LHC Injection Protection

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Outline

→ Introduction

→ LHC injection

  ↳ Recap of injection losses (Evian '19)

  ↳ TCT losses rise in 2016

  ↳ TCLIA losses with ALICE positive polarity

→ SPS extraction and Transfer lines

  ↳ TL steering and operation

  ↳ TCDI settings management and interlock

→ What will change after LS2?

→ Conclusions and summary

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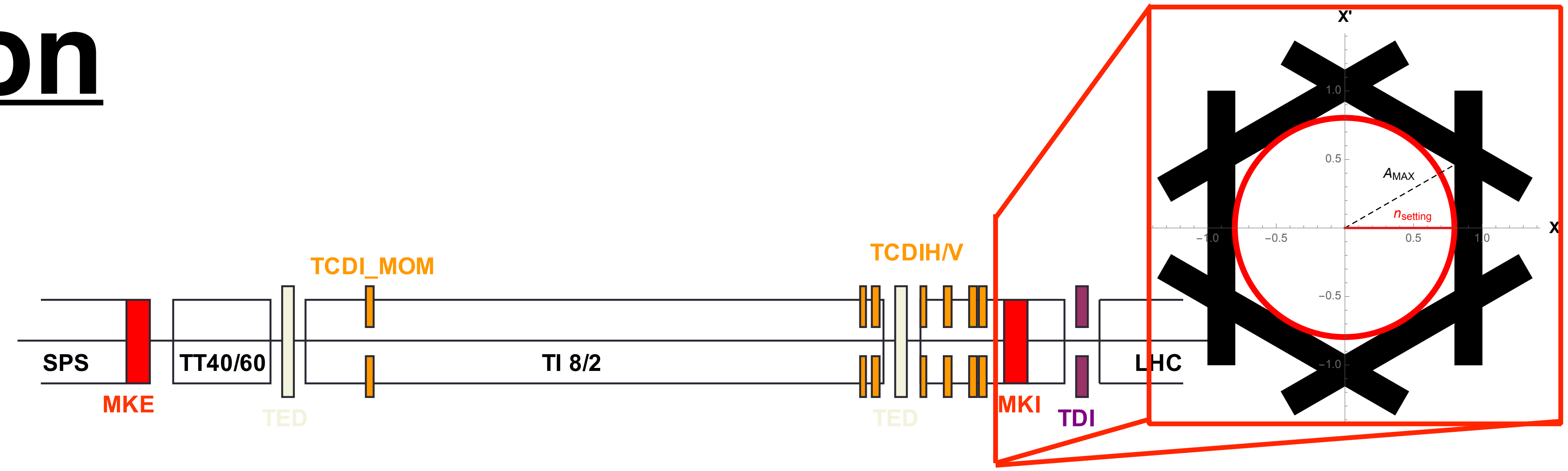
Introduction



→ **SPS-to-LHC transfer lines equipped with 3 main protection systems:**

↳ FEI (Fast Extraction Interlock) to detect extraction elements current difference wrt to defined settings and thresholds

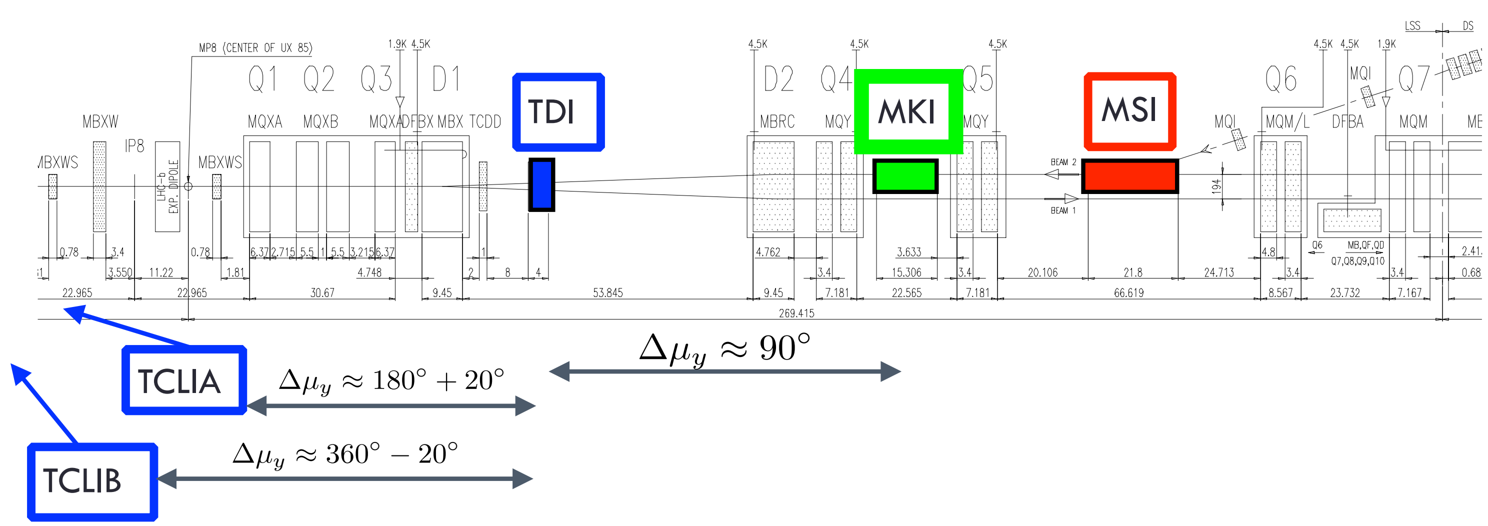
↳ FMCM (Fast Magnet Current Change Monitors) to detect fast variations of ΔI/I of main elements in TI2/8 (including septa)

↳ TCDI (Transfer line collimators) to cover any other failures (or ultra-fast) that could produce oscillations with amplitude larger than 6.4 sigma and being injected into the LHC

→ **LHC injection protection system is equipped with 3 passive protection elements (ultra fast failures to protect against):**

↳ TDI (Main injection dump)

↳ TCLIA and TCLIB (auxiliary devices) to protect against +/- 20 deg phase error between MKI and TDI



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Injection losses

→ Why we are that sensitive to trajectory drifts and jitters (**transverse losses, Q8, Q7, BOT**)?

↳ The TL collimators, TCDI, in order to protect the LHC aperture are sitting at 5 sigma from the defined trajectory

↳ Losses at some TCDIs are seen (showers) at LHC BLMs in IP2 and IP8

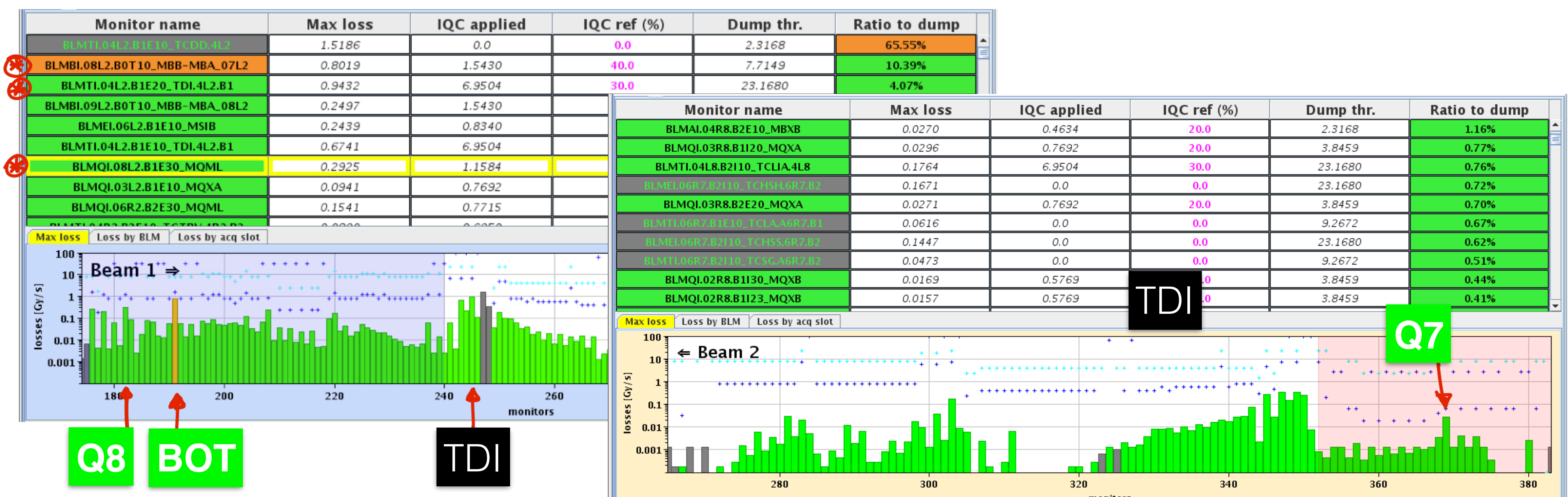
- Some locations are much more sensitive to this issue => **for example in TI2, which is the most sensitive**, the TCDIH.29205 is very close to the Q8 BLM and to the interconnection between MBB-MBA (BOT)

↳ **Steering clearly helps!**

→ Another source of losses at injection is the presence of satellites at both extremities of the injected beam (**longitudinal losses TDI**)

↳ This manifests itself still with injection losses (mainly at the TDI!)

↳ **Steering is useless in this case!**

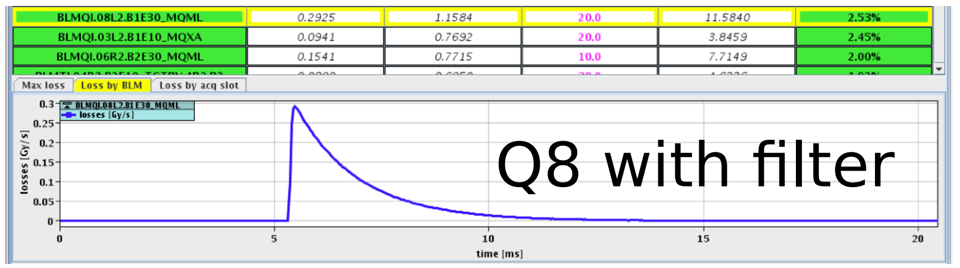


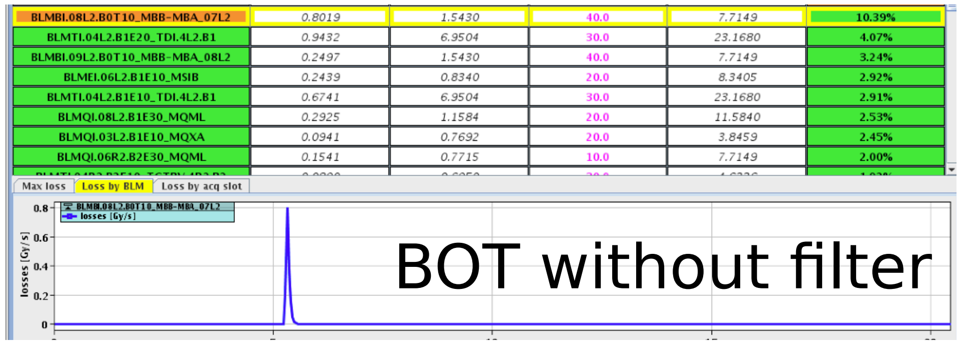
Monitor name	Max loss	IQC applied	IQC ref (%)	Dump thr.	Ratio to dump
BLMTI.04L2.B1E10_TCDD.4L2	1.5186	0.0	0.0	2.3168	65.55%
BLMBI.08L2.B0T10_MBB-MBA_07L2	0.8019	1.5430	40.0	7.7149	10.39%
BLMTI.04L2.B1E20_TDI.4L2.B1	0.9432	6.9504	30.0	23.1680	4.07%
BLMBI.09L2.B0T10_MBB-MBA_08L2	0.2497	1.5430			
BLMEI.06L2.B1E10_MSIB	0.2439	0.8340			
BLMTI.04L2.B1E10_TDI.4L2.B1	0.6741	6.9504			
BLMQI.08L2.B1E30_MQML	0.2925	1.1584			
BLMQI.03L2.B1E10_MQXA	0.0941	0.7692			
BLMQI.06R2.B2E30_MQML	0.1541	0.7715			

Monitor name	Max loss	IQC applied	IQC ref (%)	Dump thr.	Ratio to dump
BLMAI.04R8.B2E10_MBXB	0.0270	0.4634	20.0	2.3168	1.16%
BLMQI.03R8.B1I20_MQXA	0.0296	0.7692	20.0	3.8459	0.77%
BLMTI.04L8.B2I10_TCLIA.4L8	0.1764	6.9504	30.0	23.1680	0.76%
BLMEI.06R7.B2I10_TCHSH.6R7.B2	0.1671	0.0	0.0	23.1680	0.72%
BLMQI.03R8.B2E20_MQXA	0.0271	0.7692	20.0	3.8459	0.70%
BLMTI.06R7.B1E10_TCLA.A6R7.B1	0.0616	0.0	0.0	9.2672	0.67%
BLMEI.06R7.B2I10_TCHSS.6R7.B2	0.1447	0.0	0.0	23.1680	0.62%
BLMTI.06R7.B2I10_TCSG.A6R7.B2	0.0473	0.0	0.0	9.2672	0.51%
BLMQI.02R8.B1I30_MQXB	0.0169	0.5769	[illegible]	3.8459	0.44%
BLMQI.02R8.B1I23_MQXB	0.0157	0.5769	[illegible]	3.8459	0.41%

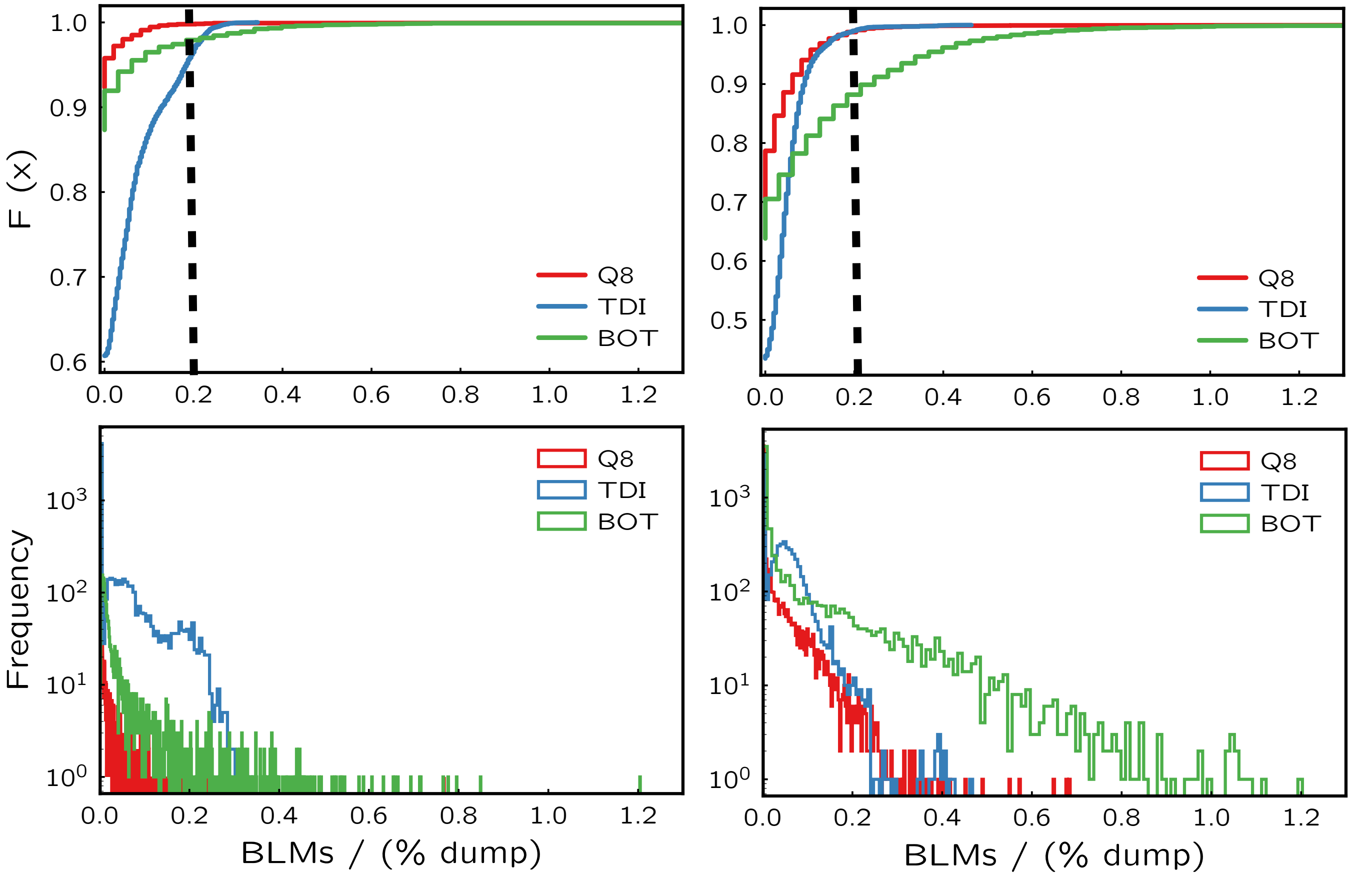
Injection losses in 2017/18

- → Losses at injection of B1 are slightly different between 2017 and 2018
  - ↳ **In 2017, about 97% of injections recorded losses below 20% of dump threshold** at the "injection quality" BLMs - losses dominated by the TDI (longitudinal) => better in 2018!
  - ↳ **In 2018, we had 87% of injections below 20% dump threshold**, dominated by the interconnection BLM (transverse)
    - ‣ Comparing the readings at the Q8, in 2017 basically all (>99%) events were below 10% of dump threshold, instead in 2018 this was for 95% of the injections

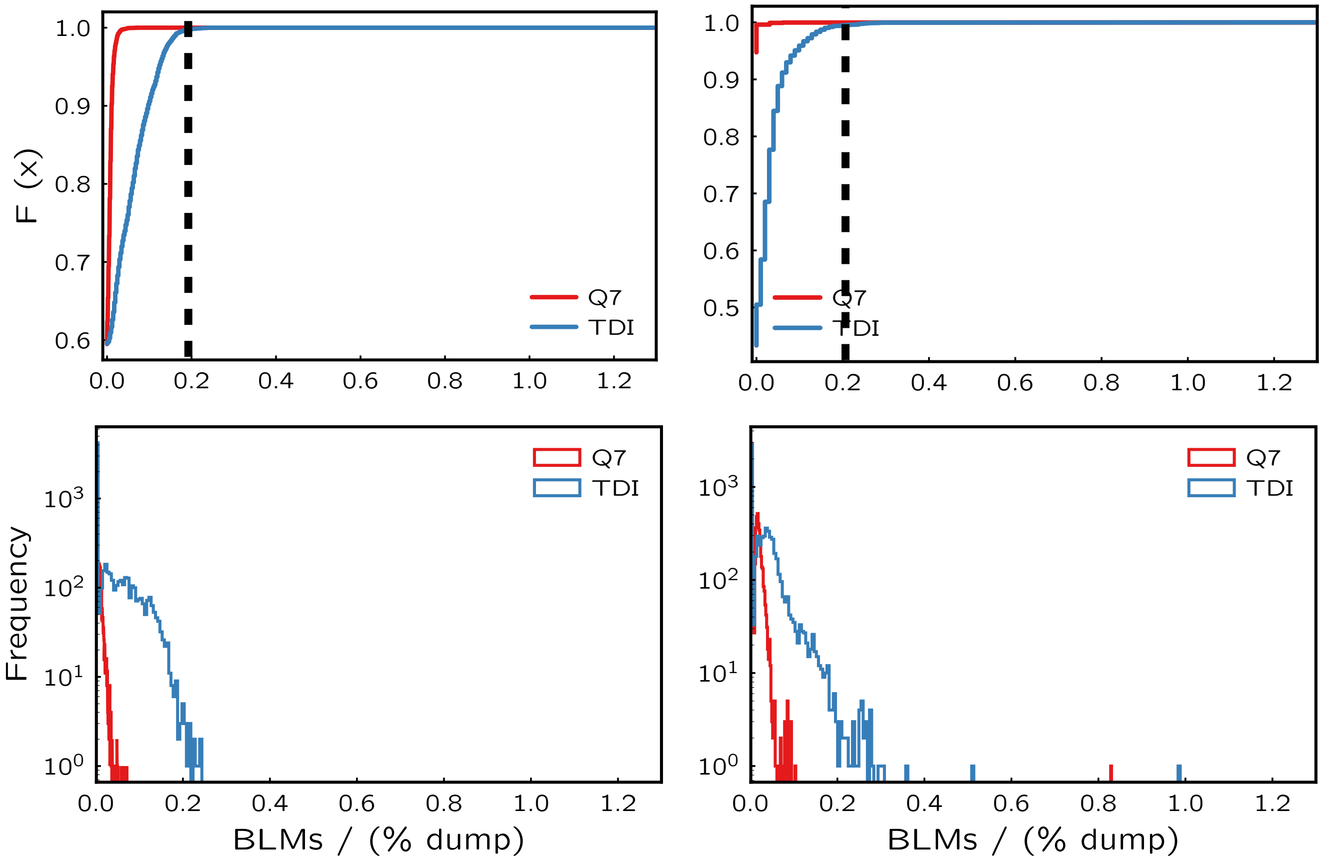




B1 2017 - 2018

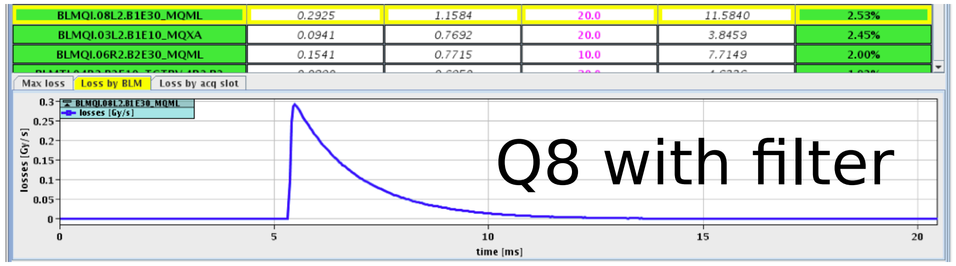


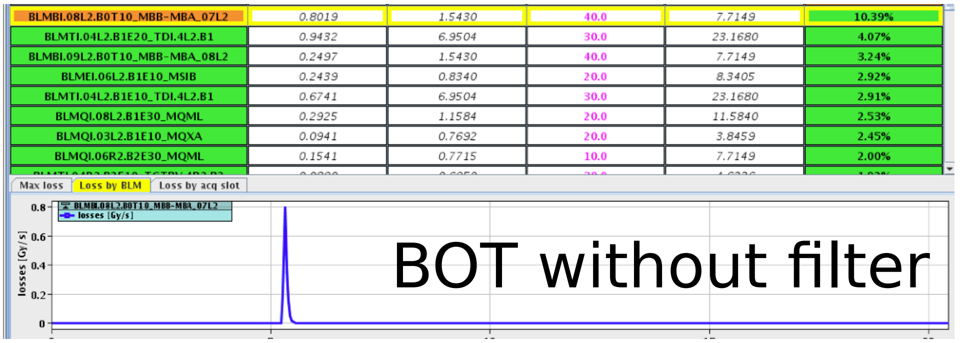
B2 2017 - 2018



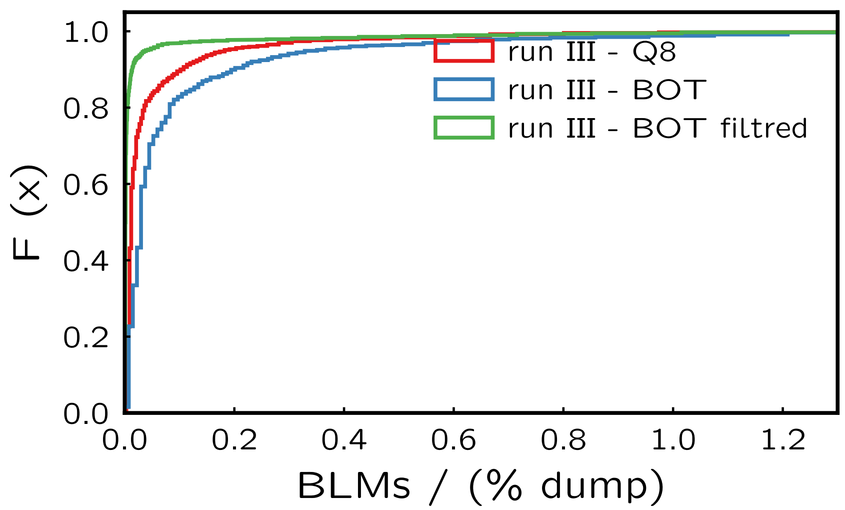
Expected losses at injection run III

- Using an empirical model built with 2018 loss data, we can try to extrapolate the expected losses at injection during run III
  - **Re-introduce filter on BOT BLM as in Q8** => factor 20 reduction - **this has been discussed and it will happen**
  - Then we can look at both 2017-like year or 2018-like, i.e. in terms of stability
  - Assumptions:
    - BCMS: I_b = 1.4x10^{11} p/b, same emittance as 2018, 240 bunches
    - Standard: I_b = 1.8x10^{11} p/b, 20% larger emittance than 2018, 288 bunches

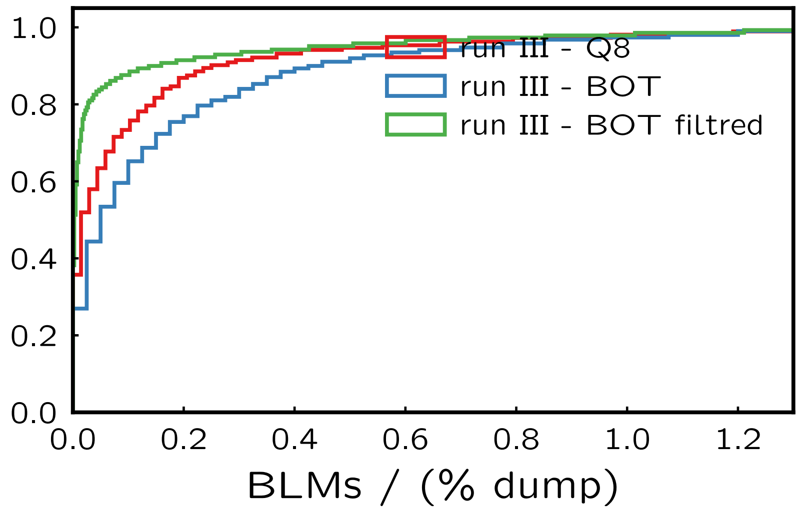




BCMS - based on 2017



BCMS - based on 2018



Predictions for run III

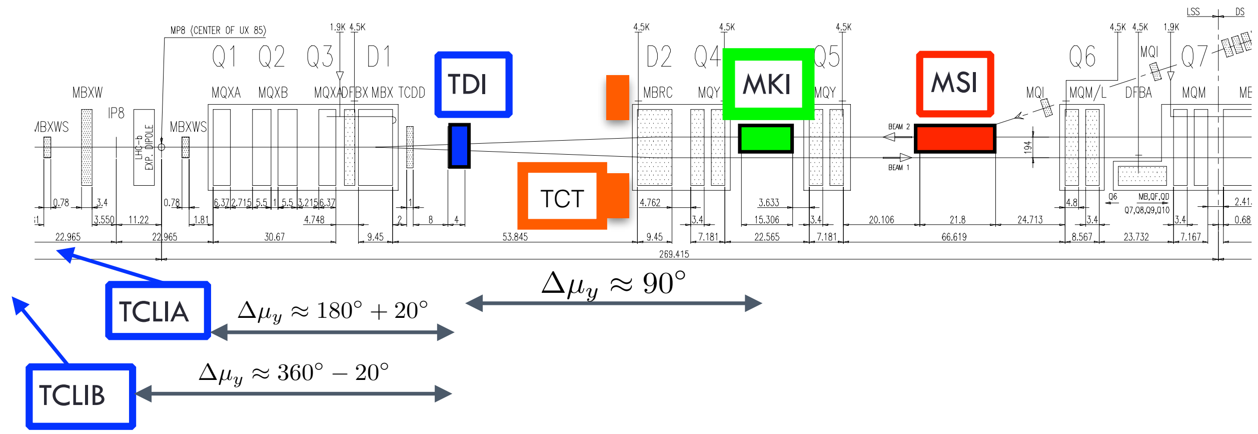
	Q8 < 20%	BOT < 20%
2017	> 99%	98%
2018	> 99%	87%
Run III (BCMS)	**86-95%**	**92-98% (WF)**
Run III (Std)	**65-70%**	**75-85% (WF)**

Please note that these predictions do NOT consider longer TCDIs nor changes in shielding!

TCT losses rise in 2016

→ **TCT sits between the MKI and the TDI**

↳ It had initial settings of +/- 25 mm (double sided device)

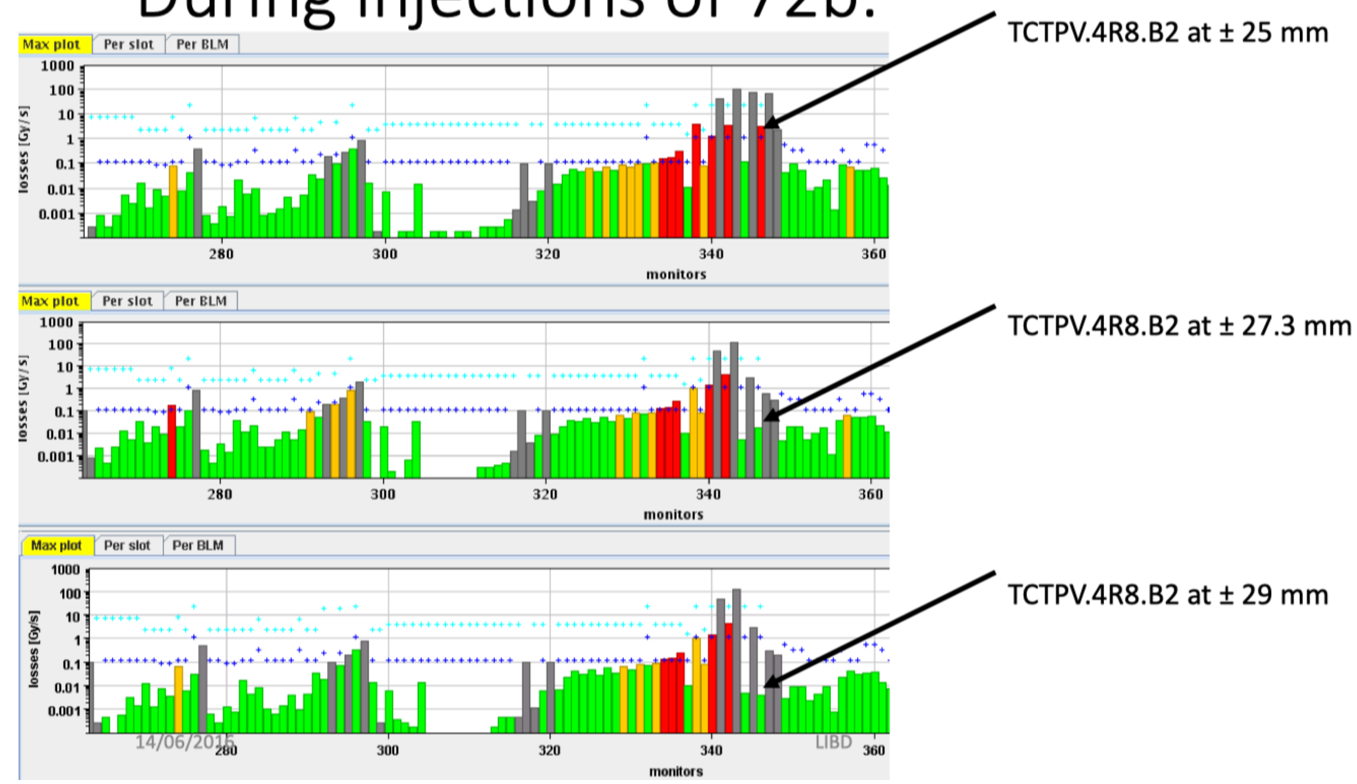


→ Very high losses recorded during injection (**up to 80% DT**) on B2

↳ This was seen as losses undoubtedly upstream of the TDI

↳ Losses thresholds increased up to the electronic limits of the short RS before stopping (to better reflect the time constant of the filter)

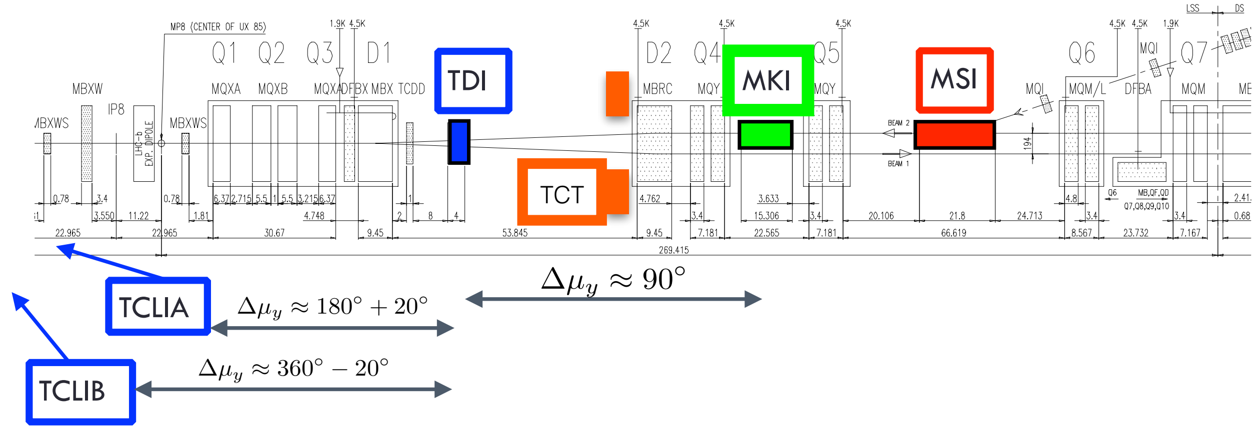
During injections of 72b:



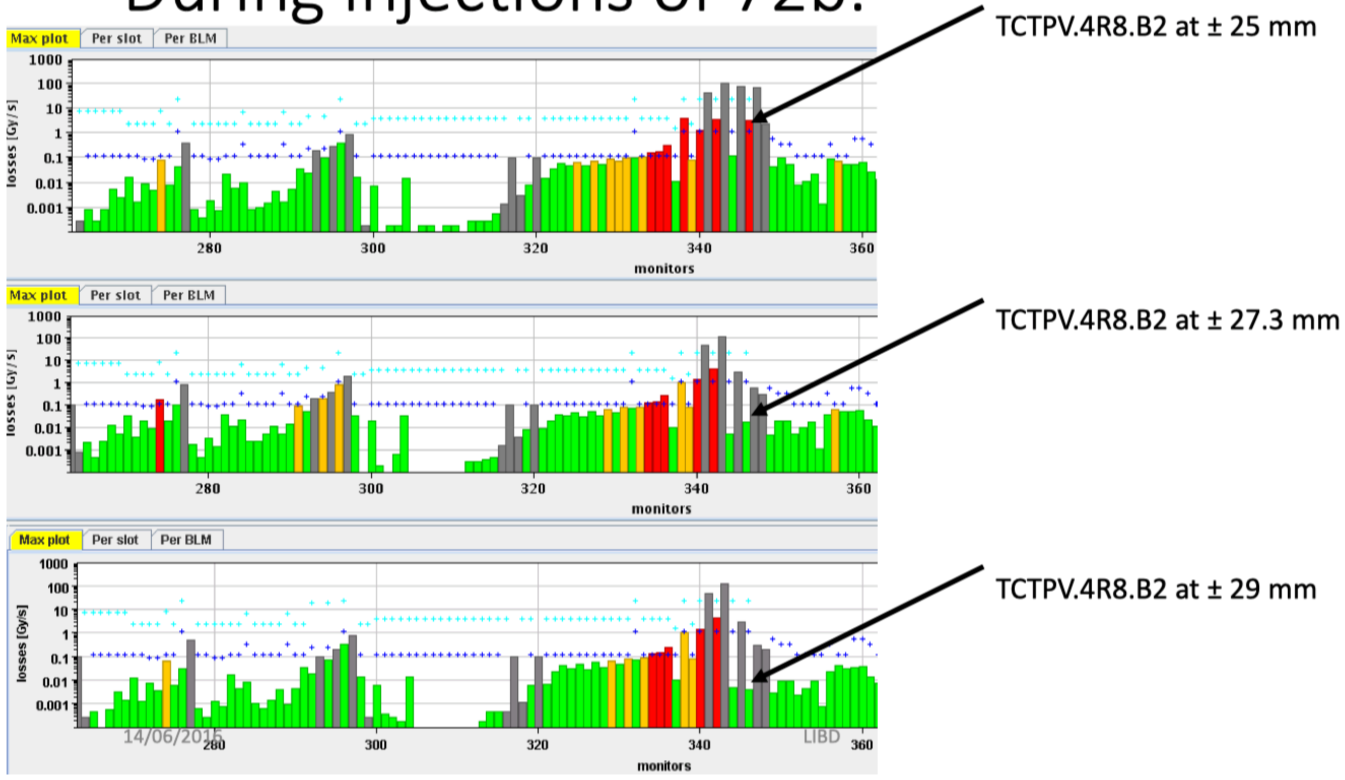
TCT losses rise in 2016

→ **B2 was much more sensitive** due to the different vertical trajectory of the beam at the TCT location in case of no kick from MKI

→ **Settings increased to +/- 29 mm** to have the TCT at a safe distance from dumped injected beam accounting also for possible errors



During injections of 72b:

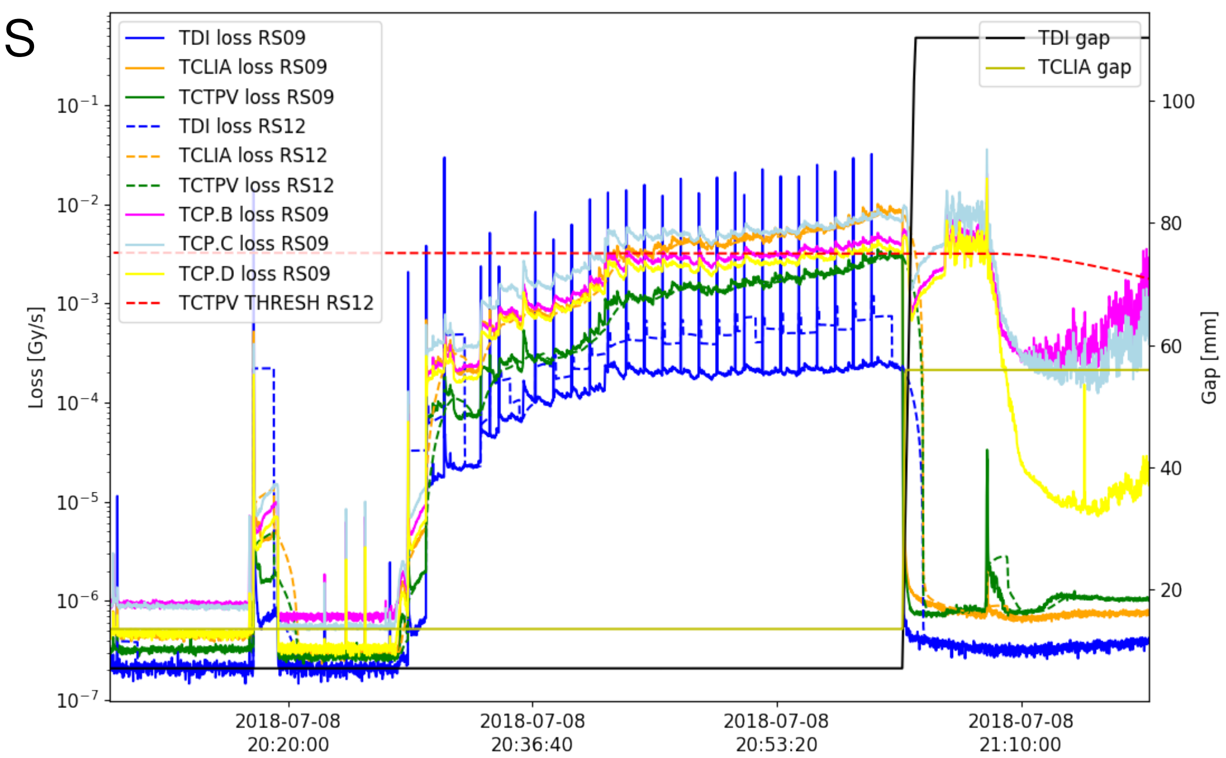


B2		Beam offset – MKI 0%	Beam sigma	Impact
Old settings TCTPV	± 25 mm	+ 24.9 mm	0.6 mm	grazing
New settings TCTPV	± 29 mm	+ 24.9 mm	0.6 mm	6.83 sigma

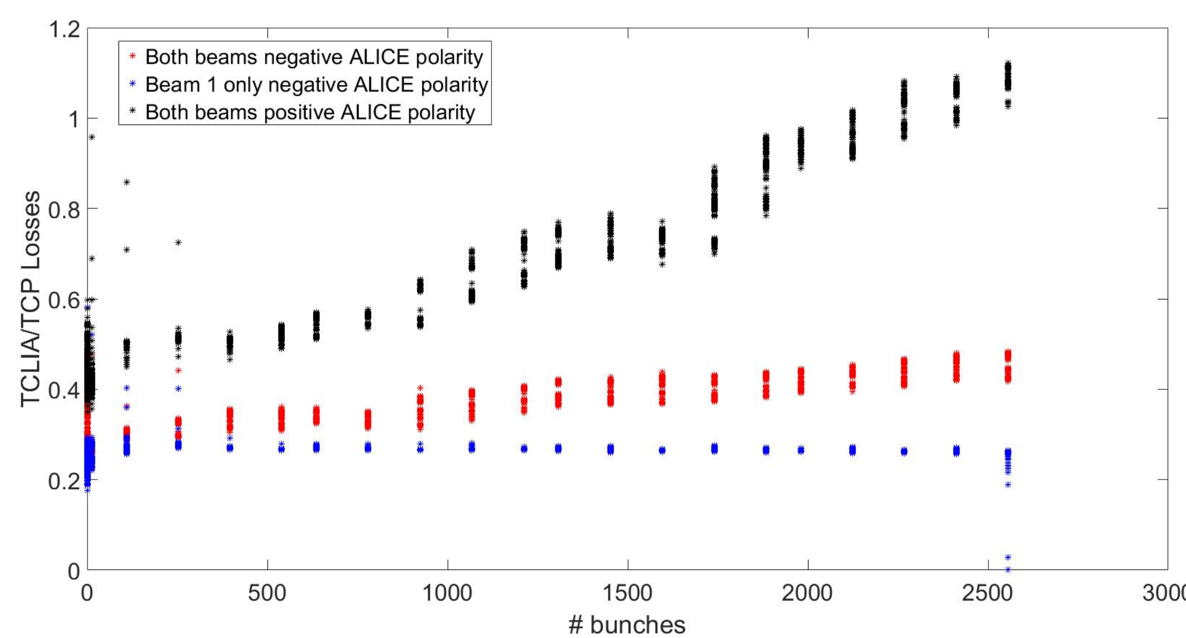
B1		Beam offset – MKI 0%	Beam sigma	Impact
Old settings TCTPV	± 25 mm	+ 20.8 mm	0.6 mm	7 sigma
New settings TCTPV	± 29 mm	+ 20.8 mm	0.6 mm	13.6 sigma

TCLIA losses with ALICE positive polarity

- The TCLIA sees in the same tank both beams (E-could?)
- After TS1 in 2018, ALICE polarity was reversed (positive)
- Dump during B1 injection for losses at the TCT of B2 (cross talk) => Found missing compensation bump for ALICE positive polarity



- Beam observations:
  - Higher losses at the TCLIA - possible hierarchy breakage
  - Higher than normal losses at the TCLIA only seen with 2 beam in the machine
  - Correlation visible with 8poles current
  - No signs of beam beam seen according to experts…still to be investigated further the source



Lessons learned

- Injection losses showed similar behaviour in both 2017 and 2018
  - Interconnection BLM was the most sensitive one and the one showing the most number of events with injection losses above 20% DT
  - **Agreed to place filter (/20) on interconnection BLM for Run III** => in these conditions, and w/o accounting for longer TCDIL, losses are expected to be in the same ballpark as 2018 (this is only an extrapolation!)
- Two peculiar cases of losses in the injection region reported
  - **In both cases, time was needed for investigation…not easy cases!**
  - Avoid to rush to continue with physics, while trying to minimise the time needed for investigation

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TL steering and operation

- → Strategy for steering proposed in Evian this year:
  - ↳ **Set up new reference with multi-bunch ASAP** during commissioning and use it as golden trajectory for steering
    - **Periodic SVD steering cleaning** (many correctors correction) after TS (or when time allocated) to counteract drifts of corrections
  - ↳ **2x12 bunches in every filling schemes to encourage steering before filling**
    - Possible optimisation is to foresee similar filling scheme with only 1x12 bunches to switch to, in case steering not needed => implementation to be assessed
- → In addition, as transactional behaviour of LSA is on the way to be fixed thanks to the new FGCs for both TI2 and TI8, steering with trains, if in the FEI tolerances, could be allowed <u>**(only if TB fixed**</u>):
  - ↳ It needs awareness of the EIC or operator performing the steering
  - ↳ This should only be done <u>**in case it is really needed - it is strongly suggested to perform steering at the beginning with the 2x12 bunches**</u>
  - ↳ <u>**Interlock on injection oscillations amplitude will (and must) stay**</u>
    - In case injection oscillations go too high, restart with 12 bunches (re-start of fill)
    - This is essential in order to guarantee that all tolerances considered for apertures are still respected
  - ↳ This opens the possibility to investigate for **automatic algorithms to keep TL trajectory close to reference** => <u>extensive tests needed before deployment</u>

TCDI settings management and interlocks

- The management of the TCDI settings and operation were thought for single TL optics
  - In both Run I and II change of optics has happened a few times already
    - Both for actual operation and MDs
  - This will be the case also for Run III as ions will use Q26 in the SPS
- Today, all (expect for energy thresholds) settings and thresholds stored in single injection BP in the LHC
  - Change of settings based on manual trim of these values, same for rollback
    - Prone to human error
- In order to guarantee safer operation and smoother optics change, we propose to:
  - **Create 2 BP for injection for the 2 possible optics: Q20 and Q26**
  - **Keep energy thresholds as unique for all optics but more relaxed such to be compatible with all settings** (it is anyway a redundancy)
  - **Implement SW check of TCDI settings based on optics in TL** (LHC SIS?)
    - To be seen if possible and how to do that, otherwise possibility to implement that at the SPS level

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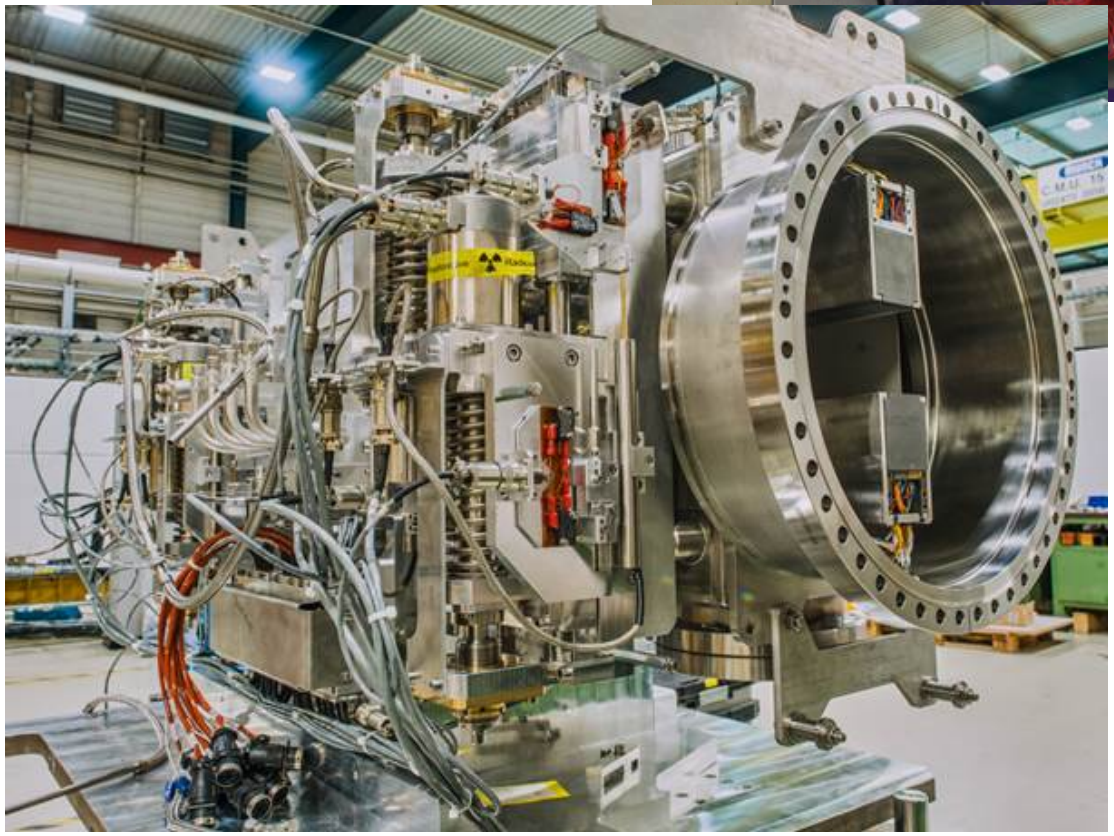
What will change after LS2?

- **New transfer line collimators to cope with the increased beam brightness towards HL-LHC**
  - TCDI from 1.2 m to 2.1 m graphite (and/or 3DCC)
  - Designed to withstand 320 bunches of 2.0e11 p/b in 1.3 um emittance
  - Re-matched optics in TI2 and TI8 to satisfy beam size requirements at $\beta_x \times \beta_y > 3600m^2$
  - <u>Same commissioning time expected</u>

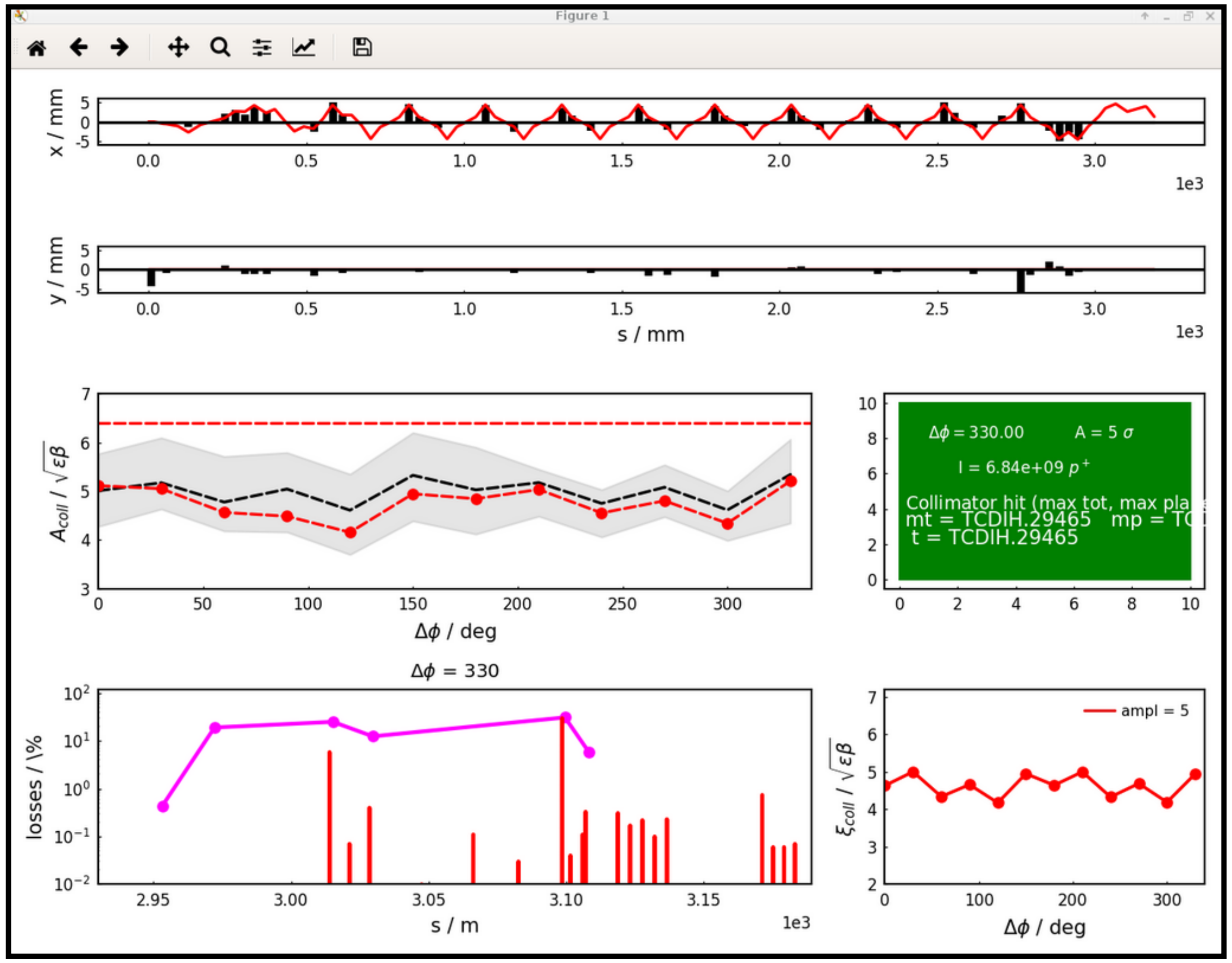
- **New LHC injection protection/dump - TDIS (segmented)**
  - From 4.185 m single-block device to 3-block device of 1.6 m length each - individually movable
    - Design to withstand all LIU/HL-LHC baseline beams up to 2.0e11 p/b in 1.37 um emittance
    - <u>May lead to faster commissioning as no angular alignment needed</u>

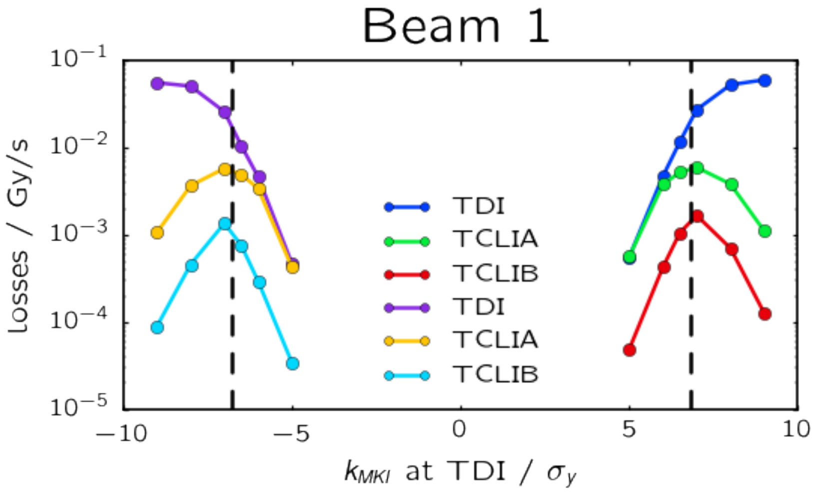


Commissioning: from run II to run III

- Commissioning of transfer lines and LHC injections been improved over the run II

- Main changes in the alignment and validation of TCDI/TDI:
  - TCDI validation procedure completely automatised and simulations available for online benchmark
    - Script/application maintained and upgraded over the years, e.g. tentative to use it for validation with ions…this will become an operational GUI
  - TCDI automatic alignment using both jaws separately
    - First version of script ready, tested (also in HiRadMat) and used for optics change with ions last year
    - It will become a GUI soon
  - Plan to investigate and implement automatic injection protection system validation, MKI waveform scan, auto-steering, etc.





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Conclusions and summary

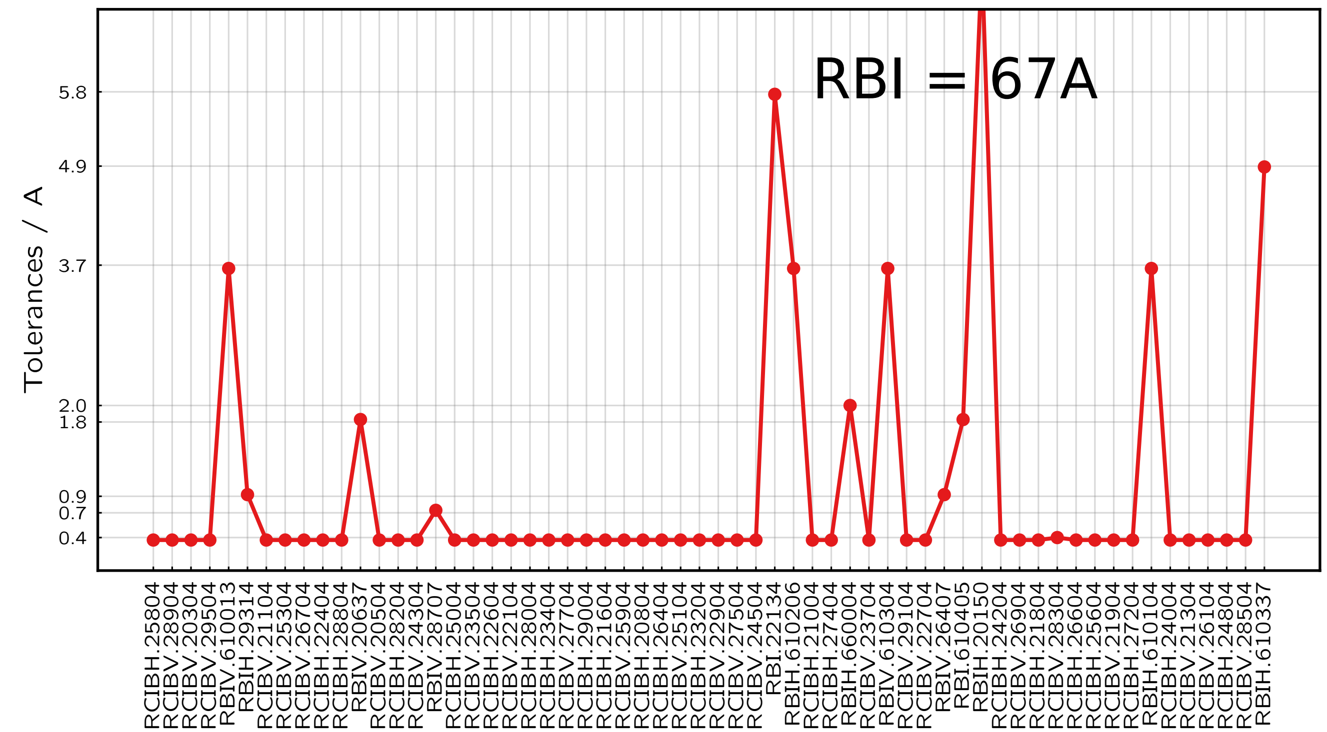
- Injection losses analysis is a powerful tool to understand beam behaviour and to ensure machine protection and availability
  - In already a few cases, it was seen how important is to carefully evaluate different scenarios
  - Time needed to properly assess the issues and propose solution => tradeoff between time to come back in physics and ensure safe machine operation
- Steering of TL is encouraged even every fill, if necessary => proposed to have 2x12 bunches in every filling scheme
  - Evaluate dynamic switch between FS with and w/o 2x12 bunches
  - If necessary, steering staying the FEI limits could also be done w/o the need to re-inject a 12 bunches (only if TB fixed)
  - Maintain present interlock on injection oscillations
  - Proposed to have 2 BP for different TL/SPS optics + SW check of settings and optics in SIS
- No significant changes in commissioning expected with new devices, it might only be faster thanks to automatisation

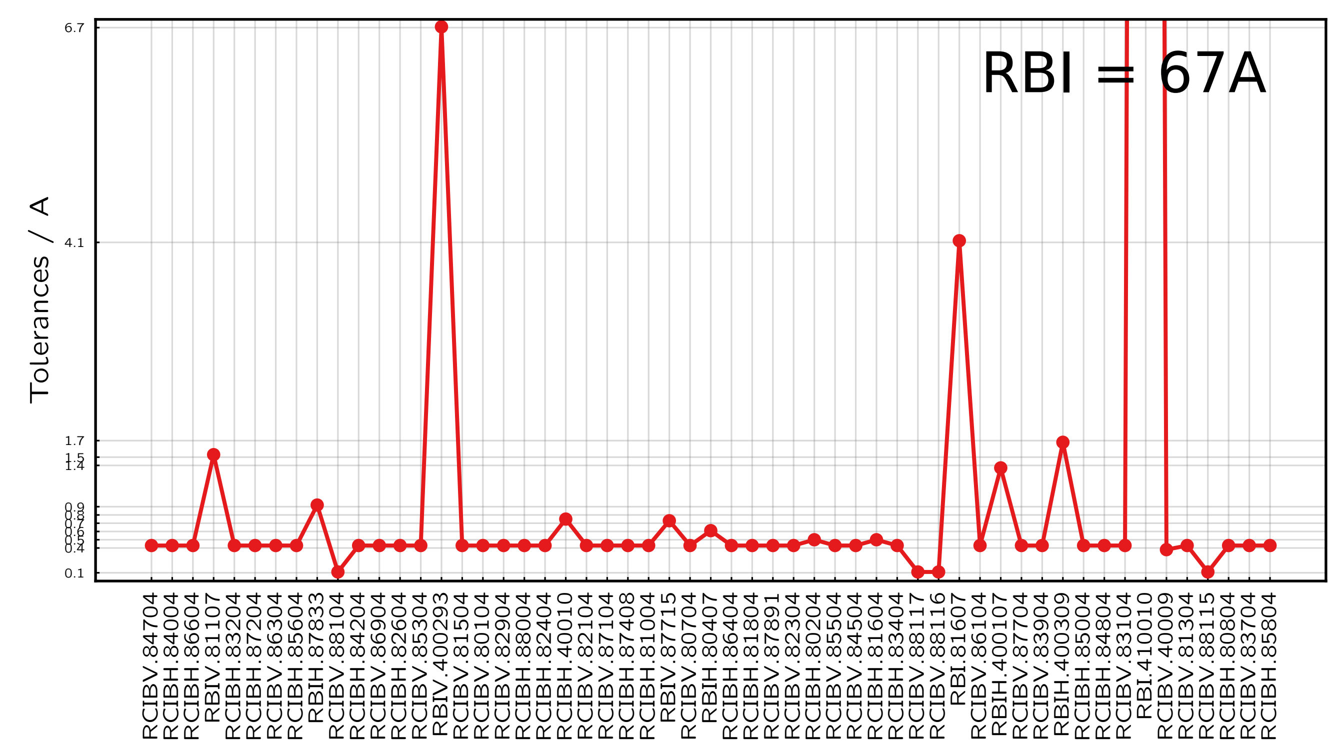
Thanks!

Backup

TL steering and operation

→ The maximum allowed kick, in either plan is about 10 urad





TCLIA losses with ALICE positive polarity

→ Test with different 8pole strengths done:

↳ With nominal current, losses at the TCLIA and constant halo re-population => this might have contributed to losses that brought to dump with positive ALICE polarity together with non-closure of bump

↳ Checked with half 8pole current…what's the conclusion here??

→ **Recommendations**:

↳ For positive ALICE polarity, CO needs to be well corrected and compensation bump activated

↳ Loss maps needed to ensure correct cleaning hierarchy