CERN

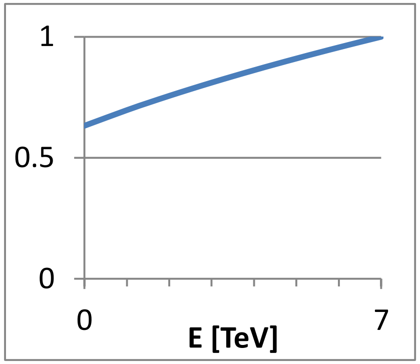
SESSION 4 Part I:

Performance limitations: 2012 review and 2015 outlook
- Cryogenics -

Content

- Beam screen cooling limitations and margins
  - Scaling laws and bunch-length dependence
  - Beam-induced heating on beam screens: Arc-cells, standalone and semi-standalone cryomagnets, Inner triplets.
  - Scaling to 2015 beam parameters
  - Local margin for beam scrubbing and e-cloud deposition
- 1.9 K cold-mass cooling limitations and margins
  - Scaling laws
  - Dynamic heat loads on cold-masses: Inner-triplet and arc cold-mass circuits
  - Scaling to 2015 beam parameters
- Cryoplant outlook and global margin
- Conclusions and new working data proposal

Scaling laws of beam-induced heating on beam screens



- Synchrotron radiation

$$Qsr = Qsr_{nom} \cdot \left(\frac{E}{E_{nom}}\right)^4 \cdot \frac{Nb}{Nb_{nom}} \cdot \frac{nb}{nb_{nom}}$$

- Image current

Magneto-resistance effect

$$Qic = Qic_{nom} \cdot \left(\frac{Nb}{Nb_{nom}}\right)^2 \cdot \frac{nb}{nb_{nom}} \cdot \left(\frac{0.60 \cdot E + 2.80}{E_{nom}}\right)^{0.5} \cdot \left(\frac{\sigma}{\sigma_{nom}}\right)^p$$

What about p ?
(p= 0 according to DR)

- With (DR data):

Qsr_{nom}= 0.165 W/m per aperture
Qic_{nom}= 0.180 W/m per aperture
E_{nom}= 7 TeV
Nb_{nom}= 1.15 10^{11} p per bunch
nb_{nom}= 2808 bunch per beam
σ_{nom}= 1.06 ns

Total BIH : *Qbs*

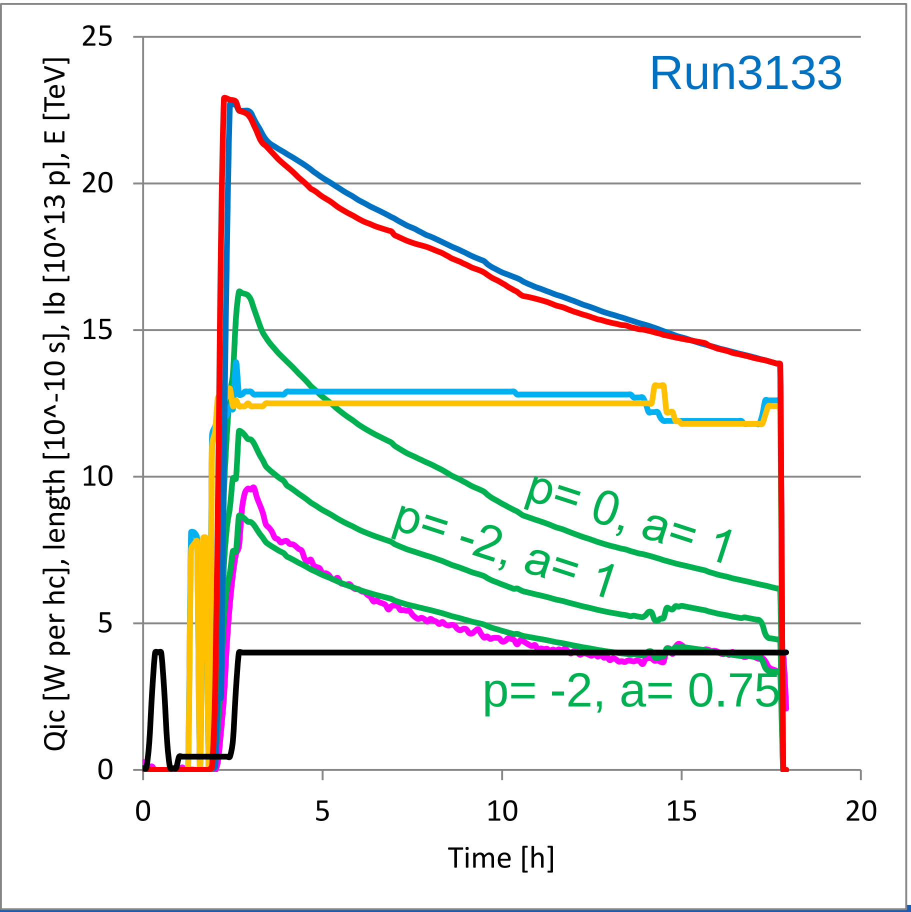
$$Qbs = Qsr + Qic$$

If e-cloud deposition negligible

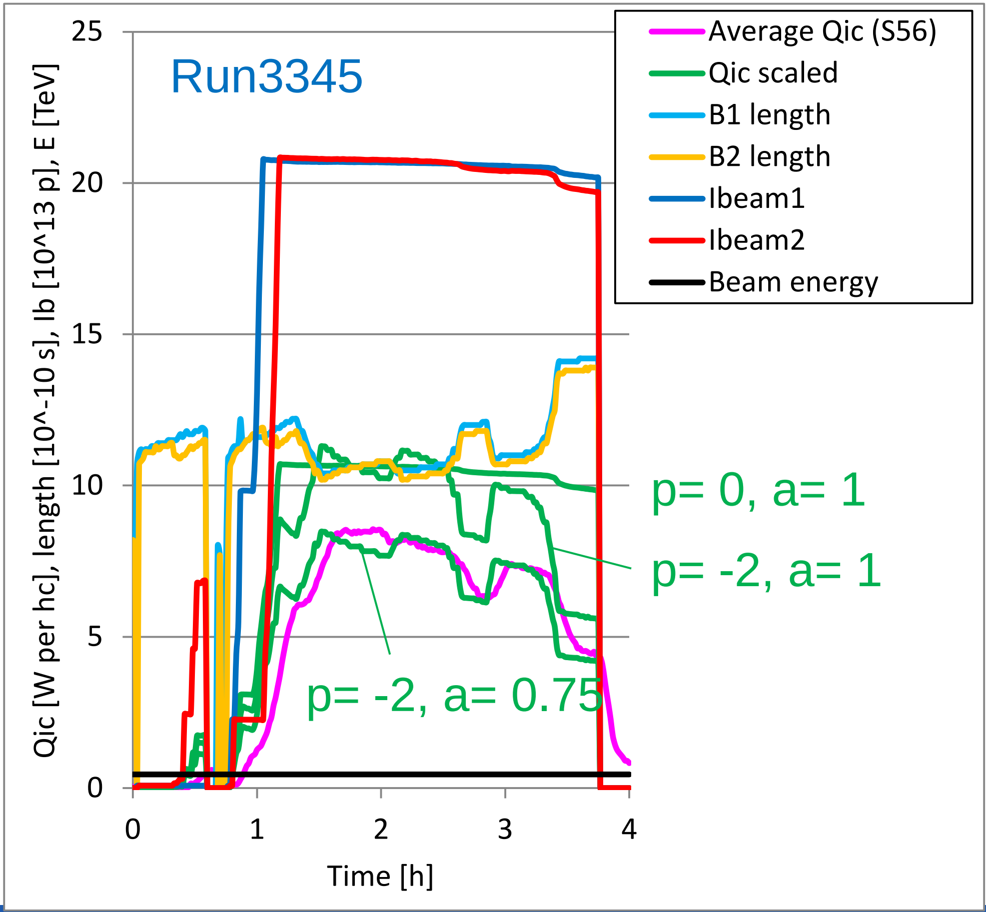
Bunch length dependence in the arc?

$$Qic = a \cdot Qic_{nom} \cdot \left(\frac{Nb}{Nb_{nom}}\right)^2 \cdot \frac{nb}{nb_{nom}} \cdot \left(\frac{0.60 \cdot E + 2.80}{E_{nom}}\right)^{0.5} \cdot \left(\frac{\sigma}{\sigma_{nom}}\right)^p$$

Qsr as expected

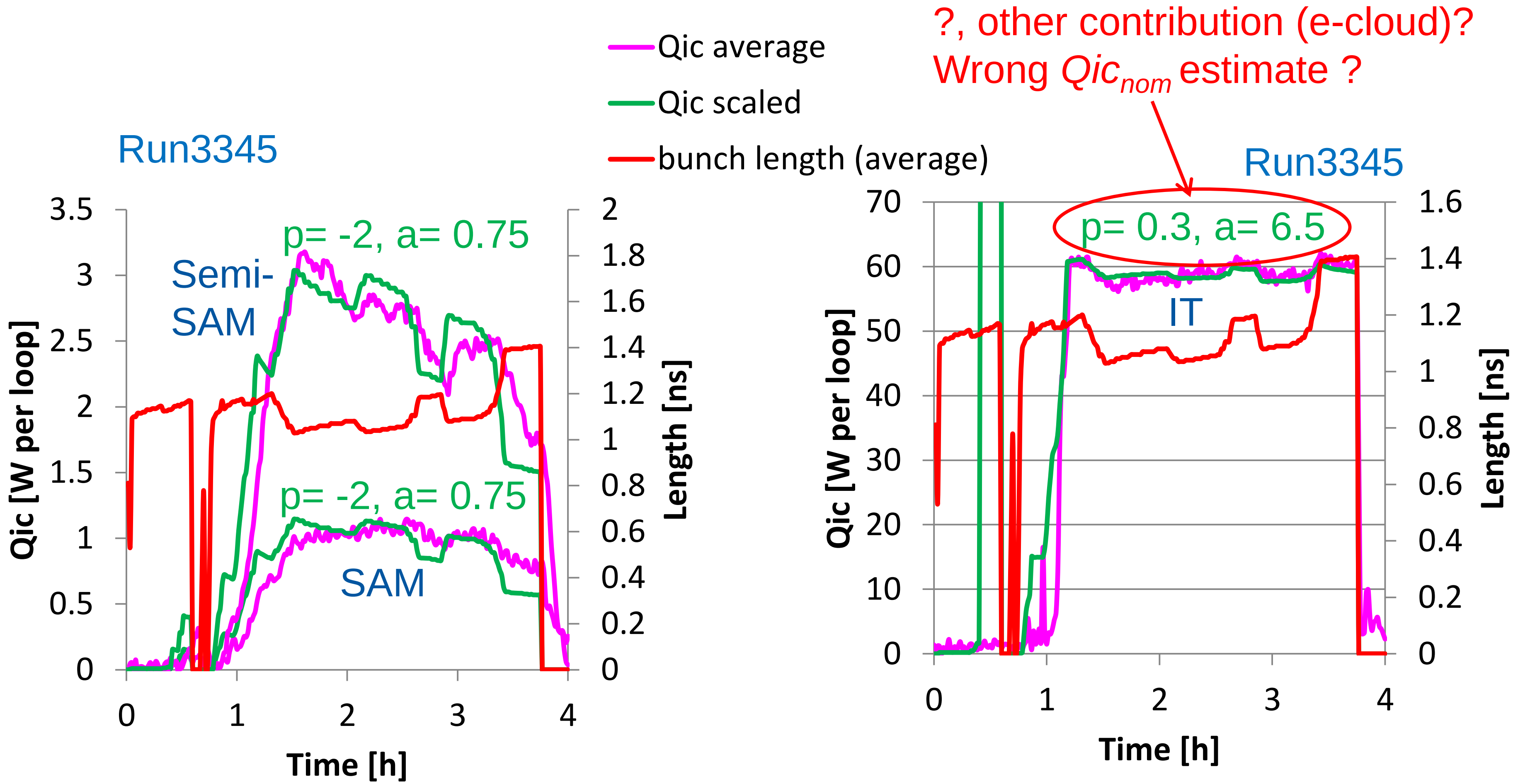


Qsr negligible (E=450 GeV)

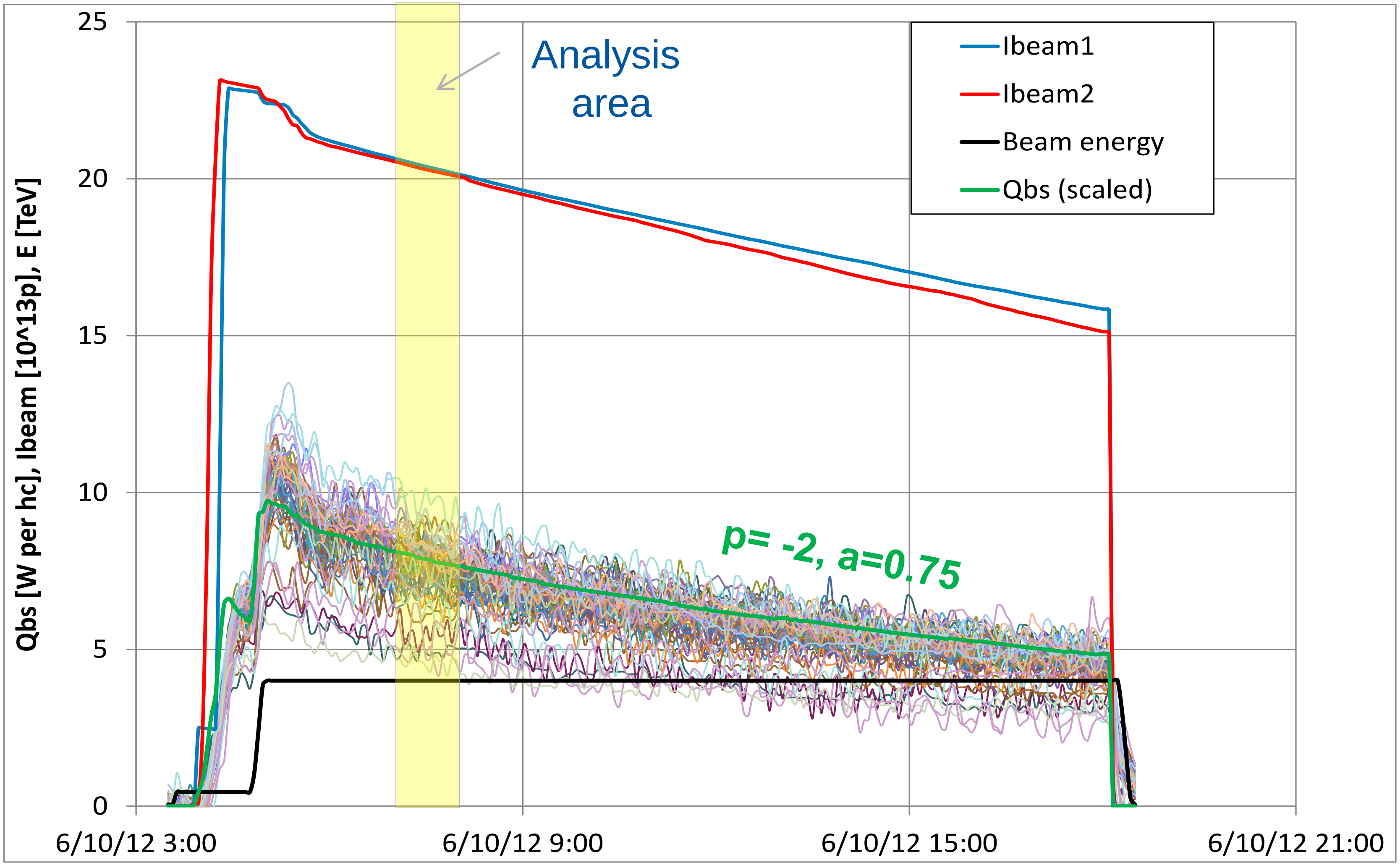


Bunch length dependence in IT and SAM?

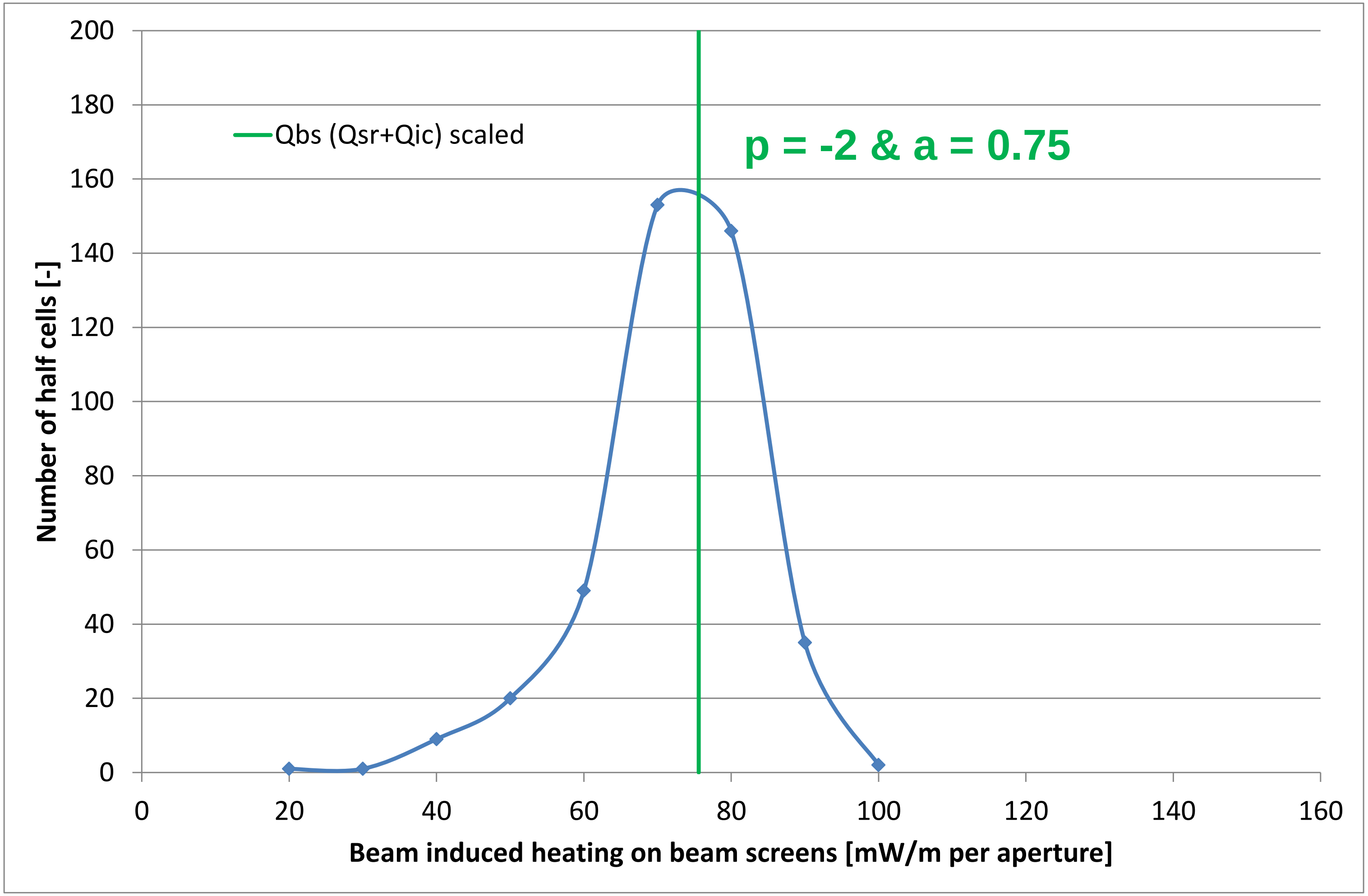
$$Qic = a \cdot Qic_{nom} \cdot \left(\frac{Nb}{Nb_{nom}}\right)^2 \cdot \frac{nb}{nb_{nom}} \cdot \left(\frac{0.60 \cdot E + 2.80}{E_{nom}}\right)^{0.5} \cdot \left(\frac{\sigma}{\sigma_{nom}}\right)^p$$



Beam induced heating in Arc half-cells (run 3134, S56 as typical)



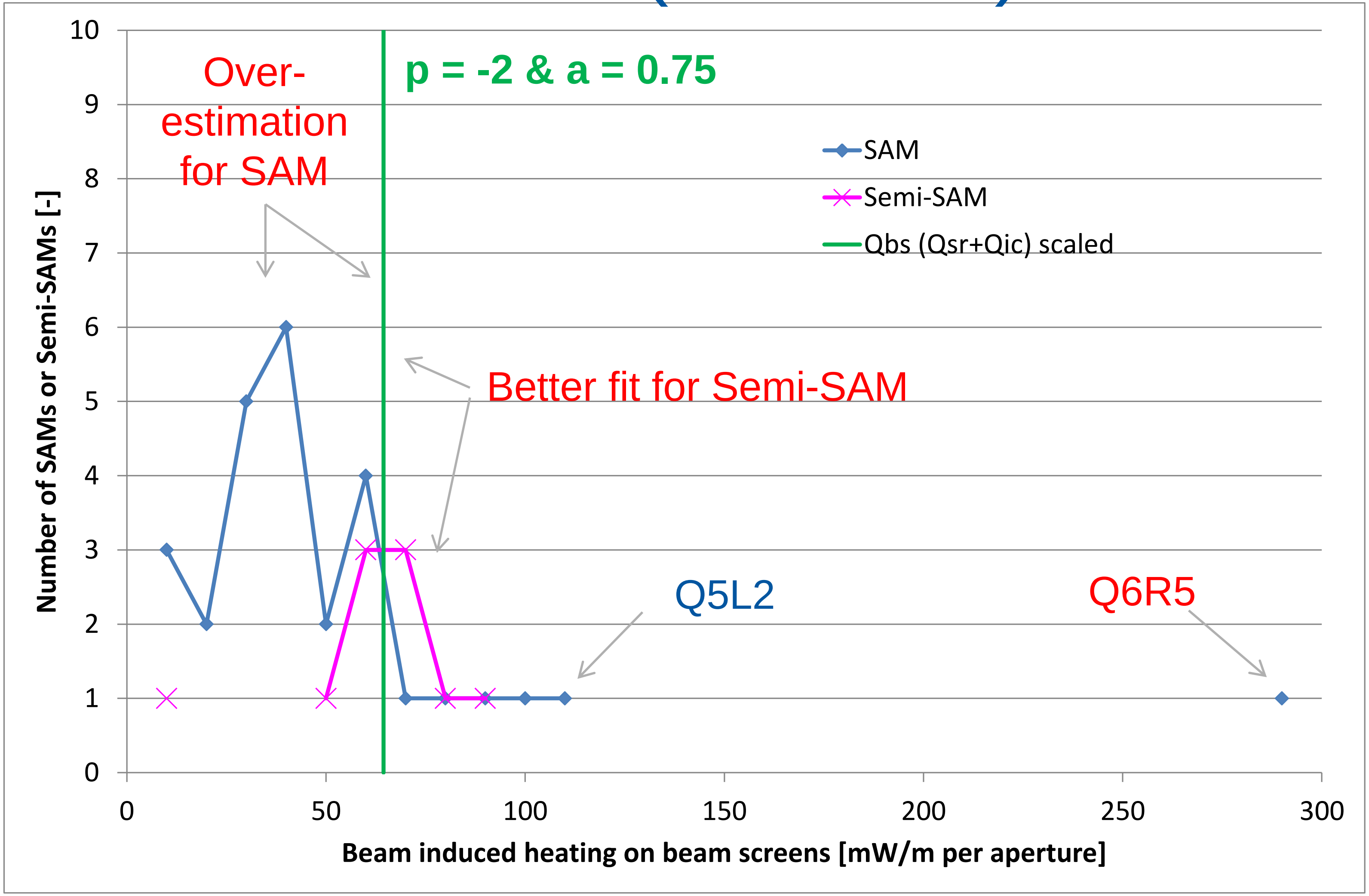
Beam induced heating distribution of Arc half-cells



SAM and semi-SAM inventory

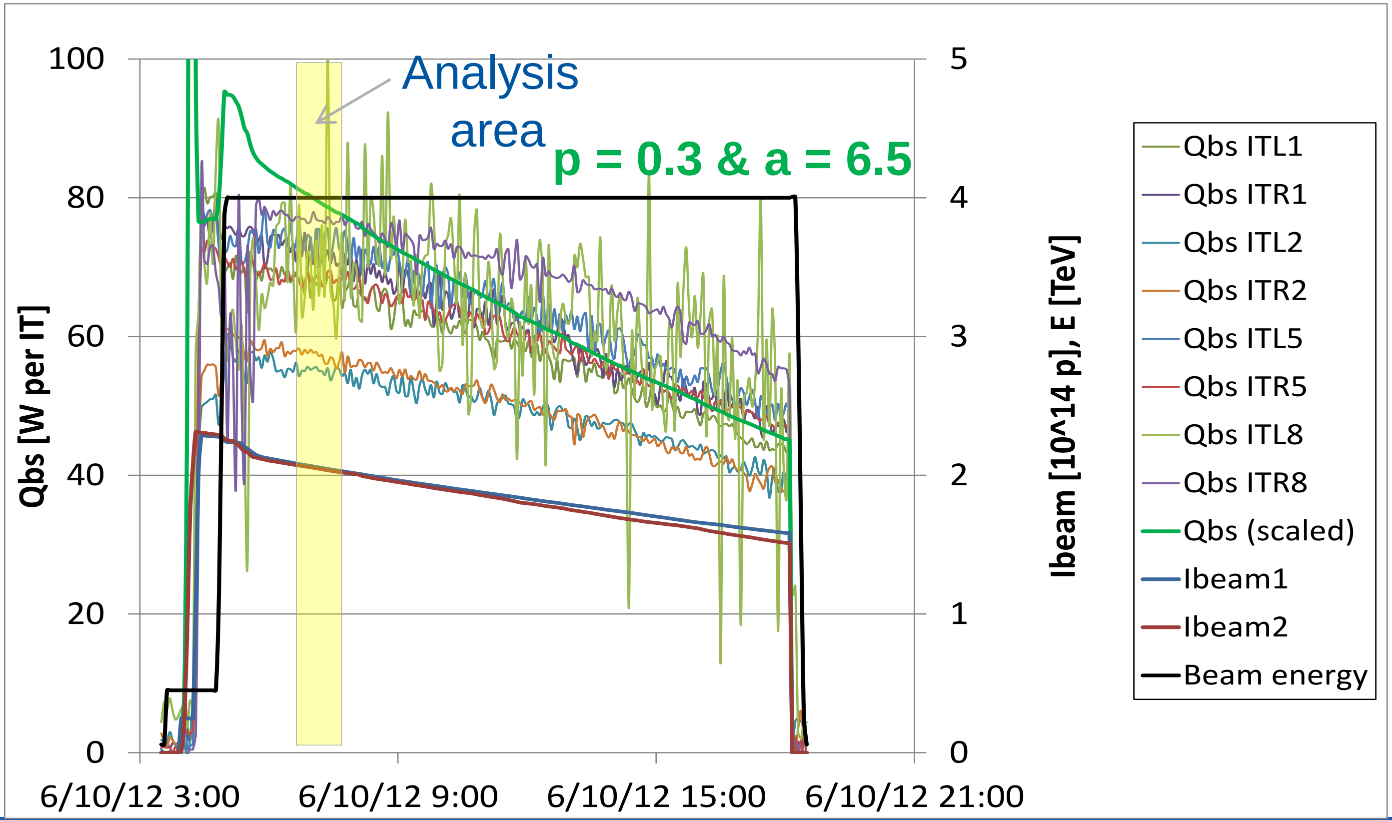
Inventory									Length [m]	CV Kvmax [m3/h]
SAM Type 1	Q5R1	Q6R1	Q6L5	Q5L5	Q5R5	Q6R5	Q6L1	Q5L1	8.2	0.02
SAM Type 2	Q6L4	Q6R4	Q5L6	Q4L6	Q4R6	Q5R6			6.9	0.03
	D3L4	D3R4							11.2	
	Q6L2	Q6R2	Q6L3	Q6R3	Q6L7	Q6R7	Q6L8	Q6R8	12.0	
	Q5L2	Q5R2	Q5L8	Q5R8					13.0	
Semi-SAM	Q5D4L4	D4Q5R4							16.7	0.05
	D2Q4R1	Q4D2L5	D2Q4R5	Q4D2L1					19.4	
	Q4D2L2	D2Q4R2	Q4D2L8	D2Q4R8					22.8	

Beam induced heating distribution of SAM & semi-SAM (run 3134)

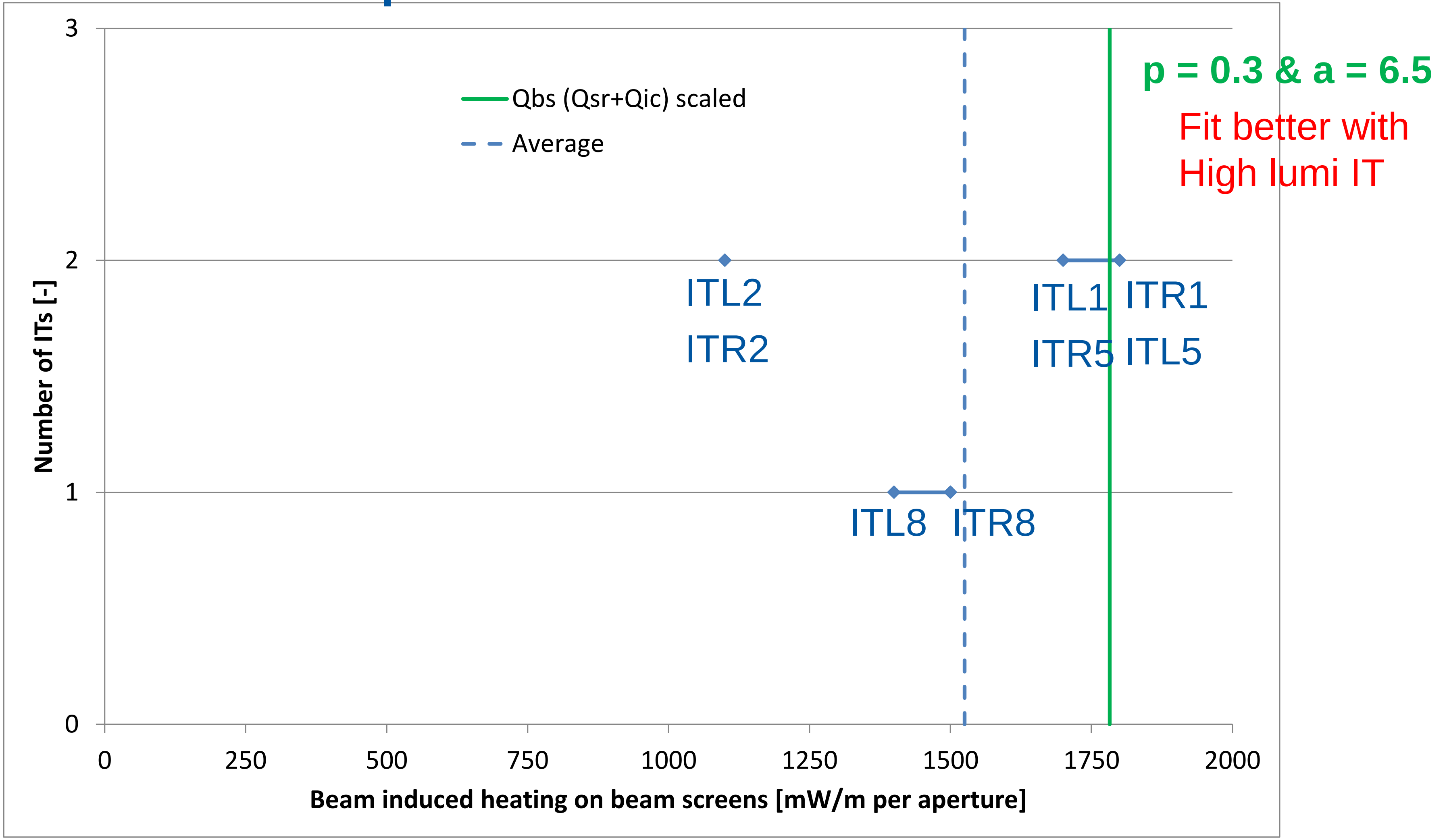


Inner triplet inventory and BS beam induced heating (run 3134)

Inventory				Length [m]
ITL1	ITR1	ITL5	ITR5	40
ITL2	ITR2	ITL8	ITR8	50



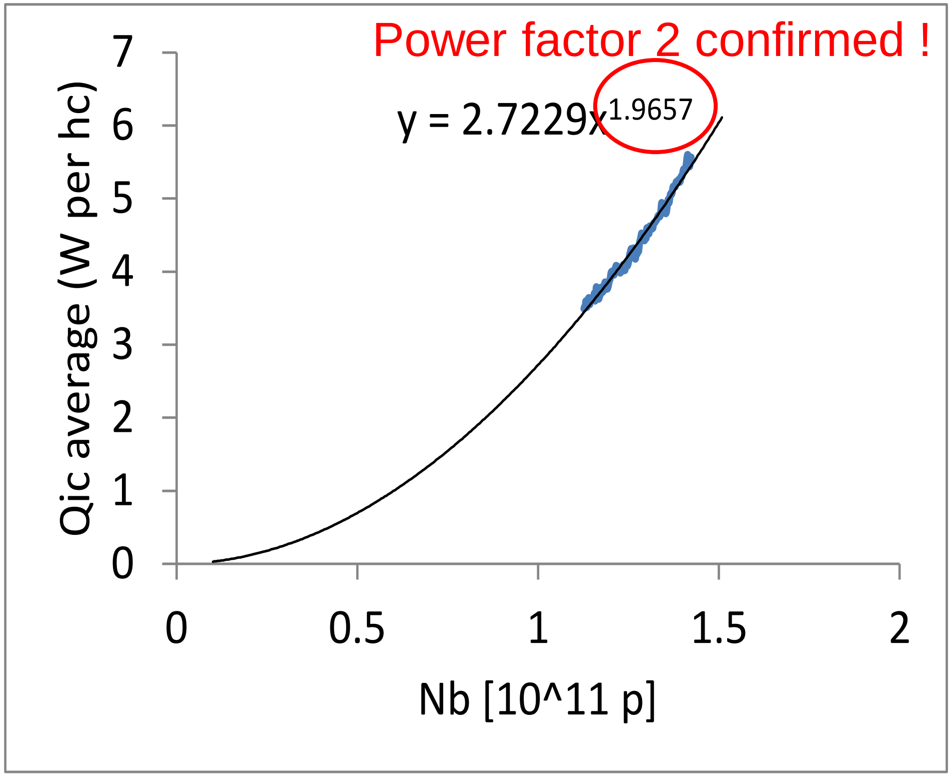
BS beam induced heating distribution of Inner Triplet



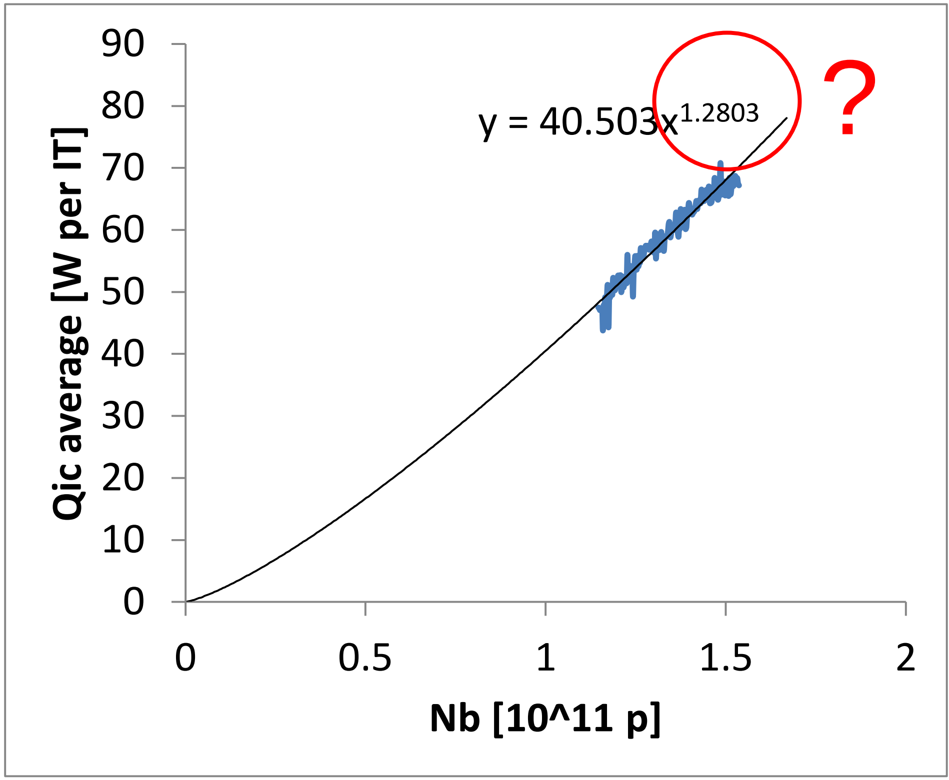
Nb dependence?

$$Qic = a \cdot Qic_{nom} \cdot \left(\frac{Nb}{Nb_{nom}}\right)^{2} \cdot \frac{nb}{nb_{nom}} \cdot \left(\frac{0.60 \cdot E + 2.80}{E_{nom}}\right)^{0.5} \cdot \left(\frac{\sigma}{\sigma_{nom}}\right)^{p}$$

Arc



IT



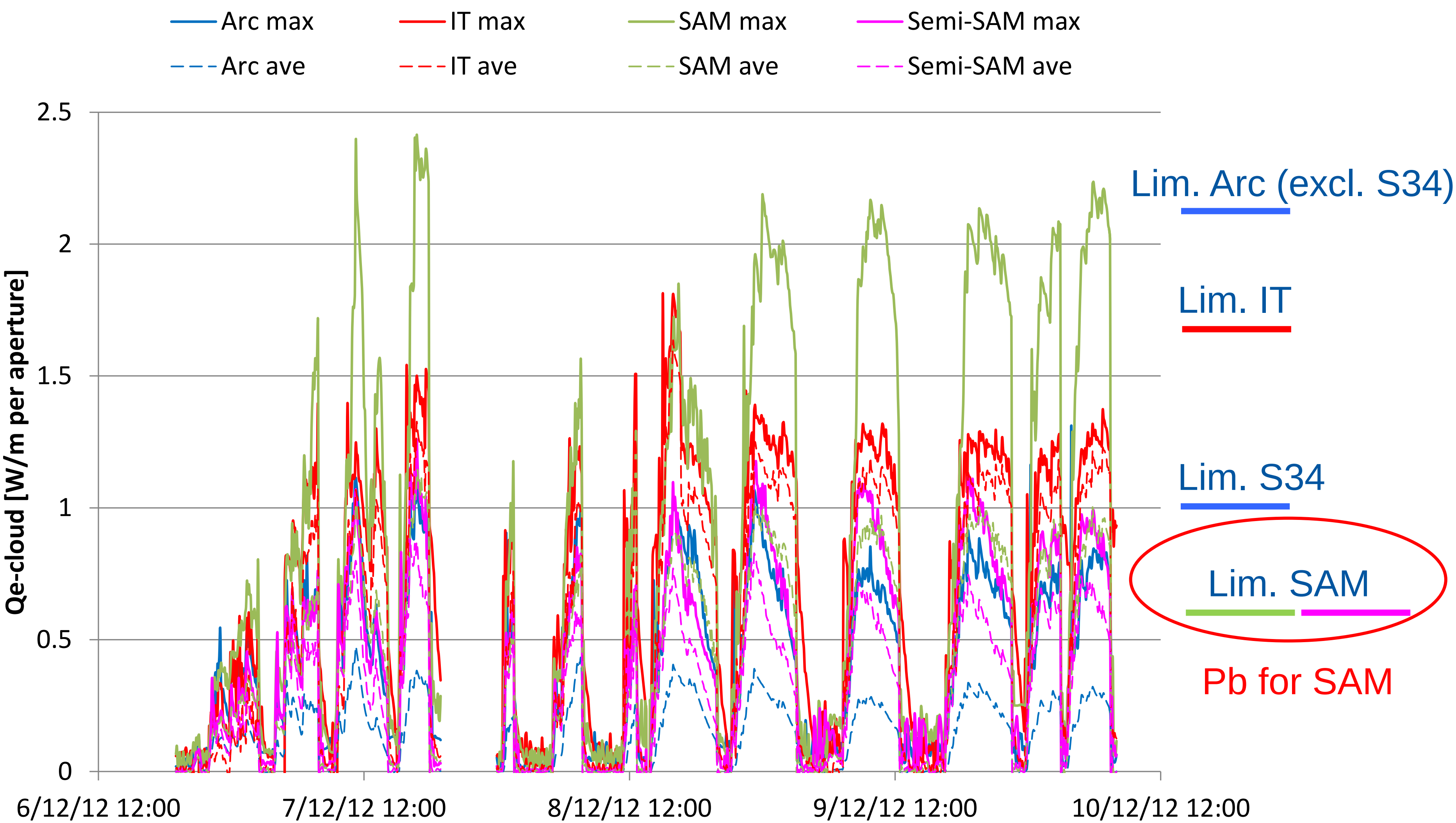
Expected beam screen heat loads with 2015 beam parameters

Sufficient?

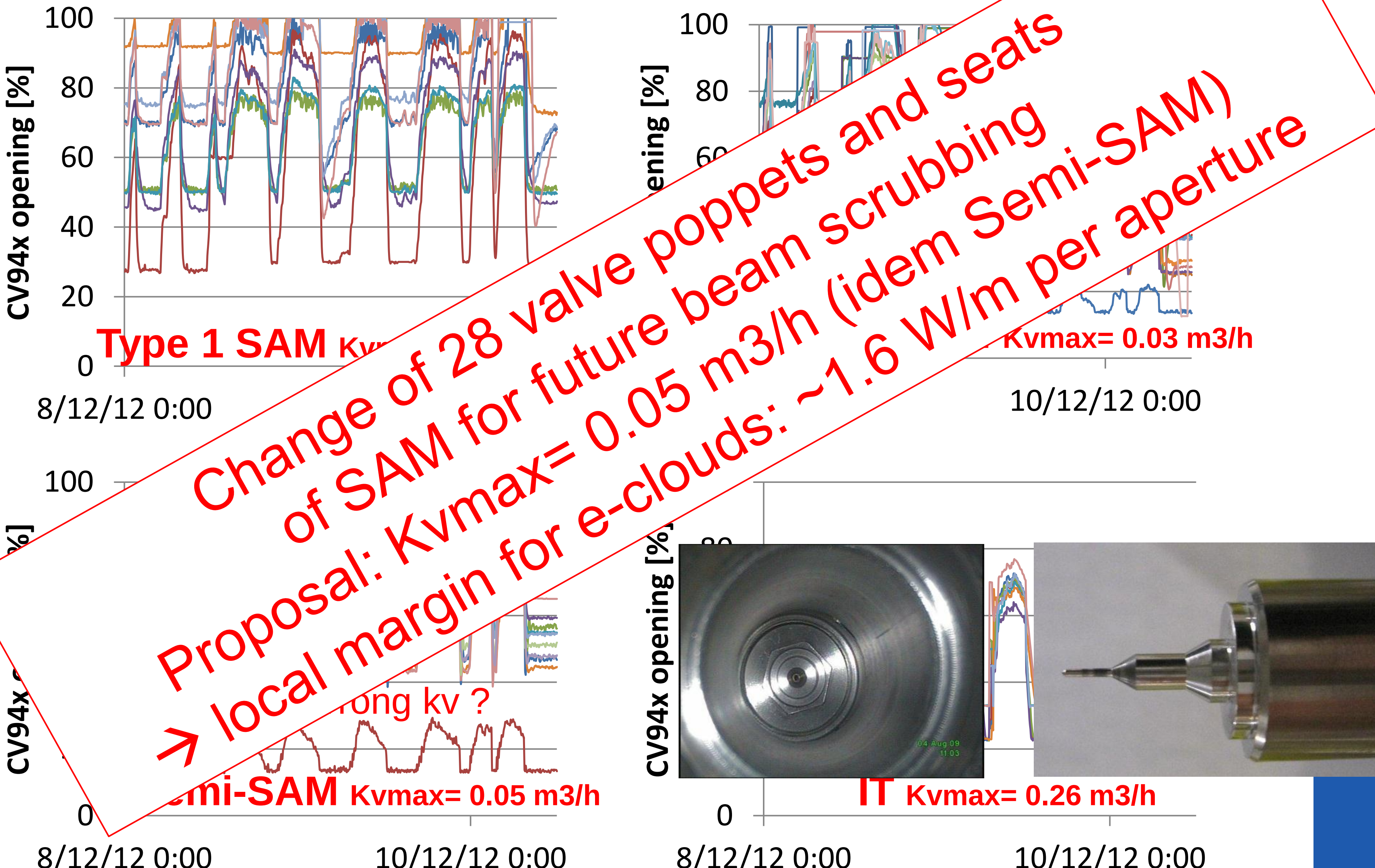
	Run 3134				25 ns 2015	50 ns 2015			
Nb [p per bunch]	1.49E+11				1.15E+11	1.6E+11			
nb [-]	1374				2760	1380			
E [TeV]	4				6.5	6.5			
σ [ns]	1.29E-09				1.06E-09	1.06E-09			
	Qs [W]	Qsr [W]	Qic [W]	Total [W]	Total scaled [W]	Total scaled [W]	Locally installed [W]	Local margin for e-cloud [W/m per aperture] 25 ns 2015	Local margin for e-cloud [W/m per aperture] 50 ns 2015
Arc half-cell	7.5	1.2	6.9	15.6	34	30	255 (140)*	2.1 (1.0)*	2.1 (1.0)*
SAM type 1	4	0	1.1	5.1	6	6	16	0.6	0.6
SAM type 2	4	0	1.7	5.7	7	7	24	0.6	0.6
Semi-SAM	5	0.5	2.9	8.4	16	15	40	0.6	0.7
SAM Q6R5	10	0	4.8	14.8	**20**	**19**	16	N/A	N/A
IT	5	0	71	76	114	89	200	1.7	2.2

(x)*: Data for S34

25 ns scrubbing run (Dec'12): e-cloud deposition



25 ns beam scrubbing in SAM and IT BS control valve opening



Change of 28 valve poppets and seats of SAM for future beam scrubbing

Proposal: Kvmax= 0.05 m3/h (idem Semi-SAM)

→ local margin for e-clouds: ~1.6 W/m per aperture

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Scaling law of dynamic heat loads on cold-masses

- Secondaries (IT): $$Qsec = Qsec_{nom} \cdot \frac{E}{E_{nom}} \cdot \frac{L}{L_{nom}}$$
- Beam-gas scattering: $$Qbgs = Qbgs_{nom} \cdot \frac{Nb}{Nb_{nom}} \cdot \frac{nb}{nb_{nom}}$$
- Resistive heating: $$Qrh = Qrh_{nom} \cdot \left(\frac{E}{E_{nom}}\right)^2$$
- With (DR data):

$Qsec_{nom}$= 182 W per high-lumi half –insertion
$Qbgs_{nom}$= 0.024 W/m per aperture
Qrh_{nom}= 0.10 W/m
E_{nom}= 7 TeV
Nb_{nom}= 1.15 10^{11} p per bunch
nb_{nom}= 2808 bunches per beam
L_{nom}= 10^{34} Hz/cm^2

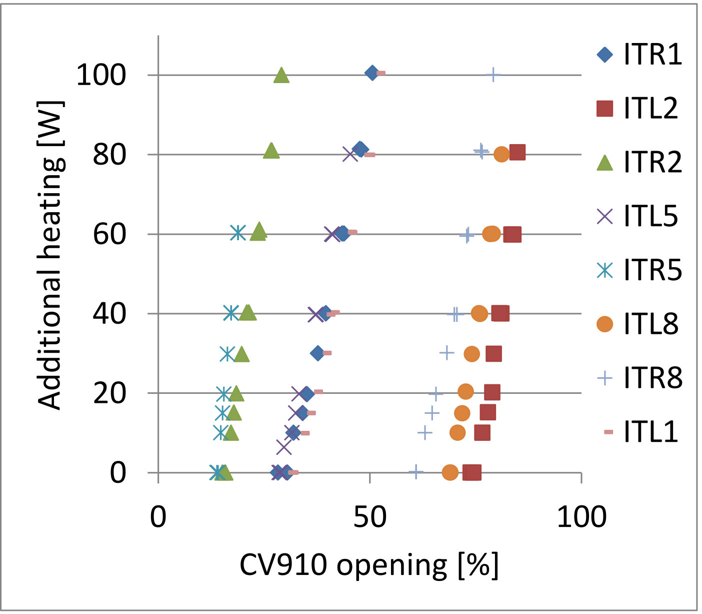
Total dynamic load : *Qdcm*

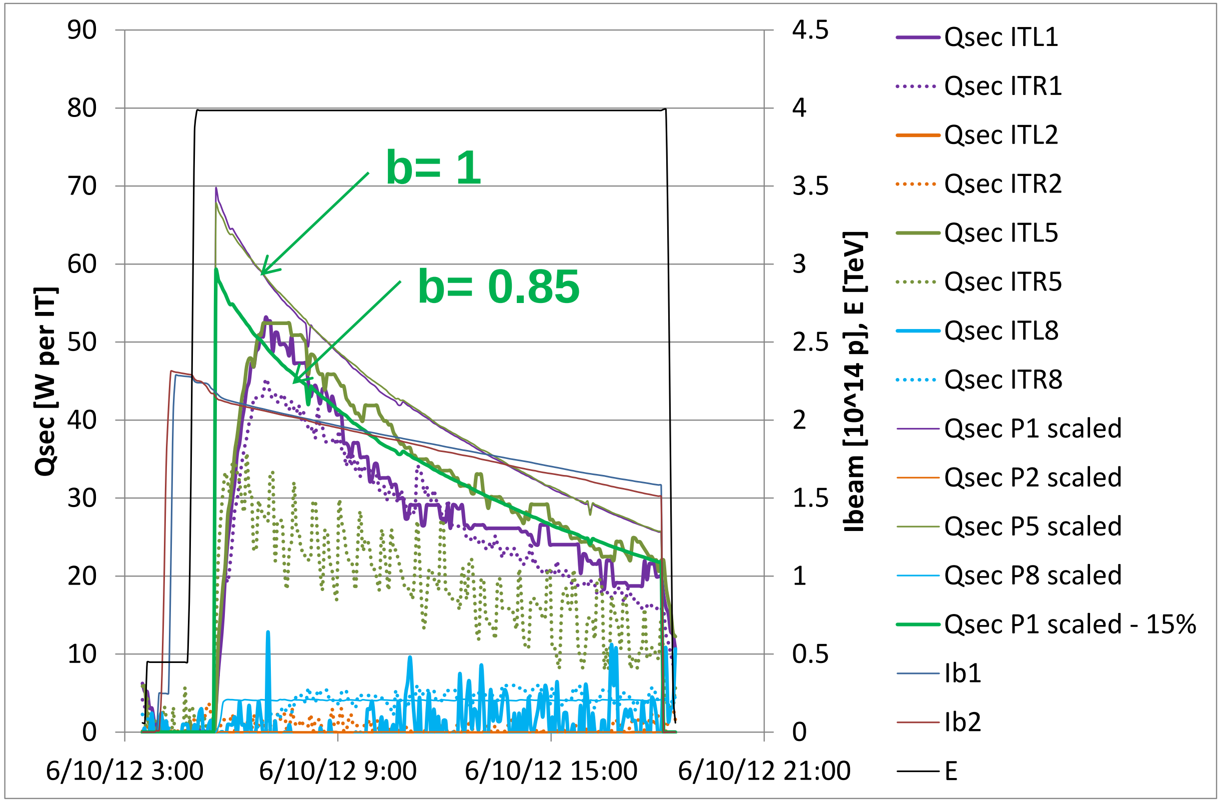
$$Qdcm = Qsec + Qbgs + Qrh$$

Secondaries deposition in Inner Triplets

$$Qsec = b \cdot Qsec_{nom} \cdot \frac{E}{E_{nom}} \cdot \frac{L}{L_{nom}}$$

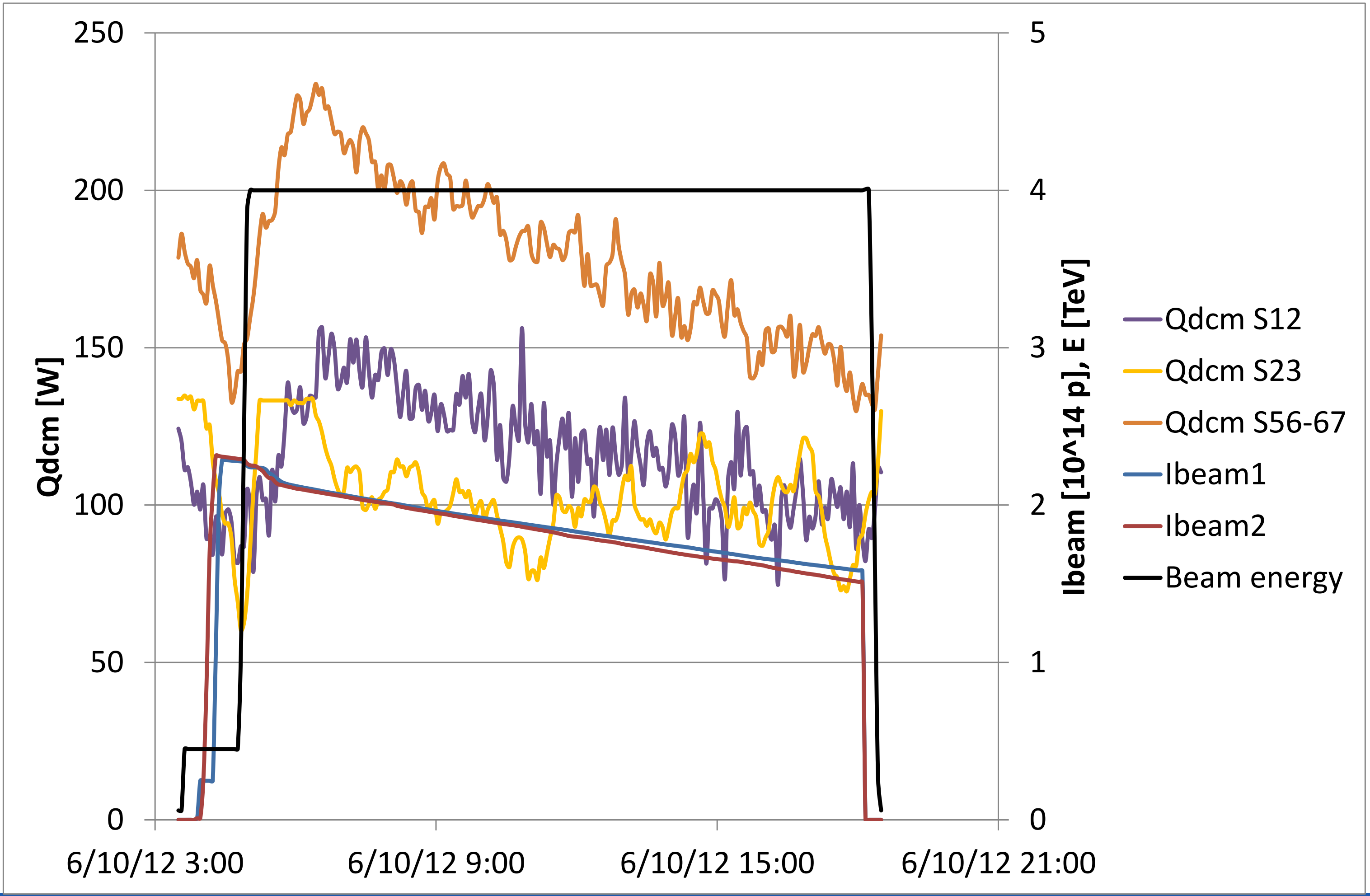
Measurement method: calibration of the extra-opening of the control valves versus a known electrical heating deposition





Dynamic heat load (full sector) (Run 3134)

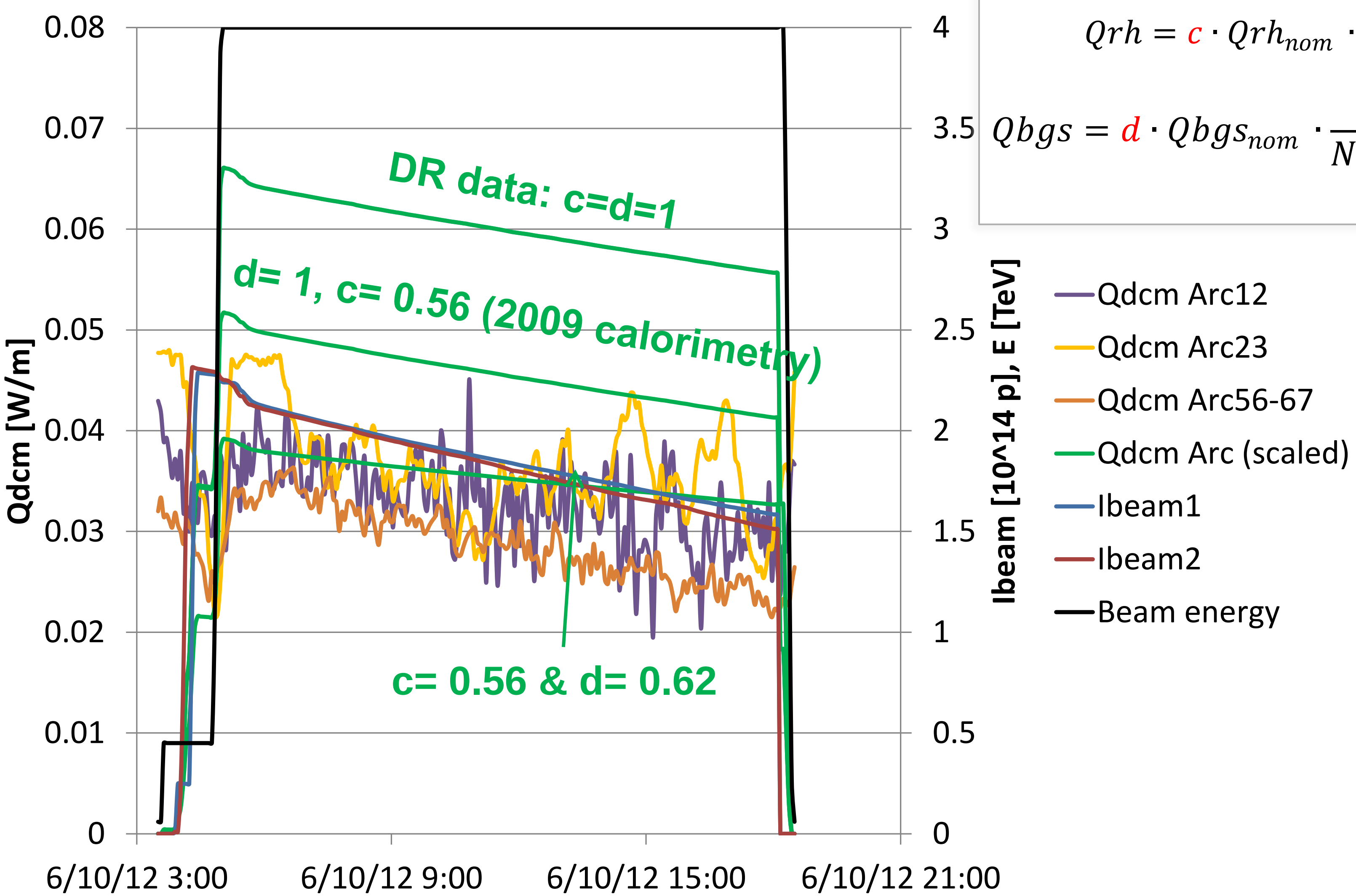
Measurement method: variation of the cold compressor pumping flow (S12, S56 & S67) or return module heating (S23).



Specific dynamic loads in Arc cold-masses

$$Qrh = c \cdot Qrh_{nom} \cdot \left(\frac{E}{E_{nom}}\right)^2$$

$$Qbgs = d \cdot Qbgs_{nom} \cdot \frac{Nb}{Nb_{nom}} \cdot \frac{nb}{nb_{nom}}$$



Expected 1.9 K heat loads with 2015 beam parameters

	Run 3134	25 ns 2015	50 ns 2015
Nb [p per bunch]	1.52E+11	1.15E+11	1.60E+11
nb [-]	1374	2760	1380
E [TeV]	4	6.5	6.5
L [Hz/cm2]	6.70E+33	1.00E+34	1.00E+34

Lmax compatible with local margin: 1.75E34

	Qs [W]	Qrh [W]	Qbgs [W]	Qsec [W]	Total [W]	Total scaled [W] (25 ns 2015)	Total scaled [W] (50 ns 2015)	Locally installed [W]	Local margin [W] 25 ns 2015	Local margin [W] 50 ns 2015
Arc cell	18	2.3	2	0.0	23	27	26	90(1)	63	64
DS cell	25	1.9	2	0.0	29	33	32	140(1)	107	108
ITL1	60	0.6	0.6	60	121	208	208	320(2)	112*	112*
ITR1	52	0.6	0.6	60	113	200	200	320(2)	120	120
ITL2	110	0.6	0.8	0.0	111	113	113	140(1)	27*	27*
ITR2	50	0.6	0.8	0.0	51	53	53	140(1)	87*	87*
ITL5	50	0.6	0.6	60	111	198	198	320(2)	122	122
ITR5	47	0.6	0.6	60	108	195	195	320(2)	125*	125*
ITL8	80	0.6	0.8	3.6	85	86	86	140(1)	54*	54*
ITR8	46	0.6	0.8	3.6	51	52	52	140(1)	88*	88*

(1): limited by sub-cooling heat exchanger

(2): limited by bayonet heat exchanger (IT)

*: could be jeopardized by NC braid

Recommendations:

Remove NC braids on ITL1, ITL2, ITR5 & ITL8. Add missing braids in ITR2 & ITR8.
(ITR1 & ITL5 already consolidated)

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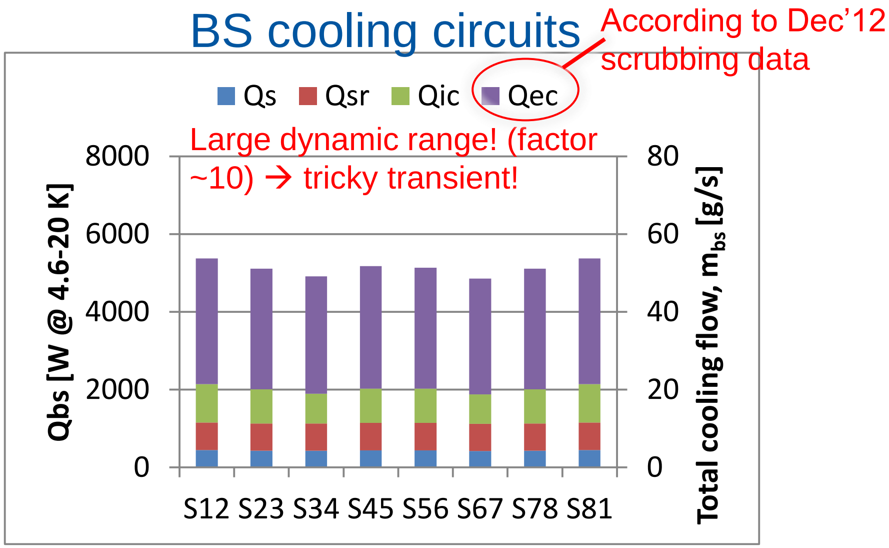
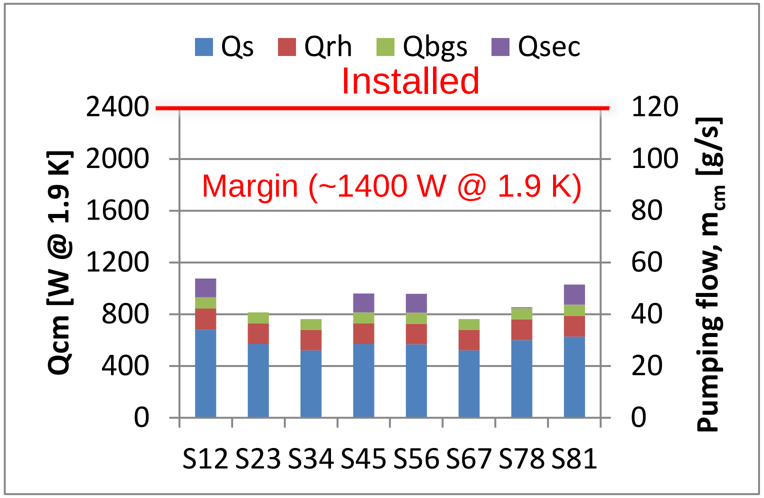
Cryoplant outlook and global margins

(for 25 ns 2015 beam parameters)

BS cooling circuits

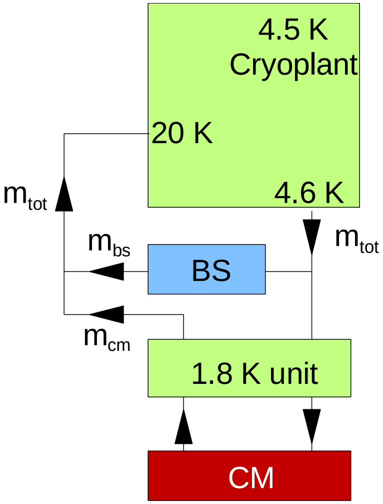


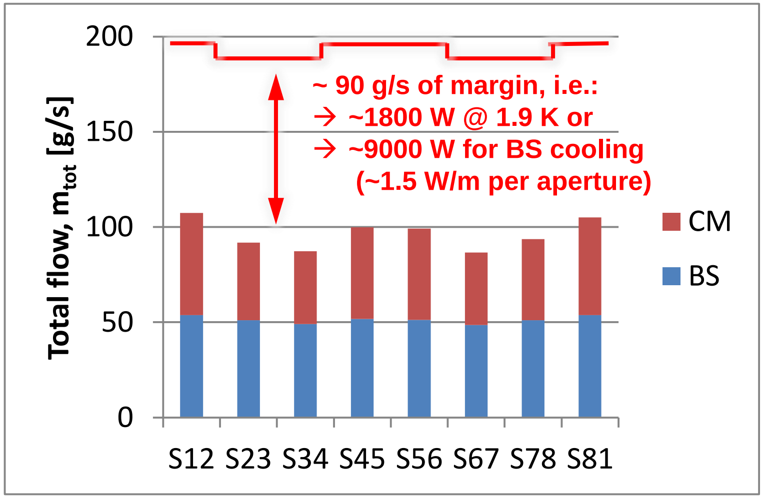
1.9 K cold-mass circuits



Installed refrigeration capacity

Temperature level		High-load sector	Low-load sector
50-75 K	[W]	33000	31000
4.6-20 K	[W]	**7700**	**7600**
4.5 K	[W]	300	150
1.9 K LHe	[W]	**2400**	**2100**
4 K VLP	[W]	430	380
20-280 K	[g.s-1]	41	27





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New working data proposal

				DR data	New working data	Delta%
Beam-screens @ 4.6-20 K	Qsr_{nom}		[mW/m per aperture]	165	**165**	**0%**
	Qic_{nom}	Arc & DS	[mW/m per aperture]	180	**135**	**-25%**
		IT	[mW/m]	360	**2340**	**550%** ?
Cold-masses @ 1.9 K	$Qbgs_{nom}$		[mW/m per aperture]	24	**15**	**-38%**
	Qrh_{nom}		[mW/m]	100	**56**	**-44%**
	$Qsec_{nom}$		[W per half-insertion]	182	**155**	**-15%**

$$Qsr = Qsr_{nom} \cdot \left(\frac{E}{E_{nom}}\right)^4 \cdot \frac{Nb}{Nb_{nom}} \cdot \frac{nb}{nb_{nom}}$$

$$Qic = Qic_{nom} \cdot \left(\frac{Nb}{Nb_{nom}}\right)^2 \cdot \frac{nb}{nb_{nom}} \cdot \left(\frac{0.7189 \cdot E + 1.967}{E_{nom}}\right)^{0.5} \cdot \left(\frac{\sigma}{\sigma_{nom}}\right)^p$$

$$Qbgs = Qbgs_{nom} \cdot \frac{Nb}{Nb_{nom}} \cdot \frac{nb}{nb_{nom}}$$

$$Qrh = Qrh_{nom} \cdot \left(\frac{E}{E_{nom}}\right)^2$$

$$Qsec = Qsec_{nom} \cdot \frac{E}{E_{nom}} \cdot \frac{L}{L_{nom}}$$

With:
E_{nom}= 7 TeV
Nb_{nom}= 1.15 10^{11} p per bunch
nb_{nom}= 2808 bunches per beam
σ_{nom}= 1.06 ns
L_{nom}= 10^{34} Hz/cm^2

p= -2 for arc cells, semi-SAM & SAM
p= 0.3 ? for inner triplets

Conclusion

- 2012 50-ns runs have been analysed and dynamic loads have been measured on the beam-screen (BS) and 1.9-K cold-mass circuits:
  - Globally below expectation w/r to DR scaling except for IT (BS) and Q6R5 (BS).

- Scaling with 2015 beam parameters shows sufficient margin with respect to local and global cooling limitations by implementing the following consolidations:
  - Consolidation of the Cu braid configuration on 6/8 IT (planned for LS1)
  - Increase of the maximum flow coefficient of the BS control valve of the standalone magnets (seat and poppet exchange) → compatible with e-cloud deposition of 1.6 W/m per aperture → to be planned for LS1

- 25-ns beam scrubbing run in Dec'12 has identified or confirmed:
  - A tricky transient to be controlled due to the large dynamic range seen by the 500 local control loops and by the 8 cryoplants → new control principle under investigation.
  - A discrepancy (factor 2) between the cryogenic heat load measurement (typically 20 kW) and the RF power (typically 40 kW) → under investigation by assessing the power dissipated in the warm sections (~3 km) and by assessing the extra capacity supplied by the cryoplants during the scrubbing.

Many thanks to the Cryo-operation team for the tuning of the loops and to Serge Claudet for useful discussions

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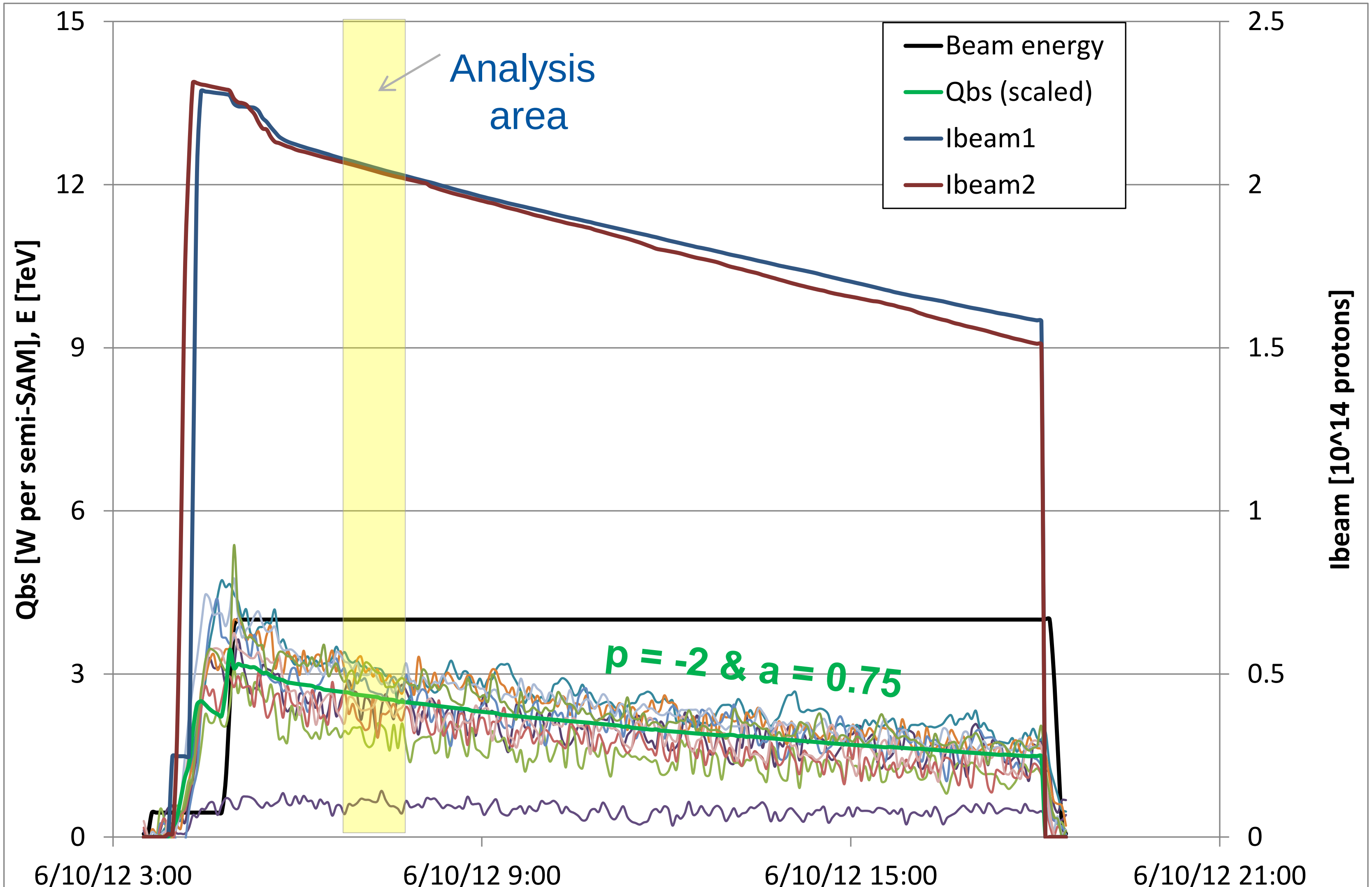
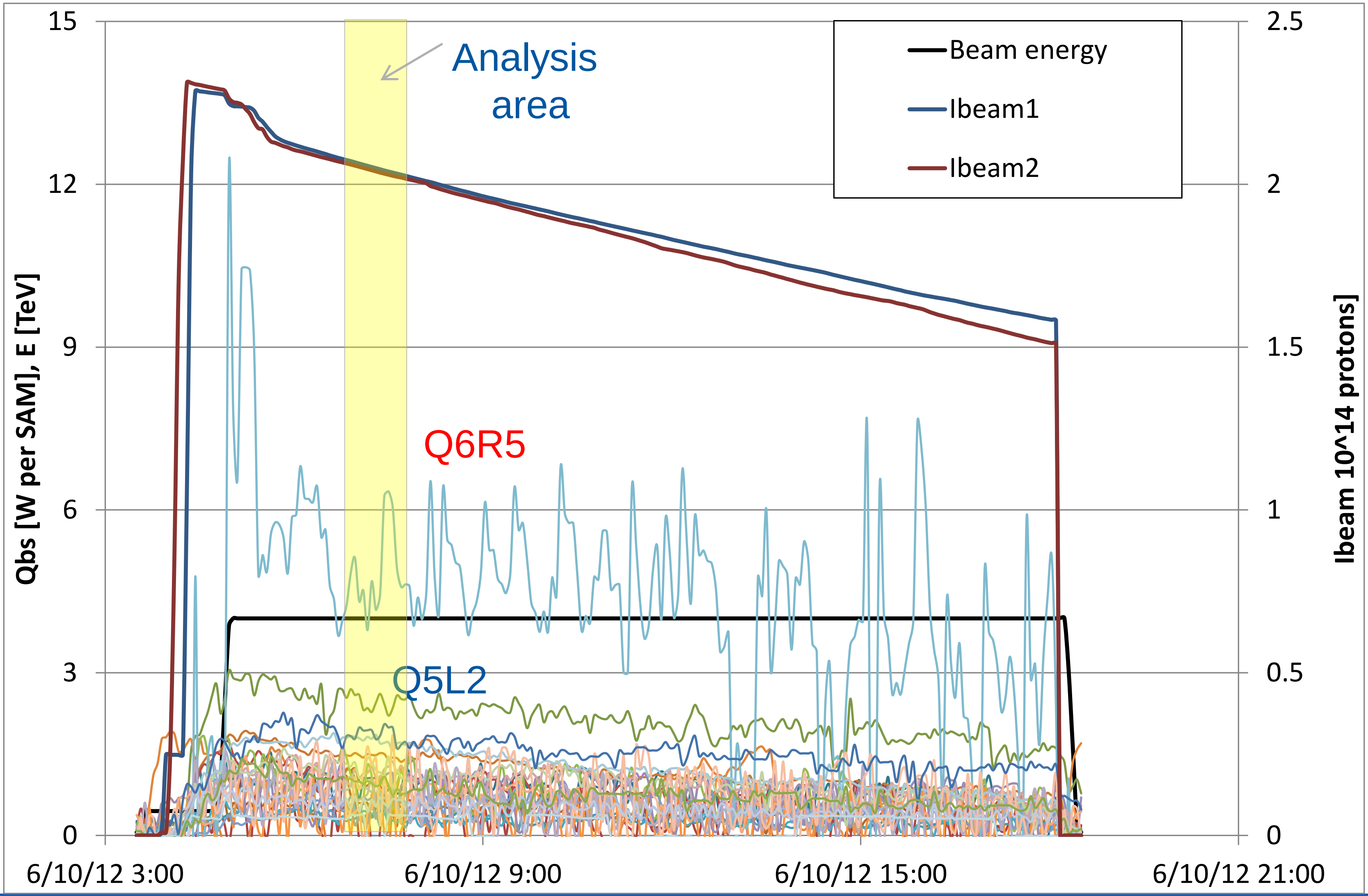
Backup slides

Beam-induced heating in semi-SAM (Run 3134)

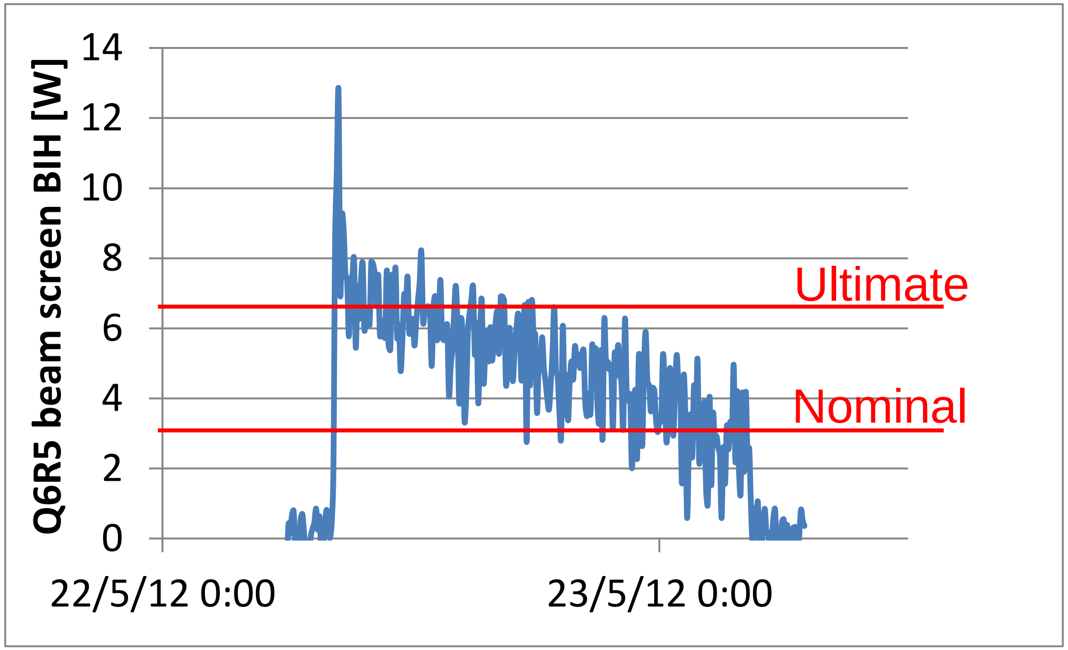


Beam-induced heating in SAM (run 3134)



Q6R5 investigation: cooling loop design

- Expected heat loads
  - Static heat inleaks: 4 W
  - BIH nominal: 3 W
  - BIH ultimate: 6.5 W
- Installed cooling capacity:
  - (Q_static + Q_dyn_ultimate) x 1.5 → 16 W

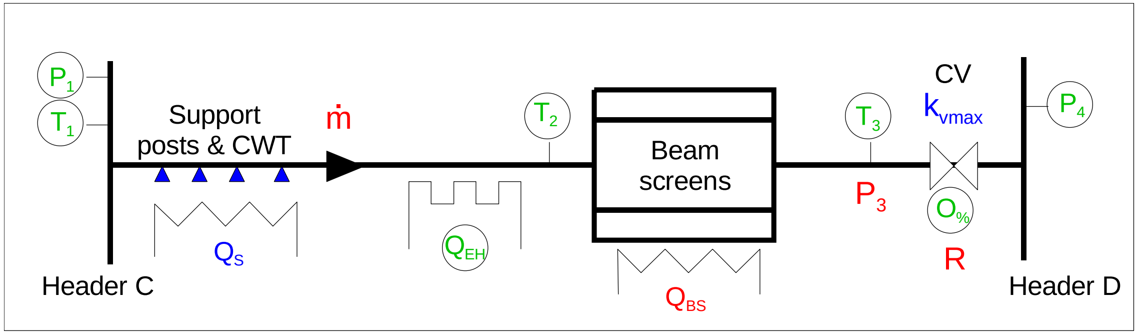


Today beam induced heating already above expected ultimate !

→ CV valve reaches its maximum limit (100 %)

→ Consolidation need: reduce the heat loads or increase the cooling capacity

Q6R5 investigation: What about static heat inleaks Qs ?



Specific calibrations without beam at constant CV valve opening and with different electrical heating Q_{EH} allow to assess the static heat inleaks:

→ Qs= ~10 W (4 W expected)

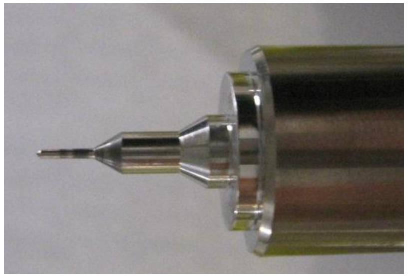
Today, installed capacity already reached
→ CV valve reaches its maximum limit (100 %)
→ Consolidation need: reduce the heat loads or increase the cooling capacity

Q6R5 investigation: Consolidation?

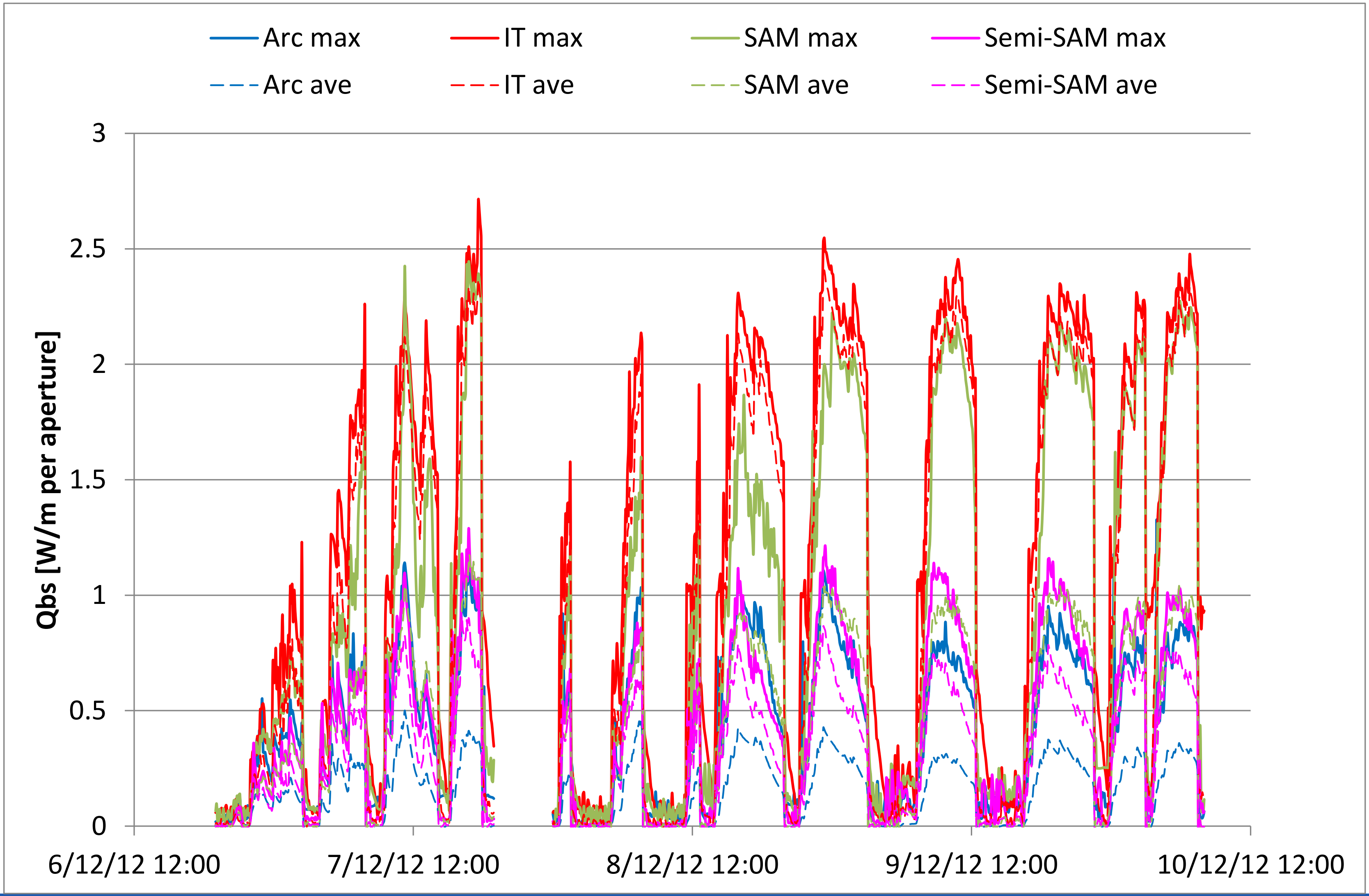
- Cooling loop at the limit due to the cumulative effect of:
  - too high heat inleaks (Qs) (support posts?, CWT?, QRL jumper?...)
  - too high BIH (Q_{BIH}) (Cu resistivity?, HOM in CWT?, TOTEM?, other?...)
- However, the heat loads are still safe w/r to heat exchange and material properties (low risk of degradations)… but what about beam and vacuum stability ?

- Consolidation options:
  - Removal and change of beam screens and CWT: Not possible in situ. Could partially solve Qs issue. Heavy operation.
  - Change of cryomagnet: Spare could be prepared in parallel with operation. Could solve Qs issue if QRL is OK. Heavy operation.
  - Increase of cooling capacity: Change the valve poppet and seat. The lightest consolidation.

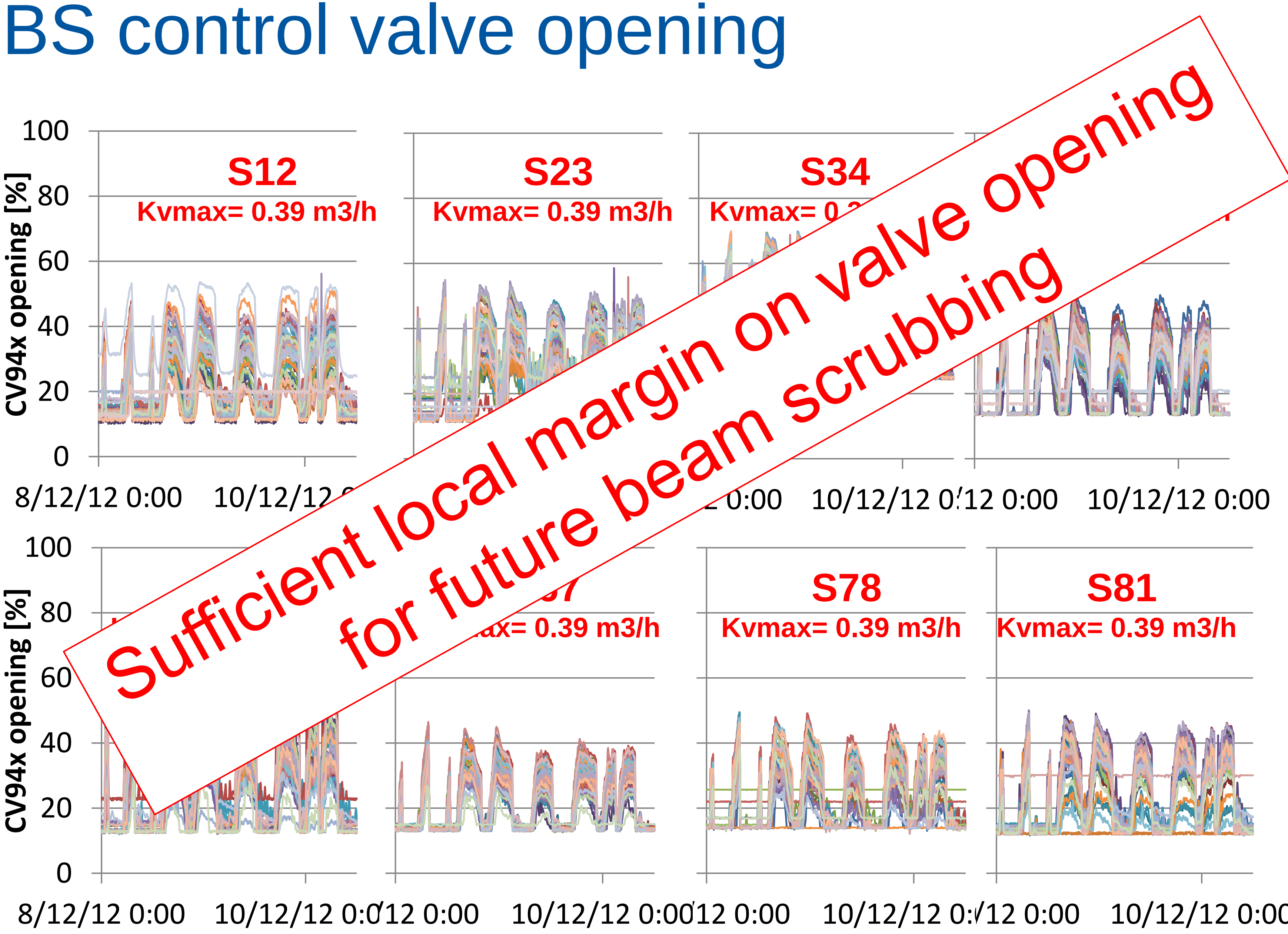
If 20-30 W of beam induced heating is acceptable for beams and vacuum, the increase of the cooling capacity by changing the valve poppet and seat is definitely recommended.



25 ns scrubbing run (Dec'12): Qbs deposition



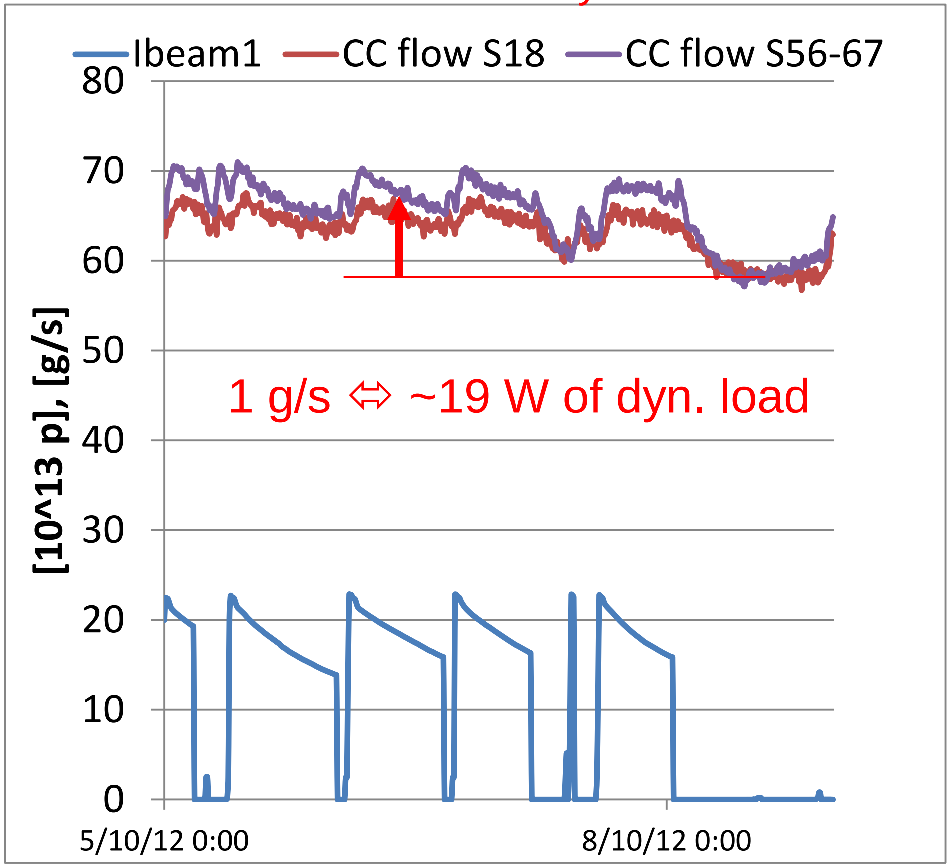
25 ns beam scrubbing in Arcs
BS control valve opening



Total dynamic load on sector cold masses

Measurement method: variation of the cold compressor pumping flow (S12, S56 & S67) or return module (RM) heating (S23).

Flow increase due to dynamic loads



Heating reduction to balance dynamic loads