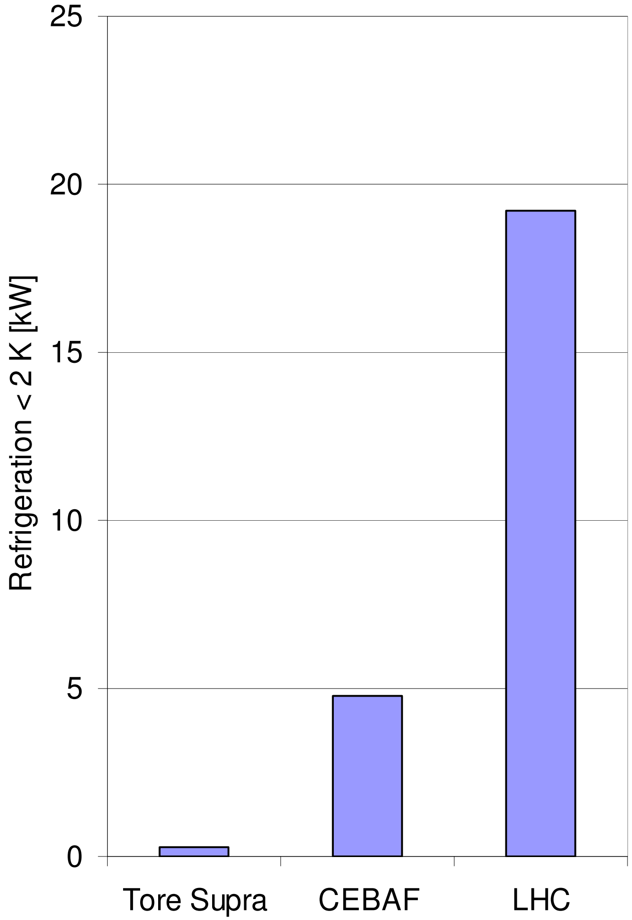


Large-scale superfluid helium systems

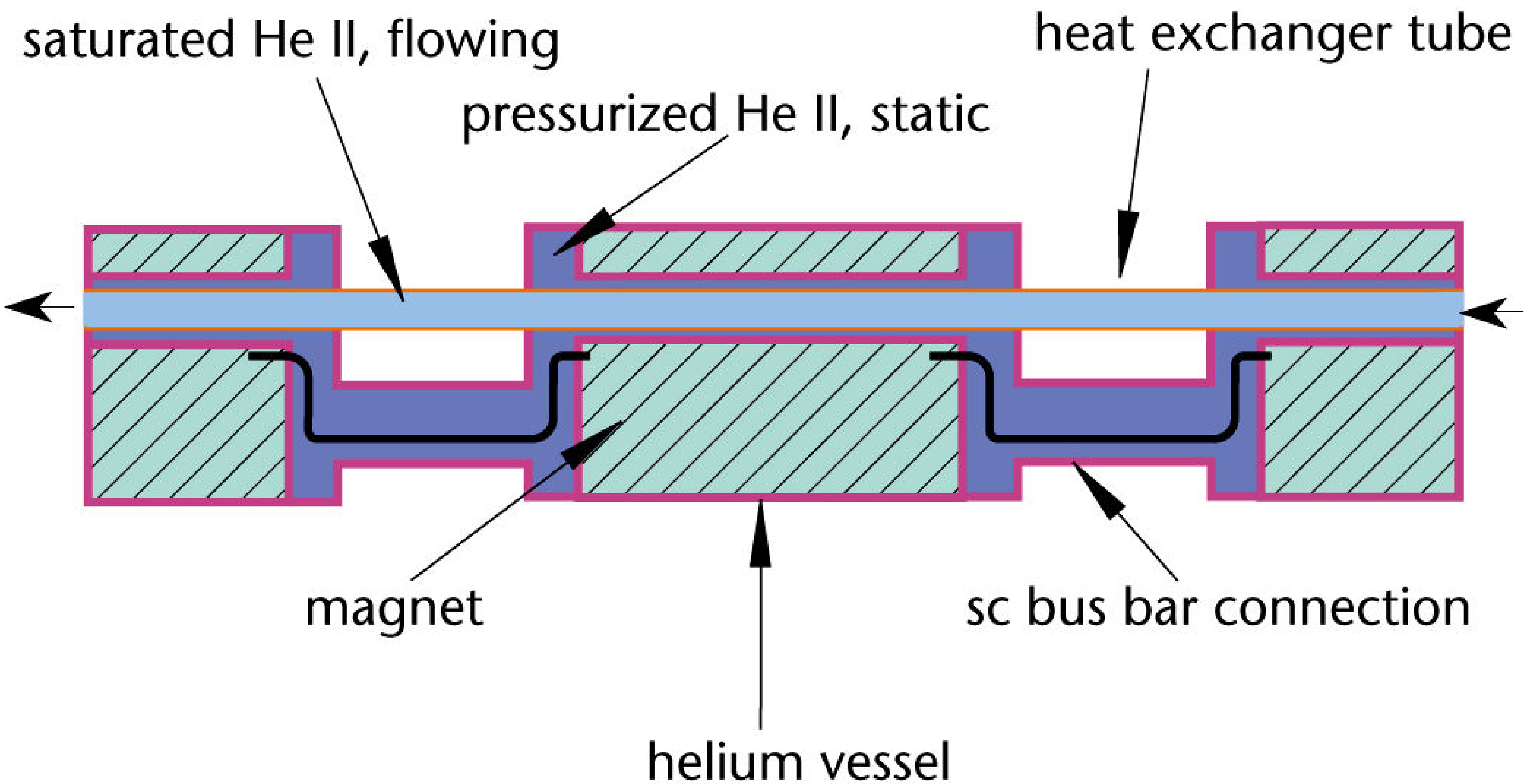
He II inventory

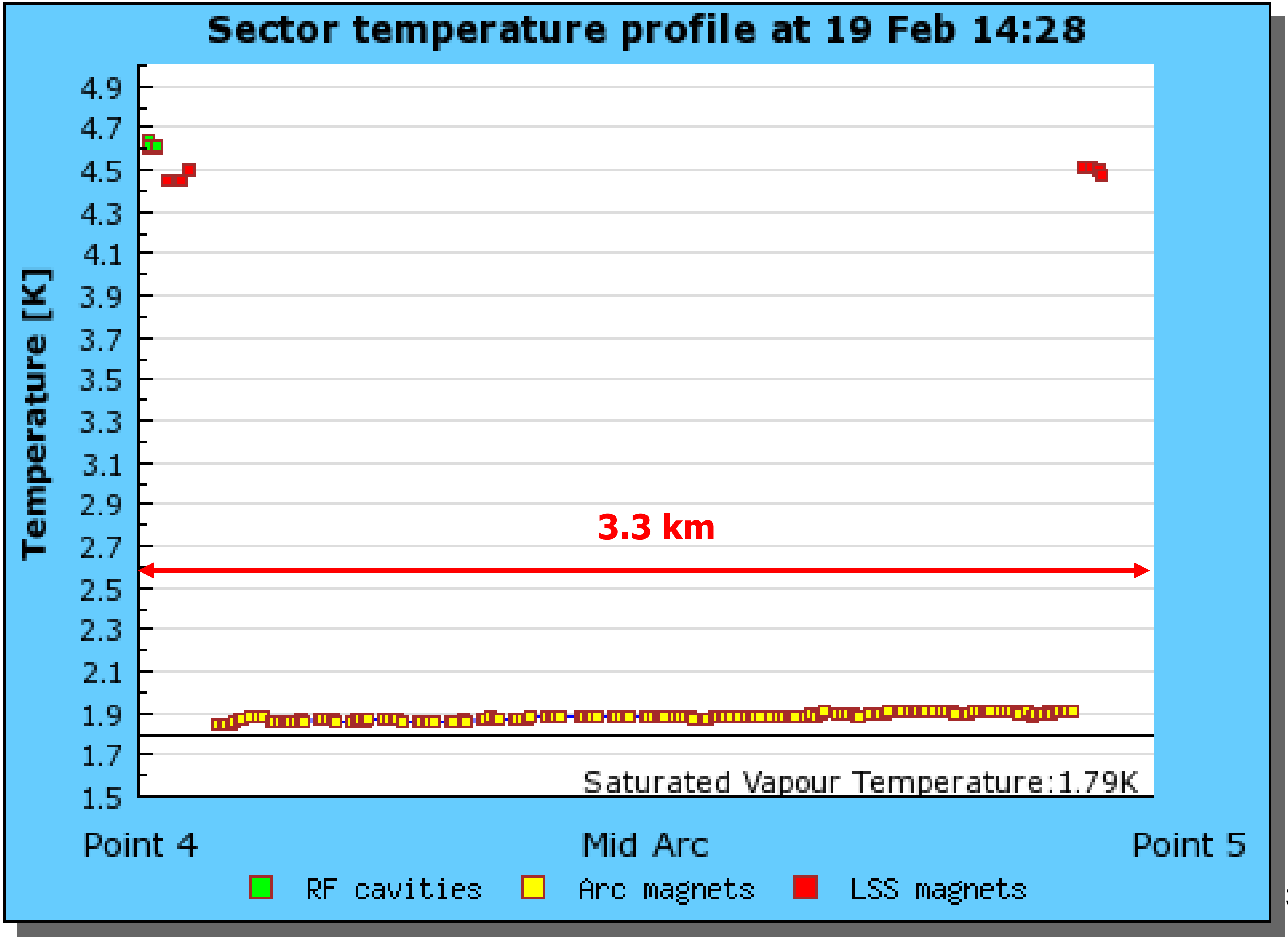


Refrigeration power < 2 K



LHC magnet string cooling scheme

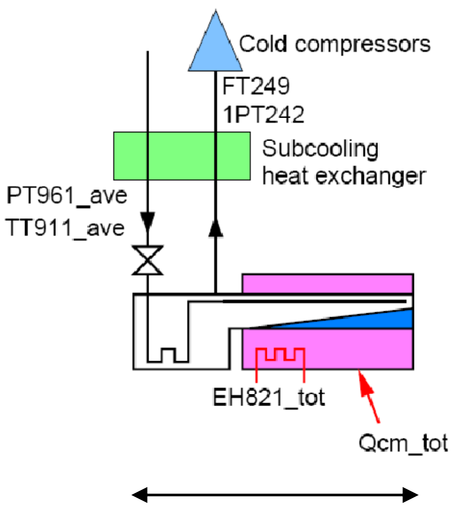



Sector temperature profile at 19 Feb 14:28
Temperature [K]
4.9
4.7
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
2.7
2.5
2.3
2.1
1.9
1.7
1.5
3.3 km
Saturated Vapour Temperature:1.79K
Point 4
Mid Arc
Point 5
RF cavities
Arc magnets
LSS magnets

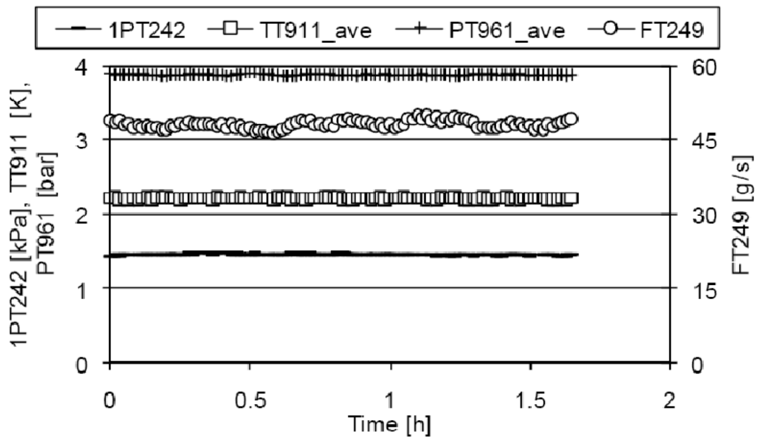
Precooling 37’000 t magnets with 10’000 t liquid nitrogen

Cooldown to 80 K: 600 kW per sector
with up to ~5 tons/h liquid nitrogen

Heat inleak measurements on full sectors confirm thermal budget



LHC sector (3.3 km)

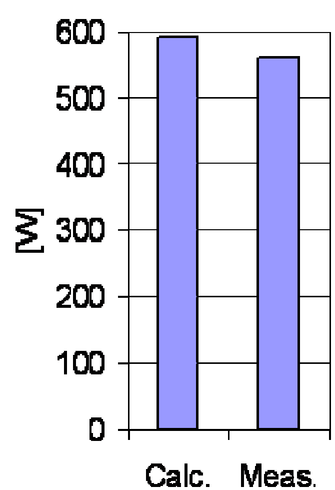


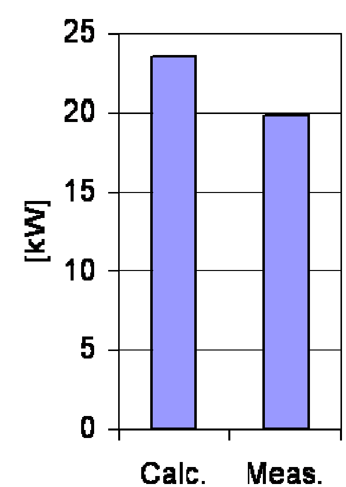
Temperatures and pressures stabilized, flow-rate integrated

Measured

$$\dot{Q} = \dot{m}\,\Delta h(P,T)$$

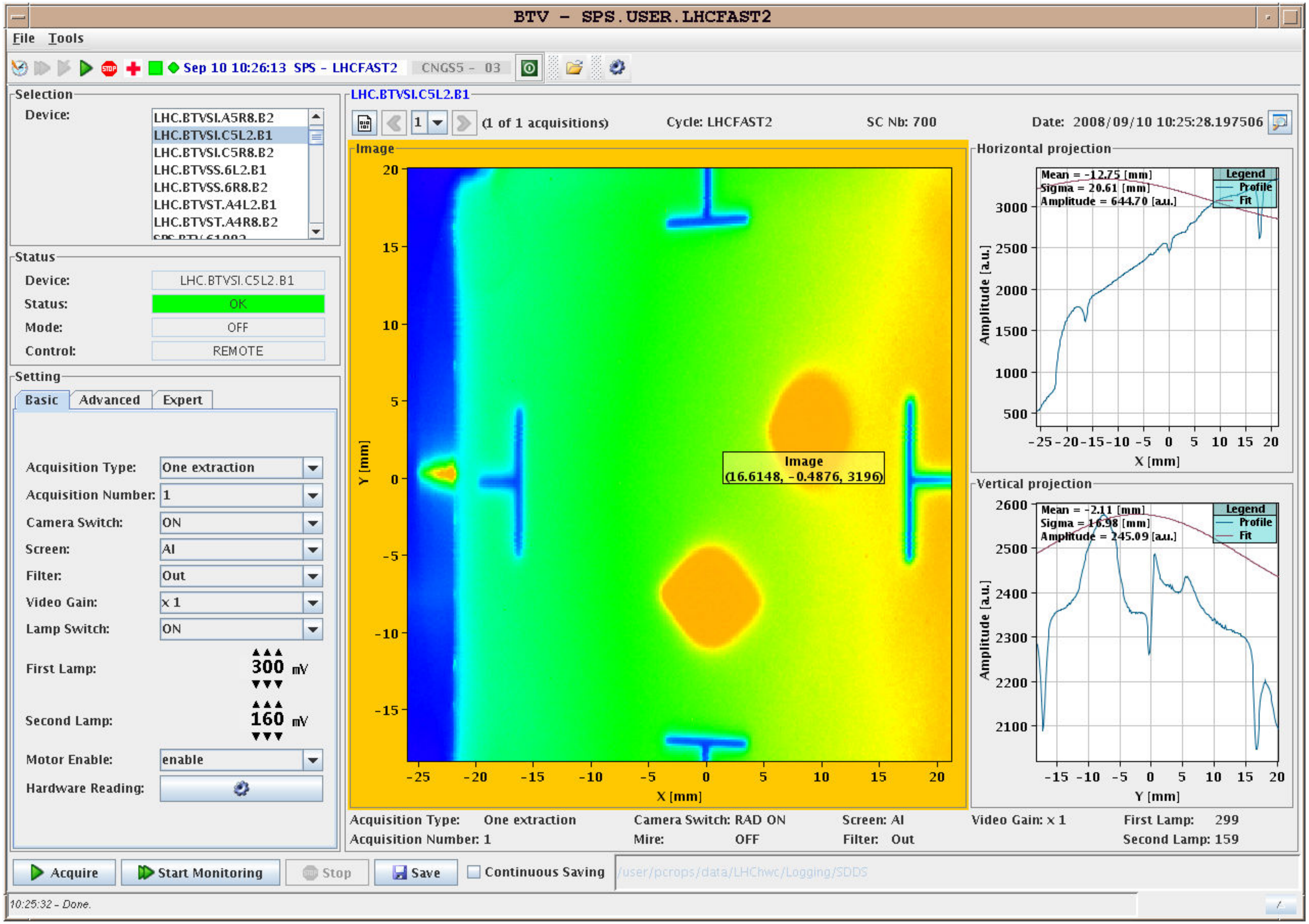
He property tables





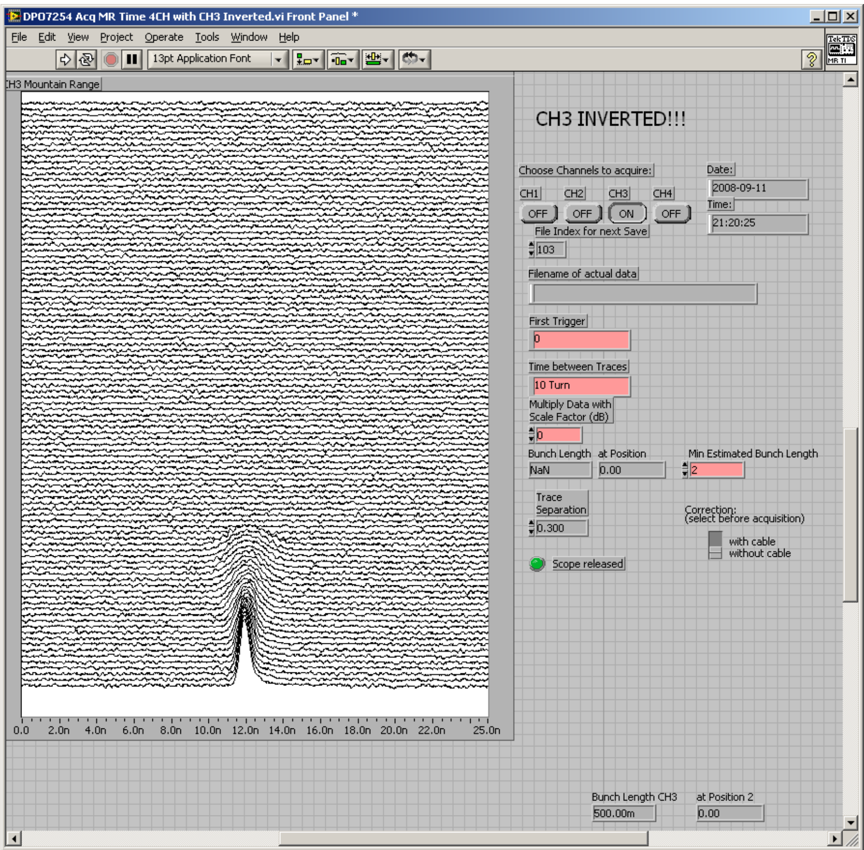
10 September 2008 - first beam in LHC

Beam on turns 1 and 2 – 10 September 2008

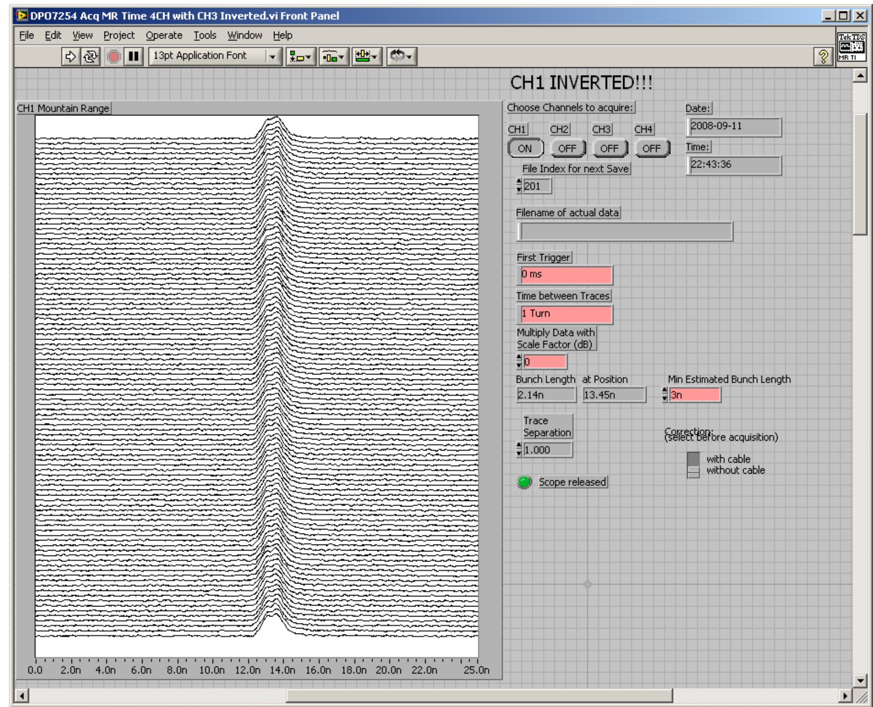


Beam capture by RF

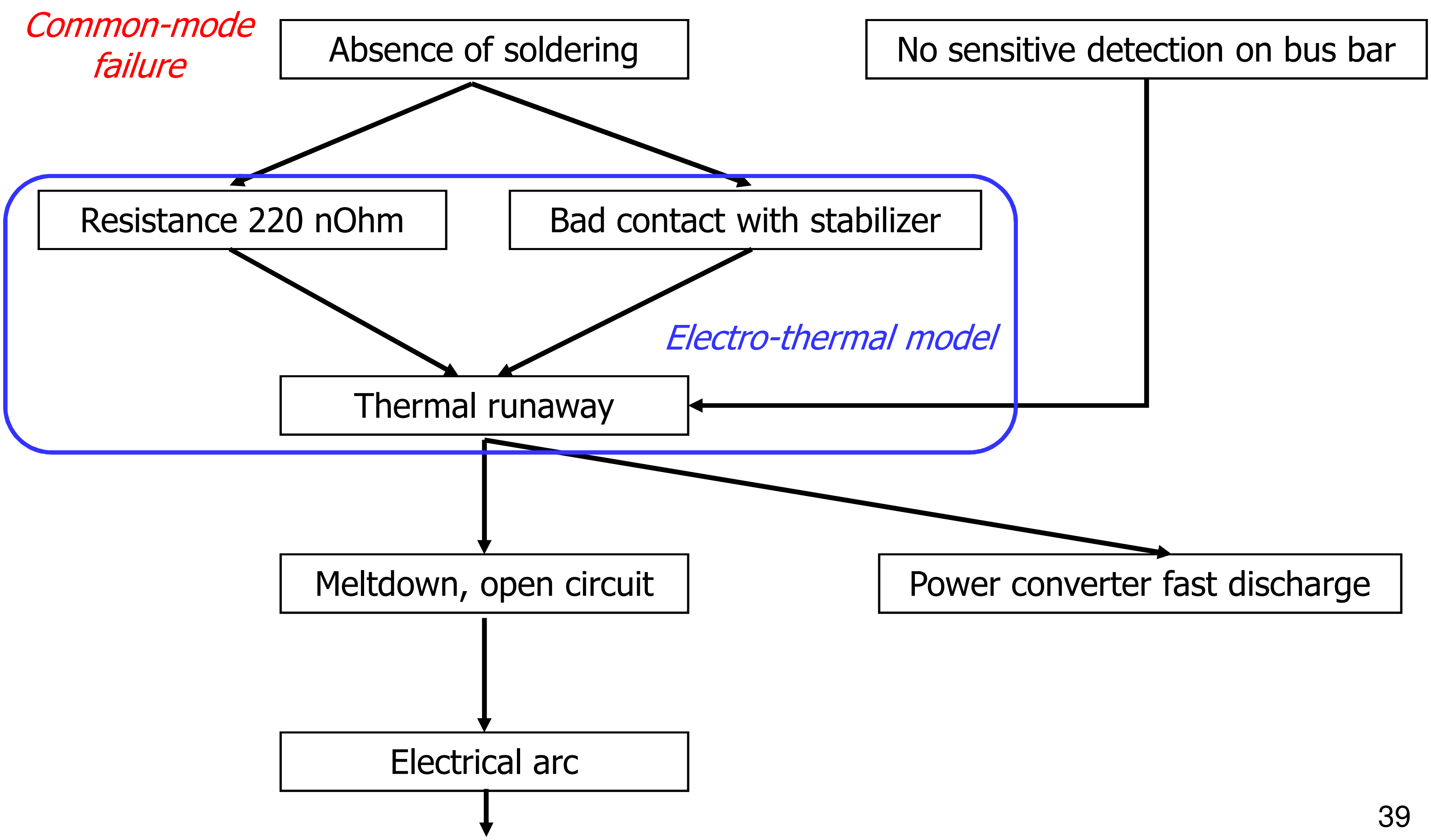
No RF, debunching in ~ 250 turns



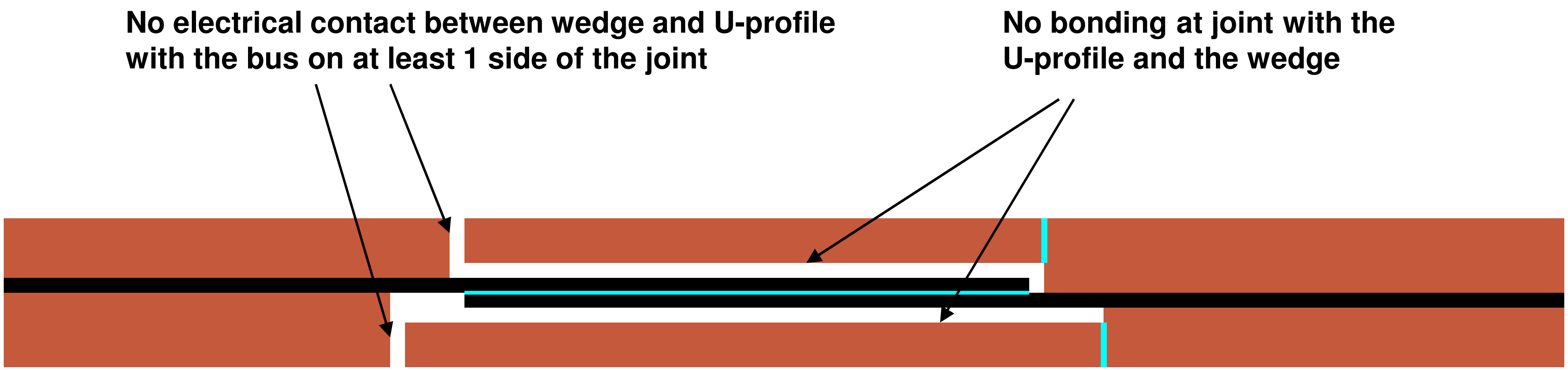
RF on



Fault tree of 19 September 2008 incident [1/3]



A resistive joint of about 220 nΩ with bad electrical and thermal contacts with the stabilizer

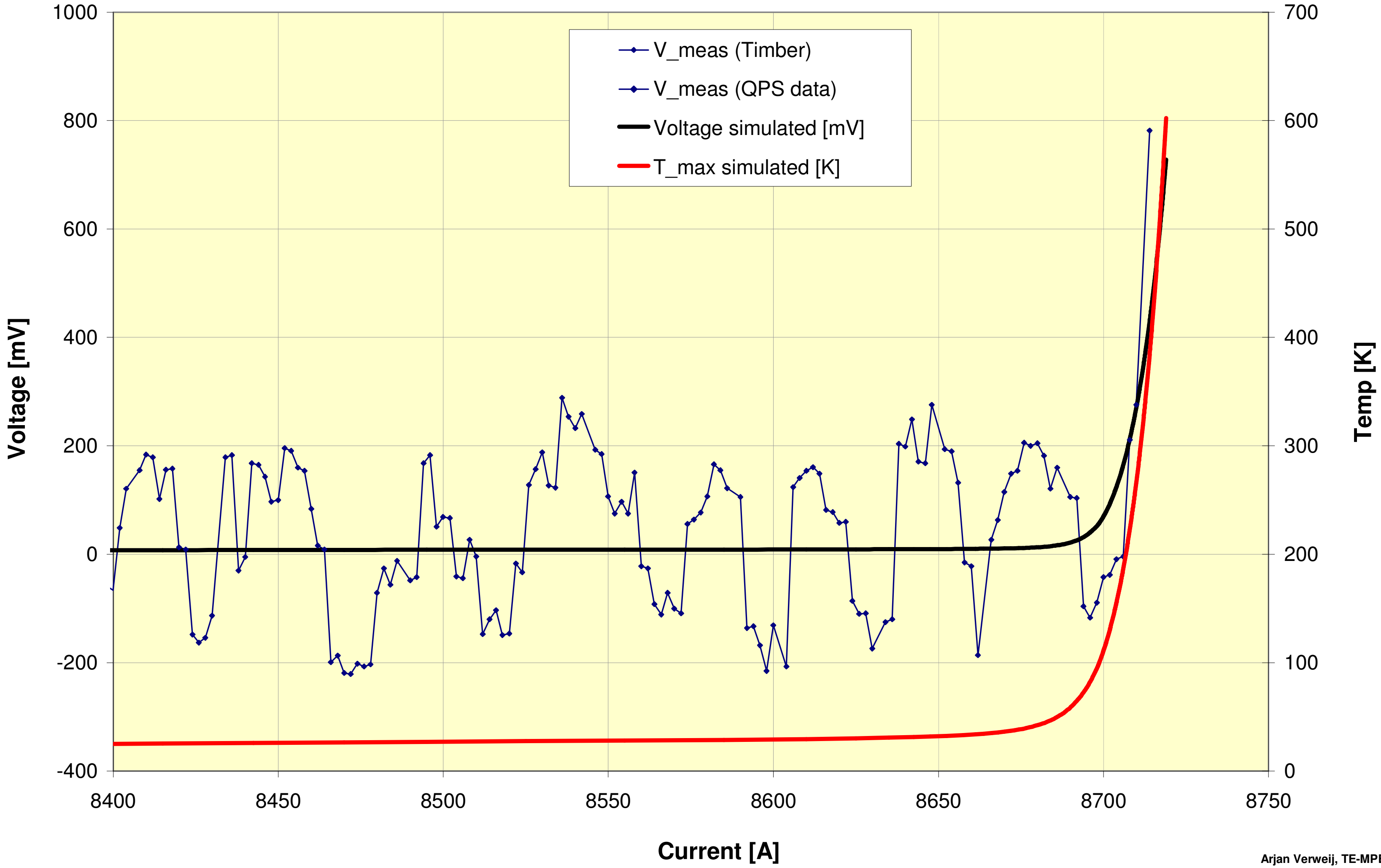


⇒ Loss of clamping pressure on the joint, and between joint and stabilizer

⇒ Degradation of transverse contact between superconducting cable and stabilizer

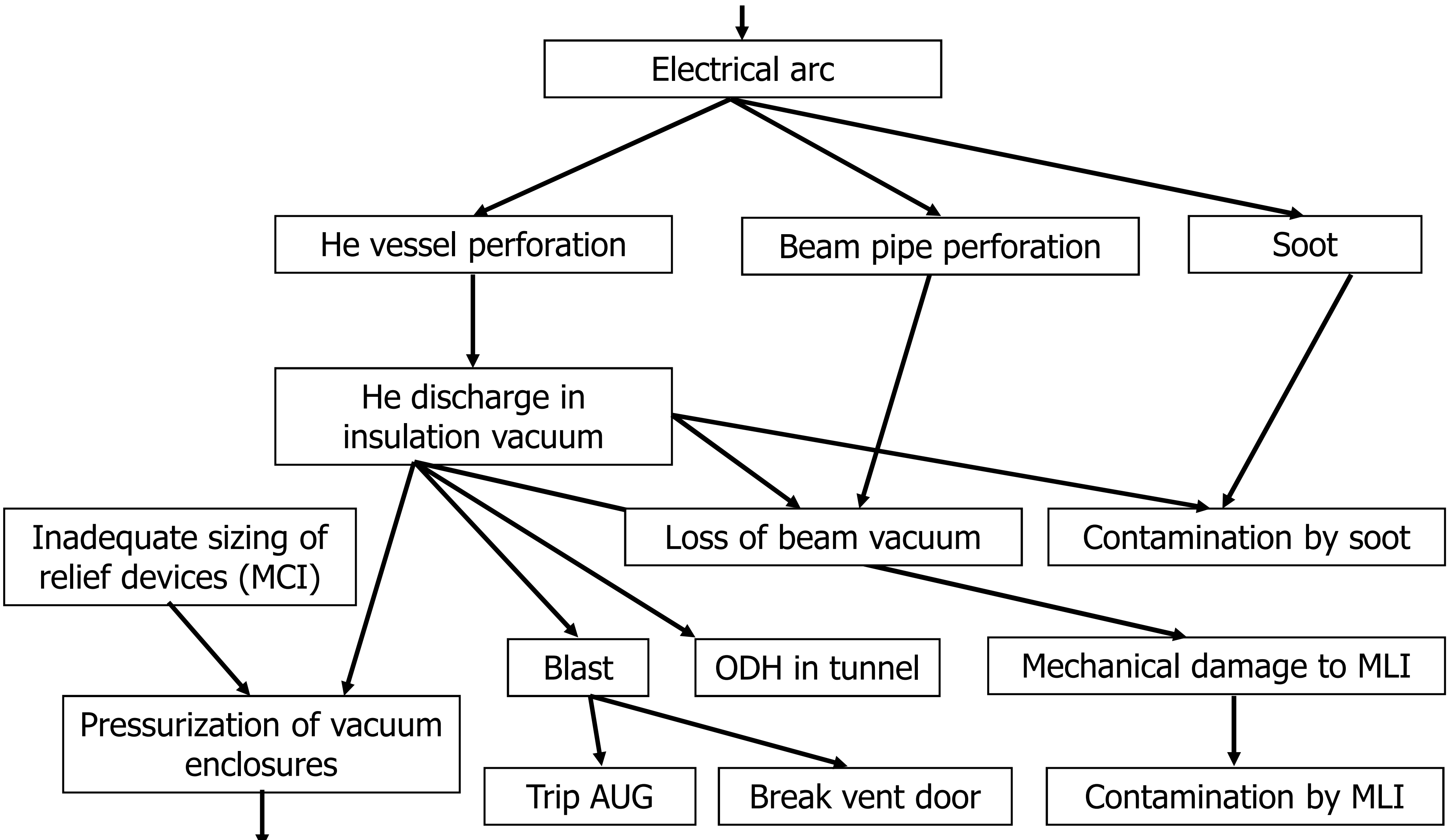
⇒ Interruption of longitudinal electrical continuity in stabilizer

Measured vs simulated incident with 220 nΩ joint and bad contact with U-profile and wedge

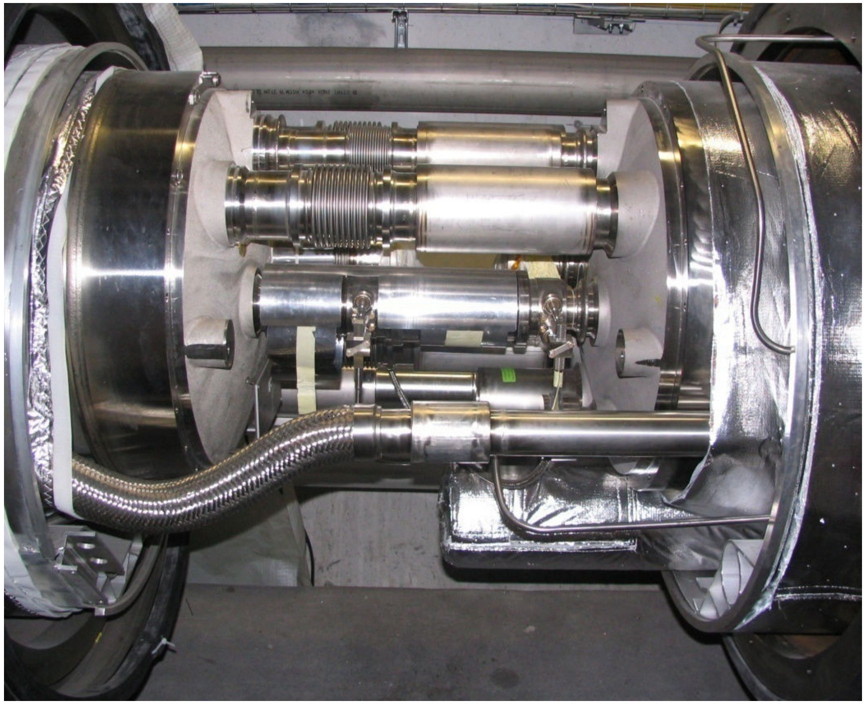


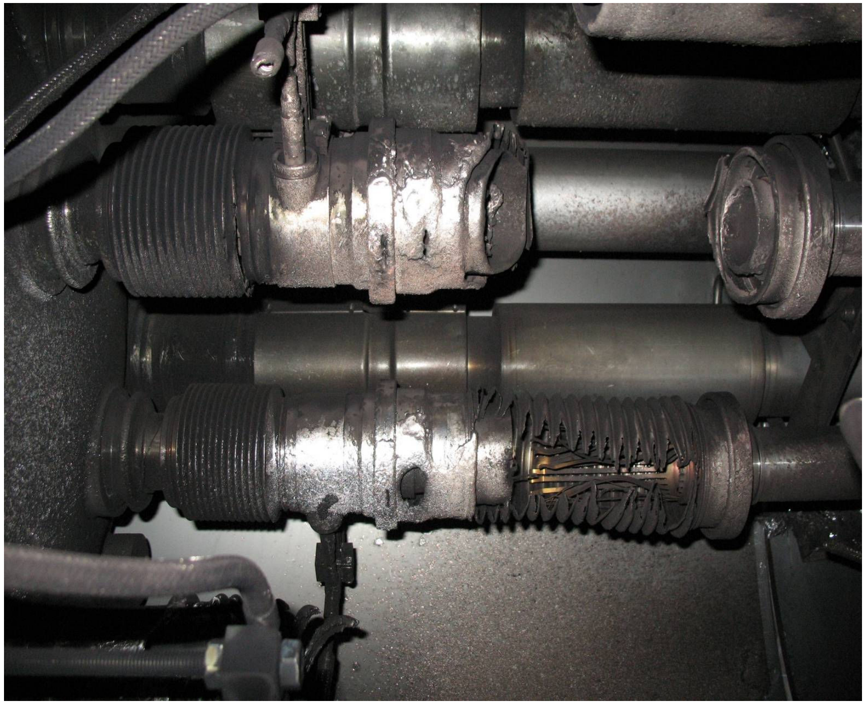
Arjan Verweij, TE-MPE

Fault tree of 19 September 2008 incident [2/3]

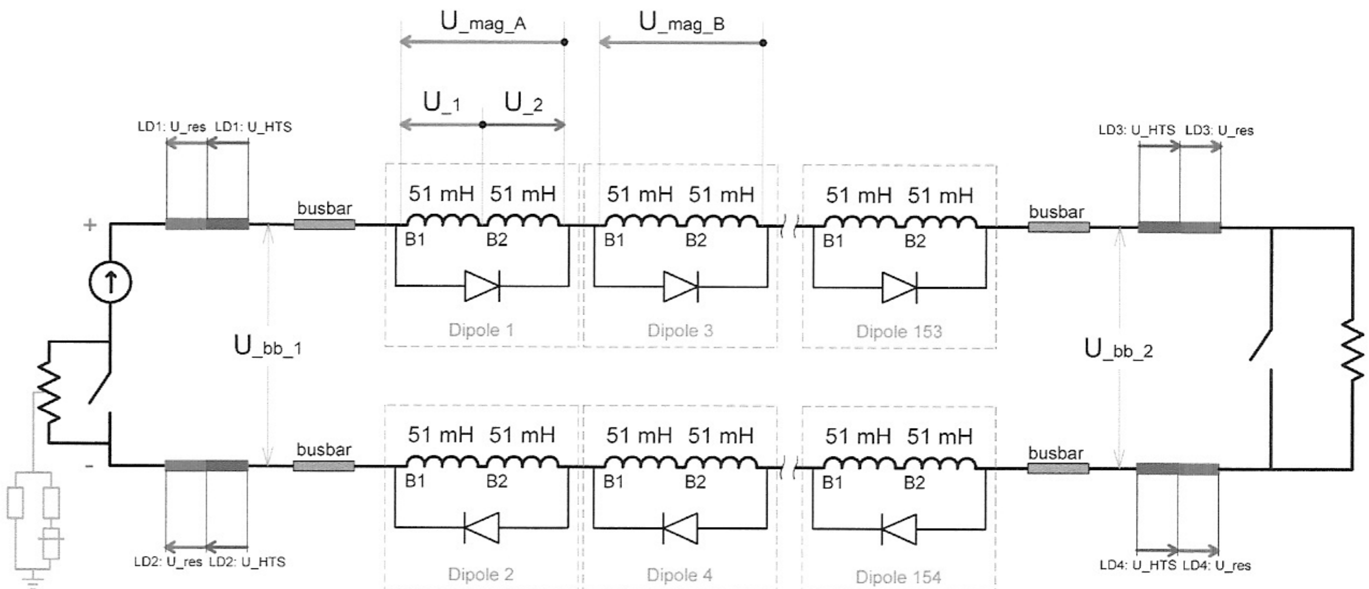


Electrical arc between two magnets



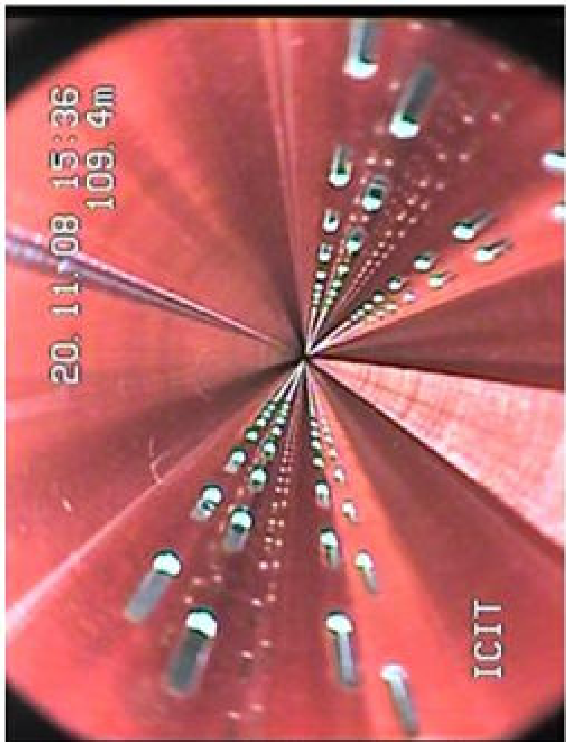


Balance of energy dissipation during the incident



Energy	MJ	%
Stored in the magnets	595.0	100
Dissipated in UJ33 discharge resistor	71.0	12
Dissipated in UA43 discharge resistor	104.8	18
Dissipated in cold mass	144.4	24
Dissipated in electrical arcs	274.8	46

Beam vacuum contamination

<table>
<tr>
<td>Beam Screen (BS) : The red color is characteristic of a clean copper surface</td>
<td>BS with some contamination by super-isolation (MLI multi layer insulation)</td>
<td>BS with soot contamination. The grey color varies depending on the thickness of the soot, from grey to dark.</td>
</tr>
<tr>
<td>
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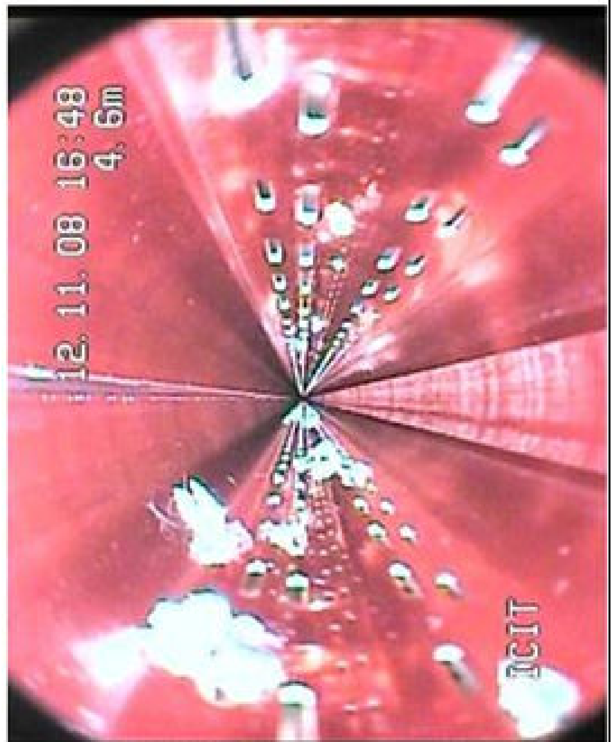
<td>
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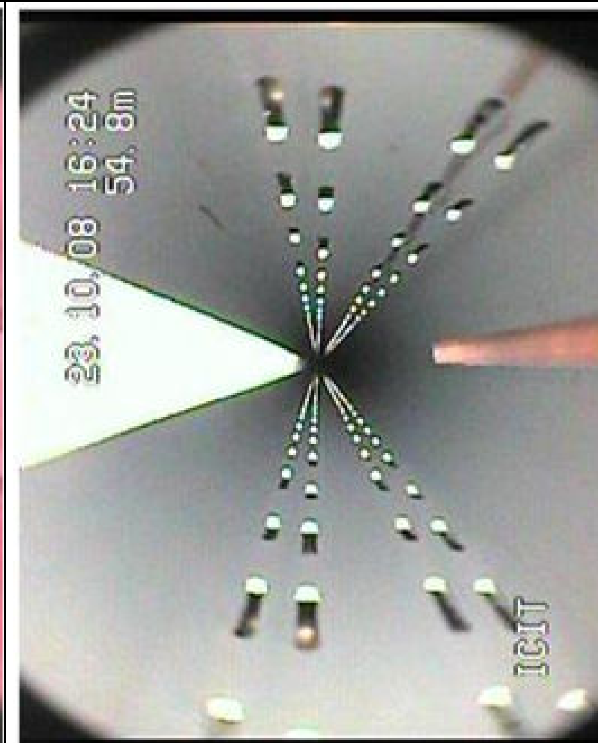
<td>
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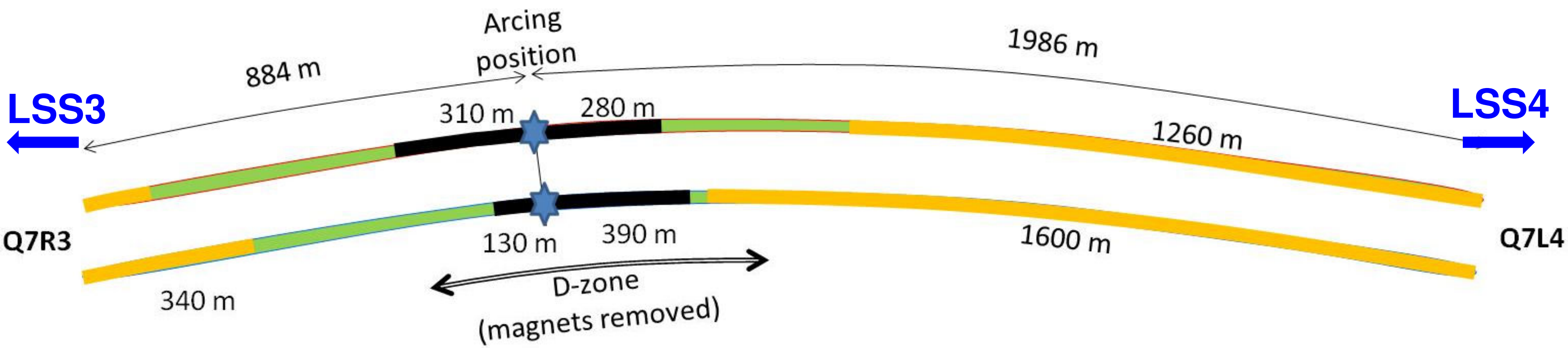
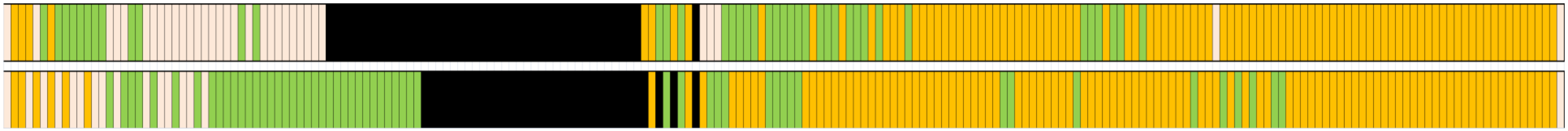
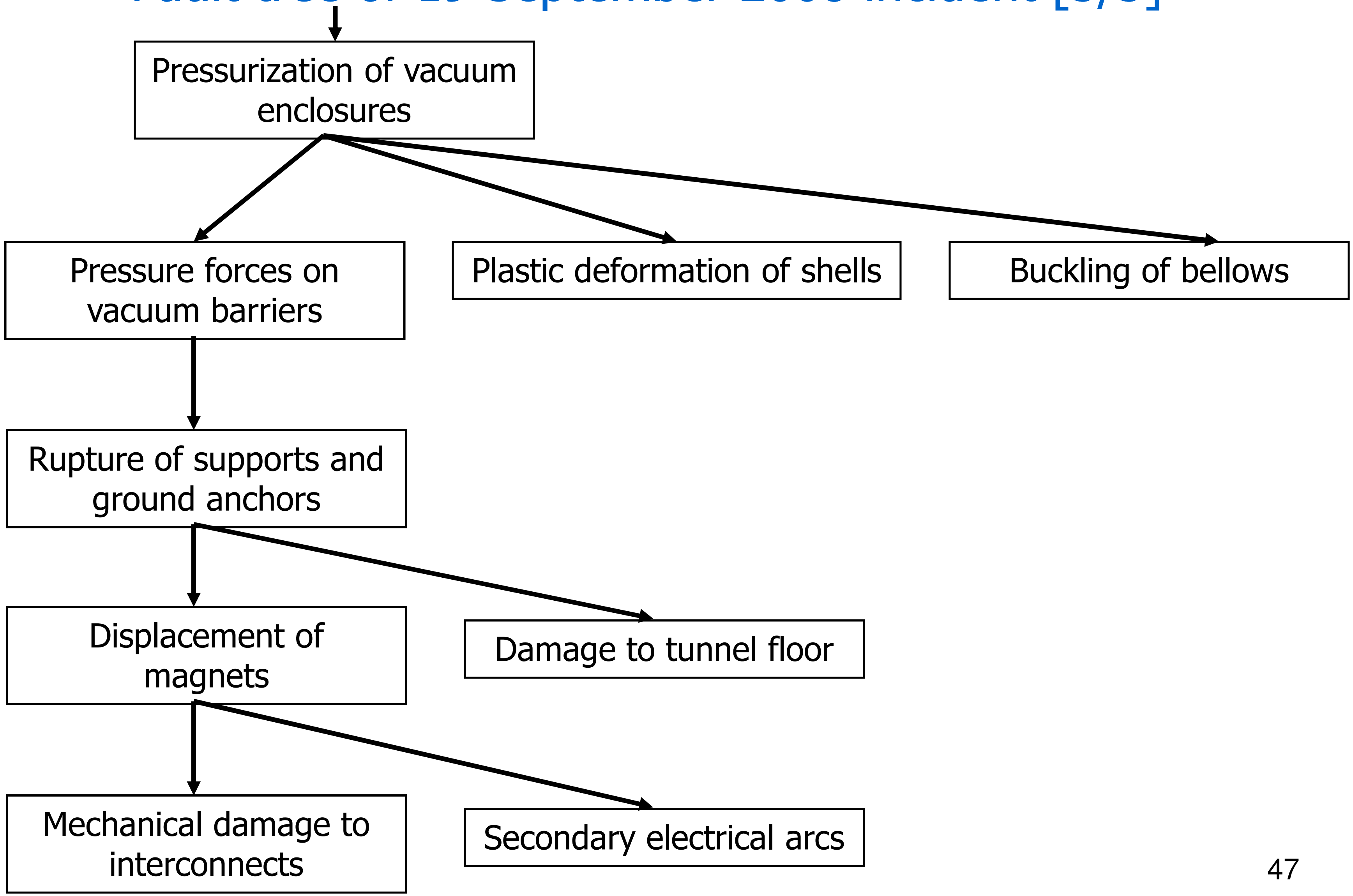
Extent of beam vacuum contamination



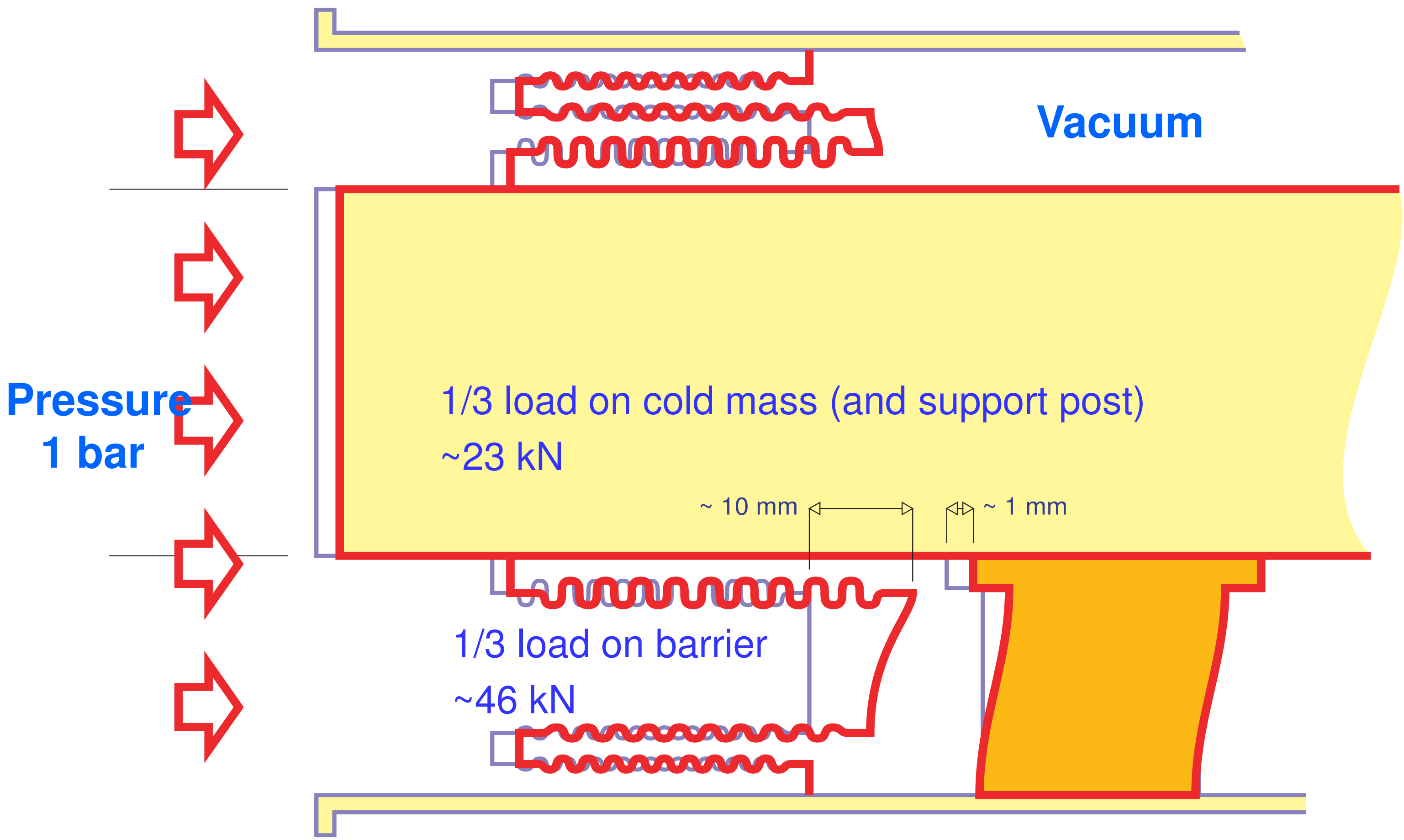


	Ok
	Debris
	MLI
	Soot

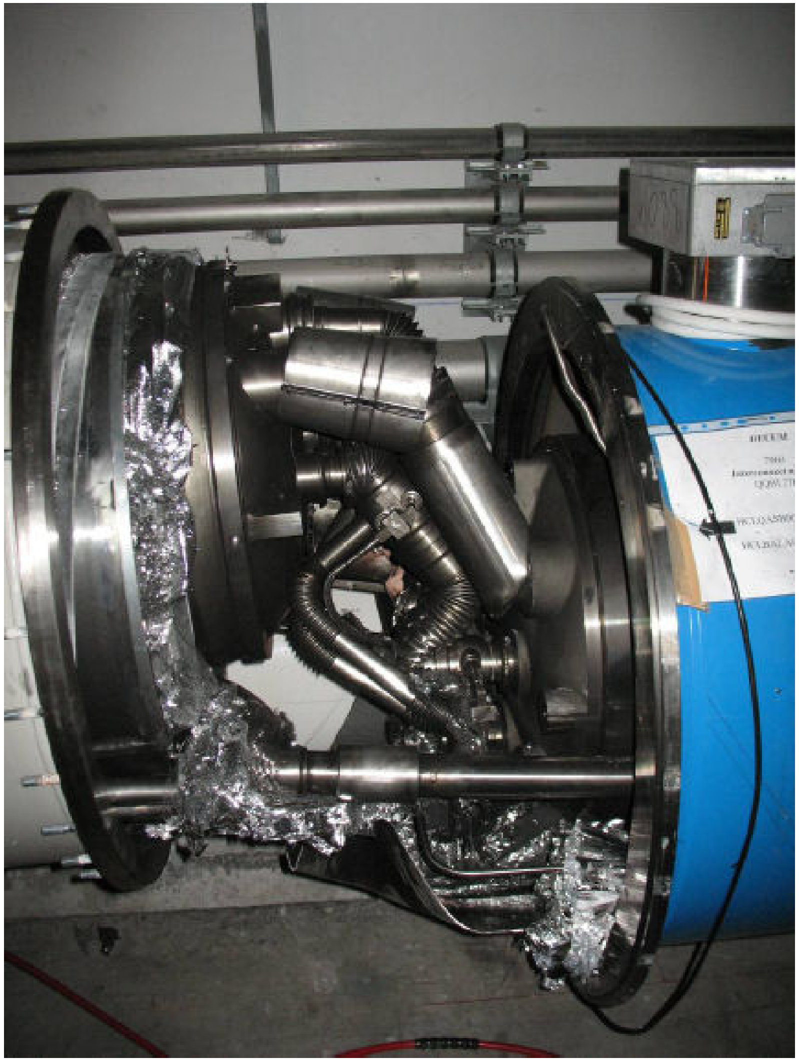
Fault tree of 19 September 2008 incident [3/3]



Pressure forces on insulation vacuum barrier



Collateral damage: magnet displacements

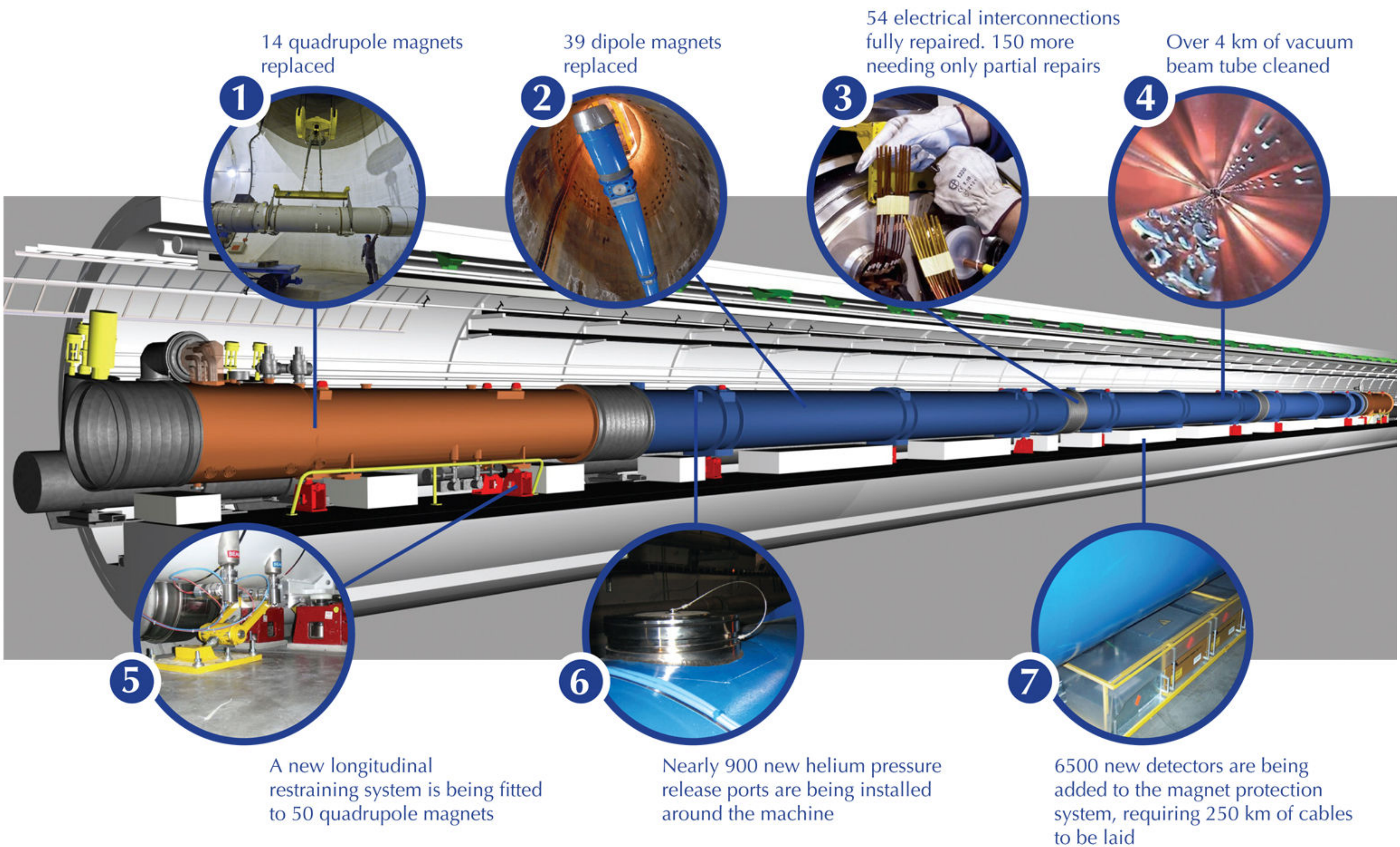


Collateral damage: ground supports

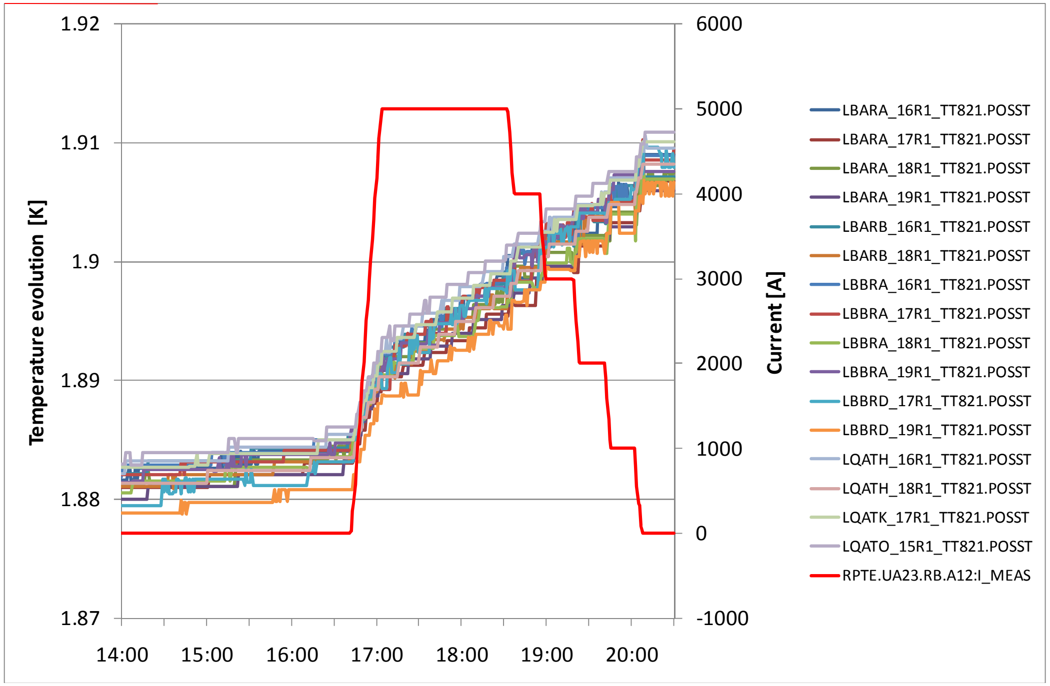
Removal of damaged magnet from the tunnel

Revived assembly area for magnet repair

Reinstallation of last repaired magnet (30 April 2009)


14 quadrupole magnets replaced
39 dipole magnets replaced
54 electrical interconnections fully repaired. 150 more needing only partial repairs
Over 4 km of vacuum beam tube cleaned
A new longitudinal restraining system is being fitted to 50 quadrupole magnets
Nearly 900 new helium pressure release ports are being installed around the machine
6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid
1
2
3
4
5
6
7

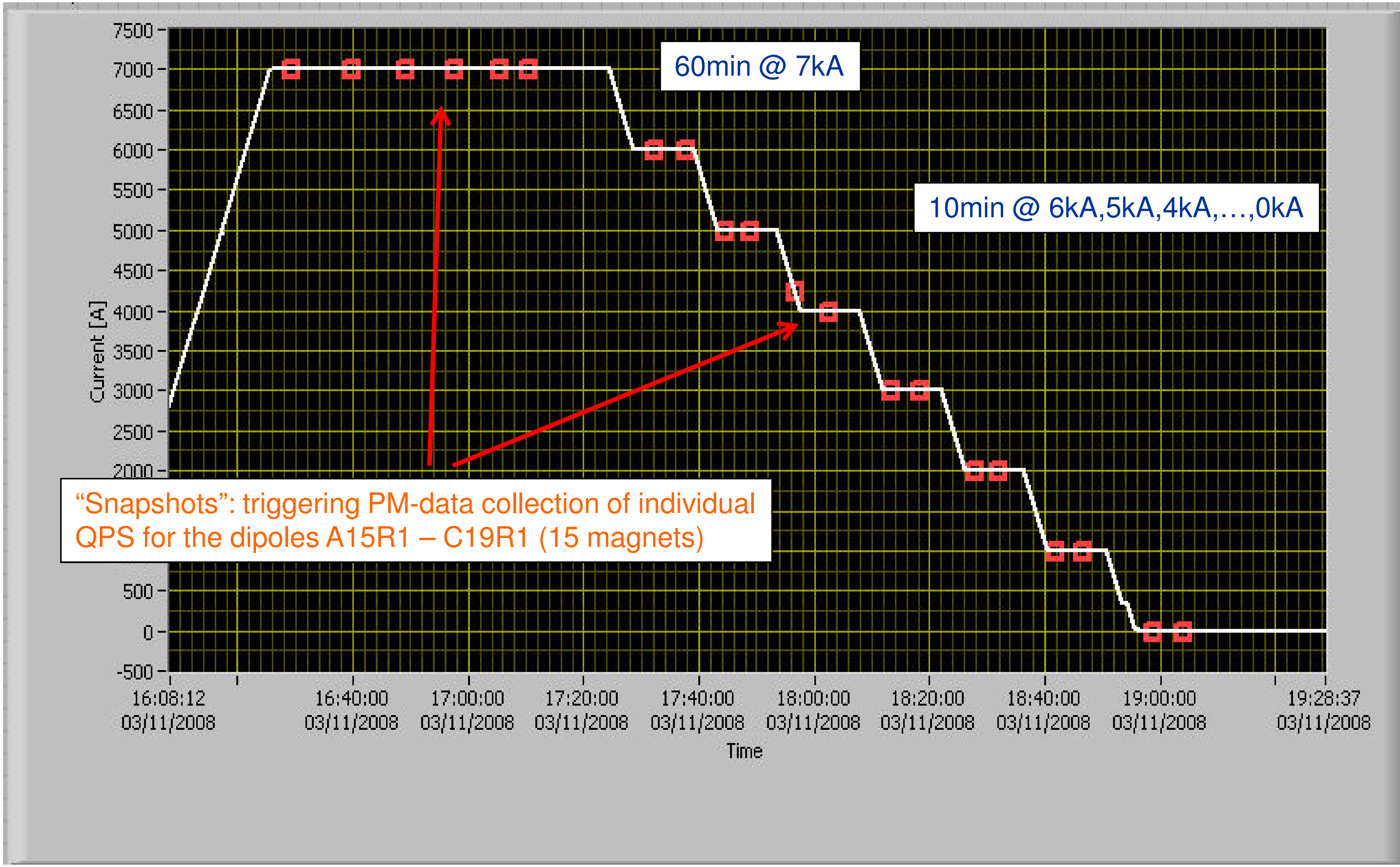
Precision thermometry allows calorimetric detection of faulty joints at safe powering level



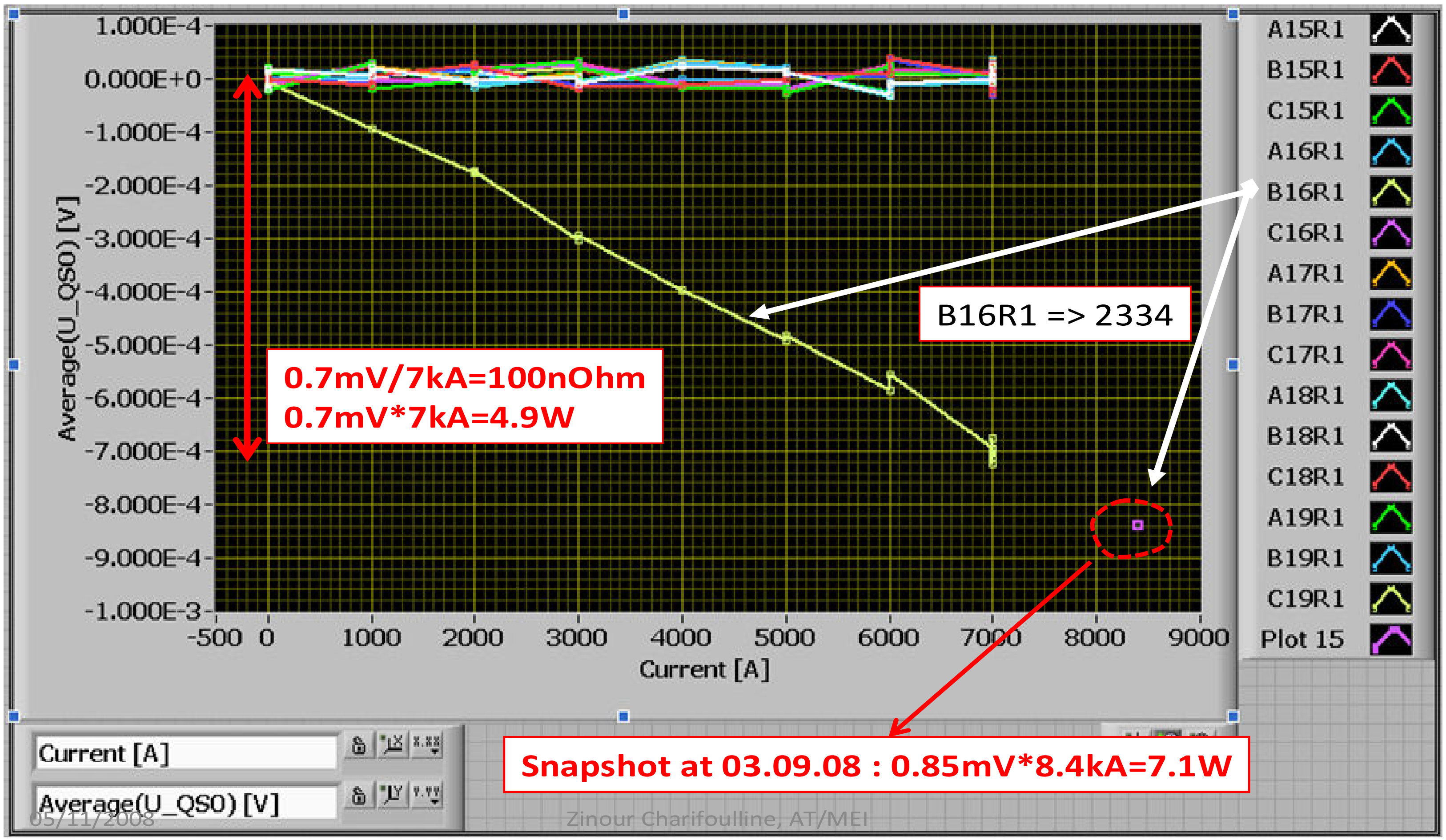
Current	Total (measured)		Nominal Splices*	Add. local dissipation	Uncertainty
[A]	[mW/m]	[W]	[W]	[W]	[W]
3000	4.4	1.0	0.4	0.6	0.6
5000	14.9	3.2	1.1	2.1	0.6
7000	32.2	6.9	2.1	4.8	0.6

→ Local resistance: ~90 nΩ, confirmed by electrical measurement

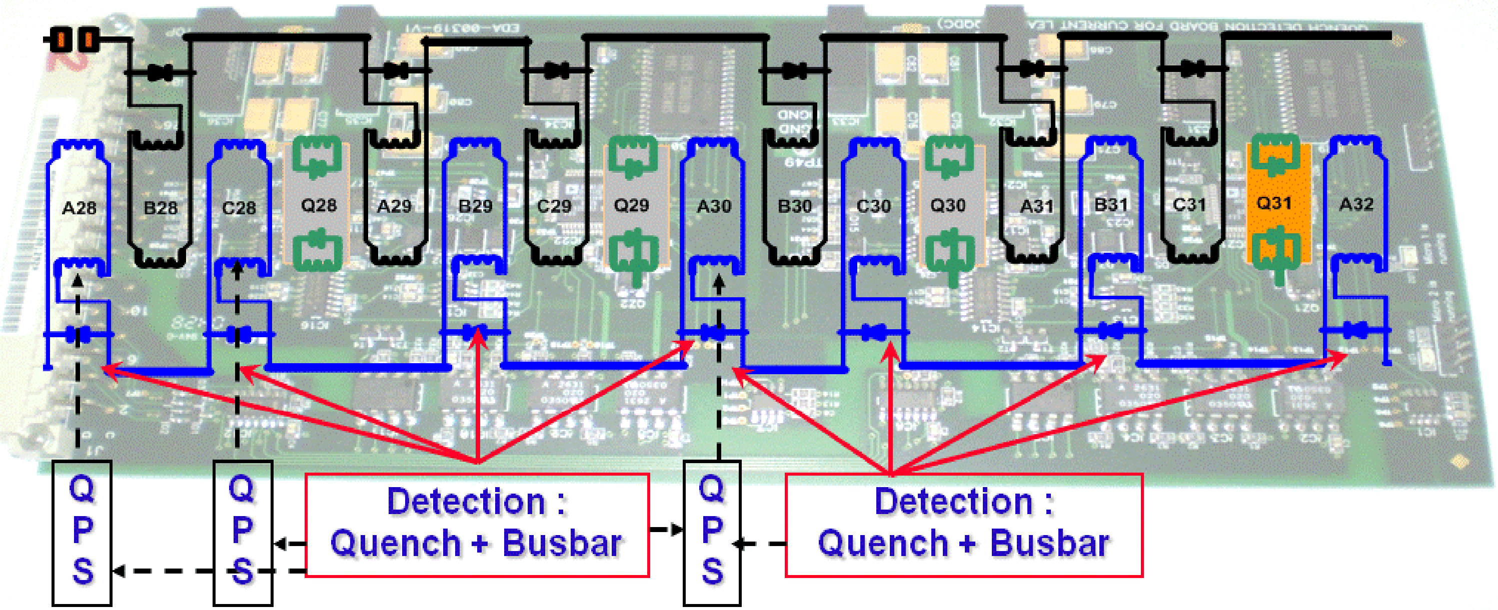
Joint measurements by QPS « snapshot »



Measurement of 100 nΩ anomalous joint resistance by QPS « snapshot »



Design of new protection system for LHC Bus Bars



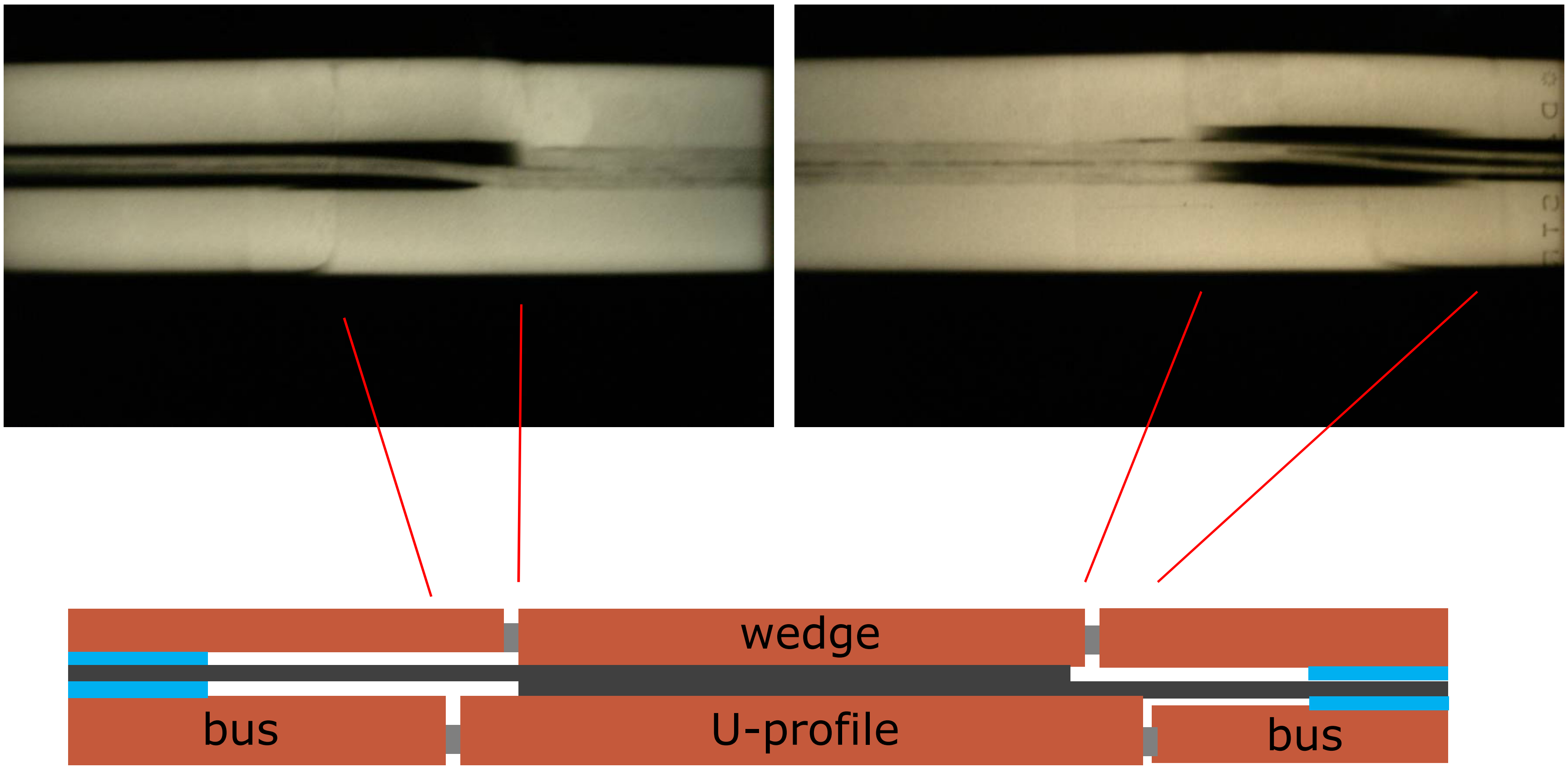
Splices measured in the LHC with 0.1 nΩ accuracy
3000 times more sensitive protection (0.3 mV) tested experimentally
180 km of instrumentation cable to install
Manufacturing of > 6000 electronic boards and 450 crates launched

Abnormal resistance in joints

- Resistance of joints in bus bars can be measured to few nΩ by calorimetric and electrical methods at cryogenic temperature
  - Dipole circuits checked (except sector 3-4) by end 2008 and faulty or doubtful joints re-done
  - New QPS will continuously monitor joints at 0.3 mV threshold
- Bad contacts between SC cable and stabilizer more difficult to detect
  - Methods
    - DC electrical measurements of copper stabilizer at room temperature or 80 K, global (non-invasive) or local (invasive)
    - Ultrasound or gamma-ray imaging (invasive)
  - Five sectors measured at room temperature (resolution 20-30 $\mu\Omega$, highest excess resistance measured ~50 $\mu\Omega$) and three at 80 K
  - Acceptable values of resistance, i.e. maximum length of un-stabilized SC cable, found from
    - Thermal-electrical model
    - Model joint measurements at high current on test facility

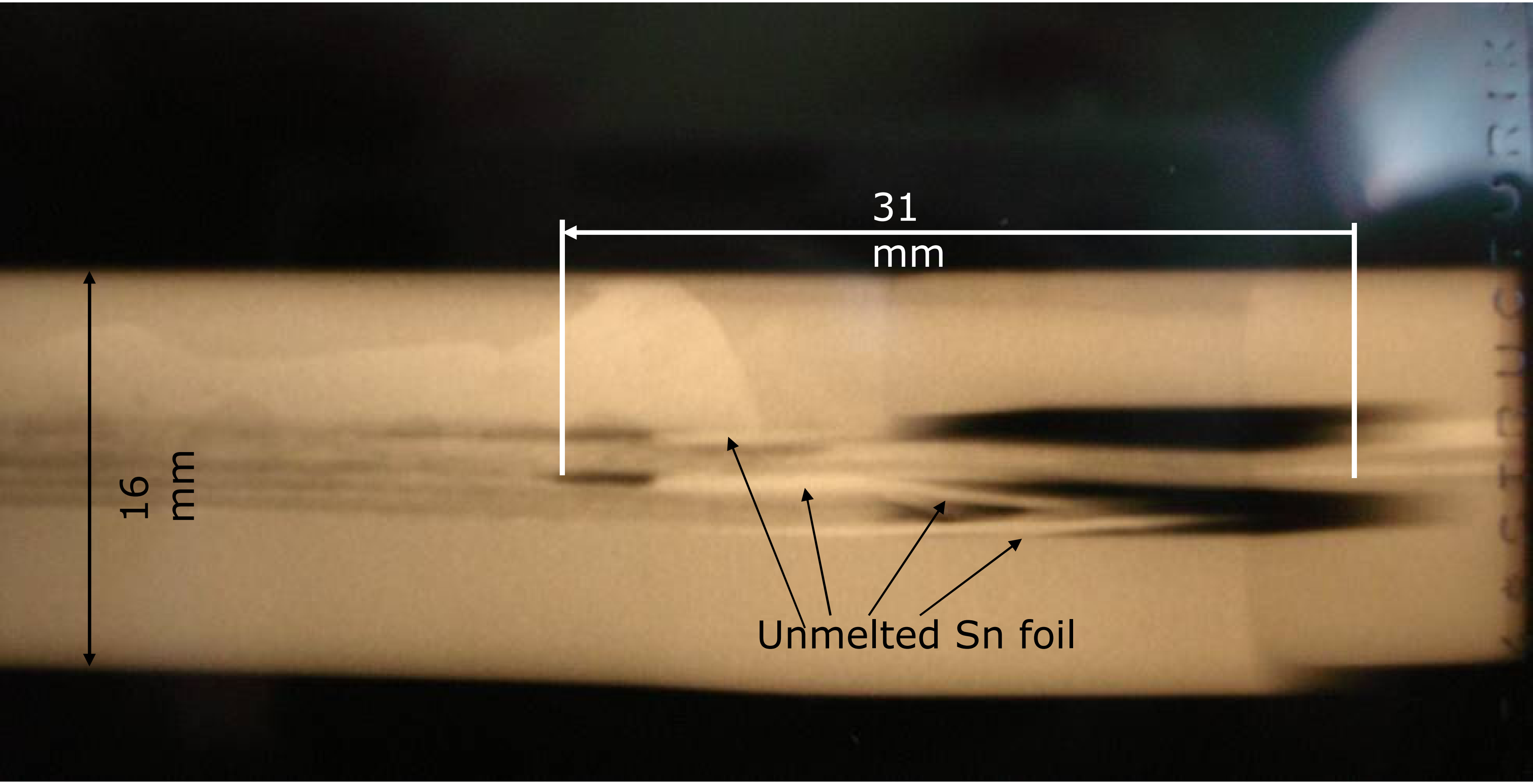
Bad contact between SC cable and stabilizer

Origin: overheating and outflow of Sn-Ag solder

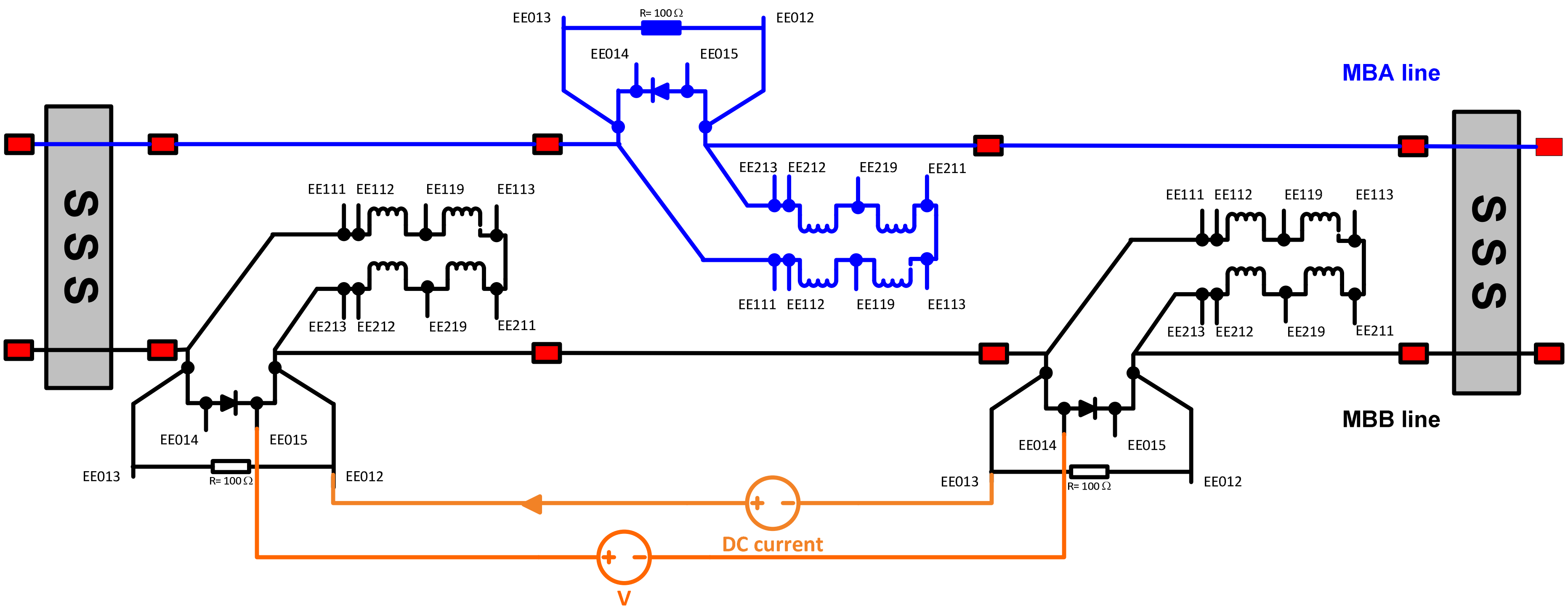


Bad contact between SC cable and stabilizer

Origin: underheating and partly unmelted Sn-Ag solder foil

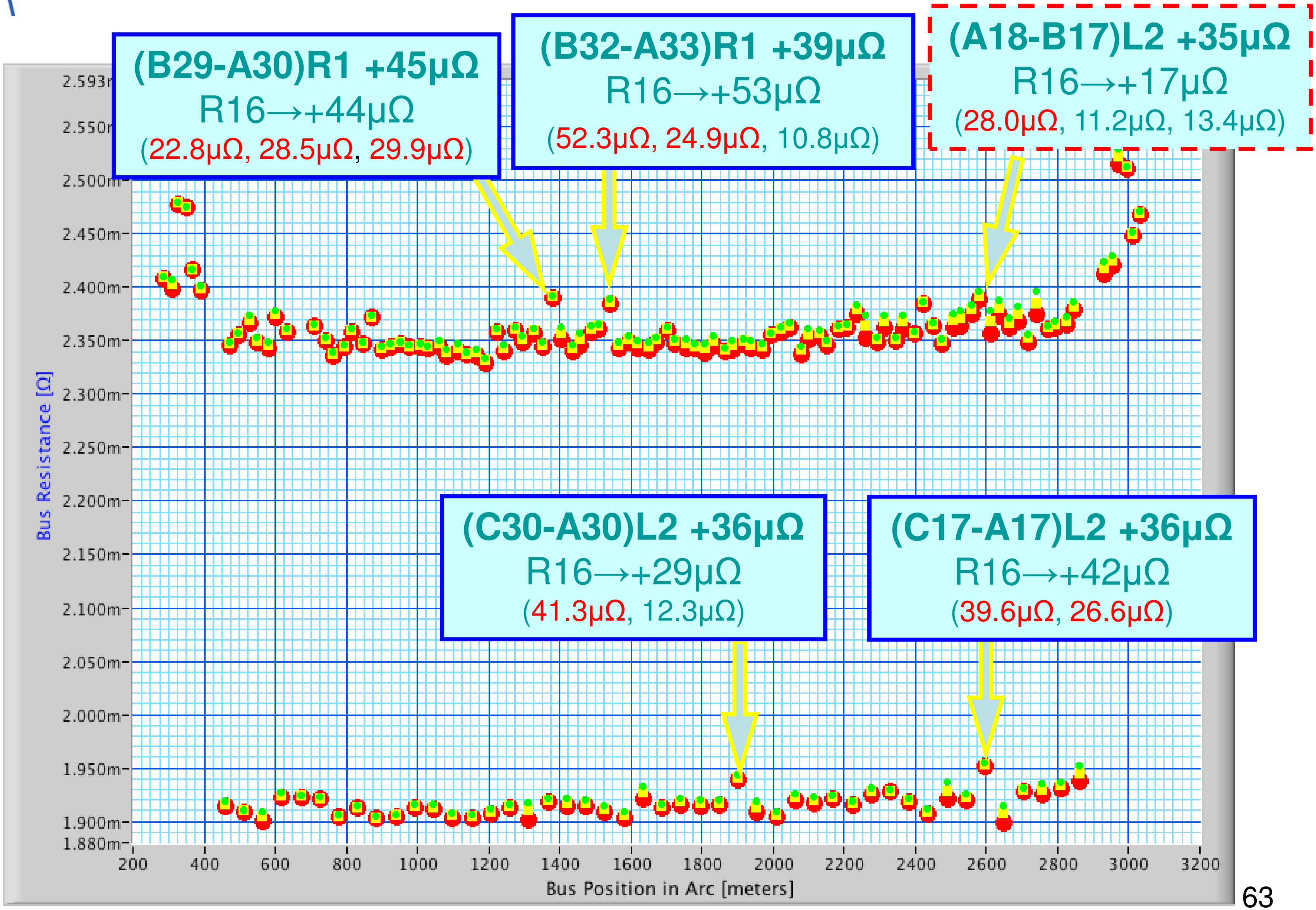


Non-invasive DC resistance measurements



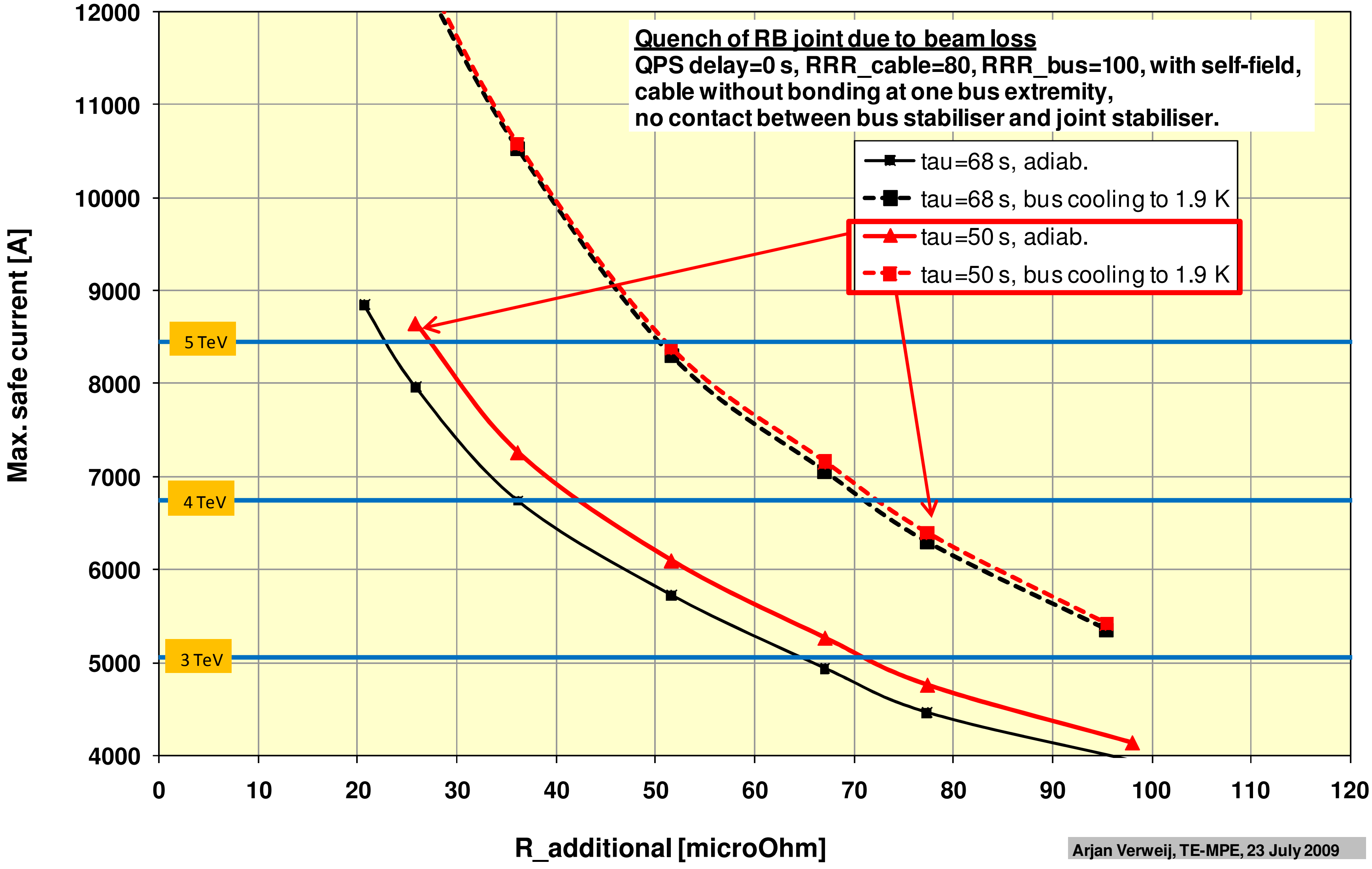
American Linear Collider Physics Group

Courtesy R. Flora, C. Scheuerlein



Thermal-electrical model

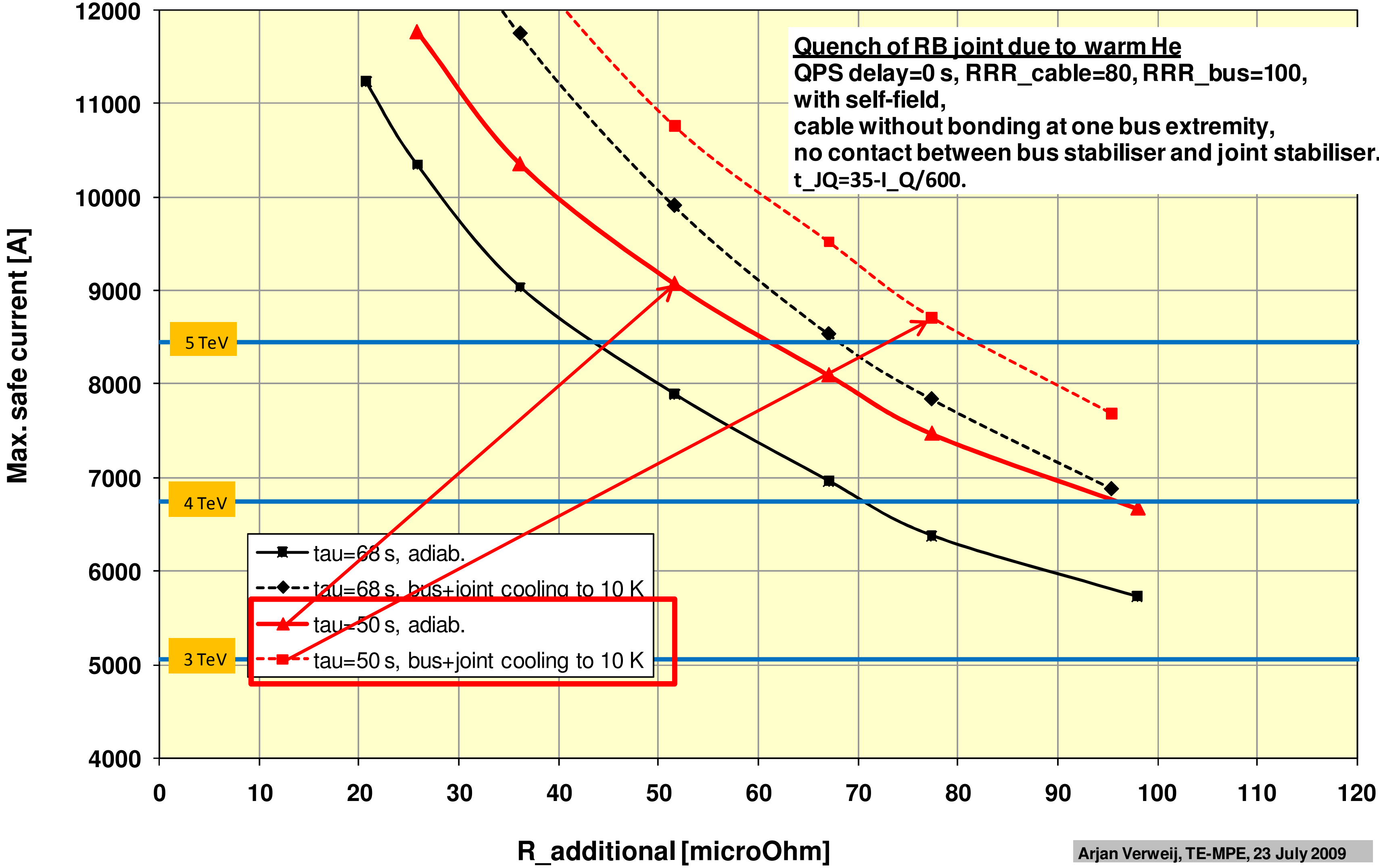
Simultaneous quench of bus bar and magnet



Arjan Verweij, TE-MPE, 23 July 2009

Thermal-electrical model

Quench propagation from magnet to bus bar

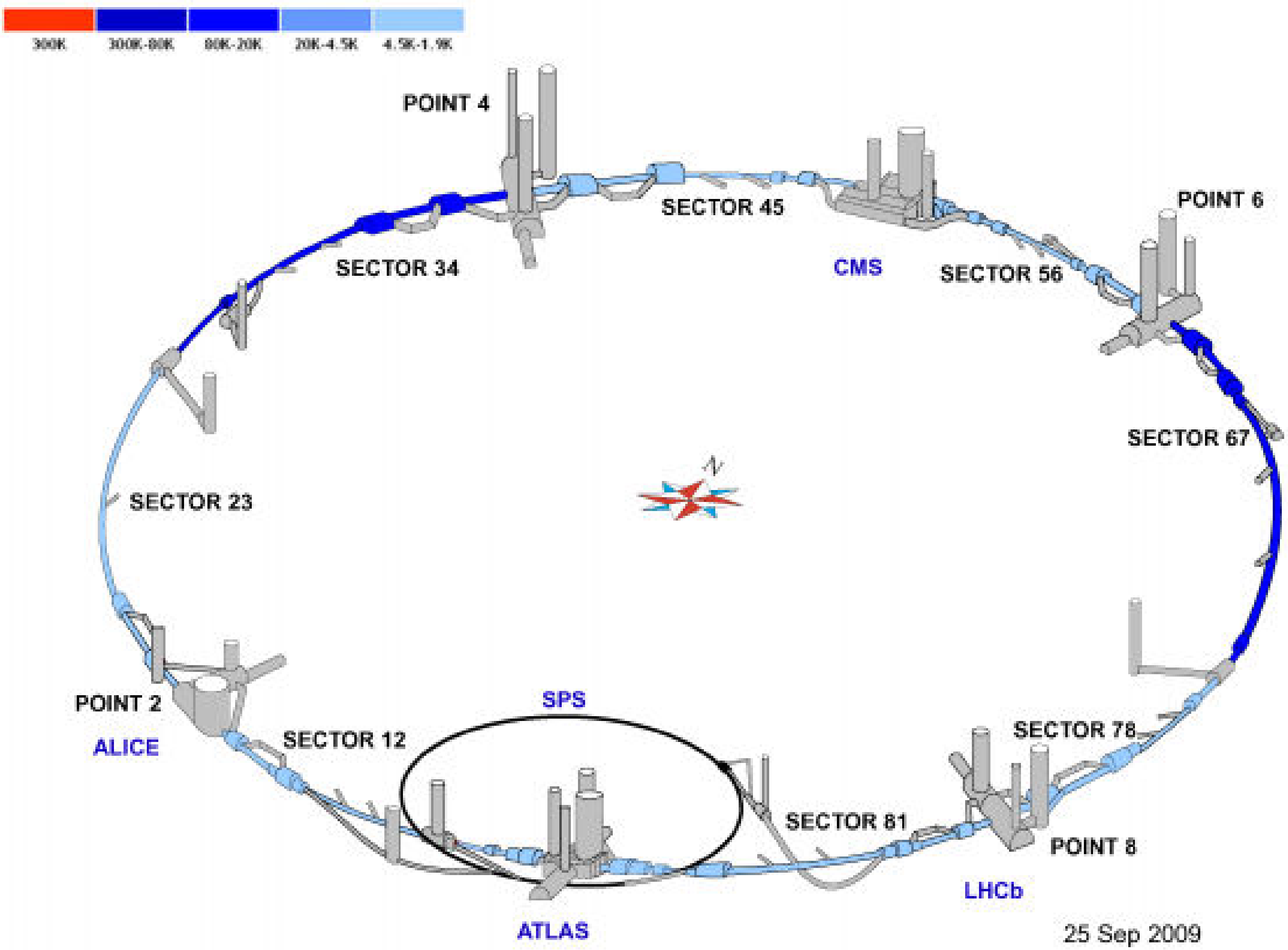


Arjan Verweij, TE-MPE, 23 July 2009

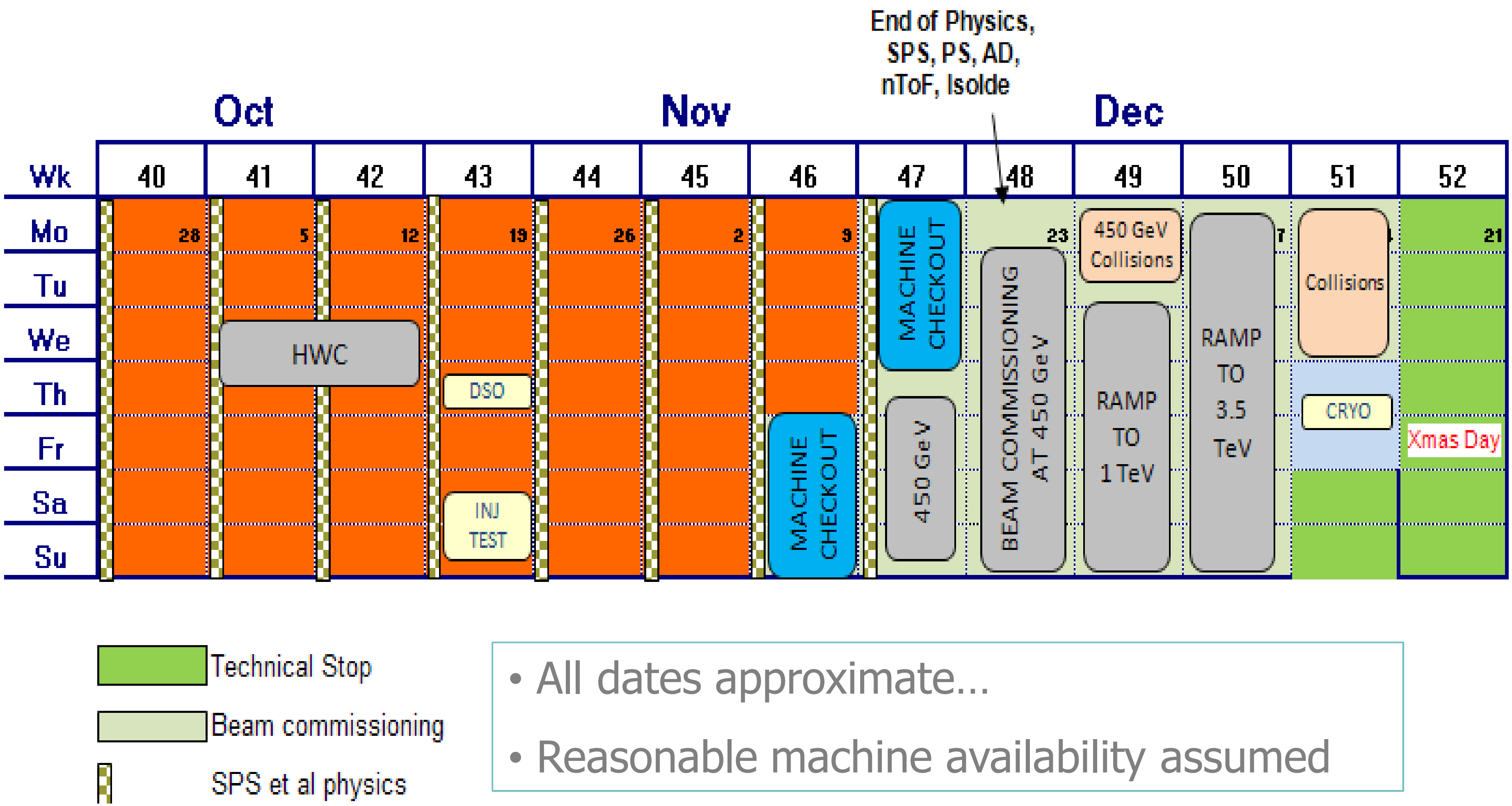
Beam energy roadmap

- Discharge time constant reduced
  - From 104 s to 50 s for dipole circuit (new configuration of resistors)
  - From 30 s to 9.4 s for quadrupole circuits (new resistors)
- Initial operation at 3.5 TeV/beam with fast discharge very safe
  - Safety factor > 2 on worst measured joint
  - Gain operating experience, monitor quenches
  - Meanwhile, perform joint measurements at high current on test facility
- Decision in Spring 2010 on next higher operating energy levels, up to about 5 TeV/beam
- Consolidation shutdown end 2010 to allow rampup to ~ 7 TeV/beam
  - Joints: selective or integral repair (reliable non-invasive diagnostics ?)
  - In-situ retraining of magnets

On line at http://lhc.web.cern.ch/lhc/

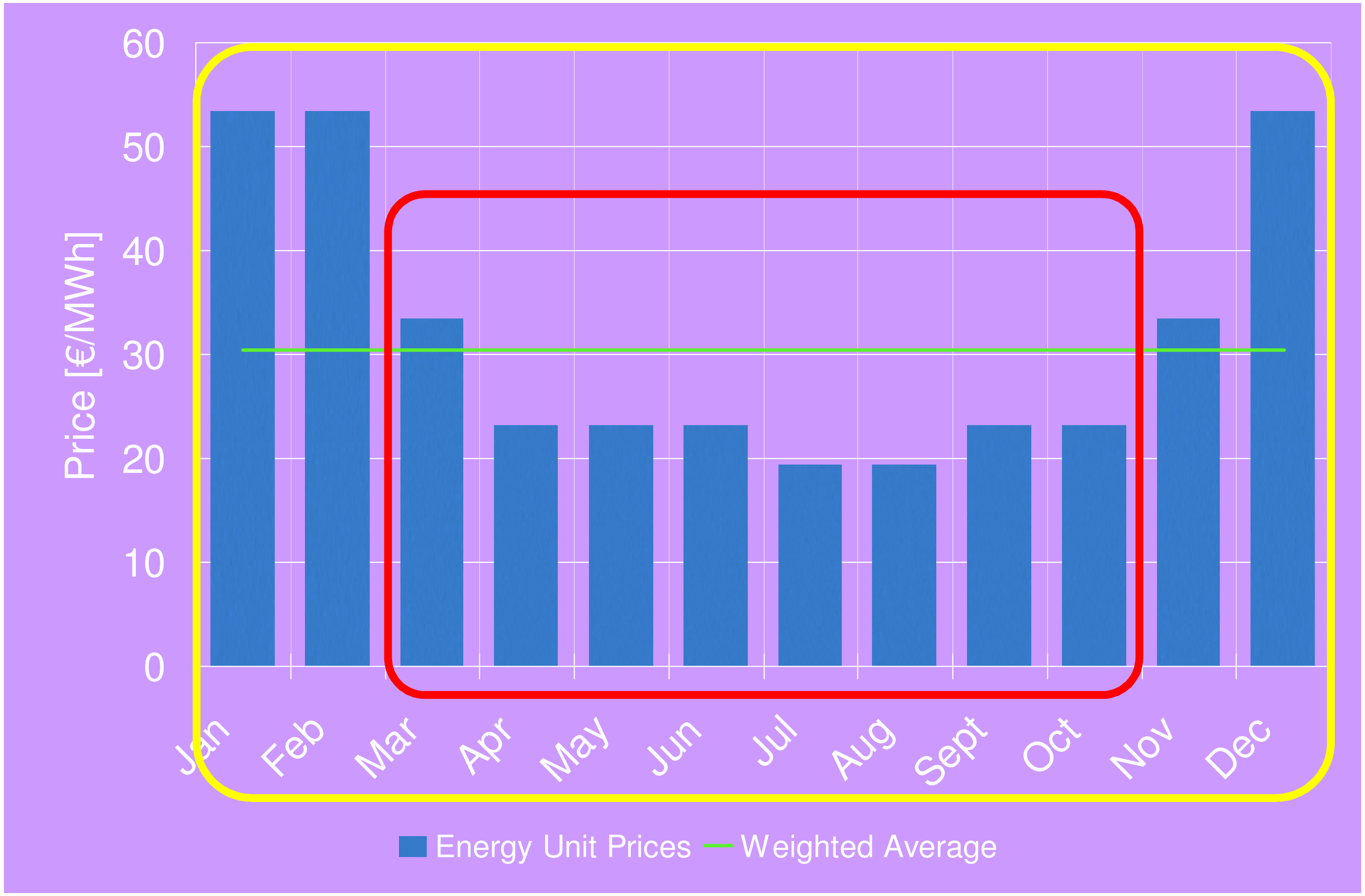


Tentative schedule 2009

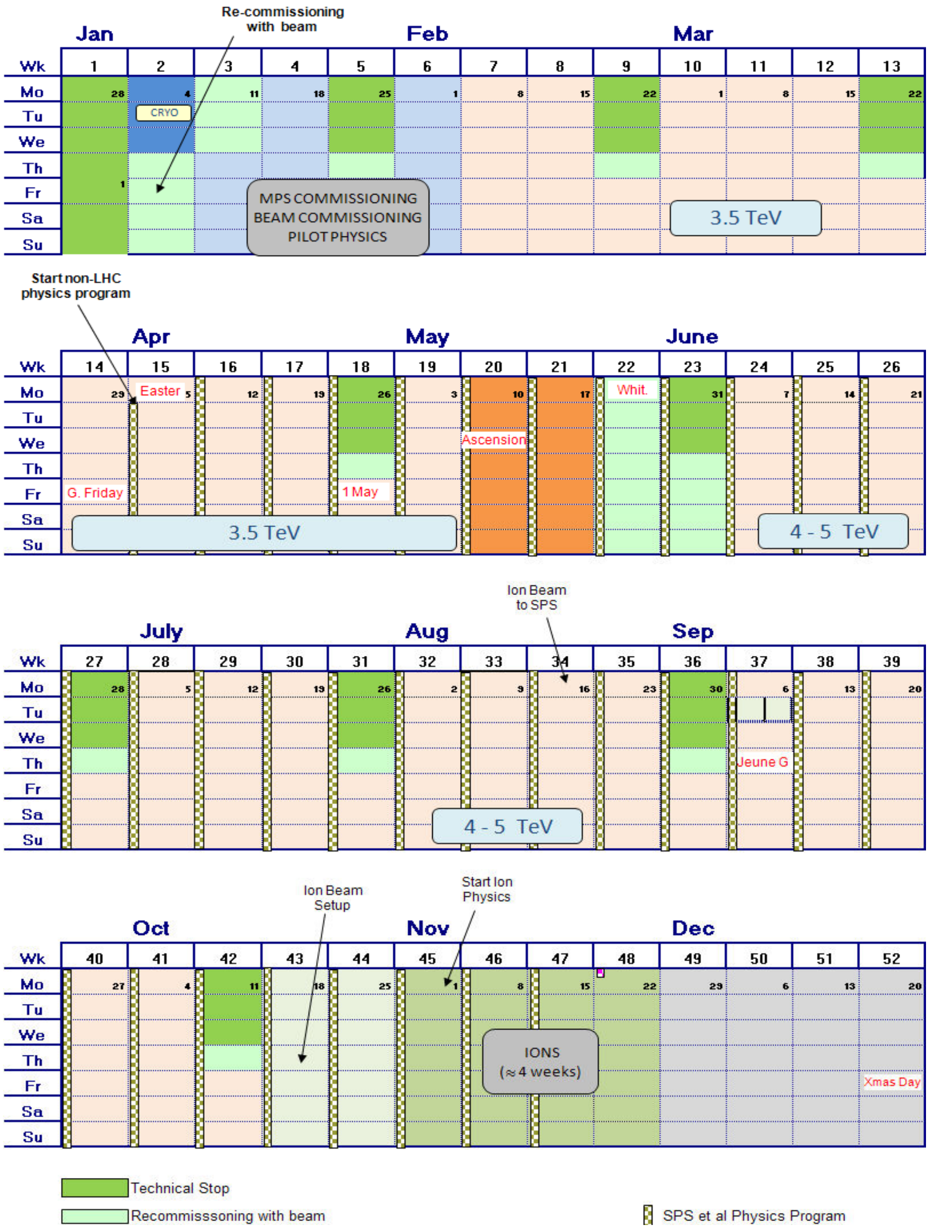


- All dates approximate…
- Reasonable machine availability assumed

Running throughout winter
Data: best EDF electricity tariff



LHC 2010 – very tentative



- 1 month pilot & commissioning
- 3 month 3.5 TeV
- 1 month step-up
- 5 month 4 - 5 TeV
- 1 month ions