LHC injection system along run II

F. M. Velotti, M. Barnes, W. Bartmann, C. Bracco, B. Goddard,
V. Kain, A. Lechner, G. Trad, V. Vlachodimitropoulos, J. Wenninger

…and thanks a lot to T.Argyropoulos, M. Pojer,
B. Salvachua and the whole SPS and LHC shift crews

Outline

- LHC injection system availability 2018
- Evolution of injection system over run II
  - MKI run II evolution
  - TDI run II evolution
- SPS-to-LHC transfer line: steering and losses
  - Steering frequency in 2017/18
  - Steering analysis
  - Injection losses in 2017/18
  - Transverse losses - TI2 and TI8
  - Expected injection losses for run III
- Commissioning: from run II to run III
- Limitations from injection devices post-LS2
  - Can we reach 1.8e11 ppb in 1.8 um?
- Conclusions

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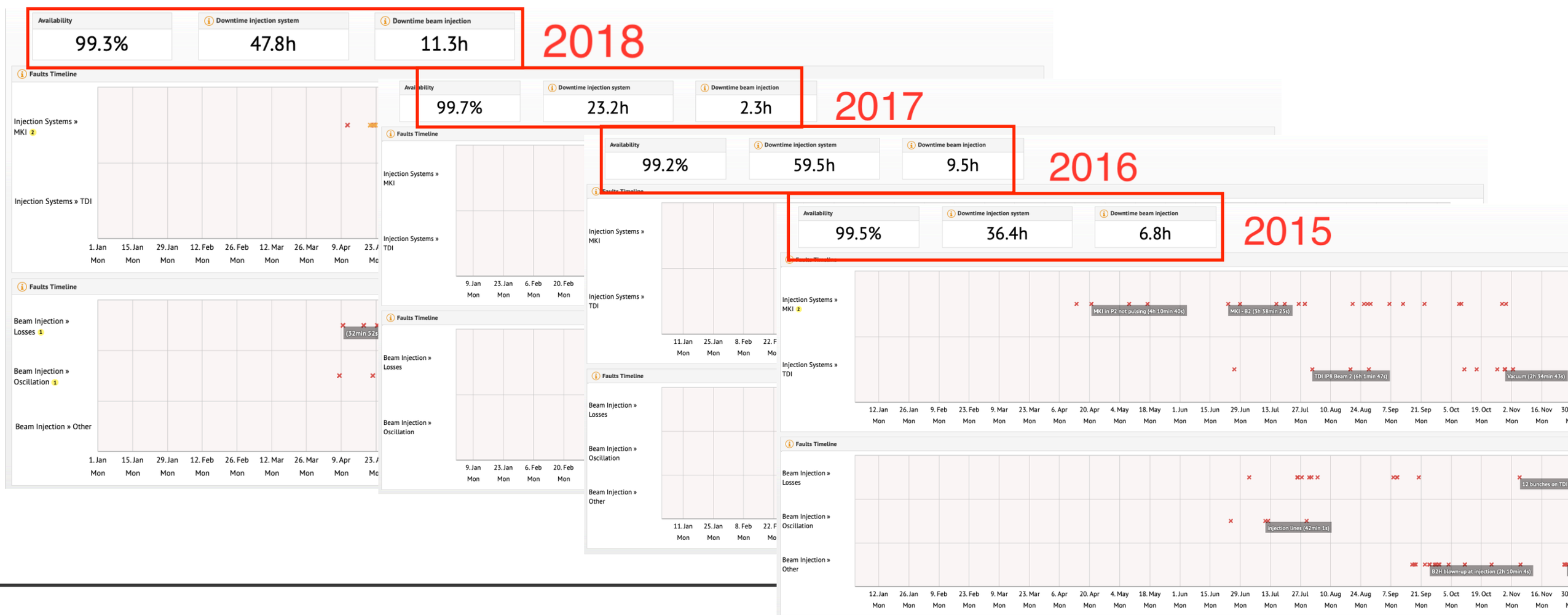
LHC injection system availability 2018

- 99.3% availability (48h on average) of the LHC injection system in 2018
  - Slightly worse than 2017, which was the best year in terms of availability for run II



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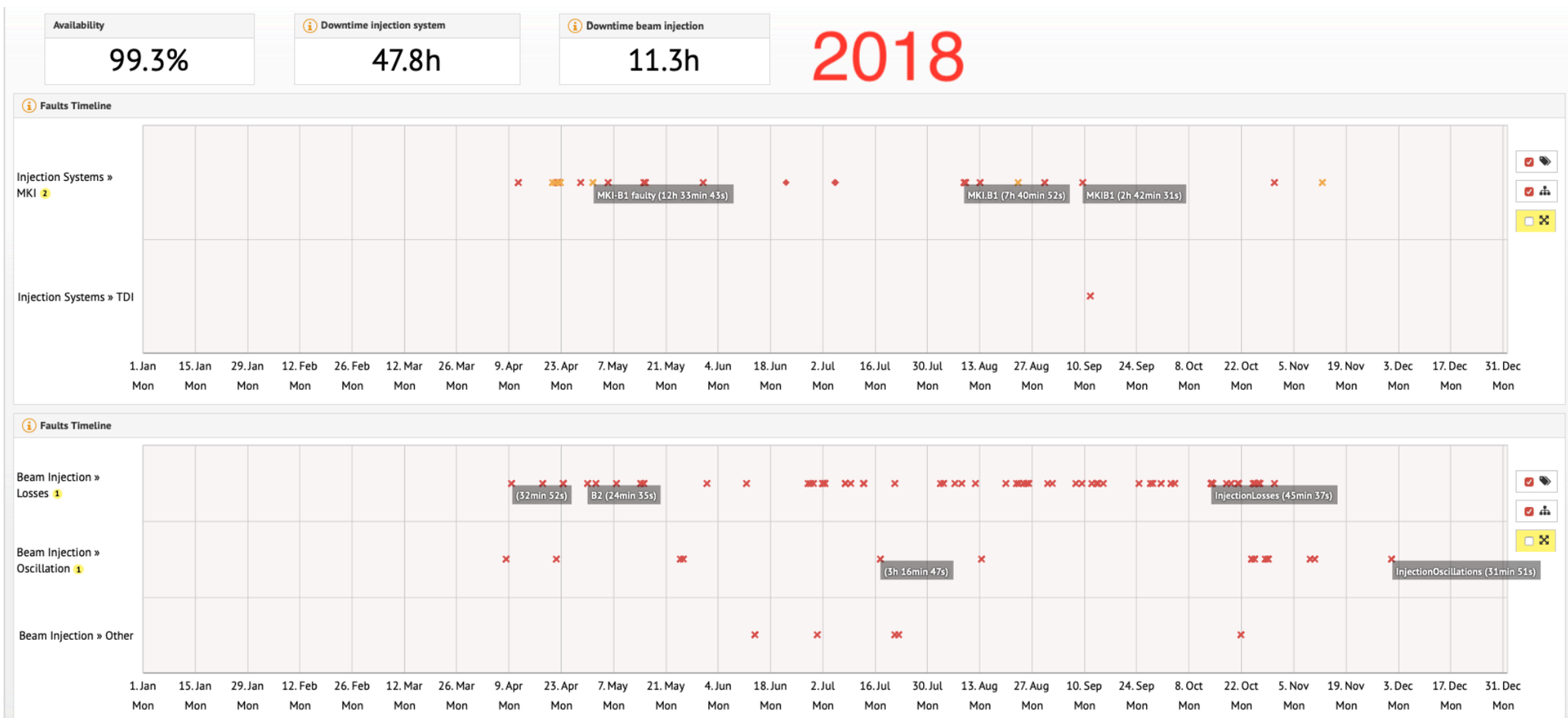
  - Slightly worse than 2017, which was the best year in terms of availability for run II

- Main faults where related to the MKI
  - Faulty delay board caused about 7h downtime
    - Problem understood and countermeasures being put in place during LS2
  - Electrical breakdown in MKI2B and consequent suspicious vacuum activity
    - The MKI2B will be replaced during LS2 with the so-called “MKI-cool” (see later in this talk)



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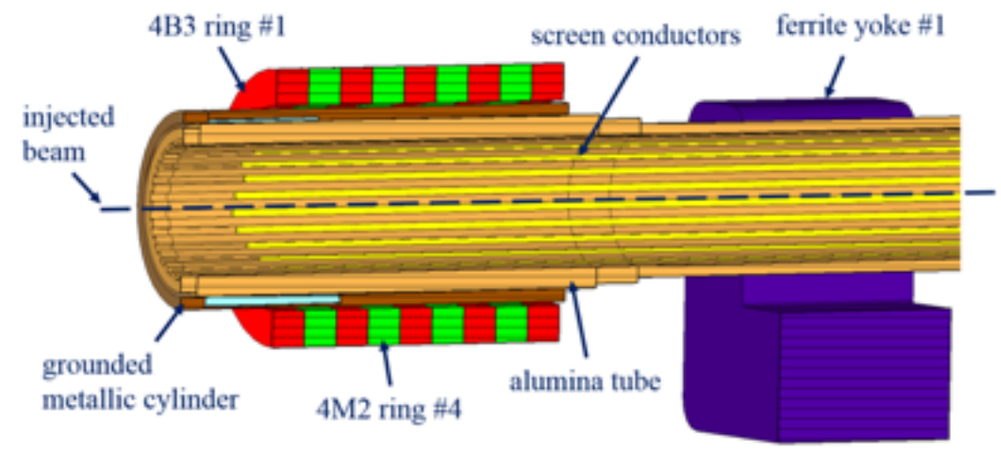
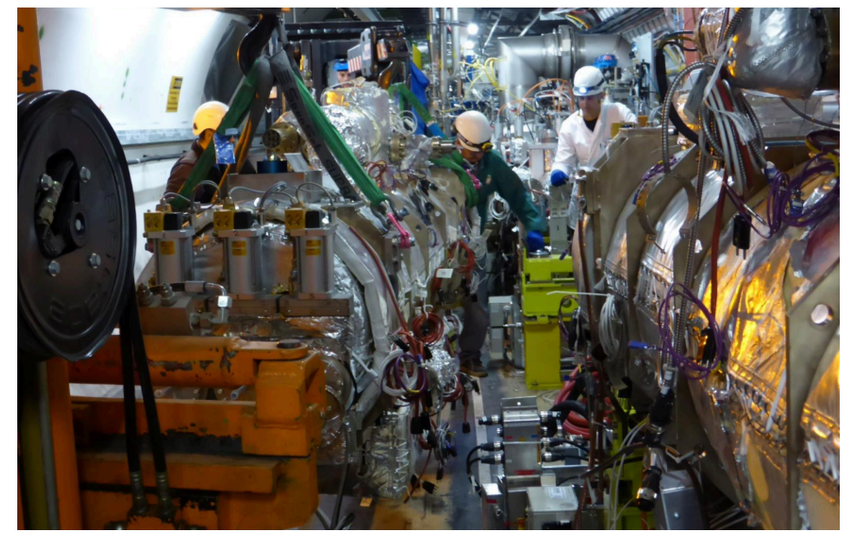
MKI run II evolution

- During LS1, substantial upgrade of the MKIs performed:
  - Upgrade of MKI beam screens adding screen conductors to reduce beam induced heating => this **removed max number of bunches limits from run I (post-LS1 design)**
  - Upgrade of the vacuum systems on the interconnections between Q5 and MKIs (EYETS16/17)
    - Interconnects NEG coated and NEG cartridge integrated => **During the rest of run II, no issues seen with MKI vacuum interlocks**

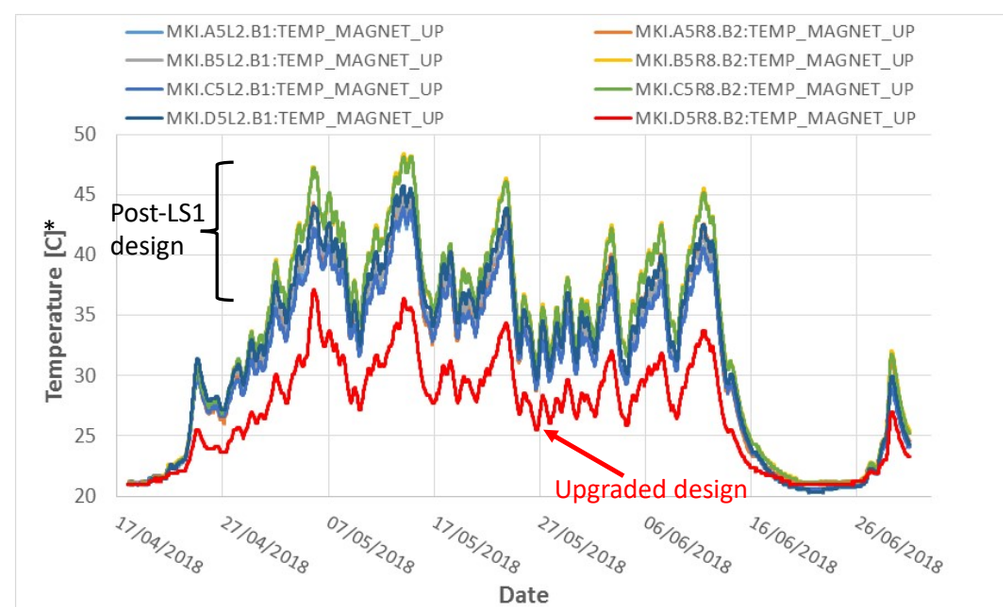




- MKI2D exchanged during 2016-TS3
  - Following the deteriorating situation of the high-impedance contact within the MKI2D magnet, it was decided to replace the magnet (same design as post-LS1 version)

- **MKI8D replaced during 17/18 YETS with upgraded version**
  - Cr_2O_3 coating on the inner part of the alumina tube
    - Rapid reduction of dynamic vacuum during scrubbing
    - Conditioned dynamic vacuum a factor 3 better than previous MKI8D
  - Modified beam screen design (part of HL-LHC baseline design)
    - Aim to reduce beam induced heating in the ferrite yoke and re-direct it to easier-to-cool areas (rings)
  - **Significant improvements observed during 2018 run**

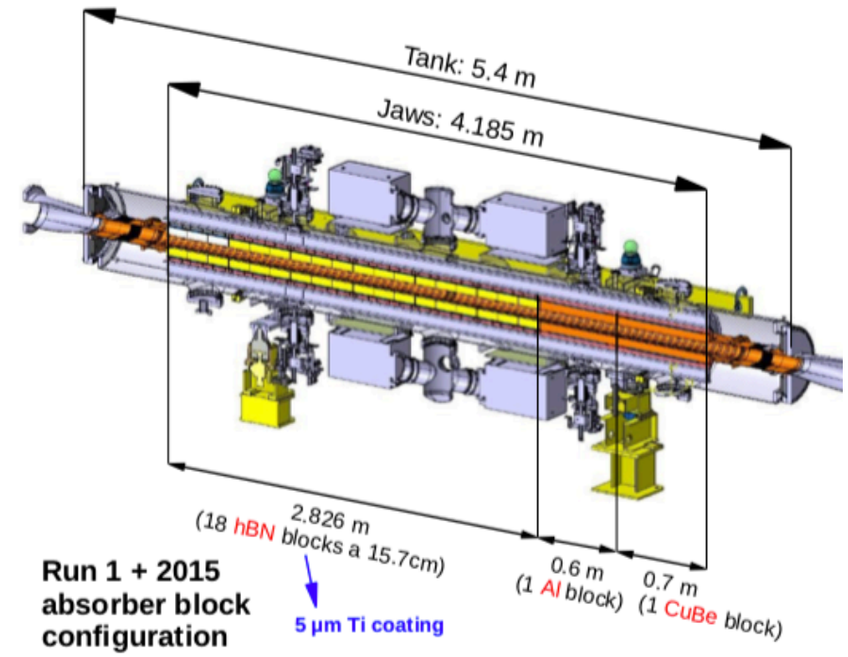
- **MKI post-LS1 design defines the present limitations!**



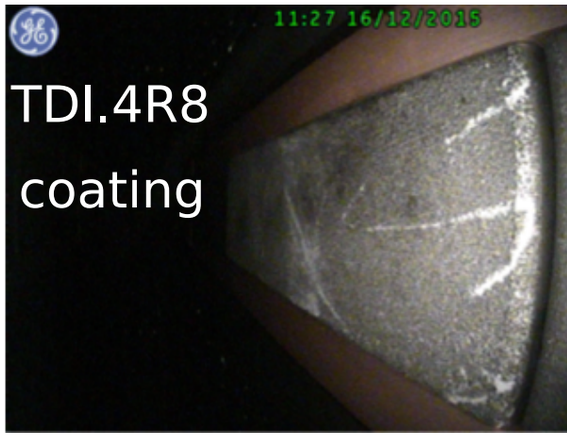
TDI run II evolution [1, 2]

- **The TDI suffered several issues during run I and posed operational limitations**
  - Starting from LS1, two major stages of upgrades took place: during LS1 itself and during YETS 15/16

- **Modifications during LS1:**
  - NEG cartridges, Ti coating on Aluminium, reinforced beam screen, temperature probes
  - At restart in 2015, **the TDI.4R8 was the one suffered the most:**
    - Large vacuum spikes during injection and pressure build up (=> dumps)
    - Beam-based measurements (impedance team) shown significant discrepancies between the TDI in IP2 and IP8 => **Ti coating in TDI.4R8 found severely degraded**
  - During 2015, the spare hBN blocks of the TDIs were treated in vacuum at high temperatures => 20% of the blocks cracked after 800° C and 50% after 1000° C
    - **Limits put on operation to prevent failure of the TDIs (details in LMC 215/217)**



Manufacturer specs: Tmax=1150° C
(in inert atmosphere)



Beam type Run 2	TDI limitation 2015 hBN
Standard 25 nsec	144 bunches
BCMS 25 nsec	96 bunches
50 nsec	108 bunches

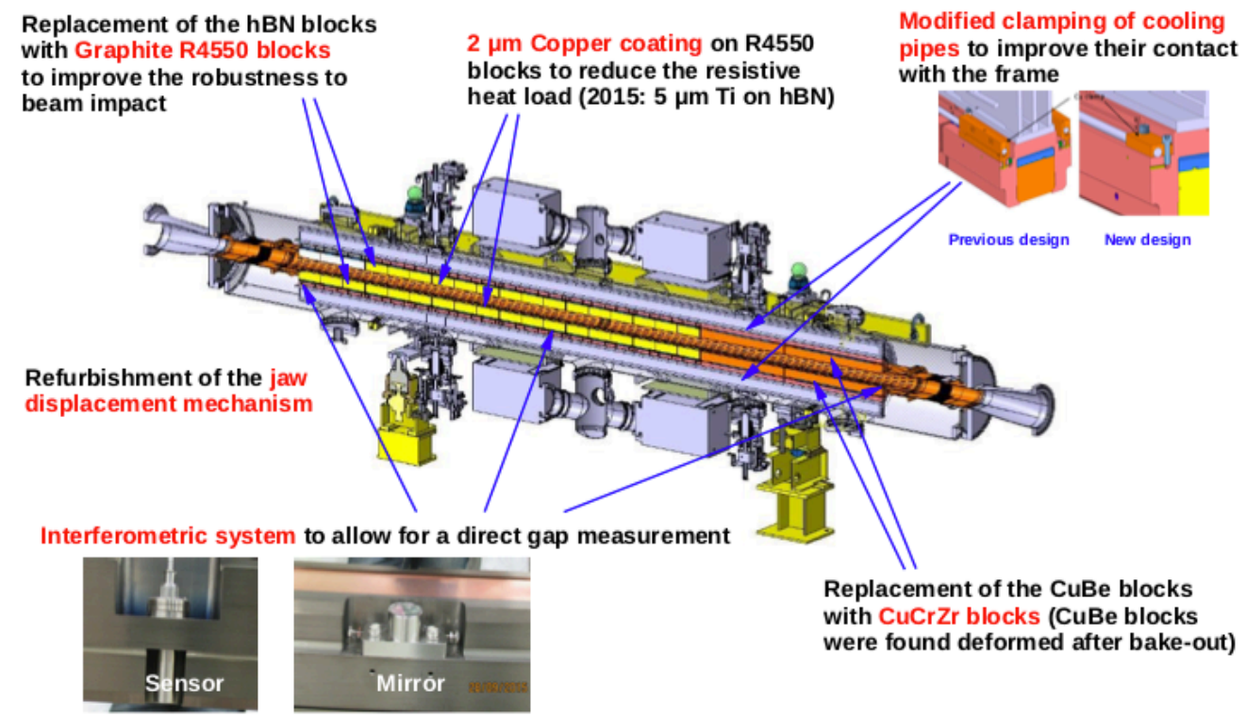
[1] **A. Lechner,** "Summary of issues with the present TDI – the TDI history in a nutshell"
[2] **A. Lechner,** "TDI - past observations/limitations and improvements for 2016"

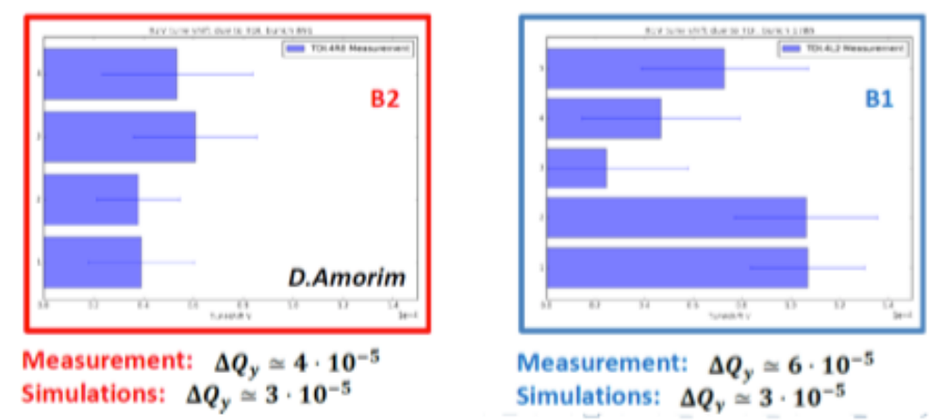
TDI run II evolution [1, 2] - 2

→ **Modification during 2015/16 YETS:**

- ↳ Replacement of hBN blocks with R4550 graphite, copper coating on graphite blocks, modified clamping of cooling pipes, added an interferometric system, replacement of CuBe blocks with CuCrZr
- ↳ **Operational limits from TDI removed for the rest of run II**
  - Beam-based measurements (impedance team) showed the expected improvement coming from the replacement of hBN blocks with R4550 and their coating
- ↳ Main issue observed during 2016: strong pressure increase in the TDI.4R8 during jaw movement. This showed conditioning effects

→ **Very smooth operation from 2016!**





Beam type Run 2	TDI limitation 2015 hBN	Outlook 2016
Standard 25 nsec	144 bunches	288 bunches
BCMS 25 nsec	96 bunches	144 bunches (TCDIs)
50 nsec	108 bunches	144 bunches

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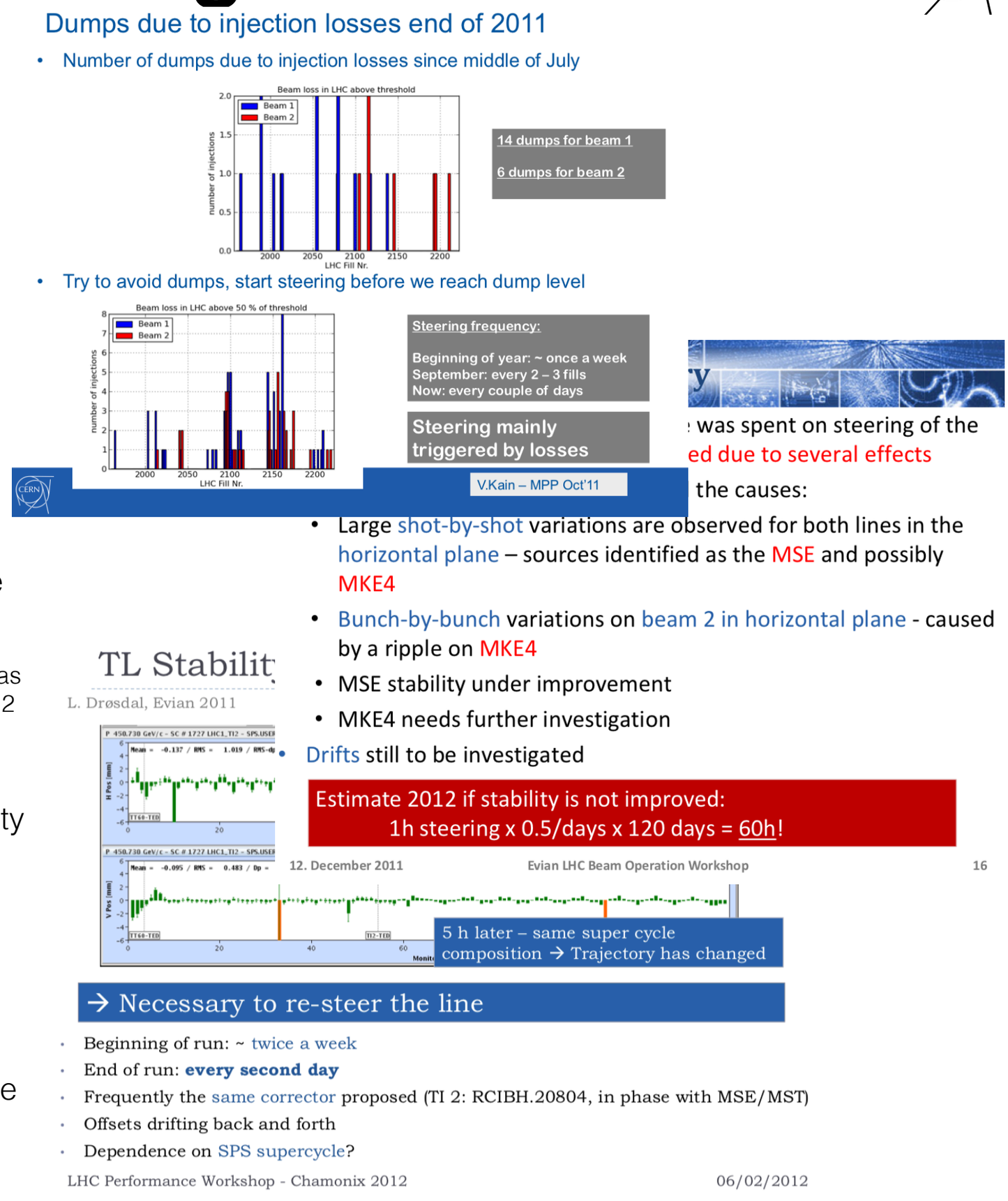
SPS-to-LHC TL: steering and losses

- SPS-to-LHC transfer line trajectory stability has been a topic of studies since run I (L. Drosdal, V. Kain, C. Bracco, W. Bartmann, etc.)
  - Two source of horizontal trajectory variations were identified: shot-to-shot variations and long term drifts (vertically both lines are very stable)
  - Shot-to-shot variations:
    - For TI2, the main source was identified to be the MSE in LSS6
      - In the winter stop 2011/12 the MSE power supply was improved and the current jitter halved => the factor 2 improvement was also measured as trajectory jitter during 2012 start up
    - For TI8, 2 main sources of trajectory instability were isolated as the MKE and MSE in LSS4
  - Trajectory slow drifts:
    - For TI2, the main sources were identified as the SPS orbit and the MSE
    - For TI8, the main source was identified as the SPS orbit



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    - For TI8, the main source was identified as the SPS orbit

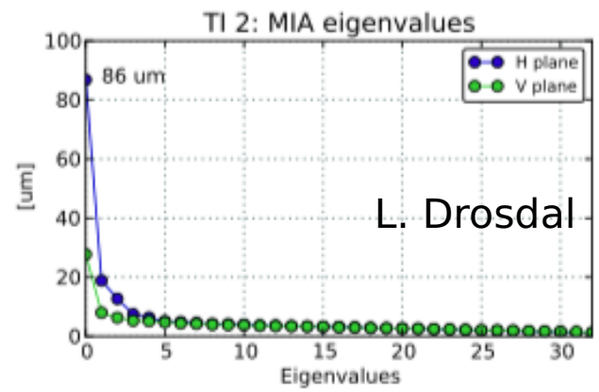


Figure 3: MIA eigenvalues for TI 2 June 2011 extraction test. One strong eigenvalue in the horizontal plane is found.

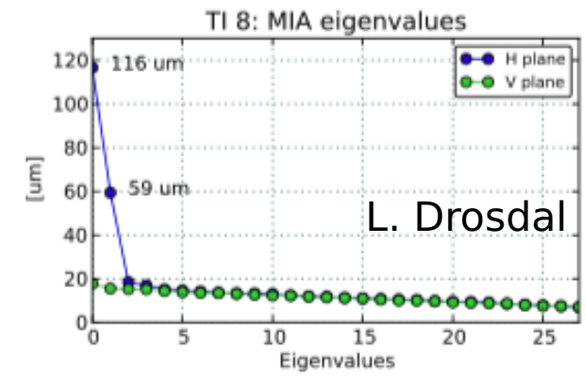
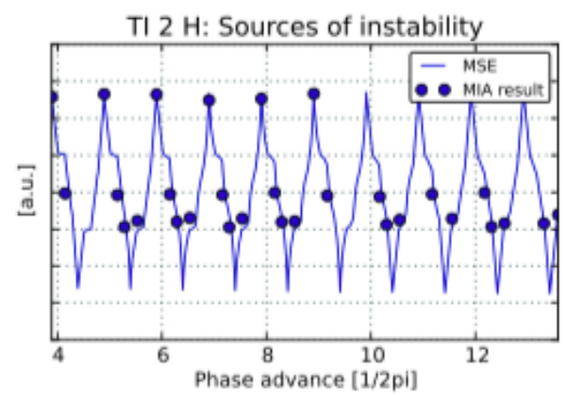
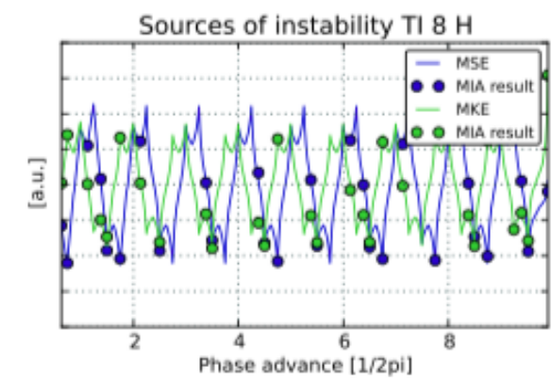
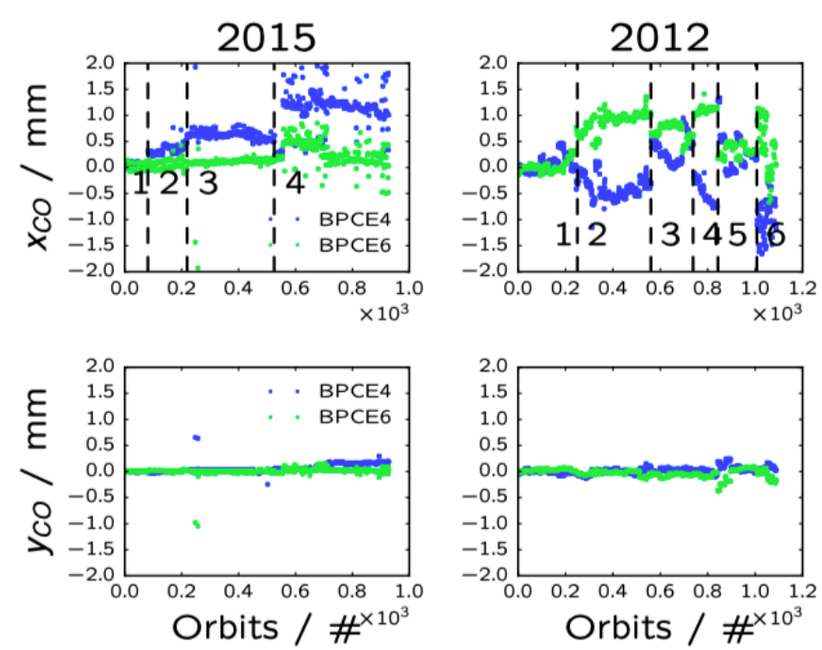


Figure 6: The first stability study of TI 8 in 2011 shows two strong sources of shot-by-shot variations in the horizontal plane.







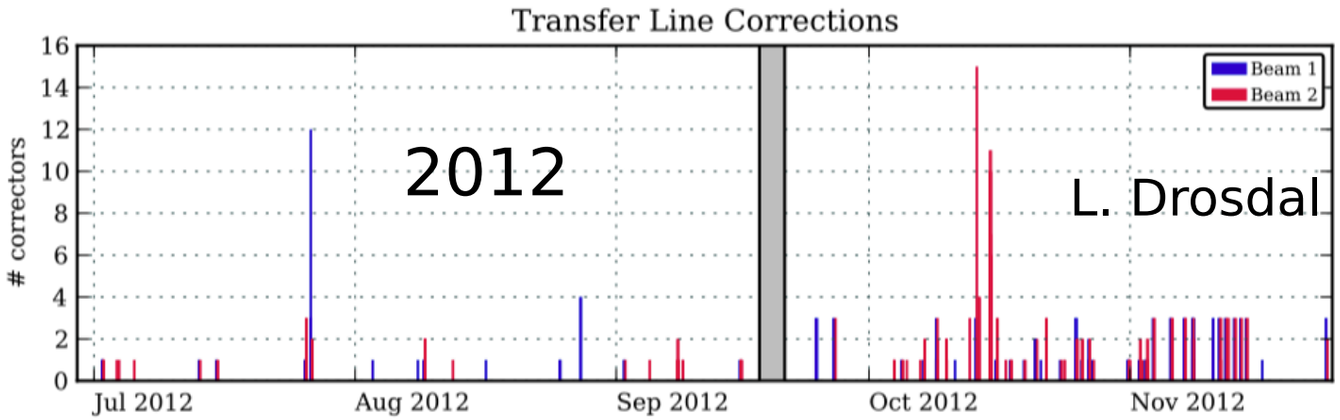
Steering frequency in 2017/18

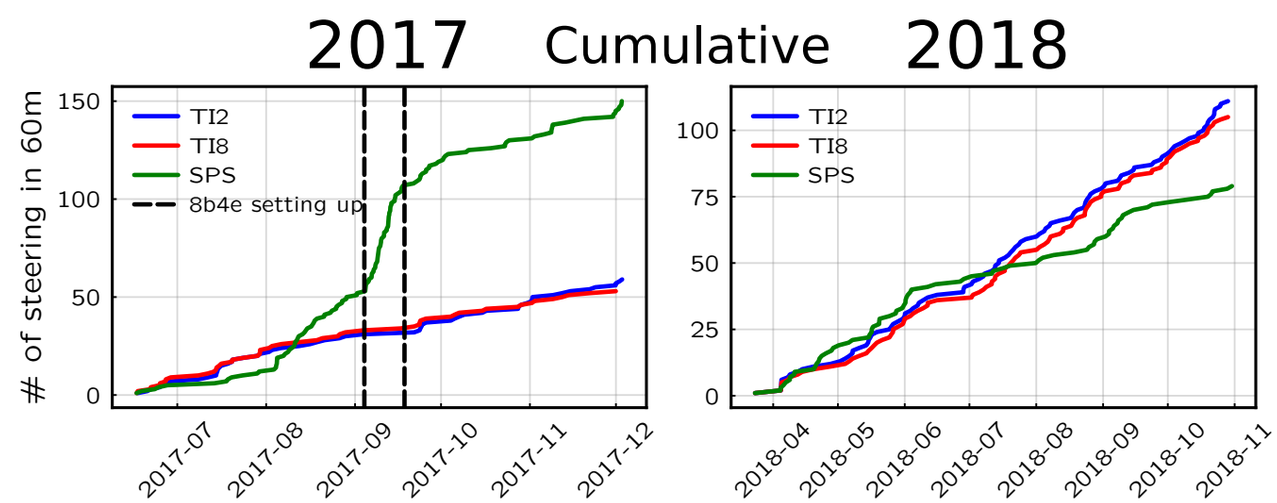
→ **How much TI2 and TI8 have been steered?**

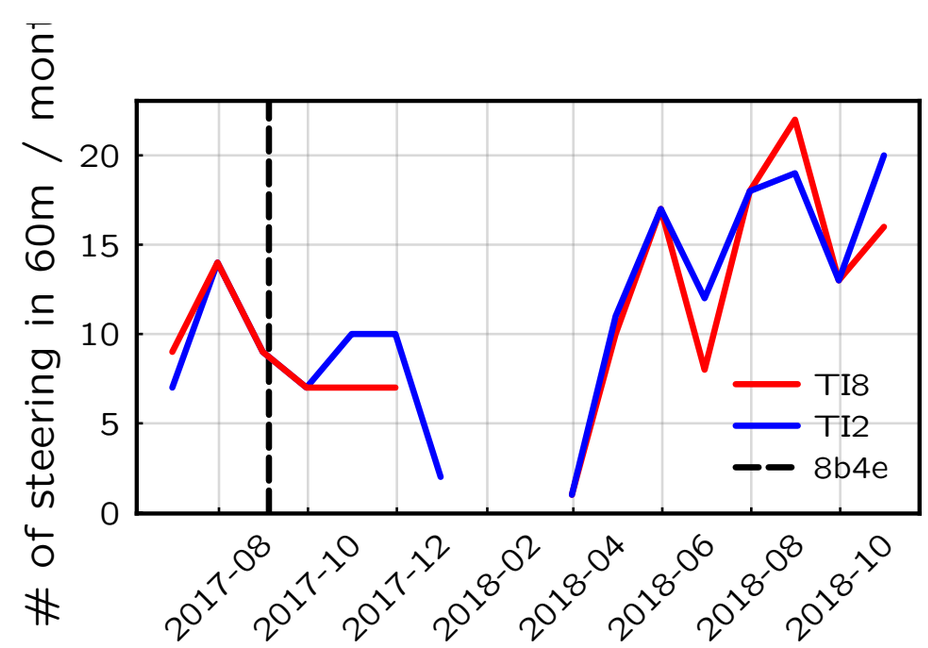
- ↳ Comparing 2017 and 2018, it seems that this year the total number of steering iterations was almost doubled for both lines
- ↳ There is also a trend in number of steering iterations per month building up in 2018, instead almost constant in 2017
- ↳ Also in 2012, though, there was an increase in steering frequency during the last part of the year. That also corresponded with the change from Q26 to Q20

→ **Comparing this with the SPS injection:**

- ↳ 2017: SPS injection was treated without the concept of golden trajectory and golden orbit at injection
- ↳ 2018: Introducing golden orbit and trajectory halved the steering iterations in TT10
- ↳ Hence the most fair comparison between TT10 and TI2/8 is in 2018, where we had about 25% more steering interactions in TI2/8 than TT10 => including also TT2 there is **very little difference between them!**



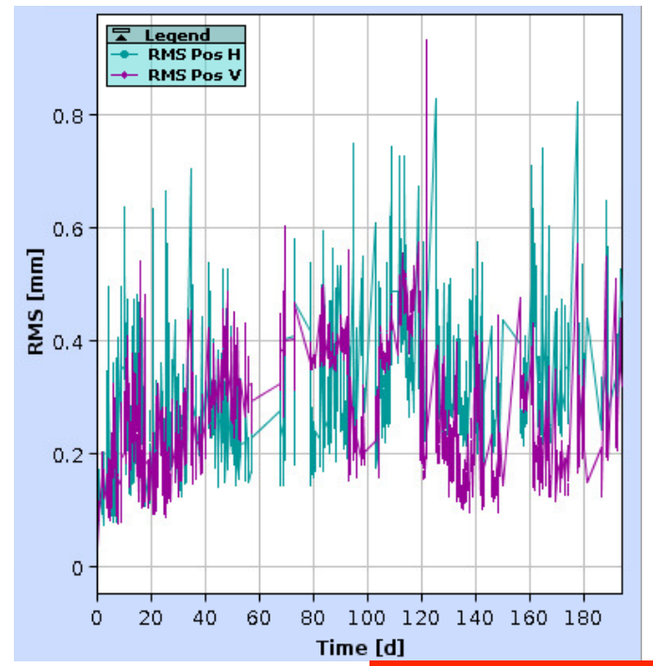




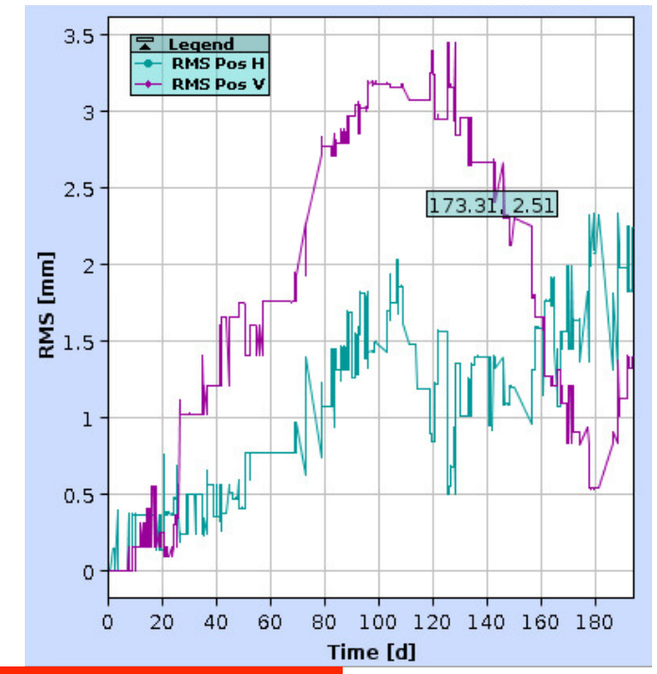
Steering analysis in 2018 - TI2

- **Jorg's TL steering analysis for TI2:**
  - The final trajectory rms of TI2 is rather stable along the year => variation in 0.4 mm range
  - De-convoluting all corrections:
    - A large variation in V (almost twice than in H) observed during the middle of the year, but then it drifted back…
    - Instead the amplitude of the change keeps growing in the H plane
  - If the TT60 correctors (larger strengths) are left out, the changes in rms are much smaller => this indicates that the changes are dominated by the SPS orbit (H, V)/ extraction elements (H)

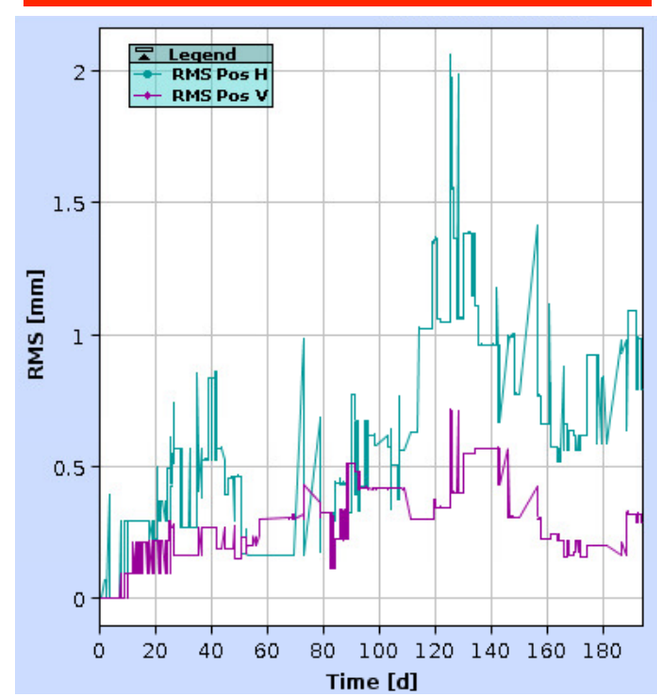
Pure TI2 rms



TI2 rms from 2018 corrections



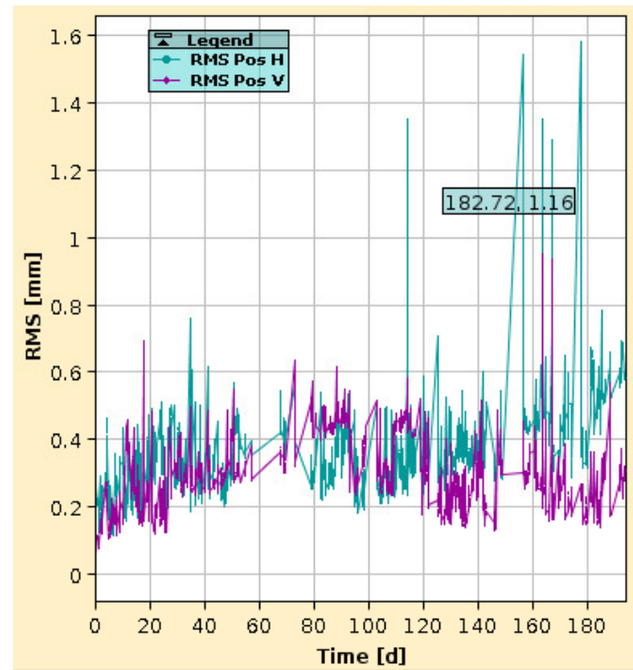
TI2 rms from 2018 corrections w/o TT60



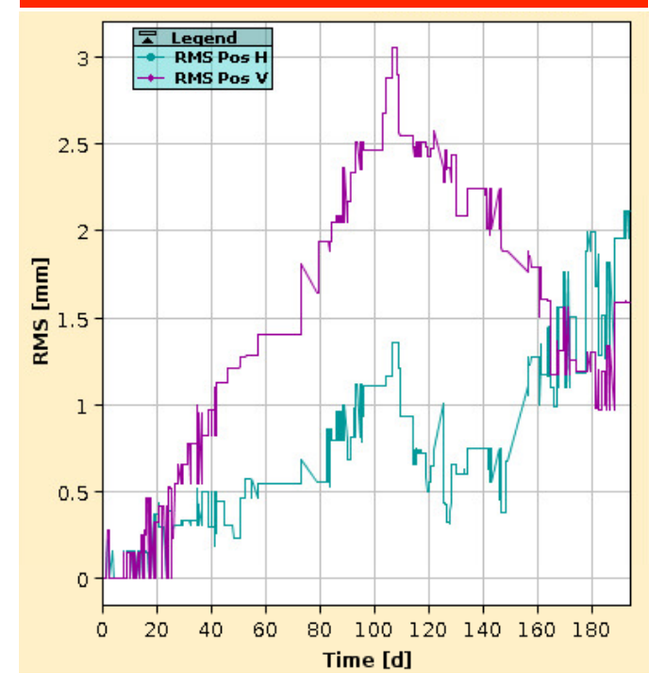
Steering analysis in 2018 - TI8

- **Jorg's TL steering analysis for TI8:**
  - The final trajectory rms of TI8 is rather stable along the year => variation in 0.4 mm range
  - De-convoluting all corrections:
    - A large variation in V (almost twice than in H) observed during the middle of the year, but then it drifted back…as for TI2
    - Instead the amplitude of the change keeps growing in the H plane
  - If the TT40 correctors (larger strengths) are left out, the changes in rms are much smaller mainly in V => this indicates that the changes are dominated by the SPS orbit (H, V)/extraction elements (H)

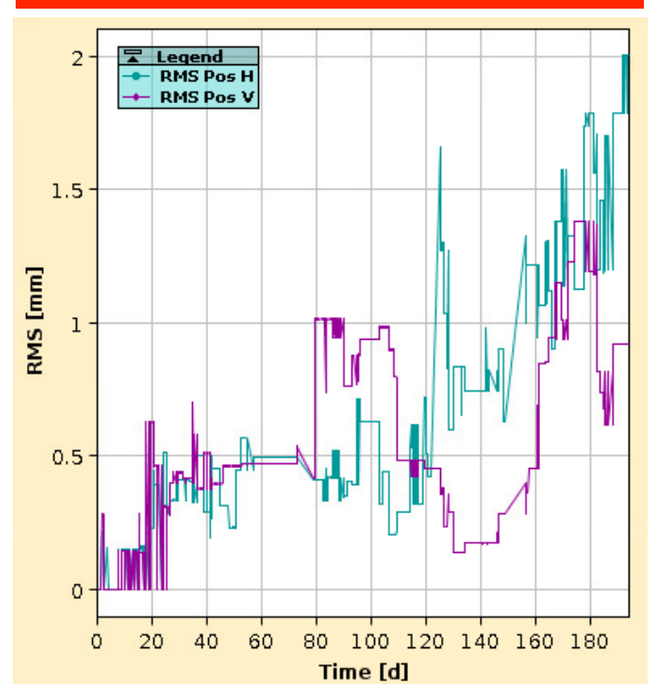
Pure TI8 rms



TI8 rms from 2018 corrections



TI8 rms from 2018 corrections w/o TT40



Steering analysis in 2018

→ **Possible to correct back to May multi-bunch trajectory with many SVD eigenvalues**

- Better for TI2 as it seems that for TI8 there is an energy error like where its amplitude varies in time…to be investigated further

→ **TI2 and TI8 correction and steering strategy:**

↳ Proposed to take a clean reference with multi-bunch beam ASAP and use it as golden for steering

- Perform some SVD cleaning with many eigenvalues after TS (or when time allocated)

↳ Place 2 (or better 3) x12bunches in every filling schemes to allow, or better encourage, for possible steering at every fill

- Even better, have two compatible filling schemes ready, one with 3x12bunches and one with single 12bunches for a dynamic switch in case steering not necessary…

Injection losses

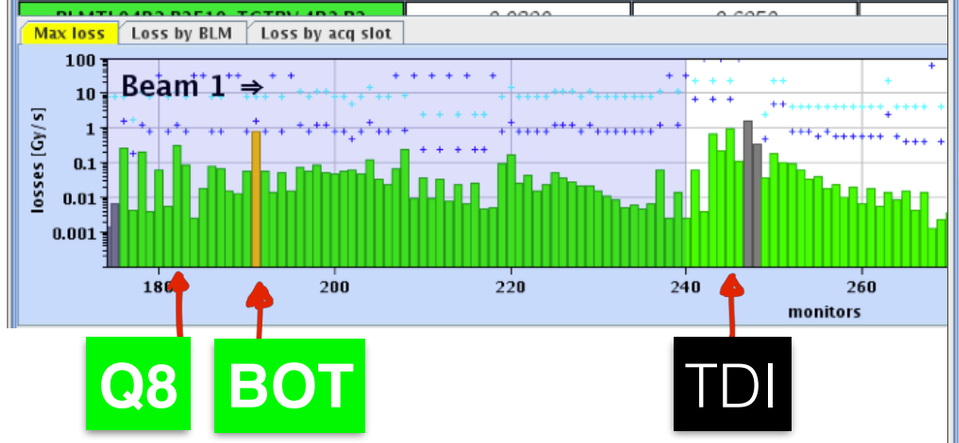
→ Why we are that sensitive to trajectory drifts and jitters (**transverse losses, Q7, Q8, BOT**)?

- ↳ 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!**

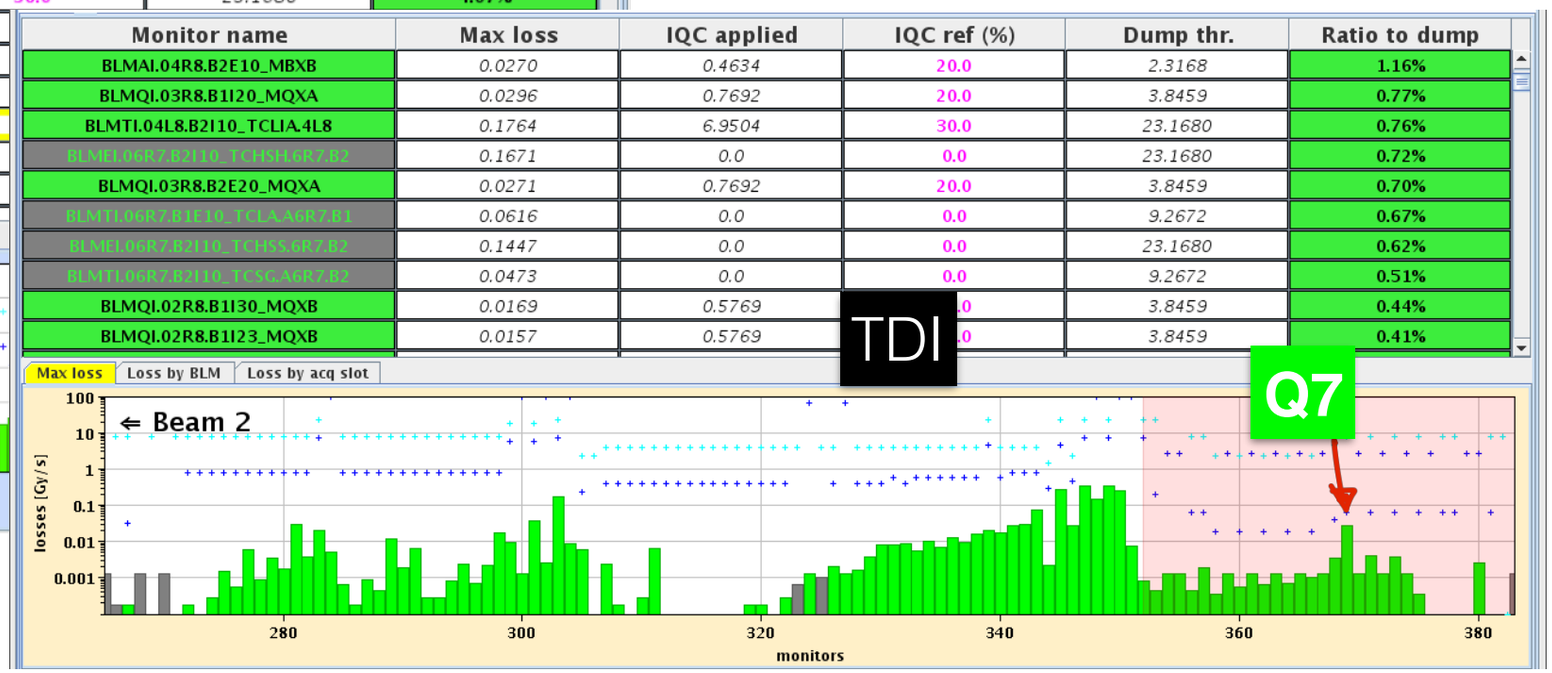
→ Another source of losses at injection is the presence of satellites at both extremities of the injected beam (**longitudinal losses** TDI)

- ↳ 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			



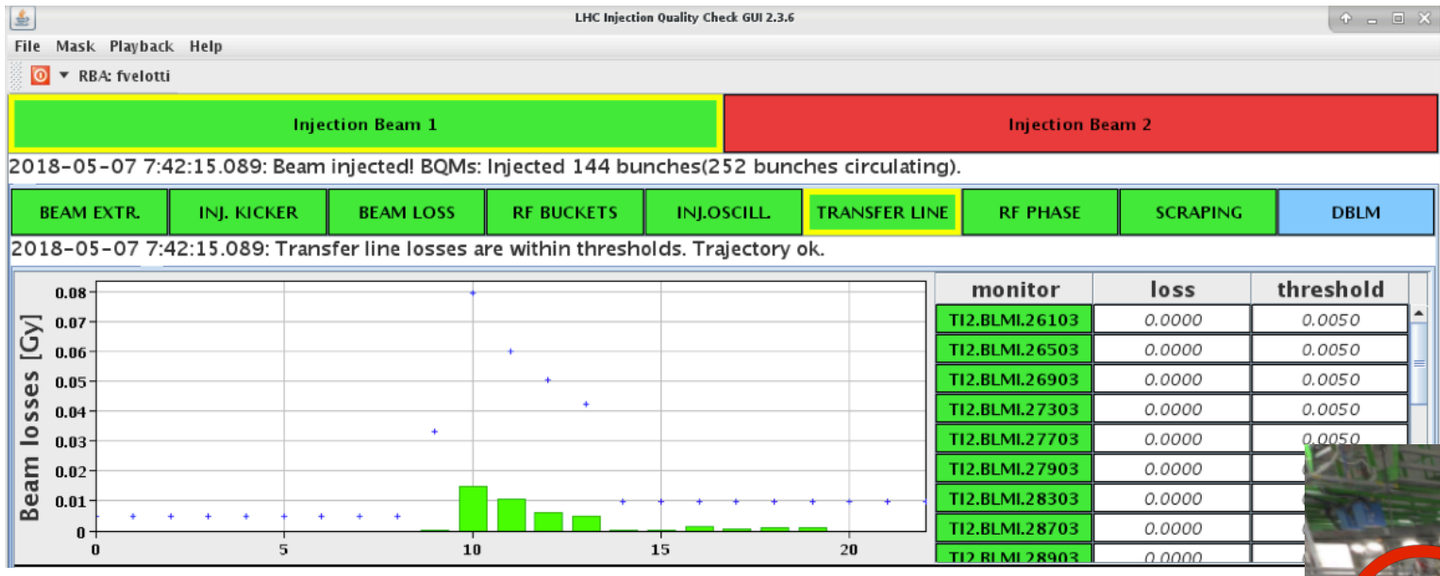
Monitor name	Max loss	IQC applied	IQC ref (%)	Dump thr.	Ratio to dump
BLMAI.04R8.B2E10_MBXB	0.0270	0.4634	20.0	2.3168	1.16%
BLMQI.03R8.B1I20_MQXA	0.0296	0.7692	20.0	3.8459	0.77%
BLMTI.04L8.B2I10_TCLIA.4L8	0.1764	6.9504	30.0	23.1680	0.76%
BLMEI.06R7.B2I10_TCHSH.6R7.B2	0.1671	0.0	0.0	23.1680	0.72%
BLMQI.03R8.B2E20_MQXA	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%

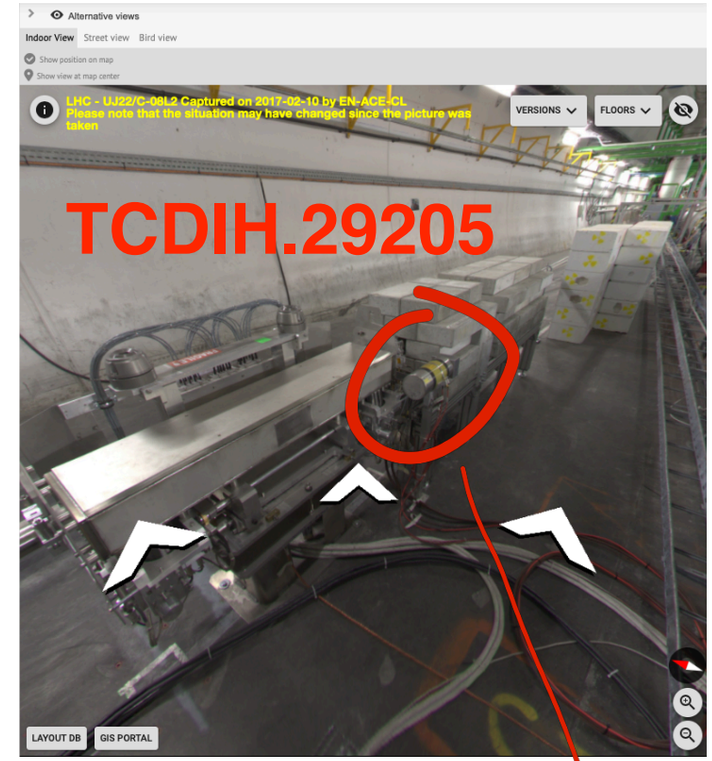


Injection losses - B1 transverse

→ BLMQI.08L2.B1E30_MQML:LOSS_RS01 (Q8)

→ BLMBI.08L2.B0T10_MBB-MBA_07L2:LOSS_RS01 (BOT)





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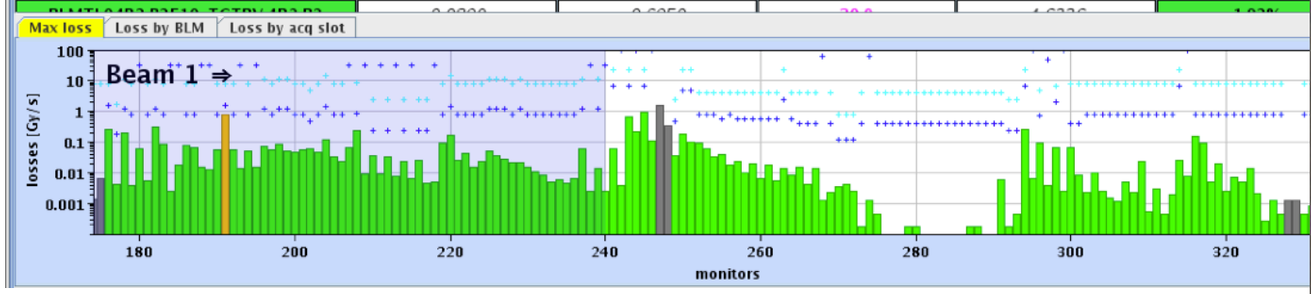
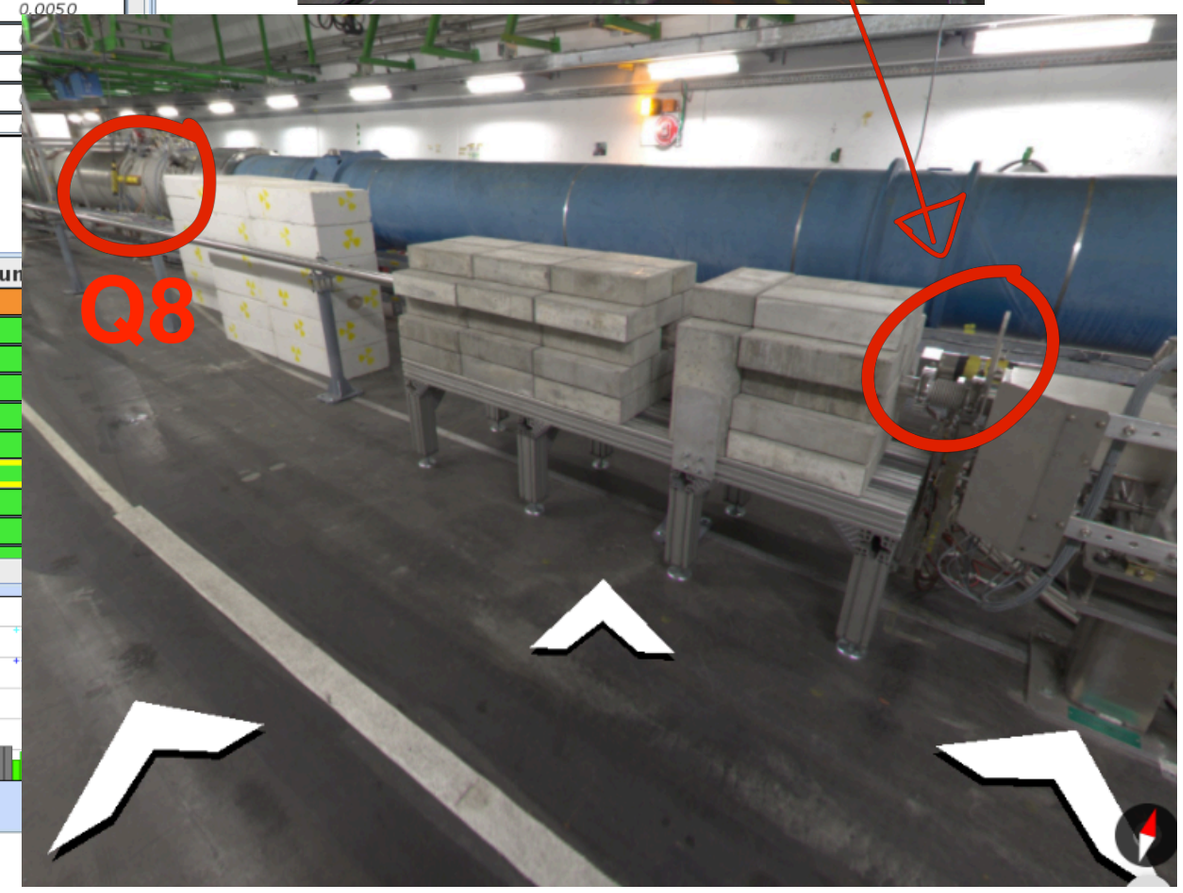
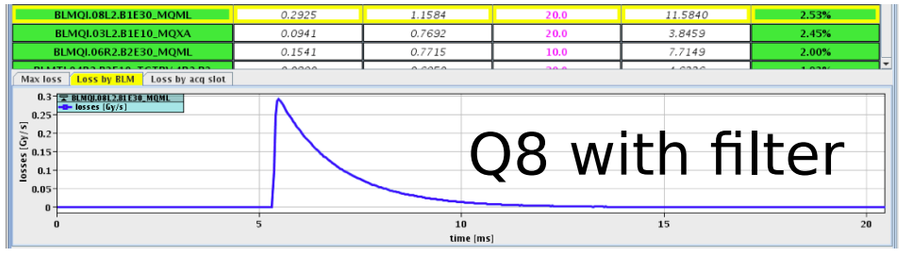
BLMBI.08L2.B0T10_MBB-MBA_07L2	0.8019	1.5430	40.0	7.7149	10.39%
BLMTI.04L2.B1E20_TDI.4L2.B1	0.9432	6.9504	30.0	23.1680	4.07%
BLMBI.09L2.B0T10_MBB-MBA_08L2	0.2497	1.5430	40.0	7.7149	3.24%
BLMEI.06L2.B1E10_MSIB	0.2439	0.8340	20.0	8.3405	2.92%
BLMTI.04L2.B1E10_TDI.4L2.B1	0.6741	6.9504	30.0	23.1680	2.91%
BLMQI.08L2.B1E30_MQML	0.2925	1.1584	20.0	11.5840	2.53%
BLMQI.03L2.B1E10_MQXA	0.0941	0.7692	20.0	3.8459	2.45%
BLMQI.06R2.B2E30_MQML	0.1541	0.7715	10.0	7.7149	2.00%

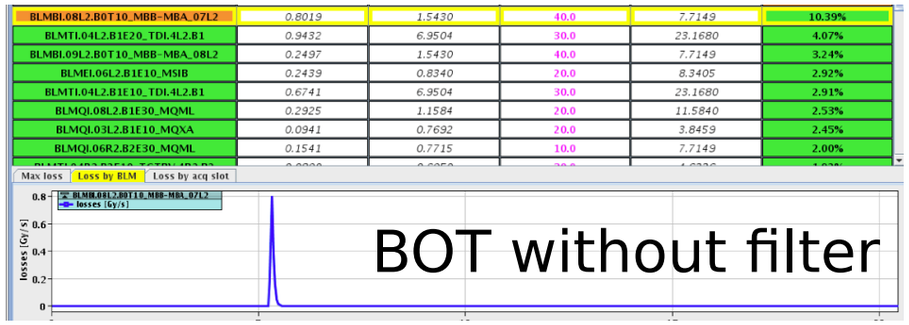




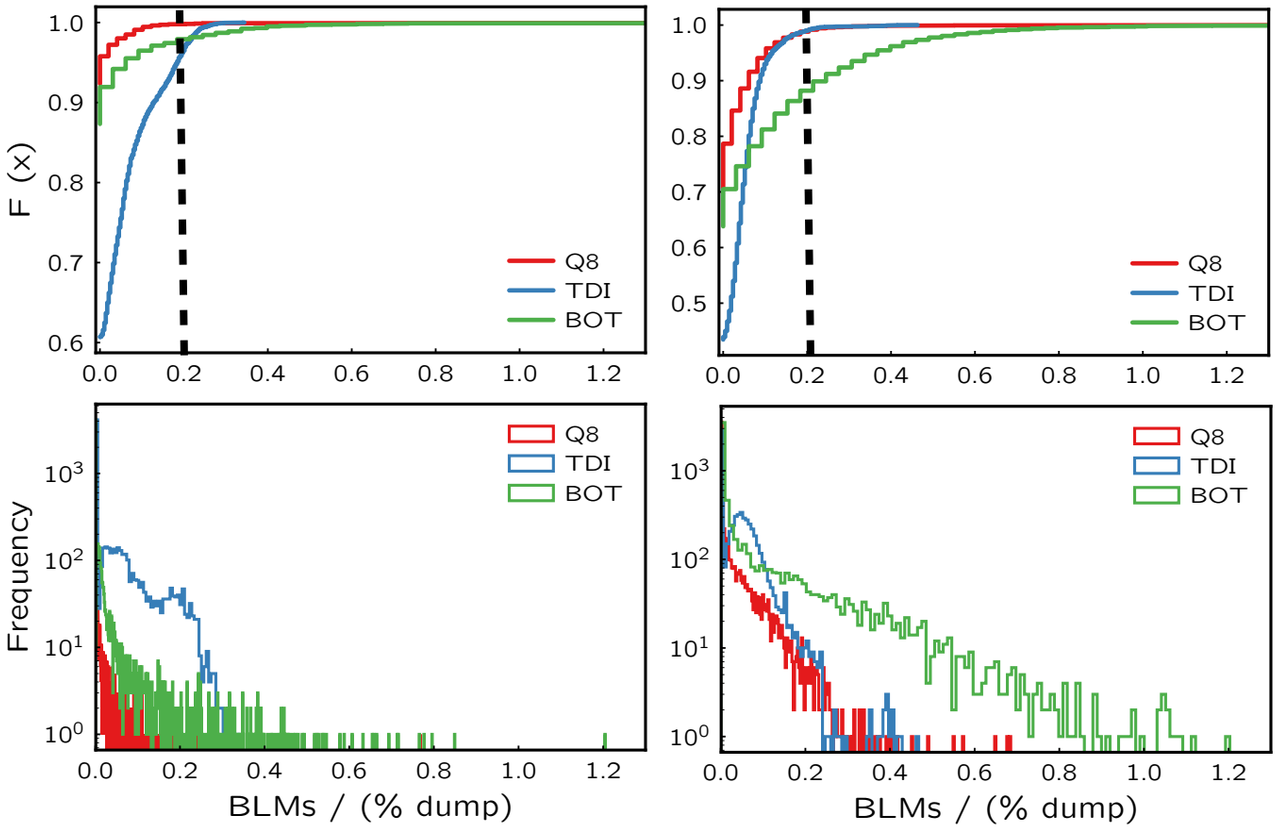
Injection losses in 2017/18

- 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

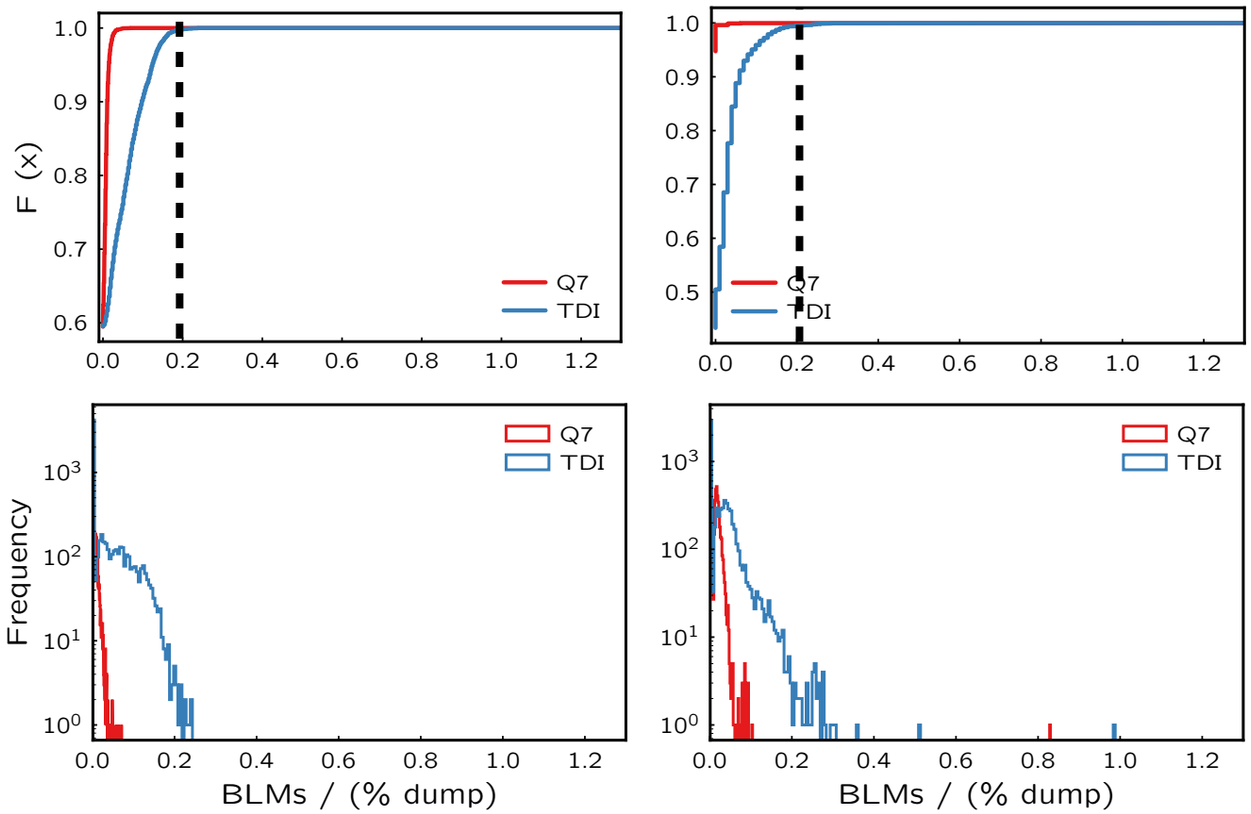




B1 2017 - 2018

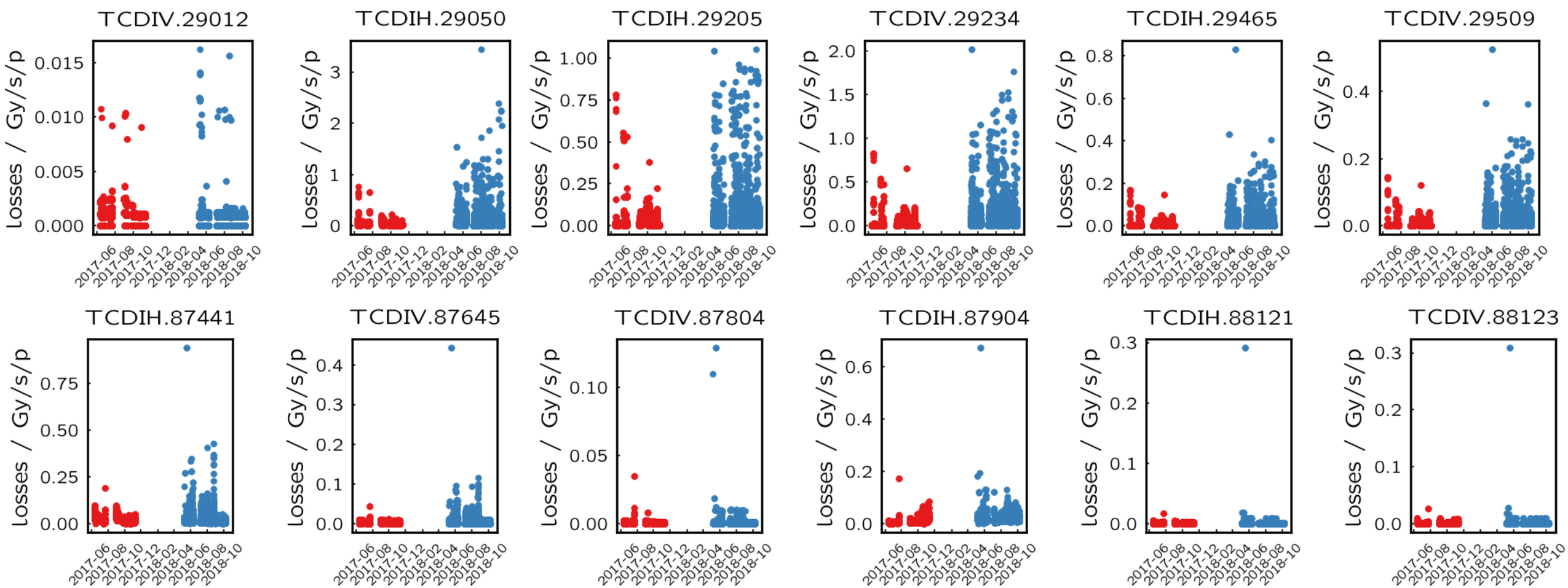


B2 2017 - 2018



Transverse losses 2017/18

- Normalised transverse losses at the TCDIs comparable between 2017 and 2018
  - In 2018 clear increase in spread - it seems more severe in TI2 than TI8
  - MSE.6?

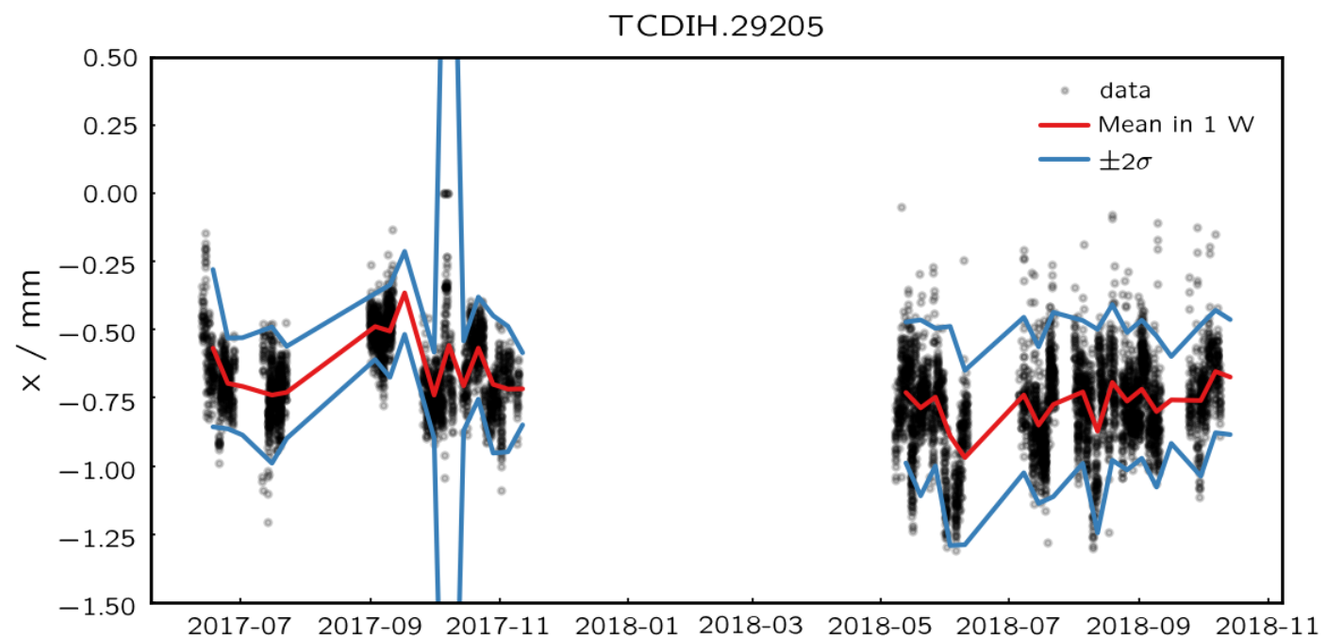


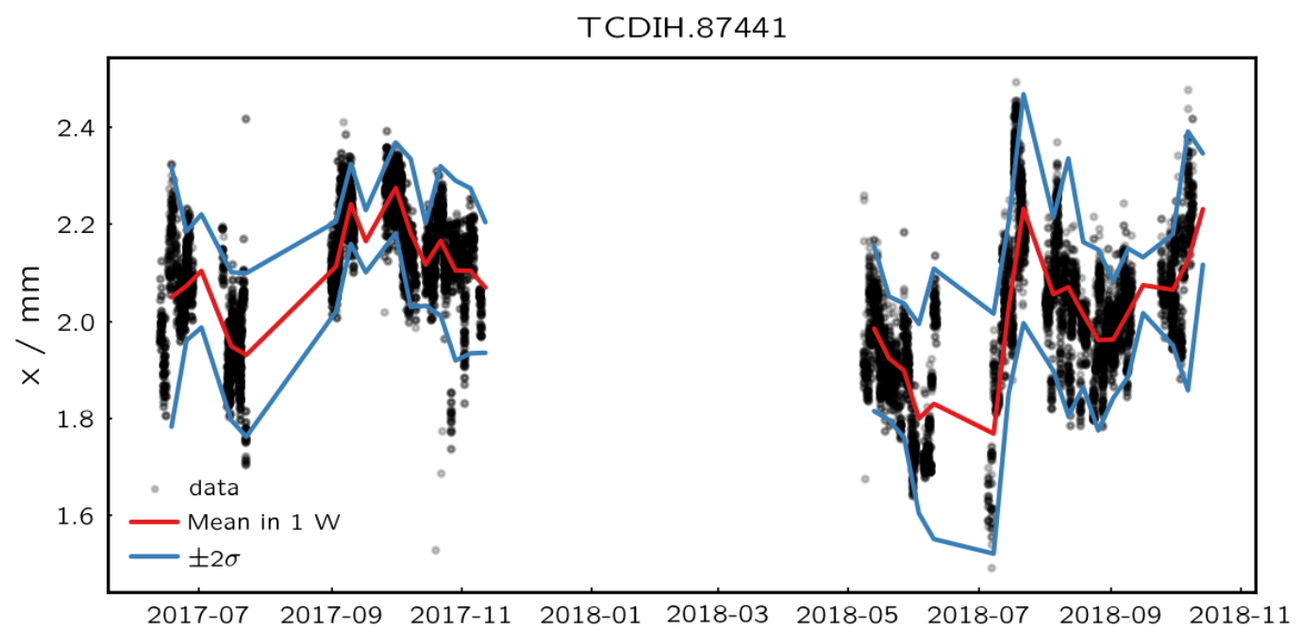
Transverse losses 2017/18

→ Trajectory jitter at the TCDIH.29205 and TCDIH.87441 over a week seems larger in 2018 than 2017

↳ Reasons still to be investigated

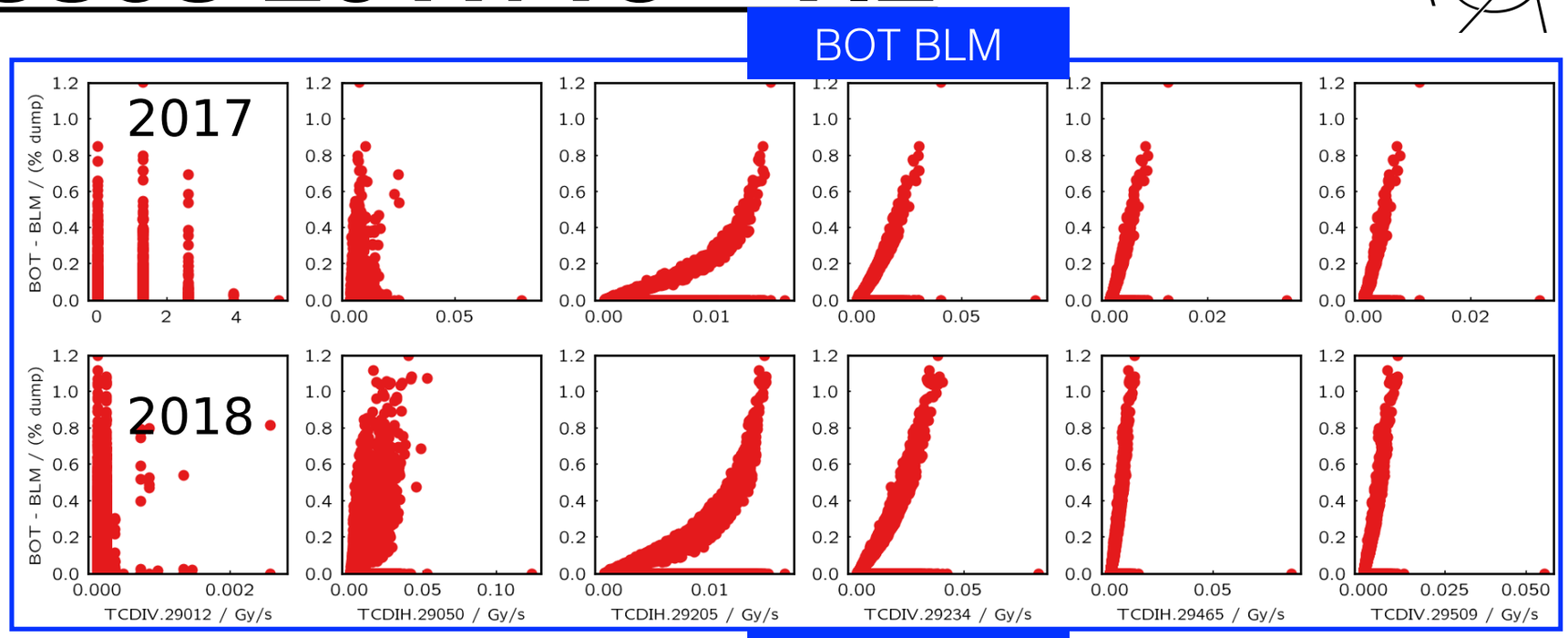
→ Worth it to re-check stability and compare to numbers obtained in the past years

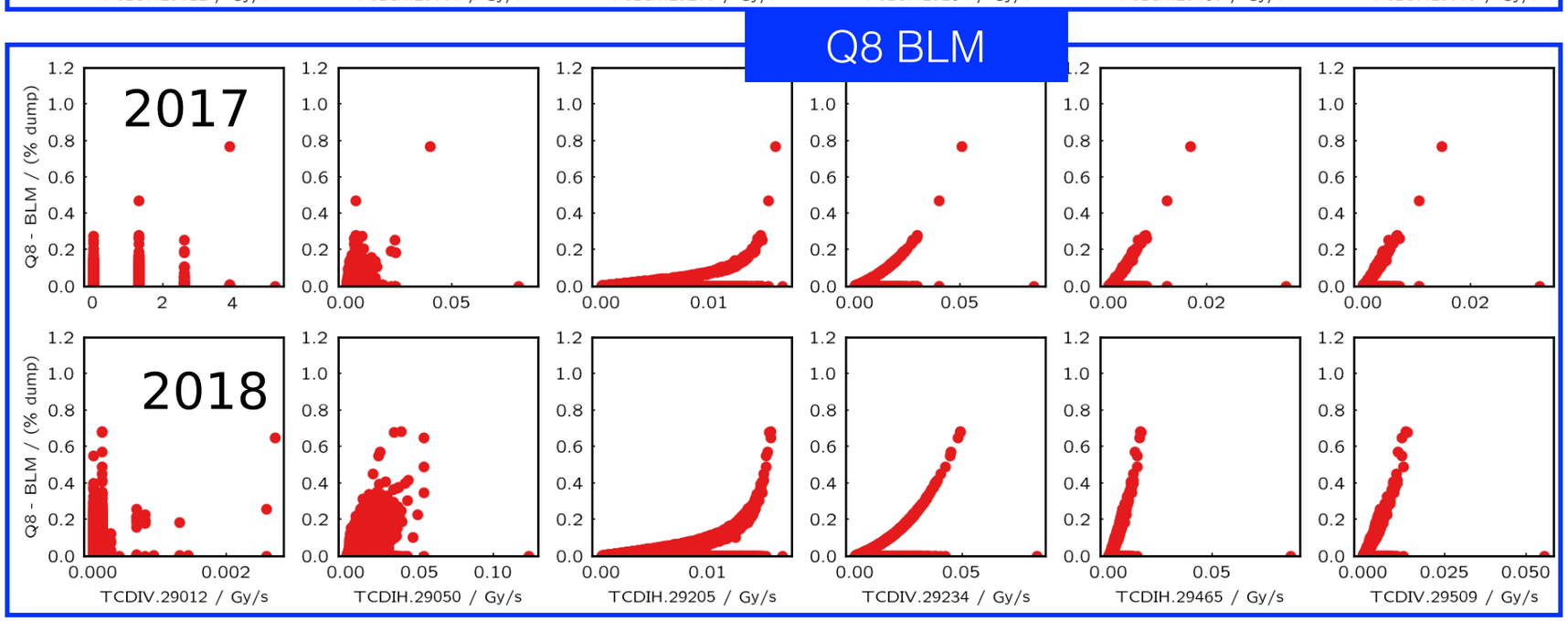


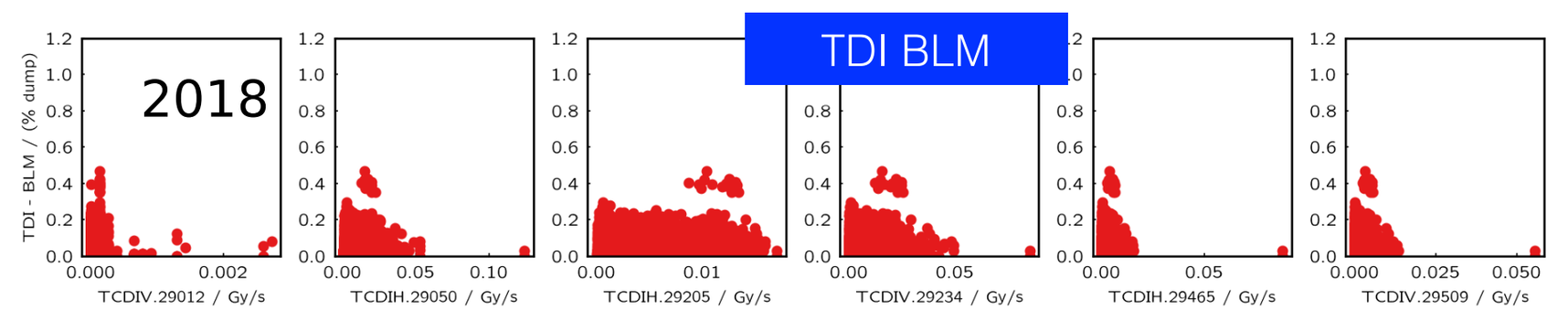


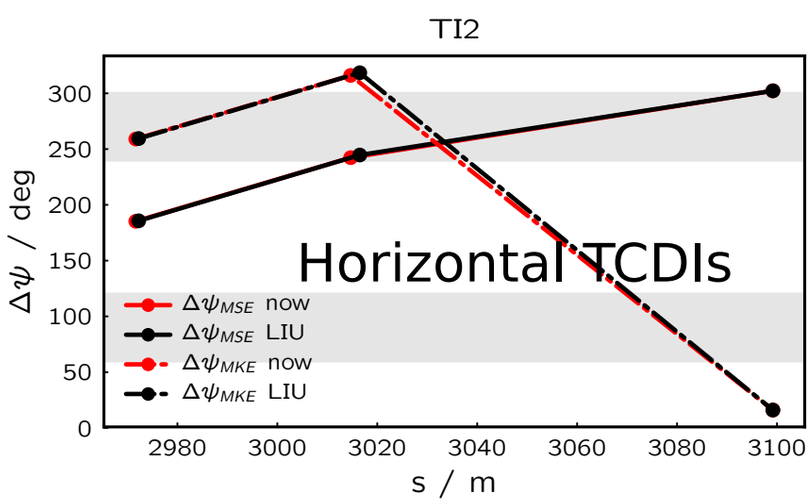
Transverse losses 2017/18 - TI2

- Correlation between losses at the 3 critical BLMs and all TCDI BLMs
- There are correlation paths, as expected
- First 2 TCDIH seems to be the first to be hit (showering on the downstream ones)
  - This is also in agreement with Lene's conclusions about being the MSE and MKE the sources of jitter
- Completely uncorrelated losses at the TCDIs with TDI!









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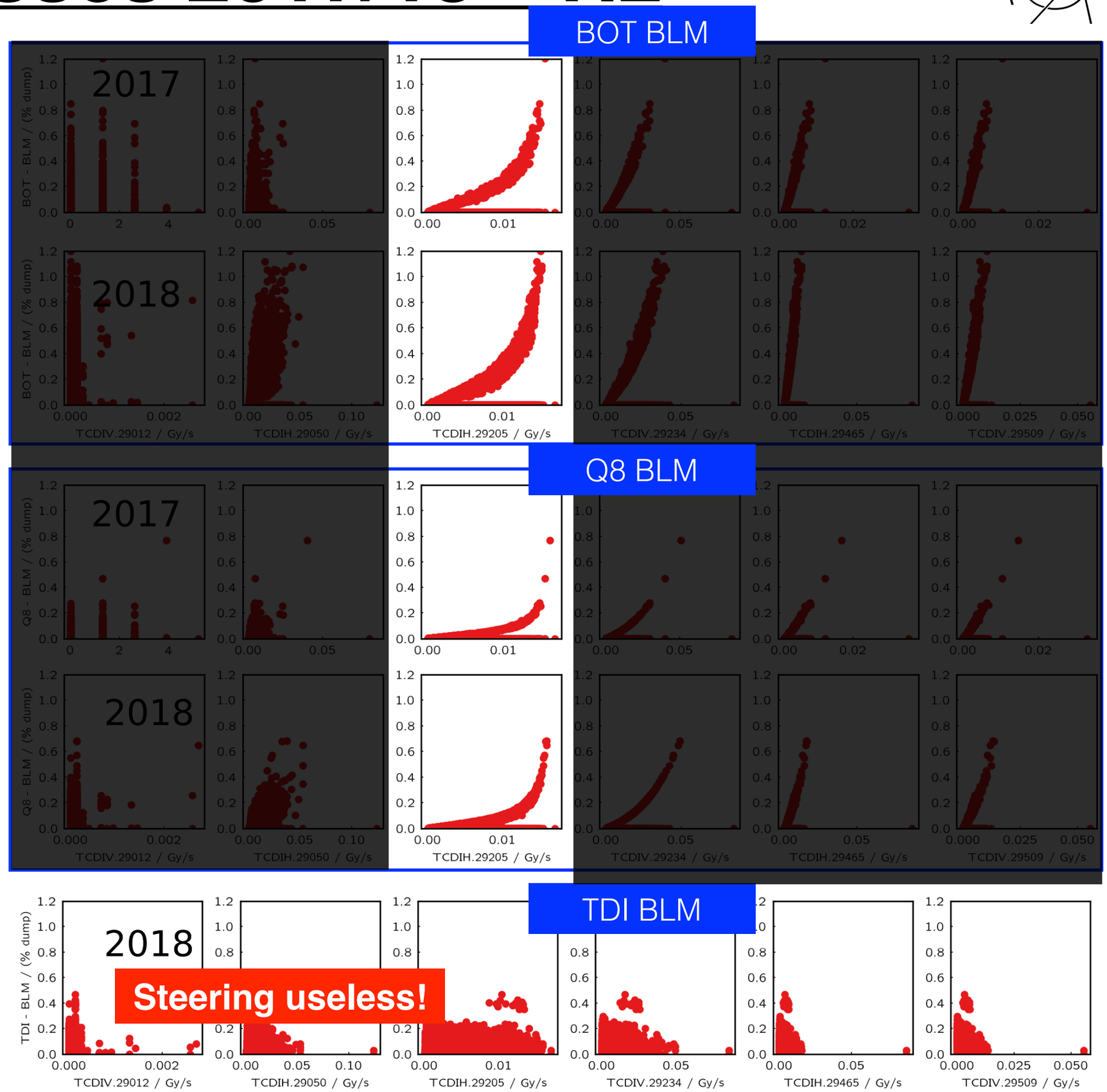
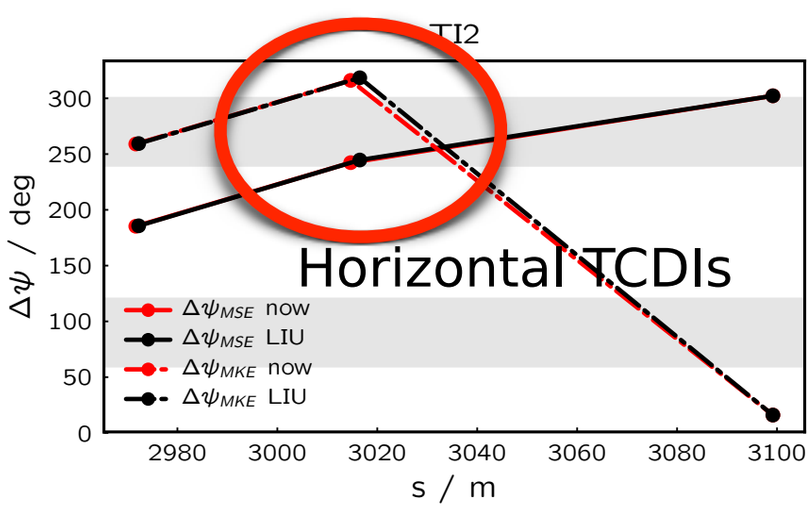
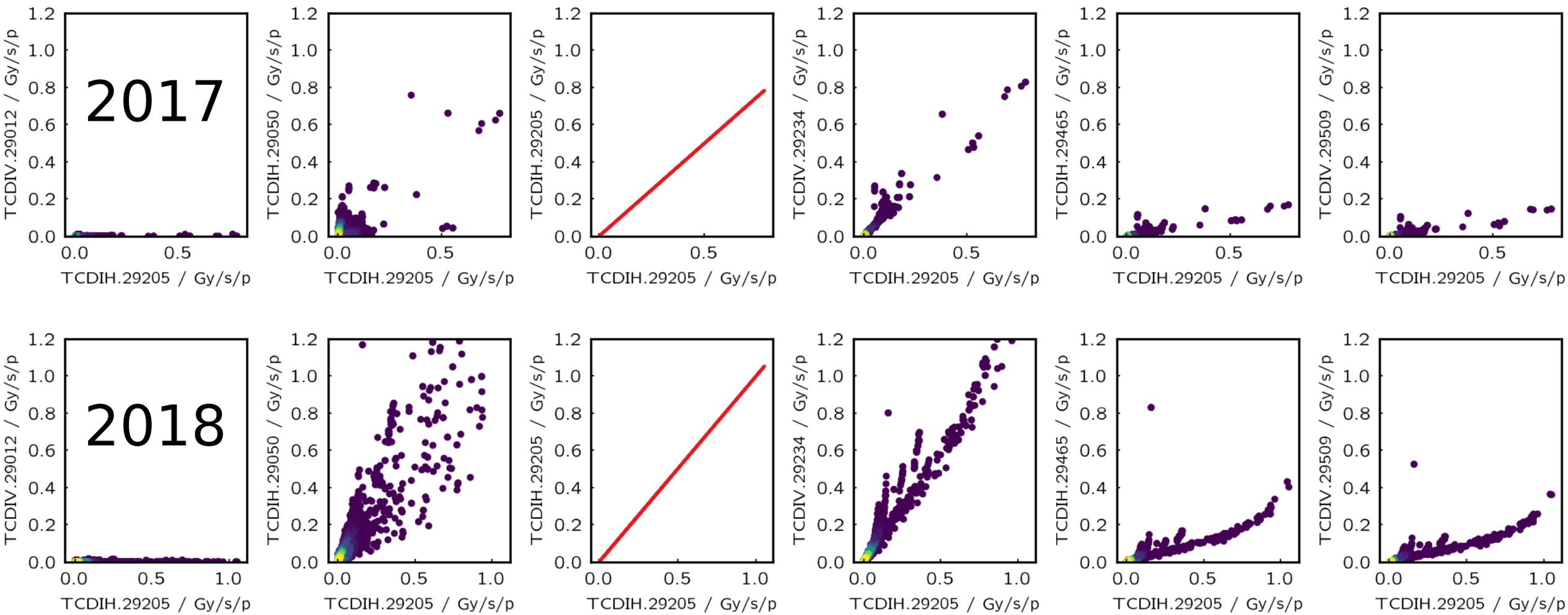




Transverse losses 2017/18 - TI2

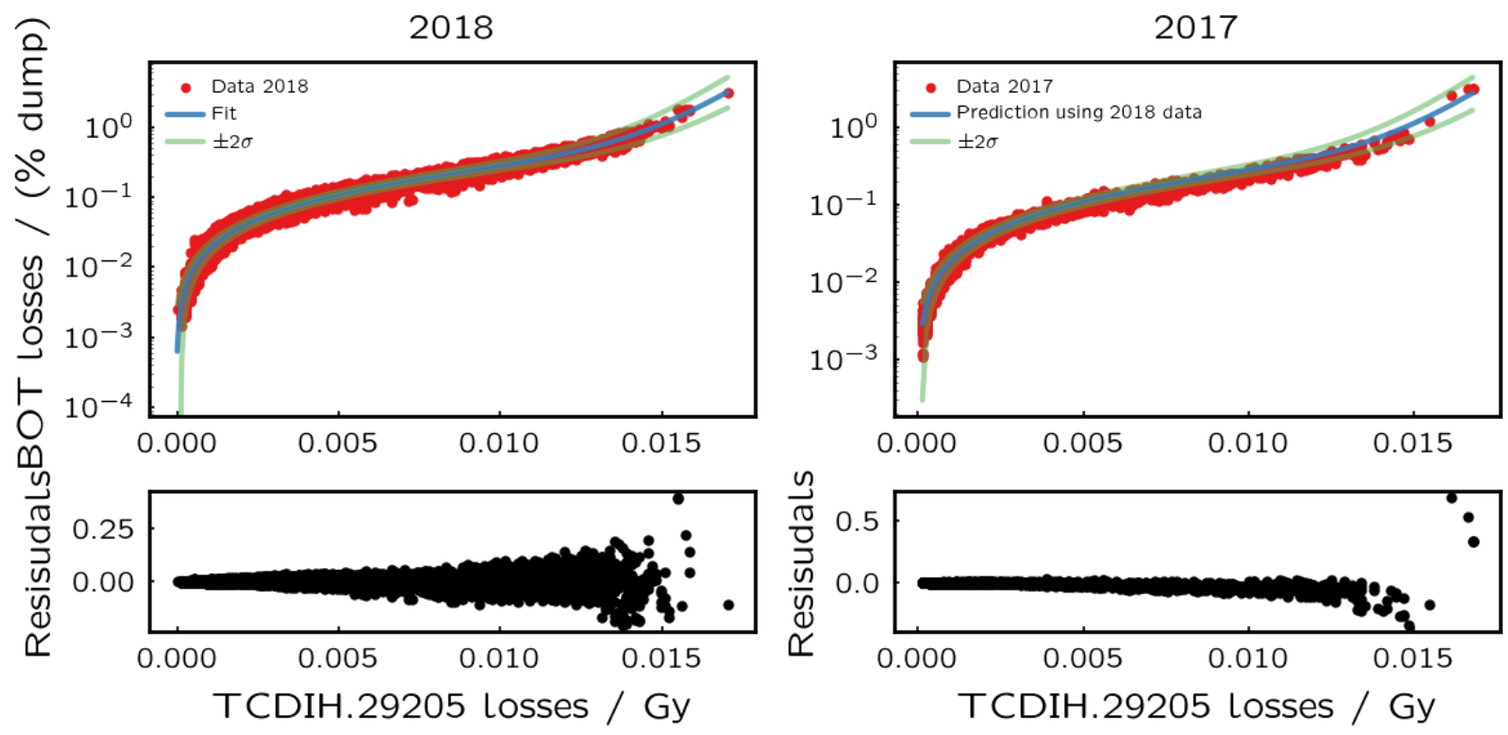
- TCDIH.29050 is the one with usually the highest losses readings
  - TCDIH.29205 is the first (longitudinally) exhibiting the most clear correlation pattern with the “injection quality” LHC BLMs

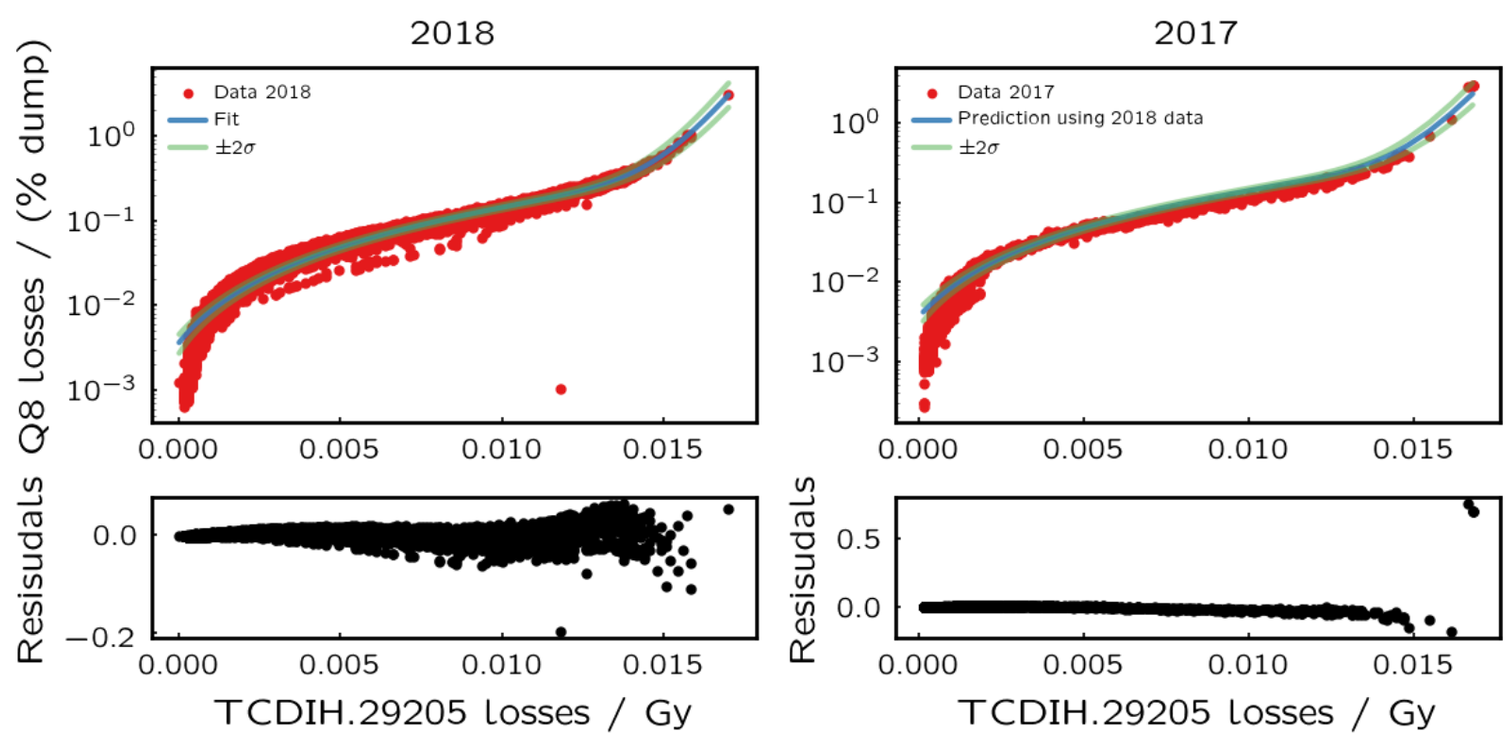
- Correlation plots between all TCDI BLMs and the TCDIH.29205:
  - Linear correlation between the 29050 and 29205, although not so good
  - “Thanks” to the larger amount of data at higher losses in 2018, clearer correlation plots => <u>all losses recorded at the TCDIs after the 29205 seem to be dominated by losses/showers from TCDIH.29205 => very “good” phase with MSE.6</u>



Transverse losses 2017/18 - TI2

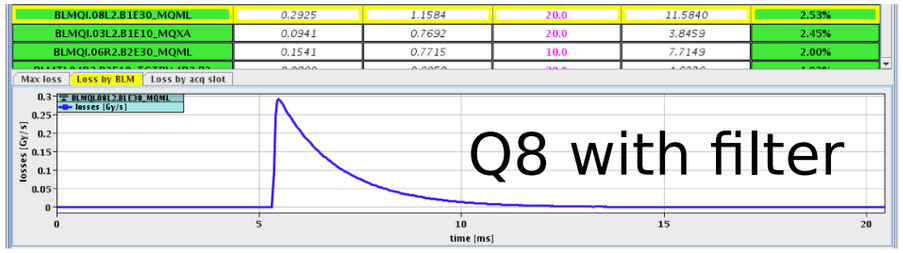
- Using the correlation pattern shown between TCDIH.29205 losses and Q8 and BOT BLM readings, data can be fit and make an empirical model
  - Using a simple polynomial + exponential fit the data in 2017 can be reconstructed using the model obtained from 2018 data
    - Still some systematics…
  - This may be useful to evaluate and optimise BLM shielding for the new TCDILs and to extrapolate expected injection losses for run III

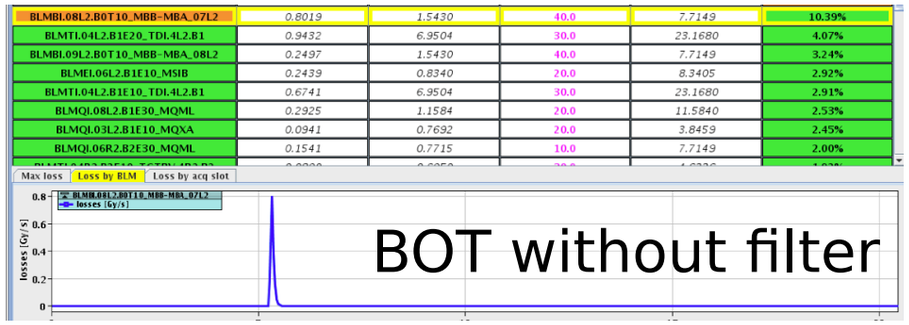




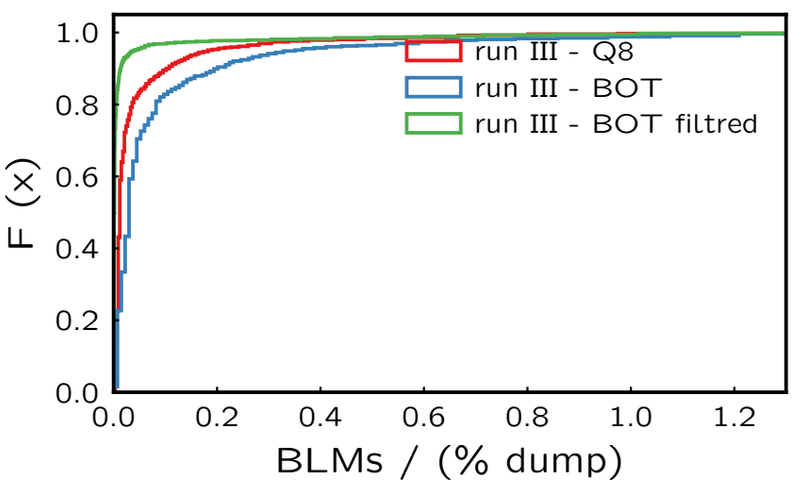
Expected losses at injection run III

- Using what was just discussed, we can try to extrapolate the expected losses at injection over run III
  - **Proposal to re-introduce filter on BOT BLM as in Q8** => factor 20 reduction
  - The 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



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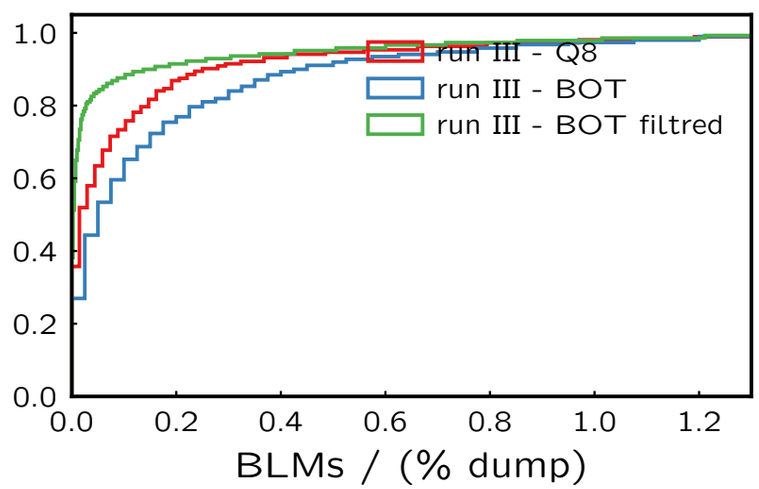

Predictions for run III

	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!

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  - Steering analysis
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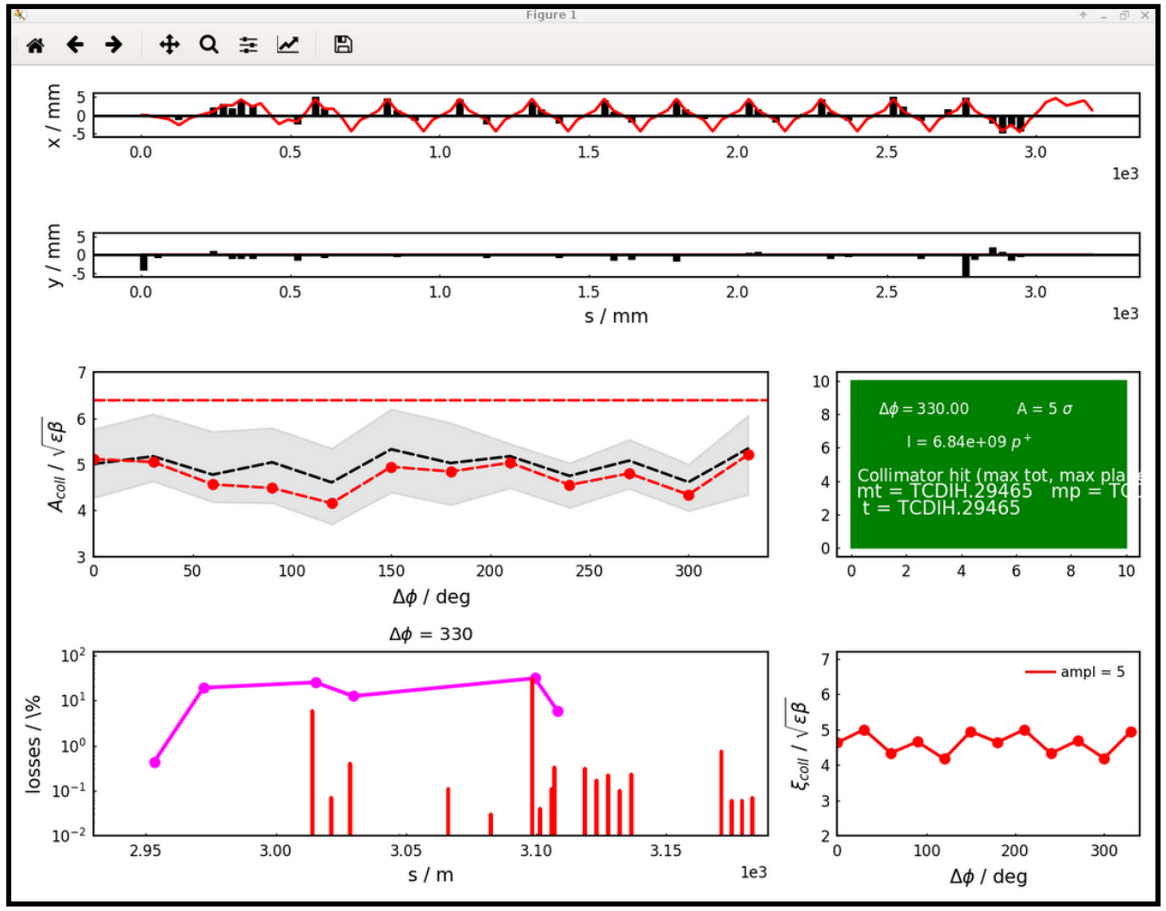
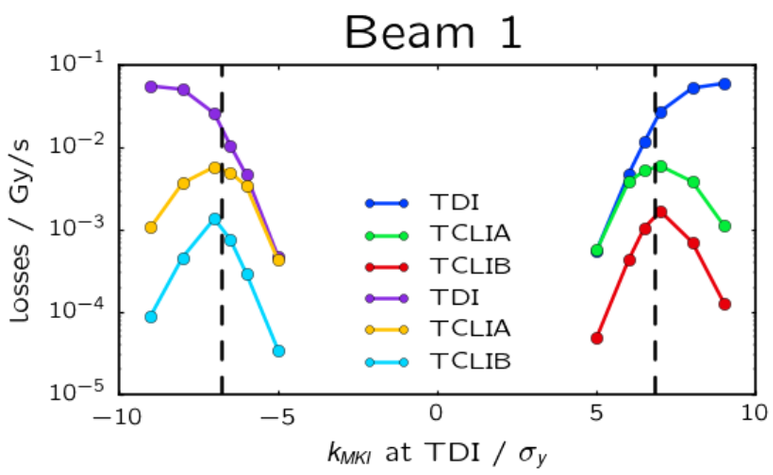
- Limitations from injection devices post-LS2
  - Can we reach 1.8e11 ppb in 1.8 um?
- Conclusions

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, etc.

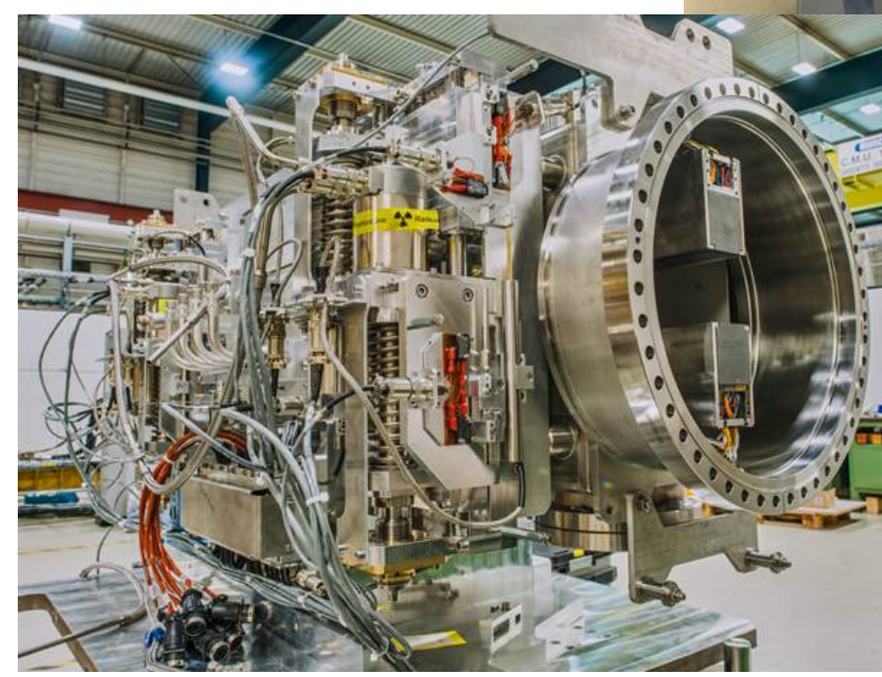




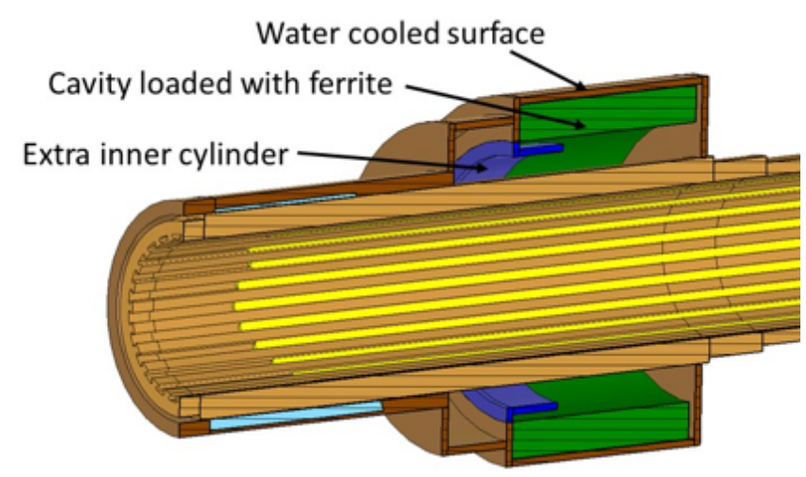
What will change after LS2?

- **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 288 bunches of 2.0e11 p/b in 1.3 um emittance
  - Re-matched optics in TI2 and TI8 to satisfy beam size requirements at $\beta_x \times \beta_y > 3600 m^2$

- **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



- **Replacement of MKI2B with "MKI Cool" to complete new MKI design validation**
  - Water cooling of surface in contact with ferrite rings
  - It will give even better thermal performance than MKI8D
  - Limits for run III still dictated by post-LS1 design (6 of 8 magnets)



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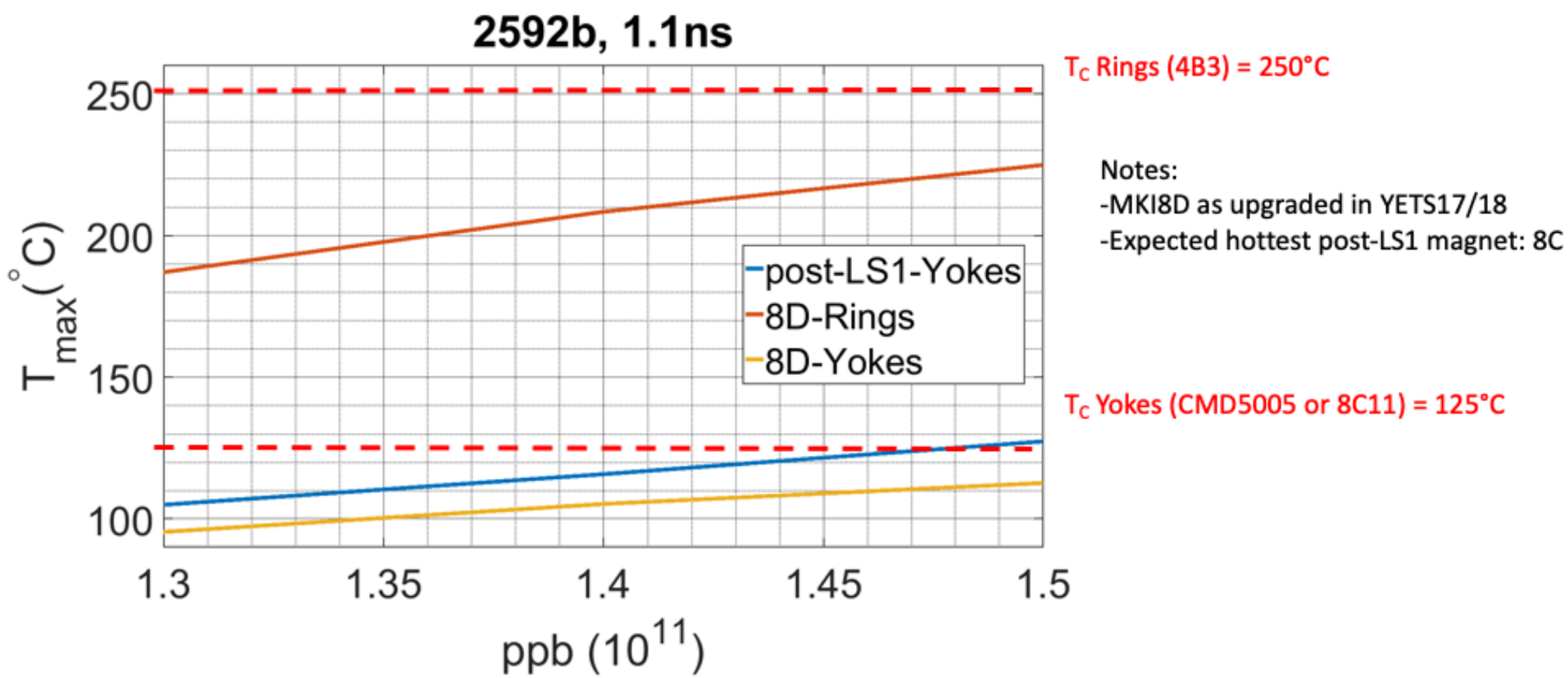
Limitations from injection devices post-LS2

- Limit to LIU/HL-LHC baseline parameters for transported/injected beam from the SPS to the LHC
  - New TCDIL and new TDIS
- MKI limits for injected beam:
  - Up to 7.8 us pulse length operated so far - OK for 240 bunches per train (8.2 us might be in reach, if needed, but to be evaluated in MD first)
- MKI limits to max number of storable bunches given by post-LS1 magnets installed
  - Details in: V. Vlachodimitropoulos, “Hardware limitations at injection” (https://indico.cern.ch/event/663598/) and “Update on MKI impedance studies” (https://indico.cern.ch/event/734086/)



Can we reach 1.8e11 p/b in 1.8 μm?

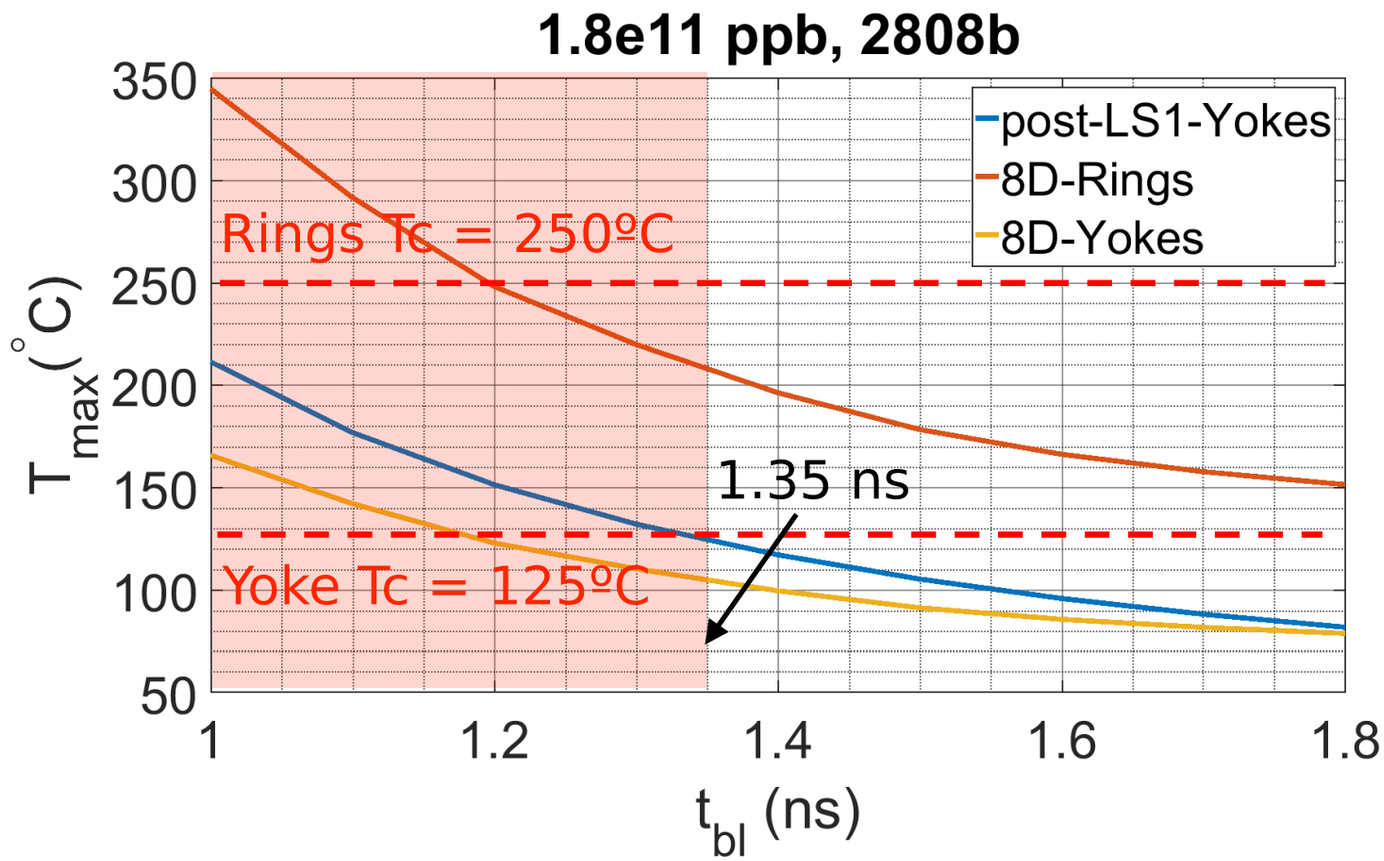
→ **OK for TCDIL and TDIS**

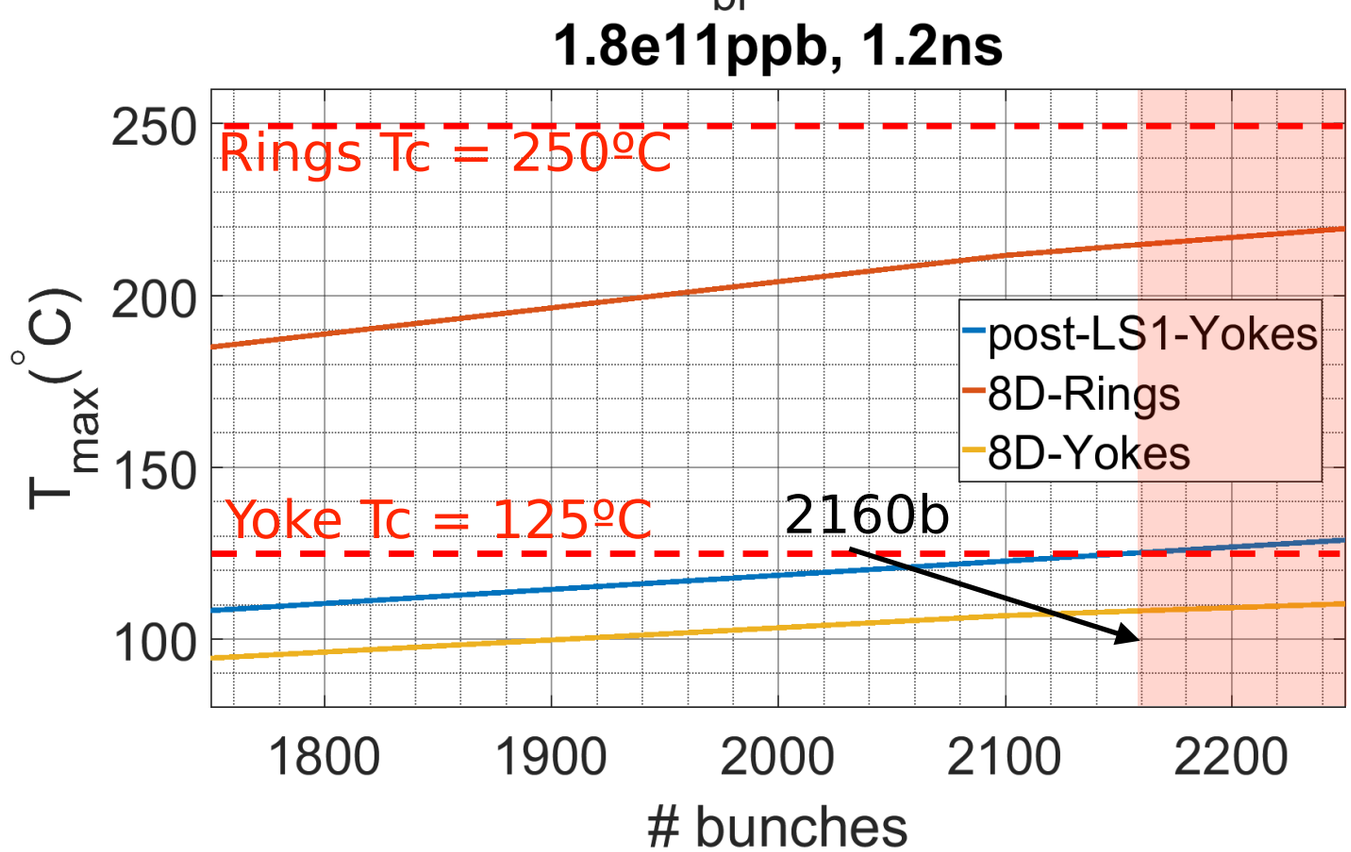
→ **MKI:**

- ↳ Steady state approach used
- ↳ Assuming 2808b with 1.8e11 p/b, equidistant and equi-populated bunches with Gaussian longitudinal profile
- ↳ Assuming 1.8e11 p/b, t_{bl} = 1.2ns, equidistant and equi-populated bunches with Gaussian longitudinal profile

→ These limits are intended for normal operation. In case of usage for specific tests, **depending on the operational conditions foreseen (previous cool down, time at flat top, etc.), allowed parameters (N of bunches and bunch length) to be evaluated**

=> 1.8e11 p/b not excluded and OK for normal operation with limitations as indicated in the plots!





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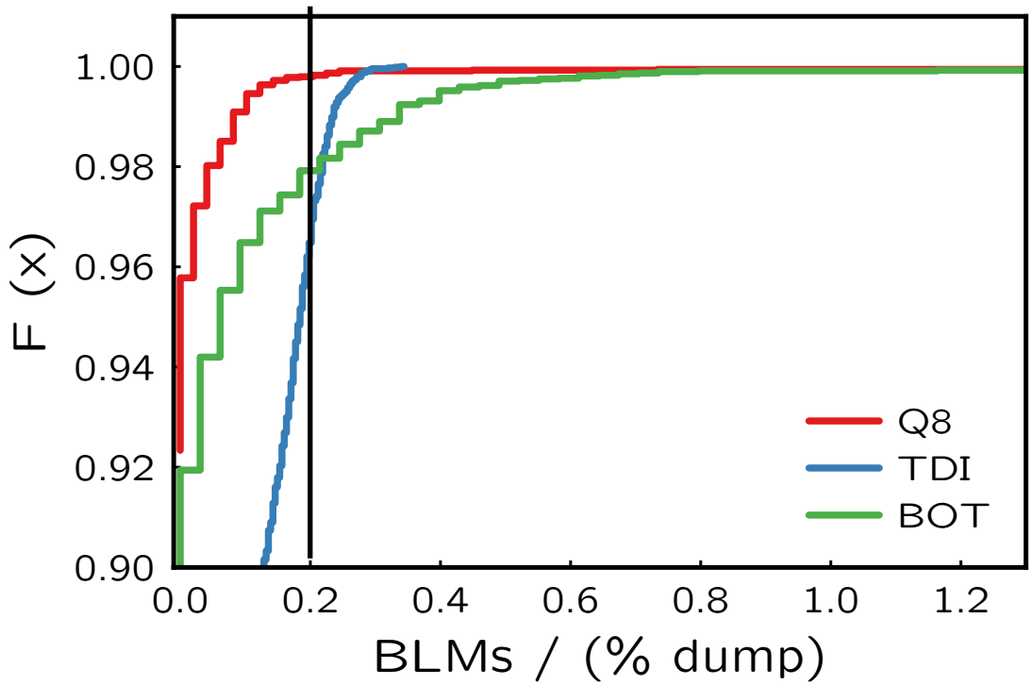
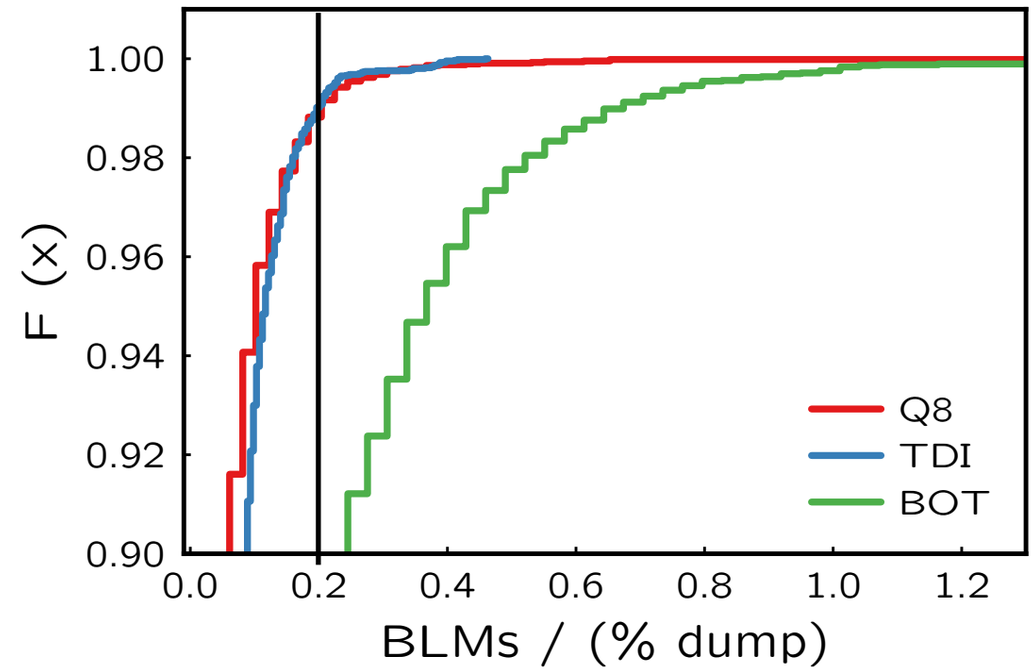
Conclusions

- Significant changes over run II for both MKI and TDI
  - These changes permitted to achieve the last year performances maintaining the expected availability from the systems and machine protection
- The TL steering frequency topic came back this year due to losses at injection, mainly for B1
  - Indeed the steering frequency increased towards the end of the year, as already observed during last year of run I
  - TL steering analysis (Jorg) shown slow drifts, mainly in the H plane, increasing until the end of the year and pointing towards SPS orbit/extraction elements
    - In agreement with 2012 studies
    - **Proposed "TL steering cleaning" campaign after TS to restore initial multi-bunch trajectory (reference)**
    - **Proposed to include 2 (or 3) x 12bunches in every filling scheme to allow/encourage steering at every injection => possibly with the possibility to dynamically change filling scheme**
  - Steering directly linked to injection losses
    - In 2018, better longitudinal losses performance than 2017. In 2018, worse transverse losses, especially B1, as expected
    - One of the main issues was the lack of filter on interconnection BLM MBB-MBA - very close to TCDIH.29205:
      - **Propose to implement filter on this BLM - discussion already started with threshold WG. Details to be evaluated also accounting for new TCDIL and shielding**
    - Trajectory jitter at the TCDIs seems to have gotten worse and this seems to point towards the MSE in LSS6 - more analysis needed - model of the whole SPS extraction in TLs too. Constant follow up
- For run III, new TCDIL and TDIS will make the LHC injection protection system ready for LIU beams
  - For 1.8e11 p/b in 1.8 um:
    - **No limits for TDIS and TCDIL**
    - **Heating of the MKI with post-LS1 design define the normal operational limitations on max number of bunches storable and bunch length or cool-down. Details of operation at this intensity to be discussed but not showstoppers**

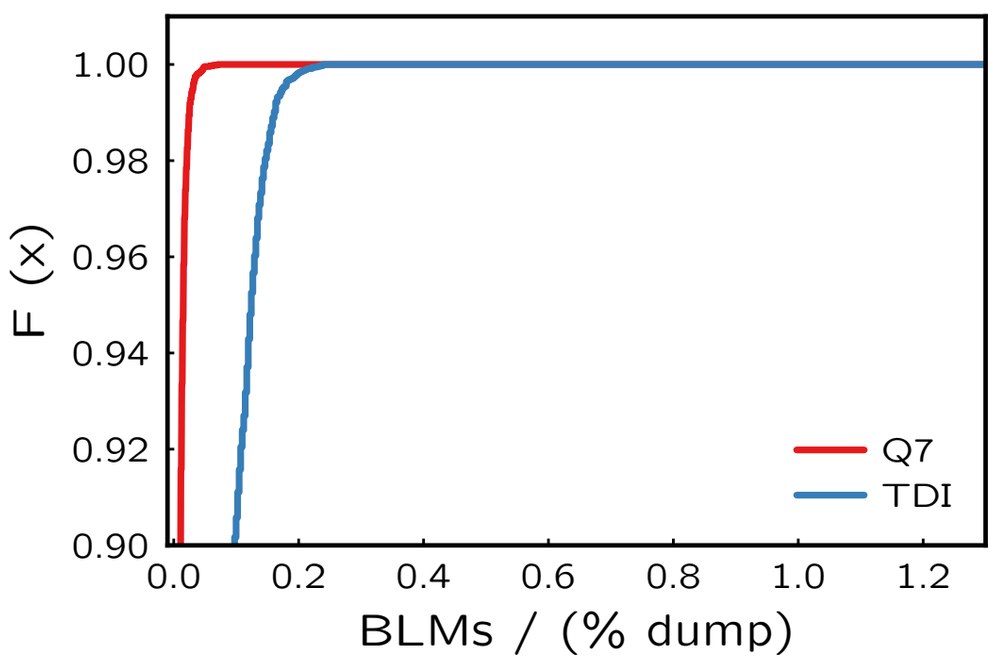
Thank you!

Zoom in

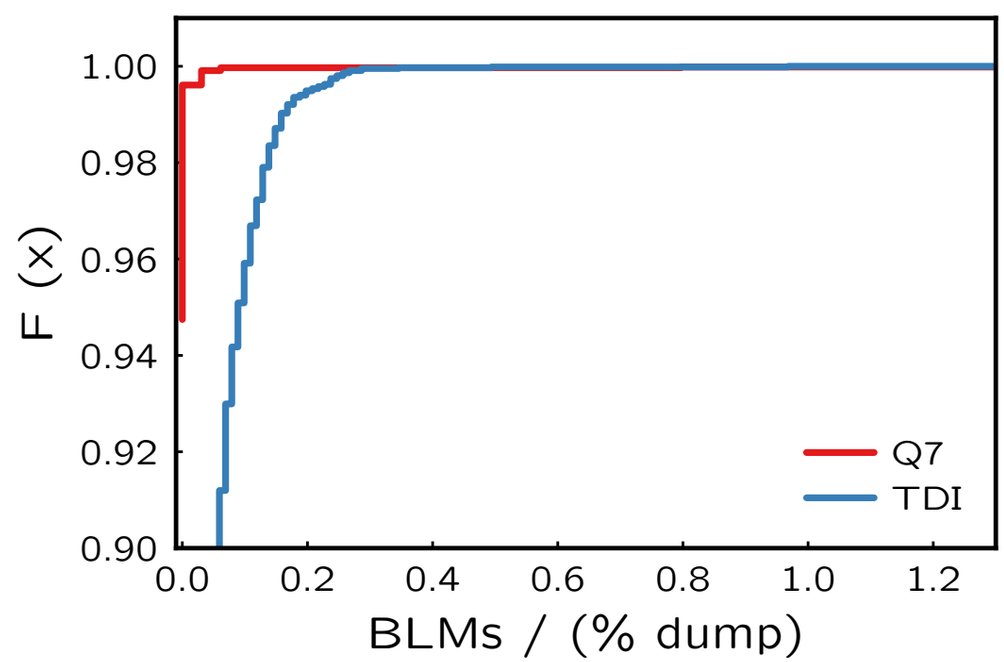




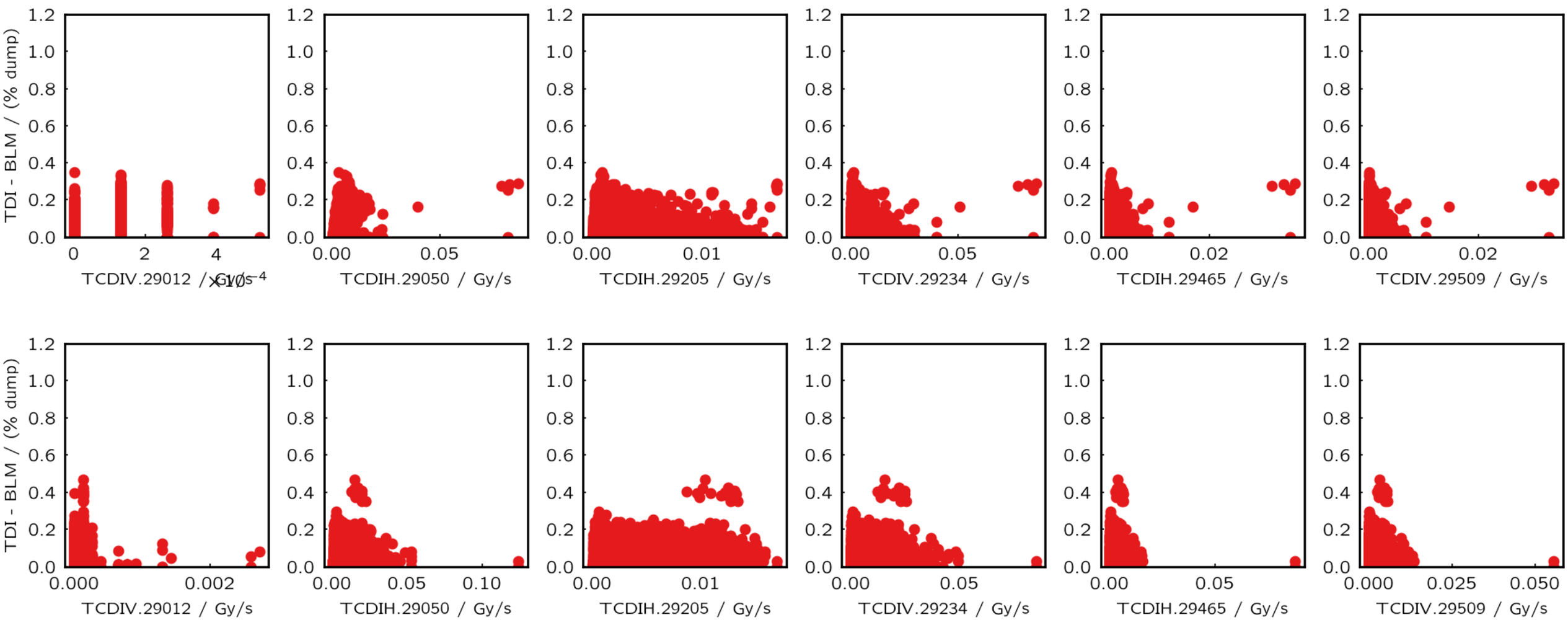
2017



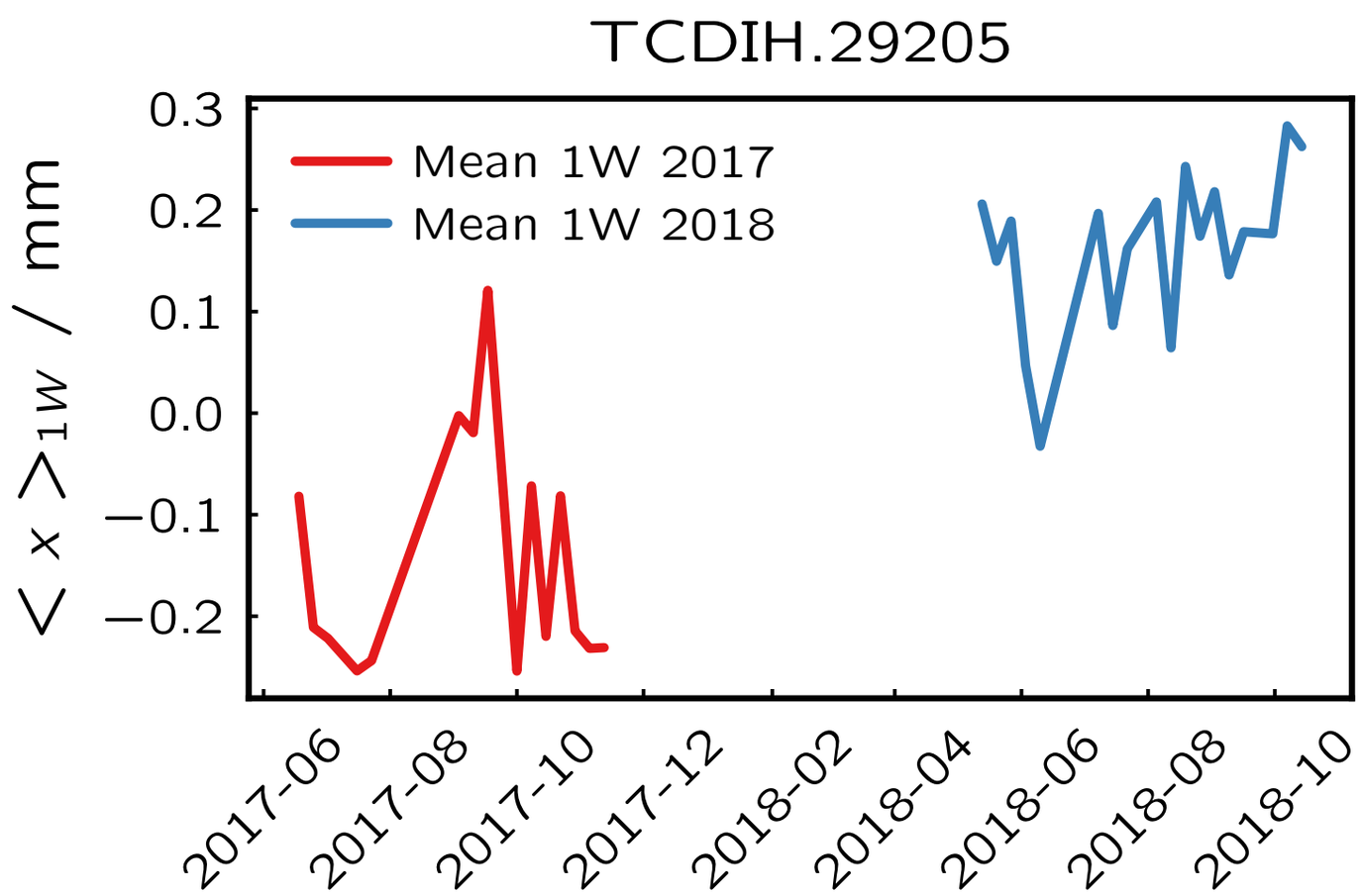
2018



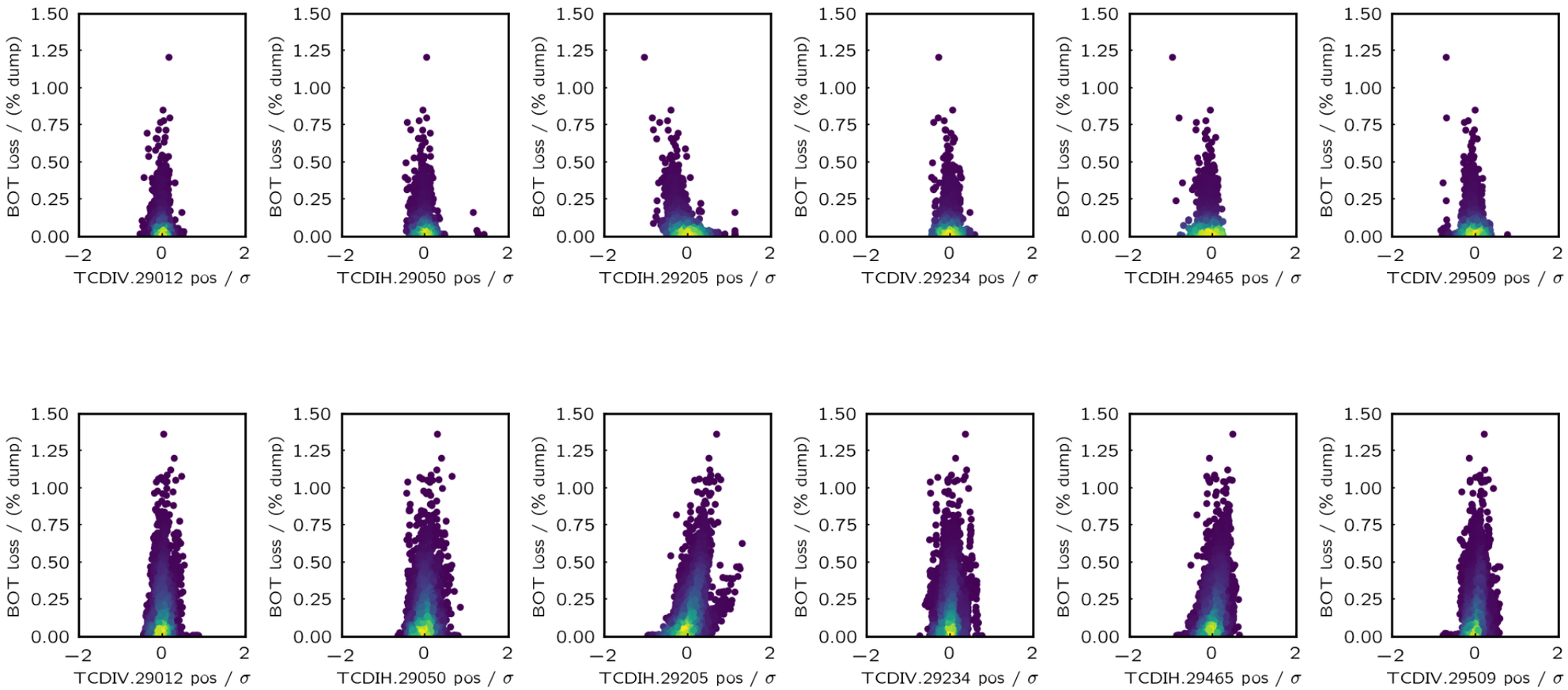
TDI VS TCDI losses 17/18



Mean trajectory evolution TCDIH



Injection losses VS TCDI_pos



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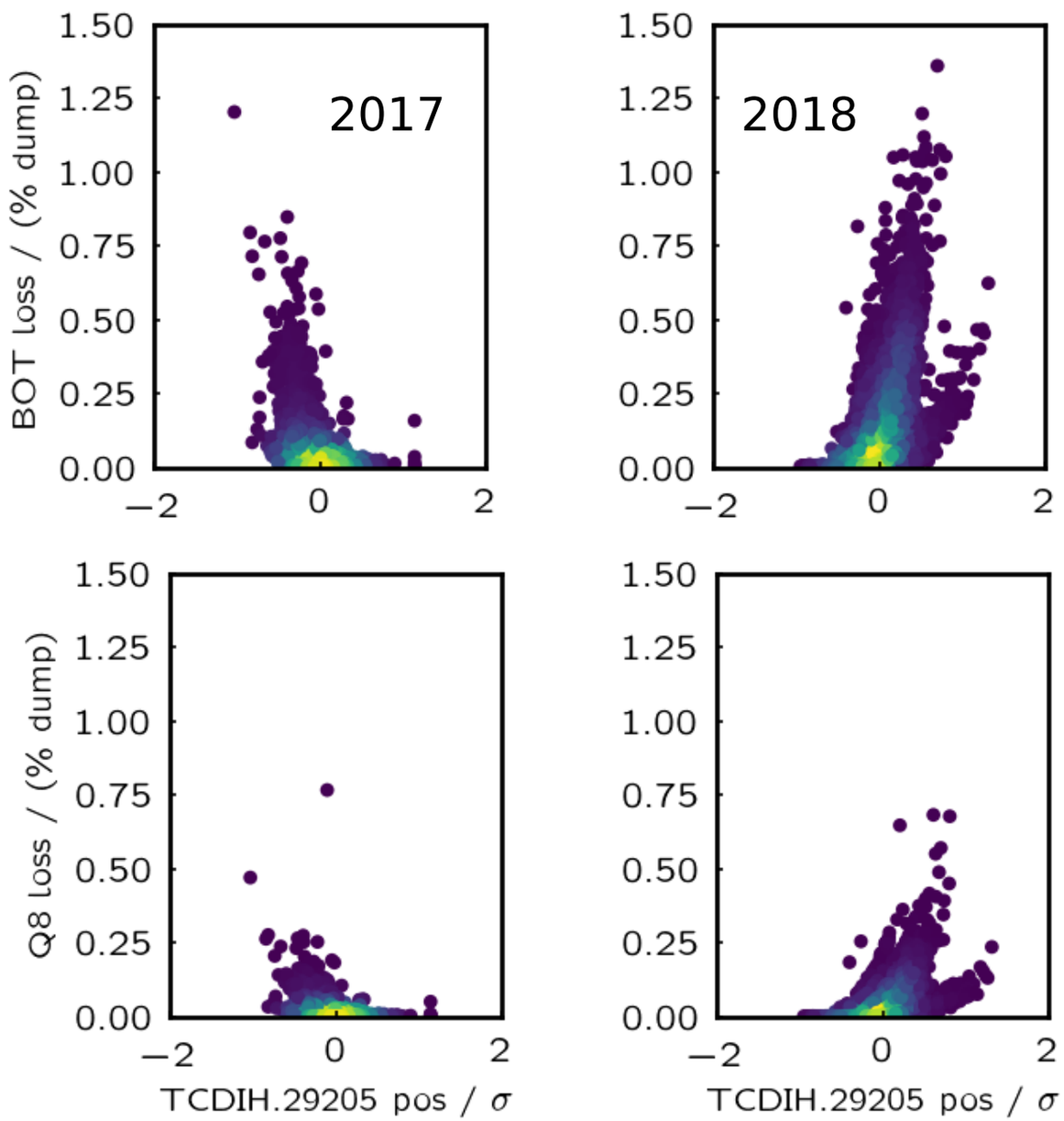
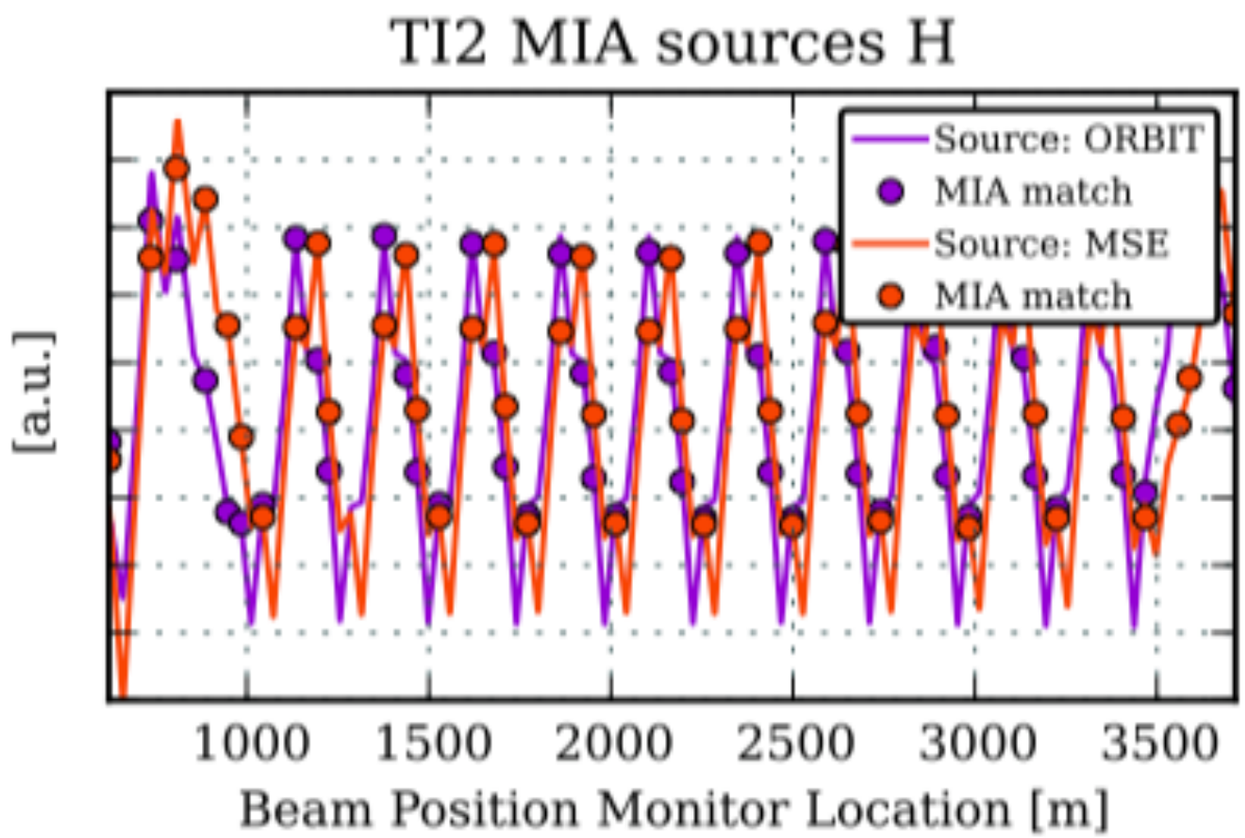


Source of TI2 drifts

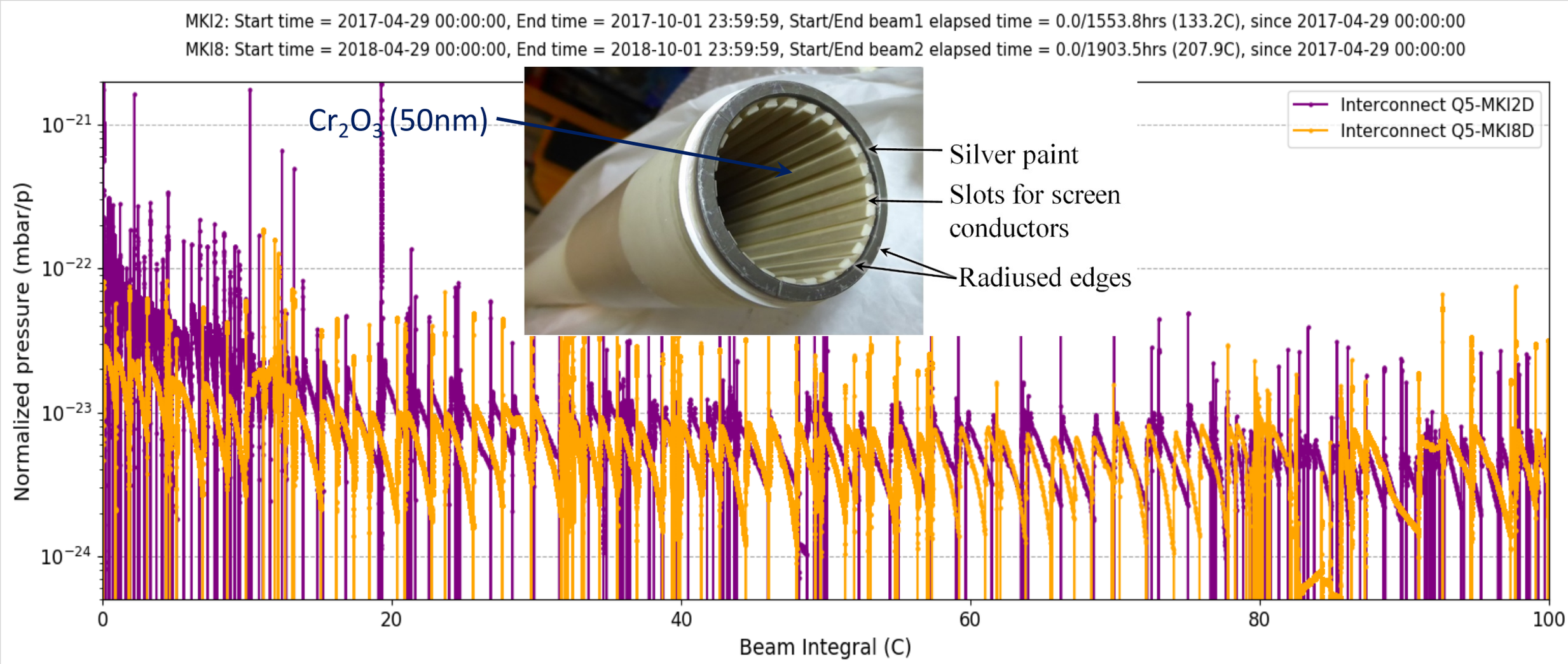
L. Drosdal, "ANALYSIS OF LHC TRANSFER LINE TRAJECTORY DRIFTS:

http://lss.fnal.gov/archive/2013/conf/fermilab-conf-13-125-apc.pdf



Cr_2O_3 coating ⇨ faster beam conditioning

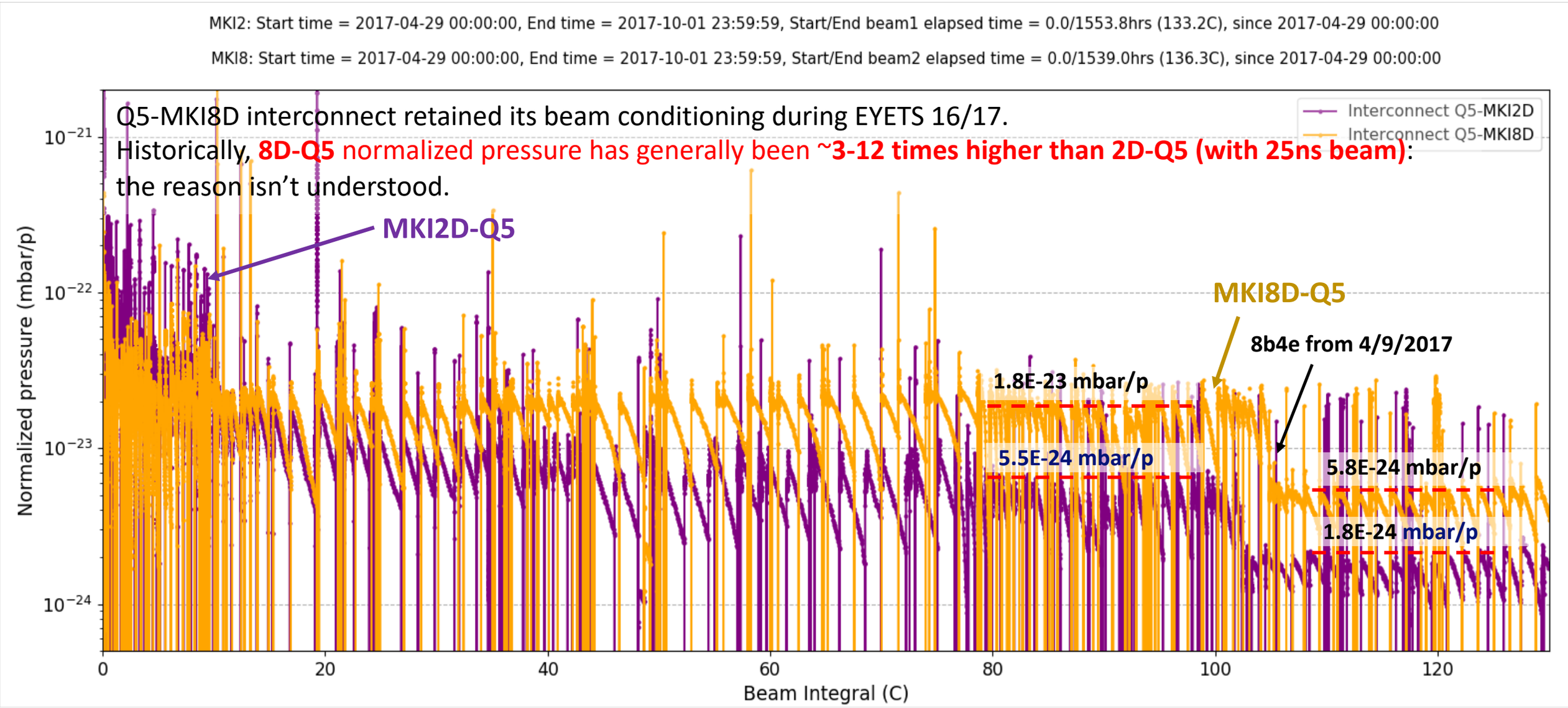
MKI2D-Q5 @ 2017 & MKI8D-Q5 @ 2018: Normalized pressure for MKI interconnects



The alumina tube of the upgraded MKI8D, coated with 50nm of Cr_2O_3, shows faster conditioning with beam than the uncoated (MKI2D) tube.

MKI2/8D-Q5 normalized pressures after YETS 2016-17

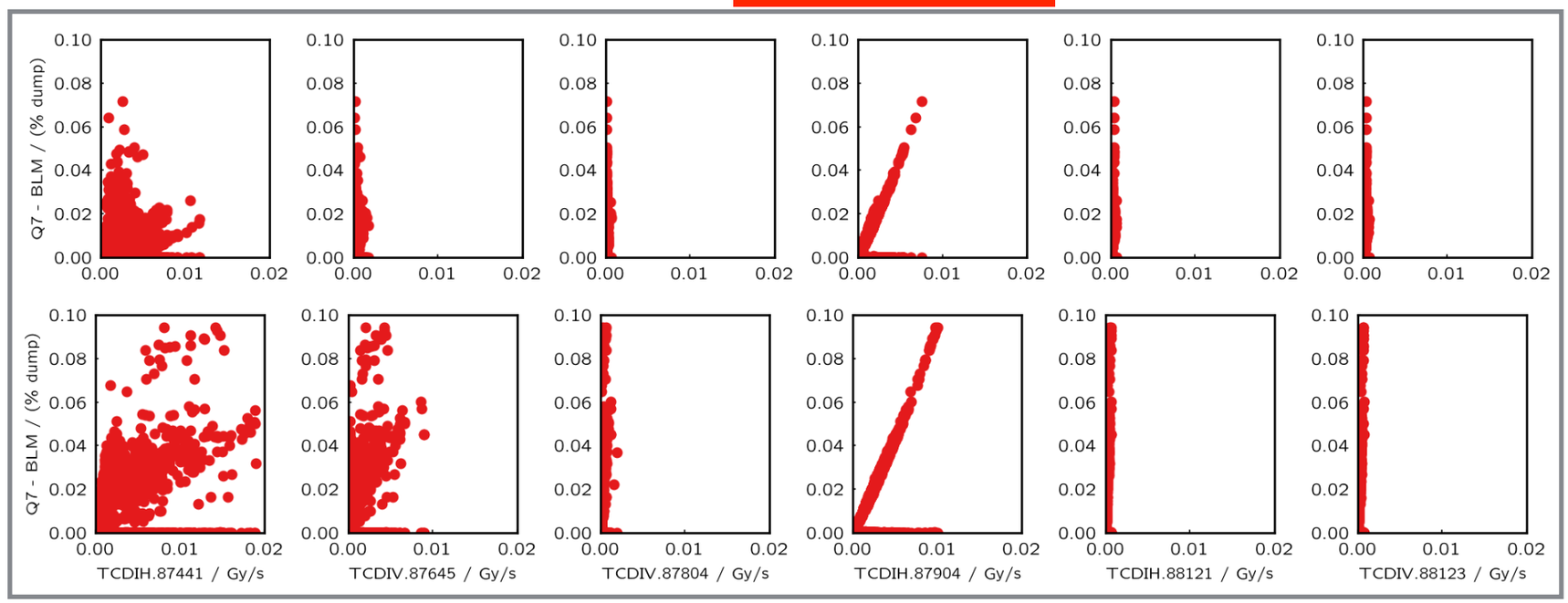
MKI*D-Q5, 2017: Normalized pressure for interconnects vs ***Beam Integral*** *("old" MKI8D, "new" MKI2D)*



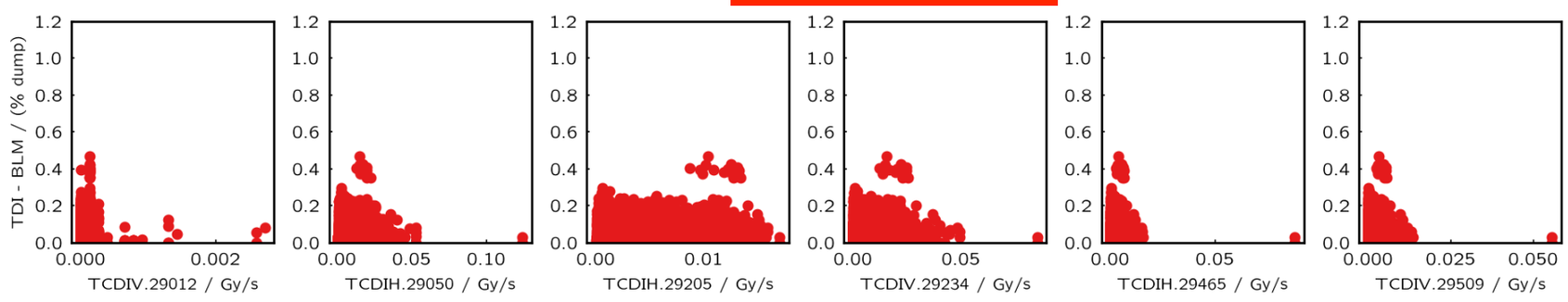
Transverse losses 2017/18 - TI8

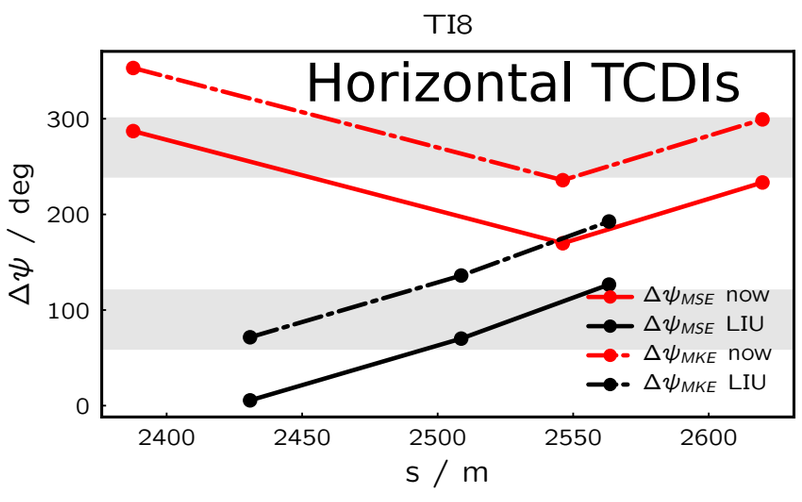
- → Correlation between losses at the 2 critical BLMs and all TCDI BLMs
- → First 2 TCDIHs show non-random patters with the Q7 BLMs
- → Completely uncorrelated losses at the TCDIs with TDI!
- → As losses were very well under control, main focus on B1/TI2

Q7 BLM



TDI BLM





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