Abort Gap Keeper (AGK) and Abort Gap Protection

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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 µs 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
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

Bunch center expected to hit the TCDQ

- 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
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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Fixed AGK:
TSU → Analog Optical TX → Analog Optical RX → Fast Inhibit Board

New variable AGK:
TSU → Digital Optical TX → Digital Optical RX → Fine Delay (1ns res) → Fast Inhibit Board
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N. Magnin

2017/12/13
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

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

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

112b 8b4e: Corrected filling scheme

Last 8 bunches injected onto MKI falling edge

Last 7 bunches injected into abort gap
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 2\textsuperscript{nd} turn.
- Clean dump in XPOC
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...

[Image: 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

Start of rise time (extracted at 2nd turn)

Simulated beam position

End of rise time (Bucket 1)

Abort Gap
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.

<table>
<thead>
<tr>
<th>Energy</th>
<th>TCDQ position</th>
<th># of bunches that would hit the TCDQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td>~16 mm</td>
<td>~14</td>
</tr>
<tr>
<td>6.5 TeV</td>
<td>~4 mm</td>
<td>~21</td>
</tr>
</tbody>
</table>

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
• [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

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

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

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)

- TSU → Analog Optical TX → Analog Optical RX → Fast Inhibit Board

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

- TSU → Analog Optical TX → Analog Optical RX → CTRV Delay → Fast Inhibit Board

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

- TSU → Digital Optical TX → Digital Optical RX → Fine Delay (1ns res) → Fast Inhibit Board

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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