Results of studies on dilution kickers for HL-LHC

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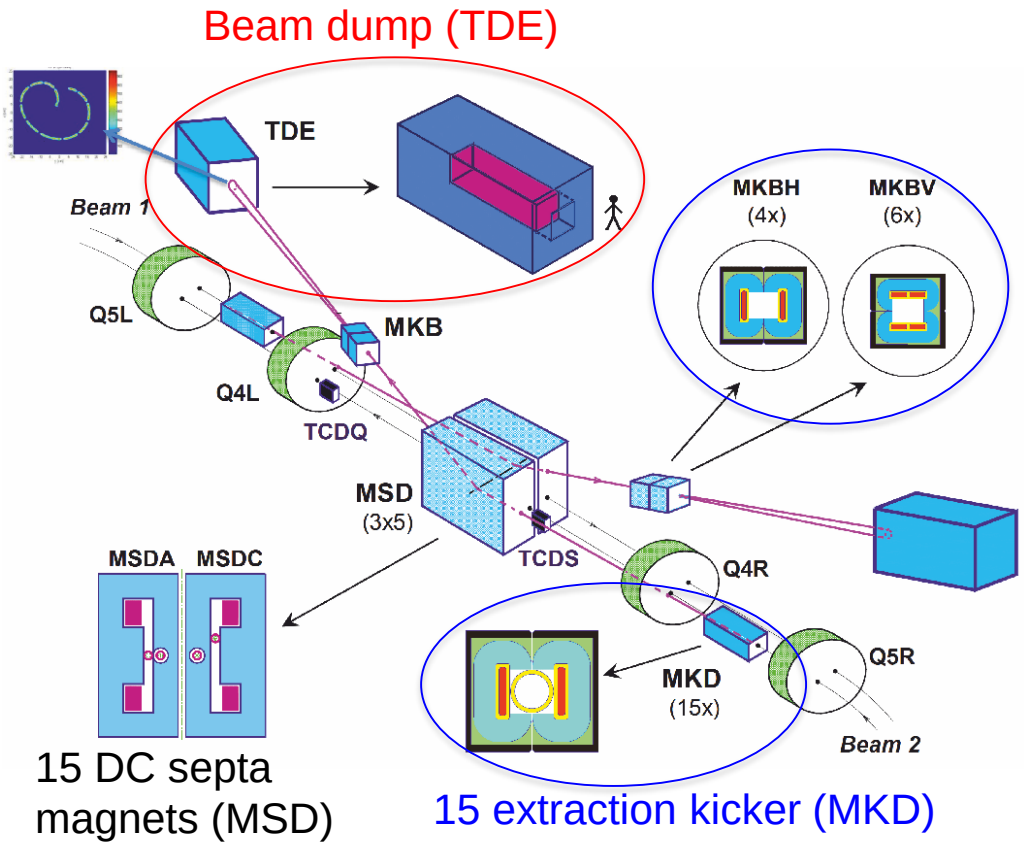
14 November 2017 – 7th HL-LHC Collaboration Meeting

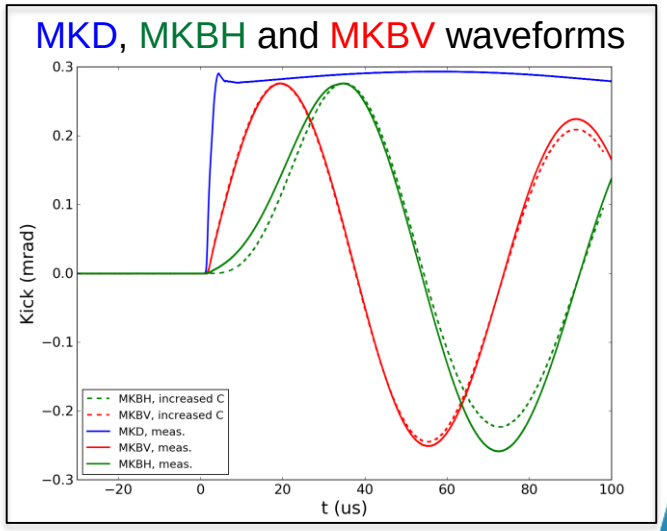
Outline

1) Dilution system: Introduction
2) Dilution system: Failure cases
3) Mitigations and upgrades
    1) Upgrade of MKBH generators (LS2)
    2) Upgrade to 6 horizontal dilution kickers?
    3) Retrigger system for dilution kickers?
4) Conclusions and summary

LHC Dilution System



- 10 Dilution Kicker (MKB)
- 4 MKBH operated at ~27 kV (7 TeV)
- 6 MKBV operated at ~16 kV (7 TeV)
- Same maximum kick angle in both planes (~ 0.28 mrad)



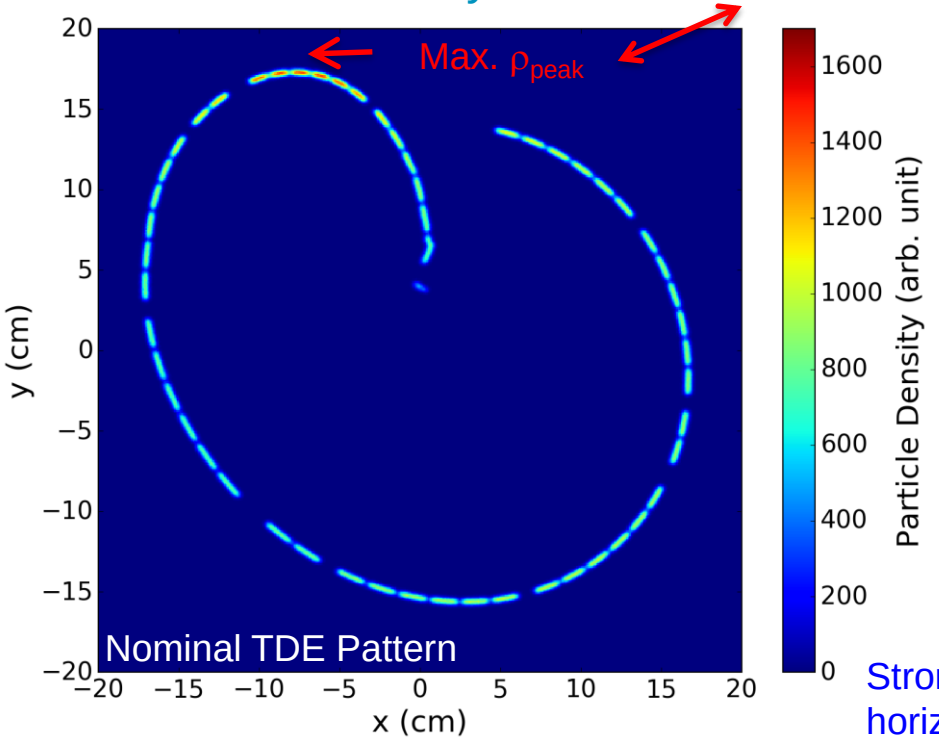
C. Bracco et al., LHC Performance Workshop, Chamonix, 26/01/2016

LHC Dilution System

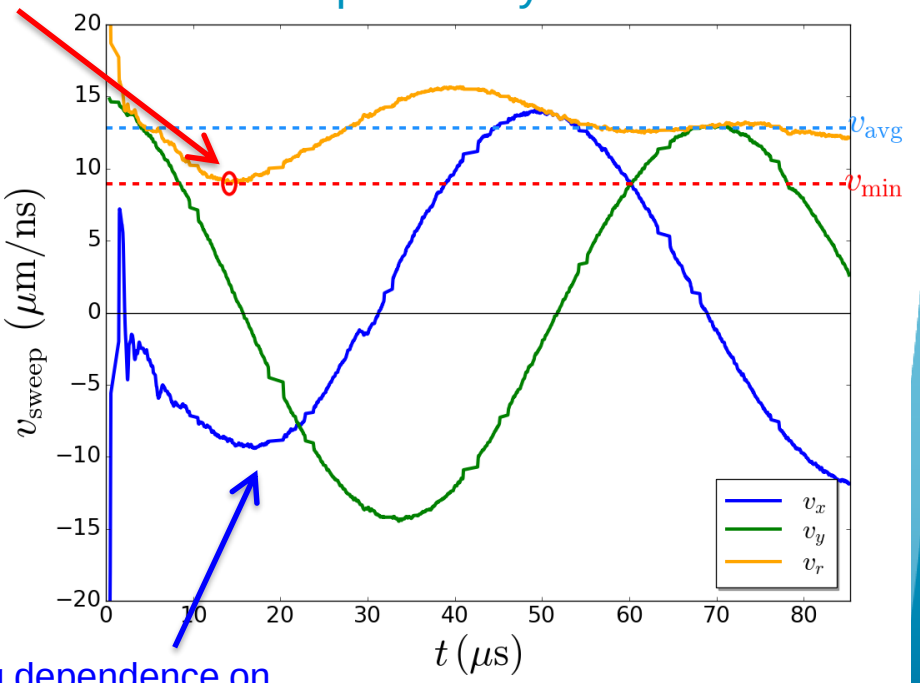
- Upgrade strategy focused on horizontal dilution kickers (MKBH):
  - Higher failure probability (operation at higher voltage)
  - Higher failure sensitivity (4 instead of 6 modules)
  - Higher failure impact (loss of horizontal deflection is more critical)

Proton Density at TDE

v_{min} = 9.0 µm/ns



Sweep Velocity at TDE



Strong dependence on horizontal sweep velocity.

MKB Erratics 2015-2017 (Operation)

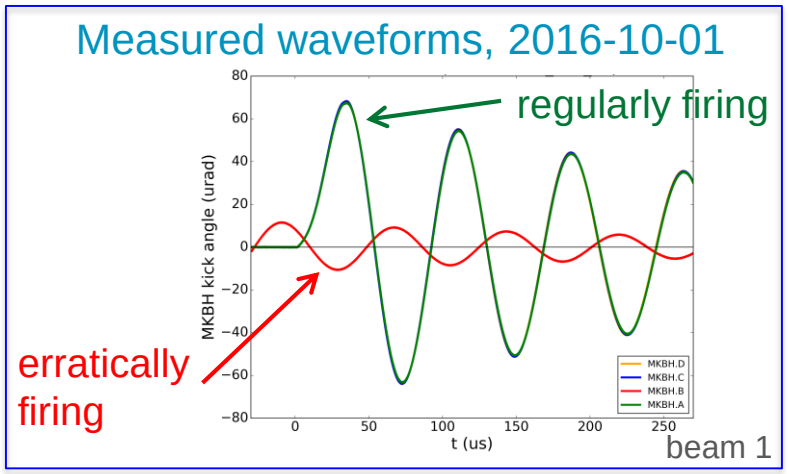
- Erratic firing only occurred for MKBH: 4x in 2015 and 2x in 2016, none in 2017.
- Antiphase can reduce effective dilution

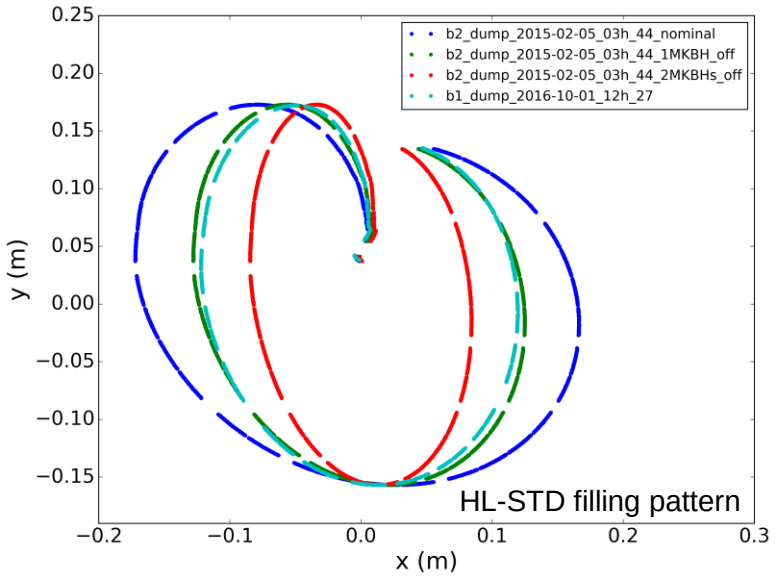
Event	Gen.	t_{delay} (us)	N_p p+	#bun-ches
2015-04-26_08h_16	A/B2	1 028	1.0e10	1
2015-04-27_09h_00	A/B2	1 208	9.4e10	1
2015-05-31_00h_56	A/B2	1 020	2.39e11	7
2015-10-24_20h_48	A/B2	1 049	1.93e14	1824
2016-10-01_12h_27	B/B1	654	1.5e14	2220
2016-10-04_18h_19	B/B2	1 029	1.42e11	5

Effective dilution: 71.5%

74%

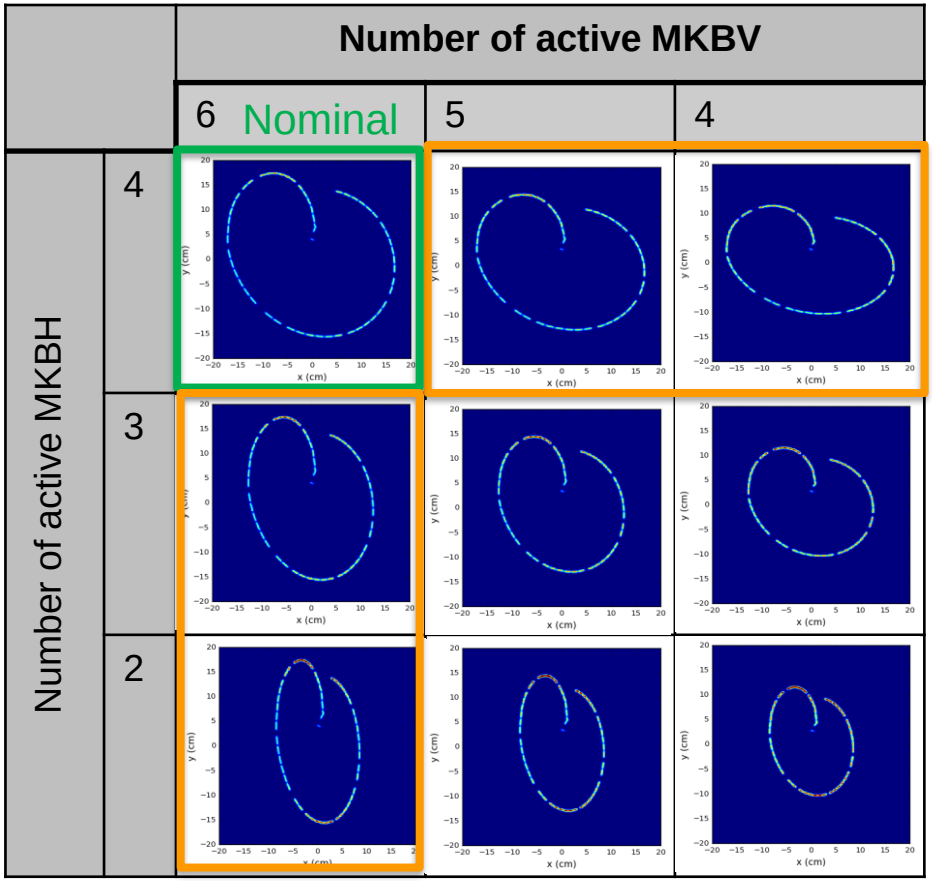
All events occurred at 6.5 TeV





Dilution System – Failure Cases

- Loss of up to 2 MKB in one plane
  - Loss of dilution due to flash-over during dump execution
  - Erratic firing of one MKB in antiphase to remaining MKBs
- New failure mode observed during tests in 2016 (parasitic e-m coupling) could potentially lead to loss of >50% of dilution in one plane due to phase opposition between the MKBs

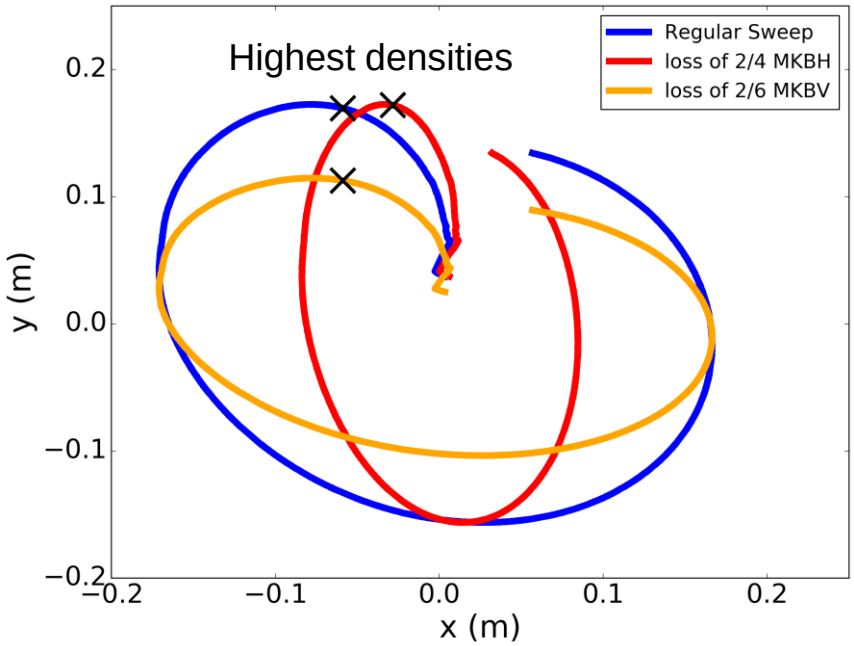


HL-LHC BCMS Filling Pattern

Dilution System – Energy deposition

- High temperatures in the dump core reached. → *See talk by M. Frankl*
- For final conclusion about acceptable level, stress analyses based on the detailed characterization of the dump-material properties required → *See talk by T. Polzin*
- Expected thermo-mechanical stresses in the upstream and downstream windows are beyond the yield strength for failure case of 2 missing MKBH → *See talk by T. Polzin*

Beam sweep patterns at dump



Temperature in dump core

Compared to 1000°C for LHC STD beams, 1.3e11 p+

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

HL-STD beam, 2.3e11 ppb, 2748b, 2.08 um

Compared to 1400°C for LHC STD beams, 1.3e11 p+

M. Frankl

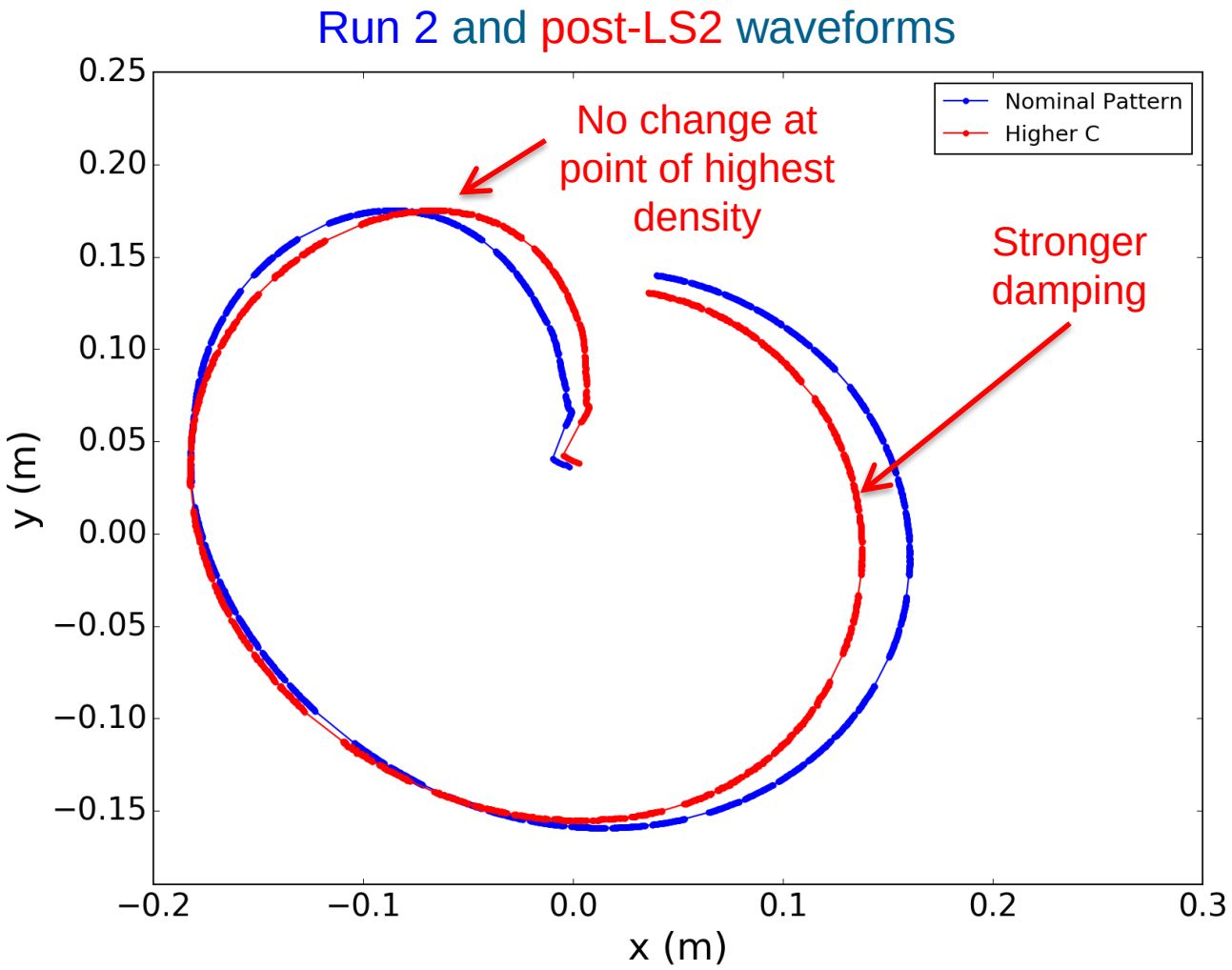
Dilution System – Challenges and Mitigations

- **High sensitivity on failures of MKBH**
  → Upgrade MKBH generators (LS2)
  → Install 2 additional MKBH (LS3)?

- **High temperatures in dump**
  → Install 2 additional MKBH (LS3) and increase total horizontal dilution?

- **New failure mode (coupling) can lead to loss of >50% of dilution in one plane**
  → MKB retriggering in case of erratic firing (LS2)

MKBH Generator Upgrades (LS2)



- MKBH generators will be upgraded in LS2, allowing to operate at ~10% lower voltage
- Reduced probability of erratic firing
- No increase in the energy deposition (FLUKA simulations by M. Frankl).

Dilution System – Challenges and Mitigations

- **High sensitivity on failures of MKBH**

  → Upgrade MKBH generators (LS2)

  → Install 2 additional MKBH (LS3)?

- **High temperatures in dump**

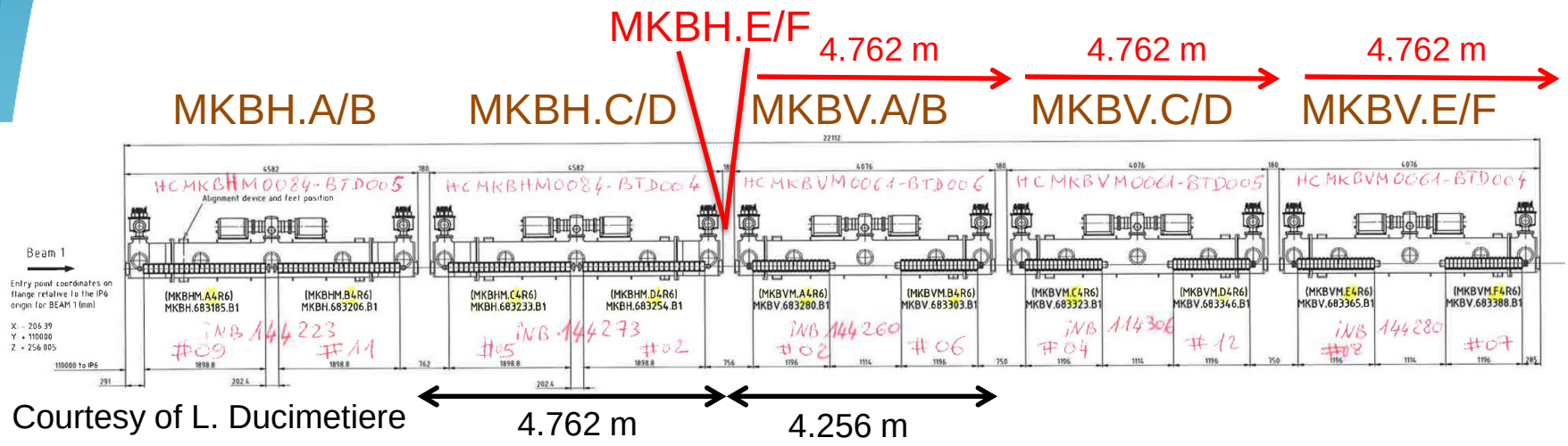
  → Install 2 additional MKBH (LS3) and increase total horizontal dilution?

- **New failure mode (coupling) can lead to loss of >50% of dilution in one plane**

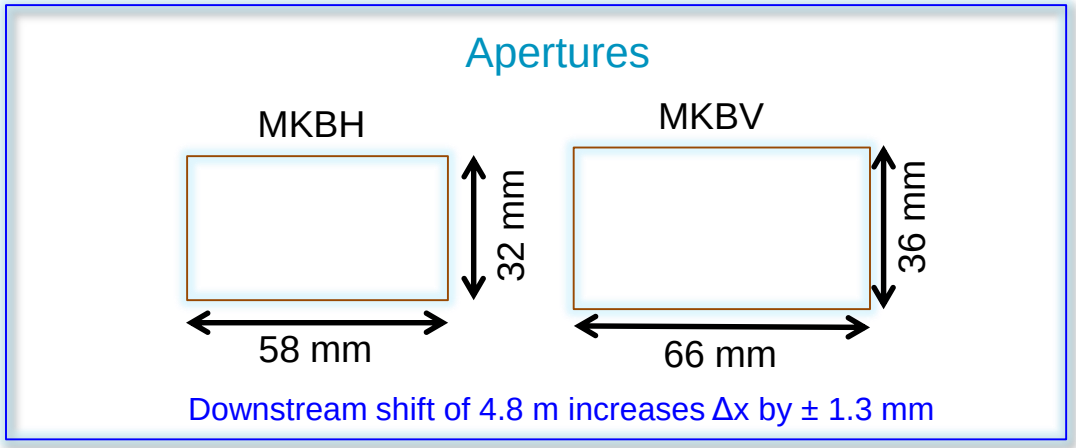
  → MKB retriggering in case of erratic firing (LS2)

Upgrade to 6 MKBH

Insert 2 additional horizontal dilution kicker



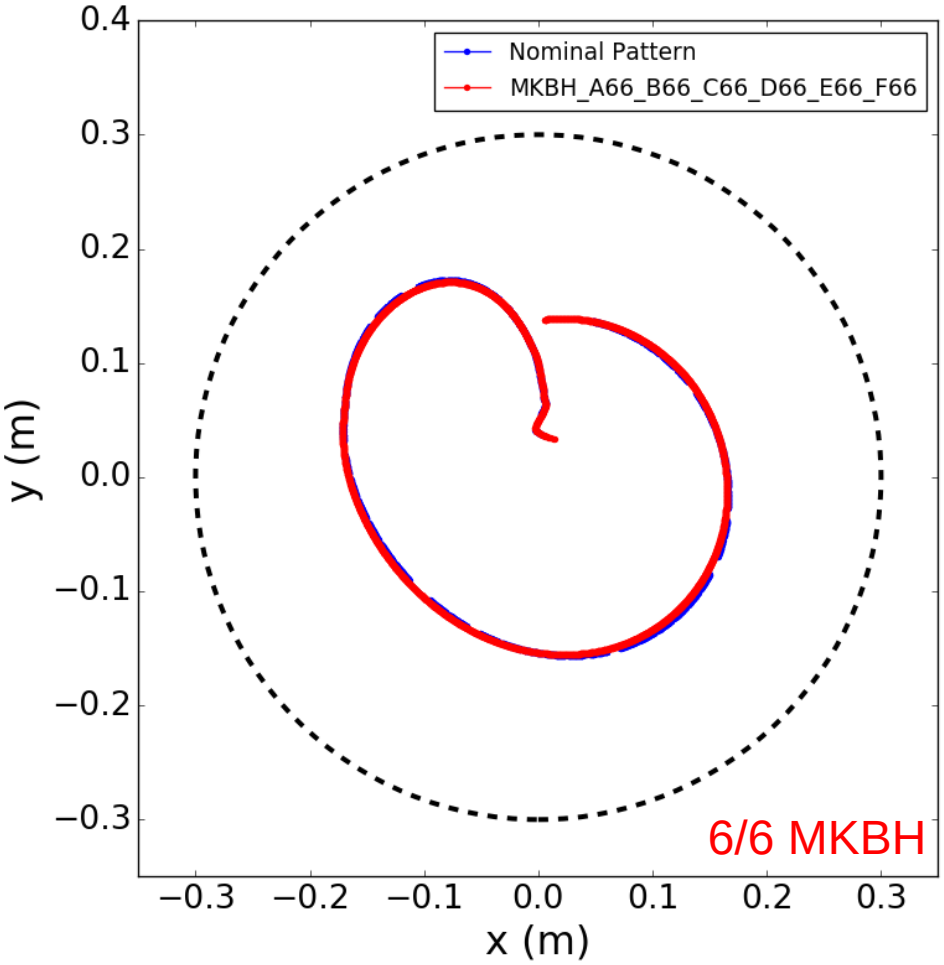
Courtesy of L. Ducimetiere



Sweep Pattern with 6 MKBH

For beam and aperture studies:

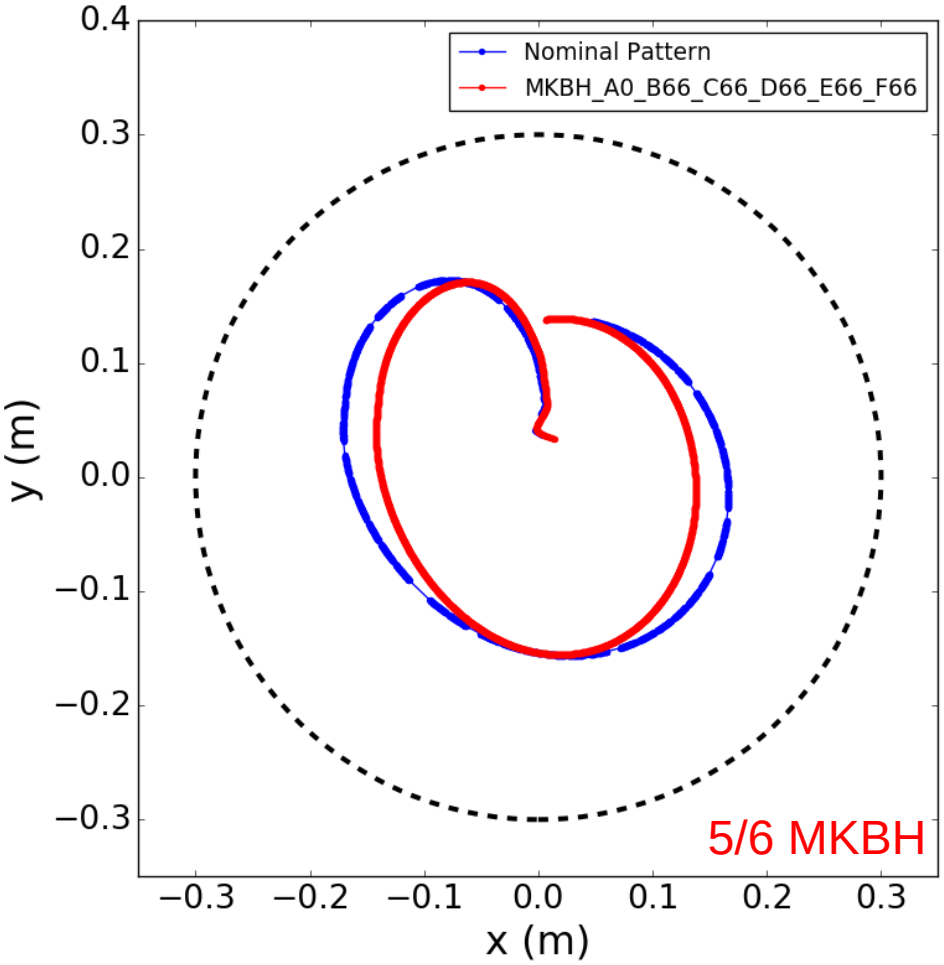
- included 2 additional MKBH after MKBH.D in the MADX sequence,
- shifted all MKBVs upstream by 4.762m,
- kept MKBV strength constant.



- Same total horizontal kick strength, i.e. nominal MKBH voltage reduced by 4/6

Sweep Pattern with 6 MKBH

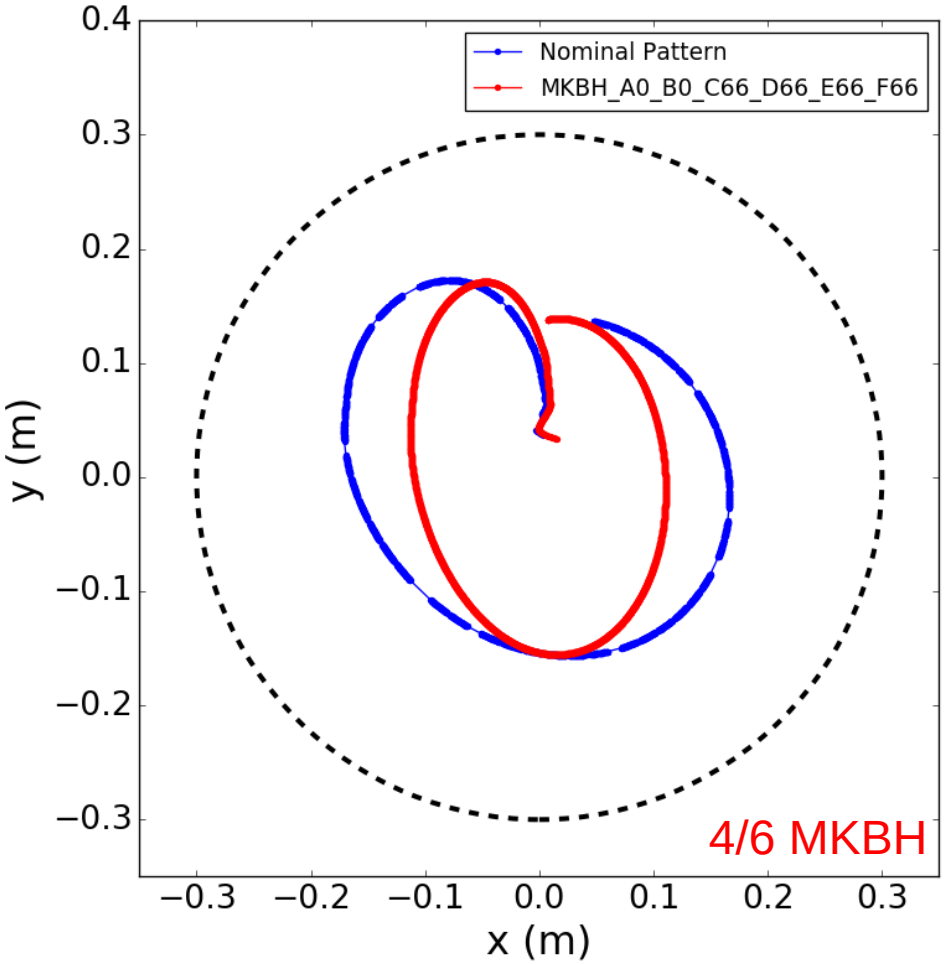
Failure sensitivity reduced



- Same total horizontal kick strength, i.e. nominal MKBH voltage reduced by 4/6

Sweep Pattern with 6 MKBH

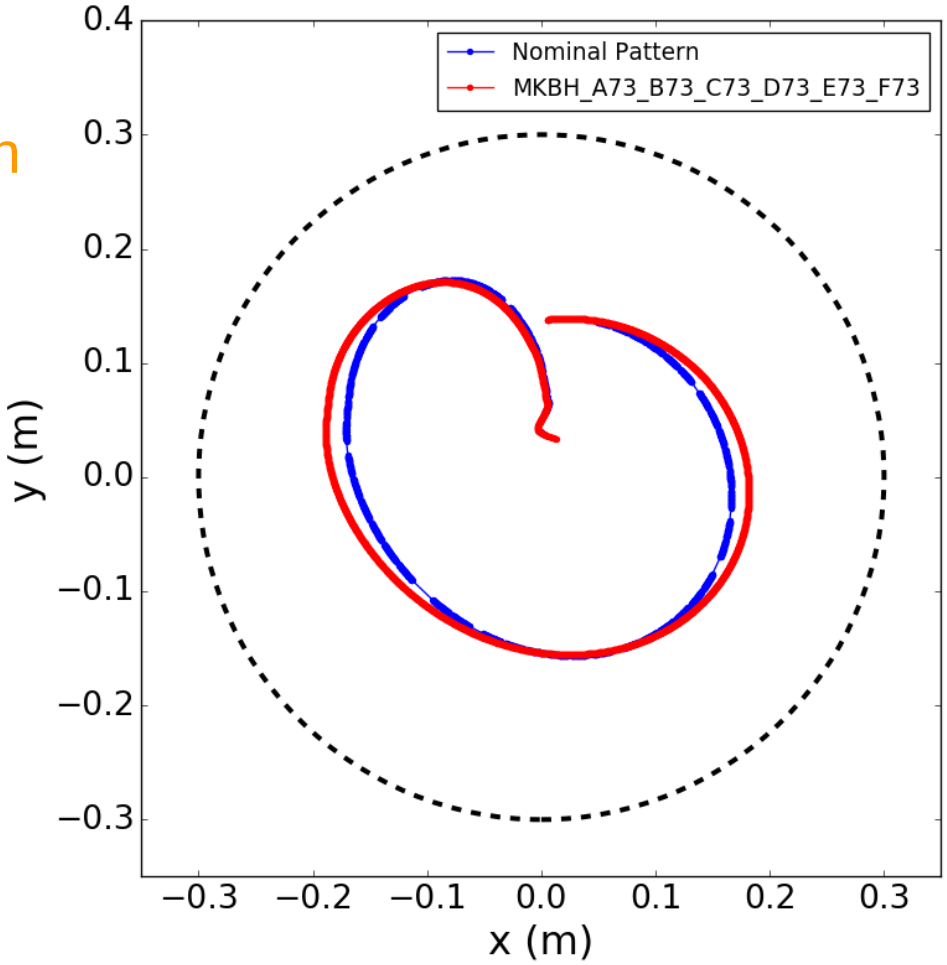
Failure sensitivity reduced



- Same total horizontal kick strength, i.e. nominal MKBH voltage reduced by 4/6
- Now, loss of 33.3% of dilution – instead of 50% for 2/4 MKBH
- FLUKA results → *see talk by M. Frankl*

Sweep Pattern with 6 MKBH

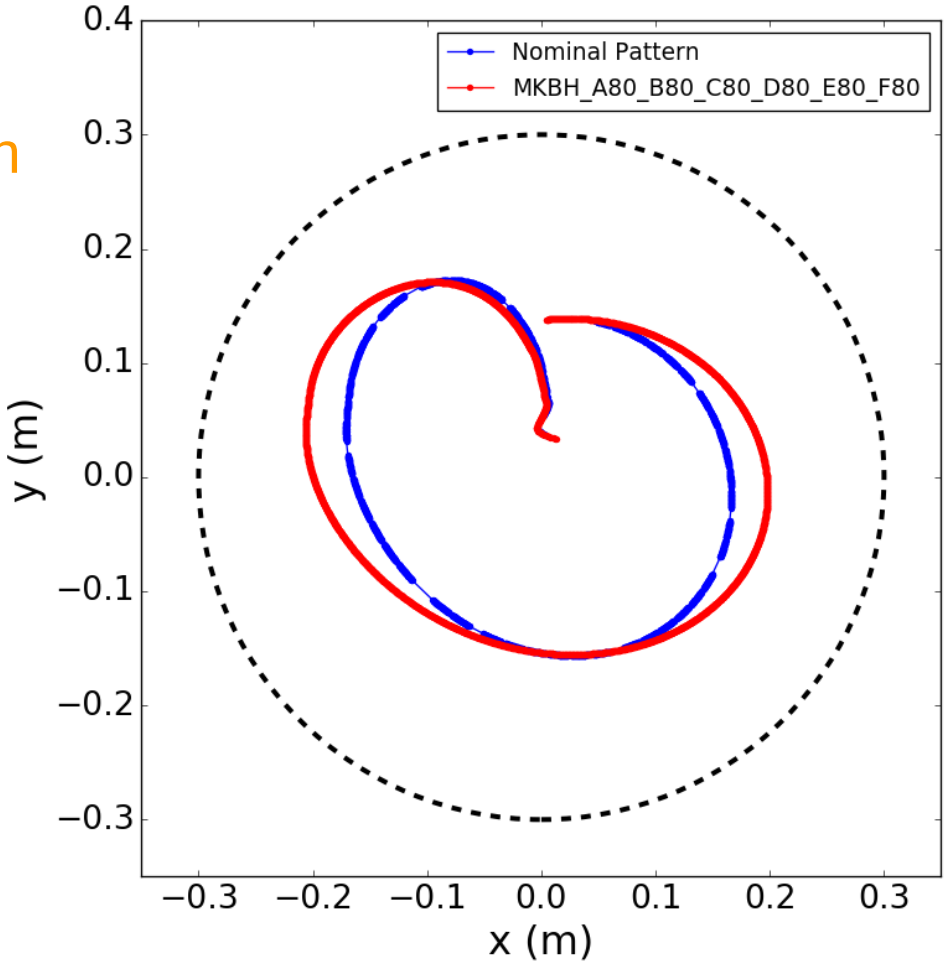
Increasing the dilution strength



- MKBH kick scaled by 110%
- 6/6 MKBH

Sweep Pattern with 6 MKBH

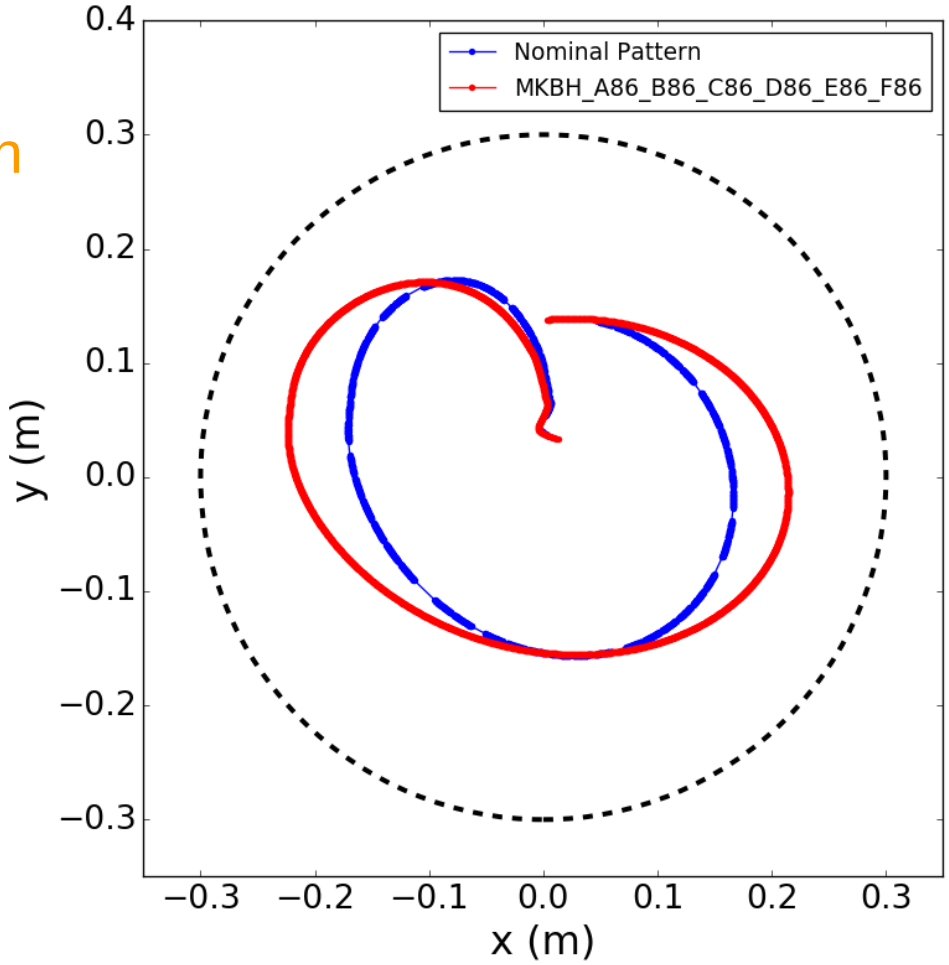
Increasing the dilution strength



- MKBH kick scaled by 120%
- 6/6 MKBH

Sweep Pattern with 6 MKBH

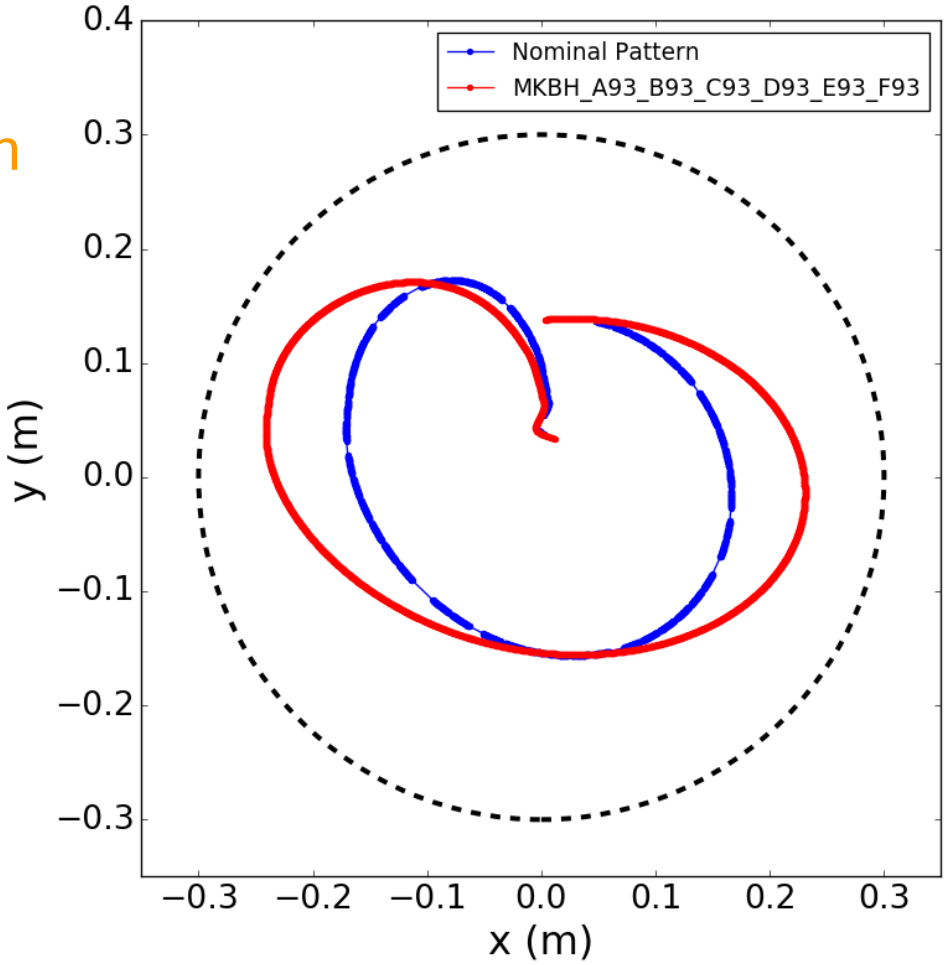
Increasing the dilution strength



- MKBH kick scaled by 130%
- 6/6 MKBH

Sweep Pattern with 6 MKBH

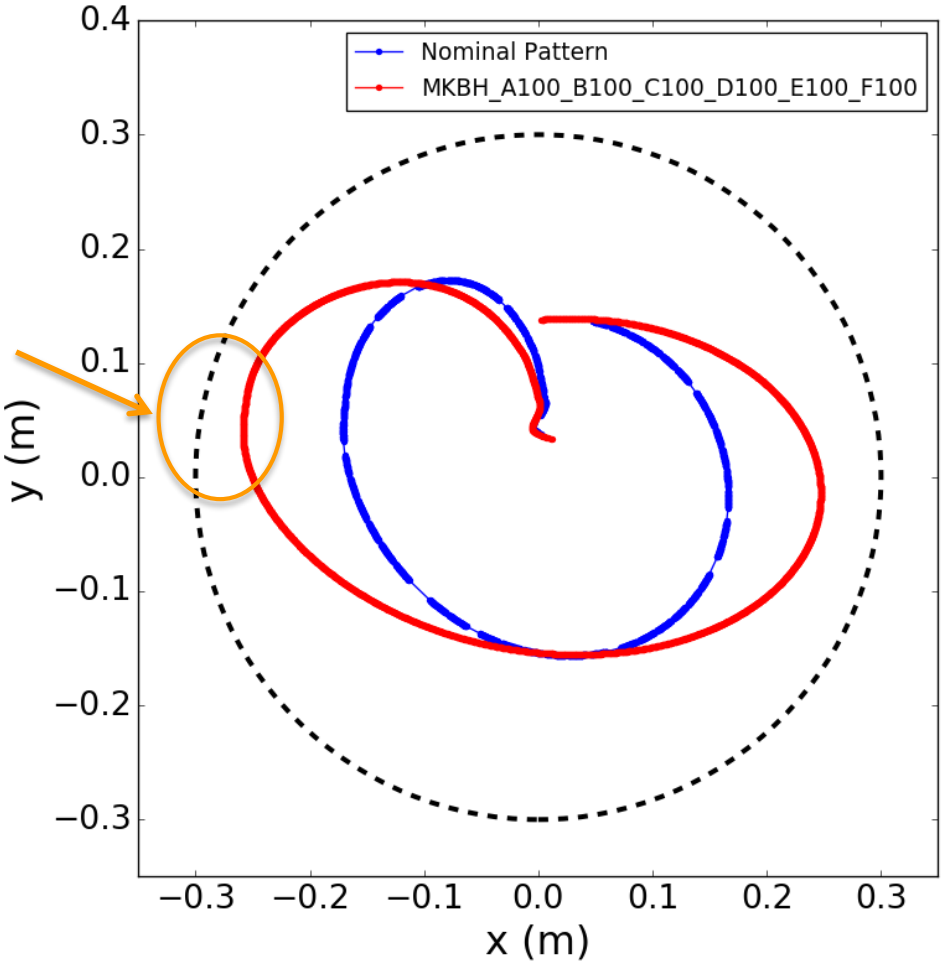
Increasing the dilution strength



- MKBH kick scaled by 140%
- 6/6 MKBH

Sweep Pattern with 6 MKBH

Dilution might be limited by energy-deposition due to secondary particles escaping the graphite core.



- MKBH kick scaled by 150%
- 6/6 MKBH
- This corresponds to the same individual MKBH kick as today
- FLUKA results will be presented by M. Frankl

Upgrade to 6 MKBH: Conclusion

- Installation of 2 additional MKBH looks promising, because it would…
  - 1) reduce failure sensitivity from 2/4 to 2/6 MKBH missing
  - 2) reduce failure probability (if operated at lower voltage)
  - 3) provide margin to increase horizontal dilution, which would reduce the peak energy deposition at the TDE → *See talk by M. Frankl*
- Studies (failure cases, apertures, integration) ongoing.

Dilution System – Challenges and Mitigations

- **High sensitivity on failures of MKBH**

  → Upgrade MKBH generators (LS2)

  → Install 2 additional MKBH (LS3)?

- **High temperatures in dump**

  → Install 2 additional MKBH (LS3) and increase total horizontal dilution?

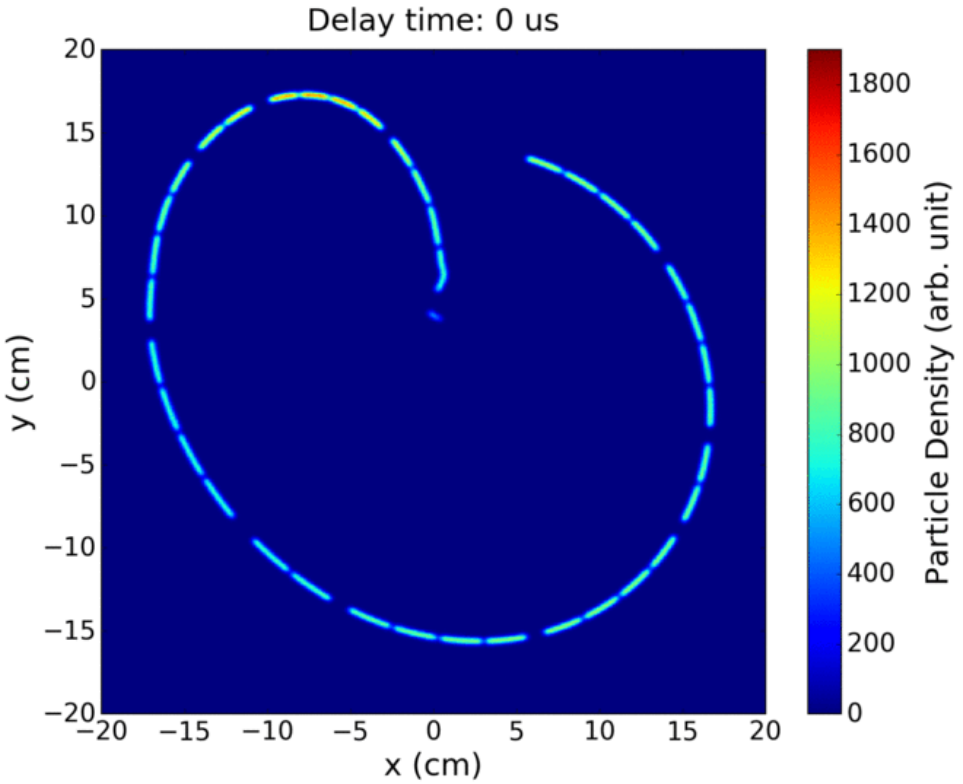
- **New failure mode (coupling) can lead to loss of >50% of dilution in one plane**

  → MKB retriggering in case of erratic firing?

MKB Coupling and Retriggering

- Short-term mitigation implemented during EYETS 2016/17.
- Possible long-term mitigation by immediate MKB retriggering in case of erratic firing.
- Assuming that an asynchronous beam dump should be avoided, this implies that the MKD are now fired with a certain time delay [0 µs… 89 µs] *after* the MKB, thus significantly changing the TDE pattern.
- Reliability studies ongoing. Earliest implementation in LS2.

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



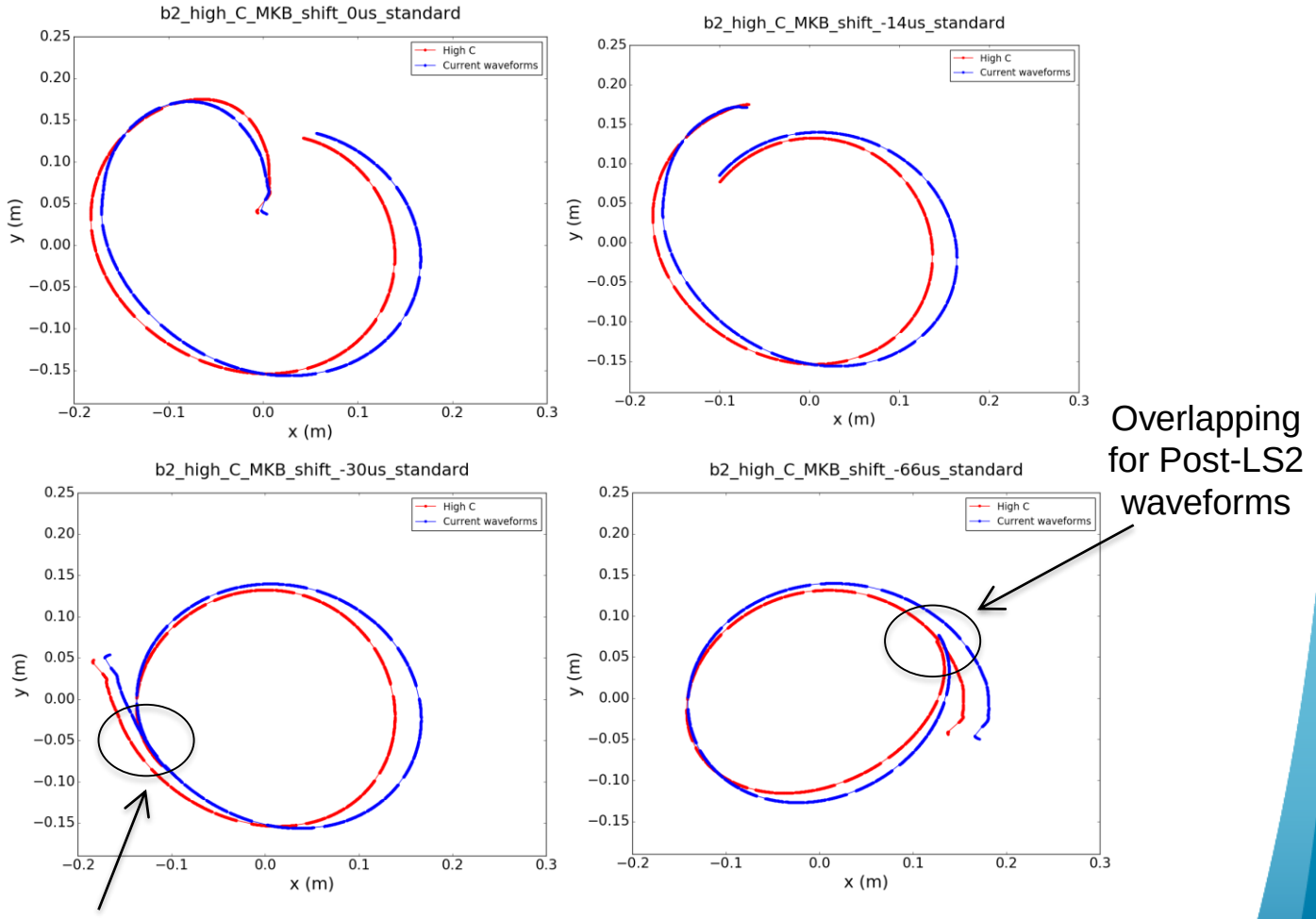
HL-STD, Run 2 waveforms

More details in: C. Wiesner et al., IPAC'16, WEPIK033

Retriggering of the Dilution Kickers (MKB)

- Higher damping of post-LS2 waveforms changes energy deposition for the retrigger scenario
- For FLUKA results → *see talk by M. Frankl*
- For Stress analysis → *see talk by T. Polzin*

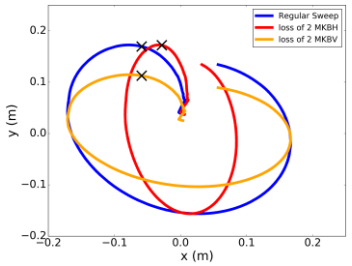
Retrigger sweep patterns for Run 2 and Post-LS2 waveforms

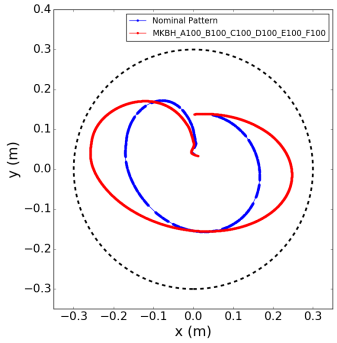


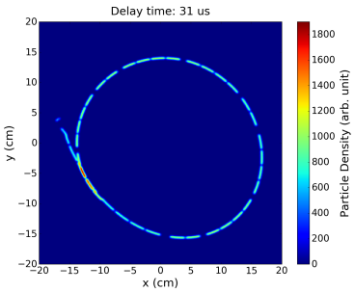
Note: MKD&MKB gain factor implemented for new simulations.

Conclusions and HL-LHC Upgrade Strategy

- **High sensitivity on failures of MKBH**
  → Upgrade MKBH generators (LS2)
  Thus, reduced failure probability
  → Install 2 additional MKBH (LS3)?
  Thus, reduced failure sensitivity (and probability)
- **High temperatures in dump**
  → Install 2 additional MKBH (LS3) and increase total horizontal dilution?
  Thus, lower peak energy-deposition at TDE
  → If required, upgrade of dump windows/core
  Thus, higher robustness and stress resistance
- **New failure mode (coupling) can lead to loss of >50% of dilution in one plane**
  → MKB retriggering in case of erratic firing?
  Thus, no risk of phase opposition between MKBs

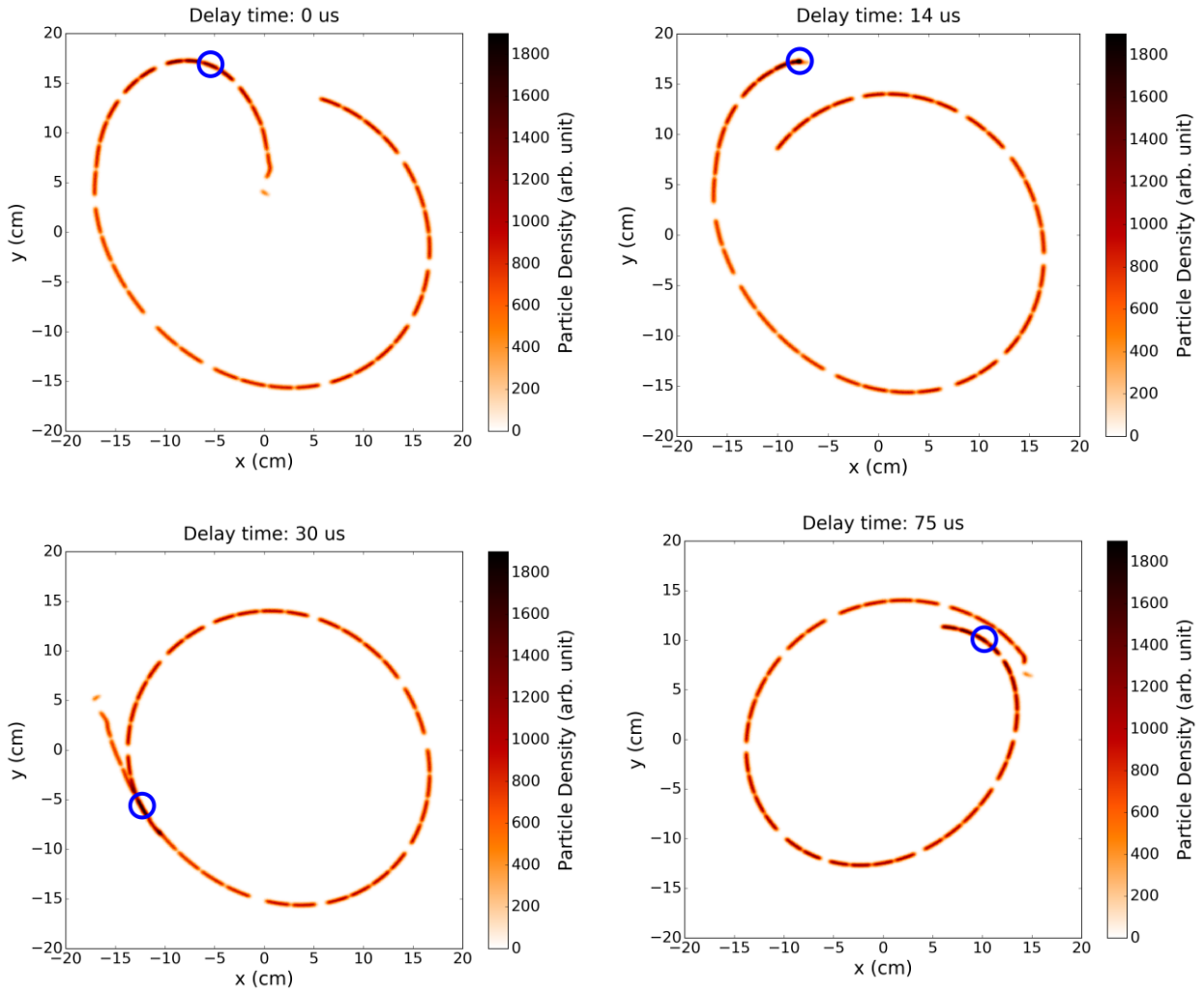






Thank you for your attention

Retriggering of the Dilution Kickers (MKB)



HL-STD, Run 2 waveforms