# LHC Dilution Kicker Flash-Over and Impact to the HL-LHC upgrade Plans and Needs

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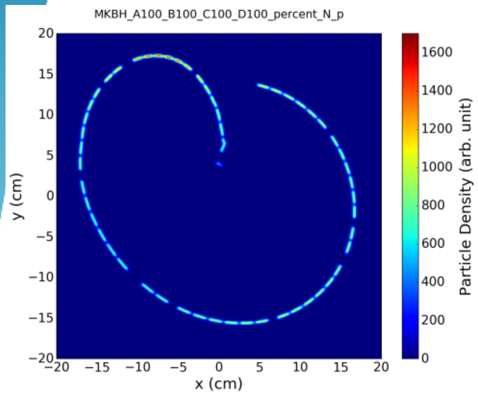
Acknowledgments: M.I. Frankl, A. Lechner, T. Polzin, L. Richtmann

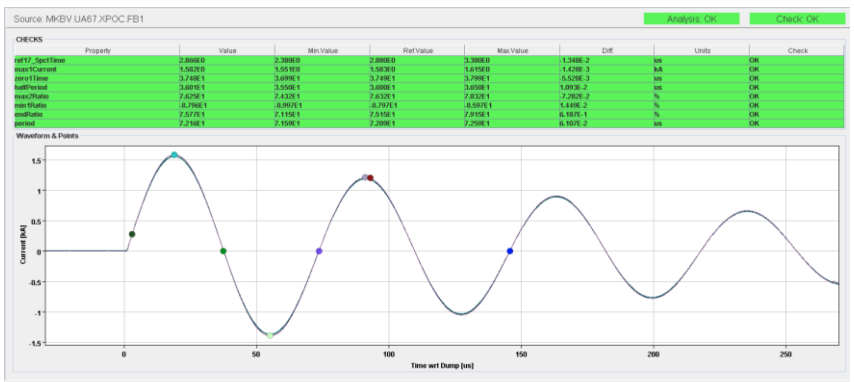
# Outlines

- Dilution kickers
- Failure scenarios:
  - Original assumptions
  - New findings
  - Mitigations
- Conclusions

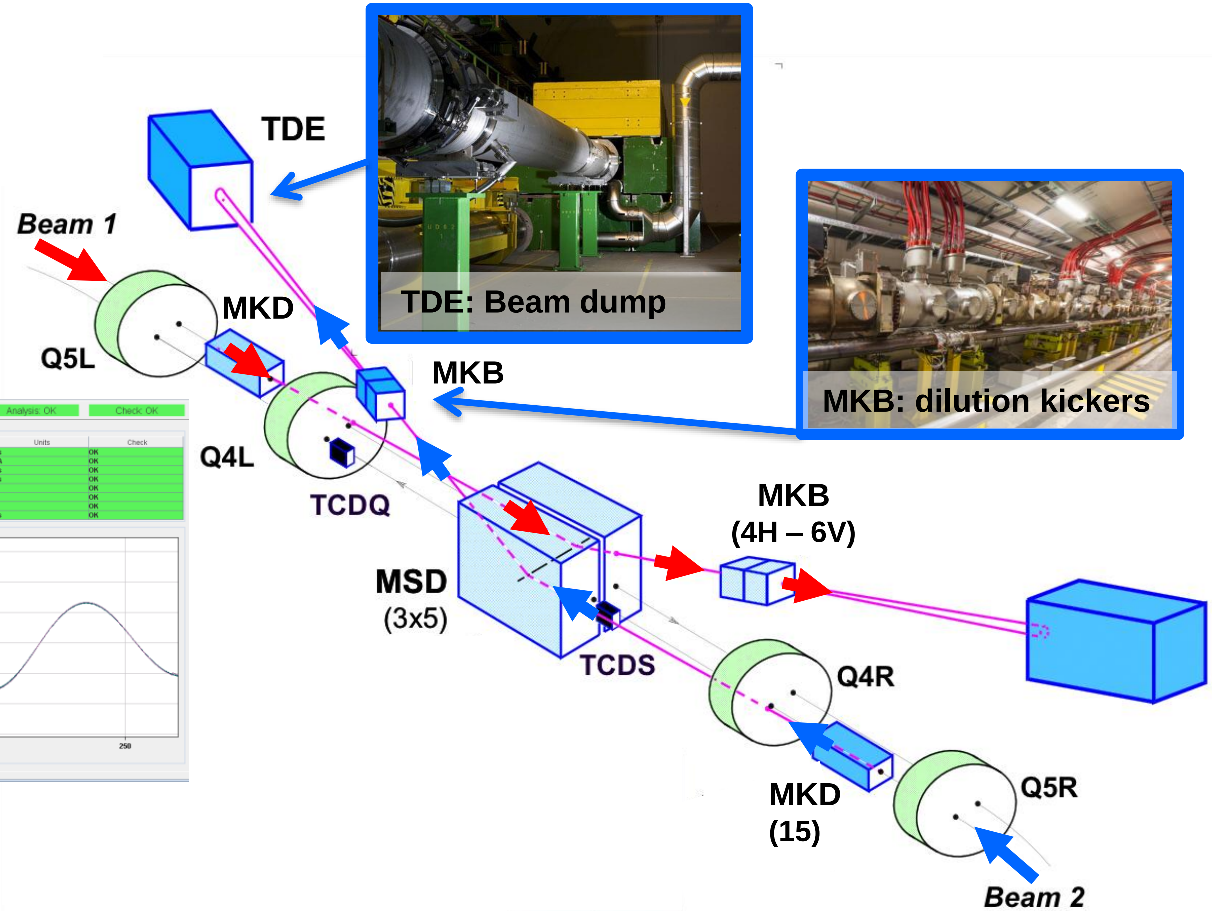
Budget and manpower estimates are still being evaluated and are not included in this talk (info for next PSM on November 22nd)

# MKB Dilution Kickers

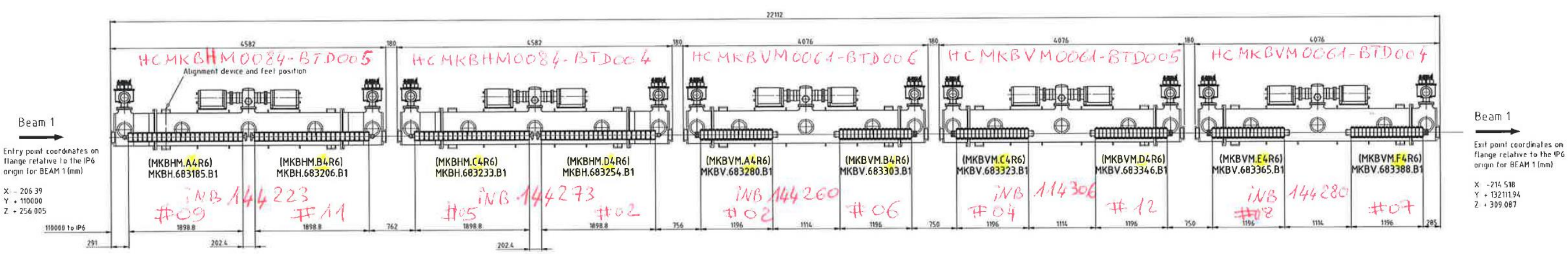



| Property | Value | Min.Value | Ref.Value | Max.Value | Diff. | Units | Check |
|---|---|---|---|---|---|---|---|
| ref17_5pctTime | 2.866E0 | 2.380E0 | 2.880E0 | 3.380E0 | -1.348E-2 | us | OK |
| max1Current | 1.582E0 | 1.551E0 | 1.583E0 | 1.615E0 | -1.428E-3 | kA | OK |
| zero1Time | 3.748E1 | 3.699E1 | 3.749E1 | 3.799E1 | -5.520E-3 | us | OK |
| halfPeriod | 3.601E1 | 3.550E1 | 3.600E1 | 3.650E1 | 1.093E-2 | us | OK |
| max2Ratio | 7.625E1 | 7.432E1 | 7.632E1 | 7.832E1 | -7.282E-2 | % | OK |
| min1Ratio | -8.796E1 | -8.997E1 | -8.797E1 | -8.597E1 | 1.449E-2 | % | OK |
| endRatio | 7.577E1 | 7.115E1 | 7.515E1 | 7.915E1 | 6.187E-1 | % | OK |
| period | 7.216E1 | 7.159E1 | 7.209E1 | 7.259E1 | 6.107E-2 | us | OK |




MKBH.A/B MKBH.C/D MKBV.A/B MKBV.C/D MKBV.E/F



# To Keep in Mind

- The **voltage** in the **MKBH generators** is **higher than** in the **MKBV** generators (4 against 6)

- The **voltage** in the **magnet** is **slightly higher** for the **MKBV than MKBH** (**larger** MKBV pole gap for **aperture** reasons)

- The **likelihood** of an **erratic** is **proportional** to the **voltage** in the **generator** (i.e. to the beam energy)

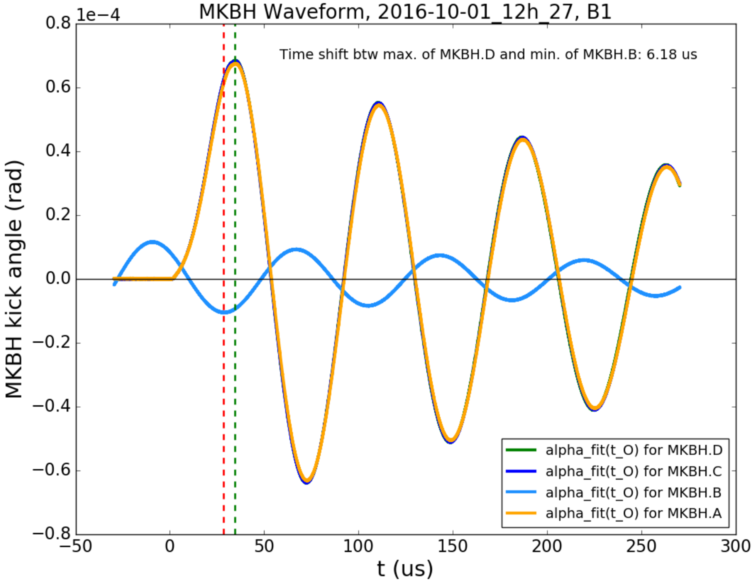
- The **likelihood** of a **flashover** is **proportional** to the **voltage** in the **magnet** (i.e. to the beam energy)

- The **upgrade** to **reduce** the **voltage in the generator will not reduce the voltage in the magnet** (same voltage for operation at 6.5 TeV and higher for 7-7.5 TeV) ➔ **higher risk of flashover at higher energy**

# MKB Dilution Kickers - Failures

Original assumptions

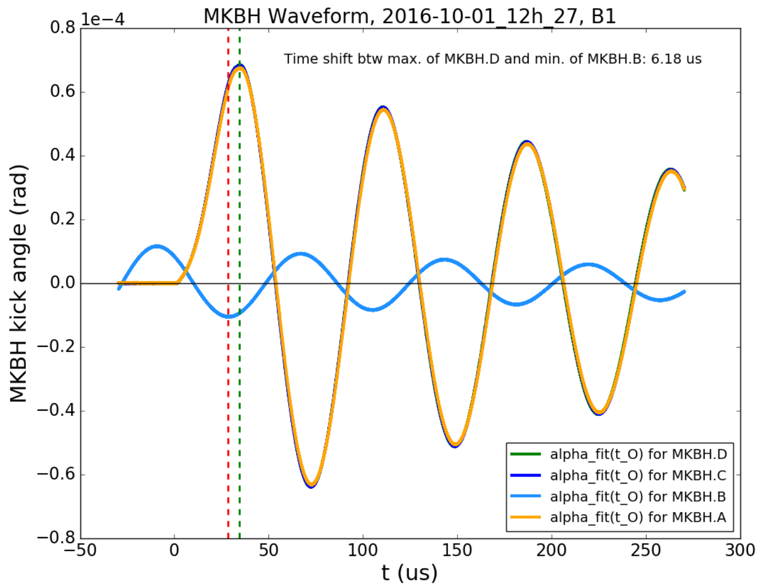
- Horizontal plane more critical since 4 kickers only
- **Erratic firing** of one MKB: risk of phase opposition ➔ 50% dilution left in H plane

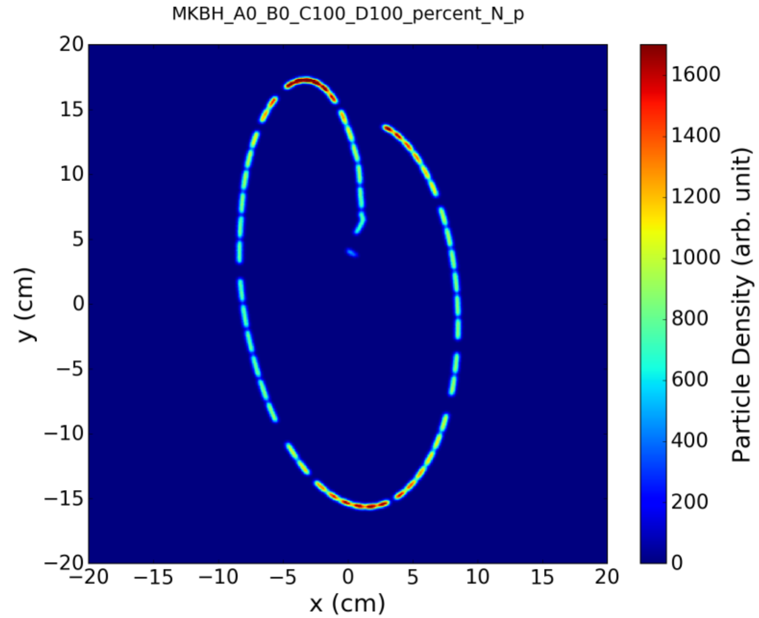


# MKB Dilution Kickers - Failures

Original assumptions

- Horizontal plane more critical since 4 kickers only
- **Erratic firing** of one MKB: risk of phase opposition ➔ 50% dilution left in H plane
- **Flashover** simultaneously affecting two MKBs sharing the same vacuum tank ➔ 50% dilution left in H plane



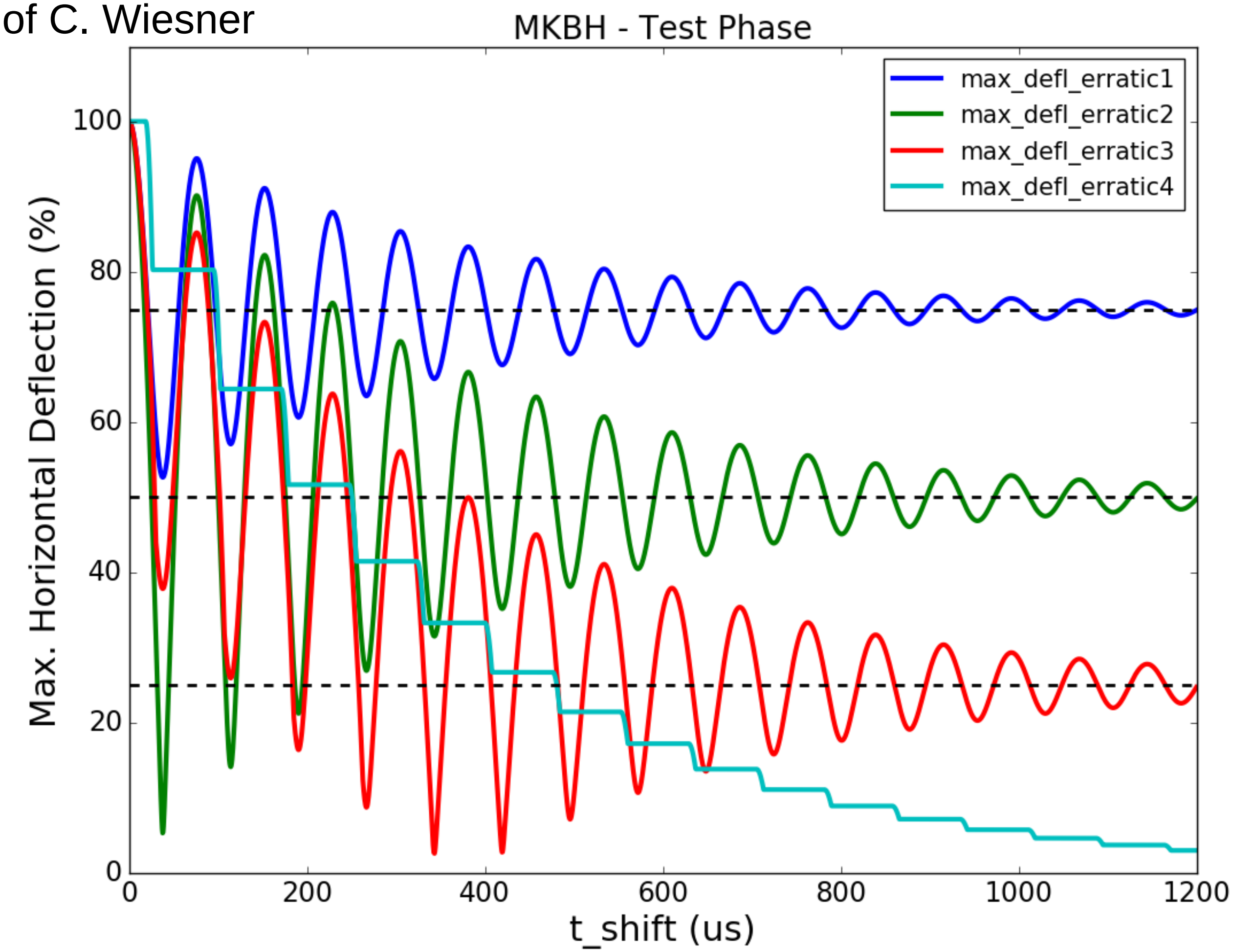

Original worst failure case: two missing horizontal dilution kickers

Courtesy of C. Wiesner

# New Failure Case: EM Coupling

- New failure case: **parasitic EM coupling between MKB generators**
- Possible losing more than 50% of the horizontal dilution (in case of antiphase)

Courtesy of C. Wiesner




For t→∞
$\alpha_{max}$ → 75%
(loss of 1 MKBH)

For t→∞
$\alpha_{max}$ → 50%
(loss of 2 MKBH)

For t→∞
$\alpha_{max}$ → 25%
(loss of 3 MKBH)

For t→∞
$\alpha_{max}$ → 0%
(loss of 4 MKBH)

# Energy Deposition Studies

Peak Temperatures at existing TDE and windows: HL-STD and BCMS Beams

## BCMS

*Upstream Window*

| °C | | # active MKBV | | |
|---|---|---|---|---|
| | | 6 | 5 | 4 |
| # active MKBH | 4 | 56 | 57 | 62 |
| | 3 | 66 | 67 | 67 |
| | 2 | 83 | 84 | 85 |

*Low-Density Graphite Core*

| °C | | # active MKBV | | |
|---|---|---|---|---|
| | | 6 | 5 | 4 |
| # active MKBH | 4 | 1650 | 1670 | 1725 |
| | 3 | 1980 | 2000 | 2050 |
| | 2 | 2500 | 2540 | 2590 |

*Downstream Window*

| °C | | # active MKBV | | |
|---|---|---|---|---|
| | | 6 | 5 | 4 |
| # active MKBH | 4 | 150 | 155 | 170 |
| | 3 | 180 | 185 | 195 |
| | 2 | 220 | 230 | 245 |

## STD

*Low-Density Graphite Core*

| °C | | # active MKBV | | |
|---|---|---|---|---|
| | | 6 | 5 | 4 |
| # active MKBH | 4 | 1860 | 1900 | 1960 |
| | 3 | 2240 | 2270 | 2330 |
| | 2 | 2840 | 2890 | 2960 |

*Downstream Window*

| °C | | # active MKBV | | |
|---|---|---|---|---|
| | | 6 | 5 | 4 |
| # active MKBH | 4 | 170 | 175 | 190 |
| | 3 | 200 | 210 | 220 |
| | 2 | 245 | 260 | 275 |

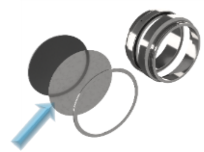
- BCMS beams more critical for upstream window in terms of peak energy density
- HL-LHC standard more critical for core and downstream window since shower development dominant effect



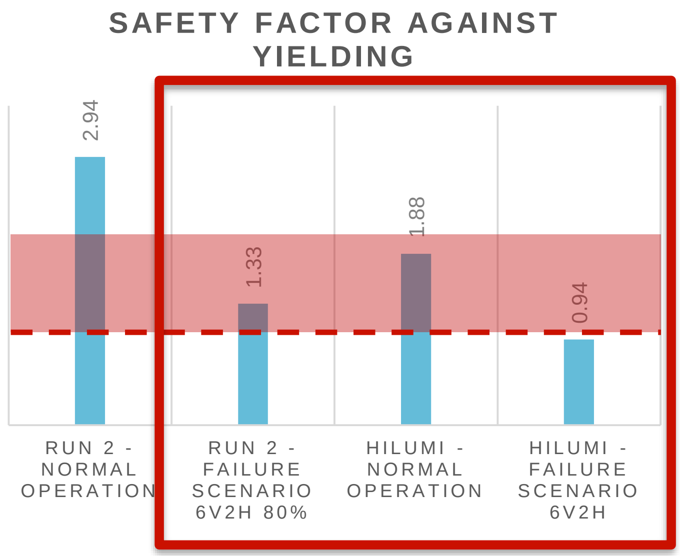
Courtesy of M.I. Frankl

# Energy Deposition and Thermo-mechanical stress Studies

## CfC + 316L Upstream Window

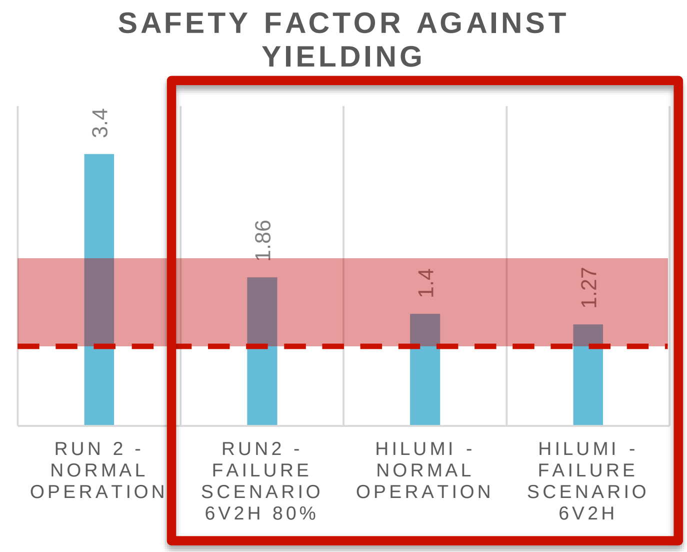


Safety margin
Deals with uncertainties




Lower limit
Underneath, the material deforms permanently

## TiGr2 Downstream Window

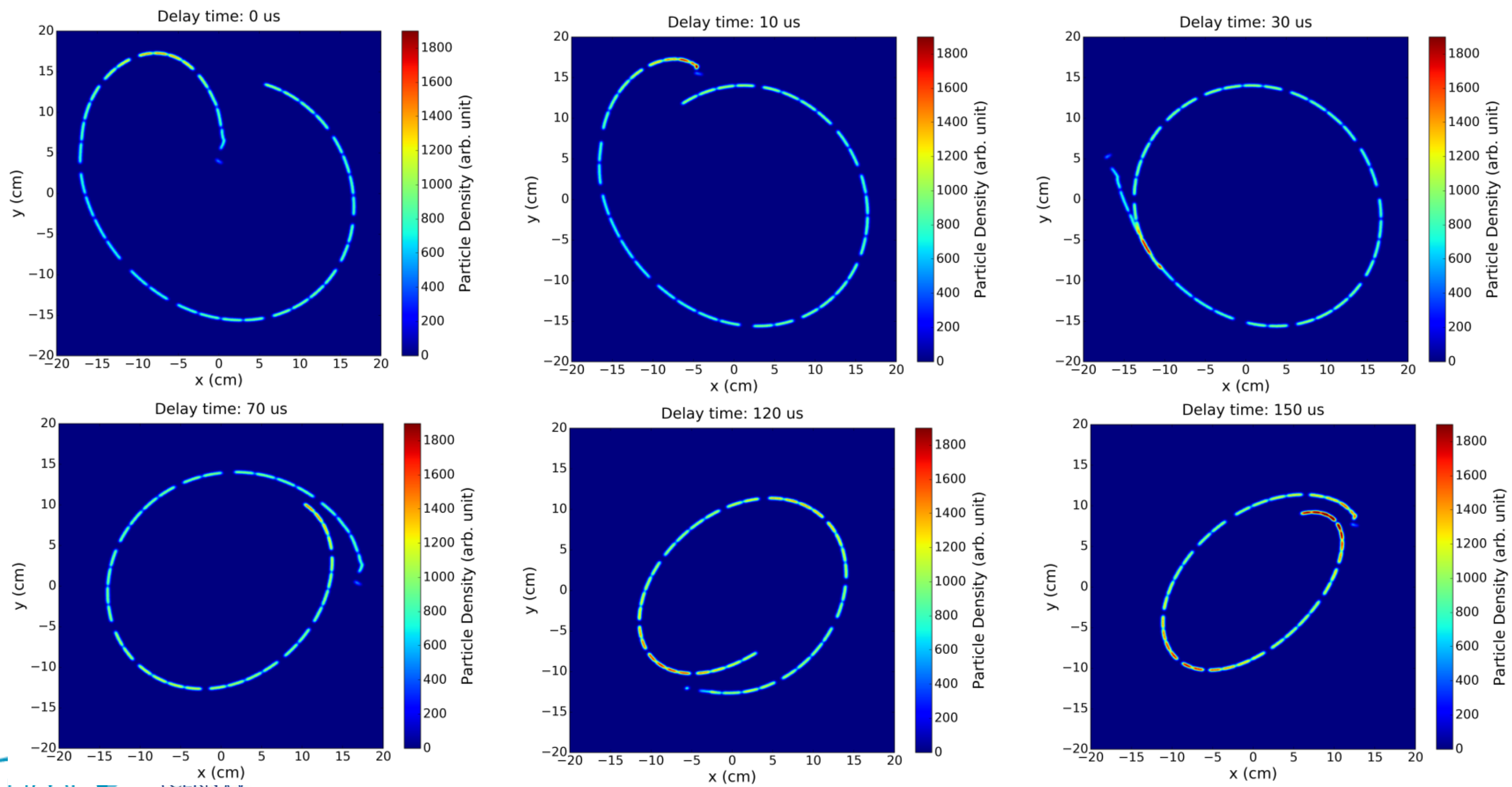



- The expected stress levels in the windows are too high for a long-term and reliable operation ➔ upgrade of windows required
- Thermal characterization of Sigraflex core only up to 1900 °C and mechanical characterization challenging. Ongoing studies!

Courtesy of T. Polzin

# Mitigations Against Erratics

- **Reduce MKBH generator voltage** by increasing capacitance
- In case of erratic all the remaining **MKBs** are **re-triggered** ➔ synchronous beam dump request*
  - No more risk of anti-phase in case of erratic
  - Different sweep pattern depending on MKD-MKB delay




Courtesy of C. Wiesner

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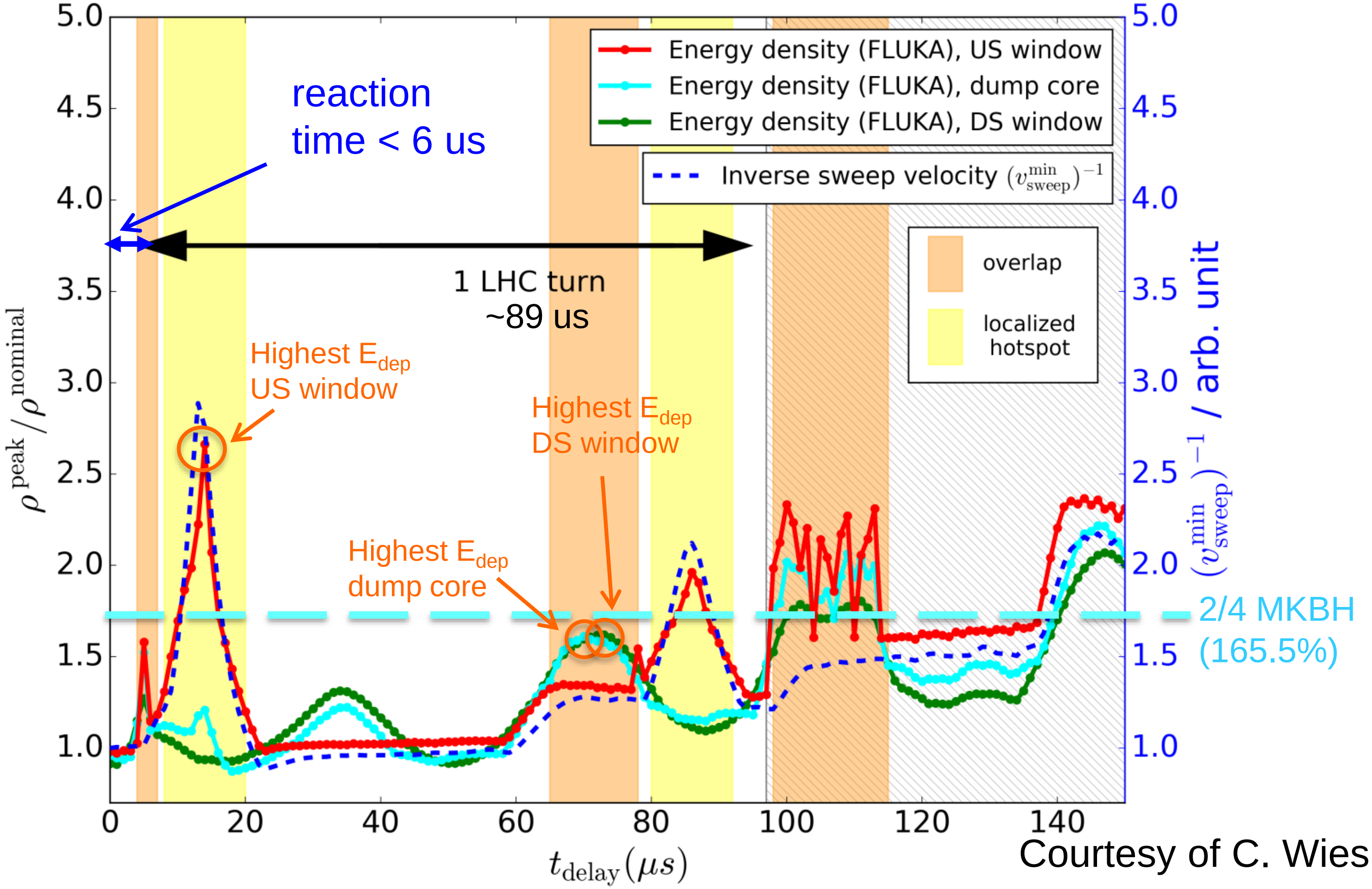


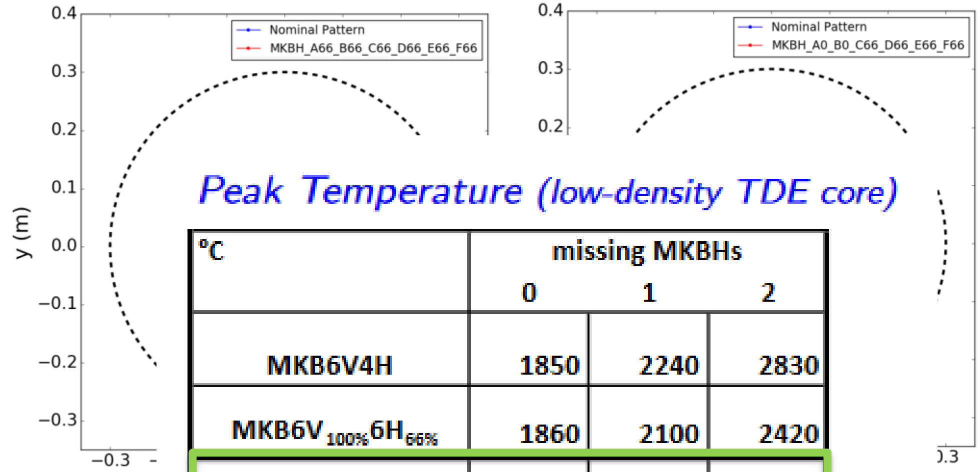

Courtesy of C. Wiesner

# Mitigations Against Erratics

Add two MKBHs (reduce sensitivity to failure)

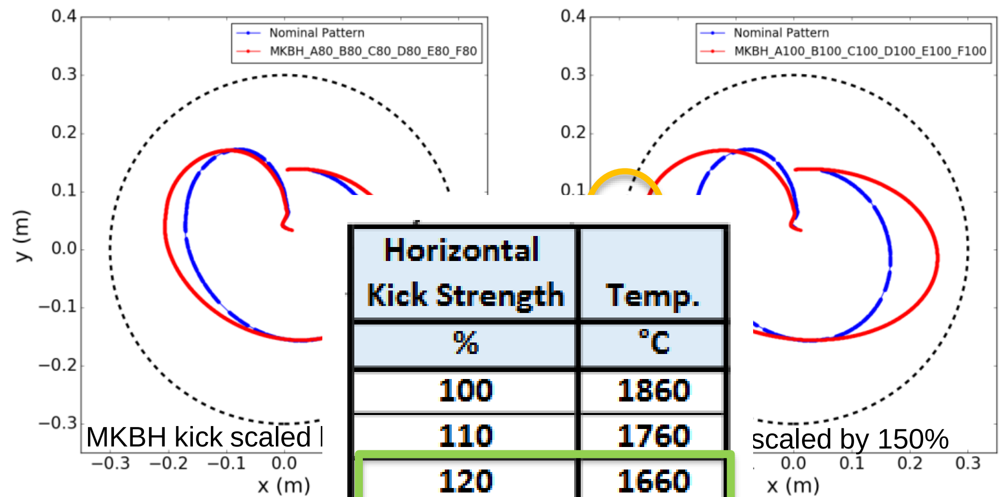
- Approach 1: **keep present dilution→ reduces voltage (risk of erratic)** for each MKBH generator to $V_{new} \approx 67\% \cdot V_0 \approx 18$ kV
- Approach 2: **increase total dilution (**less voltage reduction)→ **reduce peak energy-deposition** in TDE during **nominal operation** and in case of **failure**

**Reduce failure sensitivity** (from 2/4 missing to 2/6 missing)




*Peak Temperature (low-density TDE core)*

| °C | missing MKBHs | | |
|---|---|---|---|
| | 0 | 1 | 2 |
| MKB6V4H | 1850 | 2240 | 2830 |
| MKB6V$_{100\%}$6H$_{66\%}$ | 1860 | 2100 | 2420 |
| *Difference* | +10 | -140 | -410 |



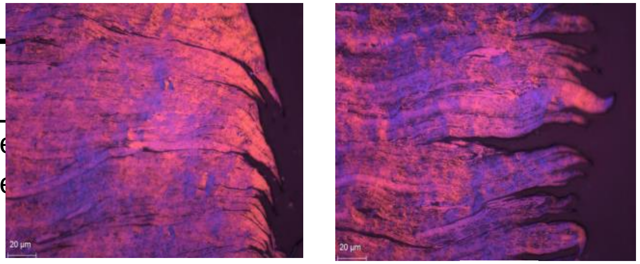

| Horizontal Kick Strength | Temp. |
|---|---|
| % | °C |
| 100 | 1860 |
| 110 | 1760 |
| 120 | 1660 |
| 130 | 1580 |
| 140 | 1510 |
| 150 | 1440 |

Courtesy of C. Wiesner and M.I. Frankl

# Other Dump Issues

- Oxidation

SEM picture of cross section of a Sigraflex sheet
1000s at 1200°C

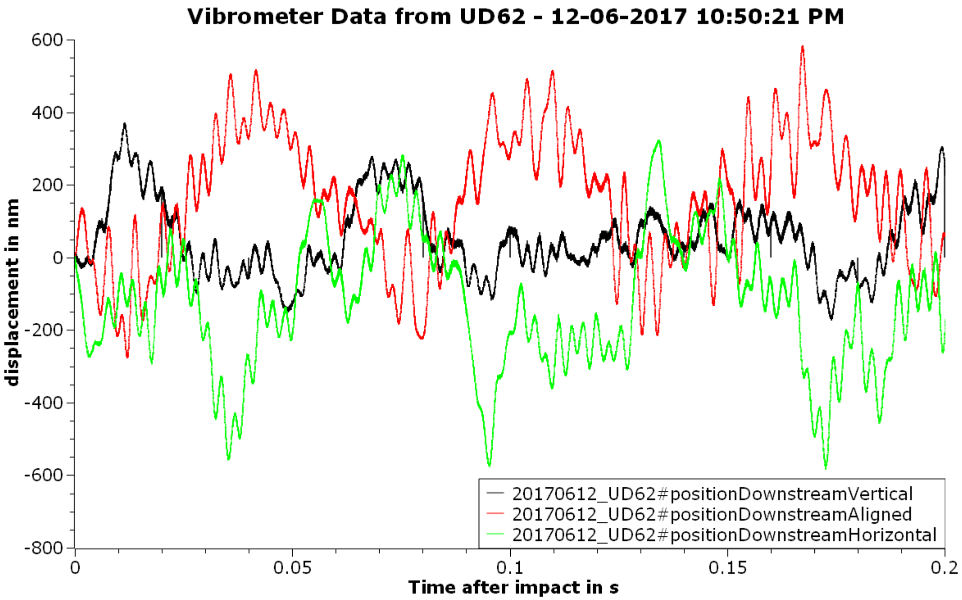


Argon Air

| | | | Mass Loss | | |
|---|---|---|---|---|---|
| Temperature | Time | Atmosphere | Sigrafine | Sigraflex | Comment |
| 2500°C | 1s | 15ml Air | 0.03% | 0.11% | Mean of 3 samples in 5 experime |
| 2500°C | 10s | 150ml Air | 0.66% | 0.99% | Mean of 3 samples in 5 experime |
| 2500°C | 100s | 1200ml Air | 5.80% | 16% | Mean of 3 samples in 2/3 experiments; Standard deviation: 7.4%/16.5% |
| 1200°C | 1000s | Air | 3.96% | 25.50% | Mean of 6 samples in 1 experiment |
| 1200°C | 100s | Air | 0.49% | 2.50% | Mean of 5 samples in 1 experiment |
| 1500°C; cool down in air to 150°C | 10s – 20s | Air | 1.6% | 2.5% | Mean of 2 experiments with 1 sample each |

- Vibrations

- HL-LHC beams worsening the present situation
- Small benefit for nominal operation with additional H dilution (lower temperature rise in dump core)

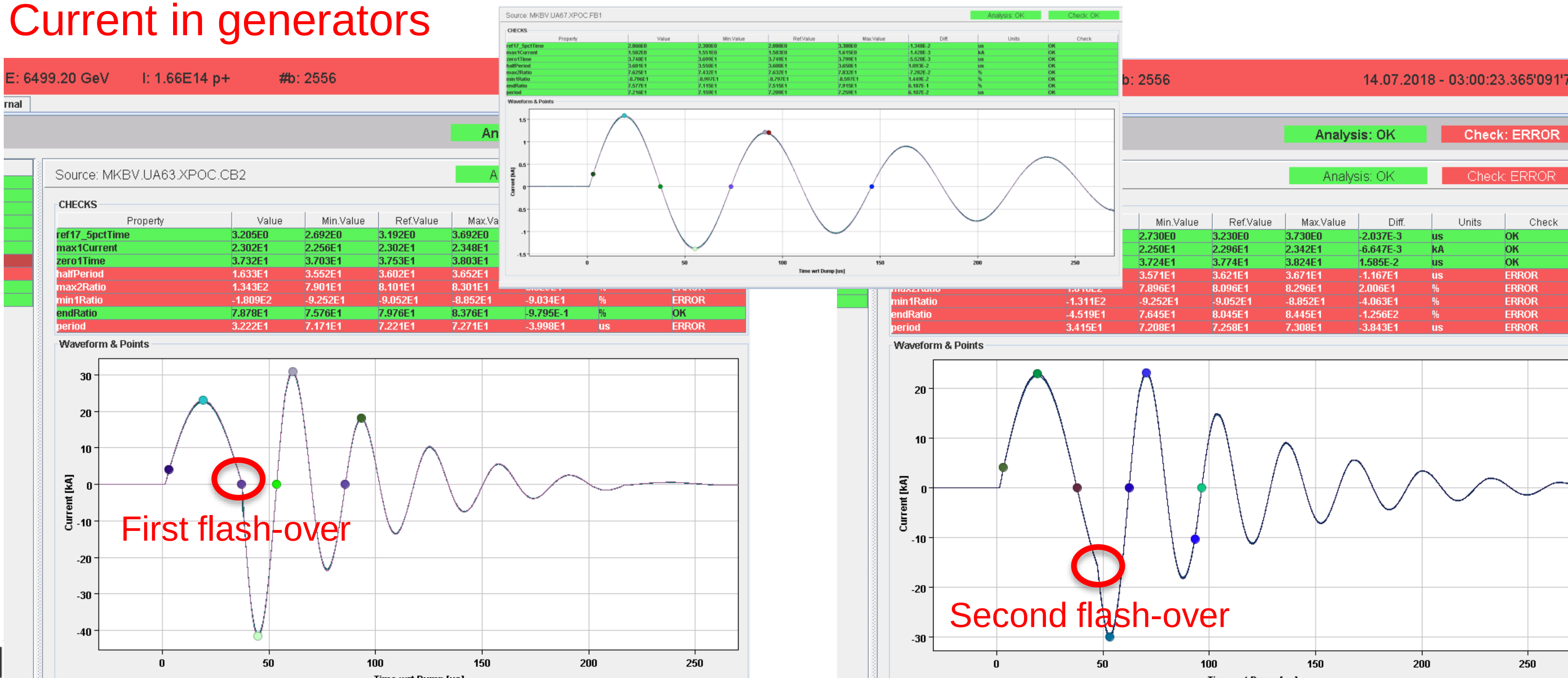



Courtesy of T. Polzin

# MKBV Flash-over on July 14th 2018

- B2, 2556 bunches at 6.5 TeV
- First flash-over with beam, previous event during lab test in 2008
- Programmed dump, 37 µs after the start of the dump a flash-over occurred in magnet MKBV.C, 10 us later propagated to MKBV.D (both magnets in same tank)

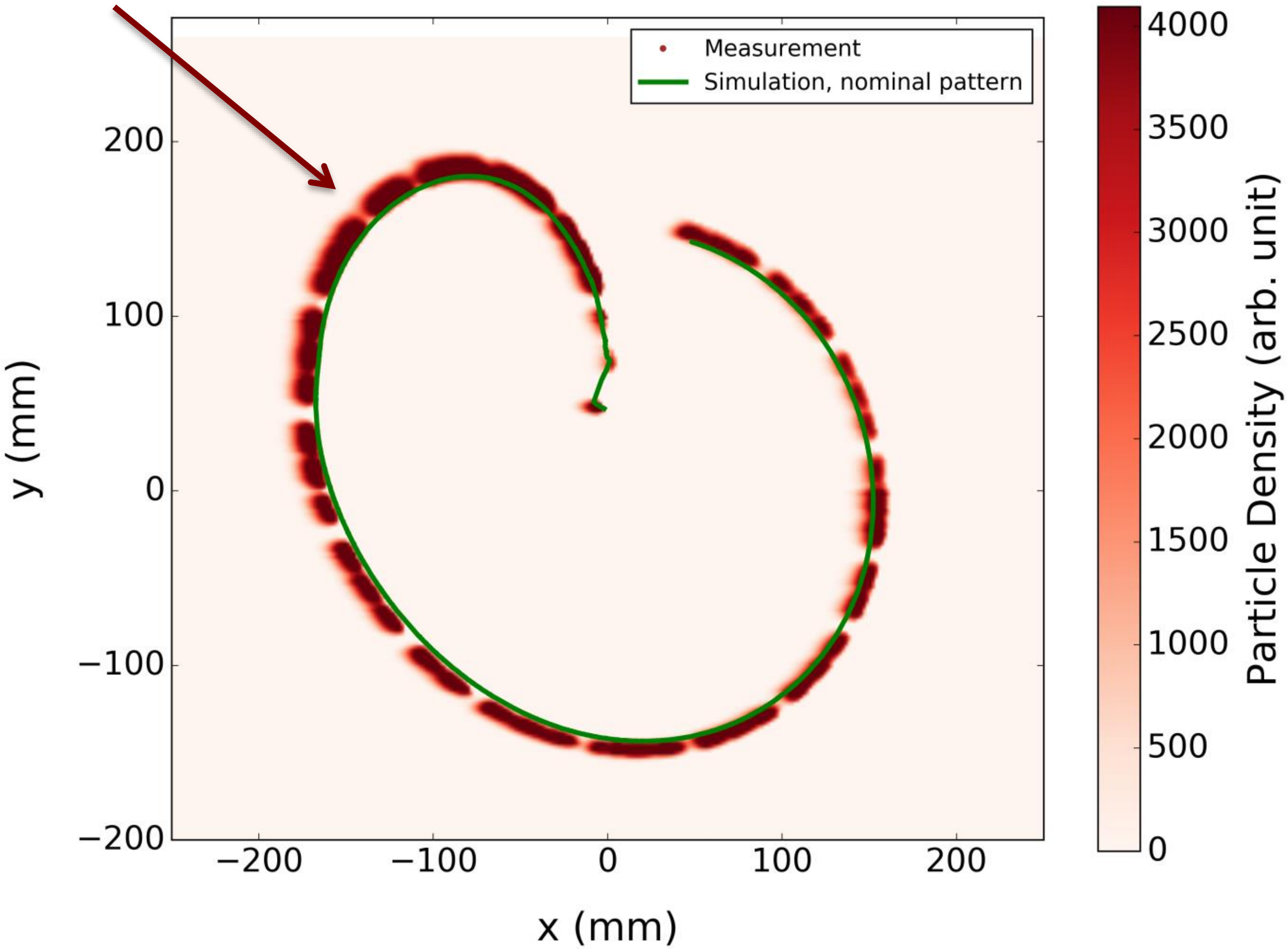
Current in generators



# Nominal pattern

**Nominal dump**
2018-07-12, 13h52

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

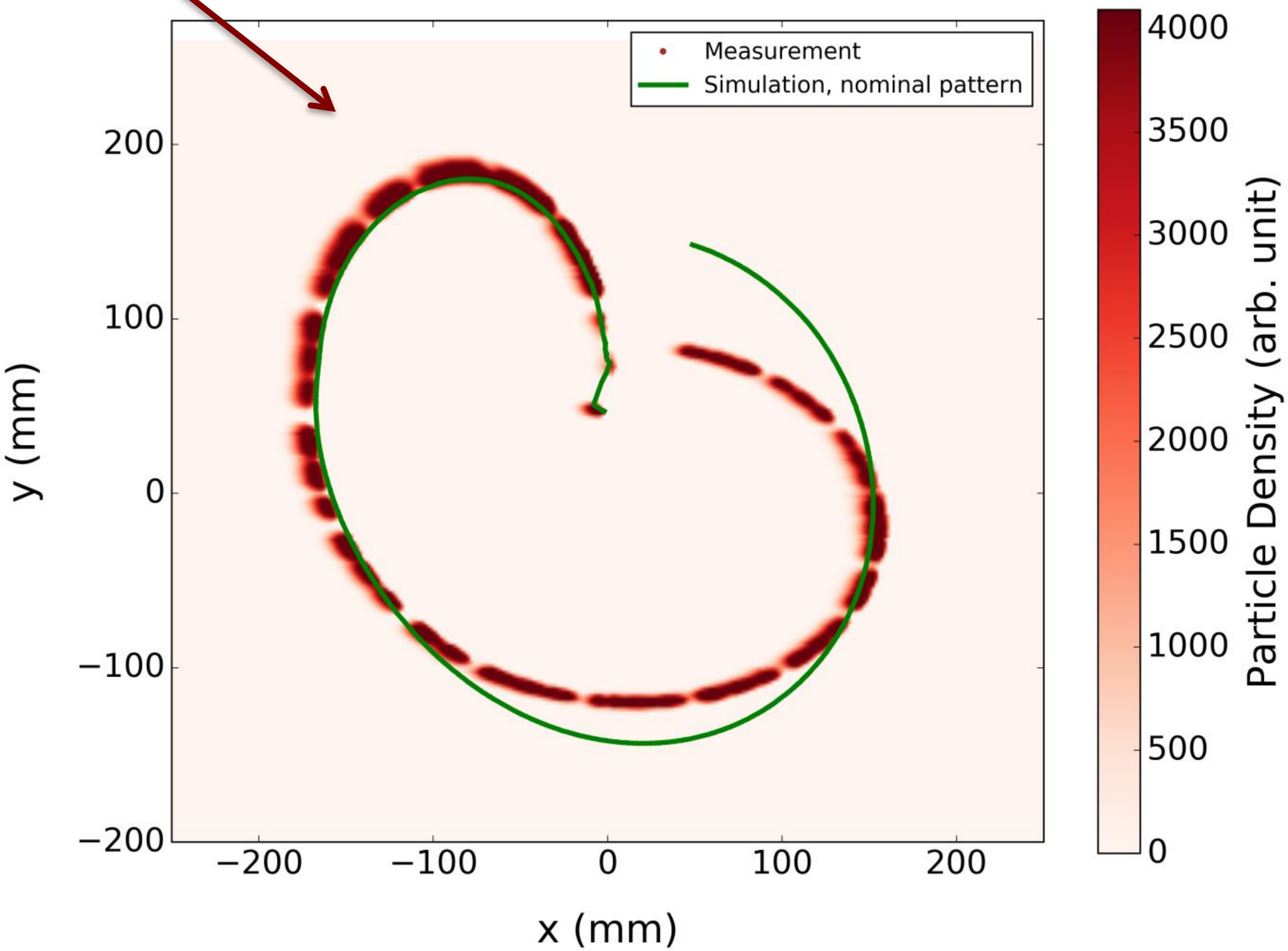



Courtesy of C. Wiesner

# MKBV Flash-over

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

**MKBV flash-over**
2018-07-14, 03h00

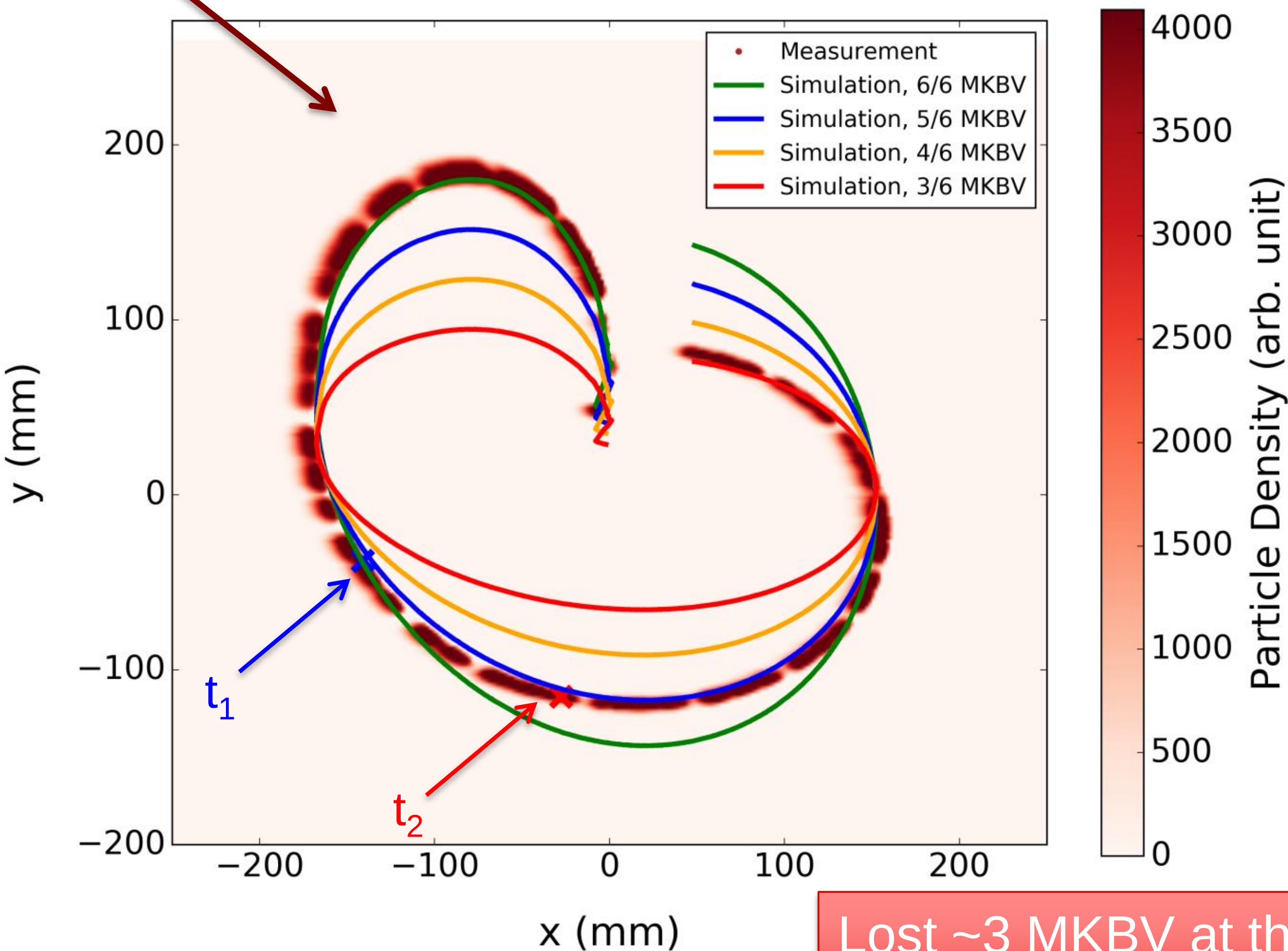



Courtesy of C. Wiesner

# MKBV Flash-over

**MKBV flash-over**
2018-07-14, 03h00

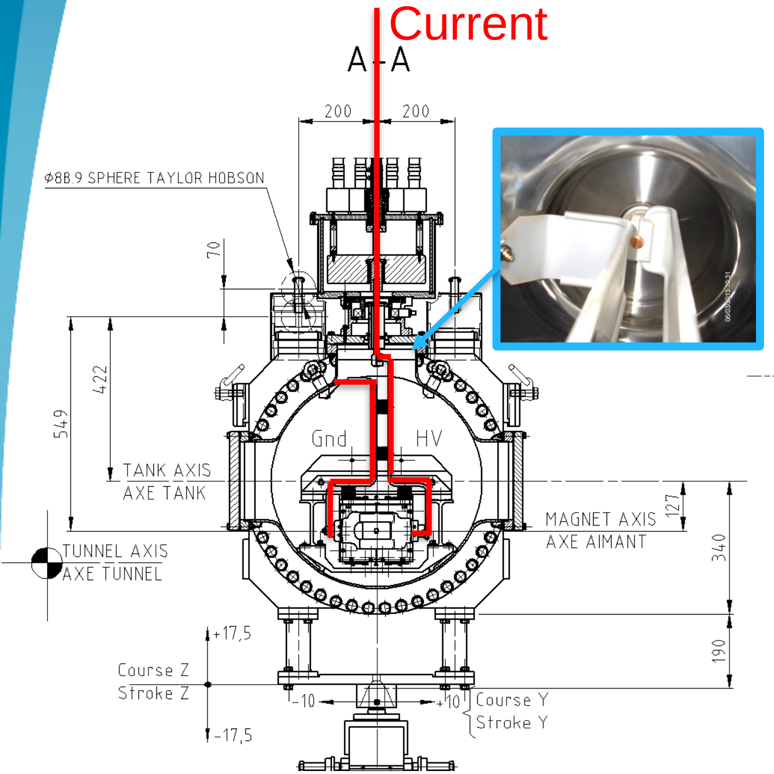
Simulated pattern using waveform from 2016-07-22, 17h01 (B2).
Center position fitted and vertical size scaled by 1.04

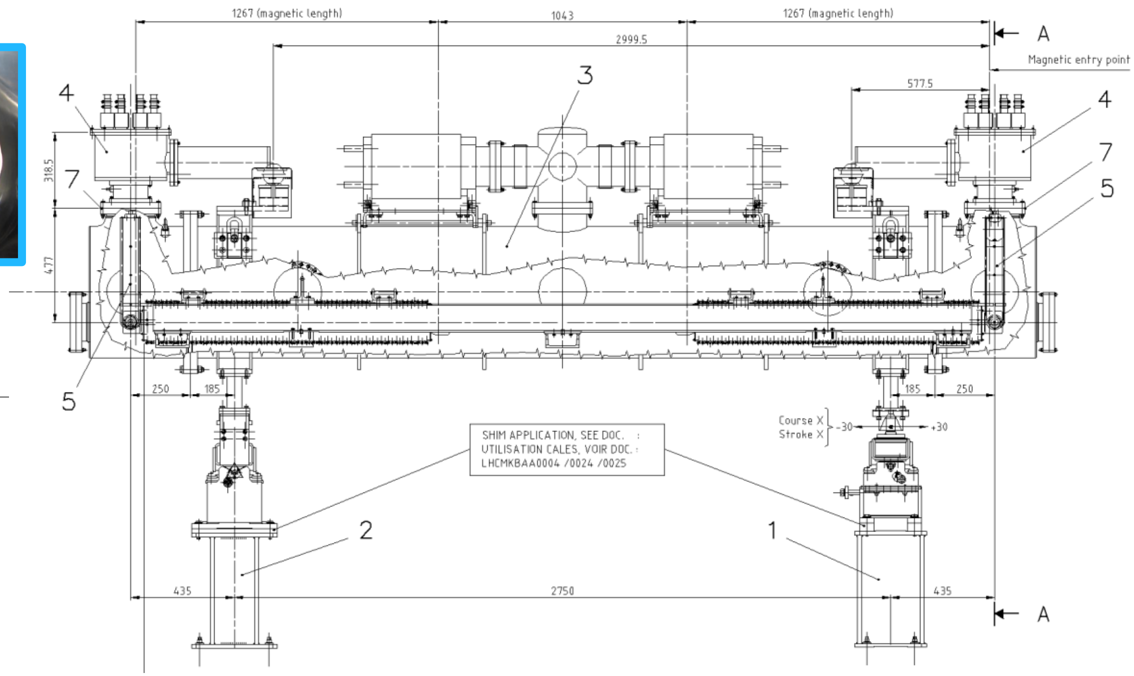



Lost ~3 MKBV at the end of the sweep

# MKB Flash-over: What Happened?

HV Generator



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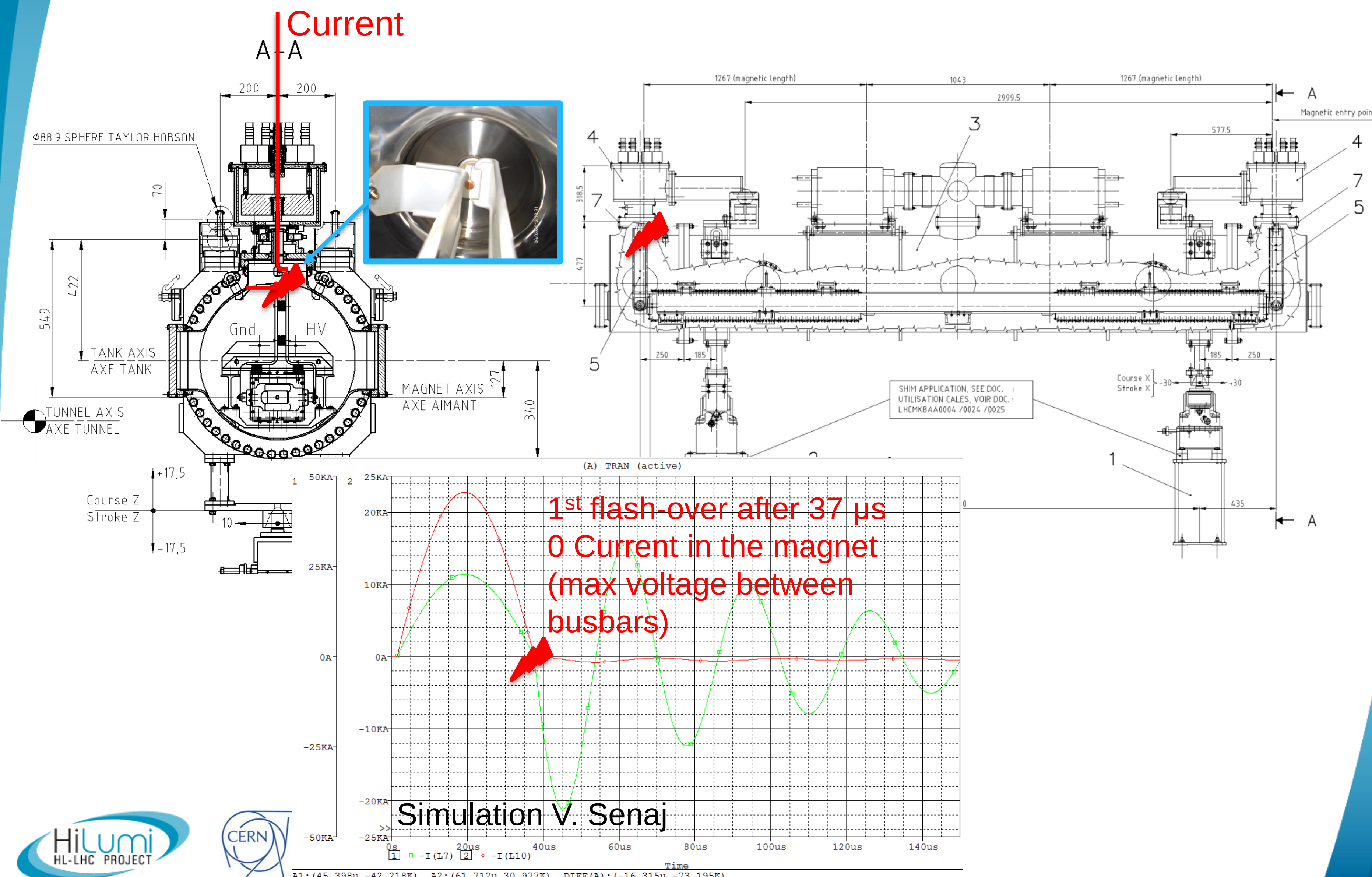

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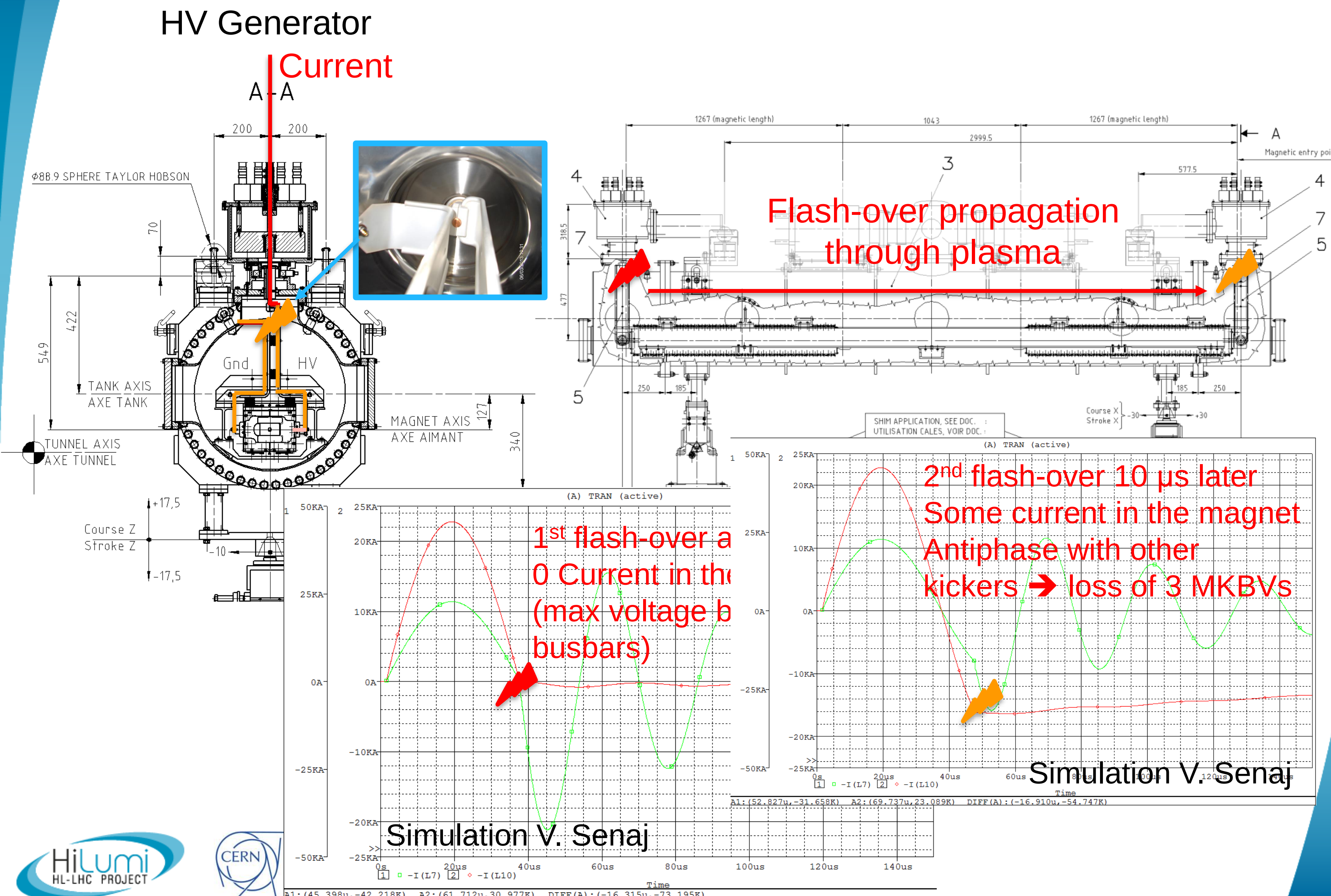
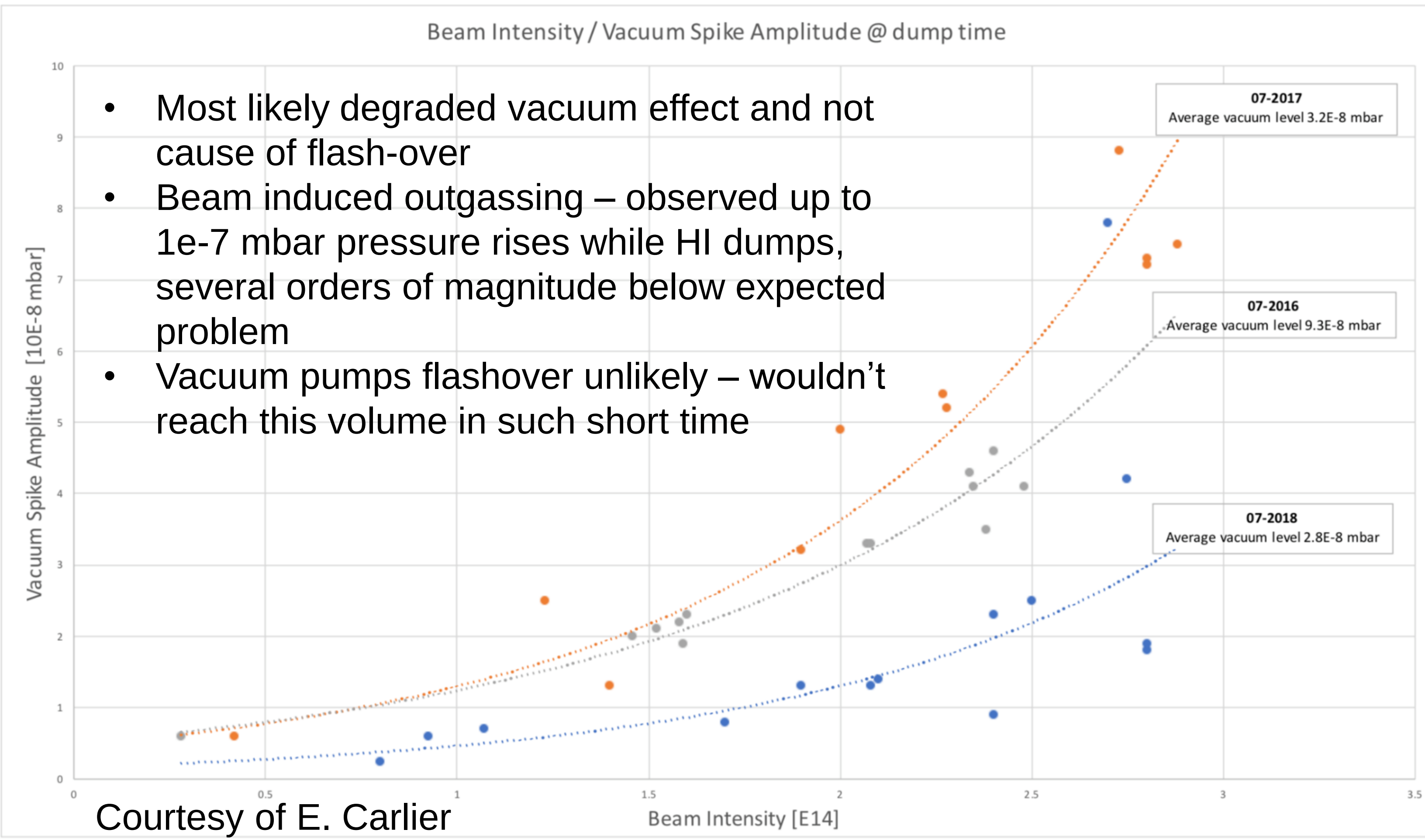


# Vacuum vs intensity

- Vacuum baseline:
  - 2016: 1e-7 mbar
  - 2017: 3e-8 mbar
  - 2018: 3e-8 mbar

Beam induced vacuum spikes:
0.1 – 1 e-7 mbar

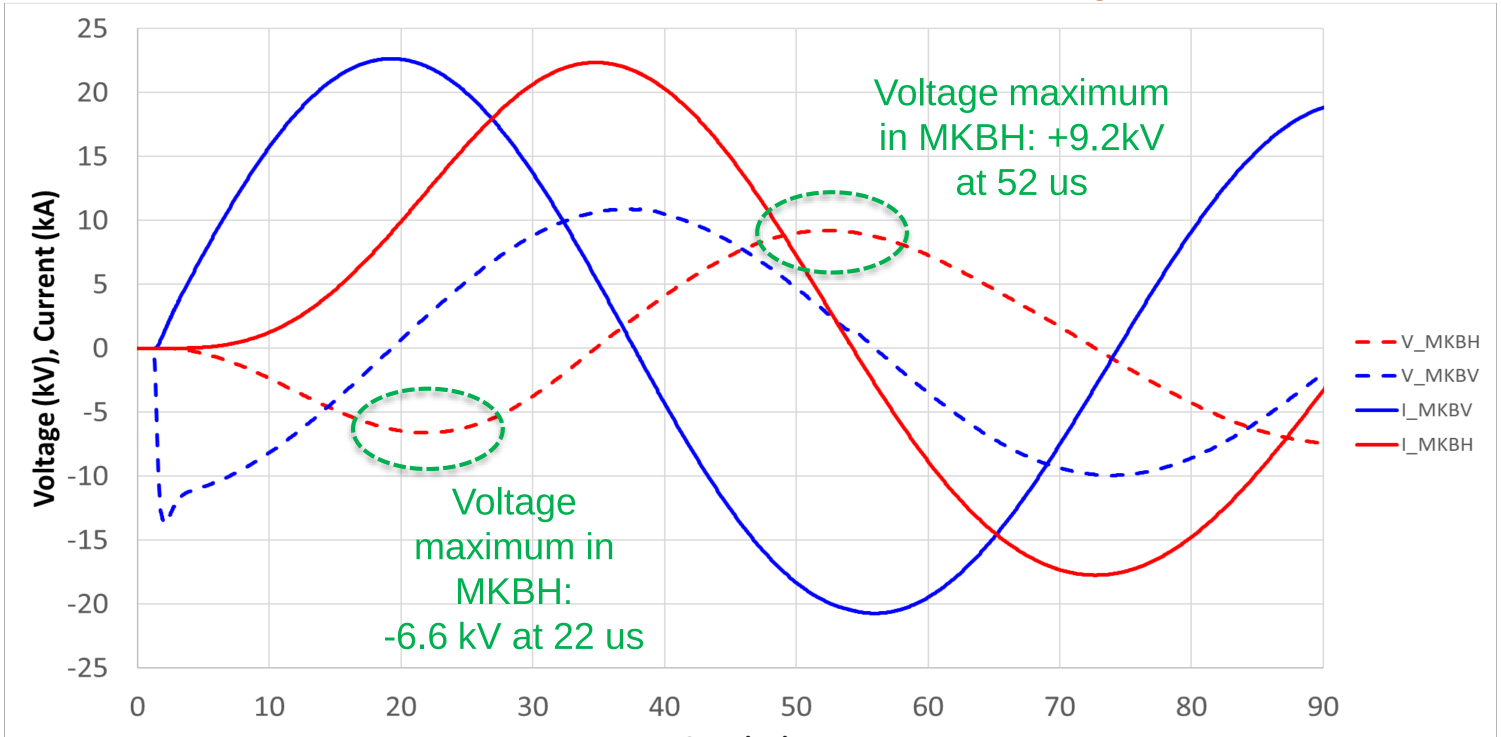



- Most likely degraded vacuum effect and not cause of flash-over
- Beam induced outgassing – observed up to 1e-7 mbar pressure rises while HI dumps, several orders of magnitude below expected problem
- Vacuum pumps flashover unlikely – wouldn’t reach this volume in such short time

Courtesy of E. Carlier

# Effect of Flash-Over in MKBH

Simulated voltage and current in MKBs



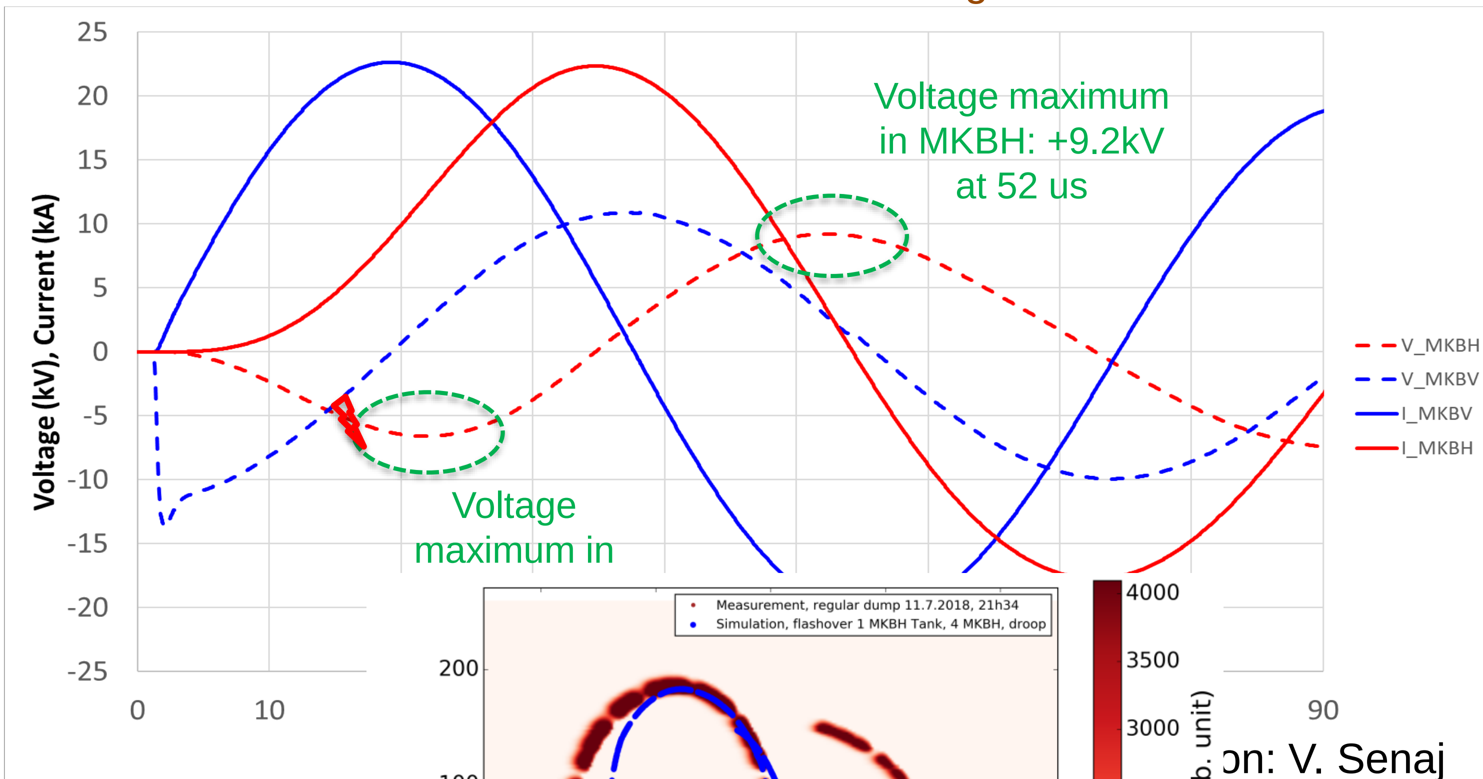

PSpice simulation: V. Senaj

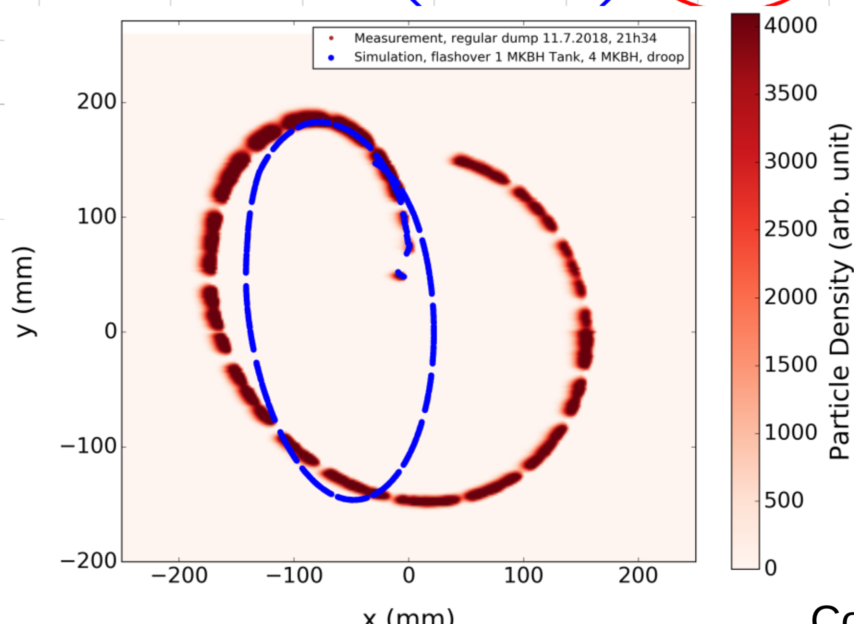
Simulations performed assuming:
Flashover affects both magnets in the same tank (no propagation to adjacent ones)
First flashover occurring around maximum voltage (+/- 20%) in the magnet
Delay between first and second flashover: 10 us
Current in magnet coil constant after flashover (slow decay of ~8% over 50 us)

Courtesy of C. Wiesner

# Effect of Flash-Over in MKBH

Simulated voltage and current in MKBs for 6.5 TeV




Courtesy of C. Wiesner

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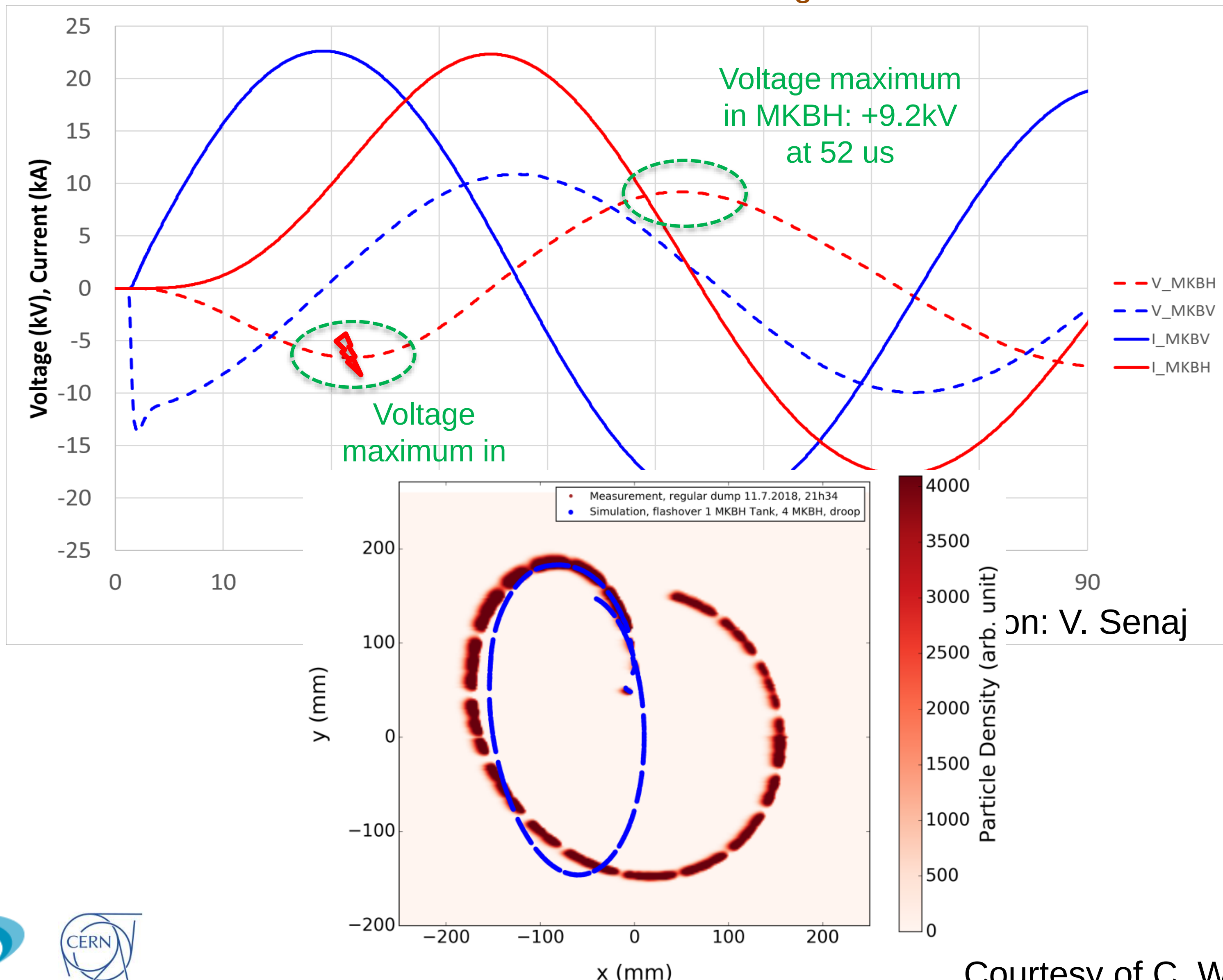


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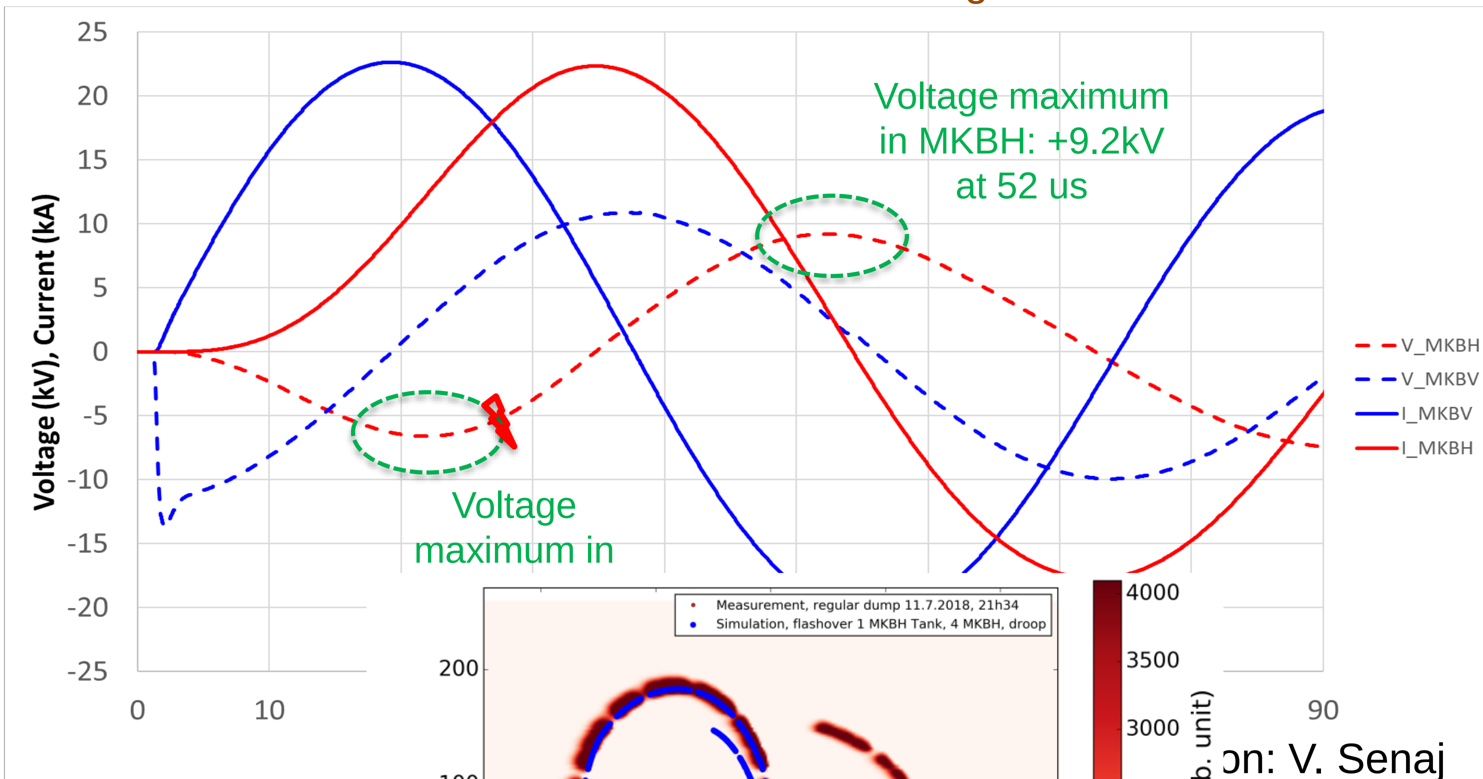


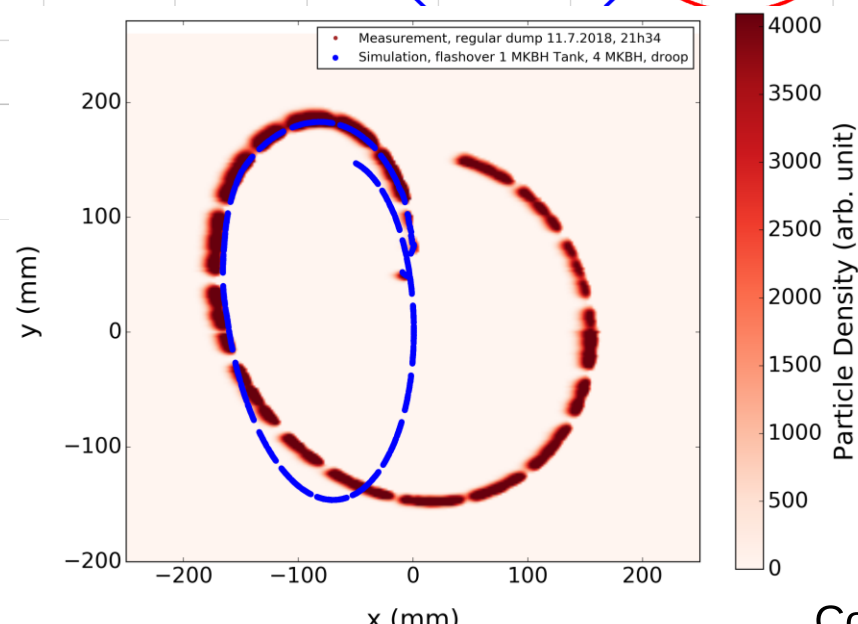


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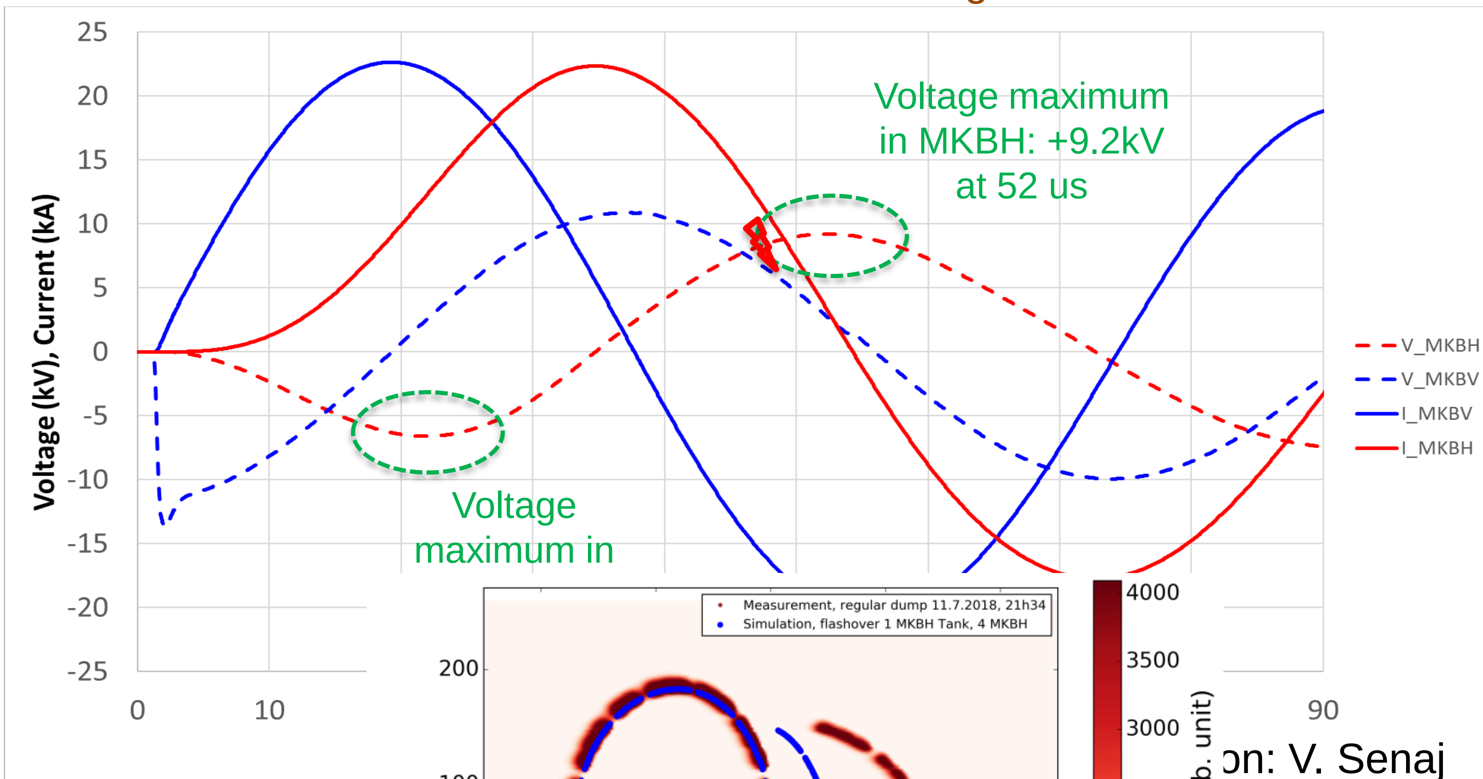


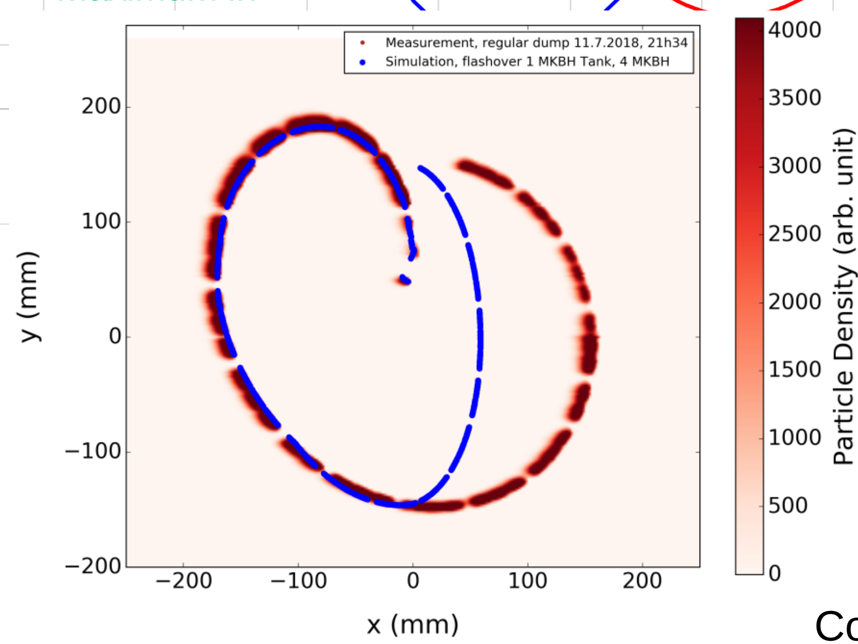


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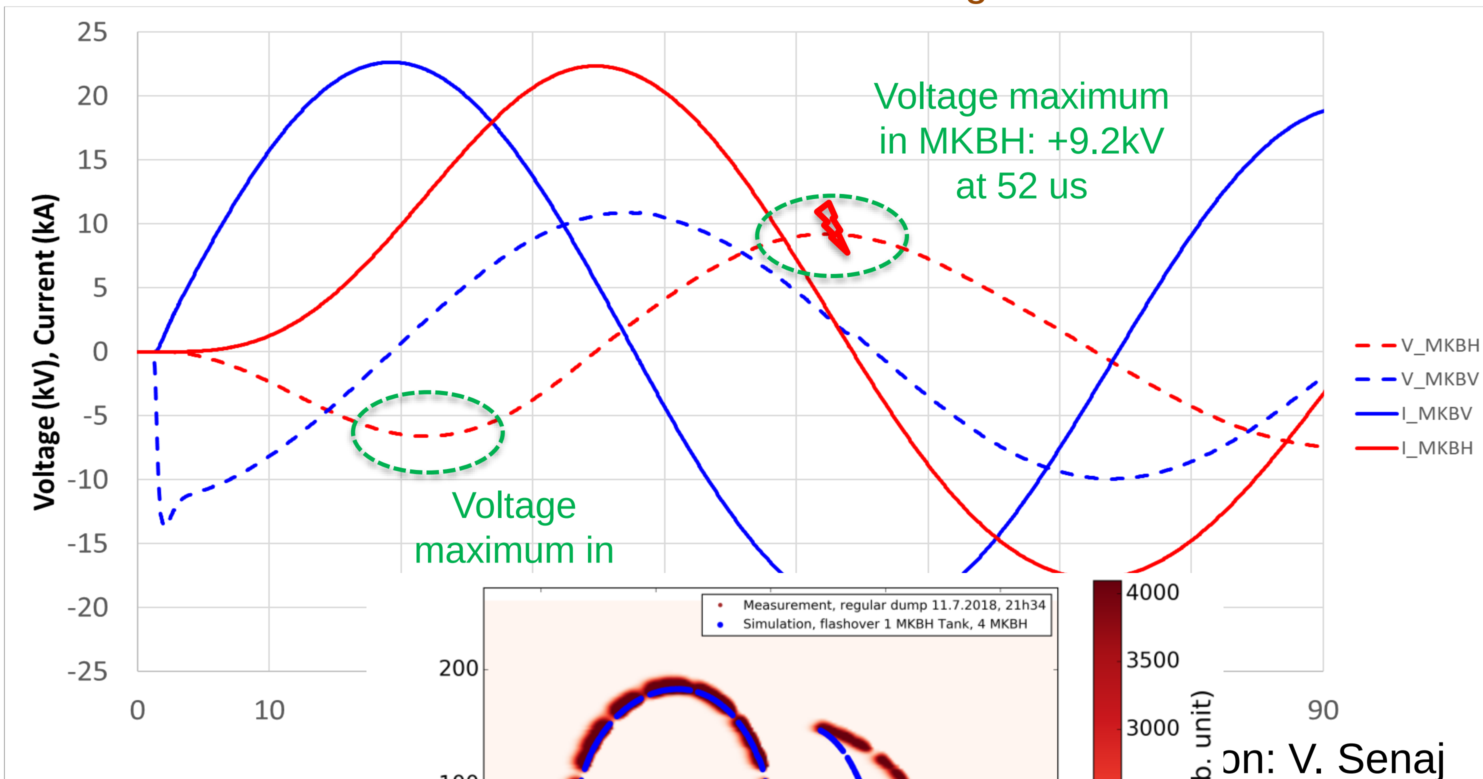


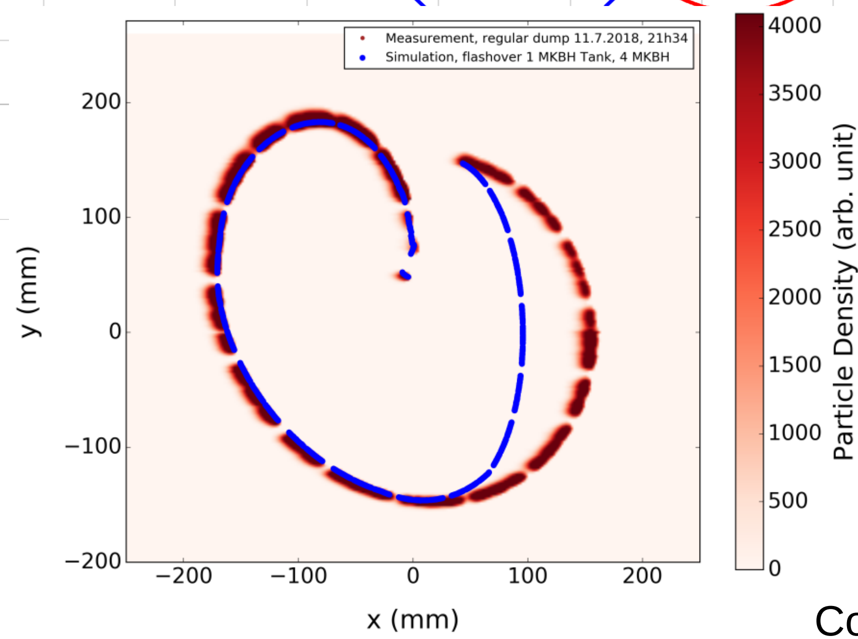


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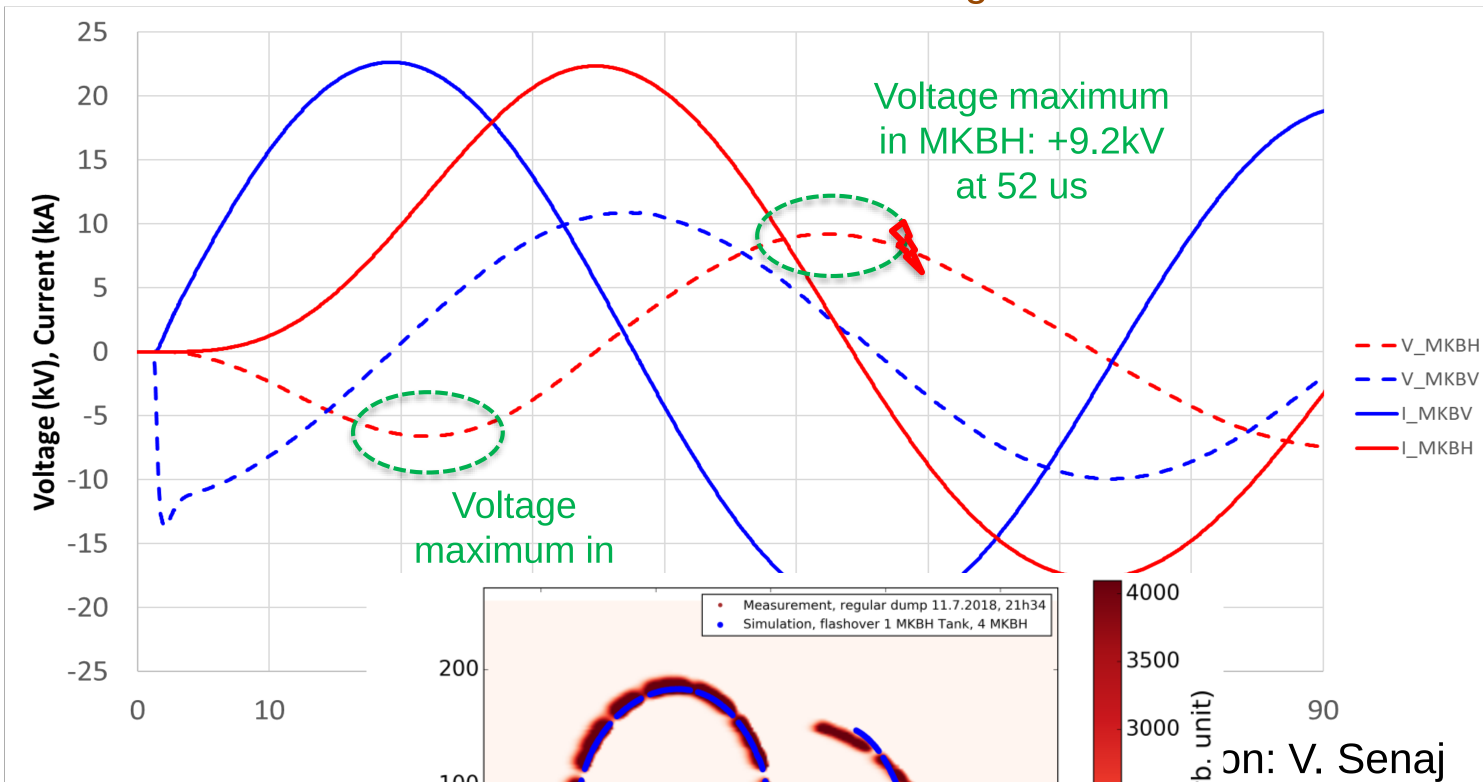
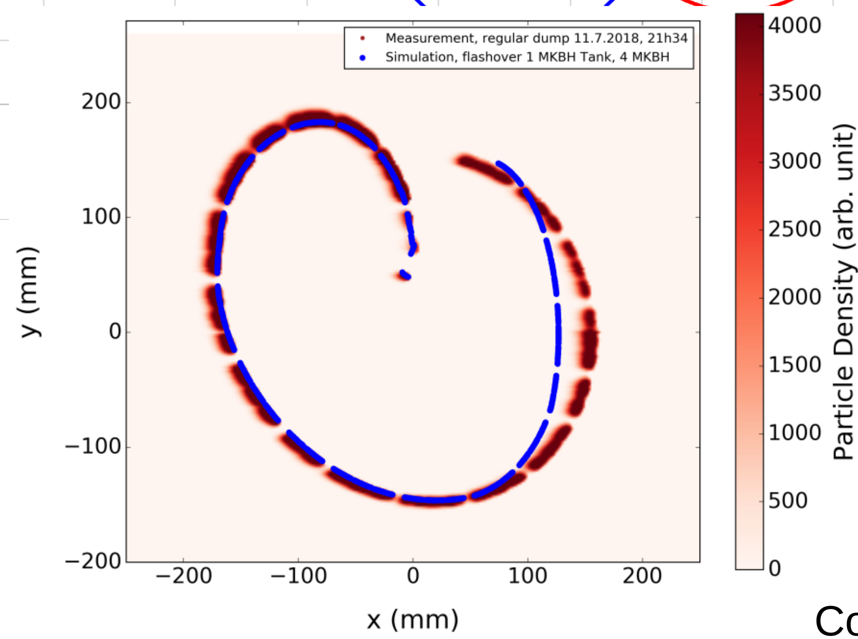
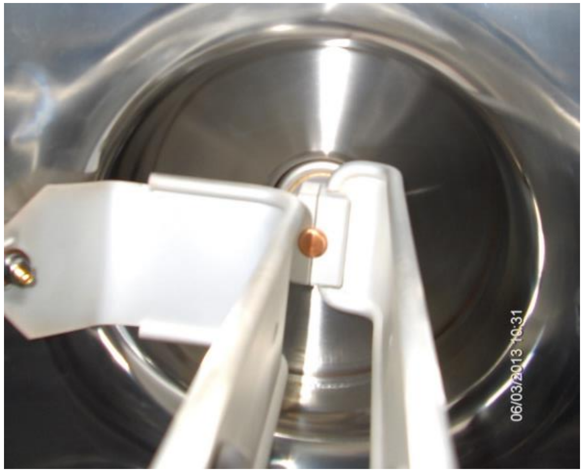


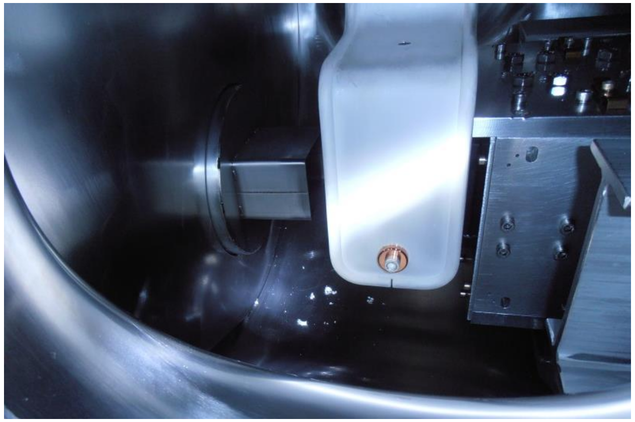

Courtesy of C. Wiesner

# New Proposed Baseline

1. Addition of two MKBH per beam by LS3
   - Only fully reliable solution to reduce risk (lower voltage) and sensitivity to any possible failure of MKBH
   - Possibility of increasing dilution at the dump and reduce energy density and thus temperature increase during nominal operation (thermo-mechanical studies needed)




2. Improve insulation of the HV busbars (if present understanding of flashover origin confirmed during visual inspection)



Expected impact on intensity reach after LS2
➔ effects and possible mitigations are being evaluated

# Updated Worst cases – MKBH flashover

**Estimated density increase compared to nominal pattern (BCMS)**

| | US Win | TDE | Flashover probabilty | Worst case flashover time [16 us… 28 us] |
|---|---|---|---|---|
| 4/4 MKBH | 100% | 100% | | |
| 2/4 MKBH | 191% | 173% | | |
| Flashover – 4 MKBH | 209% | 192% | As today | 16 us |
| Flashover – 6 MKBH at 67% voltage | 164% | 170% | Significantly reduced | 28 us |
| Flashover – 6 MKBH at 80% voltage | 118% | 153% | Reduced | 19 us (US win) / 28 us (TDE) |

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

Preliminary

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

# Conclusions

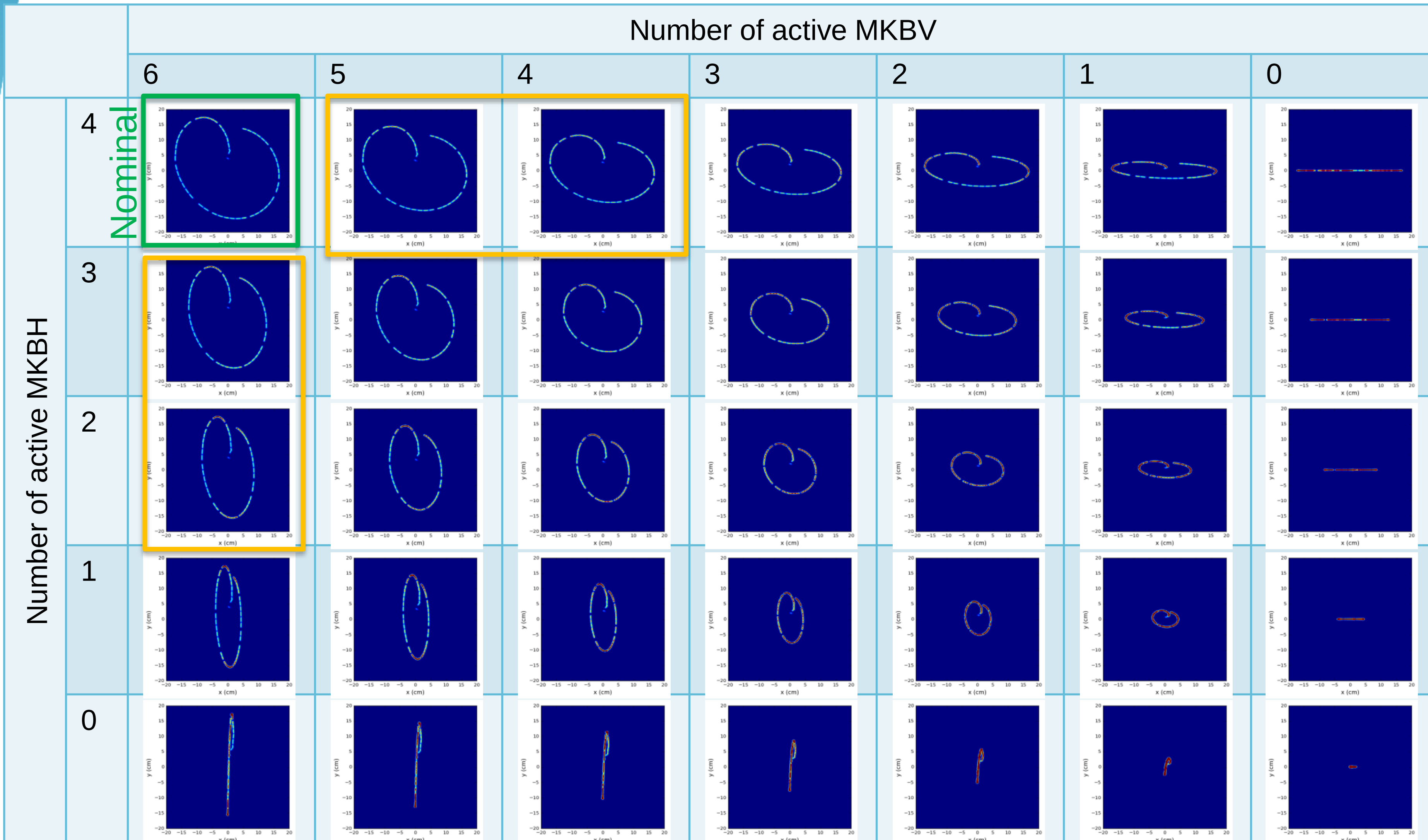
- 6 Vertical and 4 horizontal kickers are used to dilute the beam and minimize the local energy density at the dump
- **Originally**, two **worst failure scenarios** were considered (worst failure in H plane since only 4 kickers installed):
  - **Erratic** of 1 kicker plus perfect antiphase ➔ **2 missing MKBHs**
  - **Simultaneous flash-over** in 2 magnets sharing vacuum tank ➔ **2 missing MKBHs**
- **New failure scenarios** were discovered in operation:
  - **EM coupling** ➔ multiple erratic plus **antiphase** ➔ **more than 2 missing MKBHs**
  - **Delayed flashover** in magnets sharing vacuum tank ➔ **up to 3 missing MKBHs**
- Strong impact on dump windows (and core?) survival in case of failure when operating with high intensity beams
- Planned mitigations for erratic:
  - **Reduce voltage** in MKBH generators ➔ reduce risk of erratic
  - **MKB re-triggering** ➔ avoid anti-phase

  } Present baseline
  - Possible **option of adding two MKBHs** (with same or increased dilution) to reduce voltage and sensitivity to failures was **being studied**
- **New proposed baseline** (new failure case after 2018 flash-over event):
  - **Add two MKBHs** (with same or increased dilution) ➔ reduce voltage and sensitivity to failures
  - Improve **isolation of HV busbars** ➔ reduce risk of flash-over

***Thank you for your attention!***

# Missing MKBs

HL-LHC BCMS Filling Pattern, MKBs always synchronous with MKDs




Courtesy of C. Wiesner