MKB re-triggering: motivation, technical implementation, reliability analysis and expected energy deposition on dump block as function of triggering delay between MKBs and MKDs

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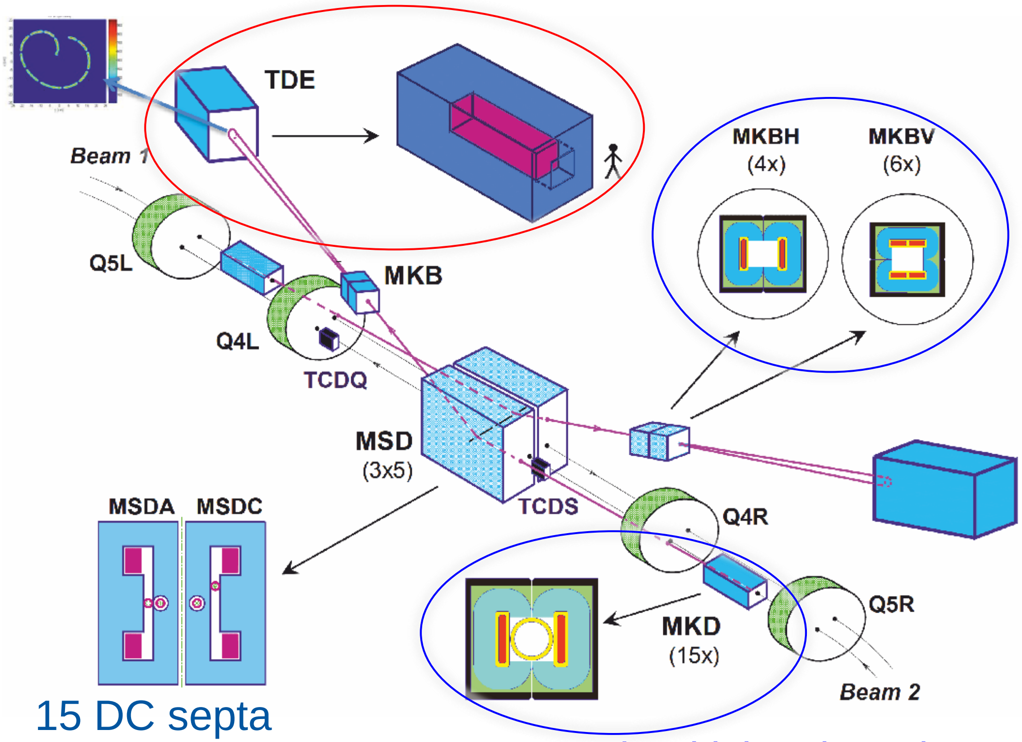
With input from M. Frankl, T. Polzin

Outline

1) Introduction: LHC dilution system and traditional failure cases
2) The challenge: new common cause failure (coupling)
3) The (possible) mitigation: retrigger system for the MKBs
    1) Two implementations: more asynch. dumps vs. more complexity
    2) Reliability analysis
    3) Energy deposition in the dump
4) Conclusions and summary

LHC Dilution System

Beam dump (TDE)



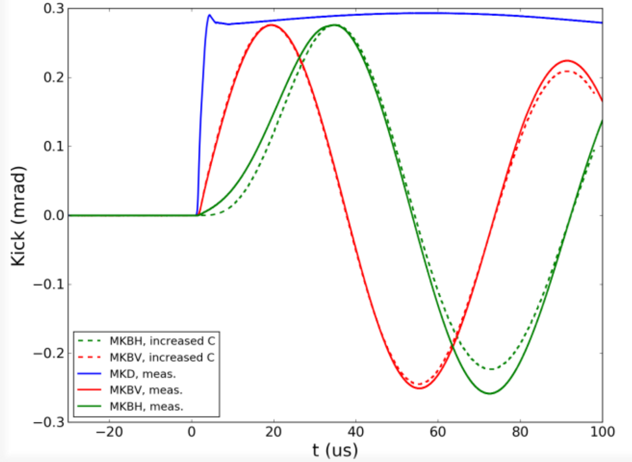
15 DC septa magnets (MSD)

15 extraction kicker (MKD)

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

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

MKD, MKBH and MKBV waveforms



Failure Cases: Flash-over

1) Loss of dilution of **2 MKB (located in one vacuum tank) due to flash-over** during dump execution

Peak temperature in dump core

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

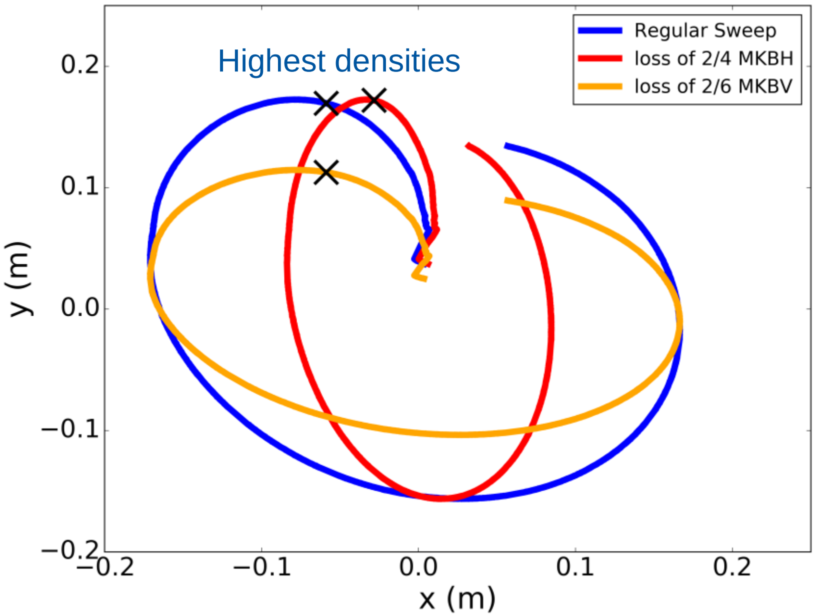
1000°C for LHC STD beams, 1.3e11 p+

1400°C for LHC STD beams, 1.3e11 p+

M. Frankl

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

Beam sweep patterns at dump



Not clear if local damage in dump core could occur even for a regular dump of a HL-STD beam due to thermo-mechanical stresses. For final conclusion, stress analyses based on the detailed characterization of the dump-material properties are required. Results expected for beginning of 2019.

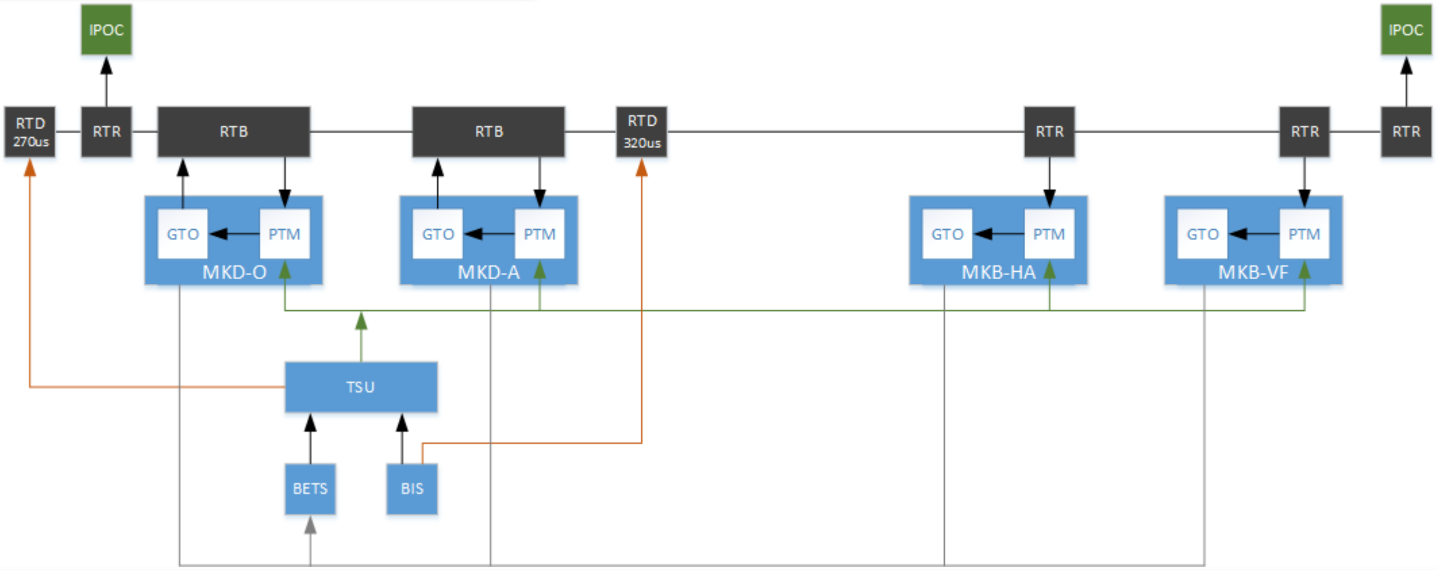
Worst-case failure (to be accepted for any upgrade): **2 MKBH missing**

Failure Cases: Erratic Firing

2) **Erratic pre-firing of one MKB**

- Occurred 4x in 2015 and 2x in 2016, 0x in 2017 during beam operation

Erratic firing of MKB
→ Voltage drop is detected by the **BETS**
→ **Synchronous dump** is executed.
Total reaction time can vary between 207 us and 1300 us
→ **Risk of antiphase** between pre-firing and remaining MKBs



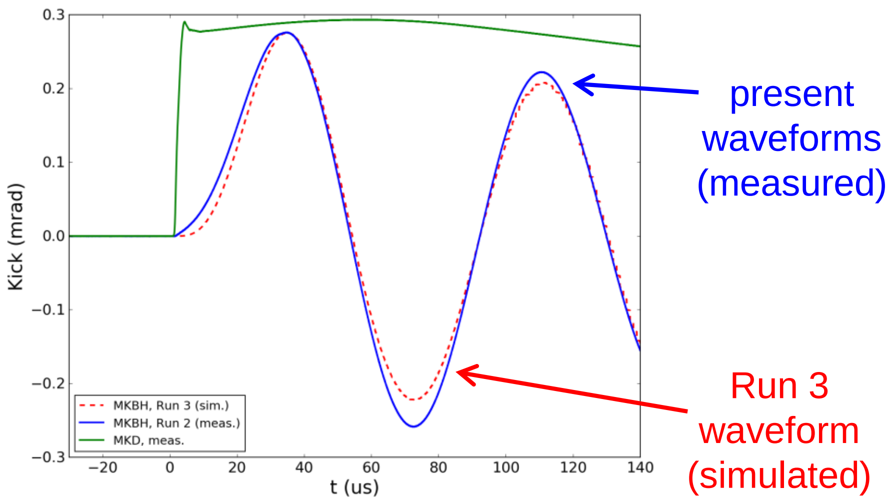
N. Magnin,
N. Voumard

Failure Cases: Erratic Firing

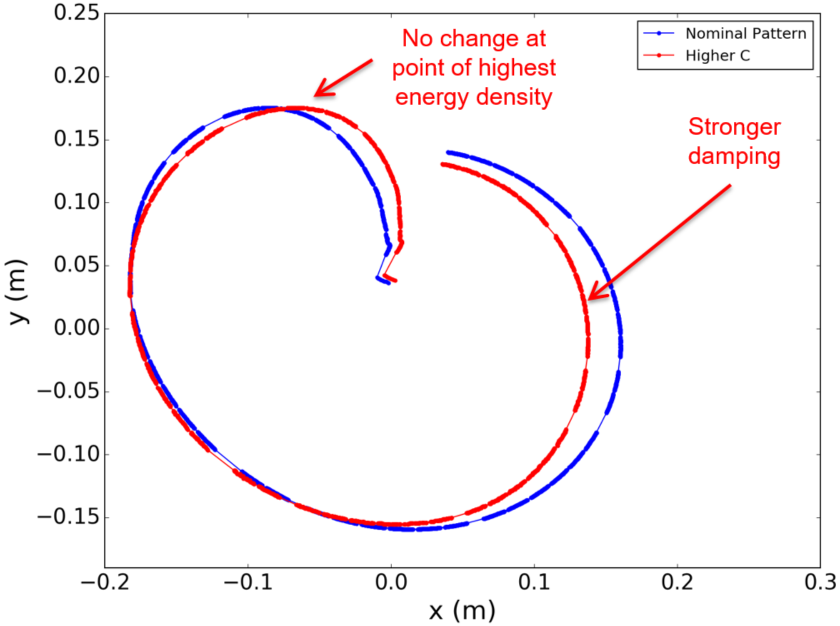
2) **Erratic pre-firing of one MKB**

- MKBH generators will be upgraded in LS2 to operate at ~10% lower voltage with reduced probability of erratic pre-firing. → Side-effect: higher damping of waveforms

MKBH waveforms



Nominal sweep pattern at the dump for Run 2 and Run 3 waveforms



Run 3 waveforms by V. Senaj

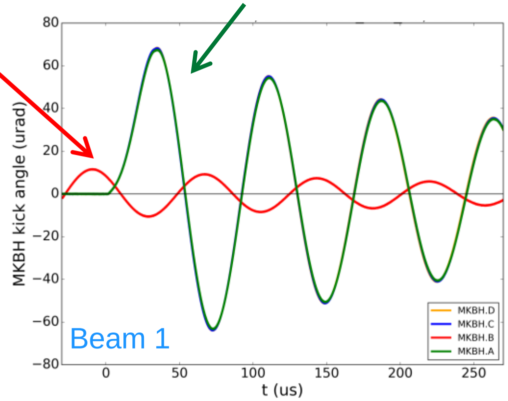
Failure Cases: Erratic Firing

2) **Erratic pre-firing of one MKB**
Worst case: Pre-firing MKB in antiphase to remaining MKBs, decreasing the horizontal dilution by
< 37% (≈ 1.5 MKBH) for Run 2 and
< 31% (≈ 1.25 MKBH) for Run 3
waveforms.

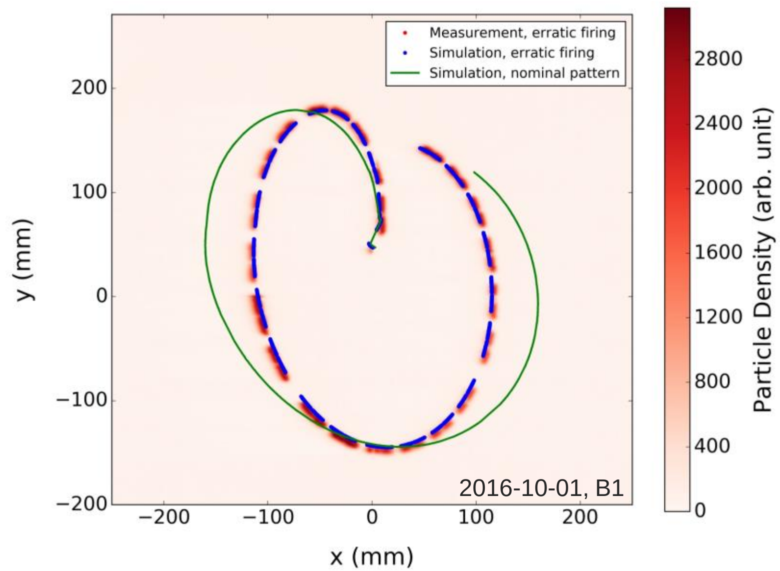
Measured MKB waveforms, 01.10.2016

erratically pre-firing MKBH

regularly firing MKBHs



Measurement and simulation of erratically firing MKBH, 01.10.2016



→ Horizontal dilution reduced by ~28.5% (= 1.14 missing MKBH)

Conclusion:
Antiphase not critical for *single* erratic, but potentially critical for *multi-erratic*.

The Challenge:
New Common-Cause Failure

New Common-Cause Failure Case

3) **Common-cause failure mode** identified: Pre-firing of more than 1 MKB due to

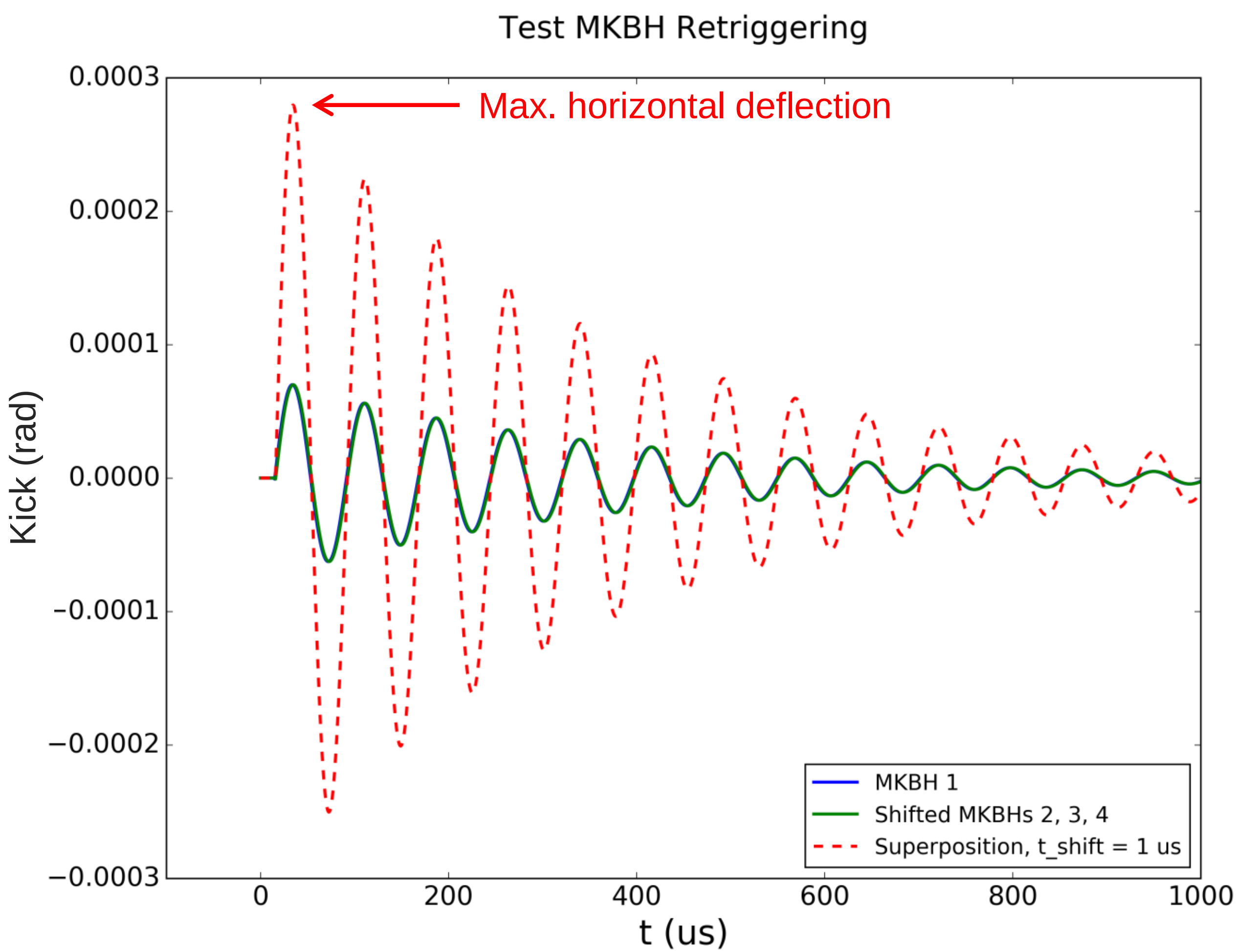
- parasitic electromagnetic coupling between generators (observed during tests in 2016),
- noise (above the trigger threshold) on the retrigger line.

Can potentially lead to loss of more than 50% of dilution in one plane due to antiphase between the MKBs.

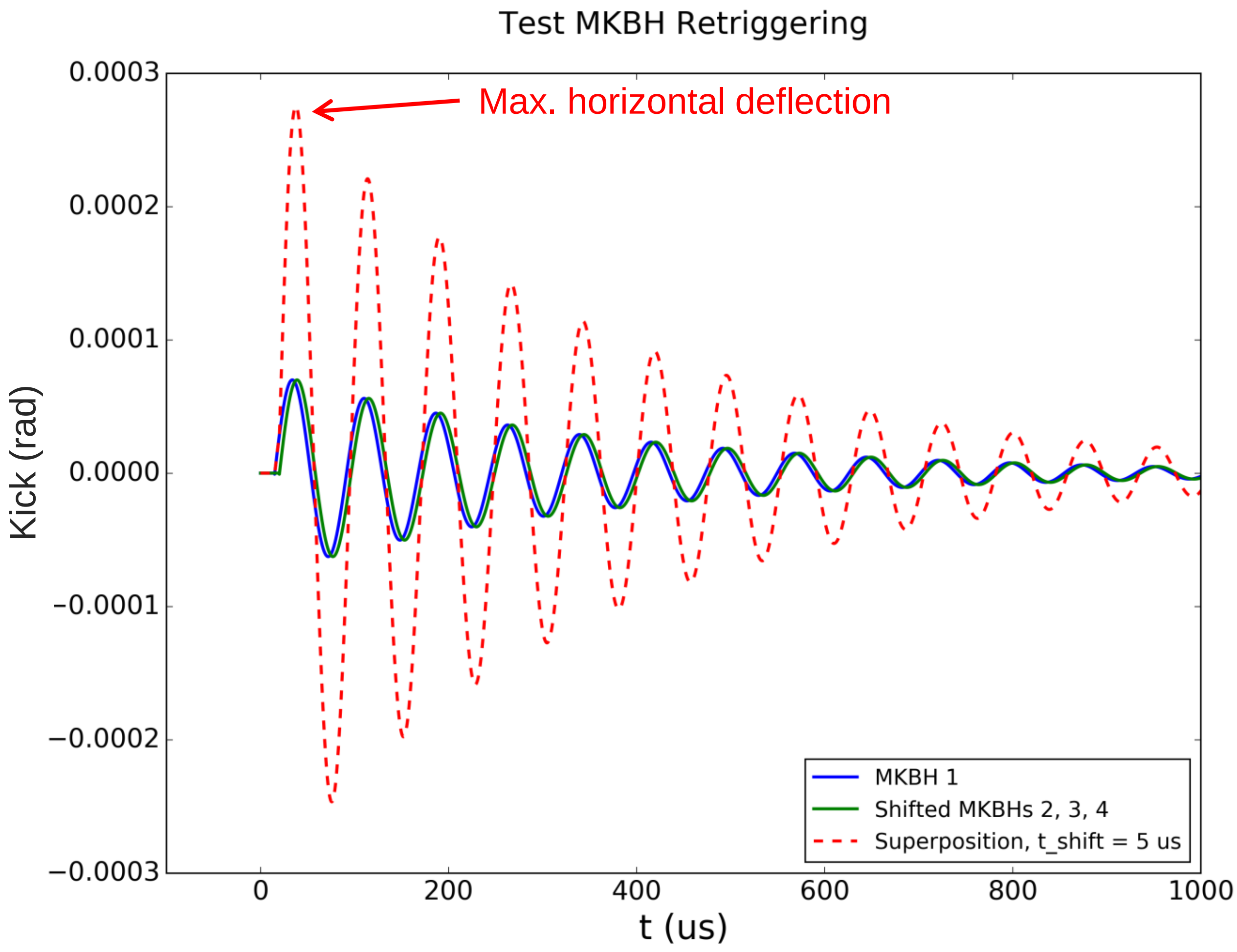
- Short-term mitigation (common mode filtering and insulation of retrigger boxes) implemented during EYETS 2016/17
- However, not clear if immunity margin is sufficient for future operation at 7 TeV
- Presently, coupling can not be excluded for Run 3

MKB Coupling: Antiphase

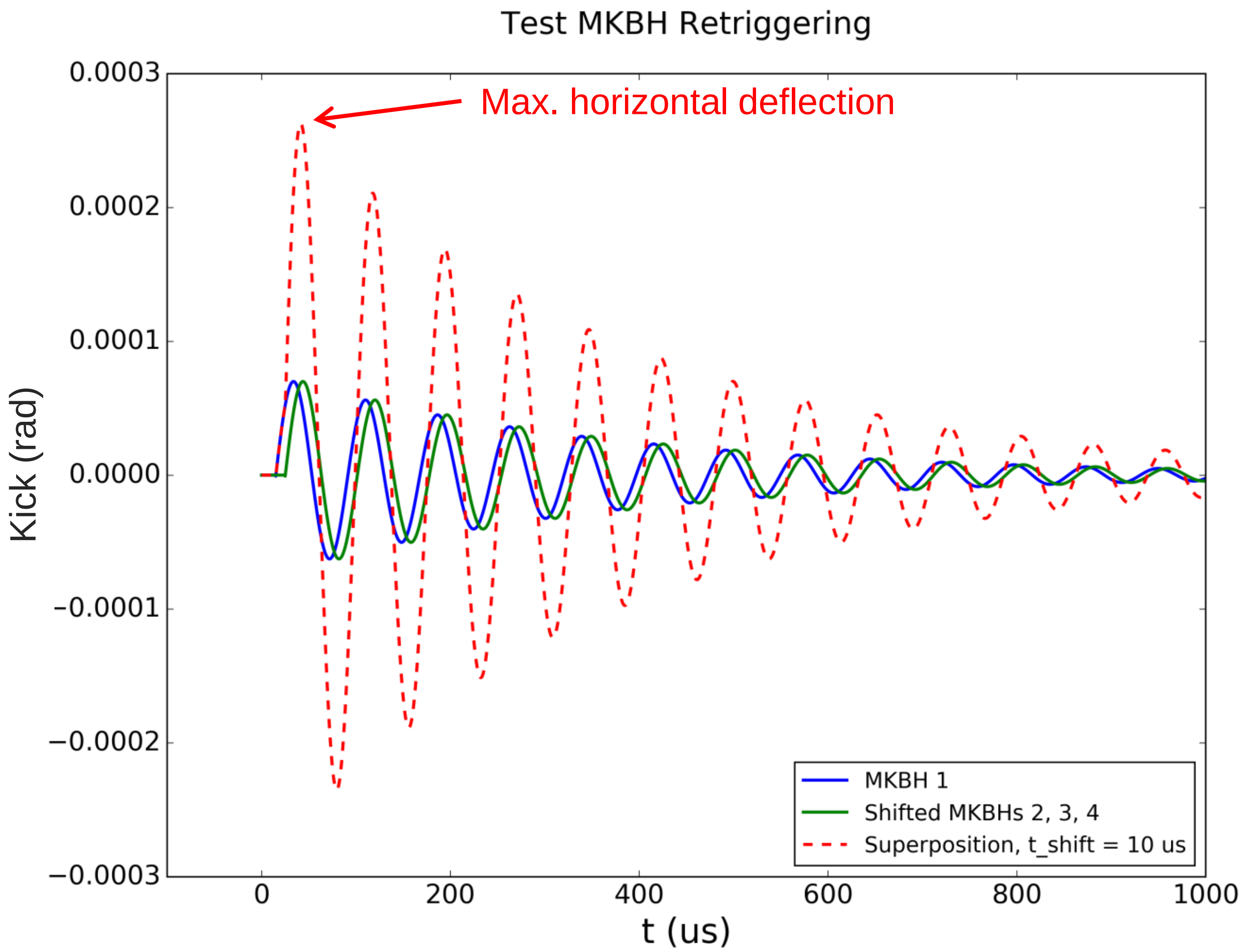
Assumptions:
No phase shift between MKBH 2,3 and 4



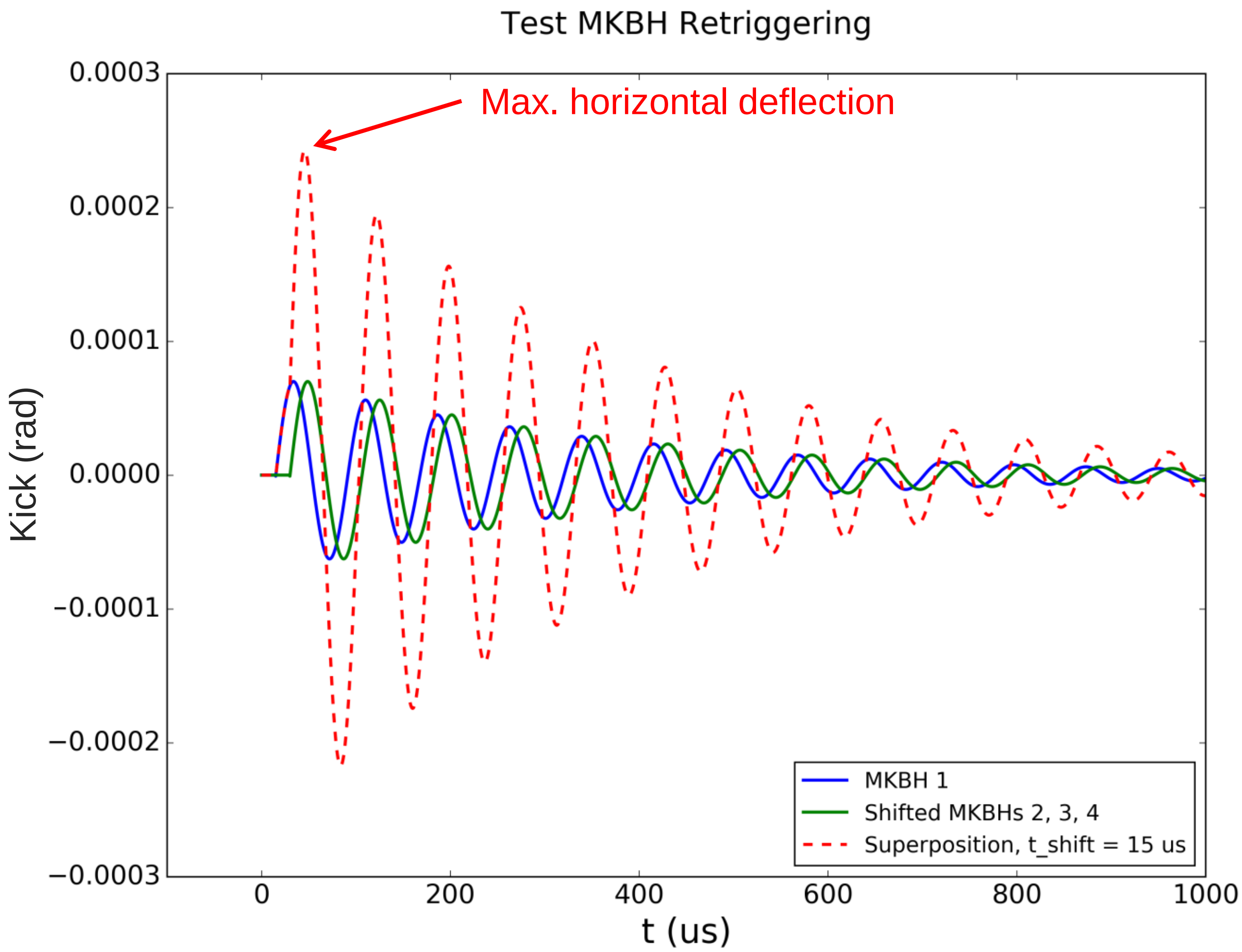
MKB Coupling: Antiphase



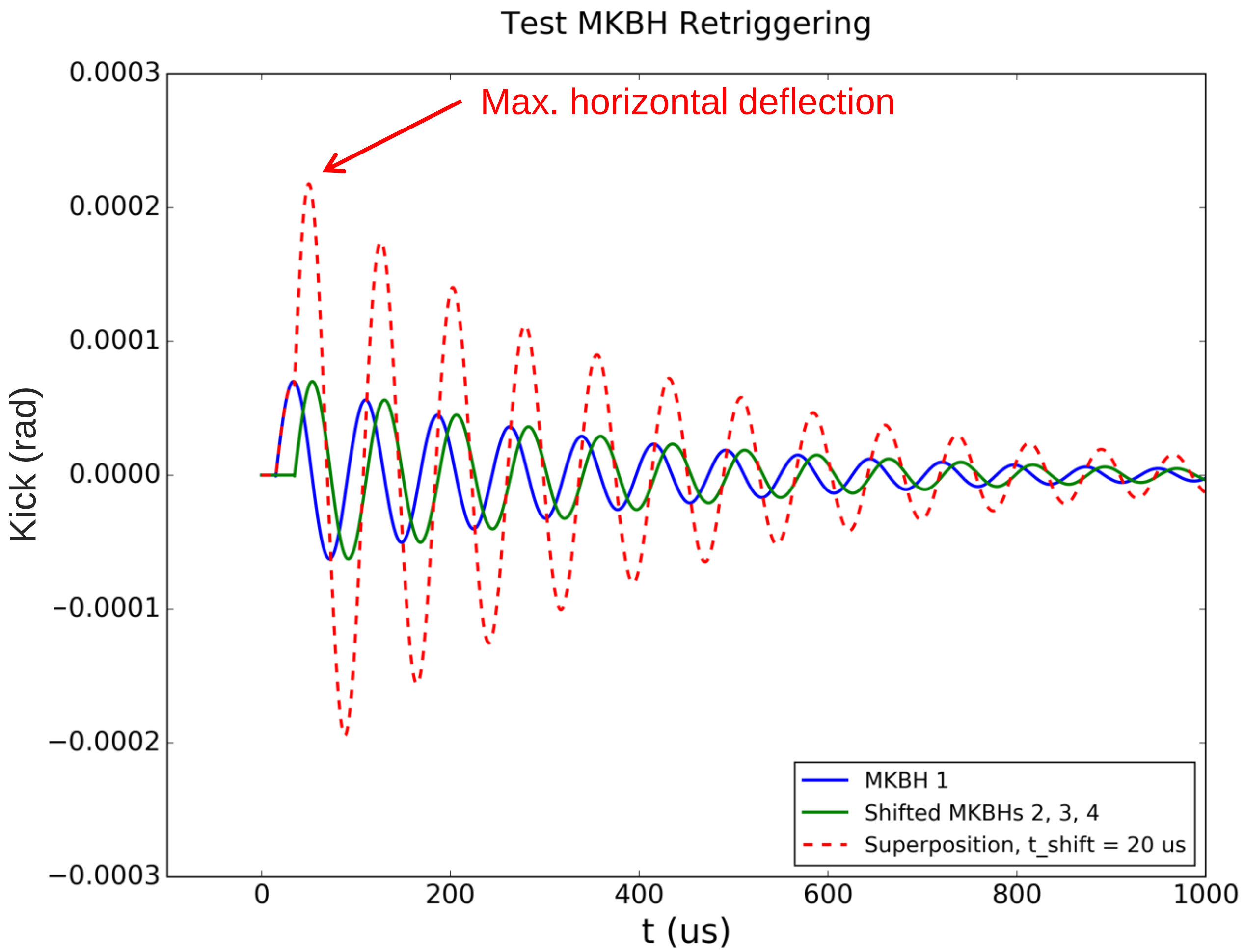
MKB Coupling: Antiphase



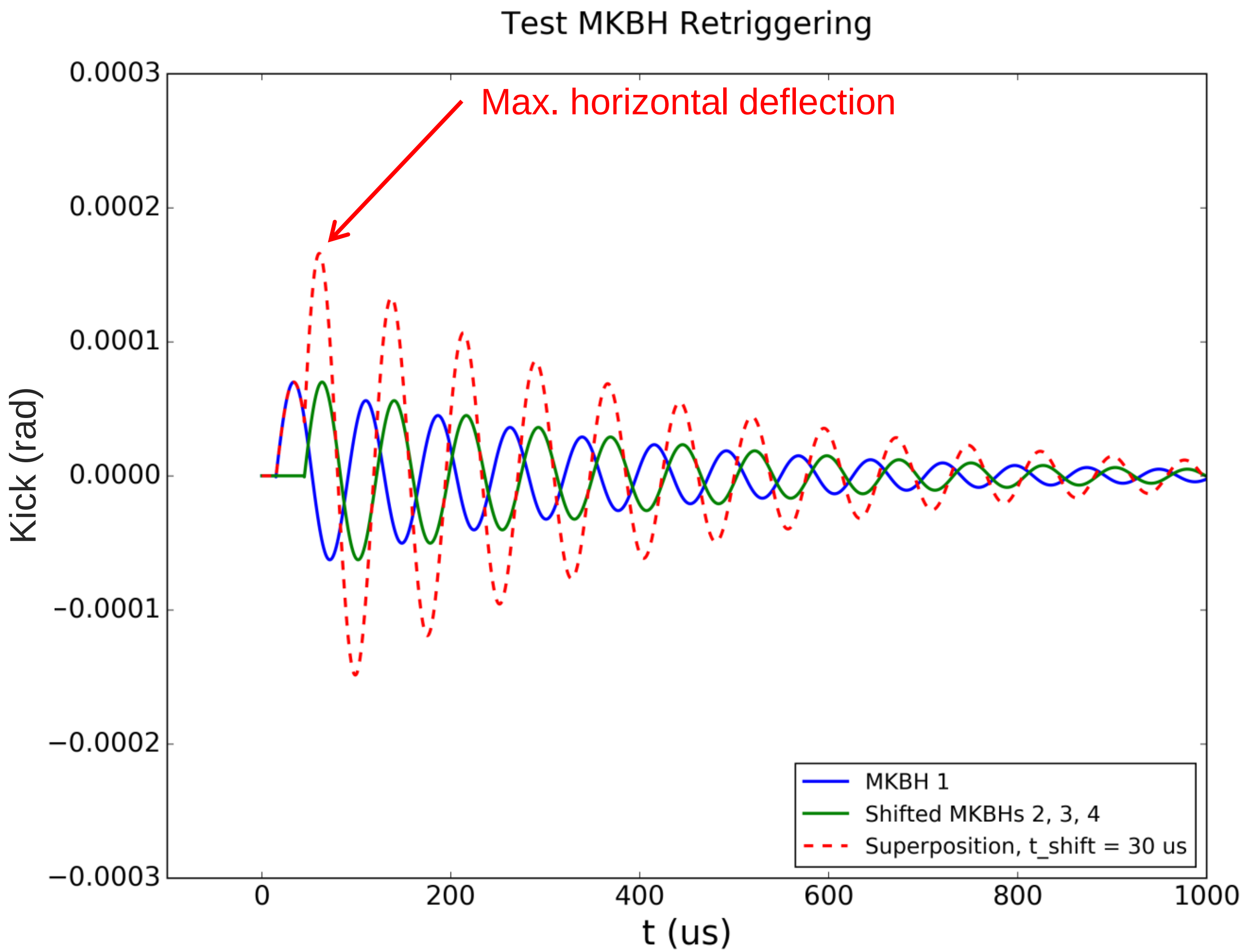
MKB Coupling: Antiphase



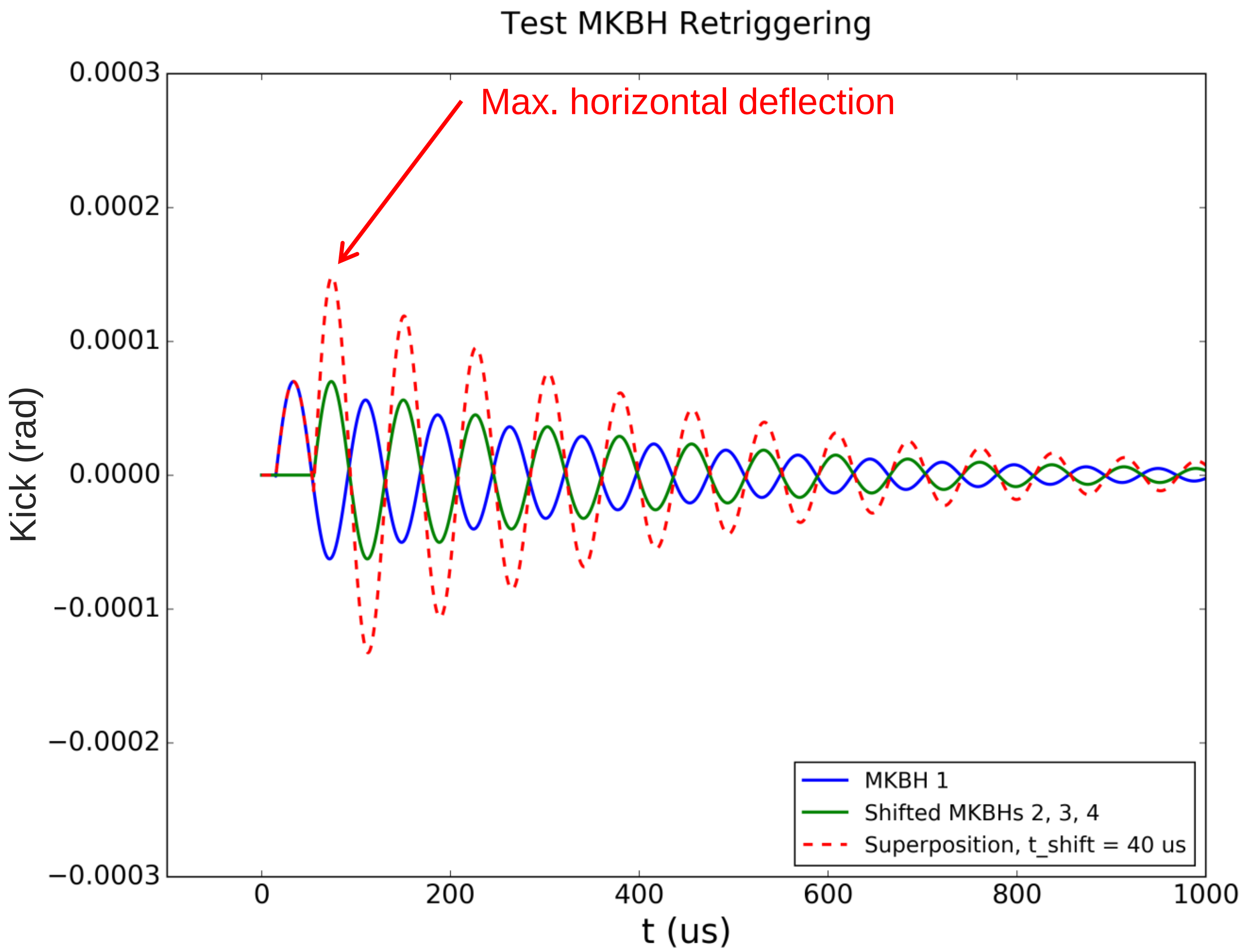
MKB Coupling: Antiphase



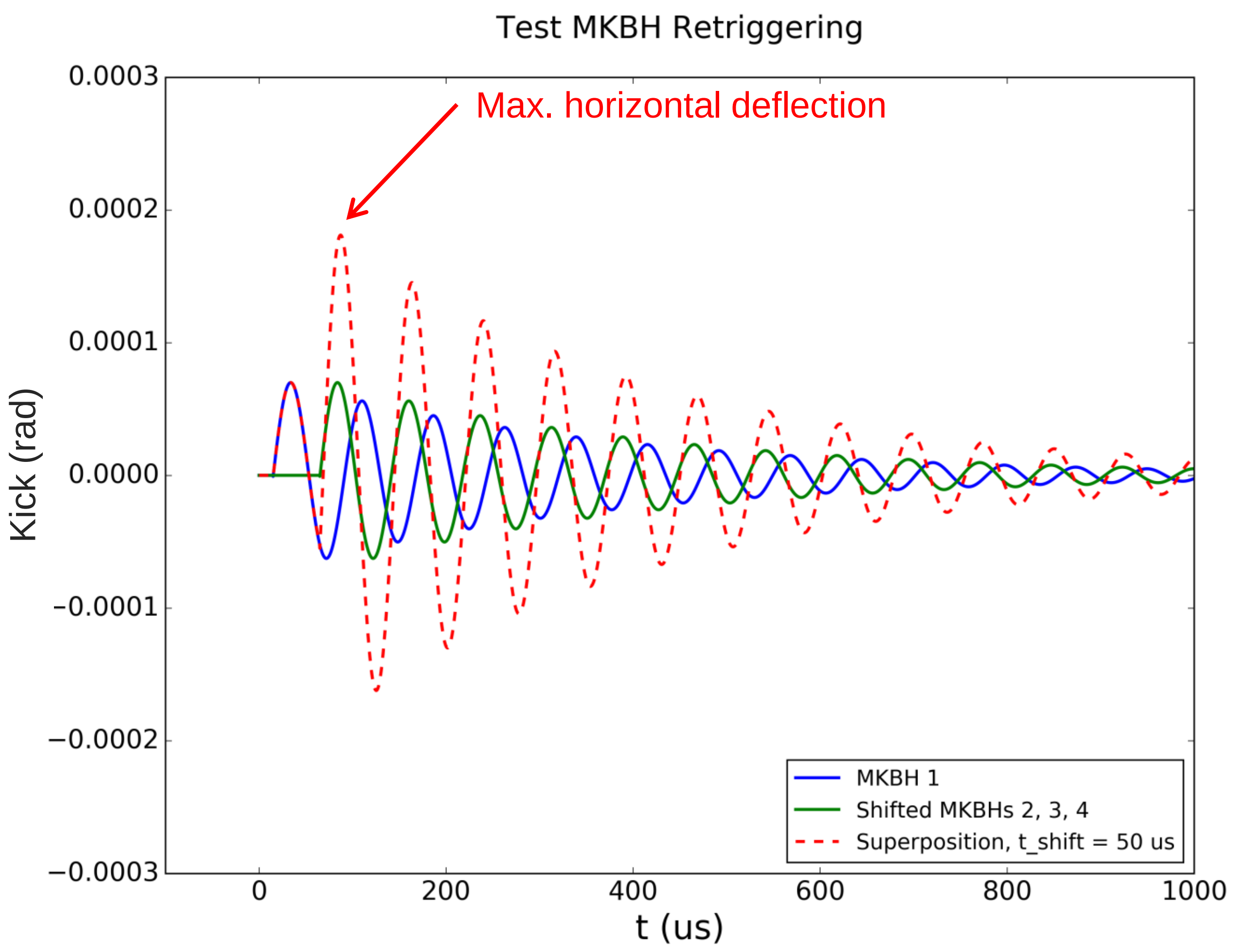
MKB Coupling: Antiphase



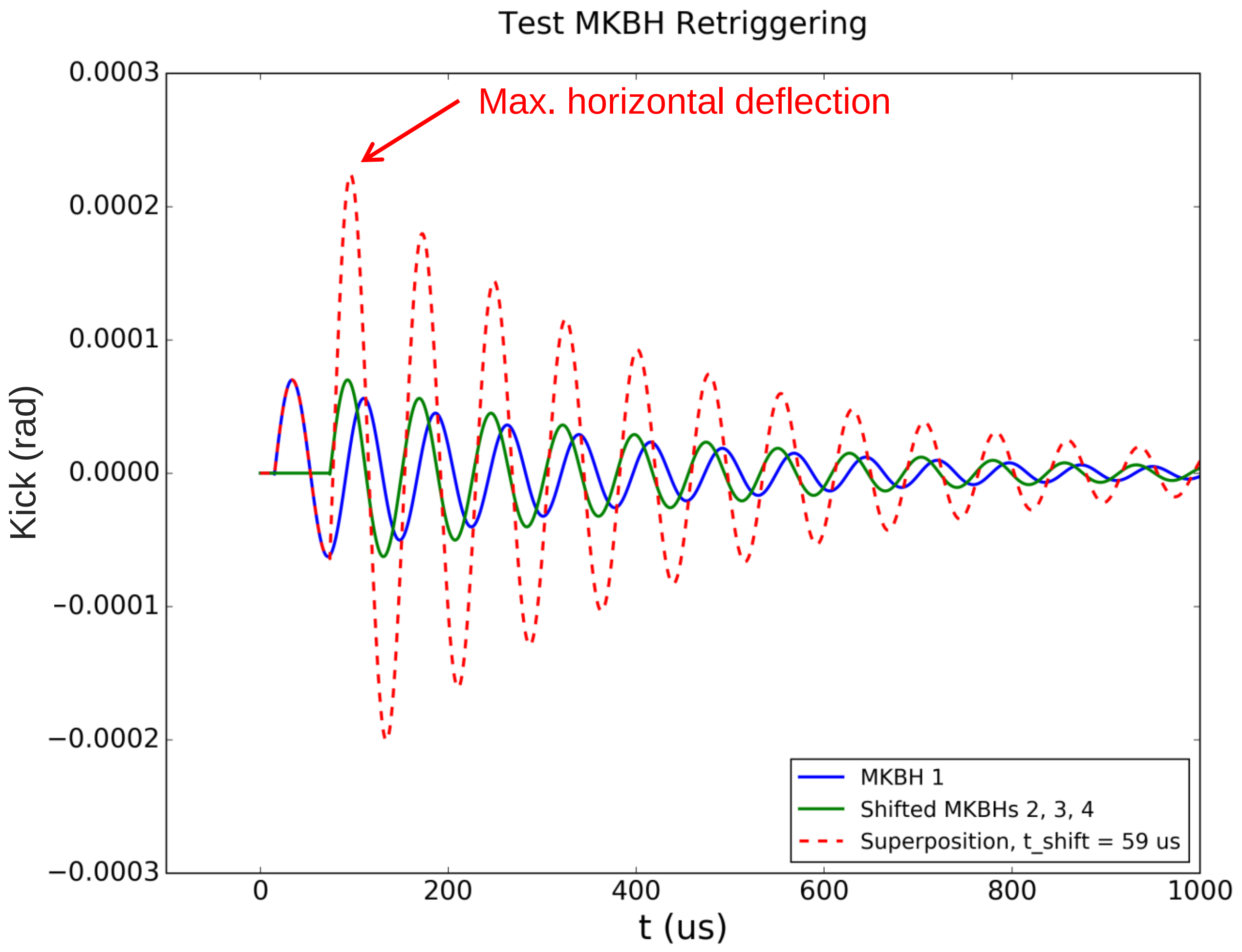
MKB Coupling: Antiphase



MKB Coupling: Antiphase



MKB Coupling: Antiphase

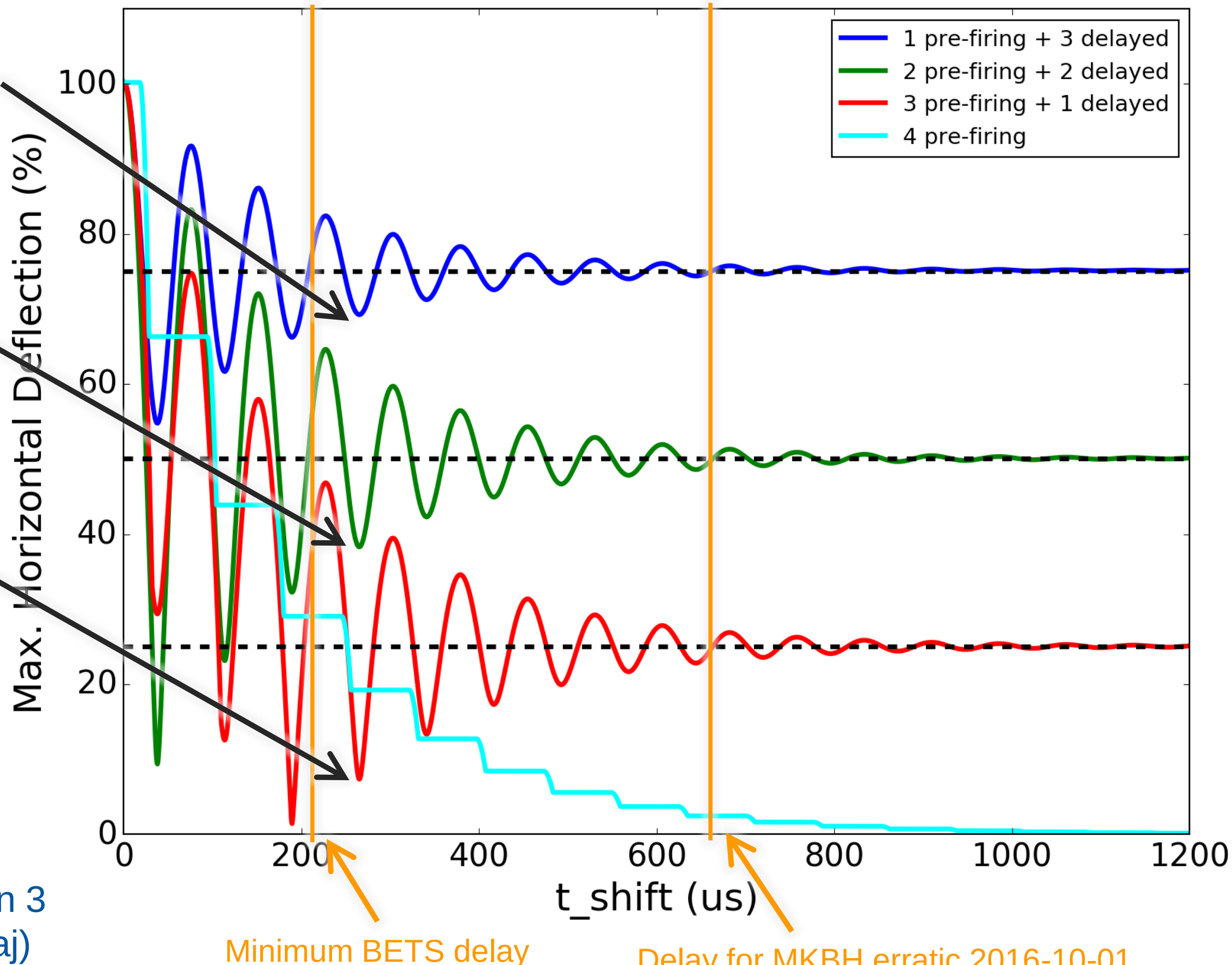


MKB Coupling: Reduced Dilution

Single erratic
Worst case: 69%

Double erratic
Worst case: 38%

Triple erratic
Worst case: 7%



For t→∞
α_{max} → 75%
(loss of 1 MKBH)

For t→∞
α_{max} → 50%
(loss of 2 MKBH)

For t→∞
α_{max} → 25%
(loss of 3 MKBH)

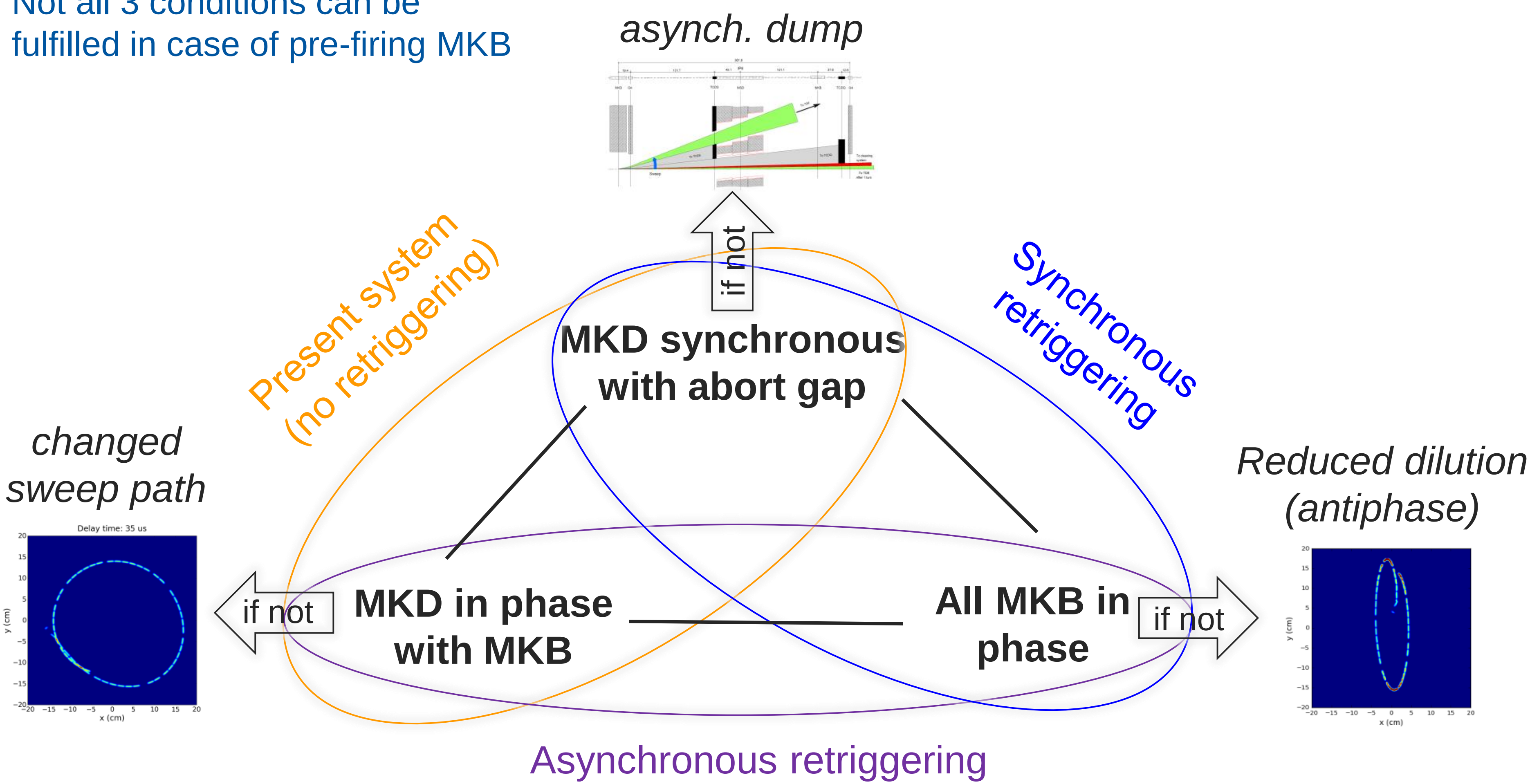
For t→∞
α_{max} → 0%
(loss of 4 MKBH)

4 MKBH,
using simulated Run 3
waveforms (V. Senaj)

The Solution?
MKB Retrigger System

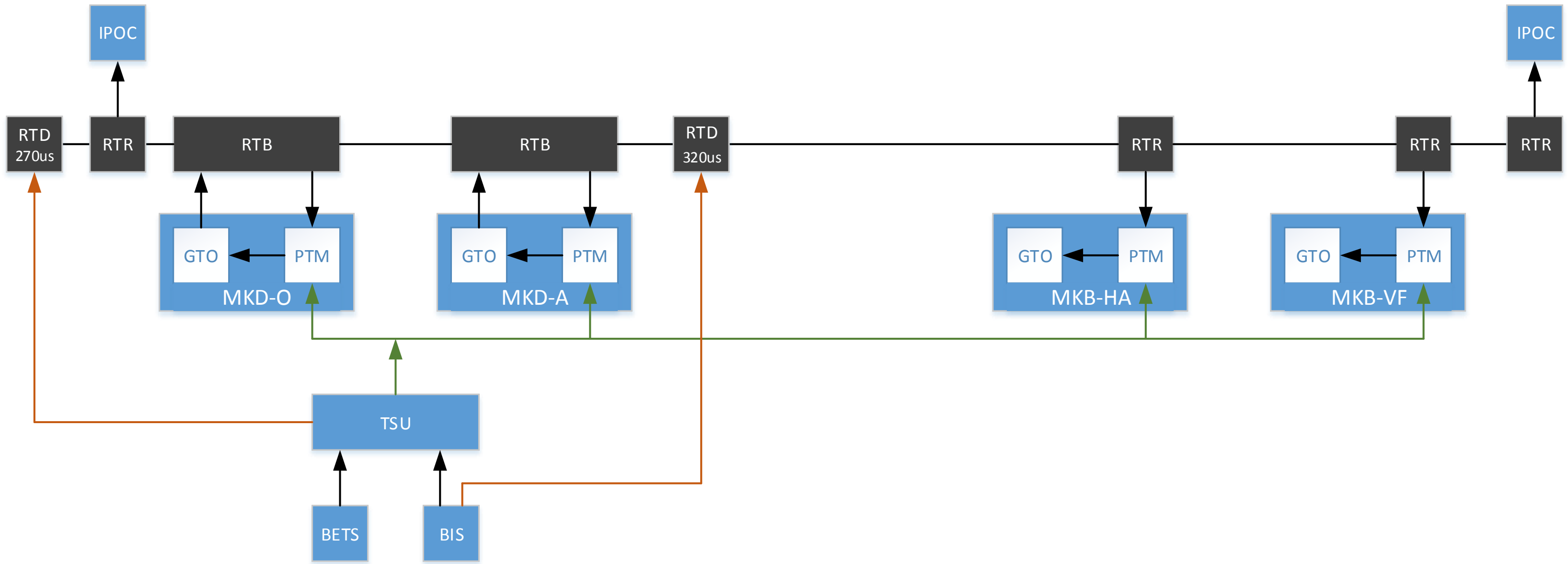
LBDS timing triangle

Not all 3 conditions can be fulfilled in case of pre-firing MKB



Present System

No MKB retriggering



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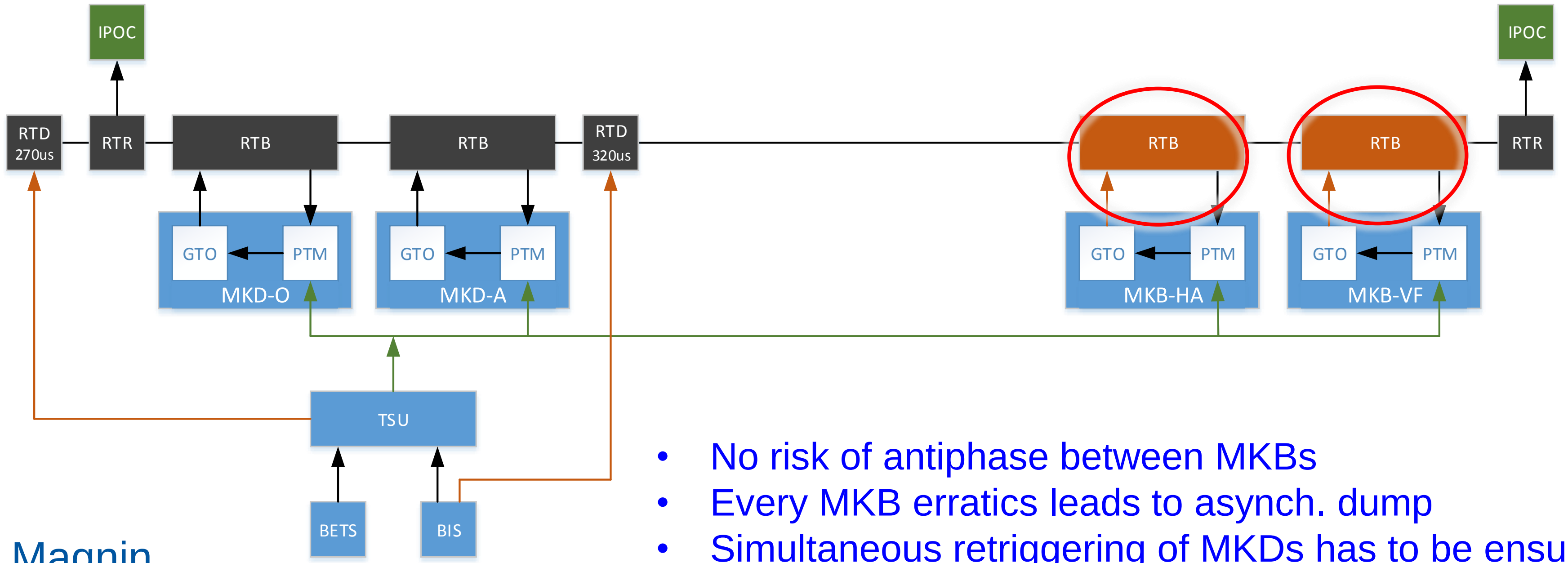
Asynchronous Retriggering (Option 1)

- MKB erratic → retrigger all MKB → execute asynchronous dump
- Direct connection of MKB to retrigger line

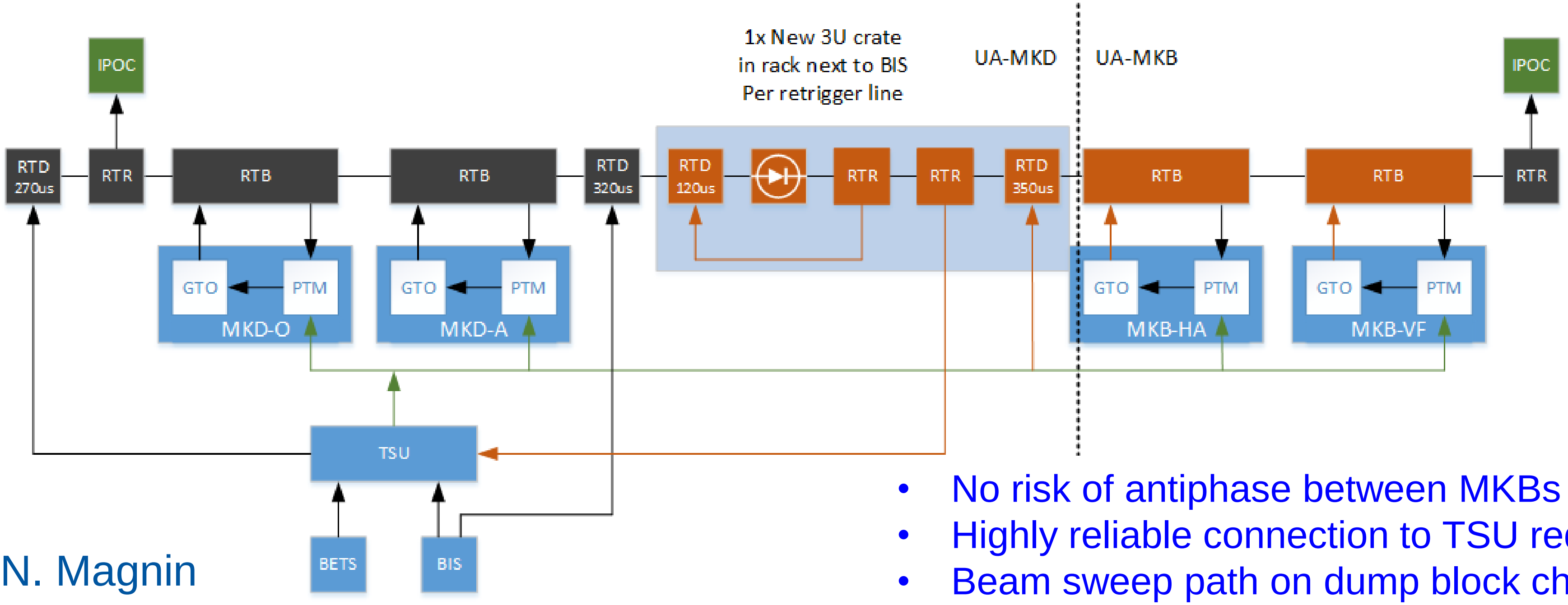


- No risk of antiphase between MKBs
- Every MKB erratics leads to asynch. dump
- Simultaneous retriggering of MKDs has to be ensured

N. Magnin

Synchronous Retriggering (Option 2)

- MKB erratic → retrigger all MKB → execute synchronous dump
- Direct connection of MKB to retrigger line
- Connection to TSU
  - Using 'External Trigger' (Inject & Dump input). No change in TSU hard-/firmware required
- Decoupling box (diode) on retrigger line to avoid asynch. dump
- Retrigger delays (RTD) to be used for XPOC analysis
- Option 2b: Add a delayed asynchronous path (after 120us delay)



- No risk of antiphase between MKBs
- Highly reliable connection to TSU required
- Beam sweep path on dump block changes

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Reliability Studies

MKB Retrigger Strategy

Run 3 waveforms
4 MKBH

	Current System – no coupling	Current System - coupling	Asynch. retriggering	Synch. retriggering	Synch. retriggering + delayed asynch. dump
Amplitude of horizontal waveform	69%...82% (single erratic and BETS delay > 220us)	38%...65% (double erratic) 7%...60% (triple erratic)	~100% → Asynch. losses	~100% but change of TDE pattern	~100% but change of TDE pattern
How can "loss of dilution" failure occur?	Loss of most dilution in one plane only if 2 uncorrelated MKBH erratics occur in the same time interval, e.g. 200 us	Loss of most dilution in one plane, if antiphase.	As today	Loss of most dilution in both planes • **if TSU chain fails in case of MKB erratic** or • both diodes (A/B) fail in open circuit in case of MKD erratic	Loss of most dilution in both planes • if TSU chain and TDU chain fail in case of MKB erratic or • **both diodes (A/B) fail in open circuit in case of MKD erratic**
Failure mode	independent	**common cause**	-	independent	independent

Reliability Analysis

	Current System – no coupling	Current System - coupling	Asynch. retriggering	Synch. retriggering	Synch. retriggering + delayed asynch. dump
"Loss of dilution"?	Only for double failure	If antiphase	As today	Failure of **TSU chain** or failure of both diodes	Failure of TSU chain and TDU chain or **failure of both diodes**
MTTF for "loss of dilution" case	For double erratic: 2.5e6 y; For double MKBH erratic with antiphase: 3.8e7 y	Difficult to quantify. For 1 multi-erratic/100 erratics: 25 y For 1 multi-erratic/1e4 erratics: 2500 y	As today	~6.3e5 years	~3e12 years
Additional asynch. dumps	0	0	1 to 4 (every MKB erratic)	8e-6 per beam and year	0.001 per beam and year
Additional synch. dumps	0	0	0	0.01 per beam and year	0.013 per beam and year

Conclusion: For preferred solution, calculated probability of "no dilution" failure is negligible and the expected increase in asynch. dumps per year is not relevant.

Reliability analysis: E. Renner

Energy Deposition

Beam Sweep Patterns

In case of an MKB erratic and synchronous retriggering, the **MKDs are now fired with a certain time delay *after* the MKBs:**

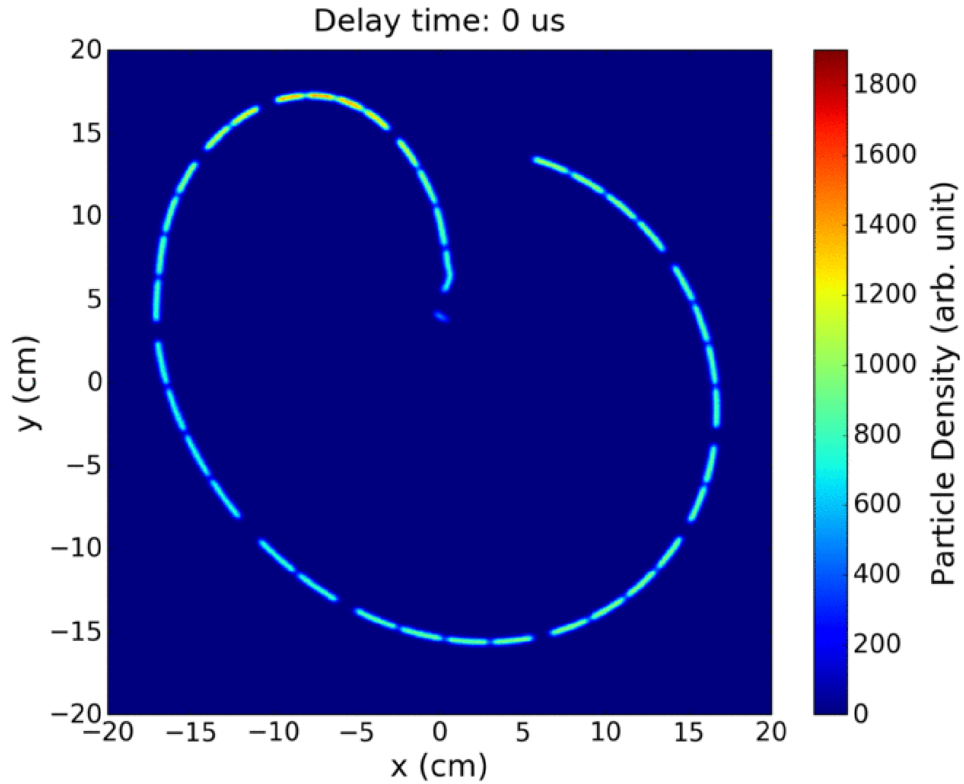
$$t_{\text{delay}} = t_{\text{react}} + \Delta t_{\text{AG}}$$

t_{react}: < 6 us $\quad$ Δt_{AG}: 0..89 us

→ beam sweep path depends on the position of the abort gap

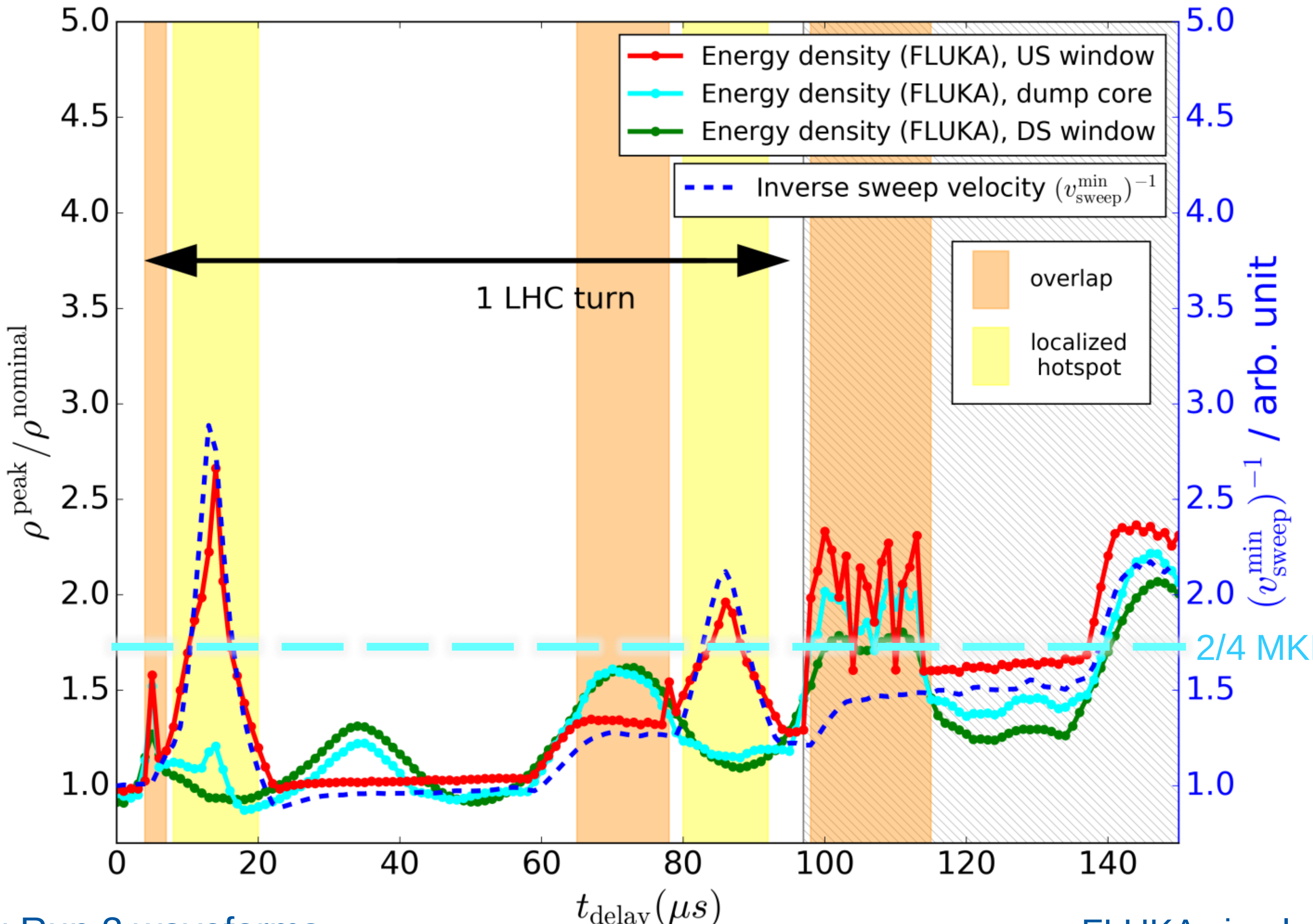
Energy deposition and thermo-mechanical stresses in the dump core, and the upstream (US) and downstream (DS) window have to be studied.

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



HL-STD, **Run 2** waveforms

Energy Deposition

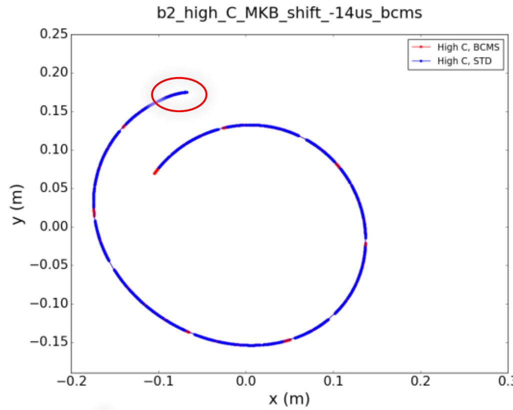


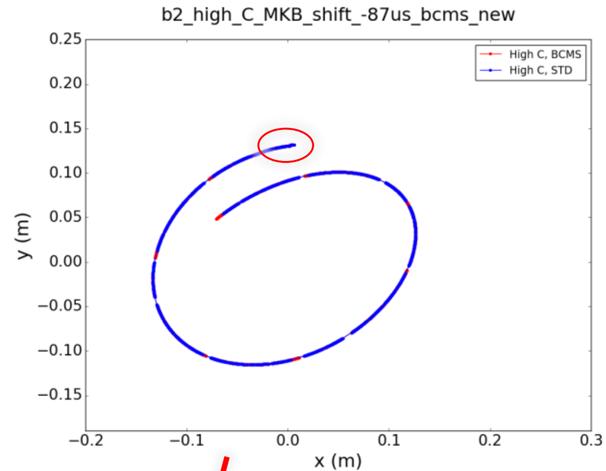
Simulated using Run 3 waveforms

FLUKA simulations: M. Frankl

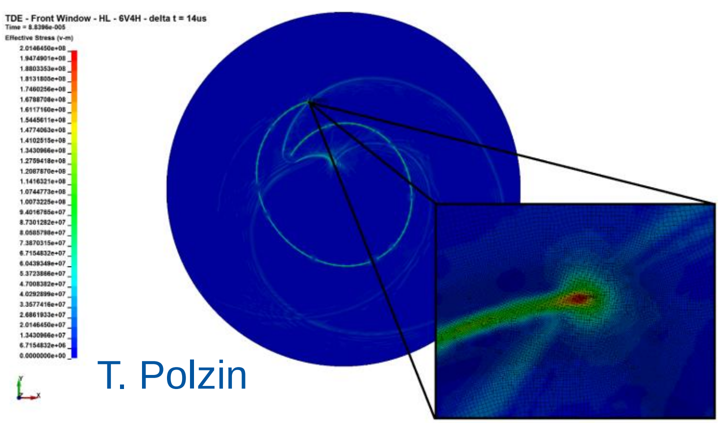
Energy Deposition

- Localized hotspot due to MKD overshoot reducing the MKBH sweep velocity
- Most relevant for US window





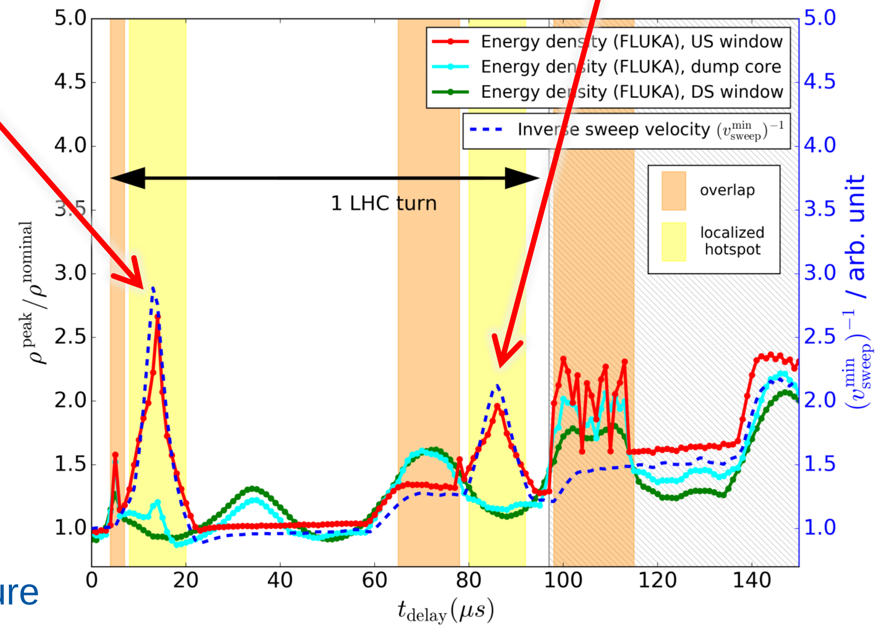
Thermo-mechanical stresses, US window



T. Polzin

$$S_y = \frac{240\ \text{MPa}}{200\ \text{MPa}} = 1.19$$

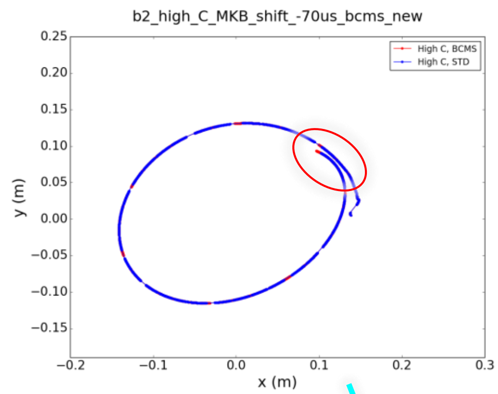
Lower stresses than for failure case of 2 MKBH missing

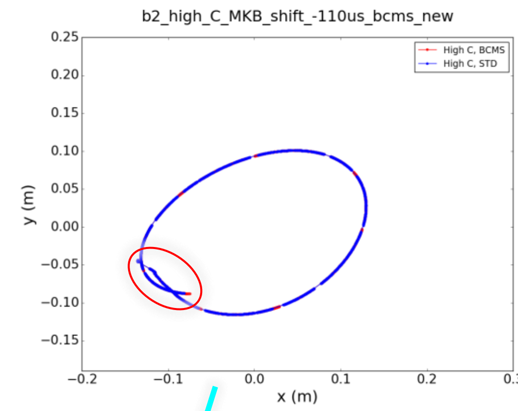


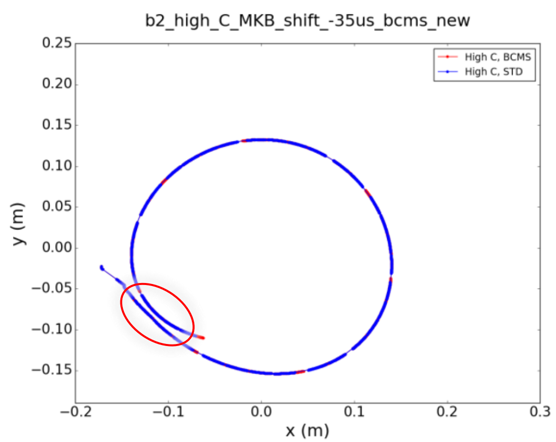
FLUKA simulations: M. Frankl

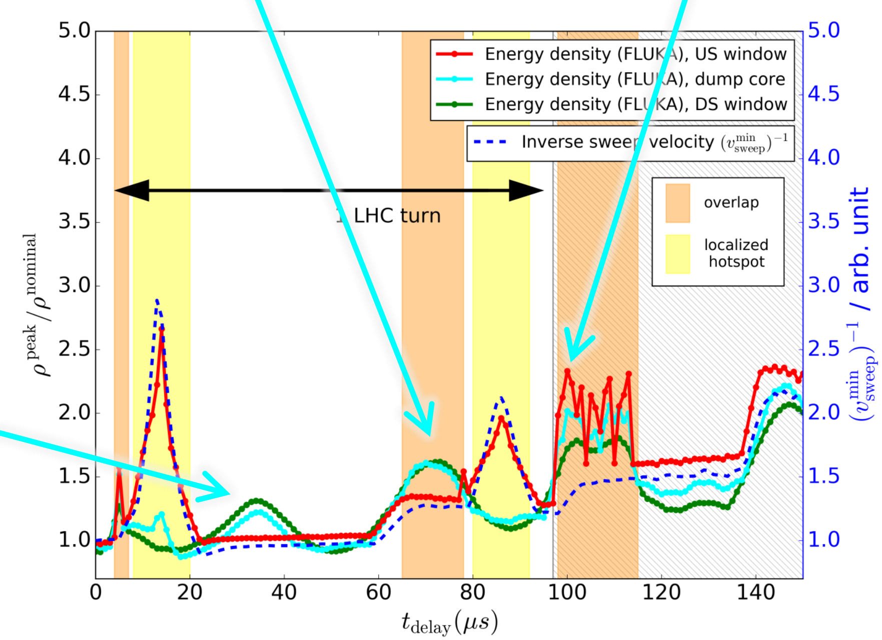
Energy Deposition

- Beam sweep path can overlap (or nearly overlap)
- Peak energy density is increased





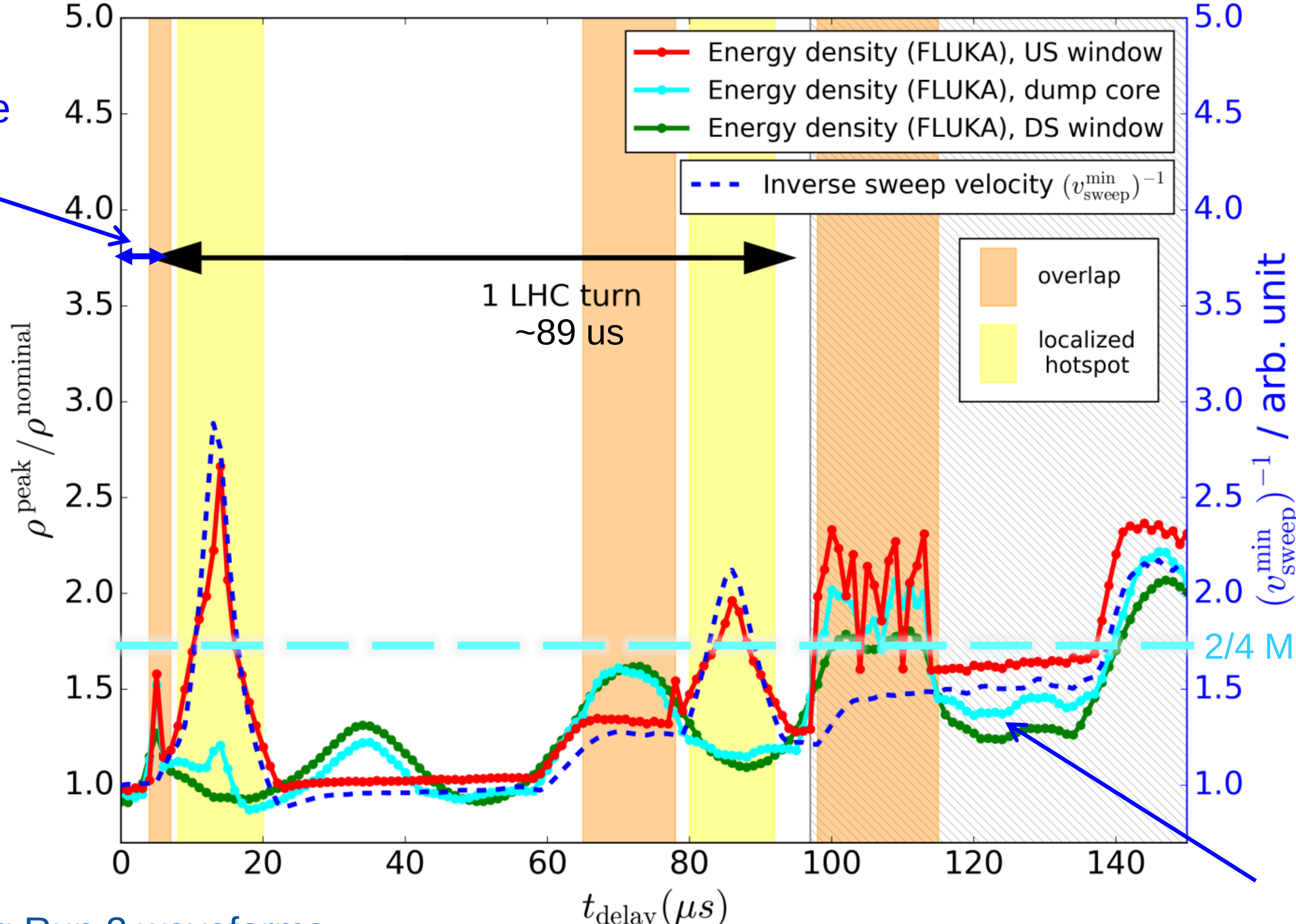




FLUKA simulations: M. Frankl

Energy Deposition

Reaction time should be below 6 us



Proposed asynch. dump delay time: 120 us

Simulated using Run 3 waveforms

FLUKA simulations: M. Frankl

Energy Deposition: Summary

	T_{peak} dump core	Safety factor S_y US window	Safety factor S_y DS window
Nominal	1860 °C	1.8	1.3
2/4 MKBH missing	2840 °C	0.9	1.1
Retrigger worst case (t_{delay} <98us)	2760 °C (for 70 us delay)	1.2 (for 14 us delay)	**To be checked**
Worst-case filling pattern	STD	BCMS	STD

M. Frankl, T. Polzin

- Dump upstream (US) and downstream (DS) windows: Safety factor $\mathbf{S_y \geq 2}$ for thermo-mechanical stresses is considered **safe for operation**.
- Permanent deformation is expected for $\mathbf{S_y < 1}$.
- Upgrade of windows with Ti Gr5 should increase the yield strength sufficiently.

Conclusion: For the dump core and the US window, **the worst-case sweep paths for the retrigger scenario are less critical than the case '2 MKBH missing'.** To be confirmed for DS window.
So far, no show stopper for the retrigger implementation identified.

Assumed parameters: STD: 2748b, 2.3e11 ppb, 2.08 um, 7 TeV; BCMS: 2604b, 2.0e11 ppb, 1.37 um, 7 TeV
Remark: FLUKA calculations will be repeated with new baseline HL-LHC parameters (no significant change expected)

Conclusions

- Accepted worst-case failure: **Loss of 2 MKBH**
- **New common-cause failure** can lead to loss of more than 50% of horizontal dilution. Occurrence cannot be excluded for Run 3.
- Possible solution is **MKB retrigger system:** mitigates common-cause failure (e.g. coupling)
- Option 1: MKB retriggering + asynch. dump: Easiest implementation, but expected asynch. dumps increase from 1 to 2..5 per beam and year. Potential issue for availability.
- Option 2a: MKB retriggering + synch. dump
- **Option 2b: MKB retriggering + synch. dump + delayed asynch. dump (120 us)**
  - More complex implementation. Reliability analysis showed:
    - Calculated probability for “no dilution” failure is negligible (MTTF ~1e12 years) and expected increase in asynch. dumps per year is not relevant (1 per 1000 years and beam)
  - Changed sweep path on the dump (in case of MKB erratic):
    - Worst-cases (filling pattern and retrigger delay) identified. They are, so far, less critical than failure case ‘2 MKBH missing’ for the US window and the dump core. To be confirmed for the DS window.
- Option 2b is discussed in ABT as preferred solution for implementation in LS2.
- Long-term option: Mitigate common-cause failure by redesign of LBDS retrigger topology and system grounding. Not feasible for LS2. Under study for LS3.

Thank you for your attention!

What to do?

Run 3 waveforms
4 MKBH

	Max. horiz. deflection, single erratic	Max. horiz. deflection, double erratic	Max. horiz. deflection, triple erratic	Required changes
Current situation: BETS reacts with delay time [210us…1296us]	69%...82% (for BETS delay > 207 us)	38%...65% (for BETS delay > 207 us)	7%...60% (for BETS delay > 207 us)	None
1) Directly request **synch. dump** (do no retrigger MKBs)	55%...99%	9%...98%	29%...99%	Fast erratic detection
2) **Synchronous MKB retriggering**	~100% → change of sweep path on dump	~100% → change of sweep path on dump	~100% → change of sweep path on dump	MKB retrigger system
3) **Asynchronous MKB retriggering**	~100% Asynch. losses	~100% Asynch. losses	~100% Asynch. losses	MKB retrigger system
4) Increase **delay time**, e.g. >1.5ms	~75%	~50%	~25%	Add time delay
5) Increase **damping factor**	→ 75% (small change of TDE pattern)	→ 50% (small change of TDE pattern)	→ 25% (small change of TDE pattern)	Modify generator

1) Worst case becomes more severe for double erratic
4) & 5) Only acceptable for single and double erratic
2) & 3) Valid for all number of erratics

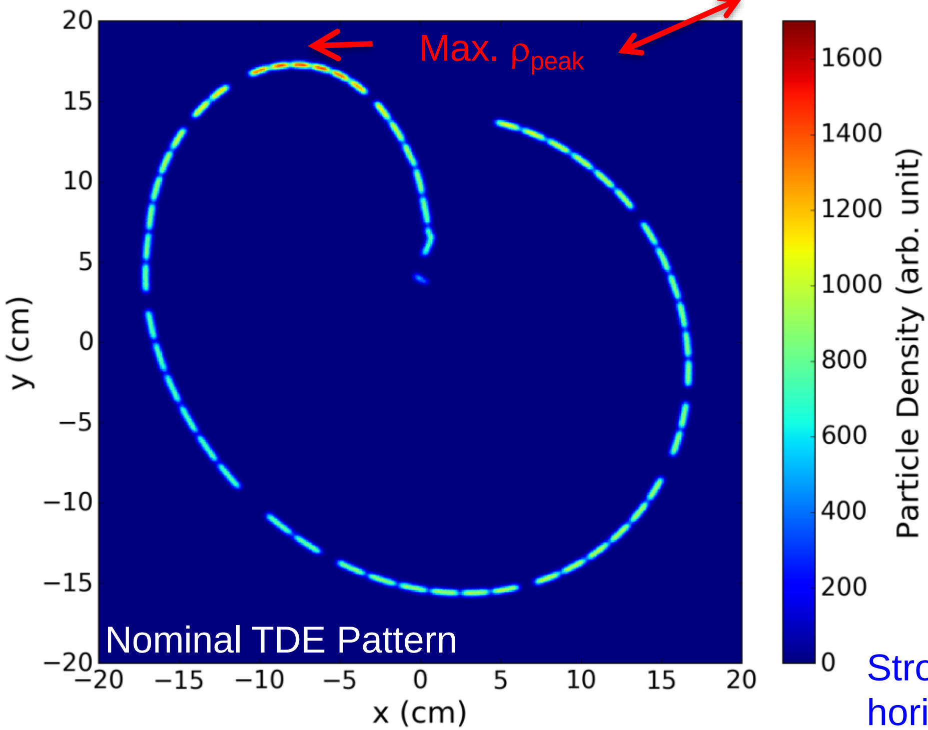
Dilution Strength – Nominal Case

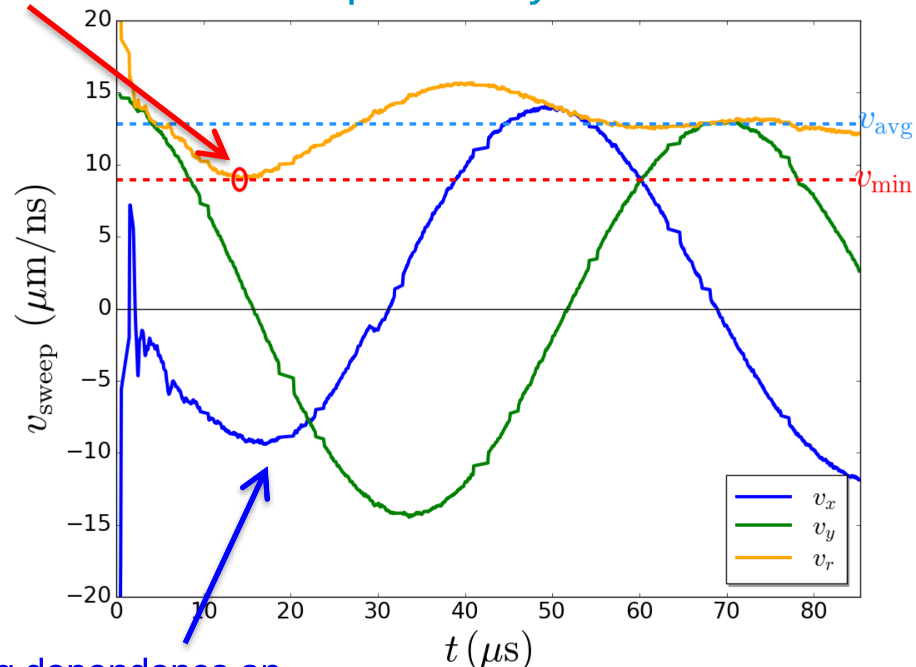
- MKBH:
  - Higher failure probability (operation at higher voltage)
  - Higher failure sensitivity (4 instead of 6 modules)
  - Higher failure impact (loss of horizontal deflection is more critical)

Proton Density at TDE

v_{min} = 9.0 µm/ns

Sweep Velocity at TDE





Strong dependence on horizontal sweep velocity.

MKB Erratics in operation: 2015 to 2017

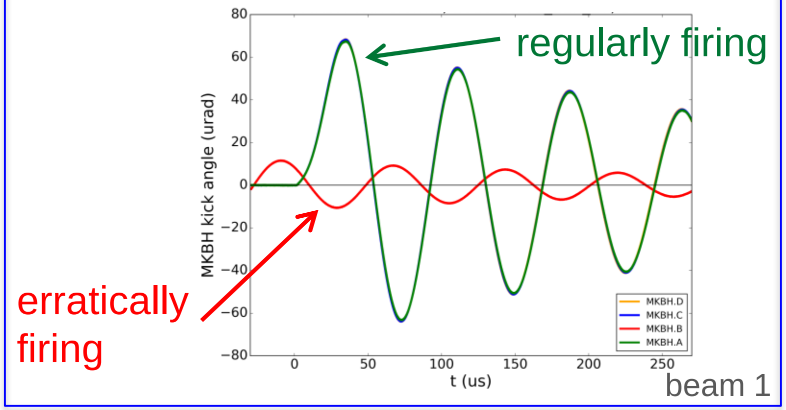
- Erratic firing only occurred for single MKBH: 4x in 2015 and 2x in 2016, none in 2017.
- Antiphase can reduce effective dilution

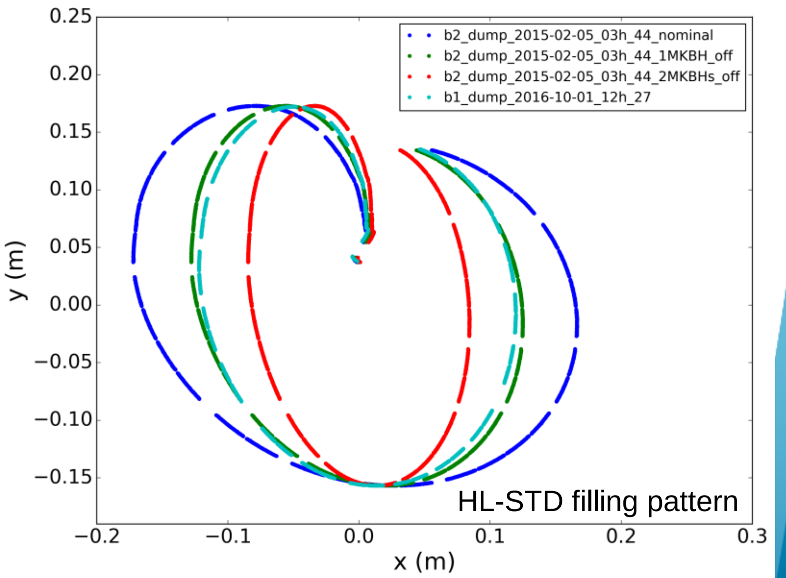
Event	Gen.	t_{delay} (us)	N_p p+	#bun-ches
2015-04-26_08h_16	A/B2	1 028	1.0e10	1
2015-04-27_09h_00	A/B2	1 208	9.4e10	1
2015-05-31_00h_56	A/B2	1 020	2.39e11	7
2015-10-24_20h_48	A/B2	1 049	1.93e14	1824
2016-10-01_12h_27	B/B1	654	1.5e14	2220
2016-10-04_18h_19	B/B2	1 029	1.42e11	5

All events occurred at 6.5 TeV

Effective dilution: 71.5% (2016-10-01_12h_27)

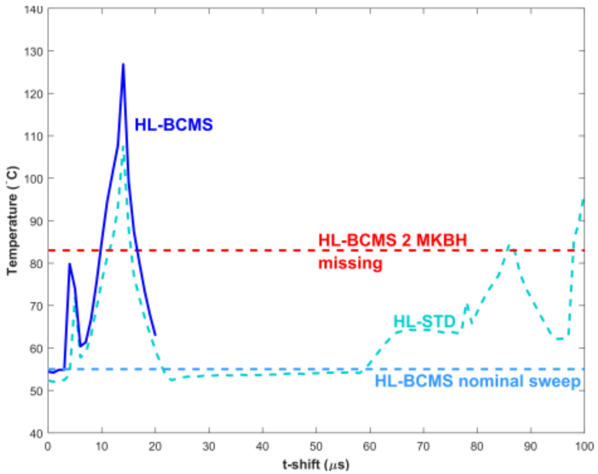
74% (2016-10-04_18h_19)



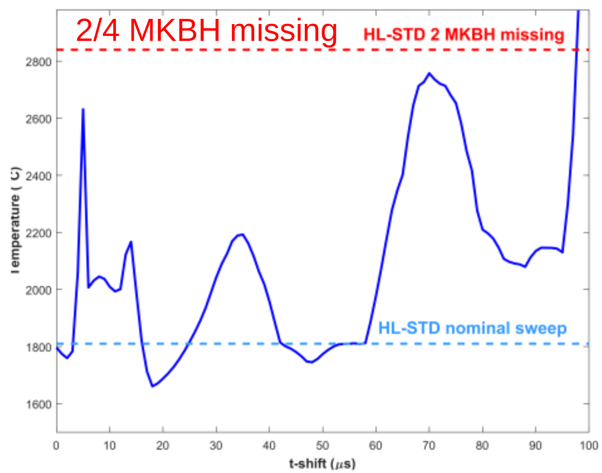


Temperature (Run 3 waveforms)

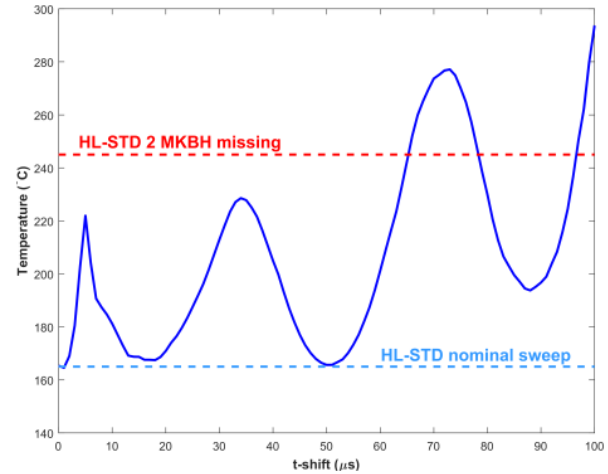
Upstream Window



Core



Downstream Window



- **Core:** For all relevant time delays **peak temperatures** stay **well below** the temperature level in the scenario of a HL-STD beam dump **missing the dilution of 2 MKBHs**
- **Windows:** **For most time delays** the peak temperature is **below the level of the case with 2 MKBHs missing**. In upstream window at $t_{delay} = 14\,\mu s$, however, a significantly higher temperature is expected.

→ *Thermo-mechanical responses to be analyzed*

M. Frankl, 7th HL-LHC Collaboration Meeting, November 14th, 2017

Failure Modes and Specifications

A. No/delayed MKB triggering resulting in insufficient dilution $(\boldsymbol{FM_A})$

- ➢**Failure rate < 1 in 10^6 years**

B. Additional asynchronous dump due to system upgrade $(\boldsymbol{FM_B})$

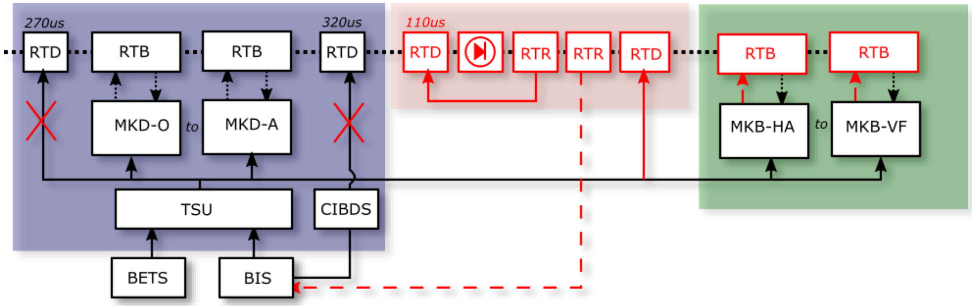
- ➢**max. 1 per year and beam**

C. Additional synchronous dump due to system upgrade $(\boldsymbol{FM_C})$

- ➢**max. 1 per year and beam**

D. Detectable failures requiring downtime and maintenance** $(\boldsymbol{FM_D})$

- ➢**max. 1 per year and beam**



Quantitative Fault Tree Analysis – Basic Failure Model

General Assumptions:

- constant component failure rates
- periodic inspection: ‘as good as new’
- no common cause failures for first assessment. Impact of dependencies evaluated in sensitivity analysis
- failure of one comp. does not increase/influence other component failure rates

Methodology:

- analytical solution (python model)
- benchmark with reliability workbench Isograph
- slight differences in results can be explained by numerical integration errors

Identification of System Blocks & Prediction

	assumed failure rates per beam (FIT)	~MTTF per beam [years]	Source (pessimistic estimations)
MKB	5E5	**0.25** yrs **(4 per year)**	operation
MKD	2.5E5	**0.5** yrs **(2 per year)**	operation
Diode	20	6 E3 yrs	prediction MIL-217F (2 FIT)
TDU	results of [1]		[1]
Connectors TDU	15	8 E3 yrs	[1]
TFO spurious. trigger	250	500 yrs	[2-4]
Link from RTL to BIS or TSU missing	10 (specification – no design)	1.3E4 yrs	specified / no system design
TSU to MKD trigger missing	10	1.3E4 yrs	[2-4]: 4E-10 /h

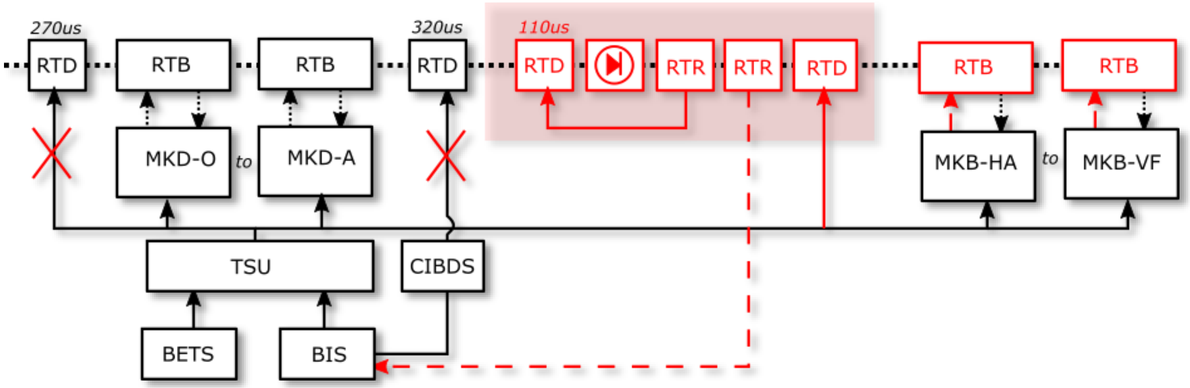
runtime: 20h/400 runs

[1] V. Vatansever, CERN-Thesis, 2014: Reliability Analysis of the new link between the Beam Interlock System and the LHC Beam Dumping System
[2] R. Filipini, Dependability Analysis of a Safety Critical System, 2006
[3] R. Filipini: Reliability Analysis of the Trigger Synchronisation and Distribution System of the LHC Beam Dumping System
[4] Review of the LBDS Safety and Reliability Analysis in the Light of the Operational Experience during the Period 2010-2012]

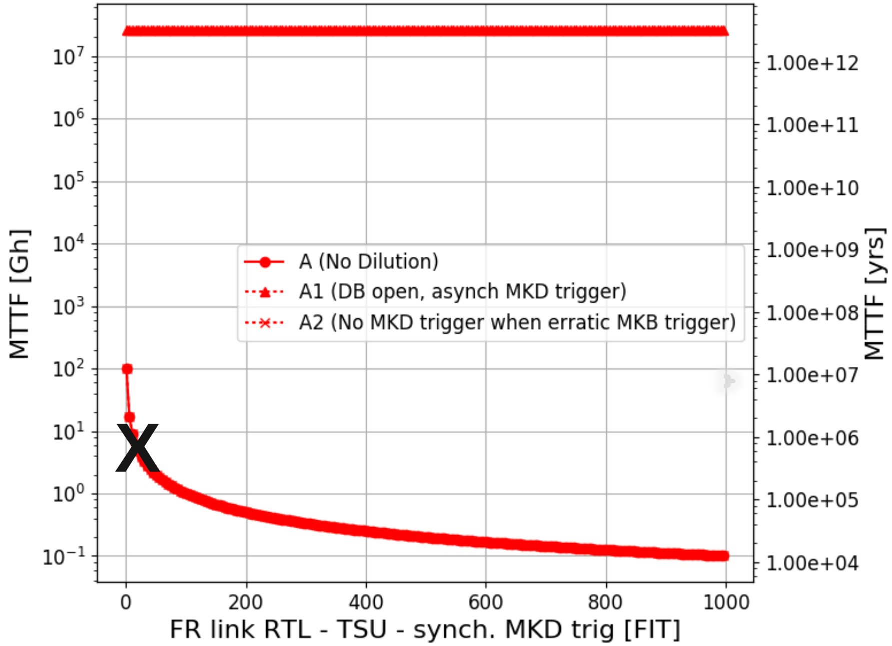
Results: Summary

Failure Modes	Layout 1 (1DB) operational years	Layout 2 (2DB) MTTF [Gh] / operation years	Layout 3 (No Loop in RTL) MTTF [Gh] / operation years
No Dilution	$3.2 \cdot 10^{12}\ yrs$	$7.5\ 10^{11}\ yrs$	$6.3 \cdot 10^{5}\ yrs$
Additional asynch. dump	$1008\ yrs$	$1012\ yrs$	$2.5\ 10^{5}\ yrs$
Additional synch dump	$75\ yrs$	$47\ yrs$	$94\ yrs$
Downtime / No beam permit	$105 yrs$	$71 yrs$	$168\ yrs$

All results should be multiplied by time(top energy)/(total Runtime)



Sensitivity: No Dilution / link from RTL to TSU



Conclusion

Detailed analysis of Link from RTL to TSU necessary.

Directly to TSU: passive

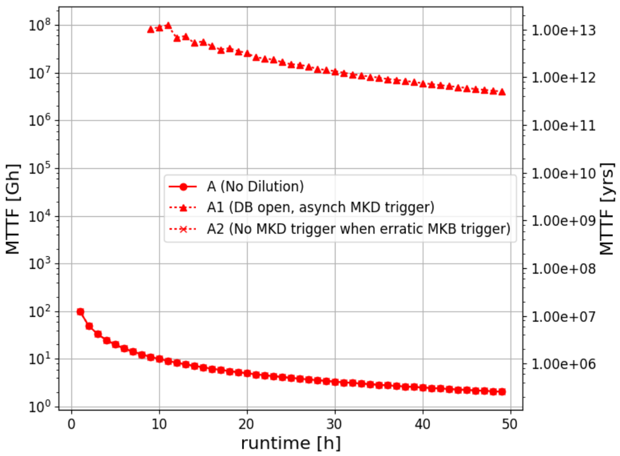
RTL-CIBU-BIS: active (monostable).

- ➢ Seems feasible if redundant paths

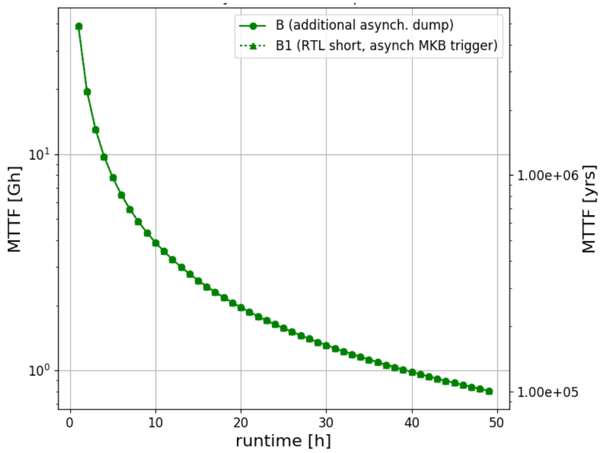
Failure Modes	Layout 1 (1DB) operational years	Layout 2 (2DB) MTTF [Gh] / operation years	Layout 3 (No Loop in RTL) MTTF [Gh] / operation years
No Dilution	$3.2 \cdot 10^{12}\ yrs$	$7.5\ 10^{11}\ yrs$	$6.3 \cdot 10^{5}\ yrs$
Additional asynch. dump	$1008\ yrs$	$1012\ yrs$	$2.5\ 10^{5}\ yrs$
Additional synch dump	$75\ yrs$	$47\ yrs$	$94\ yrs$
Downtime / No beam permit	$105 yrs$	$71 yrs$	$168\ yrs$

Sensitivity to Runtime

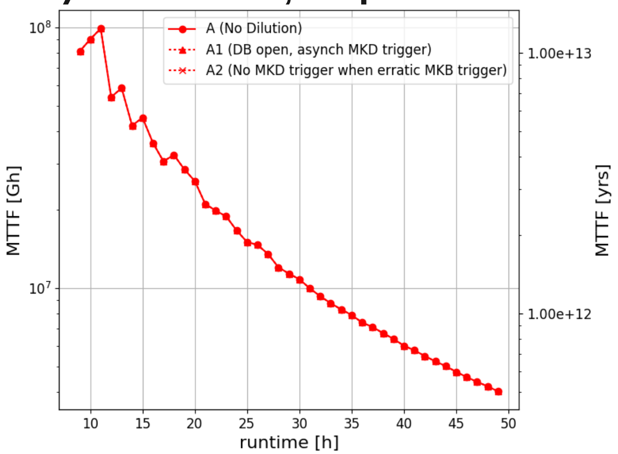
3) No Dilution, no loop in RTL



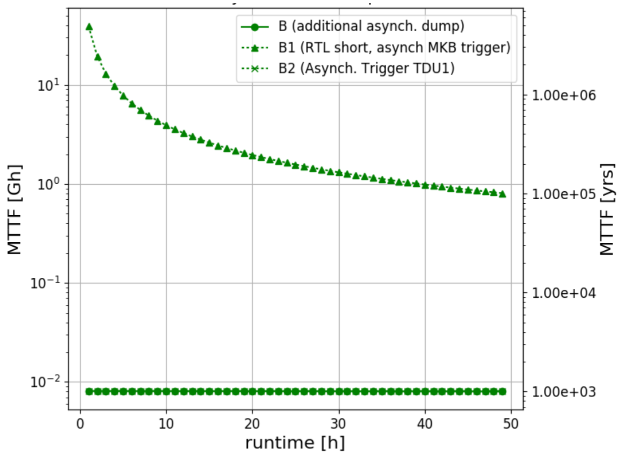
3) add. asynch. dump, no loop in RTL



1) No Dilution, loop in RTL



1) add. asynch dump, loop in RTL



Remark:

FM 'Synch. Dump' & 'maintenance' are dominated by OR junctions – no difference for runtime variation

LHC parameters

	T_{peak} dump core	Safety factor S_y US window	Safety factor S_y DS window
Nominal	1000 °C	2.7	3.1
2/4 MKBH missing	1400 °C	?	?
Retrig. worst case	?	?	?
Worst-case filling pattern	STD	BCMS	STD

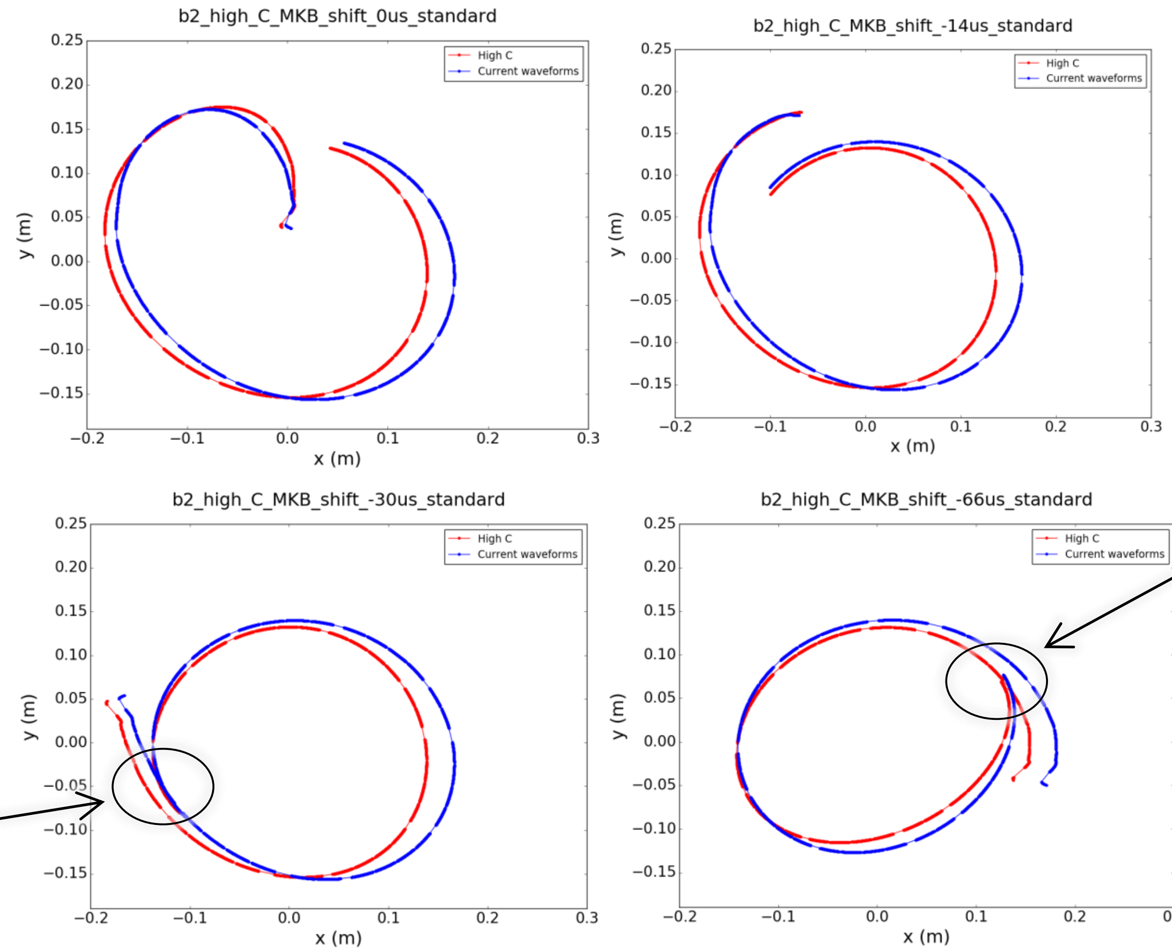
Assumed parameters: STD: 2556b, 1.3e11 ppb, 2.6 um, 6.5 TeV; BCMS: 2556b, 1.3e11 ppb, 1.37 um, 6.5 TeV

M. Frankl, T. Polzin

Retrigger Patterns (Post-LS2 waveforms)

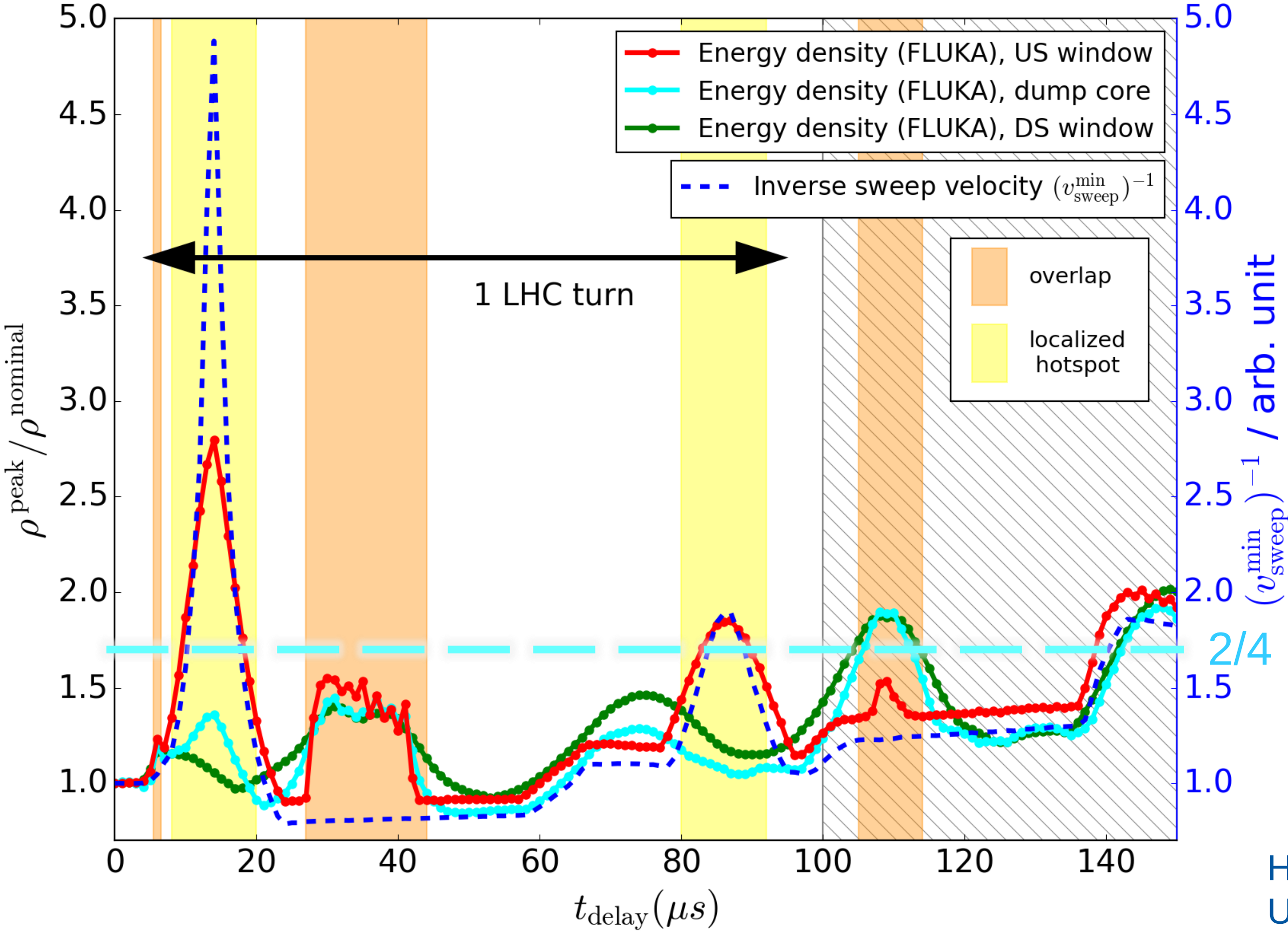
- Higher damping of post-LS2 waveforms changes energy deposition for the retrigger scenario

Retrigger sweep patterns for Run 2 and Post-LS2 waveforms



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

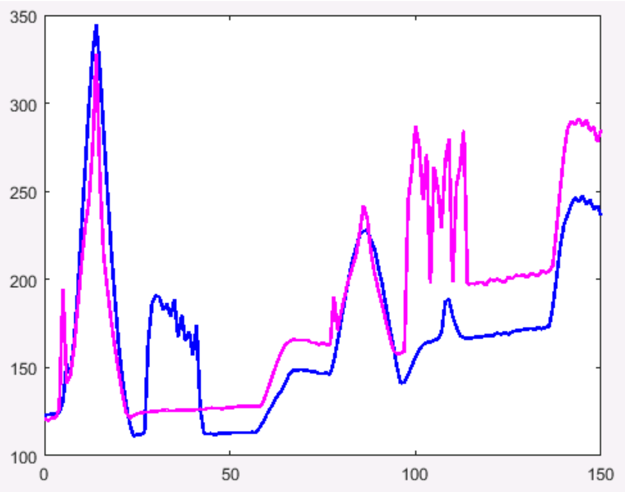
Energy deposition: current waveforms



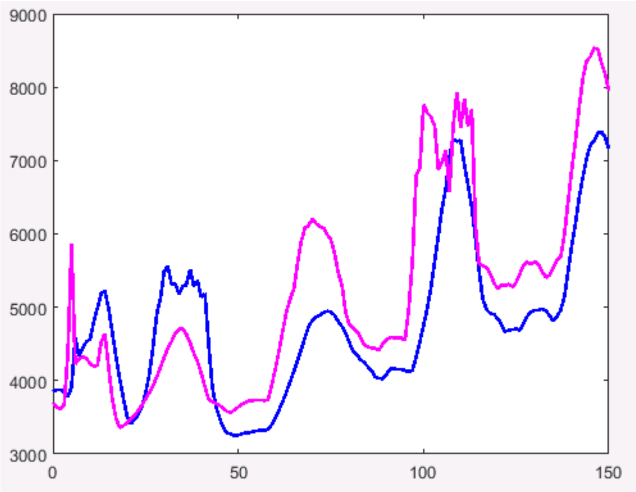
HL-LHC standard filling scheme.
Using current waveforms.

Energy deposition: Comparison

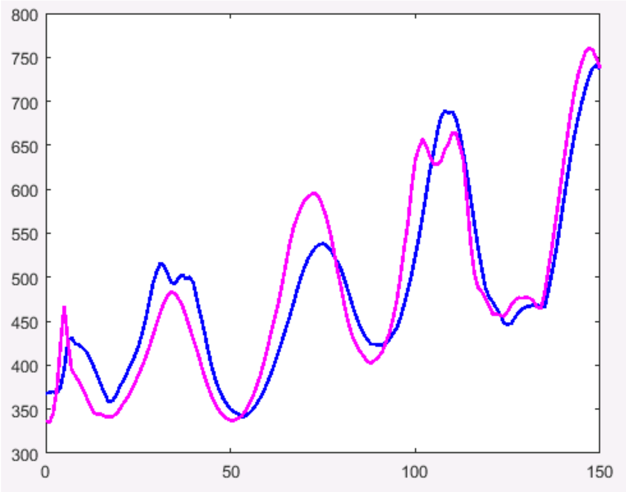
US Window



Core



DS Window



Current waveforms
Run 3 waveforms

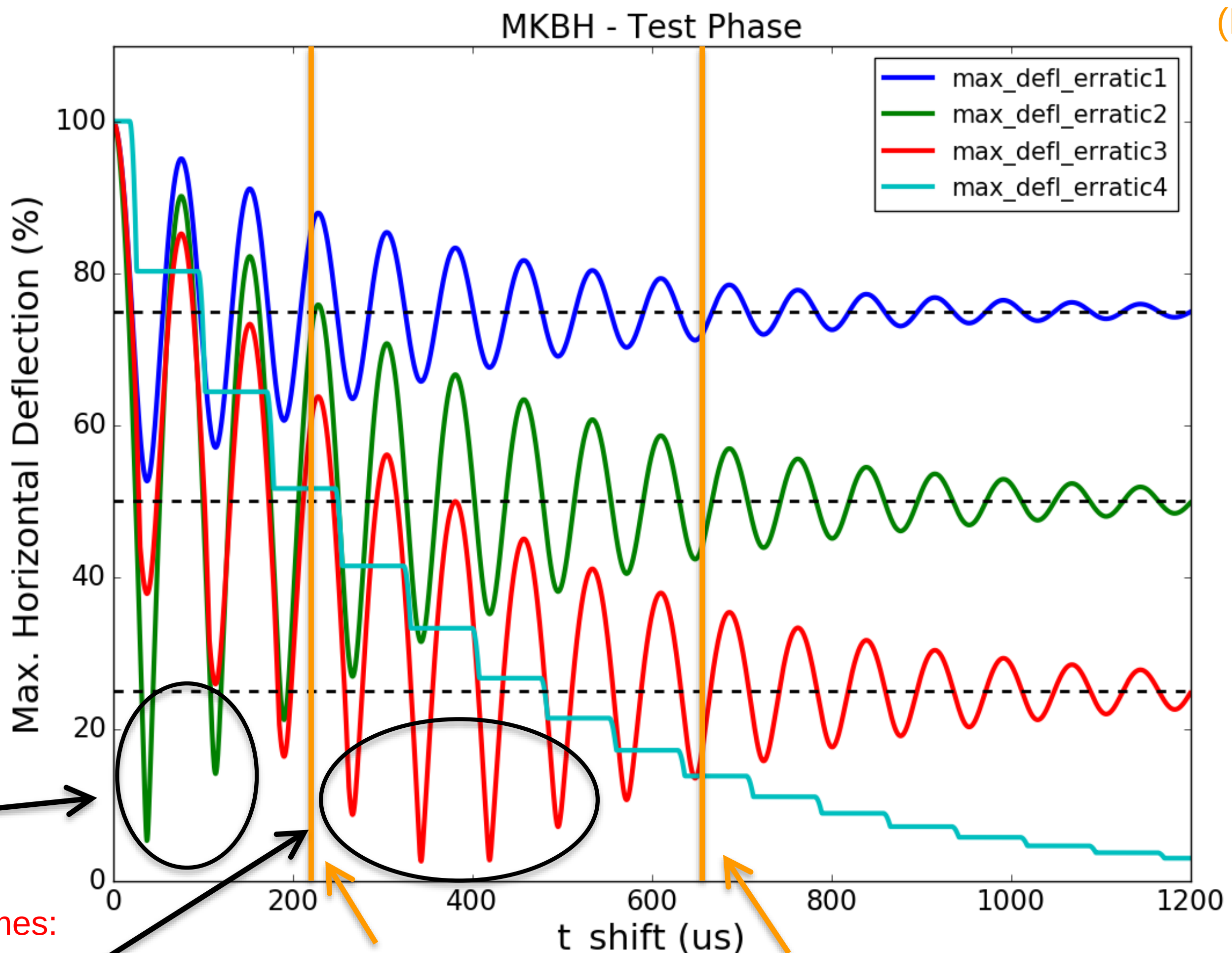
M. Frankl

MKB Coupling: Dilution Impact

Current configuration

BETS reaction time:
~210us…~1296us
(N. Voumard)

Erratic of 1:
Always uncritical
(>50%)



For t→∞
α_{max} → 75%
(loss of 1 MKBH)

For t→∞
α_{max} → 50%
(loss of 2 MKBH)

For t→∞
α_{max} → 25%
(loss of 3 MKBH)

For t→∞
α_{max} → 0%
(loss of 4 MKBH)

Shorter delay times very critical for erratic of 2

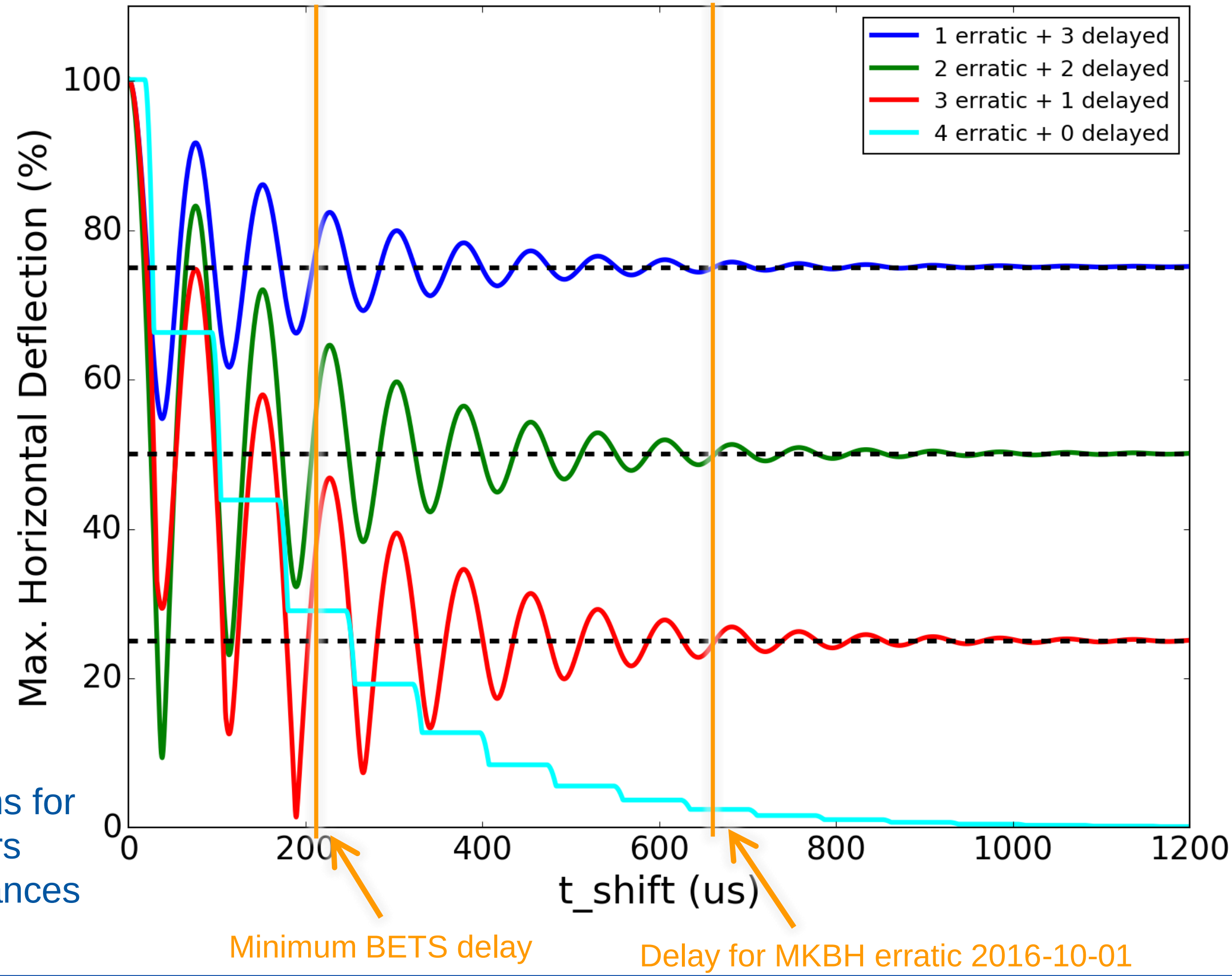
For current delay times: triple erratic is worst case

Minimum BETS delay

Delay for MKBH erratic 2016-10-01

MKB Coupling: Dilution Impact

Run 3: Higher damping (new MKB generators), 4 MKBH



For t→∞
α_{max} → 75%
(loss of 1 MKBH)

For t→∞
α_{max} → 50%
(loss of 2 MKBH)

For t→∞
α_{max} → 25%
(loss of 3 MKBH)

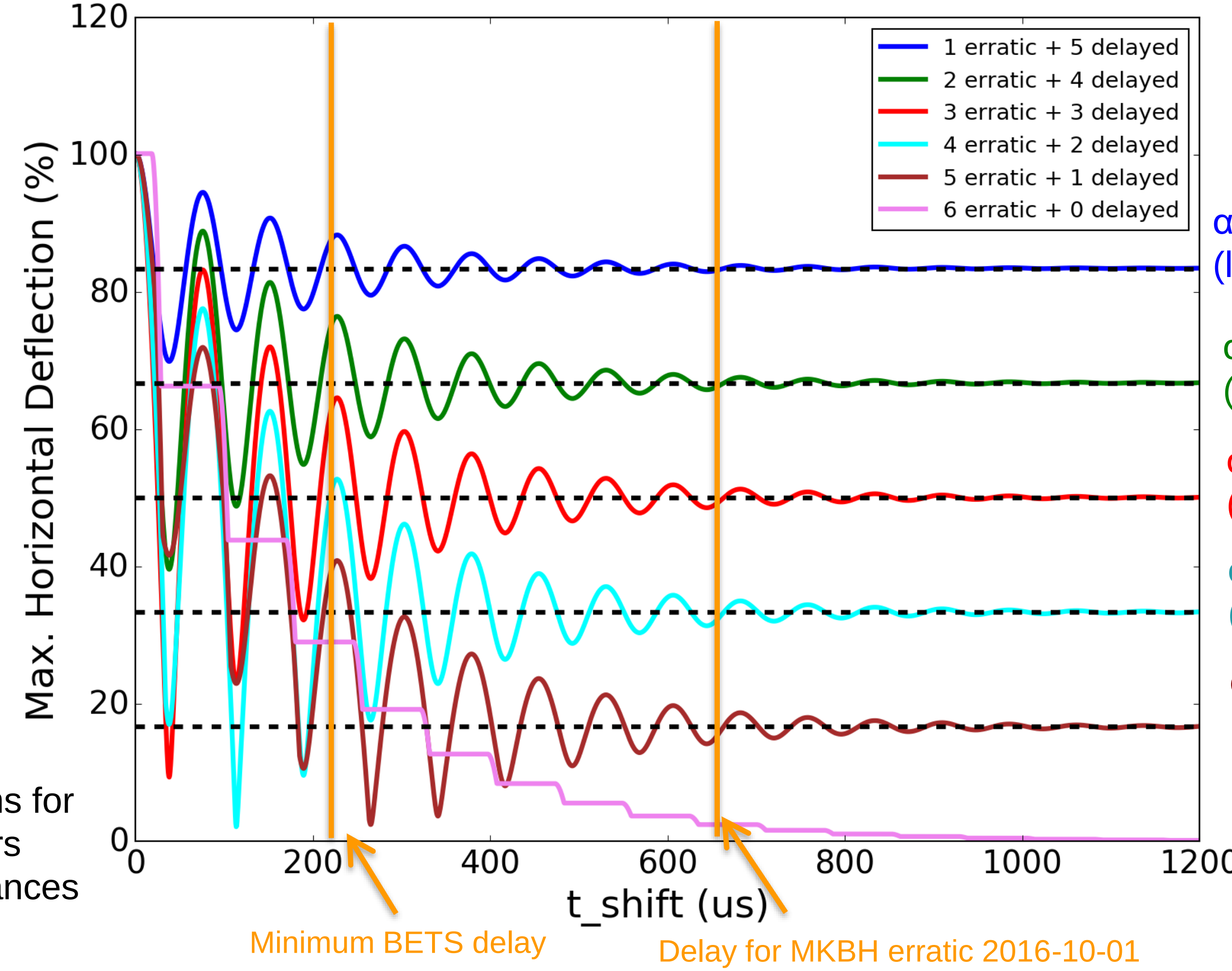
For t→∞
α_{max} → 0%
(loss of 4 MKBH)

Calculated using simulated waveforms for new MKB generators with higher capacitances (V. Senaj).

MKB Coupling: Dilution Impact

HL-LHC: Higher damping (new MKB generators), 6 MKBH

6 MKBH instead of 4 MKBH



For t→∞

α_{max} → 83.3% (loss of 1 MKBH)

α_{max} → 66.7% (loss of 2 MKBH)

α_{max} → 50% (loss of 3 MKBH)

α_{max} → 33.3% (loss of 4 MKBH)

α_{max} → 16.7% (loss of 5 MKBH)

α_{max} → 0% (loss of 6 MKBH)

Calculated using simulated waveforms for new MKB generators with higher capacitances (V. Senaj).

Failure Cases: Energy Deposition

- *Studies ongoing: which temperature rise and dynamic stresses for dump core and windows are acceptable?*
- Assumption for this talk: **loss of >50% of dilution in one plane is not acceptable for HL-LHC parameters**

	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

K	number active MKBV						
number active MKBH	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

K	number active MKBV						
number active MKBH	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