Cryogenic Operation and Beam Loading

R. Giachino  CERN  Shut Down Lectures
Outline

1. Introduction
2. Beam loading
3. Beam Screen
4. Cryogenic Operation 2015
5. Cryogenic outlook 2016
6. Conclusions

- Acknowledgement: K.Brodzinski, E.Roger, G.Iadarola, S.Claudet, B.Bradu (EN/ICE), M.Pojer, G.Ferlin, Cryo team
LHC distribution scheme

Cryo distribution scheme

8 x 18 kW @ 4.5 K
1'800 SC magnets
24 km and 20 kW @ 1.9 K
36'000 tons @ 1.9 K
96 tons of He

Cryogenic plant

Cryoplants at five points, separate ring cryoline, 107 m long strings
Compressor station refrigerator

Compressor station of LHC 18 kW@ 4.5 K helium

4.2MW input power

Bldg: 15m x 25m

Oil/Helium Coolers  Compressors  Motors
Oil-injected screw compressor

(derived from Industrial refrigeration, compressed air)

3000 rpm

6 tons

≈1m
Process diagram, LHC refrigerator 18 kW @ 4.5 K

- LN2 (cool-down)
- Heat exchangers
- Adsorbers (remove impurities)
- Nidrogen
- Turbines
- Cold box

Temperature levels:
- 300 K
- 75 K
- 50 K
- 20 K
- 4.5 K

4.5 K supply
20 K return
50 K supply
75 K return

LHC Seminar 04/09/03
LHC 18 kW @ 4.5 K helium cryoplants

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

Diameter: 4 m
Length: 20 m
Weight: 100 tons

600 Input/Output signals

Air Liquide

Linde
CRYO TEMPERATURE LEVELS

In view of the high thermodynamic cost of refrigeration at 1.8 K, the thermal design of the LHC cryogenic components aims at intercepting the largest fraction of applied heat loads at higher temperature, hence the multiple, staged temperature levels in the system. The temperature levels are:

• 50 K to 75 K for thermal shield as a first major heat intercept, sheltering the cold mass from the bulk of heat in-leaks from ambient.

• 4.6 K to 20 K for lower temperature heat interception and for the cooling of the beam screens which protect the magnet cold bore from beam-induced loads.

• 1.9 K quasi-isothermal superfluid helium for cooling the magnet cold mass.

• 4.5 K normal saturated helium for cooling special superconducting magnets in insertion regions, superconducting acceleration cavities, and the lower sections of high temperature superconductor (HTS) current leads.

• 20 K to 300 K cooling for the resistive upper sections of HTS current leads [14]
**Beam-induced heat loads** are deposited in the cryo-magnets through several processes and by the circulating and colliding proton beams themselves. They depend strongly on the **energy**, the **bunch intensity, number** and **length** of the circulating bunches as well as on the **luminosity** in collision. The various beam-induced loads are:

- **Synchrotron radiation** from the bending magnet, mostly absorbed by the beam screens,
- **Resistive dissipation** of beam image currents induced in the resistive walls and geometrical singularities of the beam channel,
- **Impingement of photo-electrons** accelerated by the beam potential ("electron clouds"), mostly adsorbed by the beam screen,
- **Nuclear inelastic beam-gas scattering** corresponding to a continuous distributed loss of particles from the circulating beam,
- **Continuous random loss of particles** escaping the collimation system, mostly absorbed by the cold mass helium bath close to the high-luminosity experimental areas,
- **RF losses** in superconducting acceleration cavities; in nominal conditions, RF losses are 200 W per half insertion.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Nominal</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature level</td>
<td>4.6-20 K</td>
<td>4.6-20 K</td>
</tr>
<tr>
<td>Synchrotron radiation</td>
<td>330</td>
<td>500</td>
</tr>
<tr>
<td>Image current</td>
<td>360</td>
<td>820</td>
</tr>
<tr>
<td>Photo-electron cloud *</td>
<td>890</td>
<td>3040</td>
</tr>
<tr>
<td>Beam-gas scattering</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Random particle loss</td>
<td>0-0.1</td>
<td>0-0.3</td>
</tr>
<tr>
<td>Total beam-induced *</td>
<td>1580</td>
<td>4360</td>
</tr>
</tbody>
</table>

* After beam cleaning
Beam Screen heat load estimation

\[ Q_{\text{dbs}} = Q_{\text{sr}} + Q_{\text{ic}} + Q_{\text{ec}} \]

1. Synchrotron radiations

\[ Q_{\text{sr}} = Q_{\text{srnom}} \cdot L \cdot \left( \frac{E}{E_{\text{nom}}} \right)^4 \cdot \left( \frac{N_b}{N_{b\text{nom}}} \right) \cdot \left( \frac{n_b}{n_{b\text{nom}}} \right) \]

2. Image current

\[ Q_{\text{ic}} = Q_{\text{icnom}} \cdot L \cdot \left( \frac{0.6 \cdot E + 2800}{E_{\text{nom}}} \right)^{0.5} \cdot \left( \frac{N_b}{N_{b\text{nom}}} \right)^2 \cdot \left( \frac{n_b}{n_{b\text{nom}}} \right) \cdot \left( \frac{\sigma}{\sigma_{\text{nom}}} \right)^p \]

3. Electron cloud

\[ Q_{\text{ec}} = \left[ K_{\text{eci}} \cdot \frac{q_{\text{eci}}}{2} \cdot \left( 1 - \frac{E - E_{\text{inj}}}{E_{\text{ramp}} - E_{\text{inj}}} \right) + K_{\text{ecr}} \cdot \frac{q_{\text{ecr}}}{2} \cdot \left( \frac{E - E_{\text{inj}}}{E_{\text{ramp}} - E_{\text{inj}}} \right) \right] \cdot n_b \cdot \frac{N_b}{N_{b\text{nom}}} \]

- SR and IC comes from LHC design reports and are OK with measurements
- EC mentioned in LHC design report is much lower than measurements
  - New EC equation based on physics elaborated by EN/ICE and BE/ABP
  - Equation scaled according to measurements in different sectors (qeci/qecr)
  - Equation scaled according to machine cleaning (Keci and Kecr)
**Transient Modes**

**Ramping the magnetic fields up and down** will generate additional transient heat loads in the superfluid helium due to the eddy currents developed in the superconducting cables. Raising the current to its nominal value (6.5 TeV equivalent) in 1200s is expected to dissipate 480 J of energy per metre length of main dipole. This represents a power of approximately 0.4 W per metre.

In the case of a resistive transition or in case of an emergency, it must be possible to ramp the full current down to zero in 80 s. This will result in an energy dissipation of 3000 J per metre of magnet. This represents a power of approximately 38 W per metre.

The only practical way to absorb these transient heat loads and keep the temperature below 1.9 K during ramping-up and below the lambda line during fast ramp-down is to make use of the heat capacity of the liquid helium contained in the magnet冷-masses. About 15 l of liquid helium per metre length is sufficient to cope with the loads to be buffered.
The beams circulate in two ultra-high vacuum chambers, \( P \sim 10^{-10} \text{ mbar} \).

- A Copper beam screen protects the bore of the magnet from heat deposition due to image currents, synchrotron light etc from the beam.
- The beam screen is cooled to \( T = 4-20 \text{ K} \).
Why LHC has beam screens?

![Functional design map of beam screen](Figure 4)

*Courtesy of V. Baglin*
**Fill 3134**
October 2012 (Run1)
Physics 50 ns @ 4 TeV
I = 2.3e14 p+/beam
1374 bunches/beam

**Electron clouds became huge!**
(*much more than expectations!!!*)

**Fill 4485**
October 2015 (Run2)
Physics 25 ns @ 6.5 TeV
I = 2.12e14 p+/beam
1825 bunches/beam

- Several beam dumps because of too high temperature in beam screens during beam injections.
- Cryogenic plants were at their upper limits and LHC commissioning was frozen because of that (impossible to put more particles in the machine.)
• In the first stages, even with relatively low number of bunches, strong transients of the beam screen temperatures were observed, leading to loss of cryo-conditions:
  o Intensity ramp-up performed in “mini-steps” for fine tuning of cryo-regulations
  o During the first stages, injection speed often decreased to control beam screen temperatures
  o Limitation from transients strongly mitigated over the year by:
    o Modified Cryo Maintain rules to allow for larger temperature excursion
    o Improvement on cryogenic feed-forward control
The **e-cloud thermal effect** requires from cryogenics:

Fast *dynamic increase of cooling capacity* during **injection and ramp** or *fast dynamic decrease* of the capacity during the **dump**

- Fast *dynamic control logic* applied on local **BS cooling loops**:
  - by anticipation to **Thermal load** triggered with number of injected bunches
- **Thermal capacity buffer**
  - of ~1.5 kW @ 4.5 K prepared before each beam injection
- **Modification of Cryo Maintain interlock**
  - $T=30\,K$ during 30 s, $>> T=40\,K$, 30 min

Large *continue demand for cooling capacity* during related fill

- Process optimization – already well done, not a lot of margin left (limitations on main refrigerators)
- Apply solution of equal split of return flow (3 valves to be changed)
Figure 11.5 Cryogenic flow-scheme and instrumentation of a LHC lattice cell
Beam screen and installed capacity

Heat loads: \(Q_s\) – static heat load, \(Q_{EH}\) – electrical heater, \(Q_{BS}\) – from beam operation

(ARCs: EH is used now out of beam operation periods to avoid low velocity helium stream oscillations in BS circuit, LSS: in permanent use for stability ~300 W/sector)

**Table 11.11: Installed refrigeration capacity in the LHC sectors**

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>High-load sector</th>
<th>Low-load sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-75 K</td>
<td>[W]</td>
<td>33000</td>
</tr>
<tr>
<td>4.6-20 K</td>
<td>[W]</td>
<td>7700</td>
</tr>
<tr>
<td>4.5 K</td>
<td>[W]</td>
<td>300</td>
</tr>
<tr>
<td>1.9 K LHe</td>
<td>[W]</td>
<td>2400</td>
</tr>
<tr>
<td>4 K VLP</td>
<td>[W]</td>
<td>430</td>
</tr>
<tr>
<td>20-280 K</td>
<td>[g.s(^{-1})]</td>
<td>41</td>
</tr>
</tbody>
</table>

**Table 11.8: Distributed steady-state beam-induced loads in an LHC cell [mW m\(^{-1}\)]**

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<tr>
<td>Synchrotron radiation</td>
<td>330</td>
<td>1</td>
</tr>
<tr>
<td>Image current</td>
<td>360</td>
<td>1</td>
</tr>
<tr>
<td>Photo-electron cloud</td>
<td>890</td>
<td>9</td>
</tr>
<tr>
<td>Beam-gas scattering</td>
<td>0.4</td>
<td>48</td>
</tr>
<tr>
<td>Random particle loss</td>
<td>0.0 1</td>
<td>0.32</td>
</tr>
<tr>
<td>Total beam-induced</td>
<td>1580</td>
<td>59-91</td>
</tr>
</tbody>
</table>

* After beam cleaning

**85 W/half cell**

**Exercise for s1-2:**
Input: \(Q_s=400\) W, \(EH=49\) W, \(Q_{qrl}=630\) W, \(P_{ref}=7700\) W, \(L_{totBS}=6033\) m  
Calculation: \((7700-1079)/6033=1.1\) W/m/a \(\rightarrow 2*53*1.1=116\) W/half cell

**Exercise for 2-3:**
Input: \(Q_s=400\) W, \(EH=49\) W, \(Q_{qrl}=570\) W, \(P_{ref}=7600\) W, \(L_{totBS}=5971\) m  
Calculation: \((7600-1019)/5971=1.1\) W/m/a \(\rightarrow 2*53*1.1=116\) W/half cell
➢ Implementation of a Feed-Forward action to anticipate beam induced heat load and to stay below 20 K for any beam parameter.

Heat loads: $Q_s$ – static heat load, $Q_{EH}$ – electrical heater, $Q_{BS}$ – from beam operation

(ARCs: EH is used now out of beam operation periods to avoid low velocity helium stream oscillations in BS circuit, LSS: in permanent use for stability ~300 W/sector)
Ideally Cryo could use Injection scheme pattern, Nbunches, 25nsec, etc) feed into an algorithm
The electrical heater setting and the BS valve adjustment will be automated to cool down the BS temperature and keep the loop stable.

Heat loads: $Q_s$ – static heat load, $Q_{EH}$ – electrical heater, $Q_{BS}$ – from beam operation

(ARCs: EH is used now out of beam operation periods to avoid low velocity helium stream oscillations in BS circuit, LSS: in permanent use for stability ~300 W/sector)
Before injection cryo anticipate the heating by adjusting the electrical heater.

A clear improvement by end 2015 due to the Feed Forward and Operational experience.

Aim to stabilize all sectors at 18-20 K.

During injection Opening Control valve 35-40% to increase the flux while we increase the number of bunches.
During 2015 run still need some Cryo adjust time before ramp
The output beam loading reading takes up to 2 mins then 5-10 mins adjustments.
Often last sector to be stable was 23
Aim to stabilize all sectors at **18-20 K**
Beam Loading during the ramp is due to Transient Modes + Synchrotron radiation
- Electron cloud effect increase mainly due to SR
- Output Temperature ramp and Flat Top 18-20 K
- Electrical Heater off during the ramp.
Beam Loading during Ramp

Opening Pressure valve 45-50% increase the flux to compensate the output temperature

- Increased **longitudinal emittance blow-up** on the ramp
- **optimized filling scheme** to gain additional margin
Temperature drop at the end of ramp
The transient heat load disappear and PLC > FF try to mitigate the effect.

- Beam Screen Temp at squeeze, collide & physics is constant
- Electron cloud effect constant
- Output Temperature Flat Top 20 K
The BS set point temp will now be increased to 20-22 K
The temperature controller will reduce the flux of the Control Valve accordingly
This operation will maintain the BS cooling capacity. (cold box level 30%)
Beam Loading drop to zero after Beam Dump. **Output Temp decrease toward 8 K**

- **Set point BS temp to 13-17** Temp Controller drive the Electrical heater toward injection level (1200 W) to compensate the Beam loading loss.
Temperature increase + Valve closing 14-15 K setting back to pre-injection
BS – physics from 7th Sep. to 2nd Nov.

- **116 W/half cell** is the limit coming from installed capacity of the cryogenic plants for BS cooling.
- Needed capacity between 116 W/half cell and 160 W/half cell is covered thanks to lower capacity taken from the refrigerator for **1.9 K cooling loop**.
- **1.5 W/m/a = 160 W/half cell** is considered as feasible limit applicable for all sectors (currently except s2-3).
- Sector 2-3 is presently almost at its limit estimated of ~135 W/half cell.
  - source of this anomaly is under investigation.

In 2016 we will be able to provide at least the same capacity as in 2015.

installed capacity + margin form 1.9K unit at lower flow than designed.

limit S23

installed capacity limit for 4.5-20K

Theoretical LHC nominal heatloads

W/hc

p+/bunch
Scrubbing accumulated during the physics

At the end of the p-p run we repeated an early fill of the intensity ramp-up

- **Very similar beam conditions** (filling pattern, bunch intensity, bunch length)
- After 2 months, significant **reduction visible in all arcs** (30% to 60% depending on the sector)
- Reduction observed **mainly in dipole magnets** (higher SEY threshold compared to quads)

14 September

4 November
Situation at the end of the p-p run

Achieved in 2015: **2244b.** in trains of 36b.

- **Factor 3 spread** among heat loads in different sectors! - reason not clear
  - Sectors 81, 12 and 23 close to the **limit** with this filling scheme
  - Sectors 34, 45, 56, 67 have already enough margin to accommodate the nominal beam
Cooling capacity of A and B are designed to cover nominal LHC operation with equal margins on LL and HL sectors.

**BUT:**

1. w/o dynamic load B has more capacity margin than A -> easier recoveries,
2. B is more reliable for operation because of its design.

Thanks to build-in interplant connections some special configurations were possible during Run1 and Run2 (2015) for problems mitigation, lower power consumption or optimize for availability and helium losses.
Proposed configuration (two 4.5 K cold boxes + one cold pumping unit) was tested end of LS1 and put in production for a first time during Run2.

Stop of some Cold Pumping Units is possible thanks to overcapacity margin, lower than expected heat load at 1.9 K and built-in interplants piping in cryogenic infrastructure. (P2/P18 – more difficult – tests to be done hopefully during YETS).

**Main benefit:**
less rotating machines => less failures => more availability
... but with 10-20 % longer recovery time in case of failures

Limitations:
- Some modifications in hardware still to be studied and applied for better process control, optimization and gain in the capacity for 4.5 K – 20 K cooling – see next slide
Currently 1.9 K return flow is unbalanced affecting operational stability and performance of the refrigerators. To resolve the issue 3 valves design must be more precise to control the flow – to be studied and approved –→ prototype for EYETS –→ production for LS2 (such operation was not foreseen originally)
Leak in LHCB 4.5 K refrigerator at P8 declared on 18 June 2015 (TS1)

Consequences:
- vacuum diffusion pump stopped, lowered capacity on P8 cryo plant,
- frequent CM losses on DFBMI because of poor quality of supercritical helium in QRL upstream the filling valve.

Corrective and compensatory measures:
- Cold compressor connected to QSRB (for economizer mode)
- Roots pumping unit connected
- Spare roots in situ
- Process adaptation to minimize the leak

Repairs planned during 4 weeks in January 2016
Main failures 2/2

Main machines which required replacement:

3 turbines failures on 4.5 K refrigerators:
P18: TU2 – replaced with LN2 during repair time
P18: TU3 – replaced with spare
P2: TU2 – replaced with LN2 during repairs

1 warm compressor failure:
P4: HP compressor CP6
Systematic vibration measurements (1/month) allow for in advance detection of the problem to avoid serious damage and high repairs cost of affected machine
From June 2009 until now: 8 warm compressors had to be repaired (7 of firm “A”, and 1 from firm “B”)

16 RFL valves failures (needed for AL turbines to control axial profile of the shaft temperature). Replacement study is launched (two offers already received), prototypes to be installed on the cold boxes in 2016

4 PLCs failures – progressive replacement is underway by a new product with “anti-crash firmware”. Status: 2/3 replaced during 2015 TSs, remaining part to be done during YETS.
Statistics for Run2 (2015) period from 5th April to 14th December 2015

CRYO AVAILABILITY SUMMARY FROM RUN 1 TO RUN 2

- **2010**
  - Supply: 91.5%
  - Users: 89.7%
  - Cryo: 4.2%
  - CRYO SEU: 0.2%
  - Global AV: 92.1%

- **2011**
  - Supply: 5.2%
  - Users: 2.5%
  - Cryo: 3.5%
  - CRYO SEU: 0.5%
  - Global AV: 89.7%

- **2012**
  - Supply: 0.7%
  - Users: 0.2%
  - Cryo: 0.5%
  - CRYO SEU: 1.0%
  - Global AV: 94.5%

- **2015**
  - Supply: 1.1%
  - Users: 2.1%
  - Cryo: 4.7%
  - Global AV: 92.1%

- **2015**
  - Supply: 1.1%
  - Users: 2.1%
  - CRYO SEU: 1.3%
  - Global AV: 92.1%
YETS main activities

**Preparation and conditioning:**
- P8 s7-8 and s8-1 – to be emptied from LHe and conditioned with GHe at ~30 K
- All other sectors: LSS+IT emptied and kept at 30 K, ARC conditioned with LHe at ~4 K

**Main repairs and consolidations:**
- P8 QSRB cold box leak repairs – between 5th and 29th January 2016
- PLCs: upgrade to new generation firmware to be completed in January 2016
- Replacement of active charcoal at P6 - done, P4 and P8
- P4 and P6 QSCAs: preparation for installation of additional oil filtering coalescers (coalescers ordered, integration study underway, installation probably during TS1)
- Updates in software and multiple other maintenance and repairs activities

*Ready for start up 2016*
Run2 (2016) operating scenario

To be tested during YETS
Conclusion

- LHC beam screen temperature is highly disturbed by the beam.
  - Need to anticipate the heat load before its effects on cryogenics.
  - If the temperature is not well controlled: beam dump or cryogenic plant limits

- Important work done by EN-ICE and TE-CRG
  - Dynamic simulations to understand and validate new control strategies.
  - New control strategies have been deployed during 2015 in the 590 loops.

- The feed-forward controls show a significant improvement in 2015
  - LHC was ramped-up to 2.7e14 protons in 2244 bunches.

  - Beam screen heat load estimation will be improved during YETS
    - More precise FF action
    - Easier and better tuning by cryo operators to follow the machine evolutions
Conclusions

• Cryogenic Run2 was a success with CM availability at 92.1 %
• New configuration was applied and validated
• Main failure – 4.5 K refrigerator – repaired in January 2016
• LS1 consolidations visibly >> R2E!, 0 SEU cases declared in 2015)
• e-cloud thermal effect pushed the LHC cryo to the limits of capacity (over originally installed capacity foreseen for 4.5 -20 K)

• Run2 (2016): referring to lesson learned in 2015, cryogenics guaranties at least the same level of capacity as done during run in 2015.
• Correct dealing with any higher heat load is not guaranteed and must be analyzed and tested.
Standard cells (≈27/sector)

- Cool-down using mostly Flow controllers
- P, T, L controllers at operating conditions
Situation at the end of the p-p run

Achieved in 2015: 2244b.

- Factor 3 spread among heat loads in different sectors!
- Reason not clear
- Sectors 81, 12 and 23 close to the limit
- Sectors 34, 45, 56, 67 have already enough margin to accommodate the nominal beam 2244b.

On the difference among sectors:
- It is not a measurement artefact (test cells calibrated with heaters)
- In 2012 distribution was different (S45 and S56 were the worse at the time)
- It is there with only beam 1 (and gives half the value)
- It was observed also with 50 ns, then disappeared with scrubbing
- It was observed with doublets (see later)
- Difference is increasing with time (good sectors condition faster)
- There is no dependence on the radial position of the beam (tested +/- 0.2 mm)
- Thermal cycle of the beam screen has no effect on the heat load
- High heat load sectors seem to have larger integrated BLM signals
Control improvements for LHC Run 2

- Identify the process dynamics to tune PI loops correctly
- Add time filter on the measurements to remove the noise
- Set-point change with beam operation

- Add a Feed-Forward action to PIDs:
  - Estimate the BS heat load
  - FF on the valve to kill overshoot
  - FF on the heater to save power
  - Intuitive to understand
  - Scalable (590 loops in total)
  - Easy to tune for operators
  - No manual actions
  - Stay in acceptable temperatures during injection and ramp
  - Minimize as much as possible the refrigerator heat load

⇒ Important coordination between ICE and CRG to setup all these new features in 2015.

⇒ The difficulty is to predict the heat load