Abort Gap Keeper (AGK) and Abort Gap Protection

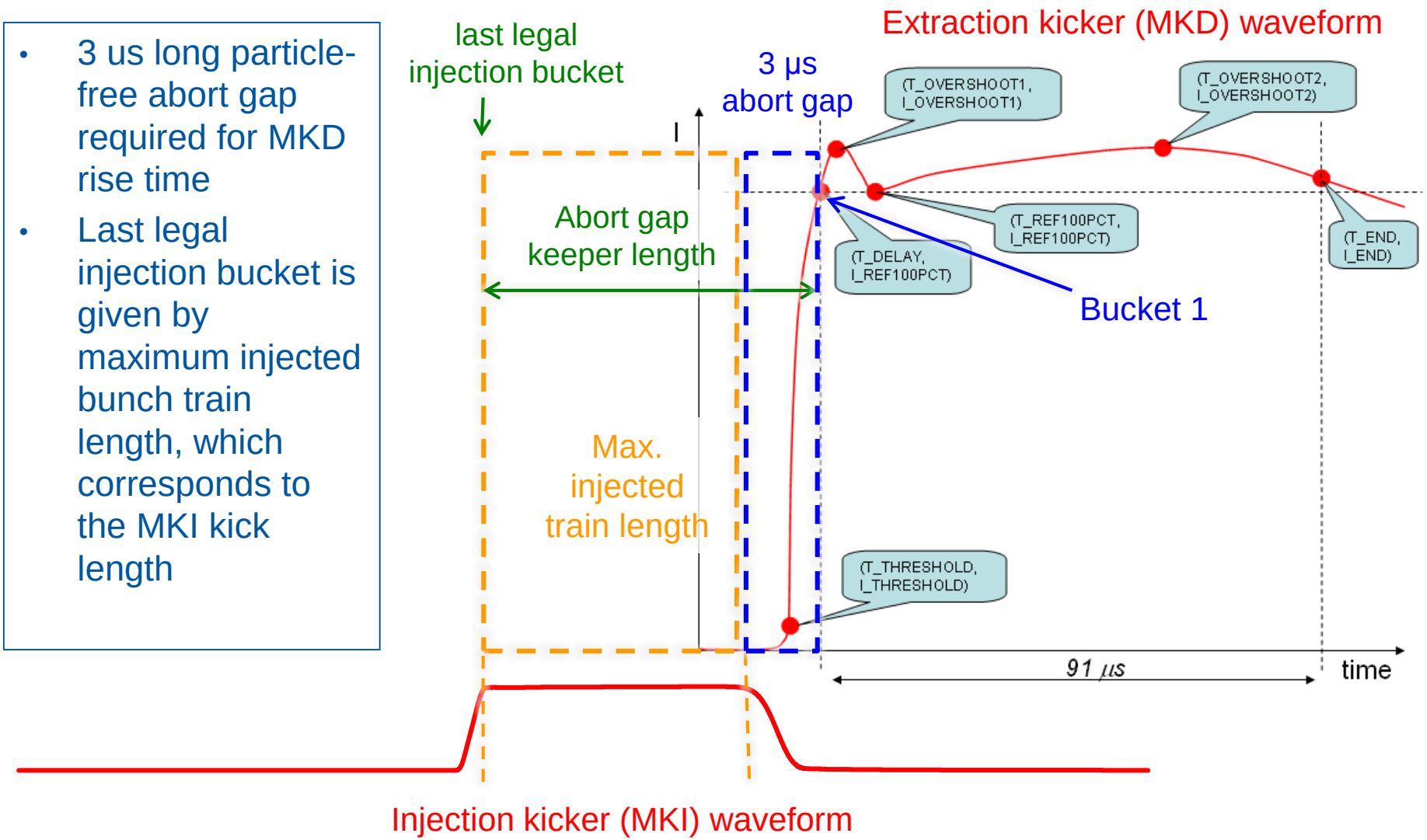
C. Wiesner, W. Bartmann, C. Bracco, E. Carlier, M. Fraser, B. Goddard, D. Jacquet, N. Magnin, J. Wenninger

Outline

- Introduction: Abort gap and why do we have to protect it?
- Abort Gap Keeper (AGK) and how we protect the abort gap?
  - New variable AGK
  - Injecting into the abort gap: 04.09.2017 incident and lessons learned
  - Current protection scheme
- Summary and conclusions
- Outlook and further improvements?

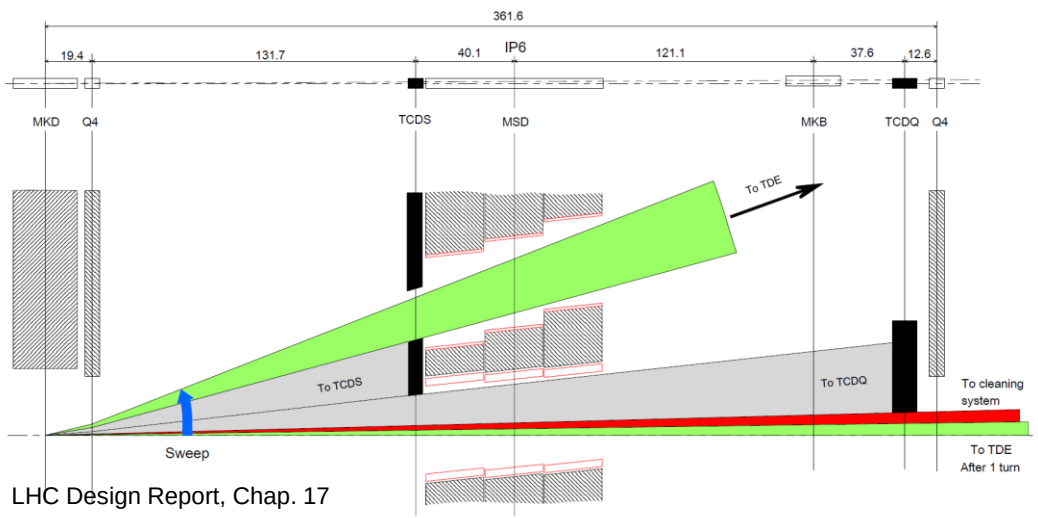
Abort Gap

- 3 us long particle-free abort gap required for MKD rise time
- Last legal injection bucket is given by maximum injected bunch train length, which corresponds to the MKI kick length

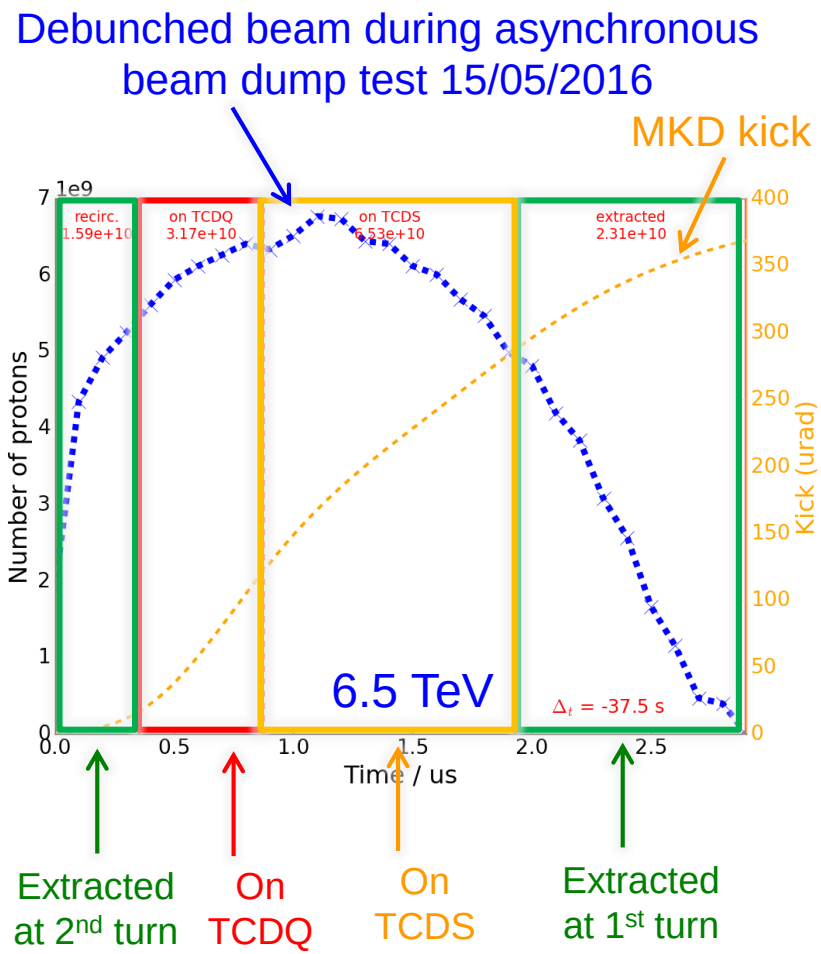


Abort Gap and Beam Losses

- Firing of MKDs with beam present leads to an asynchronous beam dump, where beam is swept over the machine aperture.
- Possible causes:
  - Loss of synchronisation (i.e. TSU failure)
  - MKD erratic
  - Accidental injection into the abort gap



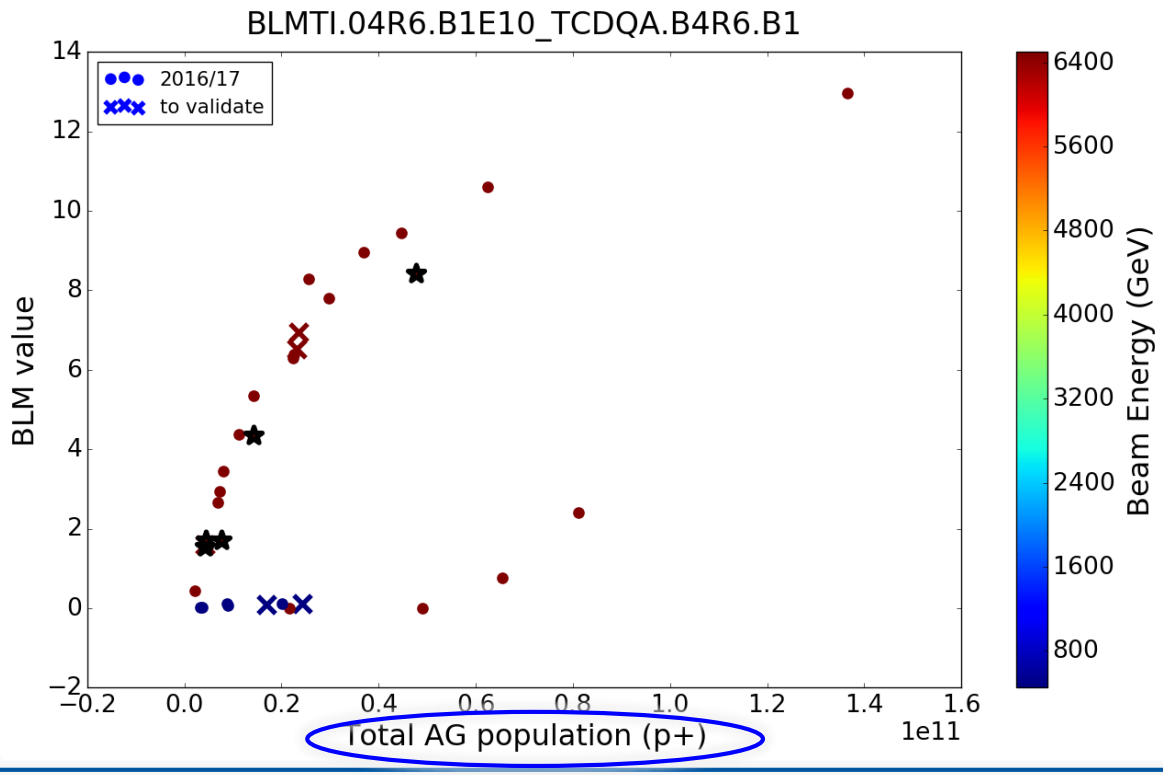
LHC Design Report, Chap. 17



Measured Beam Losses at TCDQ

Loss profile strongly depends on abort gap distribution

Beam losses over **total abort-gap population** during asynchronous beam dump tests 2016/17

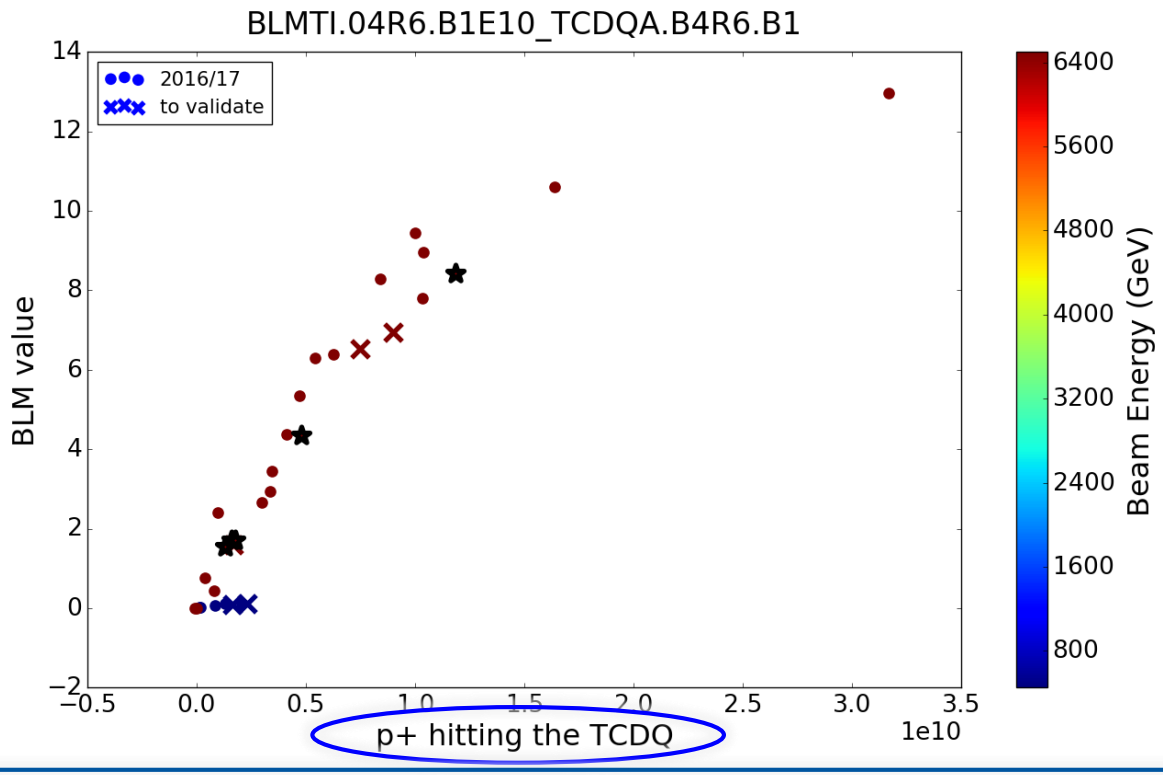


No clear correlation between BLM values and total abort-gap population

Measured Beam Losses at TCDQ

Loss profile strongly depends on abort gap distribution

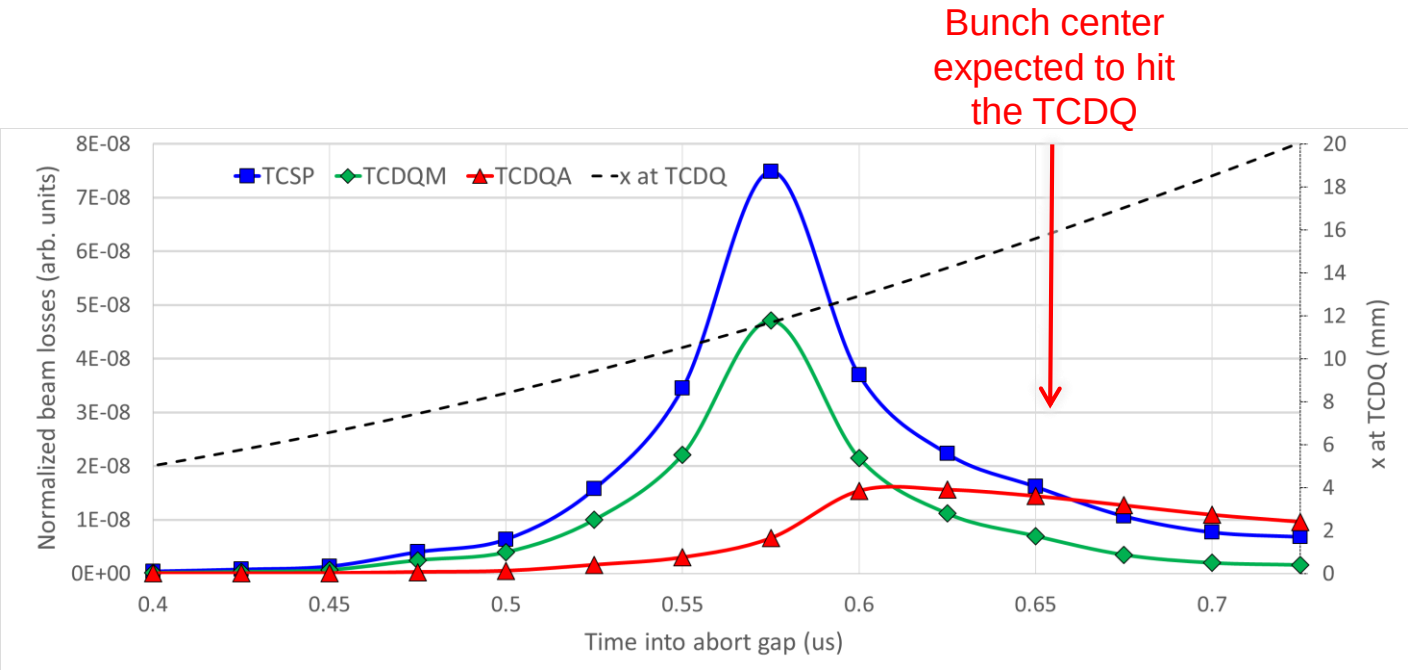
Beam losses over **protons calculated to hit the TCDQ** during asynchronous beam dump tests 2016/17



BLM values correlate with p+ losses on the TCDQ

Measured Beam Losses at TCDQ

Most critical impact region is close to the TCDQ edge



- Single pilot bunches at 450 GeV on TCDQ
- TCDQ at 16 mm
- TCSP at 15 mm

Preliminary results, MD2930, 3.12.2017, Beam 1

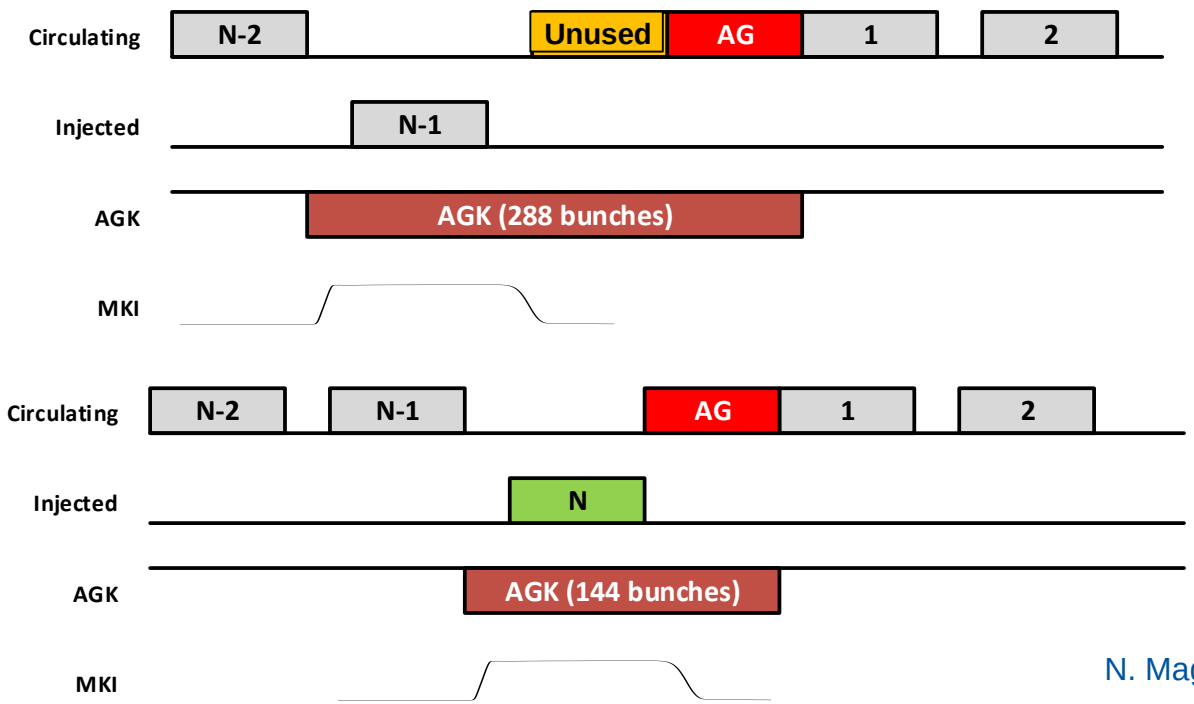
Abort Gap Keeper (AGK)

Hard-coded AGK (until 2016):

- Fixed for e.g. 288 bunches
- For shorter trains: loss of luminosity
- Change required new TSU firmware, intervention in the tunnel and revalidation

Old Setup

New Setup

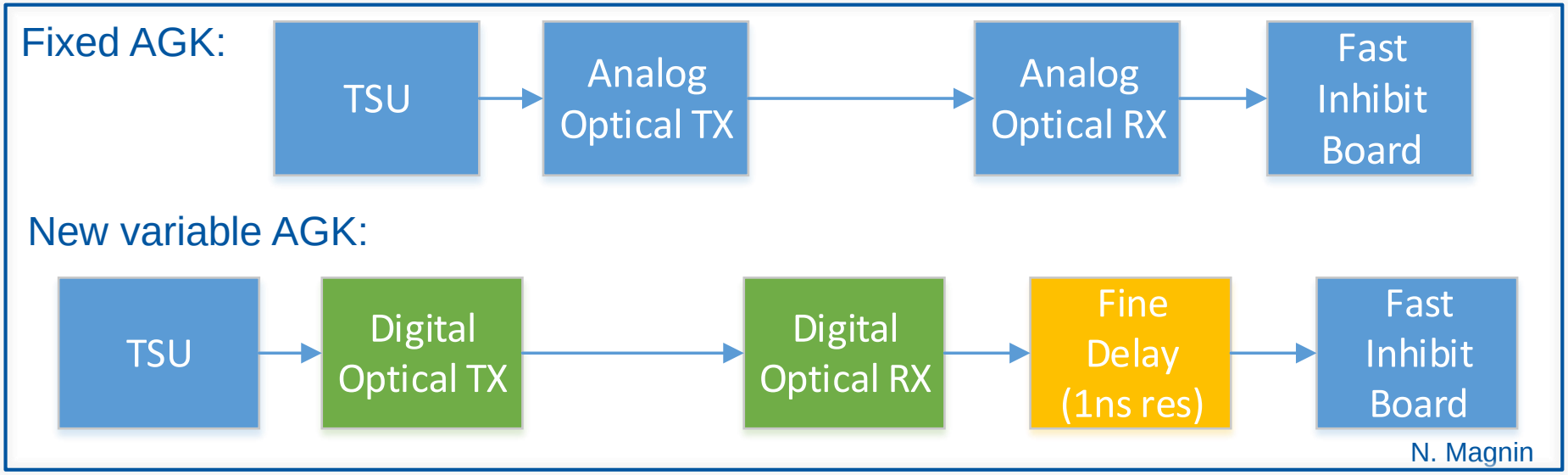


N. Magnin

Abort Gap Keeper (AGK)

Variable AGK (since 2017)

- Temporary implementation in 2016. Consolidated during EYETS16-17
- Regenerates a new AGK window at the MKI level
- The Fine Delay card is used to generate the variable length AGK signal at P2/8
- Allows software change of AGK length
- After every change, revalidation of AGK settings with beam required [1]



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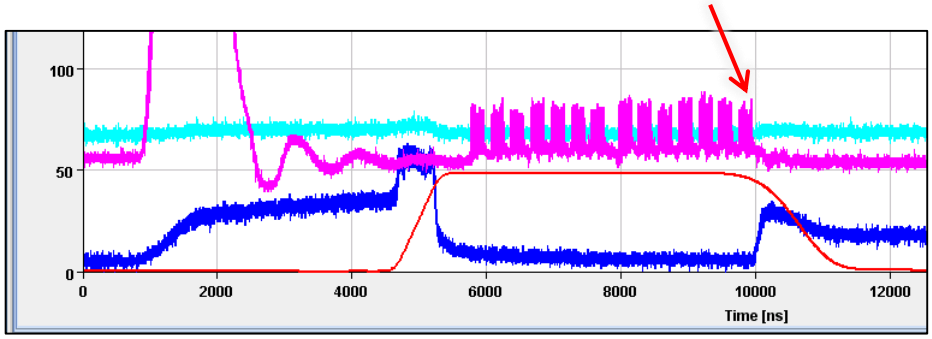
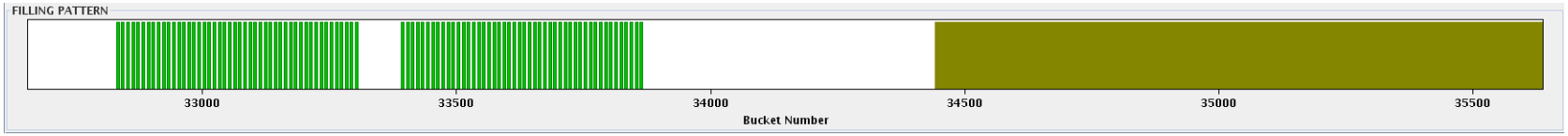
Filling Scheme Change: 4.9.2017

- The MKI was set up for 144 bunches (3 x 48 BCMS) which require 160 bunch slots
- 8b4e has 56 bunches in 80 bunch slots per PS batch. Two PS batches injected into LHC: 112 bunches in 168 bunch slots
- This caused the MKI to be too short by 8 bunches - injection still within tolerances
- First bucket of last train not in abort gap – therefore no interlock

Last 8 bunches injected onto MKI falling edge

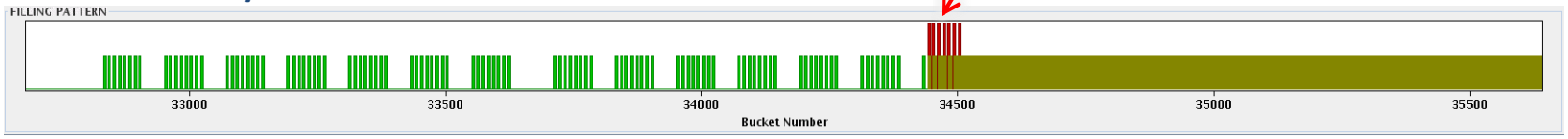


144b BCMS: 2x 72/25ns + 225ns:

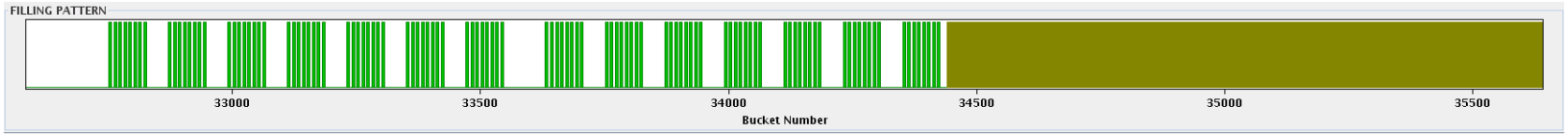


112b 8b4e: 2x80/25ns + 225ns:

Last 7 bunches injected into abort gap



112b 8b4e: Corrected filling scheme

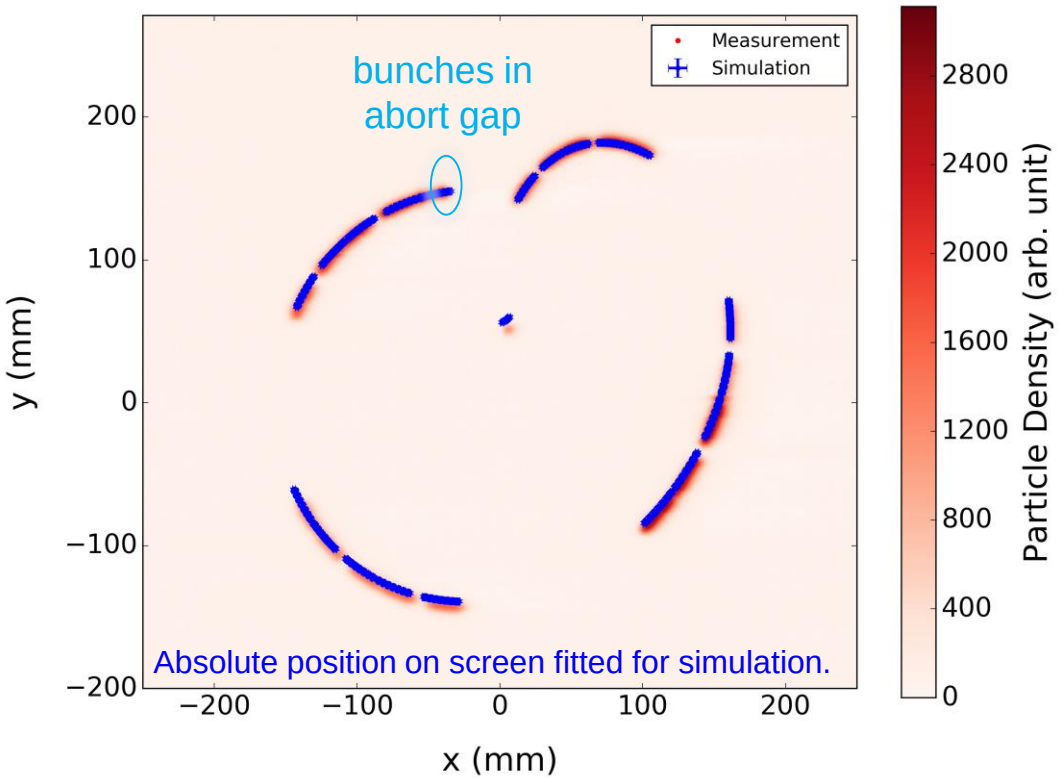


Courtesy W. Bartmann, N. Magnin

Filling Scheme Change: 4.9.2017

- Beam dumped by operators during the ramp (~2 TeV)
- Bunches in abort gap received small kicks between 0.15 µrad and 1.2 µrad, corresponding to 50 µm to 400 µm horizontal offset at TCDQ (<1 sigma for flat-top values).
- Recirculated and dumped at 2nd turn.
- Clean dump in XPOC

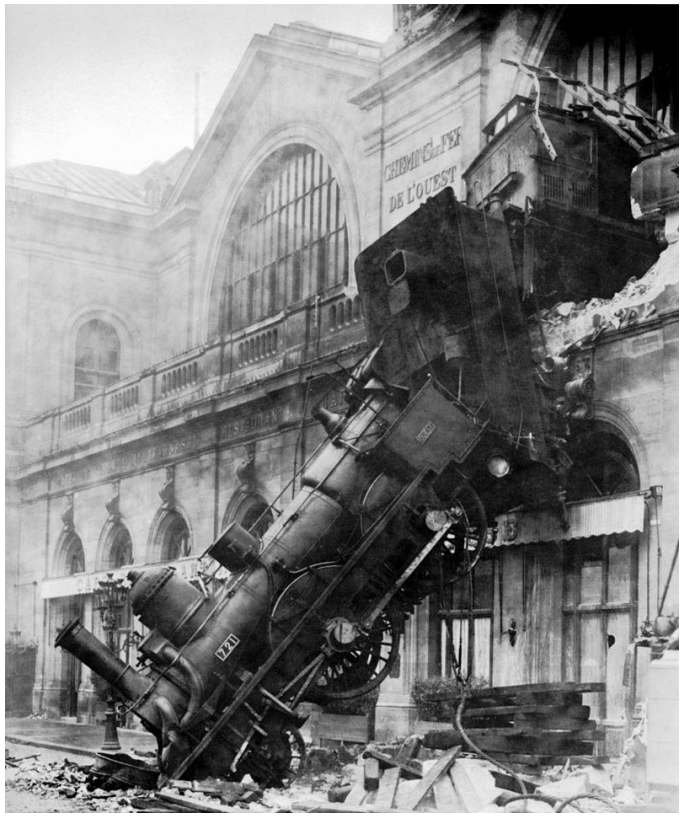
BTVDD image



Lessons learned…

- Injection Sequencer now blocks (not only warns) if train length does not match with MKI length
- Lack of protection closed…
  - Only first requested bucket was checked for injection in abort gap
  - Issue was present also with hard-coded AGK, but never appeared
  - New SIS checks implemented, e.g. check for last injected bucket
- Change of filling pattern now requires EDMS document

Never inject too long trains…



https://en.wikipedia.org/wiki/Montparnasse_derailment#/media/File:Train_wreck_at_Montparnasse_1895.jpg

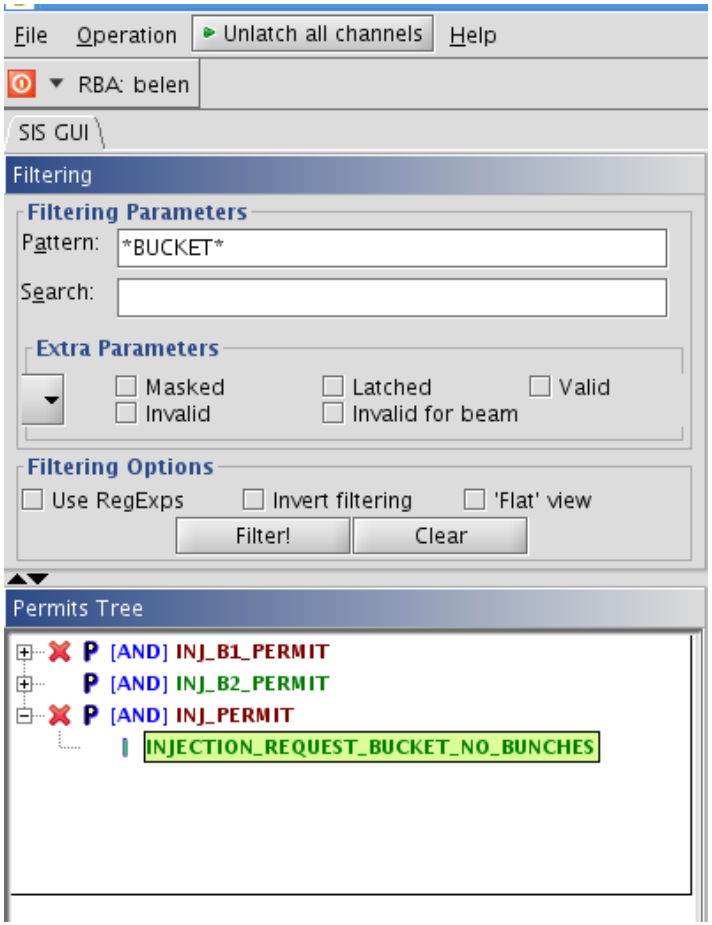
Current Protection Scheme

Injection sequencer

- blocks if train length is > MKI kick length
- warns if first requested bucket is inside abort gap

Abort-gap relevant interlocks in SIS:

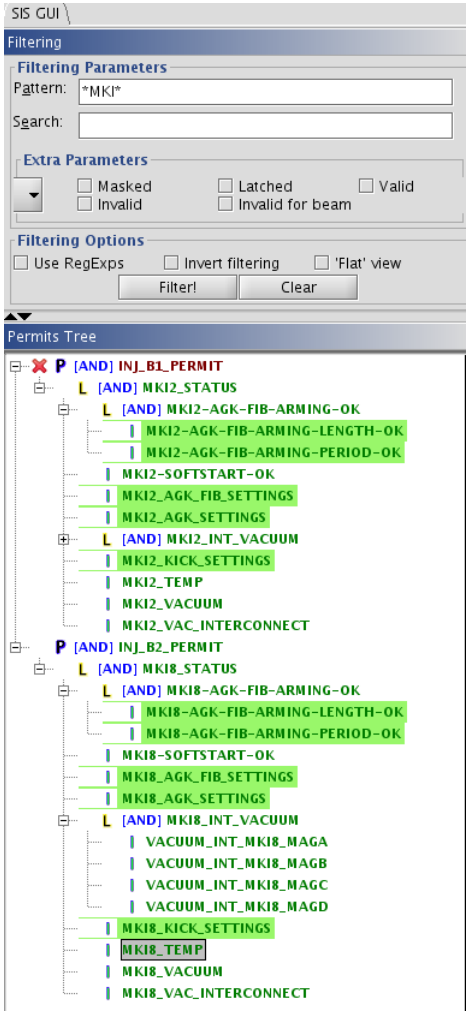
- **INJ_PERMIT** tree:
  - SPS_BQM
    - Checks that the SPS train length (BQM) is consistent with MKI kick length (SIS setting)
    - Checks that last injected bunch will not be in the abort gap
  - INJECTION_REQUEST_BUCKET_NO_BUNCHES
    - Checks that the requested injection bucket is not inside the AGK forbidden region (SIS setting)
    - Checks that the requested number of bunches does not exceed the allowed limit (SIS setting)



For the details of the protection settings in the Injection Sequencer and SIS see D. Jacquet, J. Wenninger [2]

Current Protection Scheme

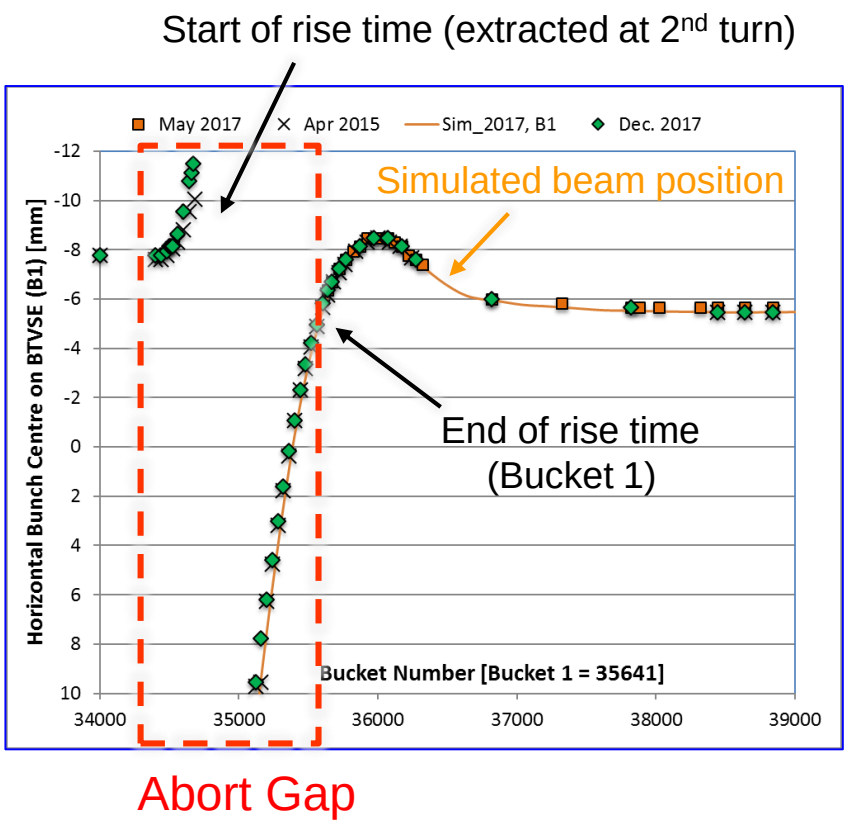
- **INJ_B1(2)_PERMIT** trees:
  - Check that the requested injection bucket for B1(2) is not inside the AGK forbidden region (SIS setting)
    - INJECTION_BUCKETB1(2)
  - Check consistency of AGK/MKI/FIB settings against SIS settings:
    - MKI2(8)_STATUS/MKI2(8)_AGK_SETTINGS
    - MKI2(8)_STATUS/MKI2(8)_KICK_SETTINGS
    - MKI2(8)_STATUS/MKI2(8)_AGK_FIB_SETTINGS
  - Check FIB arming length/period is within tolerances:
    - MKI2(8)_STATUS/MKI2(8)-AGK-FIB-ARMING-OK/MKI2(8)-AGK-FIB-ARMING-LENGTH-OK
    - MKI2(8)_STATUS/MKI2(8)-AGK-FIB-ARMING-OK/MKI2(8)-AGK-FIB-ARMING-PERIOD-OK
- **All SIS interlocks are currently maskable**
- **Injection BIS**
  - MKI2/8 BETS/AGK/Erratic
- No check of MKI fine delay settings



For the details of the protection settings in the Injection Sequencer and SIS see D. Jacquet, J. Wenninger [2]

Injecting into the Abort Gap

- Two MDs that required injection into the Abort Gap in MD4:
  - "MKD rise time"
  - "Asynch. dump test with bunched beam"
- Required masking of SIS interlocks, and ignoring Injection Sequencer warning
- MKI fine delay settings used to move abort gap. No direct change of AGK settings…
- Procedure to inject into the abort gap without intervention in the tunnel established in MDs
  - Could be used for regular re-measurement of the MKD rise time, e.g. during commissioning?
- Better protection for MKI fine delay settings has to be implemented



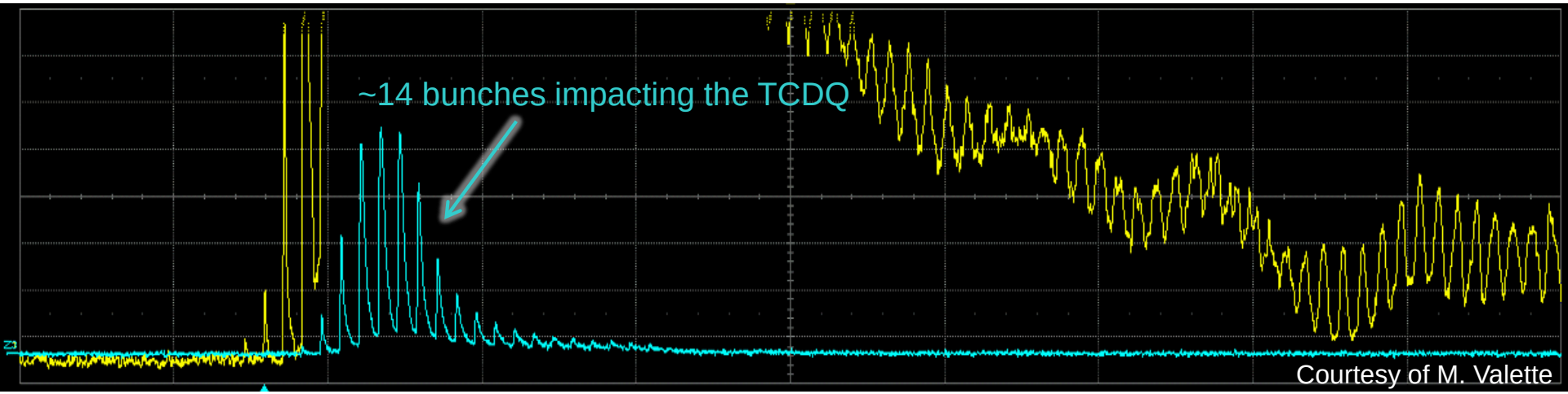
Energy Dependence

MD2930:

- Even full 450-GeV train with nominal intensities (1.25e11 p+) on TCDQ did not lead to magnet quench
- However, at 6.5 TeV, single pilot (1.9e10 p+) caused quench

Therefore, ramping with beam in the abort gap is main risk.

Energy	TCDQ position	# of bunches that would hit the TCDQ
450 GeV	~16 mm	~14
6.5 TeV	~4 mm	~21



Diamond BLM signal for train of 48 bunches at 450 GeV in abort gap (MD2930, 3.12.2017)

Summary and Conclusions

- Variable AGK allows change of filling pattern without access to the tunnel
- Revalidation procedure established [1]
- Lack of protection closed in SIS and additional protection implemented
- Injection Sequencer now blocks (not only warns) if MKI length does not match with train length
- Change of filling pattern now requires EDMS document

Outlook and Further Improvements?

- Implement **sequencer task "check abort gap population before ramp"**?
- **MKI fine delay settings** now in LSA. Check correct settings in SIS or MCS check in sequencer?
- Check in **IQC relative position of AGK with respect to MKI** waveform?
- Check in **IQC if injection occurred into the abort gap**?

References

- [1] N. Magnin, Operational Procedure, Procedure to change the length of LBDS Abort Gap Keeper, to be published
- [2] D. Jacquet, J. Wenninger, Injection sequencer and SIS protections against incorrect injection requests (into the AG), November 2017
- [3] LHC Operational Procedure, Asynchronous beam dump validation test, EDMS No. 1698830

Thank you for your attention!

Backup Slides

Required Abort-Gap Margin

- LBDS jitter of +/- 20 ns
- Orbit change at TCDQ might lead to particles hitting TCDQ later/earlier
  - Present software interlock level for orbit excursion at TCDQ corresponds to shift of ~40ns (1.2 mm, top energy) or ~67ns (2 mm, injection energy), respectively.
- MKD waveform changes for each energy: ~60 ns change
- Different types of MKD erratic might lead to different rise times
- Low-loss extraction must also be assured for abnormal conditions:
  - Only 14/15 MKDs firing
  - Orbit excursions of up to 4 mm
  - …
- MKD generator hardware changes might increase rise time

MKD Waveform – Delay Times

Earliest case (2-3 TeV):
Bucket 1 is placed
~60 ns earlier

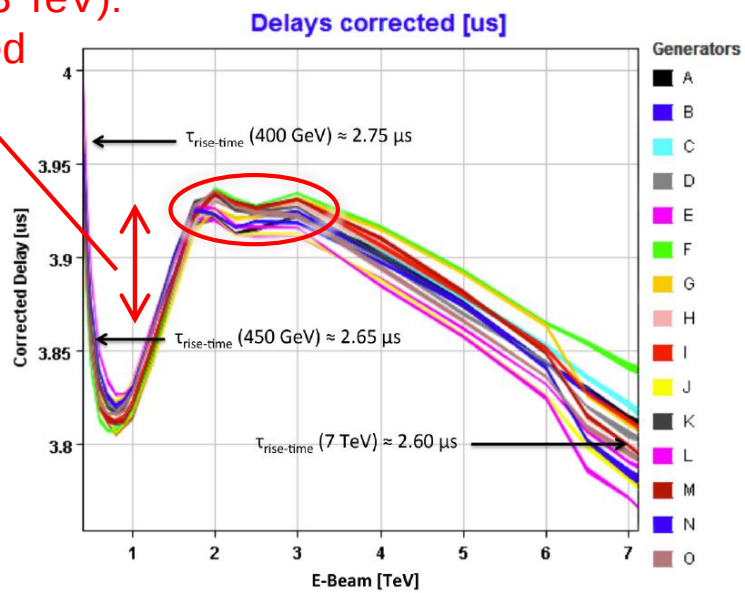
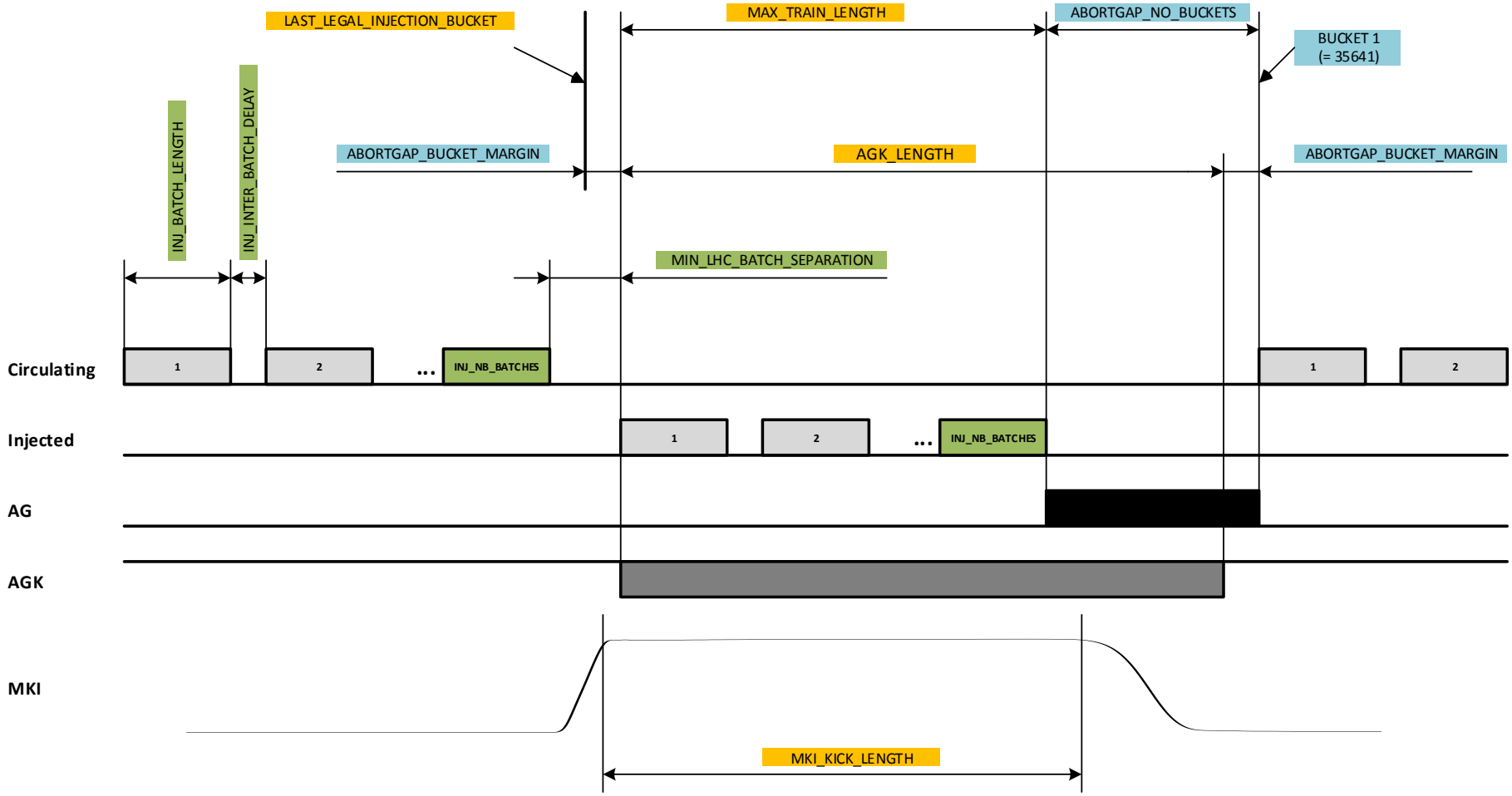


Figure 2: Measured values of T_{DELAY} including computed trigger delay corrections to synchronise the LBDS.

M.A. Fraser *et al.*, "A Beam-Based Measurement of the LHC Beam Dump Kicker Waveform", in *Proc. IPAC'16*, Busan, Korea, May 2016, paper THPOR052, pp. 3911-3913.

Note: Orbit bump away from TCDQ corresponds to shift of ~40ns (1.2 mm, top energy) or ~67ns (2 mm, injection energy)

Overview of AGK Parameters

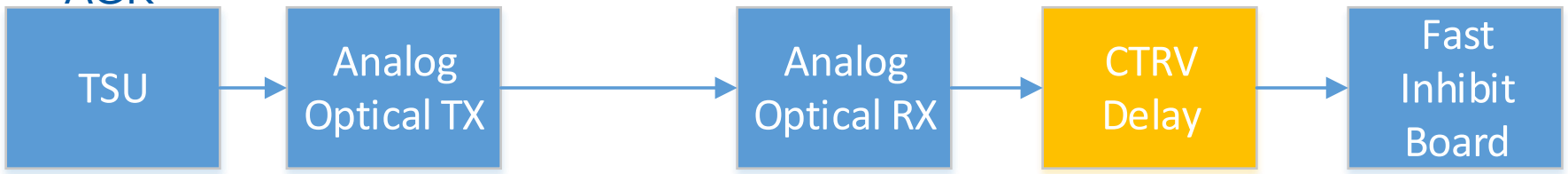


N. Magnin, Operational Procedure, Procedure to change the length of LBDS Abort Gap Keeper, to be published

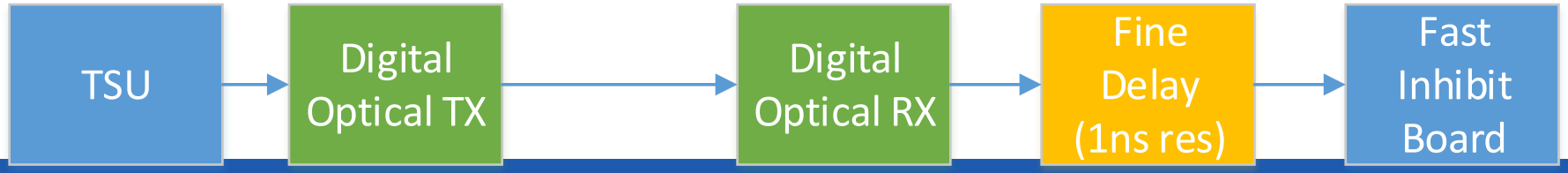
New optical link and delay

Previous analog optical transmission with fixed length (AGK length fixed by TSU)

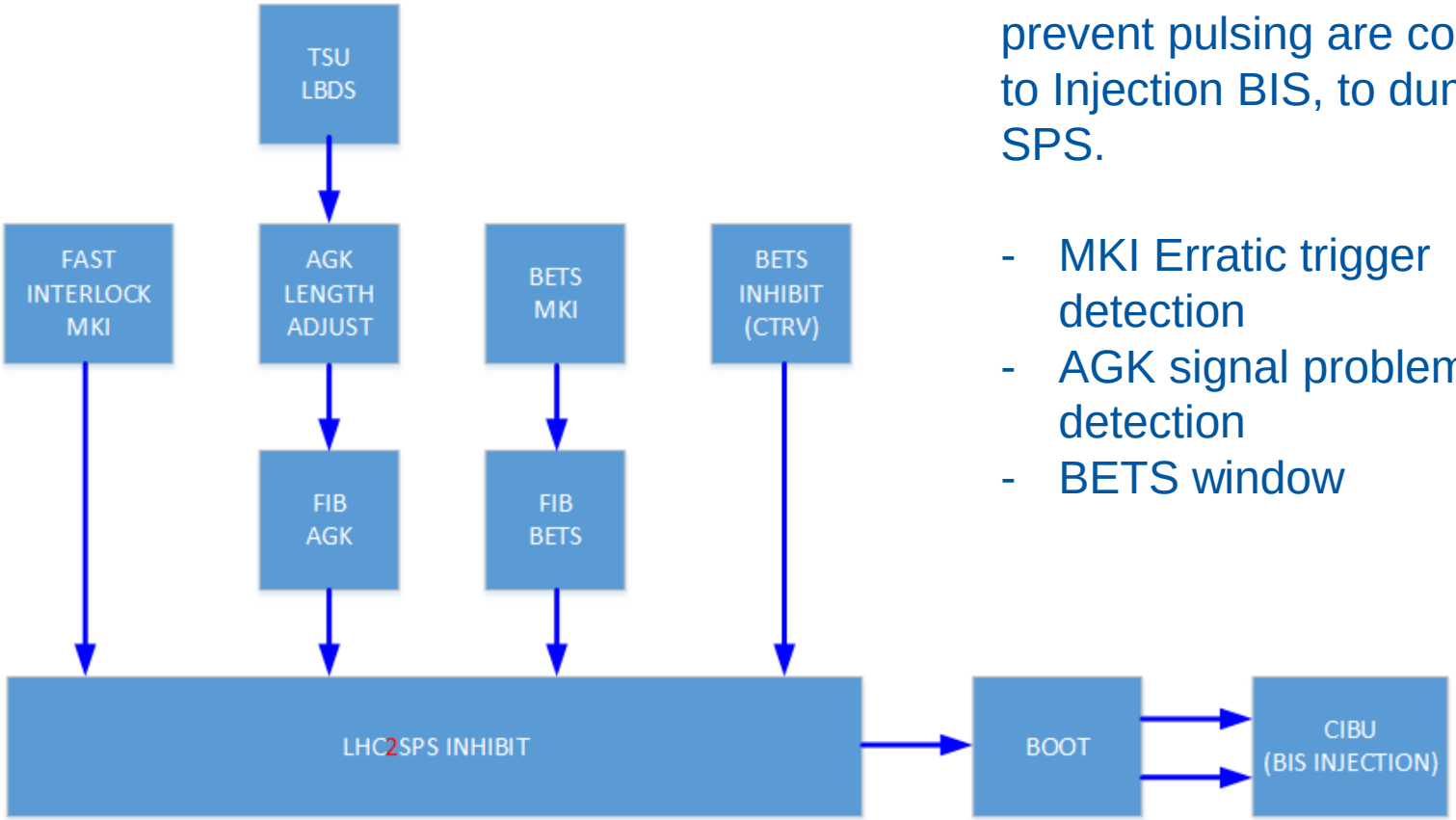
During Summer 2016, addition of CTRV delay to regenerate the AGK



During EYETS, upgrade of optical transmission (Only a pulse is transmitted)



SPS to LHC Inhibit



MKI fast interlocks that could prevent pulsing are connected to Injection BIS, to dump in SPS.

- MKI Erratic trigger detection
- AGK signal problem detection
- BETS window

Asynchronous Dump Tests

- Asynch. beam dump tests to validate extraction protection functionality
- Energy-deposition and quench behaviour not fully understood
- Does it make sense to change our asynch. dump test procedure, e.g. at 450 GeV? Regularly perform asynchronous tests with bunched beam?

8b4e: implications on injection

- 8b4e has 56 bunches in 80 bunch slots per PS batch
  - two PS batches injected into LHC: 112 bunches in 168 bunch slots
- The MKI was set up for 144 bunches (3 x 48 BCMS) which require 160 bunch slots
- This caused the MKI to be too short by 8 bunches - injection still within tolerance
  - Losses on TDI from satellites good < 12%
  - Losses transversely also good
  - Injection oscillations show increasing oscillations for the last ~6 bunches, better visible for B1 than for B2

Courtesy W.Bartmann, N.Magnin et al