Beam induced heat loads on HL-LHC Beam Screens

G. Iadarola with input from:
G. Arduini, D. Berkowitz Zamora, S. Claudet, P. Dijkstal, R. De Maria,
L. Mether, E. Metral, G. Rumolo, G. Skripka

HLLHC-TCC Meeting, 2 November 2017

Outline

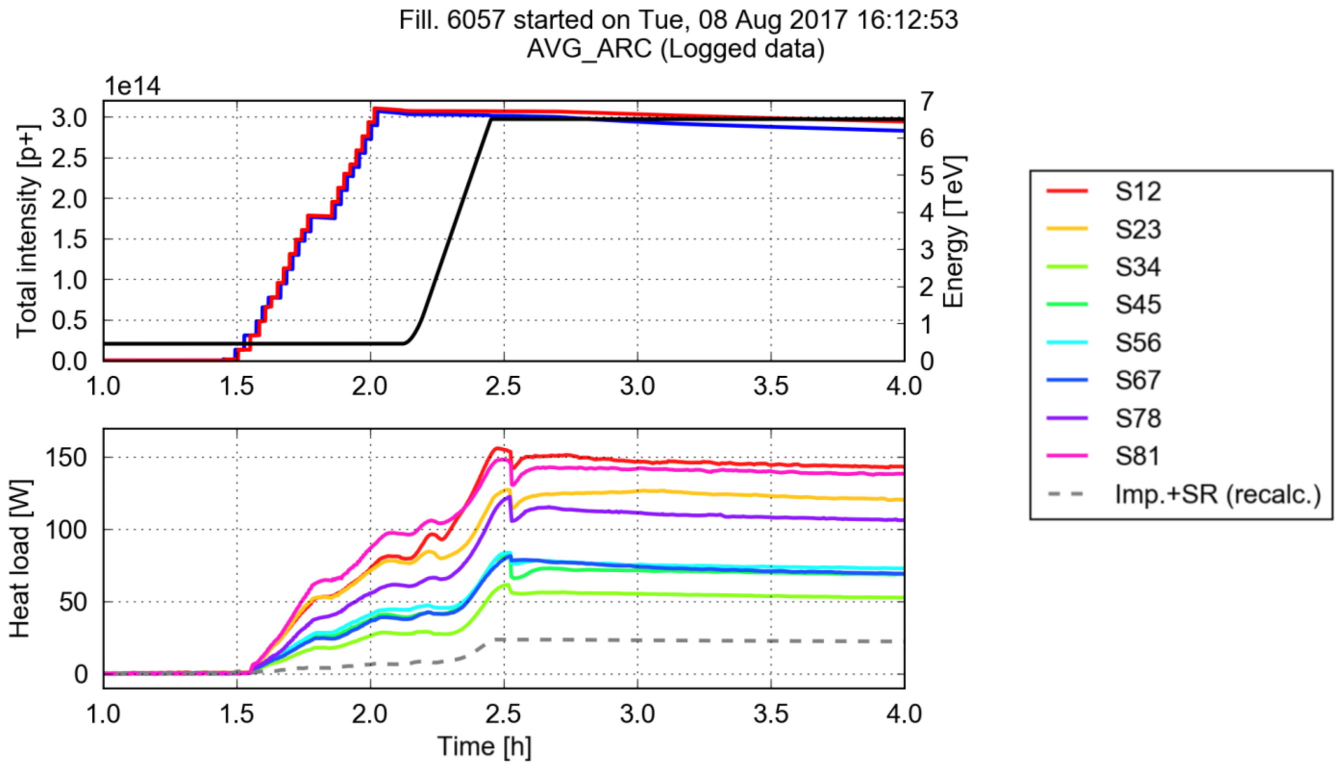
- **LHC experience**
- **Estimates for HL-LHC**
  - Arcs
  - Inner triplets
  - Other LSS magnets
- **Backup scenario: 8b+4e scheme**

Outline

- **LHC experience**
- **Estimates for HL-LHC**
  - Arcs
  - Inner triplets
  - Other LSS magnets
- **Backup scenario: 8b+4e scheme**

A **challenge for LHC operation with 25 ns in Run 2**: total load on the cryo-plants dominated by beam induced heating on arc beam screens

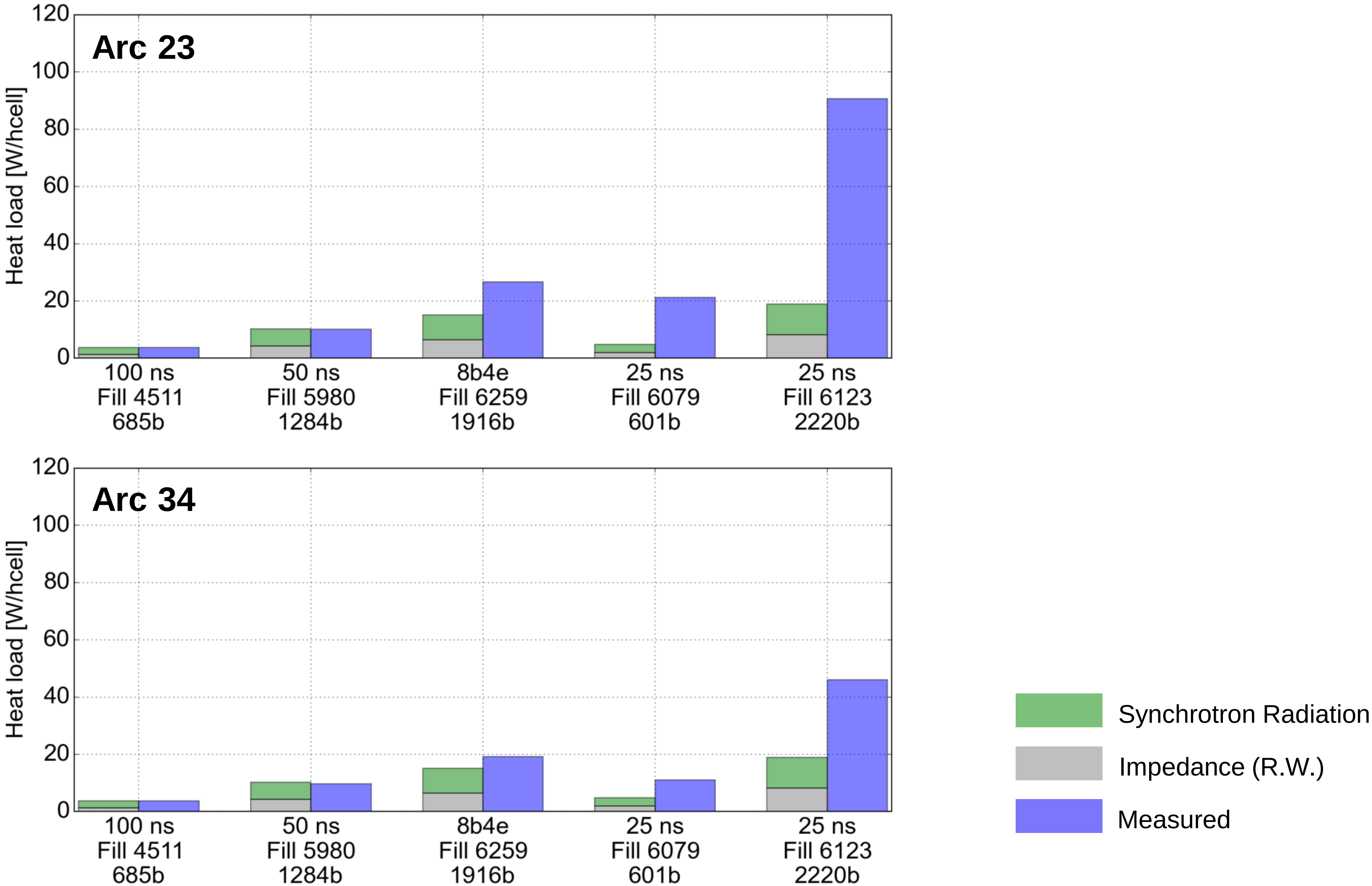
- Much **larger** than expected from **impedance and synchrotron radiation**
- Large **differences observed between sectors**
- Several observed features compatible with **e-cloud effects**
- Being followed-up by dedicated **Task Force** led by L. Tavian



More info can be found here

LHC experience: dependence on bunch pattern

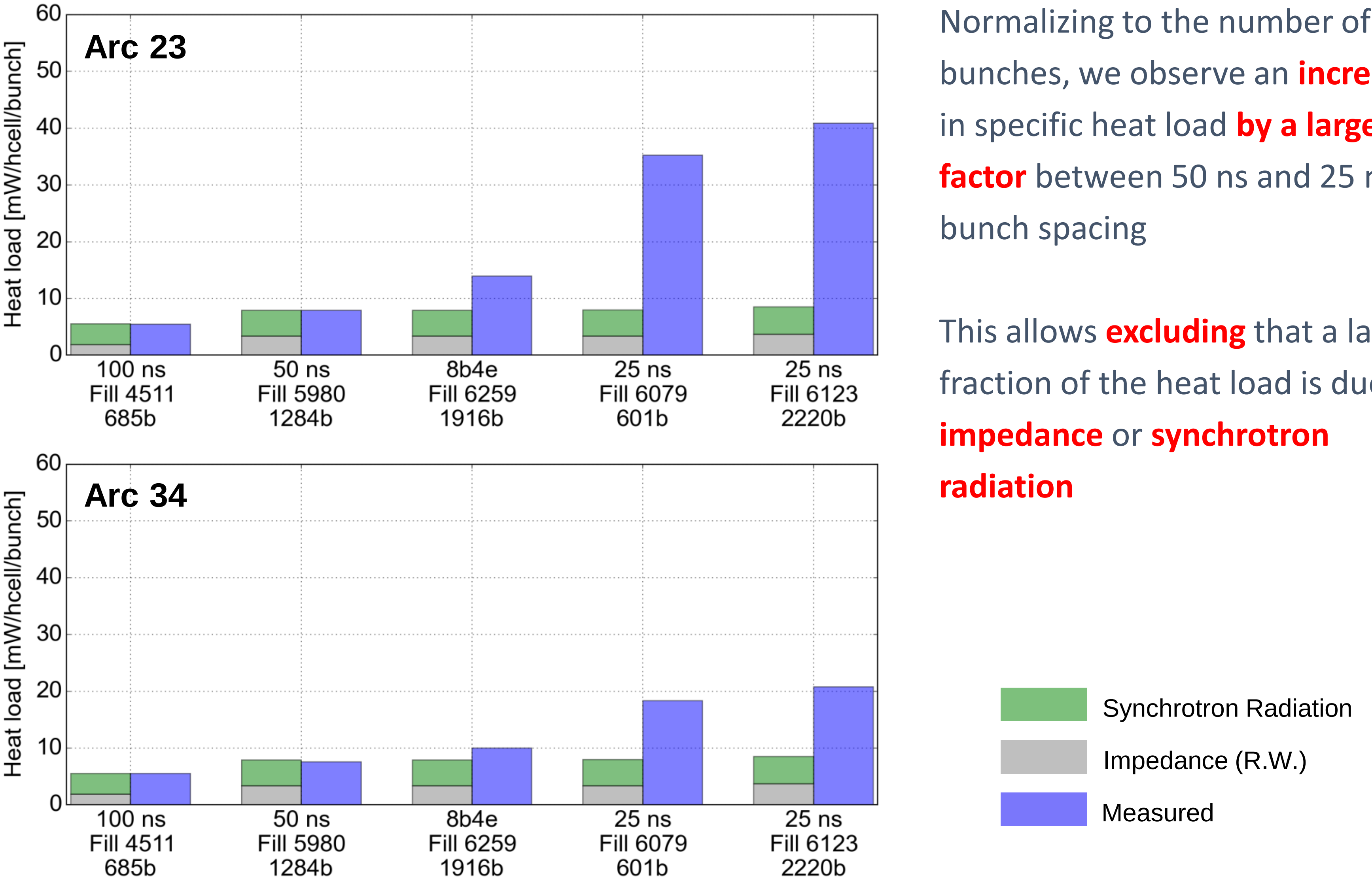
A strong dependence on the **bunch spacing** is found



More info can be found here

LHC experience: dependence on bunch pattern

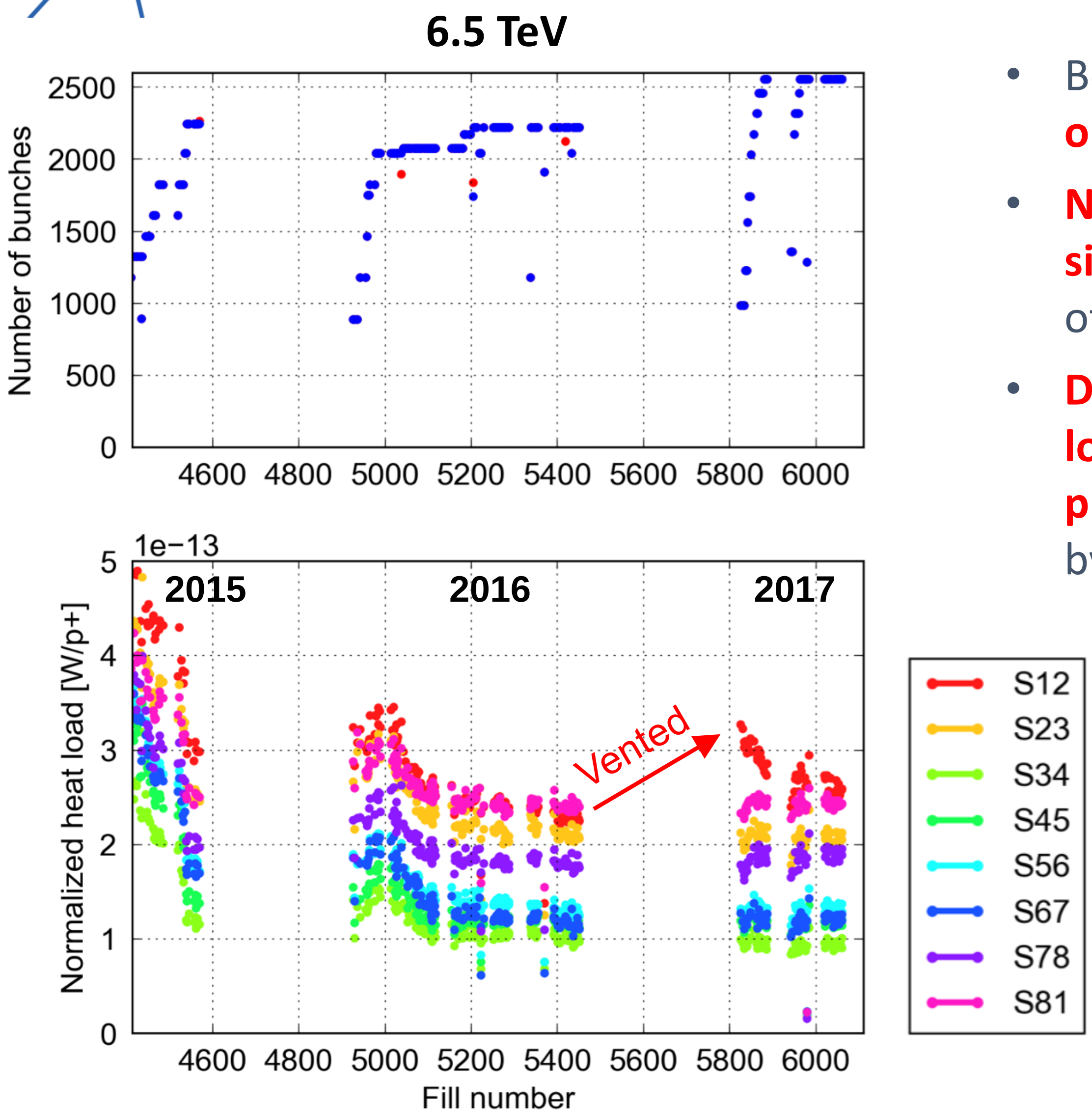
A strong dependence on the **bunch spacing** is found



Normalizing to the number of bunches, we observe an **increase** in specific heat load **by a large factor** between 50 ns and 25 ns bunch spacing

This allows **excluding** that a large fraction of the heat load is due to **impedance** or **synchrotron radiation**

LHC experience: evolution during Run2



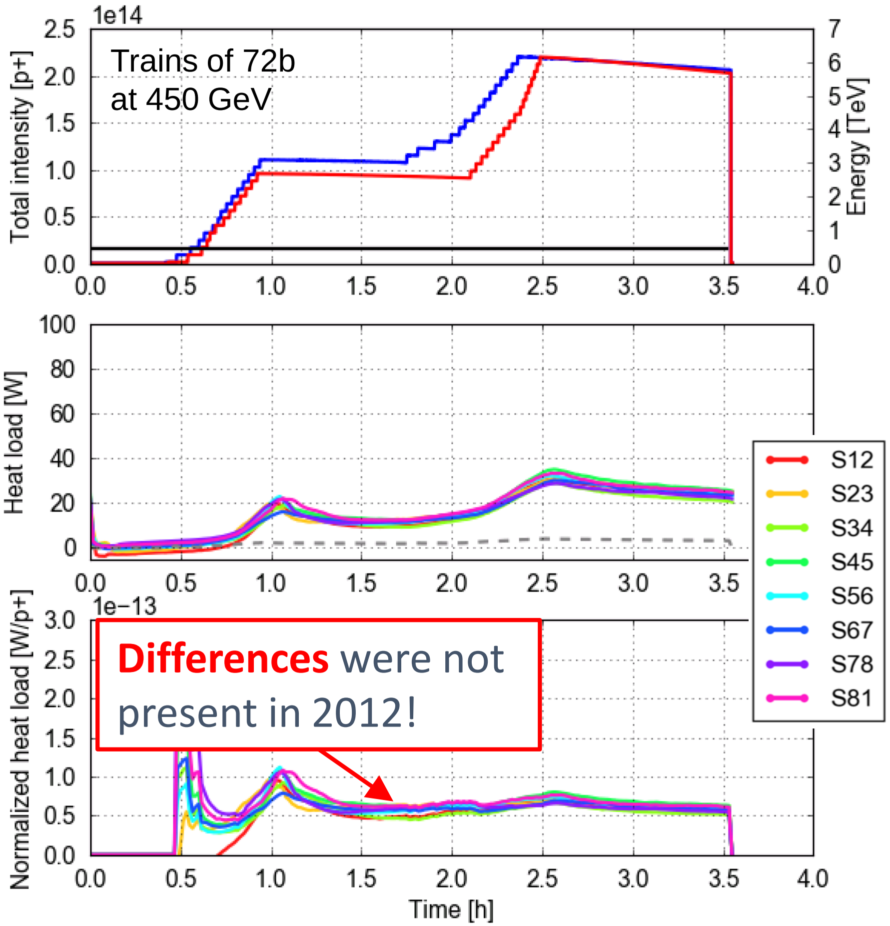
- Beam induced **scrubbing was observed at the beginning of Run 2**
- **No significant evolution is observed since mid 2016** (with the exception of S12 vented in the EYETS 2016-17)
- **Differences in normalized heat loads among sectors stayed practically unchanged** (unaffected by scrubbing)

More info can be found here

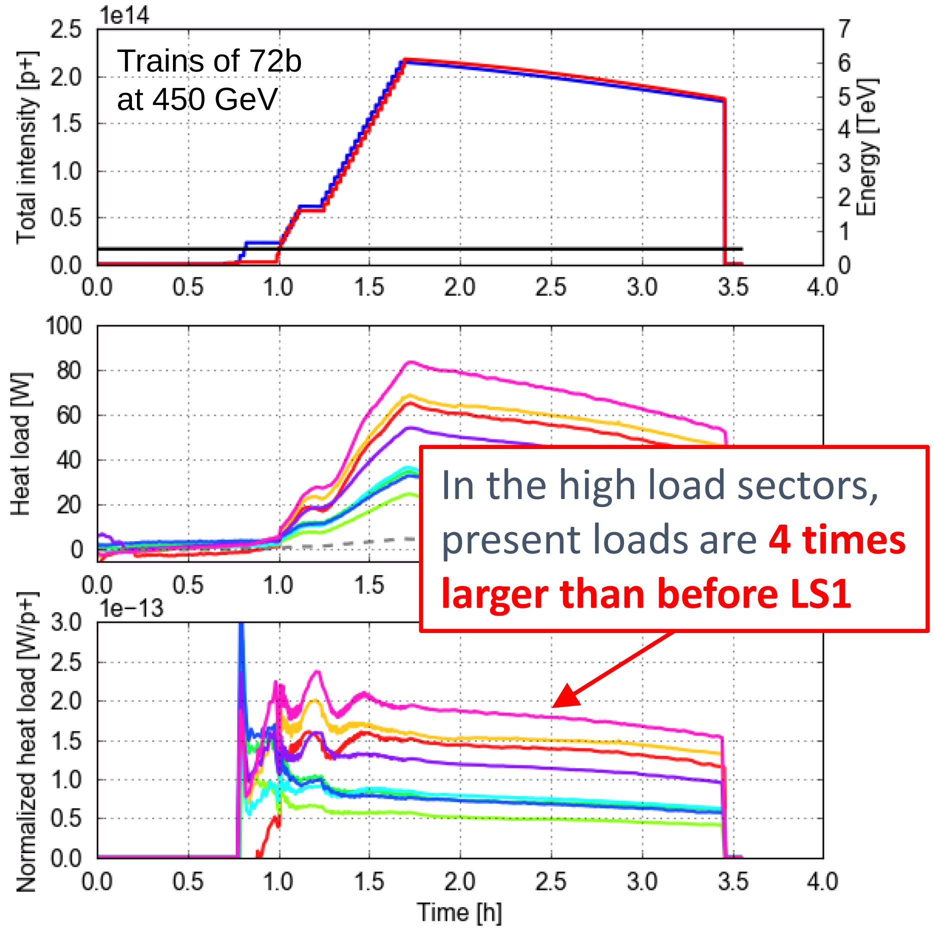
LHC experience: before and after LS1

- We used the raw data recorded during tests with 25 ns in 2012 at that time to **reconstruct the cell-cy-cell heat load** → can be directly compared with Run 2 data

2012 (after 3 d of scrubbing at 450 GeV)



2017 (after 7 d of scrubbing at 450 GeV)



- It is **fundamental to avoid further degradation** in view of HL-LHC

More info can be found here

Outline

- **LHC experience**
- **Estimates for HL-LHC**
  - Arcs
  - Inner triplets
  - Other LSS magnets
- **Backup scenario: 8b+4e scheme**

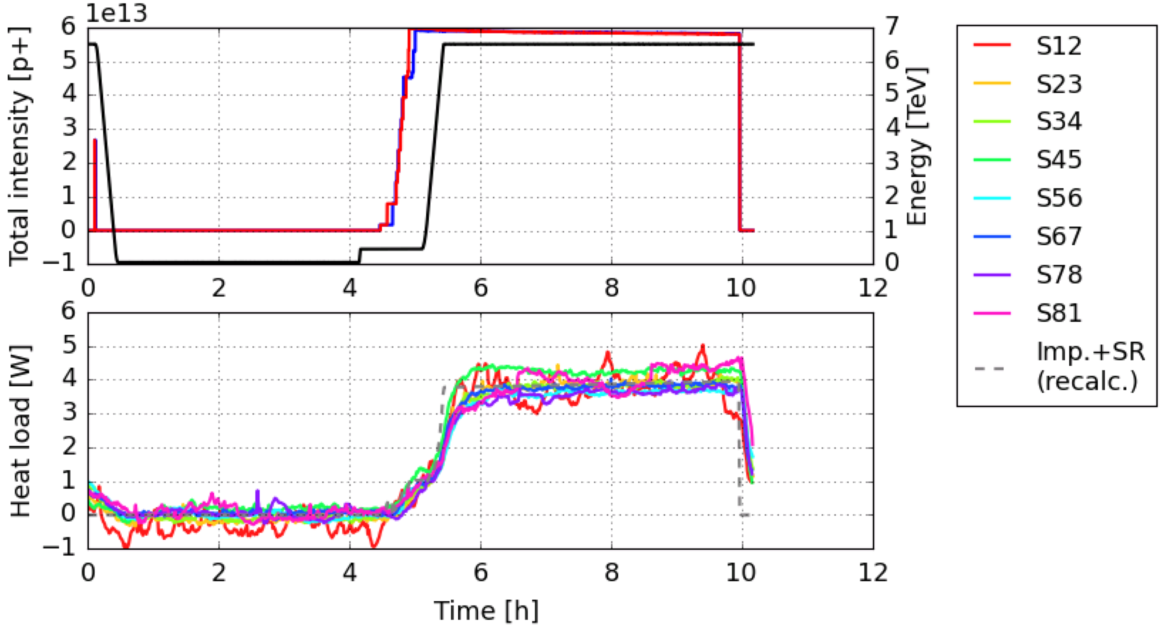
Heat load estimates for HL-LHC

Collaboration between WP2 and WP9 to build a **full inventory** of expected beam induced heating on the beam screens for HL-LHC:

- Effects taken into account:
  - **Synchrotron radiation** (analytic estimates, relevant only for the arcs)
  - **Impedance heating** (analytic estimate, taking into account effect of temperature, magnetic field, longitudinal weld)
  - **Electron cloud effects** (based on numerical simulations)

Estimates **crosschecked** against studies done at the time of the LHC design and against machine observations

Bunch spacing: 100 ns (2015)

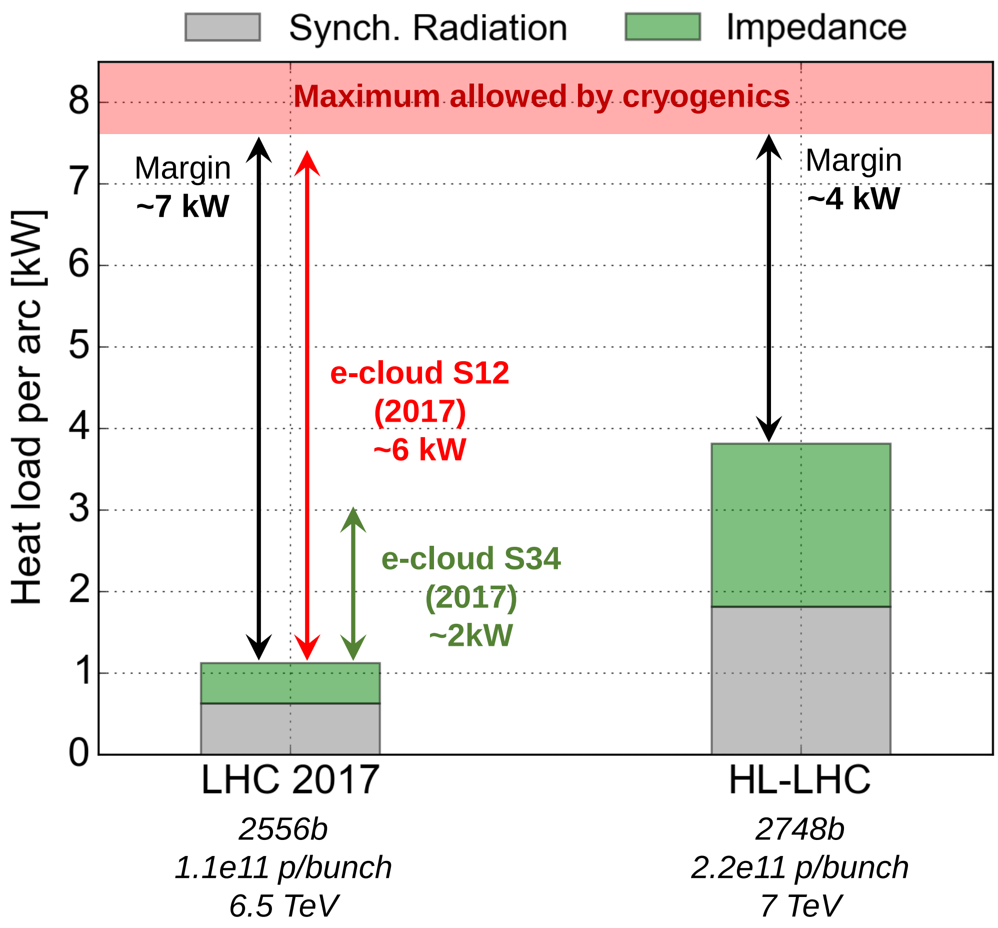


Outline

- LHC experience
- **Estimates for HL-LHC**
    - Arcs
    - Inner triplets
    - Other LSS magnets
- Backup scenario: 8b+4e scheme

Arc heat loads from impedance and synchrotron radiation

- In **Run 2** configuration: small contributions from **impedance and synchrotron radiation** → used large available **margins to cope with e-cloud**
- When moving to **larger beam intensities** (and to 7 TeV) the **margin reduces strongly**

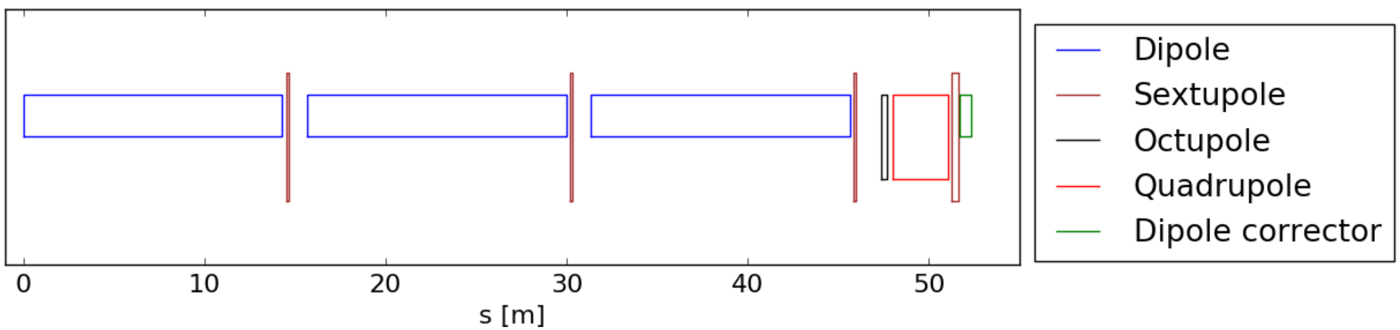


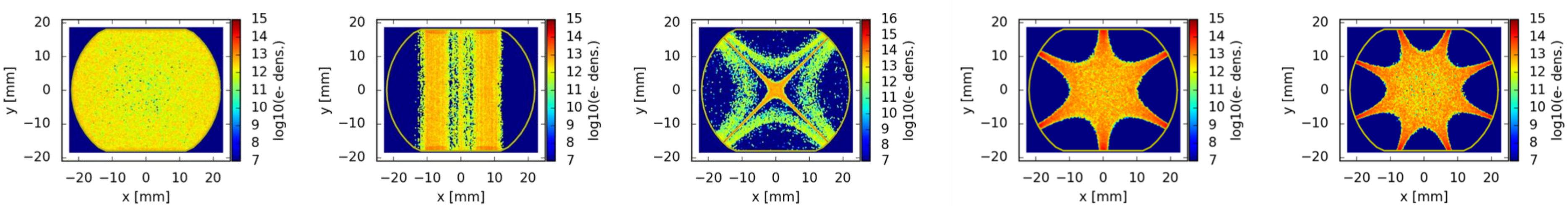
Arc heat loads from e-cloud – the model

Estimates for the arcs are **more delicate** than for IRs due to the important **role of photoelectrons** generated by the beam **synchrotron radiation**

Decided to focus on the present LHC at first to develop a **solid model** to be then applied for HL-LHC predictions (performed **literature review** to identify the best available knowledge on **photoelectron yield for the LHC beam screens,** correctly handling the effect of the saw-tooth)

The defined models have been used to simulate the **relevant element of the arc half-cell**



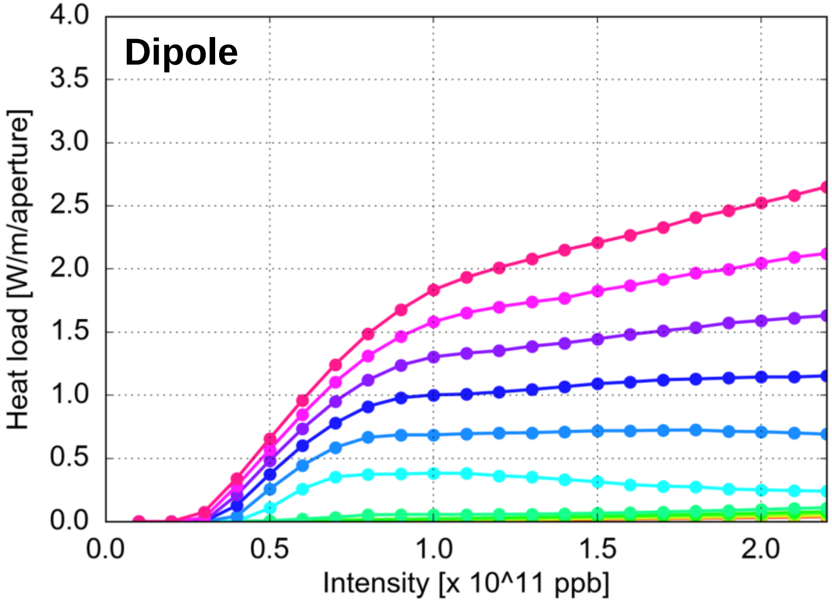


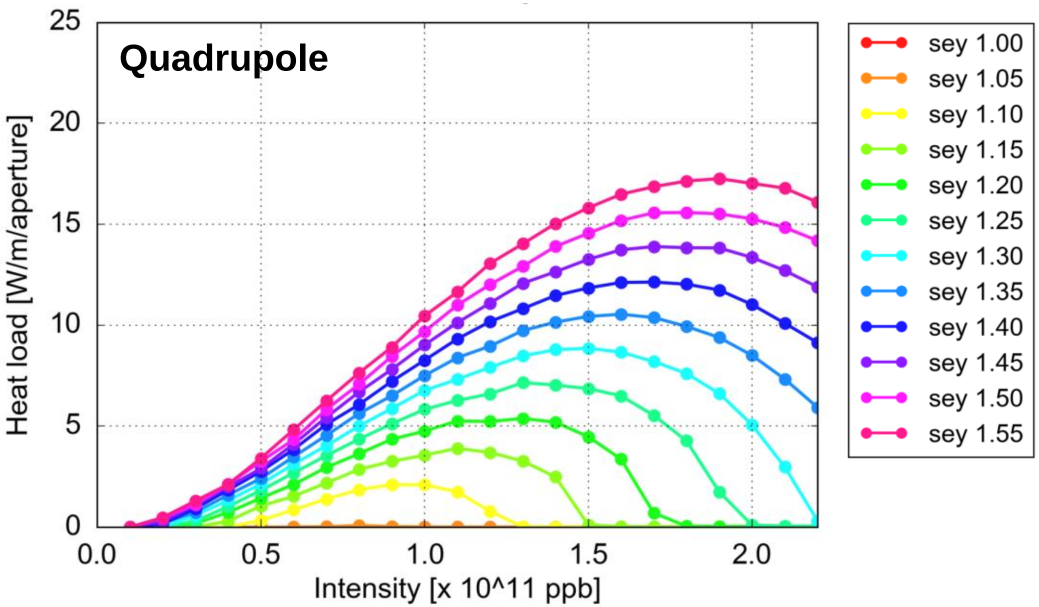
Details in P. Dijkstal et al., "Simulation studies on the electron cloud build-up in the elements of the LHC Arcs at 6.5 TeV", [*CERN-ACC-NOTE-2017-0057*]

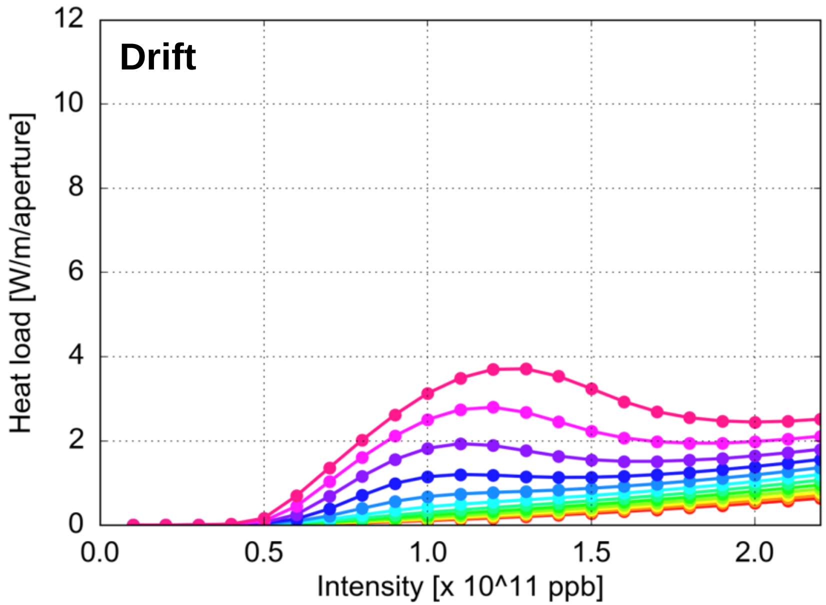
Arc heat loads – effect of bunch intensity

Assessed with PyECLOUD simulations:

- The **dependence** of the heat load **on the bunch intensity** strongly depends on the **surface properties** (SEY parameter)
- The expected dependence on the bunch intensity is **strongly non linear**
- Full **experimental validation** of these curves **possible only after LS2**



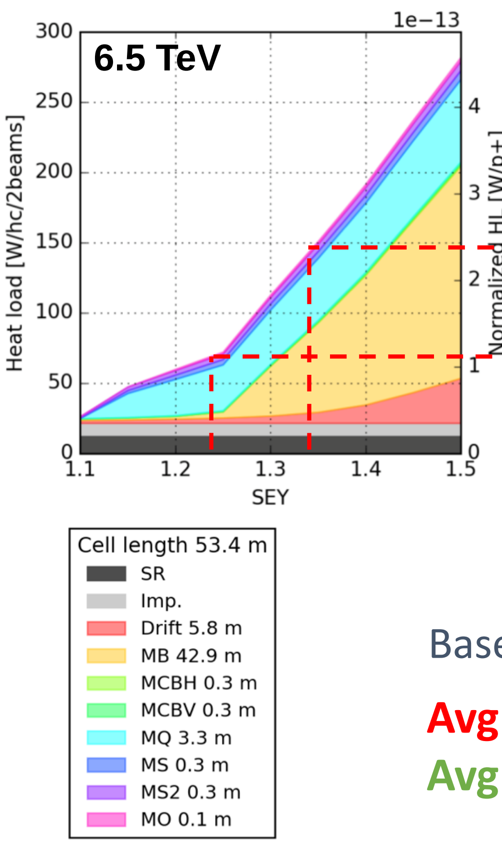




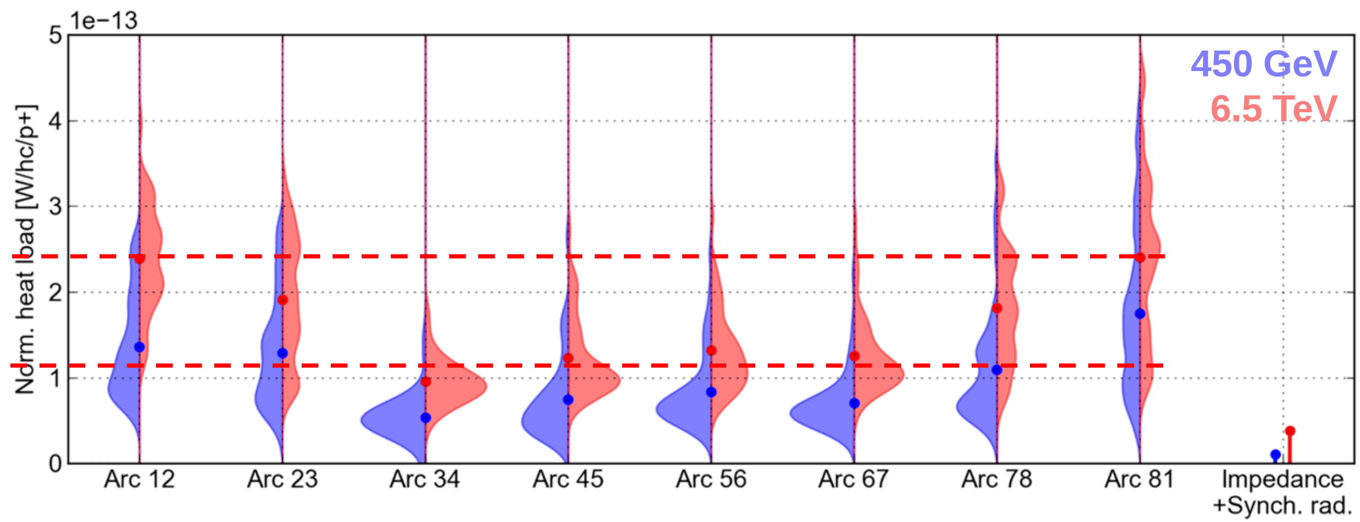
SEY estimates for present LHC

SEY estimates can be made by comparing **heat load measurements** against simulations for LHC beam parameters (assuming uniform SEY over each half cell)

Simulations



Measurements

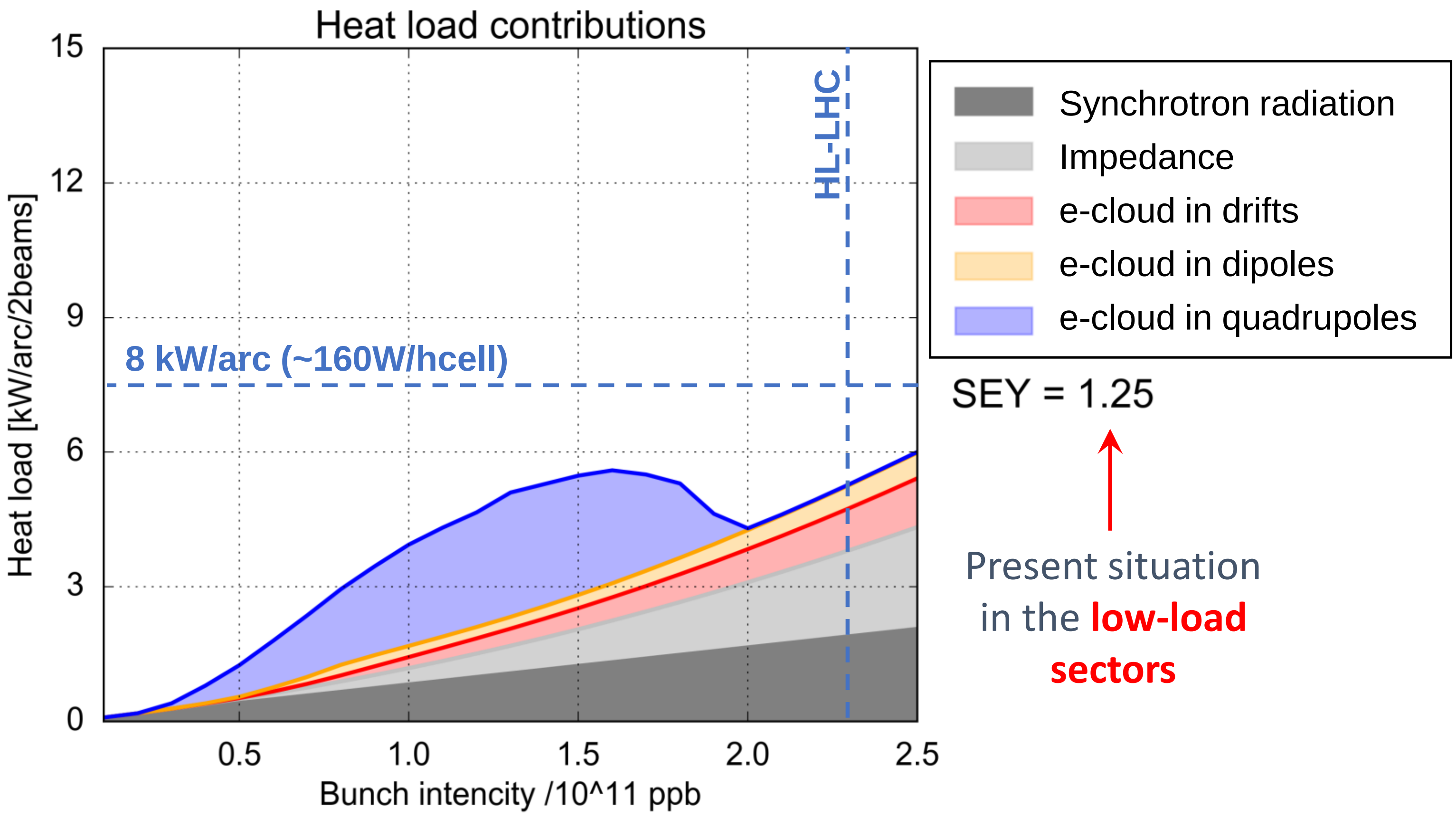


Based on these assumptions:

Avg. high load sectors (S12, S81): SEY = ~1.35

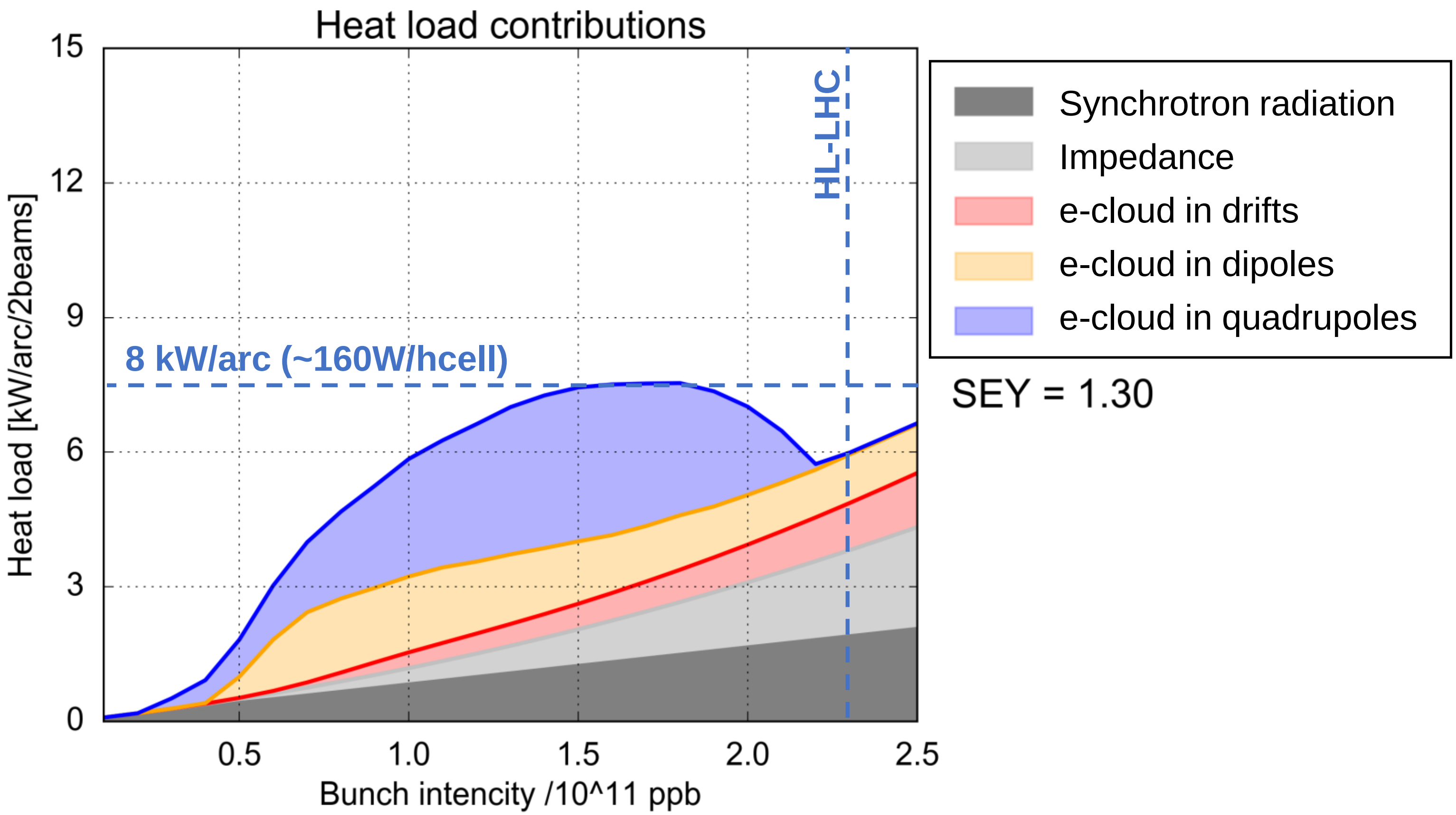
Avg. low load sectors (S34, S45, S56, S67): SEY = ~1.25

Arc heat loads: simulations for HL-LHC



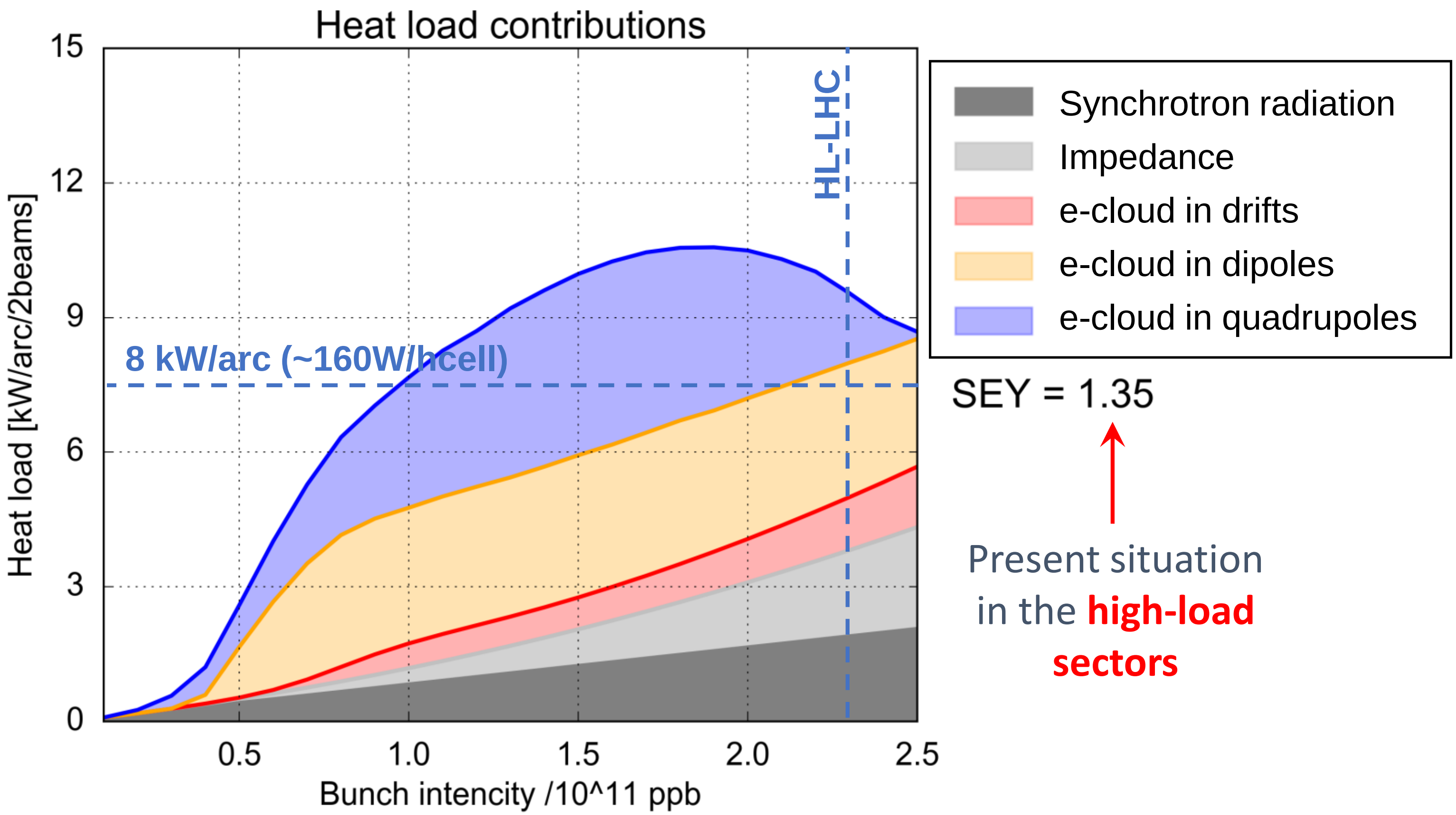
- For high bunch intensity **significant heat load is observed already for low SEY** (from impedance, synchrotron radiation, photoelectrons in the drifts)
- Present conditioning achieved in the **low-load sectors** is **compatible with HL-LHC**

Arc heat loads: simulations for HL-LHC



- For high bunch intensity **significant heat load is observed already for low SEY** (from impedance, synchrotron radiation, photoelectrons in the drifts)
- Present conditioning achieved in the **low-load sectors** is **compatible with HL-LHC**

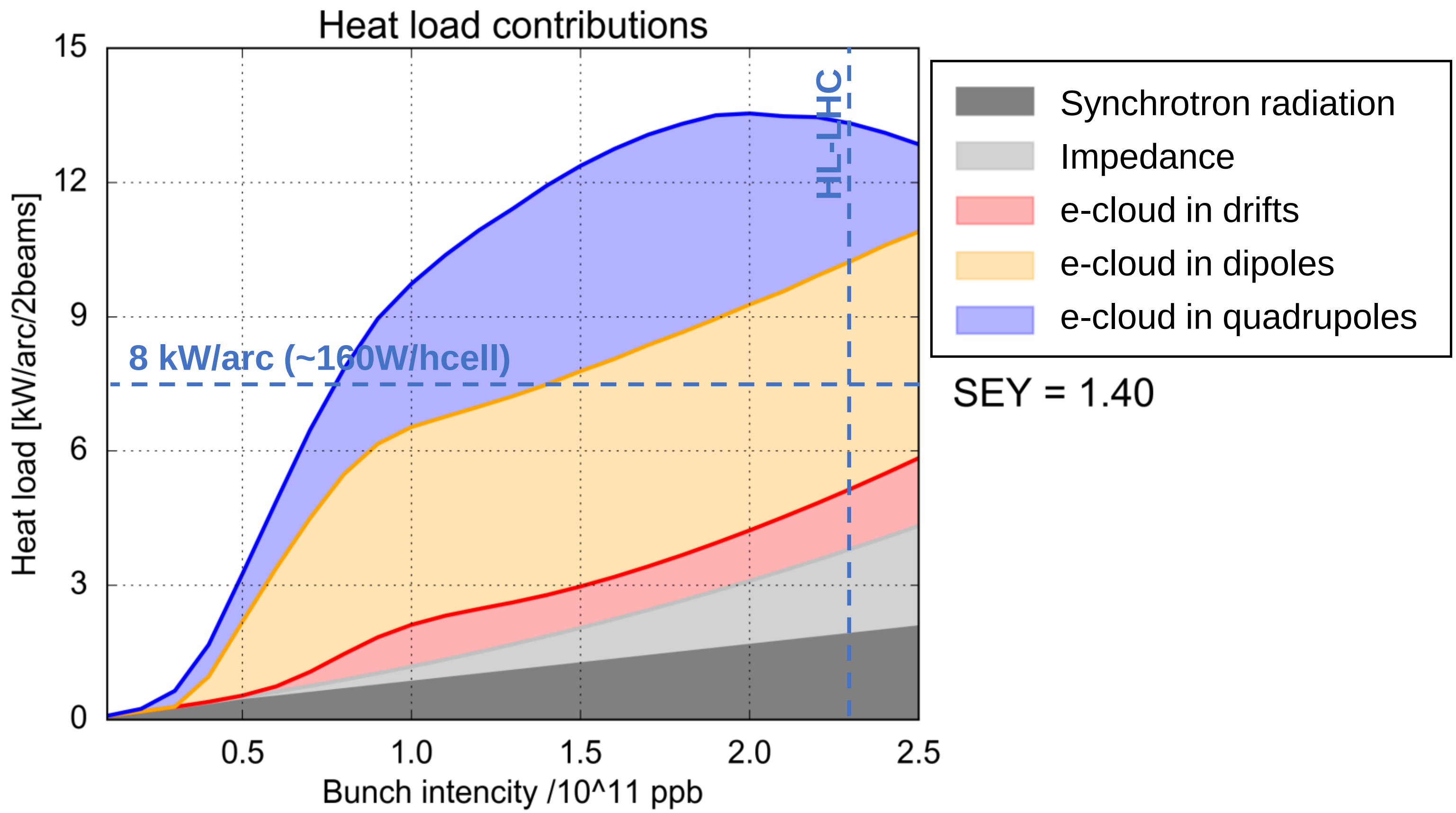
Arc heat loads: simulations for HL-LHC



- For high bunch intensity **significant heat load is observed already for low SEY** (from impedance, synchrotron radiation, photoelectrons in the drifts)
- Present conditioning achieved in the **low-load sectors** is **compatible with HL-LHC**
- Expected heat load for the **high-load sectors** is **~10 kW/arc → not acceptable for HL-LHC**

  → Ongoing work to identify and suppress the source of differences among arcs is very important for HL-LHC

Arc heat loads: simulations for HL-LHC



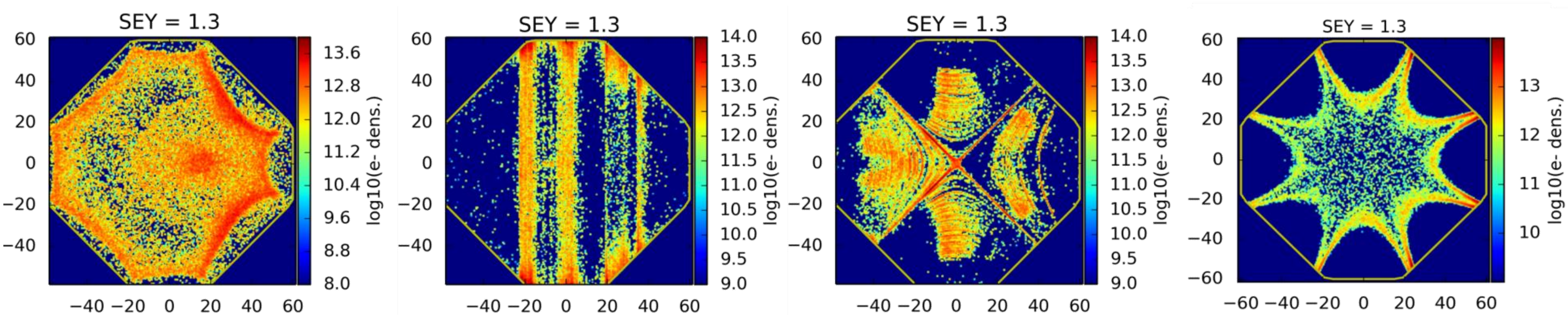
- For high bunch intensity **significant heat load is observed already for low SEY** (from impedance, synchrotron radiation, photoelectrons in the drifts)
- Present conditioning achieved in the **low-load sectors** is **compatible with HL-LHC**
- Expected heat load for the **high-load sectors** is **~10 kW/arc → not acceptable for HL-LHC**

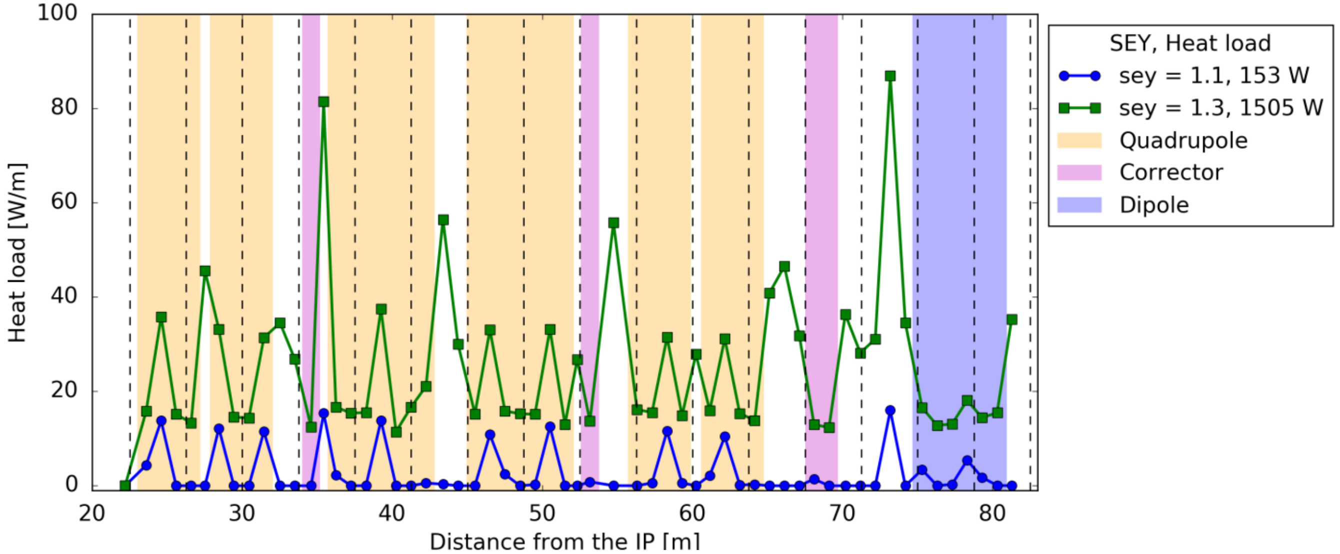
  → Ongoing work to identify and suppress the source of differences among arcs is very important for HL-LHC

Outline

- LHC experience
- **Estimates for HL-LHC**
  - Arcs
  - Inner triplets
  - Other LSS magnets
- Backup scenario: 8b+4e scheme

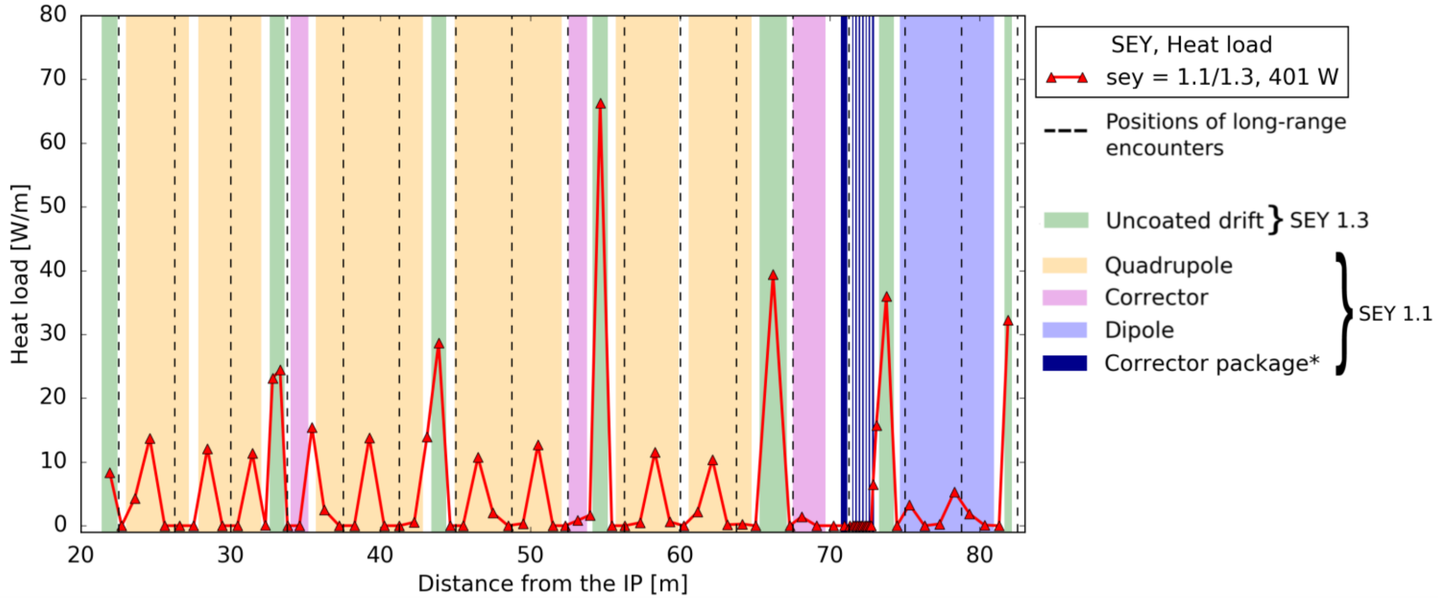
- **Impedance** heating: estimated taking into account impact of magnetic fields and temperature (assumed to be 70 K for IP1&5 and 20 K for IP2&8)
- **e-cloud** heating: studied with macroparticle simulations:
  - e-cloud mitigation by **surface treatment (a-C coating) is foreseen**
  - **Baffle plates** (with low SEY) will be installed behind the pumping slots to avoid direct impacts of the electrons on the cold bore
  - Heavy simulation studies: device needs to be sliced to take into account different time of arrivals, transverse positions and sizes of the two beams





Coating with SEY<1.1 **provides a strong heat load reduction**

- To asses the impact of having short uncoated sections (bellows, BPMs) we simulated the case in which **all sections outside the cold masses have SEY_{max} = 1.3**



Triplets in IR1&5

Detailed tables have been compiled

Name	Length	Field config.	Chamber	Impedance (T_BS=70 K)	e-cloud (SEY=1.1/1.3(UncDrifts))	Total
ITQ1R5	11.6 m		BSHL_Q1	4.1 W	61.9 W	66.0 W
MQXFA.A1R5	4.2 m	quad	BSHL_Q1	1.5 W	19.0 W	
MQXFA.B1R5	4.2 m	quad	BSHL_Q1	1.5 W	24.7 W	
Drifts	1.7 m	drift	BSHL_Q1	0.6 W	0.1 W	
UncoatedDrifts	1.5 m	drift	BSHL_Q1	0.5 W	18.2 W	
ITQ2Q3R5	49.1 m		BSHL_Q23	15.3 W	338.0 W	353.3 W
MQXFB.A2R5	7.2 m	quad	BSHL_Q23	2.3 W	17.3 W	
MQXFB.B2R5	7.2 m	quad	BSHL_Q23	2.3 W	26.4 W	
MQXFA.A3R5	4.2 m	quad	BSHL_Q23	1.3 W	13.2 W	
MQXFA.B3R5	4.2 m	quad	BSHL_Q23	1.3 W	13.6 W	
MBXF.4R5	6.3 m	dip	BSHL_Q23	2.0 W	11.4 W	
MCBXFBV.A2R5 MCBXFBH.A2R5	1.2 m	dip	BSHL_Q23	0.4 W	0.0 W	
MCBXFBV.B2R5 MCBXFBH.B2R5	1.2 m	dip	BSHL_Q23	0.4 W	1.0 W	
MCBXFAV.3R5 MCBXFAH.3R5	2.2 m	dip	BSHL_Q23	0.7 W	1.5 W	
MCTXF.3R5	0.4 m	dodecap	BSHL_Q23	0.1 W	0.0 W	
MCTSXF.3R5	0.1 m	skew dodecap	BSHL_Q23	0.0 W	0.0 W	
MCDXF.3R5	0.1 m	decap	BSHL_Q23	0.0 W	0.0 W	
MCDSXF.3R5	0.1 m	skew decap	BSHL_Q23	0.0 W	0.0 W	
MCOXF.3R5	0.1 m	oct	BSHL_Q23	0.0 W	0.0 W	
MCOSXF.3R5	0.1 m	skew oct	BSHL_Q23	0.0 W	0.0 W	
MCSXF.3R5	0.1 m	sext	BSHL_Q23	0.0 W	0.0 W	
MCSSXF.3R5	0.1 m	skew sext	BSHL_Q23	0.0 W	0.7 W	
Drifts	8.6 m	drift	BSHL_Q23	2.6 W	21.1 W	
UncoatedDrifts	5.9 m	drift	BSHL_Q23	1.8 W	232.5 W	
Total IT R5						**419.4 W**

See also G. Skripka and G. Iadarola, "Beam-induced heat loads on the beam screens of the inner triplets for the HL-LHC", to be published, draft available here

Triplets in IR2&8

Detailed tables have been compiled

Studies performed also for Inner Triplets in IR2 and IR8

Name	Length	Field config.	Chamber	Impedance (T_BS= 20 K)	e-cloud (SEY=1.1/1.3 (UncDrifts))	Total
ITQ1R8	9.8 m		BSMQ_Q1-R	5.2 W	9.5 W	14.7 W
MQXA.1R8	6.4 m	quad	BSMQ_Q1-R	3.5 W	0.7 W	
MCBXH.1R8						
MCBXV.1R8	0.5 m	dip	BSMQ_Q1-R	0.2 W	0.0 W	
Drifts	0.9 m	drift	BSMQ_Q1-R	0.4 W	0.0 W	
UncoatedDrifts	2.1 m	drift	BSMQ_Q1-R	1.0 W	8.8 W	
ITQ2Q3R8	23.7 m		BSMQ_2	9.3 W	43.1 W	52.4 W
MQXB.A2R8	5.5 m	quad	BSMQ_2	2.3 W	3.9 W	
MQXB.B2R8	5.5 m	quad	BSMQ_2	2.3 W	9.1 W	
MQXA.3R8	6.4 m	quad	BSMQ_2	2.6 W	7.4 W	
MCBXH.2R8						
MCBXV.2R8	0.5 m	dip	BSMQ_2	0.2 W	0.0 W	
MCBXH.3R8						
MCBXV.3R8	0.5 m	dip	BSMQ_2	0.2 W	0.0 W	
Drifts	2.9 m	drift	BSMQ_2	1.0 W	0.0 W	
UncoatedDrifts	2.5 m	drift	BSMQ_2	0.8 W	22.7 W	
ITD1R8	13.9 m		BSMB_1	4.2 W	10.4 W	14.6 W
MBX.4R8	9.5 m	dip	BSMB_1	3.0 W	9.7 W	
Drifts	4.4 m	drift	BSMB_1	1.2 W	0.8 W	
UncoatedDrifts	0.0 m	drift	BSMB_1	0.0 W	0.0 W	
Total IT R8						**81.7 W**

See also G. Skripka and G. Iadarola, "Beam-induced heat loads on the beam screens of the inner triplets for the HL-LHC", to be published, draft available [here]

Inner triplets

	SEY = 1.3	SEY = 1.1	SEY=1.1 (cold masses) SEY=1.3 (elsewhere)
Inner Triplet IR1&5	1.5 kW	170 W	420 W
Inner Triplet IR2&8	1 kW	50 W	82 W

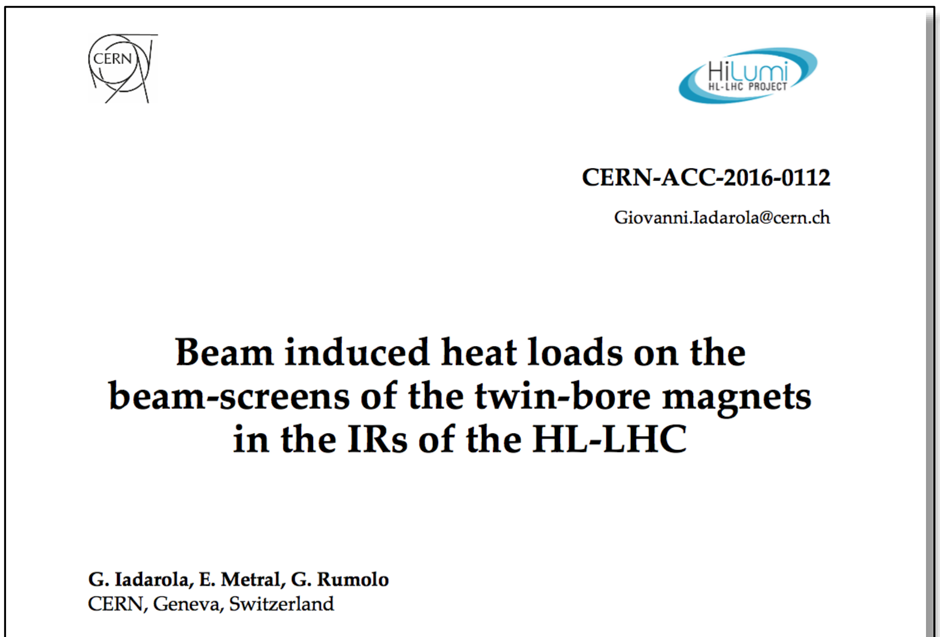
- Large heat load **reduction (10-fold) expected from low SEY coating**
- Significant load added by e-cloud in **un-coated drifts** between the cold masses, especially in **IR1&5**. Proposed strategy:
  - Length of uncoated parts should be minimized
  - Remaining load should be taken into account in the design of new cryo for IR1&5 (info provided to WP9)
  - Impact on beam stability needs to be crosschecked
- Ongoing work: quantify effect of possible **electron accumulation** over many turns in the low SEY range (1.0<SEY<1.1)

Outline

- LHC experience
- **Estimates for HL-LHC**
    - Arcs
    - Inner triplets
    - Other LSS magnets
- Backup scenario: 8b+4e scheme

Twin-bore magnets in the LSS

- Heat load estimates have been carried out also for all cold **twin-bore magnets in the insertion regions**
- The main results are available at: https://cds.cern.ch/record/2217217?ln=en

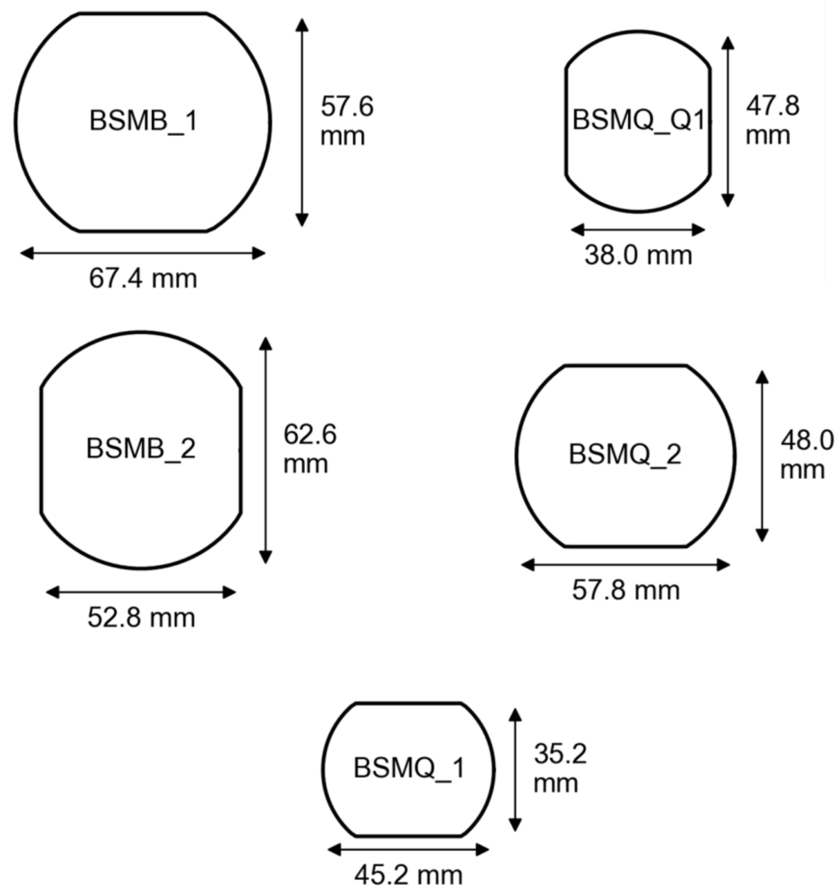

CERN-ACC-2016-0112

Giovanni.Iadarola@cern.ch

Beam induced heat loads on the beam-screens of the twin-bore magnets in the IRs of the HL-LHC

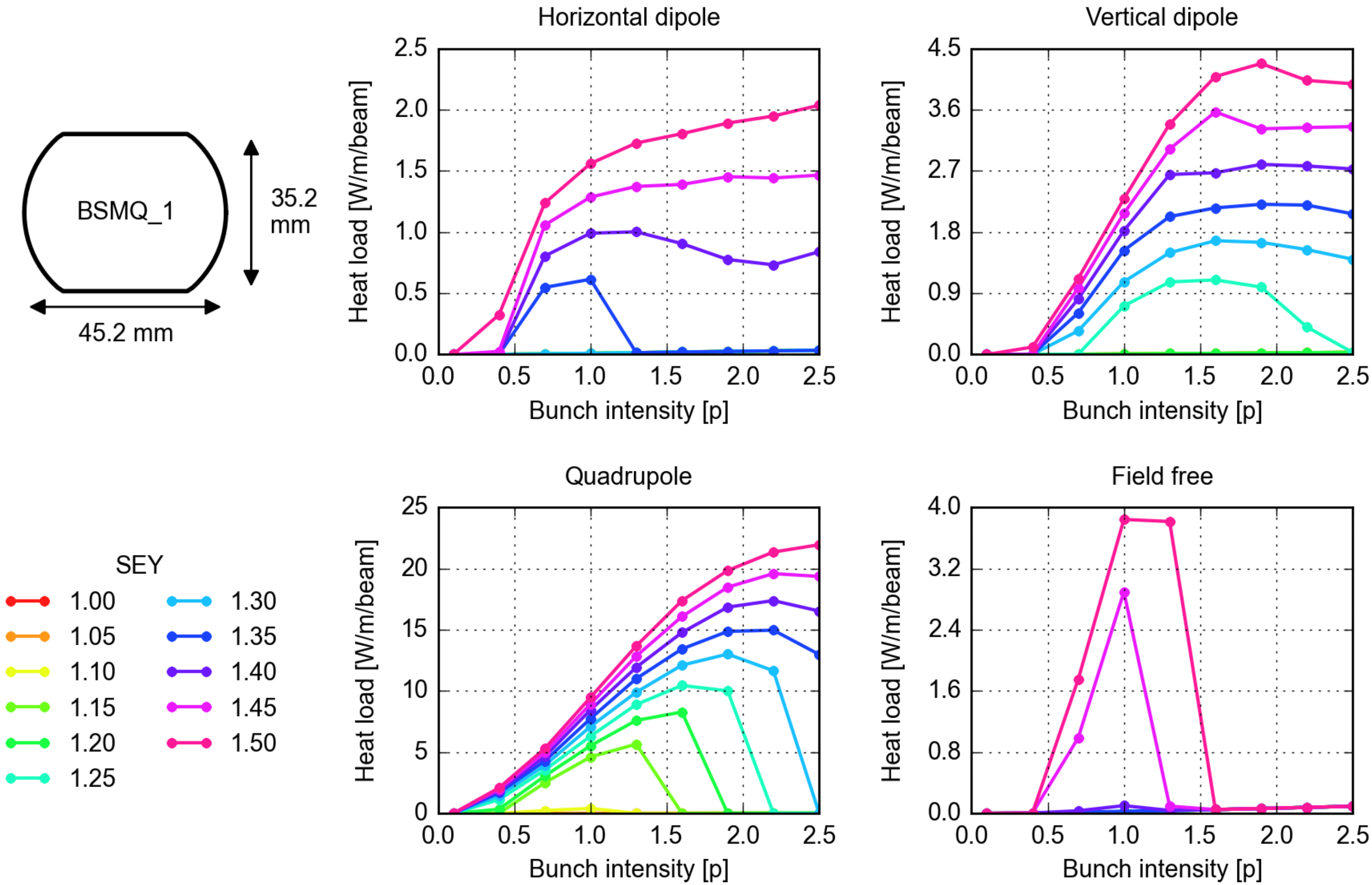
G. Iadarola, E. Metral, G. Rumolo
CERN, Geneva, Switzerland

Naming convention used in the following



Twin-bore magnets in the LSS

- For each chamber type the heat load from **e-cloud has been evaluated for different magnetic field** configurations



Twin-bore magnets in the LSS

- Generated a **table** for each IR, combining the estimates from **impedance and e-cloud effects**

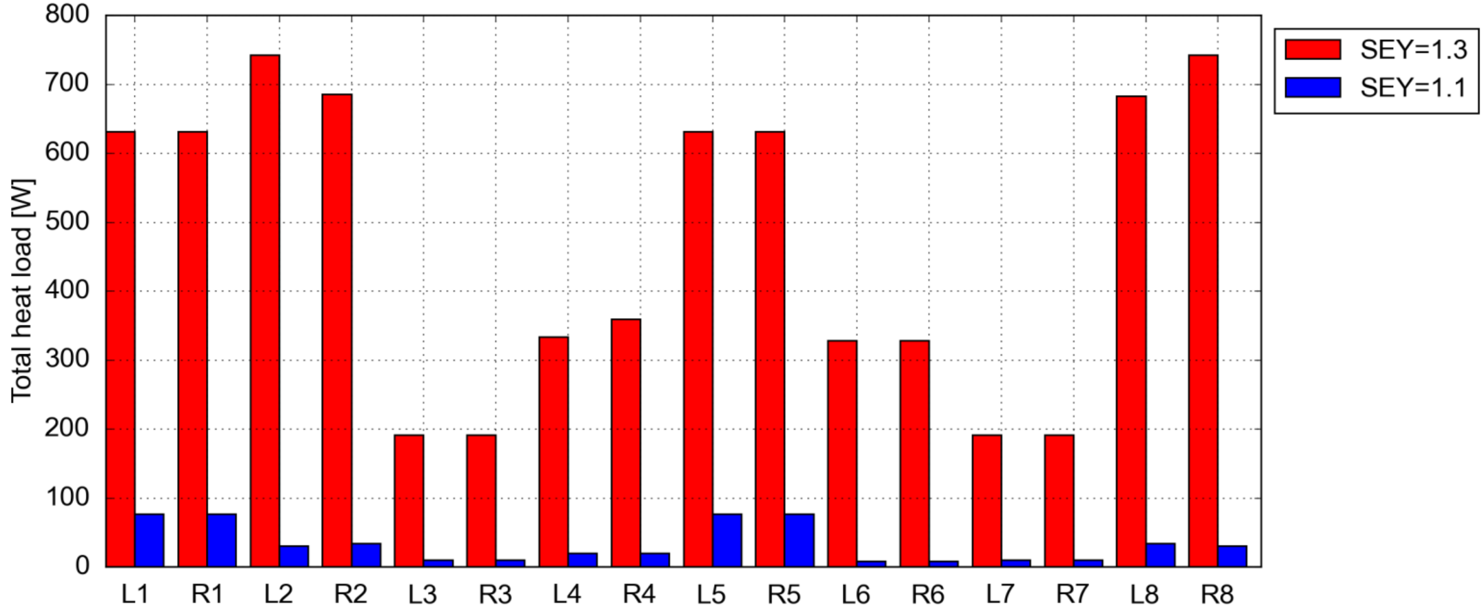
Name	Length	Field config.	Chamber	Impedance (T_BS=20 K)	e-cloud (SEY=1.3/1.1)	Total (SEY=1.3/1.1)
D2L1	13.2 m		BSHL_D2	3.6 W	227.0/46.3 W	230.6/49.9 W
MBRD.4L1.B1	7.8 m	dip	BSHL_D2	2.2 W	110.6 W/31.5 W	
MCBRDH.4L1.B1	1.8 m	dip	BSHL_D2	0.5 W	25.6 W/7.3 W	
MCBRDV.4L1.B1	1.8 m	dip	BSHL_D2	0.5 W	25.5 W/7.3 W	
Drifts	1.8 m	drift	BSHL_D2	0.4 W	65.3 W/0.2 W	
Q4L1	9.0 m		BSHL_Q4	3.1 W	155.1/12.8 W	158.2/15.9 W
MQYY.4L1.B1	3.8 m	quad	BSHL_Q4	1.4 W	107.5 W/0.1 W	
MCBYYH.4L1.B1	1.8 m	dip	BSHL_Q4	0.6 W	24.1 W/6.3 W	
MCBYYV.4L1.B1	1.8 m	dip	BSHL_Q4	0.6 W	23.3 W/6.2 W	
Drifts	1.6 m	drift	BSHL_Q4	0.5 W	0.2 W/0.2 W	
Q5L1	8.7 m		BSMQ_2	4.2 W	120.8/0.6 W	125.0/4.8 W
MQY.5L1.B1	3.4 m	quad	BSMQ_2	1.8 W	104.5 W/0.1 W	
MCBYV.A5L1.B1	0.9 m	dip	BSMQ_2	0.4 W	6.2 W/0.0 W	
MCBYH.5L1.B1	0.9 m	dip	BSMQ_2	0.4 W	3.6 W/0.0 W	
MCBYV.B5L1.B1	0.9 m	dip	BSMQ_2	0.4 W	6.2 W/0.0 W	
Drifts	2.6 m	drift	BSMQ_2	1.2 W	0.3 W/0.3 W	
Q6L1	6.9 m		BSMQ_1	5.3 W	112.2/0.4 W	117.4/5.7 W
MQML.6L1.B1	4.8 m	quad	BSMQ_1	3.7 W	111.9 W/0.2 W	
MCBCH.6L1.B1	0.9 m	dip	BSMQ_1	0.7 W	0.1 W/0.1 W	
Drifts	1.2 m	drift	BSMQ_1	0.8 W	0.2 W/0.2 W	
Total LSS						**631.3/76.3 W**

Dipole correctors and "drifts" can be non-negligible w.r.t. total!

For SEY =1.3 **e-cloud contribution is dominant**

Surface treatment providing **SEY=1.1 very effective in reducing the heat load**

Twin-bore magnets in the LSS



- The **experimental IRs** are by far the most critical (due to larger number of cold devices)
  - Load **IR2 and IR8** will affect the neighboring arcs

    → Low SEY coating of the matching sections is desirable, especially at R2 and L8 which are cooled by less powerful cryoplants (see presentation by WP9)
  - **IR1 and IR5** will be equipped with **dedicated cryoplants** → if not coated, load of matching sections needs to be taken into account in the design (info provided to WP9)
  - Presently **baffle plates** are installed behind pumping slots of all SAM magnets (to support hydrogen cryosorber) → if no drawback, this should be kept also for magnets operated at 1.9 K

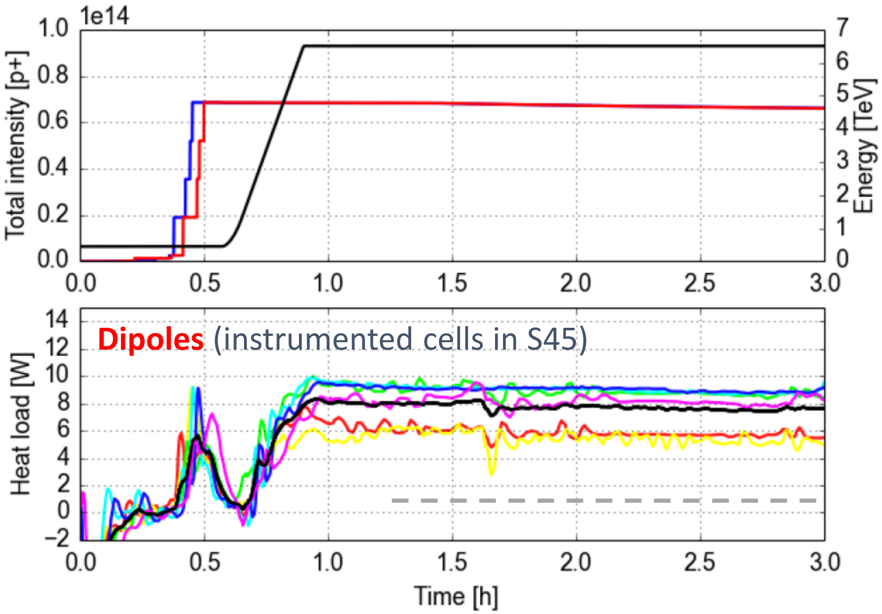
Outline

- **LHC experience**
- **Estimates for HL-LHC**
  - Arcs
  - Inner triplets
  - Other LSS magnets
- **Backup scenario: 8b+4e scheme**

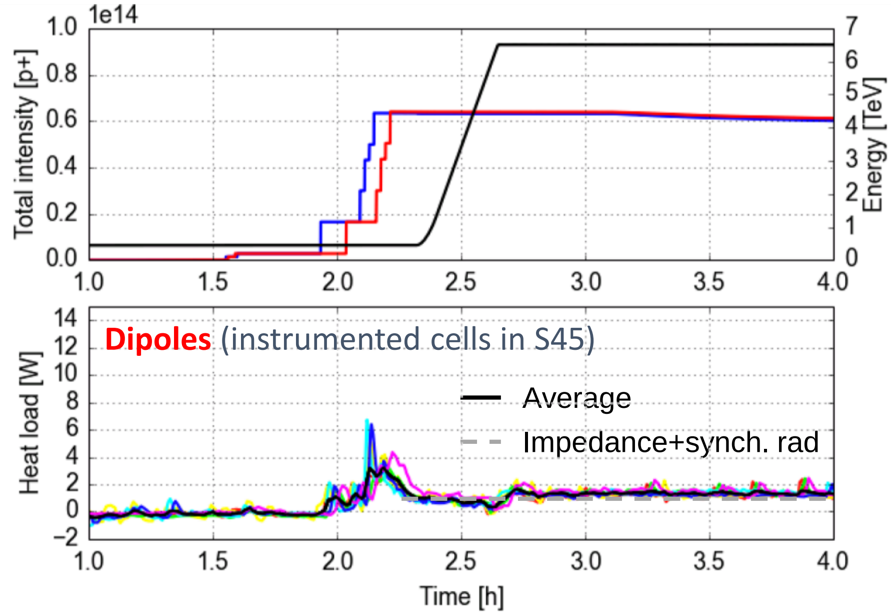
Filling pattern designed to **suppress the e-cloud build-up (~30 % less bunches w.r.t. nominal)**

- **Confirmed experimentally in the LHC** in 2015
- Included in the **HL-LHC TDR as backup scenario** in case issues with e-cloud

Standard 25 ns beam



“8b+4e” beam

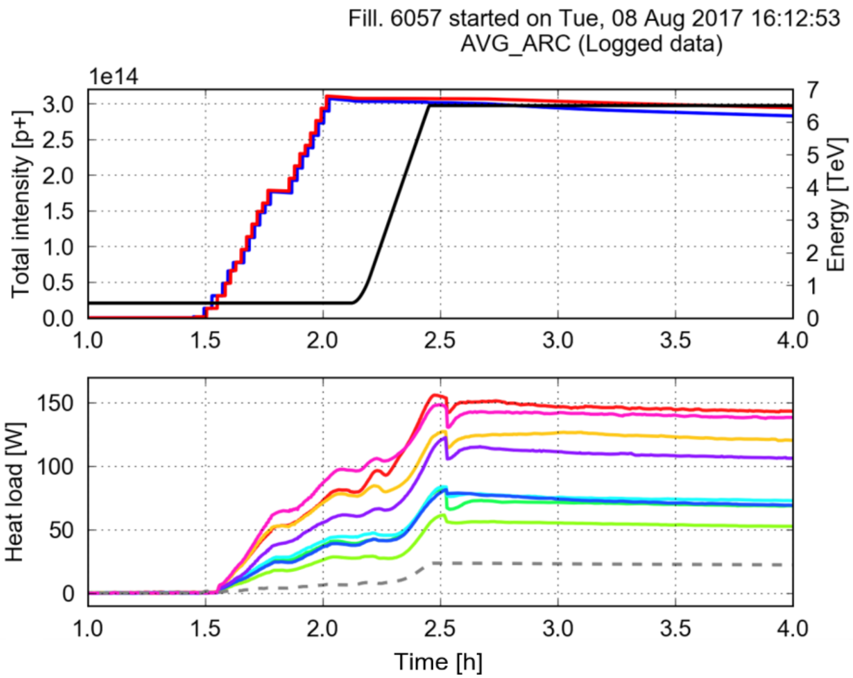


8b+4e scheme

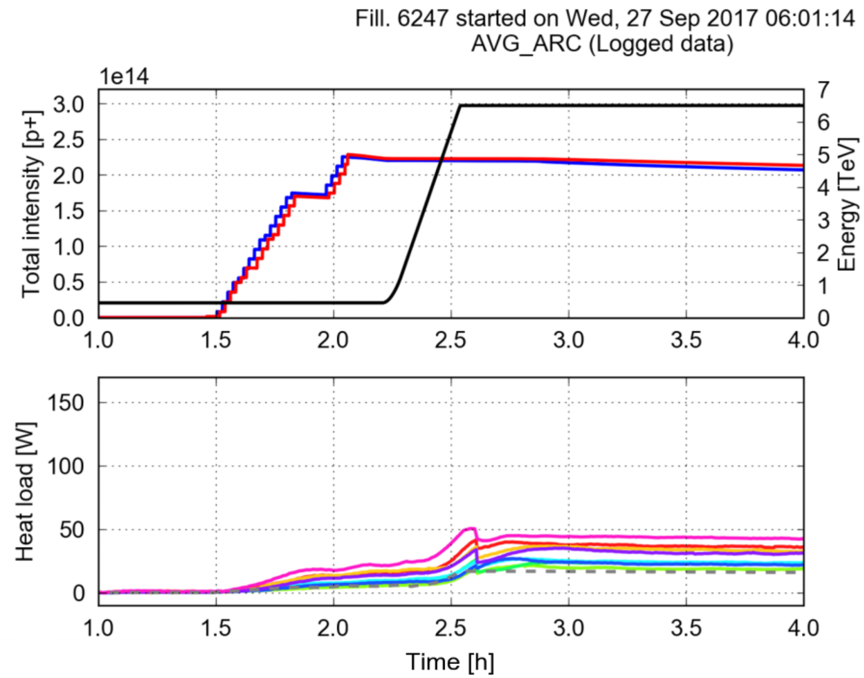
Filling pattern designed to **suppress the e-cloud build-up (~30 % less bunches w.r.t. nominal)**

- **Confirmed experimentally in the LHC** in 2015
- Included in the **HL-LHC TDR as backup scenario** in case issues with e-cloud
- Used in **operation** in the last part of the **2017 Run** (to mitigate fast losses in 16L2)
- Standard 25 ns trains and 8b4e trains can be **combined in the same filling scheme** in order to adapt the heat load to the available cooling capacity ([tested in MD in 2016]())

25 ns (2556b)



8b+4e (1916b)



Summary and conclusions

Collaboration between WP2 and WP9 to build a **full inventory** of expected beam induced heating on the beam screens for HL-LHC. Main outcomes:

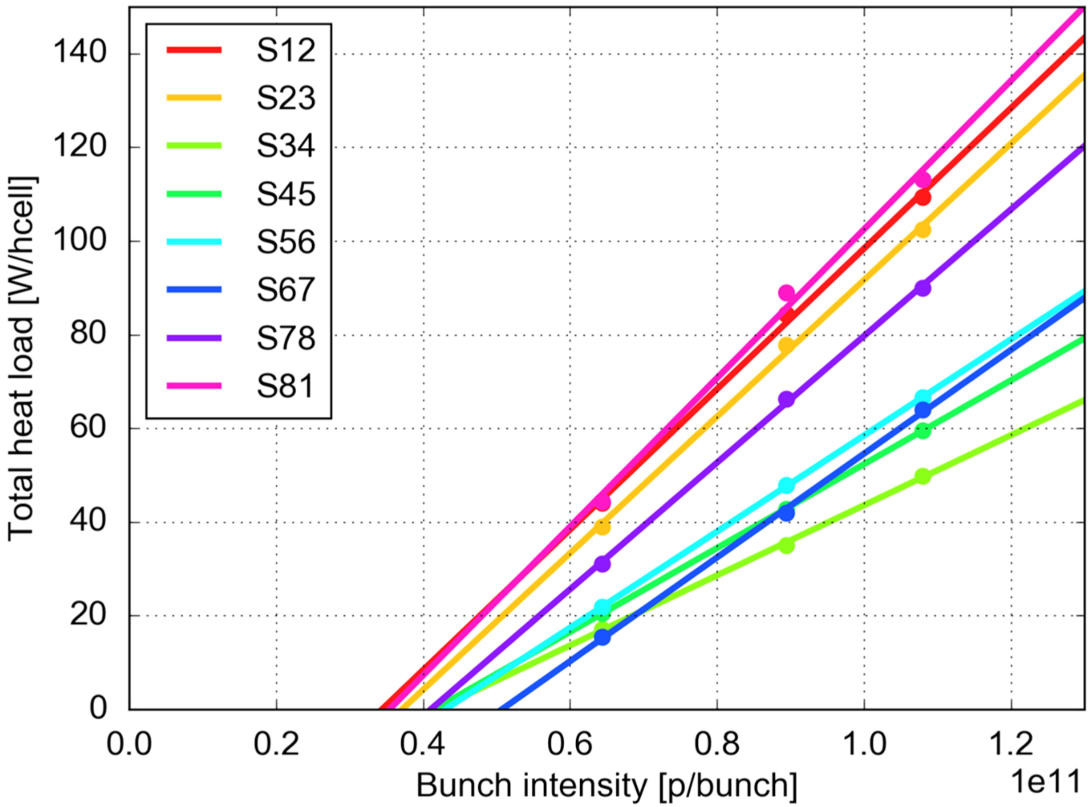
- **Arc beam screens** (assuming that heat load differences are due to different SEY):
  - Present conditioning state of the **low load sectors** (S34, S45, S56, S67) should allow operation with **HL-LHC beam parameters within the present available cooling capacity**
  - The estimated load for the **high load sectors** (S12, S23 S78, S81) is of the order of **10 kW (more than presently available)** → ongoing work to identify and suppress the source of these differences is fundamental for HL-LHC
- **Inner Triplets:** large heat load **reduction (10-fold) expected from low SEY coating**
  - Significant load added by e-cloud in **un-coated drifts** between the cold masses, especially in **IR1&5** → length of uncoated parts should be minimized, remaining load should be taken into account for cryo-plant design
- **Other LSS magnets**: the **experimental IRs** are by far the most critical (due to larger number of cold devices)
  - Load in **IR2 and IR8** will affect the neighboring arcs → Low SEY coating of the matching sections is desirable, especially at R2 and L8 (ex-LEP cryoplants)
- If no drawback, **baffle plates** should be installed behind the pumping slots of all devices
- Tests in 2015-16 and operation in 2017 confirmed the effectiveness of the **8b+4e scheme** for heat load mitigation (HL-LHC backup scenario)

Thanks for your attention!

Heat load estimates: impact of the filling scheme

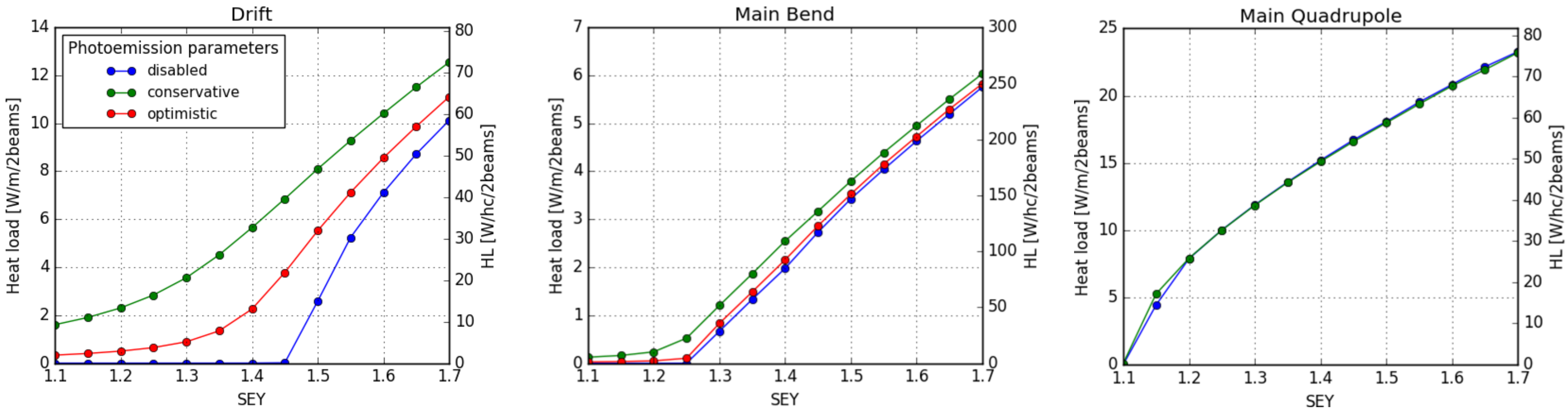
Intensity dependence measured in MD in 2016 keeping the same bunch length and filling scheme

- Measured points are fitting quite well with **linear dependence** with **intensity threshold** in the range 0.4 to 0.7 x 10^{11} p/bunch
- **Dependence is quite steep** → effect can be sizable when increasing the bunch charge from 1.1 x 10^{11} p/bunch to 1.3 x 10^{11} p/bunch



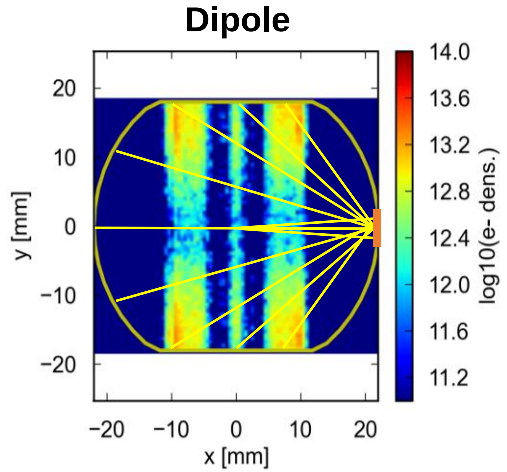
Arc heat loads – results for LHC beam parameters

The defined models have been used to simulate all the element of the arc half-cell



The **impact of the photoelectrons** is very **strong the drift sections**:

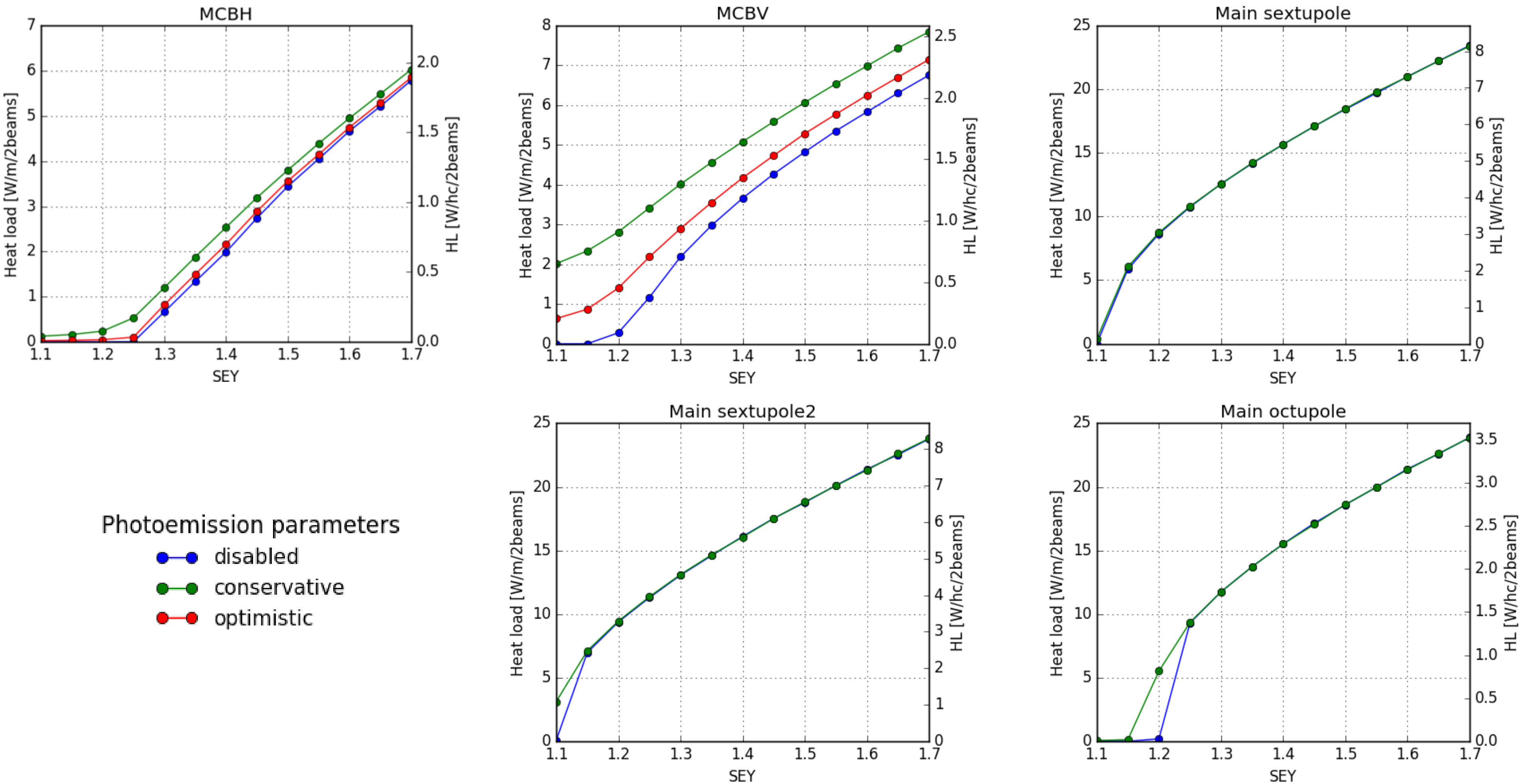
- For the other elements, in the presence of a vertical magnetic field, only photoelectrons from reflected photons (<10%) can be accelerated by the beam and contribute to the heat load



Details in P. Dijkstal et al., "Simulation studies on the electron cloud build-up in the elements of the LHC Arcs at 6.5 TeV", to be published, draft available here

Arc heat loads – results for LHC beam parameters

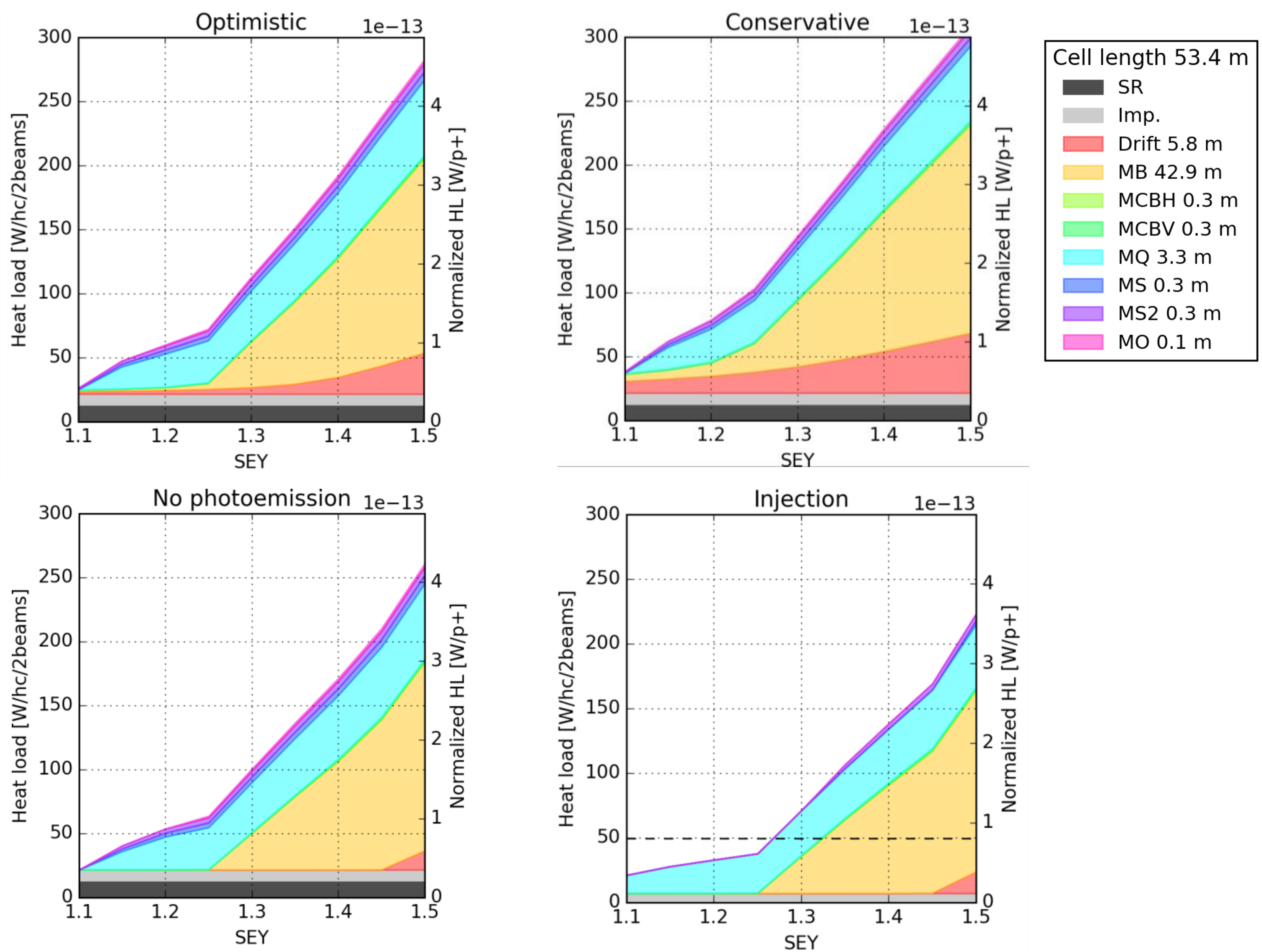
The defined models have been used to simulate all the element of the arc half-cell



Details in P. Dijkstal et al., "Simulation studies on the electron cloud build-up in the elements of the LHC Arcs at 6.5 TeV", to be published, draft available here

Arc heat loads – results for LHC beam parameters

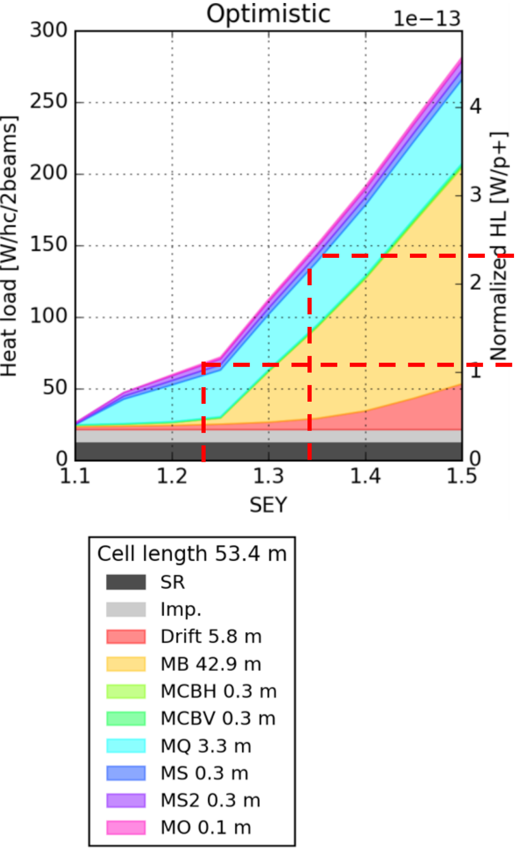
Total loads
(assuming SEY uniform in the cell)



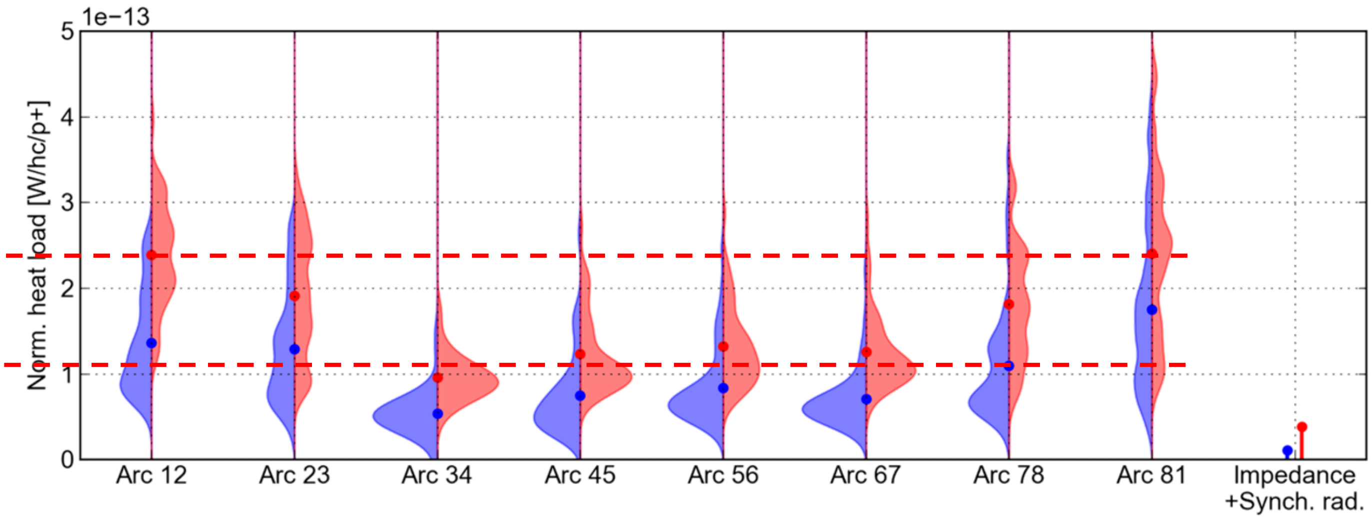
Details in P. Dijkstal et al., "Simulation studies on the electron cloud build-up in the elements of the LHC Arcs at 6.5 TeV", to be published, draft available [here]

Comparison against simulations - optimistic

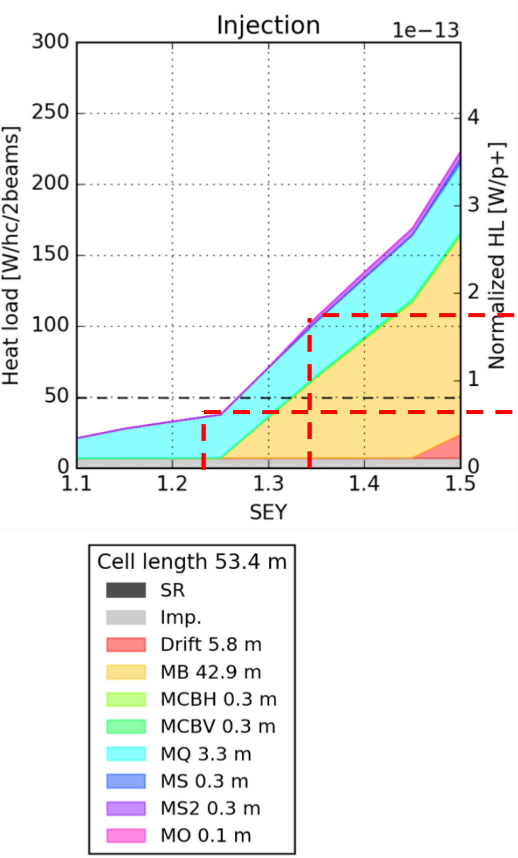
Simulations

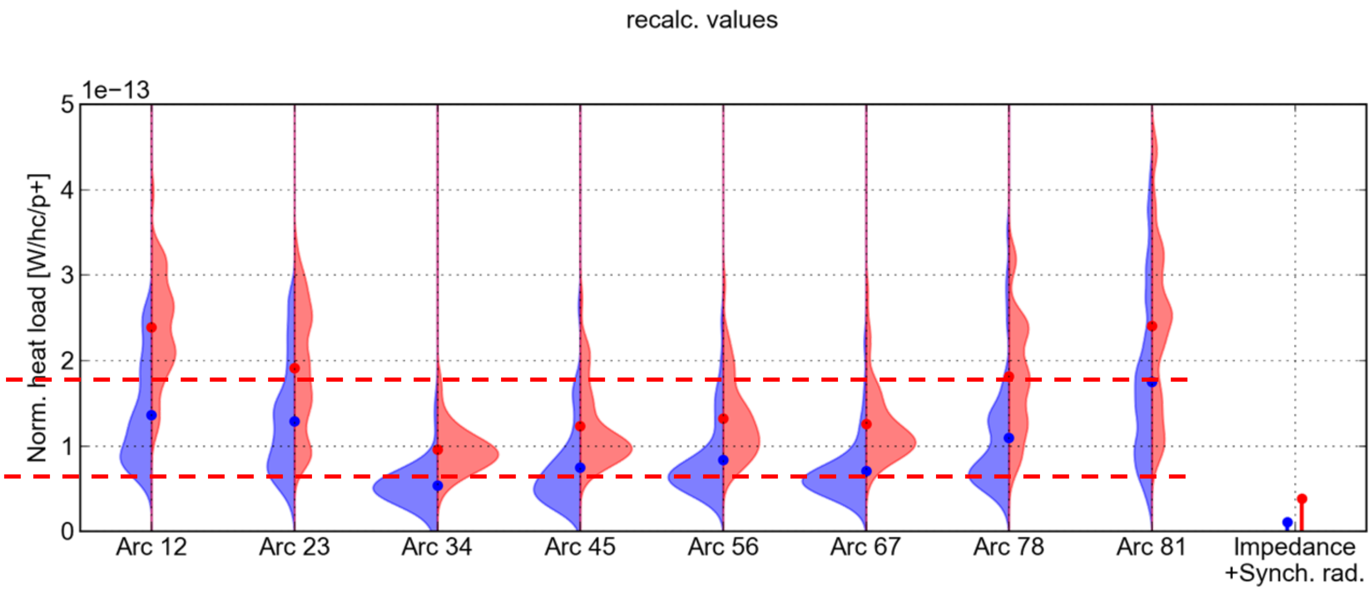


Measurements



Comparison against simulations - optimistic (using averages)





	(blue)	(red)
Fill	6054	6054
Started on	07 Aug 2017 14:15	07 Aug 2017 14:15
T_sample [h]	2.58	3.10
Energy [GeV]	450	6499
N_bunches (B1/B2)	2556/2556	2556/2556
Intensity (B1/B2) [p]	2.94e14/3.03e14	2.91e14/3.01e14
Bun.len. (B1/B2) [ns]	1.27/1.29	1.07/1.07
H.L. exp. imped. [W]	6.47	10.15
H.L. exp. synrad [W]	0.00	12.61
H.L. exp. imp.+SR [W/p+]	1.08e-14	3.84e-14
T_nobeam [h]	1.90	1.90

25 ns (2556b)

8b+4e (1916b)