Beam induced heat load in the cold elements of the IRs

G. Iadarola, E. Metral, G. Rumolo, C. Zannini

Acknowledgments:

G. Arduini, R. De Maria, L. Mether, R. Tomas

4th Joint HiLumi LHC - LARP Annual Meeting, 17-21 November 2014, KEK, Japan

Outline

- **Introduction**
- **Heat load from the beam screen impedance**
- **Heat load from e-cloud effects**
- **Estimation results:**
    - Matching quadrupoles
    - Separation dipoles
    - Inner triplets
    - TAXS absorber

Beam induced heat load in the IRs cold magnets

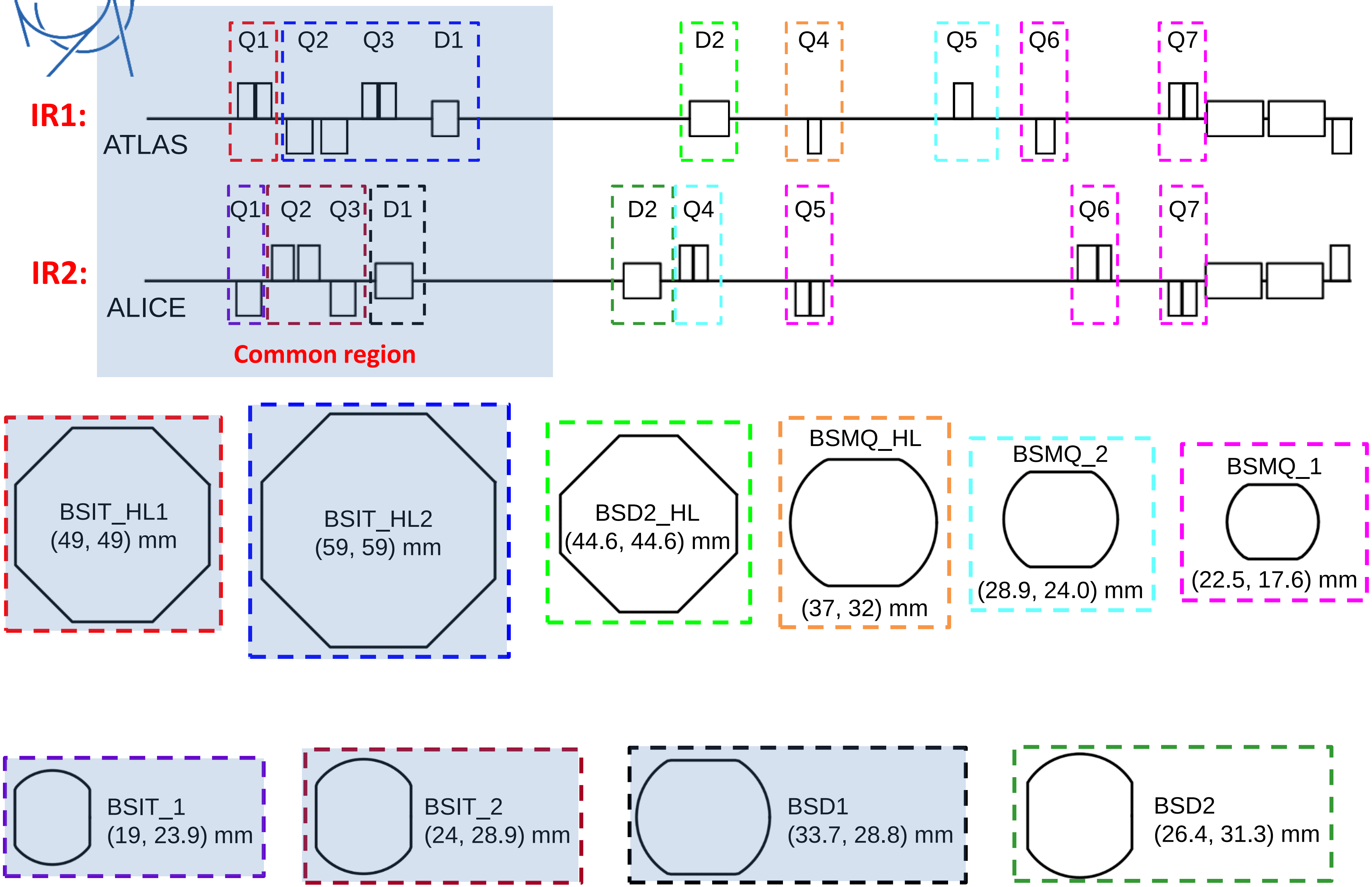
- **Beam induced heating** on the **beam screen of the superconducting magnets** of the experimental IRs come mainly from:
  - **Longitudinal impedance** of the beam screens
  - **Electron cloud** effects

  (**Synchrotron radiation** contribution results to be negligible in the IRs, see A. Rossi and F. Zimmermann, LHC Project Report 675)

- **Impedance and electron cloud studies** are being conduced within Task 2.4 in order to **estimate the expected heat load** in each device and **identify possible performance bottlenecks**

- Special care in the calculation had to be taken for the devices installed in the **common regions** (where the two beams share the same chamber) i.e. the Inner Triplets and the D1 dipoles

Beam screen geometries in the IRs (HL-LHC)



Semi-apertures, beam screens can be rotated

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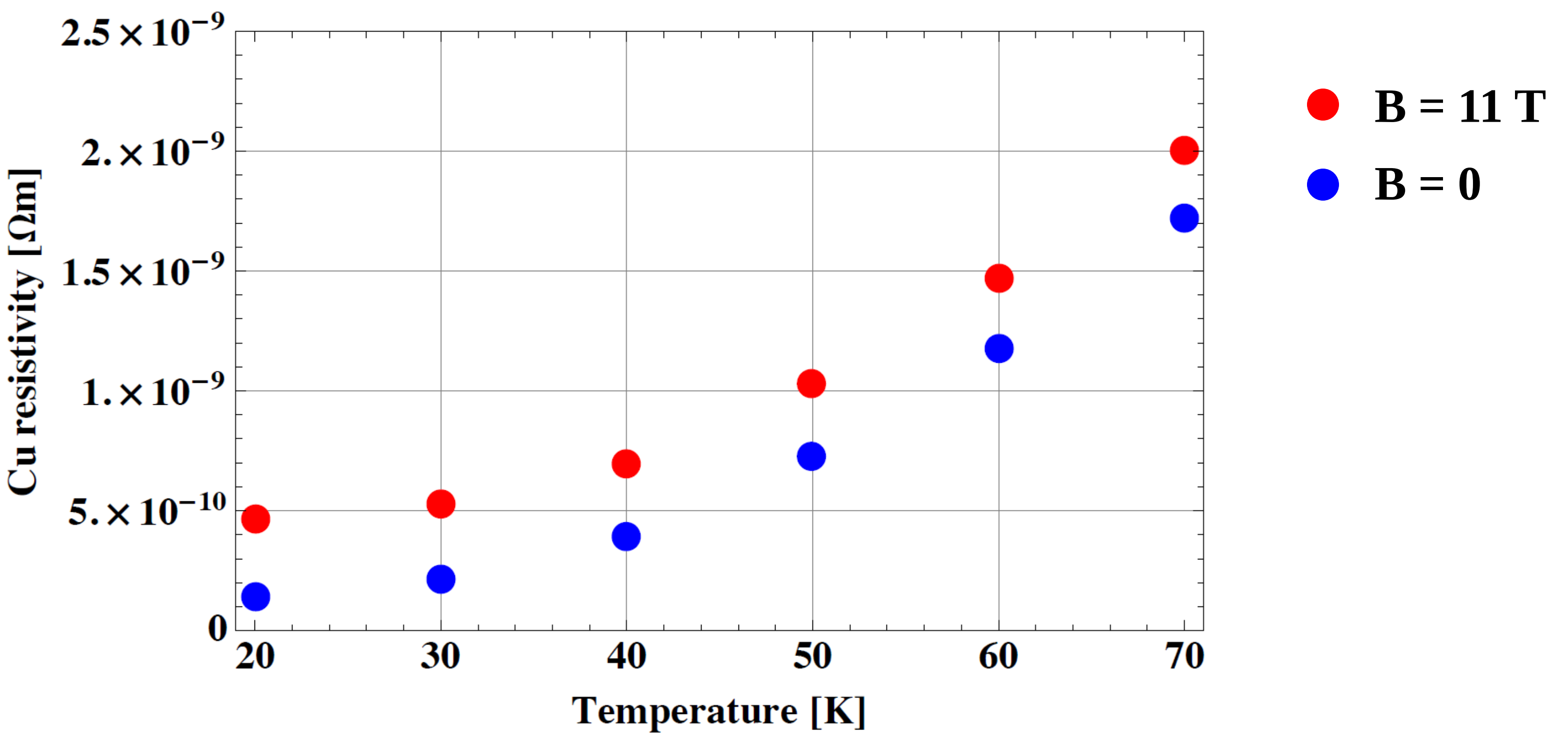
Heat load from the beam screen impedance

E. Metral and C. Zannini

Several **non idealities** have been taken into account:

- Dependence of the beam screen **resistivity** on:
  - Operating **temperature**
  - Applied **magnetic field** (magneto-resistance effect)



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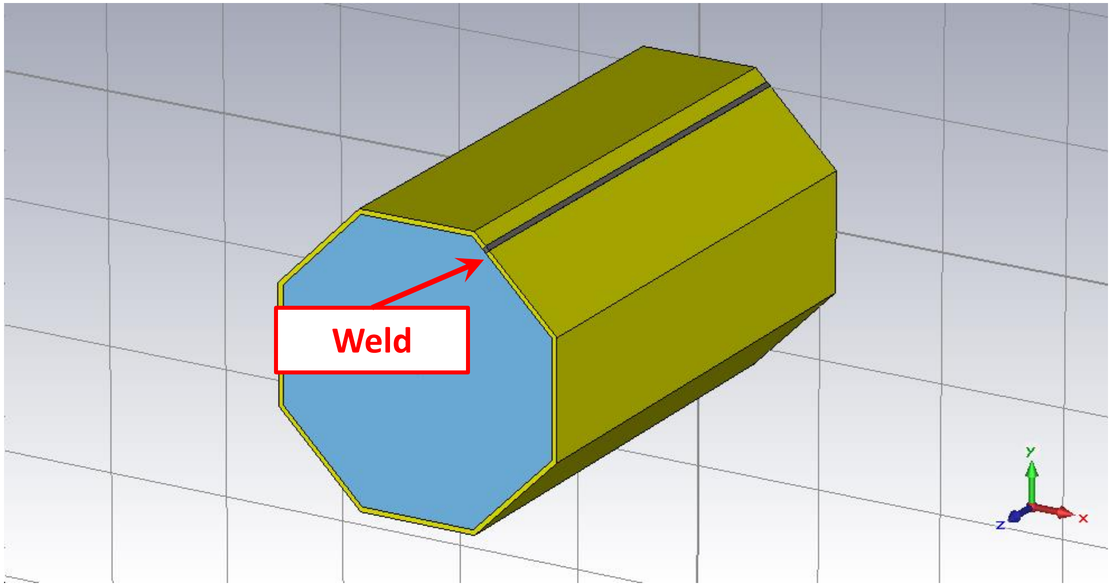

Heat load from the beam screen impedance

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Several **non idealities** have been taken into account:

- Dependence of the beam screen **resistivity** on:
  - Operating **temperature**
  - Applied **magnetic field** (magneto-resistance effect)
- **Weld** in the beam screen
- Presence of the **two (off-centered) counter-rotating beams** in the same beam screen (for Inner Triplets and D1 dipoles)

The calculations done with the **simple formula** (1 layer of Cu, 1 beam) have been crosschecked using **full time domain simulations** (done with CST® Particle Studio) and a **newly developed formula** for heat load evaluation in the common regions

$$\Delta W(s) = \left(\frac{\omega_0}{\pi}\right)^2 \sum_{p=0}^{\infty} |\Lambda(p\omega_0)|^2 \left\{ \mathrm{Re}\left[Z_{||}^0(p\omega_0)\right] + [\Delta y_1(s) + \Delta y_2(s)]\, \mathrm{Re}\left[Z_{||}^1(p\omega_0)\right] \right\} (1 - \cos p\omega_0\tau_s)$$

Heat load density at section s

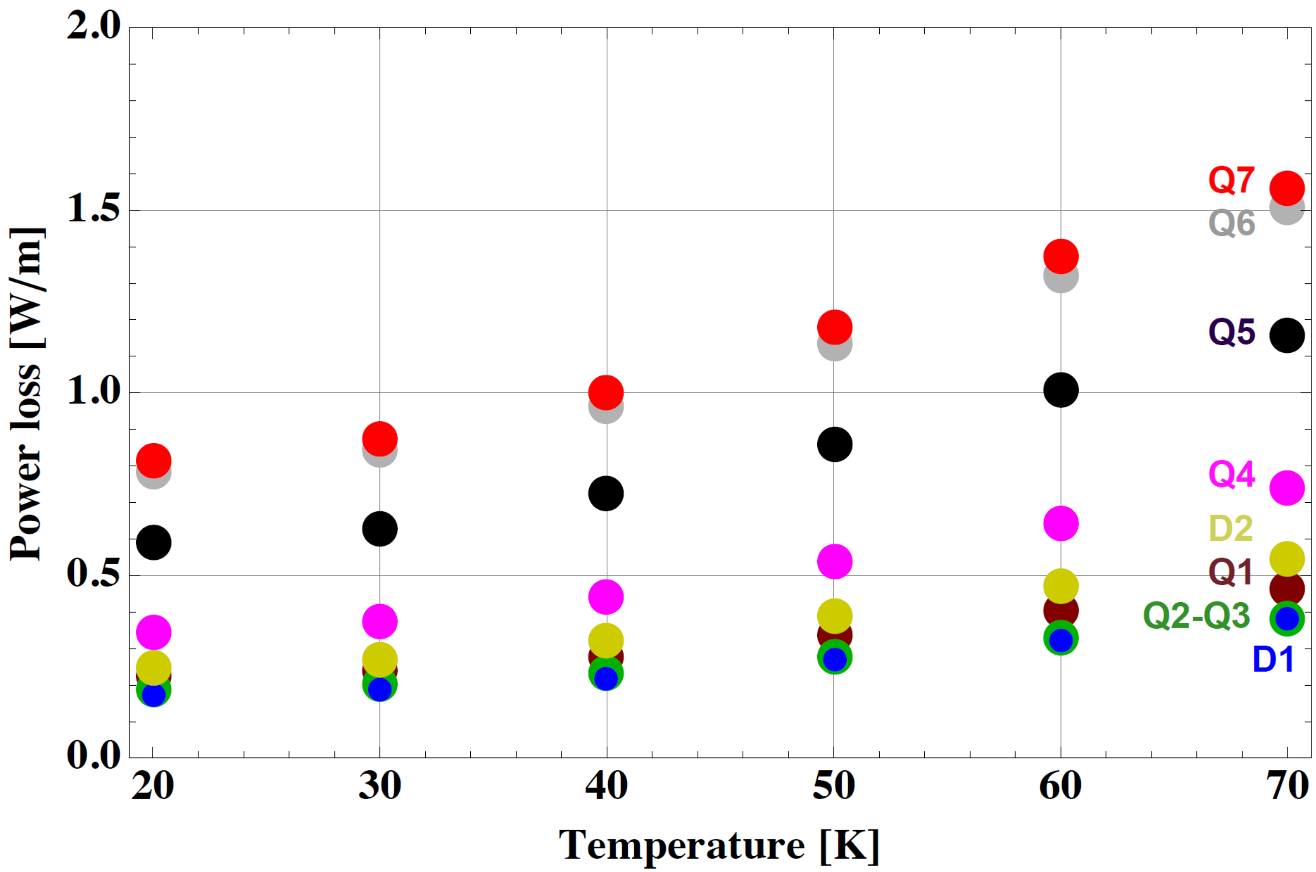
Delay between the two beams at section s

Heat load from the beam screen impedance

E. Metral and C. Zannini

Impact of the **operating temperature** up to about **factor 2**

Values **well within the available cooling capacity** (4.8 W/m)



For details, see E. Metral and C. Zannini, "Temperature effects on image current losses in the triplets", 33rd HiLumi WP2 Task Leader Meeting, Friday, September 5, 2014

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Heat load due to electron cloud: experience

Already during **Run 1** electron cloud effects were observed in most of the cold magnets of the LHC including the dipoles and quadrupoles in the IRs

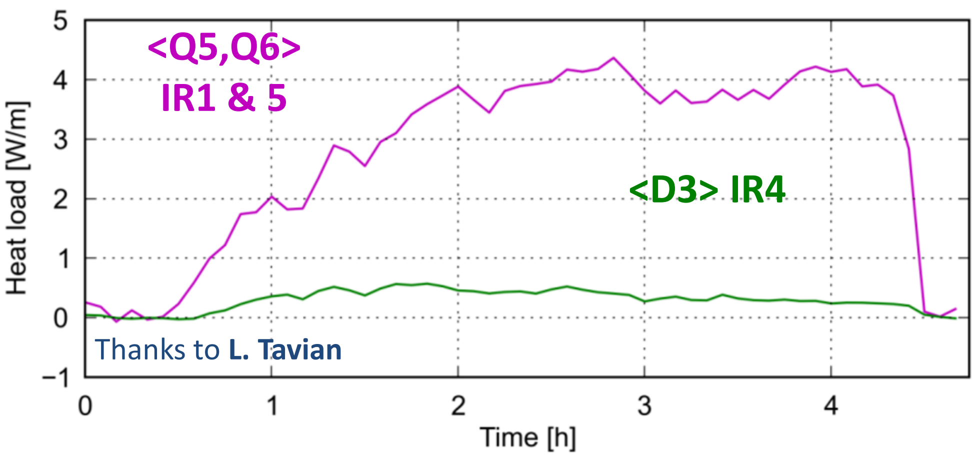
→ Strong **heat load measured by the cryogenic system**

With **50 ns bunch** spacing the e-cloud could be fully suppressed **by beam induced scrubbing** (i.e. SEY reduction due to electron bombardment) in most of the machine

→ e-cloud was still present in the **inner triplets** (with two circulating beams)

With **25 ns spacing**, scrubbing runs performed in 2011 and 2012 (~5 days in total) allowed to achieve a strong **mitigation of the e-cloud but not its full suppression**

→ During the tests with 25 ns beams (2012), the heat load in the **Q5 and Q6 matching quadrupoles** was **at the limit of the available cooling capacity** and was limiting the number of nominal bunches that could be stored in the LHC



Heat load due to electron cloud: HL-LHC studies

We launched a **PyECLOUD simulation campaign** in order to estimate the **heat load** expected from electron cloud in each device as a function of **the Secondary Electron Yield (SEY)** of the beam screen surface

→ This will help us to decide where we need to put in place **SEY reduction through amorphous carbon (a-C) coating**, developed by TE-VSC at CERN and presently tested with beam at cryogenic temperature in the COLDEX experiment at the SPS

For this study we profited of several **improvements we implemented in the PyECLOUD** code during 2014, the most important being:

→ **Accurate (phase space volume preserving) tracking algorithm**, crucial for accurate electron tracking in a strong quadrupolar field

→ Accurate modeling of the realistic **boundary shape in the Poisson solver** (Shortley-Weller approach)

→ Systematic **convergence studies** to understand the numerical properties of the newly implemented algorithms

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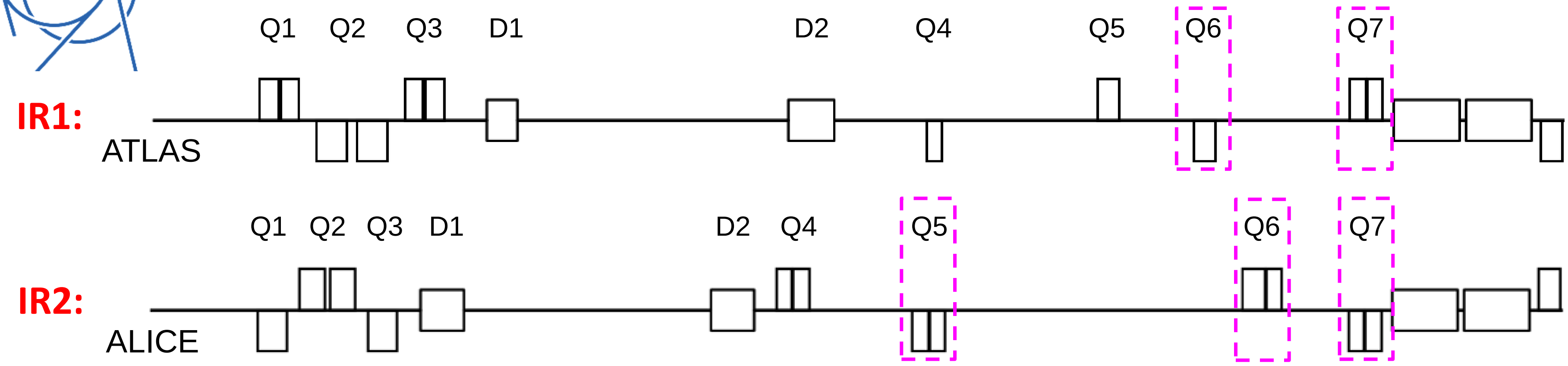
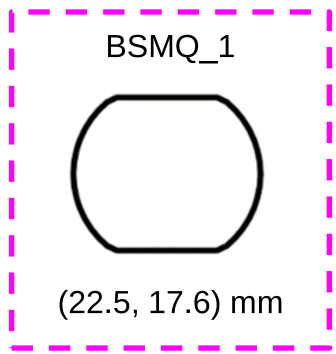
Beam screens in matching quadrupoles (Type 1)





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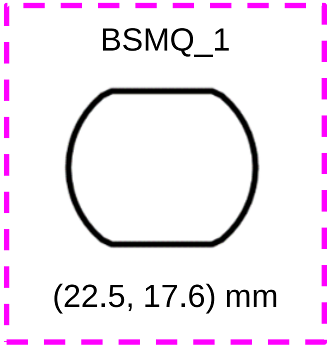
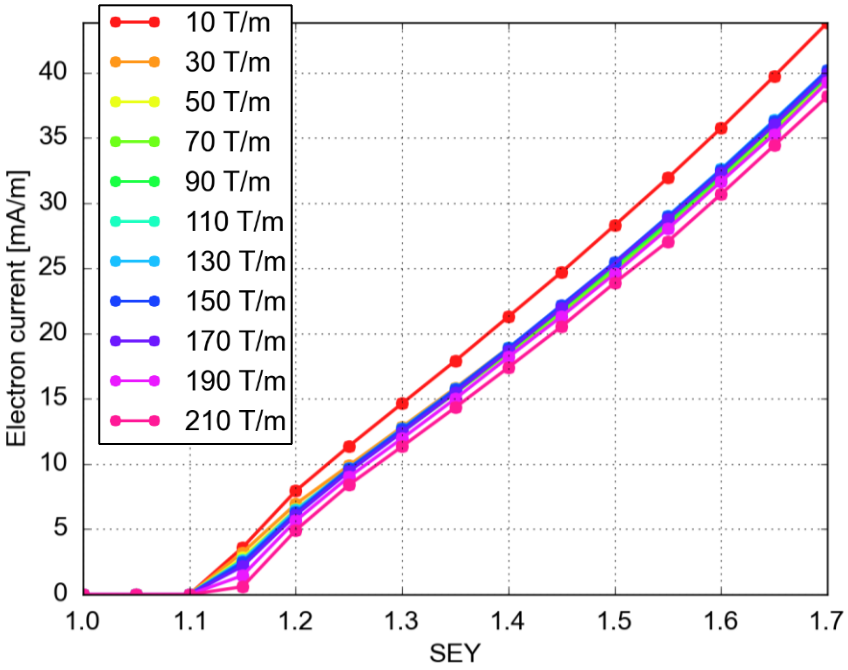
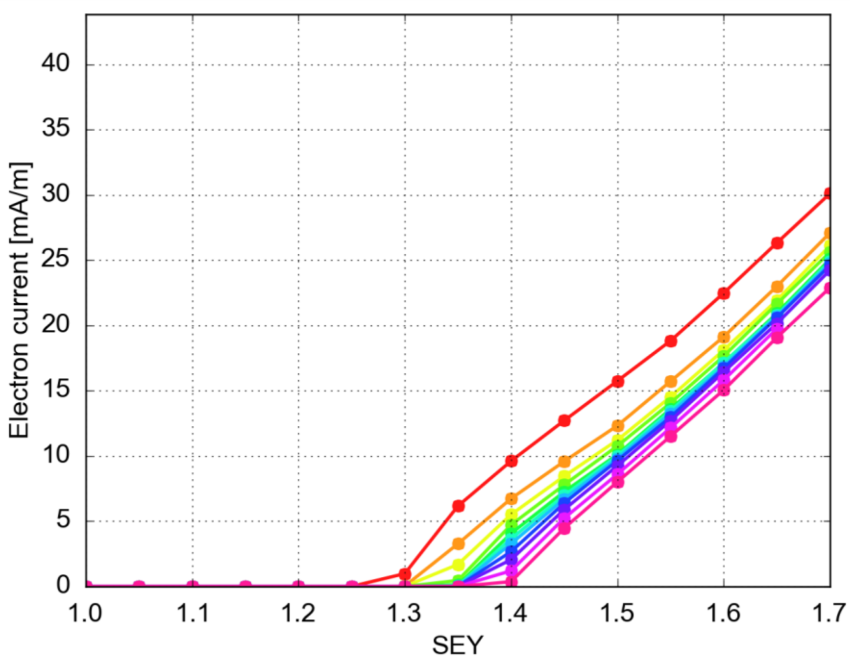


- Beam screen shape **very similar to that of the LHC arcs**
- The dependence on the **magnetic gradient** is quite weak
- The increase in bunch intensity causes a **slight decrease of the electron flux** and **a slight increase of the multipacting threshold**

1.15×10^{11} ppb



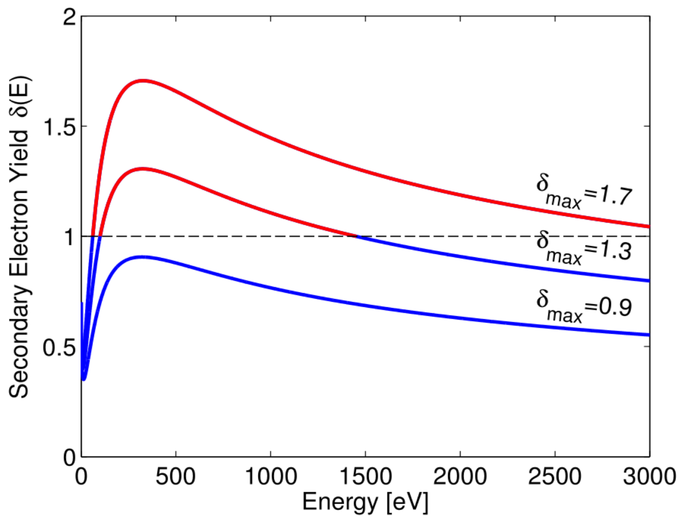
2.20×10^{11} ppb



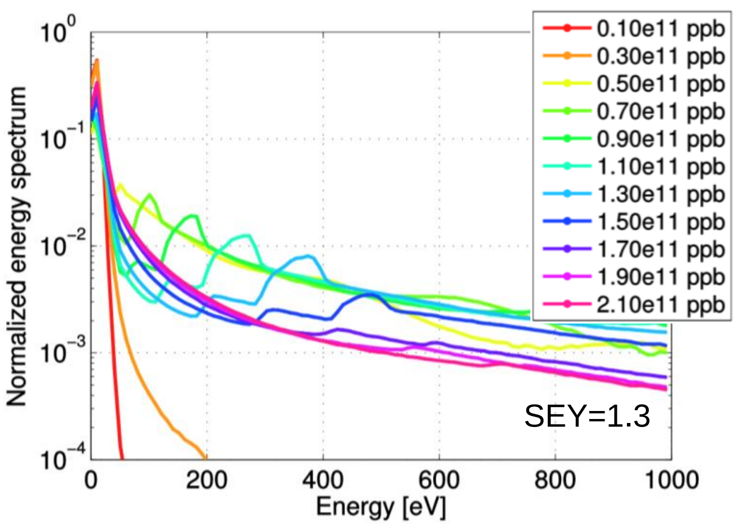
Beam screens in matching quadrupoles (Type 1)

Underlying mechanism:

When the SEY decreases the **energy window for multipacting** becomes narrower



For high bunch intensity the e- spectrum drifts to higher energies and can move outside the most efficient region



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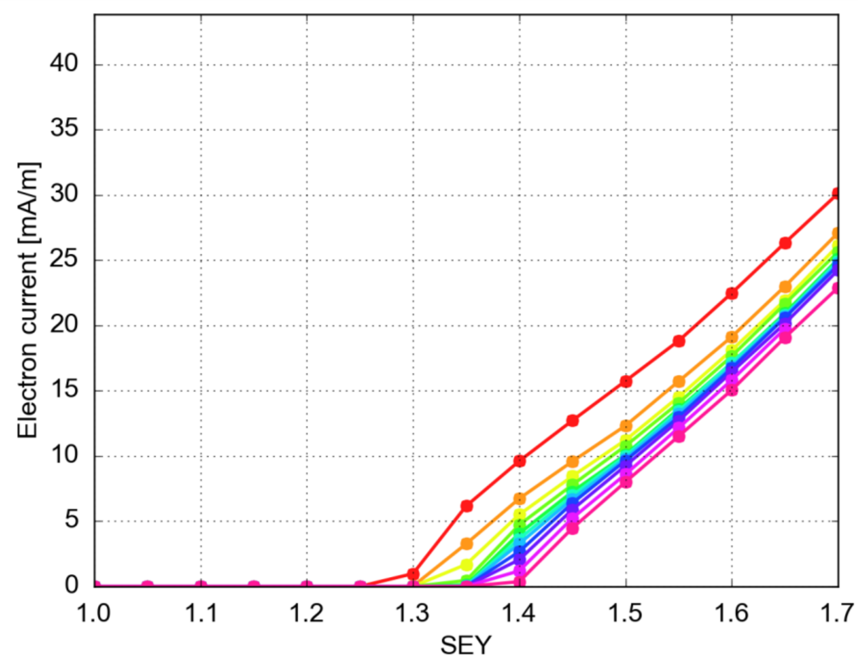

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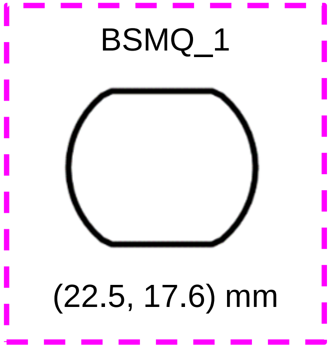

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- e-cloud mitigation through **scrubbing, low SEY coating (a-C) and/or clearing electrodes is needed** to operate within the cryo cooling capacity

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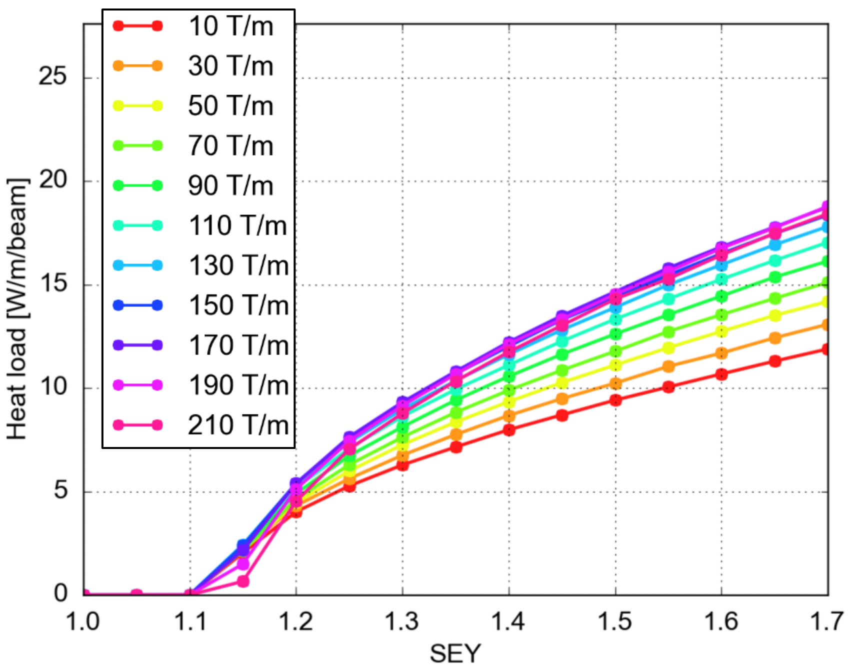

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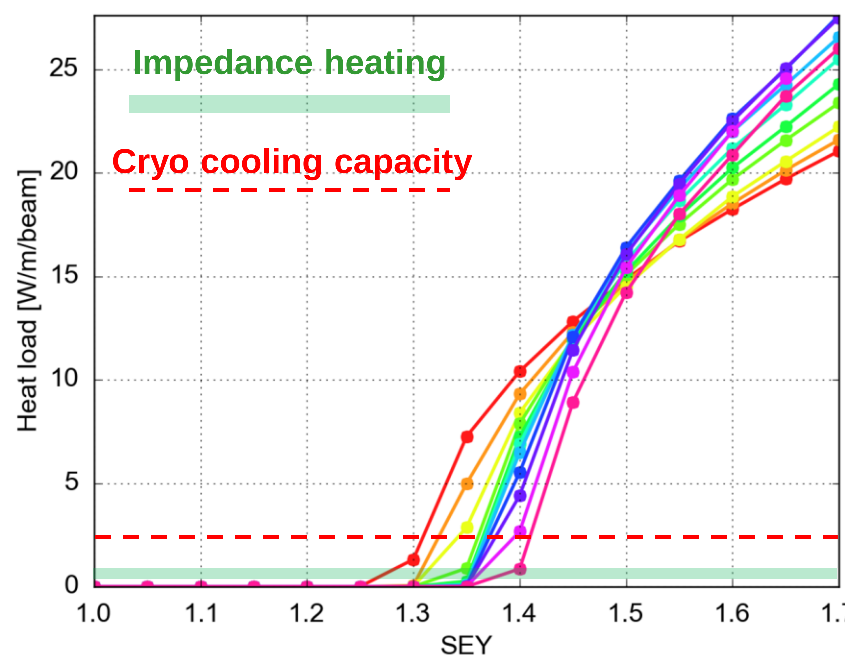

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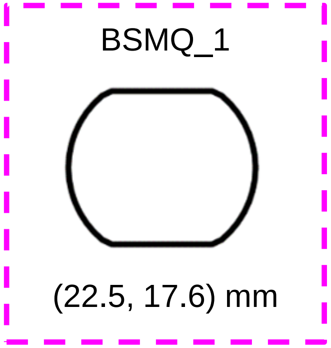

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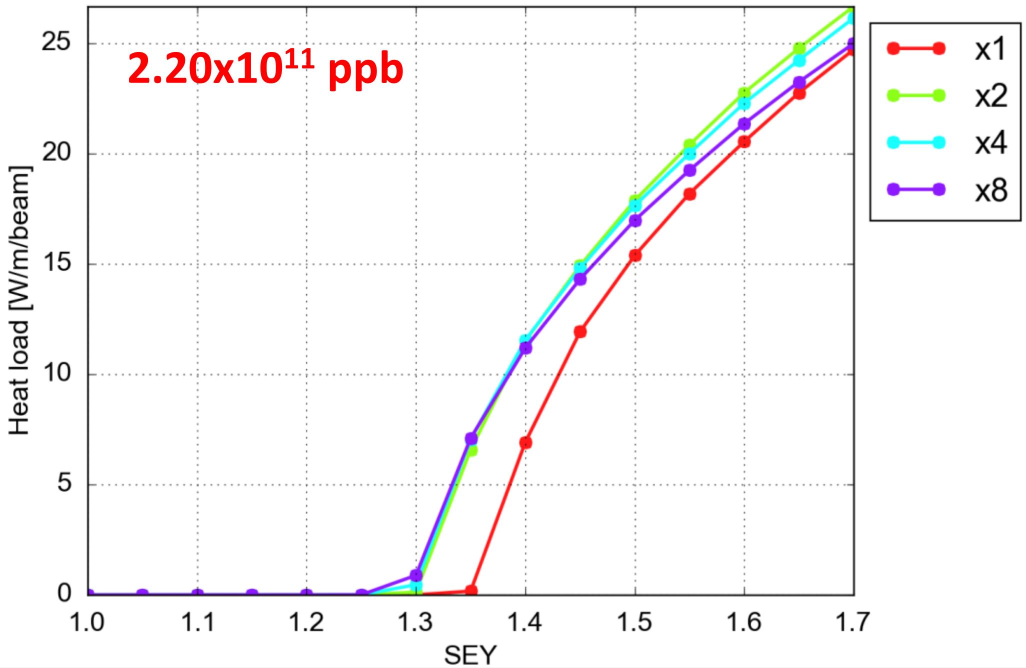
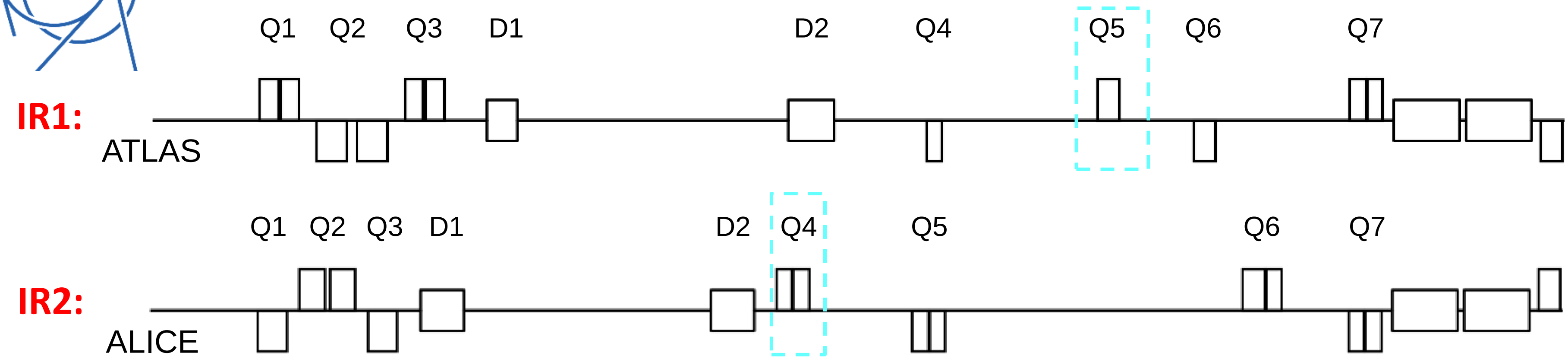
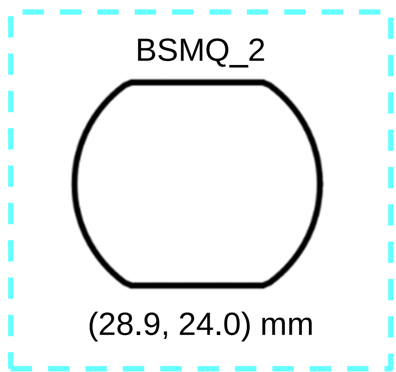


Beam size factor

w.r.t. fully squeezed round optics

Beam screens in matching quadrupoles (Type 2)





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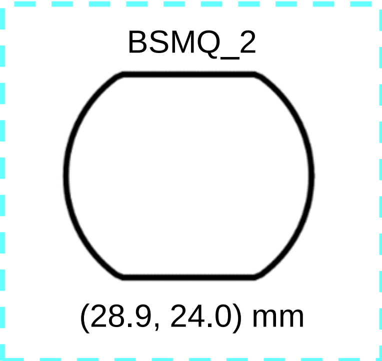

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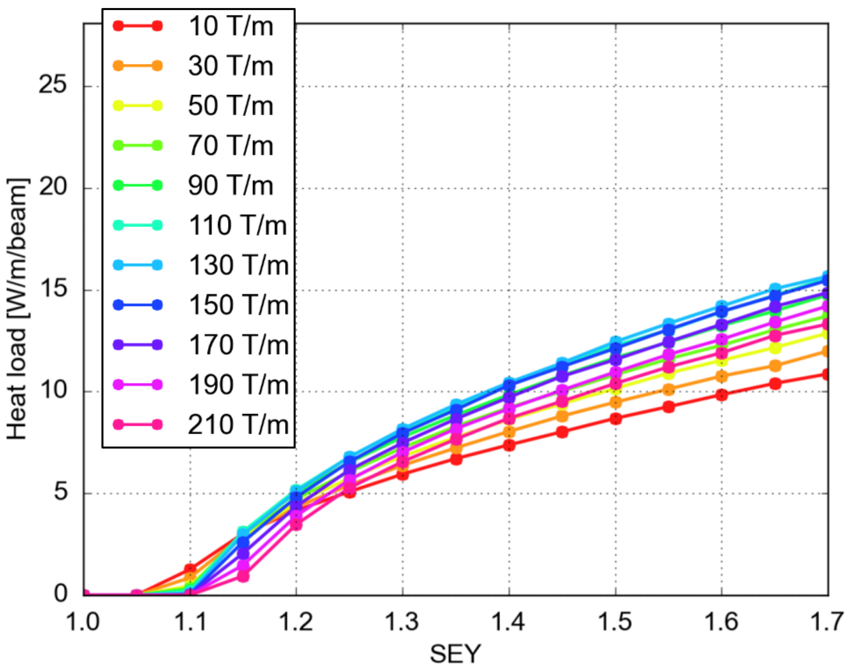
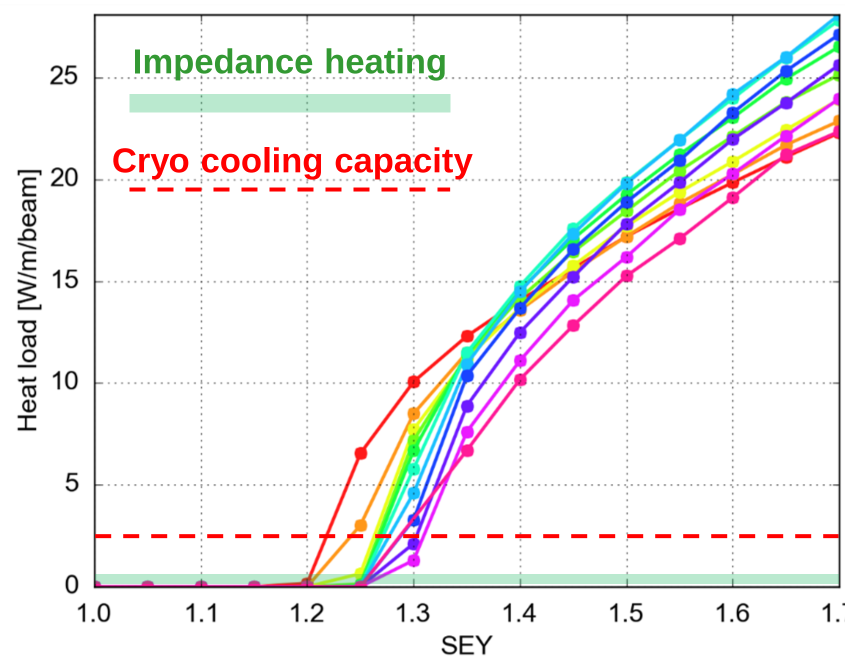


2.20×10^{11} ppb



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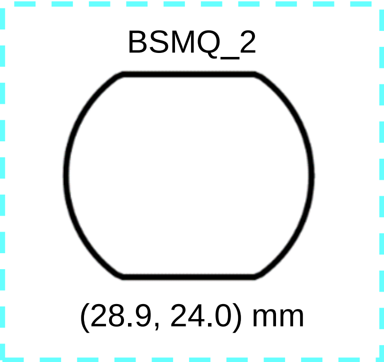

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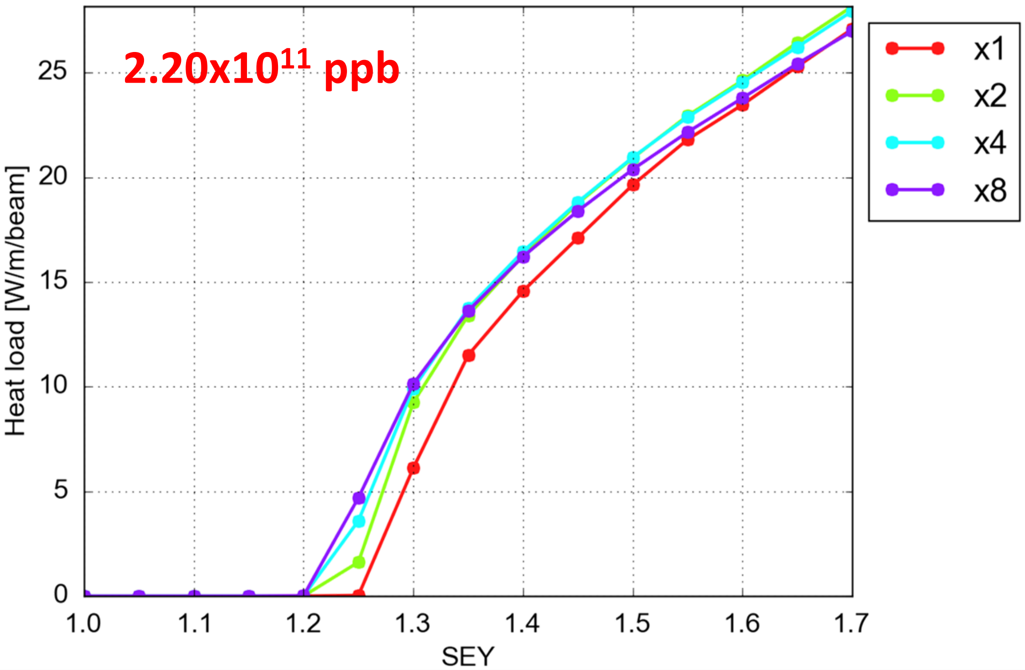
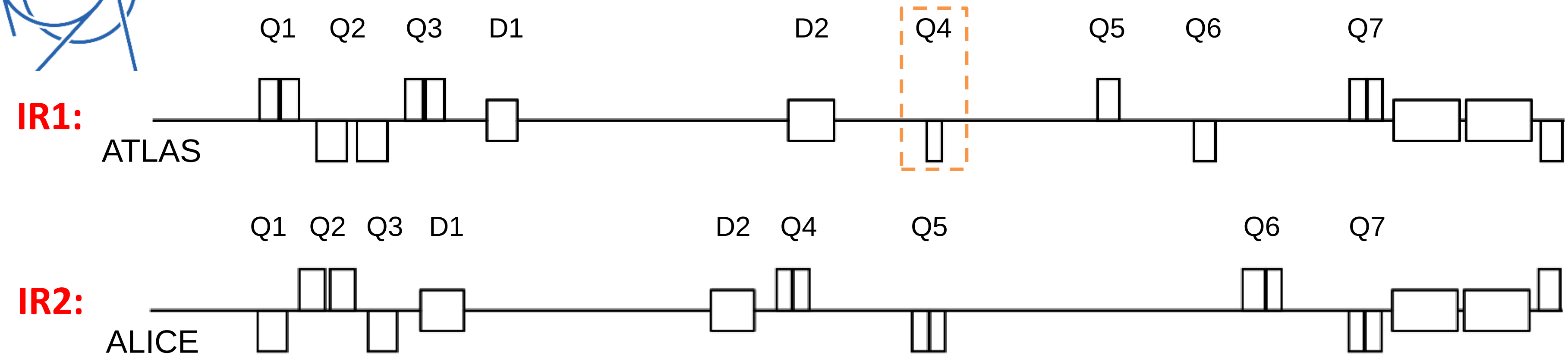
- The **dependence on the beam size** is quite **weak**

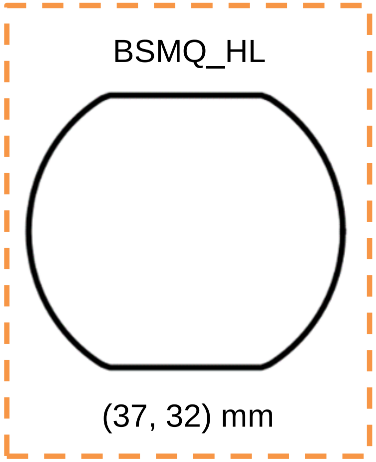


Beam size factor

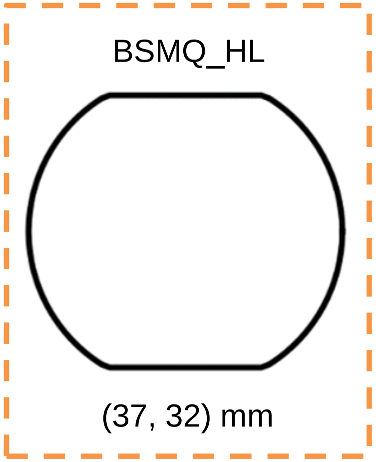
w.r.t. fully squeezed round optics

Beam screens in matching quadrupoles (Type HL)





Beam screens in matching quadrupoles (Type HL)



- Beam screen shape **not installed in the present machine**
- The dependence on the **magnetic gradient** is quite weak
- **Multipacting threshold** very similar for nominal and HL-LHC intensity
- **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

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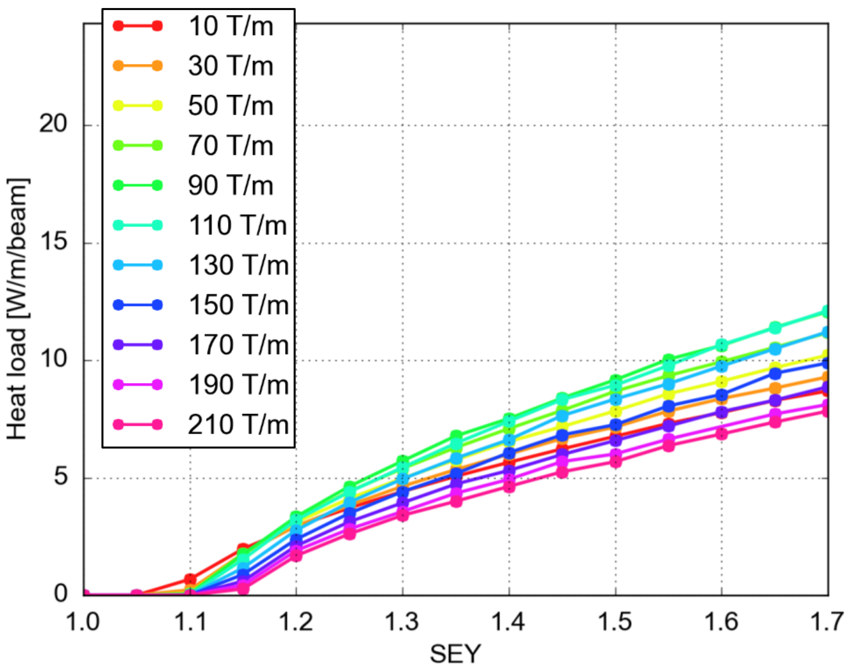

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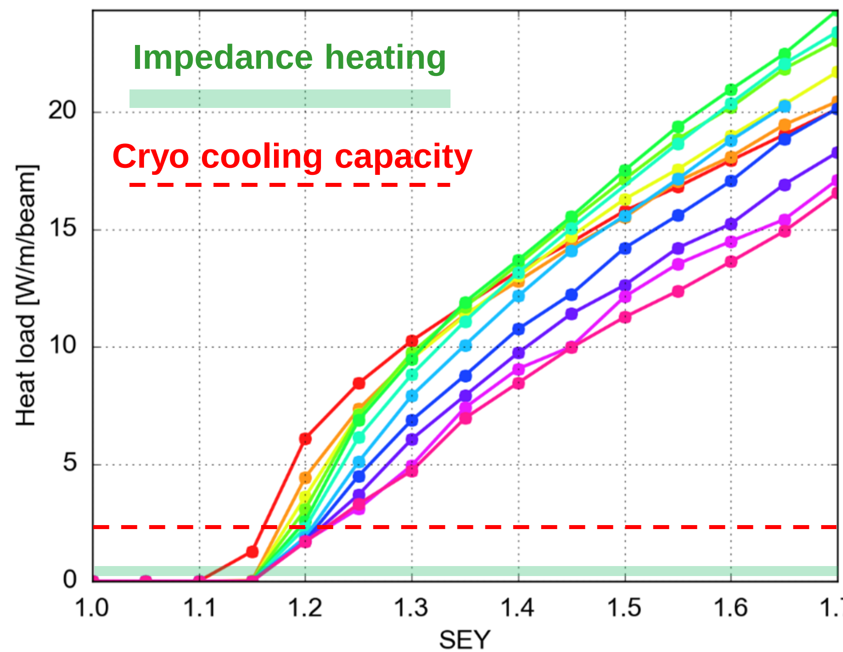
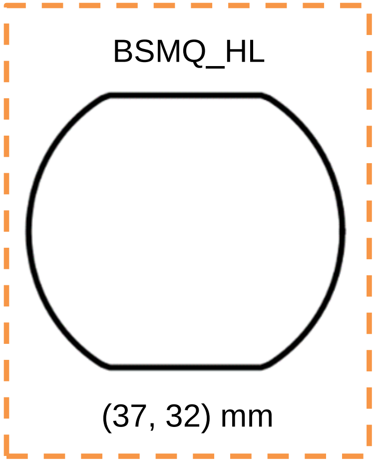


Beam screens in matching quadrupoles (Type HL)



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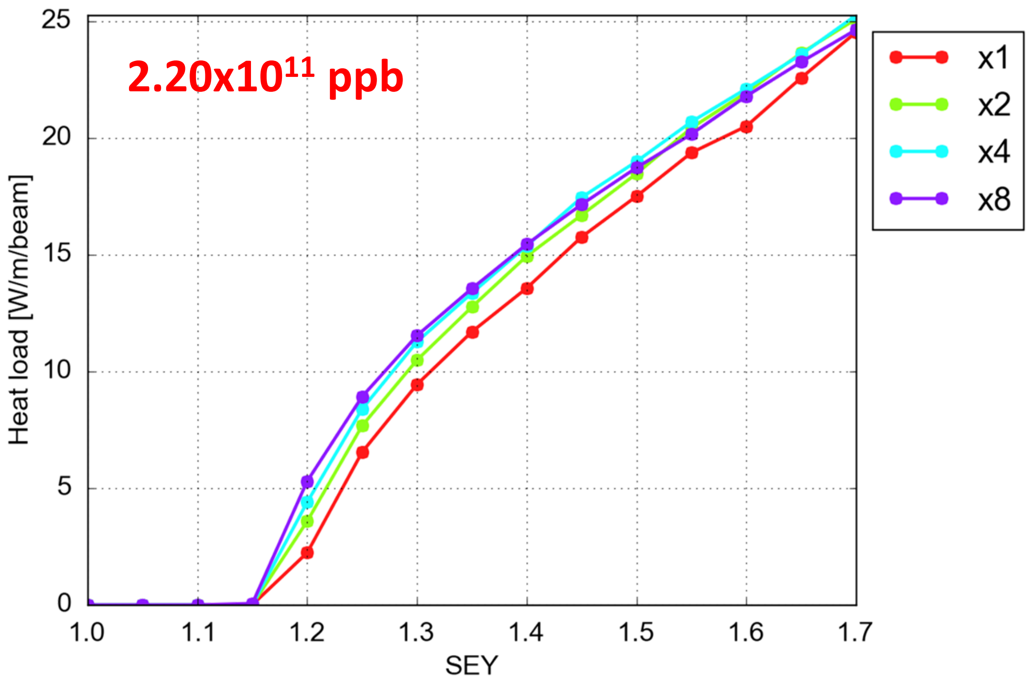
- **Heat load** is **stronger** for HL-LHC intensity
- e-cloud mitigation through **scrubbing, low SEY coating (a-C) and/or clearing electrodes is needed** to operate within the cryo cooling capacity
- The **dependence on the beam size** is quite **weak**



Beam size factor

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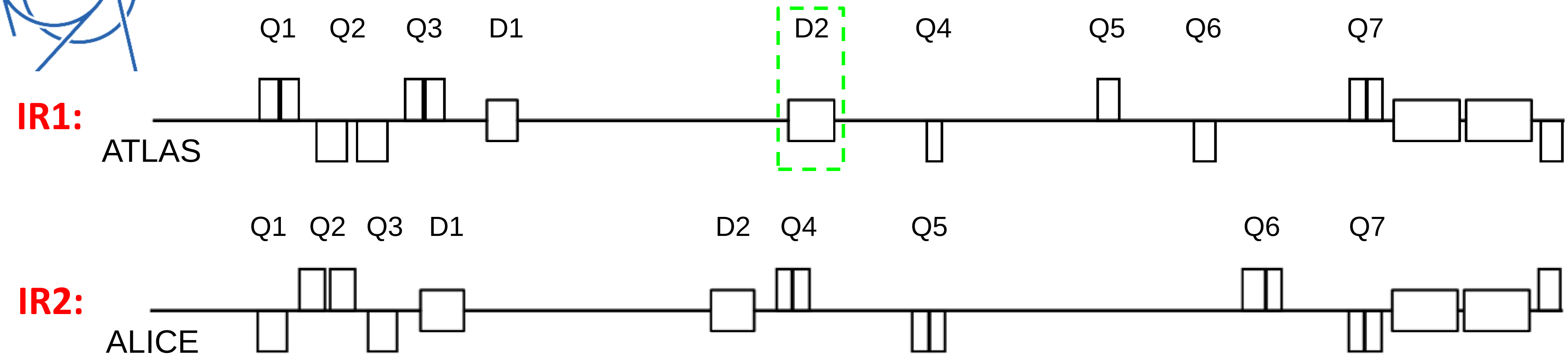
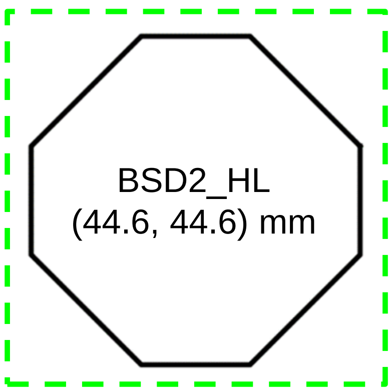
Beam screen in D2 separation dipoles (IR1&5)





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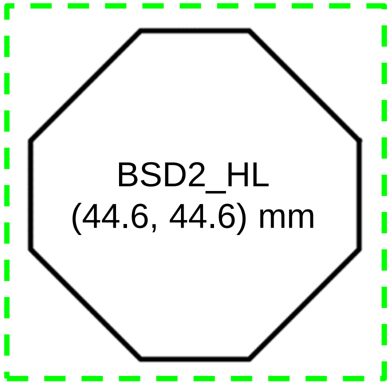
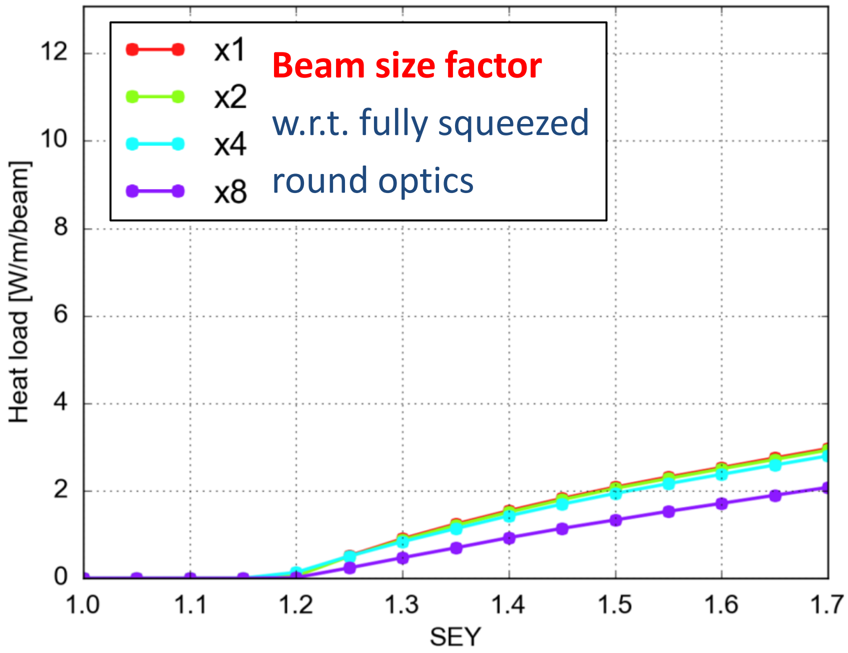


- The increase in bunch intensity causes a **decrease of the multipacting threshold**
- For all the SEY values the **heat load is stronger for HL-LHC intensity**
- The dependence on the **beam size** is quite **weak**
- e-cloud suppression through **low SEY coating (a-C)** e-cloud mitigation through **scrubbing, low SEY coating (a-C) and/or clearing electrodes is needed** to operate within the cryo cooling capacity

1.15×10^{11} ppb



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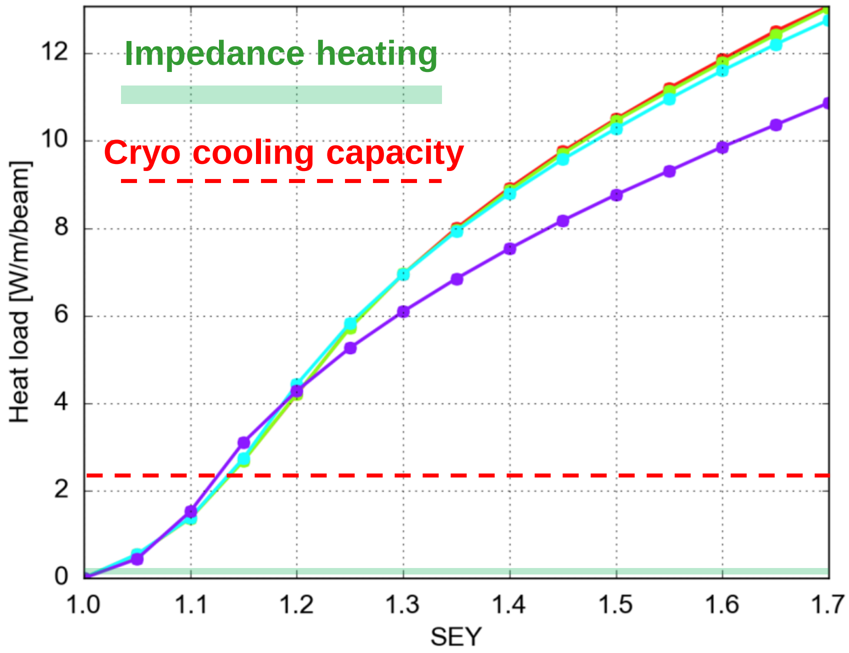
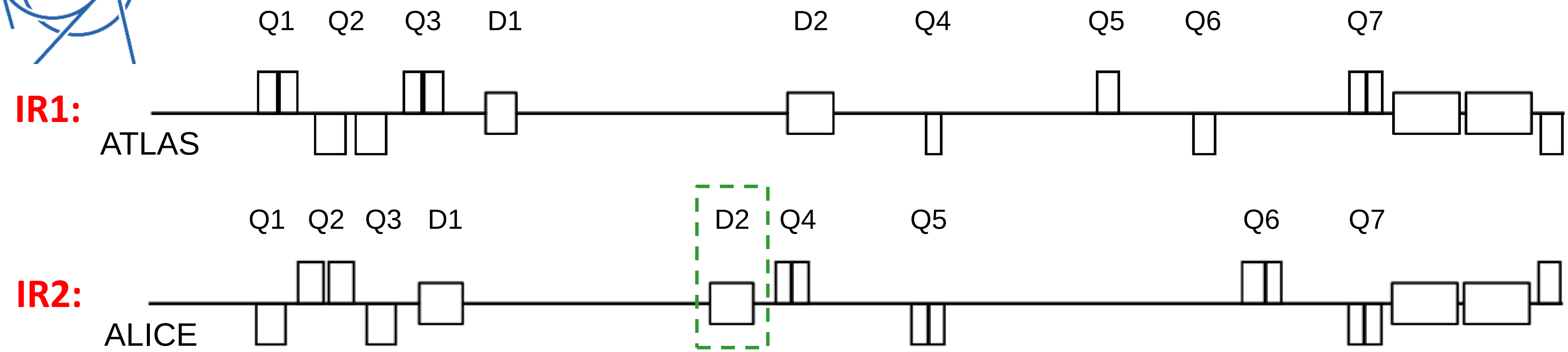
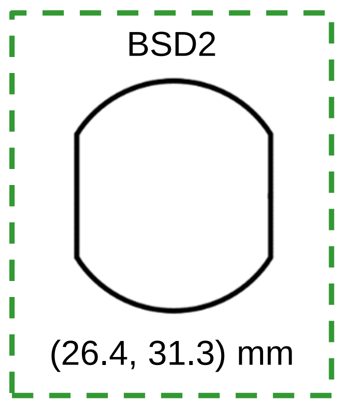


Beam screen in D2 separation dipoles (IR2&8)





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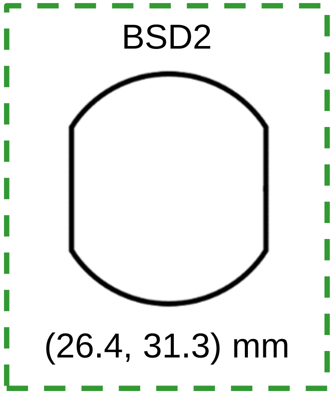
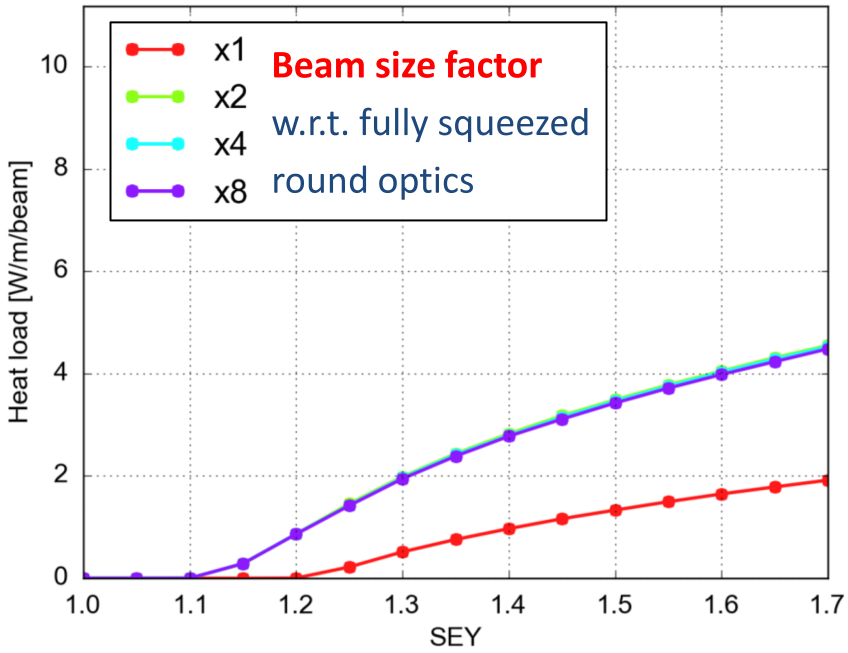


- The increase in bunch intensity causes a **decrease of the multipacting threshold**
- For all the SEY values the **heat load is stronger for HL-LHC intensity**
- The dependence on the **beam size** is quite **weak** (except for the smallest, → simulation numerically quite challenging, further checks needed)
- e-cloud mitigation through **scrubbing, low SEY coating (a-C) and/or clearing electrodes is needed** to operate within the cryo cooling capacity

1.15×10^{11} ppb



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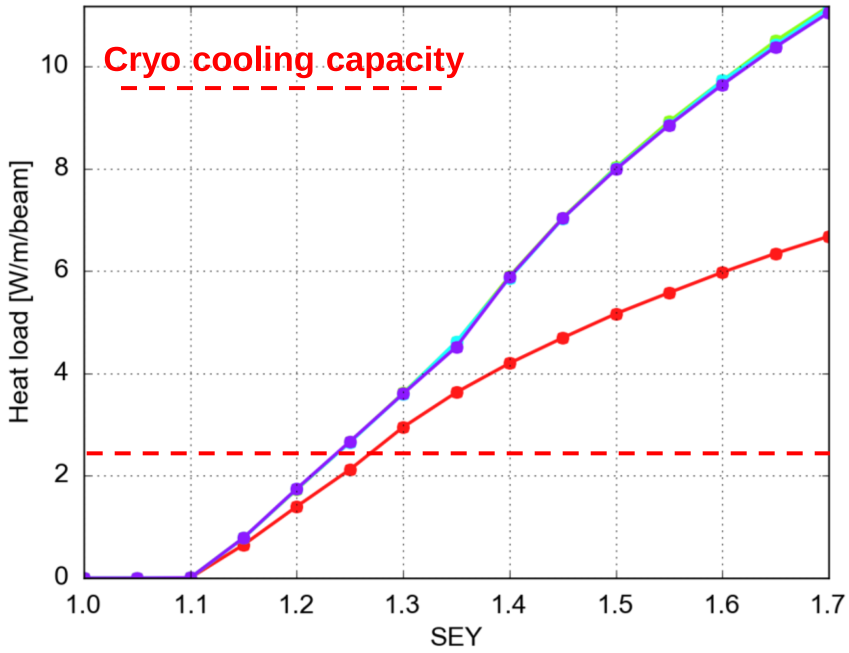

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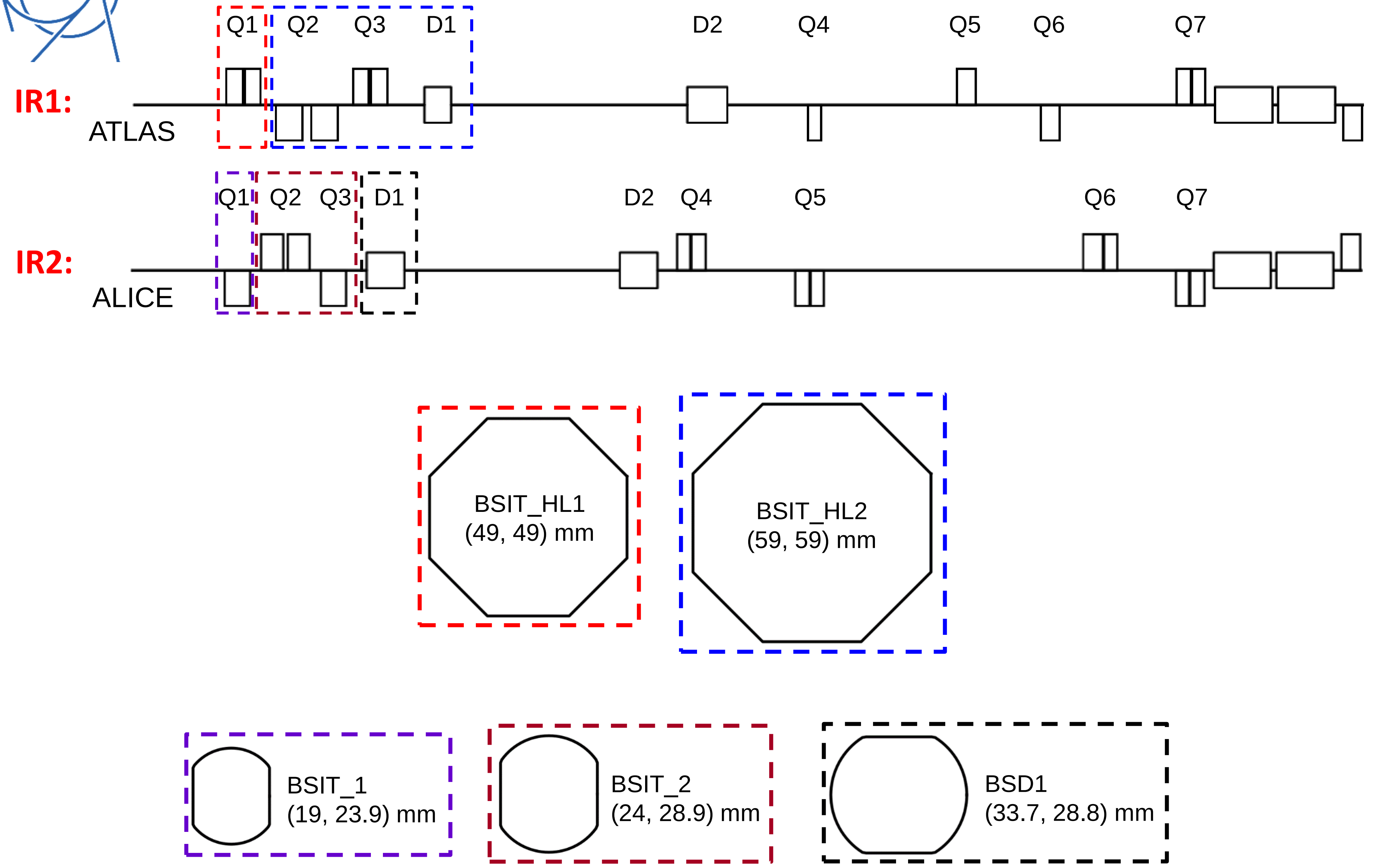
Inner triplets and D1 dipoles



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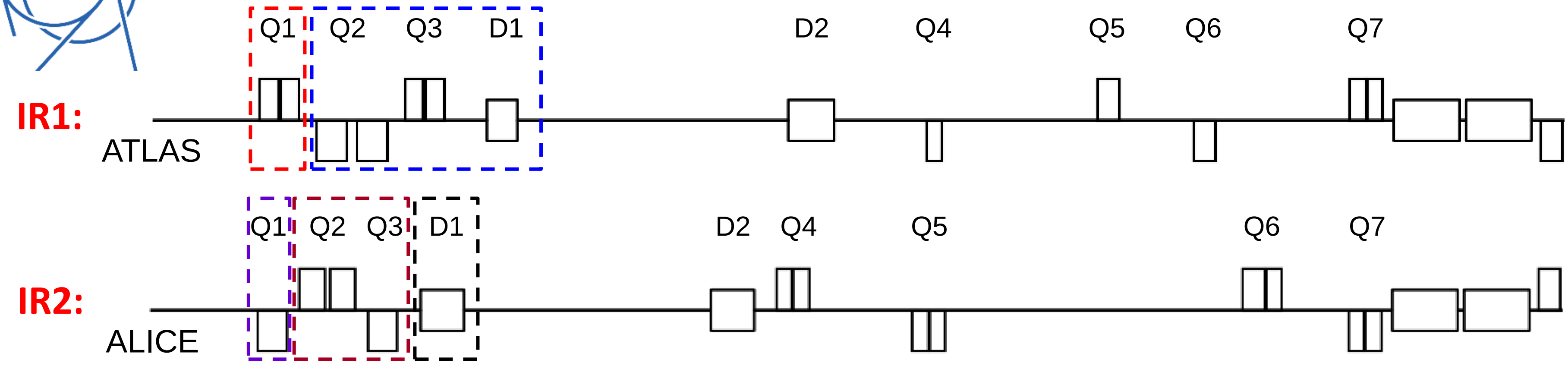
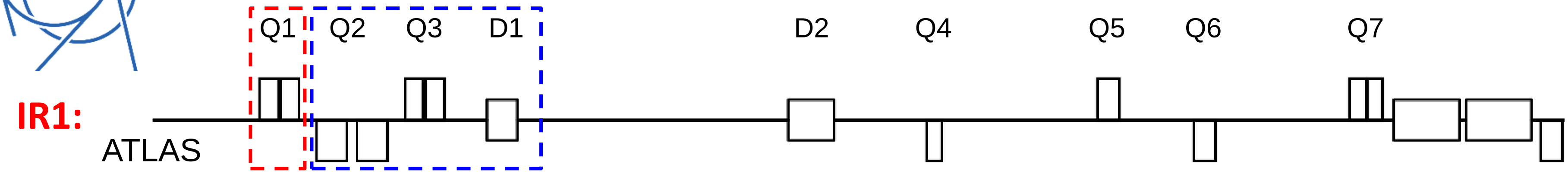
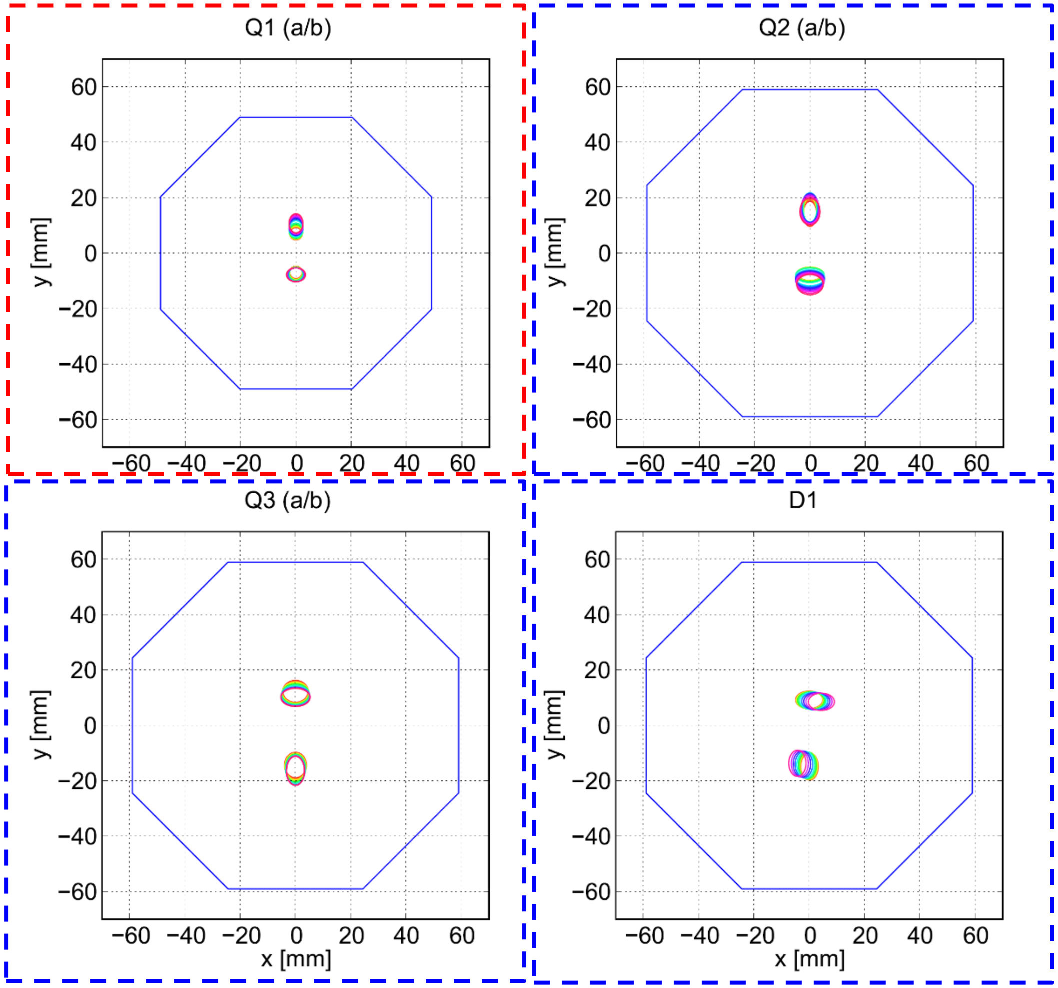


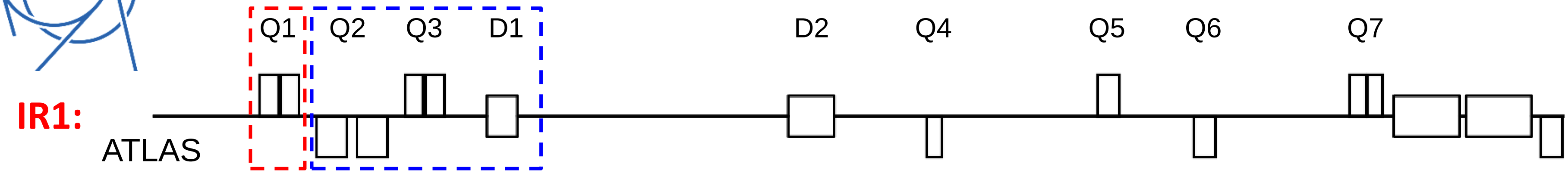
- In these devices **the two beams share the same chamber**:
  → PyECLOUD simulations were performed at **different positions along the triplet** to correctly account for the different **position, size and arrival time** of the two beam at the different beam locations
- Results for the new triplets in IR 1&5 were already presented in Daresbury. Recently we have **re-checked this simulation campaign** with the improved tracking and space charge routines
  → Effects visible but small
- Simulations were performed also for the **Inner Triplets in IR2 for the HL-LHC beam parameters**

Inner triplets and D1 dipoles (IR1&5)



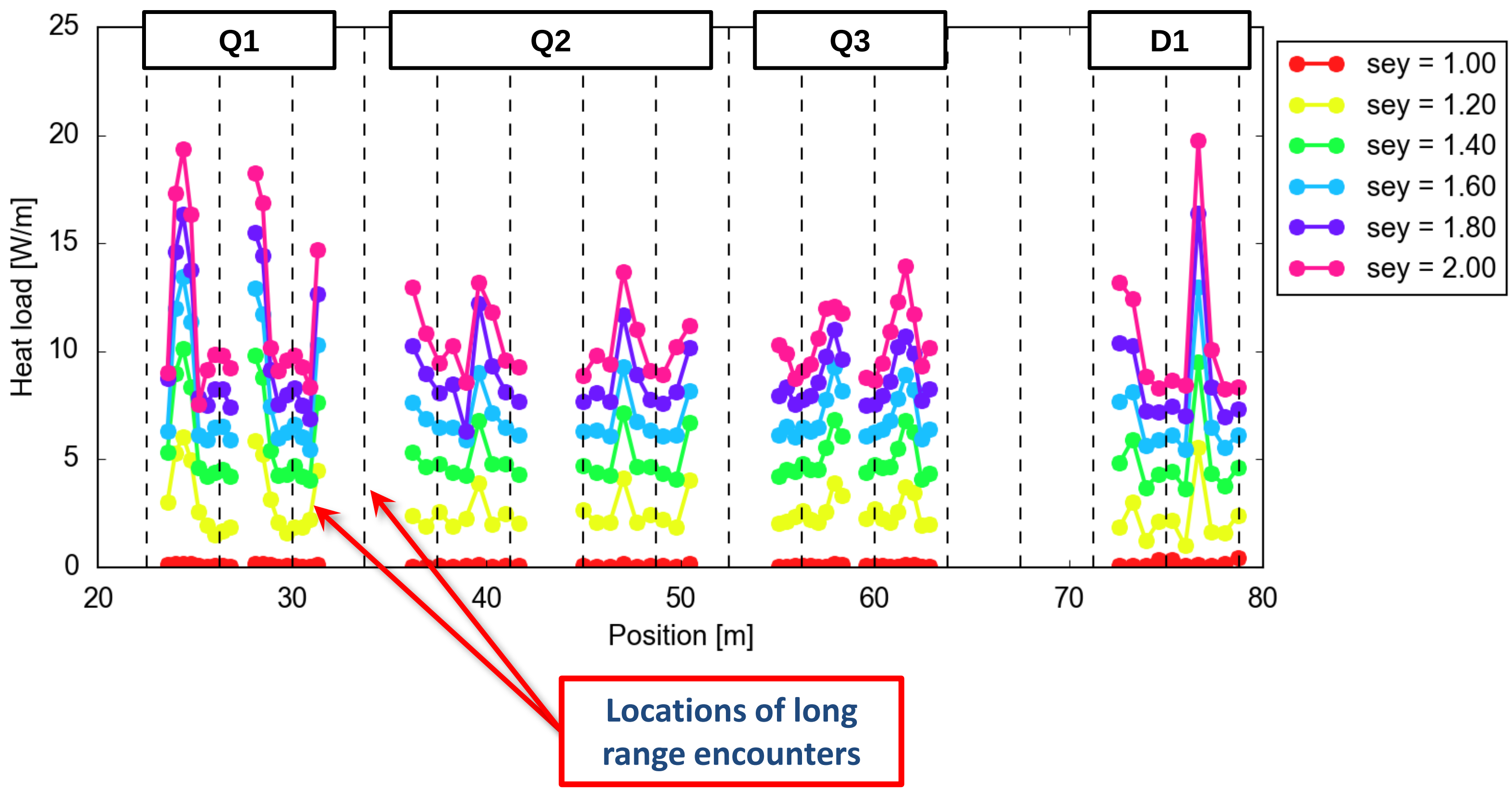


Inner triplets and D1 dipoles (IR1&5)

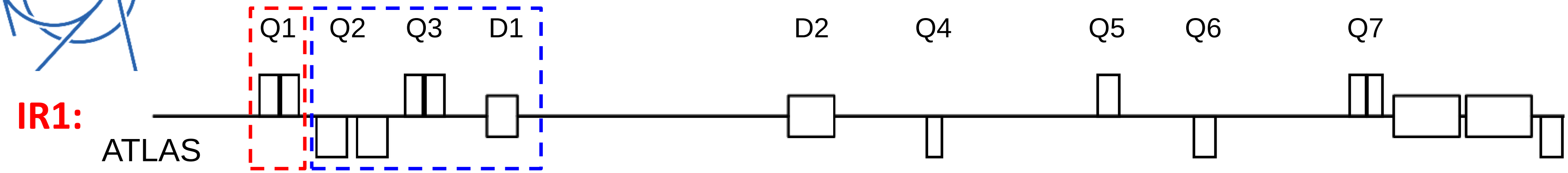


EC much weaker close to **long range encounters**

Modules with the **same beam screen and field structure** behave very similarly



Inner triplets and D1 dipoles (IR1&5)



EC much weaker close to **long range encounters**

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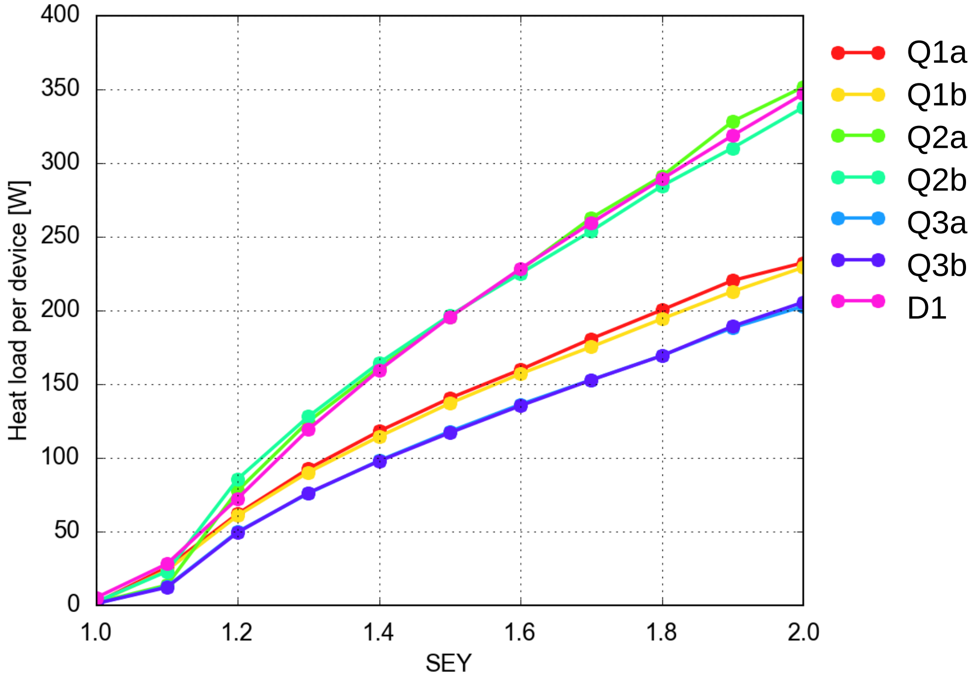
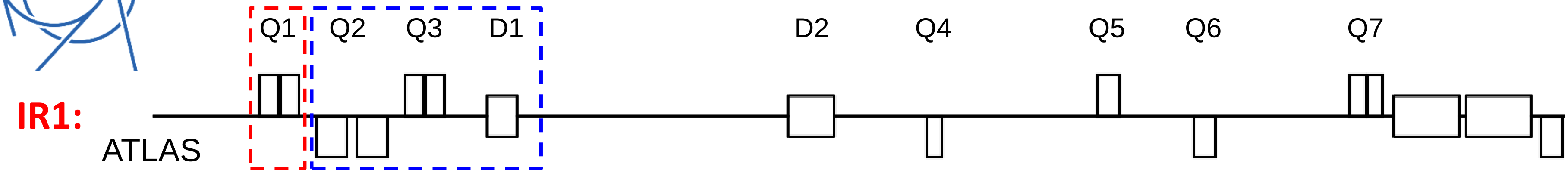
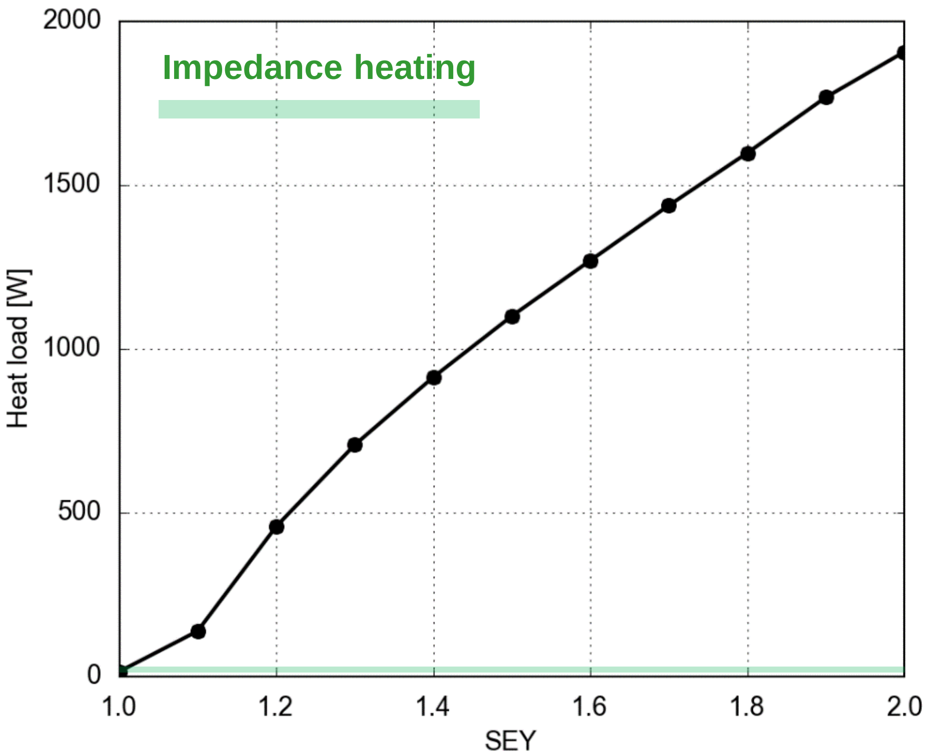


Inner triplets and D1 dipoles (IR1&5)

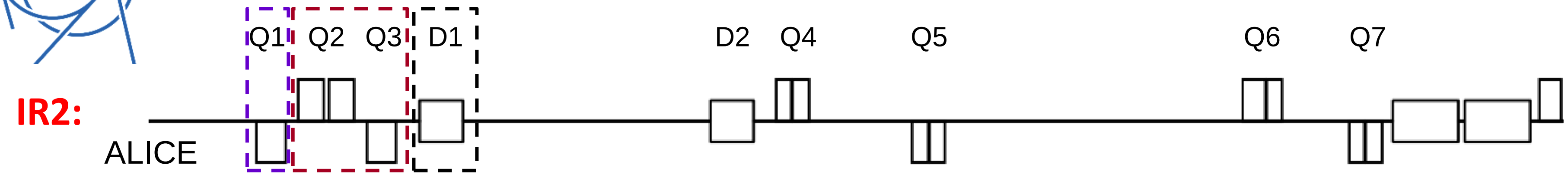


Total heat load on the beam screen cooling circuit



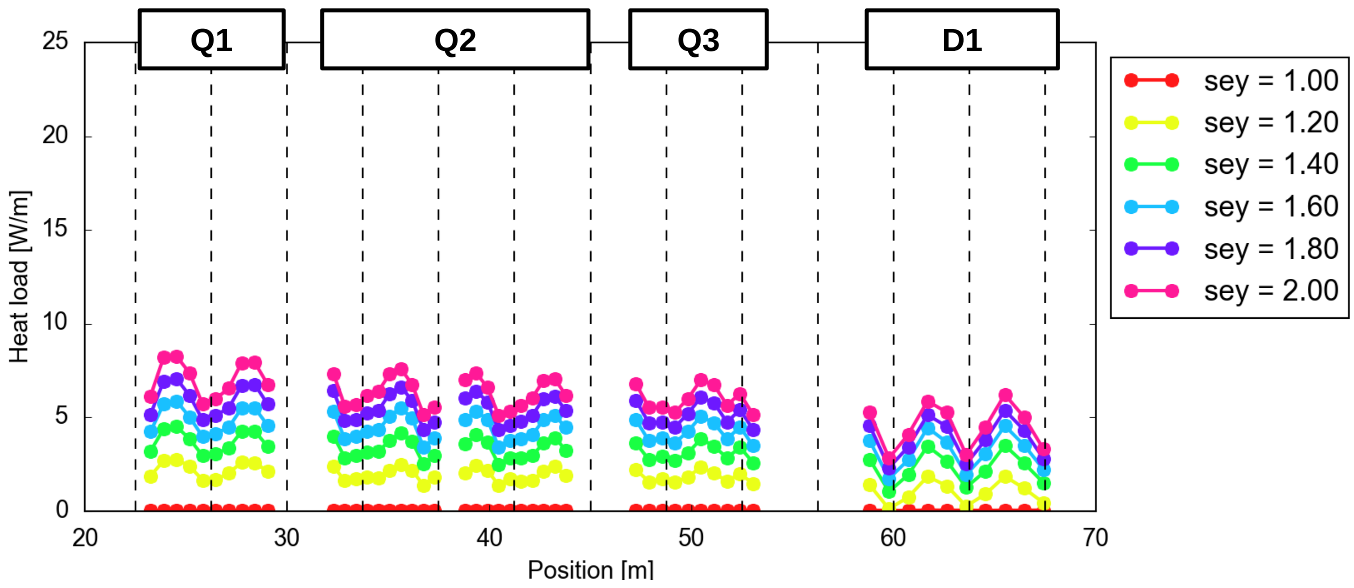
- **E-cloud suppression absolutely needed** to operate with a reasonable heat load
- **a-C coating** presently under test in COLDEX at the SPS looks very promising
- **Clearing electrodes** could be a valid alternative and add some margin

Inner triplets and D1 dipoles (IR2&8)

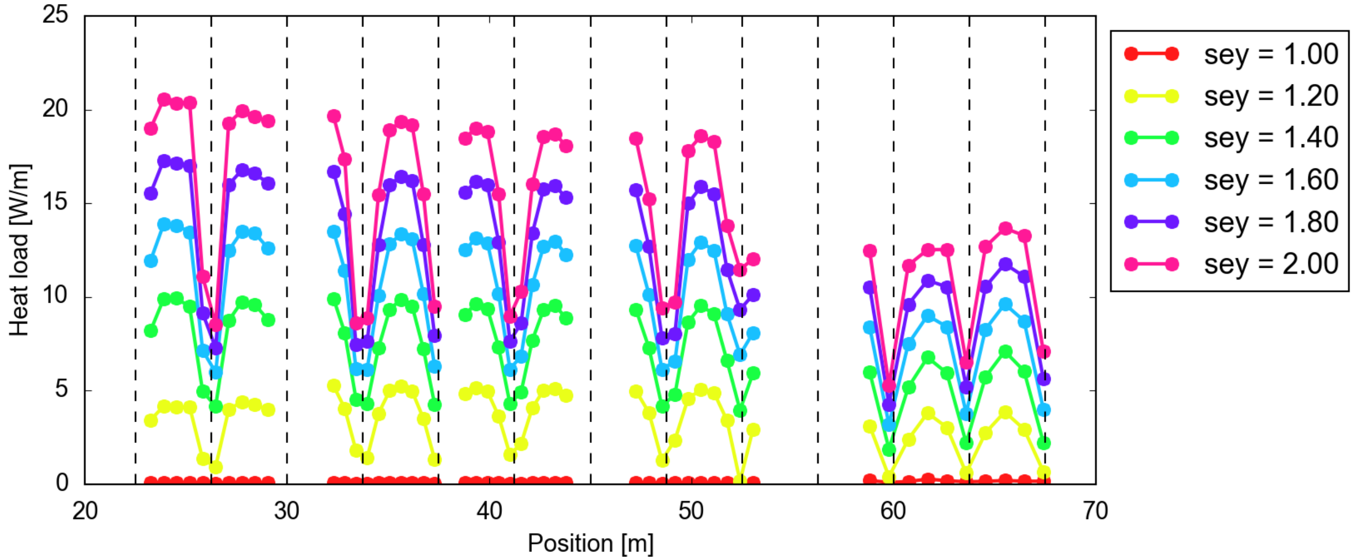


Inner triplets and D1 dipoles (IR2&8)

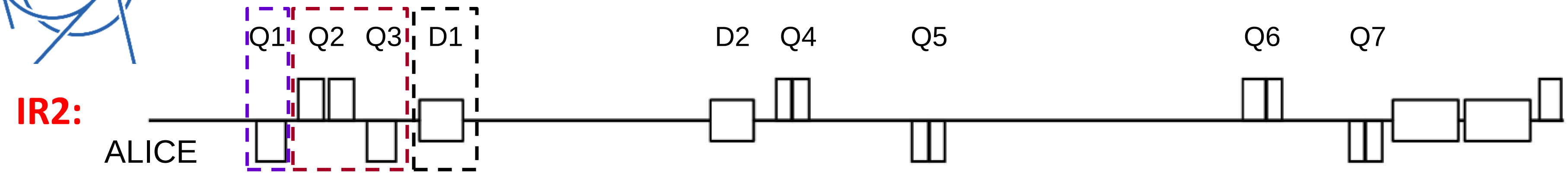
Nominal LHC



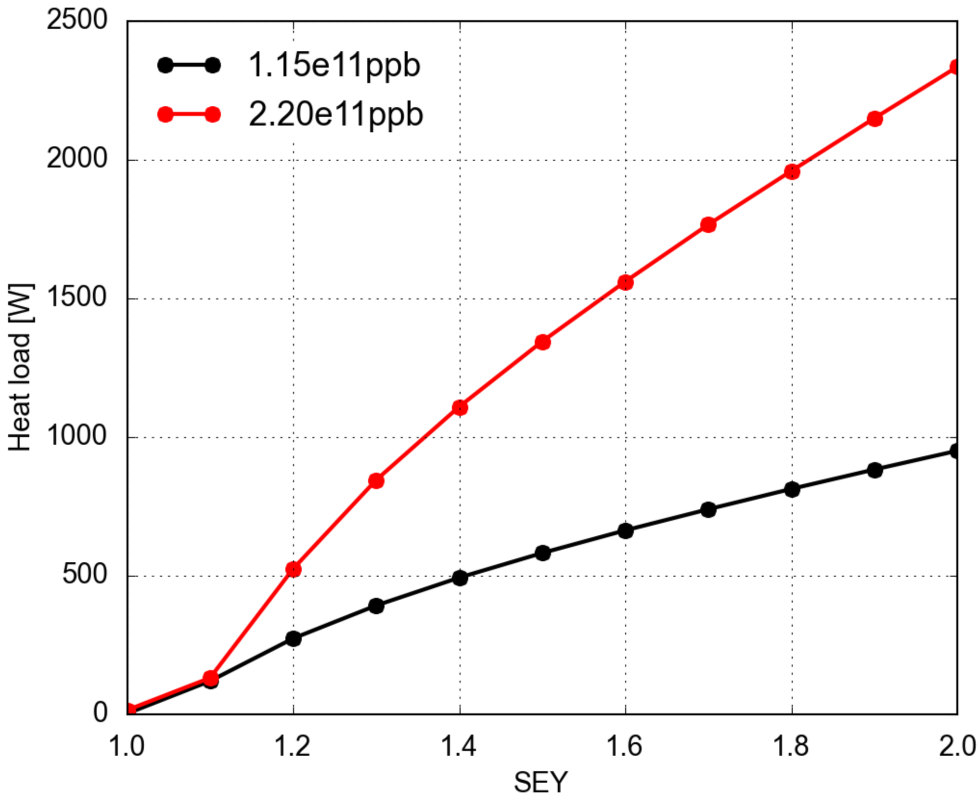
HL-LHC



Inner triplets and D1 dipoles (IR2&8)



Total heat load on the beam screen cooling circuit



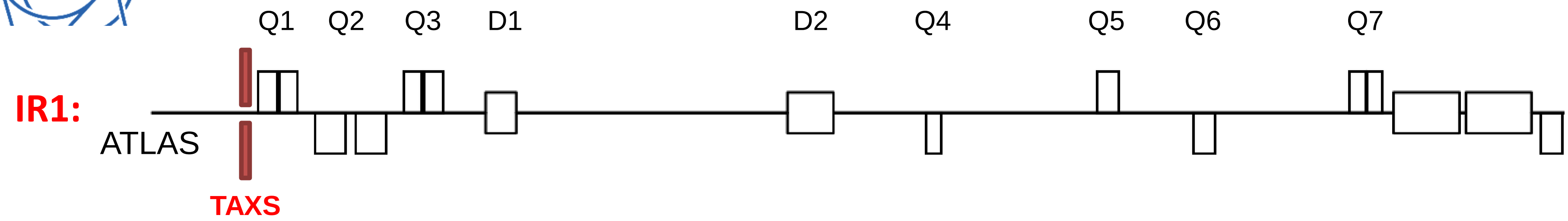
Similar considerations as for IR1&5:

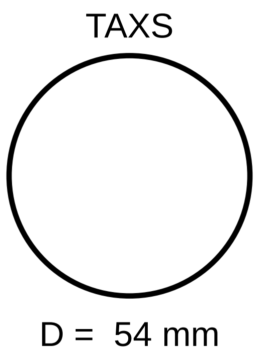
- **E-cloud suppression absolutely needed** to operate with a reasonable heat load.
- **a-C coating** presently under test in COLDEX at the SPS looks very promising
- **Clearing electrodes** could be a valid alternative and add some margin

Outline

- Introduction
- Heat load from the beam screen impedance
- Heat load from e-cloud effects
- **Estimation results:**
    - Matching quadrupoles
    - Separation dipoles
    - Inner triplets
    - TAXS absorber

TAXS absorber

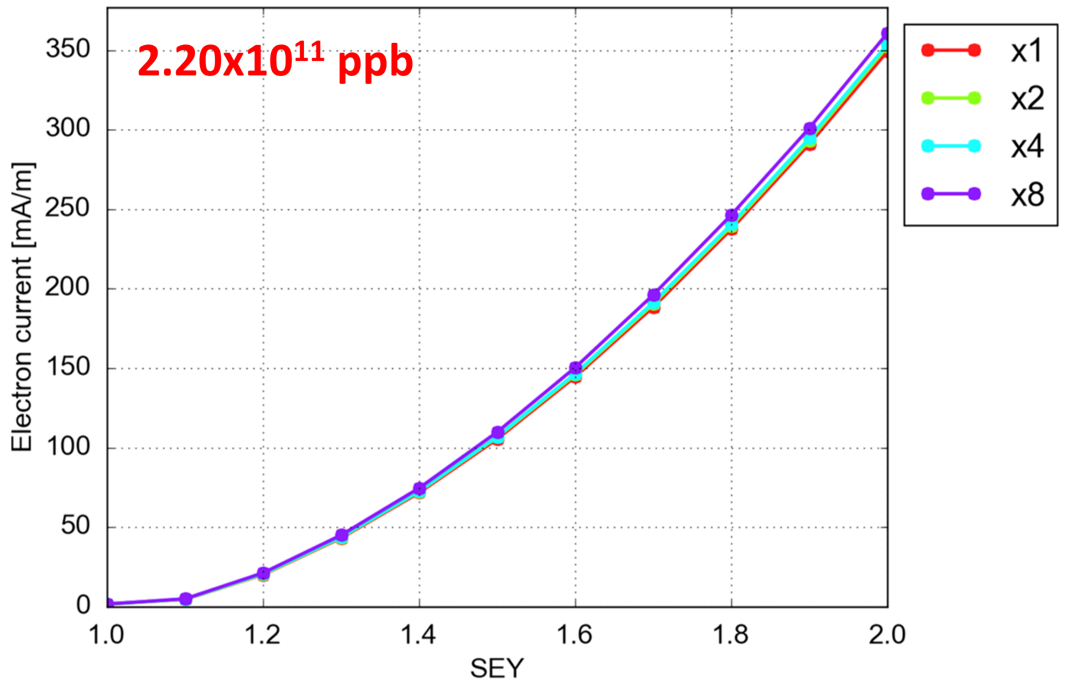




Close to the experiment → e-cloud induced outgassing can have an **impact on background**

Placed in the **common region** (in between long range encounters)

→ **Multipacting threshold quite low**



$\beta_{x,y}$ factor
w.r.t. fully squeezed round optics

Summary and conclusions

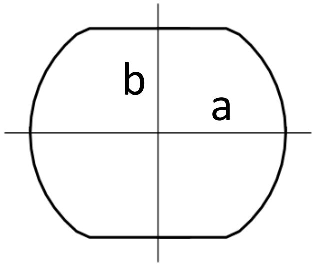
- **Beam induced heating** from **beam impedance** and **e-cloud** effects have been evaluated for the beam screen of the superconducting magnets of the experimental IRs

- The **impedance** calculations has taken into account several non idealities (dependence on temperature, magneto-resistance effect, weld, two counter-rotating beams in the common region)
  - The estimated contribution results to be **well within the available cooling capacity** in all cases

- The **e-cloud** studies, conduced through PyECLOUD simulations, have explored the heat load dependence on SEY, magnetic gradient (for the quadrupoles) and beam size
  - For all the devices, **low SEY needs to be achieved** in order to operate within the available cooling capacity limits
  - Full **suppression through scrubbing looks unlikely** for the devices with lower multipacting threshold (e.g. triplets) → need for active measures like **amorphous carbon coating** of the beam screens (presently under test in COLDEX at the SPS) and/or **clearing electrodes**

Thanks for your attention!

Matching section IP5 - Present LHC



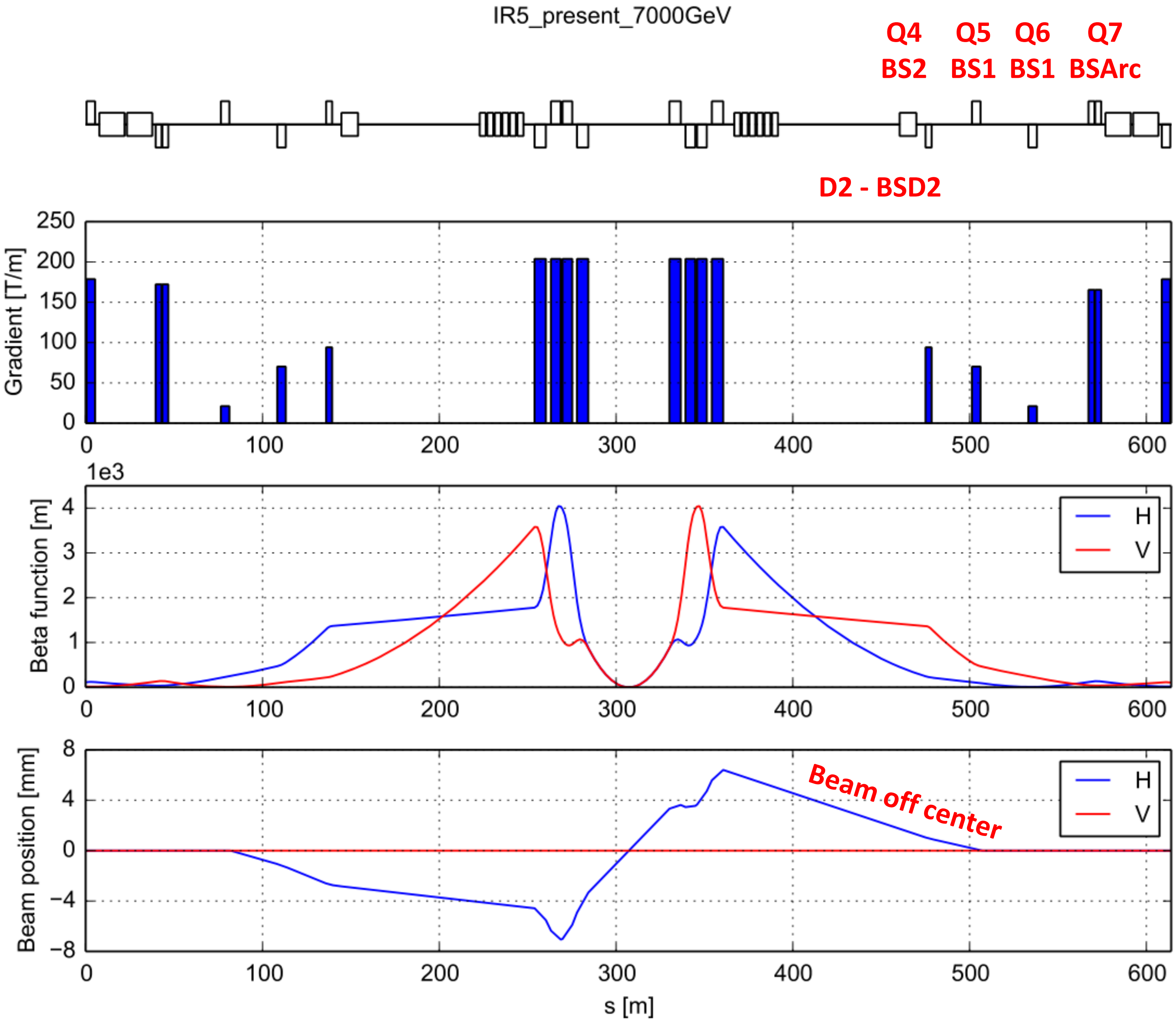
BSArc
a=22, b=17.15

BS1
a=22.5, b=17.6

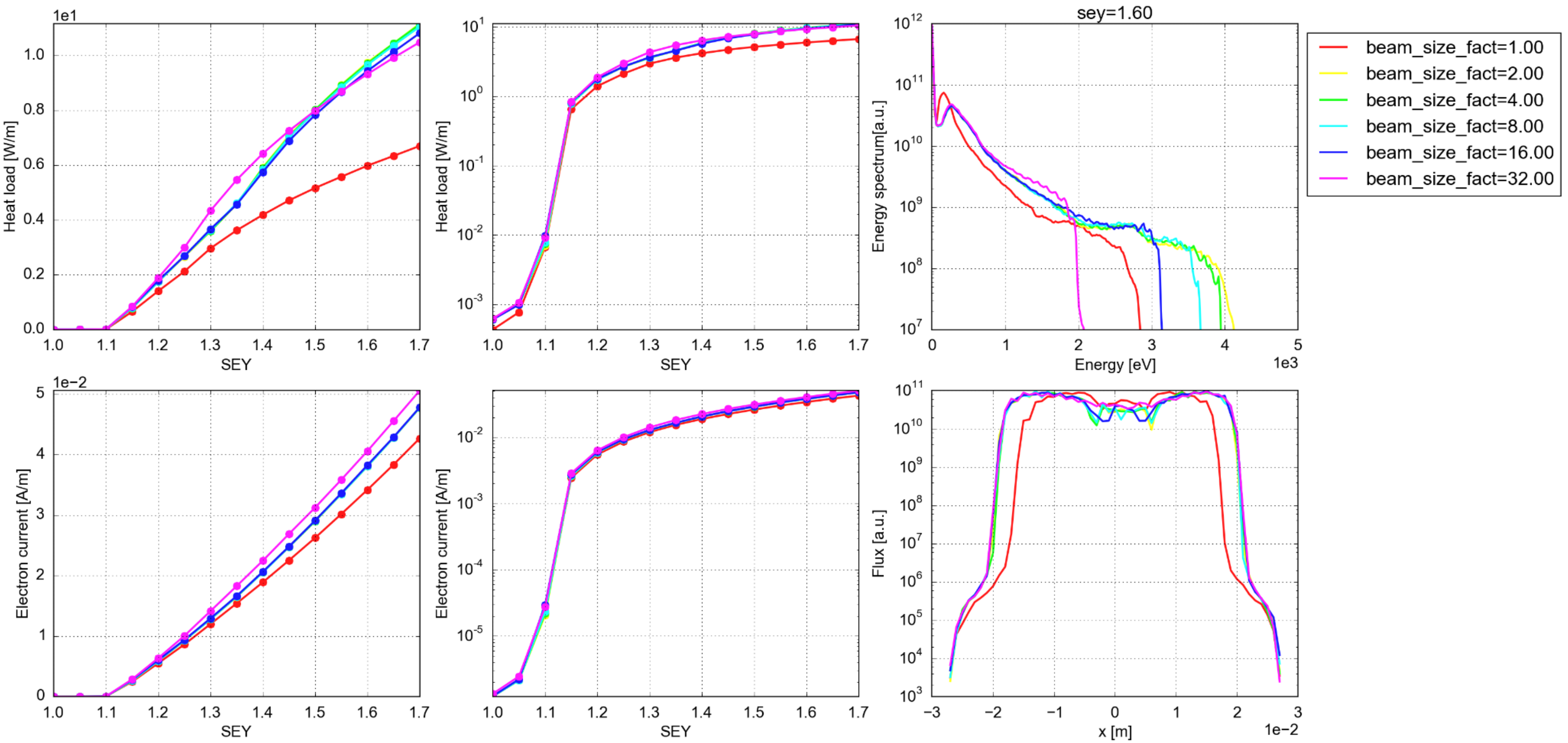
BS2
a=28.9, b=24

BSD2
a=31.3, b=26.4

Beam screens
can be rotated



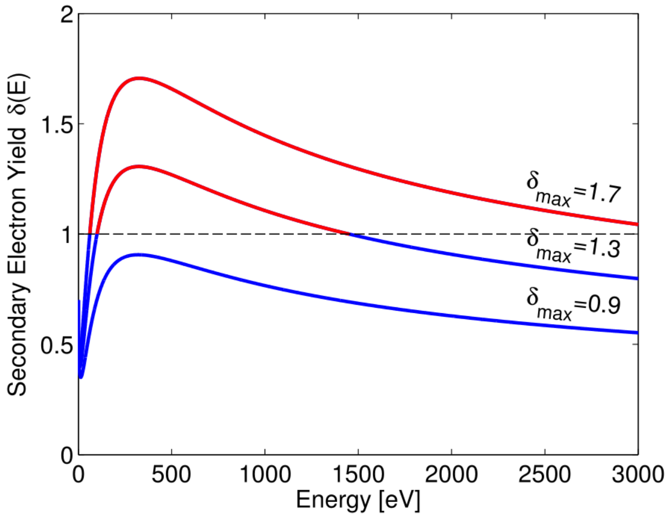
LHC_D2R2_7000GeV_hl2.20e11ppb



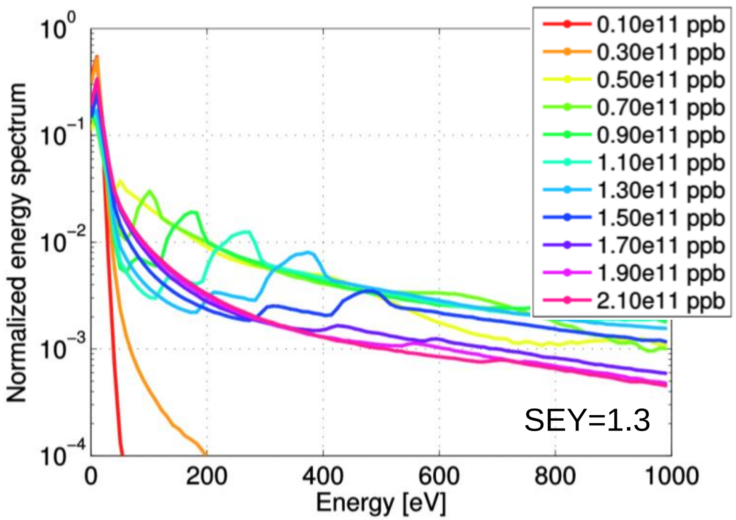
Bunch intensity dependence for the arc main magnets

Underlying mechanism:

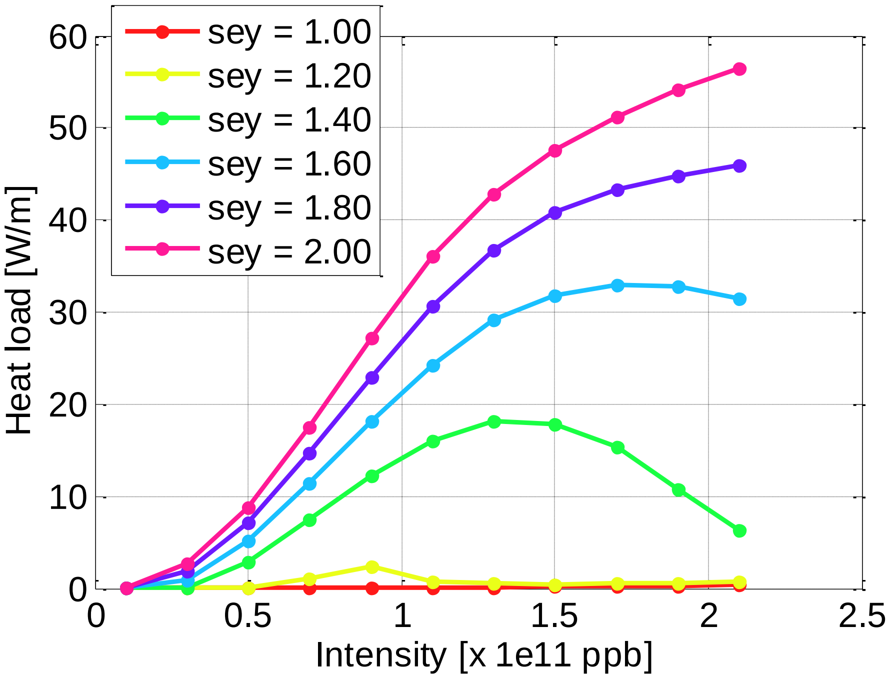
- When the SEY decreases the energy window for multipacting becomes narrower



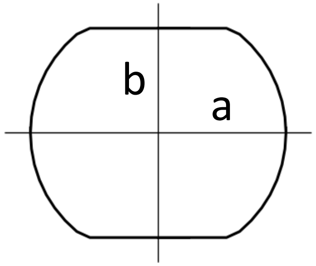
- For high bunch intensity the e- spectrum drifts to higher energies



Quadrupole



Matching section IP5 – HL-LHC



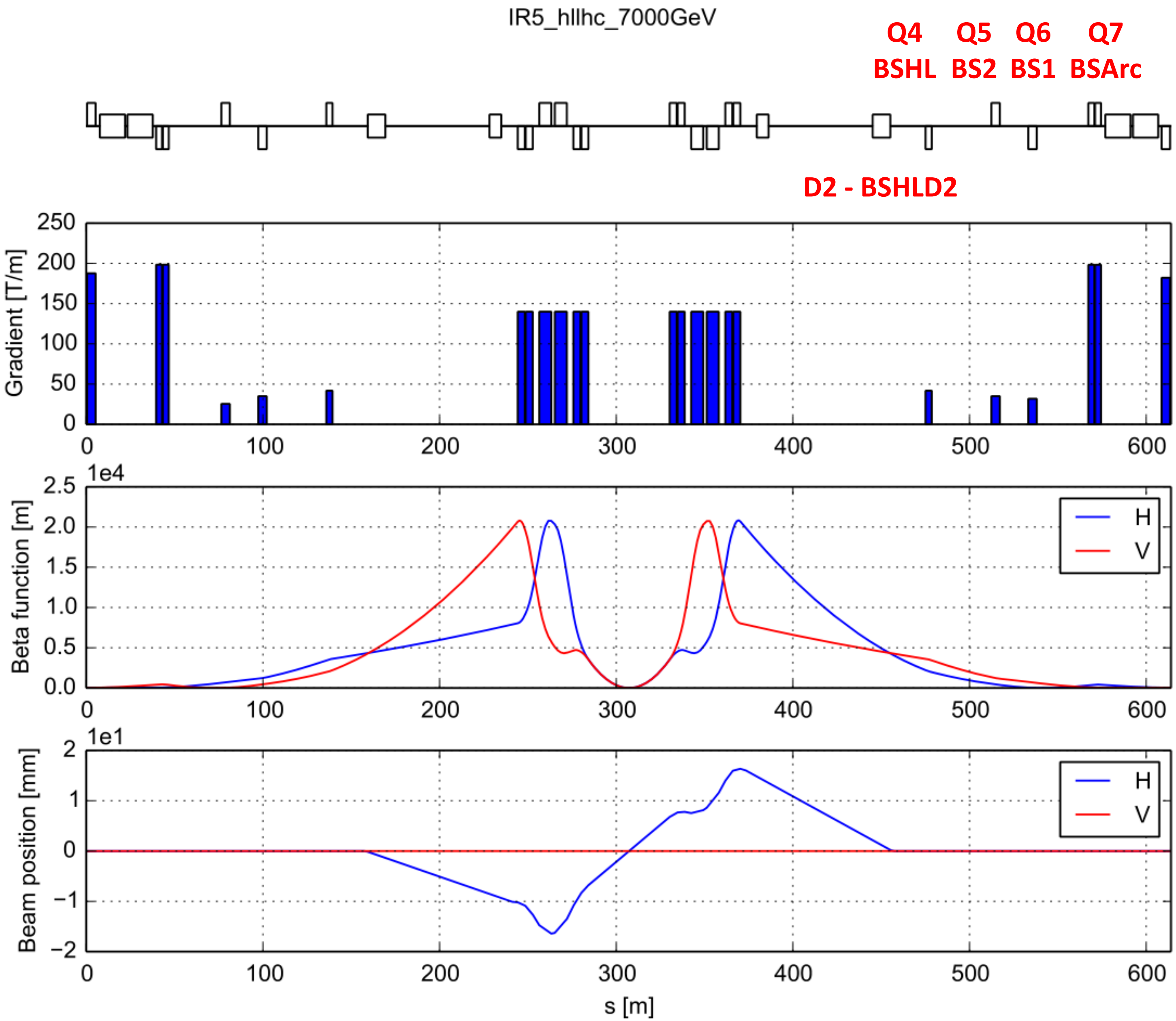
BSArc
a=22, b=17.15

BS1
a=22.5, b=17.6

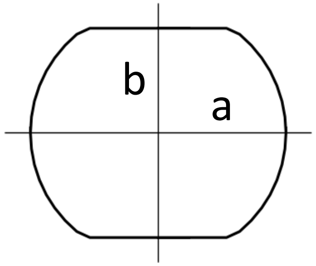
BS2
a=28.9, b=24

BSHL
a=37, b=32

BSHLD2
a=41, b=36



Matching section IP2 – Present LHC



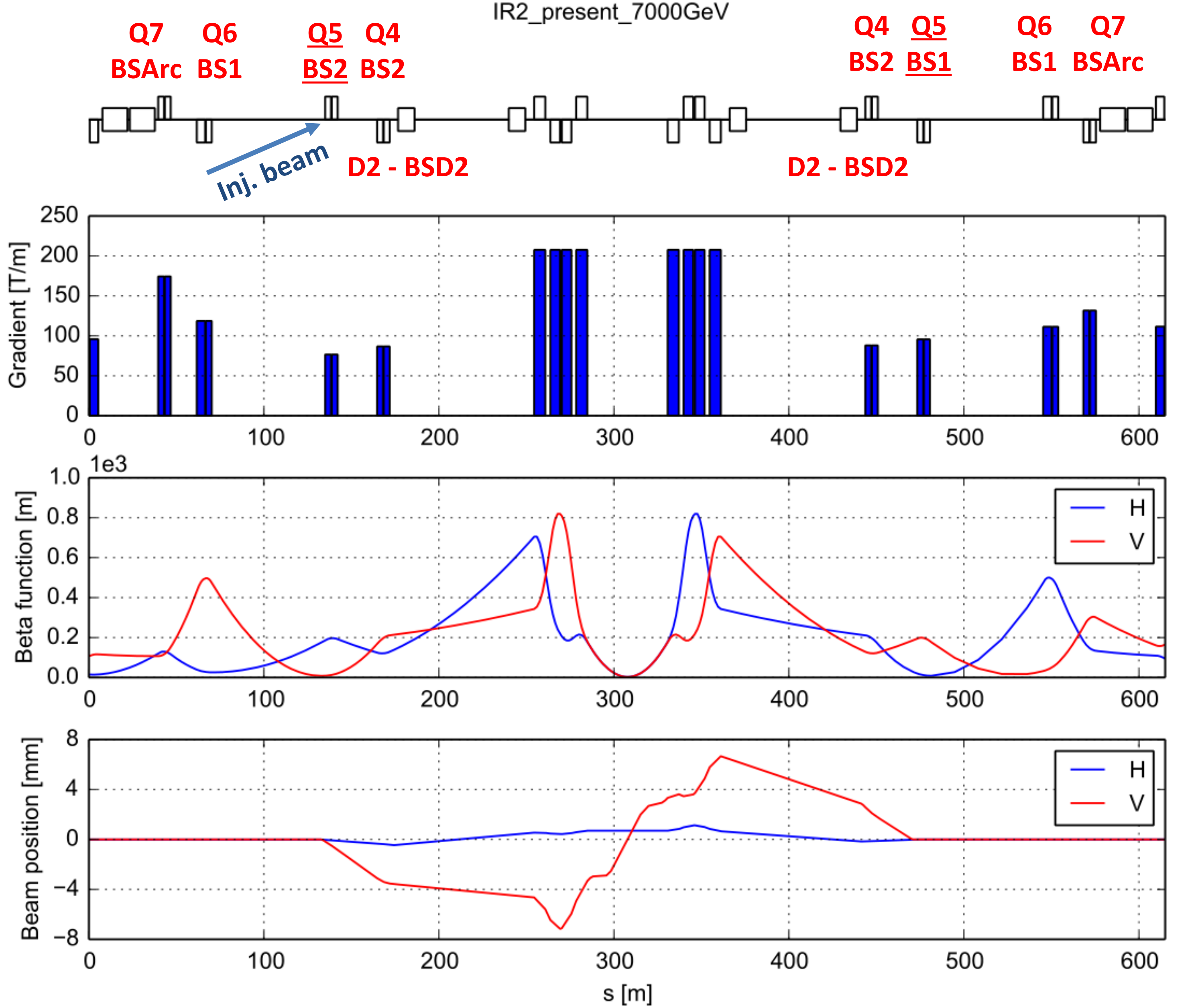
BSArc
a=22, b=17.15

BS1
a=22.5, b=17.6

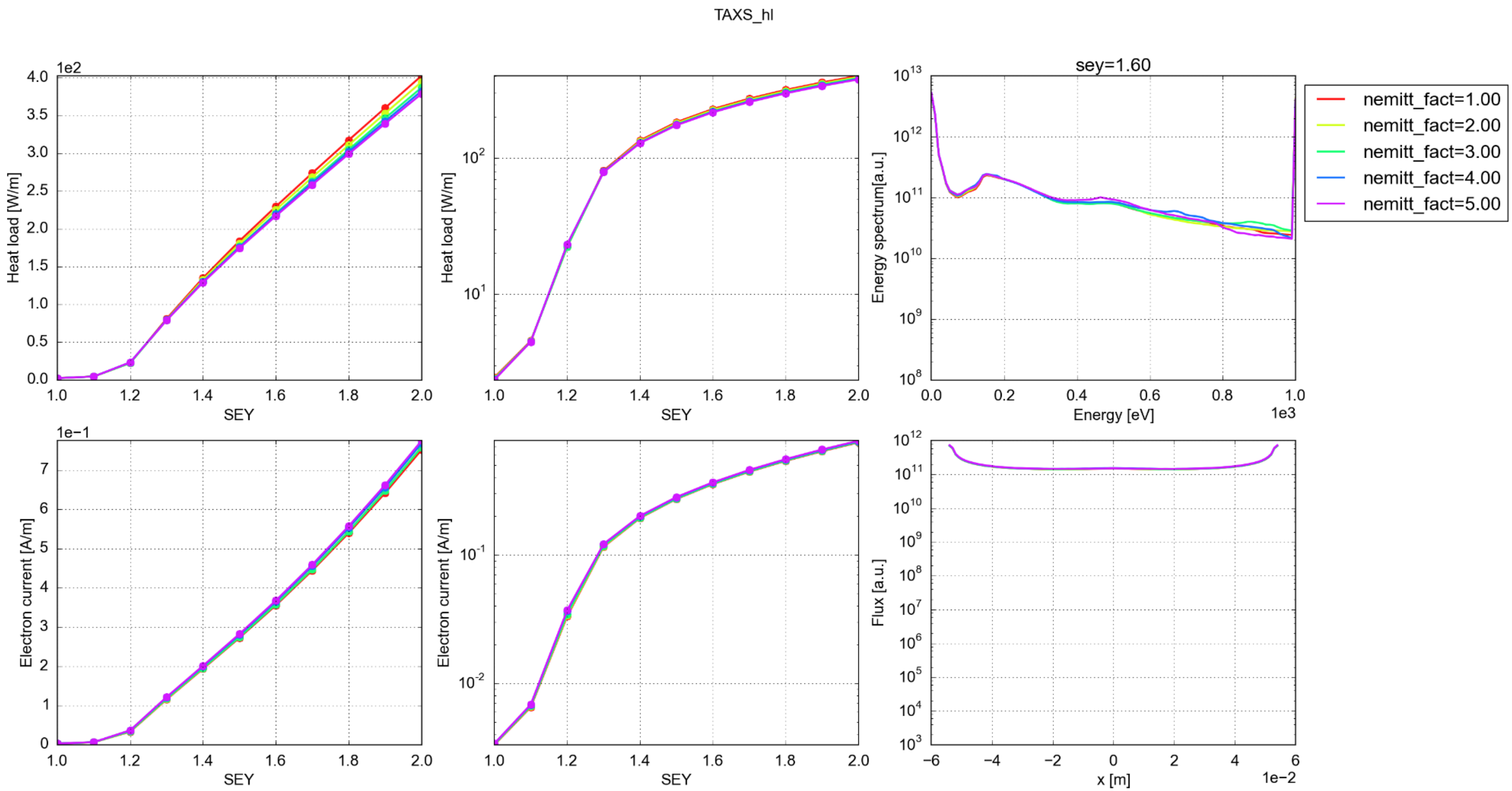
BS2
a=28.9, b=24

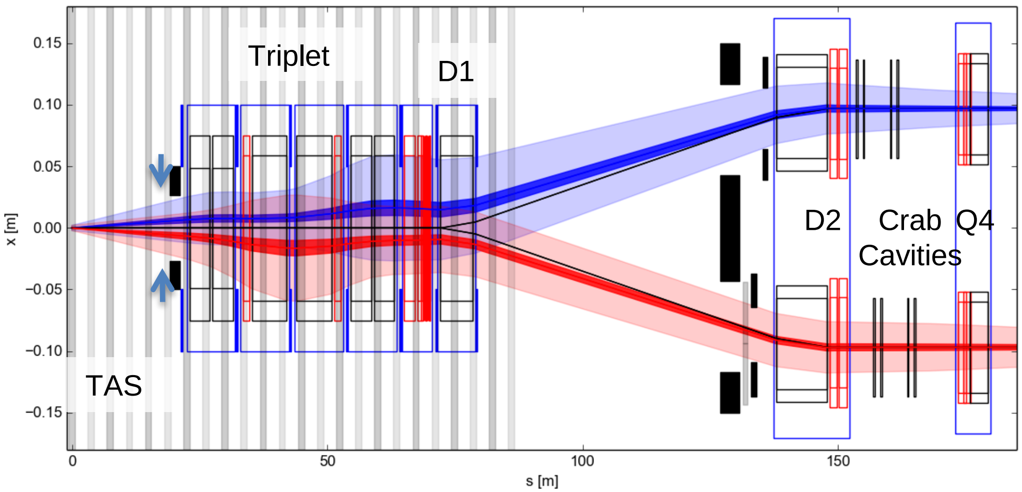
BSD2
a=31.3, b=26.4

Beam screens can be rotated



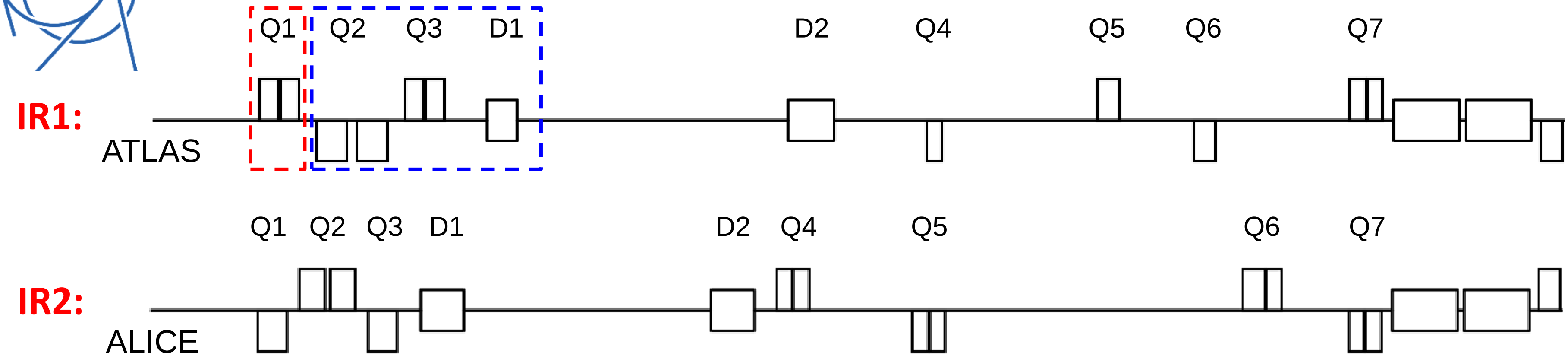
TAXS

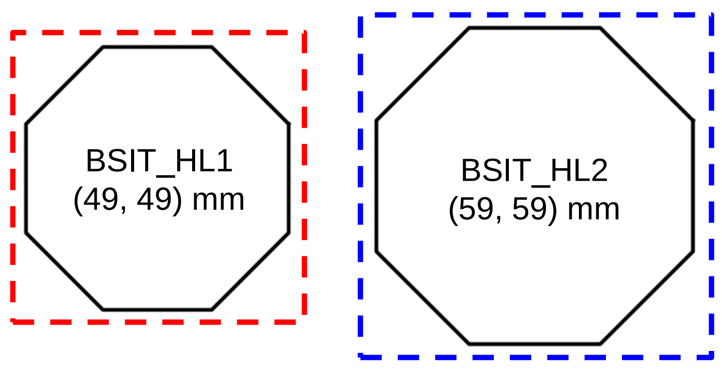

TAXS_hl
sey=1.60
nemitt_fact=1.00
nemitt_fact=2.00
nemitt_fact=3.00
nemitt_fact=4.00
nemitt_fact=5.00
Heat load [W/m]
Electron current [A/m]
Energy spectrum[a.u.]
Flux [a.u.]
SEY
Energy [eV]
x [m]
1e2
1e-1
1e3
1e-2



Right side of IR1/IR5

Inner triplets (IR1&5)





Heat load due to impedance

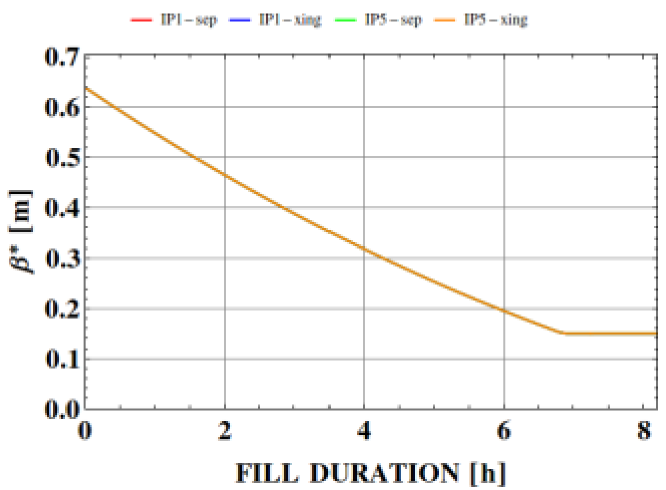
Impact of the operating temperature up to about factor 2

Values well within the available cooling capacity (4.8 W/m)

SUMMARY TABLE (two 25 ns beams, WITH weld)						
Power loss [W/m] (2.2E11, 2748, 7.55)	20 K	30 K	40 K	50 K	60 K	70 K
Q1 (49 mm – 6.9 T)	0.23	0.24	0.28	0.34	0.40	0.47
Q2-Q3 (59 mm – 8.3 T)	0.19	0.20	0.23	0.28	0.33	0.38
D1 (59 mm – 5.6 T)	0.17	0.19	0.22	0.27	0.32	0.38
D2 (42 mm – 4.5 T)	0.25	0.27	0.32	0.39	0.47	0.54
Q4 (32 mm – 3.7 T)	0.34	0.37	0.44	0.54	0.64	0.74
Q5 (22 mm – 4.4 T)	0.59	0.63	0.72	0.86	1.01	1.16
Q6 (17.7 mm – 3.5 T)	0.79	0.84	0.96	1.14	1.32	1.51
Q7 (17.2 mm – 3.4 T)	0.82	0.87	1.00	1.18	1.37	1.56

On the ramp:
Change in p = 7000/450 = 15.5
Change in beam size (sqrt) = 3.94

Change in beta* during levelling
0.65/0.15 = 4.33
Change in beam size= 2.08



Beta x,y arcs = 85, 90
Beta max match Q IR1 = 500
Factor on beam size = 2.3

Paper zimmermann
http://cds.cern.ch/record/645173?ln=en