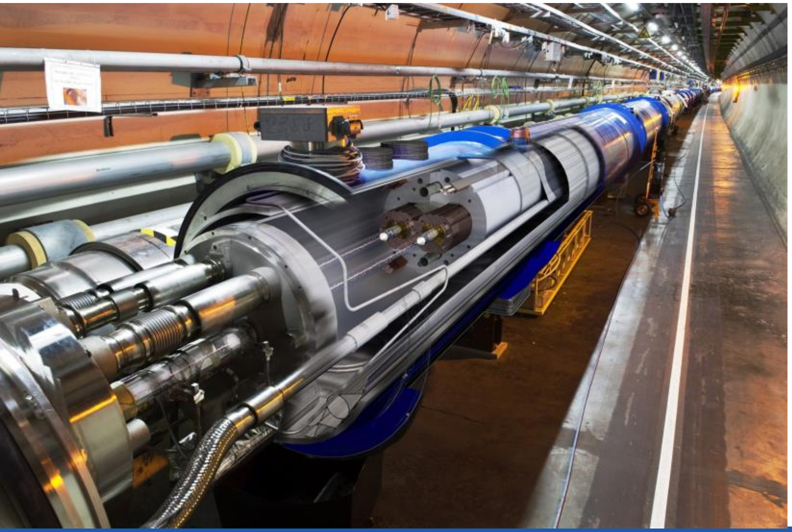
C1Or1B-05

Cryogenic management of the LHC Run 2 dynamic heat loads



B. Bradu*, K. Brodzinski, G. Ferlin

European Organization for Nuclear Research
CERN, Geneva, Switzerland

**e-mail: benjamin.bradu@cern.ch*

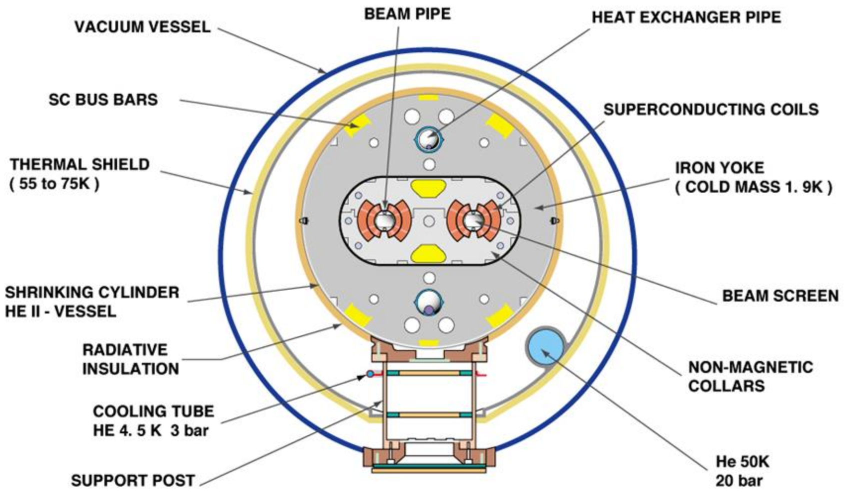
Contents

- **Introduction**

- **Dynamic heat load measurements**
  - In Cold Mass @ 1.9 K
  - In Beam Screens @ 4.6 K - 20 K

- **Temperature transient management**
  - In Cold Mass @ 1.9 K
  - In Beam Screens @ 4.6 K - 20 K

- **Conclusion**



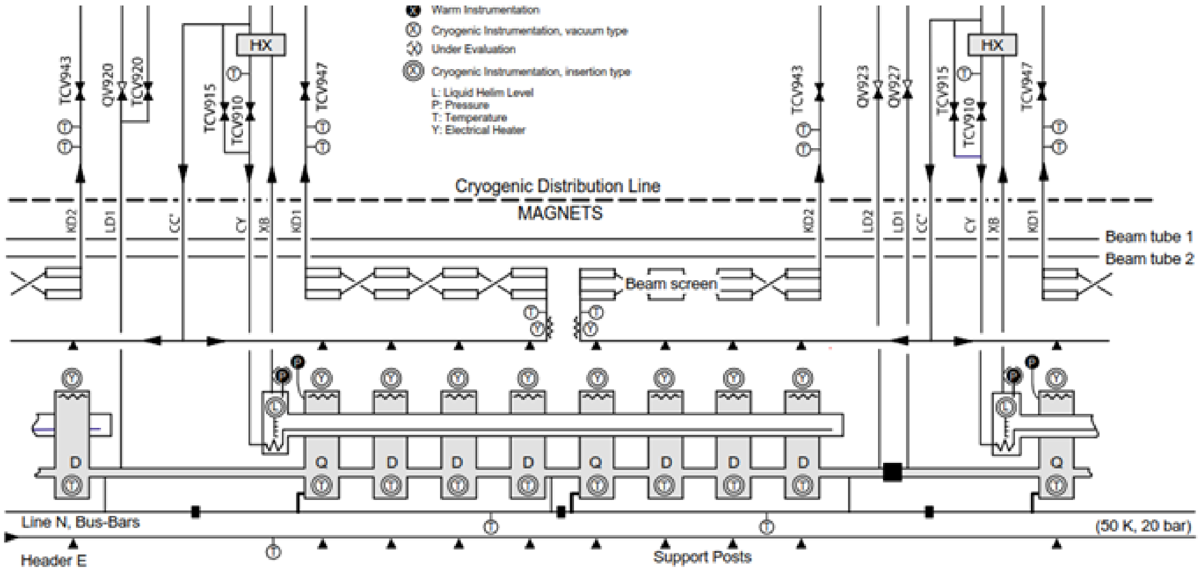
Introduction

- LHC Run 2 is now over (Apr. 2015-Dec. 2018)
  - Much larger heat loads on LHC cryogenics compared to Run 1
- Almost nominal energy was reached: $E = 6.5\ TeV$
  - Dynamic heat loads in superconducting magnets during energy ramp-up/down
- Nominal beam intensity was reached : $I = 3.2 \cdot 10^{14}$ p^+/beam
  - Bunch spacing of 25 ns (was 50 ns in Run 1)
  - Dynamic heat loads in superconducting magnets
  - Dynamic heat loads in Beam screens
- Double nominal luminosity was reached: : $L = 2.1 \cdot 10^{34}\ cm^{-2} \cdot s^{-1}$
  - Dynamic heat loads in Inner Triplet magnets (around collision points)
  - Dynamic heat loads in Inner Triplet Beam screens (around collision points)

Dynamic heat loads in Cold Masses

- Dynamic heat loads on superconducting magnet cold masses (CM):
  - **Resistive Heating** (RH): Heat load due to resistive welds on superconducting circuits
  - **Beam induced heat loads** (BIHL): Beam gas scattering in vacuum and beam losses
  - **Secondaries** (SEC): Heat load generated by collision debris in Inner Triplet magnets
  - **Magnetization Losses** (ML): Heat loads due to eddy currents during the magnet ramp-up/down (active during 20 min only, damped in static superfluid helium bath).

- 224 CM cooling loops over the 27 km of the LHC
  - Cooled in a Claudet bath maintained at 1.9 K with a bayonet HX supplied by superfluid helium
  - 216 cooling loops in the ARC (107m per loop)
  - 8 Inner Triplet cooling loops around the 4 collision points (~ 50 m per loop)
  - 4 Inner Triplet cooling loops have significant secondaries heat loads (around ATLAS and CMS)



CERN

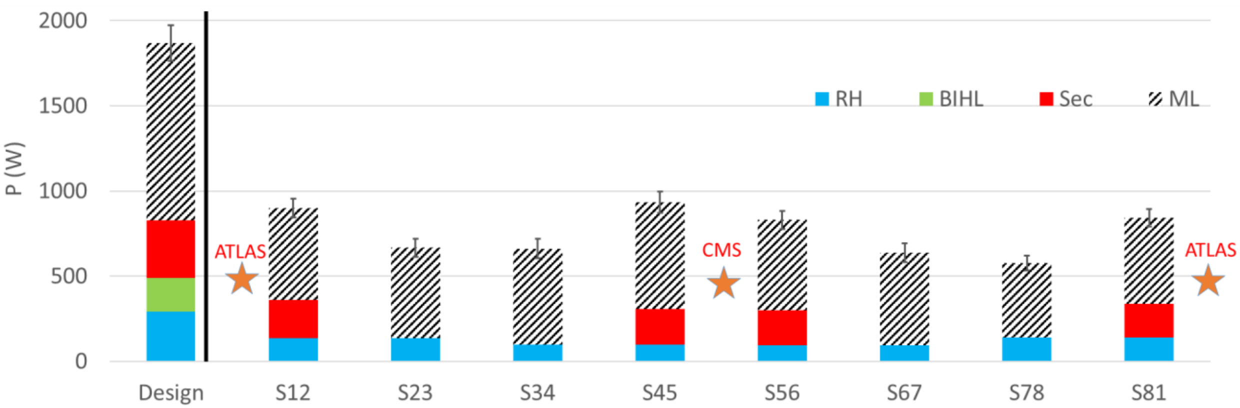
Dynamic heat loads in Cold Masses

- Measurement method
  - Energy balance performed on each sector (3.3 km) using the measured cold-compressor mass flow (m_{CC})

$$\Delta Q_{CM} = \frac{1}{2}\cdot\Delta\dot{m}_{CC}\cdot L_{He} + (M_{He}\cdot Cv_{He} + M_{mag}\cdot Cp_{mag})\cdot\frac{\Delta T_{mag}}{\Delta t} - \Delta Q_{EH}$$

  - Select 5 LHC fills to distinguish each hat load contributor
  - Scale each contributor for a chosen reference fill (Fill #6675 in May 2018)

Fill	**Date**	**Energy** (GeV)	**Intensity** $(p^+/beam)$	**Luminosity** $(cm^{-2}\cdot s^{-1})$	**Dyn. Heat loads**
No Beam	28 July 2018	450	0.0	0.0	None
6975	25 July 2018	450/6500	$1.0\cdot10^{11}$	0.0	ML
6868	01 July 2018	6500	$1.0\cdot10^{13}$	0.0	RH
6909	10 July 2018	6500	$1.8\cdot10^{14}$	$5\cdot10^{32}$	RH+BIHL
6675	12 May 2018	6500	$3.0\cdot10^{14}$	$2\cdot10^{34}$	RH+BIHL+Sec



CM dynamic heat loads @ 1.9 K on the 8 LHC sectors for Fill 6675 compared to LHC Design report

Results

RH twice smaller than expected
➔ very low splice resistance

BIHL are below meas. precision (<5 W)
➔ very good beam vacuum

Sec are slightly lower than expected

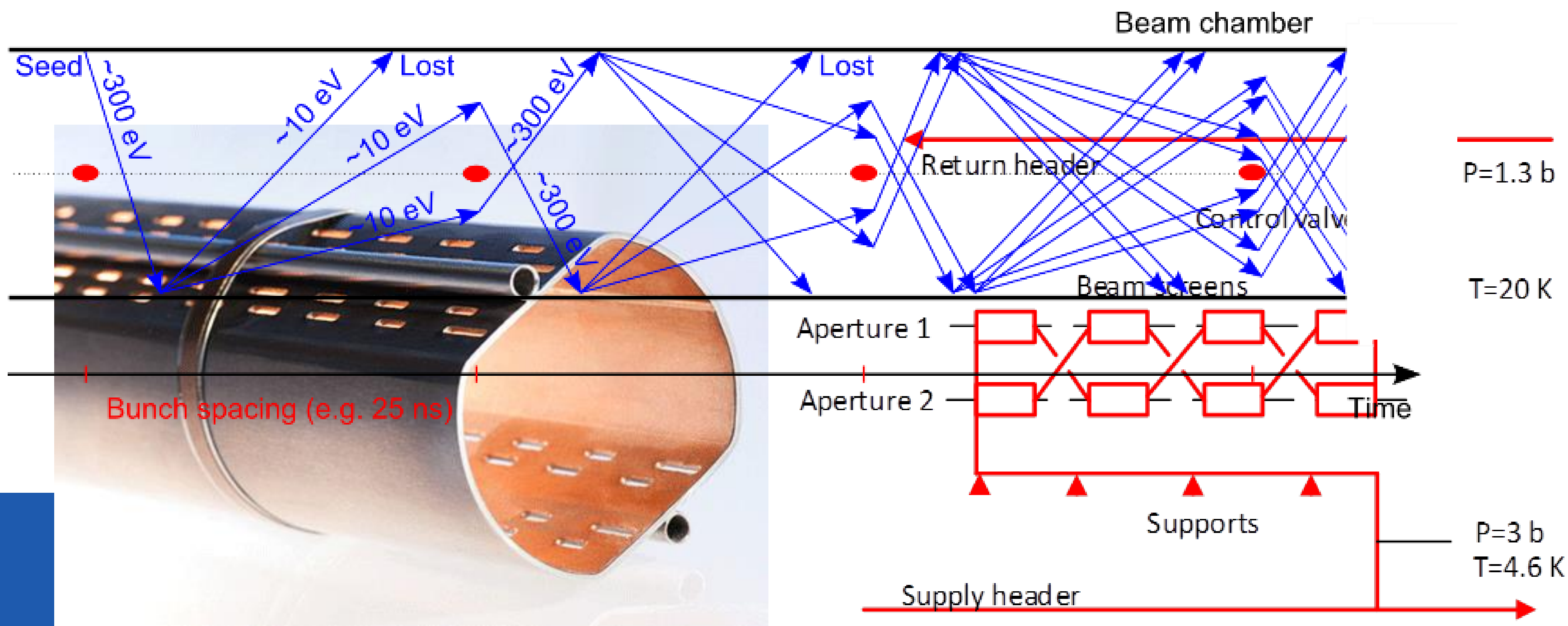
ML are twice smaller than expected

Total dynamic heat loads are twice smaller than design values

Dynamic heat loads in Beam Screens

- Dynamic heat loads on beam screens (BS):
  - **Synchrotron radiation** (SR): beams produce photons intercepted by the beam screens
  - **Image current** (IC): generated by the beam on the beam screen surface due to its impedance
  - **Electron cloud** (EC): Generated by a multipacting effect when photo-electrons emitted from the beam screen are re-accelerated by the beam if the bunch spacing is 25 ns.

- 485 BS cooling loops over the 27 km of the LHC (53 m each)
  - Cooled by conduction through cooling pipes supplied by supercritical helium at 3 bar and 4.6 K
  - 4 parallel cooling pipes of 3.7 mm each on the 2 apertures



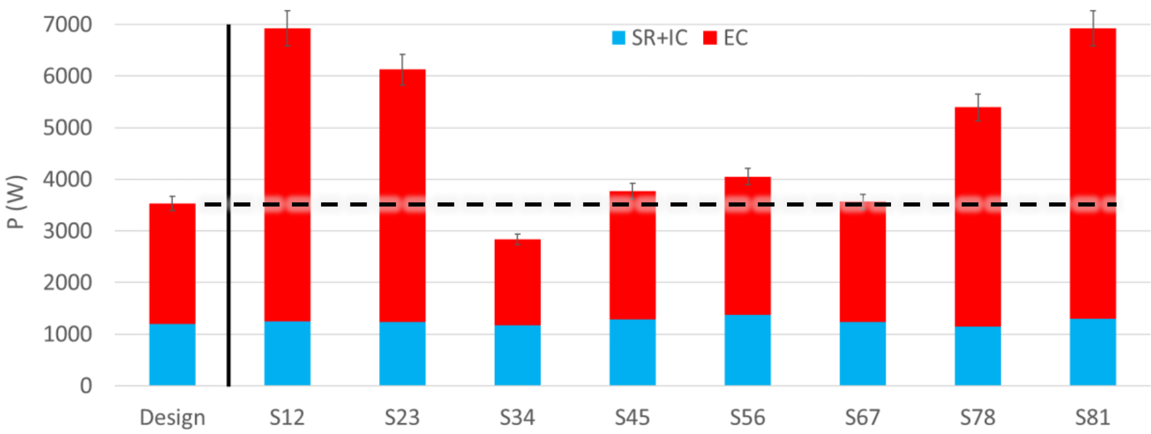
Dynamic heat loads in Beam Screens

- Measurement method
  - Enthalpy balance performed on each BS loop (53 m) using valve mass flows and sum over a sector

$$\dot{Q}_{BS} = \sum (\dot{m} \cdot \Delta H - \dot{Q}_S - EH)$$

  - Select 2 LHC fills to distinguish SR/IC and EC heat loads
  - Scale each contributor for a chosen reference fill (Fill #6675 during May 2018)

Fill	Date	Energy (GeV)	Intensity $(p^+/beam)$	Inj. scheme	Dyn Heat loads
Fill 5980	22 July 2017	6500 GeV	$1.4 \cdot 10^{14}$	STD-50ns	SR+IC
Fill 6675	12 May 2018	6500 GeV	$3.0 \cdot 10^{14}$	BCMS-25ns	SR+IC+EC



BS dynamic heat loads at 4.6 K – 20 K on the 8 LHC sectors for Fill 6675 compared to LHC Design report

Results

SR&IC are in agreement with expectations.

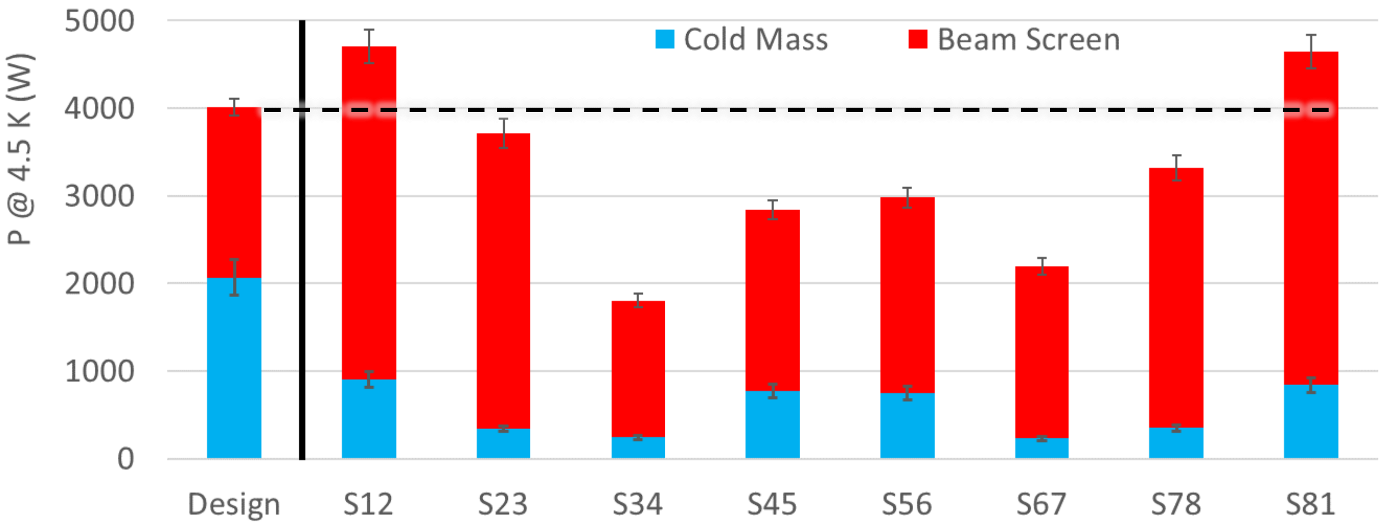
EC heat loads are very different along the machine. **4 sectors have significant extra-heat loads.**

- Probably due to different *Second Electron Yield* (SEY), depending on the BS surface properties.
- A dedicated *Task Forced* is studying this issue at CERN to understand it and solve it to not limit the machine performance in future.

Dynamic heat loads summary

- Total equivalent dynamic heat loads @ 4.5 K
  - At the end, all the dynamic heat loads are applied on 4.5 K refrigerators
  - Exergetic balances allows us to estimate the equivalent total heat loads at 4.5 K.

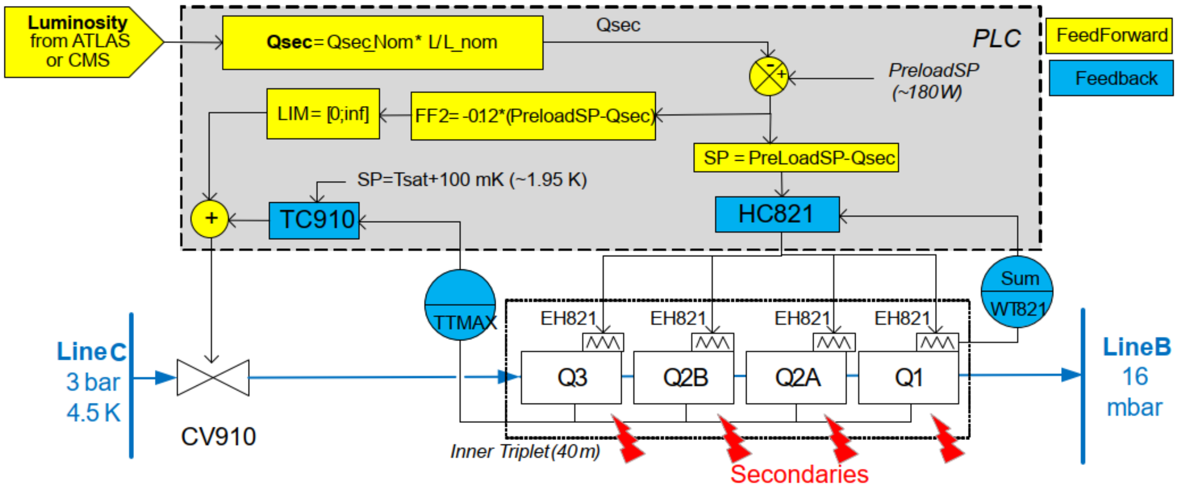
- Results
  - 4 sectors (S34,45,56,67) are below the expected values
  - 2 sectors (S23,78) are almost at the LHC design report values
  - 2 sectors (S12,81) have a total dynamic heat loads slightly above the LHC Design report, representing 25% of total refrigeration capacity.

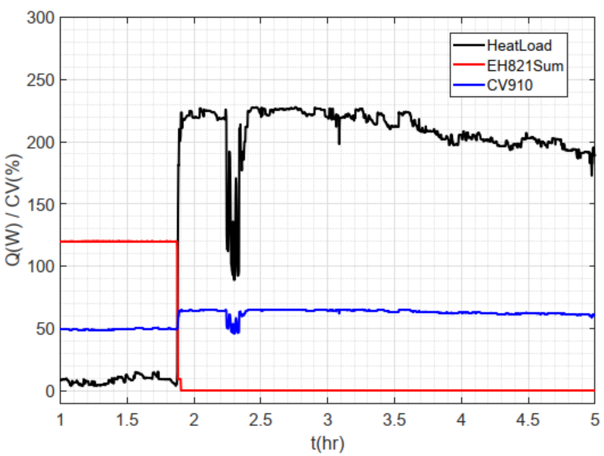


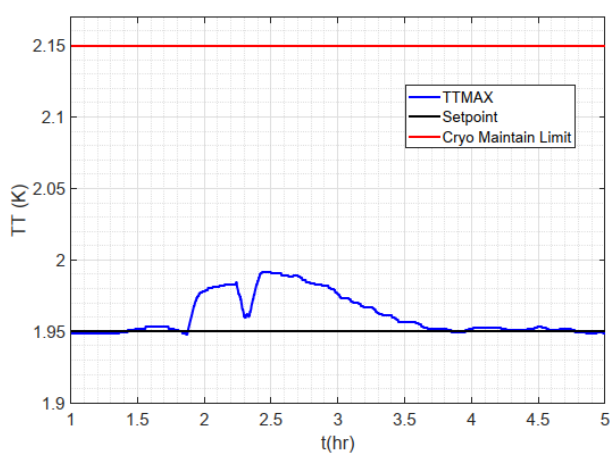
Total equivalent dynamic heat loads at 4.5 K on the 8 LHC sectors for Fill 6675 compared to LHC Design report

Transient management in Cold masses

- **Standard cells in ARC**: no transient issue, conventional PID control is suitable
- **Inner Triplets** around collision points: magnet temperature transient issue with secondaries heat loads arriving instantaneously with the luminosity (collisions).
  - **Pre-loading** of magnets with electrical heaters when no luminosity
  - Adding **Feed-Forward** actions on electrical heaters and cooling valves based on luminosity to compute in real-time the expected heat loads.







Results

Electrical heater is stopping when collisions starts and cooling valve anticipates its opening with Feed-Forward.

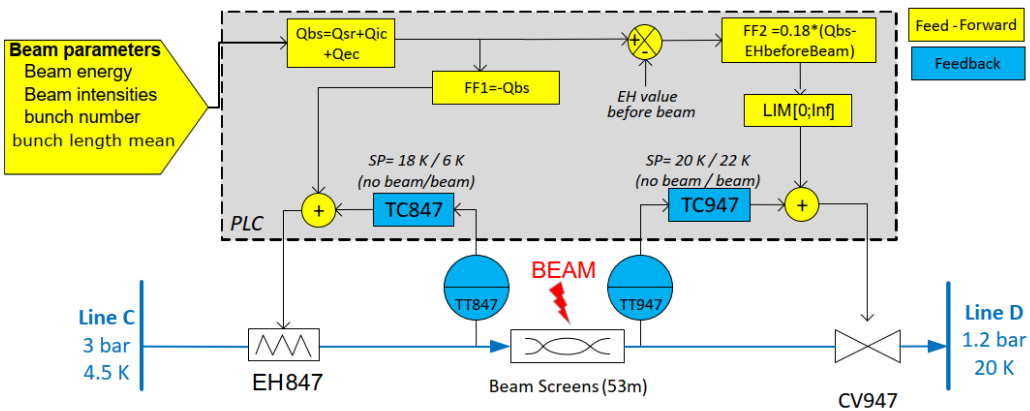
➔Temperature transient well controlled staying far from the cryo maintain limit (2.15 K) allowing the magnet powering.

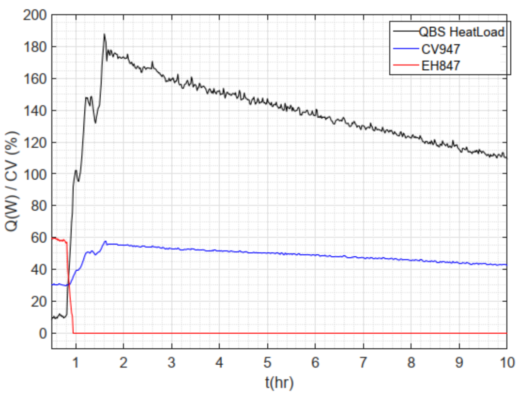
Transient management in Beam Screens

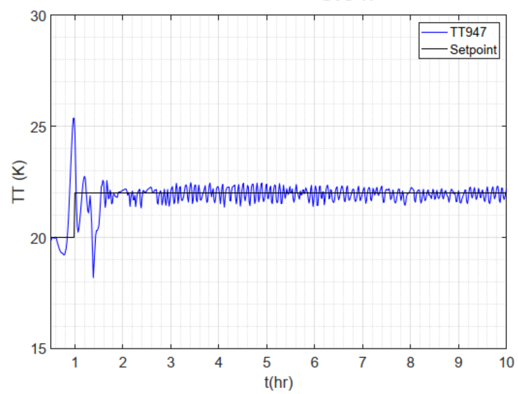
- When running at 25 ns, PID control loop cannot manage properly the transients with EC heat loads
  - **Pre-loading** of beam screens with electrical heaters when no beam
  - Adding **Feed-Forward** actions on electrical heaters and cooling valves based on beam parameters to compute in real-time the expected heat loads.
  - As the 585 cooling loops have different EC heat loads, about **1 500 tuning parameters** were introduced to scale properly the Feed-forward actions on each cooling loop using an automatic script.

$$Q_{sr} = Q_{srnom} \cdot L \cdot \left(\frac{E}{E_{nom}}\right)^4 \cdot \left(\frac{Nb}{Nb_{nom}}\right) \cdot \left(\frac{nb}{nb_{nom}}\right) \qquad Q_{ic} = Q_{icnom} \cdot L \cdot \left(\frac{0.6 \cdot E + 2800}{E_{nom}}\right)^{0.5} \cdot \left(\frac{Nb}{Nb_{nom}}\right)^2 \cdot \left(\frac{nb}{nb_{nom}}\right) \cdot \left(\frac{\sigma}{\sigma_{nom}}\right)^p$$

$$Q_{ec} = \left[K_{eci} \cdot \frac{q_{eci}}{2} \cdot \left(1 - \frac{E - E_{inj}}{E_{ramp} - E_{inj}}\right) + K_{ecr} \cdot \frac{q_{ecr}}{2} \cdot \left(\frac{E - E_{inj}}{E_{ramp} - E_{inj}}\right)\right] \cdot n_b \cdot \frac{Nb - Nb_0}{Nb_{nom} - Nb_0}$$







Results

Electrical heater is progressively stopping during beam injection and cooling valve anticipates its opening with Feed-Forward.

➔Temperature transient well controlled staying far from the cryo maintain limit (30 K) and ensuring a constant return temperature to refrigerators.

Conclusion

- Dynamic heat loads generated during the Run 2 have been assessed
  - Cold mass heat loads are twice smaller than the design
  - Beam screens have extra heat loads in 4 sectors, probably due to electron-clouds

- The Feed-Forward control have been deployed and tuned individually on the 485 beam screen loops and on the 4 Inner Triplet cooling loops
  - LHC cryogenics is close to the optimal operation.
  - LHC cryogenics did not limit the LHC operation during the Run 2.

- In the future
  - **LHC Run 3** (2021-2023): beam intensities will be doubled with the same peak luminosity
    - ✓ Current strategies should be still valid
    - ✓ The maximum cryogenic capacity could be reached in several places if EC heat loads stay as it is

  - **HL-LHC** (From 2026): ARC cryogenic heat loads should be similar to Run 3 but the luminosity will be multiplied by a factor 3 in Inner Triplets.
    - ✓ Current strategies should be still valid for the ARC
    - ✓ The new Inner Triplets will have new dedicated cryogenic plants to manage their dynamic heat loads
      - ➔ Some cryogenic power will be recovered in the ARC around ATLAS and CMS