



Potential HL-LHC performance limitations from MKI and dump system

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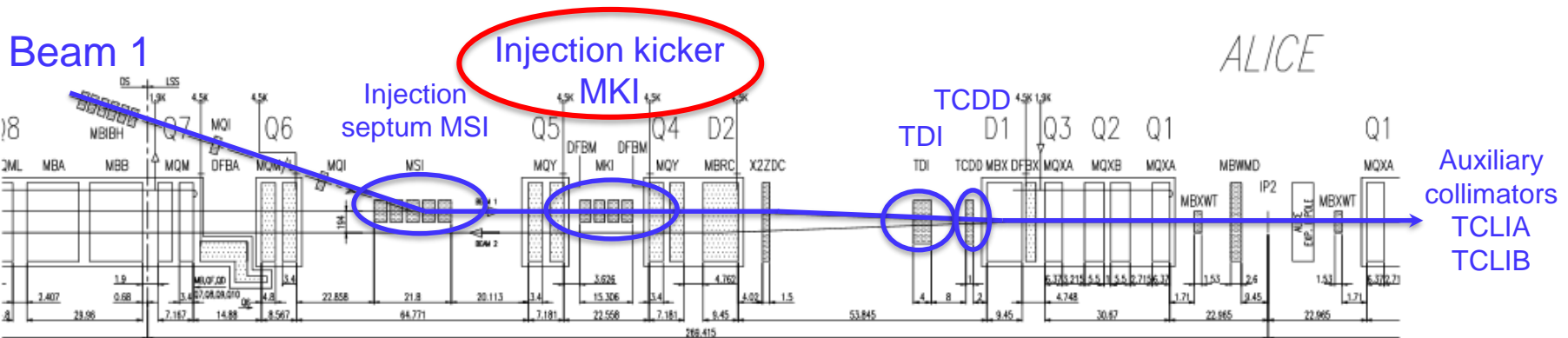
16 November 2017 – 7th HL-LHC Collaboration Meeting

Outline

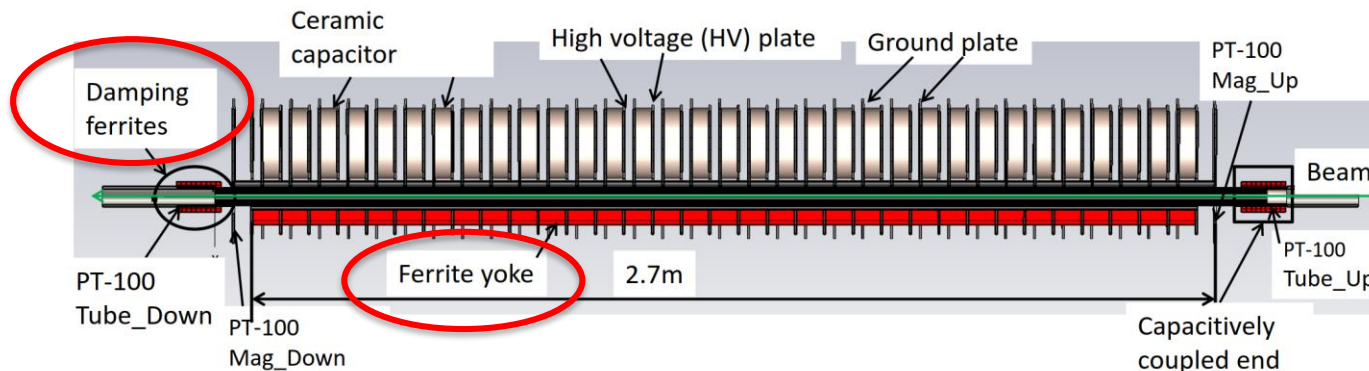
- 1) Injection Kickers (MKI): potential limitations and planned upgrades
 - Introduction
 - MKI: E-clouds and vacuum
 - MKI: Impedance and beam-induced heating
- 2) Beam Dump System: potential limitations and planned upgrades
 - Introduction
 - Extraction protection devices
 - Dilution system and beam dump
- 3) Summary and conclusion

LHC Injection Kickers (MKI)

- 4 injection kickers (MKI) per beam
- Fast pulsed transmission line kicker



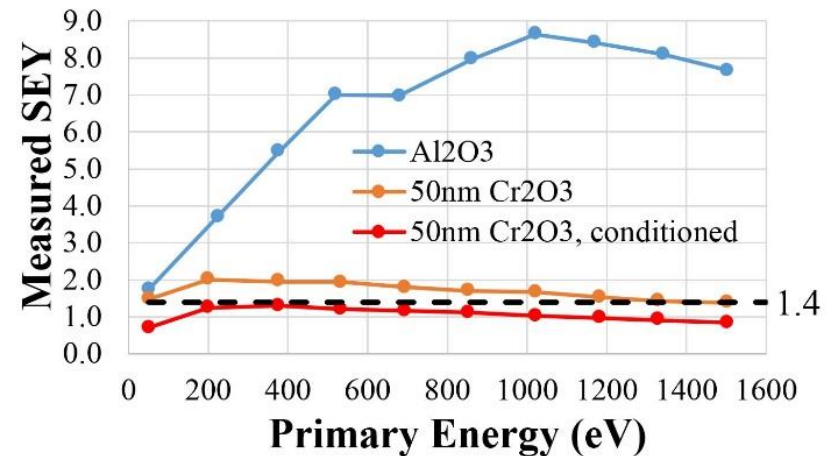
MKI schematic view



H. Day, CERN-THESIS-2013-083, p. 175

MKI: E-clouds and vacuum

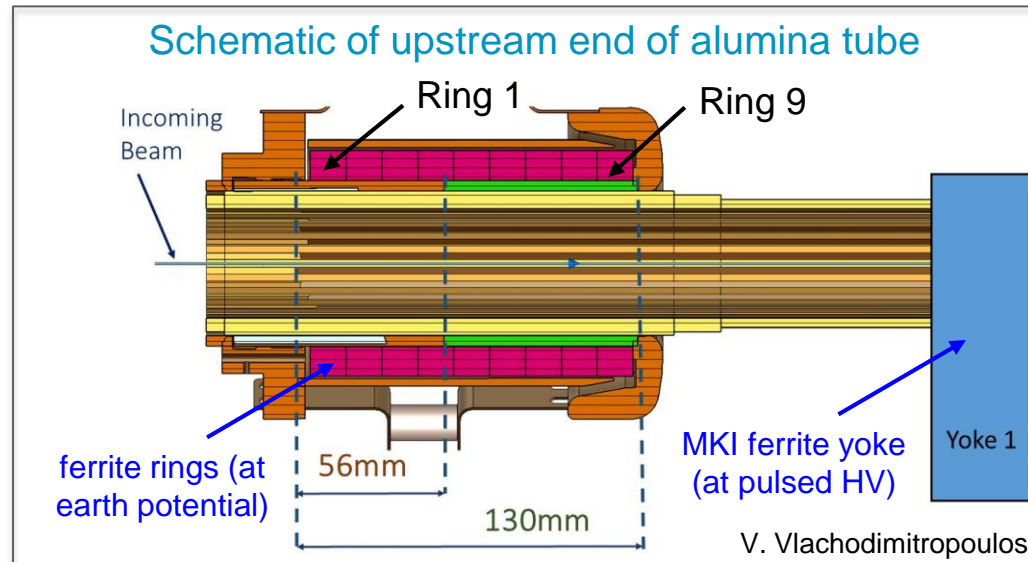
- 2016: MKI8D dynamic vacuum pressure rise limited high-intensity injection. Attributed to e-cloud effects due to high SEY of alumina tube.
- Reduction of Al_2O_3 SEY with Cr_2O_3 coating successfully measured in the lab. Dedicated MD in SPS showed clear signs of conditioning with beam.
- In addition, measurements show no increase of dust particles/potential UFOs.
- For validation, one upgraded MKI will be installed during YETS 2017-18.
- No limit from MKI dynamic pressure rise expected for HL-LHC.**



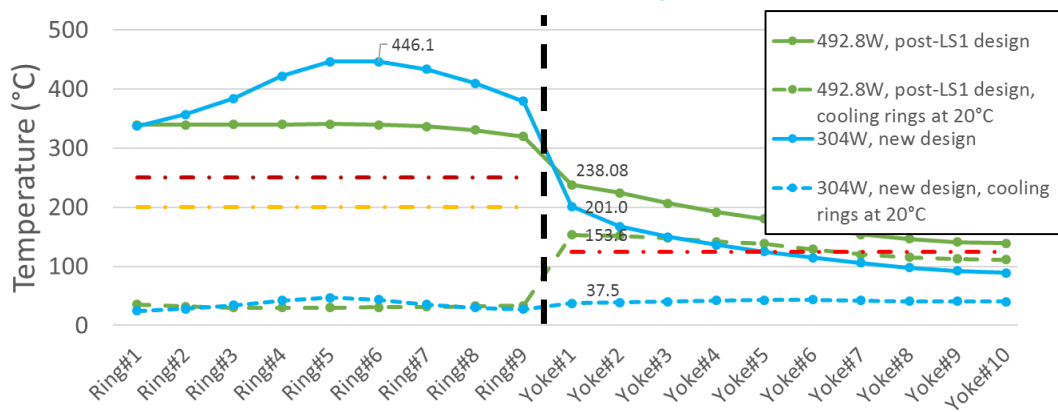
Lab measurements courtesy of E. Garcia-Tabares Valdivieso & H. Neupert

MKI: Beam-induced heating

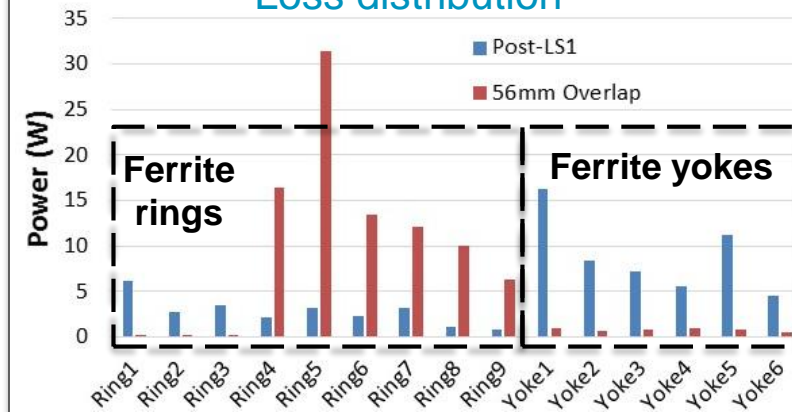
- With present design, temperatures in MKI yoke would be well above the Curie temperatures for HL-LHC beams.
- New beam screen design:
 - reduces the total power loss,
 - moves the main losses from the yoke to the ferrite rings,
 - allows direct water cooling of only the ferrite rings (at earth potential).



Temperature predictions assuming steady-state losses



Loss distribution



Calculation for 1.15×10^{11} p+, 2808b, $t_b = 1$ ns

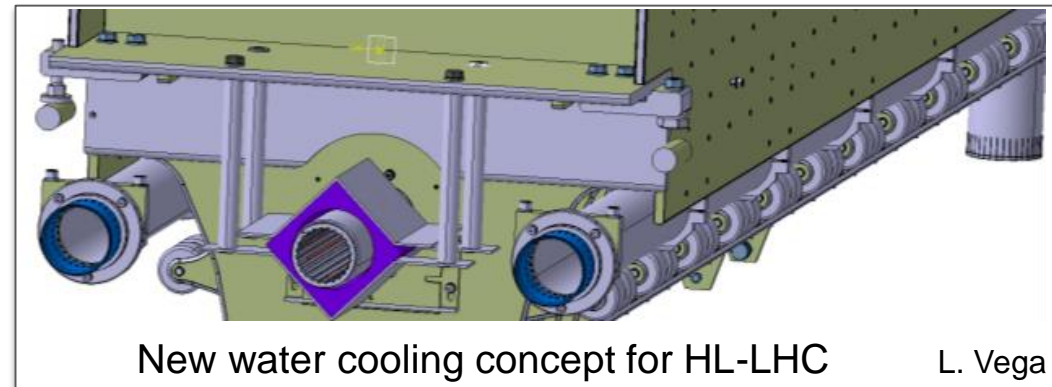
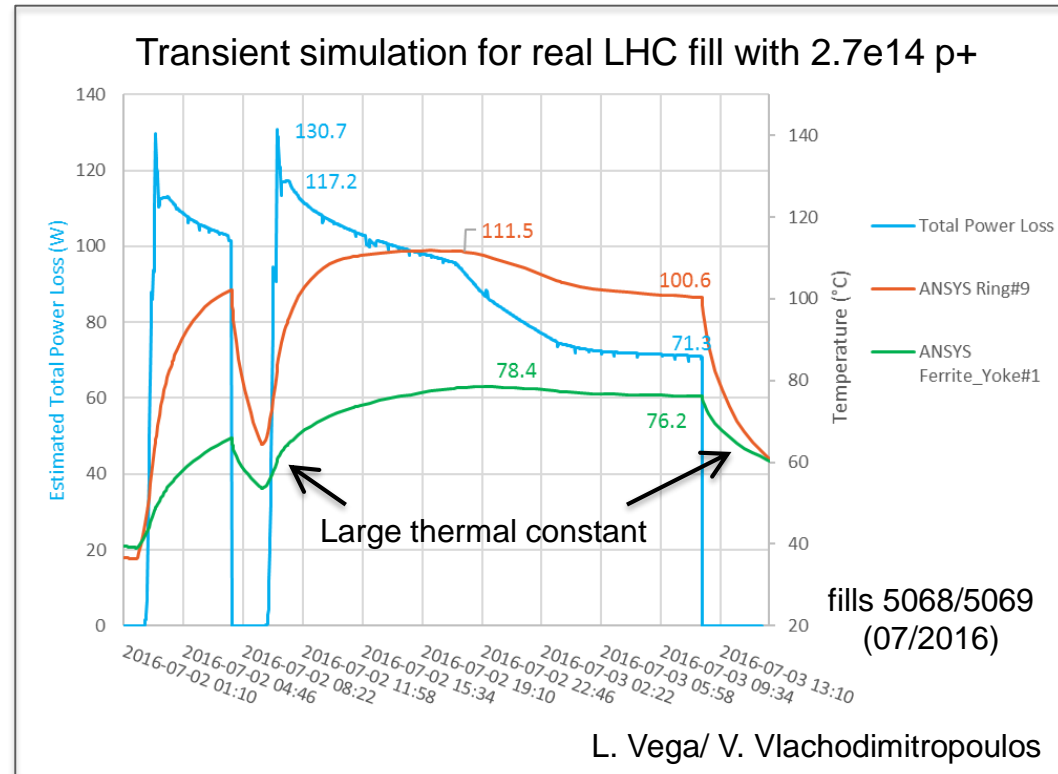
V. Vlachodimitropoulos

L. Vega

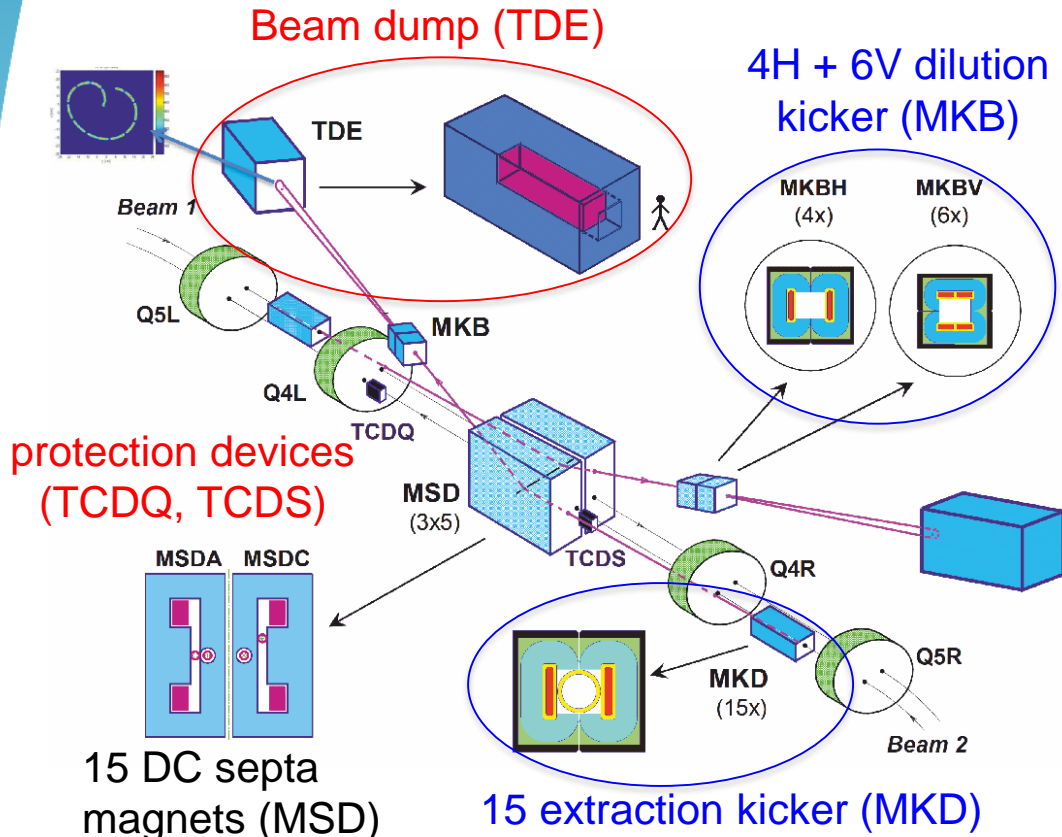
Calculations for 2.2×10^{11} p+, 2748b, $t_b = 1$ ns

MKI: Beam-induced heating

- No limitations expected for HL-LHC with new beam screen and water-cooling system (LS3).
- For Run 3, beam-induced heating is expected to limit availability/ intensity to slightly greater than nominal LHC parameters ($\sim 1.2e11$ ppb, 2808 bunches, 1ns bunch length).
- However, these temperature predictions are based on worst-case, steady-state-loss assumptions.
- Temperature predictions will be validated with new MKI prototype to be installed in YETS 2017/18 (new beam screen but without active cooling).



LHC Beam Dump System



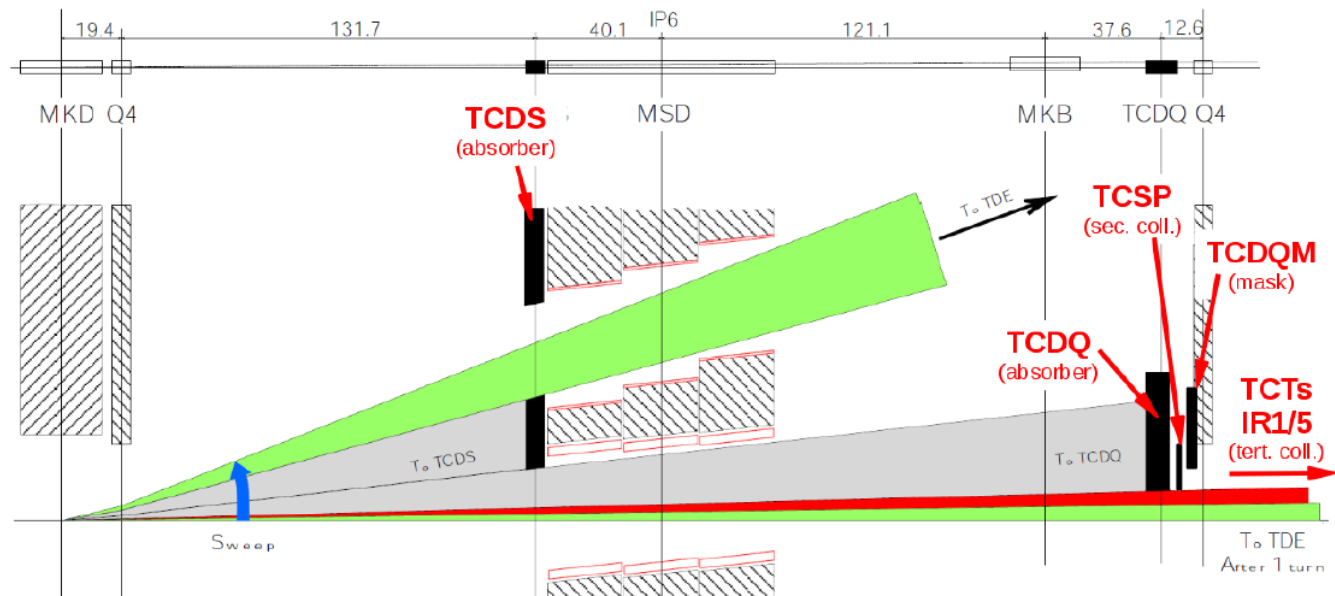
Current challenges and potential limitations:

- Beam losses in case of an asynchronous beam dump
- Failures of (horizontal) dilution kicker
- High temperatures and stresses in dump and dump windows

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

Extraction Protection Devices

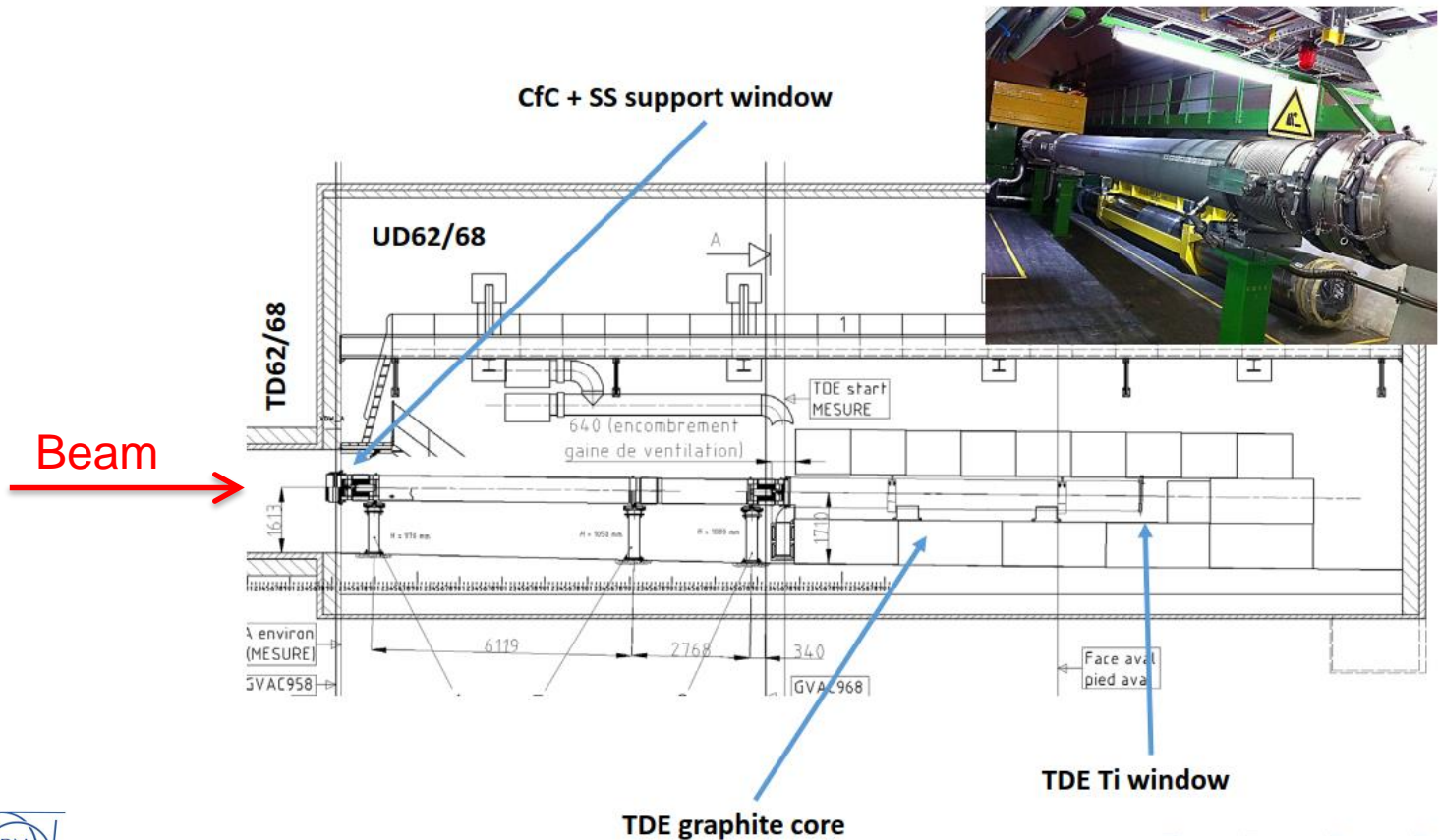
- TCDQ is ready for HL-LHC parameters** ($2.3e11$ ppb, $2.08 \mu\text{m}$) with the constraint of a minimum allowed gap > 3 mm. Including 1.2 mm orbit drift, 0.3 mm setup/optics errors, 0.4 mm dispersion offset gives **minimum allowed gap > 4.9 mm for current tolerances**.
- TCDS**: Present setup with 2 modules should withstand asynchronous dump for HL-LHC intensities, but risk of Ti plastification cannot be ruled out. **Upgrade with 3rd module for LS3 is anyway included in baseline** to prevent possible non-conformity.



For full list of optics constraints see C. Bracco, 30th HL-LHC TCC, 08.06.2017

Beam Dump (TDE)

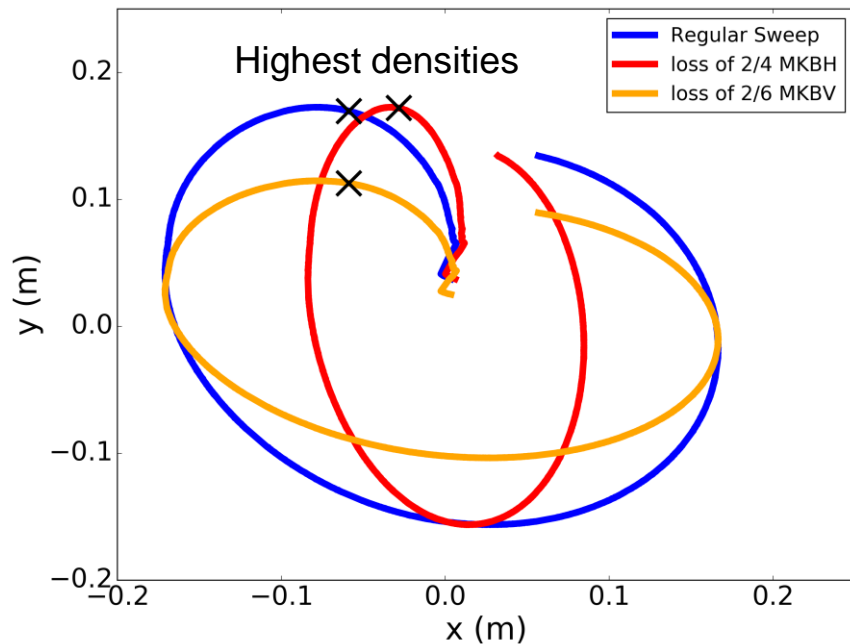
- Main dump components:
 - ~8 m long graphite dump core,
 - upstream window made of 15 mm CfC and a 0.2 mm thin stainless steel foil,
 - 10 mm titanium (grade 2) downstream window.



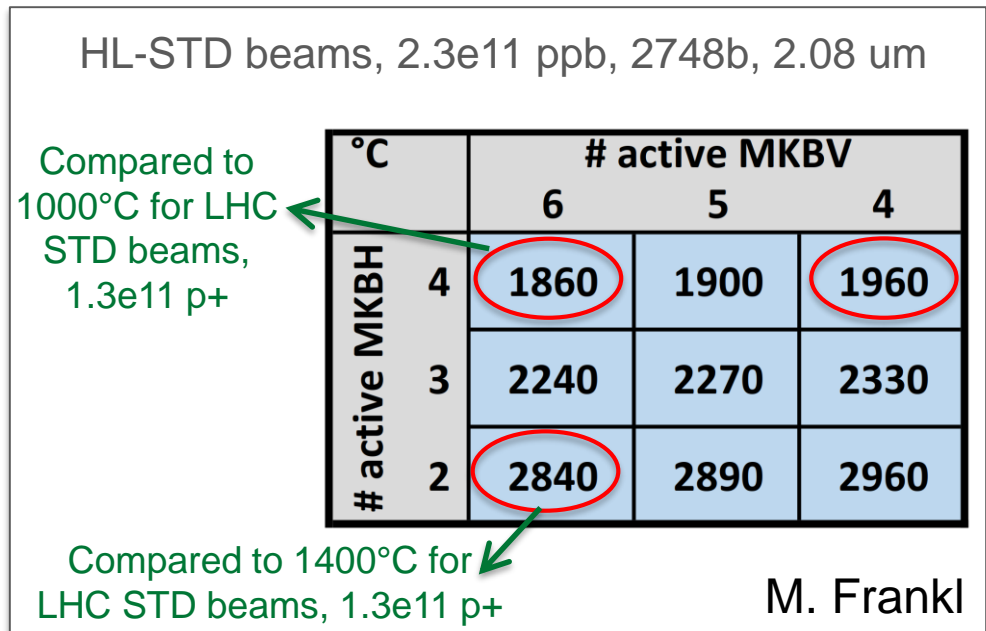
Beam Dump Core

- Studied beam sweep patterns and energy deposition for regular sweep and for failure cases of up to 2 missing dilution kickers
- High temperatures in the dump core reached. Not clear if local damage in dump core could occur even for a regular dump of a HL-STD beam due to stresses.
- For final conclusion, stress analyses based on the detailed characterization of the dump-material properties are required.

Beam sweep patterns at dump



Temperature in dump core



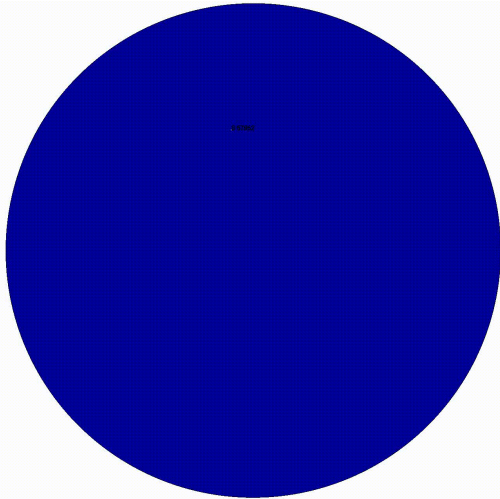
Beam Dump Windows

- Expected thermo-mechanical stresses in the upstream and downstream windows are beyond the yield strength for failure case of 2 missing MKBH.

Upstream window (2 missing MKBH)

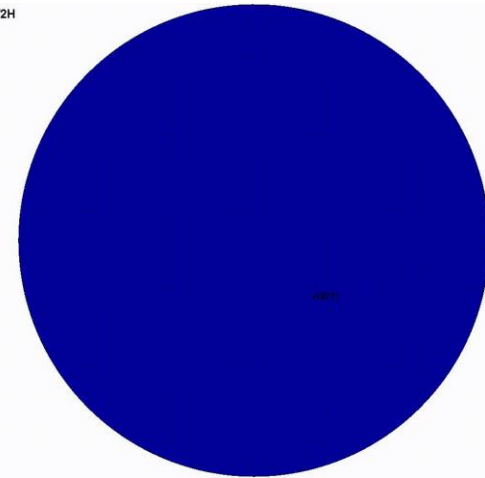
Downstream window (2 missing MKBH)

TDE - Front Window - R3 - 6V2H
Time = 0
Contours of Effective Stress (v-m)
max IP value
max=0, at elem# 17667
max displacement factor=0



Effective Stress (v-m)
2.8624896e+08
2.7670733e+08
2.6716570e+08
2.5762406e+08
2.4808243e+08
2.3854080e+08
2.2899917e+08
2.1945754e+08
2.0991590e+08
2.0037427e+08
1.9083264e+08
1.8129101e+08
1.7174938e+08
1.6220774e+08
1.5266611e+08
1.4312448e+08
1.3358285e+08
1.2404122e+08
1.1449959e+08
1.0495795e+08
9.5416320e+07
8.5874688e+07
7.6333056e+07
6.6791424e+07
5.7249792e+07
4.7708160e+07
3.8166528e+07
2.8624896e+07
1.9083264e+07
9.5416320e+06
0.0000000e+00

TDE - Down-Stream Window - HL6V2H
Time = 0
Contours of Effective Stress (v-m)
max=0, at elem# 1



Effective Stress (v-m)
1.8775174e+08
1.8149335e+08
1.7523496e+08
1.6897657e+08
1.6271818e+08
1.5645979e+08
1.5020140e+08
1.4394300e+08
1.3768461e+08
1.3142622e+08
1.2516783e+08
1.1890944e+08
1.1265105e+08
1.0639265e+08
1.0013426e+08
9.387572e+07
8.7617481e+07
8.1359089e+07
7.5100698e+07
6.8842306e+07
6.2583915e+07
5.6325232e+07
5.0067132e+07
4.3808740e+07
3.7550349e+07
3.1291957e+07
2.5033566e+07
1.8775174e+07
1.2516783e+07
6.2583915e+06
0.0000000e+00

HL-BCMS, 2.0e11 ppb, 2604b, 1.37 μm

HL-STD, 2.3e11 ppb, 2748b, 2.08 μm

Maximum v. Mises stress	286 MPa
Temperature in the peak	85°C
Yield strength at 100°C	250 MPa
Safety factor against yielding	0.87

Maximum v. Mises stress	188 MPa
Temperature in the peak	145°C
Yield strength at 200°C	140 MPa
Safety factor against yielding	0.74

0.2 mm stainless steel

T. Polzin

10 mm Ti

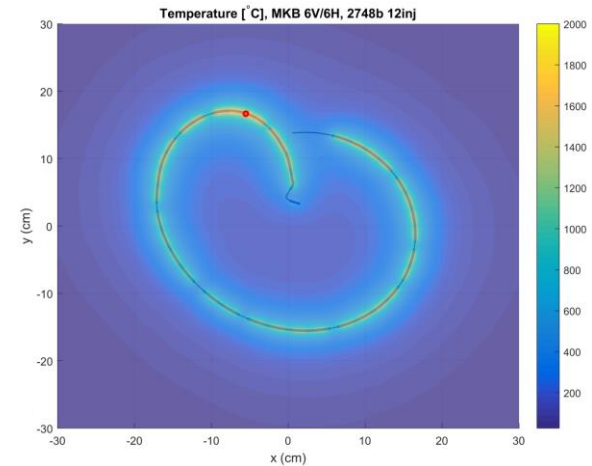
Upgrade of Dump and Dilution System

- Upgrade of dump windows and dump infrastructure (nitrogen support line) required.
- Upgrade from 4 to 6 horizontal dilution kickers (MKBH)** has potential to significantly reduce peak temperatures in dump core.
- Potential gain and feasibility of dump core/vessel and dilution upgrade is being studied to define a strategy in 2020.

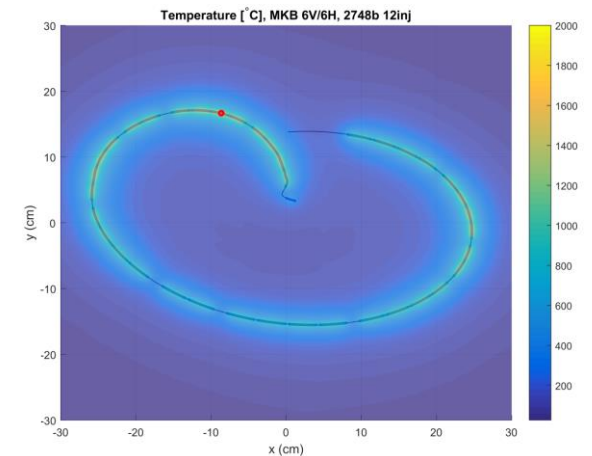
Peak temperature in dump core for HL-STD beam, $2.3e11$ ppb, 2748b, $2.08 \mu\text{m}$

2/4 MKBH missing	2/6 MKBH missing	2/6 MKBH missing (and increased dilution)
2840°C	2420°C	1860°C

Nominal Dilution



Increased horizontal dilution

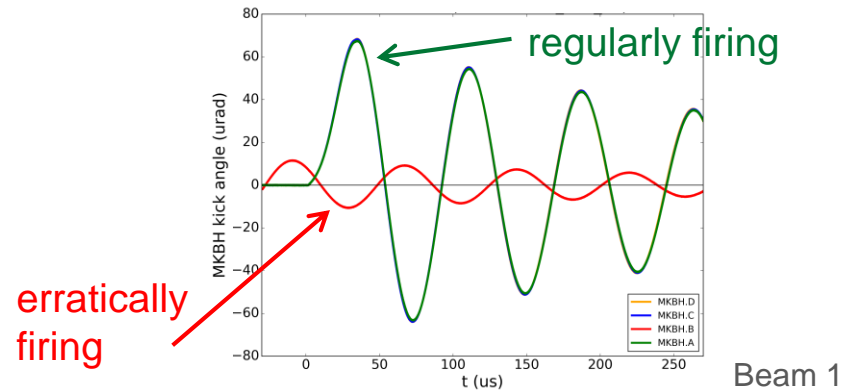


M. Frankl

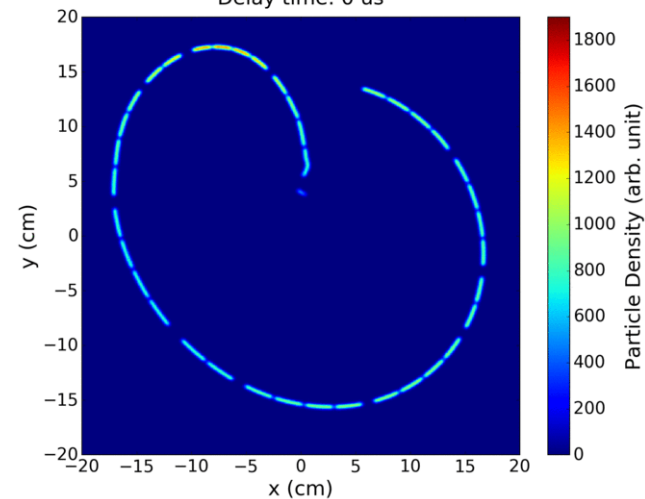
Dilution Kicker: Coupling and Retriggering

- New possible failure case observed during tests in 2016: parasitic EM coupling between MKB generators
- Erratic firing of more than one MKBH is critical: could potentially lead to loss of >50% of dilution in one plane (due to antiphase)
- Short-term mitigation implemented during EYETS 2016/17.
- Possible long-term mitigation by immediate MKB retriggering in case of erratic firing.
- Energy-deposition and reliability studies ongoing. Earliest implementation in LS2.

Measured waveforms, 2016-10-01



Delay time: 0 us



Sweep pattern for different delay times between retriggered MKB and synchronously firing MKD

See C. Wiesner et al., IPAC'16, WEPIK033

Conclusions

- Injection Kickers (MKI)
 - Vacuum and e-cloud issue are expected to be mitigated by using Cr_2O_3 coating.
 - Beam-induced heating might limit intensity/availability in Run 3, but will be mitigated for HL-LHC with new beam screen and cooling system.
- Extraction protection devices
 - TCDQ ready for HL-LHC beams with constraints on minimum gap opening. TCDS will be upgraded in LS3.
- Dilution and dump system
 - High temperatures in dump core and large thermo-mechanical stresses in dump windows for HL-LHC beams expected.
 - Upgrade of dump windows required.
 - Strategy about dump and dilution upgrade to be defined in 2020.



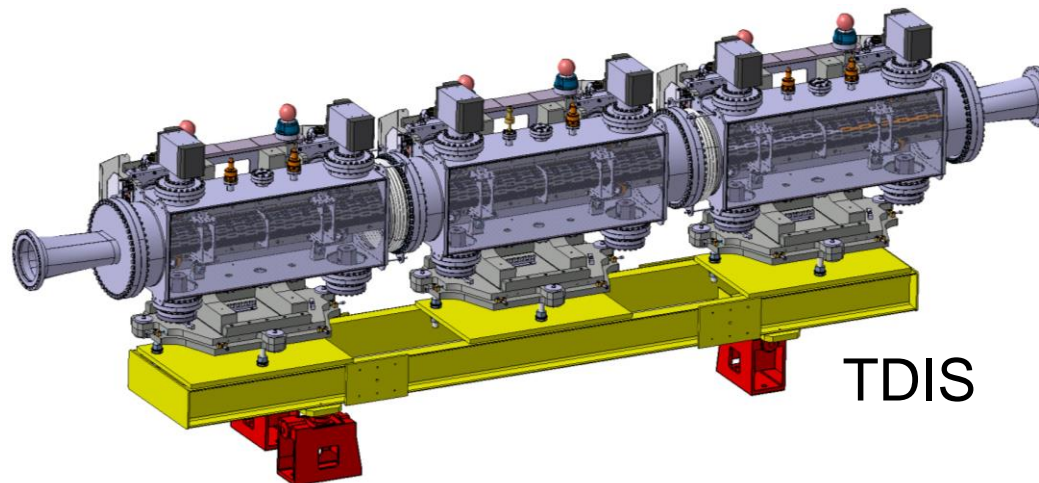
Thank you for your attention



Backup Slides

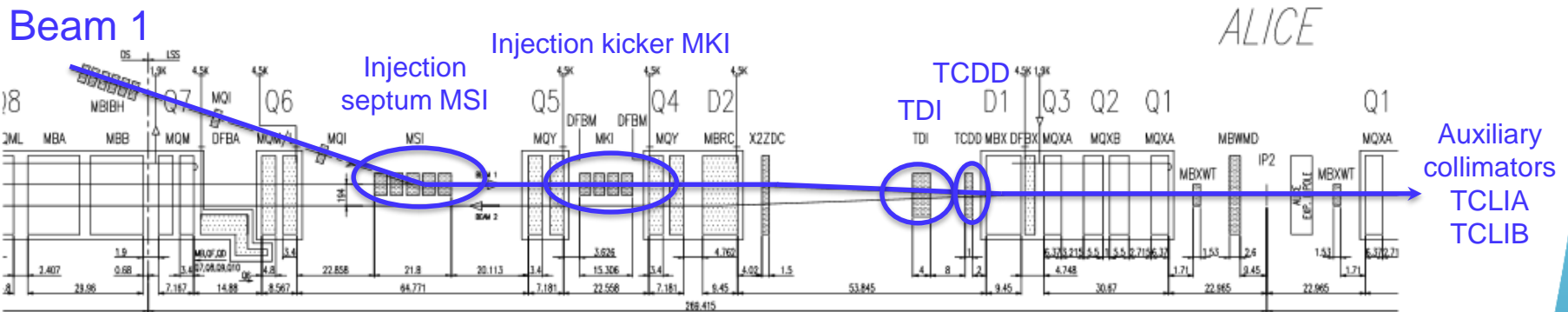
Injection protection devices

- TDI will be upgraded in LS2 to TDIS (reduced RF heating, less deformation and vacuum spikes, improved materials).
 - New design meets HL-LHC requirements for impact of 288b, 2.3×10^{11} ppb, $2.08 \mu\text{m}$
- D1 Mask: Additional passive protection that reduces energy density in D1 coil by factor of 2 (foreseen to be installed in LS2)
- Displacement of auxiliary injection protection collimator TCLIA foreseen for LS2 to allow HL-LHC Pb-Pb operation with 50 ns bunch spacing $100 \mu\text{rad}$ crossing angle in IR2



LHC Injection System

- 5 septa (MSI) and 4 fast pulsed injection kickers (MKI) per beam
- Injection beam stopper (TDI) for machine protection in case of MKI malfunctioning.
- Supplementary shielding device TCDD for D1 and auxiliary shielding TCLIA/B



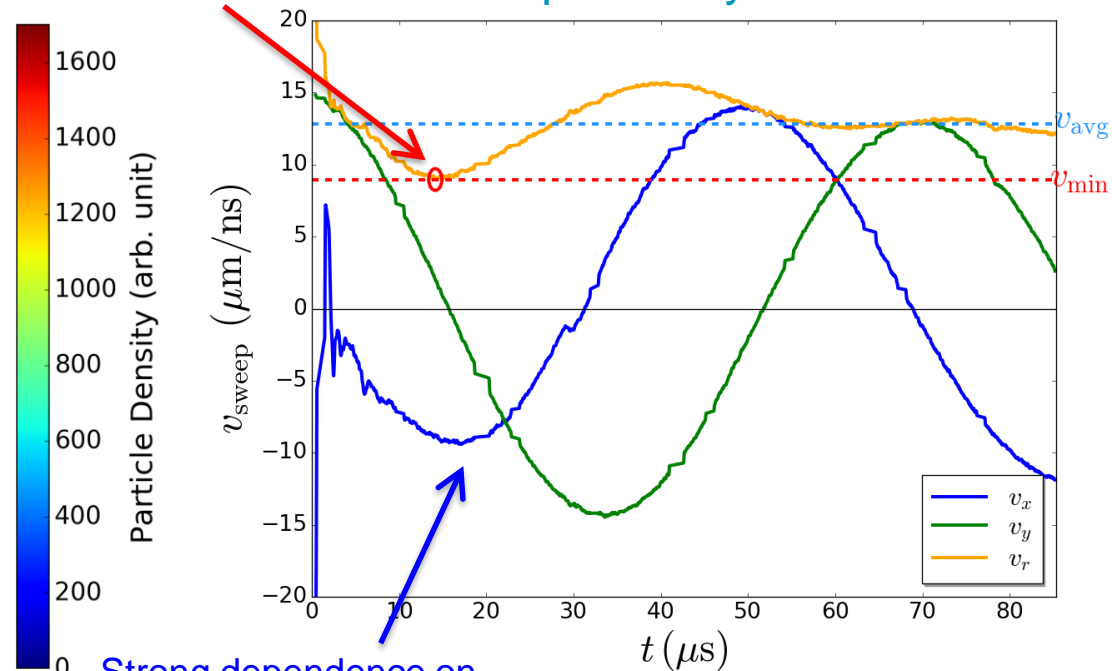
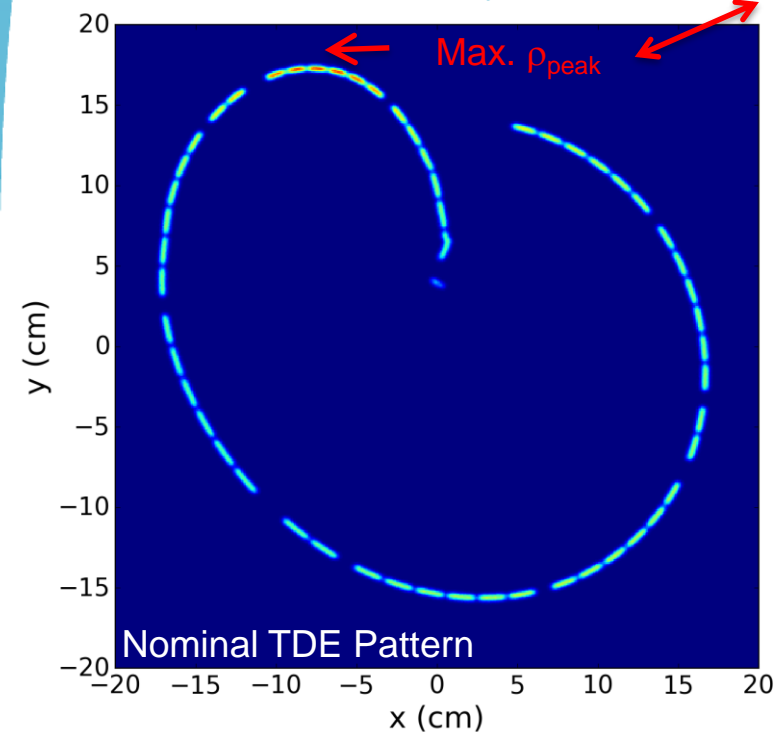
Dilution Strength – Nominal Case

- 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

$v_{\min} = 9.0 \mu\text{m/ns}$

Sweep Velocity at TDE



Strong dependence on horizontal sweep velocity.

MKB Erratics 2015-2017 (Operation)

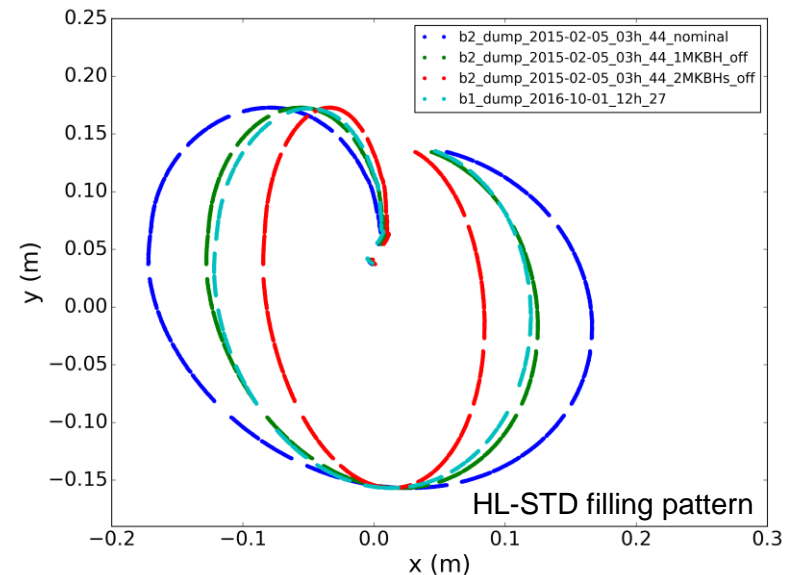
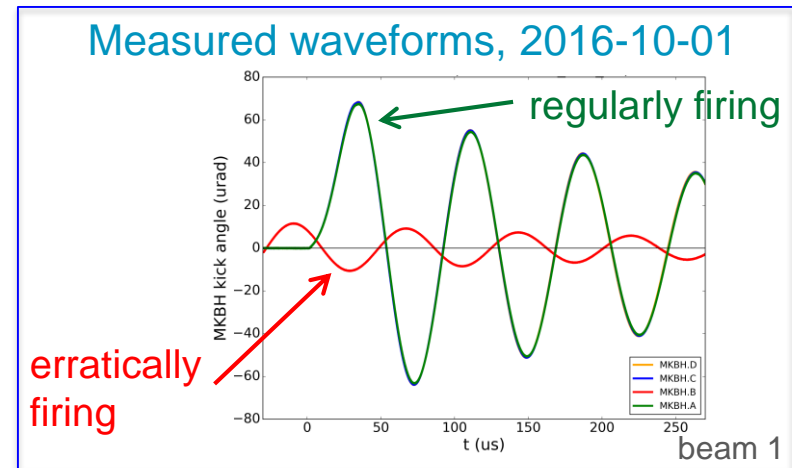
- Erratic firing only occurred for MKBH: 4x in 2015 and 2x in 2016, none in 2017.
- Antiphase can reduce effective dilution

Event	Gen.	t_{delay} (us)	N_p p+	#bunches
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: \rightarrow 71.5%

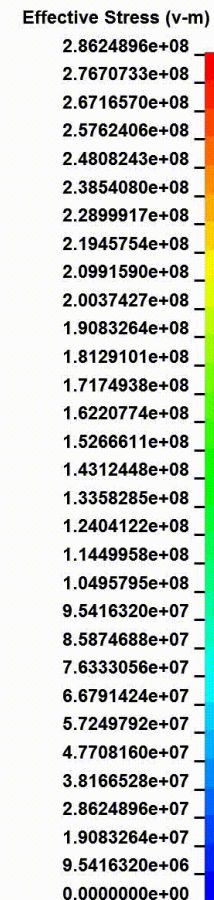
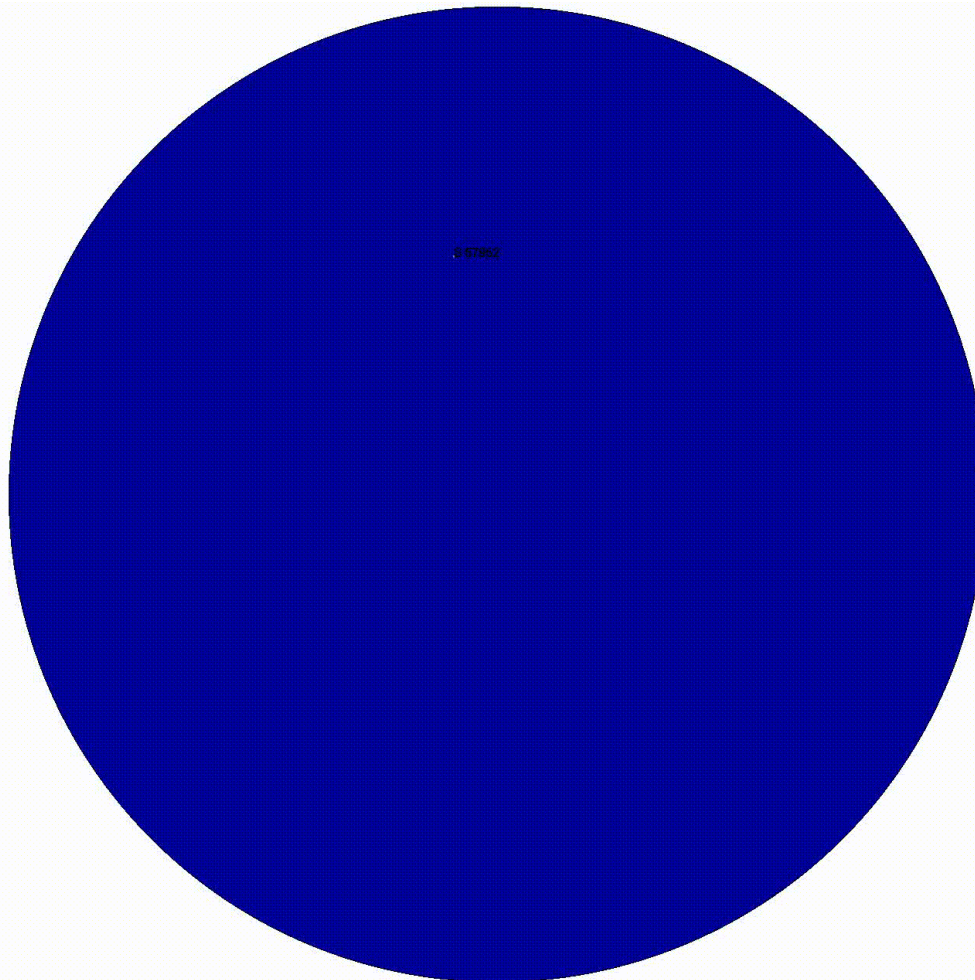
\rightarrow 74%

All events occurred at 6.5 TeV



Dynamic stresses in upstream window in case of 2 MKBH missing

TDE - Front Window - R3 - 6V2H
Time = 0
Contours of Effective Stress (v-m)
max IP. value
max=0, at elem# 17667
max displacement factor=0



T. Polzin

Beam Parameters and Filling Schemes

Simulations were carried out assuming the following **beam parameters**:

	RUN 2 (6.5 TeV)	HL-LHC (7 TeV)
BCMS	$I_b = 1.3 \times 10^{11}$ ppb	$I_b = 2.0 \times 10^{11}$ ppb
	$\epsilon_{x,y}^n = 1.37$ $\mu\text{m rad}$	$\epsilon_{x,y}^n = 1.37$ $\mu\text{m rad}$
STD	$I_b = 1.3 \times 10^{11}$ ppb	$I_b = 2.3 \times 10^{11}$ ppb
	$\epsilon_{x,y}^n = 2.6$ $\mu\text{m rad}$	$\epsilon_{x,y}^n = 2.08$ $\mu\text{m rad}$

Number of bunches and total beam intensities:

	RUN 2 (6.5 TeV)	HL-LHC (7 TeV)
BCMS	2556 b	2604 b
	$I_{\text{tot}} = 3.3 \times 10^{14}$ p ⁺	$I_{\text{tot}} = 5.2 \times 10^{14}$ p ⁺
STD	2556 b	2748 b
	$I_{\text{tot}} = 3.3 \times 10^{14}$ p ⁺	$I_{\text{tot}} = 6.3 \times 10^{14}$ p ⁺

(Simulations for Run 2 were performed using simulated MKB-waveforms assuming an upgrade of their capacitance (to be implemented in LS2). Nevertheless, the difference in the energy deposition calculations is only about 3% wrt present waveforms)

M. Frankl

Peak temperatures in the TDE graphite core

- Peak temperatures calculated in the **low-density graphite segment** of the TDE

RUN 2

°C		# active MKBV		
		6	5	4
# active MKBH	4	1040	1080	1170
	3	1190	1240	1300
	2	1480	1500	1570

HighLumi

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

Difference (in peak energy deposition)

%		# active MKBV		
		6	5	4
# active MKBH	4	+79	+74	+64
	3	+89	+82	+76
	2	+90	+90	+83

BCMS

°C		# active MKBV		
		6	5	4
# active MKBH	4	1010	1040	1130
	3	1140	1190	1250
	2	1420	1440	1510

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

%		# active MKBV		
		6	5	4
# active MKBH	4	+117	+113	+100
	3	+131	+121	+115
	2	+133	+133	+125

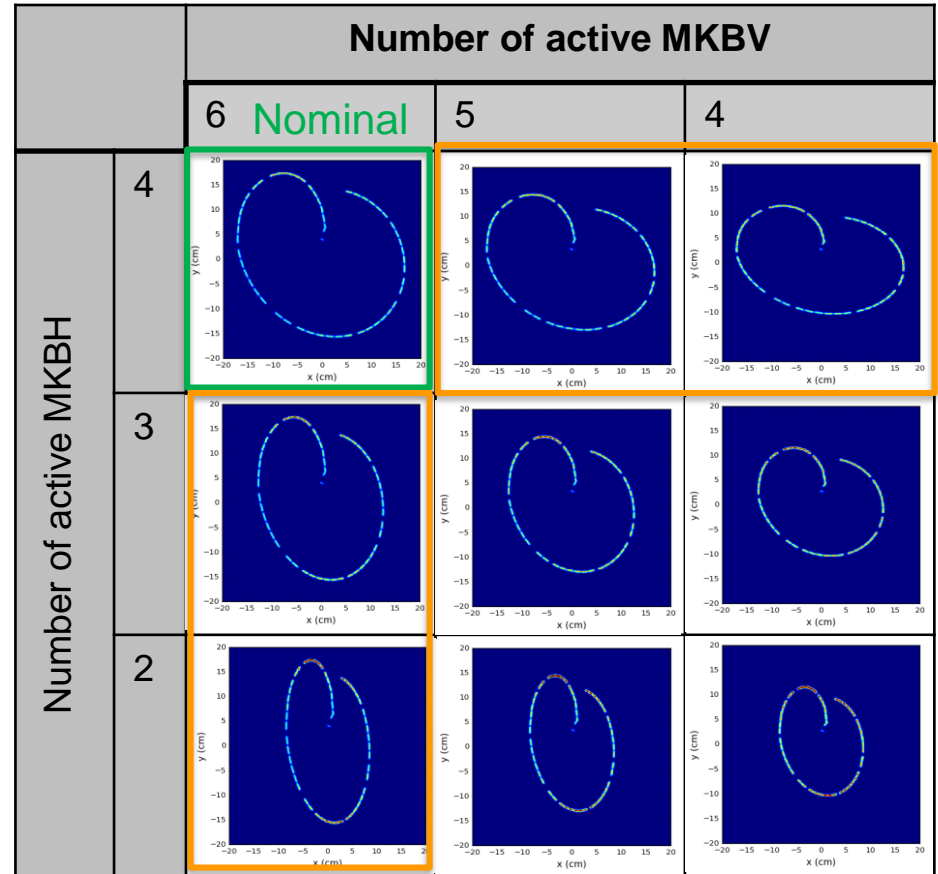
STD

- Already the peak temperature of a nominal HL-beam dump is higher than in case of 2 MKBHs missing in Run2.
- Thermo-mechanical behavior of the low-density core to be analyzed. However, comprehensive material characterization is missing up to now.

M. Frankl

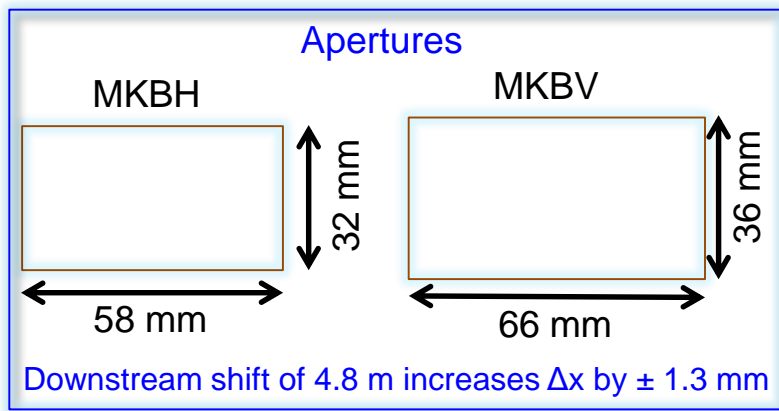
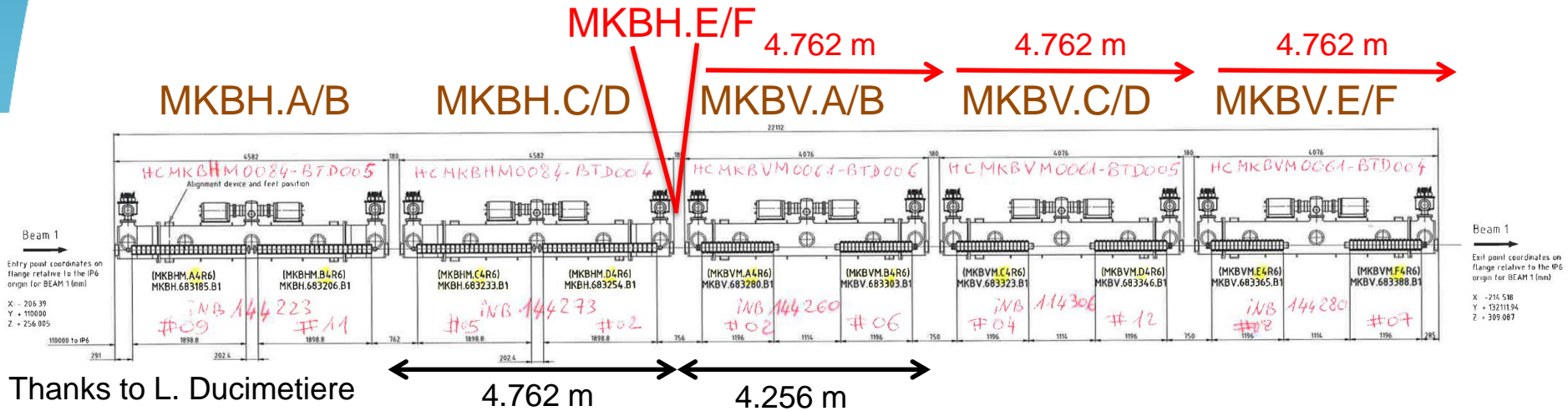
Dilution System – Failure Cases

- 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
- Newly observed failure mode (parasitic e-m coupling) could potentially lead to loss of >50% of dilution in one plane due to phase opposition between the MKB waveforms



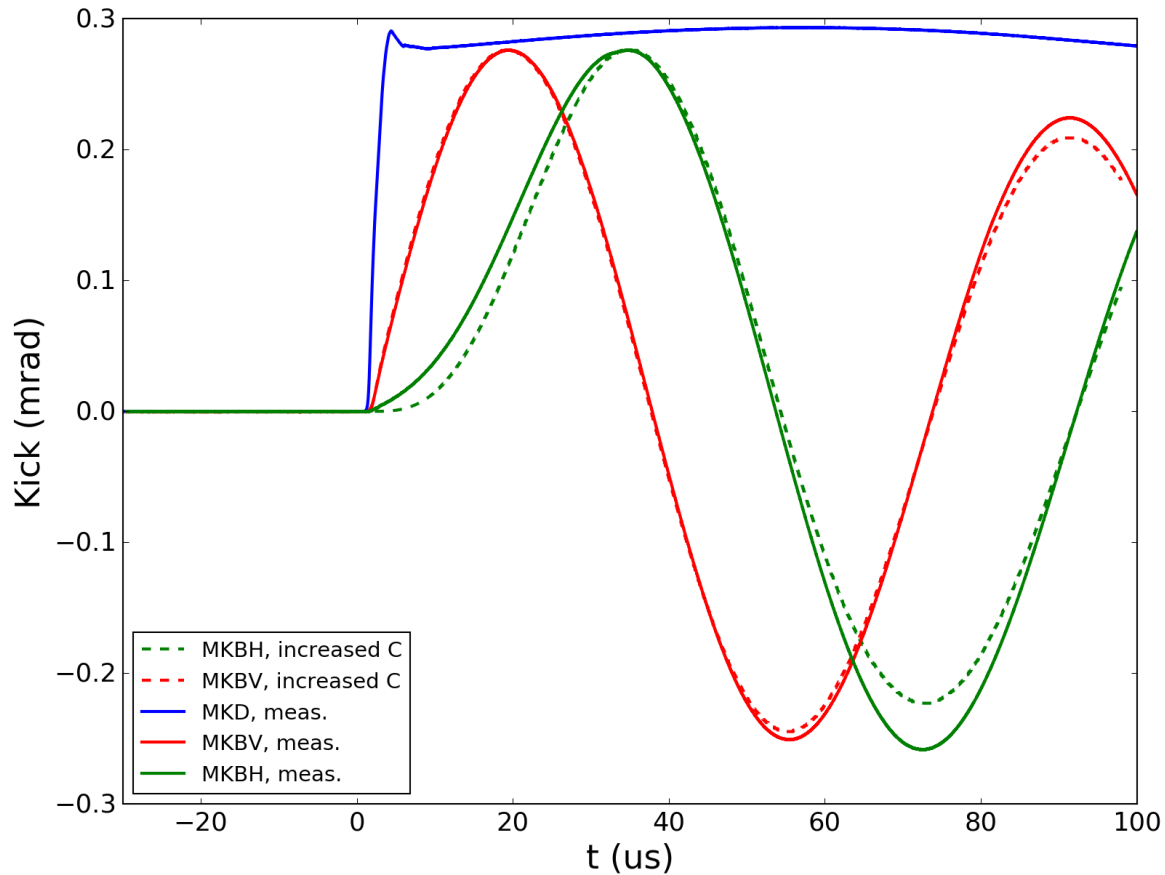
HL-LHC BCMS Filling Pattern

Adding 2 MKBH – Integration



Waveforms

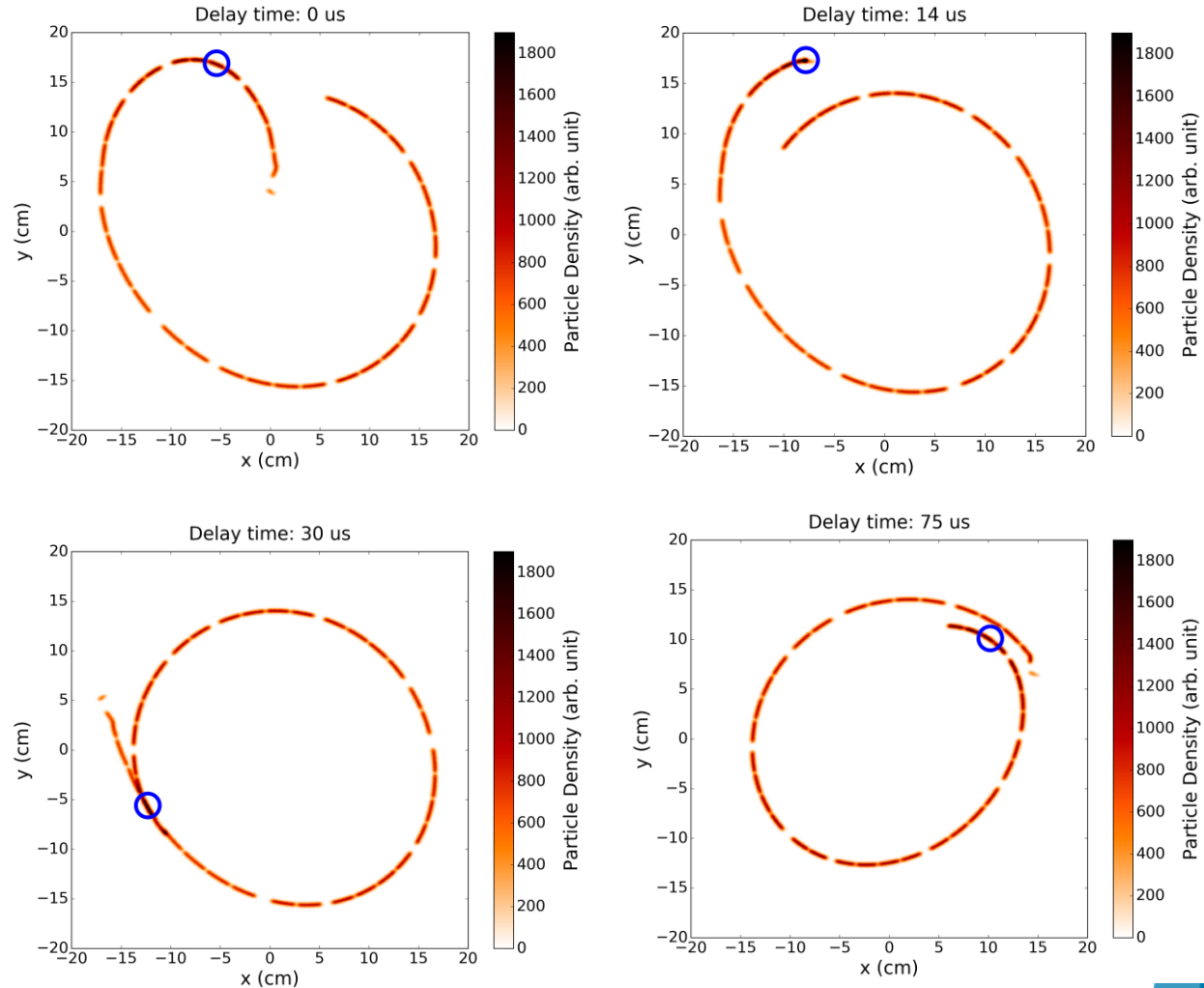
MKD, MKBH and MKBV waveforms



MKB Retriggering

- Risk of phase opposition between MKBs can be eliminated by (immediate) retriggering.
- However, assuming that an asynchronous beam dump should be avoided, this implies that the MKD are now fired with a certain time delay *after* the MKB, thus significantly changing the TDE pattern.
- Implementation is currently being studied for LS2.

HL-LHC standard filling scheme

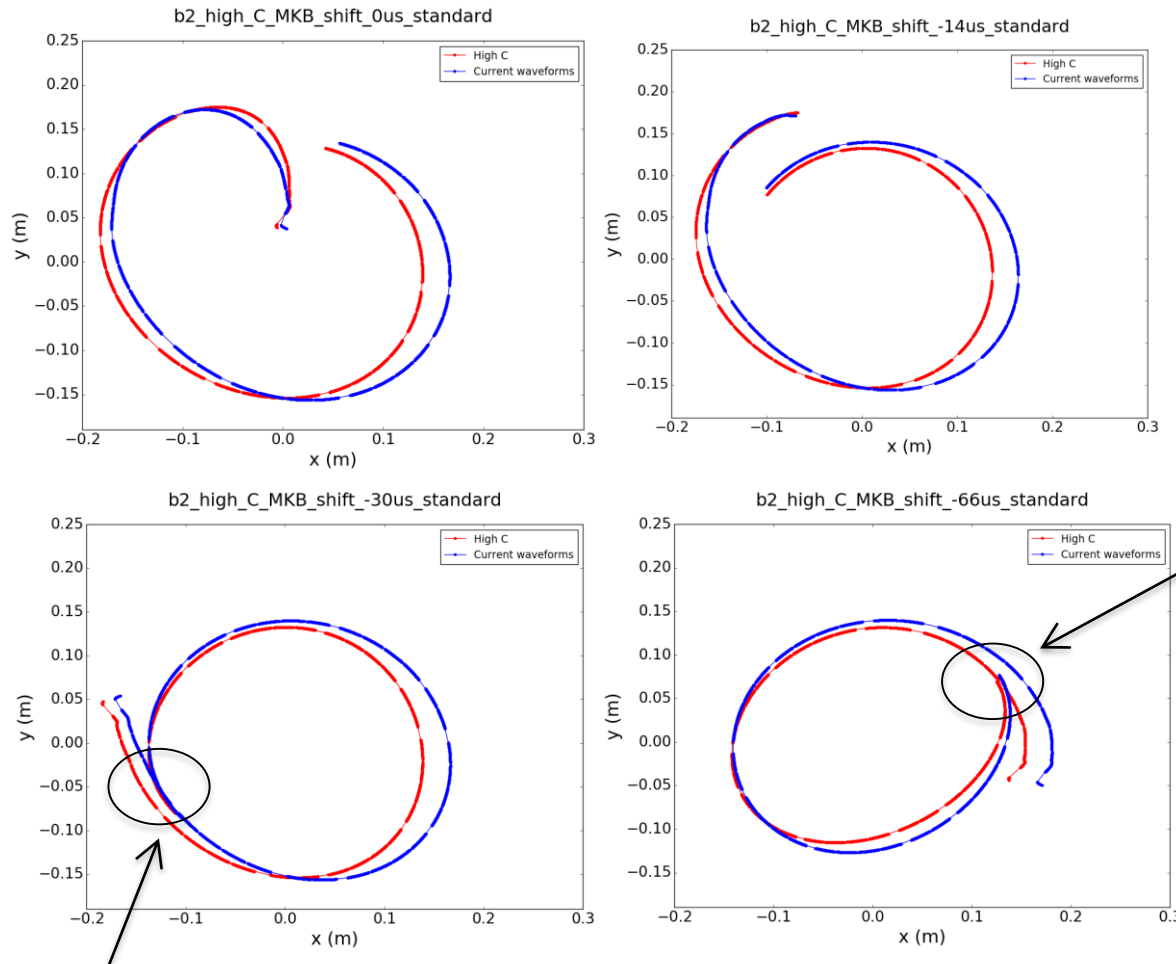


Run 2 waveforms

Retriggering of the Dilution Kickers (MKB)

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

Retrigger sweep patterns for Run 2 and Post-LS2 waveforms



Overlapping for Post-LS2 waveforms

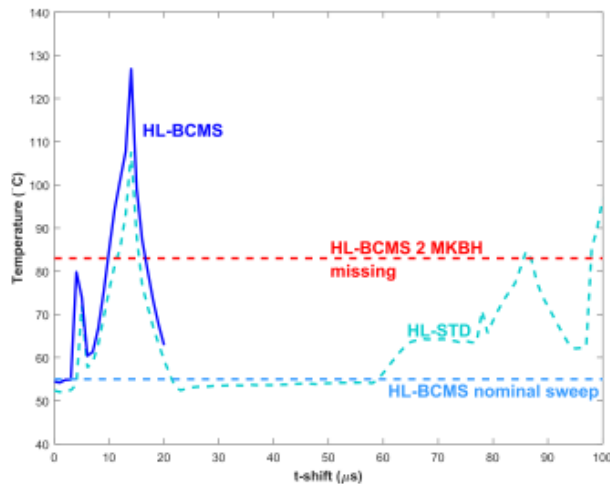
Overlapping for Run 2 waveforms

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

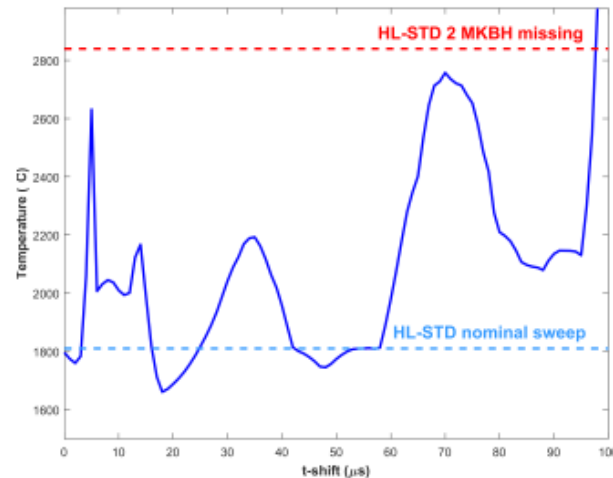
MKB-Retriggering: Temperatures in Core and Windows

- **Peak temperatures** calculated depending on the time delay between the retriggering and the arriving abort gap

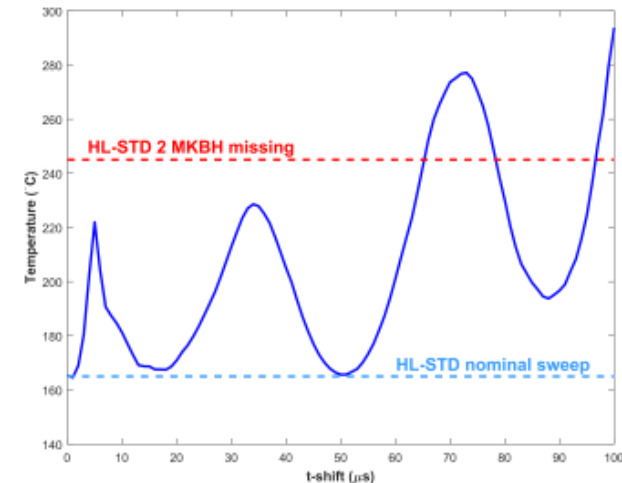
Upstream Window



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