Analysis of asynchronous beam dump test with quench and MD proposal

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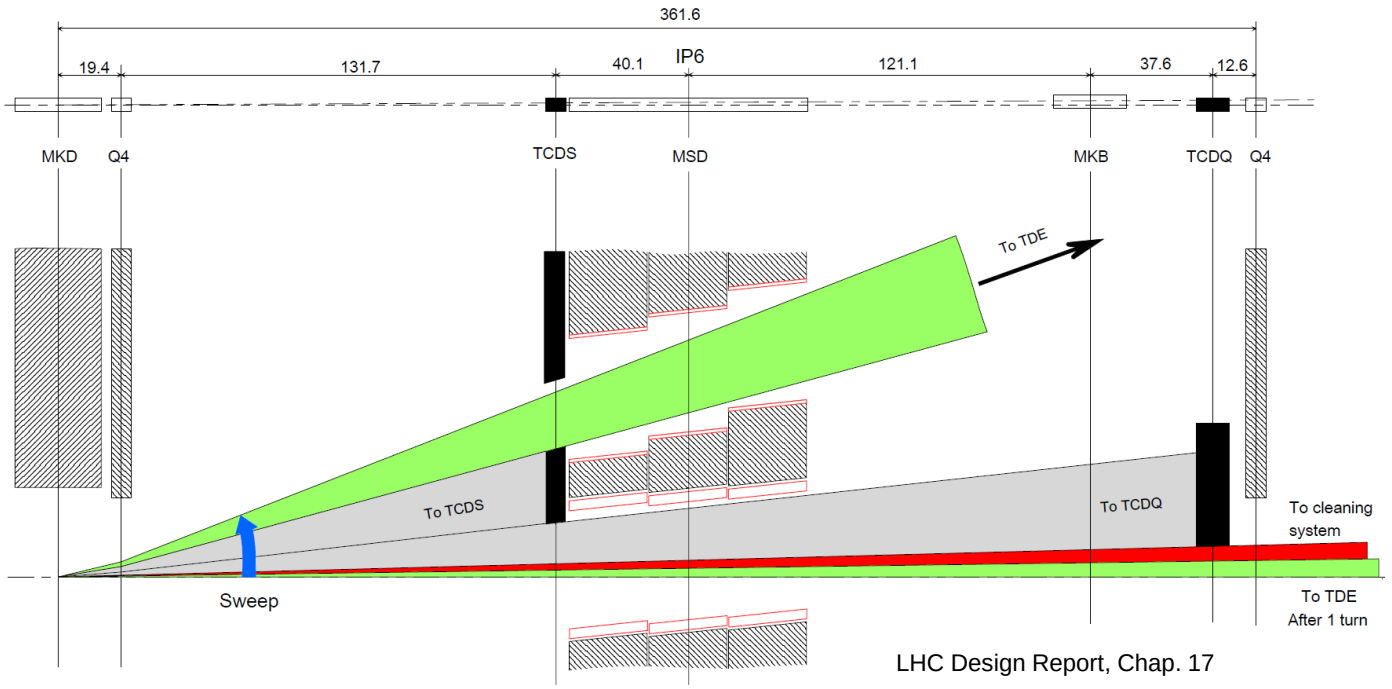
with input from M. Frankl, A. Lechner, D. Wollmann

Outline

- Introduction
- Asynch. dump test with quench (15/05/2016)
  - Abort gap population
  - RF waiting time and abort gap evolution
  - Beam losses
  - Beam simulations and energy-deposition studies
  - Quench behaviour
- Outlook: Proposed MD for asynch. dump test with bunched beam
- Conclusions

Asynch. Dump Test: Introduction

- Asynchronous beam dumps are among the most critical accepted failure cases of the LHC
- Therefore, tests are regularly performed after long shutdowns or after relevant machine changes to validate the extraction protection functionality.



LHC Design Report, Chap. 17

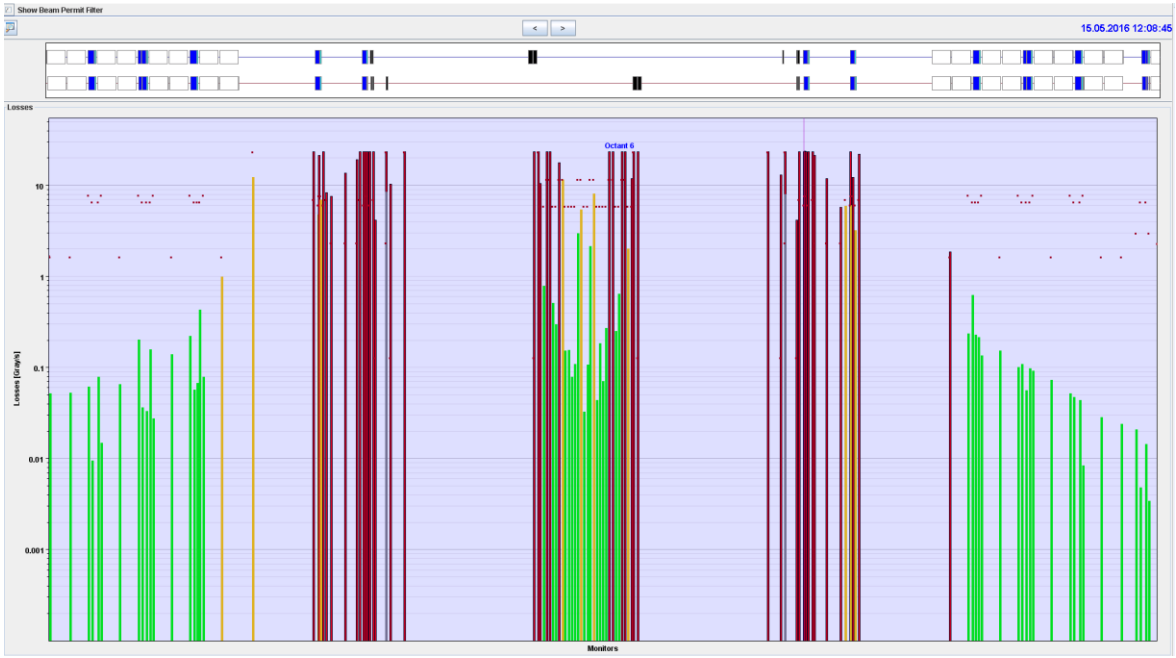
Asynch. Dump Test Procedure*

- One nominal bunch injected in Bucket 1 and scraped down to 1e10…5e10 p+
- Bump beam away from TCDQ
- Switch off RF → Bunch drifts into abort gap (synchrotron losses) and debunches
  - Top energy: both effects relevant
  - Injection energy: debunching effect is dominating
- Before dumping, wait 50 s (6.5 TeV) or 90 s (450 GeV) to have the maximum of the distribution on the TCDQ side of the abort gap

*See LHC Operational Procedure, Asynchronous beam dump validation test, EDMS No. 1698830

Asynch. dump test causing quench

- Test on 15/05/2016
- W_b = 6.5 TeV
- Collisions (VdM cycle)
- 3 buckets filled
  (2 nominals, 1 pilot?):
  - B1: Bunch 1, 1785, 3100
  - B2: Bunch 1, 891, 2100
- B1, bunch 1:
  $\varepsilon_x \approx 2.6$ µm, $\varepsilon_y \approx 11$ µm
- No scraping before test
- RF switched off at
  12:08:08.0±0.5s
- Lost “AG signal when switching OFF RF” (logbook)
- Beam dumped at
  12:08:45.770
- Quenched due to beam losses (Beam 1):
  - RQ8.R6, RQ9.R6, MB A8.R6
- No quenches in L6

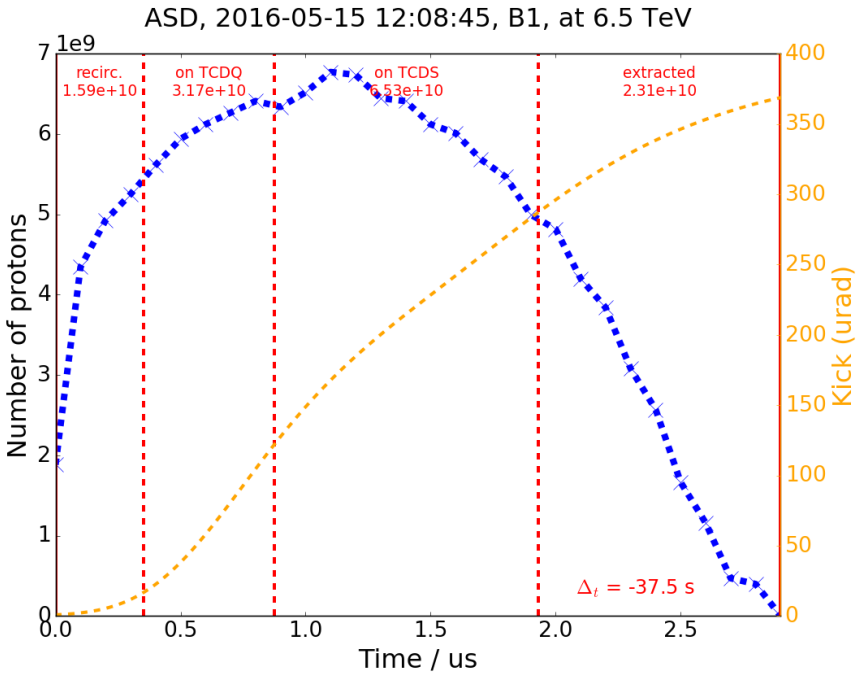


W. Bartmann, MKD generator meeting, 31/05/2016

Abort Gap Population

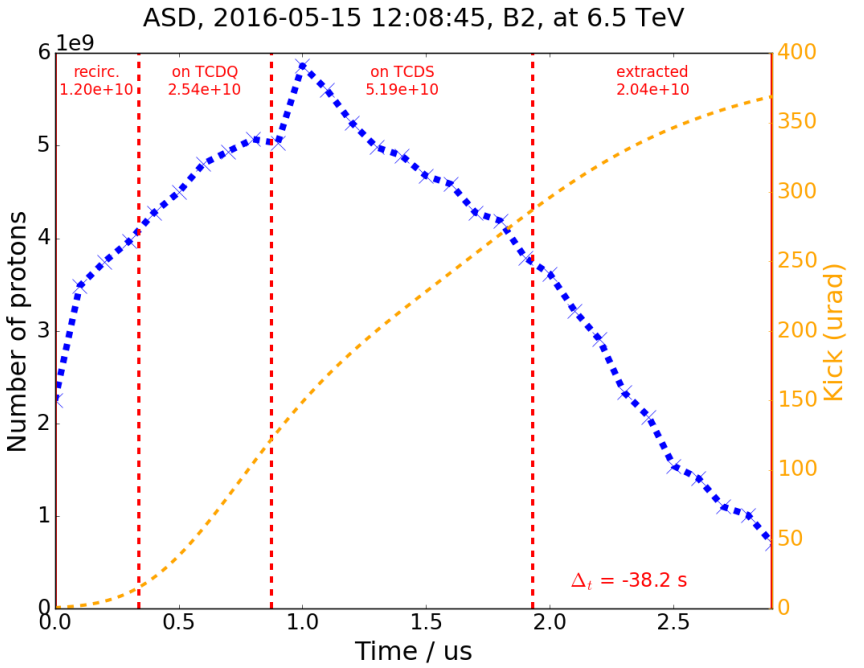
Beam 1

At dump time: 1.35e11 p+ in abort gap



Beam 2

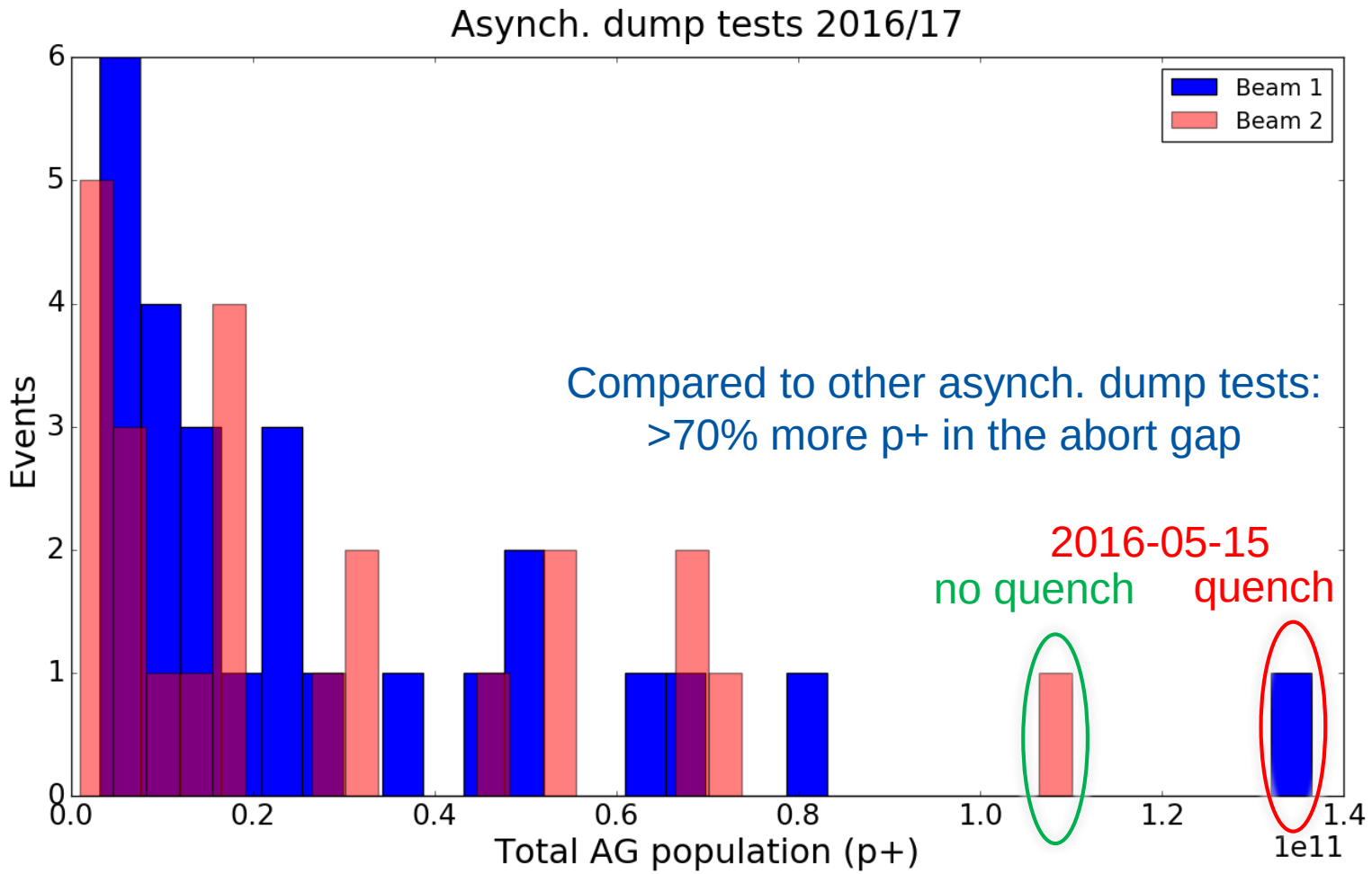
At dump time: 1.1e11 p+ in abort gap



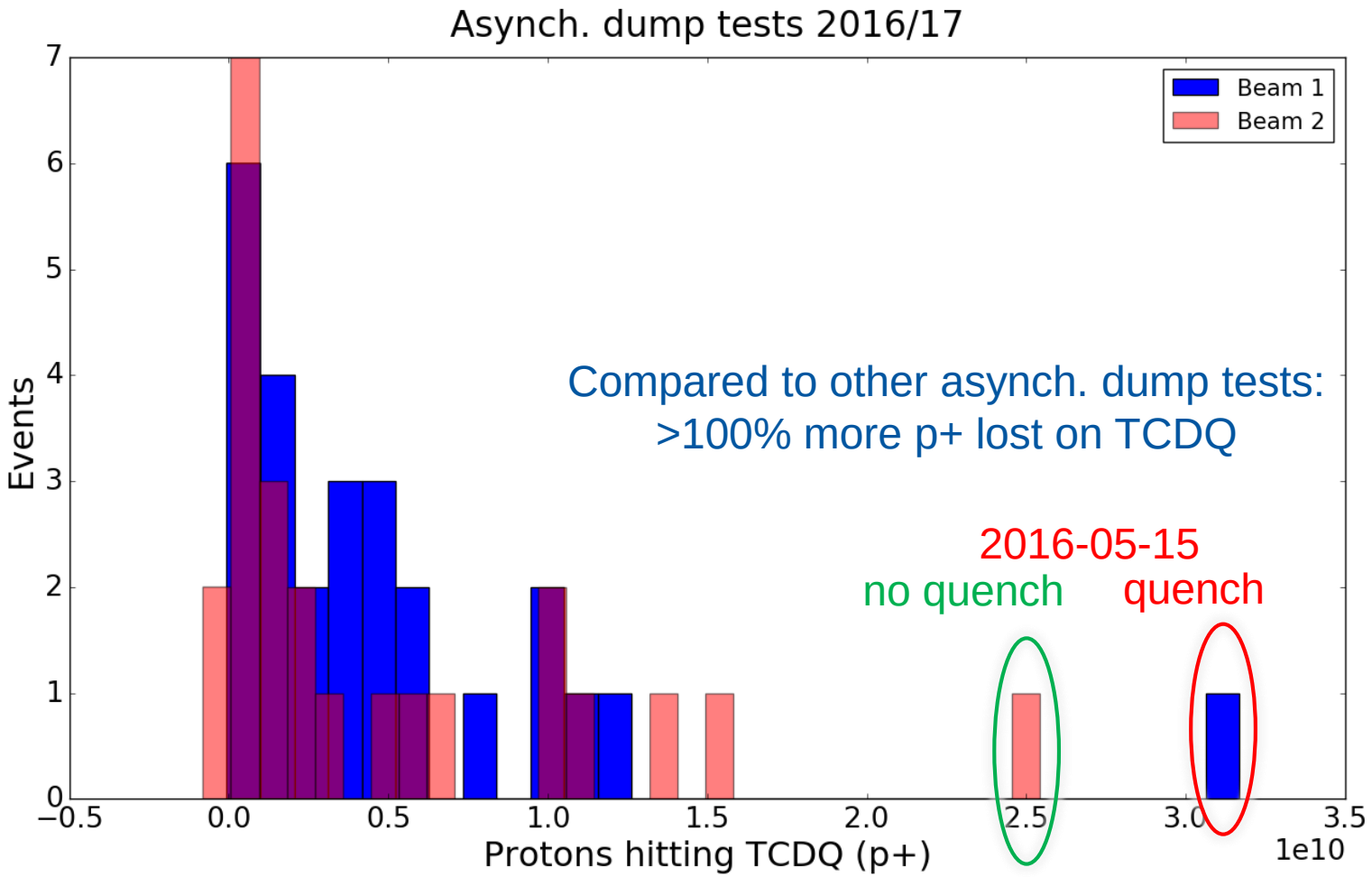
For Beam 1, ~25% more losses at the TCDQ,
i.e. a significant but not a huge difference

Thanks to S. Mazzoni and BI for the support to reconstruct the abort gap data.

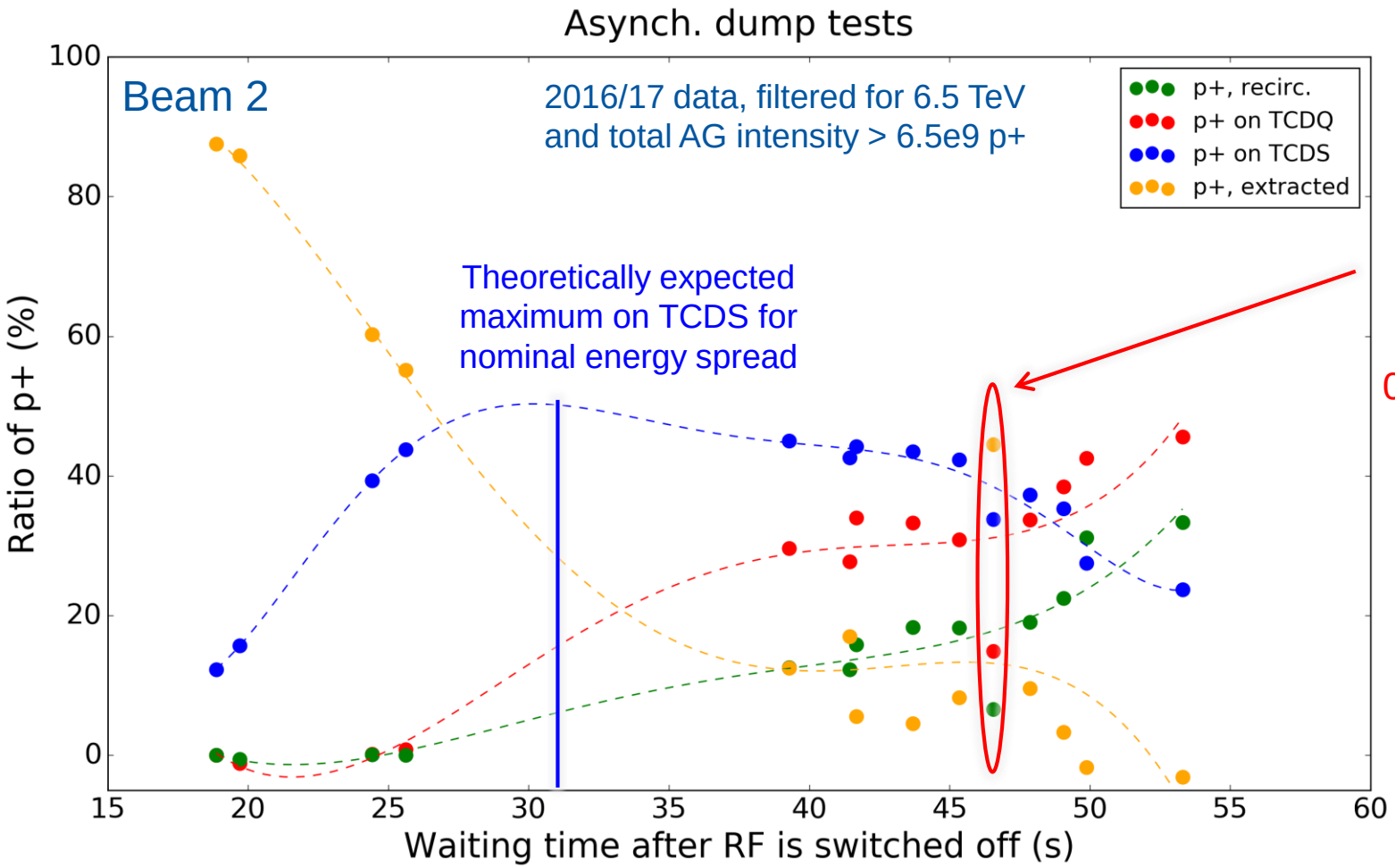
Total AG Population



Particles on TCDQ



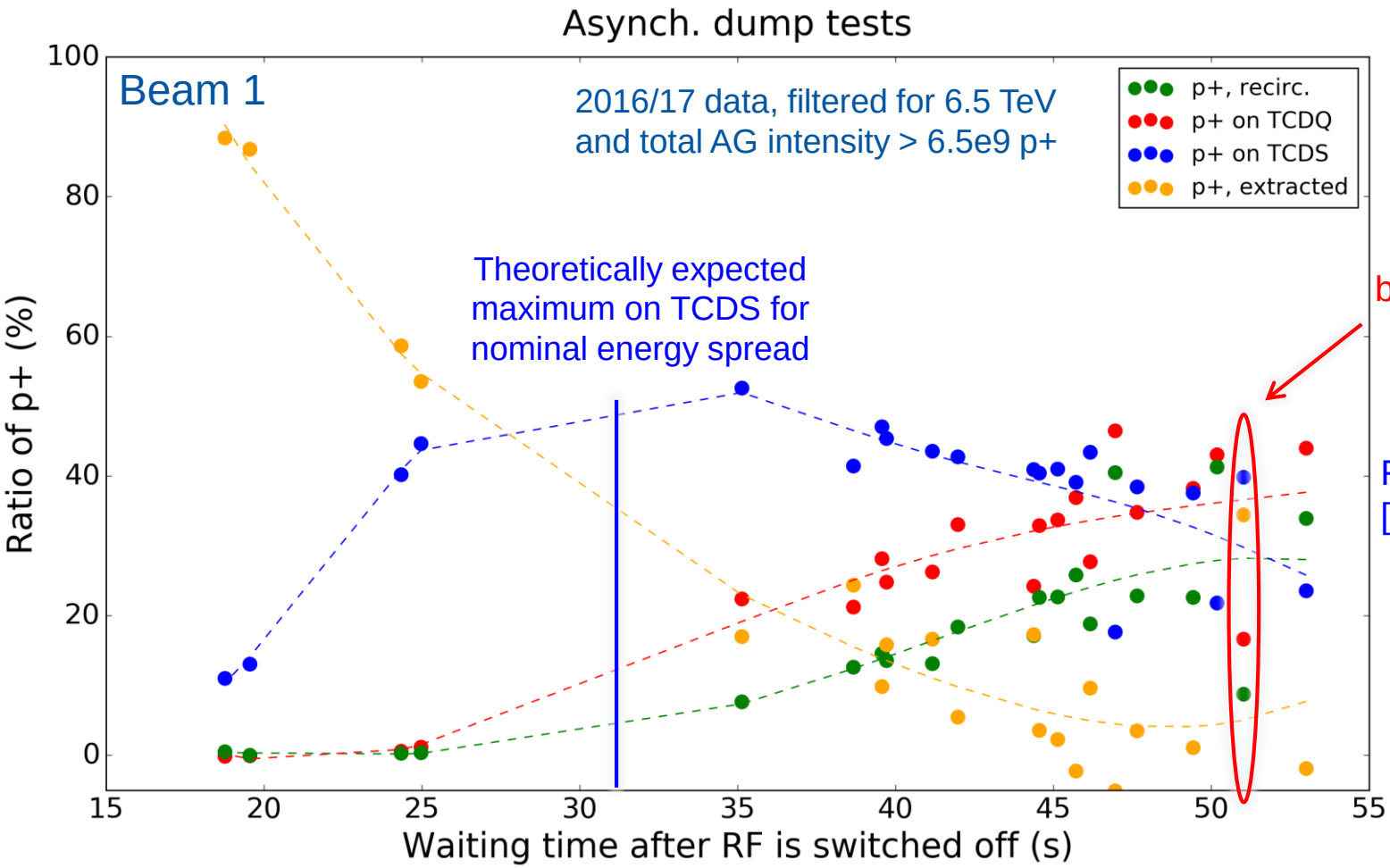
Abort Gap Evolution



Unexpected behaviour for test on '2017-07-10 11:44:00'

→ Logbook: "One RF line on B2 did not switch OFF"

Abort Gap Evolution

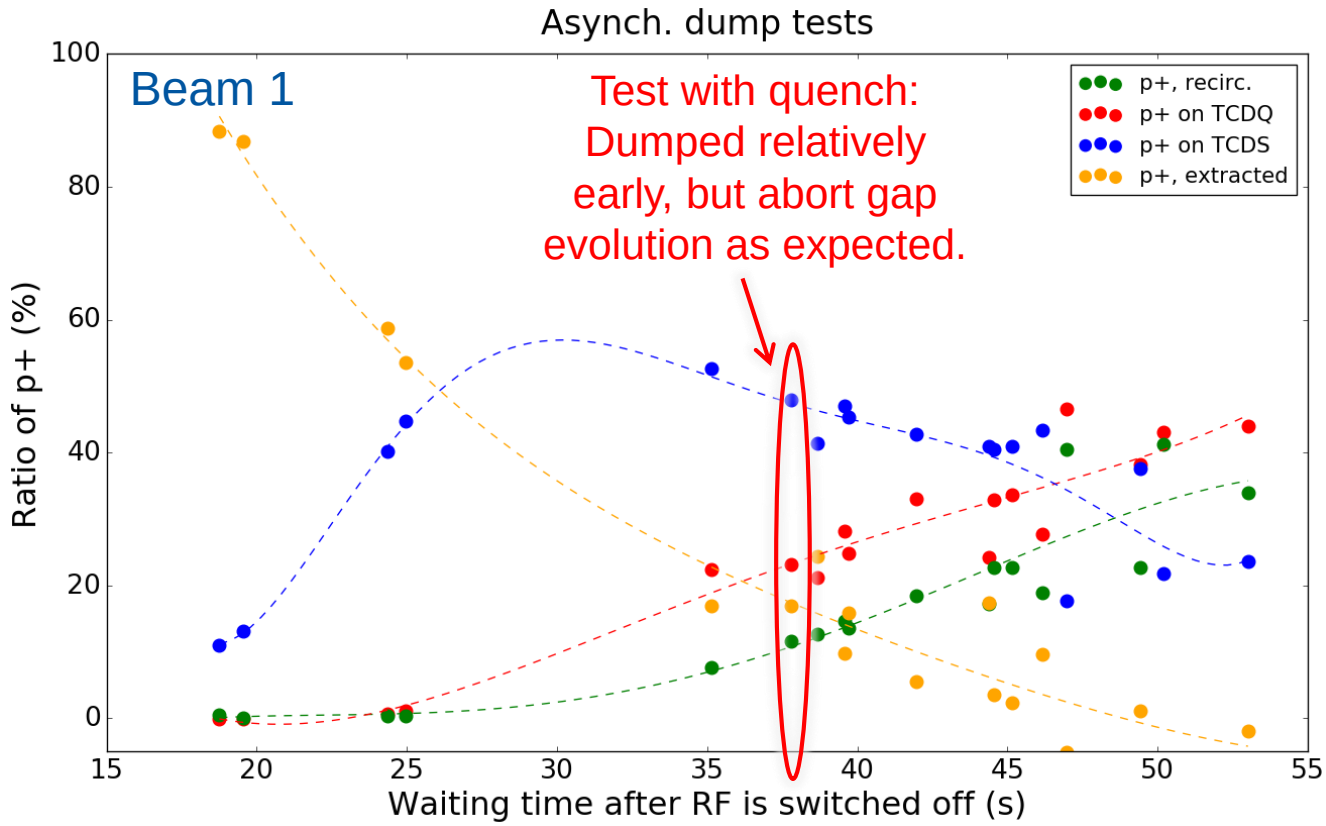


Unexpected behaviour for test on 2016-05-10

Filled buckets = [1, 1001, 18851]

Only ~2.5 us from Bucket 1

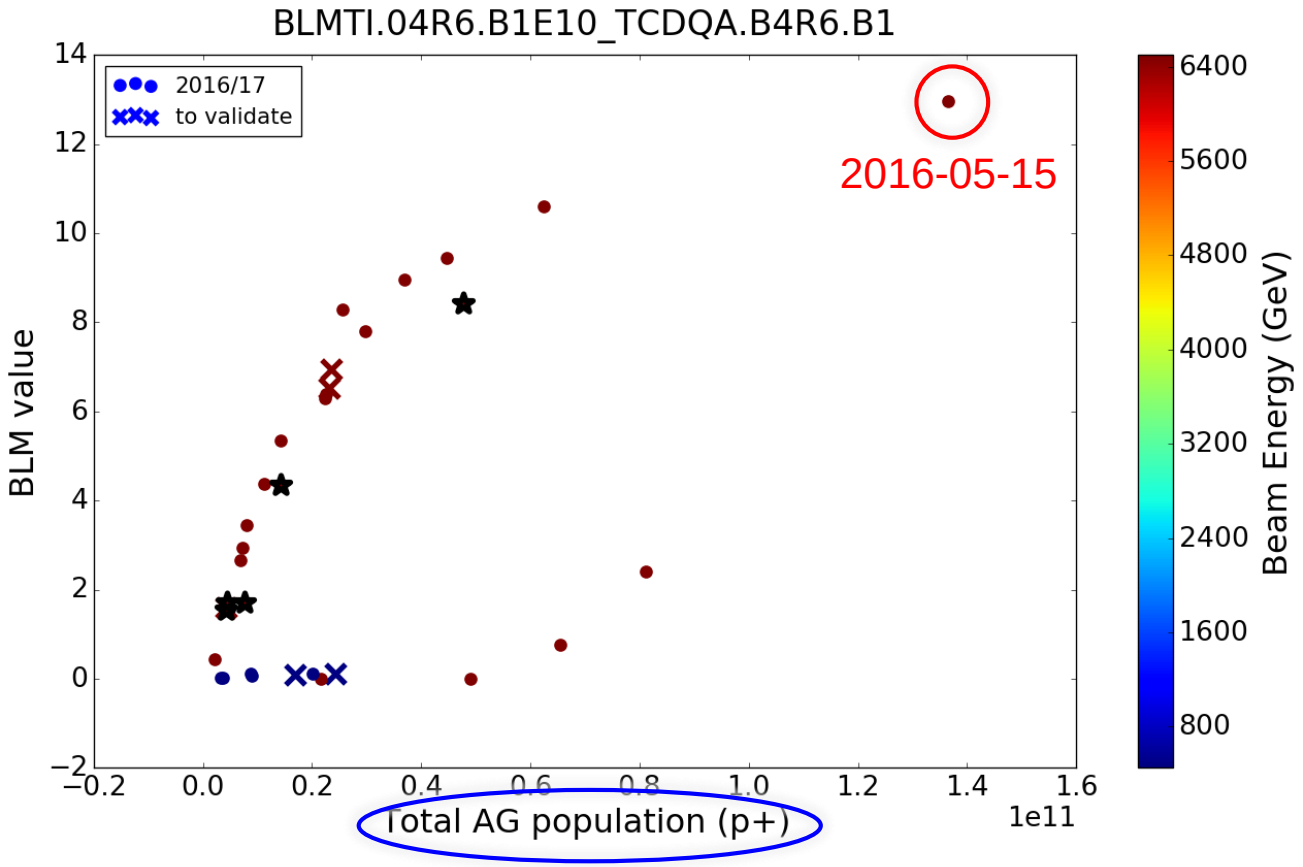
Abort Gap Evolution



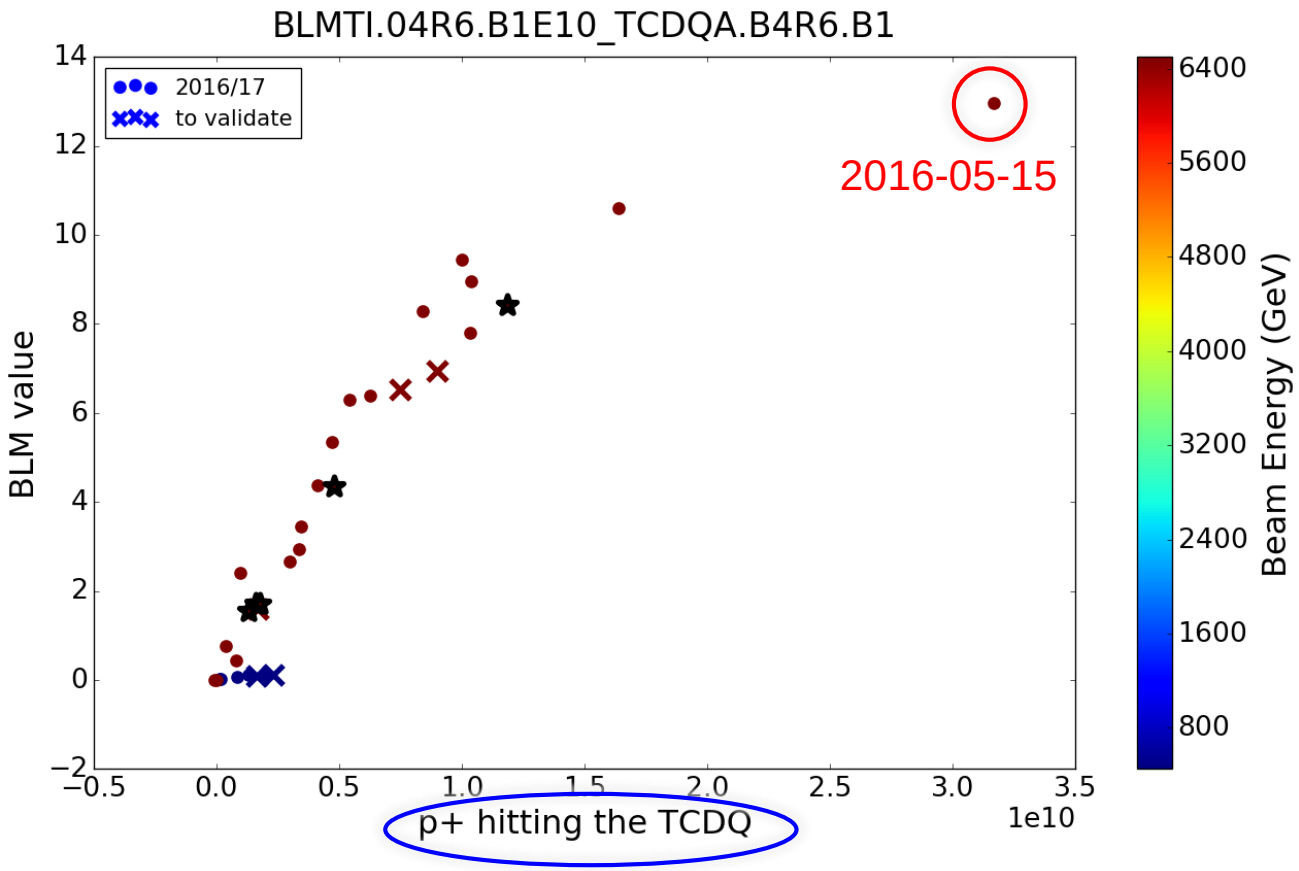
Conclusions:

- Dumped relatively early, but abort-gap evolution as expected
- No evidence for additional bunch drifting into the abort gap

Beam Losses at TCDQ



Beam Losses at TCDQ



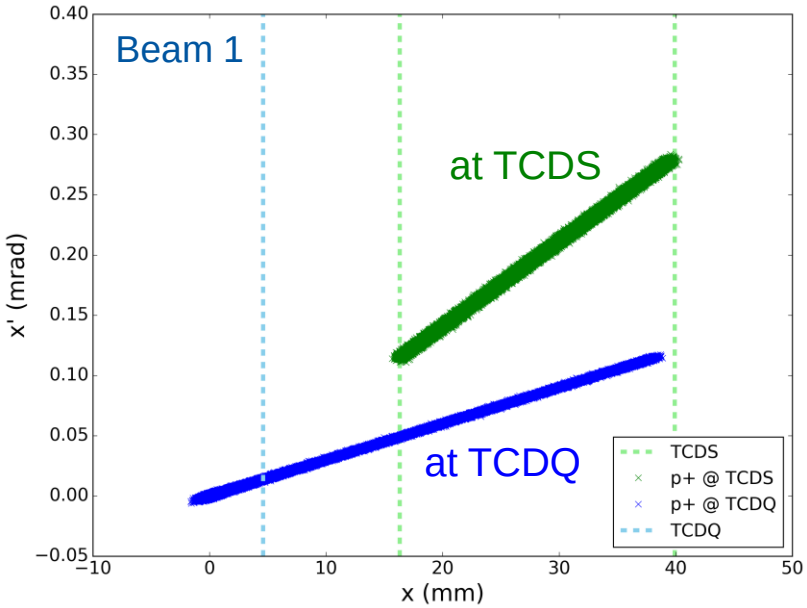
- BLM values correlate with p+ losses on the TCDQ
- Similar results for BLMs at Q4, Q5, Q8, Q9
- Saturation effect?

Beam Simulations

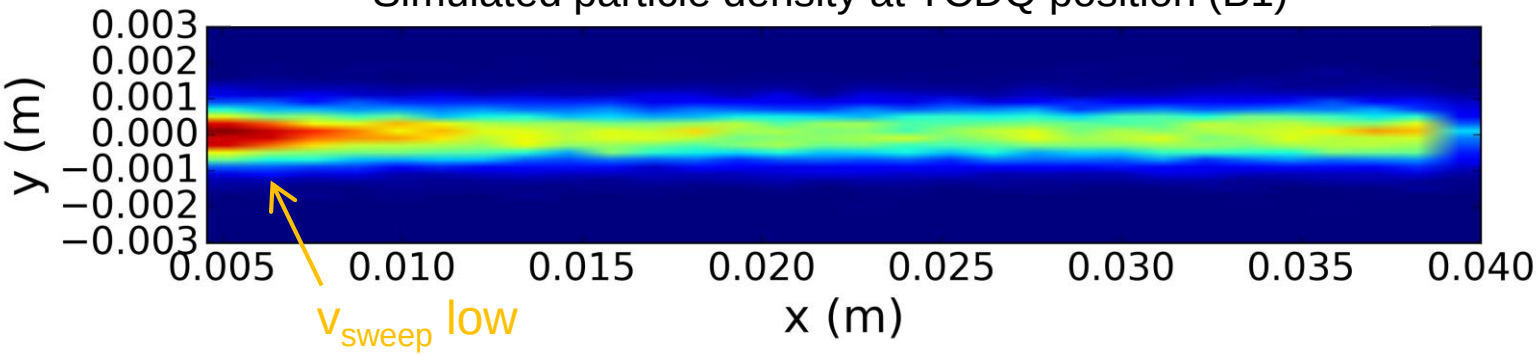
- MAD-X loop in python
- Input: measured MKD waveforms, beam emittance, abort gap spill, collimator positions
- Particles generated at TCDS and TCDQ position with 4d normal distribution
- No coupling assumed, except:

$$\langle x p_x \rangle = \langle p_x x \rangle = -\alpha_x \varepsilon_x$$
$$\langle y p_y \rangle = \langle p_y y \rangle = -\alpha_y \varepsilon_y$$

Simulated trace-space distribution

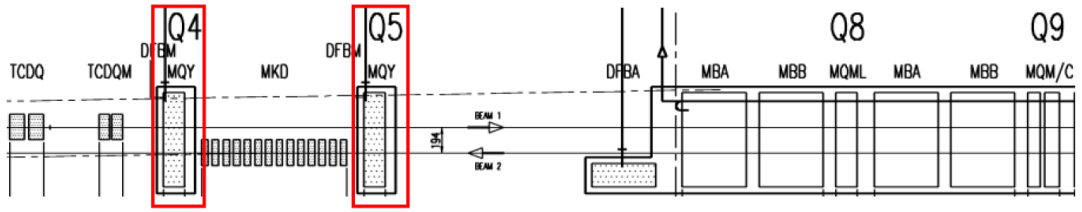


Simulated particle density at TCDQ position (B1)

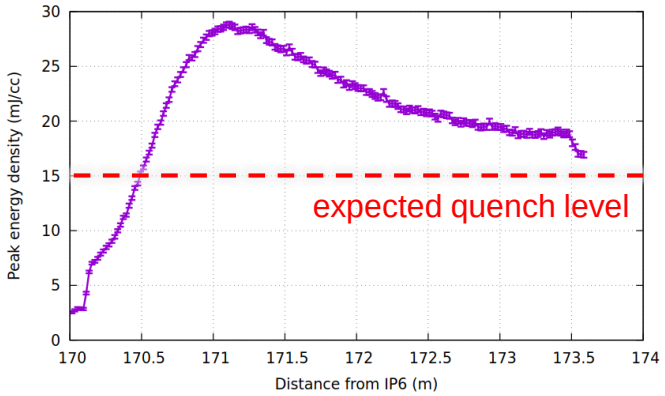


Distance TCDS-TCDQ: $\Delta s \approx 190$ m

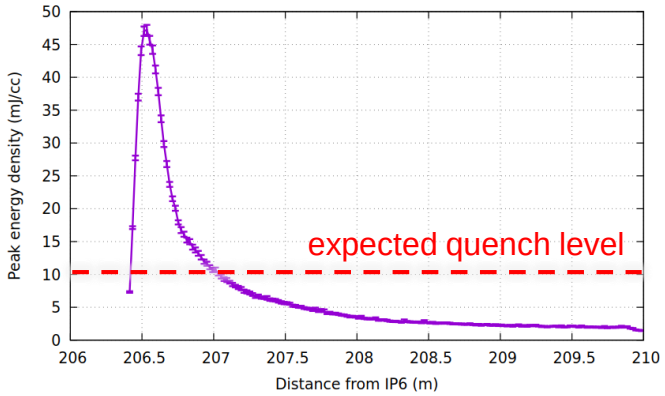
Energy Deposition



Max. energy density in Q4 coils



Max. energy density in Q5 coils



- Calculated peak energy density in Q4 coils of $\sim 30\,\mathrm{mJ/cm^3}$
- Calculated peak energy density in Q5 coils of $\sim 50\,\mathrm{mJ/cm^3}$

Conclusion: Q4 and Q5 should have quenched.

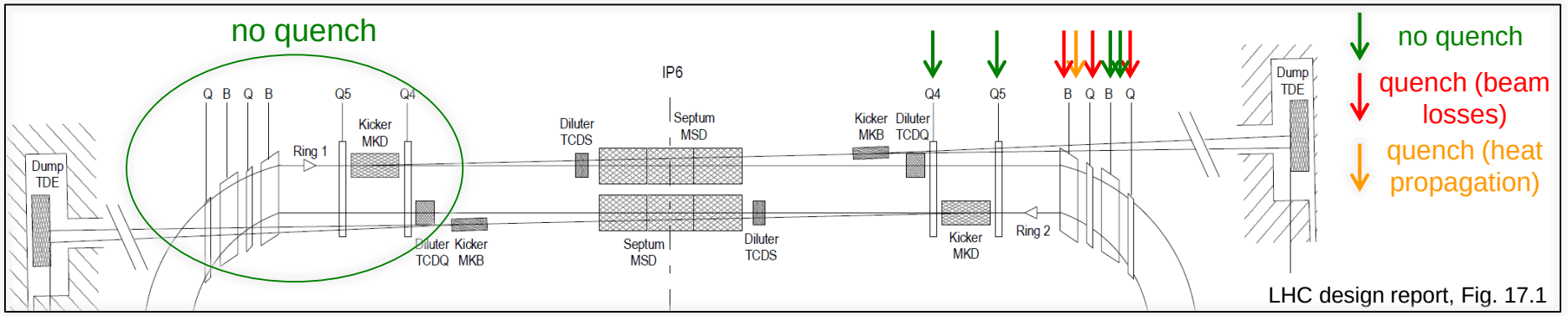
FLUKA studies by M. Frankl:
M. Frankl, A. Lechner, Energy-deposition studies, LIBD Meeting, 05.10.2017, https://indico.cern.ch/event/661534/
Magnet and quench-behaviour analysis by D. Wollmann:
D. Wollmann, Magnet quench characteristics and quench levels, LIBD Meeting, 05.10.2017, https://indico.cern.ch/event/661534/

Quench Behaviour

- Q4/Q5 (R6) should have quenched, but did not quench
- Dipoles (R6) behaved as expected
- Q8/Q9 (R6) should not have quenched, but did quench
- No quench in L6 observed
- Conclusion: The detailed reconstruction showed that the quench behaviour is not fully understood [2-4].

Magnet	T (K)	Max ρ_{energy} (mJ/cm^3)	Quench expected?	Quench observed?
MQY.4R6	4.5	30	Yes	No
MQY.5R6	4.5	50	Yes	No
MB.A8R6	1.9	27	Yes	Yes
MB.B8R6	1.9	5	No	(Yes)*
MQML.8R6	1.9	1.5	No	Yes
MB.A9R6	1.9	< 0.1	No	No
MB.B9R6	1.9	< 0.1	No	No
MQM.9R6	1.9	0.25	No	Yes

*quenched due to heat propagation



LHC design report, Fig. 17.1

Outlook: Proposal for MD5

- Idea: perform an asynchronous beam dump test with bunched beam in the abort gap
  - Clearly defined particle intensities and clearly defined bunch positions inside the abort gap
  - More realistic situation of a bunched beam hitting the TCDQ, instead of a continuous particle distribution
  - Exclude off-momentum effects
- Goal: Verify our understanding of the beam-loss behaviour, and the current beam and FLUKA models under clearly defined conditions.

Outlook: Possible MD Procedure

1) Modify variable Abort Gap Keeper (AGK) [5] to inject into the abort gap (~1 h)
2) Injection energy: Probe abort gap with pilots (~2 h)
3) Injection energy: use trains of 48 bunches (~4 h)
    1) Alternate Beam 1 and Beam 2
    2) Use two different bunch intensities (e.g. ~6e10 and ~1.25e11)
    3) Possibly test with/without orbit bump at TCDQ
4) Top energy: one (scraped) nominal (~2 h)
    1) Remark: The bunch intensities have to be defined depending on the FLUKA predictions regarding beam losses and possible quenches. Approval of the MP3 and the rMPP is required.
5) Recovery (~1 h), plus possible quench recovery time

Conclusions I

- Asynchronous beam dump tests 2016/17 analysed.
- Detailed reconstruction of the test on 15/05/2016 that lead to the quench of 4 magnets in IR6 showed:
  - Before dump: large vertical emittance for Beam 1, Bunch 1 observed.
  - AG evolution as expected (no evidence for additional bunch drifting into the AG)
  - Compared to other asynch. dump tests:
    - Total AG population: >70% more p+
    - On TCDQ: >100% more p+
  - For B1 (quench) ~25% more p+ hitting TCDQ than B2 (no quench)
  - BLM values on TCDQ, Q4, Q5, Q8, Q9 seem to correlate with expected p+ losses on TCDQ. Possible saturation effects to be followed up.

Conclusions II

- Quench behaviour not understood.
  - Q4/Q5 (R6) should have quenched, but did not quench
  - Q8/Q9 (R6) should not have quenched, but did quench
  - No quench in L6 observed
- Quench behaviour seem to indicate dispersive effect. However, off-momentum effects seem not sufficient to explain quenches. To be followed up.
- MD for asynch. dump with bunched beam in the abort gap has been proposed.

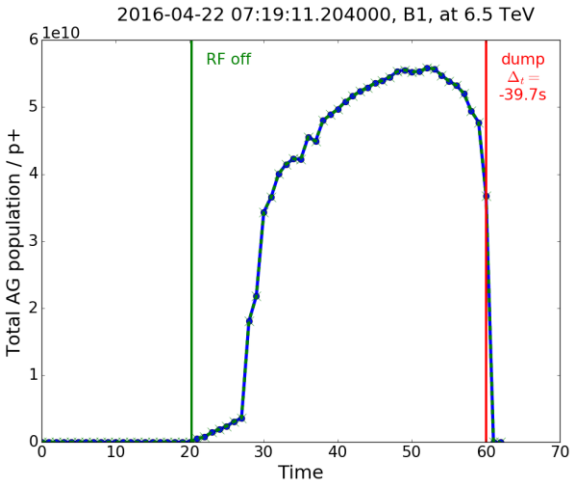
Thank you for your attention!

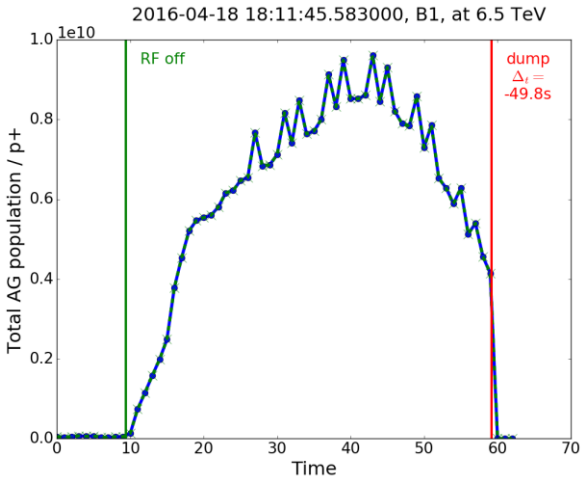
References

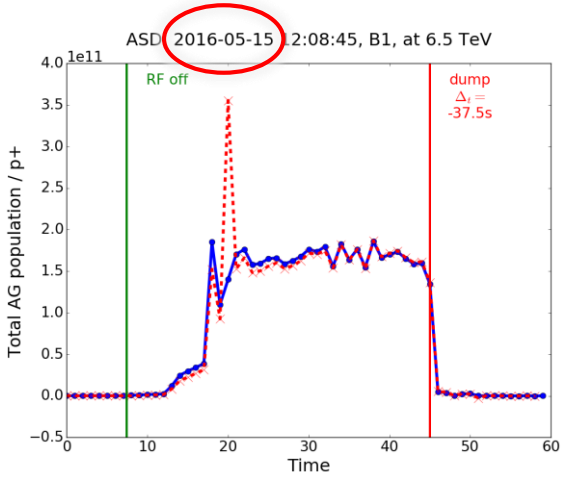
- [1] LHC Operational Procedure, Asynchronous beam dump validation test, EDMS No. 1698830
- [2] C. Wiesner, Overview of asynch. dump tests 2016/17 and asynch. dump test with quench (2016-05-15), LIBD Meeting, 05.10.2017, https://indico.cern.ch/event/661534/
- [3] D. Wollmann, Magnet quench characteristics and quench levels, LIBD Meeting, 05.10.2017, https://indico.cern.ch/event/661534/
- [4] M. Frankl, A. Lechner, Energy-deposition studies, LIBD Meeting, 05.10.2017, https://indico.cern.ch/event/661534/
- [5] N. Magnin, Operational Procedure, Procedure to change the length of LBDS Abort Gap Keeper, to be published

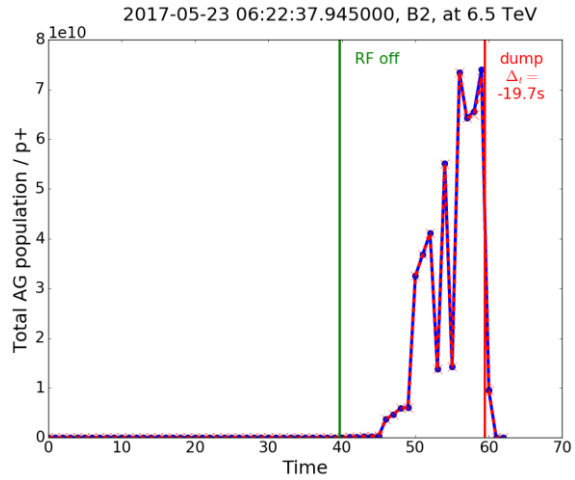
Evolution of total AG population

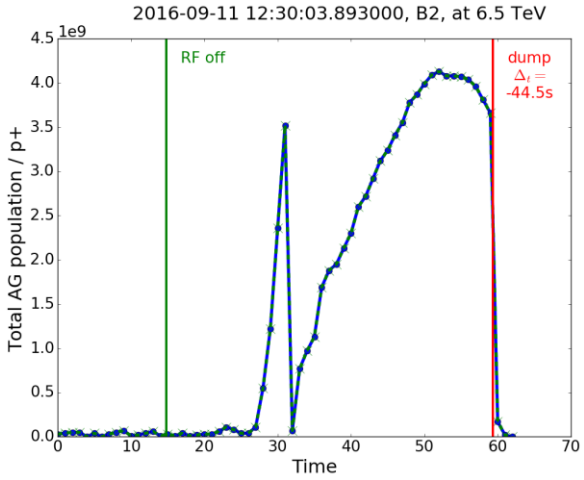
6.5 TeV

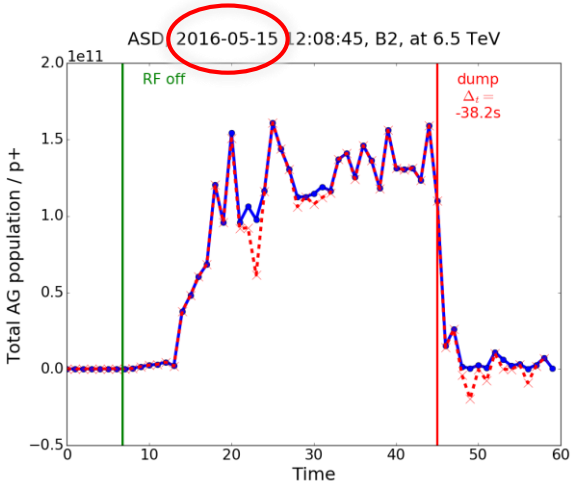












Particle simulations based on BSRA measurements of abort gap population.
Artefacts can occur during measurement due to moving of filter and changing of voltage gain for PMT.

Off-momentum effects: Energy loss

- Energy loss per turn at E_0 = 6.5 TeV:

$$U_0 = \frac{e^2}{3\epsilon_0}\left(\frac{E_0}{mc^2}\right)^4 \frac{1}{\rho_0} = -4.95\ \mathrm{keV/turn}$$

- Energy loss after 38 s without RF (assuming same energy loss for all particles):

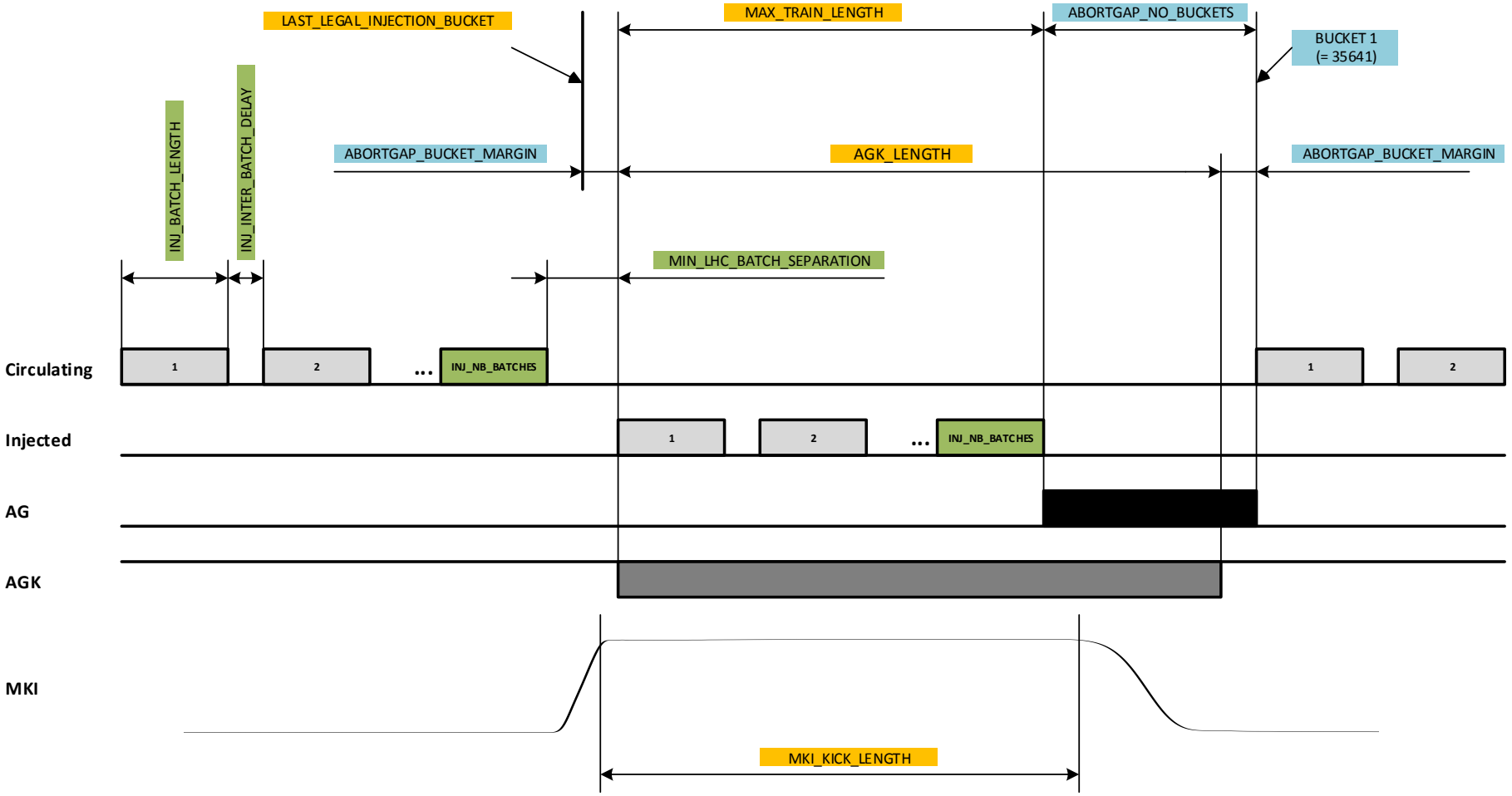
$$\Delta U = -4.95\ \mathrm{keV} \cdot 38\mathrm{s} \cdot 11.245\ \mathrm{kHz} = -2.12\ \mathrm{GeV}$$

- **Resulting energy *offset*:**

$$\frac{\Delta U}{U} = \frac{-2.23\ \mathbf{GeV}}{6.5\ \mathbf{TeV}} = -3.25 \cdot 10^{-4}$$

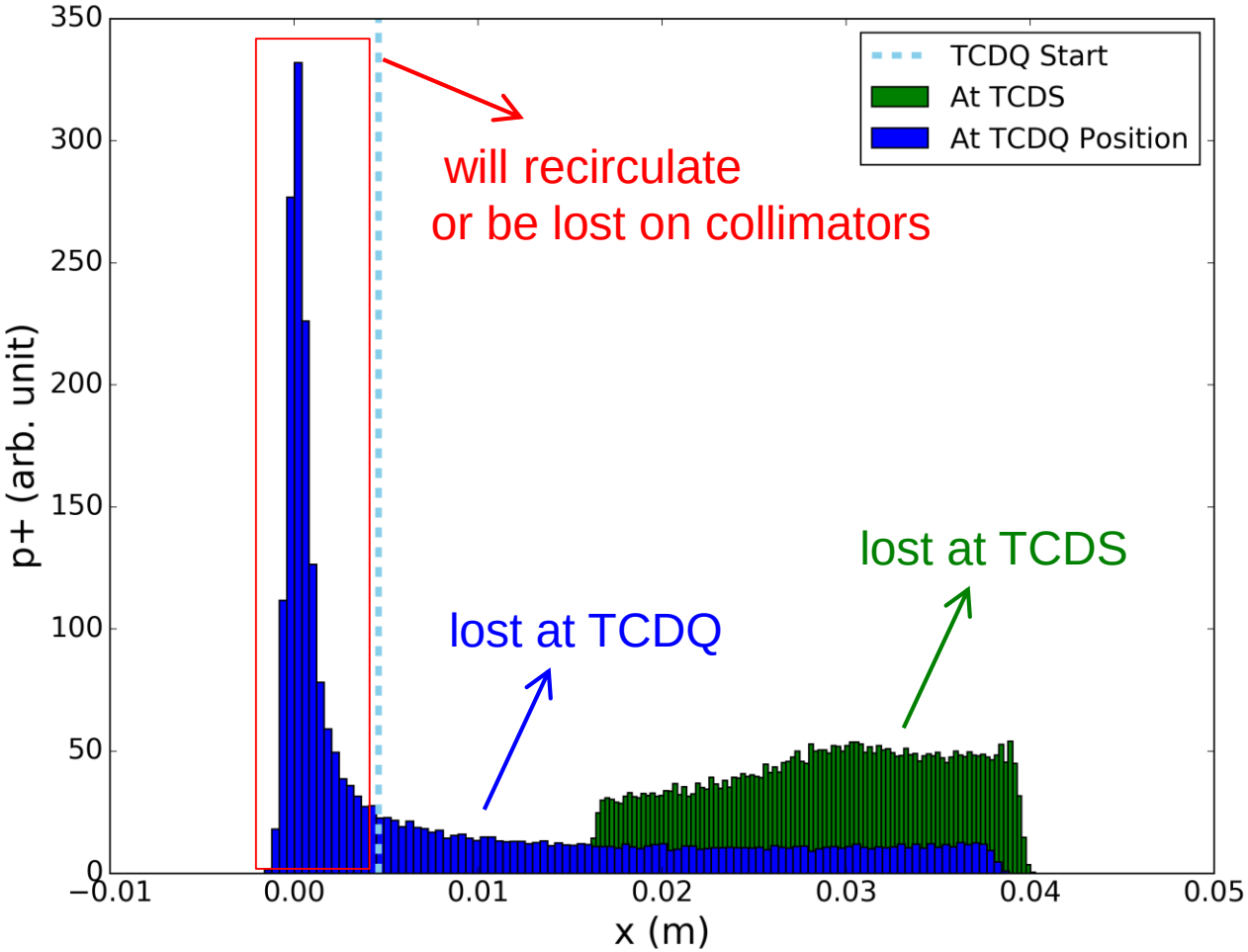
- Nominal LHC energy *spread* at 6.5 TeV:
  $\Delta p/p = \pm 1.72 \cdot 10^{-4}$ (2 sigma)
- Bucket half height ΔE/E (design report): 3.6e-4 (7 TeV)

Overview of AGK Parameters



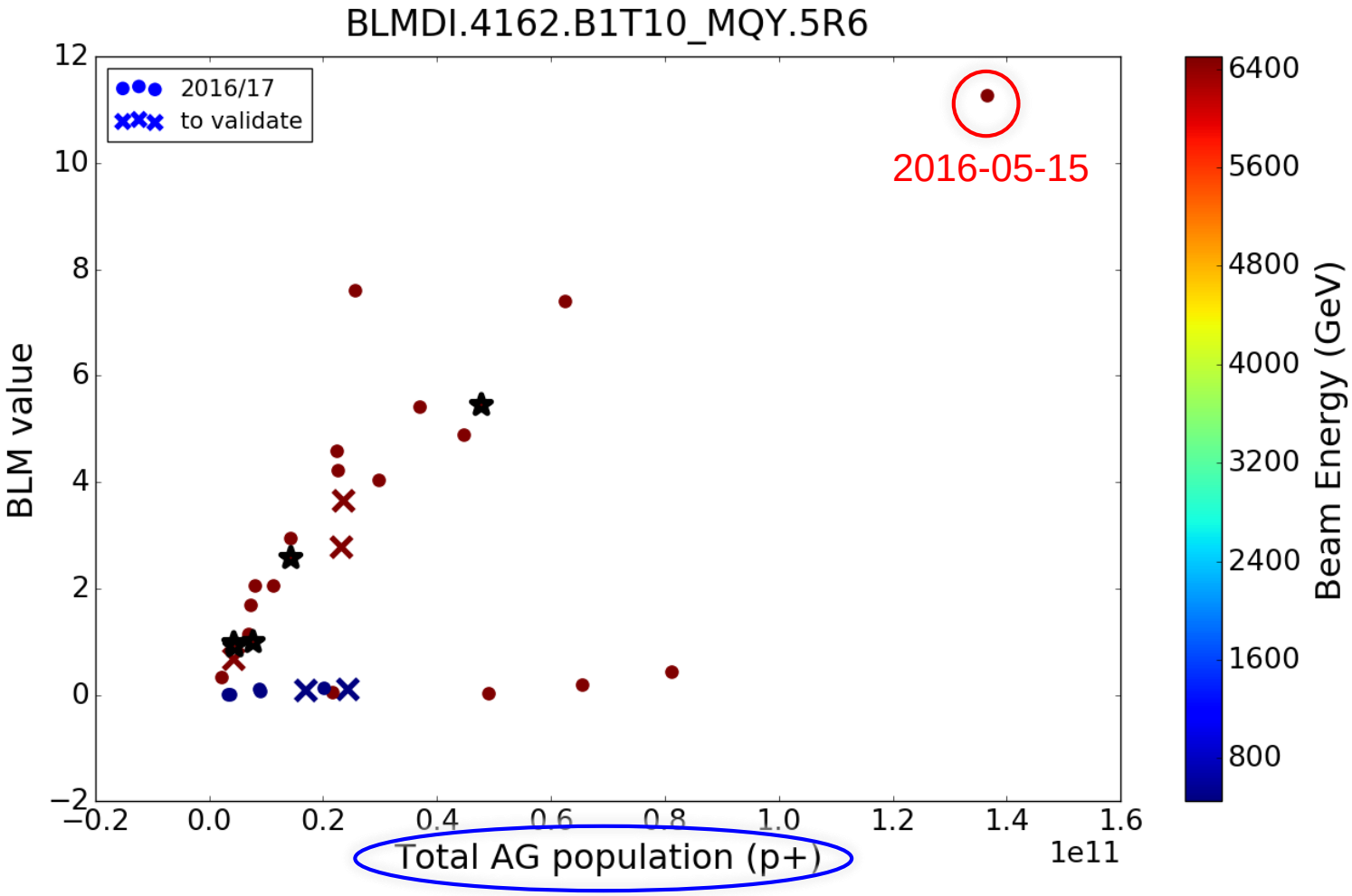
N. Magnin, Operational Procedure, Procedure to change the length of LBDS Abort Gap Keeper, to be published

Simulated Particle Distribution



Beam 1

Beam Losses at Q5



Beam Losses at Q5