Heat load estimates for the Long Straight Sections of the HL-LHC

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Many thanks to:
G. Arduini, R. De Maria, P. Fessia, L. Medina, R. Tomas

HLLHC WP2 meeting 28/06/2016

Outline

- Introduction
- Evaluation method
- Organization of results and first observations
- Impact of bunch length increase to 1.3 ns

Introduction

- Goal of the study is to provide a **comprehensive survey** of the expected heat loads on the beam screens of the LSS cold magnets (for all IRs)

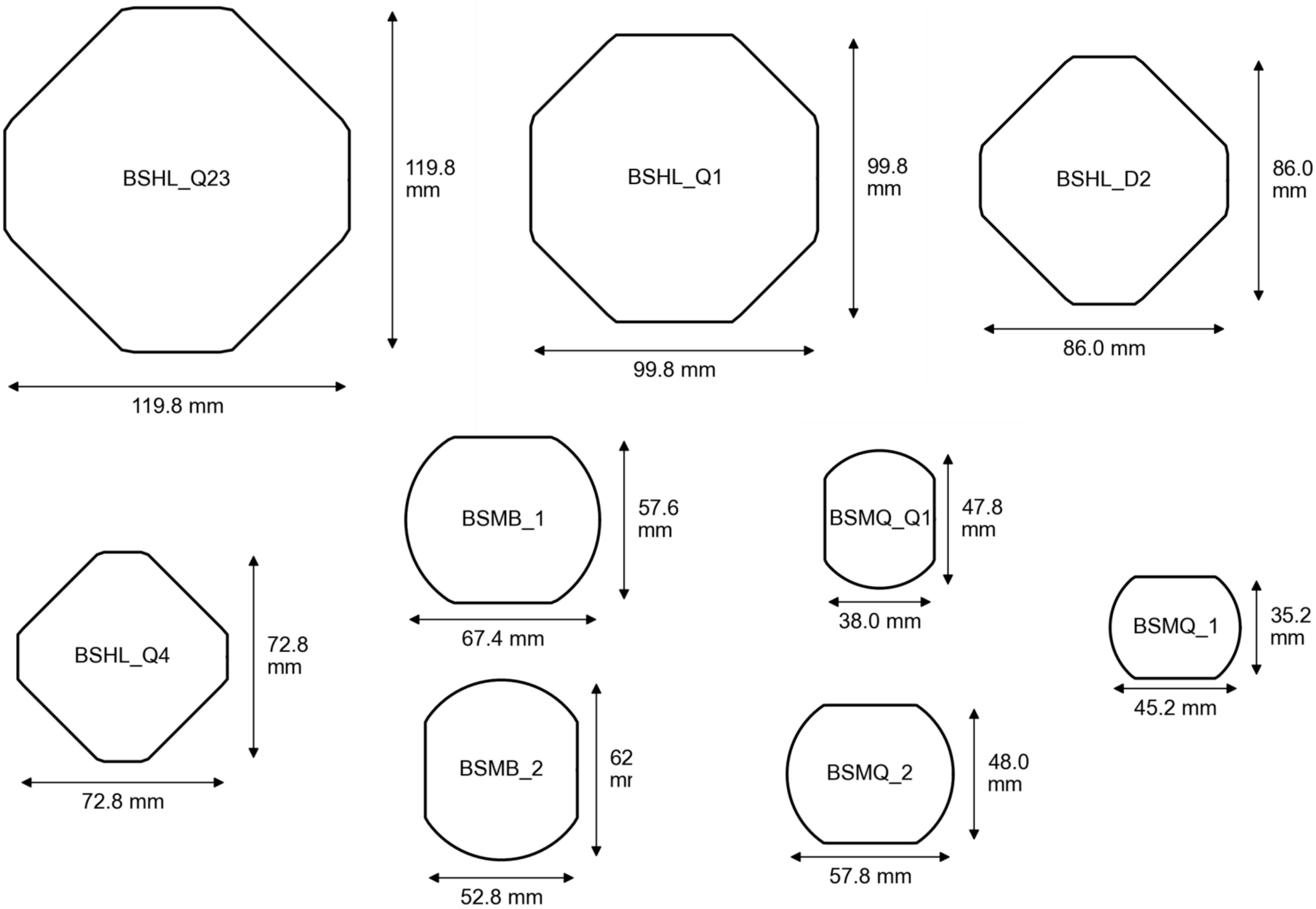
- Considered the **two main contributions**:
  - **Electron cloud**
  - **Impedance**

  Synchrotron radiation emitted in the LSSs was found to be very small (see A. Rossi at HSS meeting 20/04/2016)

- Detailed evaluation performed for **all two-aperture magnets** while for the triplet assemblies we rely on previous work

HL-LHC beam screens

Naming convention used in the following



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Evaluation of the impedance contribution

- Elias's recipe described in detail in:

  https://indico.cern.ch/event/323863/

  https://indico.cern.ch/event/323861/

- **Resistive wall formula** for circular one-layer pipe:

$$P_{loss/m}^{G,RW,1\,\mathrm{layer}} = \frac{1}{2\pi R}\,\Gamma\!\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b\, e}{2\pi}\right)^2 \sqrt{\frac{c\,\rho\, Z_0}{2}}\;\sigma_t^{-3/2}$$

where:

- $(2\pi R)$ is the LHC circumference
- $\Gamma(3/4)$ is a constant (~1.23)
- M is the number of bunches
- b is the radius
- $(N_b e)$ is the bunch charge
- ρ is the resistivity of the pipe
- Z_0 is the impedance of free space (~377 Ω)
- σ_t is the r.m.s. bunch length (in time)

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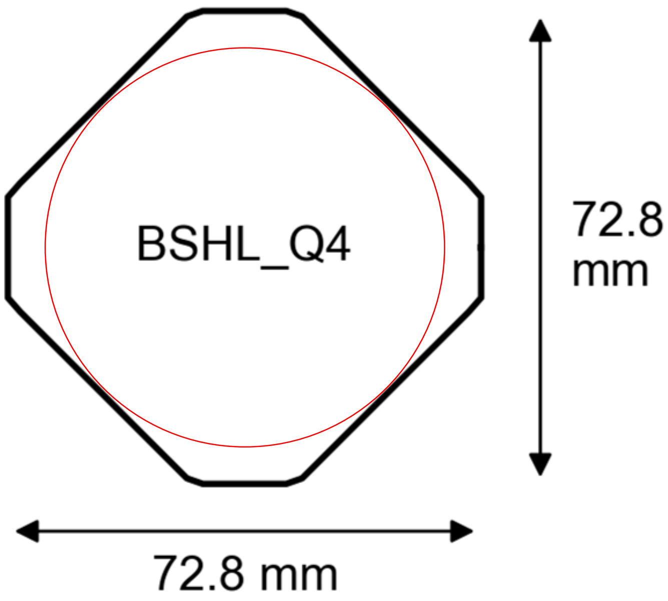
  - Chosen **radius of the largest inscribed circle**



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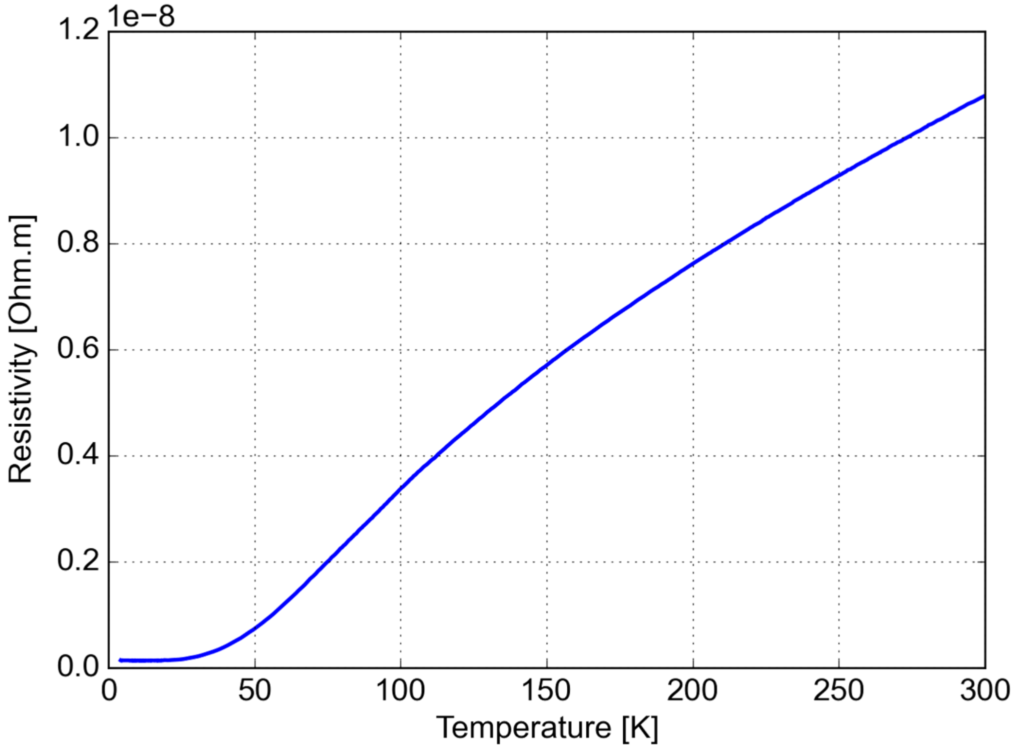

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  - **Magneto-resistive effect** given by **Kohler's law**: assumed 5 T for main dipoles (MBs), 150 T/m for main quadrupoles (MQs), 2 T for dipole correctors (MCBs)

$$\frac{\rho(B,T)-\rho_0(T)}{\rho_0(T)}=\frac{\Delta\rho}{\rho_0}=10^{-2.69}\times(B\times RRR)^{1.055}$$

where RRR is the Residual Resistivity Ratio $RRR := \frac{\rho(T=273\,\mathrm{K})}{\rho(T=4\,\mathrm{K})}$

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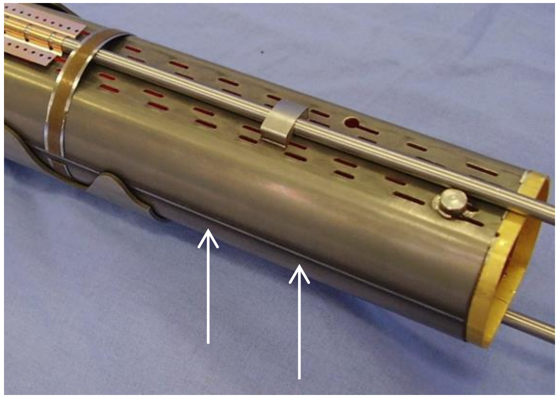
  - Effect of **longitudinal weld** (StSt) included with simple formula

$$P_{loss/m}^{Weld} \approx P_{loss/m}^{G,RW,1\,\mathrm{layer}} \times \sqrt{\frac{\rho_{SS}}{\rho_{Cu}}} \times \frac{\Delta^{Weld}}{2\pi b}$$

with ρ_{SS} = 6e-7 Ωm and Δ^{Weld} = 2 mm



Evaluation of the e-cloud contribution

For each chamber geometry, performed **PyECLOUD buildup simulations**

- Different values of **bunch intensity**
- Different values of **SEY**
- Four different different **field configurations**:
  - Horizontal dipole (1.5 T)
  - Vertical dipole (1.5 T)
  - Quadrupole (150 T/m)
  - Field free
- **Beam paramters:** Transverse beam size: 1 mm r.m.s., bunch length: 75 mm r.m.s., rescaled to 2748 bunches per beam

From **2015/16 experience**, we assume that **e-cloud saturation is reached after the first 30b. of each train**

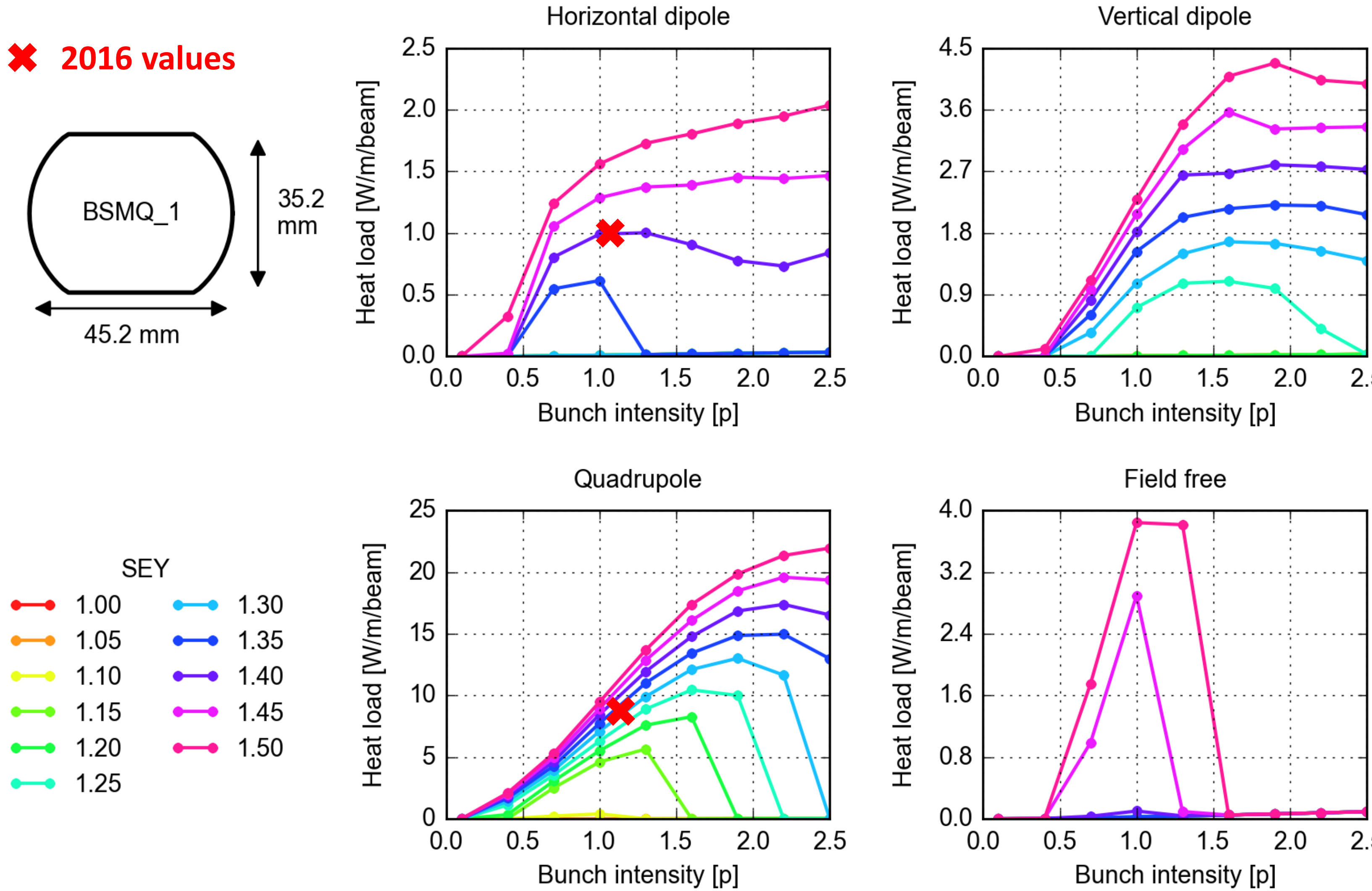
→ It makes a difference compared to past studies for SEY values close to the multipacting threshold

Heat load results from all (3240) simulations are available here

Electron cloud contributions

For each chamber **generated this set of plots**

→ plots for all chambers available here



Electron cloud contributions

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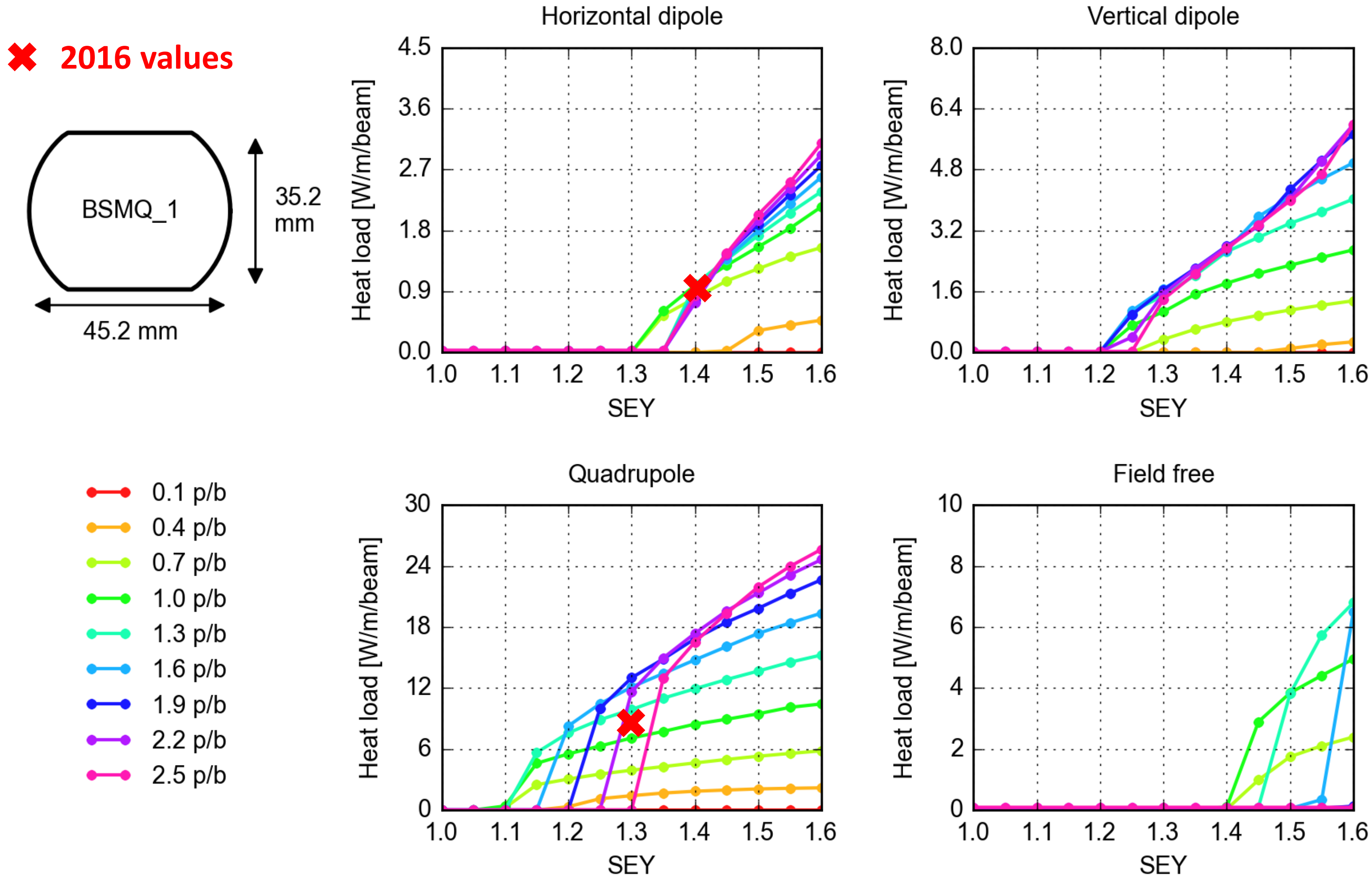

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Putting it all together

Procedure for heat load evaluation **almost fully automatized:**

1. Start with **list of cryostats** with lengths and included magnets (MBs, MQs, MCBs)
2. From **MAD** model:
   - 2.1 Identify the **chamber geometry and orientation**
   - 2.2 Identify **field configuration** from magnet name (MB*, MQ*, MCB*H*, MCB*V*)
3. For each cryostat, length not attributed to any magnets considered as **drift** (chamber assumed the same as for other elements in cryostat)
4. Compute **impedance heat load** (2.2e11 p/bunch, b.l. = 1.0 ns)
   - 4.1 Evaluate radius of inscribed circle
   - 4.2 Evaluate magnetic field at found radius
   - 4.3 Evaluate conductivity (depends on B and T)
   - 4.4 Apply resistive wall formula
   - 4.5 Correct for longitudinal weld
5. Compute **e-cloud heat** load by interrogating simulations database (2.2e11 p/bunch, SEY=1.1/1.3)
6. Sum contributions for each **cryostat**
7. Sum contributions for each **LSS**

Heat load tables

- Generated a **table** for each LSS → Full survey available [here]

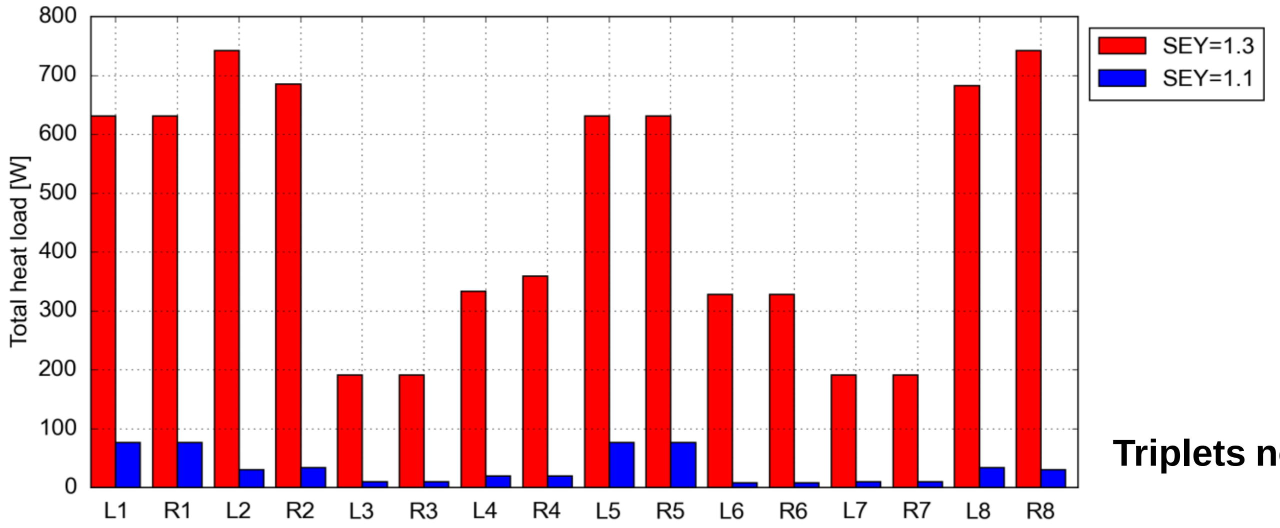
Name	Length	Field config.	Chamber	Impedance (T_BS=20 K)	e-cloud (SEY=1.3/1.1)	Total (SEY=1.3/1.1)
D2L1	13.2 m		BSHL_D2	3.6 W	227.0/46.3 W	230.6/49.9 W
MBRD.4L1.B1	7.8 m	dip	BSHL_D2	2.2 W	110.6 W/31.5 W	
MCBRDH.4L1.B1	1.8 m	dip	BSHL_D2	0.5 W	25.6 W/7.3 W	
MCBRDV.4L1.B1	1.8 m	dip	BSHL_D2	0.5 W	25.5 W/7.3 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**

Trying to summarize



Triplets not included

- For the **triplets** we can rescale the numbers obtained by Elias for the main magnets to the full triplets length (gives a pessimistic estimation) obtaining (for T=70 K and SEY =1.1)

  → **275 W** for ITs in IR1&5 and **204 W** for ITs in IR2&8

- The **experimental IRs** are by far the most critical, with heat loads of ~**1 kW per side** (including ITs)
- From the **arcs** we expect heat loads of the order of **7.3 kW per arc (with no e-cloud in dipoles)**
  - Total **synchrotron radiation = 3 kW** (70 W/hc)
  - Total **impedance = 2.4 kW** (50 W/hc)
  - Total **e-cloud in quads** (SEY 1.3) **= 1.9 kW** (42 W/hc)
- In **S12, S23, S78 and S81 the total load goes beyond 8 kW**

  → **Very little marging for e-cloud in dipoles which WE WILL need to condition**

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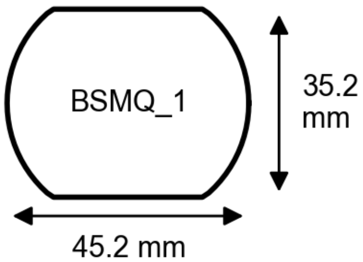
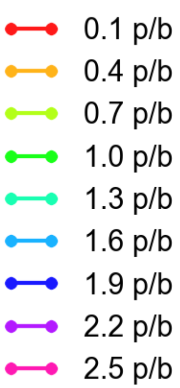
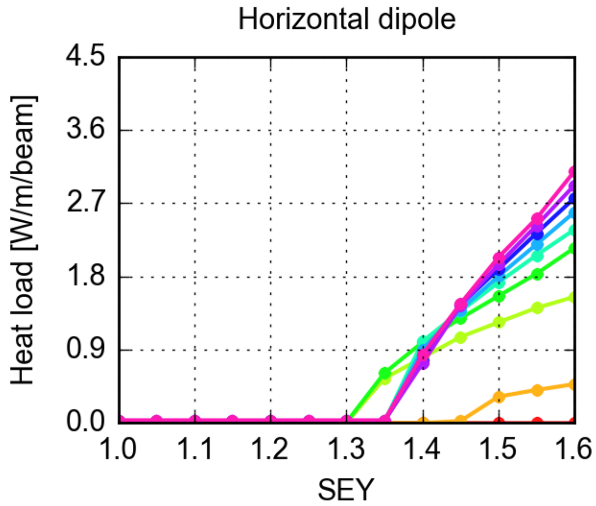
Impact of bunch length increase

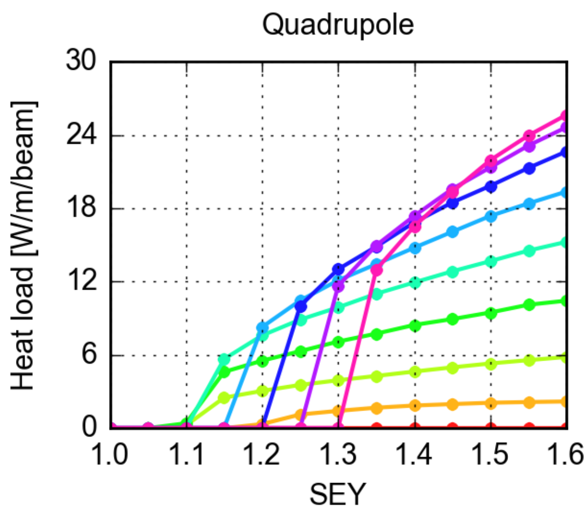
- **Very small change** (full set of results available here)



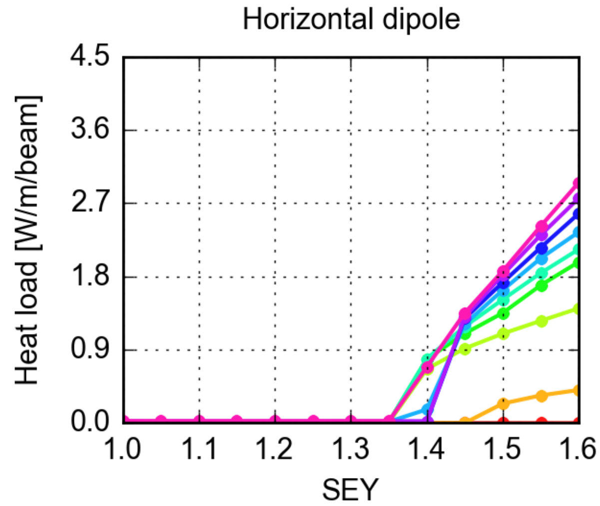


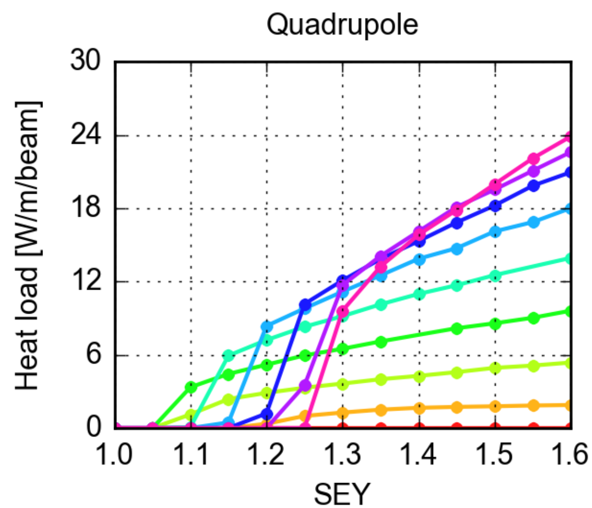
Bunch length 1 ns





Bunch length 1.3 ns

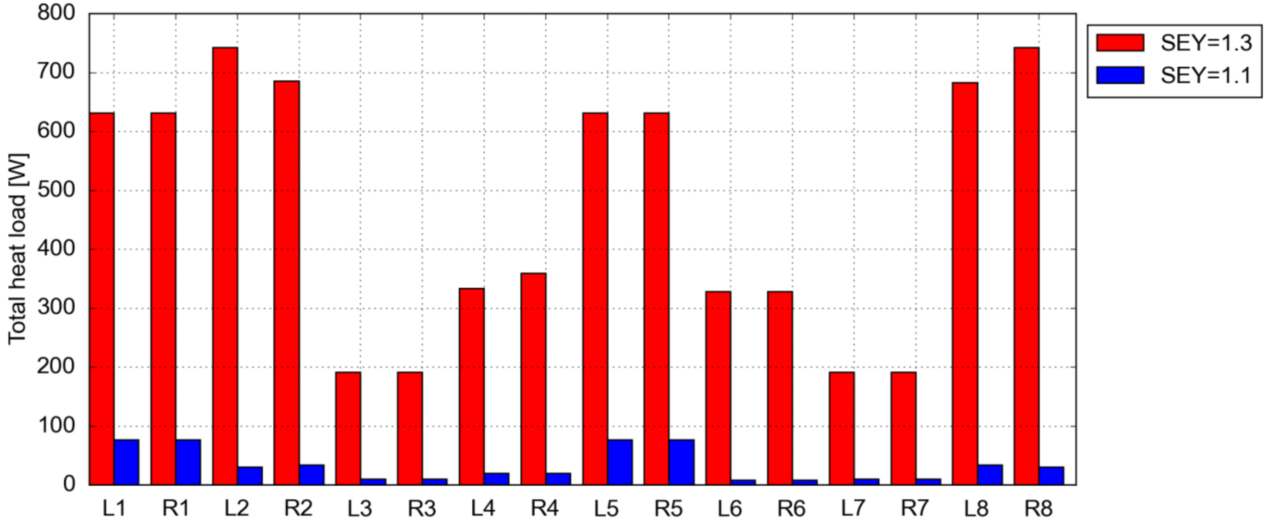




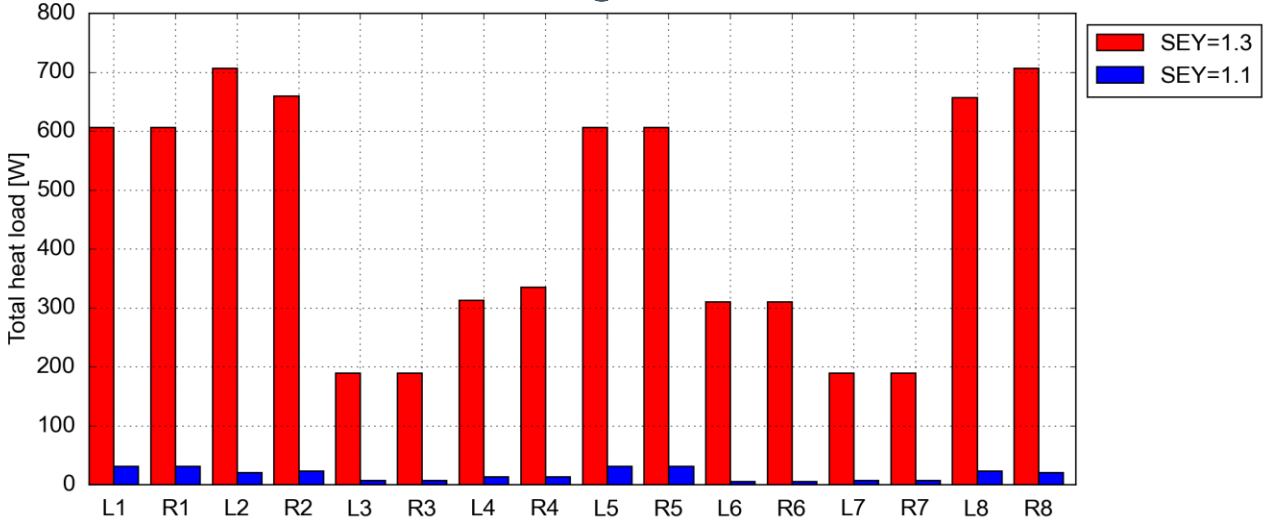
Impact of bunch length increase

- **Very small change** (due also to impedance contribution)

Bunch length 1 ns



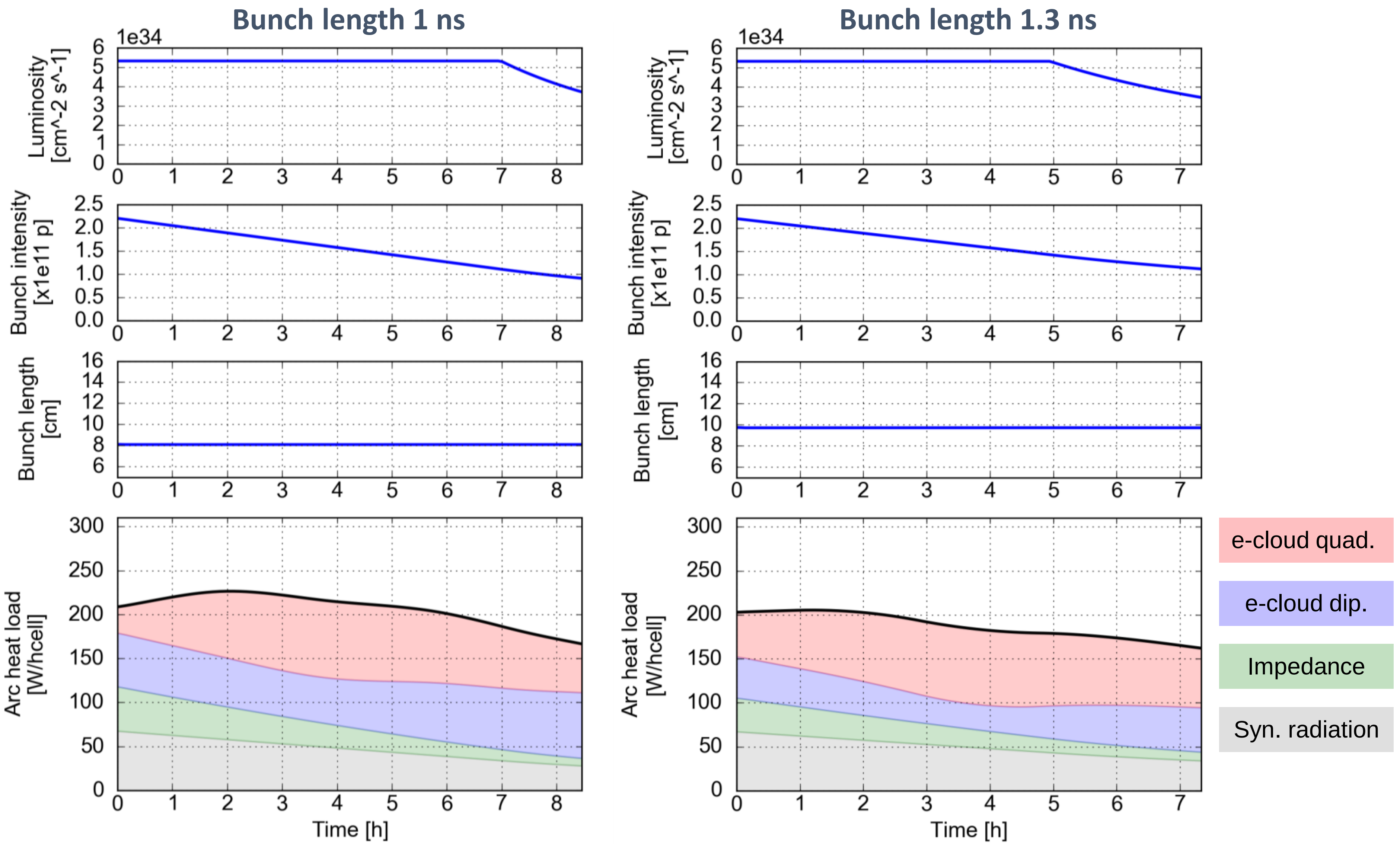
Bunch length 1.3 ns



Heat load in the arcs: bunch length 1.0 ns vs 1.3 ns

$SEY_{dip} = SEY_{quad} = \mathbf{1.40}$

- **Very small change**



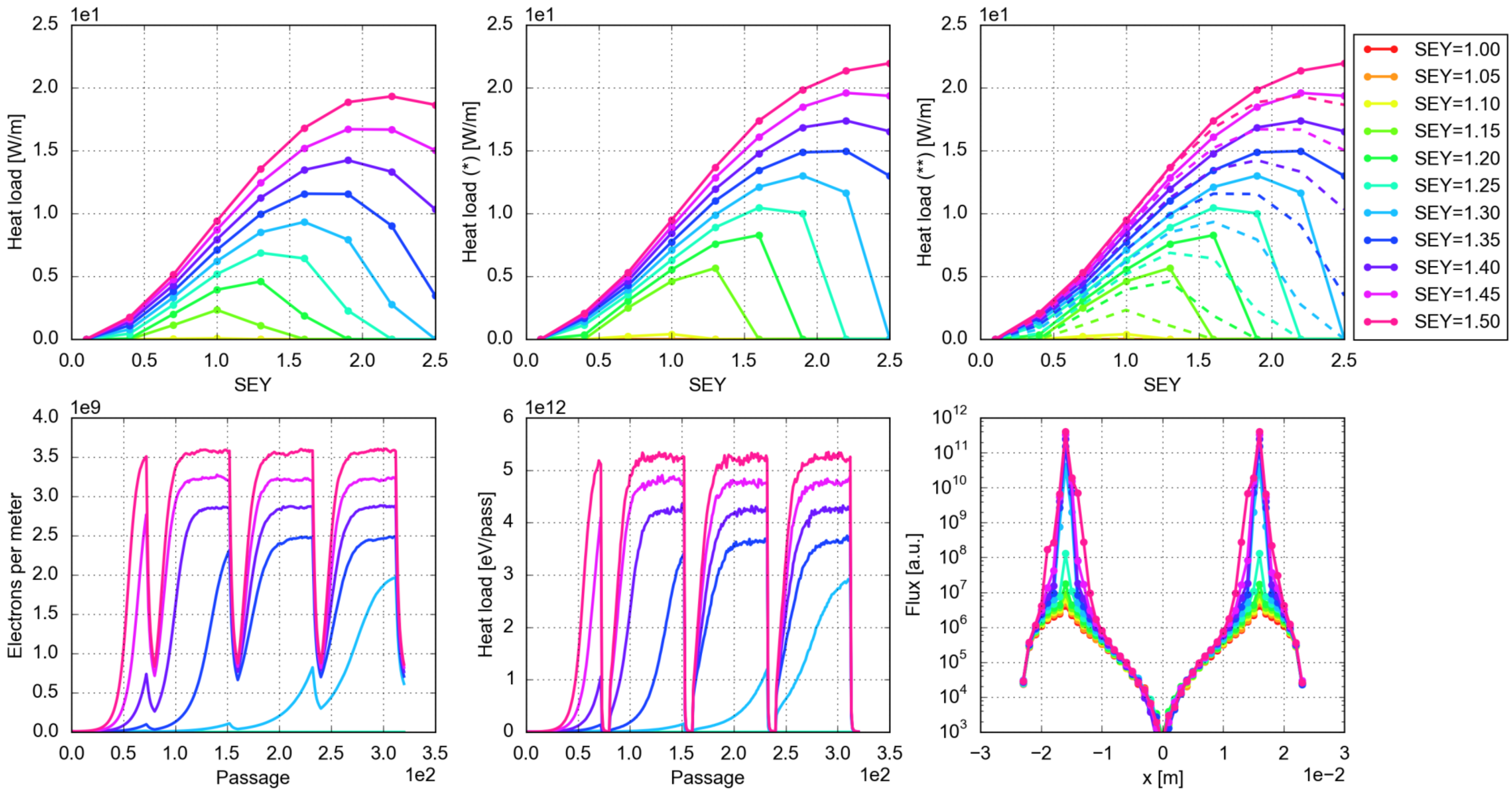
Thanks to L. Medina and R. Tomas for beam evolutions

Summary

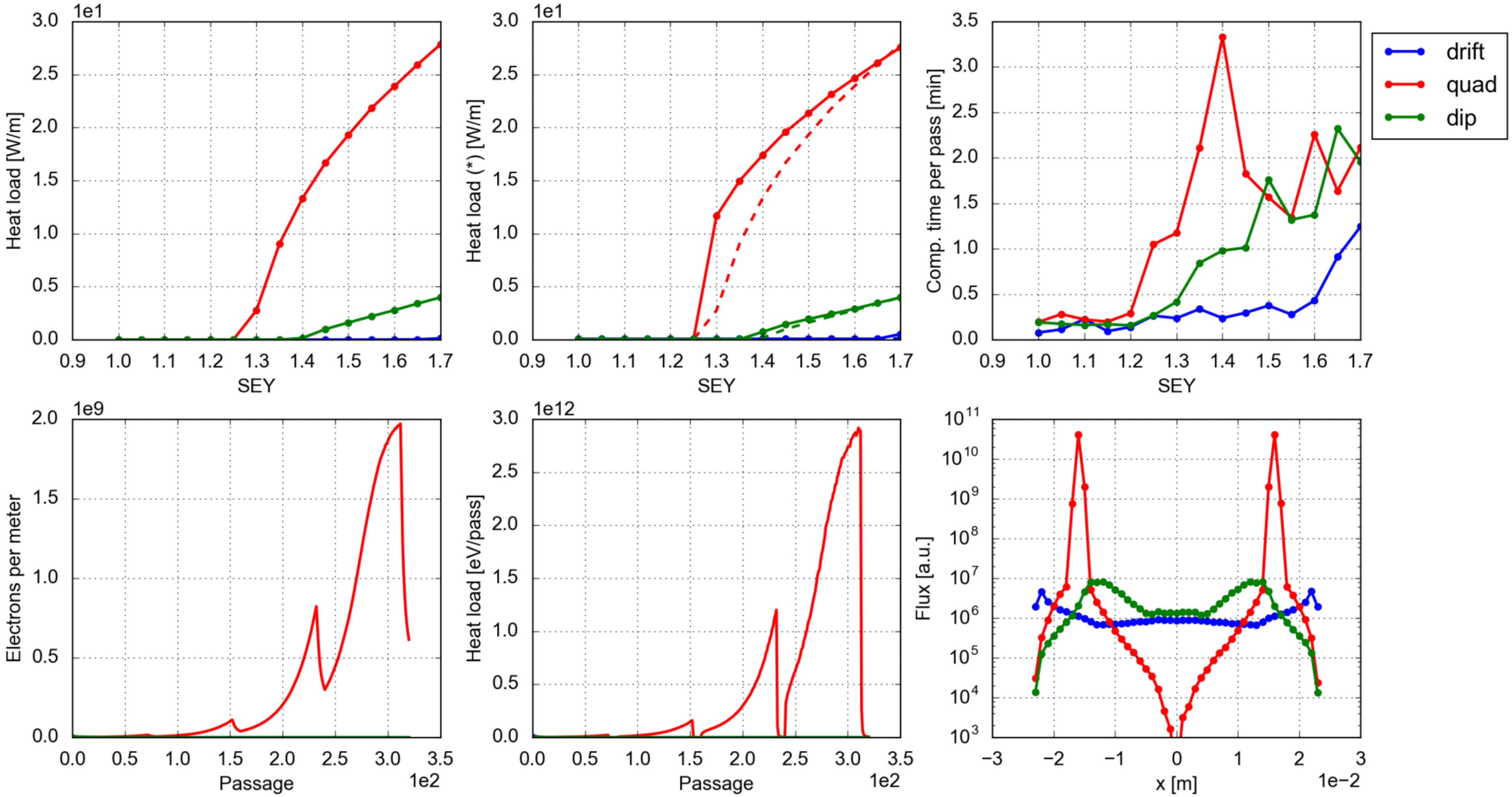
- **Heat load from impedance and e-cloud** has been estimated for all the 2-aperture magnets of the LHC Insertion Regions
- The obtained values will have **to be discussed together with the WP9** team in order to identify possible local limitations, to be mitigated with surface treatment of the beam screens
- The **experimental IRs** are by far the most critical, with heat loads of ~**1 kW per side** (including ITs)
  - From the **arcs** we expect heat loads of the order of **7.3 kW per arc (with no e-cloud in dipoles)**
  - In **S12, S23, S78 and S81** the total load goes beyond **8 kW**
    → Very little marging for e-cloud in dipoles (which will be there after Long Shutdowns)
- The impact of a **bunch length** increase to 1.3 ns is **very small**

Thanks for your attention!

BSMQ_1, quad., for the details 2.20e11ppb

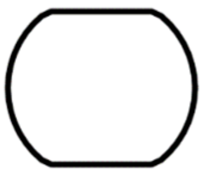


BSMQ_1, 2.20e11 ppb, for the details SEY=1.30



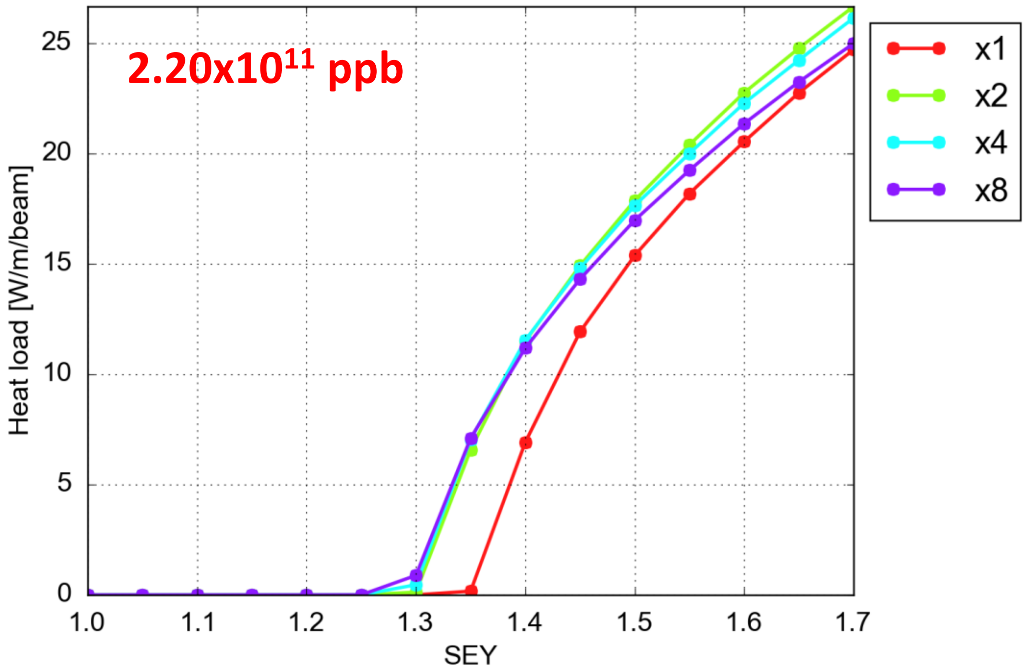
Beam screens in matching quadrupoles (Type 1)

BSMQ_1



(22.5, 17.6) mm

- Beam screen shape **very similar to that of the LHC arcs**
- The dependence on the **magnetic gradient** is quite weak
- The increase in bunch intensity causes a **slight decrease of the electron flux** and **a slight increase of the multipacting threshold**
- For large SEY the **heat load is stronger for HL-LHC intensity**
- e-cloud mitigation through **scrubbing, low SEY coating (a-C) and/or clearing electrodes is needed** to operate within the cryo cooling capacity
- The dependence on the beam size is quite weak



Beam size factor

w.r.t. fully squeezed round optics

From KEK presentation

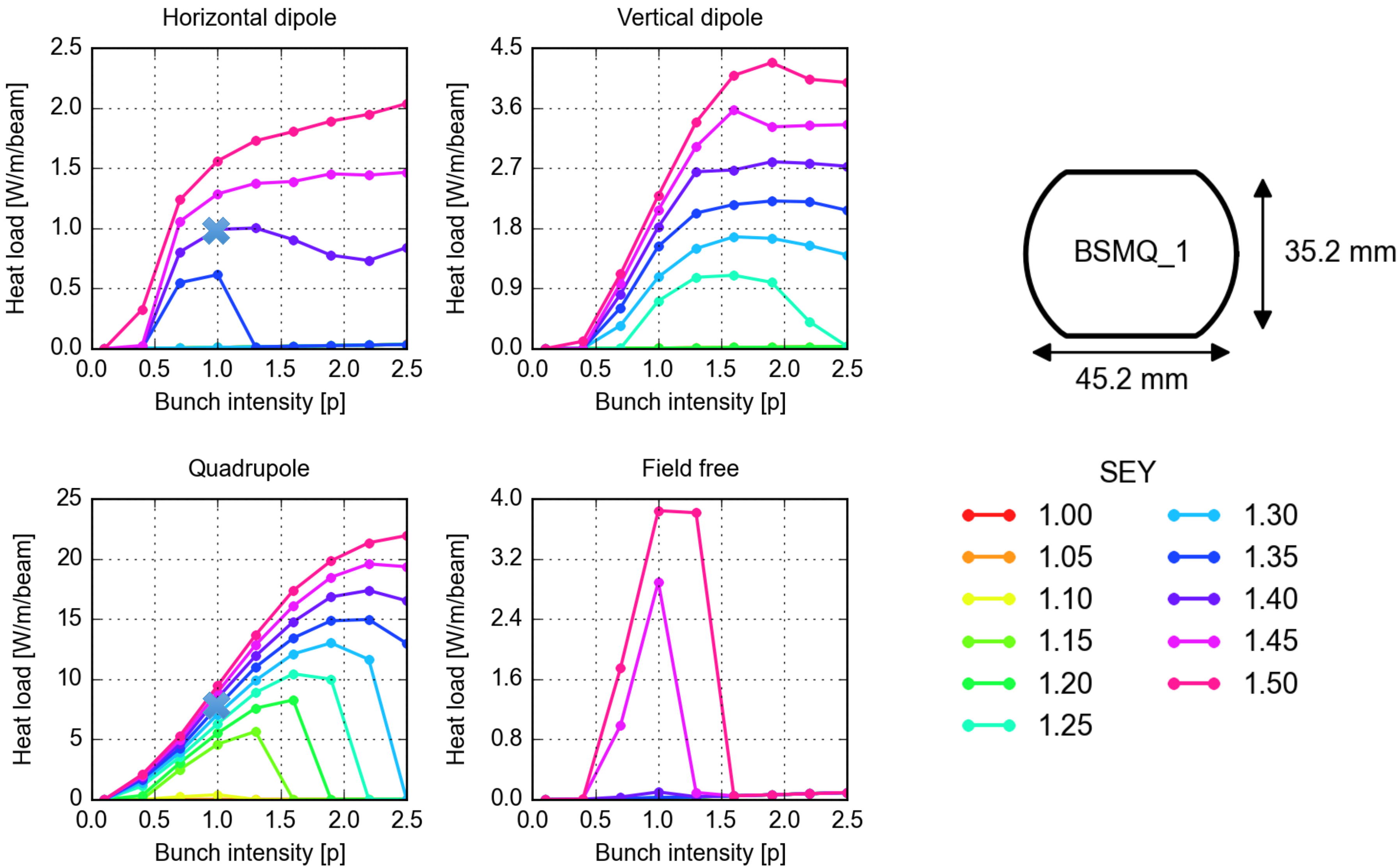
Sector 12:

LSS excluding triplets (SEY = 1.3)
LSS R1 = **631 W**
LSS L2 = **742 W**

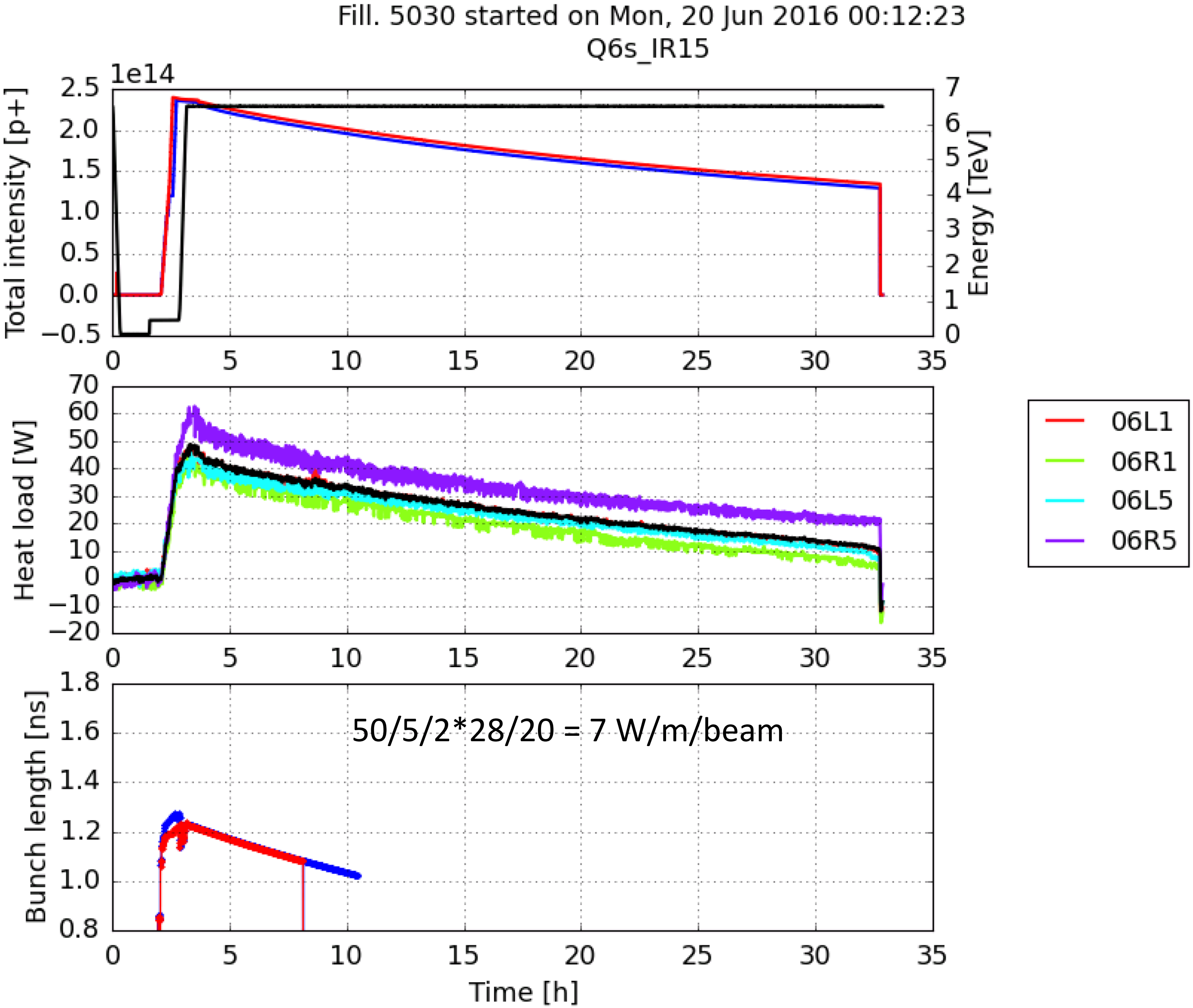
Triplets (SEY = 1.1, rescaling the load from the quads to the full length)
R1 = 160./(4*4.2+2*7.15+6.27)*64.3 = **275 W**
L2 = 150./(2*6.3+2*5.5+9.45)*45 = **204 W**

Total LSS L2 (including trieplets) = 950W
Total synchrotron radiation = 3000 W (70 W/hc)
Total impedance = 2400 W (50 W/hc)
Total e-cloud in quads (SEY 1.3) = 1900 W (42 W/hc)

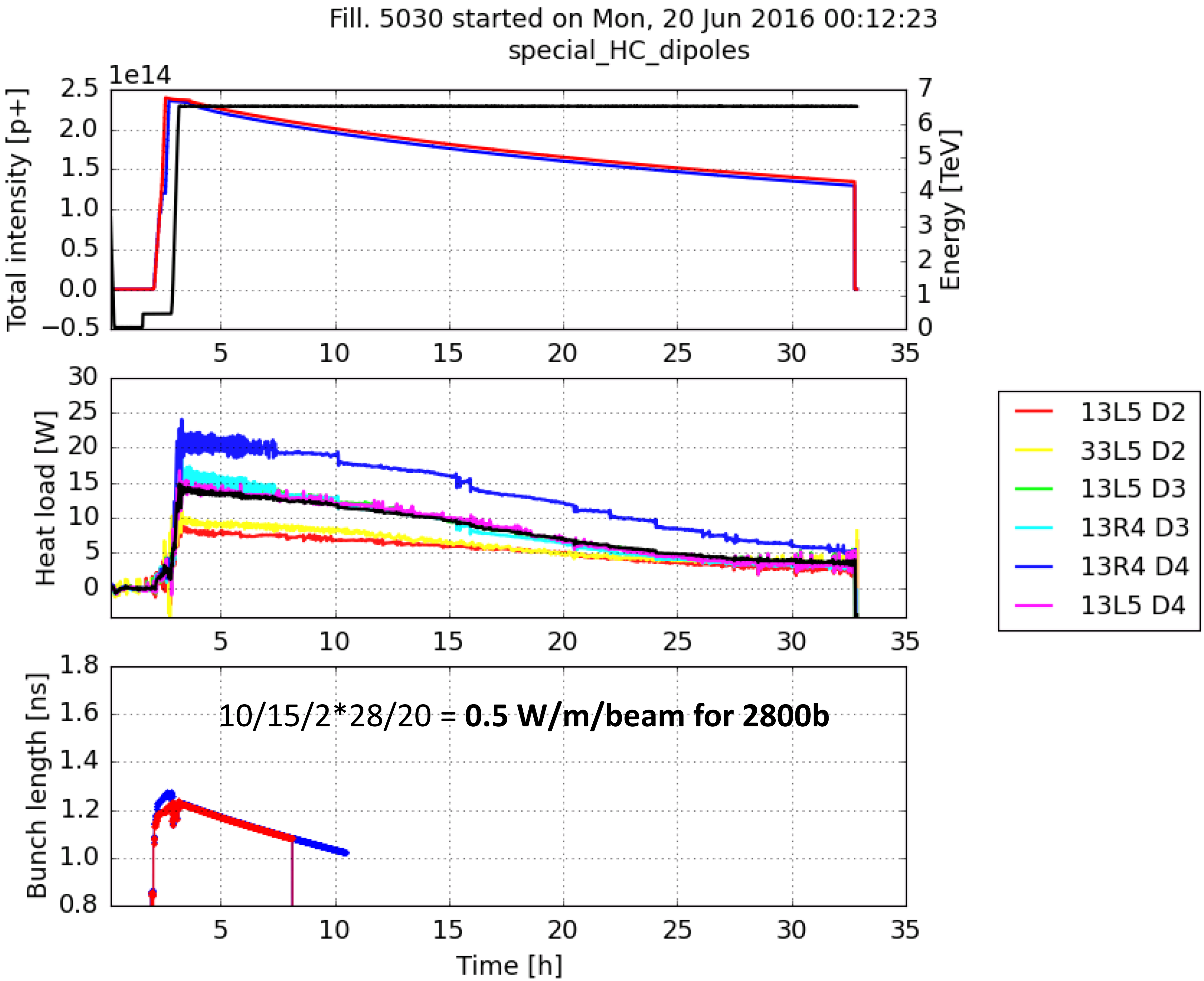
Total Sector 12 (does not include LSS R1) ~8250 W (without any e-cloud in the dipoles!)



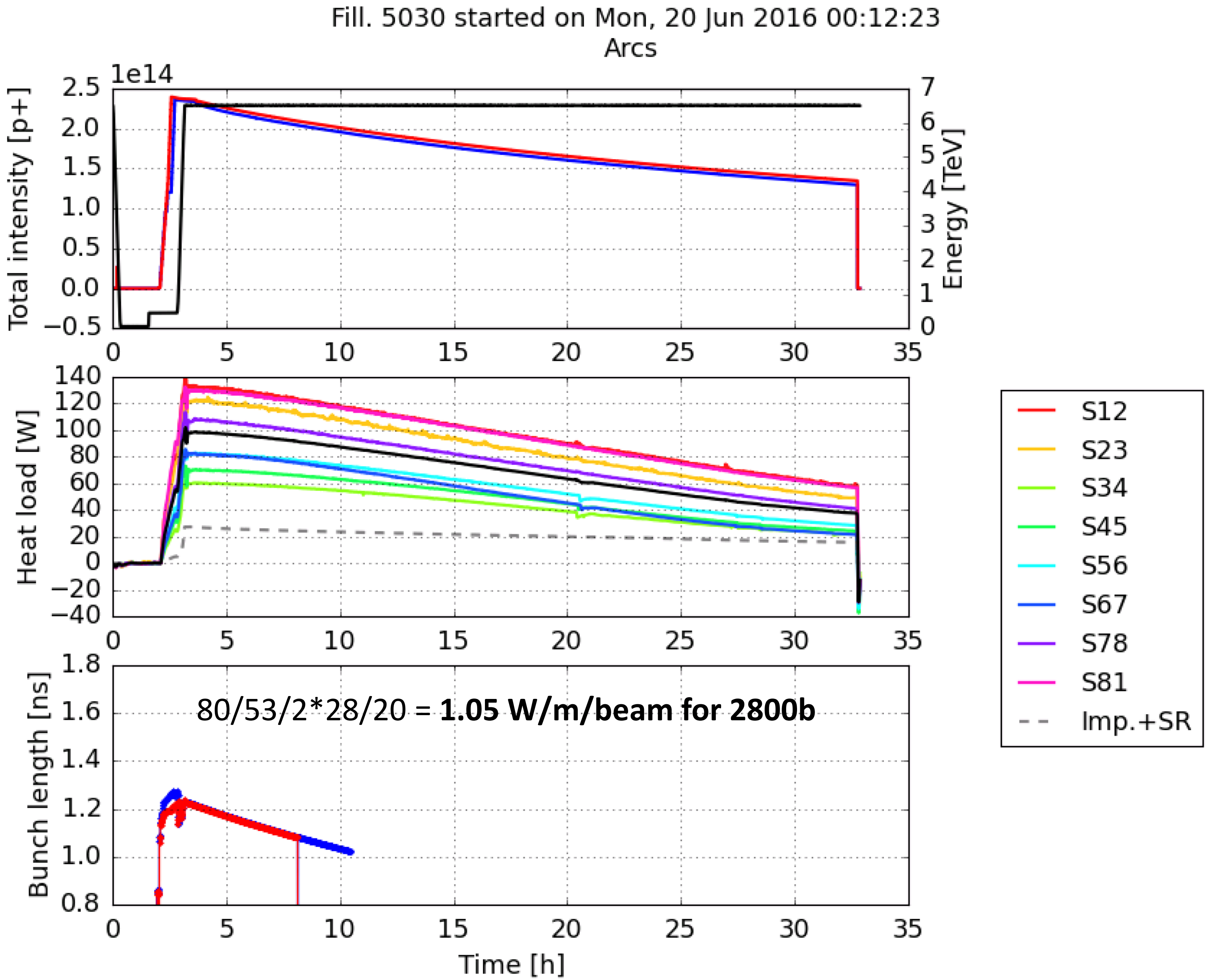
Horizontal dipole
Vertical dipole
Quadrupole
Field free
Heat load [W/m/beam]
Bunch intensity [p]
BSMQ_1
35.2 mm
45.2 mm
SEY
1.00
1.05
1.10
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50



Fill. 5030 started on Mon, 20 Jun 2016 00:12:23
Q6s_IR15
1e14
Total intensity [p+]
Energy [TeV]
Heat load [W]
06L1
06R1
06L5
06R5
Bunch length [ns]
50/5/2*28/20 = 7 W/m/beam
Time [h]



Fill. 5030 started on Mon, 20 Jun 2016 00:12:23
special_HC_dipoles
1e14
Total intensity [p+]
Energy [TeV]
Heat load [W]
13L5 D2
33L5 D2
13L5 D3
13R4 D3
13R4 D4
13L5 D4
Bunch length [ns]
10/15/2*28/20 = **0.5 W/m/beam for 2800b**
Time [h]

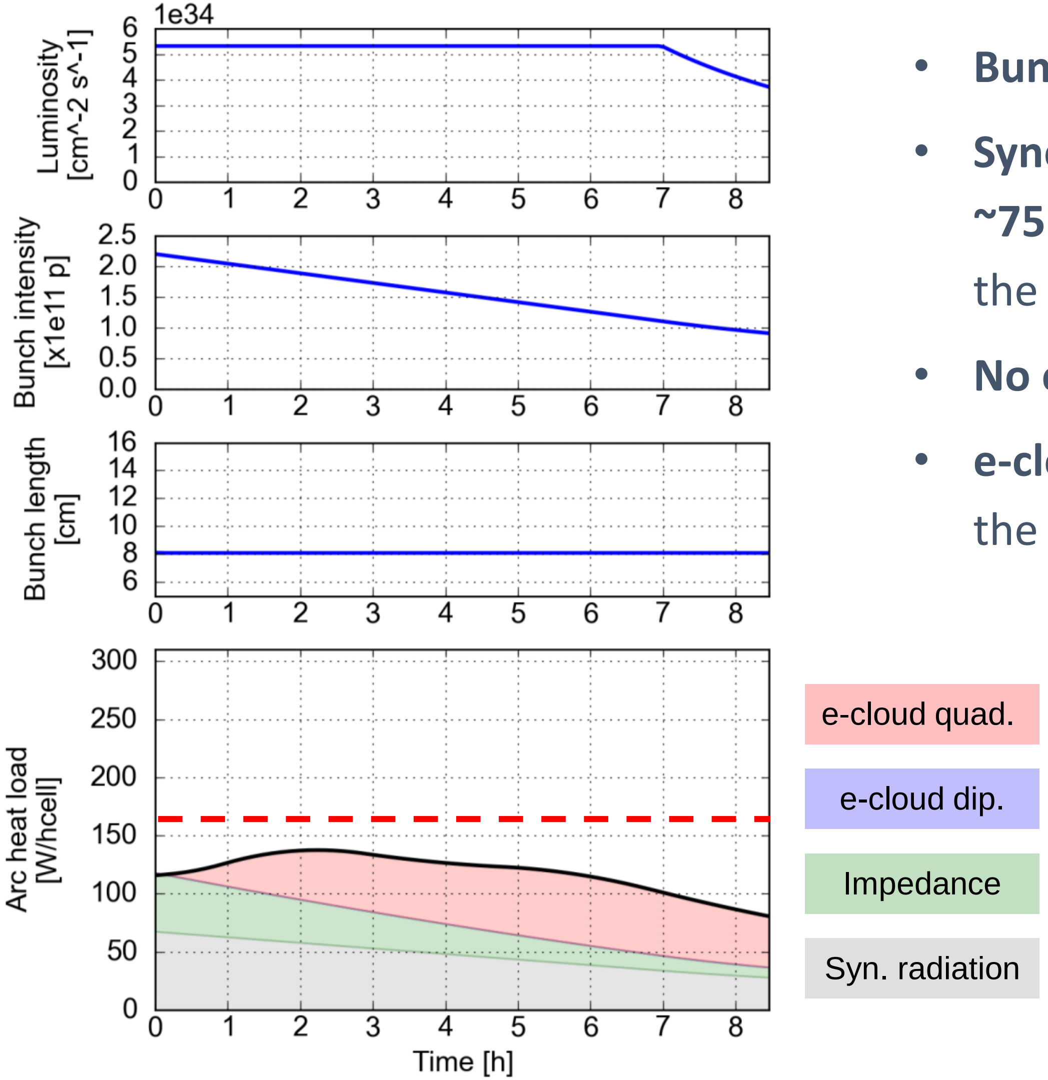


Fill. 5030 started on Mon, 20 Jun 2016 00:12:23
Arcs
1e14
Total intensity [p+]
Energy [TeV]
Heat load [W]
Bunch length [ns]
Time [h]
S12
S23
S34
S45
S56
S67
S78
S81
Imp.+SR
80/53/2*28/20 = **1.05 W/m/beam for 2800b**

Scenario 1 – e-cloud suppression achieved in dipoles

Assumption: $SEY_{dip} = SEY_{quad} = \mathbf{1.30}$

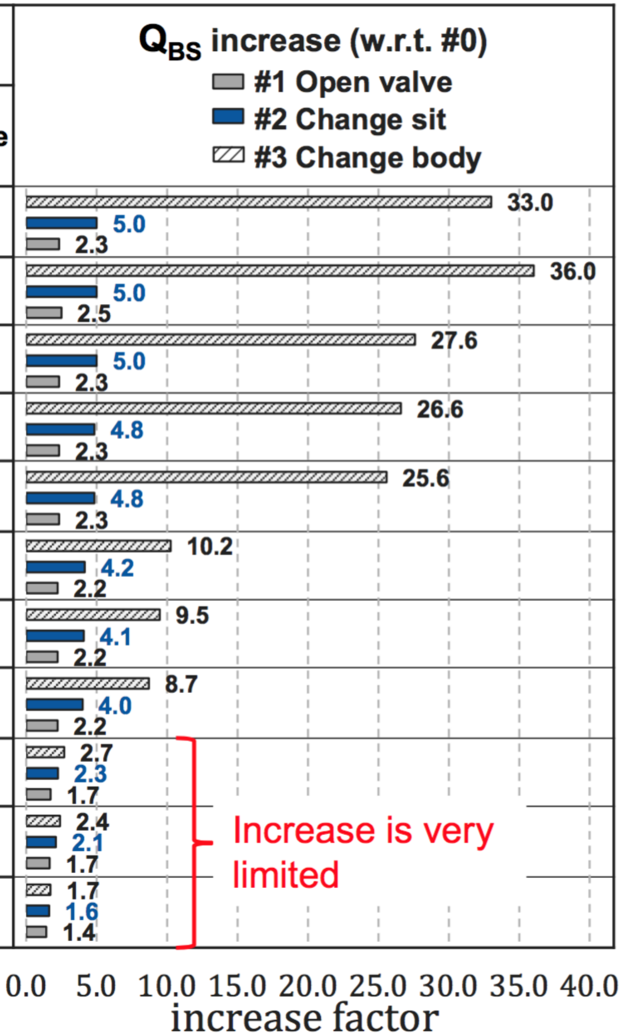
HL-LHC baseline (400 MHz)



- **Bunch length** is kept constant at 8 cm
- **Synchrotron radiation and impedance** take **~75 %** of the available cooling capacity at the beginning of the fill
- **No e-cloud in dipoles** all along the fill
- **e-cloud in the quadrupoles** appears with the decrease in intensity

Capacity increase for the different magnet types

Type	Inventory				Length [m]	Q_{BS} [W/m per aperture] #0 Op80%	#1 Op100%	#2 Change sit	#3 Change body
SAM Type 1	Q5 L/R1	Q5 L/R5	Q6 L/R1	Q6 L/R5	8.2	3.1	7.3	15.5	102.6
SAM Type 2	Q6 L/R4	Q4 L/R6	Q5 L/R6		6.9	3.7	9.2	18.5	133.1
	D3 L/R4				11.2	2.3	5.3	11.4	62.8
	Q6 L/R2	Q6 L/R3	Q6 L/R7	Q6 L/R8	12	2.1	5.0	10.3	56.5
	Q5L2	Q5R2	Q5L8	Q5R8	13	2.0	4.6	9.5	50.2
Semi-SAM	Q5D4L4	D4Q5R4			16.7	3.3	7.4	13.8	33.9
	Q4D2L1	D2Q4R1	Q4D2L5	D2Q4R5	19.4	2.8	6.4	11.6	27.0
	Q4D2L2	Q4D2R2	Q4D2L8	Q4D2R8	22.8	2.4	5.4	9.7	21.1
IT	IT L/R1	IT L/R5			35	4.0	6.9	9.0	10.8
	IT L/R2	IT L/R8			45	3.0	5.0	6.4	7.2
Arc half cell	all sectors				53.5	3.3	4.6	5.3	5.6



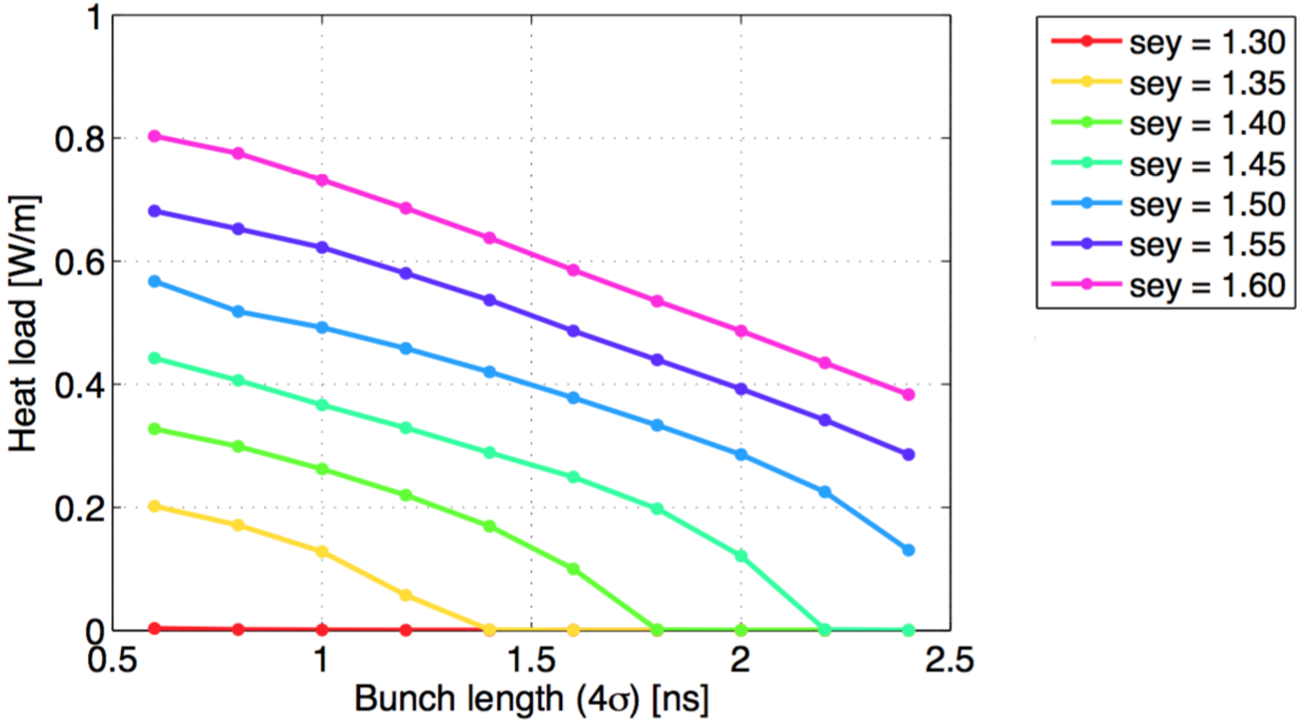
LSS2 & LSS8

Gain in cooling capacity differs from case to case

- IT & ArcCells are limited by Δp at the circuit
  → Parallelization of the BS channels proposed in previous slides
- SAMs and semi-SAMs present more margin to increase.

Bunch length reduction: heat loads

For a sample bunch train

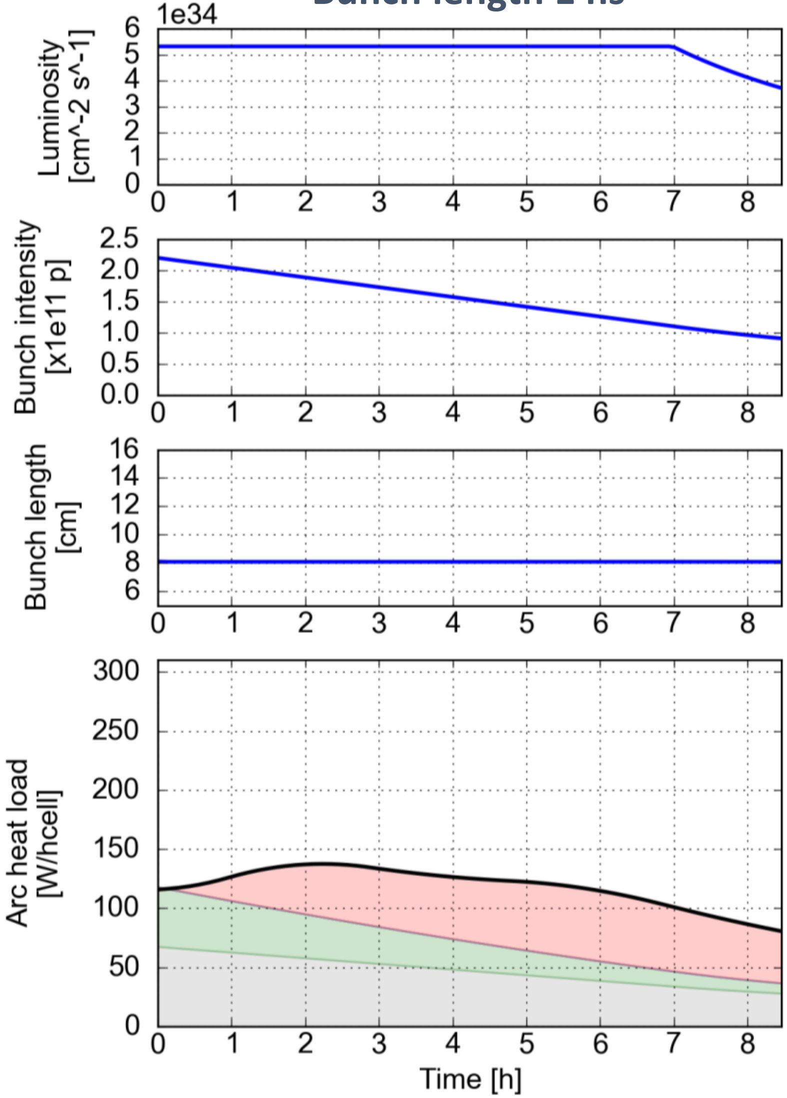


Heat load in the arcs: bunch length 1.0 ns vs 1.3 ns

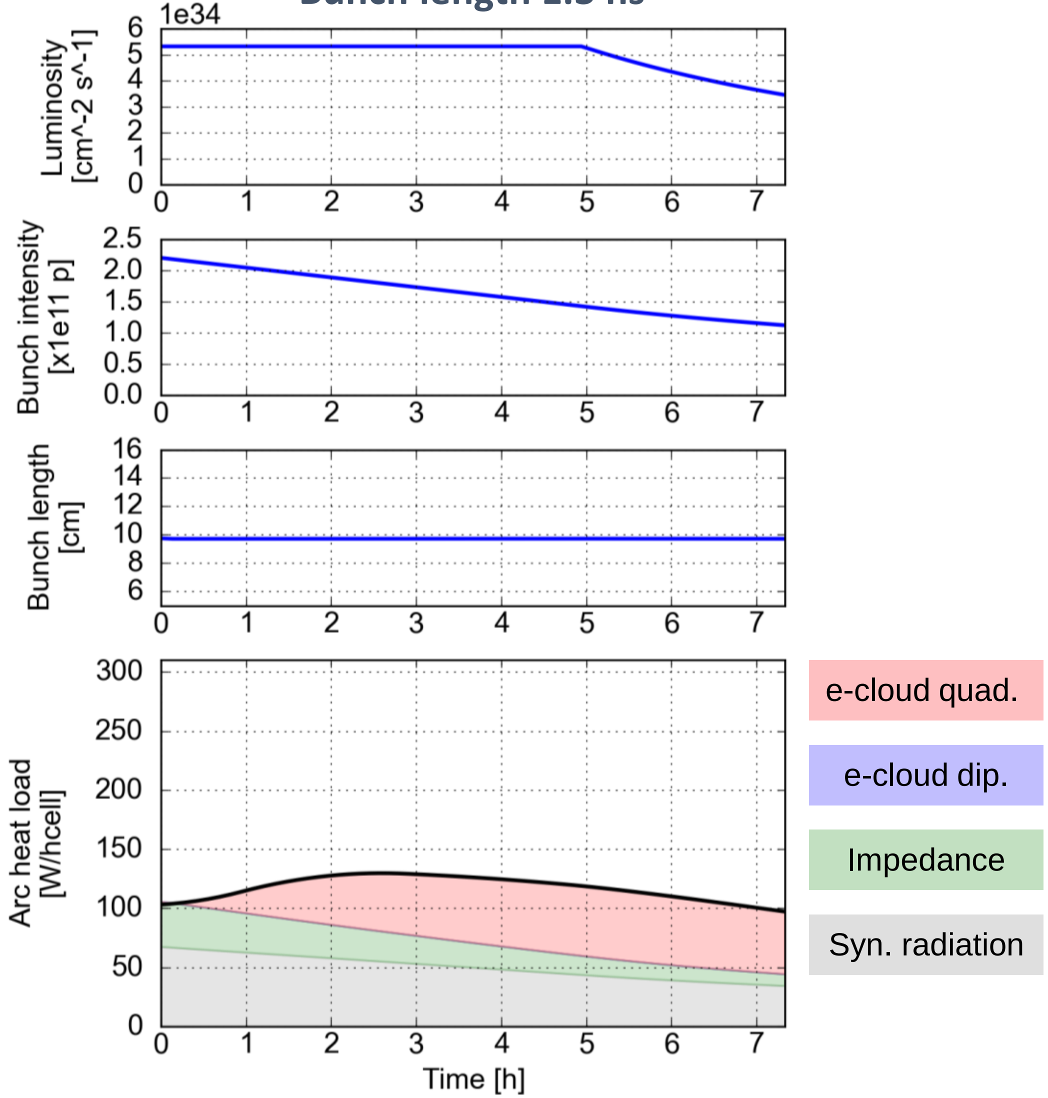
$SEY_{dip} = SEY_{quad}$ = **1.30**

- **Very small change**

Bunch length 1 ns



Bunch length 1.3 ns



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