Multi-turn losses and Cleaning

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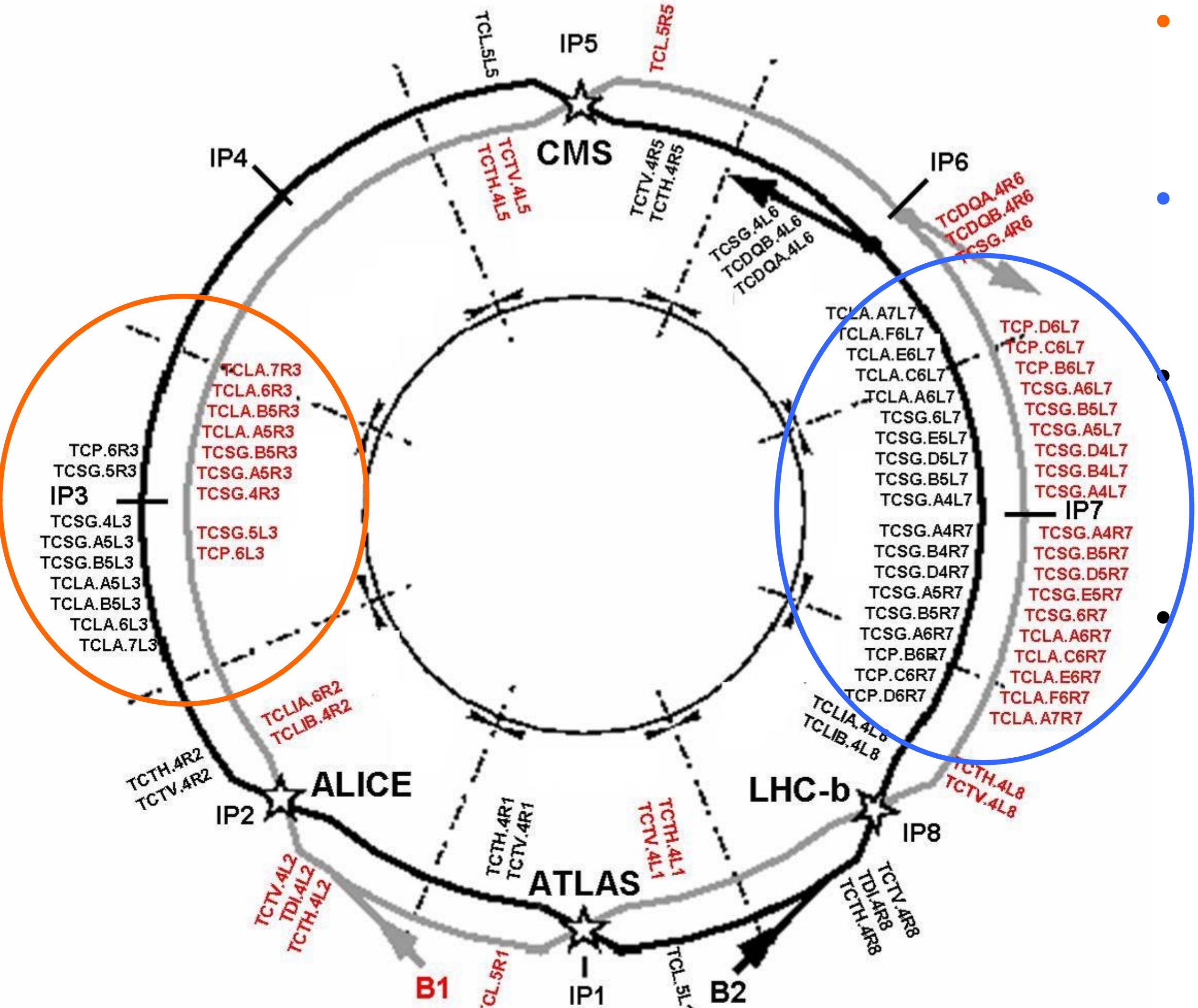
Outline

- Introduction:
  - Setup collimation system
  - Collimator Settings (intermediate settings)
  - Qualification of Cleaning
- Cleaning and passive protection: performance and problems
  - Inefficiency measurements
  - Comparison of Simulations with Measurements
  - Problems
  - Inefficiency for ions
  - Performance stability
- Collimation beam loss experience 2010 and outlook 2011:
  - Losses during high luminosity runs
  - Losses due to instabilities
  - Losses due to un-captured beam at start of ramp
- Conclusion

Phase-I Collimation System



Courtesy C. Bracco

- IR3 momentum cleaning
- IR7 betatroncleaning
- Injection and Dump collimators
- Protection of Experimental insertions and triplets (TCTs)

Collimator Settings

	Injection optics	Injection optics	Squeezed optics
Energy [GeV]	450	3500	3500
Primary cut IR7 (H, V, S) [σ]	5.7	5.7	5.7
Secondary cut IR7 (H, V, S) [σ]	6.7	8.5	8.5
Quaternary cut IR7 (H, V) [σ]	10.0	17.7	17.7
Primary cut IR3 (H) [σ]	8.0	12	12 (B1) / 10 (B2)
Secondary cut IR3 (H) [σ]	9.3	15.6	15.6
Quaternary cut IR3 (H, V) [σ]	10.0	17.6	17.6
Tertiary cut exp. (H, V) [σ]	15-25	40-70	15
TCSG/TCDQ IR6 (H) [σ]	7-8	9.3-10.6	9.3-10.6

- Additional intermediate steps: end of ramp, reduced crossing angle, β^*=7m, β^*= 3.5m separated beams
- Beam based setups performed in June 2010, with bunch trains in mid of September 2010

Beam based setup of collimators

- Goals of beam based alignment:
  - Centre collimator jaws around beam
  - Determine local beam size at collimators (at 450 GeV, nominal beam size at 3.5TeV)
  - Achieve setup of collimation system with desired hierarchy
- Net setup time: 15-20mins per collimator → automation under development
- Performed setups (2010), 44 collimators per beam, B1+B2 in parallel:
  - Injection:
    - 2 full setups (low/high intensity: ~11h / ~11h beam time)
    - 1 setup of TCTs for bunch train operation with crossing angle
    - 1 check of collimator centers for operation with ions
  - 3.5TeV:
    - 2 full setups (low/high intensity: ~13h / ~10h beam time)
    - 4 sets of TCT settings for bunch train operation plus TOTEM (~18h + ~6h beam time)
    - 1 set of TCT settings for operation with ions

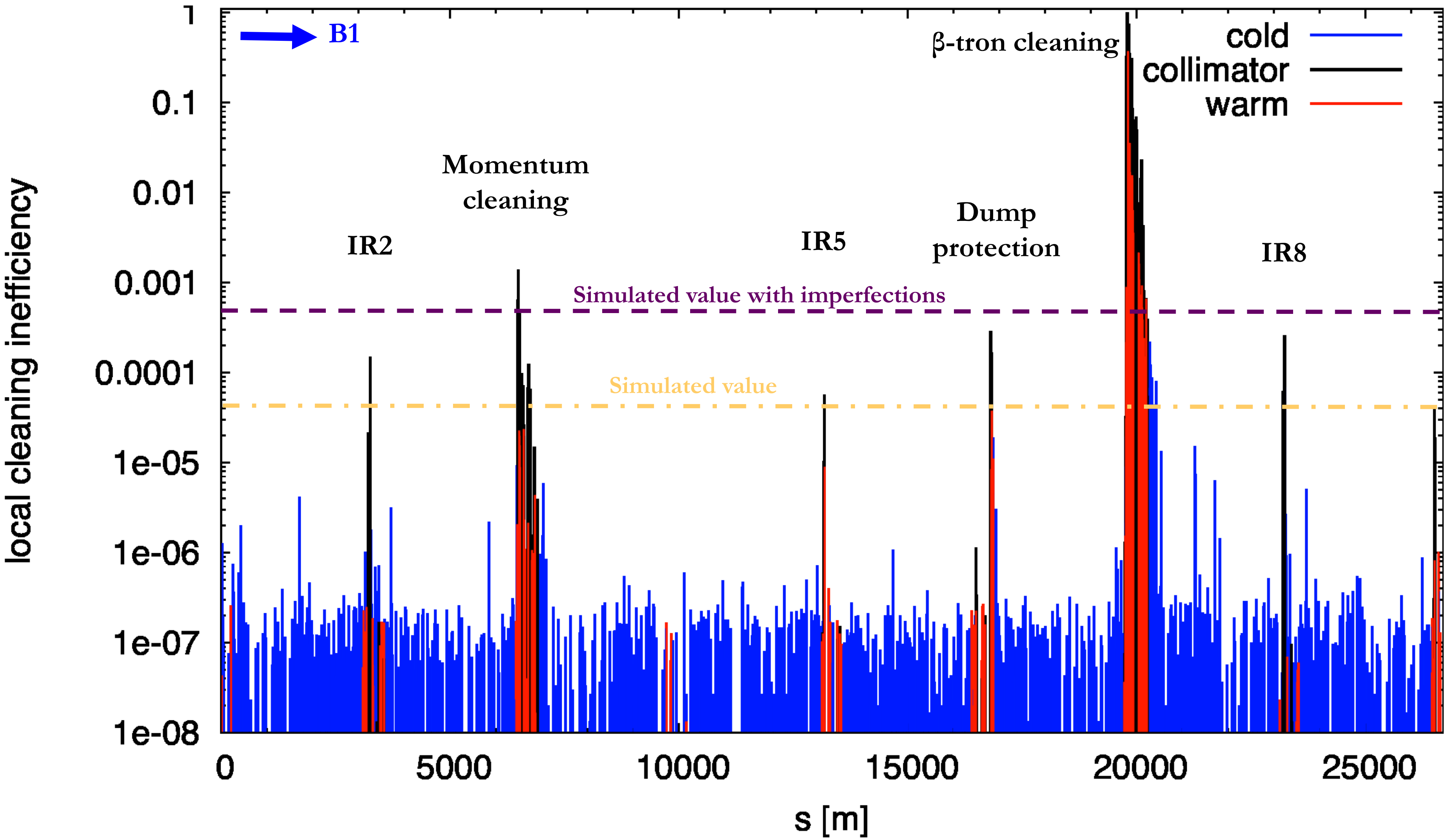
Qualification of Collimation

- The cleaning efficiency and the correct hierarchy of the collimation system are regularly qualified by intentionally creating multi-turn losses
- Losses of 30-50% of beam (1 nominal bunch) over 1-2s
- β-tron losses by crossing a third integer tune resonance (B1-h, B1-v, B2-h, B2-v)
- Momentum losses by changing the RF frequency (± 1000 Hz, B1+B2). 1000Hz to make sure that full beam is lost with off-momentum error. Could use smaller.

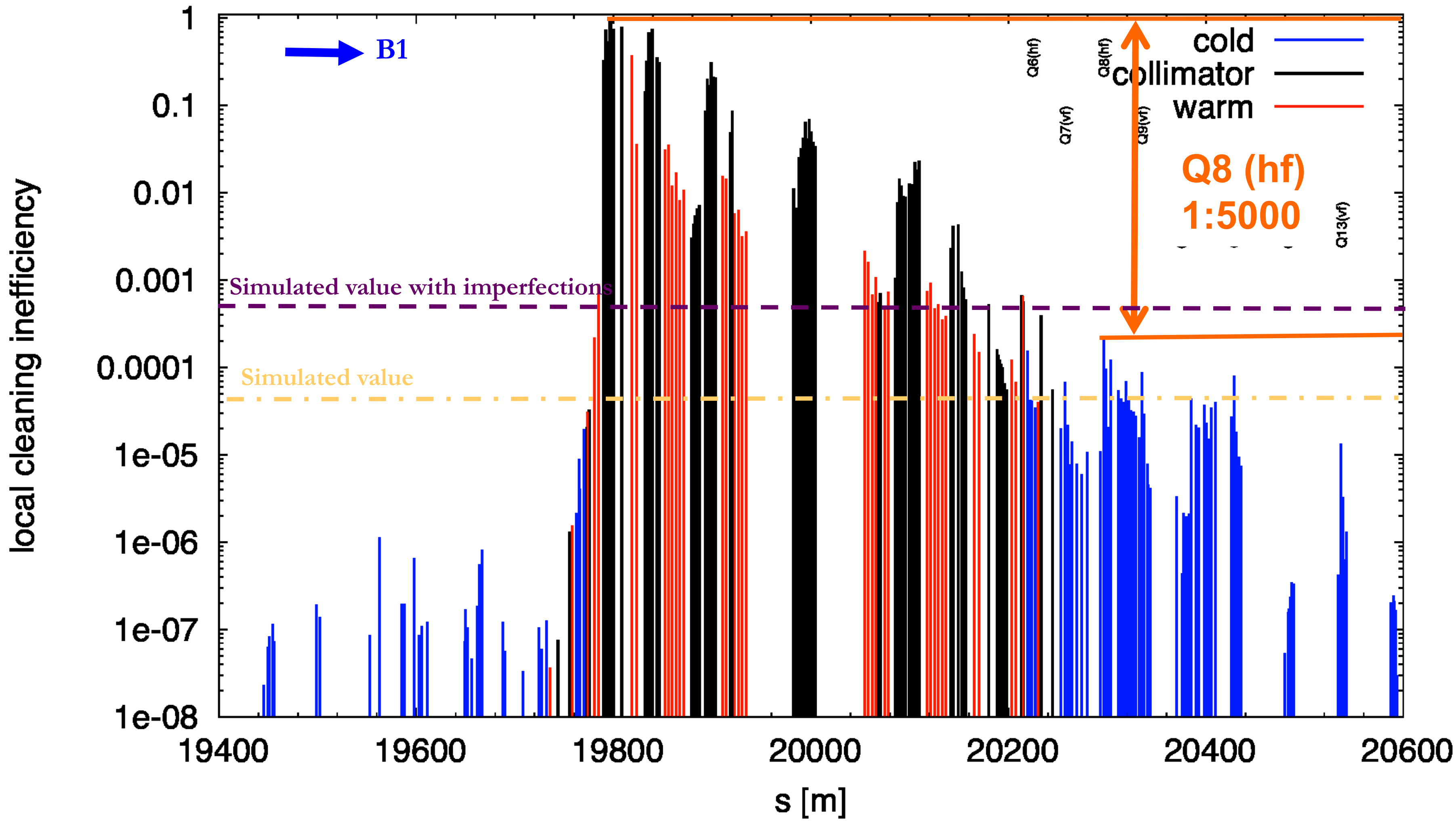
- Performed with one nominal bunch at 3.5TeV and stable beams conditions
- Needs typically two dedicated fills (reduced from 3 fills)
- Qualification of the collimation system is regularly needed to check the validity of the setup and track the changes in cleaning efficiency over time

Measured: β-tron losses, B1v, 3.5TeV, β*=3.5m

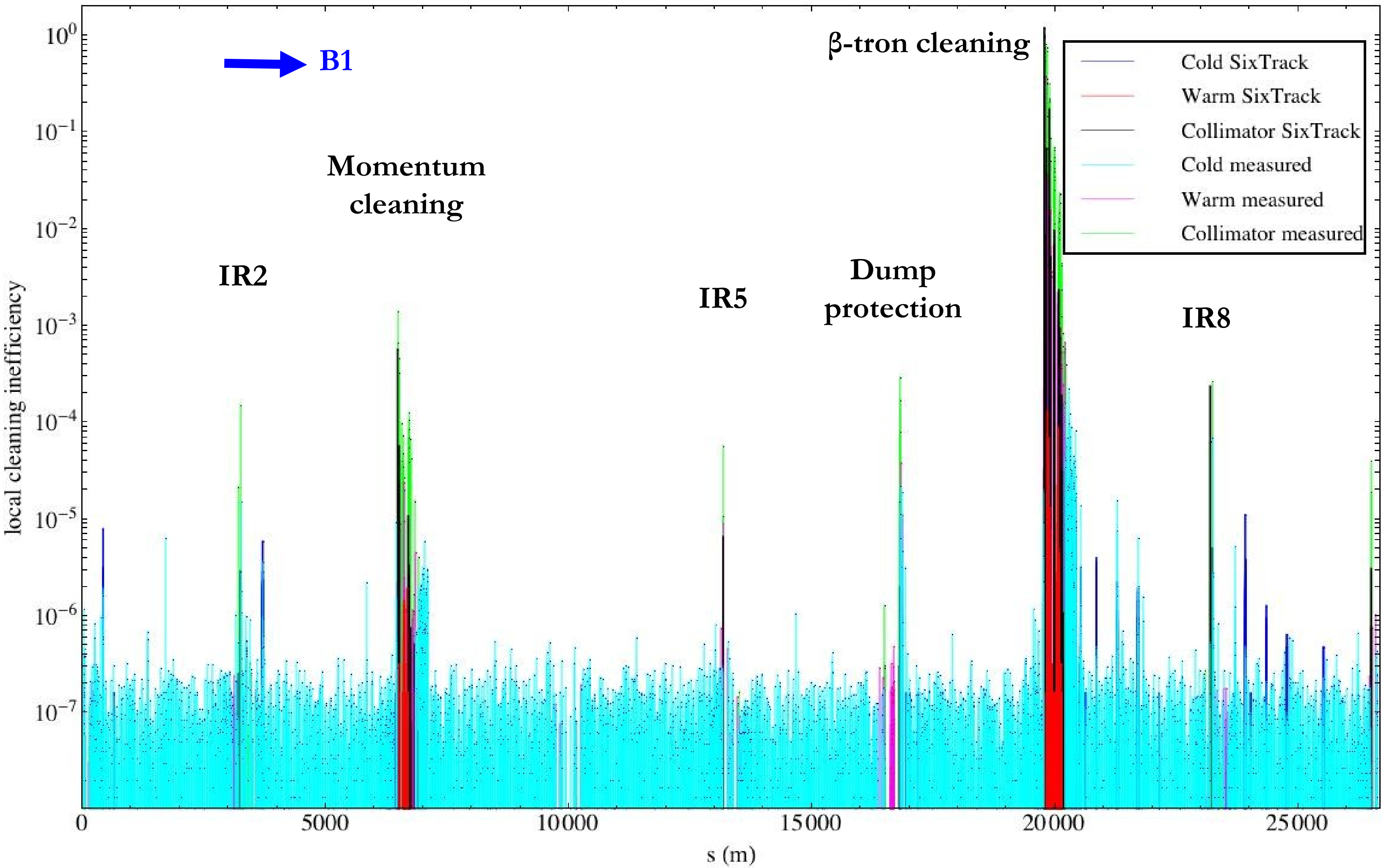
Goal: minimize blue spikes (losses to sc. Magnets)



Measured: β-tron losses, B1v, 3.5TeV, β*=3.5m, IR7



Comparison
Simulations versus Measurement
B1v, 3.5TeV, β*=3.5m

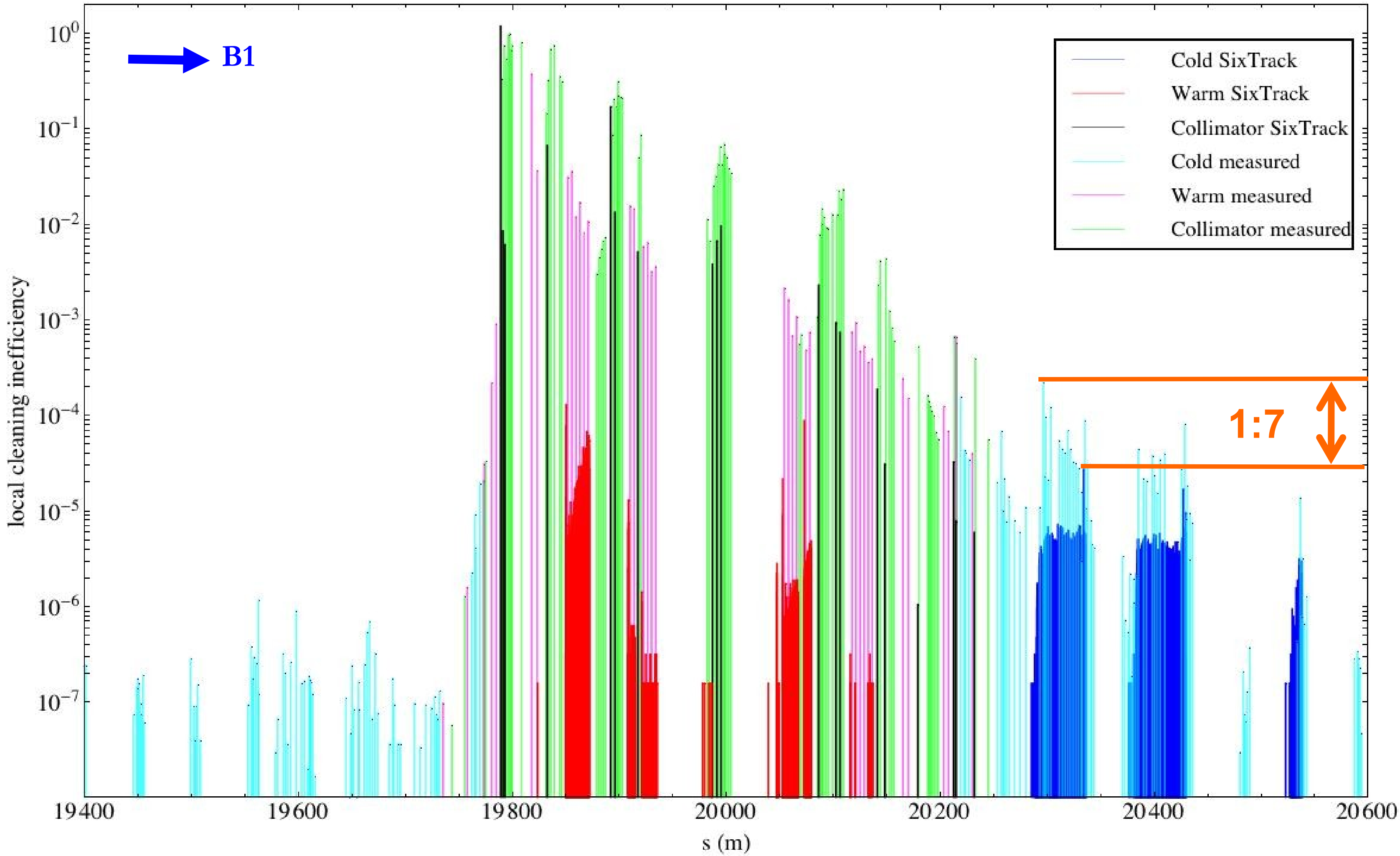


- Simulations **without** imperfections
- Measured data **with** imperfections
- good agreement between measurements and simulations!
- leakage to IR6 bigger than expected

Comparison
Simulations versus Measurement
B1v, 3.5TeV, β*=3.5m, IR7

Simulations **without** imperfections

Measured data **with** imperfections



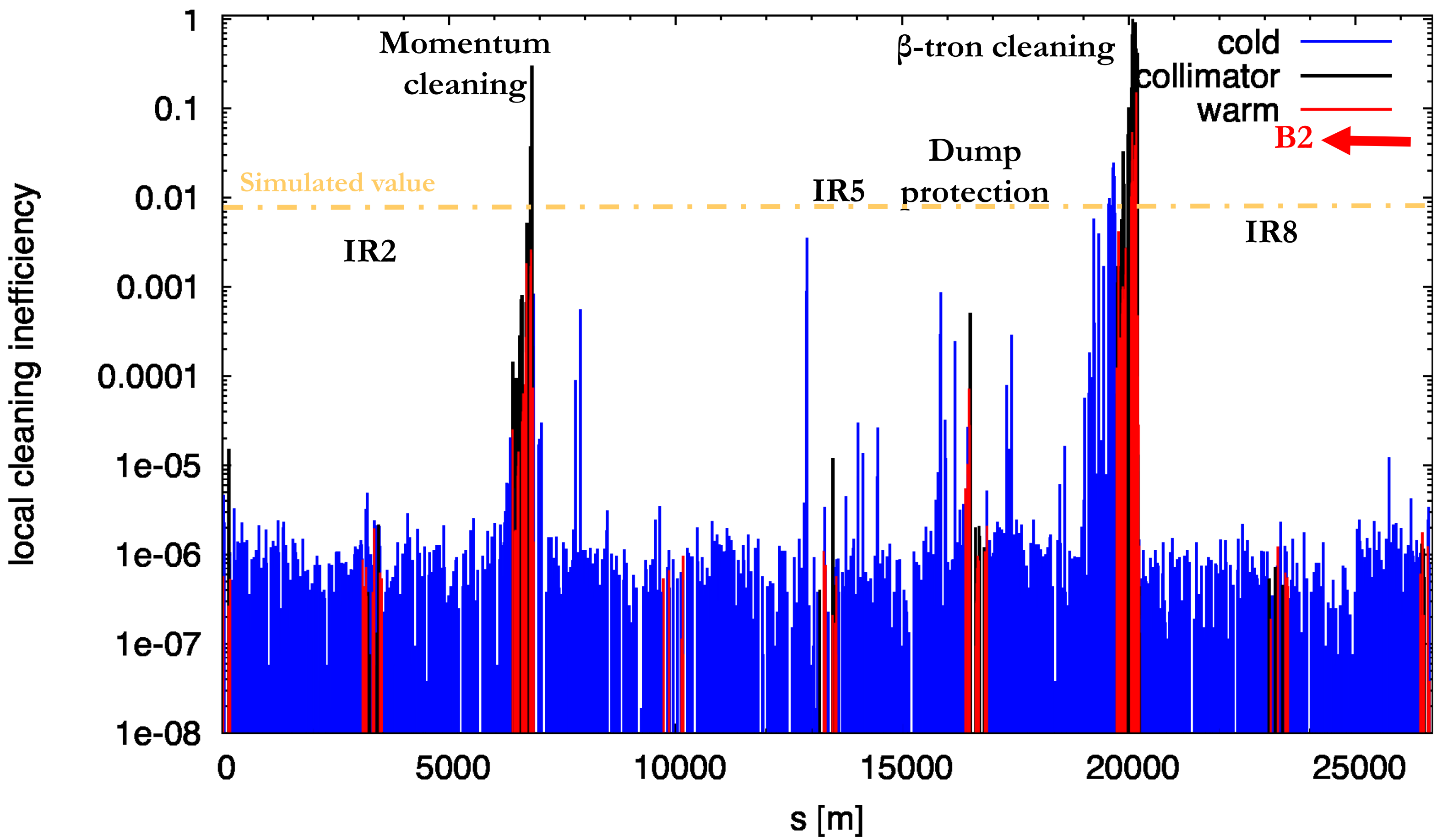
Problems with hierarchy of collimation system in 2010

- Broken hierarchy in B2 for positive off-momentum particle (IR3) :
  - Found on the 17.08.2010 during qualification campaign: TCSG in IR3 acts as primary collimator; causes higher leakage into the arc after IR3
  - Maybe been there since the high intensity setup in June (no pos. off-momentum loss maps done before)
  - Cure (in September setup for Xing-angles): after 2 re-setups of IR3 B2 collimators, closed TCP to 10 sigma (instead of 12 sigma)
- Hierarchy problem in B2 for horizontal betatron losses (IR7):
  - High luminosity runs show losses at the TCSGs as high as at the primary collimators
  - Hints for this seen in proton and ion loss maps but no decrease in cleaning efficiency
  - Cure: Re-calibrate absolute position sensors of collimators (LVDTs) and re-setup IR7 collimators. → **To be done next year**

Ions: Beam2 Leakage from IR7 Collimation Much Worse (as expected)

Betatron losses B2 v, 3.5 *Z TeV , physics conditions

- Leakage to IR7 DS higher in B2 (compared to B1) due to asymmetry of hor dispersion function between B1 and B2



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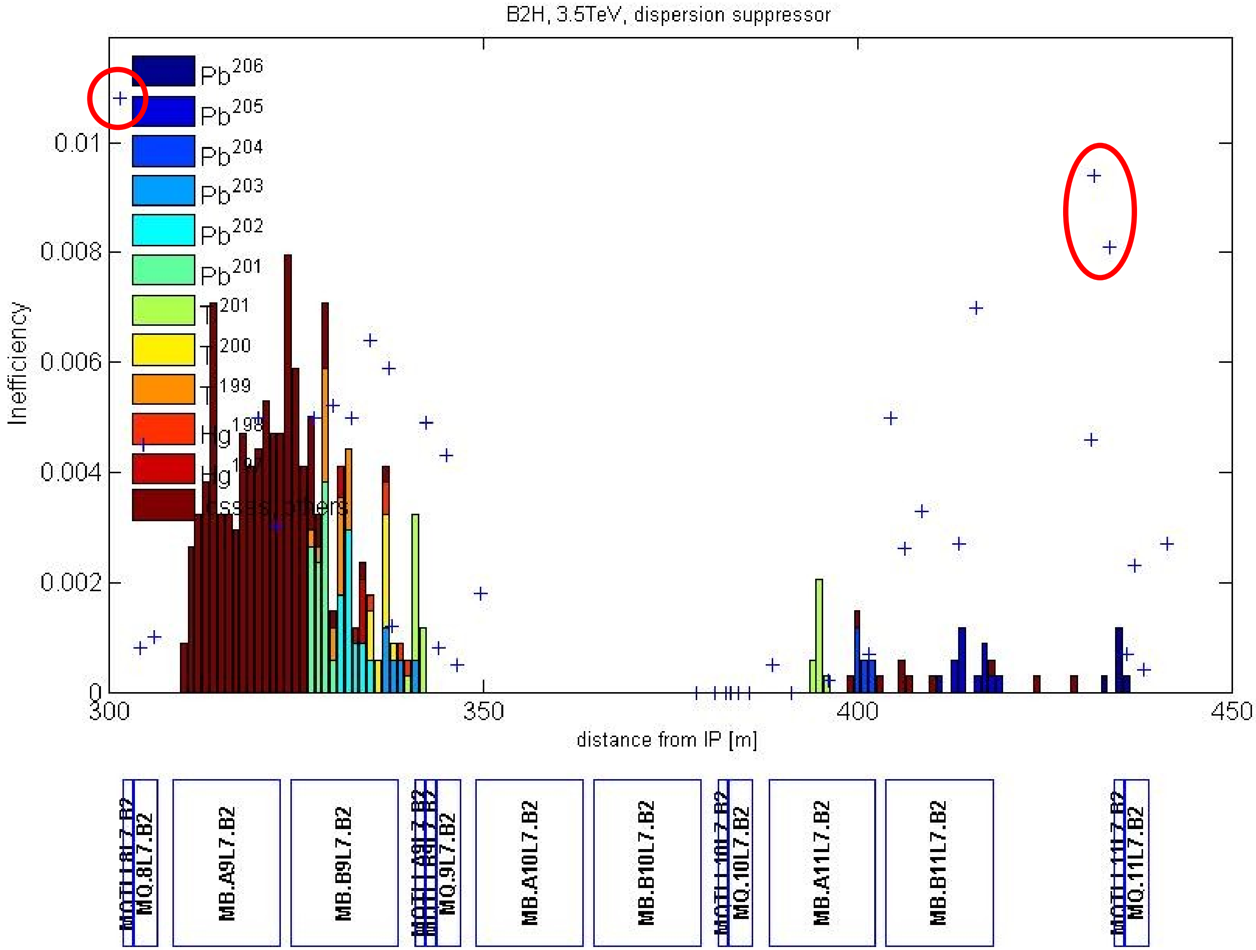
B2h, 3.5TeV *Z, β*=3.5m, DS IR7



- Simulation performed with perfect machine
- Uncertainties in cross sections for hadronic fragmentation and electrom. dissociation with Pb nuclei on carbon/tungsten (although using state of the art simulations)
- Positions of loss peaks in the dispersion suppressor can be reproduced in simulations.
- Leakage higher in measurements than in simulations
- To be understood further

Cleaning inefficiency with Ions factor 50 to 100 worse compared to protons:

Leakage for ions into specific regions (ratio to losses at highest primary collimator)

	DS	COLD	TCT
B1h	0.02	0.006	1.0e-4
B1v	0.027	0.005	0.001
B2h	0.03	0.011	8e-5
B2v	0.025	0.006	1.4e-4
B1+B2 pos. off momentum	0.045	8e-4	0.06
B1+B2 neg. off momentum	0.007	2e-4	0.005

- As expected cleaning with ions much worse (only one stage cleaning)
- Leakage in the order of percent into DS and TCTs
- Losses very localized

Change of β-tron local cleaning inefficiency (3.5 TeV, 1.3s integration)

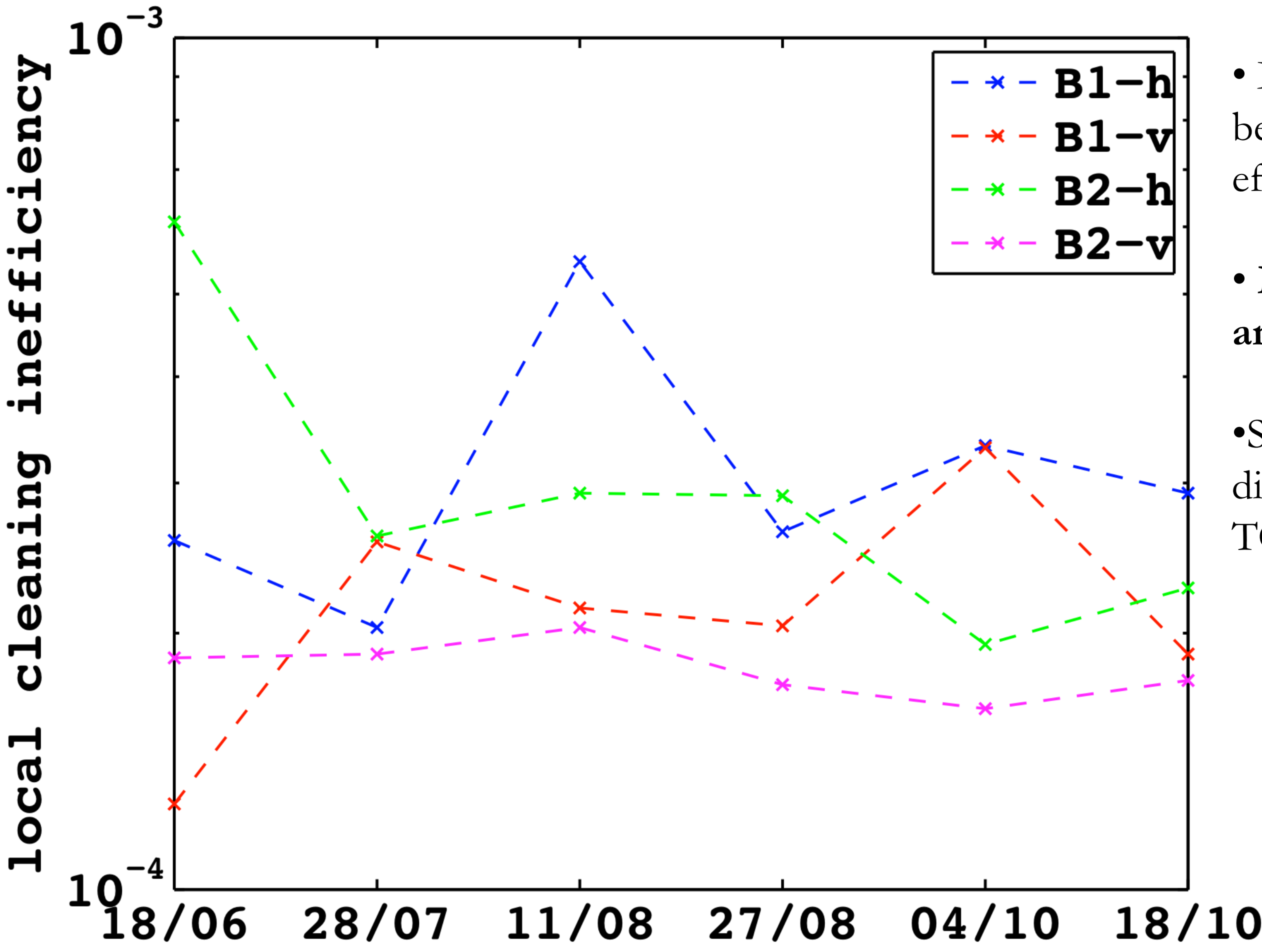
Leakage into cold aperture (Q8, IR7)

β-tron losses (cleaning inefficiency)	18.06.2010	28.07.2010	11.08.2010	27.08.2010	04.10.2010	18.10.2010
B1-H (Q8.R7)	2.57e-4	2.03e-4	5.46e-4	2.63e-4	3.32e-4	2.92e-4
B1-V (Q8.R7)	1.26e-4	2.56e-4	2.14e-4	2.04e-4	3.30e-4	1.89e-4
B2-H (Q8.L7)	6.08e-4	2.60e-4	2.92e-4	2.90e-4	1.94e-4	2.26e-4
B2-V (Q8.L7)	1.87e-4	1.89e-4	2.03e-4	1.75e-4	1.63e-4	1.76e-4

- Collimation setups in mid June and mid September
- Design cleaning inefficiency for phase I: 4.5e-5m^{-1}, with imperf. 5e-4m^{-1}

Change of β-tron local cleaning inefficiency (1.3s integration)

Leakage into cold aperture (Q8, IR7)

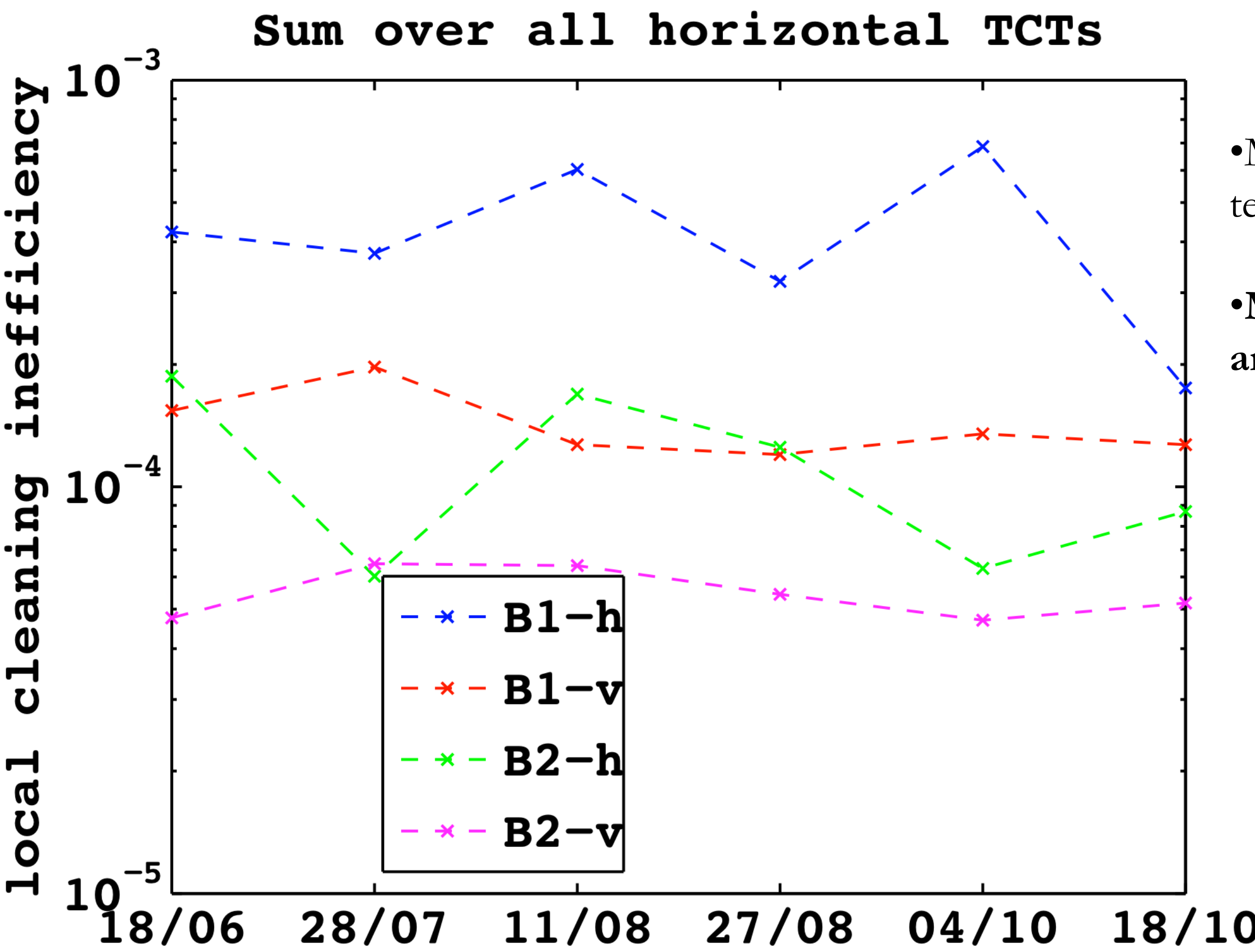


- Leakage into cold aperture varied between 1.3e-4 and 6.1e-4 (i.e. cleaning efficiency 99.939%- 99.987%)

- **Maximum variation in one plane and beam: factor of 3**

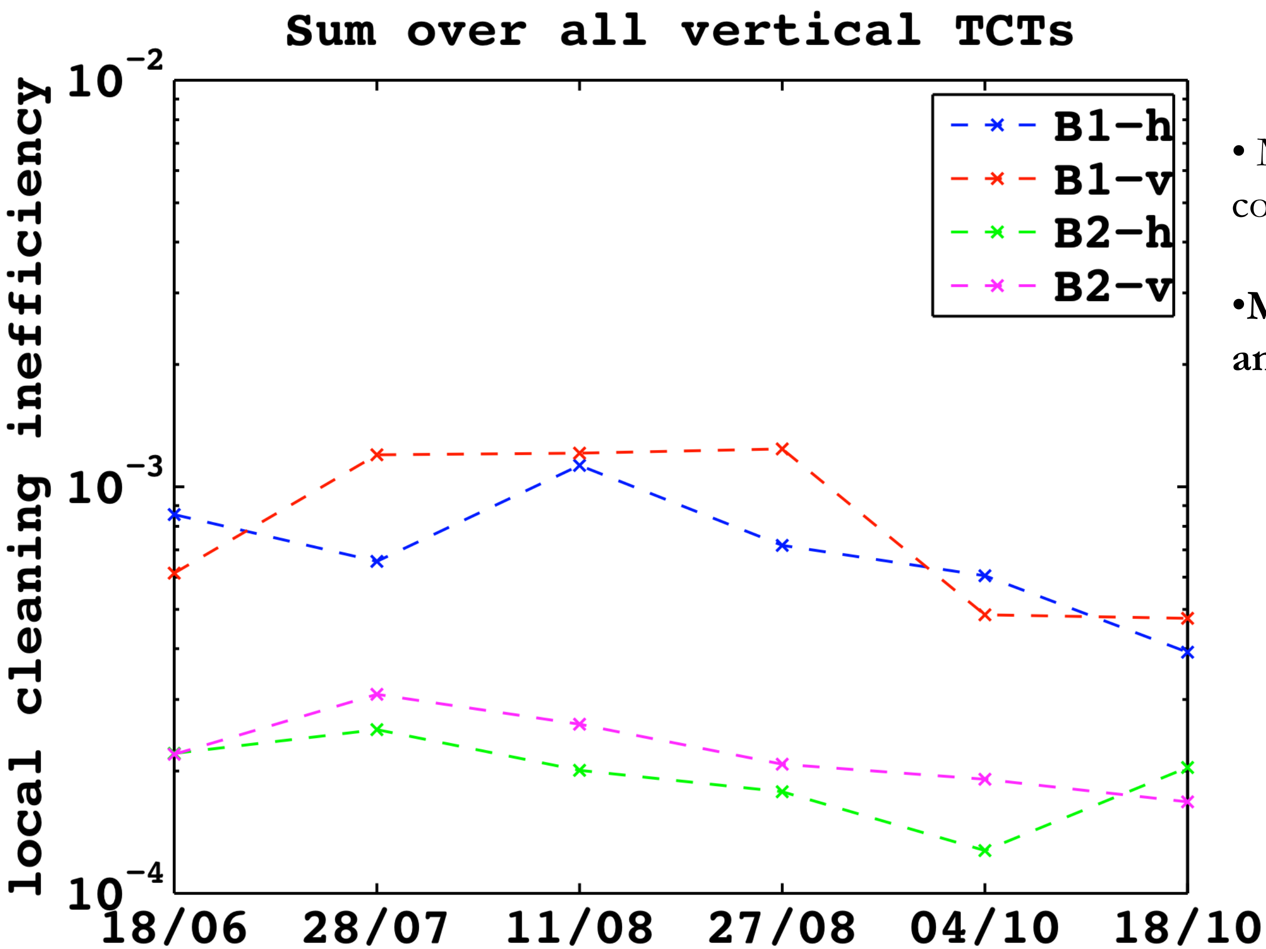
- Systematic measurement error, due to different loss response of BLMs at TCPs and sc. Magnets: factor of 2

Leakage into horizontal tertiary collimators (β-tron losses,1.3s integration)



- Maximum leakage into horizontal tertiary collimators (B1-h): 7e-4
- **Maximum variation in one plane and beam: factor of 4**

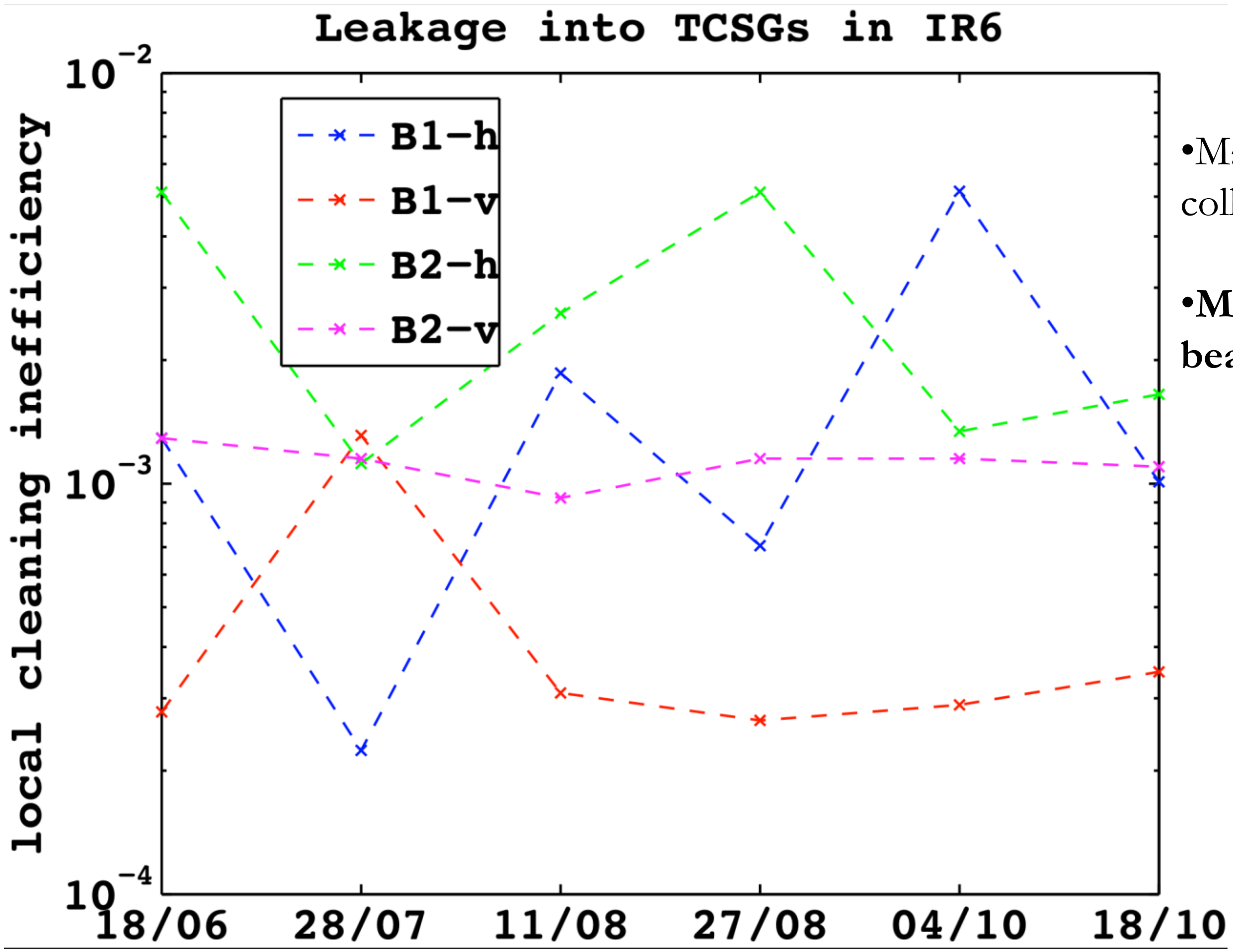
Leakage into vertical tertiary collimators (β-tron losses,1.3s integration)



- Maximum leakage into vertical tertiary collimators (B1-v): 1.25e-3

- **Maximum variation in one plane and beam: factor 2.6**

Leakage into dump protection collimators (β-tron losses,1.3s integration)



- Maximum leakage into dump protection collimator (B2-h): 5e-3
- **Maximum variation in one plane and beam (B1-h): factor 23**

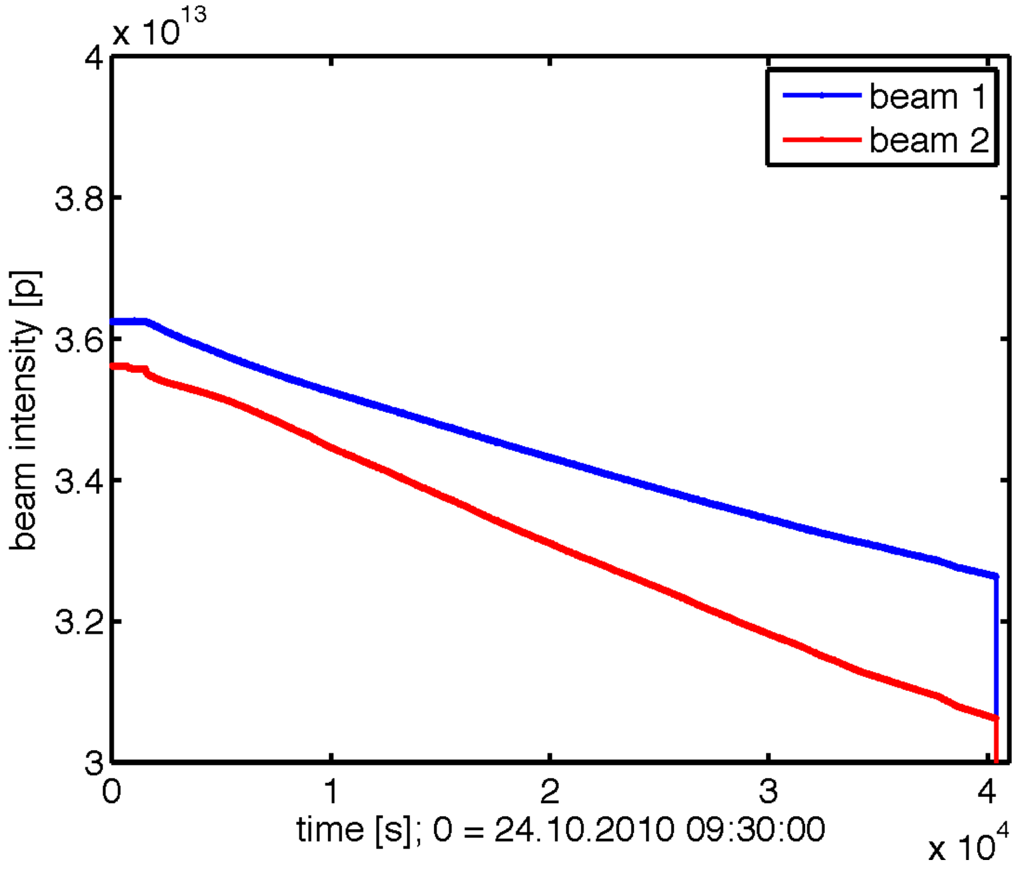
Analysis of:

- High luminosity fills (**5 x 386b, 3 x 312b**)
- Fills with instabilities (**2 x 50ns, 108b**)
- Losses due to un-bunched beam (**1 x 386b, loss of 1.6e12p per beam**)

Input:

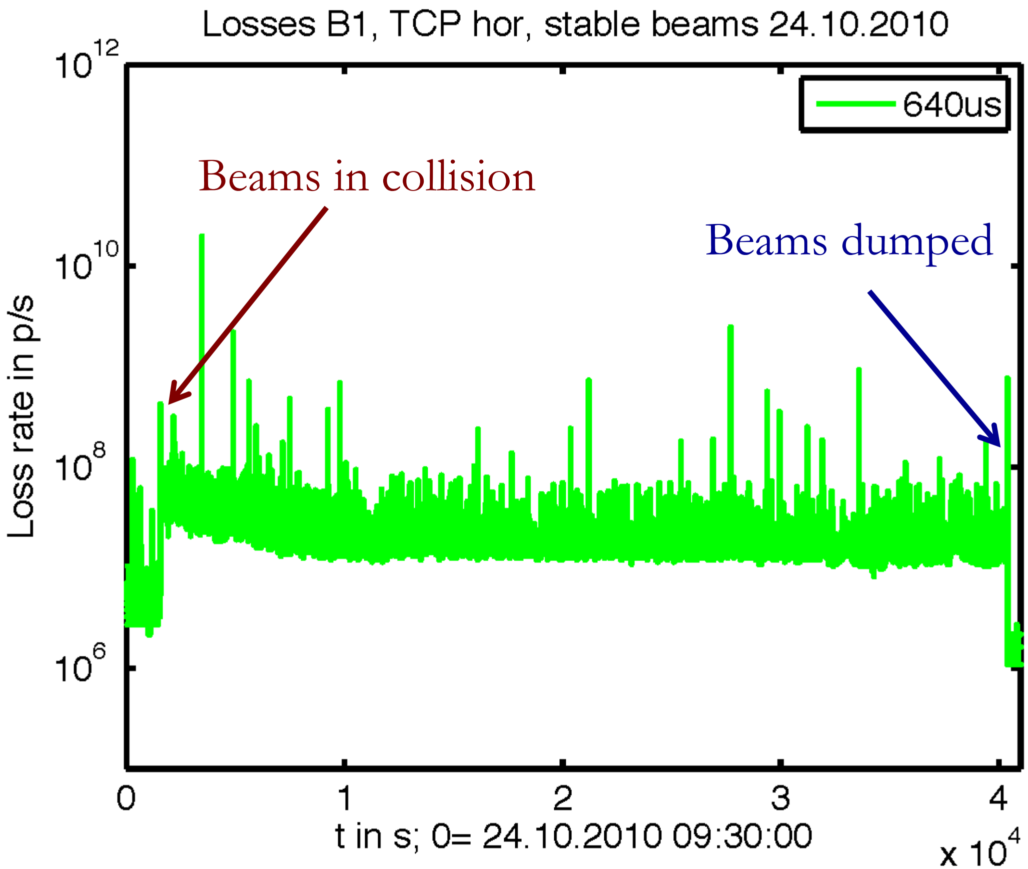
- Loss rates and instantaneous life time from BLM signals at primary collimators (calibration with scraping experiments)
- Measured cleaning efficiency
- Quench limit for transient losses @7TeV: 3.4e7p
- Quench limit for steady state losses @3.5TeV (4TeV): 2.4e7p/s/m (1.9e7 p/s/m)

Loss rate at hor. TCP in IR7 during high luminosity run, 150ns, 312b (24.10.2010)



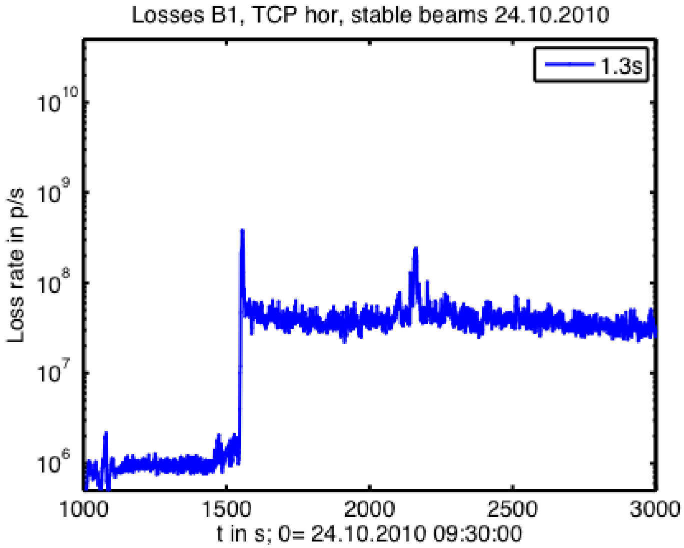
- ~12h run
- 150ns bunch spacing
- 312 bunches

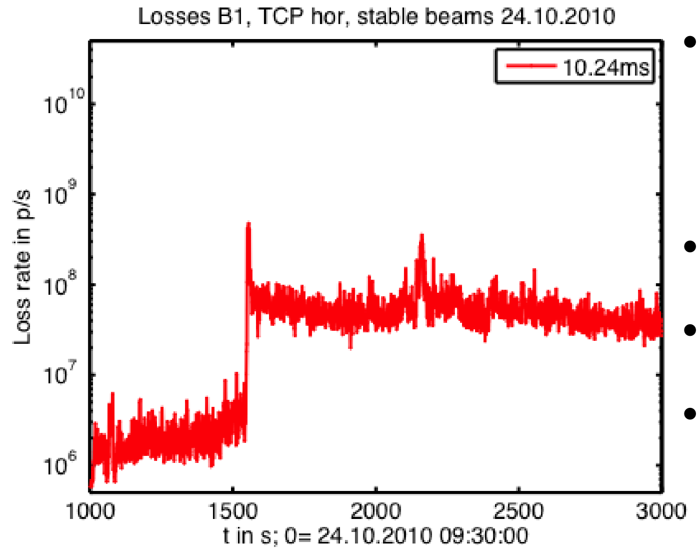
Loss rate at hor. TCP in IR7 during high luminosity run, 150ns, 312b (24.10.2010)

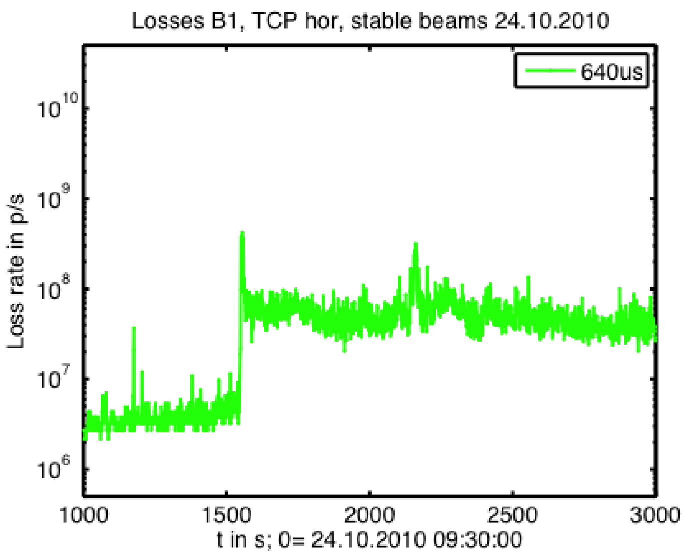


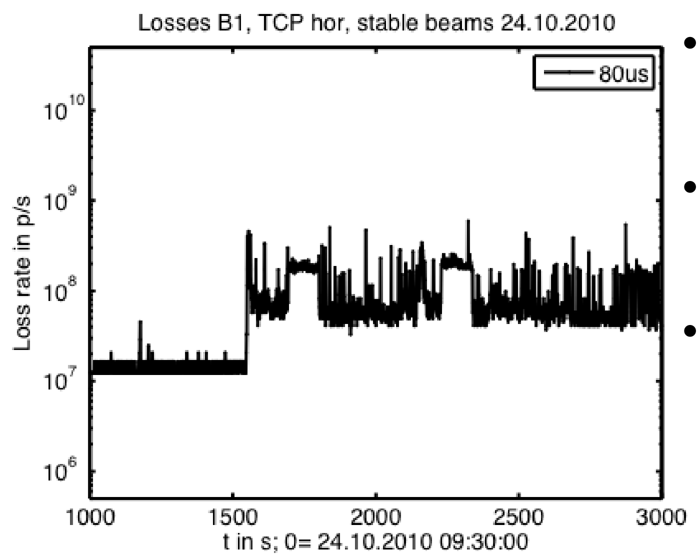
- ~12h run
- 150ns bunch spacing
- 312 bunches
- BLM signal RS04 (640us)
- Significant increase in losses when going into collisions
- Loss spike during the whole run

Loss rate at hor. TCP in IR7 during high luminosity run, 150ns, 312b (24.10.2010)









- **First 1500s in collision for different integration times**
- 150ns bunch spacing
- 312 bunches
- Significant **increase in losses** when going into collisions
- Loss spike during the whole run
- **Loss pattern** seen in all integration times
- 80us signal with lots of **loss spikes**

Loss rates and instantaneous life time for 8 high luminosity fills

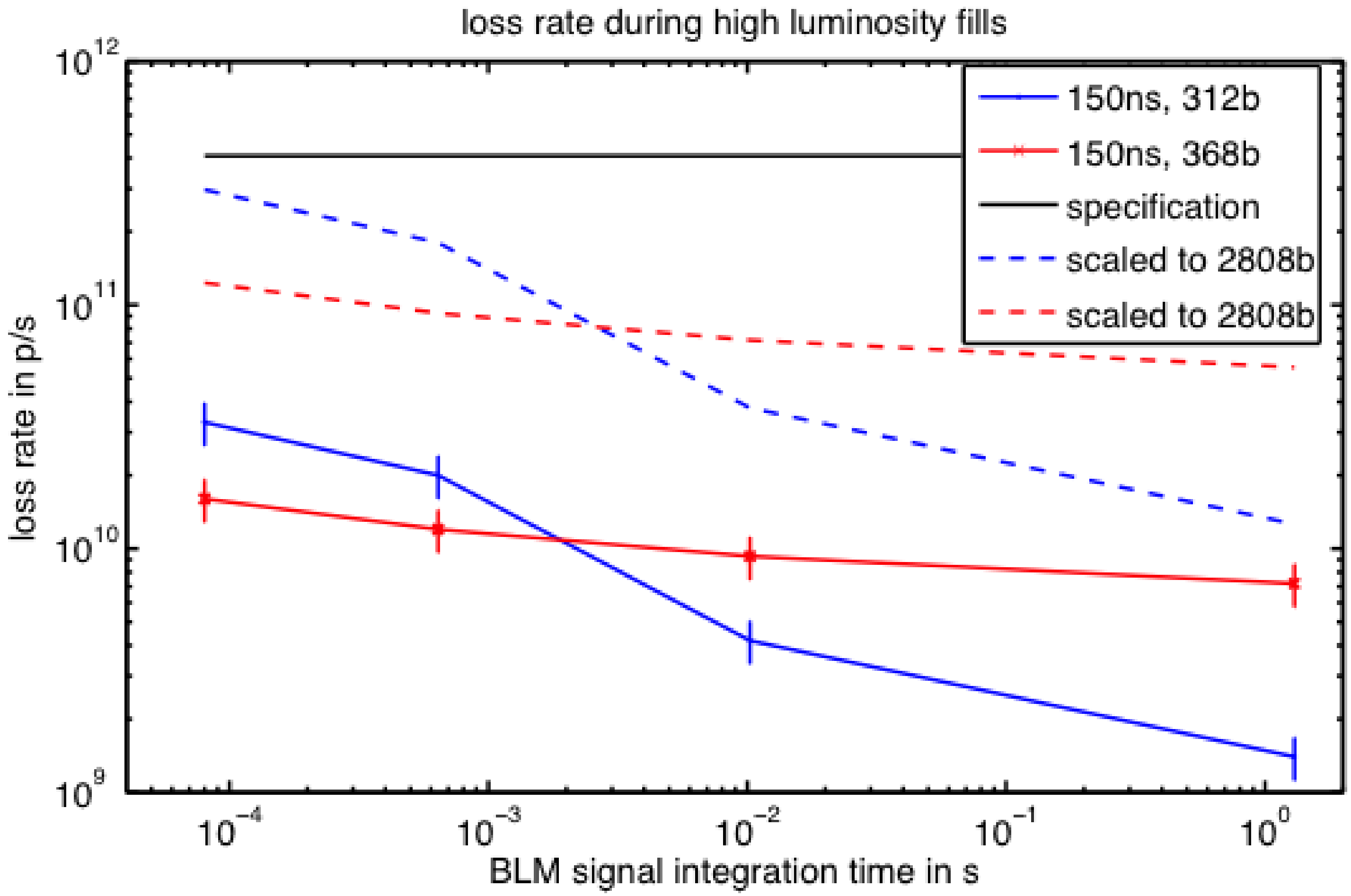
Range of highest (lowest) loss rates (life times) during high luminosity proton runs for different integration times of BLM signal:

Integration times	Runs with 312 bunches (3 runs)	Runs with 368 bunches (5 runs)
RS02 (80us)-lifetime [h]	$0.3<\tau< 2.6$	$0.6<\tau< 6.8$
Loss rate [p/s]	3.3e10> R > 2.8e9	1.6e10 > R > 1.64e9
RS04 (640us)-lifetime [h]	$0.5 <\tau< 5.5$	$1.0<\tau< 7.7$
Loss rate [p/s]	2.0e10 > R > 1.3e9	1.2e10 > R > 1.4e9
RS06 (10.24ms)-lifetime [h]	$2.3 <\tau< 6.2$	$1.3 <\tau< 21.6$
Loss rate [p/s]	4.2e9 > R > 1.6e9	9.3e9 > R > 5.5e8
RS09 (1.3s)-lifetime [h]	$6.0 <\tau< 26.5$	$1.6 <\tau< 40.6$
Loss rate [p/s]	1.4e9 > R > 3.8e8	7.2e9 > R > 3.0e8

Remarks:

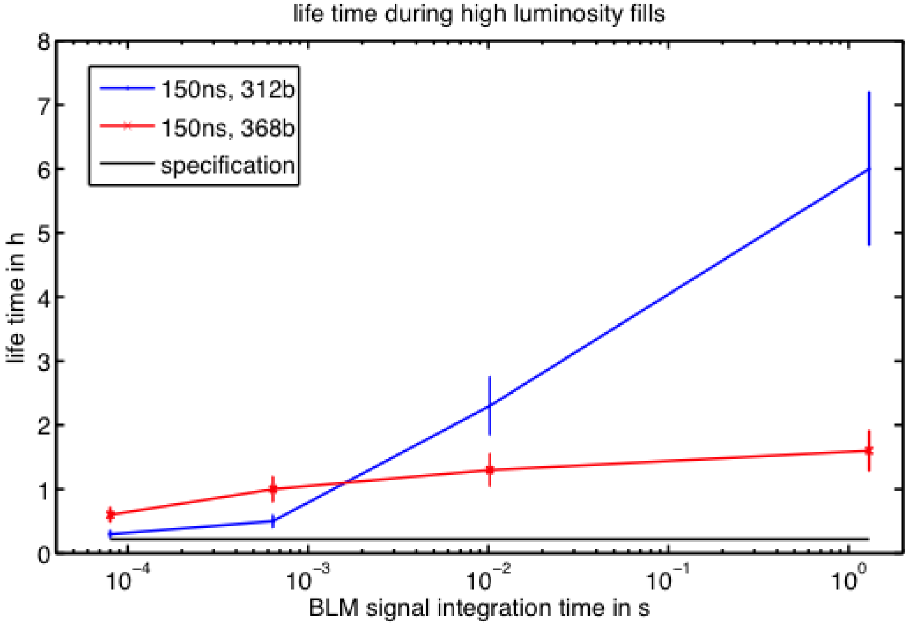
- RS02 and RS04: transient losses (1-7 turns)
- RS06 and RS09: steady state losses (115 – 14600 turns)
- B2 less loss spikes in 80us BLM signals, although the overall life time during fills is better in B1
- B2: IR7 TCSG.A6R7 at same loss level as TCPs for some fills
- Error (loss rate, life time < 20%)

Instantaneous loss rates for 312b and 368b fills compared to specifications

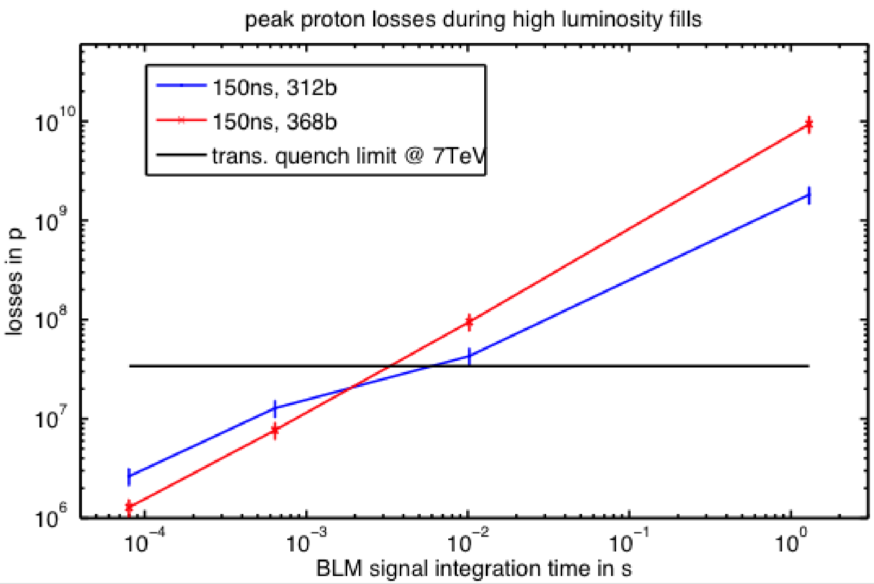


- Specified loss rate: 4.1e11p (for nominal intensity)
- Loss rate below specifications

Loss rates and instantaneous life time for 312b and 368b fills compared to specifications



- Specified life time: 0.22h = 792s
- Life times significantly above the specifications



- Transient quench limit: 3.4e7p
- RS02 and RS04 losses below transient quench limit

Comparison predicted and measured performance

Predictions: see R.W.Assmann's LMC presentation on 19.03.2009

Measured: Fill with highest loss rate: 150ns, 386b, 26.10.2010

	2009 prediction	2010 analysis	Ratio
$\tilde{\eta}$ [1/m]	2.16e-4	4e-4	**1.9**
τ [s]	500	4680	**9.4**
R_q[p/s/m] (@3.5TeV)	2.4e-7	-	-
BLM factor	0.33	-	-
BLM response	n.a.	0.36	-
FLUKA factor	3.5	-	-
$\tilde{\eta}_{corr}$ [1/m]	2.16e-4	1.44e-4	**0.66**
N^q_{tot} [p]	6.4e13	**9.1e14**	14.2

$$N^q_{tot} = \frac{\tau_{min} R_q}{\tilde{\eta}} \cdot c_{blm} \cdot c_{fluka}$$

- **Life time significantly better than expected**
- **Cleaning slightly better than expected (lower influence of imperfections due to good orbit stability)**

Comparison ratio BLM threshold to signal with life time approach (368b, 26.10.)

LHC Collimation Project CERN

- BLM:
  - Signal of highest loss in cold aperture (Q8R7): **4e-5 Gy/s**
  - Threshold for this element: **0.014 Gy/s**
  - Ratio: 0.014 / 4e-5 = 350
  - **Correction factors** (refer to discussions with BLM team):
    - 1/3 (increase of monitor factor from 0.1 to 0.3)
    - 1/3 (quench limit lower then expected)
  - Corrected BLM ratio: 39, this means **39 x 368 bunches** possible

- Cleaning and life time: $\frac{N^q_{tot}}{N^q_{26th}} = \frac{9.1e14p}{4.2e13p} = 22$, this means **22 x 368 bunches** possible

Both approaches give consistent results

Possible intensity reach for 2011

- Note:
  - We assume same stability for higher beam intensities (probably not true)
  - We do not include that performance reach is worse for higher energy (cleaning efficiency, lower margin in sc magnets, lower quench limits)
  - We do not include that cleaning efficiency can be better with nominal collimation settings (not achievable with current orbit stability)
  - Analysis is based on limited number of fills

- **3.5 TeV: 9.1e14p (> nominal)**
- **4.0 TeV (R_q=1.9e7 p/s/m): 7.28e14p (> nominal)**

- **Probably wise to take some safety margin (e.g. factor 2). Nominal beam intensity looks feasible at 3.5 TeV and 4.0 TeV if there is no bad surprise in beam stability when increasing intensity.**

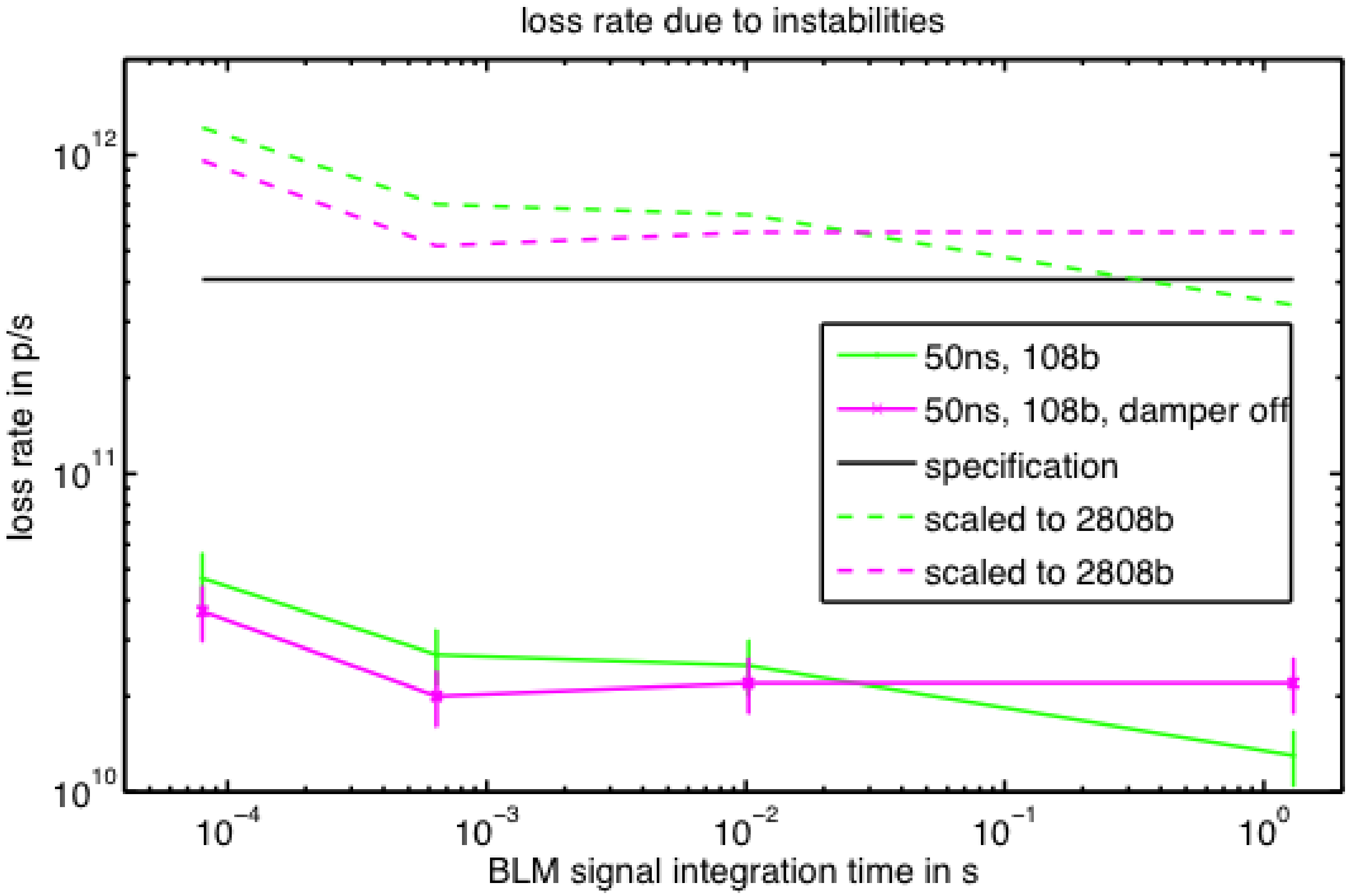
Losses due to instabilities: some examples from 50ns fills

Range of highest (lowest) loss rates (life times) during high luminosity proton runs for different integration times of BLM signal:

Integration times	50ns, 108b, end of squeeze (31.10.)	50ns, 108b, flat top, switch of transverse damper (04.11.)
RS02 (80us)-lifetime [h]	0.07	0.09
Loss rate [p/s]	4.7e10	3.7e10
RS04 (640us)-lifetime [h]	0.12	0.16
Loss rate [p/s]	2.7e10	2.0e10
RS06 (10.24ms)-lifetime [h]	0.13	0.15
Loss rate [p/s]	2.5e10	2.2e10
RS09 (1.3s)-lifetime [h]	0.24	0.15
Loss rate [p/s]	1.3e10	2.2e10

Remarks:
- RS02 and RS04: transient losses (1-7 turns)
- RS06 and RS09: steady state losses (115 – 14600 turns)
- Error in measurement of loss rate and life time < 20%

Loss rates and instantaneous life time for 50ns fills with instabilities compared to specifications



- Specified loss rate: 4.1e11p (for nominal intensity)
- Specified life time: 0.22h = 792s
- Transient quench limit: 3.4e7p

- Instabilities will limit intensity to:

3.5 TeV: 9.1e13p; **4.0 TeV: 7.2e13p**

Losses in IR3 due to un-captured beam at start of ramp (450GeV)

Highest (lowest) loss rates (life times) during start of ramp:

Integration times	Start of ramp, 368b, (27.10.)
RS02 (80us)-lifetime [h]	0.1
Loss rate [p/s]	1.1e11
RS04 (640us)-lifetime [h]	0.1
Loss rate [p/s]	1.2e11
RS06 (10.24ms)-lifetime [h]	0.1
Loss rate [p/s]	1.3e11
RS09 (1.3s)-lifetime [h]	0.13
Loss rate [p/s]	9.3e11

- 450 GeV, 368 bunches
- About one nominal bunch lost per beam (1.6e12p)
- Loss rates similar in the different integration times, i.e. continuous loss.

Remarks:
- RS02 and RS04: transient losses (1-7 turns)
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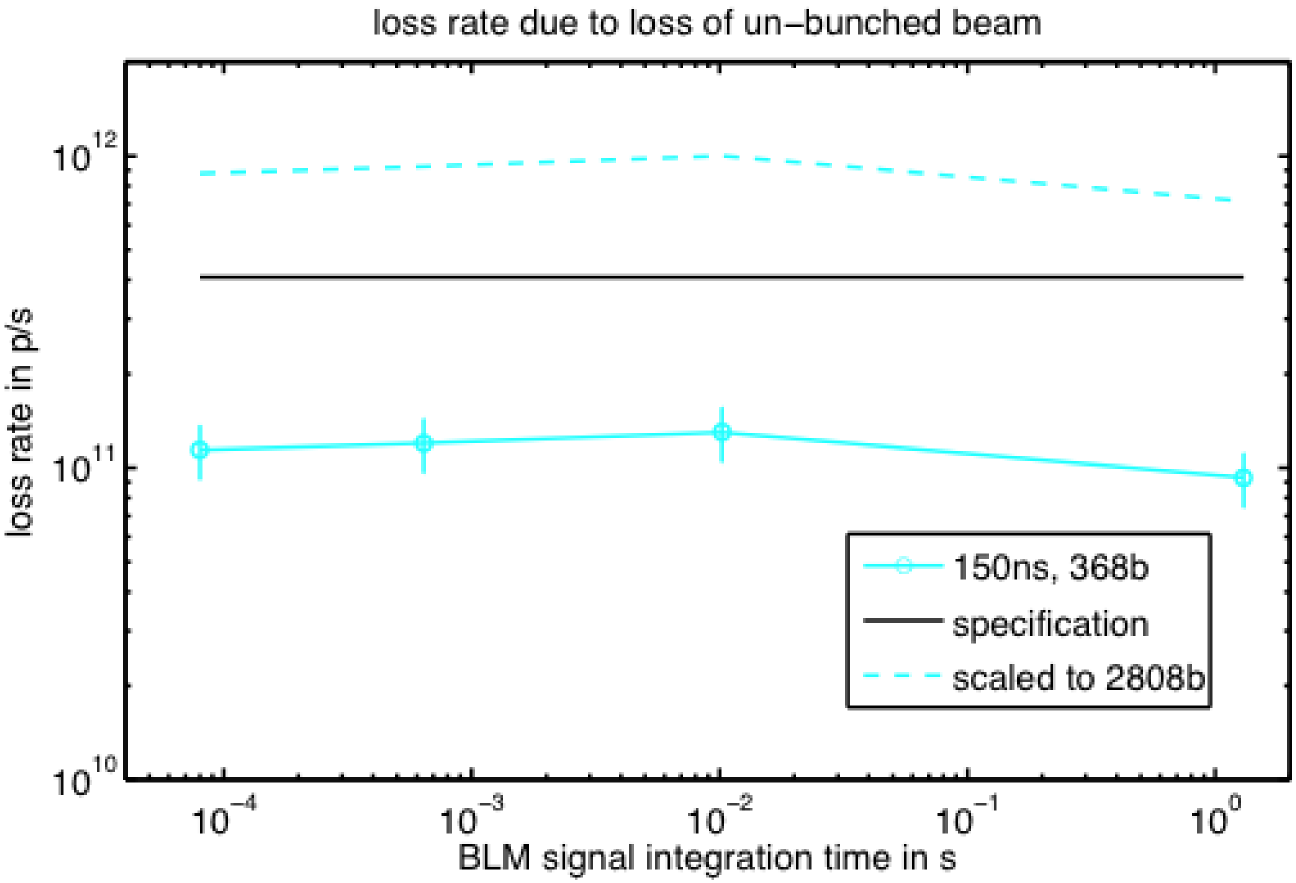
- Error (loss rate, life time < 20%)

Loss rates and instantaneous life time for fill with high loss of un-bunched beam compared to specifications



- Specified loss rate: 4.1e11p (for nominal intensity)
- Steady state quench limit: 7e8p/s/m

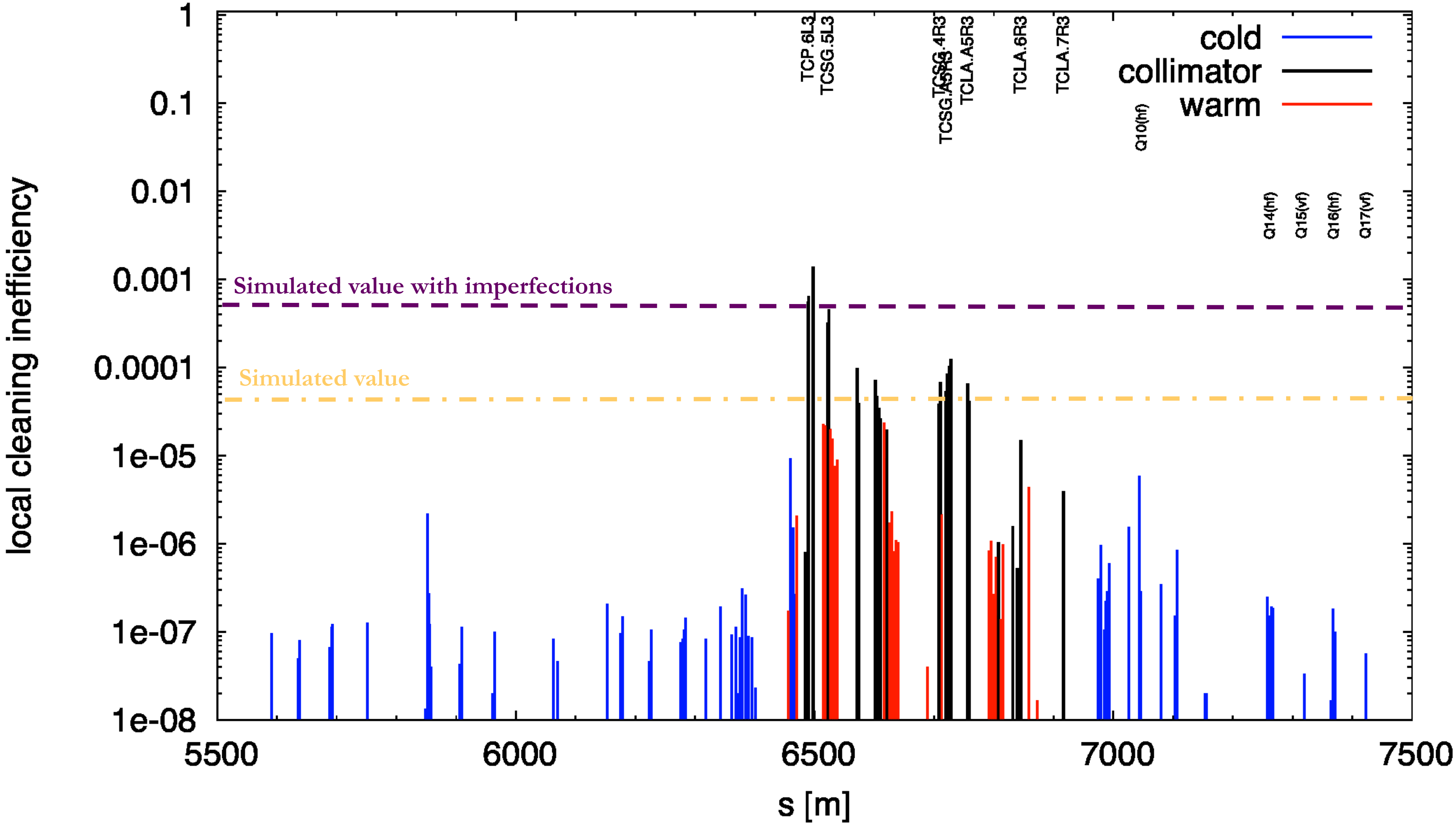
- **Intensity limit due to loss of un-bunched beam at 450GeV: 2.7e14p**
- **Note that this is the worst case 2010**

Conclusion (Preliminary)

- Phase-I LHC collimation system delivers expected collimation efficiency. Impact of imperfections factor 2 smaller than predicted (better orbit control in DS).
- Setup procedure has been refined and optimized (15-20mins per collimator needed)
- Validity of collimation setup around 5-6 months, then close to the edge (radiation profile not conform). Might require two setups in 10 months run in 2011.
- Instantaneous peak loss rate about factor 9 lower than specified: With this we should be good for nominal intensity at 3.5 and 4.0 TeV (in terms of cleaning efficiency – other issues like R2E not considered here).
- But: Instabilities can increase loss rate and therefore cause collimation induced intensity limitations (possible for higher intensities and energies).
- Cleaning with ions much less efficient than for protons (as expected): Leakage in orders of percents into DS magnets and TCTs, very localized losses.
- Intensity estimate based on these results for 7 TeV will be discussed in the Chamonix presentation

END

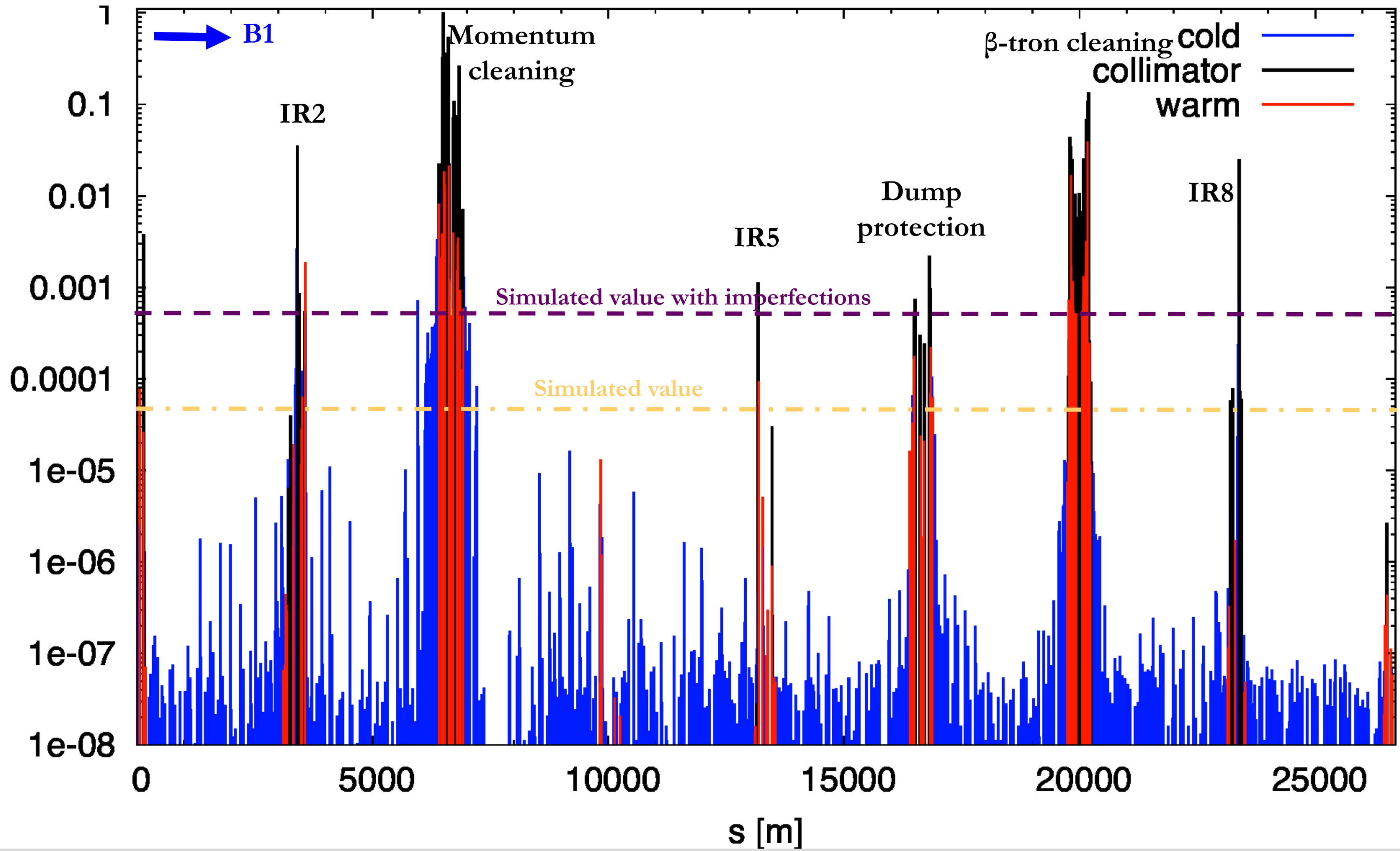
Measured: β-tron losses, B1v, 3.5TeV, β*=3.5m, IR3



Positive momentum offset, B1+B2, 3.5TeV, β*=3.5m

LHC Collimation Project

Goal: minimize blue spikes (losses to sc. Magnets)



Problems with hierarchy of collimation system in 2010

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  - Found on the 17.08.2010 during qualification campaign: TCSG in IR3 acts as primary collimator; causes higher leakage into the arc after IR3
  - Maybe been there since the high intensity setup in June (no pos. off-momentum loss maps done before)
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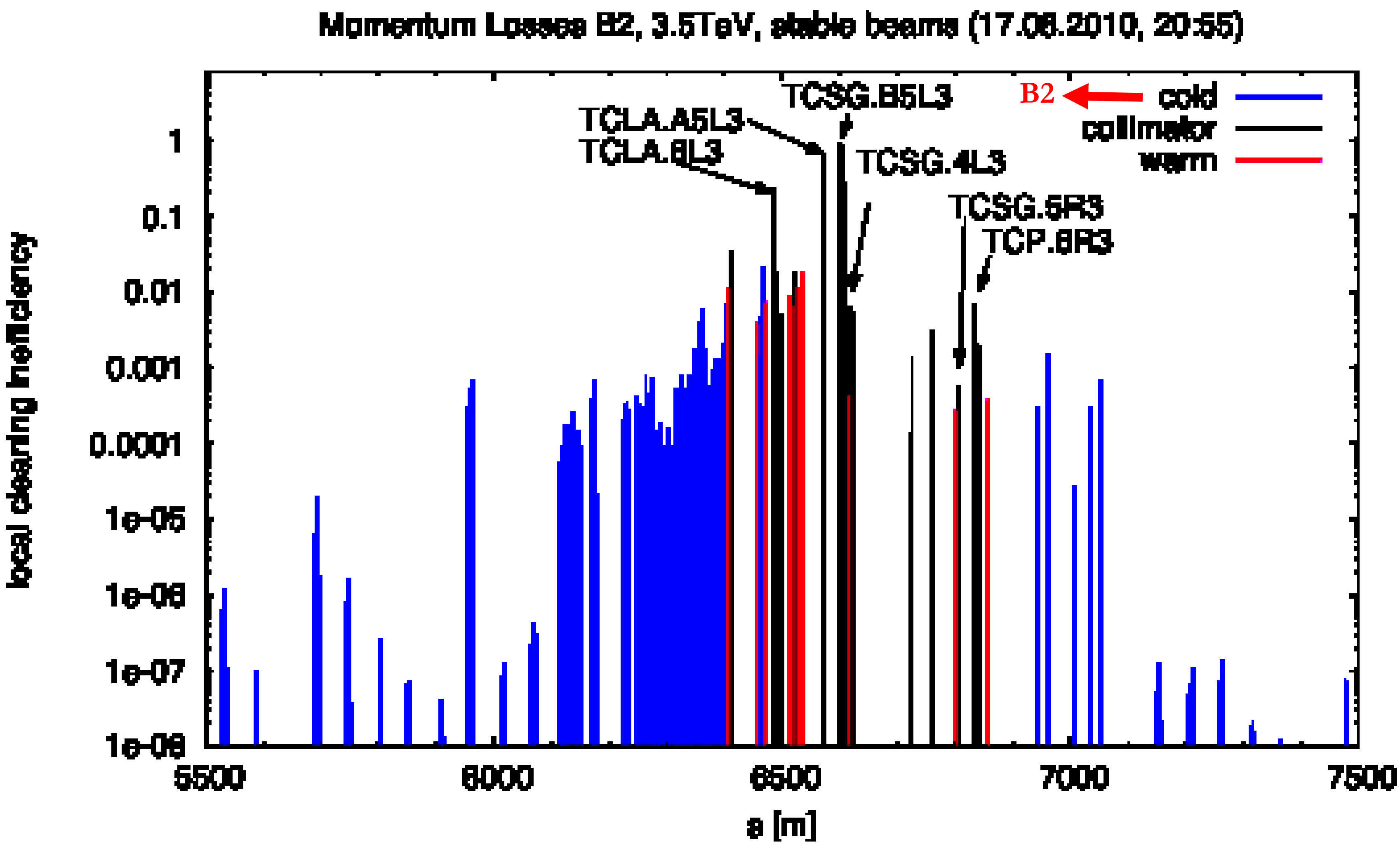
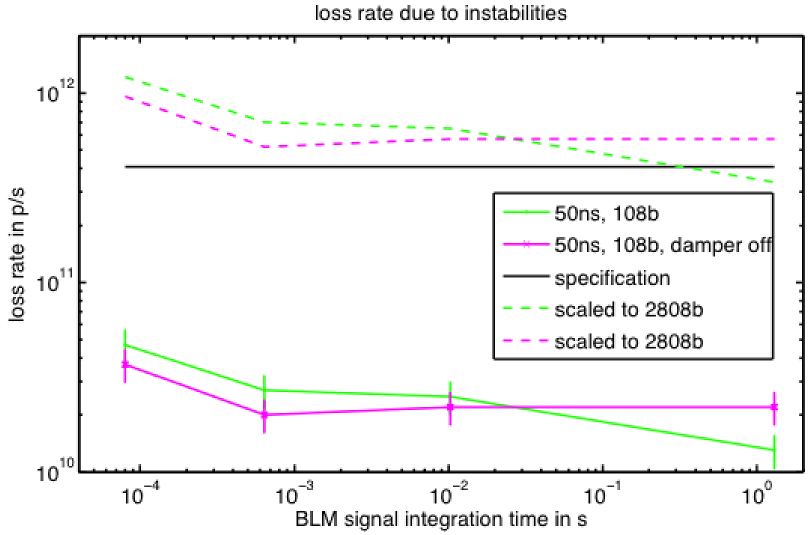
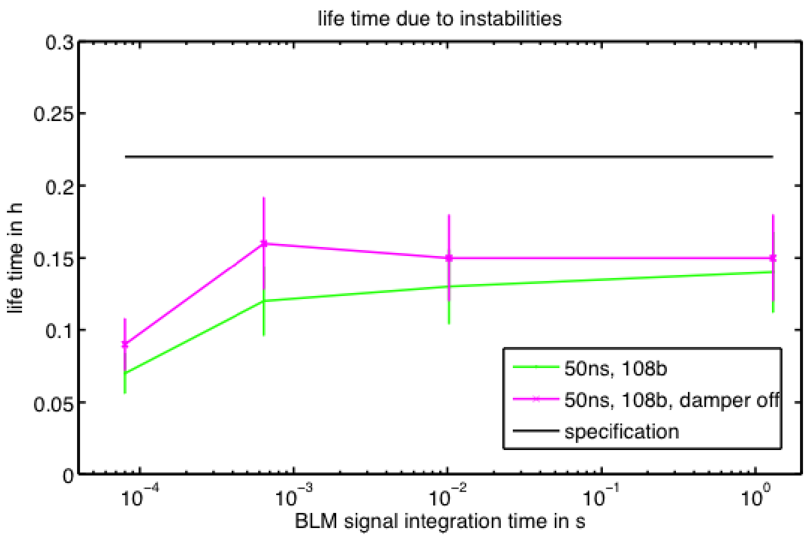
Problems with hierarchy of collimation system in 2010

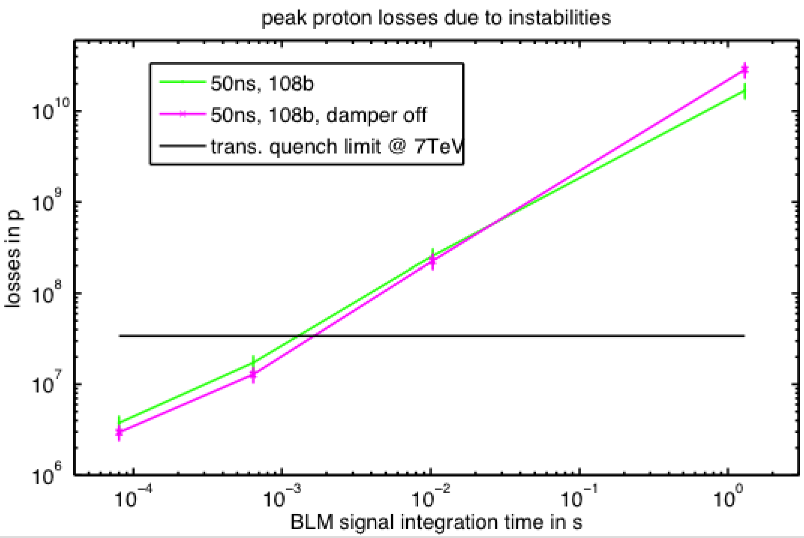


Loss rates and instantaneous life time for 50ns fills with instabilities compared to specifications

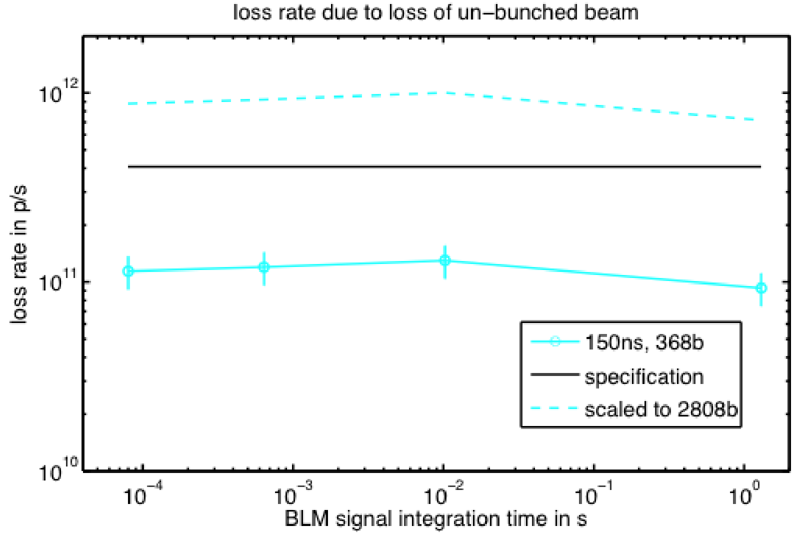


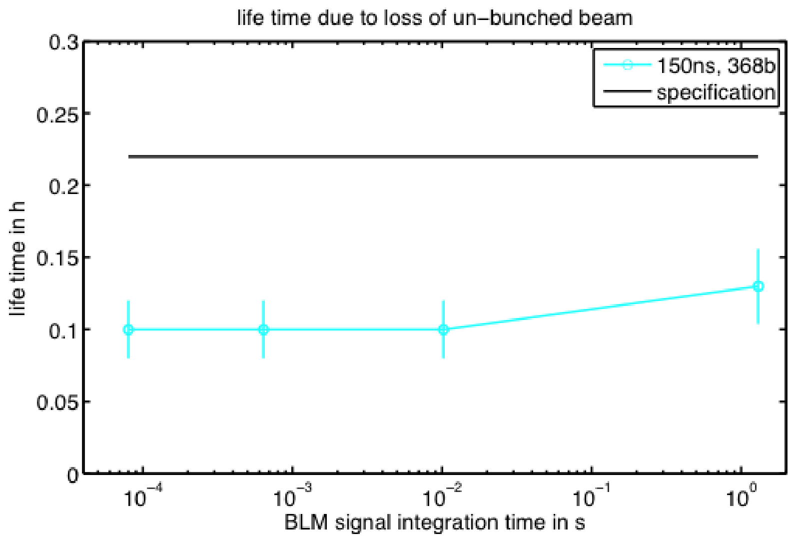


- Specified loss rate: 4.1e11p (for nominal intensity)
- Specified life time: 0.22h = 792s
- Transient quench limit: 3.4e7p
- Instabilities will limit intensity to:
  - **3.5 TeV: 9.1e13p**
  - **4.0 TeV: 7.2e13p**

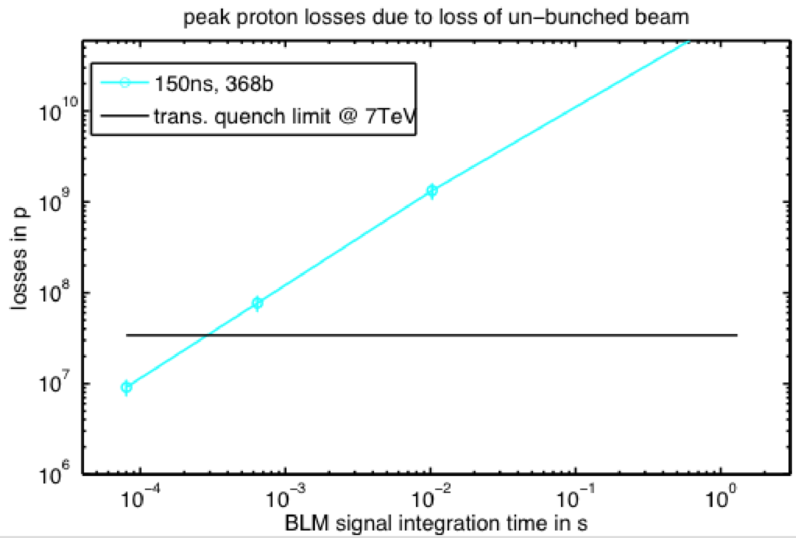


Loss rates and instantaneous life time for fill with high loss of un-bunched beam compared to specifications

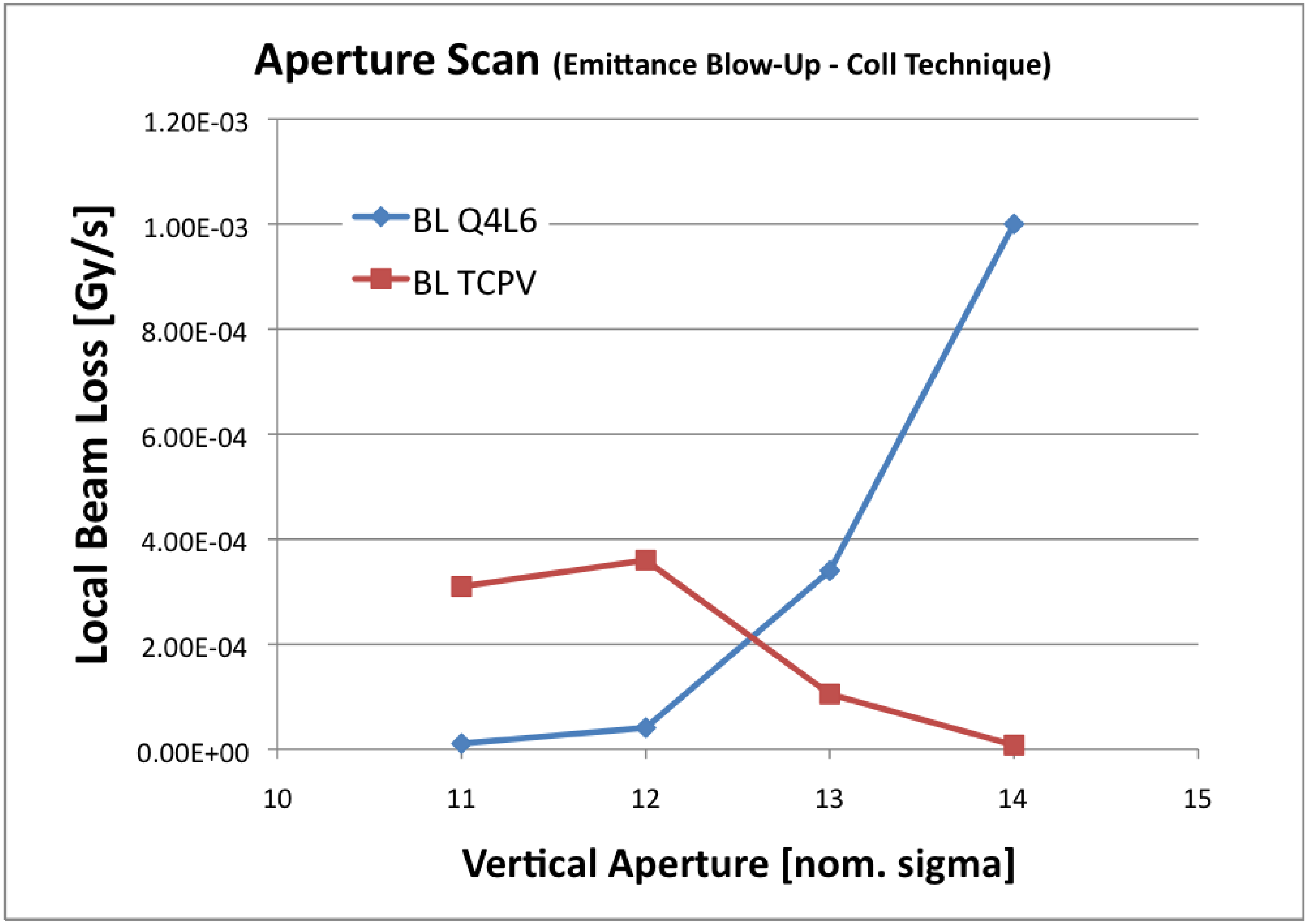




- Specified loss rate: 4.1e11p (for nominal intensity)
- Specified life time: 0.22h = 792s
- Transient quench limit: 3.4e7p
- Steady state quench limit: 7e8p/s/m
- **Intensity limit due to loss of un-bunched beam at 450GeV: 2.7e14p**
- **Note that this is the worst case 2010**



Difference of BLM response on losses in TCP and cold magnets



Calibration: BLM signal in Gy/s to loss rate in p/s