Beam screen cryogenic control improvements for the LHC run 2

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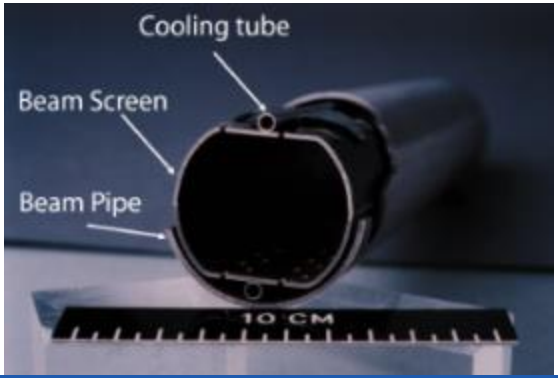
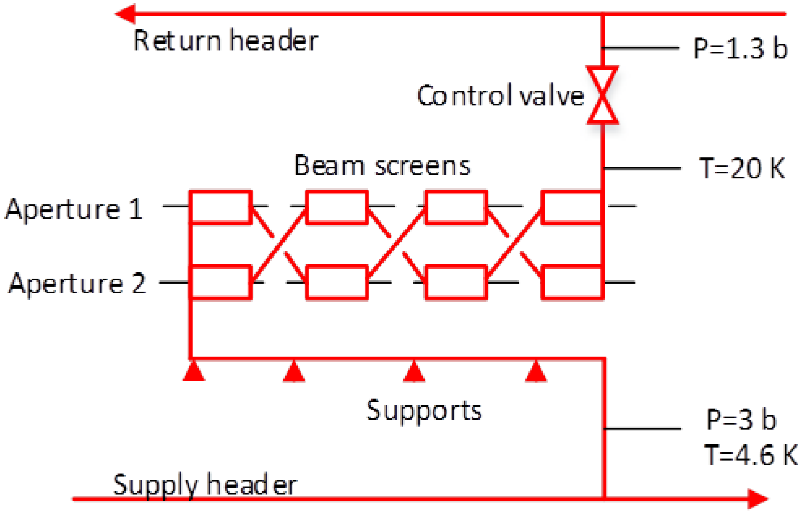
Introduction

- LHC Beam Screens
  - Ensure a good beam vacuum
  - Limit heat loads on the 1.9 K cold mass
  - Independent SC He cooling loop per half-cell (53 meters in arc)
  - 485 BS cooling loops over the 27 km of the LHC

- LHC beam screen heat loads between 4.5 K and 20 K
  - LHC Nominal Design: 85 W per half-cell
    - ✓ Synchrotron radiations: 18 W/half-cell
    - ✓ Image current: 19 W/half-cell
    - ✓ Electron cloud: 48 W/half-cell





LHC Run 1 Vs Run 2

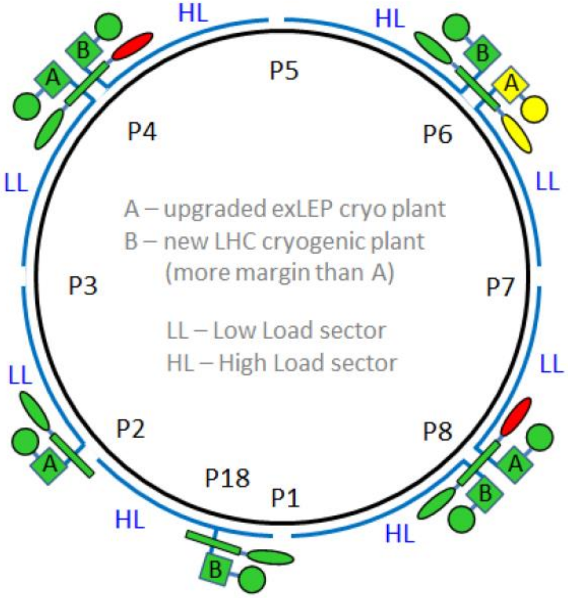
- **Run 1** (2010➔2012)
  - E = 4 TeV
  - Bunch number: ~1400 bunches (1/2 nominal)
  - Bunch spacing = 50 ns ➔ No electron clouds
  - Beam screen heat load ~ 10 W/hc in arc(but 100 W/hc in IT)

- **Run 2** (2015➔2018)
  - E = 6.5 TeV
  - Bunch number: ~2800 bunches (nominal)
  - Bunch spacing = 25 ns ➔ important electron clouds
  - Beam screen heat load ~ 85 W/hc expected in arc (lower in IT)
    - Up to 145 W/half-cell measured in 2015 with 2244 bunches !!

Beam screen and cryoplant constraints

- **Beam screen constraints**
  - Stable temperature around 20 K
    - Mini: 6 K/13 K (high/low flow) to avoid thermo-hydraulic oscillations
    - Maxi: 40 K during 30 min for vacuum (ideally below 30 K)

- **Cryoplant constraints**
  - 8 refrigerators over the 27 km
  - Refrigeration power is optimal for beam screens at 20 K
  - Refrigeration power for BS heat loads (4.5 K – 20 K)
    - Installed capacity = 116 W/hc
    - Run2: 160 W/hc thanks to less heat loads at 1.9 K
      - But limitation of 135 W/hc for S23 & S78 in 2015

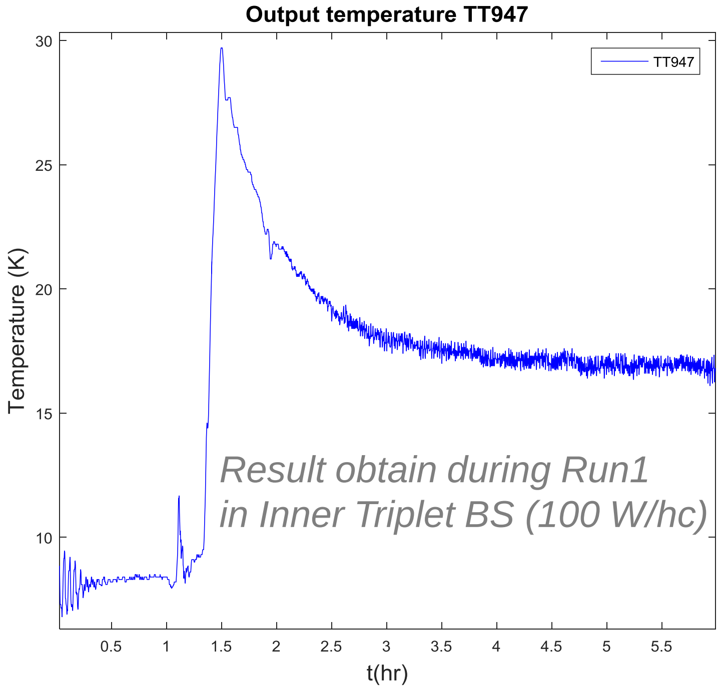


Beam screen dynamics

- Beam induced heat loads time constants
  - ✓ Beam injection: ~10 min (+5 min of delay)
  - ✓ Beam Dump: ~2 min (+5 min of delay)

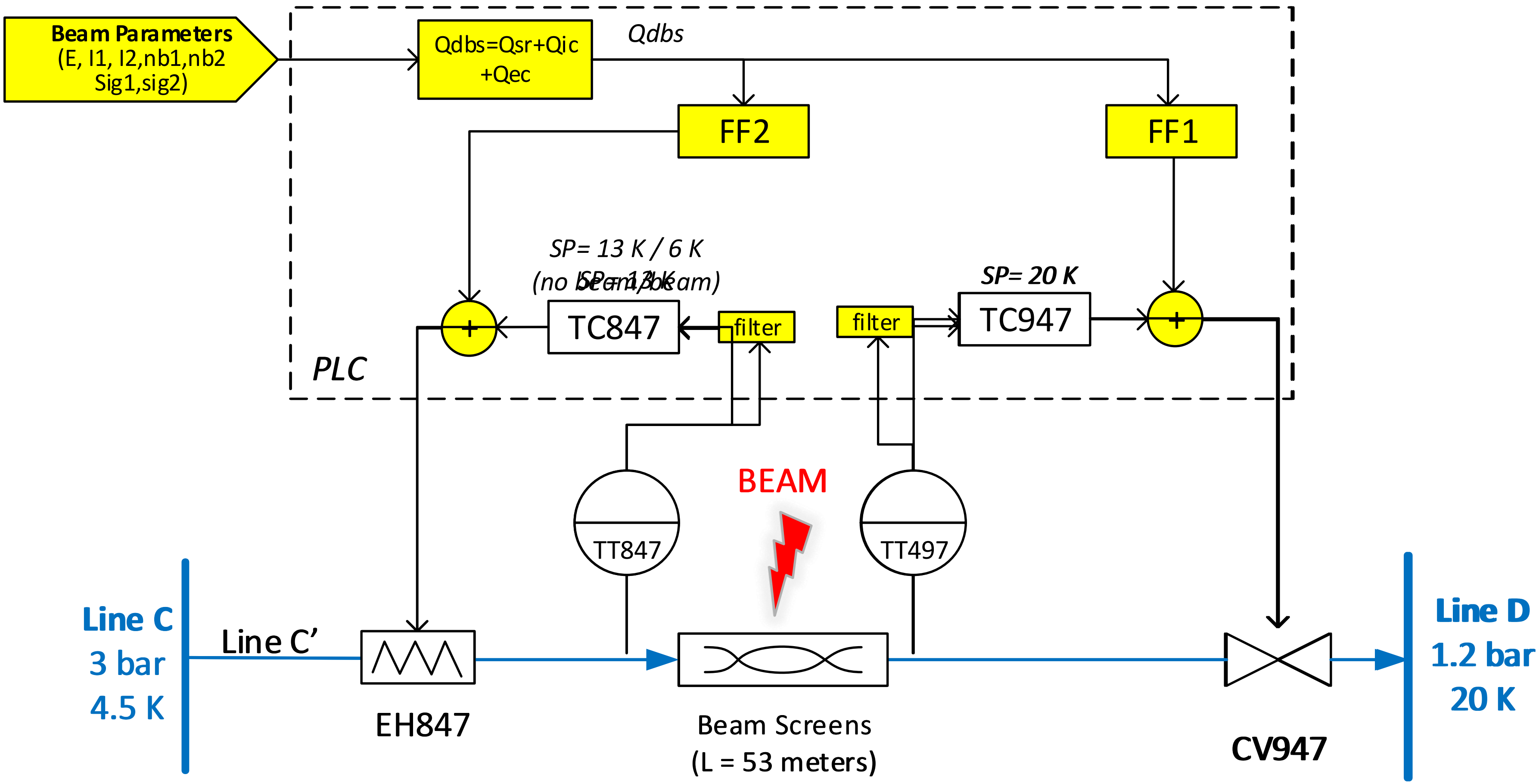
- Refrigerator time constants
  - ✓ HP adaptation: ~ 1 hour
  - ✓ Turbine power: ~20 min
  - ✓ Heater in phase separator: ~2 min

- Beam screen circuit time constants
  - ✓ Valve action: ~15 min (+5 min of delay)
  - ✓ Heater action: ~30 min (+10 min of delay)



- For Run 2:
  - ➢ Need a faster reaction for BS cooling
  - ➢ Need to minimize overshoot at beam injection and energy ramping
  - ➢ Need to optimize refrigeration power

LHC beam screen control scheme



Feed-Forward Design for the valve

Output temperature: $TT_{947} = P \cdot CV_{947} + D \cdot Q_{dbs}$

With: $P = \frac{K \cdot e^{-\tau \cdot s}}{1+T \cdot s}$ and $D = \frac{K_d \cdot e^{-\tau_d \cdot s}}{1+T_d \cdot s}$

➔ $TT_{947} = P \cdot TC_{947} \cdot e + P \cdot FF_1 \cdot Q_{dbs} + D \cdot Q_{dbs}$

To remove beam induced effect: $FF_1 = -D \cdot P^{-1}$

➔ $$FF_1 = -\frac{K_d}{K} \cdot \frac{(1 + T \cdot s) \cdot e^{(\tau - \tau_d) \cdot s}}{(1 + T_d \cdot s)}$$

After identification with real measurements performed in 2015 in arc half-cells:

K	T (s)	τ (s)	K_d	T_d (s)	τ_d (s)
0.8	960	300	0.2	40	250

➔ $$FF_1 \approx -\frac{(K_d/K)}{(1 + T_d \cdot s)}$$

(Similar approach is performed for the feed-forward action on the heater)

Beam Screen heat load estimation

$$Q_{dbs} = Q_{sr} + Q_{ic} + Q_{ec}$$

$$Q_{sr} = Q_{srnom} \cdot L \cdot \left(\frac{E}{E_{nom}}\right)^4 \cdot \left(\frac{Nb}{Nb_{nom}}\right) \cdot \left(\frac{nb}{nb_{nom}}\right)$$ (1) Synchrotron radiations

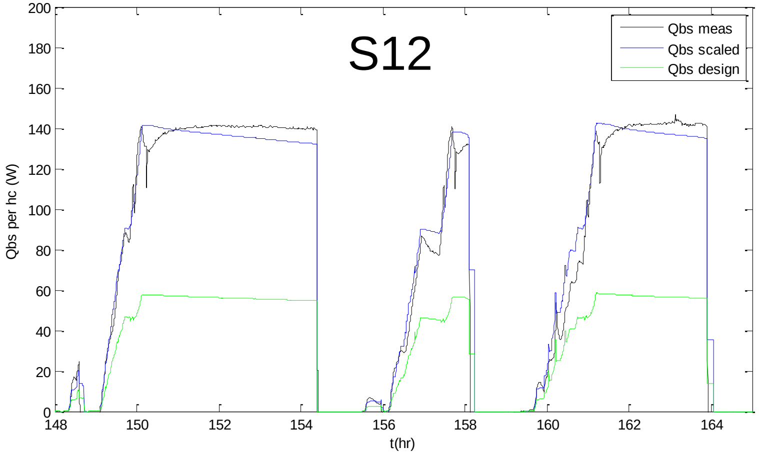
$$Q_{ic} = Q_{icnom} \cdot L \cdot \left(\frac{0.6 \cdot E + 2800}{E_{nom}}\right)^{0.5} \cdot \left(\frac{Nb}{Nb_{nom}}\right)^2 \cdot \left(\frac{nb}{nb_{nom}}\right) \cdot \left(\frac{\sigma}{\sigma_{nom}}\right)^p$$ (2) Image current

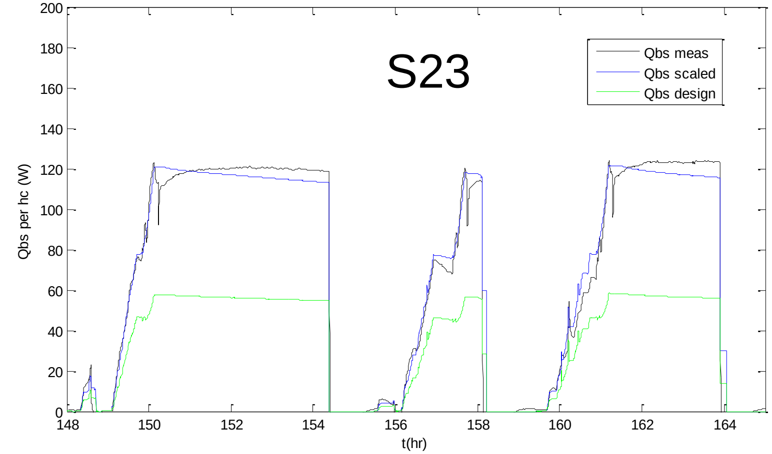
$$Q_{ec} = \left[K_{eci} \cdot \frac{q_{eci}}{2} \cdot \left(1 - \frac{E - E_{inj}}{E_{ramp} - E_{inj}}\right) + K_{ecr} \cdot \frac{q_{ecr}}{2} \cdot \left(\frac{E - E_{inj}}{E_{ramp} - E_{inj}}\right)\right] \cdot nb \cdot \frac{Nb}{Nb_{nom}}$$ (3) Electron cloud

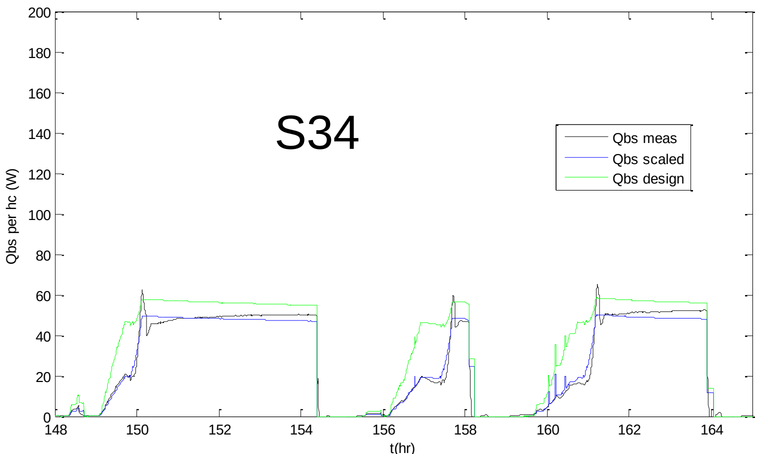
- SR and IC comes from LHC design reports and are OK with measurements
- EC mentioned in LHC design report is much lower than measurements
  - ✓ New EC equation based on physics
  - ✓ Equation scaled according to measurements in different sectors (qeci/qecr)
  - ✓ Equation scaled according to machine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

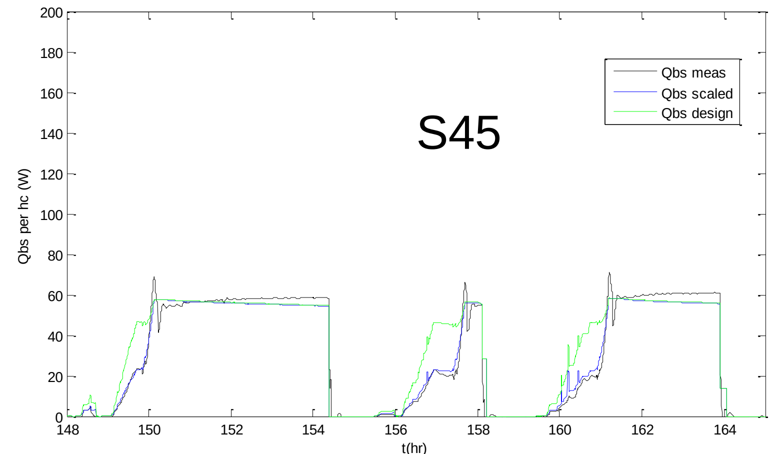
BS heat load estimation

Validation of scaling laws with LHC fills at the end of October 2015









BS heat load estimation

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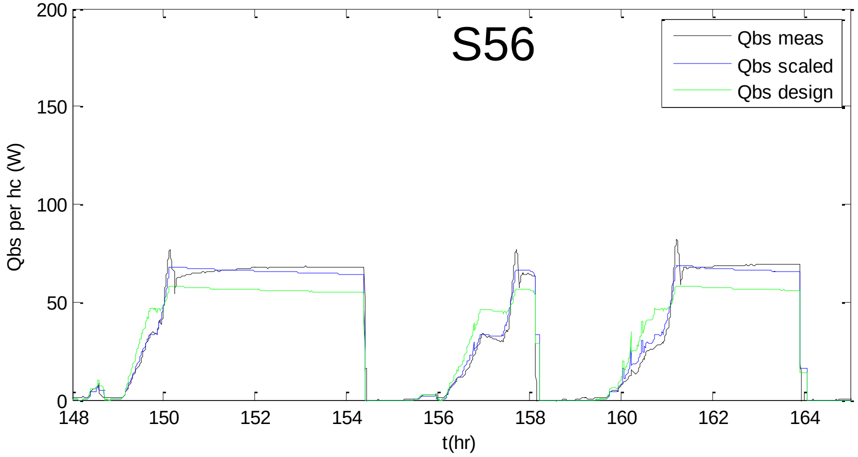
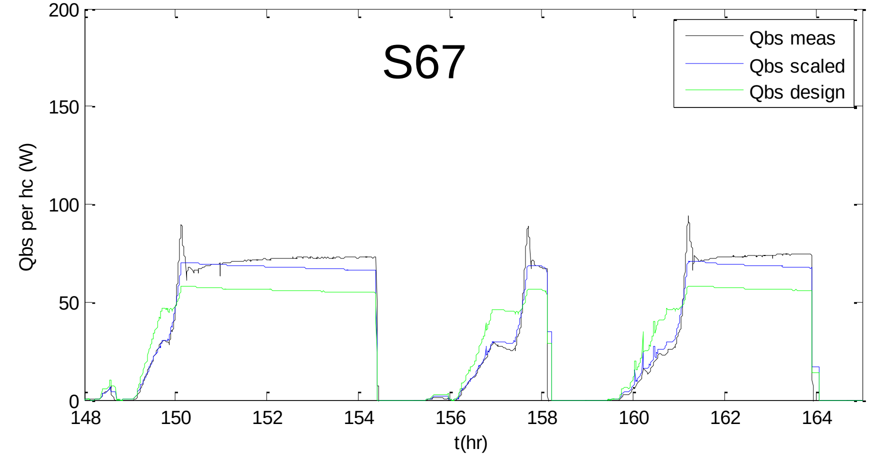
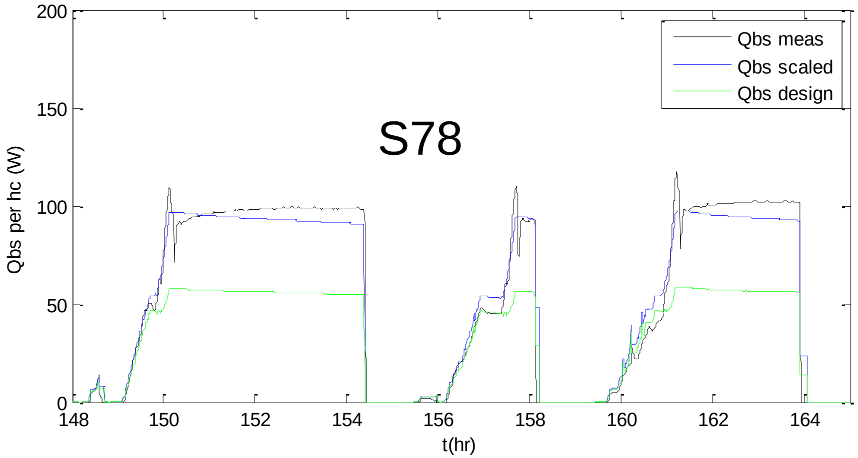
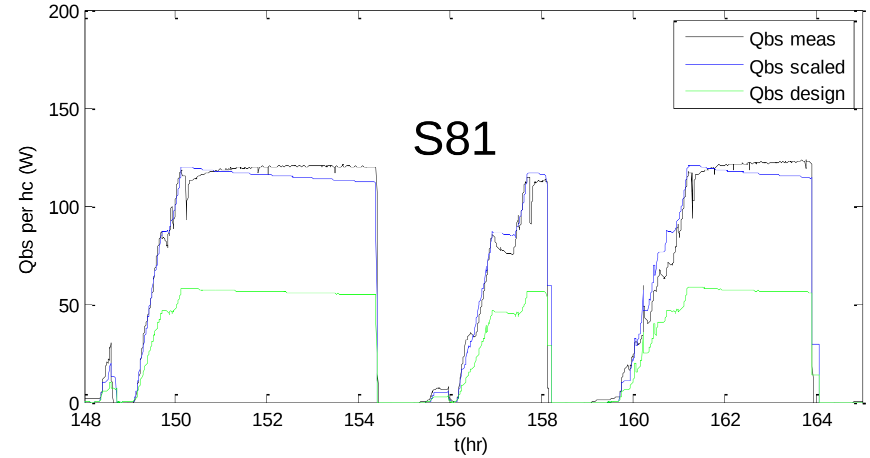
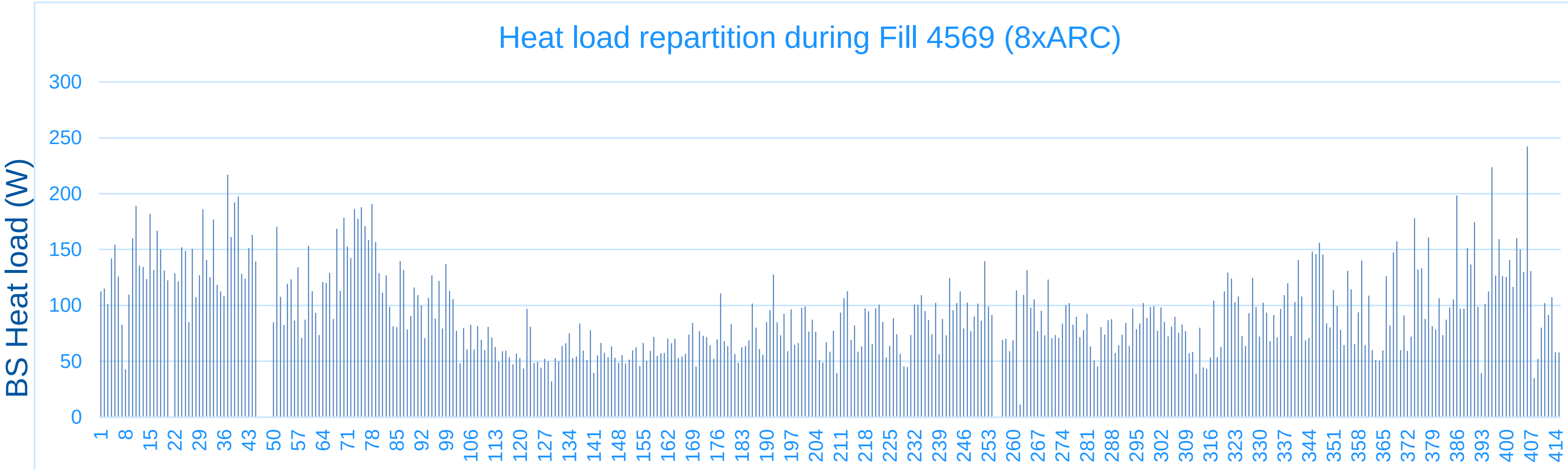


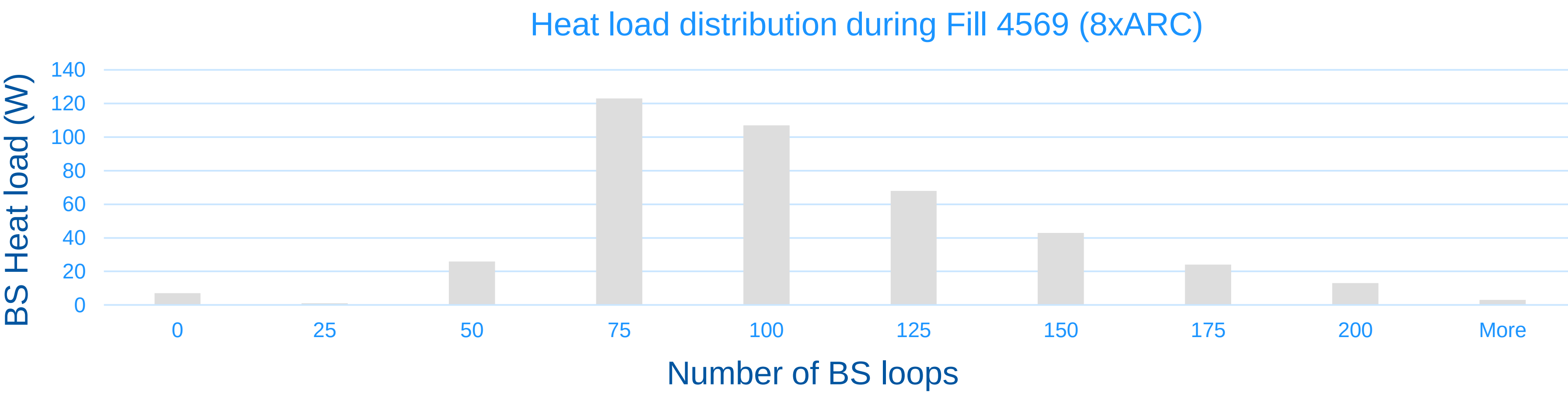






Heat Load repartition over LHC





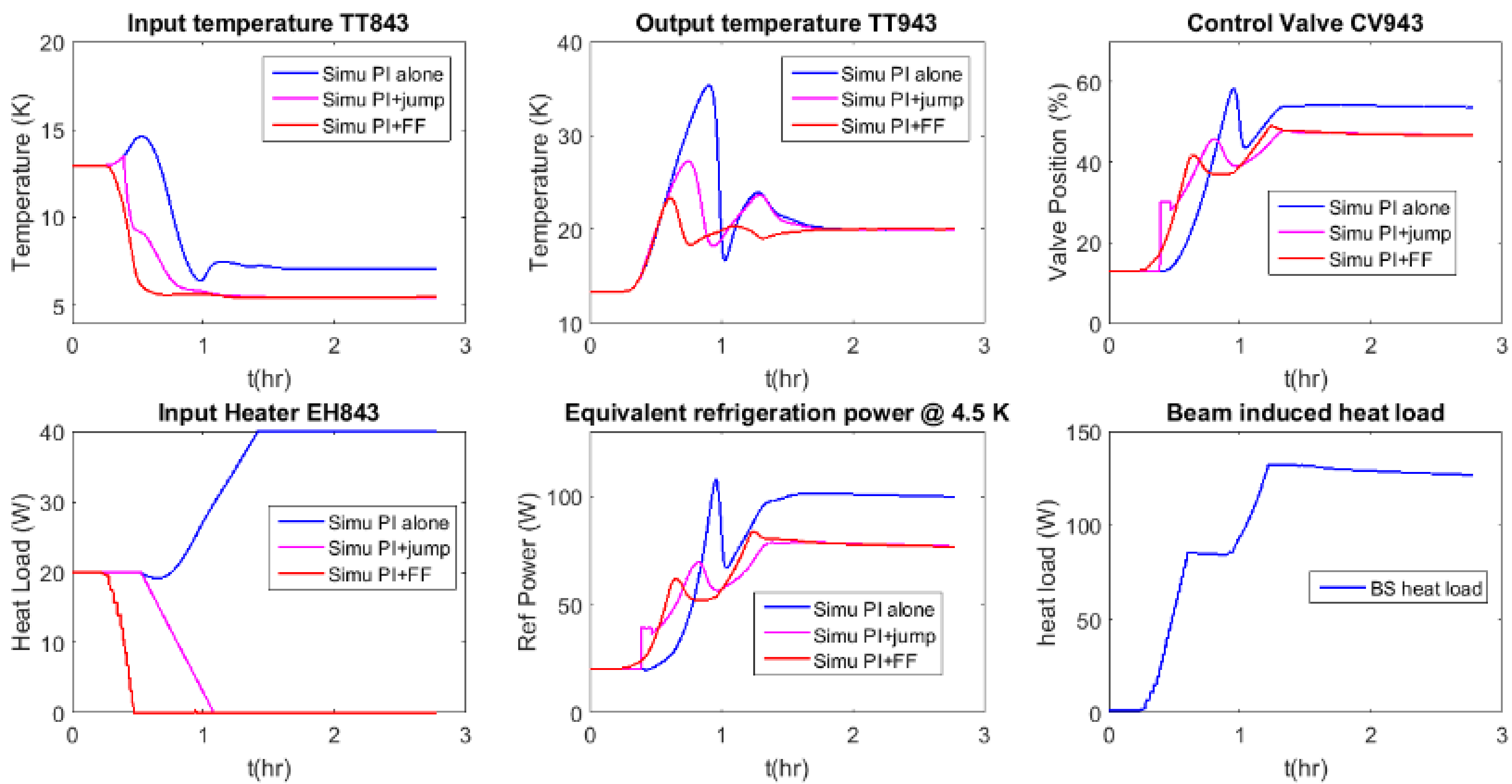
Feed-forward implementation

- 1 common feed-forward action for each ARC
  - From Q9 to Q9
  - 8 ARC in total

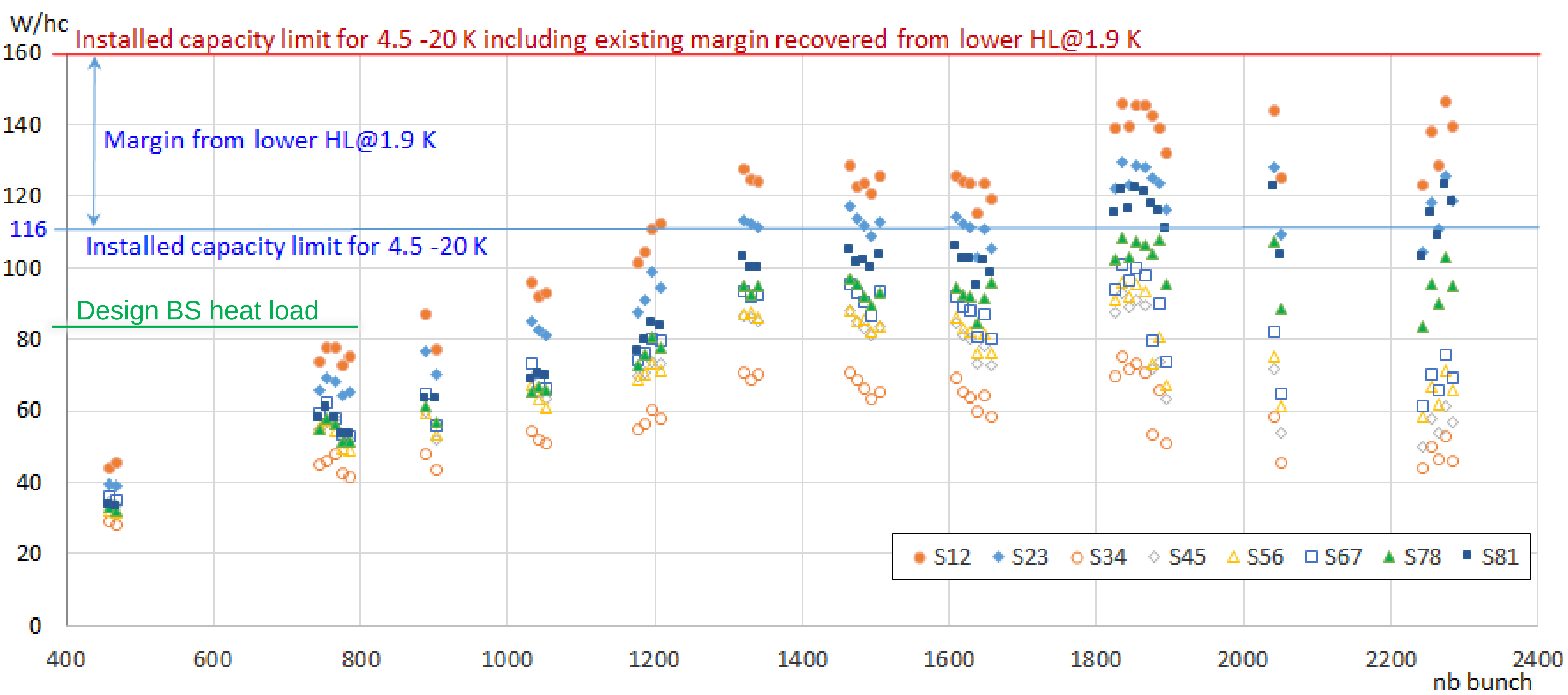
- 1 specific feed-forward action per LSS half-cell
  - From Q1 to Q7
  - 87 half-cells in total

Control validation in simulation

- Simulations performed with Ecosimpro and CRYOLIB library
- Model validation with real data obtained during the LHC Run 1
- Simulation for a heat load of 130 W per half-cell
- Comparison between 3 control schemes (PI alone / PI+jump / PI+FF)
- Validation of the feed-forward design

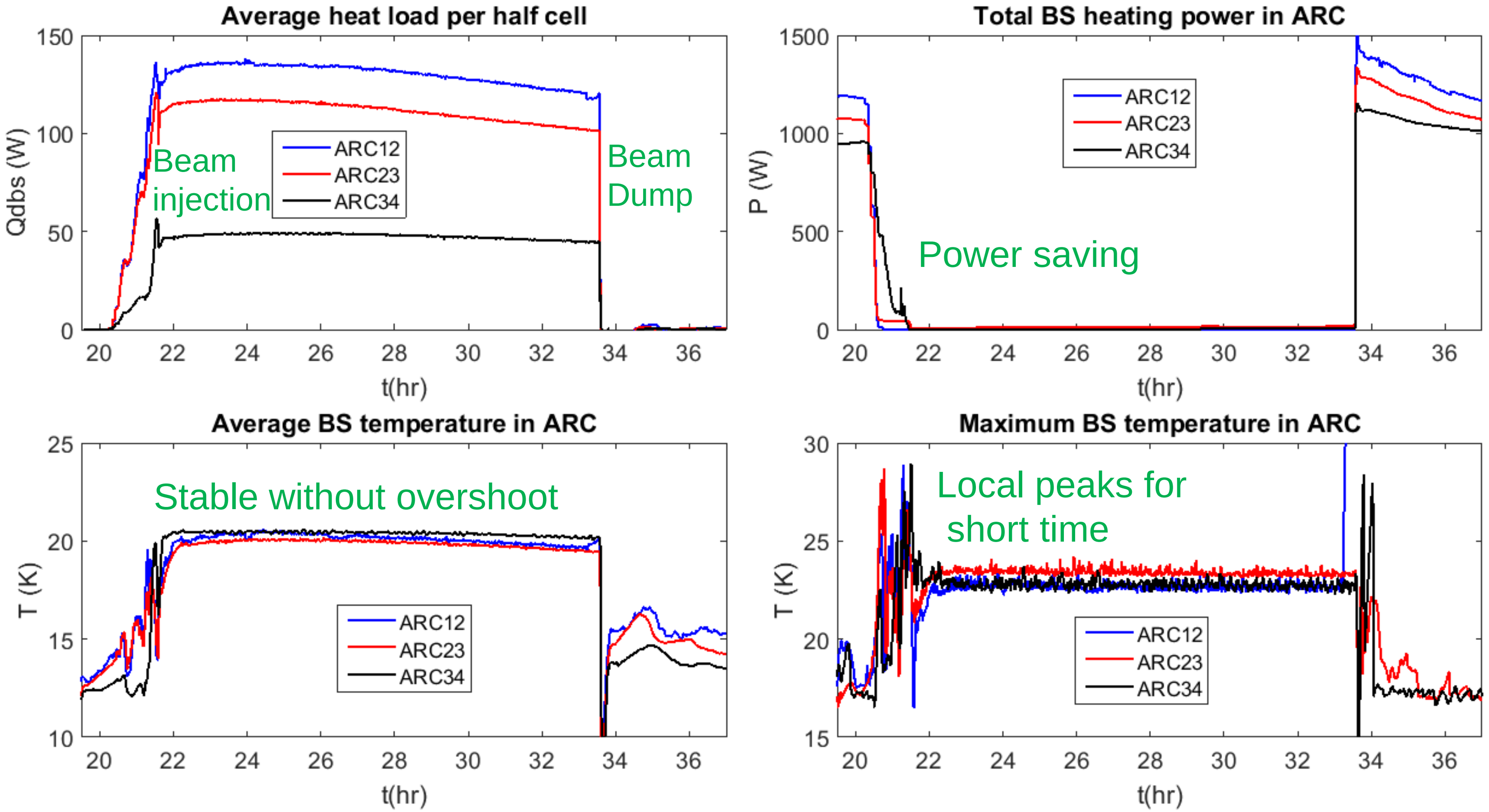


BS heat loads in Run2 (2015)



Results with improved control during LHC Run2 (2015)

- Results obtained during the LHC fill #4569 in November 2015 (2244 bunches @ 6.5 TeV)



Conclusion

- Electron clouds generate important dynamic heat loads in LHC
  - Up to 7.5 kW for 1 sector: equivalent 3.5 kW @ 4.5 K (20% of total installed refrigeration power)
- Classic feedback controllers cannot manage correctly the fast transients
  - Too important overshoot
  - Refrigeration power not optimized during transients
  - Instabilities
- Several new control schemes have been studied in simulation
  - Feed-forward actions on beam screen valves and heaters demonstrate good results
- The improved control scheme has been deployed in 2015
  - Temperature overshoot have been killed by the improved control scheme
  - Refrigeration power is optimized during transients
  - The LHC managed to reach 2244 bunches @ 6.5 TeV in 2015
- In 2016
  - Refrigeration power dedicated to BS should be increased to 160 W/hc over the LHC (S23/S78 to be confirmed)
  - Feed-forward control will be improved with a better estimation of the electron cloud heat loads based on 2015 measurements

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