Symposium for the inauguration of the LHC cryogenics
31 May to 01 June 2007

COPING WITH TRANSIENTS

L. SERIO
CERN, Geneva (Switzerland)

Contents

- Introduction
  - Systems, principles and parameters
- Cooldown
  - Principles and key figures
  - From simulations to sector cooldown
- From steady state to nominal powering
  - Principles and key figures
  - From simulations to full scale experiments
- Working with circulating beams
  - Principles and key figures
  - From simulations to full scale experiments
- Fast current discharges and quench
  - Principles and key figures
  - From simulations to full scale experiments
- Conclusion

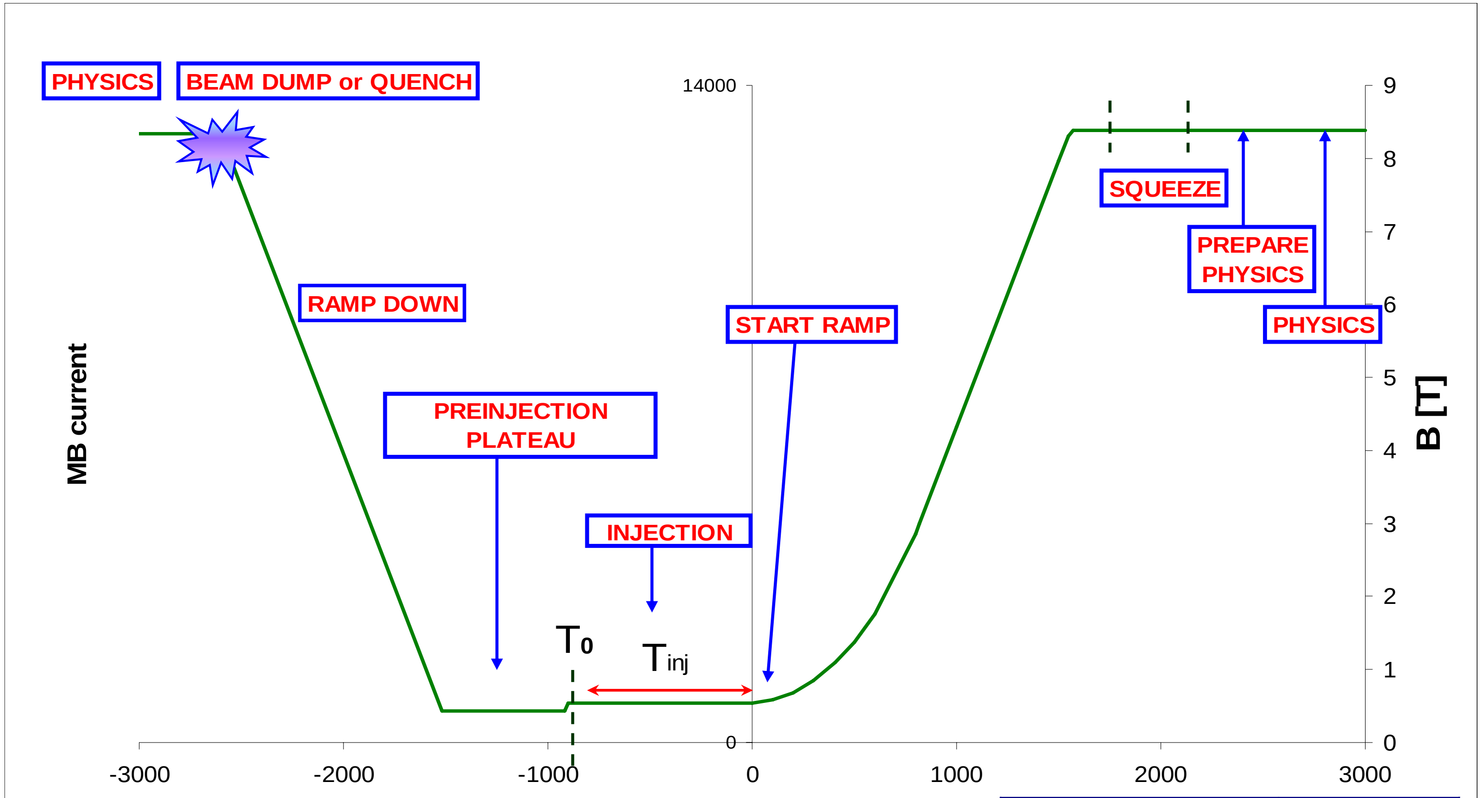
Contents

- Introduction
  - Systems, principles and parameters
- Cooldown
  - Principles and key figures
  - From simulations to sector cooldown
- From steady state to nominal powering
  - Principles and key figures
  - From simulations to full scale experiments
- Working with circulating beams
  - Principles and key figures
  - From simulations to full scale experiments
- Fast current discharges and quench
  - Principles and key figures
  - From simulations to full scale experiments
- Conclusion

LHC Parameters (p-p) impacting on Cryogenics

Circumference	26.7	km
Beam energy in collision	7	TeV
Beam energy at injection	0.45	TeV
Dipole field at 7 TeV	8.33	T
Luminosity	10^{34}	$cm^{-2}.s^{-1}$
Beam intensity	0.56	A
Energy loss per turn	6.7	keV
Critical energy of radiated photons	44.1	eV
Synchrotron power per beam	3.8	kW
Stored energy per beam	350	MJ
Operating temperature	1.9	K
Cold mass	$36.8x10^6$	kg
Helium inventory	$130x10^3$	kg

LHC operation cycles

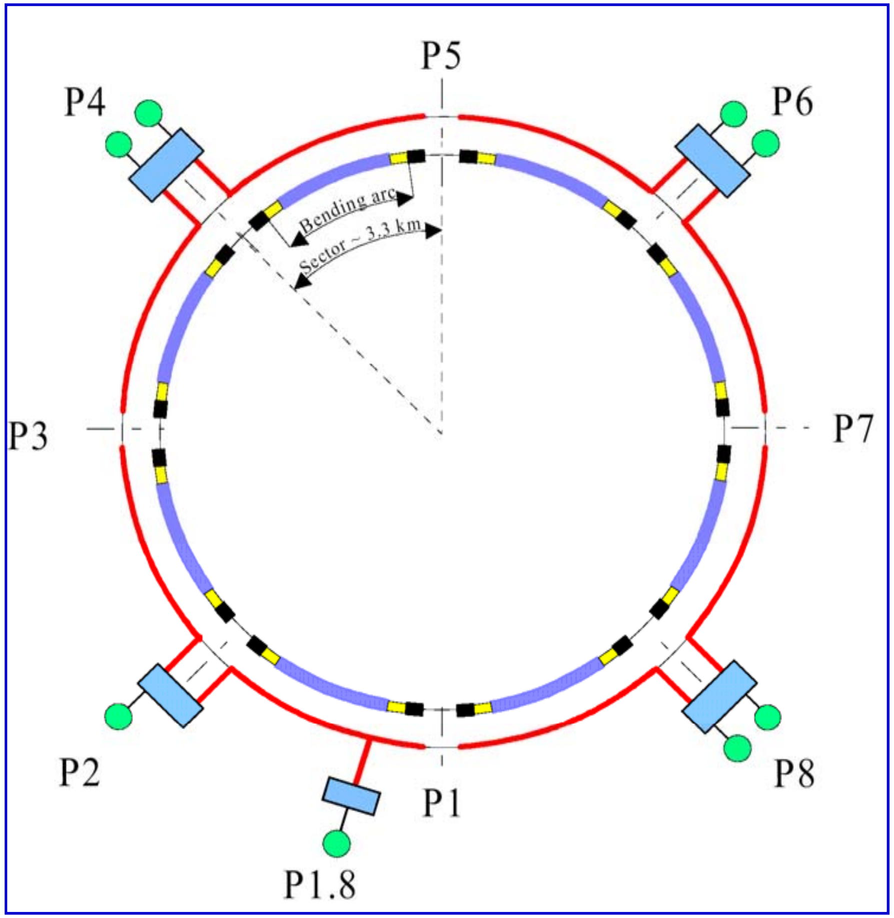


Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Cryogenic system main functions

- Cope with load variations and large dynamic range induced by the operation of the accelerator
- Cool down and fill but also empty and warm-up the huge cold mass of the LHC in a maximum time of 15 days
- Cope with the resistive transitions of the superconducting magnets minimising loss of cryogen and system perturbations
- Limit the resistive transition propagation to the neighbouring magnets and recover in few hours
- Cope with the resistive transition of a full sector
- Allow for rapid cool-down and warm-up of limited lengths of cryo-magnet strings, e.g. for repairing or exchanging a defective diode

Overview of the cryogenic system



Legend:

━ **QRL** (distribution line)

▭ **QUI** (interconnection box)

● **Refrigerator**

Legend:

▬ **Arc**

▭ **Dispersion Suppressors**

▬ **Long Staight Section**

- 5 cryogenic islands
- 8 x 4.5 K refrigerators
  - (144 kW @ 4.5 K, 600 kW precooler and heater)
- 8 x 1.8 K refrigeration units
  - (19 kW @ 1.8 K)
- 25 km of superconducting magnets in superfluid helium
  - several 1’000’s control loops:
  - 1400 for current leads
  - 320 for magnets temperature
  - 600 for beam screen
  - several 1’000’s for refrigerators

Contents

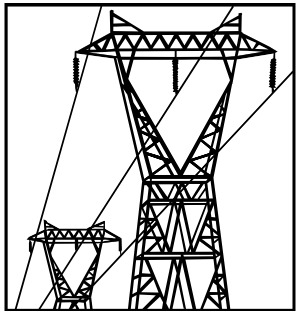
- Introduction
  - Systems, principles and parameters
- Cooldown
  - Principles and key figures
  - From simulations to sector cooldown
- From steady state to nominal powering
  - Principles and key figures
  - From simulations to full scale experiments
- Working with circulating beams
  - Principles and key figures
  - From simulations to full scale experiments
- Fast current discharges and quench
  - Principles and key figures
  - From simulations to full scale experiments
- Conclusion

LHC COOLDOWN

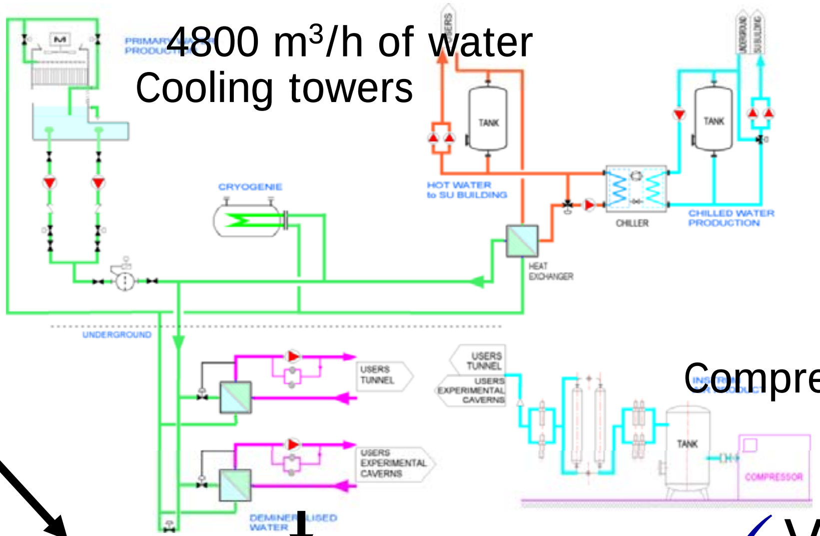
✓ Electric power

about 32 MW; 24 GWh/month

1.2 MCHF/month



✓ Cooling and ventilation



4800 m^3/h of water

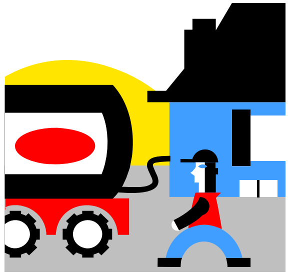
Cooling towers

Compressed air

✓ Helium and nitrogen

130 t of He – 4.3 MCHF

10’000 t of LN2 – 1.6 MCHF



CRYOGENICS

✓ Vacuum

10^{-3} mbar

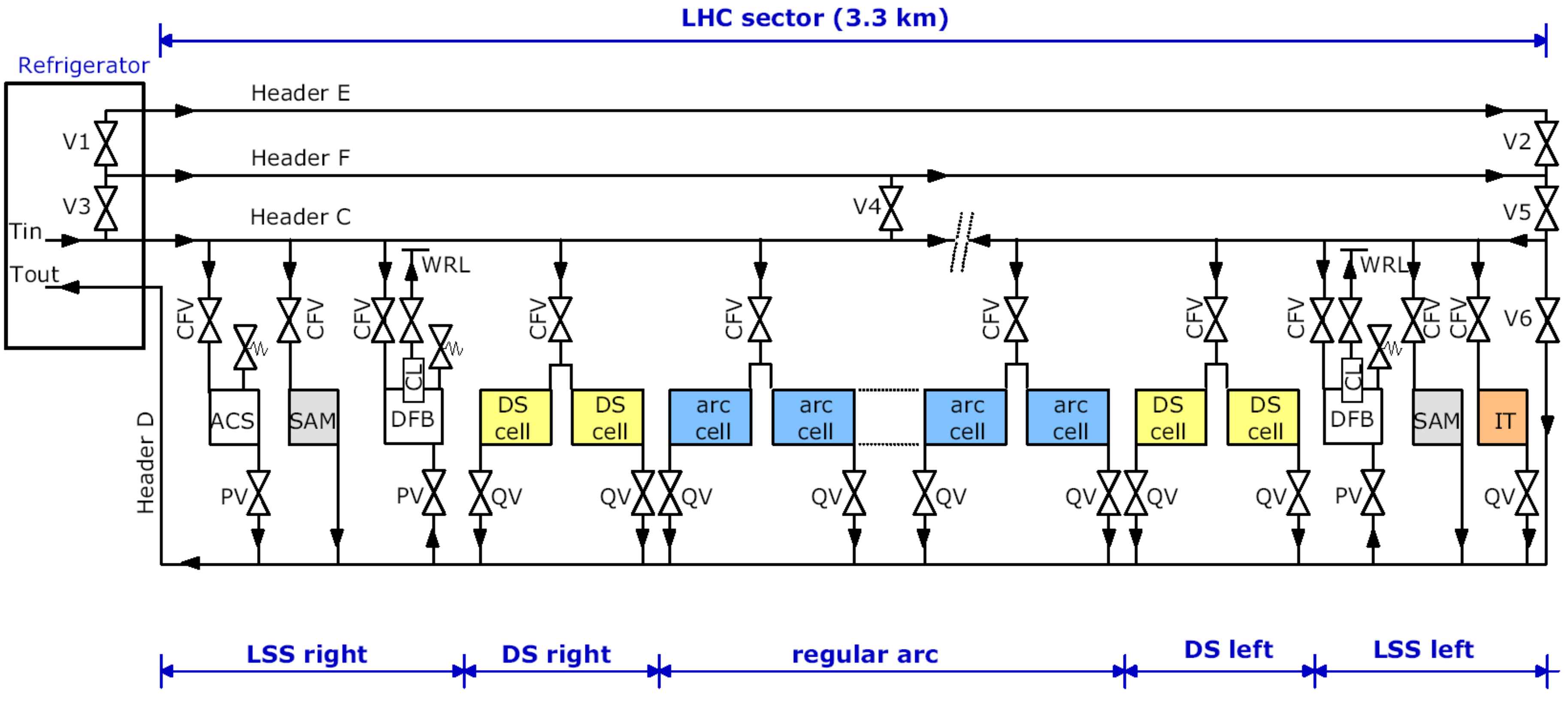
✓ Controls:

Networks, fieldbuses,

PLC, SCADA

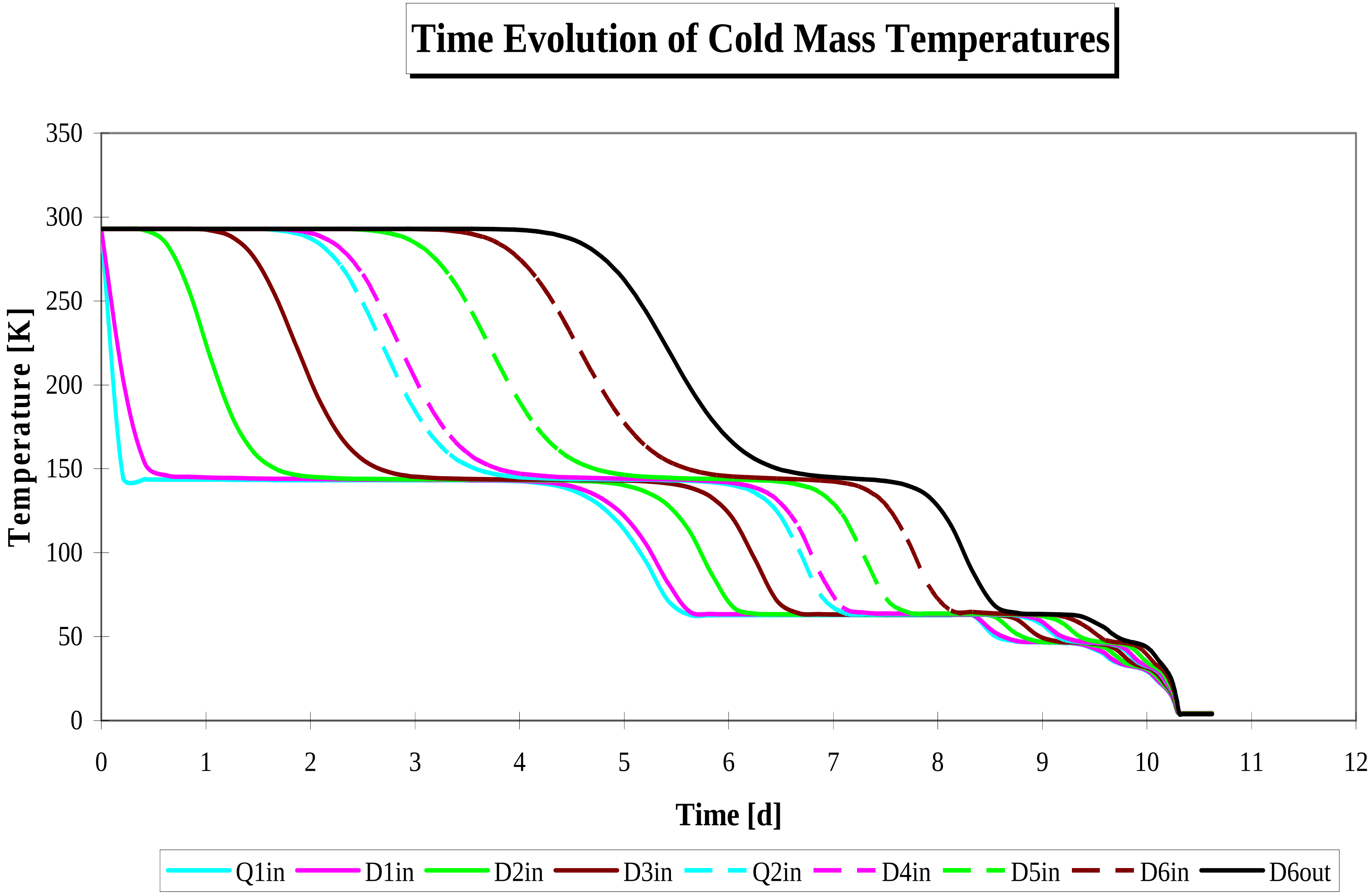
Mass to be cooled	[t]	**36’800**
Max He flow	[g/s]	**6160**
Max cooling capacity 300-160 K	[kW]	4800
Liquefaction rate	[g/s]	1000

Arc cooling principles

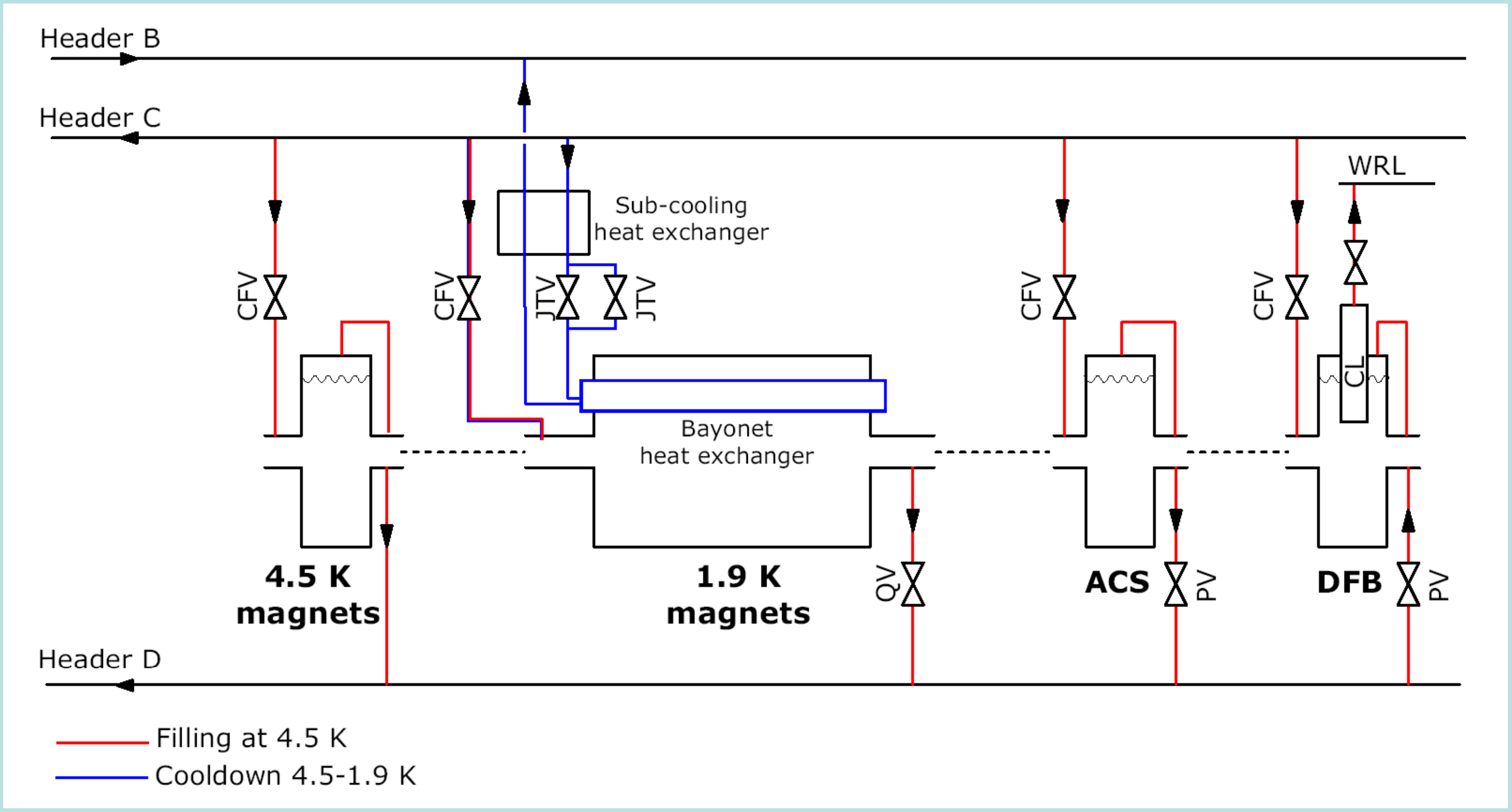


SAM = stand-alone and semi-stand alone magnets

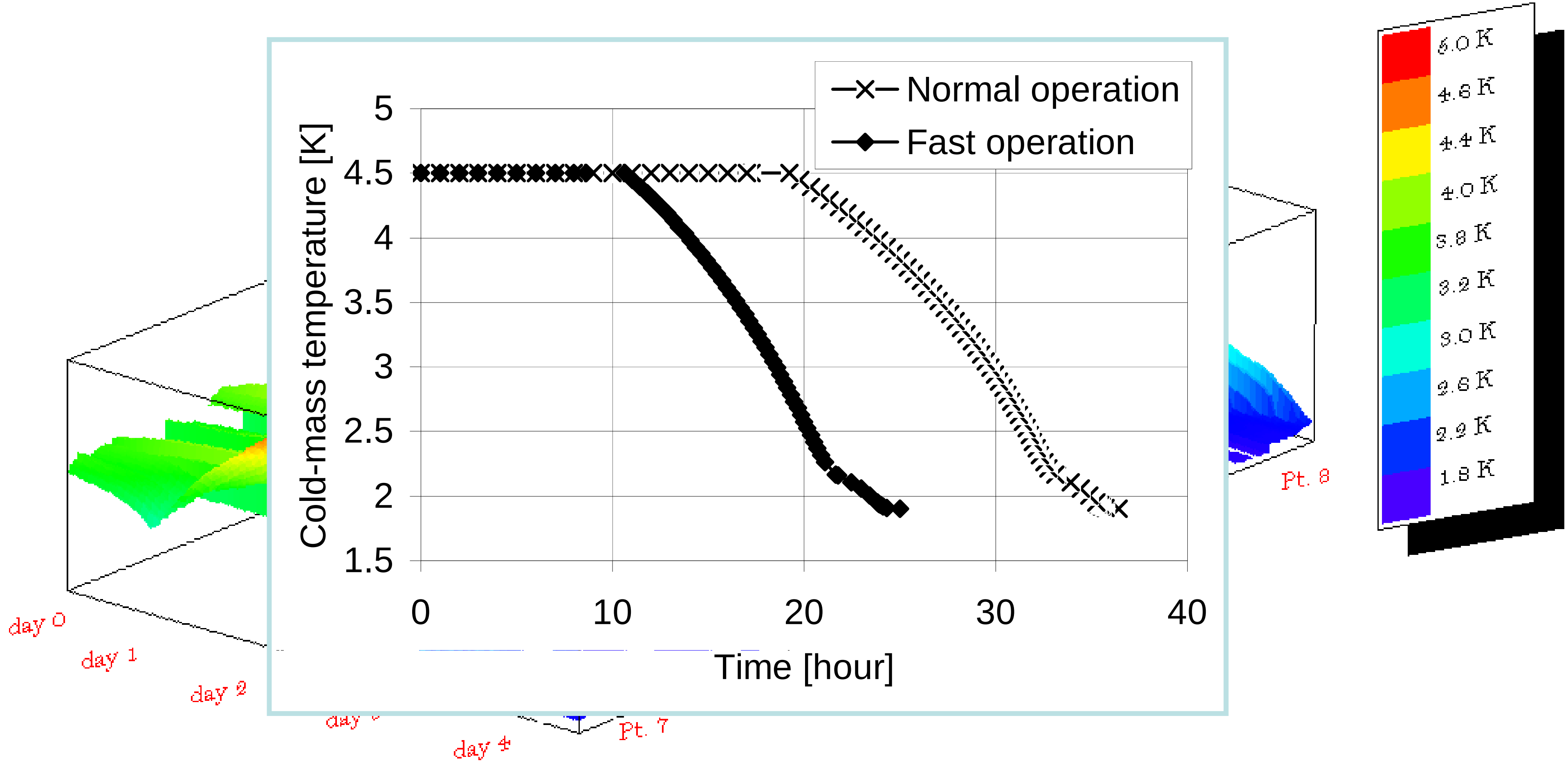
LHC COOLDOWN 300 to 4.5 K



Final cooldown to 1.9 K



LHC COOLDOWN 4.5 to 1.9 K



Contents

- Introduction
  - Systems, principles and parameters

- Cooldown
  - Principles and key figures
  - From simulations to sector cooldown

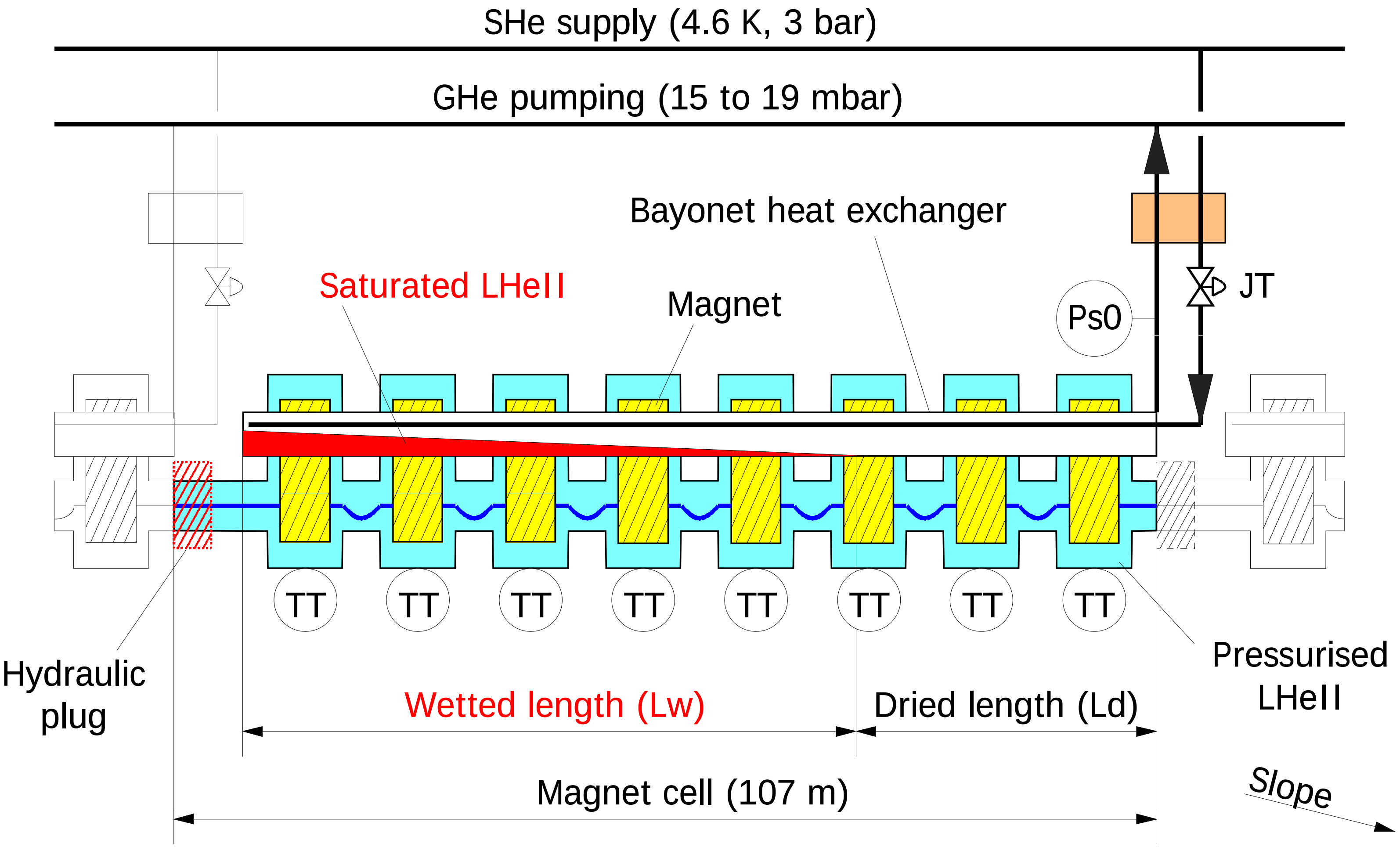
- From steady state to nominal powering
  - Principles and key figures
  - From simulations to full scale experiments

- Working with circulating beams
  - Principles and key figures
  - From simulations to full scale experiments

- Fast current discharges and quench
  - Principles and key figures
  - From simulations to full scale experiments

- Conclusion

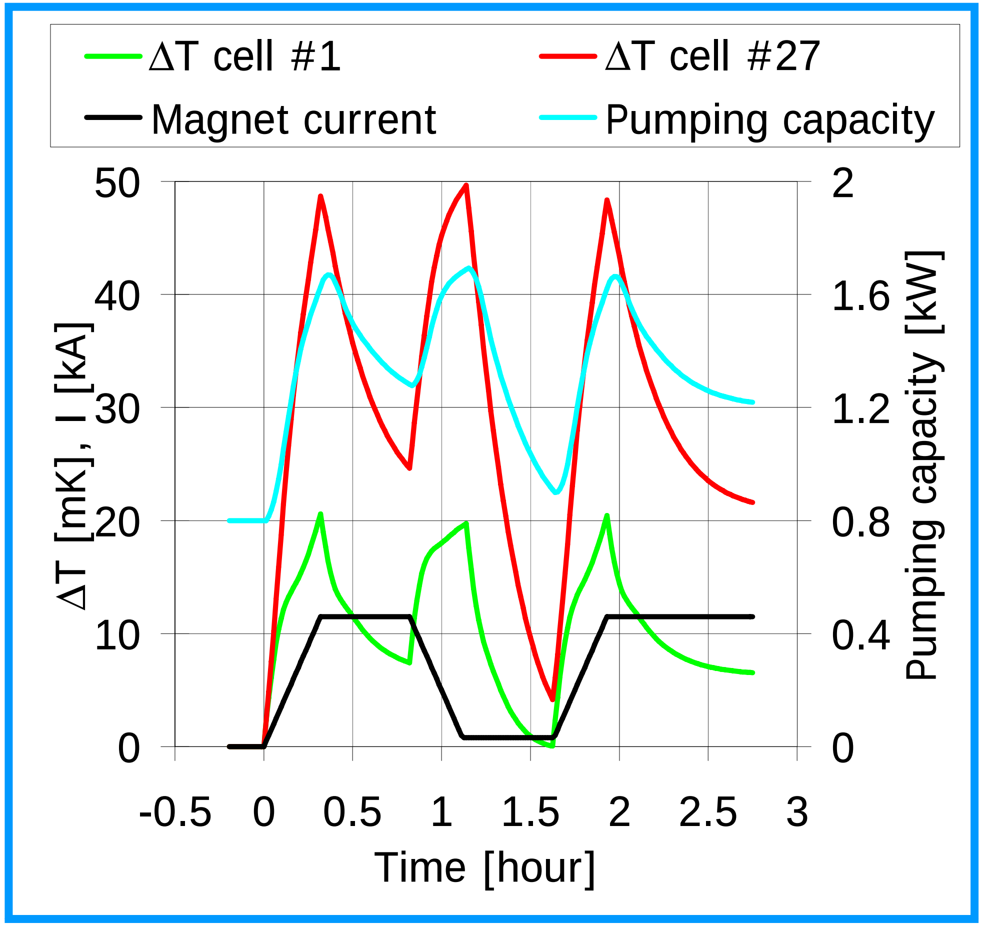
Cell Cooling Principle (I)



Cell Cooling Principle (II)

- Pressurised LHeII:
  - Content: 26 l/m
  - Free cross-section: 60 cm2
- Bayonet heat exchanger:
  - Linear thermal conductance: 120 W/m.K
  - Free inner diameter: 54 mm
- Control principle:
  - The JT valve controls the temperature difference between:
    - the maximum of cell temperature TT and
    - the saturated temperature Ts0 corresponding to Ps0.
  - As a consequence:
    - the bayonet heat exchanger is partially dried,
    - the wetted length increase with the heat deposition.

Temperature Excursion during Injection Sequence

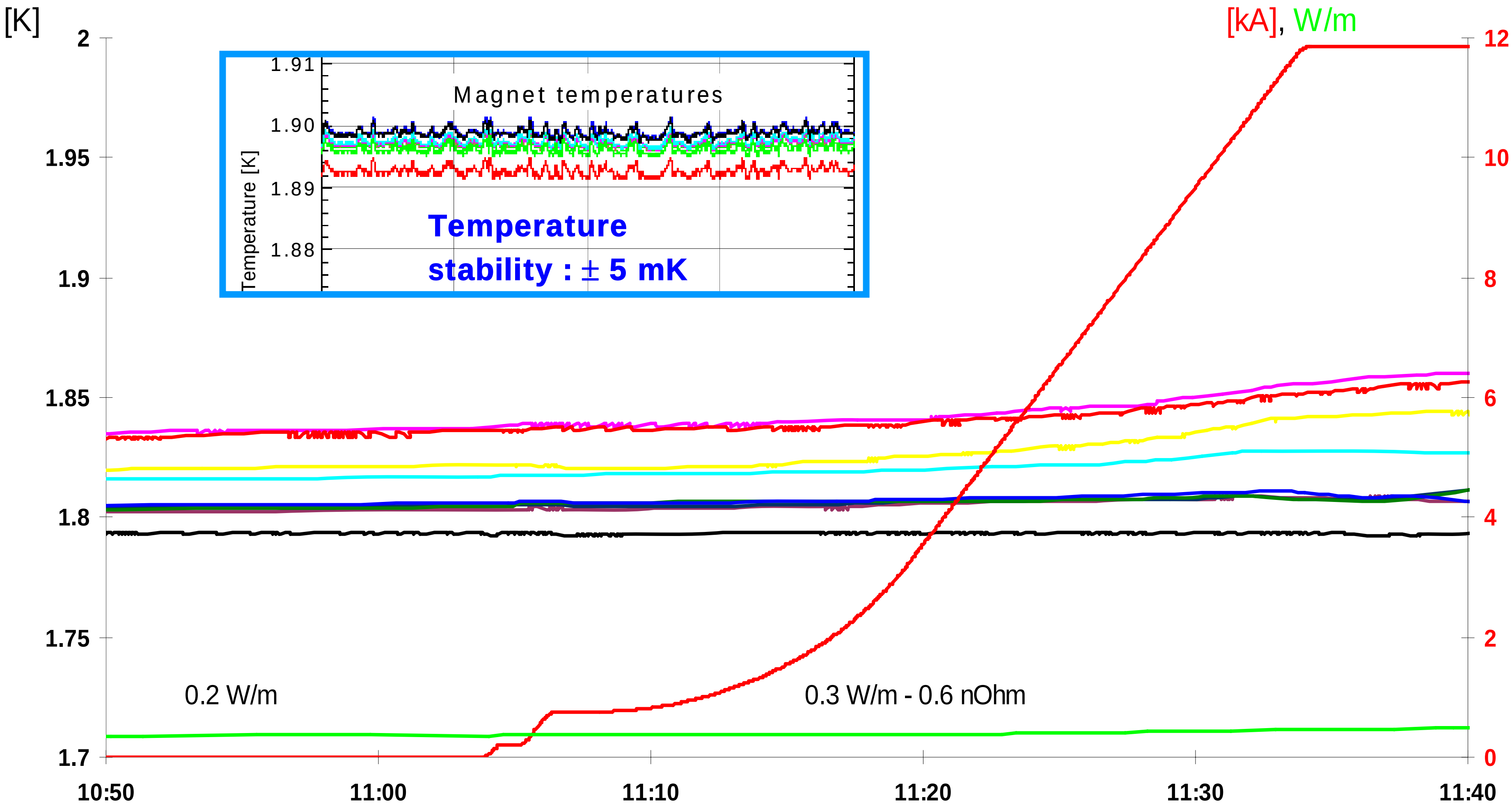


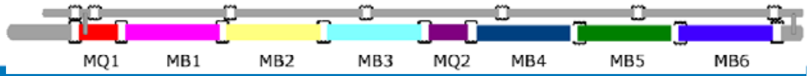
The **magnet current ramp-up and de-ramp** from 0 to 12 kA with a rate of 10 A/s (Eddy currents dissipate **480 J/m** in the cold masses)

Heat partially buffered by helium content

Maximum temperature excursion: 50 mK

Typical LHC ramp to nominal current (11860 A)





Contents

- Introduction
  - Systems, principles and parameters
- Cooldown
  - Principles and key figures
  - From simulations to sector cooldown
- From steady state to nominal powering
  - Principles and key figures
  - From simulations to full scale experiments
- Working with circulating beams
  - Principles and key figures
  - From simulations to full scale experiments
- Fast current discharges and quench
  - Principles and key figures
  - From simulations to full scale experiments
- Conclusion

Beam induced loads

Operating Conditions	**Nominal [mW/m]**		**Ultimate [mW/m]**	
Temperature level	**4.6-20 K**	**1.9 K LHe**	**4.6-20 K**	**1.9 K LHe**
Synchrotron radiation	330	1	500	1
Image current	360	1	820	2
Photo-electron cloud *	890	9	3040	30
Beam-gas scattering**	0.4	48	0.4	48
Random particle loss	0-0.1	0-32	0-0.3	0-48
Total beam-induced *	1580	59-91	4360	82-130

*: After beam cleaning

**: Improvement of the beam vacuum from nominal to ultimate

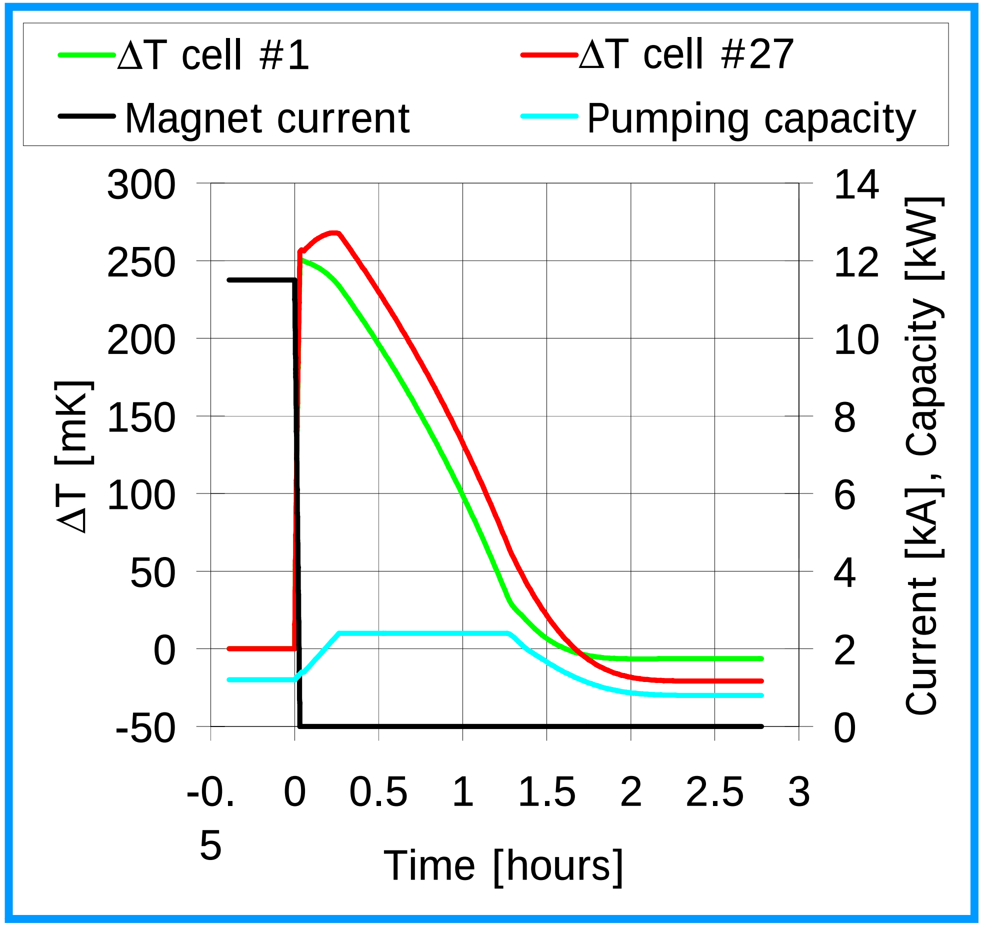
Beam Squeezing Transient

- Beam squeezing
  - Fast transient heat deposition (few minutes)
  - Heat loads (secondaries due to inelastic collisions):
    - 1.7 W/m in Nominal conditions
    - Up to 4 W/m in Ultimate conditions
    - Proportional to the beam luminosity

    ⇨ Ratio up to **20** with respect to the static heat inleaks
- Control principle
  - **Feed-forward** control for ratio **above 3**
  - **“Normal”** control for ratio **below 3**

Contents

Temperature Excursion during Fast Current Ramp-down



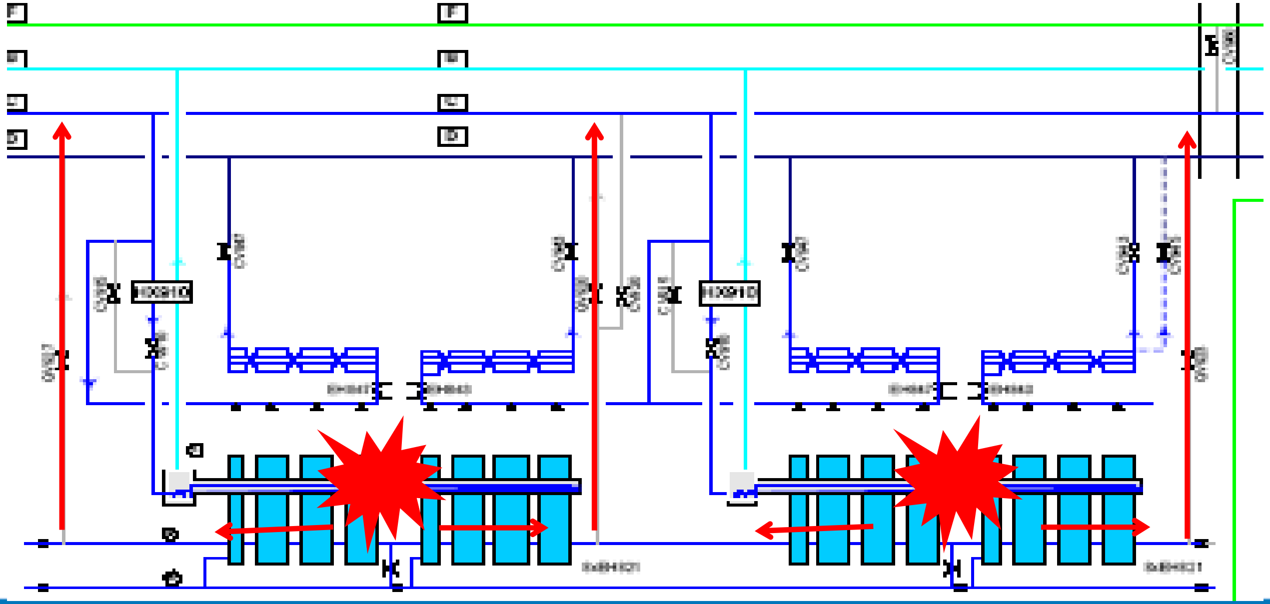
Magnet current fast ramp-down from 12 to 0 kA with a rate of 80 A/s, for which Eddy currents dissipate **3000 J/m** in the cold masses.

Magnet temperature remains below Tλ (helium stays in superfluid state)

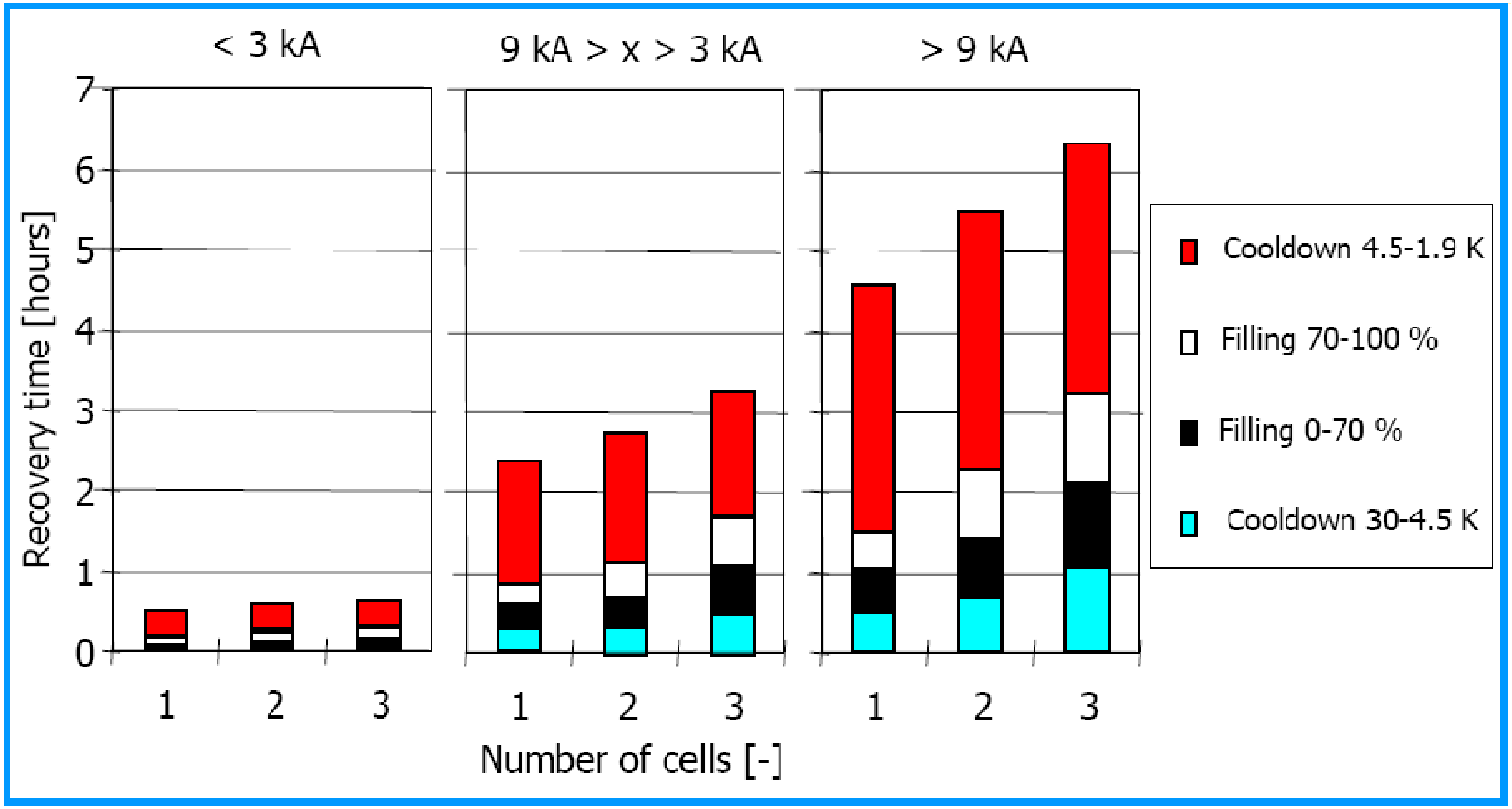
Recovery time: 2 hours

Quench and helium recovery

- 500 kJ.m^{-1} stored magnetic energy dissipated in the windings (see M. Chorowski spot)
- Pressure rise contained by discharge every 106.9 m by cold safety valves (see R. Couturier spot)
- Discharged helium buffered into header D or discharged and recovered from header D into gas storage vessels



Recovery Time after Limited Resistive Transitions



- A **resistive transition** warms up the magnets to **30 K**
- More than 14 cells or full sector ➔ recovery up to 48 hours

Contents

- Introduction
  - Systems, principles and parameters
- Cooldown
  - Principles and key figures
  - From simulations to sector cooldown
- From steady state to nominal powering
  - Principles and key figures
  - From simulations to full scale experiments
- Working with circulating beams
  - Principles and key figures
  - From simulations to full scale experiments
- Fast current discharges and quench
  - Principles and key figures
  - From simulations to full scale experiments
- Conclusion

Conclusions

- The cooling principle of the LHC magnets and the cryogenic plants will:
  - In steady-state operation, maintain the arc magnet temperature below 1.9 K with temperature stability within 10 mK
  - In-between the different steady-state operation modes, give a temperature stability within 70 mK
  - Not limit the cycle rate of injection
  - After a fast current ramp-down, maintain the magnet temperature below Tλ, but a recovery time of 2 hours is required
  - Because of local random losses, give a maximum temperature excursion of 20 mK
  - After a limited resistive transition, give a beam down time of 4 to 7 hours

- Individual system, full scale prototype and final full sector tests have validated the basic design and operating principles as well as demonstrated a high level of availability achievable after the necessary commissioning time required by this complex but performing system