Update on impact of flux jumps in 11T dipoles in Run3

D. Gamba, G. Arduini, M.C. Bastos, R. Bruce, J. Coello de Portugal, L. Fiscarelli, M. Martino, A. Mereghetti, D. Mirarchi, S. Radaelli, M. Schaumann, R. Tomas

171st HiLumi WP2 – 24th Mar 2020

Available Information

- Looking **only** at **11 T dipoles** assuming they may show a measurable effect **in Run 3**
  - Too little information about **RQX** behavior to be predictive for **HL-LHC => let's start with LHC!**

Description	Measured or Estimated	Value	Ref.
Flux jump **B1 amplitude** (all in the same "direction")	**Measured**	mean 0.2 units **peak 0.6 units**	[1,3]
Flux jump A2-like amplitude	**Measured (neglected here)**	mean 0.15 units at 17 mm	[1,3]
Trim power converter reaction	**Estimated**	6 ppm σ (of 600 A) **18 ppm 3xσ**	[2,3]
Main dipole power converter reaction	**Estimated (neglected here)**	8e-3 ppm σ (of 13 kA)	[2]
Single **flux jump duration**	**Measured** ➔ **Estimated** ➔	50 ms mean rise time **120 ms FWHM**	[1,3]
Beam energy when *most* flux jumps occur	**Measured**	≈1.2 – ≈2.4 TeV ➔ **<3 TeV** (2 – 4 kA current)	[1,3]
Frequency of the flux jumps	**Measured**	**4.4 jumps/s**	[1,3]
Number of flux jumps per fill	**Computed**	**880 jumps**	[4]
Probability of a unit to be in a jump at a given time	**Computed**	**1/2**	[4]

[1] L. Fiscarelli **– Measurements and analysis of flux jumps (indico)**
[2] M. Martino **– Impact of Flux Jumps on PC Performance (indico)**
[3] J. Coello de Portugal **– Impact of flux jumps in future colliders (PRAB)**
[4] D. Gamba **– Revisiting flux jumps impact on orbit (indico)**

Worst Case Assumptions

- Field **jumps** are given **in "units"**
  - **Amplitude** of the **kick** (in rad) is **constant** independently of energy
  - **Orbit distortion**, in σ_{beam}, **increases with energy** due to adiabatic damping

- We **assume** to have **4 11T units** installed in **LHC** after LS2
  - A **flux jump** in each unit **will cause** an **orbit jump at the TCPs**

- We assume the **worst case scenario:**
  - **Several 11T units jumping at the same time** in the worst combination
  - Each unit jumps of **0.6 units** amplitude (i.e. **peak value**!)
  - **3/1.18A TeV** energy protons/$^{208}Pb^{82+}$
    - **worst ratio** between orbit jump and beam sigma

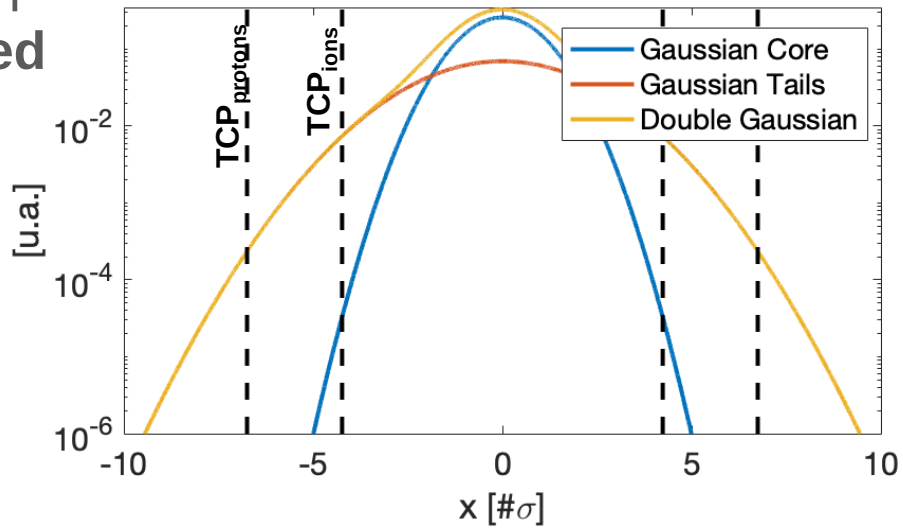
Assumption on beam distribution and TCPs

- **Double Gaussian** beam distribution measured in LHC and typically[1] **used** for **HEL simulations** [5]

$$f(x) = \frac{I_1}{\sqrt{2\pi}\sigma_1} e^{-\frac{x^2}{2\sigma_1^2}} + \frac{I_2}{\sqrt{2\pi}\sigma_2} e^{-\frac{x^2}{2\sigma_2^2}}$$

$$\text{where: } I_1/I_2 = 65/35$$

$$\sigma_2 = 2\sigma_1$$



- **TCP aperture** 5.7σ (wrt ϵ_N = 3.5 μm) equal (in mm) for protons and ions
  - Protons: **6.7 σ_{beam}** (wrt core **ϵ_N = 2.5 μm**)
    - **Conservative!:** in LHC typical measured $\epsilon_N \approx 2$ μm
  - Ions: **4.2 σ_{beam}** (wrt core **ϵ_N = 2.5 μm**)
    - **Conservative!:** nominal LIU beam $\epsilon_N \approx 1.65$ um

[1] *Reasonable average distribution over very few measurements.*

[5] P. Racano - **Review of halo measurements at Large Hadron Collider with collimator scans**. University of Rome La Sapienza - 2019.

Some Summary Numbers

	Protons – 2021	Ions – 2021
Beam emittance ϵ_N [μm]	**(2.5)**	**(2.5)**
TCP ap. (σ_{beam} for given ϵ_N)	**6.7**	**4.2**
Max orbit jump at TCP [%σ_{beam}]	**5.9**	**3.7**
Relative losses/jump [1/%σ_{beam}]	**7e-6**	**2e-4**
Max relative losses	**4.1e-5**	**7.4e-4**
Nominal beam intensity [particles]	**3.9e14 [7]**	**2.2e11 [7]**
Max particles lost at TCPs	**1.6e10 p**	**1.6e8 ions**
TCP BLM Th. RS06 (10 ms)	**1.9e10 p @3TeV**[1]	**1.6e8 ions @1.18TeV/A**[2]
TCP BLM Th. RS07 (82 ms)	**1.6e11 p @3TeV**[1]	**3.2e8 ions @1.18TeV/A**[2]

- Assuming the (reasonable) **worst flux jump scenario**, we would be **just below dump threshold** for both protons and ions.
- **Note: RS06 (10ms)** and **RS07 (82ms)** to be compared with typical **flux jump rise time (order of 50 ms)**

[1] From lossmap@3TeV, **using present threshold strategy**
[2] From lossmap@2.51TeV: **scaled down to 1.18 TeV/A**

[7] R.Tomas - **HL-LHC desiderata during Run 3** Montreux2020

Comparison to other observations

- **Loss-map** performed during **proton** ramp (@3 TeV) shows that **thresholds** (especially on **RS06**) might be **tighter than** what they **should/could be**
  - Likely, **a factor of a few to gain** – BLM thresholds due to collimation losses currently being reviewed by the BLM Threshold WG
- During **2018** run, beam losses due to **ground-motion-induced orbit jumps** (around 20-30Hz) of the order of **10% σ_{beam}** [6] – stronger than a flux jump, and at top energy
  - Losses of about **1-2e10 protons**
  - **x5 below dump threshold** (at least at TCPs on RS06, RS07, RS08)
- During the ramp **collimator jaws** move in **steps** of the order of **~2% σ_{beam}** in order to follow beam size reduction. (step time << 100 ms)
  - **no critical BLM spikes ever observed**
- While inserting **crystal collimators** (**~20% σ_{beam}**) **slow loss** up to **1.2e8 ions** observed
  - **Compatible** with assumption of **similar tail population distribution as for protons**
- **10 Hz ion-fill dumps** were triggered by orbit distortion of **≈15% σ_{beam}** and **≈110% $BLM_{thresholds}$**
  - **Scaling to flux jump case,** one would be at about **66% of $BLM_{thresholds}$**
    - **Assuming 2.51 TeV/A!** Margin would increase at 1.18 TeV/A.

[6] D. Gamba - **Impact of HL-LHC civil engineering work on the LHC** (indico).

Conclusions

- **Many unknowns, but trying to take all known margins**

- In **Run 3** we expects several **orbit jumps** at the **TCPs (worst case):**
  - up to **5.9% of σ_{beam} at 3 TeV** for protons
  - up to **3.7% of σ_{beam} at 1.18 TeV/A** for ions

- With the **present BLM thresholds,** such jumps could **induce beam losses just below dump threshold**
  - Using **very pessimistic** assumptions **on flux jumps!**
  - **Possible to gain margin** working on the **threshold settings**
    - **Under discussion** among BLM Threshold WG independently from flux jumps.

- *Consistent with several observations:*
  - **Lossmaps @3 TeV with protons**
  - **Ground-motion-induced losses** observed in 2018
  - **End-of fill crystal collimator insertion**
  - **10Hz-related ion-fill dumps**

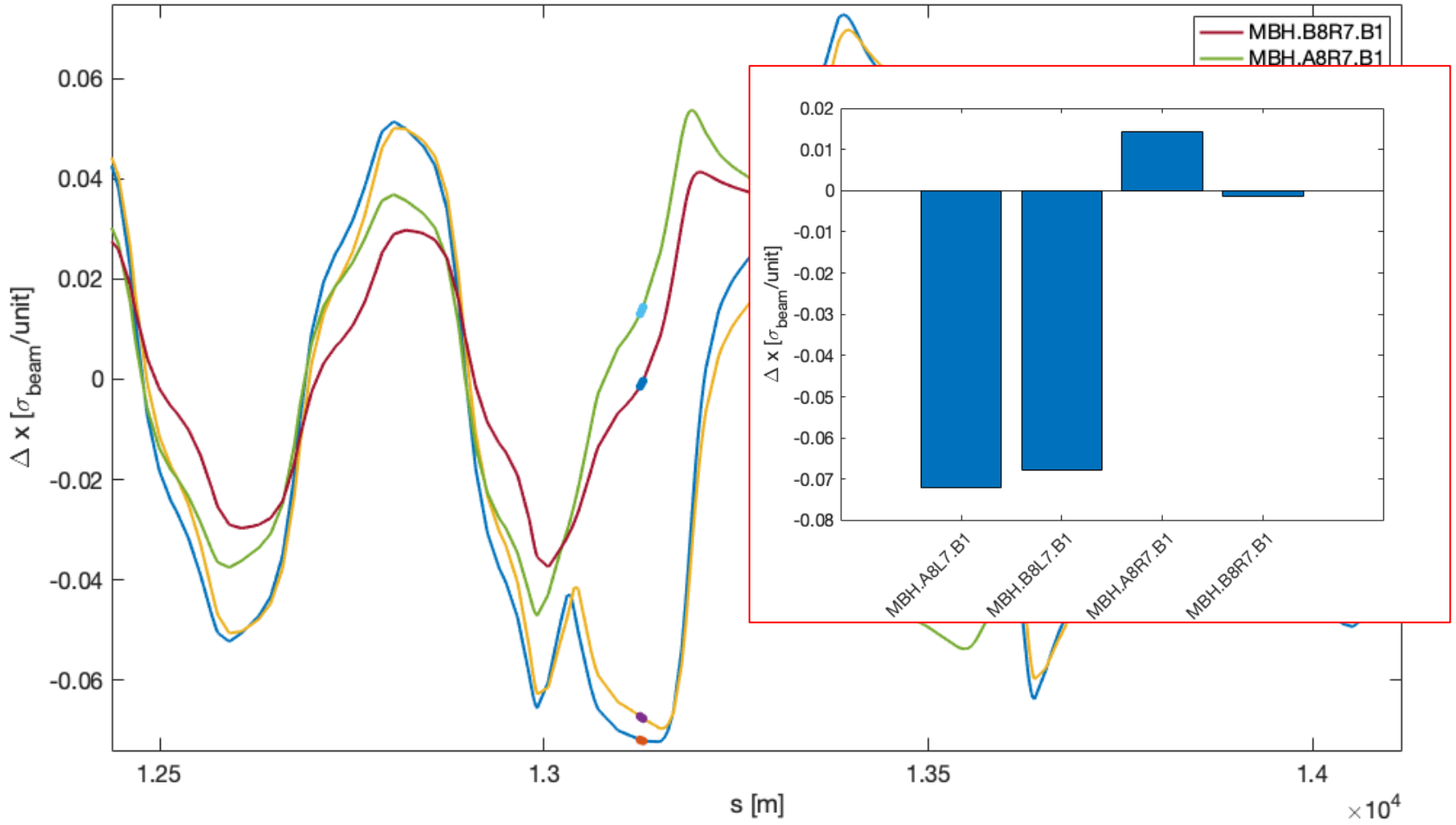
- **11T dipoles in LHC are considered safe (regarding flux jumps)**
  - Will give us the opportunity to better evaluate the impact of RQX in HL-LHC

HiLumi HL-LHC PROJECT CERN

Thank you for your attention and comments!

Backup

Impact of 11T @TCP @1m beta* @7TeV



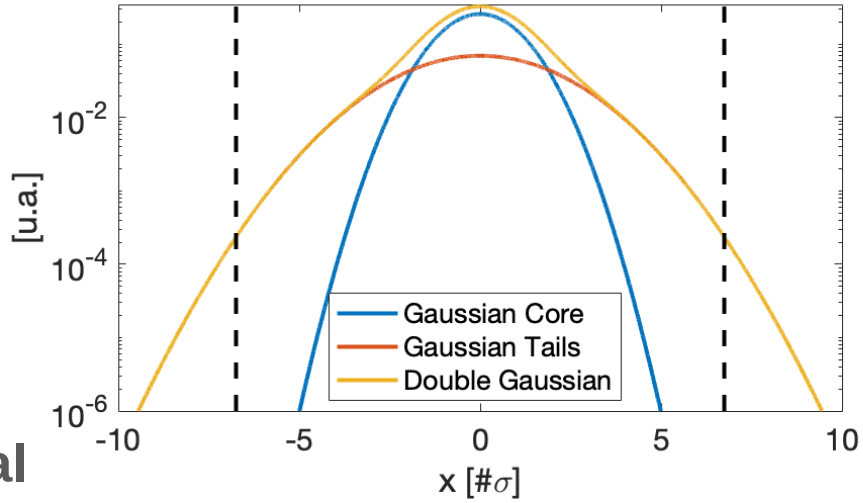
Impact on beam losses (~LHC design protons)

- **Double Gaussian** beam distribution measured in LHC and typically used for HEL simulations [5]

$$f(x) = \frac{I_1}{\sqrt{2\pi}\sigma_1} e^{-\frac{x^2}{2\sigma_1^2}} + \frac{I_2}{\sqrt{2\pi}\sigma_2} e^{-\frac{x^2}{2\sigma_2^2}}$$

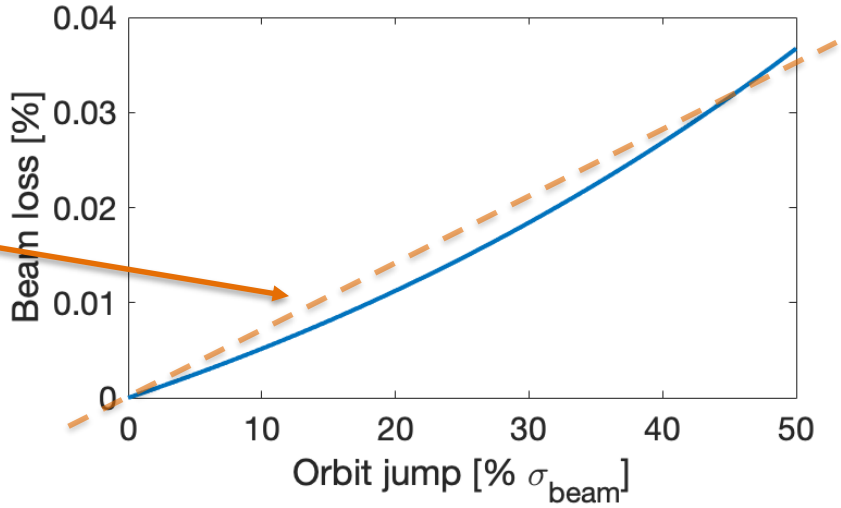
$$\text{where: } I_1/I_2 = 65/35$$

$$\sigma_2 = 2\sigma_1$$



- Losses assuming **TCP opening equal to 6.7 σ** (2.5 μm ϵ_N)
  - (equivalent to 5.7 σ (3.5 μm ϵ_N))

- **1% σ_{beam}** orbit jump induces **≈7e-6** relative beam losses.
  - **1.1 kJ** (w.r.t. 154 MJ @**3TeV**)
  - **2.3e9 protons** (w.r.t. 3.22e14 full beam)



[5] P. Racano - **Review of halo measurements at Large Hadron Collider with collimator scans**. University of Rome La Sapienza - 2019.

Impact on beam losses (~LHC ions)

- **Double Gaussian** beam distribution measured in LHC and typically used for HEL simulations

$$f(x) = \frac{I_1}{\sqrt{2\pi}\sigma_1} e^{-\frac{x^2}{2\sigma_1^2}} + \frac{I_2}{\sqrt{2\pi}\sigma_2} e^{-\frac{x^2}{2\sigma_2^2}}$$

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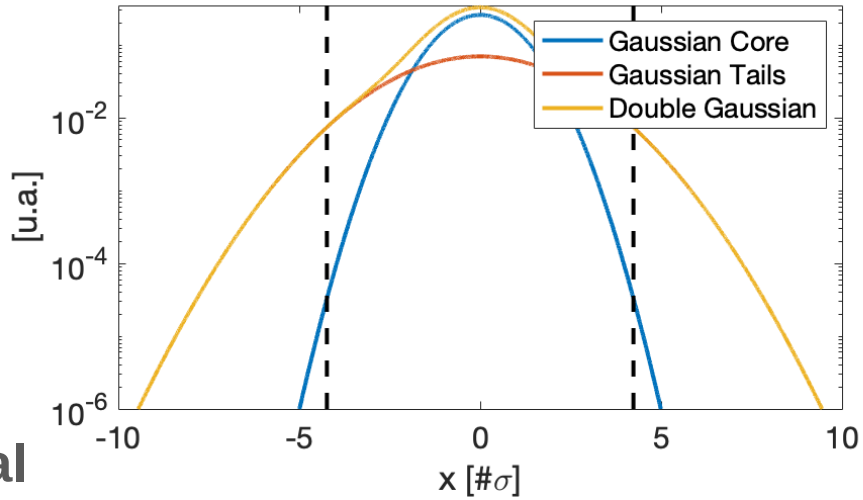
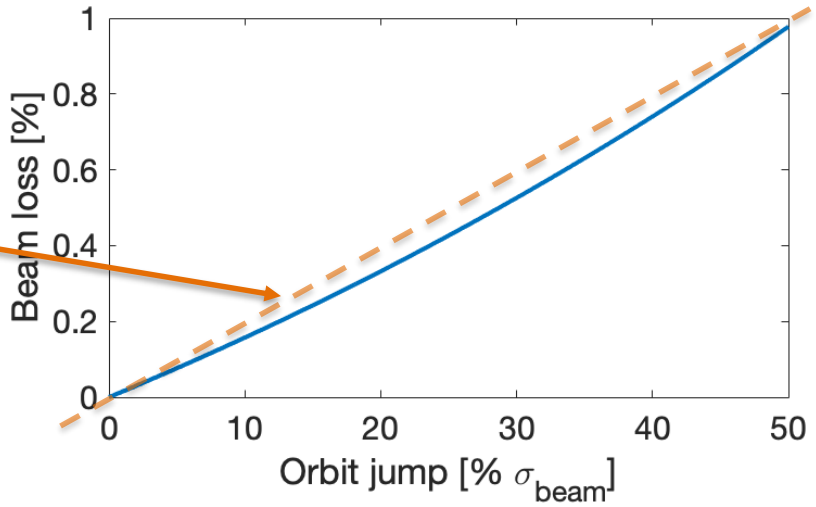


- Losses assuming **TCP opening equal to 4.2 σ** (2.5 μm ϵ_N)
  - (equivalent to 5.7 σ (3.5 μm ϵ_N) for protons)

- **1% σ_{beam}** orbit jump induces **≈2e-4** relative beam losses.
  - **1.7 kJ** (w.r.t. 8.7 MJ @**1.18A TeV**)
  - **4.4e7 ions** (w.r.t. **2.2e11 LIU** beam [6,7])



[6] J.M. Jowett - **The 2018 Heavy-ion Run of the LHC** IPAC2019
[7] R.Tomas - **HL-LHC desiderata during Run 3** Montreux2020

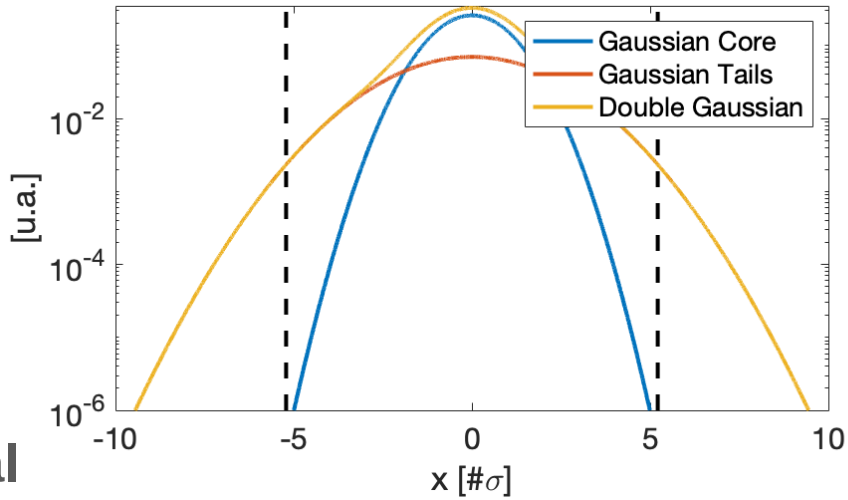
Impact on beam losses (LIU ions)

- **Double Gaussian** beam distribution measured in LHC and typically used for HEL simulations

$$f(x) = \frac{I_1}{\sqrt{2\pi}\sigma_1} e^{-\frac{x^2}{2\sigma_1^2}} + \frac{I_2}{\sqrt{2\pi}\sigma_2} e^{-\frac{x^2}{2\sigma_2^2}}$$

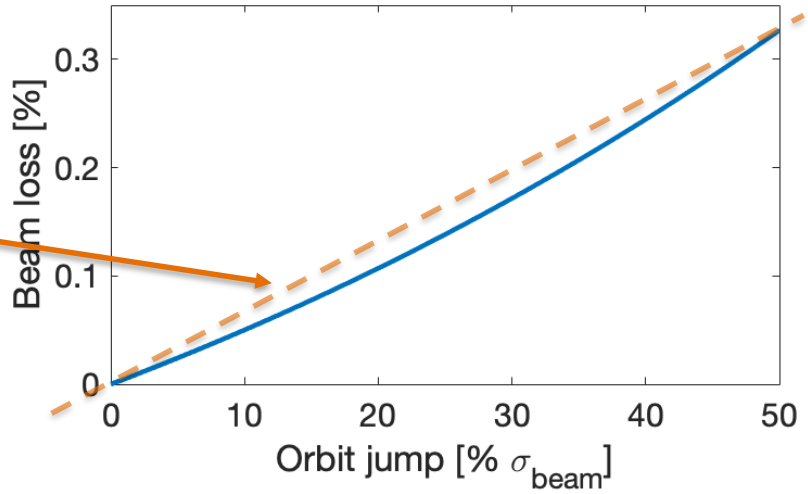
$$\text{where: } I_1/I_2 = 65/35$$

$$\sigma_2 = 2\sigma_1$$



- Losses assuming **TCP opening equal to 5.2 σ (1.65 µm ϵ_N (LIU))**
  - (equivalent to 5.7 σ (3.5 µm ϵ_N) for protons)

- **1% σ_{beam}** orbit jump induces **≈6.5e-5** relative beam losses.
  - **0.6 kJ** (w.r.t. 8.7 MJ @**1.18A TeV**)
  - **1.4e7 ions** (w.r.t. **2.2e11 LIU** beam [6,7])



[6] J.M. Jowett - **The 2018 Heavy-ion Run of the LHC** IPAC2019
[7] R.Tomas - **HL-LHC desiderata during Run 3** Montreux2020

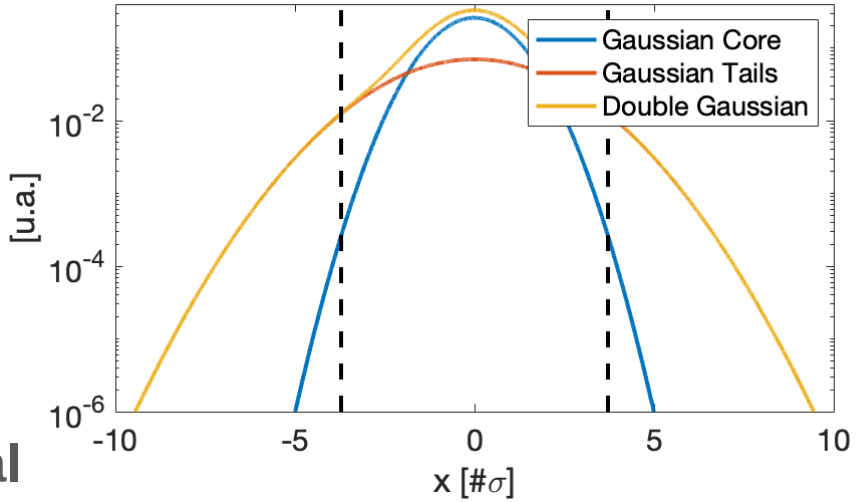
Impact on beam losses (~LHC ions - crystal)

- **Double Gaussian** beam distribution measured in LHC and typically used for HEL simulations [5]

$$f(x) = \frac{I_1}{\sqrt{2\pi}\sigma_1} e^{-\frac{x^2}{2\sigma_1^2}} + \frac{I_2}{\sqrt{2\pi}\sigma_2} e^{-\frac{x^2}{2\sigma_2^2}}$$

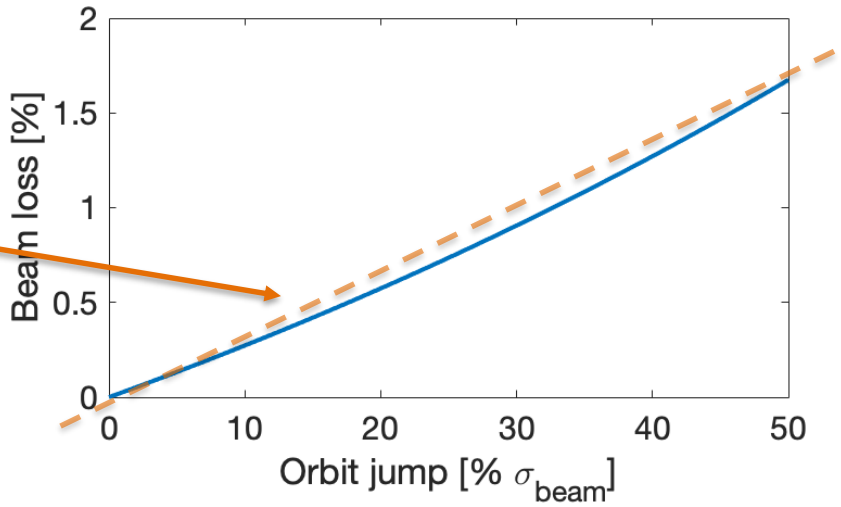
$$\text{where: } I_1/I_2 = 65/35$$

$$\sigma_2 = 2\sigma_1$$



- Losses assuming **TCP opening equal to 3.1 σ** (2.5 μm ϵ_N)
  - (equivalent to **5 σ** (3.5 μm ϵ_N for protons))

- **1% σ_{beam}** orbit jump induces **≈3.4e-4** relative beam losses.
  - **0.6 kJ** (w.r.t. **1.7 MJ @1.18A TeV**)
  - **1.5e7 protons** (w.r.t. **4.4e10 at the time**)



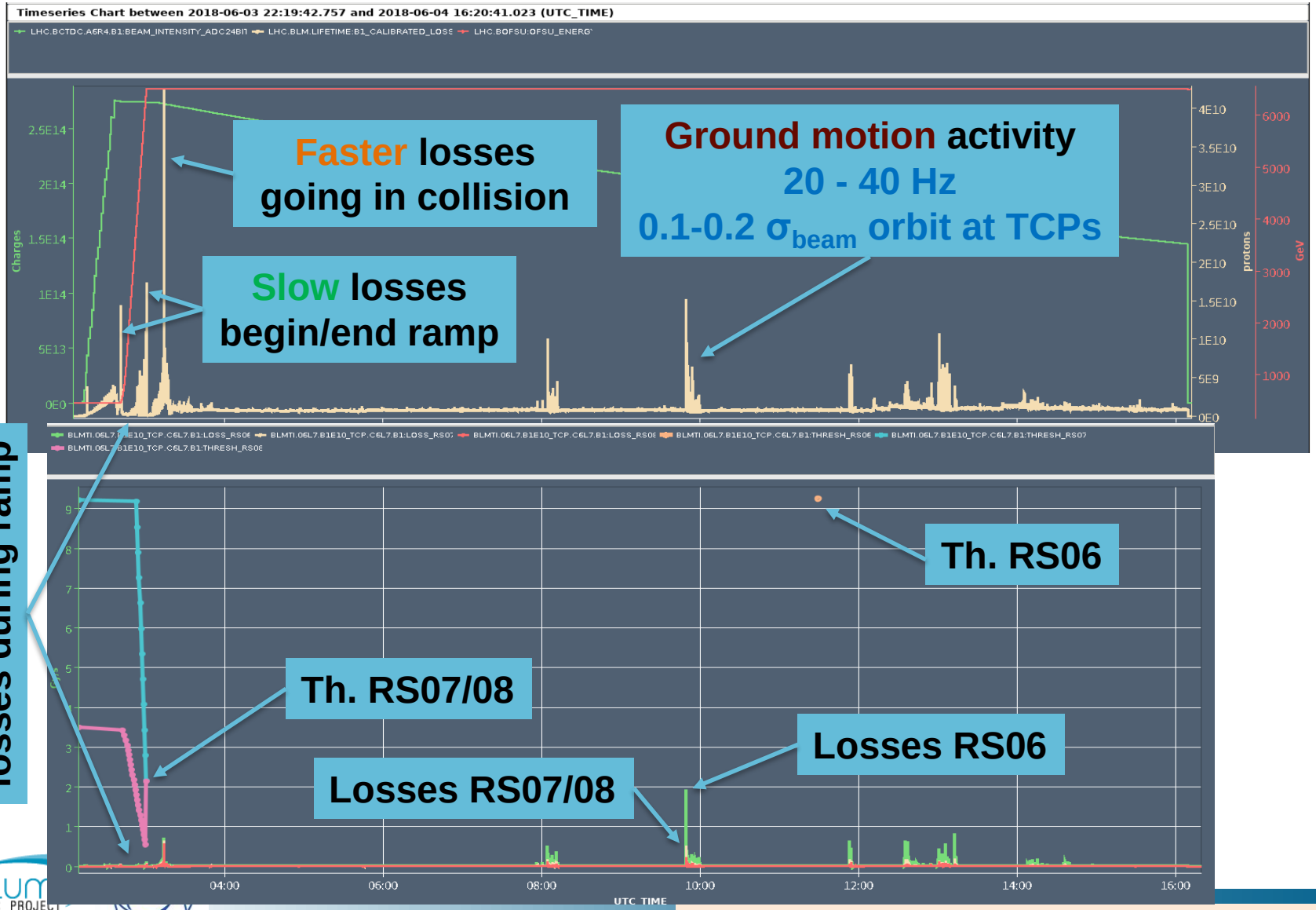
[5] P. Racano - **Review of halo measurements at Large Hadron Collider with collimator scans**. University of Rome La Sapienza - 2019.

Analysis of other observations

Ground motion – proton (Fill 6757)

Some observables (losses at TCPs)

- We were about **x5 below dump threshold** on RS06-RS07-RS08 @TCPs

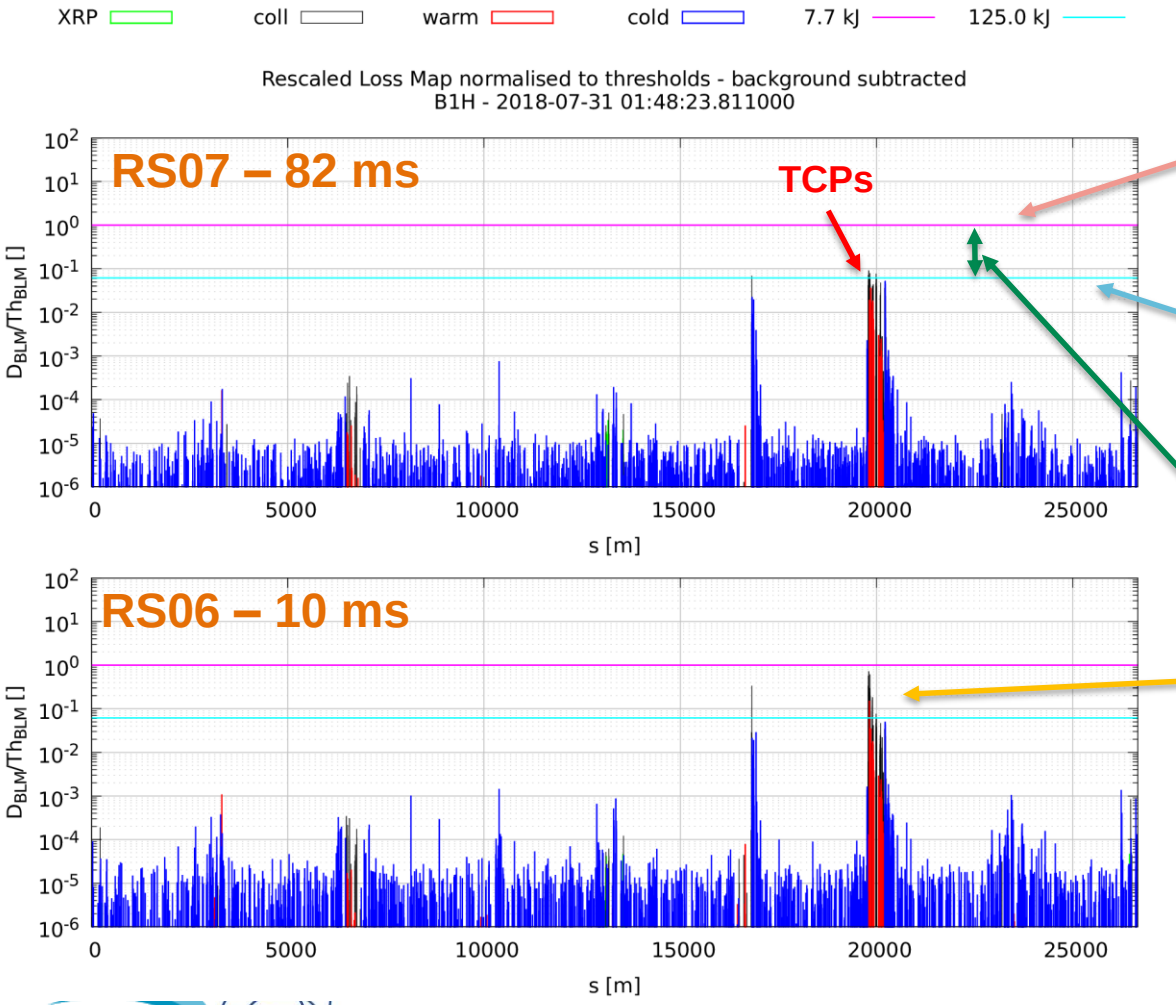


See also D.Gamba – HL-LHC Collaboration Meeting 2018 - indico

Loss Map @3 TeV

Loss-map measured at 3 TeV (B1)

- Measurement performed **loosing a pilot** (8-9e10 protons) in ~5 s.
- **Rescaling** data assuming to loose **1.6e10 protons** (assumed in slide 5) for RS06/07:



If any BLM would **hits this line**, **we should** dump the beam

In **theory**, all BLM threshold should be adjusted to be **all on this line** **(as it is for TCPs)**

In **theory**, more than **x10 below theoretical threshold**

In practice, for RS06 thresholds are set tighter than required

⇒ **With such an event, today, very close to a dump!**

⇒ **However: flux jump takes typically ~50 ms, not 10 ms!**

Courtesy A. Mereghetti

Loss Map measured at 2.51 TeV/A scaled to 1.18 TeV/A

- Assuming present thresholds, assuming to loose **1.6e8 ions**

Conservative thresholds!

Line with no particular meaning

Crystal Collimator test (Fill 7454)

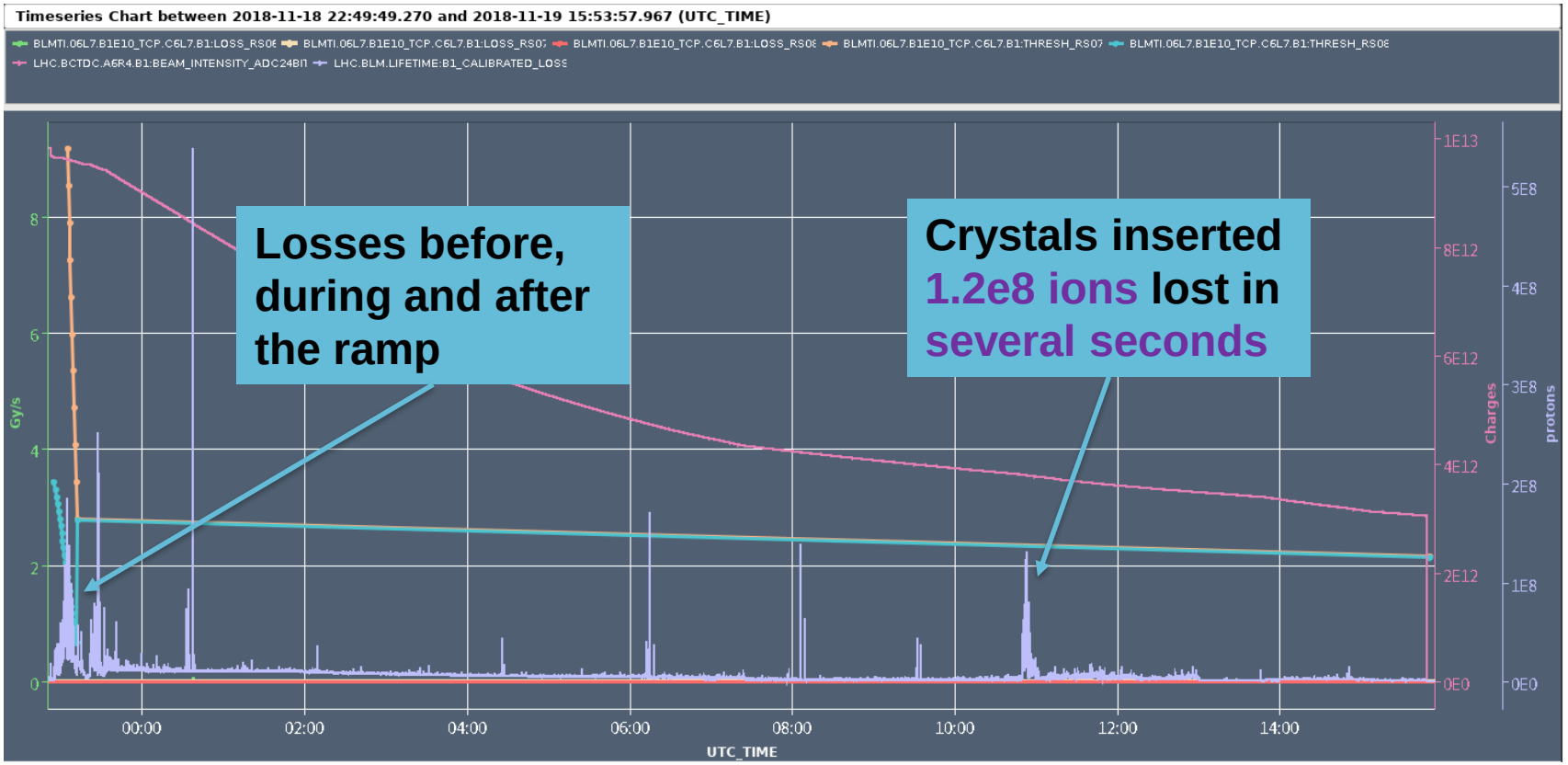
Intensity loss during crystal insertion

Crystal (Fill 7454)	FBCT				BCT			
	I_{in} (Ch)	I_{fin} (Ch)	ΔI (Ch)	$\Delta I/I_{in}$	I_{in} (Ch)	I_{fin} (Ch)	ΔI (Ch)	$\Delta I/I_{in}$
B1H	3.64e12	3.63e12	1e10	2.7e-3	3.8e12	3.79e12	1e10	2.6e-3
B1V	3.57e12	3.56e12	1e10	2.8e-3	3.73e12	3.72e12	1e10	2.7e-3

Main considerations:

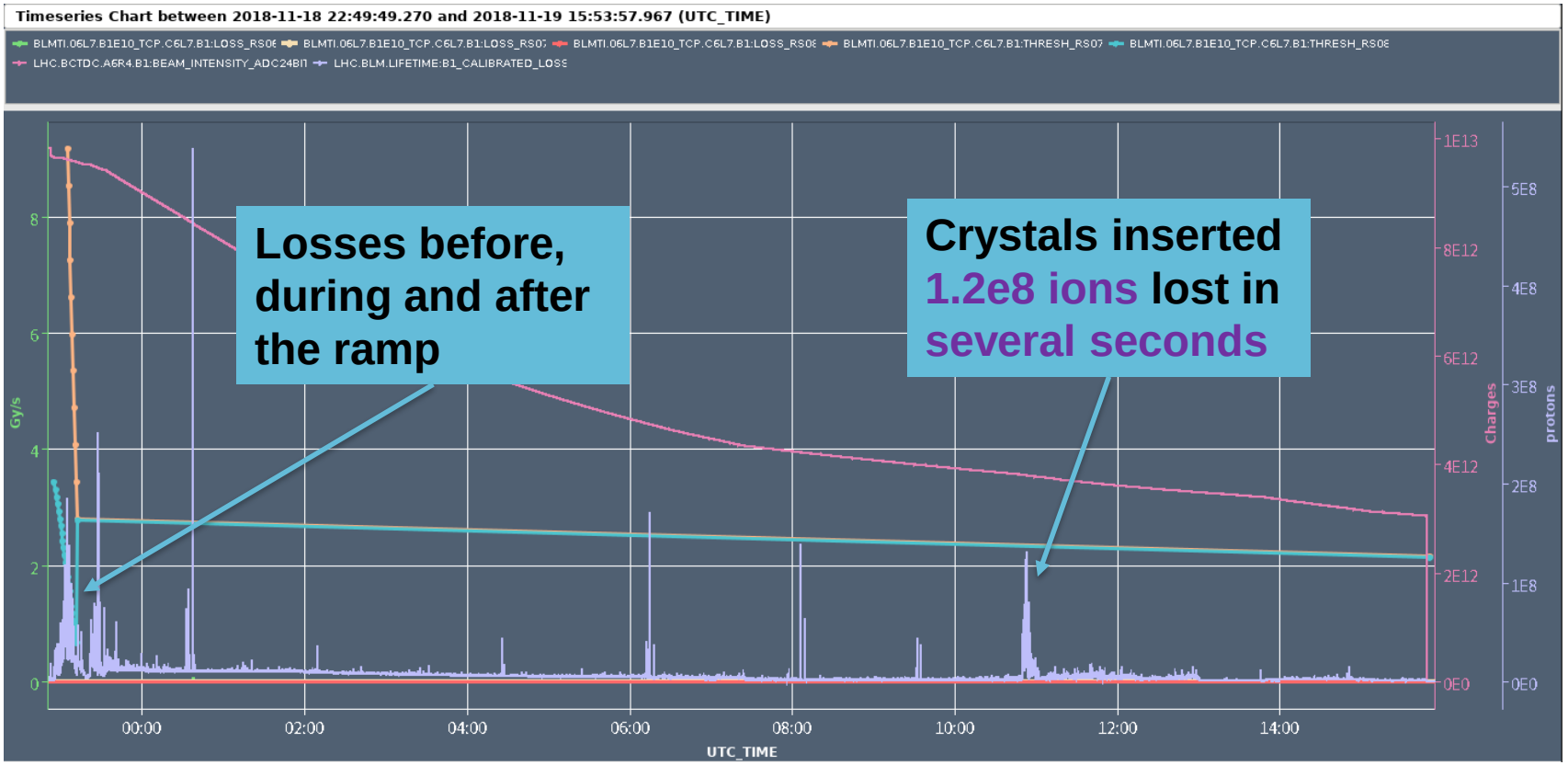
- FBCT are calibrated using BCT and the difference of absolute value between the two signal can be due to:
  - problems of calibration
  - presence of de-bunched beam to which FBCT are not sensitive
- No visible intensity loss when inserting crystals in B2:
  - Other observation shows B2 crystals primary collimation stage, thus:
    - we didn't enter of the same fraction of sigma with the crystals in the two beam (but I doubt it because the beating should be <5%)
    - the population in the B2 tails between 5.0 s and 4.75 s is less than in B1 and below the sensitivity of FBCT and BCT.
- Consider that we were in stable beams from several hours, and this is only one "measurement". Thus, any extrapolation can have significant errors.

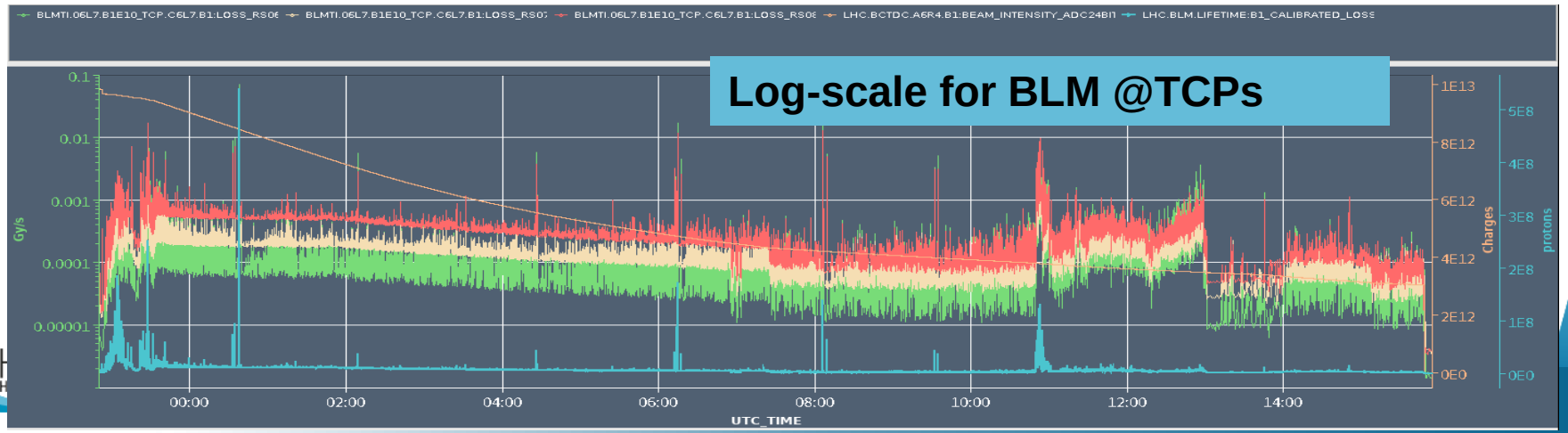
Fill 7454: crystal insertion



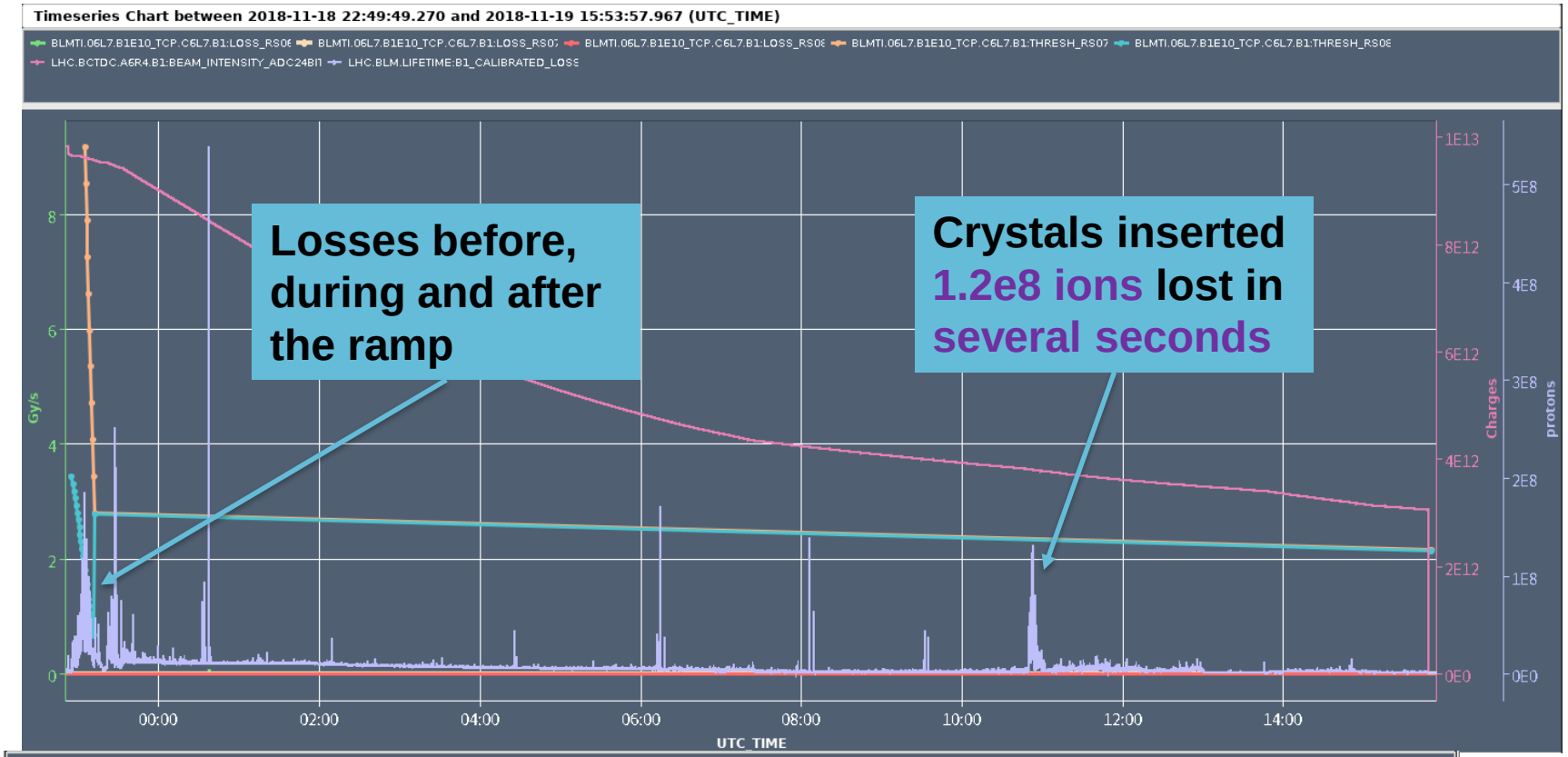
- No major BLM signal observed, despite 1.2e8 ions lost in total, **but over several seconds**.

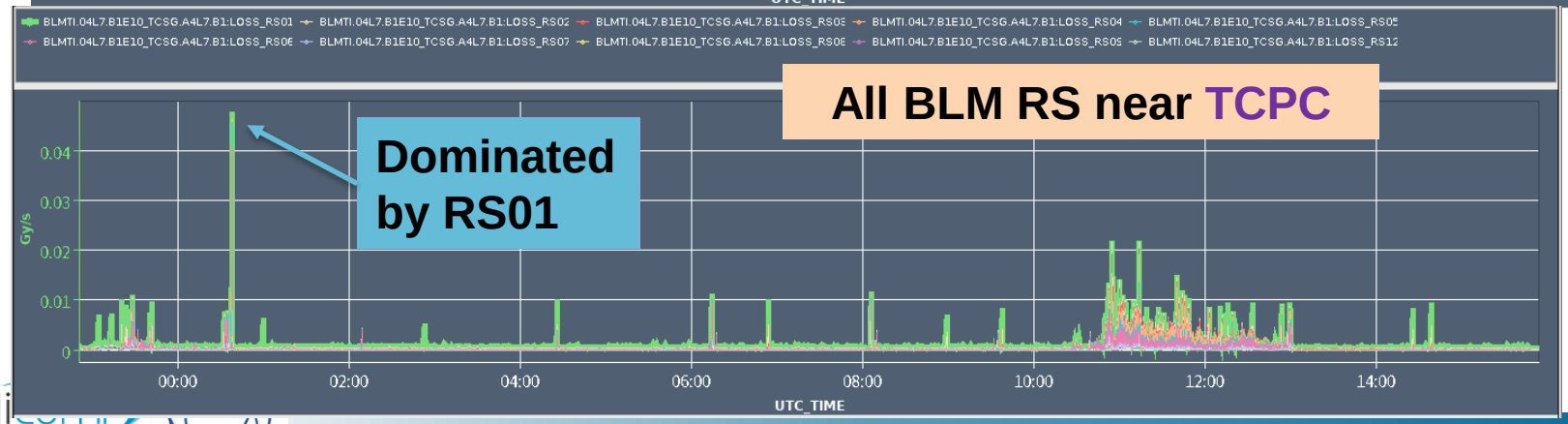
Fill 7454: crystal insertion





Fill 7454: crystal insertion





10 Hz data analysis

10 Hz-induced Pb-Pb fill dumps

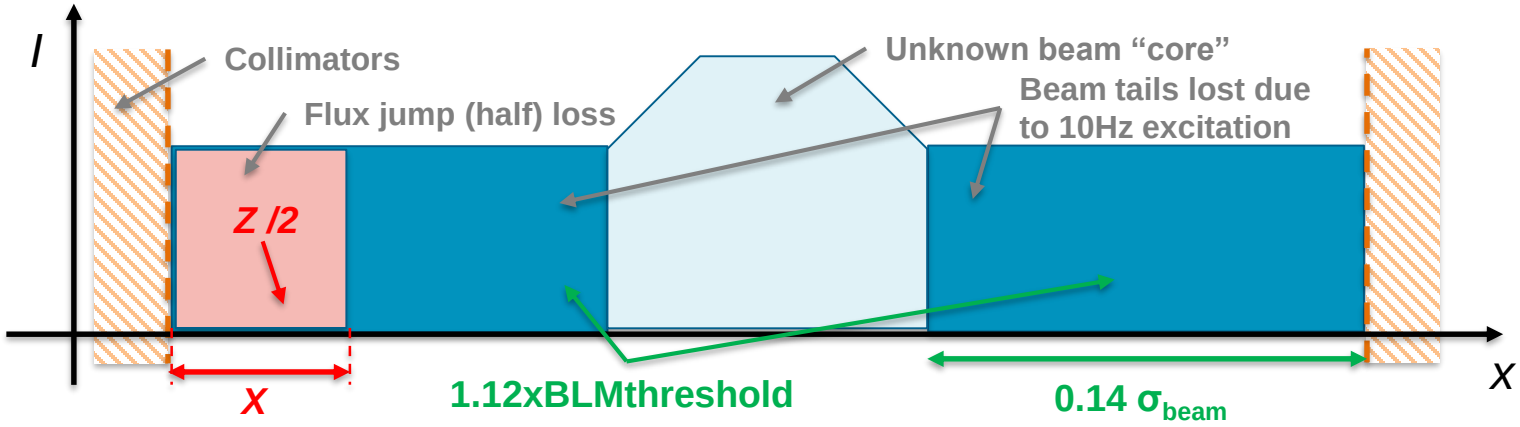
Fill	BLM	RS	Losses [Gy/s]	Threshold [Gy/s]	Ratio Loss/Th	(Pk-Pk)/2 orbit [um / σ_{beam}*]	B1 / B2 intensity [10^11]
7442	BLMTI.04R6.B2I10.TCDSA.A4R6.B2	1	0.21	0.1274	1.65	48 / 0.13	0.97/1.00
		2	0.21		1.65		
		3	0.21		1.65		
		4	0.20		1.57		
		5	0.19		1.49		
		6	0.14		1.10		
	BLMTI.05L7.B1E10_TCSG.A5L7.B1	8	0.0591	0.0583	1.01		
		9	0.0297	0.0291	1.02		
7447	BLMTI.04R6.B2I10.TCDSA.A4R6.B2	1	0.1278	0.1274	1.003	60 / **0.16**	**1.21**/1.20
	BLMTI.04L1.B1I10_TCTPH.4L1.B1	**7**	0.0039	0.0035	**1.11**		
7458	BLMTI.05L7.B1E10_TCSG.A5L7.B1	8	0.0584	0.0584	1.002	58 / 0.15	1.01/1.04
		9	0.0354	0.0291	1.21		
	BLMQI_13R7.B1E10_MQ	8	0.0035	0.0034	1.03		
7459	**BLMTI.04L1.B1I10_TCTPH.4L1.B1**	**7**	0.0039	0.0035	**1.12**	54 / **0.14**	**0.99**/1.02
	BLMQI_13R7.B1E10_MQ	8	0.0036	0.0034	1.05		
	BLMTI.05L7.B1E10_TCSG.A5L7.B1	8	0.0603	0.0583	1.03		
		9	0.0315	0.0291	1.08		
7482	BLMQI_13R7.B1E10_MQ	8	0.0036	0.0034	1.06	66 / 0.17	1.46/1.45
	BLMTI.05L7.B1E10_TCSG.A5L7.B1	8	0.0597	0.0583	1.02		

* β_x @TCP ≈ 150 m ➔ σ_{beam} ≈ 375 μm @2.51 TeV/A @2.5 um ϵ_N

Courtesy D. Mirarchi, M. Schaumann

Extrapolation of 10Hz dumps to flux jumps

- Typically dumping on RS>08 (>655 ms). A few dumps on RS07 (82 ms)
- Worst case on RS07 (fill 7459 @2.51 TeV/A):
  - 1.12xBLM$_{threshold}$ for a orbit jitter of 0.14 σ_{beam} (Pk-Pk)/2 and B1 of 0.99e11 ions
- Assuming the following scenario (not to scale):



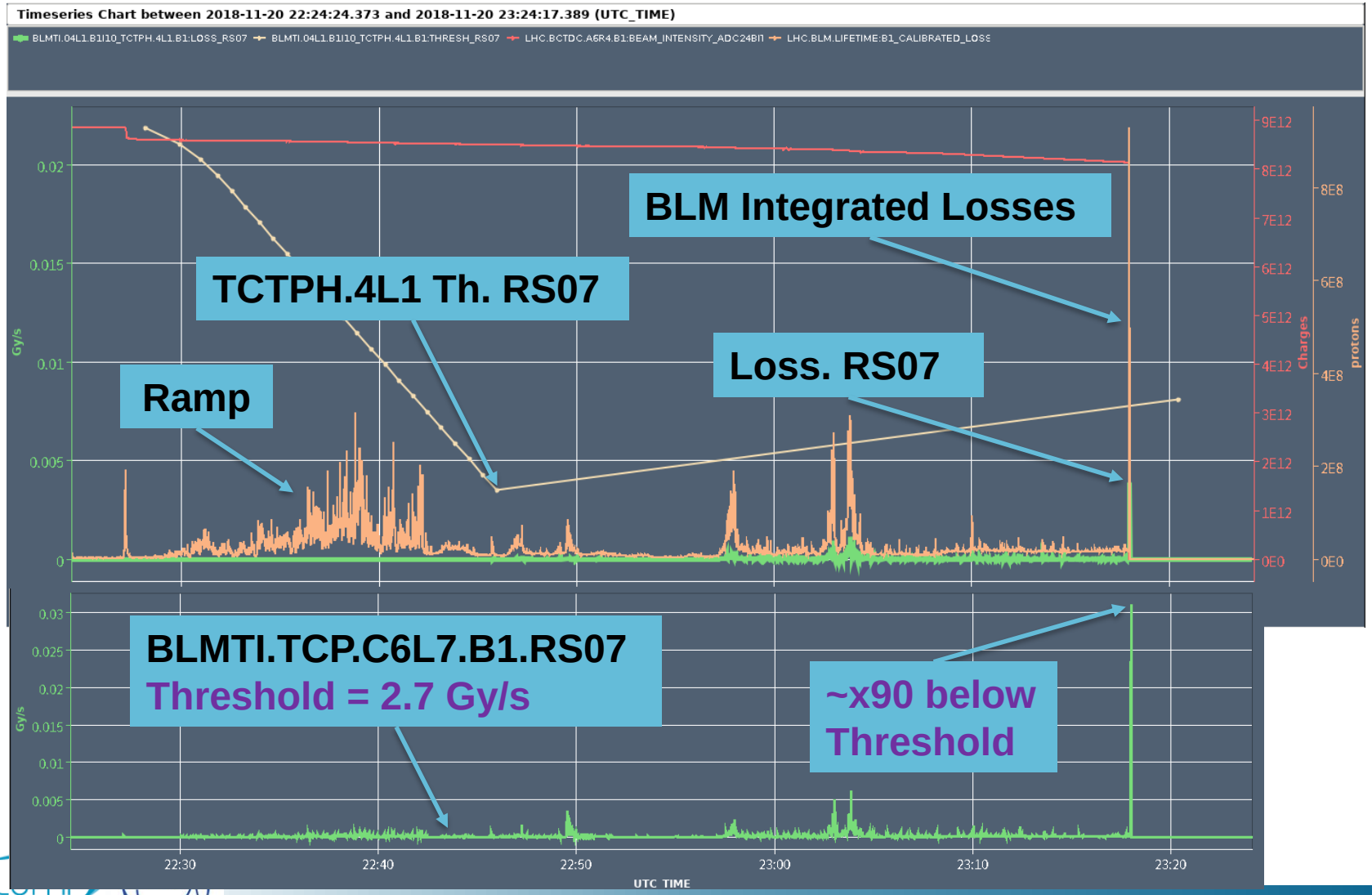
- Re-normalizing for **LIU intensity 2.2e11; ϵ_N = 2.5 um; 0.037 σ_{beam} jump**:
  - **neglecting** normalization wrt to energy (**1.18 TeV/A instead of 2.51 TeV/A**)

$$Z = 1.12 \times \frac{0.037}{0.14} \times \frac{2.2}{0.99} = 0.66$$

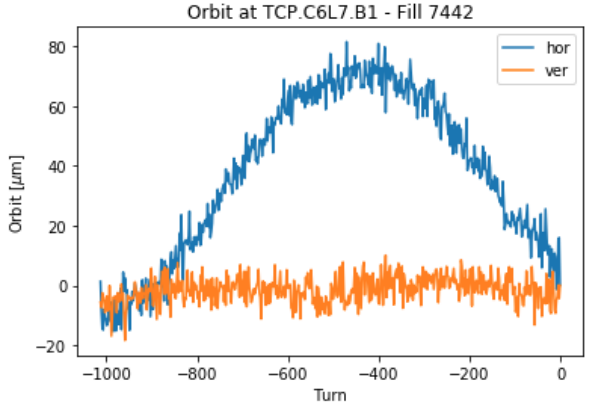
=> 66% BLM$_{threshold}$

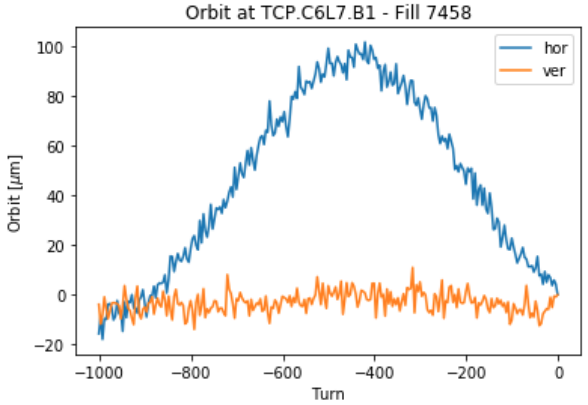
Fill 7459 – 10Hz-induced dump

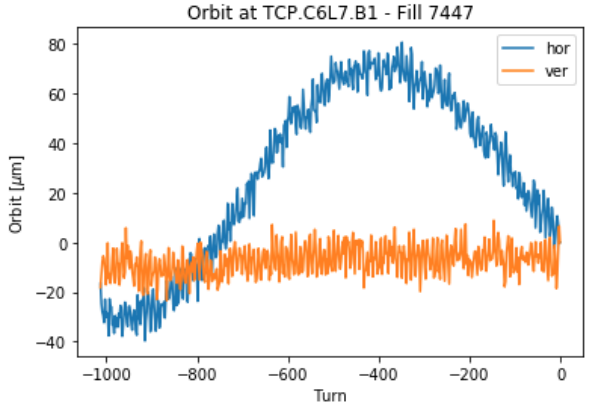
- Dumped on TCTPH.4L1, but ~**x90 below threshold at TCPs**
  - This is **normal** for ions! -> cleaning efficiency locally at TCPs is low. Fragments lost downstream

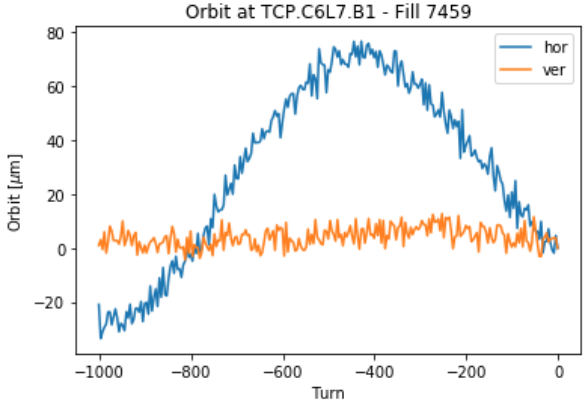


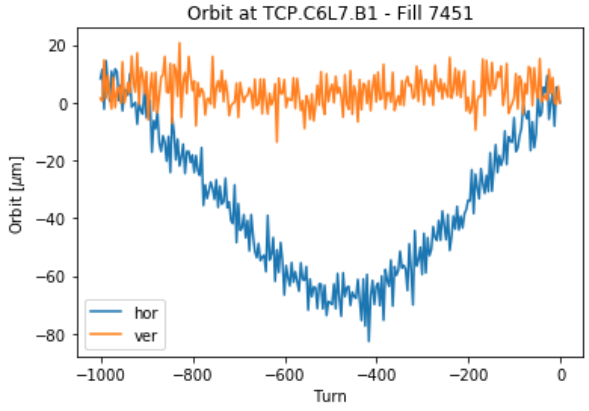
Turn-by-Turn View

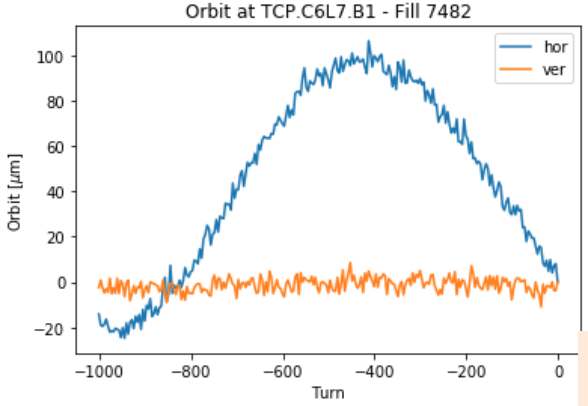












max-min value in data set (no averaging)

```
7442
Delta pos at TCP.C6L7.B1= 96.92356658966669
7447
Delta pos at TCP.C6L7.B1= 120.26509331118783
7451
Delta pos at TCP.C6L7.B1= 94.27792197679815
7458
Delta pos at TCP.C6L7.B1= 116.22714589768549
7459
Delta pos at TCP.C6L7.B1= 107.74611960443664
7482
Delta pos at TCP.C6L7.B1= 131.17636981857282
```

Courtesy M. Schaumann

Final Table

Some summary numbers

	Protons		Ions			
	~LHC	LHC-2021	LHC-crystal	LHC-10Hz dump	LHC	LHC-LIU
Beam emittance ϵ_N [μm]	(2.5)		(2.5)	(2.5)	(2.5)	1.65 [7]
TCP ap. (σ_{beam} ϵ_N =3.5 [μm])	5.7		5	5.7	5.7	
TCP ap. (σ_{beam} for given ϵ_N)	6.7		3.7	4.2	4.2	5.2
Max orbit jump at TCP [%σ_{beam}]	5.9		18.6	14	3.7	4.6
Relative losses/jump [1/%σ_{beam}]	7e-6		3.4e-4	2e-4	2e-4	6.5e-5
Max relative losses	4.1e-5		6.3e-3	2.8e-3	7.4e-4	3e-4
Total beam intensity [particles]	3.2e14 [8]	3.9e14 [7]	4.4e10	9.9e10	1.6e11 [6]	2.2e11 [7]
Max particles lost at TCPs	1.3e10	1.6e10	2.8e8	2.8e8	1.2e8	6.6e7
Observed loss [particles]	-	-	1.2e8 (during several s)	3.9e-3 Gy/s RS07	-	-
BLM Th. RS06 (10 ms) @3TeV	1.9e10 p	1.9e10 p		0.1274 Gy/s	9.5e10/20 8=4.6e8	-
BLM Th. RS07 (82 ms) @3TeV	1.6e11 p	1.6e11 p		3.5e-3 Gy/s	7.6e11/20 8 = 3.7e9	-

[6] J.M. Jowett - **The 2018 Heavy-ion Run of the LHC** IPAC2019
[7] R.Tomas - **HL-LHC desiderata during Run 3** Montreux2020
[8] **LHC Design Report**