# Energy deposition studies for extraction protection devices (TCDQ, TCDS) and the beam dump (TDE)

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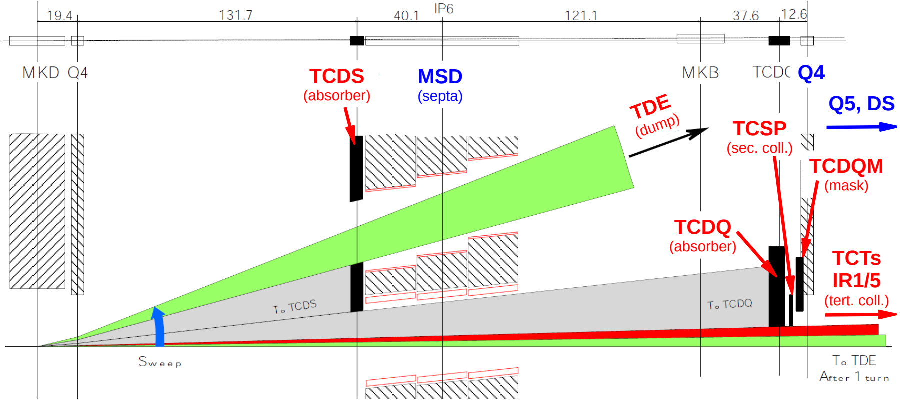
A. Perillo Marcone, F.X. Nuiry, T. Polzin, V. Rizzoglio, C. Wiesner

Studies carried out within **HL-LHC WP14**

HL-LHC Annual Meeting

Oct 18$^{th}$, 2018

# Introduction




**Outline:**

- Brief update on TCDQ (effect of smaller gaps)
- Recap of previous TCDS results + study plans for TCDS upgrade
- Summary of TDE studies (re-triggering in case of pre-fires) + first results for new flash-over scenarios

# Beam and optics parameters assumed for energy deposition studies

- **Assumed beam parameters:**

  → adopted a cautious approach, i.e. **no emittance growth and no intensity loss in ramp**

| **Beam** | $\epsilon^n_{x,y}$ | $I_b$ | **TDE component** |
|---|---|---|---|
| HL Std 25 nsec | 2.08 $\mu$m·rad | $2.3\times10^{11}$ | TDE downstream window, TDE core, TCDQ, TCDS |
| HL BCMS | 1.70 $\mu$m·rad | $2.3\times10^{11}$ | TDE upstream window (selected cases) |
| LIU BCMS | 1.37 $\mu$m·rad | $2.0\times10^{11}$ | TDE upstream window |

- **Optics:**

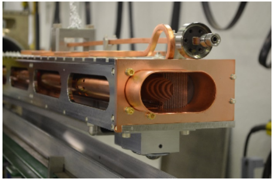
  → Studies were carried out with HL optics version V1.2

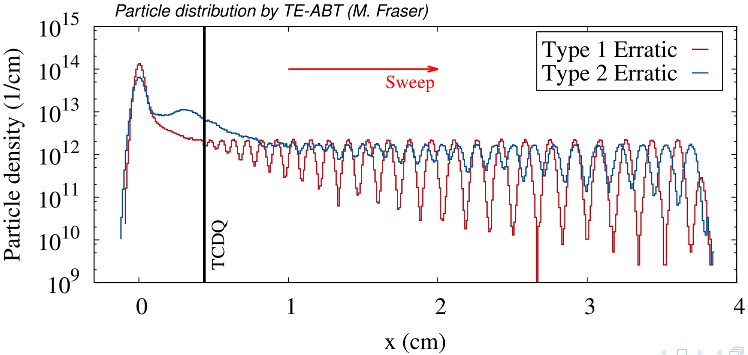
  → However, minimum $\beta$-function product at TCDQ, TCDS and TDE did only change moderately in the latest HL optics version (V1.4) - see R. De Maria, HL TCC #58, 20/09/2018

# Contents

# TCDQ upgrade history

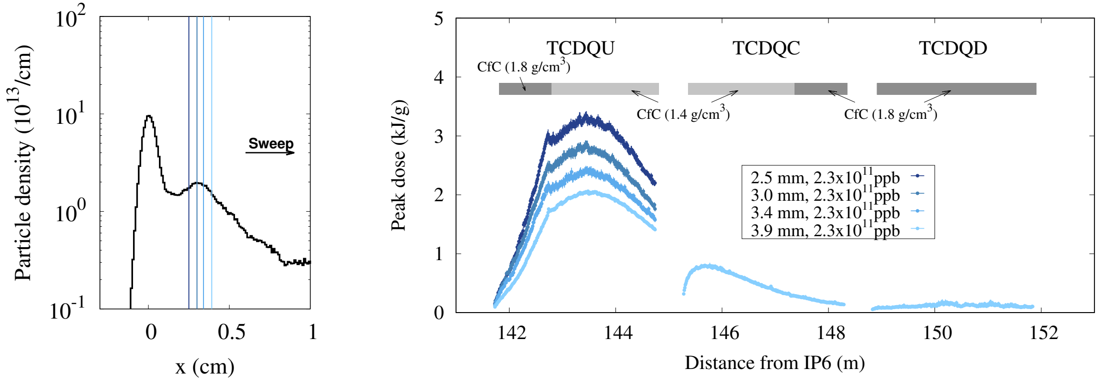
- Was **upgraded in LS1** (2→3 modules each 3 m long, Gr→CfC 1.4+1.8 g/cm$^3$)
- Upgrade studies at that time (FLUKA+ANSYS) considered HL beam parameters → load was found to be well within material limits
- However, **"new" MKD erratics observed in 2015**: particle density on TCDQ can be higher than assumed for LS1 upgrade → *might limit the allowed half-gap*
- **As of now, no further absorber material upgrade planned within HL-LHC (WP14)**





# Energy deposition in TCDQ (Type 2 MKD erratic)

*Longitudinal peak energy density profile in TCDQ for different half gaps (right figure), for a bunch intensity of* **$2.3\times10^{11}$ protons** *and an emittance of* **2.08 $\mu$m·rad***:*




→ *Not only peak dose (and hence temp.) inceases with smaller gap, but also horizontal dose gradient (temp. gradient)*

*M. Frankl*

# Energy deposition in TCDQ (Type 2 MKD erratic)

*Peak energy densities and temperatures for different half gaps and bunch intensities (temperatures rounded to 100° C):*

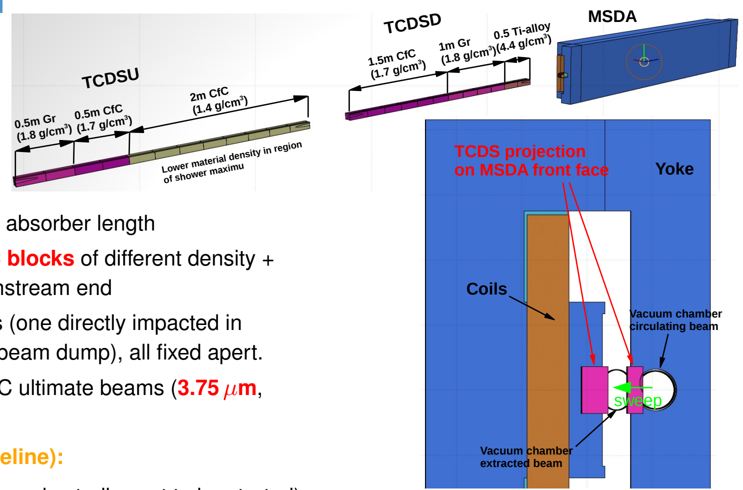
| | $1.4\times10^{11}$ | $1.7\times10^{11}$ | $2.0\times10^{11}$ | $2.3\times10^{11}$ |
|---|---|---|---|---|
| 2.5 mm | 2.0 kJ/g (1300°C) | 2.4 kJ/g (1500°C) | 2.8 kJ/g (1700°C) | 3.3 kJ/g (1900°C) |
| 3.0 mm | 1.7 kJ/g (1100°C) | 2.0 kJ/g (1300°C) | 2.4 kJ/g (1500°C) | 2.7 kJ/g (1600°C) |
| 3.4 mm | 1.5 kJ/g (1000°C) | 1.8 kJ/g (1200°C) | 2.1 kJ/g (1300°C) | 2.4 kJ/g (1500°C) |
| 3.9 mm | 1.3 kJ/g (900°C) | 1.5 kJ/g (1000°C) | 1.8 kJ/g (1200°C) | 2.1 kJ/g (1300°C) |

*M. Frankl*

→ *No simple scaling of stresses, ANSYS simulations needed – see talk of F.X. Nuiry for more details*

→ *Next: quantify energy deposition in magnets for small gaps (should still be OK)*

# Contents




- **Existing TCDS:**
  - **2 modules**, each with 3 m absorber length
  - made of **Graphite/2D CfC blocks** of different density + **Ti-alloy block** at the downstream end
  - each module has two jaws (one directly impacted in case of an asynchronous beam dump), all fixed apert.
  - has been designed for LHC ultimate beams (**3.75 $\mu$m**, **$1.7 \times 10^{11}$ ppb** )
- **HL-LHC upgrade, WP14 (baseline):**
  - 2 $\rightarrow$ 3 modules in **LS3** (upgrade studies yet to be started)

$\Rightarrow$ *impact distribution (particle density) on TCDS does not depend significantly on type of erratic*

$\Rightarrow$ *like for TCDQ, temperatures show limited sensitivity to emittance and beta-function*

# Energy deposition in TCDS (Type 2 MKD erratic)

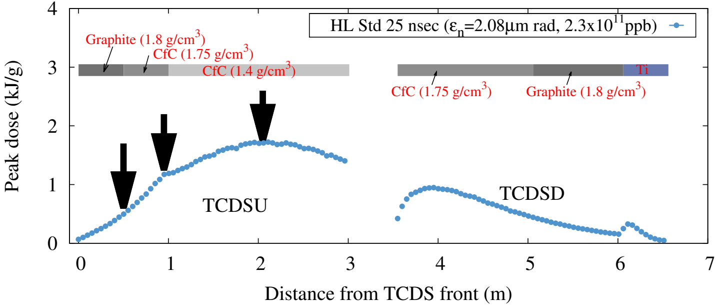
*M. Frankl, C. Di Paolo*

- *Peak temperatures and stresses for blocks with the* **highest peak load** *for a Type 2 MKD erratic*
- *Assumed a bunch intensity of* **$2.3\times10^{11}$ protons** *and an emittance of* **2.08 $\mu$m·rad**

| TCDS (low Z) | | | |
|---|---|---|---|
| Material | [illegible] | C-C 1.4 | Graphite |
| Max. Temp. [°C] | 798 | [illegible] | [illegible] |
| Max. Comp. Stress. [MPa] | **23** | **27** | [illegible] |
| Comp. Strength | 70 | 70 | 35 |
| Max. Tens. Stress. [MPa] | **18** | **51** | **38** |
| Tensile Strength | 61 | 84 | 35 |

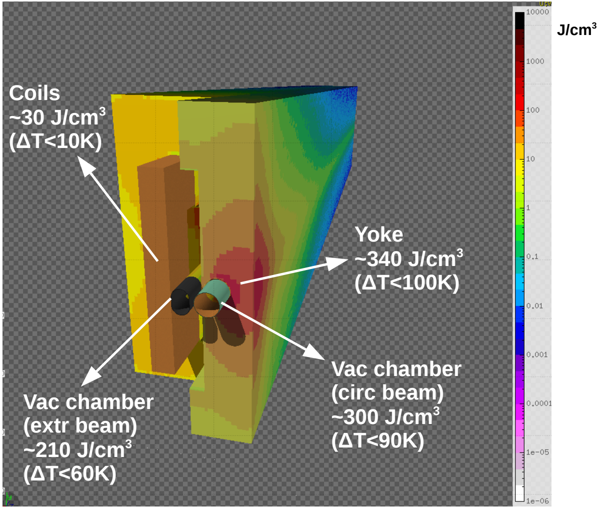
| TCDS (Ti6Al4V) | | | |
|---|---|---|---|
| | Area at Max T | Area at Max stress | Area at Max plastic strain |
| Temp. [°C] | **568** | **164** | **255** |
| | **308** | **711** | **601** |
| Yield Strength | [illegible] | [illegible] | 529 |
| Tensile Strength | 358 | 734 | 645 |

**Details in talk of F.X. Nuiry**




→ *CfC: OK, Graphite: max. tensile stress above tensile strength, Ti: plastifies (strain is 1.2%)*

# Energy deposition in septa (Type 2 MKD erratic)



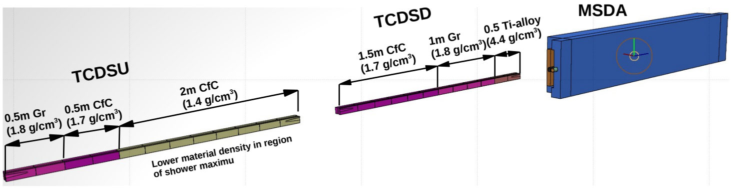

*M. Frankl*

- Energy deposition density in first MSD for a Type 2 MKD erratic
- For a bunch intensity of **2.3 $\times$ 10$^{11}$ protons** and an emittance of **2.08 $\mu$m·rad**

$\rightarrow$ *temperature increase seems not too high*

$\rightarrow$ *details to be looked at with septa experts*

# Studies for TCDS upgrade - outlook

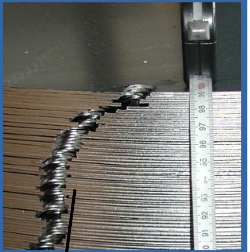


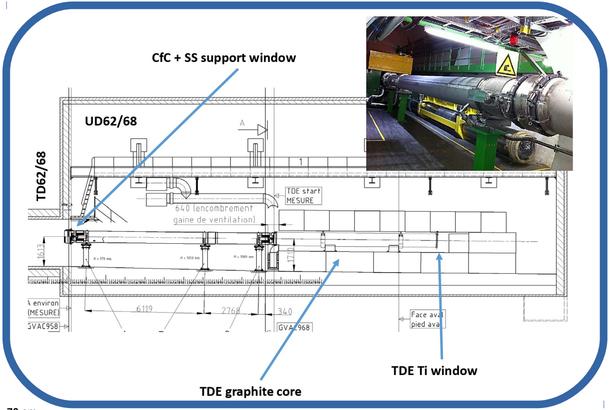

- **Some general remarks about the absorber materials:**
  - Present material sandwich → optimized for **longitudinal shower development at 7 TeV**
    - lower material density at shower maximum
    - weaker but more absorbing materials in shower build-up and shower tail region
  - Just adding a third module to the two existing ones → **non-optimal solution** (maybe even worse for TCDS) (note: the first module as it is now cannot be moved upstream since block thickness changes along TCDS)
- **Possible approach (from an absorber perspective):**
  - Design a new upstream module (to be placed upstream of the present two modules)
  - Exchange blocks in the second module (=present upstream module) → to be looked at if feasible

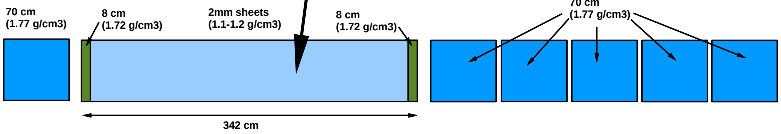
→ *will launch first conceptual studies (energy deposition) in LS2*

# Contents

***TDE core:***
*low and high-density graphite segments*






SIGRAFLEX FOIL
Characteristic data for a graphite bulk density of 1.0 g/cm³

| | | |
|---|---|---|
| Thermal stability | | Can be used from -250°C up to approx. 3000°C (in protective gas) |
| Sublimation temperature | °C | > 3000 |

# TDE windows

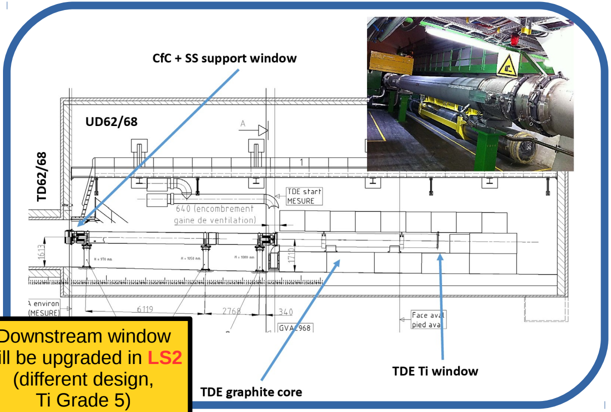
***Upstream window:*** → *exposed to swept bunches*

- **Isolates** dump transfer line **vacuum** from **nitrogen atmosphere**
- **CfC** for **robustness** reasons, **leak tightness** assured by a **thin steel layer**

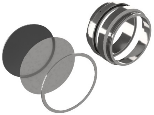
| | Thickness | Material | Density |
|---|---|---|---|
| #1 | 15 mm | CfC (® SIGRABOND 1501G) | ∼1.5 g/cm$^3$ |
| #2 | 0.2 mm | Stainless steel (AISI 316L) | 8 g/cm$^3$ |

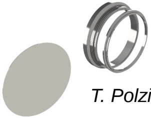
***Downstream window:*** → *exposed to longitudinal shower tail from TDE core*

| | Thickness | Material | Density |
|---|---|---|---|
| #1 | 10 mm | Titanium Grade 2 (ASTM B265) | 4.5 g/cm$^3$ |




Downstream window will be upgraded in LS2 (different design, Ti Grade 5)

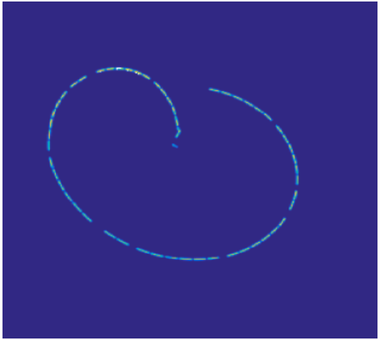




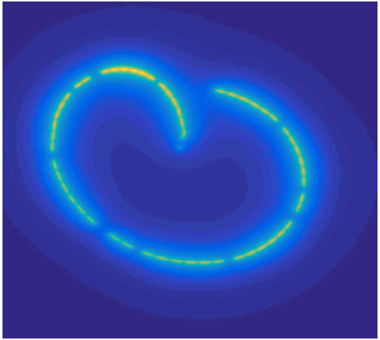
*T. Polzin*

*Transverse energy density map:*

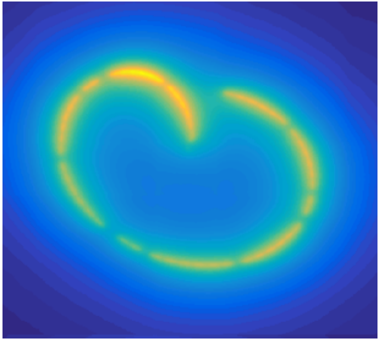
***Upstream window (steel foil):***



***Core:***



***Downstream window:***

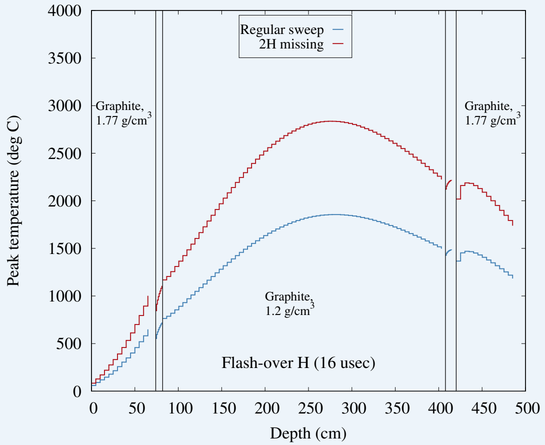


→ *plots are in arbitrary units, but should illustrate the effect of showers*

→ *peak energy density in upstream window depends on* **transverse spot size** *and* **bunch intensity**

→ *peak energy density in downstream window depends* **only on bunch intensity**

# Temperatures in the dump core with HL-LHC beams




*Peak temperatures (°C) in the TDE core for* **$2.3\times10^{11}$** *bunch intensity,* **$2.08\mu$m** *emittance*

| °C | | # active MKBV | | |
|---|---|---|---|---|
| | | 6 | 5 | 4 |
| # active MKBH | 4 | 1850 | 1890 | 1960 |
| | 3 | 2240 | 2260 | 2320 |
| | 2 | 2830 | 2890 | 2950 |

⇒ *In the case of 2H kicker failing* **peak temperature close to sublimation temperature in inert atmosphere**

⇒ *Analysis of stresses* → **better material characterization needed** *(ongoing in EN/STI/TCD)*

*Figure/table from M. Frankl*

# Dilution failure scenarios

*From C. Wiesner*

**Generator**

**Magnet (vacuum tank)**

***What we considered as worst case two years ago ...***

***Erratic pre-fire of a single MKBH***
*Loss of <40% in H plane (antiphase to other kickers)*

***Flash-over leads to loss of dilution, can affect 2 MKBHs in the same tank***
*Loss of 50% in H plane*

***What we know now ...***

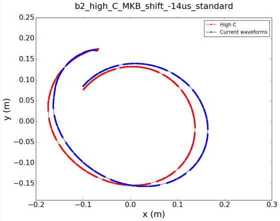
See:
MPP 27/04/2018
LMC 01/08/2018
MPP 28/09/2018
HL TCC 04/10/2018

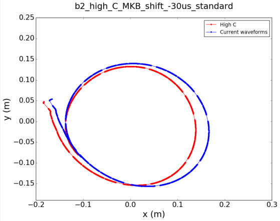
***Common cause failures can lead to pre-fire of two kickers***
*Loss of >70% in H plane in case of double erratic (antiphase to other kickers)*
**observed end of 2016**

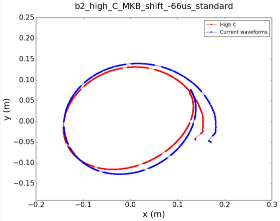
***Current can persist in magnet after flash-over, can affect 2 MKBHs in the same tank***
*Depending on phase can lead to crossing sweep pattern*
**observed in summer 2018**

**NEW**

- **Pre-firing of more than one MKB:**
  - Common cause failures identified
    - → parasitic EM coupling between generators → erratic firing of one MKB could also trigger adjacent MKBs
    - → noise on retrigger line
  - If in anti-phase with other MKBs, could lead to **loss of more than 50% of dilution in one plane**
    - → e.g. **pre-fire of 2 MKBs → worst case loss of roughly 75% (3 MKBH missing)**
- **Mitigation measure:**
  - Installation of MKB retrigger system in **LS2**: pre-fire → retrigger all MKBs → execute synchronous dump
  - **Dilution pattern changes with reaction time ($<6\ \mu$sec) + delay until arrival of abort gap ($<89\ \mu$sec)**
    → temperatures and stresses in windows (and core) depend strongly on the eventual delay



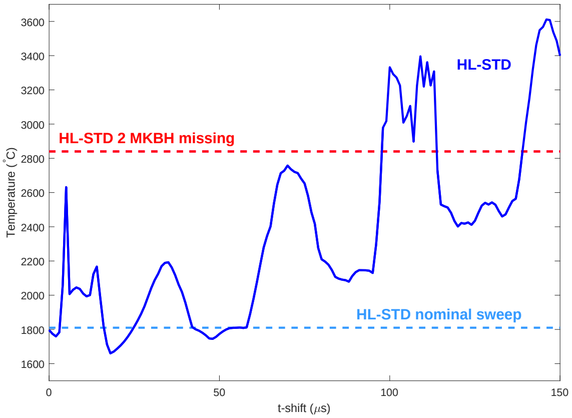




*Figures and info from C. Wiesner*

# Effect of pre-fires after LS2 upgrades

- **Effect of retriggering on peak temperature in core:**




*C. Wiesner and M. Frankl*

- *Peak temperatures in the TDE core for* **$2.3\times10^{11}$** *bunch intensity,* **$2.08\mu$m** *emittance, for different delays between erratic and arrival of abort gap*

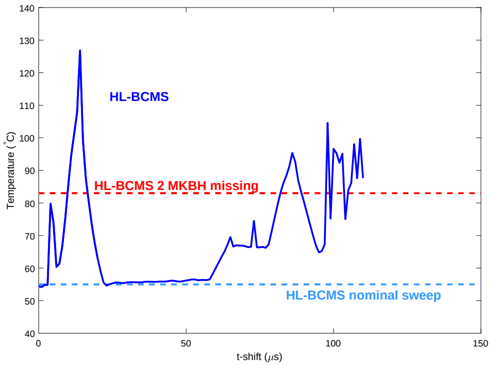
- *Figure:*
  - $\rightarrow$ *blue dashed line: regular sweep*
  - $\rightarrow$ *red dashed line: 2 MKBH missing*
  - $\rightarrow$ *dark blue line: retrigger (diff. delays)*

- *For delays $<96\mu$sec (= max. possible delay),* **peak temperature in the core smaller than for the case** *where 2oo4 MKBH missing*

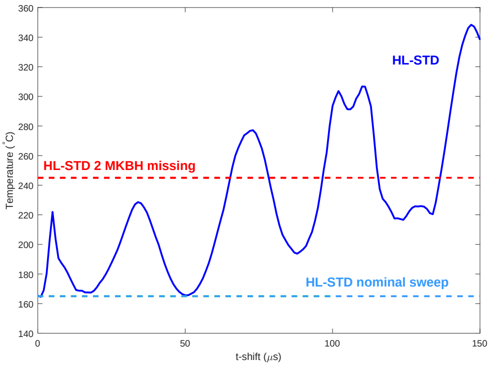
# Effect of pre-fires after LS2 upgrades

- **Effect of retriggering on peak temperature in windows:**

*Peak temp in upstream window for* **$2.0 \times 10^{11}$** *bunch intensity,* **$1.37\mu$m** *emittance (BCMS):*




*Peak temp in downstream window for* **$2.3 \times 10^{11}$** *bunch intensity,* **$2.08\mu$m** *emittance:*

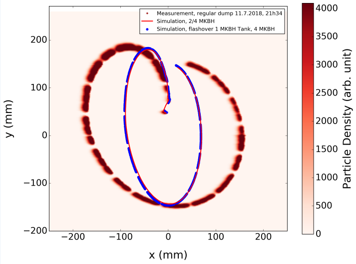



*C. Wiesner and M. Frankl*

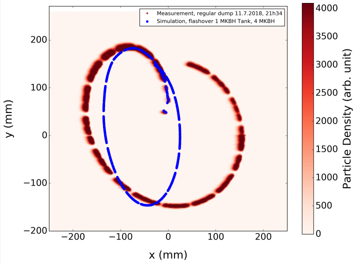
*For detailed thermo-mechanical assessment → see talk of T. Polzin.*

- **Flash-over of two MKBs in the same tank:**
  - Event in July 2018 confirmed assumption that flash-over **can propagate to second magnet in the same tank**
  - This event in itself was not the worst case (was in V plane), but showed that our previous worst-case assumption (loss of two H kickers) is not the worst flash-over case since the **current in the magnet can persist**
- **What happens if such a flash-over occurs in the horizontal plane?**

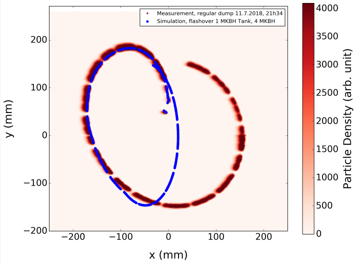
*1st flash-over@0.0 $\mu$sec:*




*1st flash-over@16 $\mu$sec:*




*1st flash-over@39 $\mu$sec:*

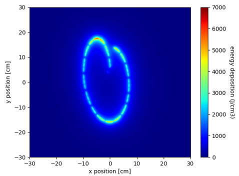



*Figures from C. Wiesner ($\Delta t$ between the 1st and 2nd flash-over fixed to 10 $\mu$sec)*

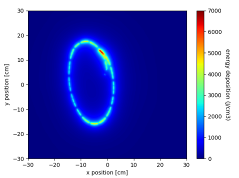
# Flash-over during dump execution

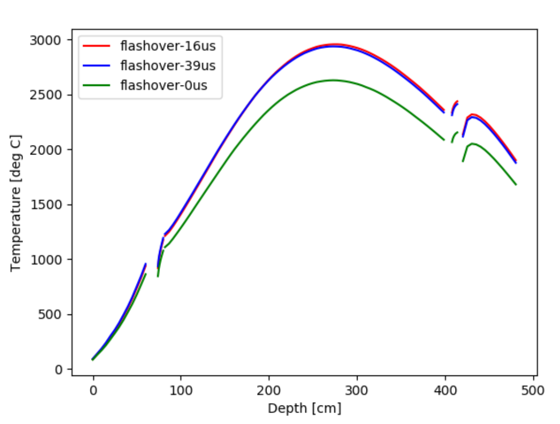
*Right figure: peak temperatures ($^\circ C$) in the TDE core for* **$2.3\times10^{11}$** *bunch intensity,* **$2.08\mu$m** *emittance:*

*1st flash-over@0.0 $\mu$sec:*




*1st flash-over@16 $\mu$sec:*




$\Rightarrow$ *Preliminary results indicate that new case gives roughly 12% higher energy density than previous worst case*

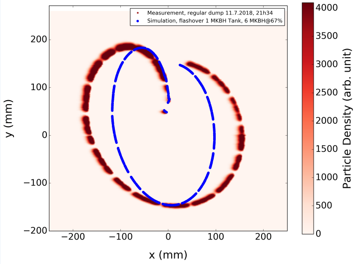
*Figures from V. Rizzoglio*

*Effect on windows to be studied*

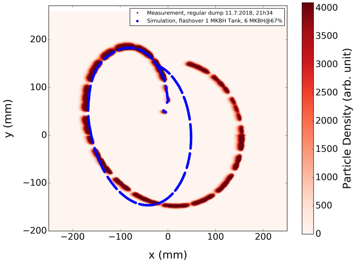
- **Short term:**
  - More systematic assessment of new flash-over failure scenarios
- **Medium term:**
  - Quantify in more detail the effect of additional dilution kickers (modified pattern, flash-over)
  - Carry out conceptual studies for alternative core materials

*Flash-over 2 MKBH in case of 6 horizontal kickers (@67% of the present nominal voltage):*

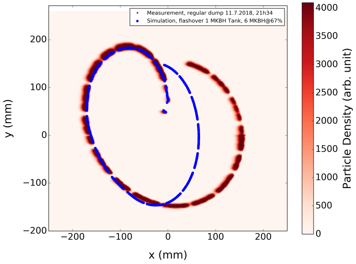
*1st flash-over@0.0 $\mu$sec:*




*1st flash-over@28 $\mu$sec:*




*1st flash-over@39 $\mu$sec:*



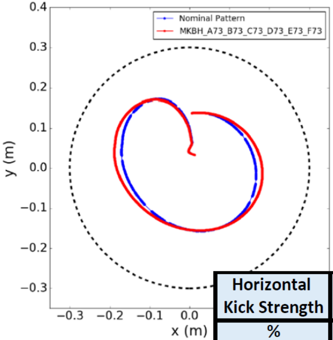

*Figures from C. Wiesner*

# Contents

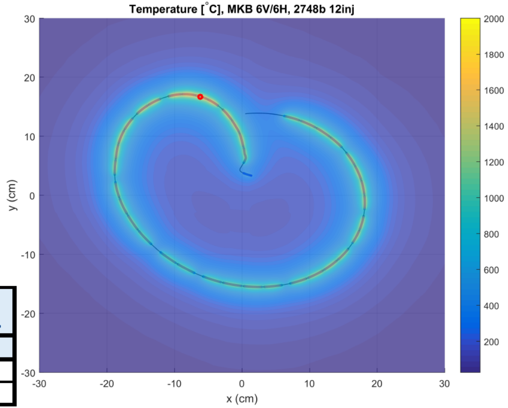
# 2 additional H kickers: increasing the kick strength?

*Peak temperature in the dump core for a regular sweep with increased H dilution strength (**2.3 × $10^{11}$ ppb**):*

*110 %*




| Horizontal Kick Strength | Temp. |
|---|---|
| % | °C |
| 100 | 1860 |
| 110 | 1760 |

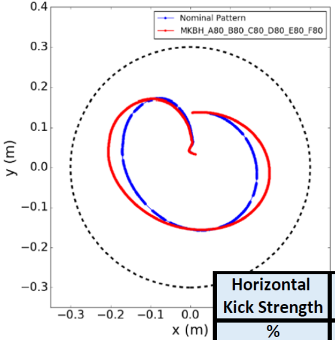



*From M. Frankl*

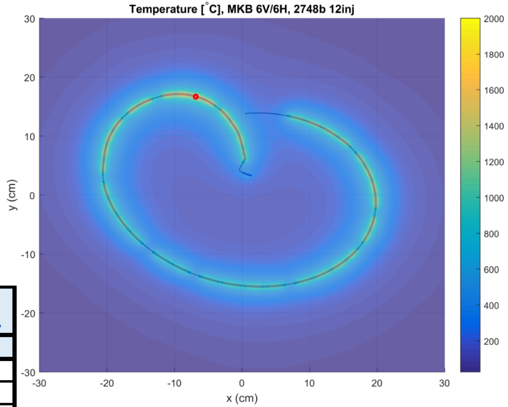
# 2 additional H kickers: increasing the kick strength?

*Peak temperature in the dump core for a regular sweep with increased H dilution strength (**$2.3\times10^{11}$ ppb**):*

*120 %*




| Horizontal Kick Strength | Temp. |
|---|---|
| % | °C |
| 100 | 1860 |
| 110 | 1760 |
| 120 | 1660 |

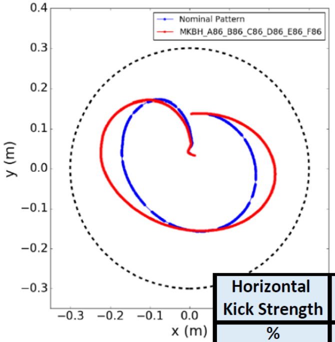



*From M. Frankl*

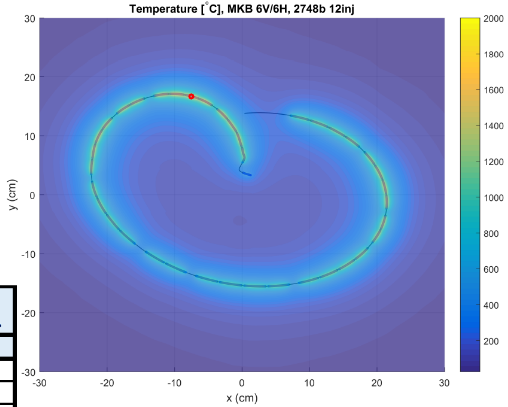
# 2 additional H kickers: increasing the kick strength?

*Peak temperature in the dump core for a regular sweep with increased H dilution strength (**$2.3\times10^{11}$ ppb**):*

*130 %*



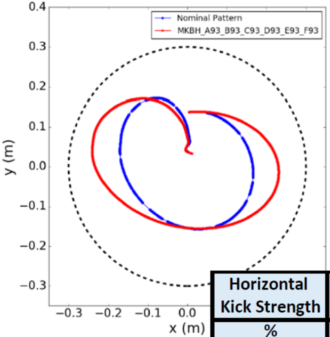

| Horizontal Kick Strength | Temp. |
|---|---|
| % | °C |
| 100 | 1860 |
| 110 | 1760 |
| 120 | 1660 |
| 130 | 1580 |

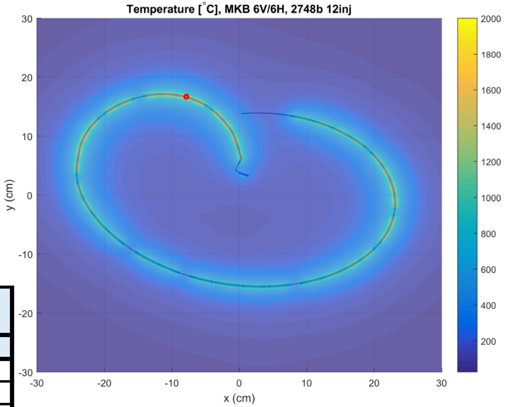



*From M. Frankl*

*Peak temperature in the dump core for a regular sweep with increased H dilution strength (**$2.3\times10^{11}$ ppb**):*

*140 %*

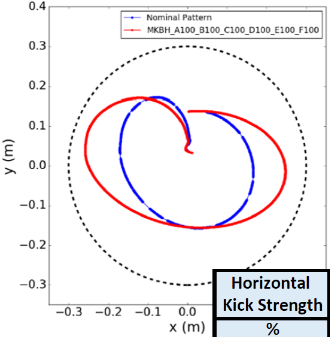


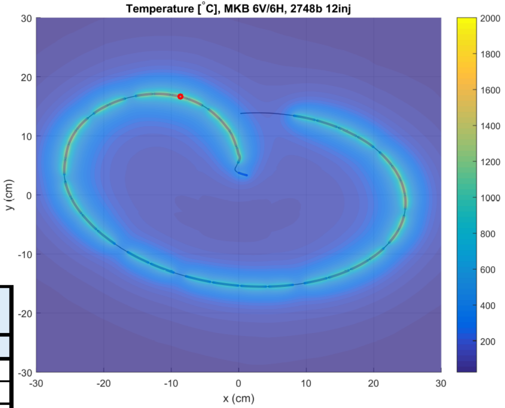

| Horizontal Kick Strength | Temp. |
|---|---|
| % | °C |
| 100 | 1860 |
| 110 | 1760 |
| 120 | 1660 |
| 130 | 1580 |
| 140 | 1510 |

*From M. Frankl*

*Peak temperature in the dump core for a regular sweep with increased H dilution strength (**2.3×10$^{11}$ ppb**):*




*150 %*



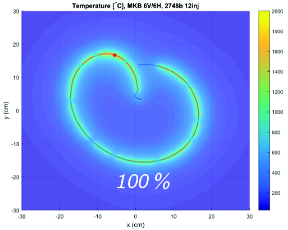

| Horizontal Kick Strength | Temp. |
|---|---|
| % | °C |
| 100 | 1860 |
| 110 | 1760 |
| 120 | 1660 |
| 130 | 1580 |
| 140 | 1510 |
| 150 | 1440 |

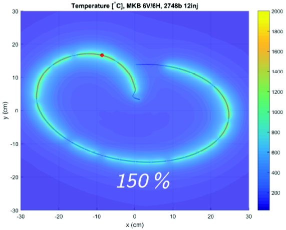
→ *Energy deposition in the steel jacket?*

→ *Energy deposition in downstream flange?*

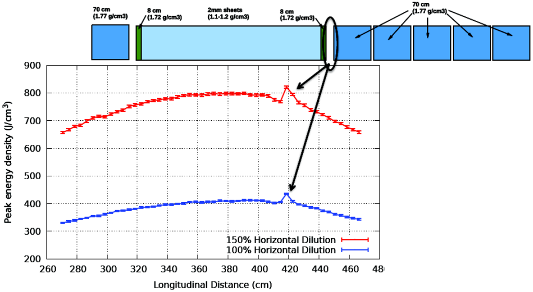
*From M. Frankl*

# 2 additional H kickers: increasing the kick strength?




- Peak energy density calculated in the stainless steel jacket:

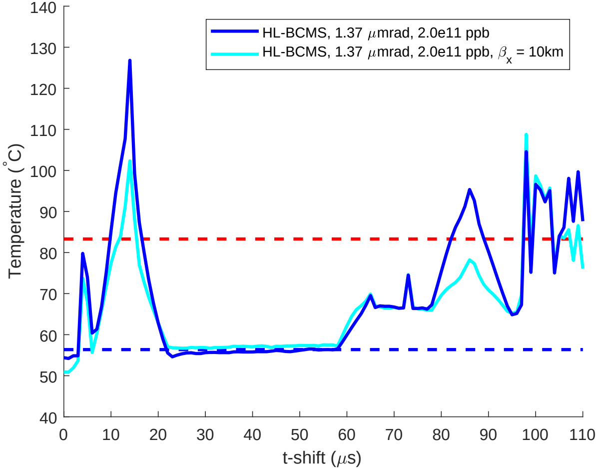



Peak energy density in the tube at 150 % horizontal dilution would roughly double compared to 100 %.

*Acceptable? → Thermo-mechanical analysis required...*

# Other measures to reduce the peak load - change of optics?

*Effect of larger $\beta_x$ on temperature in upstream windows:*




*All results are for* **2.0×10^11** *bunch intensity,* **1.37µm** *emittance (BCMS beams)*

- *Figure: peak temperatures*
  - → *dark blue solid line: $\beta_x$=5 km (now)*
  - → *light blue solid line: $\beta_x$=10 km*

  *(preliminary results)*

**→ doubling $\beta_x$ leads to a ∼20% reduction in peak temperature (for case with highest stresses)**