Summary of MKBV flashover (14.7.2018) and implications for the LHC dilution failure cases

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September, 28th 2018

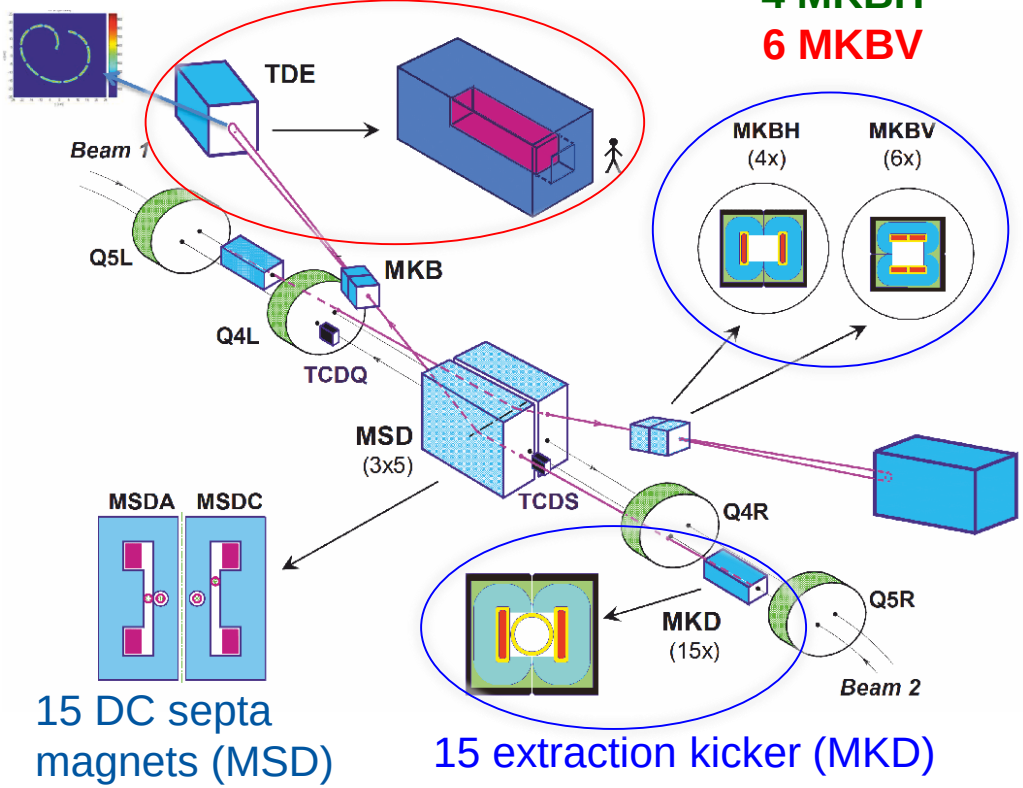
Outline

1) Introduction: dilution system and traditional failure cases
2) MKBV flashover (14.7.2018)
3) Implications of potential MKBH flashover
4) Conclusions and summary

LHC Dilution System

Beam dump (TDE)

Dilution Kicker:
4 MKBH
6 MKBV



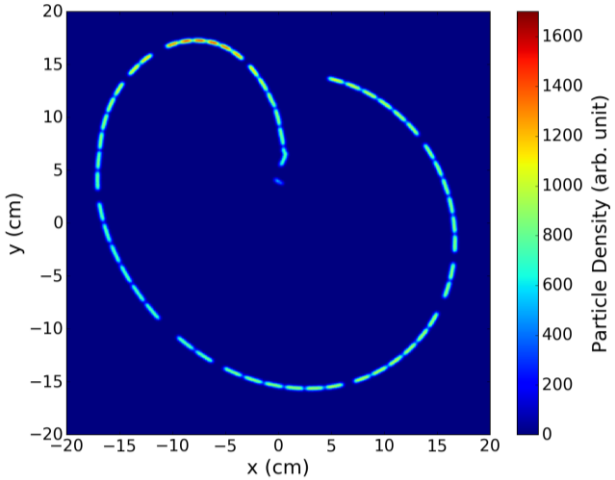
15 DC septa magnets (MSD)

15 extraction kicker (MKD)

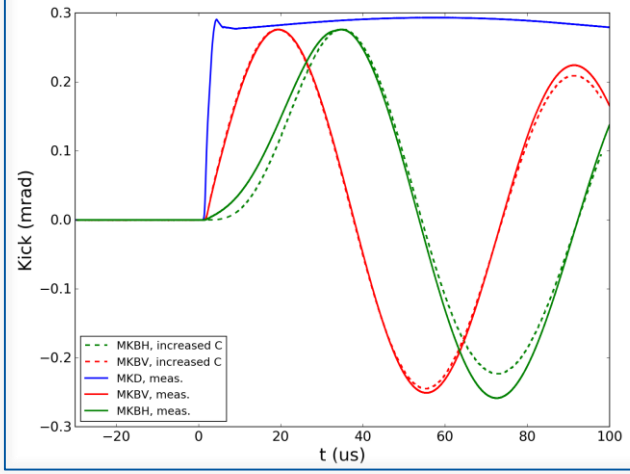
C. Bracco et al., LHC Performance Workshop, Chamonix, 26/01/2016

Total length (MKD to TDE): 976 m

Nominal dilution pattern



MKD, MKBH and MKBV waveforms



Traditional MKB Failure Cases

4 MKBH
6 MKBV

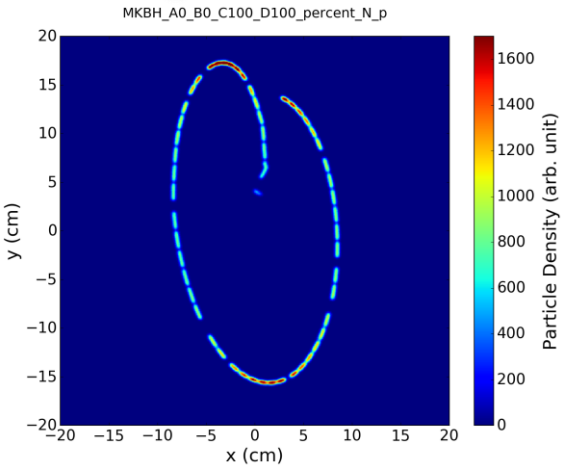
Generator → Magnet (vacuum tank) → Beam

Erratic pre-firing of **one** MKB generator:

- *Worst case*: MKBH erratic with antiphase → Loss of <40% of H dilution

Flashover

- *Worst case:* Flashover of 2 MKBH with loss of 50% H dilution



New common-cause failure identified (end of 2016): Pre-firing of more than one MKB

Traditionally assumed worst-case scenario: 2 missing MKBH

New MKB Failure Cases I

4 MKBH
6 MKBV

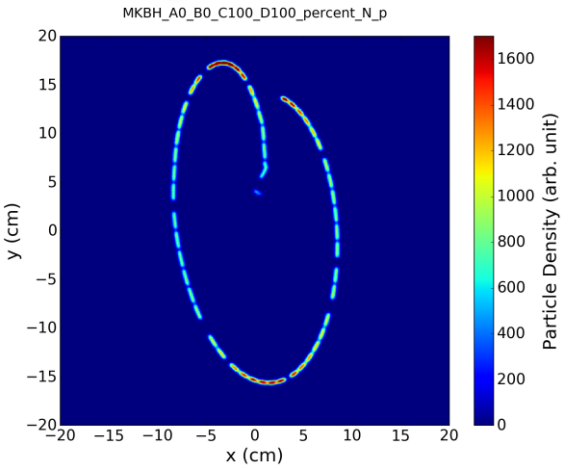
Generator → Magnet (vacuum tank) → Beam

Erratic pre-firing of **more than one** MKB generator:

- *Worst case*: MKBH erratics with antiphase → Loss of >70% of H dilution for double erratic

Flashover

- *Worst case:* Flashover of 2 MKBH with loss of 50% H dilution



Traditionally assumed worst-case scenario: 2 MKBH missing

New MKB Failure Cases I

4 MKBH
6 MKBV

Generator → Magnet (vacuum tank) → Beam

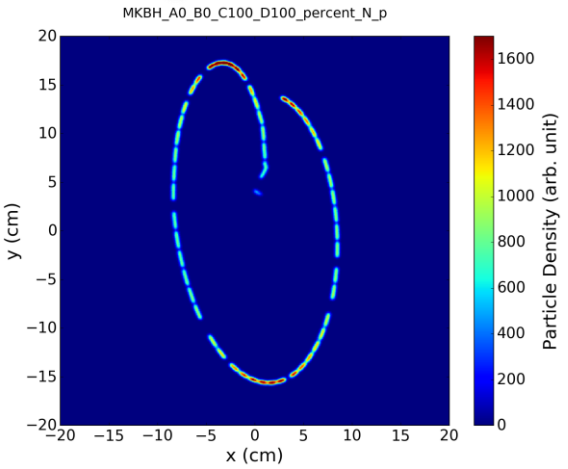
Erratic pre-firing of **more than one** MKB generator:

- *Worst case*: MKBH erratics with antiphase → Loss of >70% of H dilution for double erratic

Mitigation: reduce generator voltage / Install MKB retrigger system → MPP, 27.4.2018

Flashover

- *Worst case:* Flashover of 2 MKBH with loss of 50% H dilution



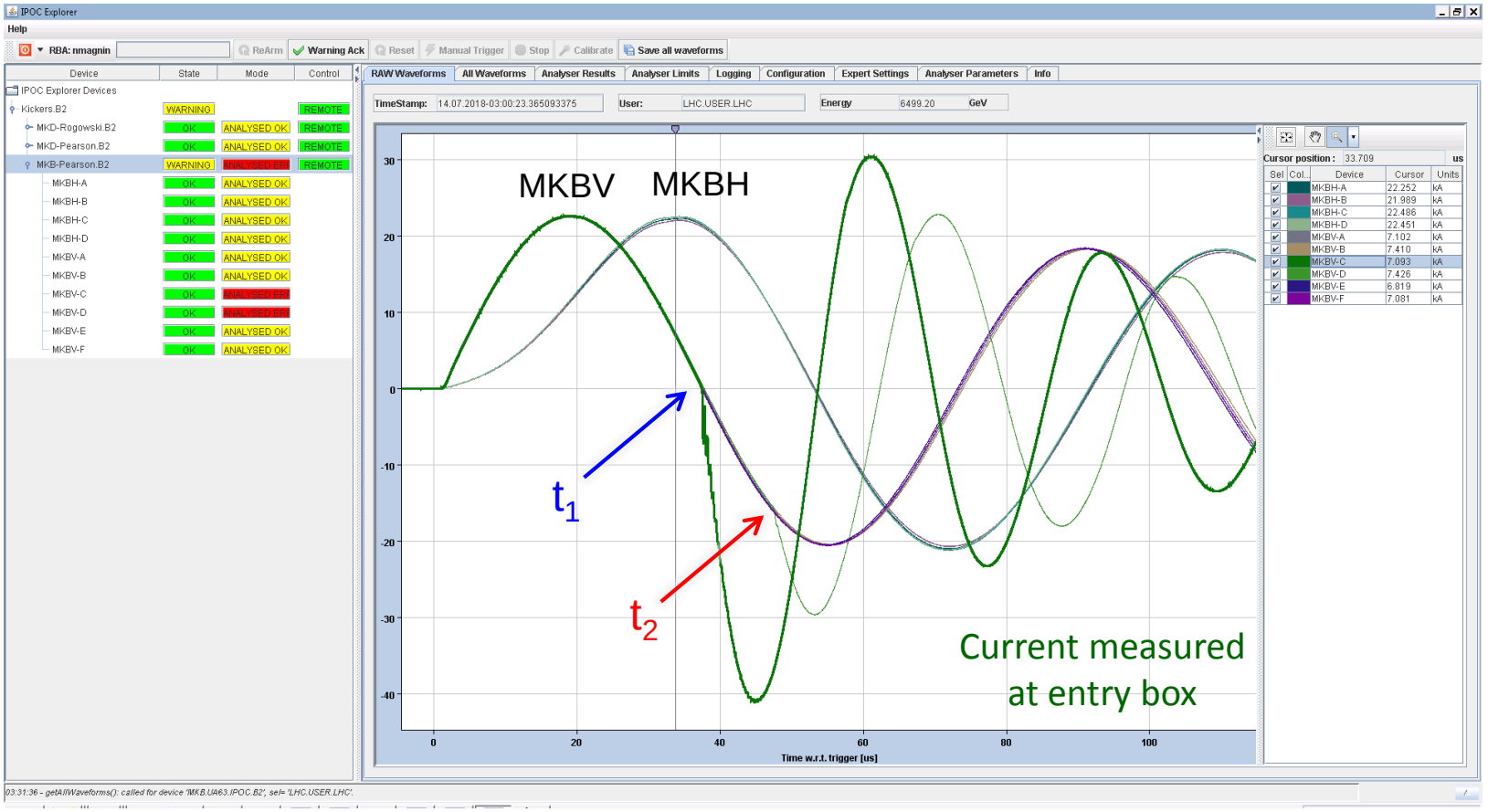
Traditionally assumed worst-case scenario: 2 MKBH missing

MKBV flashover: What happened on July 14th?

MKBV Flashover, 14.7.2018

OP dump at end of PHYSICS fill (2556b), 6.5 TeV

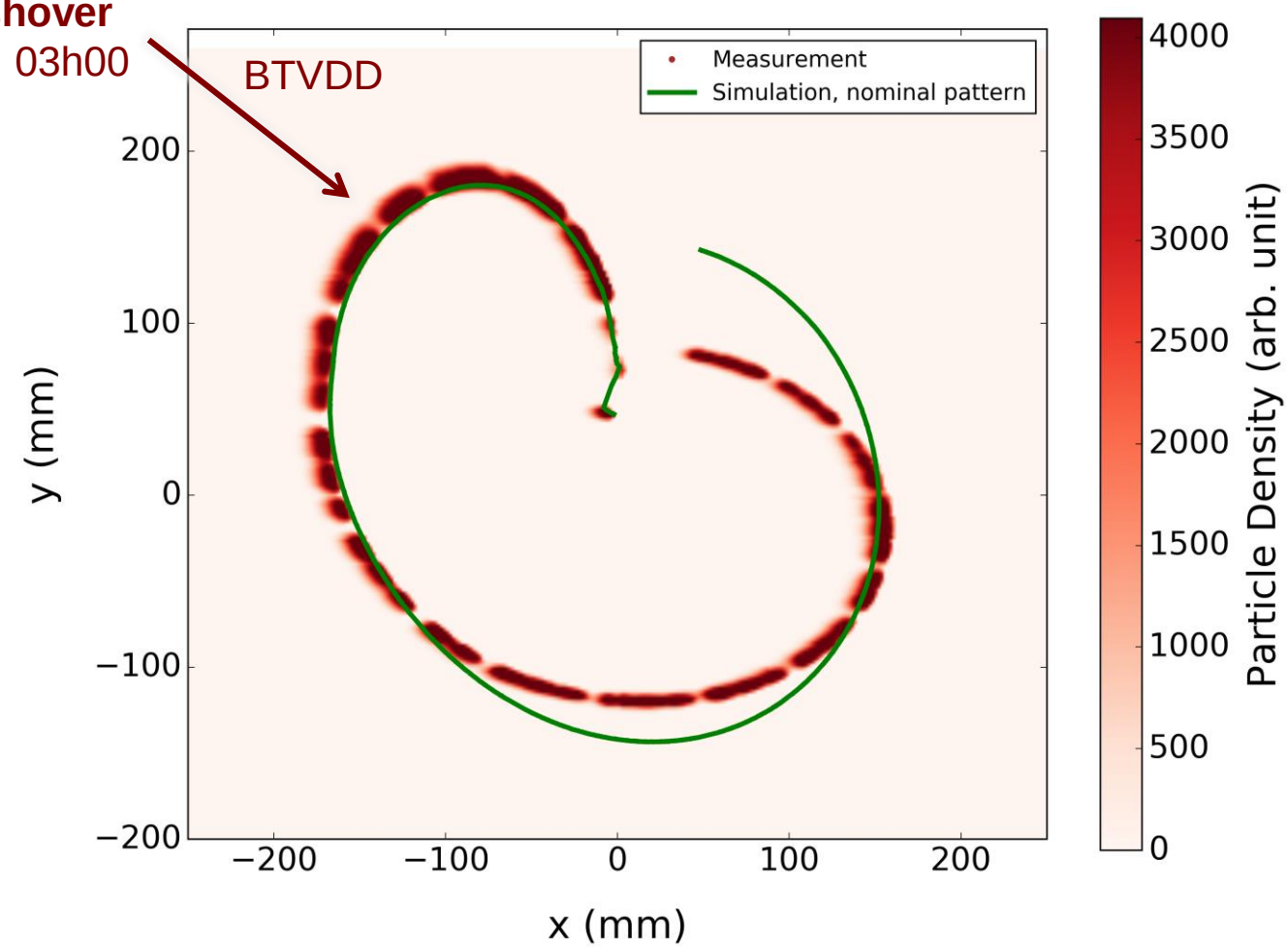
→ Flashover for MKBV.C/D (B2), located in the same vacuum tank



MKBV Flashover

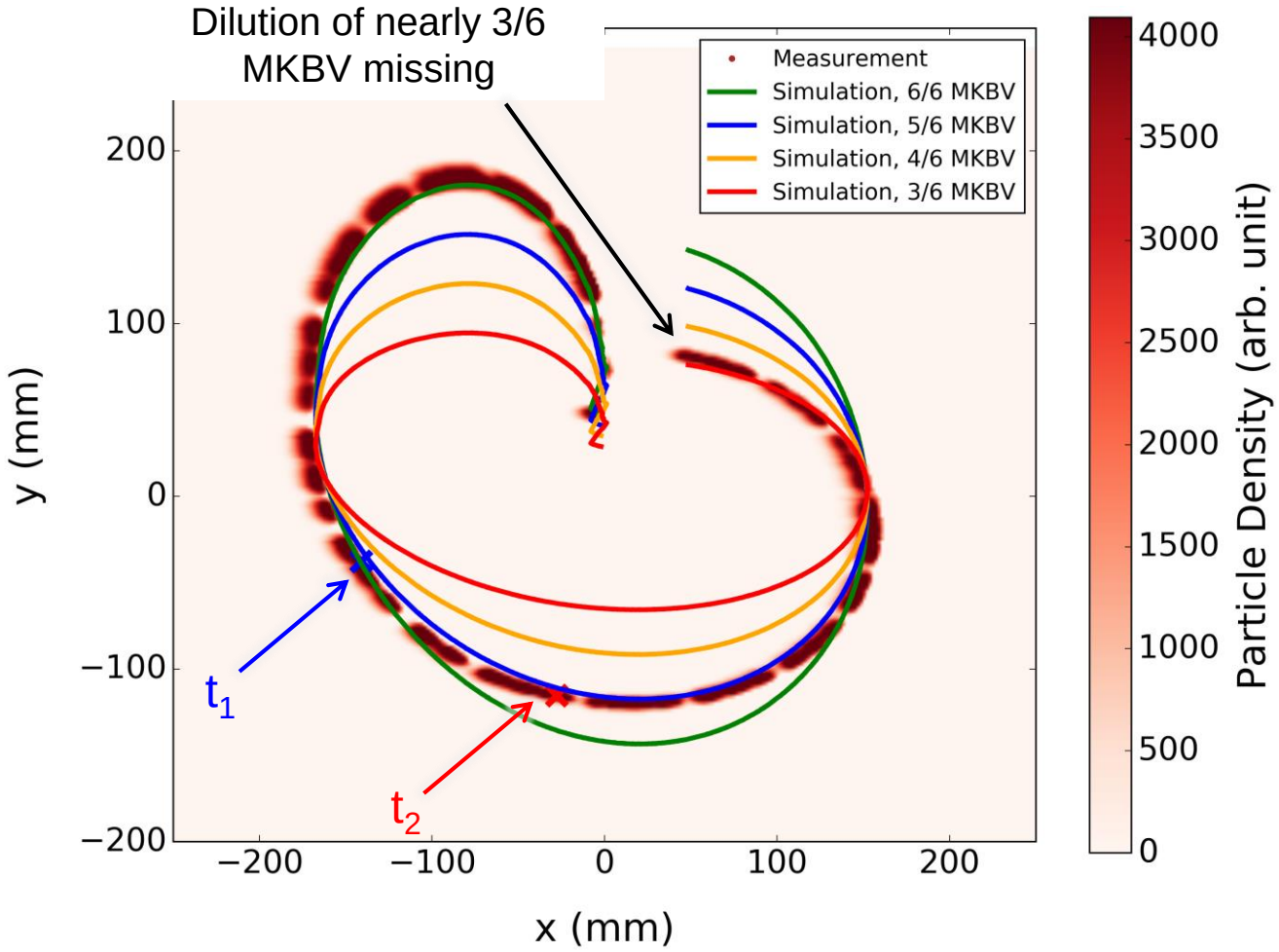
Simulated pattern using waveform
from 2016-07-22, 17h01 (B2).
Center position fitted and vertical size scaled by 1.04

MKBV flashover
2018-07-14, 03h00

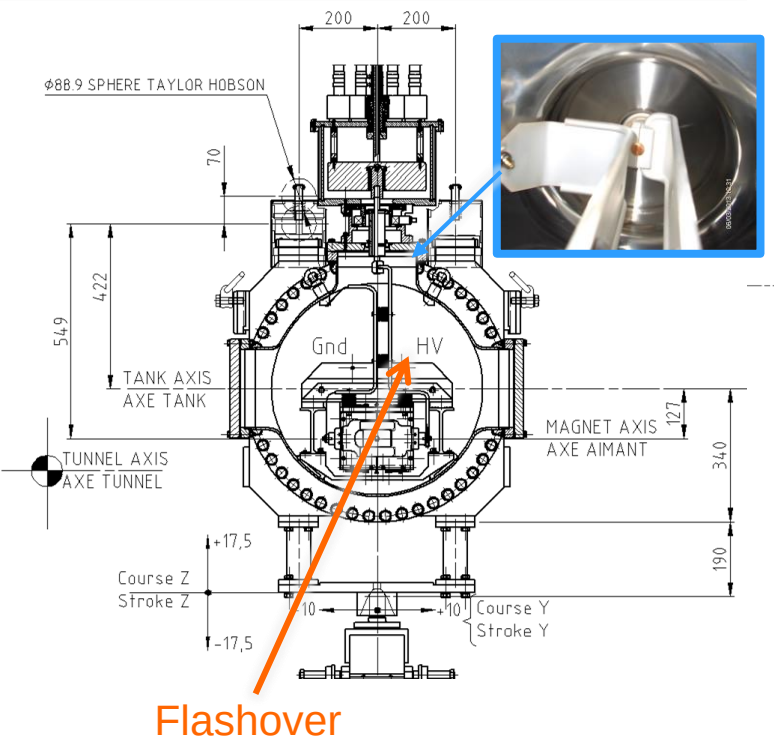


MKBV Flashover

Simulated pattern using waveform
from 2016-07-22, 17h01 (B2).
Center position fitted and vertical size scaled by 1.04

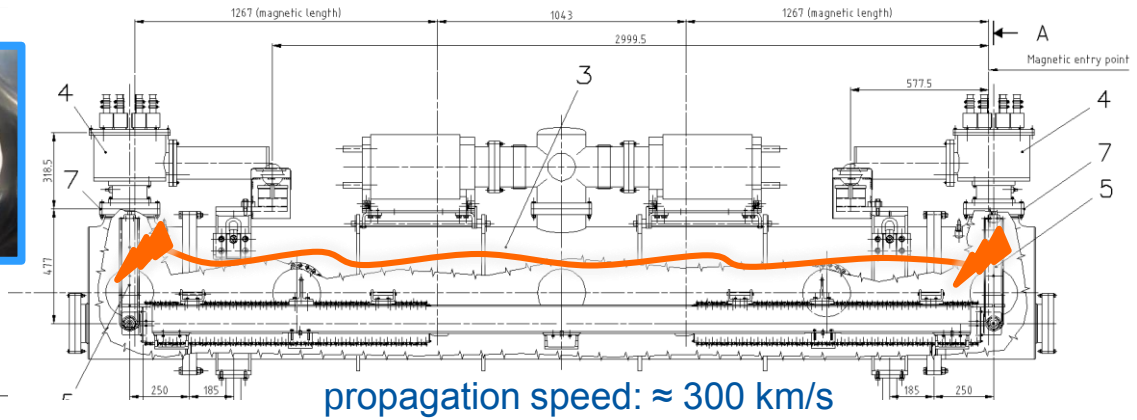


MKBV Flashover

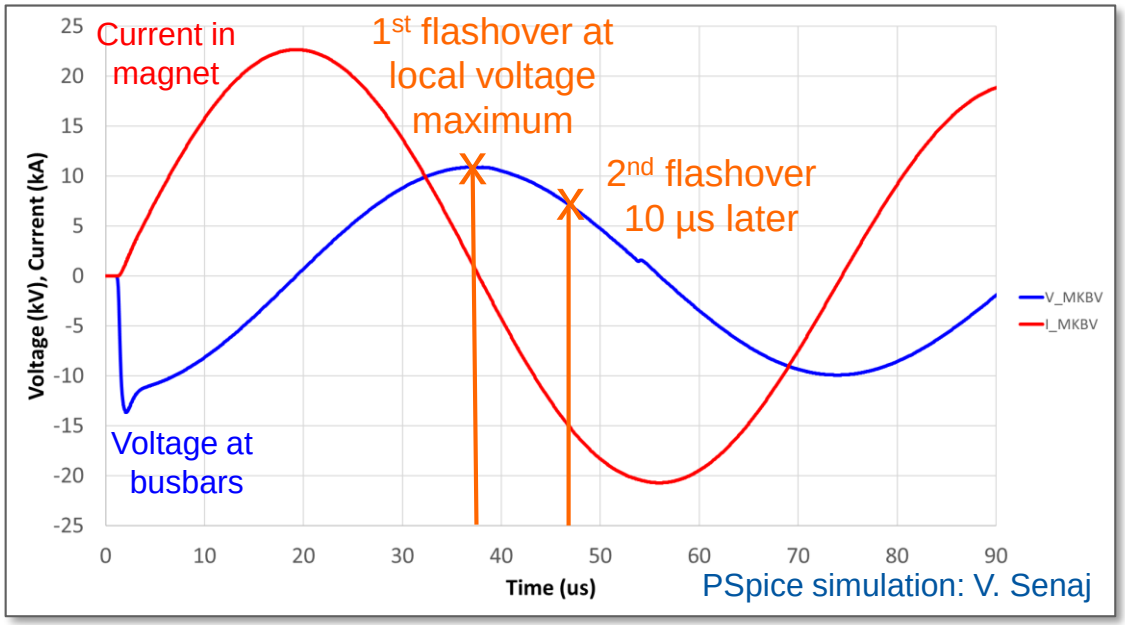


Flashover

MKBV.C/D



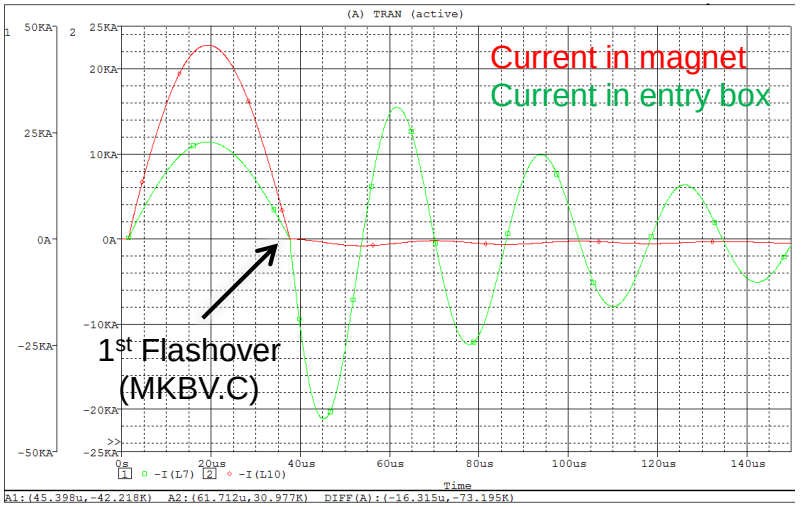
propagation speed: ≈ 300 km/s

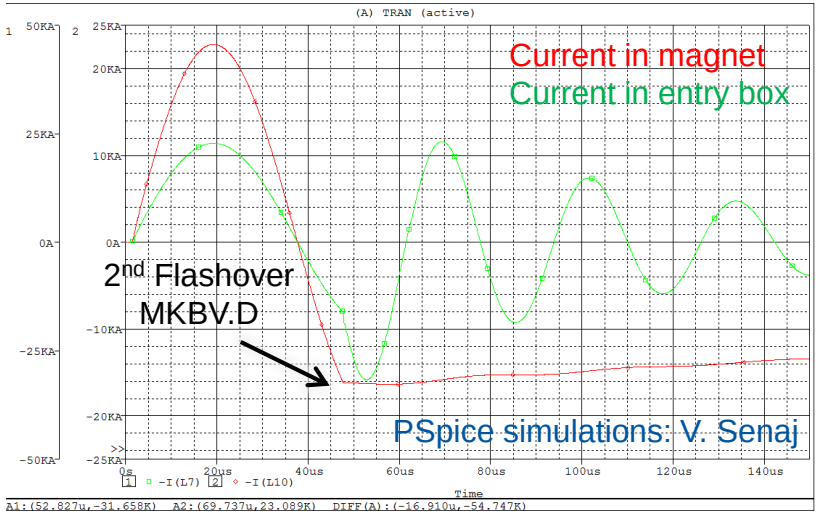


PSpice simulation: V. Senaj

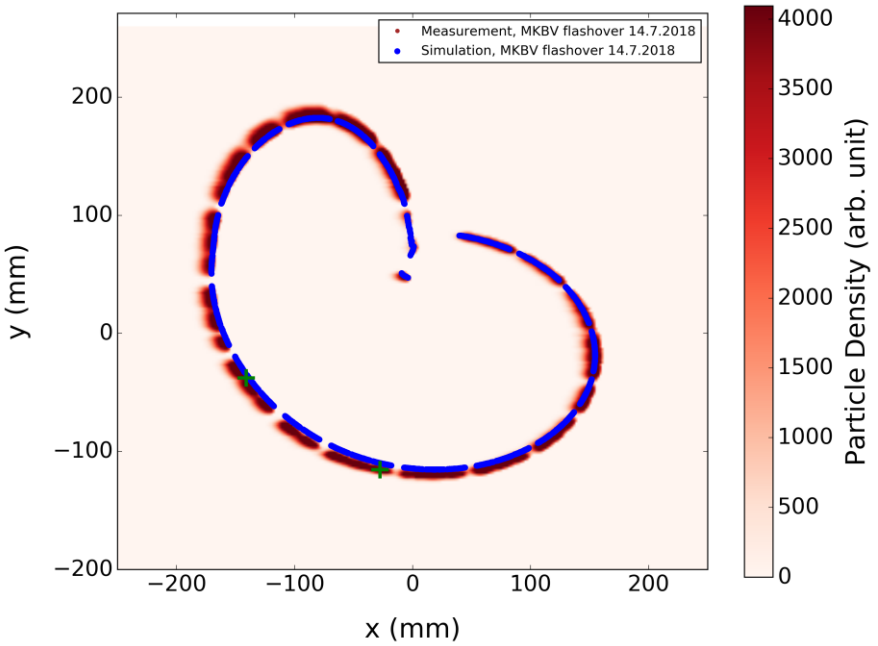
- Reason and exact location of flashover not clear
- Visual inspection in LS2

MKBV Flashover





Simulated and measured dilution patterns



- Simulated pattern fits very well to the BTVDD measurement
- Supports hypothesis that current persists in the magnet coil after flashover

MKBV Flashover – Summary

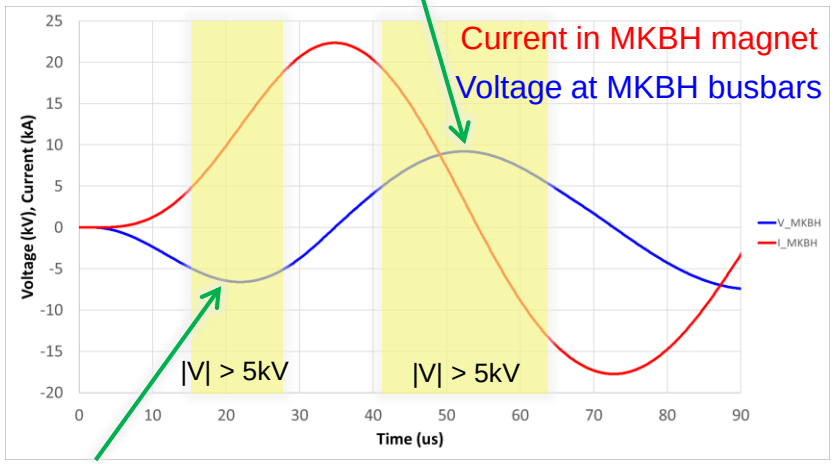
Previous assumptions	MKBV flashover, 14.7.2018
Flashover can occur during dump execution	Confirmed
Flashover can propagate to 2nd magnet in the same vacuum tank	Confirmed
Flashover leads to loss of dilution (no current in the magnet)	Confirmed for MKBV.C (flashover at zero current) Not confirmed for MKBV.D (flashover at high current)

Not critical in the vertical plane,
but can lead to a new worst case in the horizontal plane

What would happen if we had a flashover in the horizontal plane?

MKBH Flashover: Simulations

2nd voltage maximum: +9.2kV at 52 us



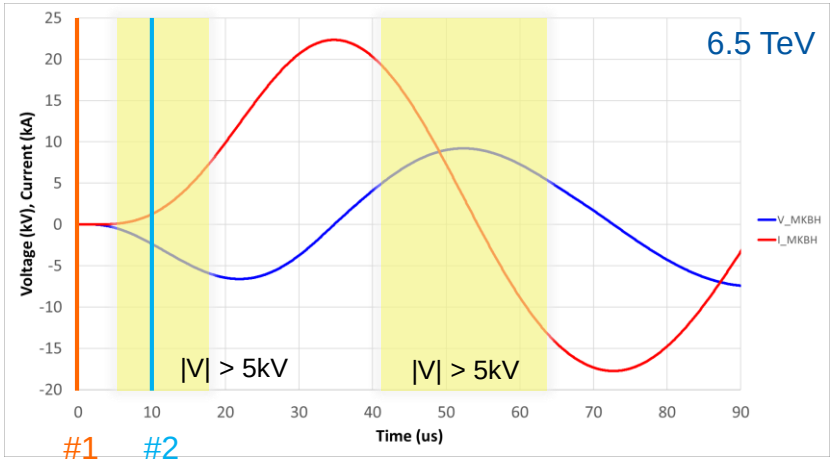
Voltage maximum: -6.6 kV at 22 us

Pspice simulation, 6.5 TeV (V. Senaj)

Assumptions for (these) beam simulations

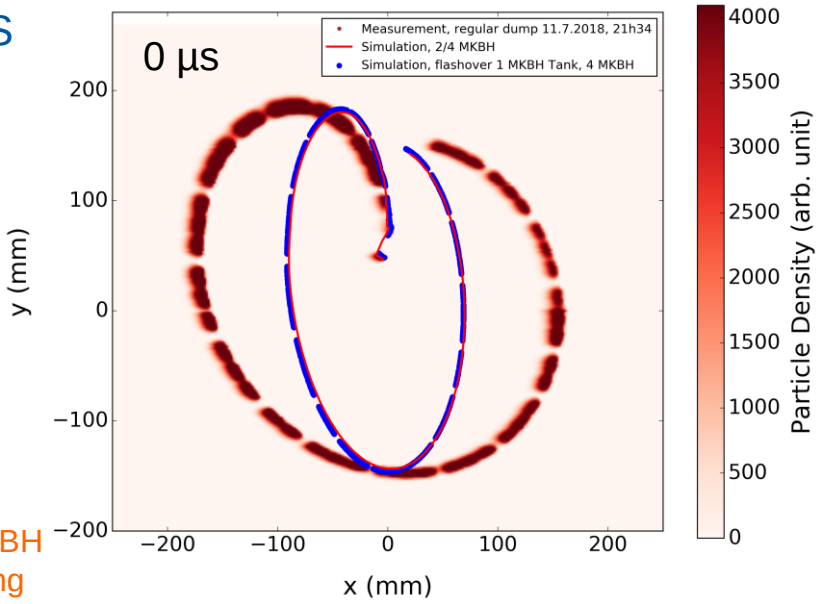
- Delay between first and second flashover: 10 us
- Current in magnet coil stays constant after flashover (PSpiece: slow decay of ~8% over 50 us)
- Estimations of p+ bunch density: L. Richtmann
- Higher voltage results in higher flashover probability, but no clear correlation/threshold

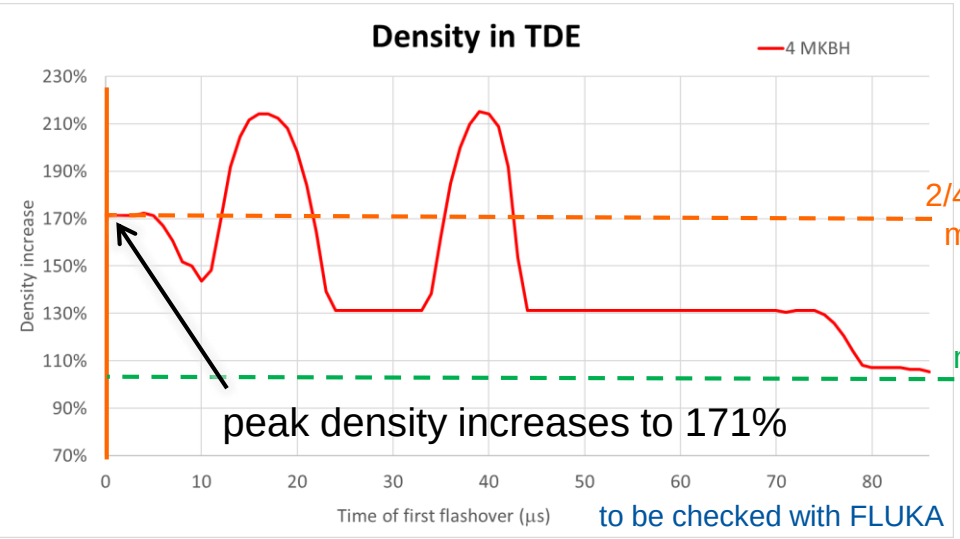
MKBH Flashover: Simulations



BCMS 2018

Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed

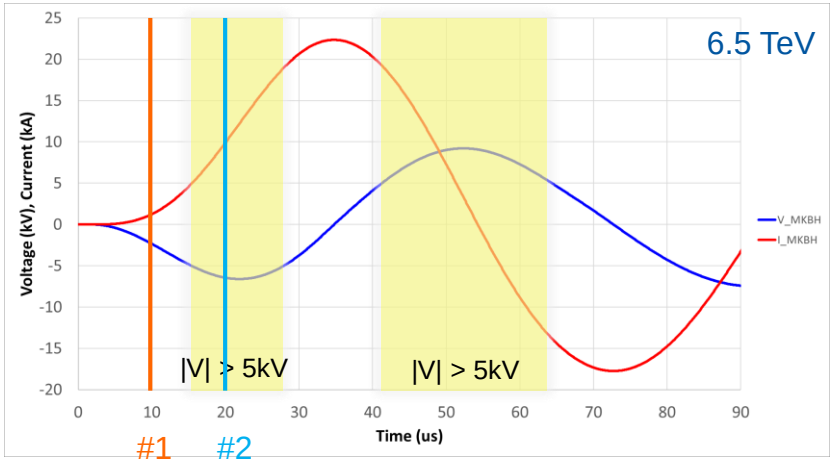


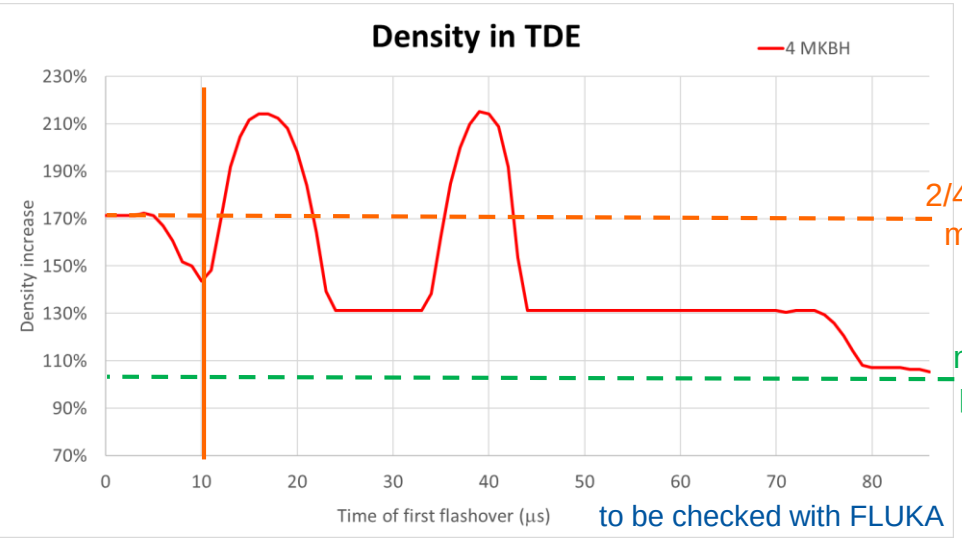


to be checked with FLUKA

Corresponds to traditionally assumed worst case of 2/4 MKBH missing

MKBH Flashover: Simulations





Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed

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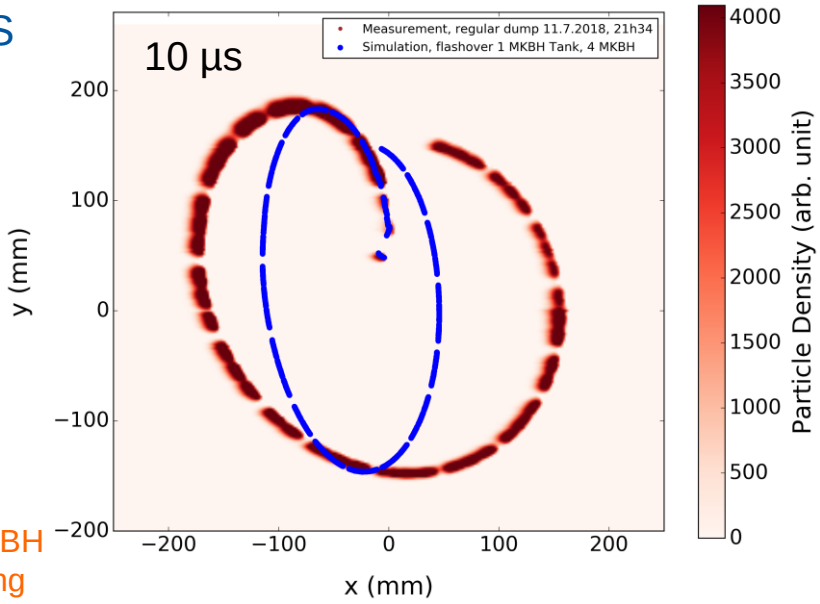
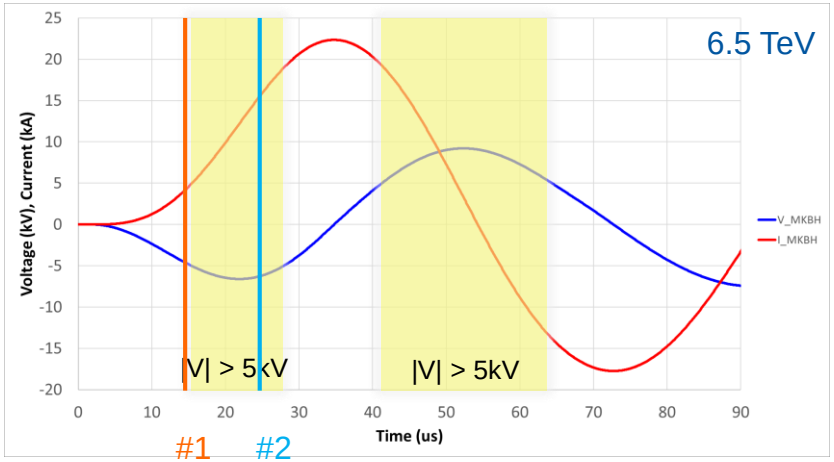
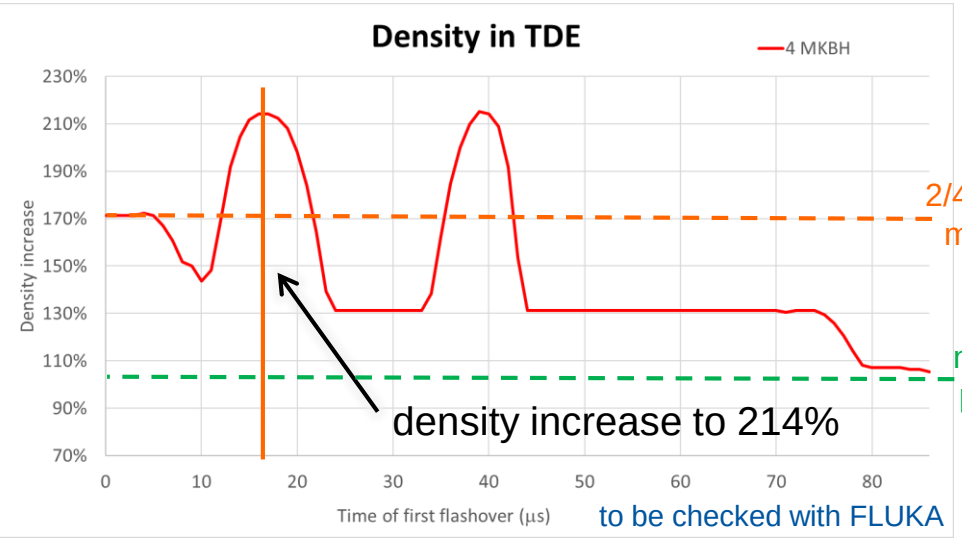


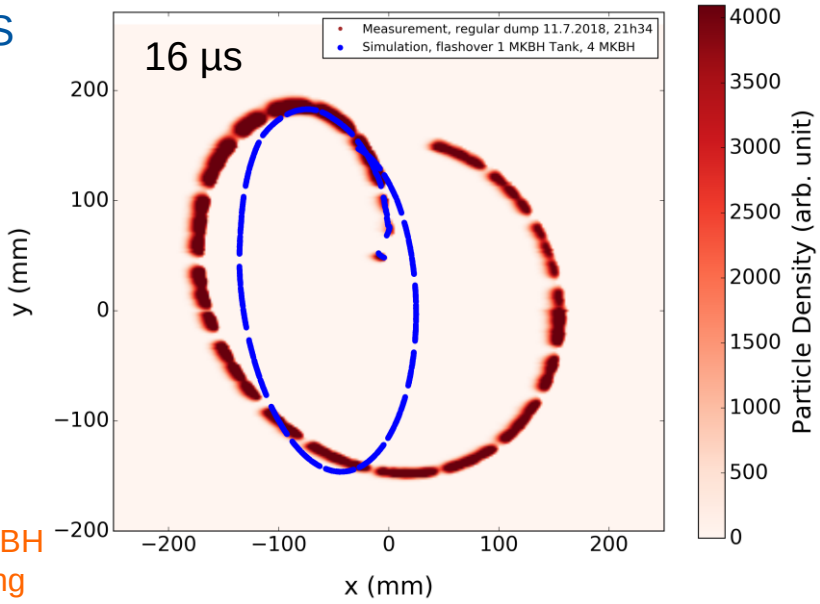
MKBH Flashover: Simulations





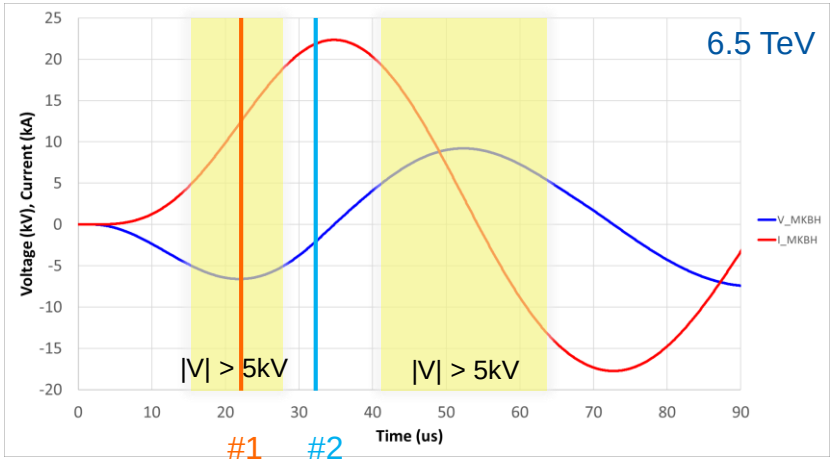
Flashover for **2 out of 4 MKBH**,
nominal deflection,
no droop assumed

BCMS 2018



Sweep path overlaps
→ New worst case
(highest density increase)

MKBH Flashover: Simulations



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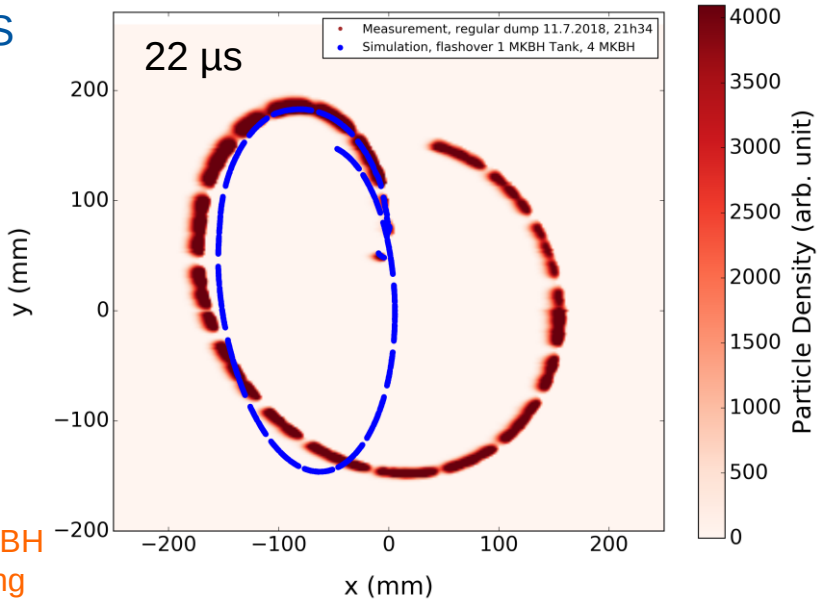
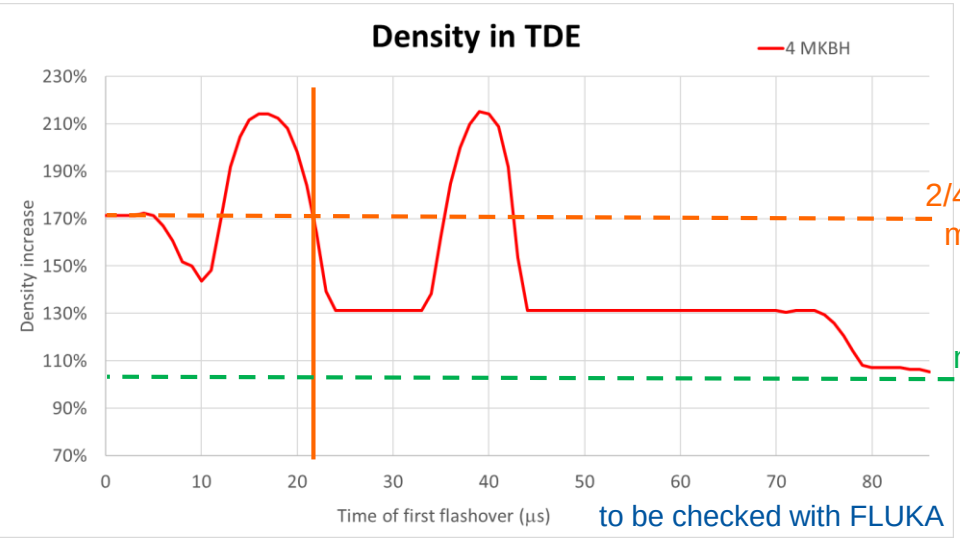
Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed

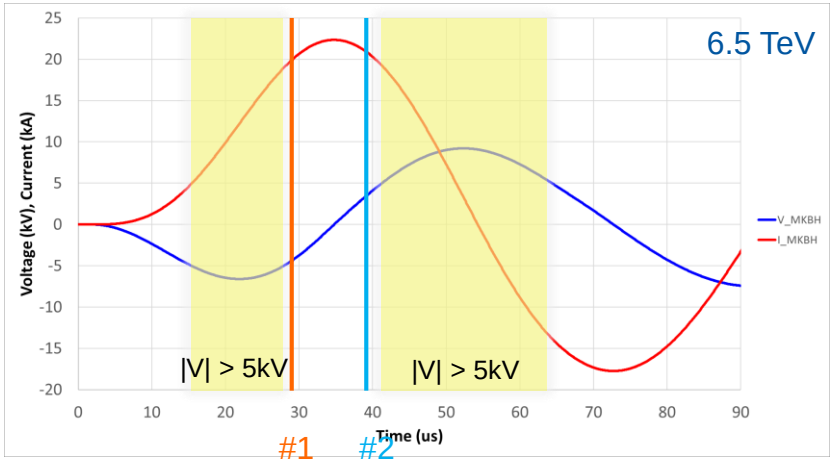




to be checked with FLUKA

Calculated density depends significantly on filling pattern in first/last part of machine.

MKBH Flashover: Simulations



#1 29 µs #2 39 µs

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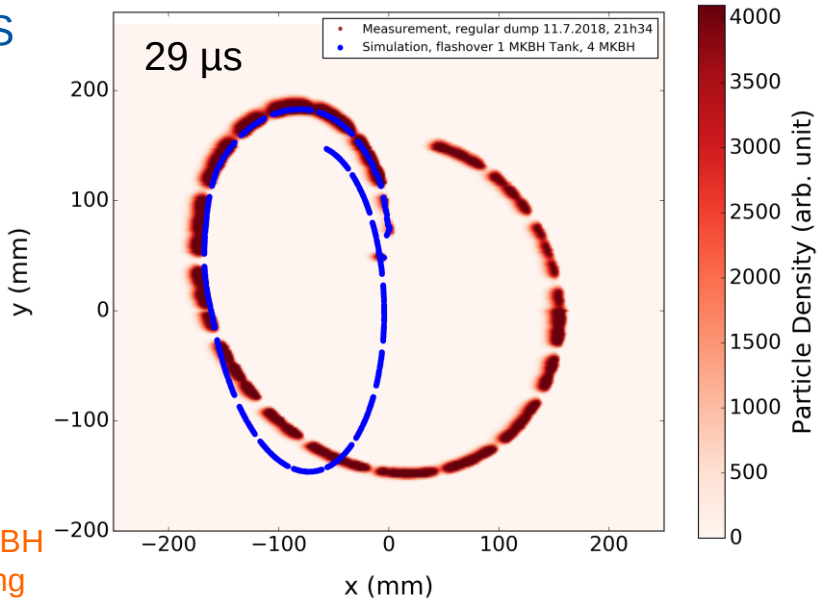
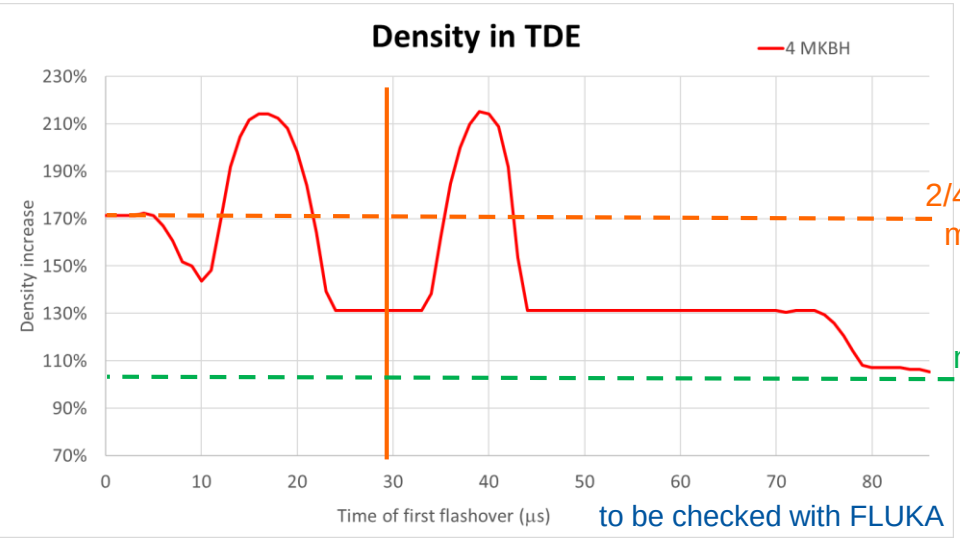
Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed



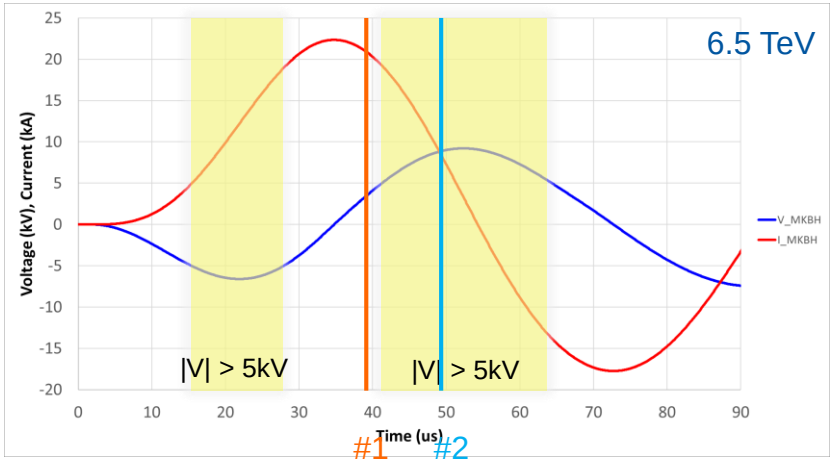


2/4 MKBH missing

nominal pattern

to be checked with FLUKA

MKBH Flashover: Simulations



#1 39 µs #2 49 µs

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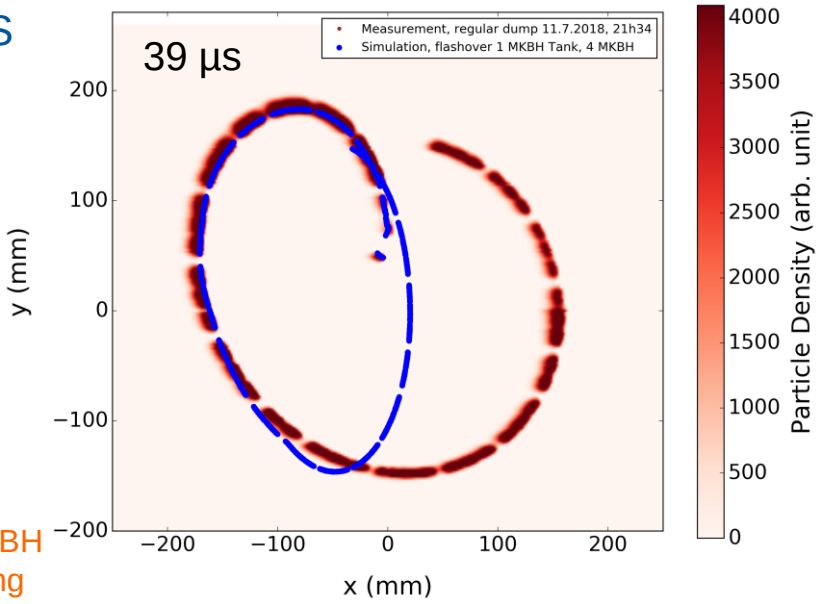
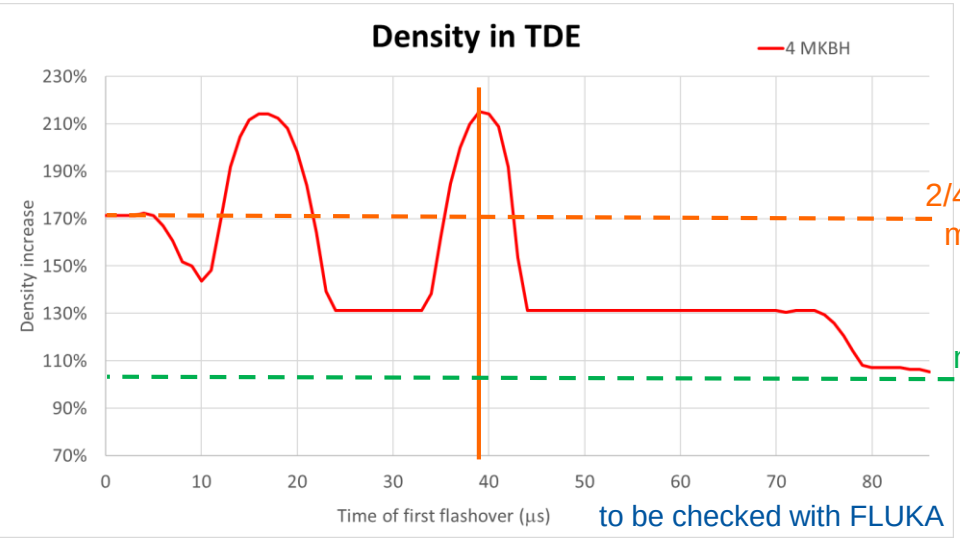
Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed



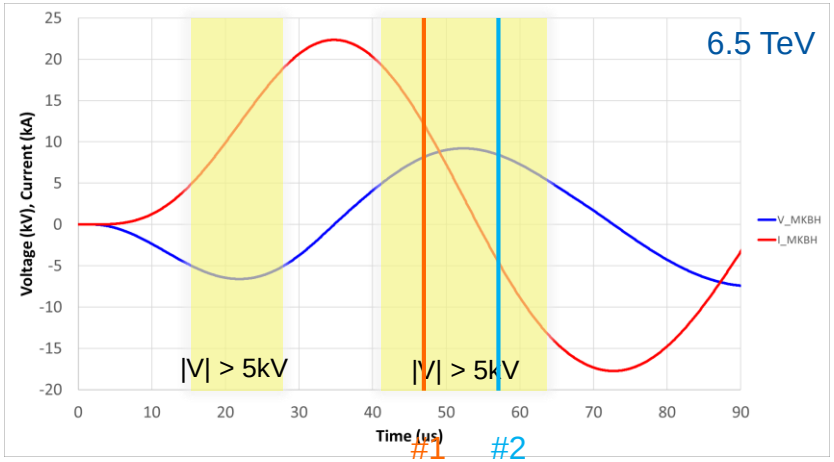


2/4 MKBH missing

nominal pattern

to be checked with FLUKA

MKBH Flashover: Simulations



#1 47 µs #2 57 µs

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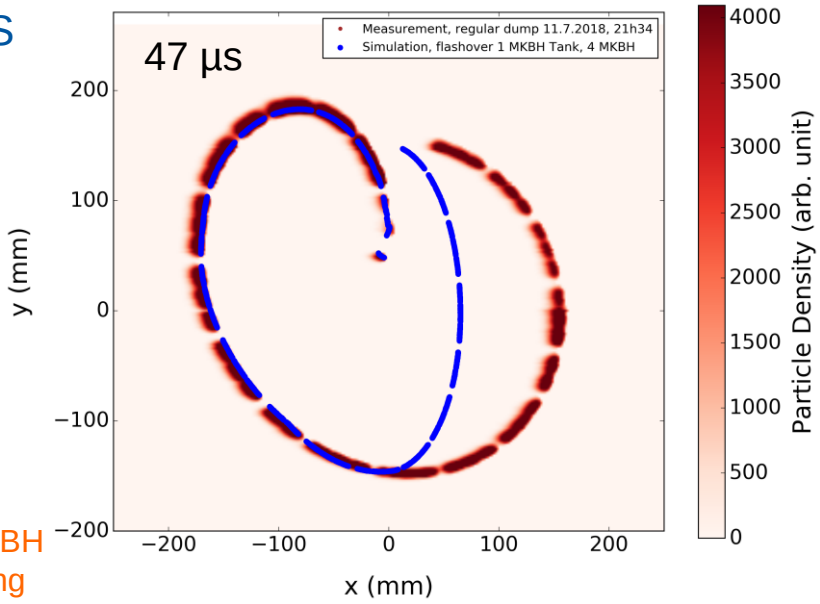
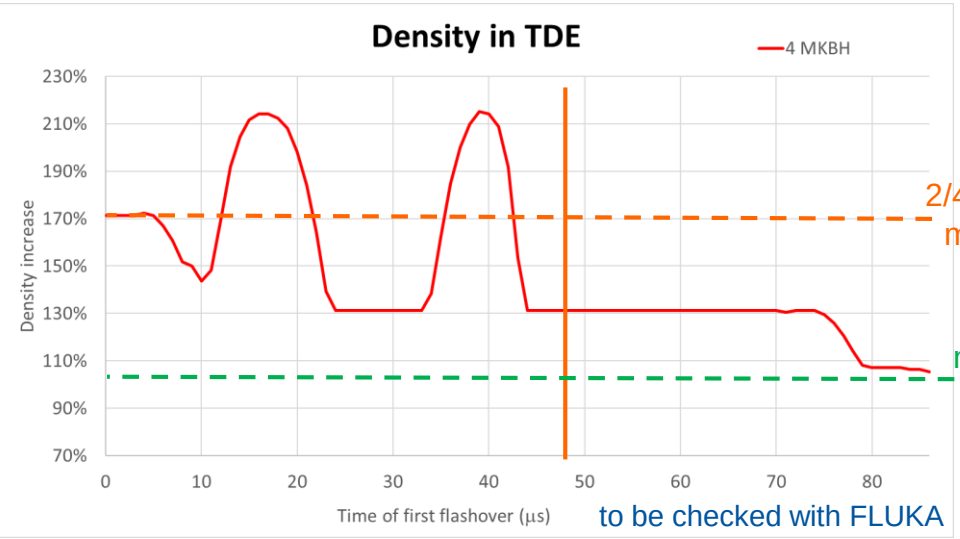
Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed

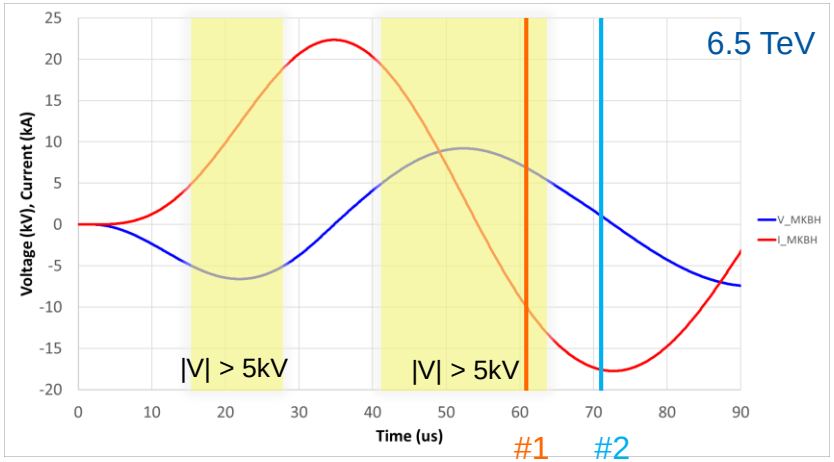




to be checked with FLUKA

Flashover close to second voltage maximum (or later) not critical.

MKBH Flashover: Simulations



#1 61 µs #2 71 µs

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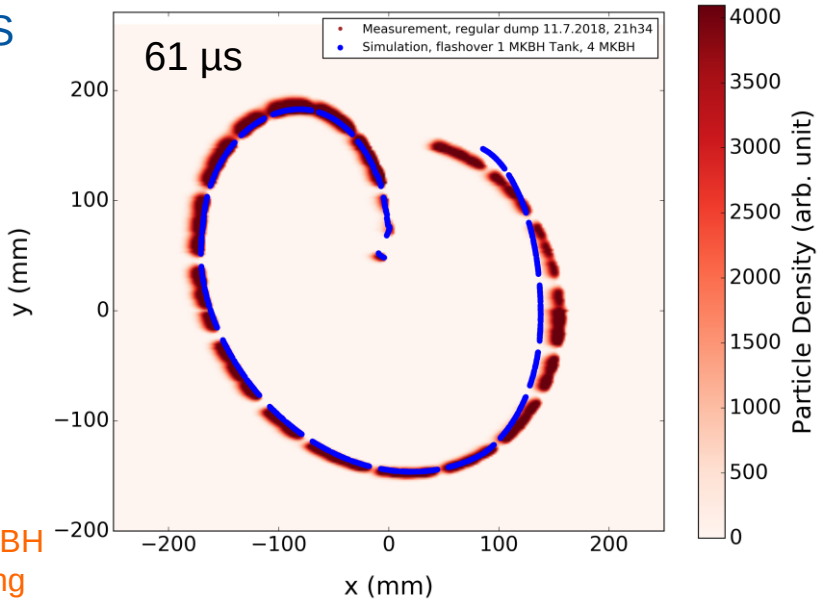
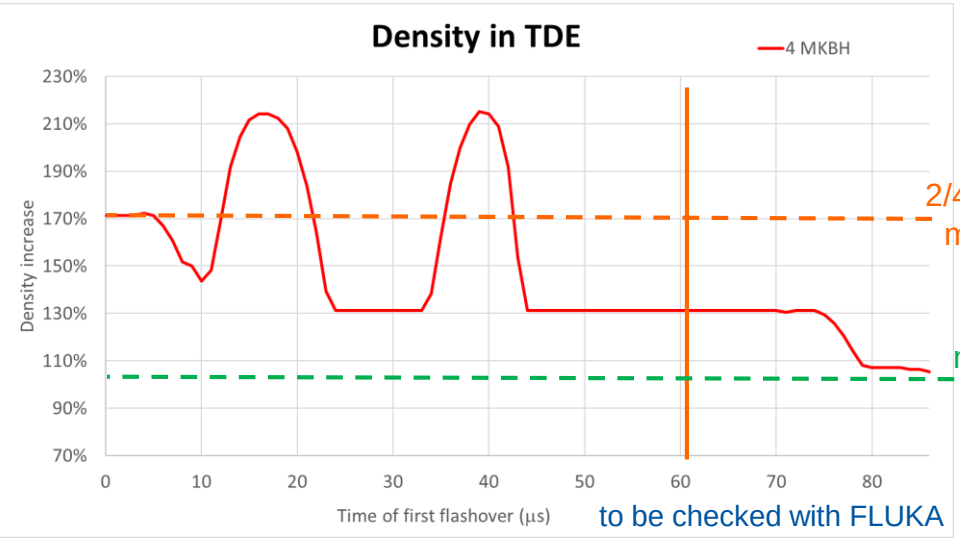
Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed



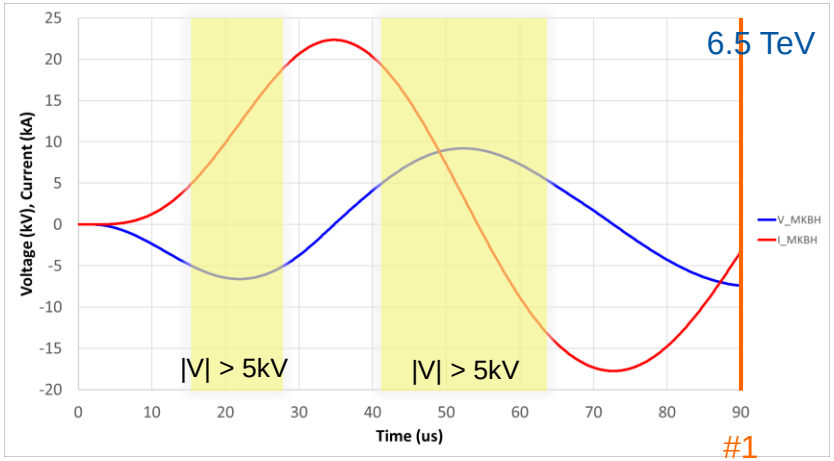


2/4 MKBH missing

nominal pattern

to be checked with FLUKA

MKBH Flashover: Simulations



#1
86 µs

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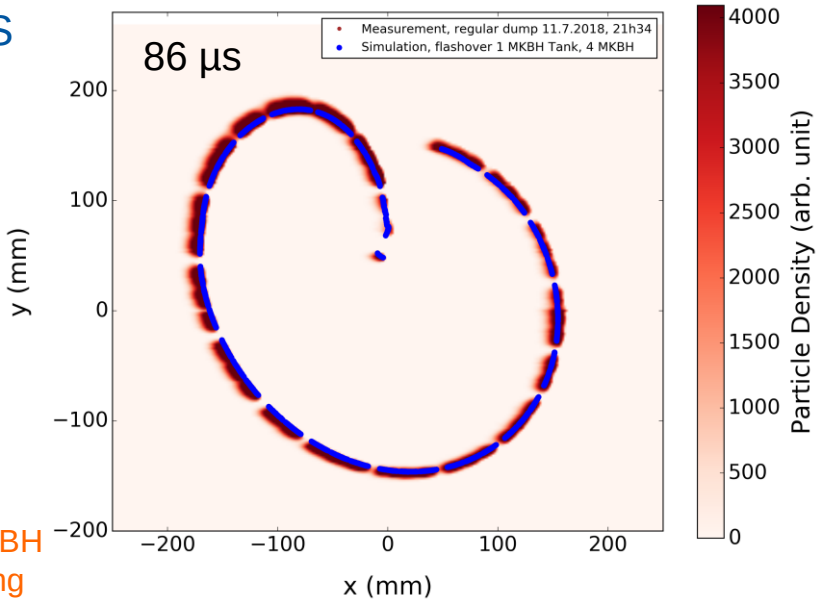
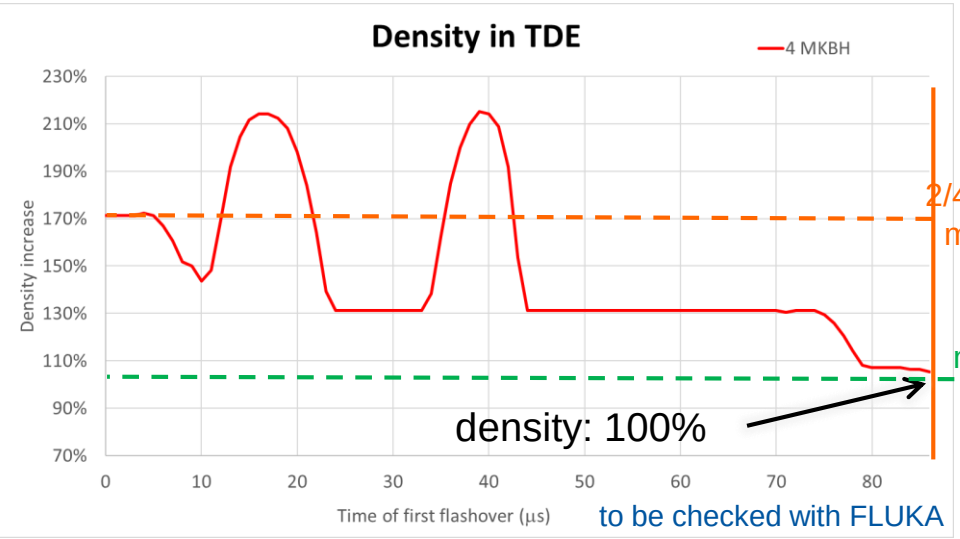
Flashover for **2 out of 4 MKBH**, nominal deflection, no droop assumed

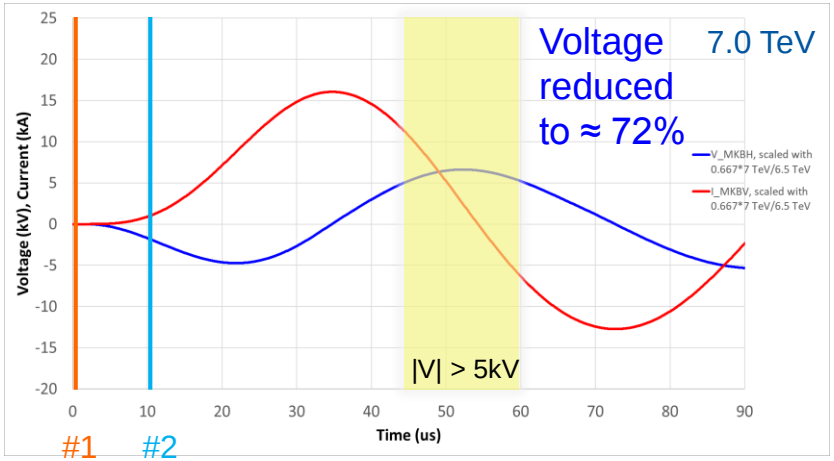




to be checked with FLUKA

What would be the effect of adding 2 more MKBH?

MKBH Flashover: Simulations



#1 0 µs #2 10 µs

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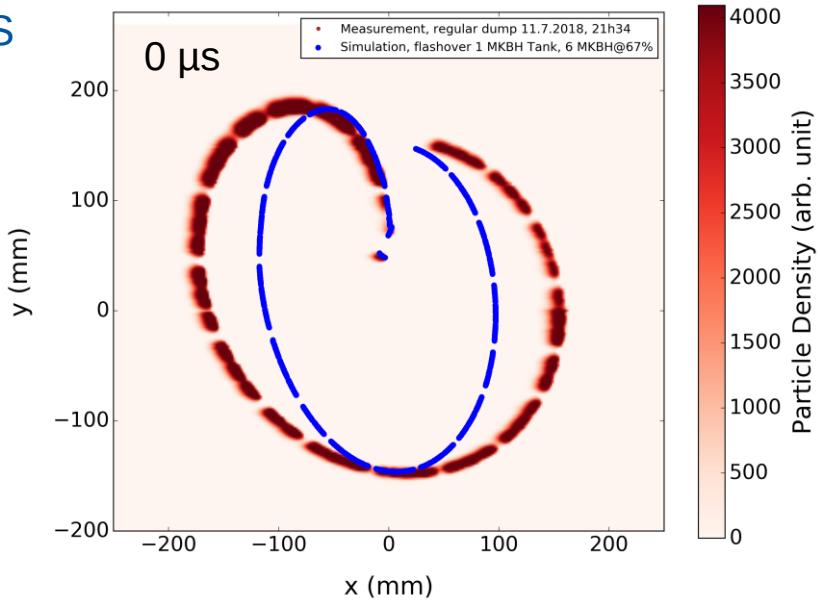
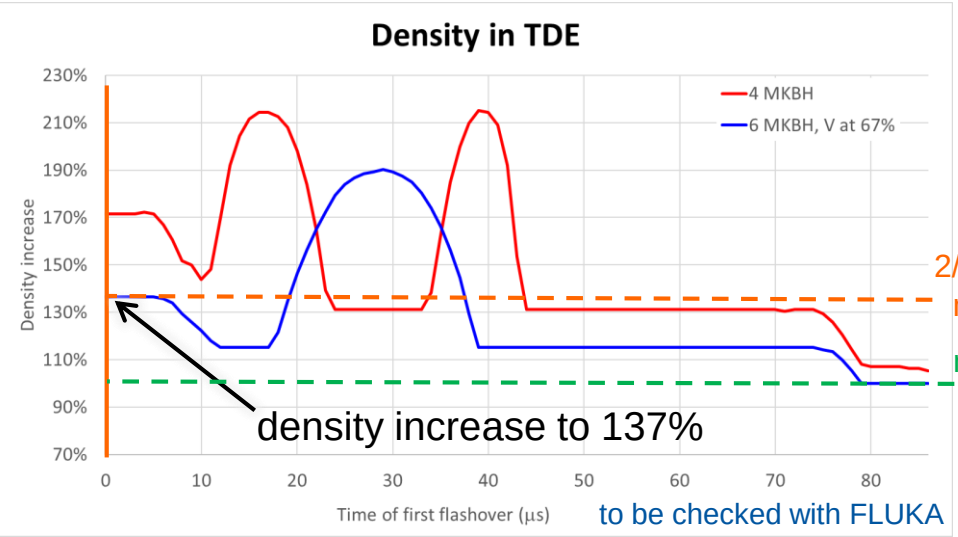
Flashover for **2 out of 6 MKBH**, nominal deflection, no droop assumed





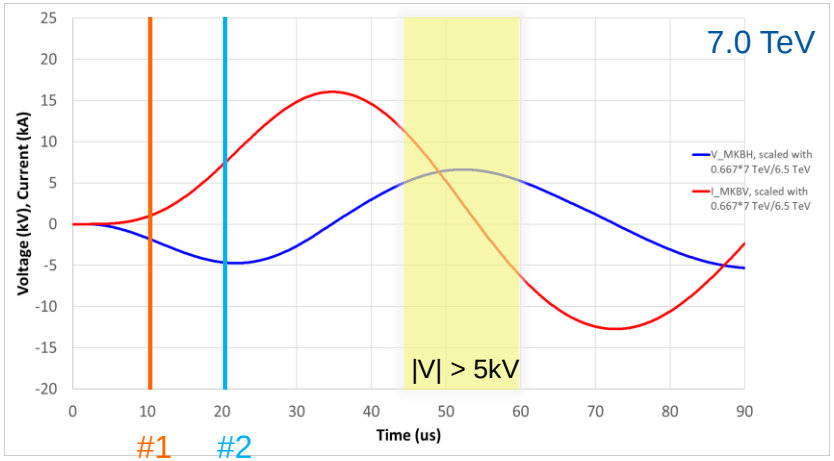
2/6 MKBH missing

nominal pattern

to be checked with FLUKA

Corresponds to failure case of 2/6 MKBH missing

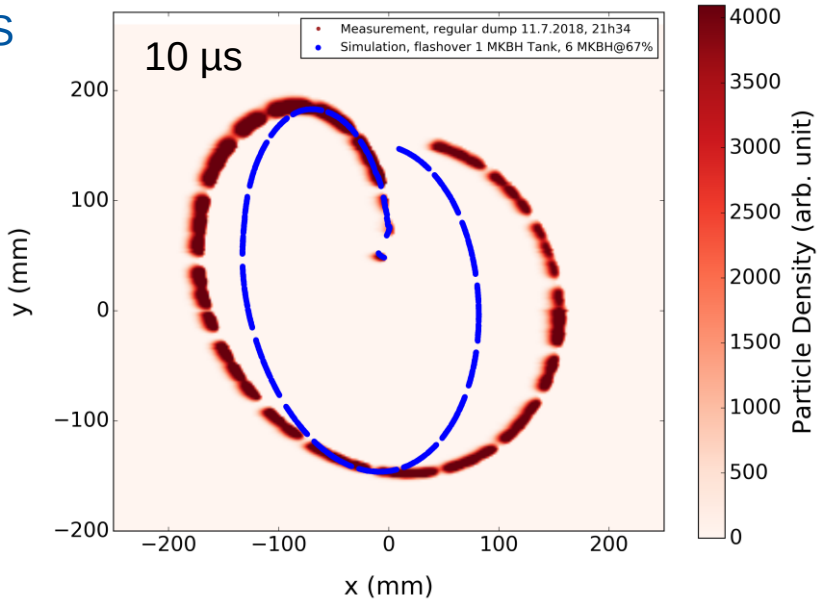
MKBH Flashover: Simulations

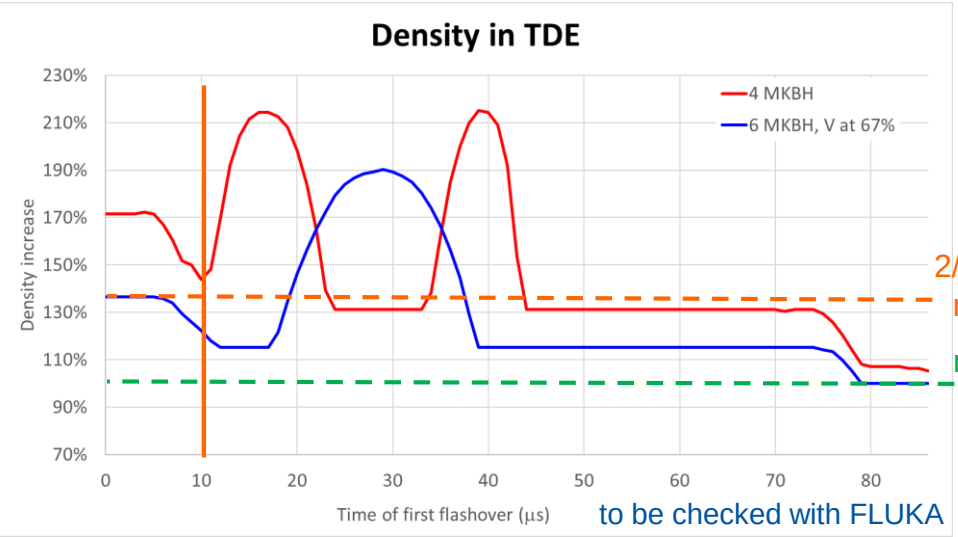


#1 10 µs #2 20 µs

BCMS 2018

Flashover for **2 out of 6 MKBH**, nominal deflection, no droop assumed



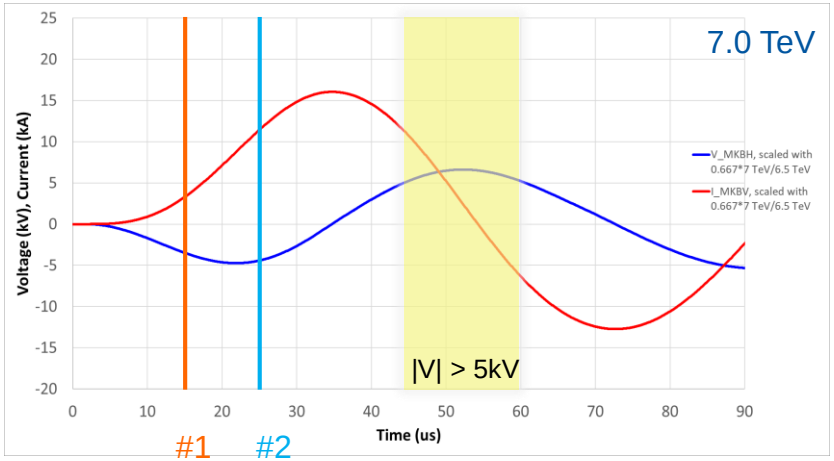


2/6 MKBH missing

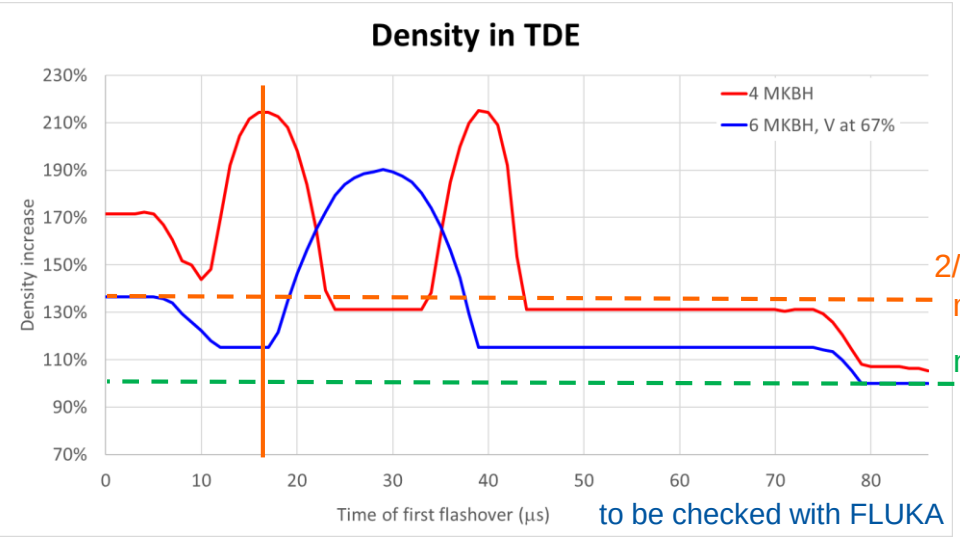
nominal pattern

to be checked with FLUKA

MKBH Flashover: Simulations



#1 16 µs #2 26 µs



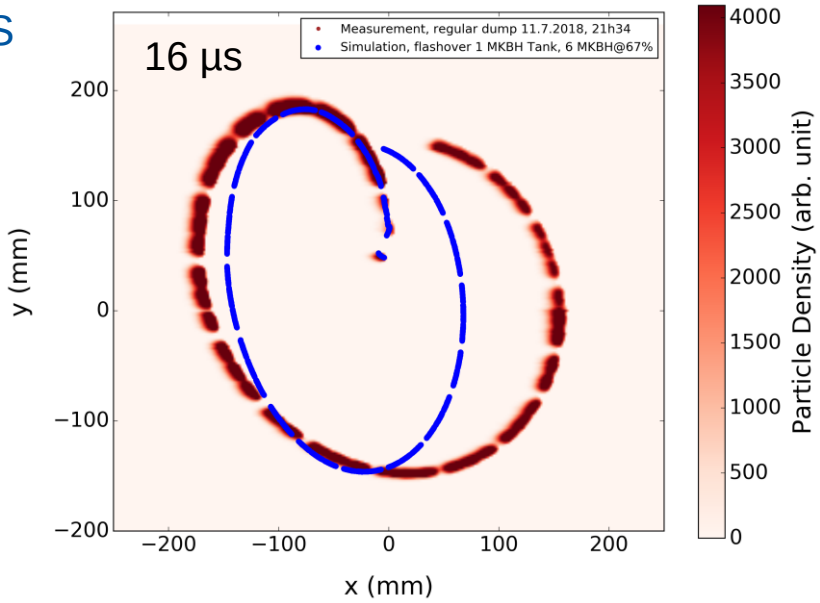
2/6 MKBH missing

nominal pattern

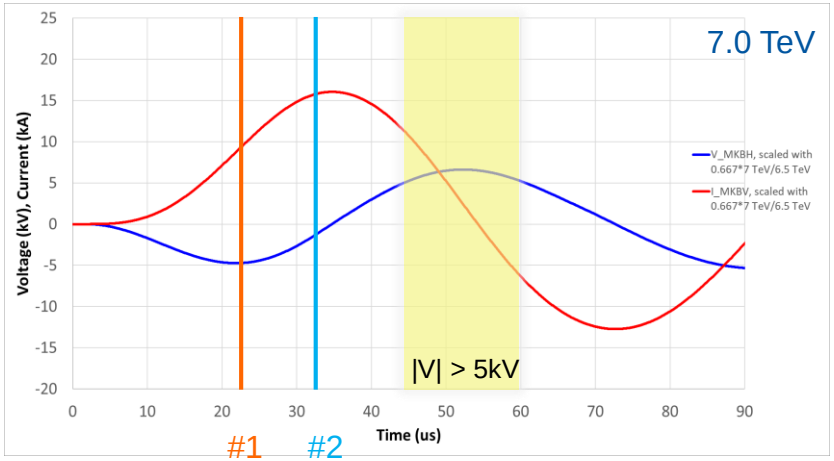
to be checked with FLUKA

Flashover for **2 out of 6 MKBH**, nominal deflection, no droop assumed

BCMS 2018

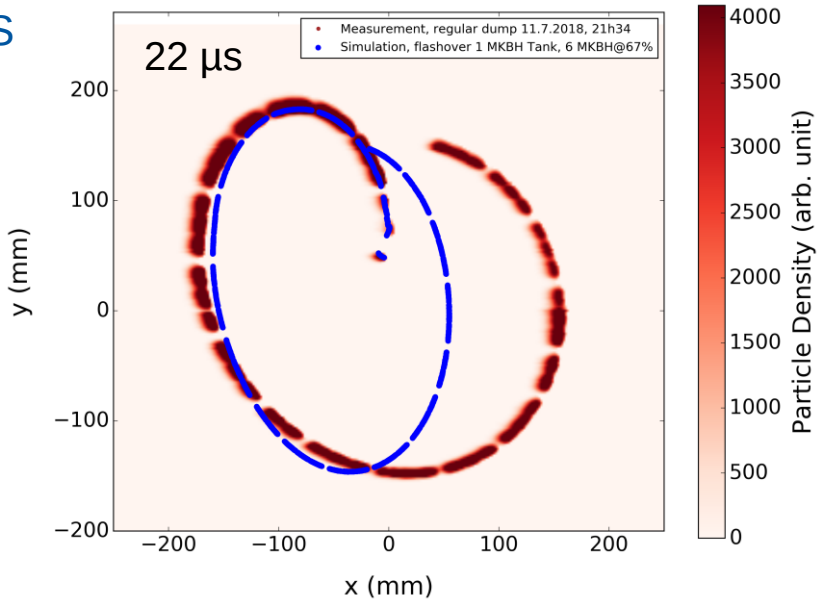


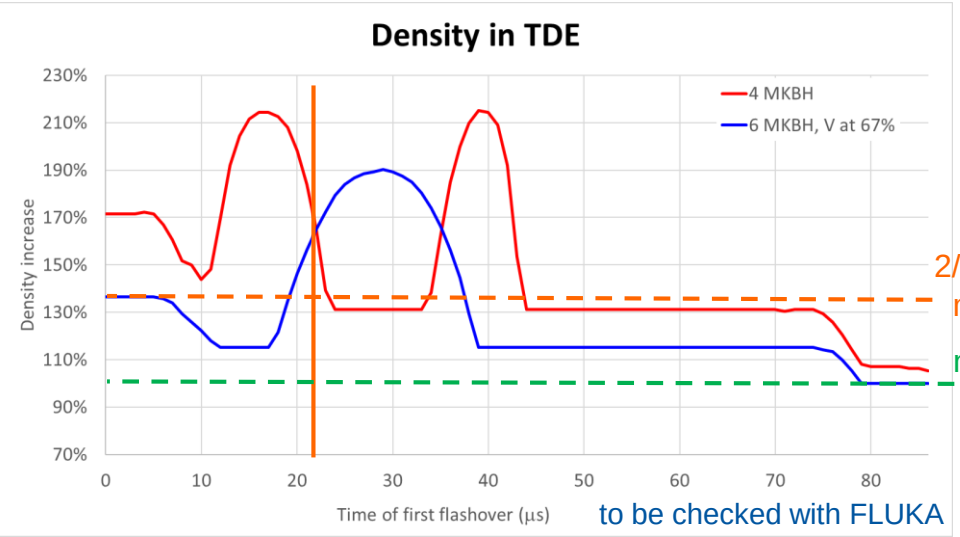
MKBH Flashover: Simulations



BCMS 2018

Flashover for **2 out of 6 MKBH**, nominal deflection, no droop assumed



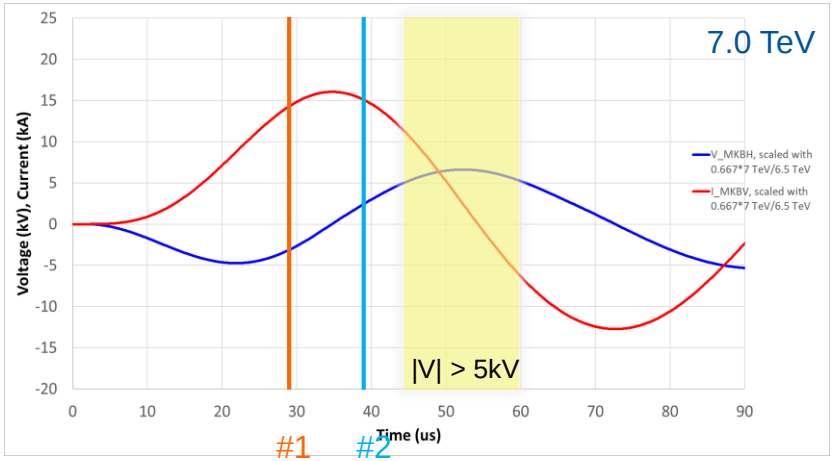


2/6 MKBH missing

nominal pattern

to be checked with FLUKA

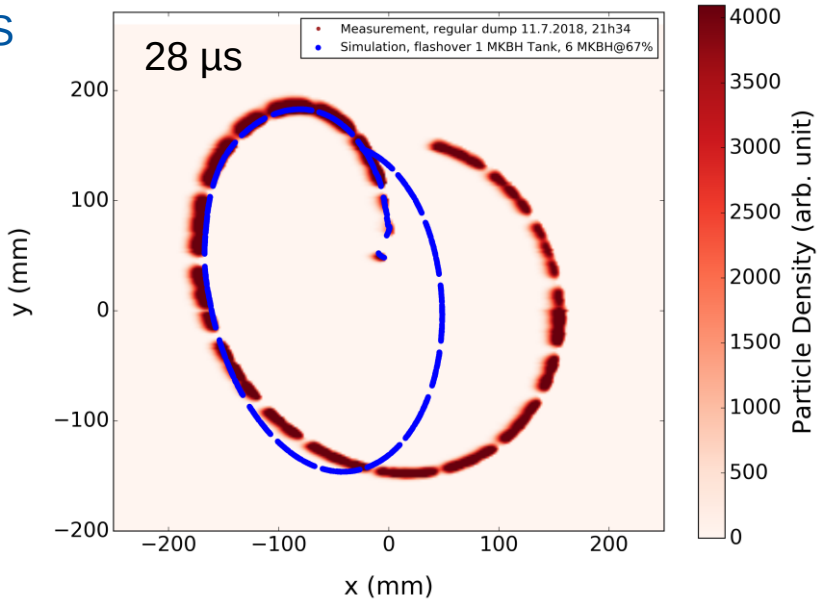
MKBH Flashover: Simulations



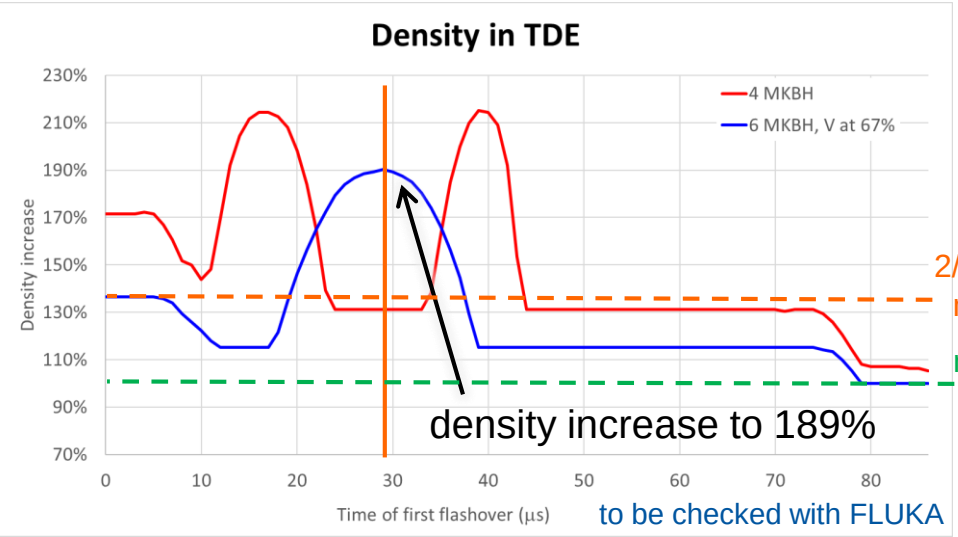
#1 28 µs #2 38 µs

BCMS 2018

Flashover for **2 out of 6 MKBH**, nominal deflection, no droop assumed



Worst-case density for flashover with 6 MKBH

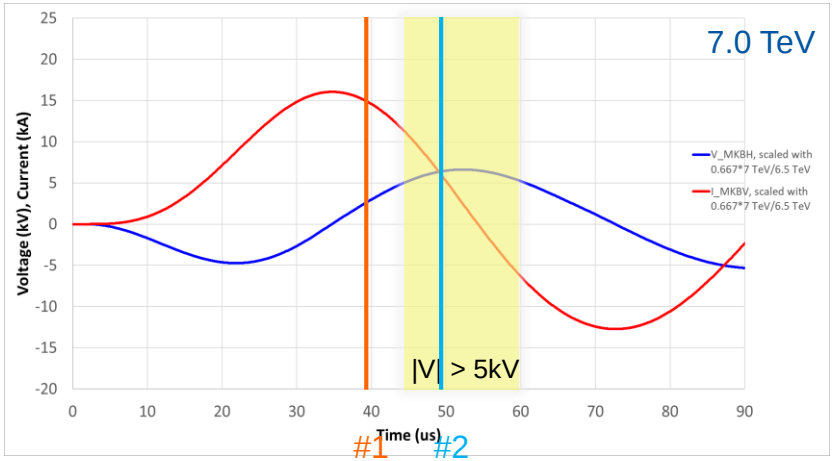


2/6 MKBH missing

nominal pattern

to be checked with FLUKA

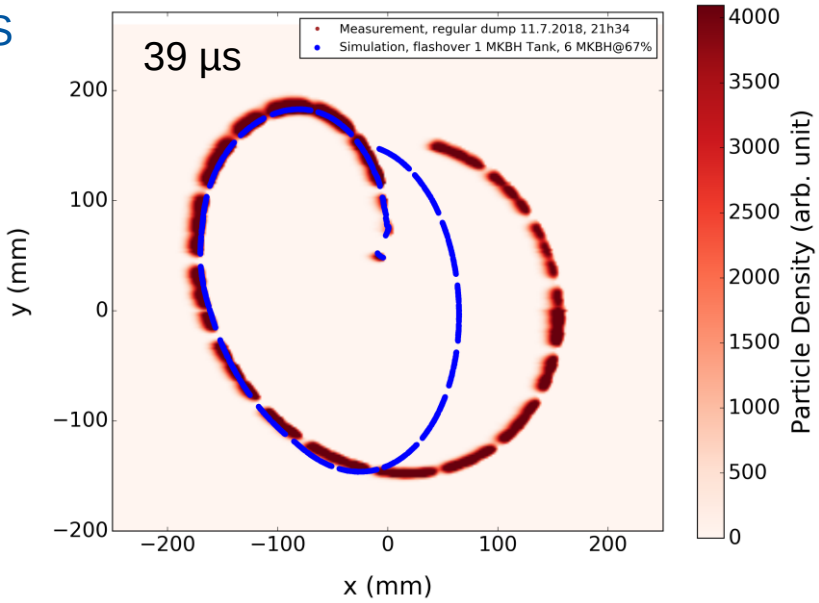
MKBH Flashover: Simulations

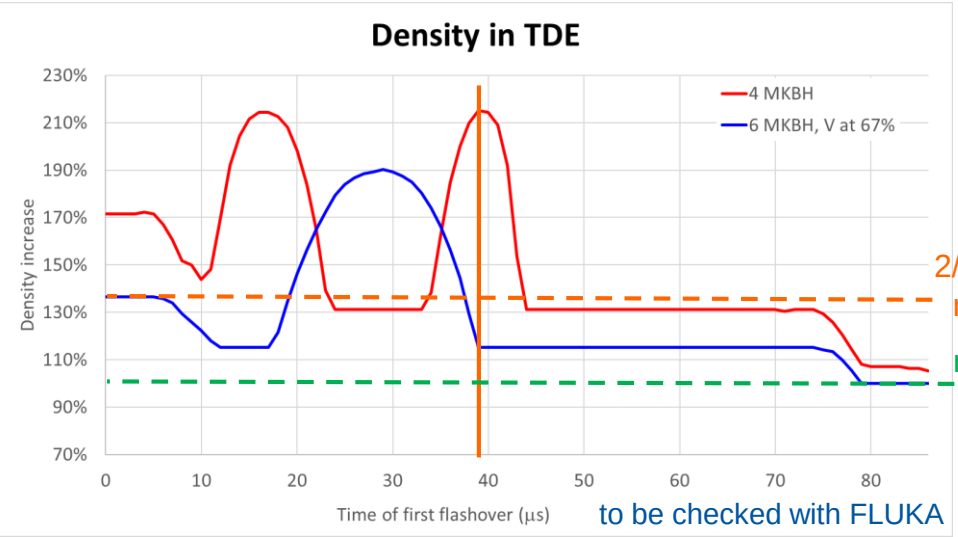


#1 39 µs #2 49 µs

BCMS 2018

Flashover for **2 out of 6 MKBH**, nominal deflection, no droop assumed



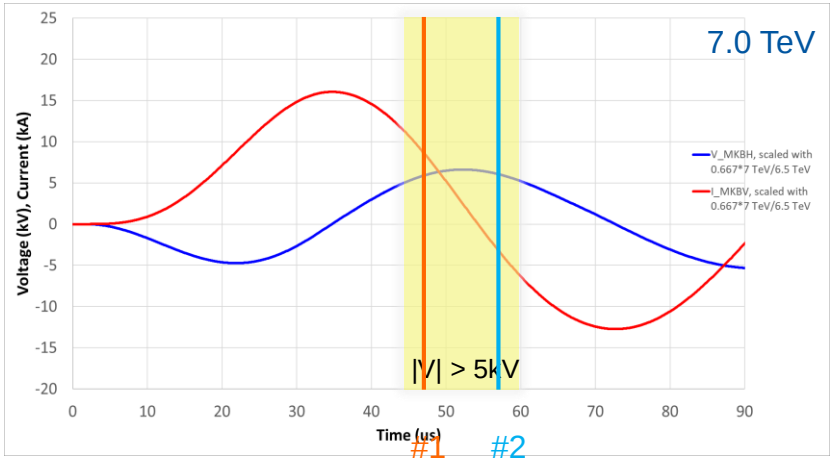


2/6 MKBH missing

nominal pattern

to be checked with FLUKA

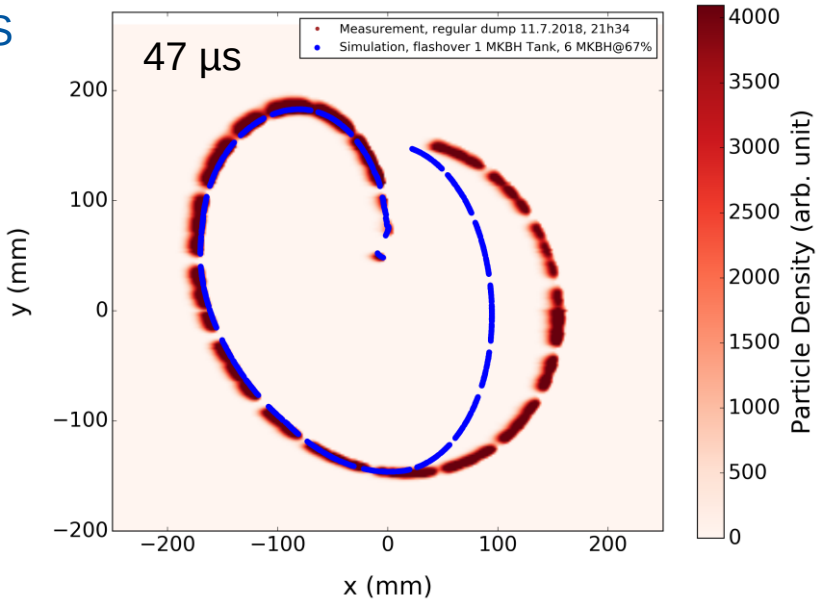
MKBH Flashover: Simulations

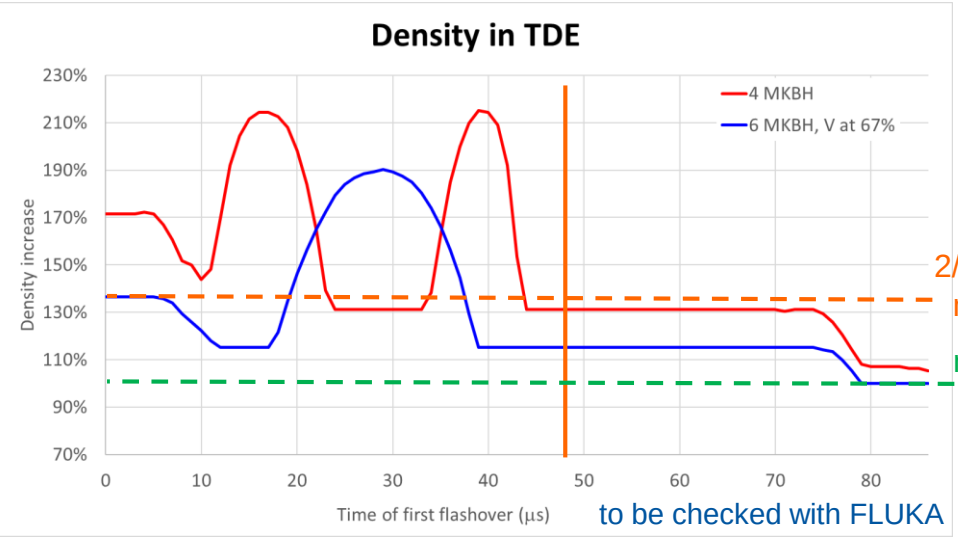


#1 47 µs #2 57 µs

BCMS 2018

Flashover for **2 out of 6 MKBH**, nominal deflection, no droop assumed





2/6 MKBH missing

nominal pattern

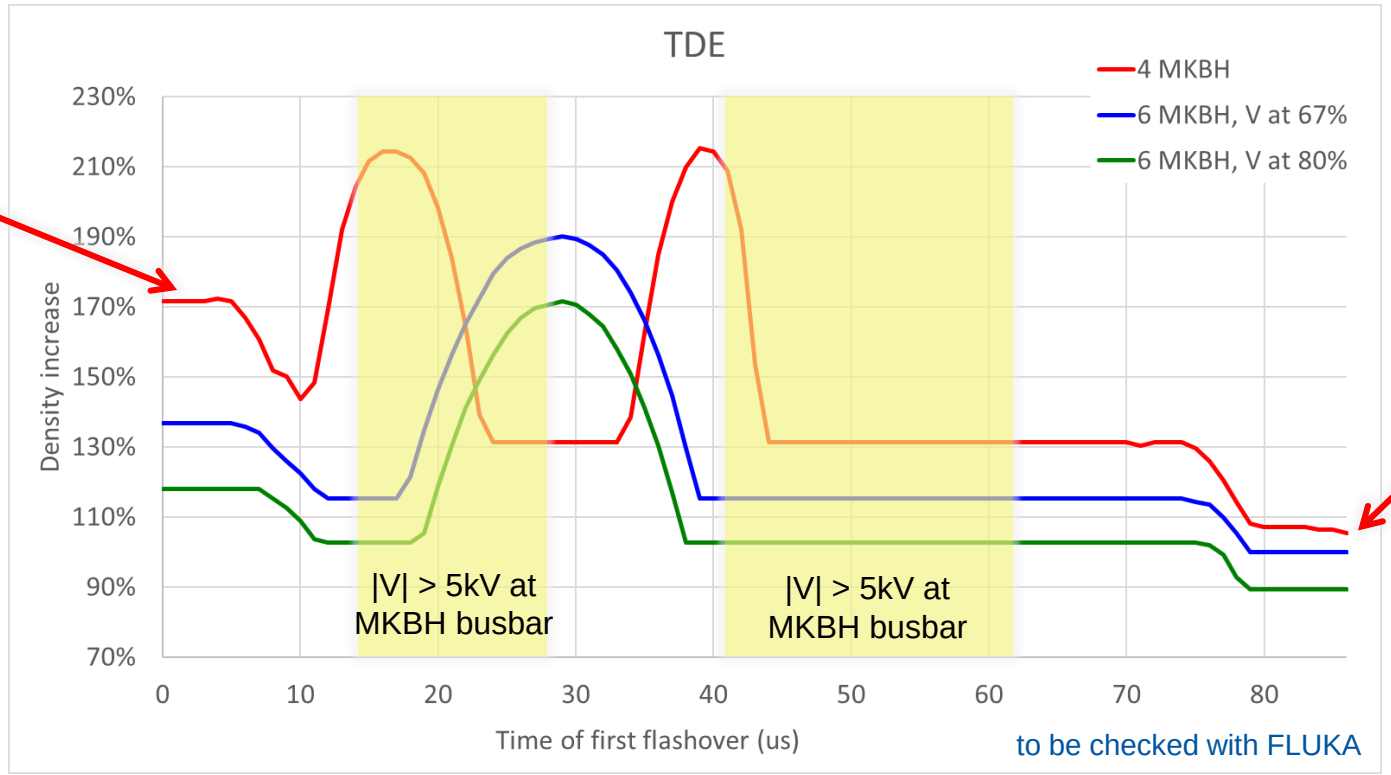
to be checked with FLUKA

Flashover close to second voltage maximum (or later) not critical.

MKBH Flashover: Summary

Estimated peak density increase compared to nominal pattern

Corresponds to 2/4 MKBH (171%)



BCMS 2018

Corresponds to nominal pattern (100%)

MKBH flashover: Worst cases

Estimated peak density increase compared to nominal pattern

	US Win	TDE	Flashover probabilty	Worst case flashover time [16 us… 28 us]
4/4 MKBH	*100%*	*100%*		
2/4 MKBH	*191%*	*171%*		
Flashover – 4 MKBH	209%	214%	As today	16 us
Flashover – 6 MKBH at 67% voltage	164%	189%	Significantly reduced	28 us
Flashover – 6 MKBH at 80% voltage	118%	171%	Reduced	19 us (US win) / 28 us (TDE)

BCMS 2018

Preliminary

- **FLUKA and thermo-mechanical studies required.**
- **To be checked for different filling patterns and different flashover characteristics**

Dilution patterns: C. Wiesner
Density estimations: L. Richtmann

New MKB Failure Cases I

4 MKBH
6 MKBV

Generator → Magnet (vacuum tank) → Beam

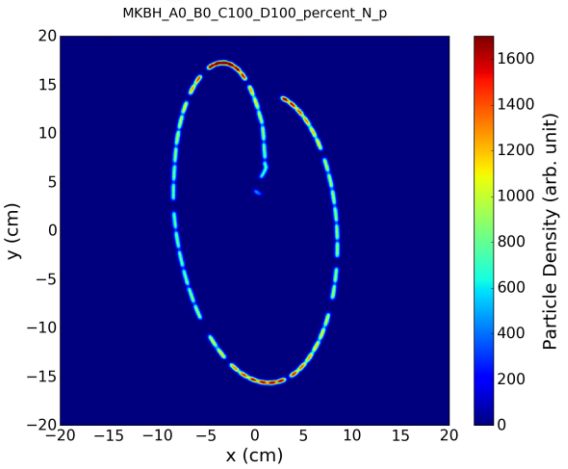
Erratic pre-firing of **more than one** MKB generator:

- *Worst case*: MKBH erratics with antiphase → Loss of >70% of H dilution for double erratic

Mitigation: reduce generator voltage / Install MKB retrigger system → MPP, 27.4.2018

Flashover

- *Worst case:* Flashover of 2 MKBH with loss of 50% H dilution



Traditionally assumed worst-case scenario: 2 MKBH missing

New MKB Failure Cases II

4 MKBH
6 MKBV

Generator → Magnet (vacuum tank) → Beam

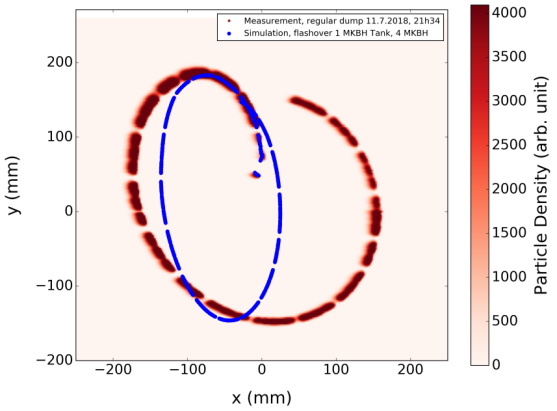
Erratic pre-firing of **more than one** MKB generator:

- *Worst case*: MKBH erratics with antiphase → Loss of >70% of H dilution for double erratic

Mitigation: reduce generator voltage / Install MKB retrigger system → MPP, 27.4.2018

Flashover

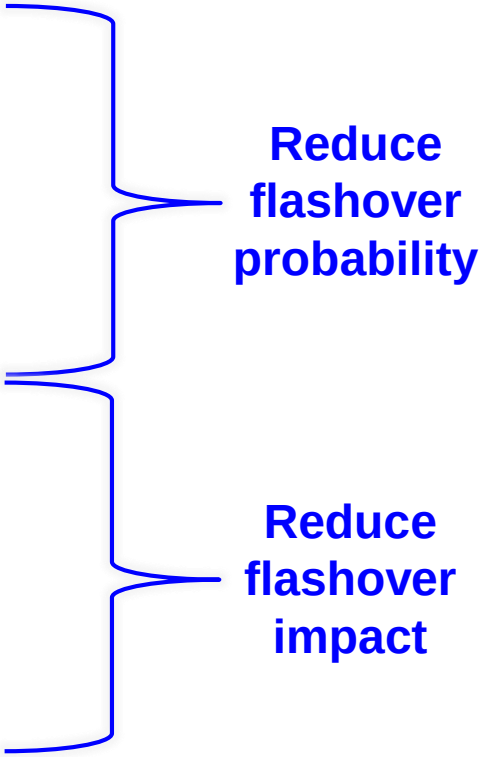
- *Worst case:* Flashover of 2 MKBH in antiphase with overlapping sweep path



New worst-case scenario: Flashover of 2 MKBH in antiphase

Flashover – Mitigation Strategy

- 20% voltage reduction at MKBV.C/D.B2 (implemented in July 2018)
- Improve insulation of HV busbars (LS2/LS3?)
- **Addition of two MKBH per beam?** (LS3?)
  - Allows voltage reduction to 67% (keeping the same total dilution)
  - Reduces failure sensitivity and worst-case density for MKBH flashover
  - Provides margin to increase total dilution, and thus reduce energy density during nominal operation and during flashover



Conclusions: MKB Failure Cases

1) Erratic pre-firing:
   - *New failure mode*: Multi-erratics
   - *Mitigation*: reduce generator voltage/ install MKB retrigger system
   - **Higher erratic probability for MKBH** (higher generator voltage)

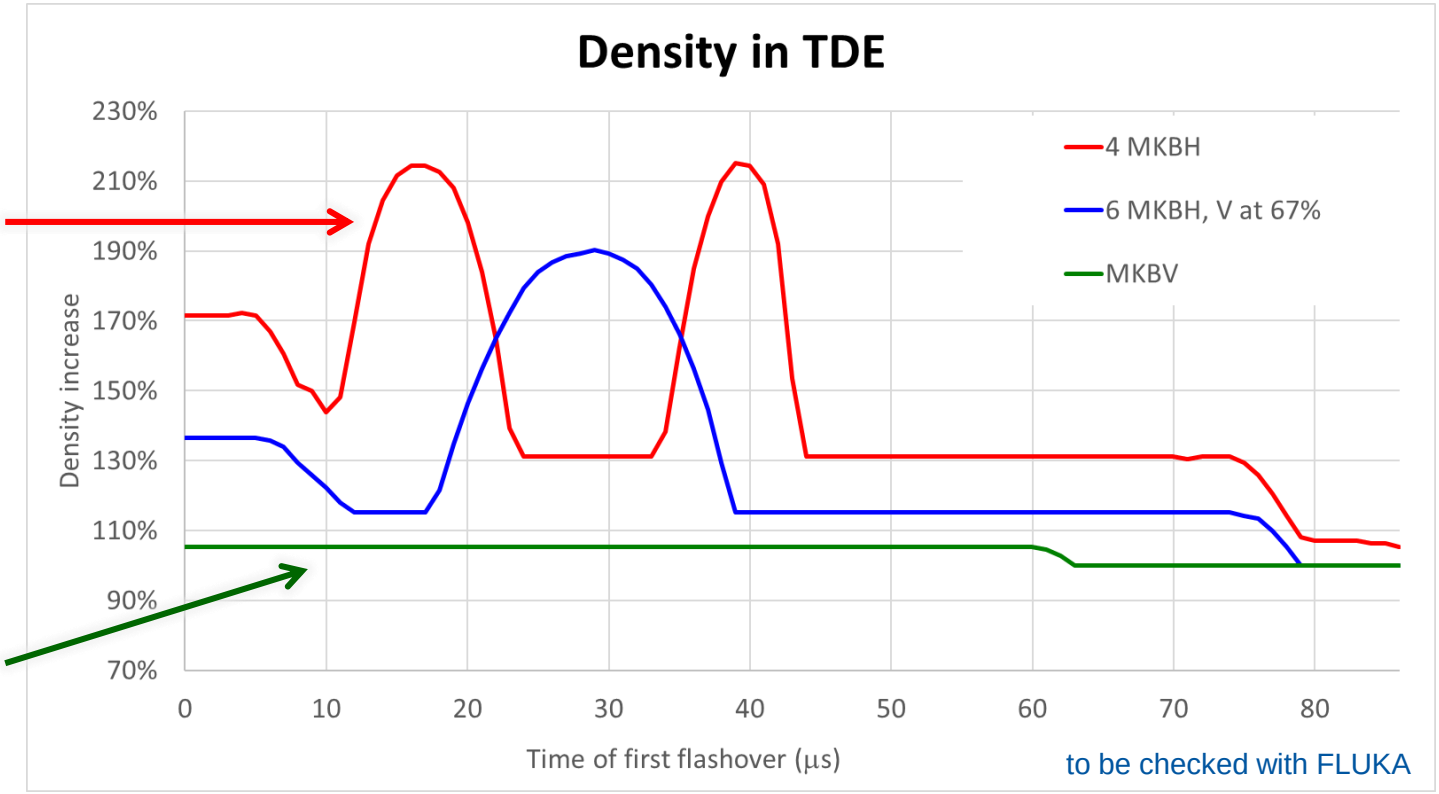
2) Flashover
   - MKBV flashover occurred on July 14th 2018
   - *New failure mode*: Magnetic field persists after flashover
   - **Flashover in MKBHs could lead to new worst case** with increased energy density. To be checked with FLUKA and thermo-mechanical stress simulations.
   - **Higher flashover probability for MKBV** (higher voltage at the busbars)
   - Voltage reduction of MKBH generators will not affect the voltage in the magnets and thus will not reduce the flashover probability
   - → Flashover probability will increase for operation at 7 TeV
   - Possible mitigation: Improve insulation of HV busbars / add 2 MKBH
- 6 MKBH would significantly reduce probability and impact of flashover

Thank you for your attention!

MKBH vs. MKBV Flashover

MKBH
flashover
→ critical

MKBV
flashover
→ not critical



Effect of Droop

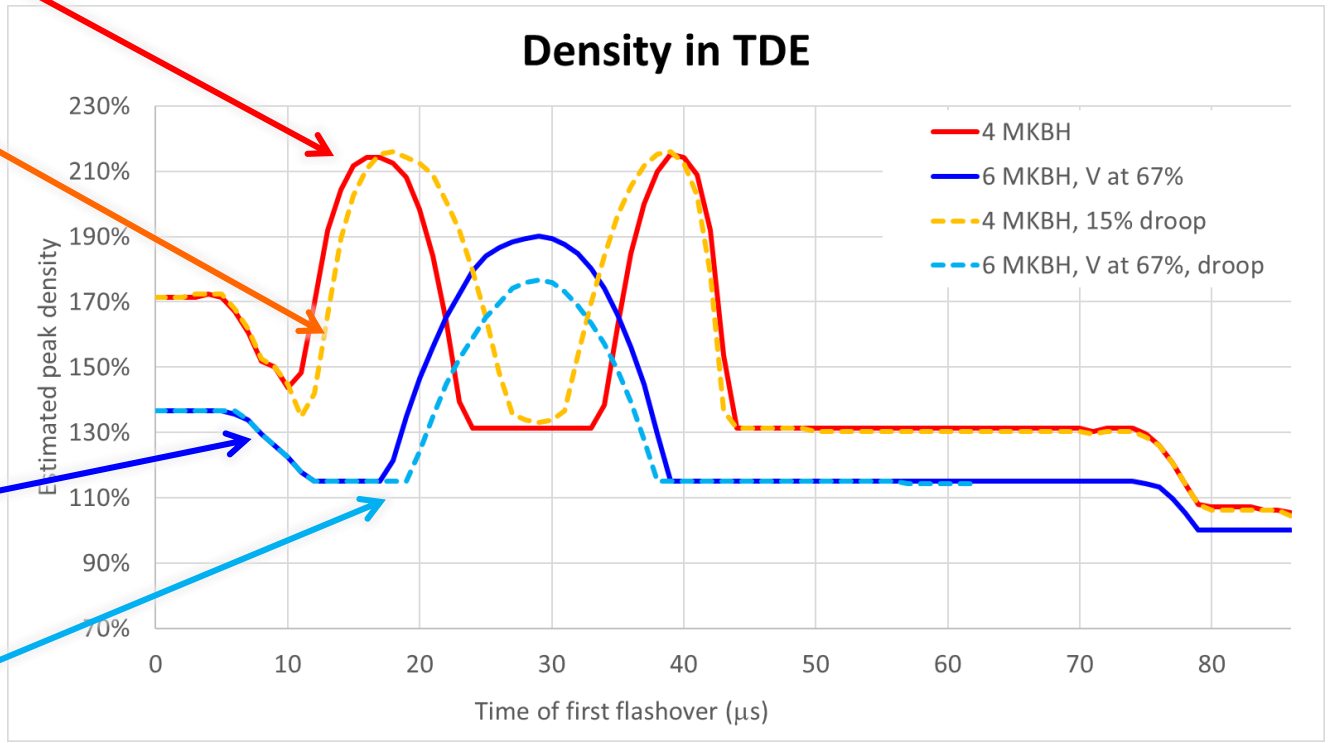
Assuming constant kick after flashover (4 MKBH)

Assuming droop after flashover (4 MKBH) → **no effect on worst case**

Assuming constant kick after flashover (6 MKBH)

Assuming droop after flashover (6 MKBH) → **worst-case density reduced**

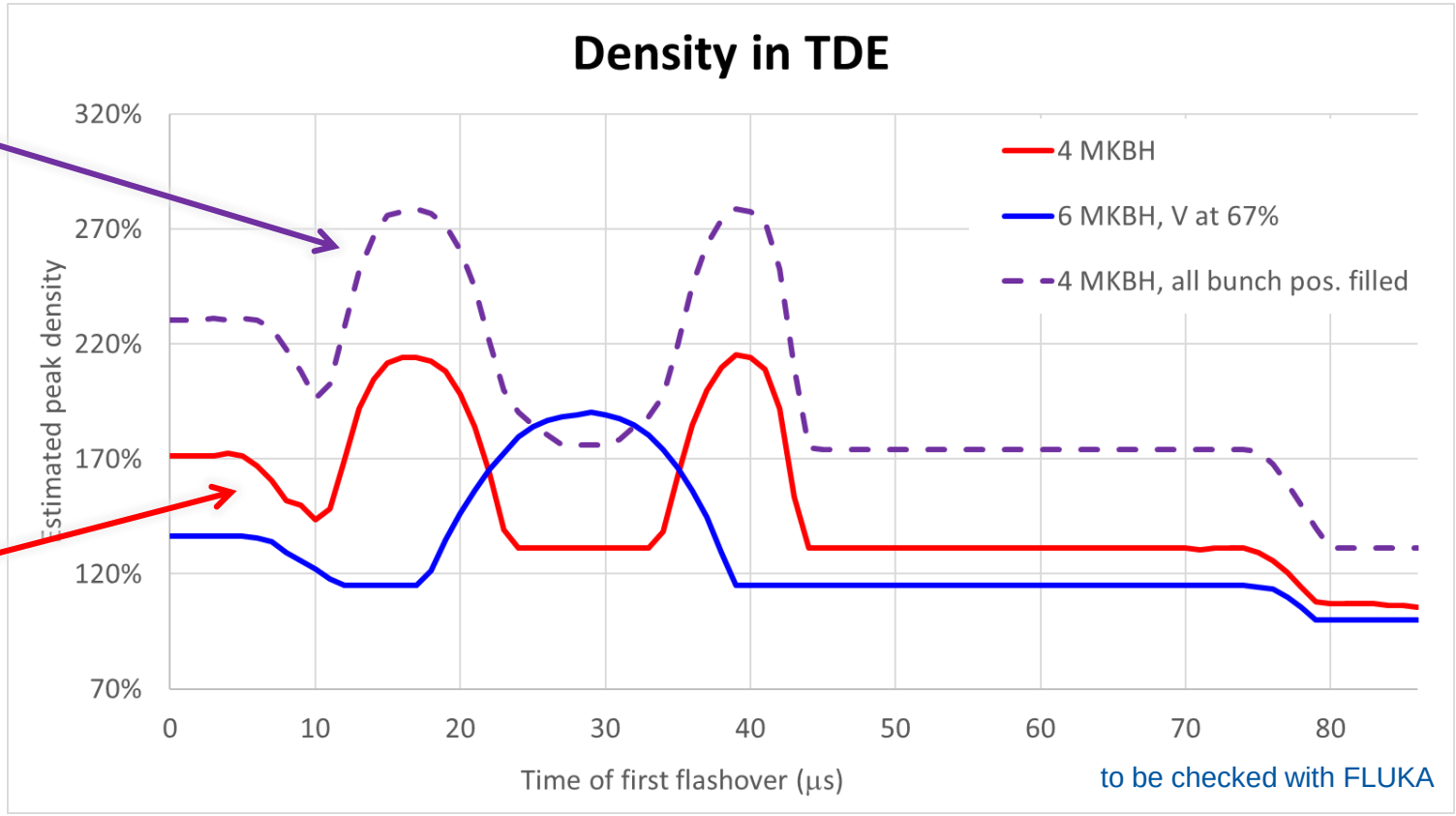
Assuming droop of 15% / 100 us



Effect of Filling Pattern

All bunch positions filled (except AG)

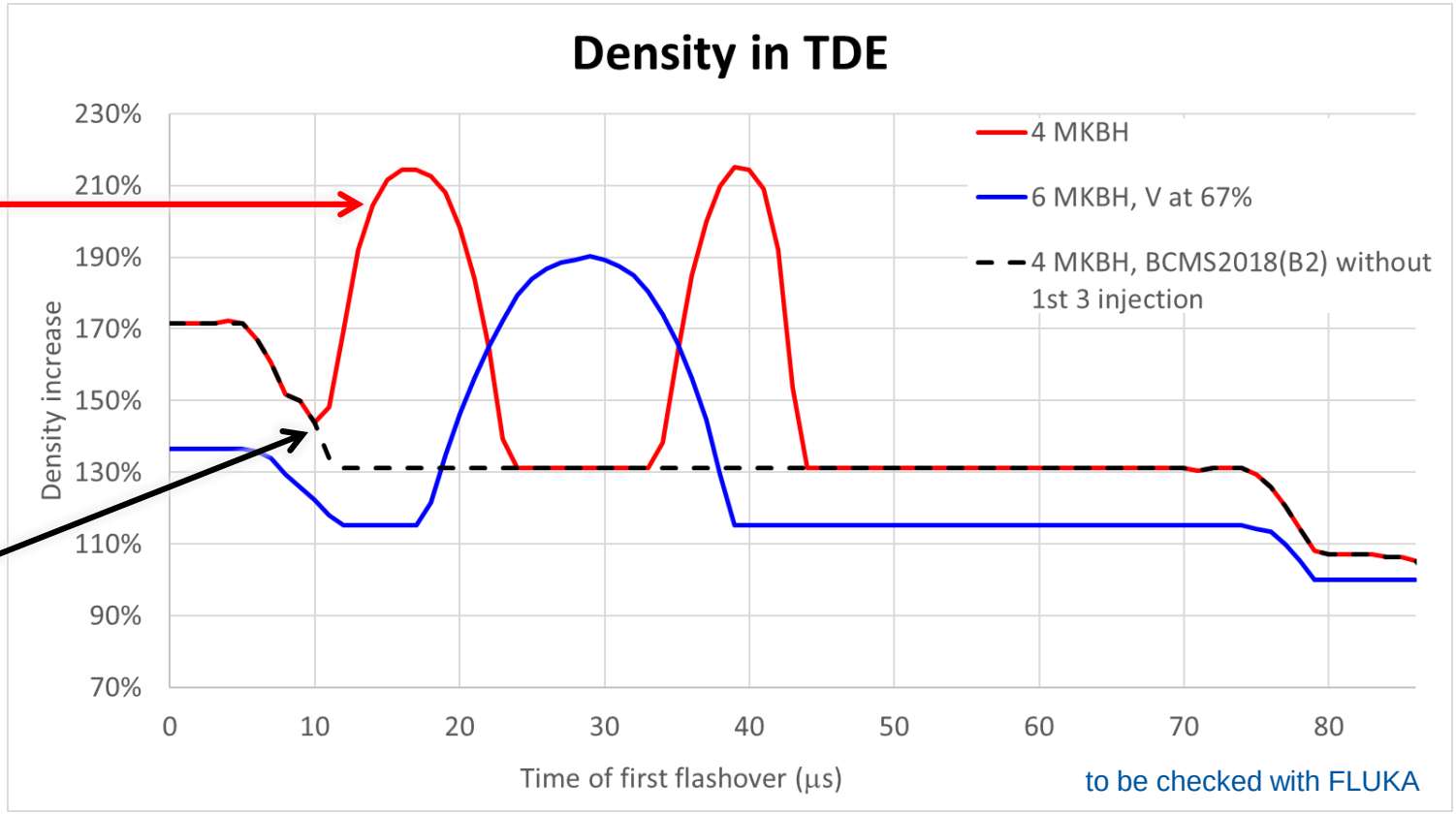
BCMS 2018 (B2)



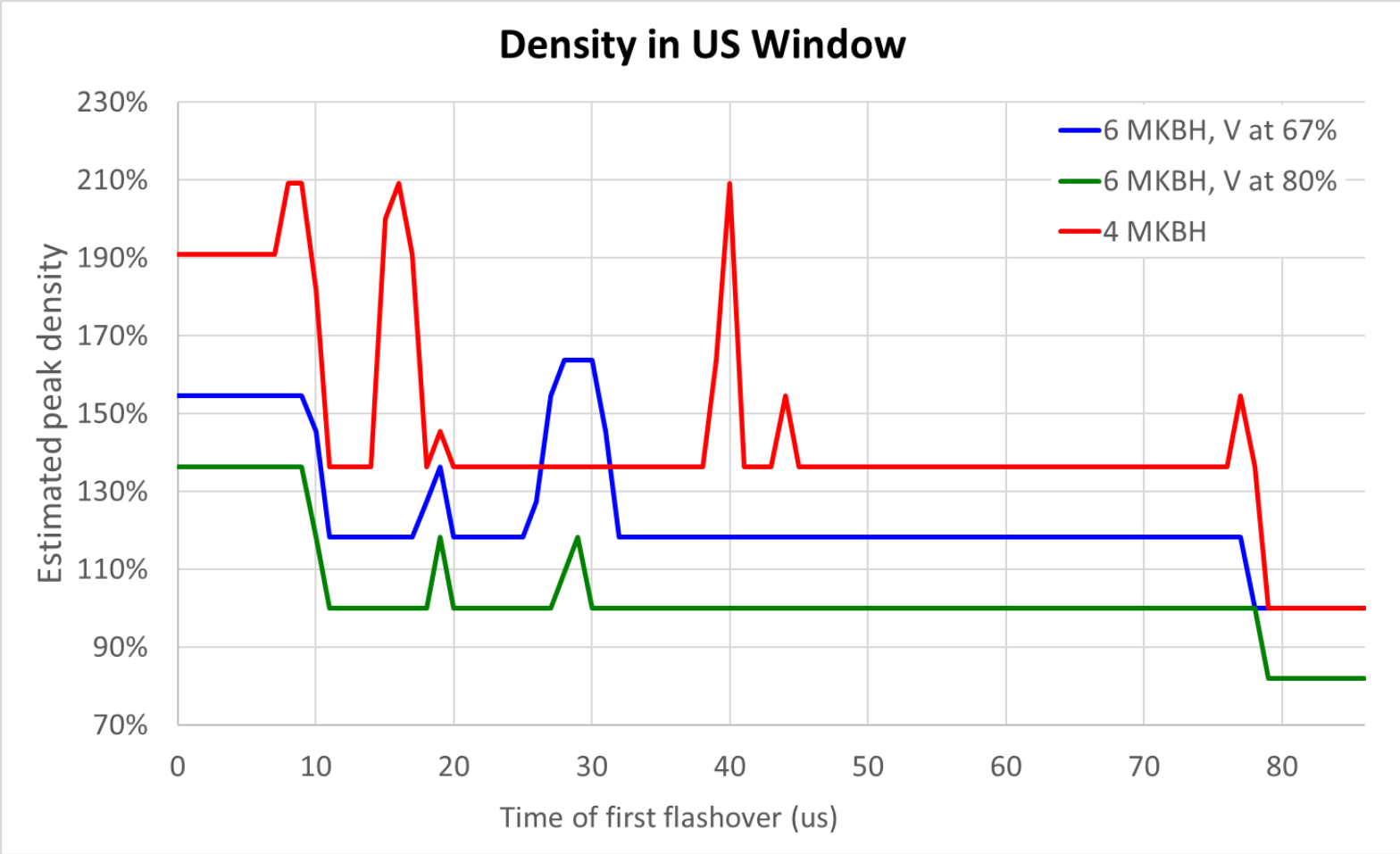
Truncated Filling Pattern

BCMS (2018)
→ Overlap

Removed first three injections (12b + 144b + 144b), BCMS 2018 (B2).
→ No overlap

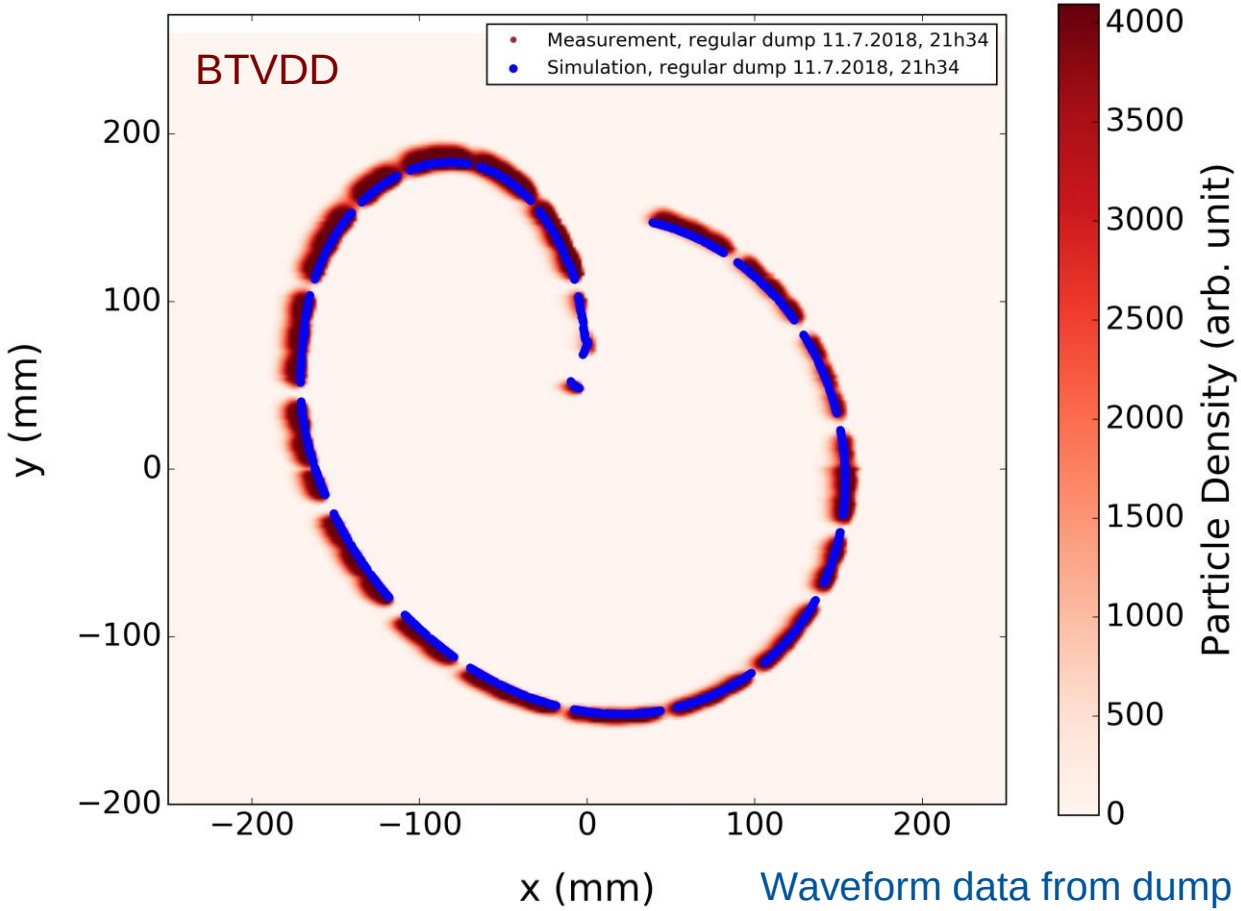


Upstream Window



Regular dump

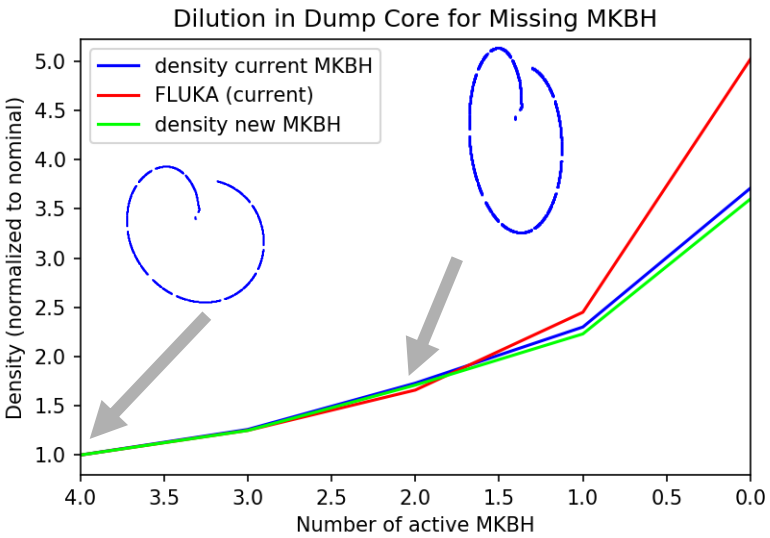
Simulated and measured dilution patterns for a nominal dump

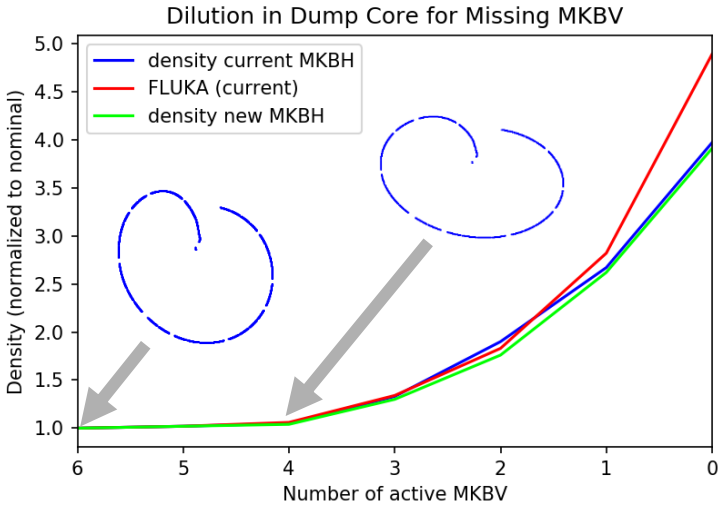


Waveform data from dump 2018-07-11, 21h34

Density Estimation

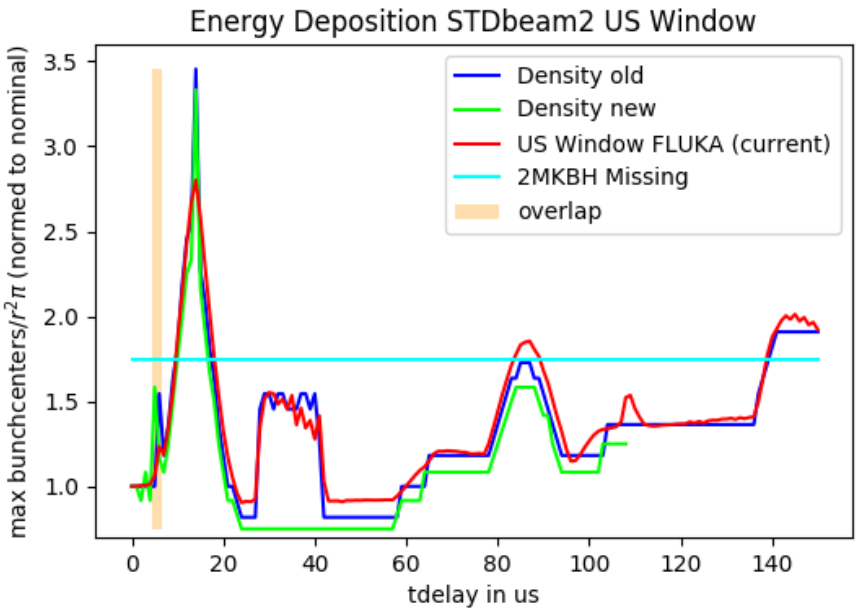
- Simple estimate: count number of bunch centers within radius R
- Use effective radii R for US Window, TDE and DS Window (compared with FLUKA)
  - US Window: R=1.3 mm (~ σ_x, ~ σ_y)
  - Core: R=16.2 mm (~ 13 σ_x, ~ 14 σ_y)
  - DS Window: 19.9 mm (~16 σ_x, ~ 18 σ_y)

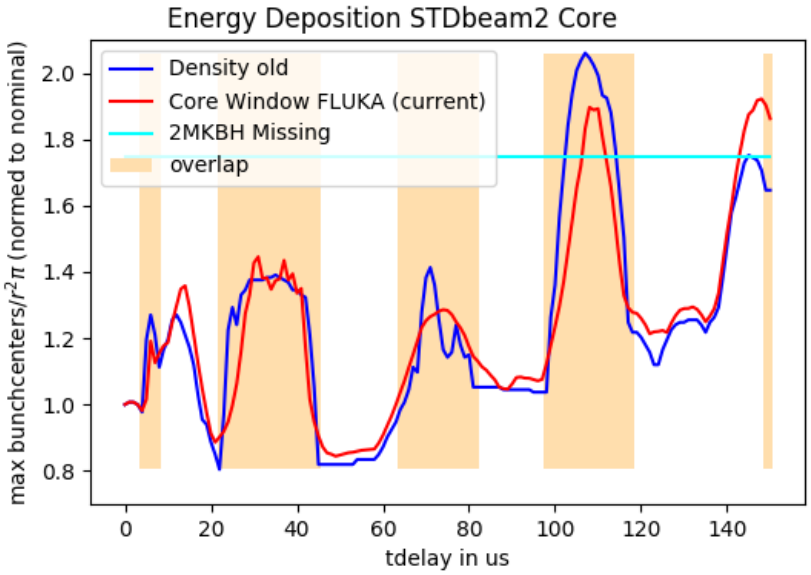




L. Richtmann

MKB Retriggering

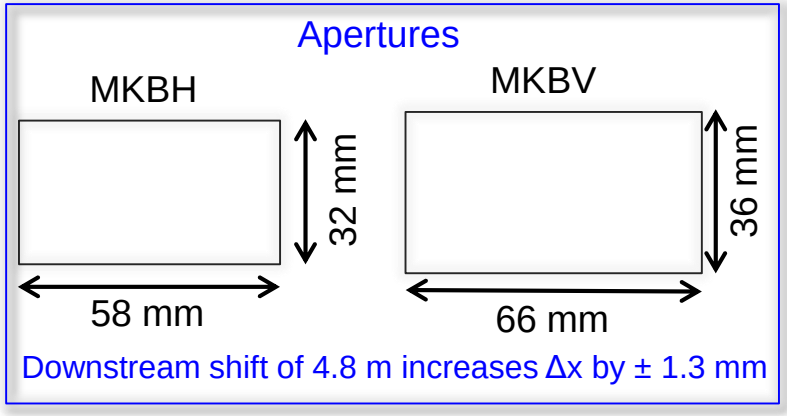


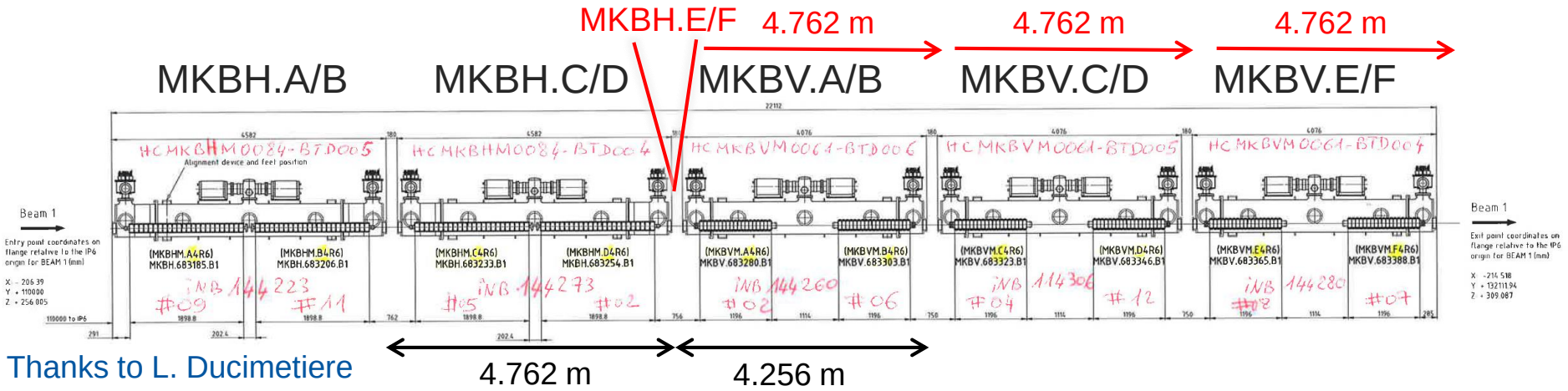


L. Richtmann

6 MKBH – Integration and Aperture

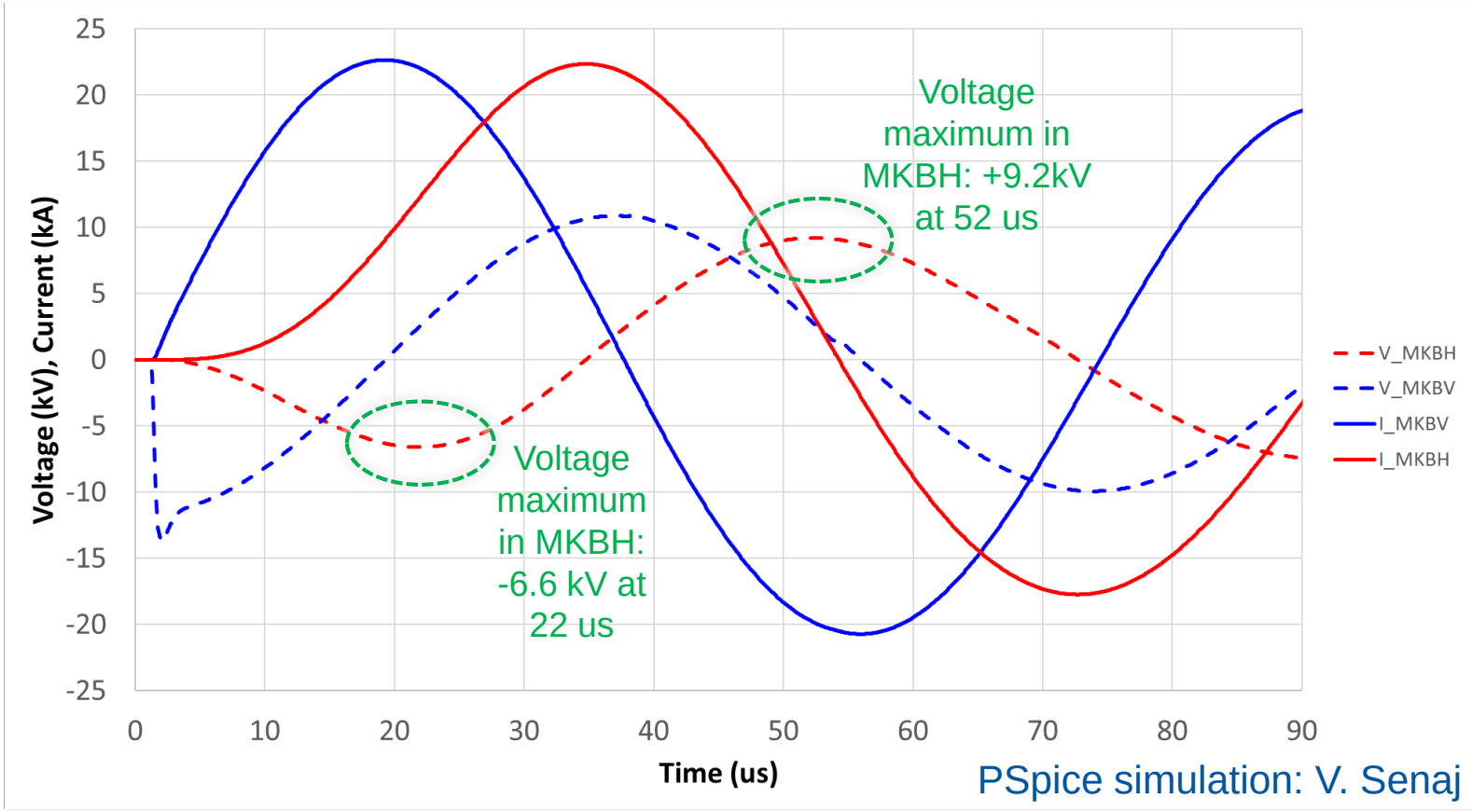
- No showstopper for integration identified
- Aperture margin to add 2 MKBHs and possibly to increase horizontal dilution
- If MKB apertures were limiting, dilution pattern could be changed with energy
  - less dilution at 450 GeV (larger σ, less energy deposition)
  - more dilution at 7.0 TeV (smaller σ, higher energy deposition)





Thanks to L. Ducimetiere

MKB Voltage and Current



Erratics: Mitigation Strategy

1) Reduce probability of erratic:

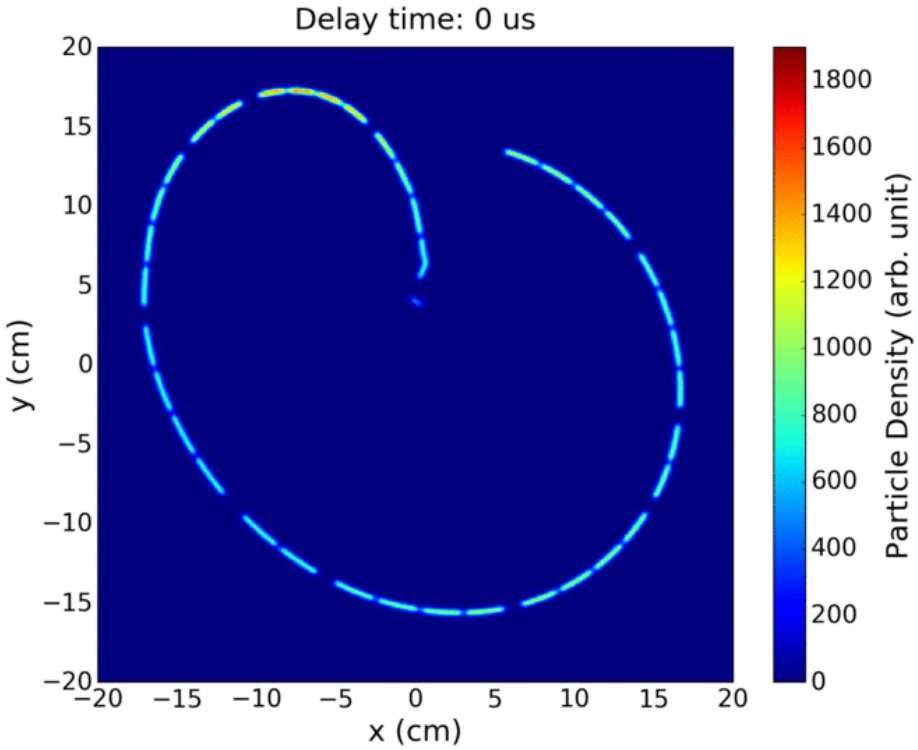
- Upgrade MKBH generator in LS2 to operate at ~10% lower voltage.

2) Reduce impact of erratic:

- Implement MKB retrigger system to eliminate risk of antiphase
  → beam sweep pattern depends on the position of the abort gap in the ring

→ *C. Wiesner et al., MPP, 27.4.2018*

Sweep patterns for different delay times between retriggered MKBs and synchronously firing MKDs



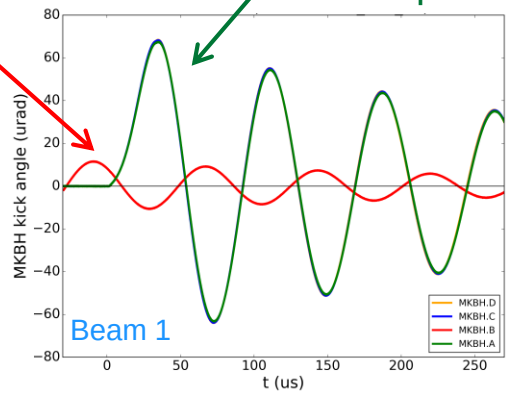
HL-STD, Run 2 waveforms

Antiphase

MKBs in antiphase

regularly firing MKBHs in antiphase

erratically pre-firing MKBH



Measured waveforms, MKB erratic, 01.10.2016

MKB Erratics in operation: 2015 to 2017

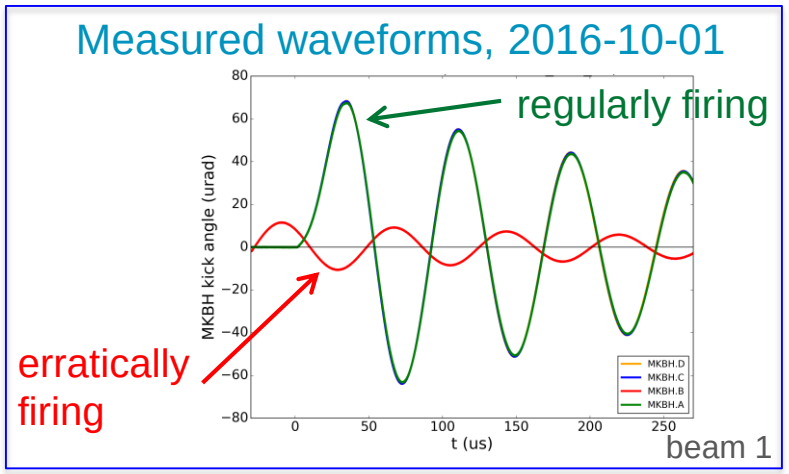
- Erratic firing only occurred for single MKBH: 4x in 2015 and 2x in 2016, none in 2017.
- Antiphase can reduce effective dilution

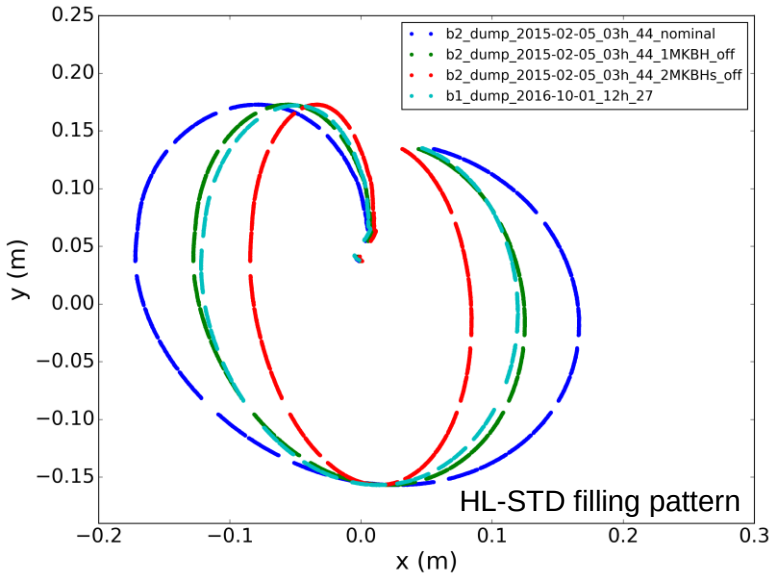
Event	Gen.	t_{delay} (us)	N_p p+	#bun-ches
2015-04-26_08h_16	A/B2	1 028	1.0e10	1
2015-04-27_09h_00	A/B2	1 208	9.4e10	1
2015-05-31_00h_56	A/B2	1 020	2.39e11	7
2015-10-24_20h_48	A/B2	1 049	1.93e14	1824
2016-10-01_12h_27	B/B1	654	1.5e14	2220
2016-10-04_18h_19	B/B2	1 029	1.42e11	5

Effective dilution: 71.5%

74%

All events occurred at 6.5 TeV





Failure Cases: Energy Deposition

	STD	BCMS
$\epsilon^{n}_{x,y}$	2.08 μm·rad	1.37 μm·rad
I_b	2.3×10^{11}	2.0×10^{11}
Filling Scheme	R3-STD	R3-BCMS
Nominal beam intensity	6.32×10^{14} p+	5.21×10^{14} p+

Maximum temperature increase in dump core:

STD

number active MKBH \ K	6	5	4	3	2	1	0
4	1827	1865	1931	2358	>3000	>3000	>3000
3	2211	2237	2294	2432	>3000	>3000	>3000
2	2807	2859	2922	>3000	>3000	>3000	>3000
1	>3000	>3000	>3000	>3000	>3000	>3000	>3000
0	>3000	>3000	>3000	>3000	>3000	>3000	>3000

BCMS

number active MKBH \ K	6	5	4	3	2	1	0
4	1622	1644	1698	2074	2690	>3000	>3000
3	1951	1979	2021	2141	2790	>3000	>3000
2	2474	2513	2563	2649	>3000	>3000	>3000
1	>3000	>3000	>3000	>3000	>3000	>3000	>3000
0	>3000	>3000	>3000	>3000	>3000	>3000	>3000

M. Frankl, Energy deposition table for dilution failures, LIBD, 20.6.2017

Dilution kicker magnet – MKBH/V

- **Magnet technology similar to MKD**
- **No need for beam screening (not on circulating beam)**
- **Magnets housed in vacuum tank**