Energy deposition and thermo-mechanical studies for the LHC dump

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On behalf of HL-LHC WP14

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Introduction

Scope of this talk:

- Overview of the beam **dump (TDE)**
- Description of a **regular beam sweep**
- **Simulation methodology** for the calculation of the energy deposition in the TDE
- **Energy deposition** results for the TDE core (**HL beam parameters** and **HL optics**):
  - HL Std 25 nsec vs. LIU BCMS
  - regular Std beam sweep vs. failure scenarios
- **Peak temperatures** in the TDE core and windows
- Assessed **stresses** in window materials based on **thermo-mechanical studies** (ANSYS)

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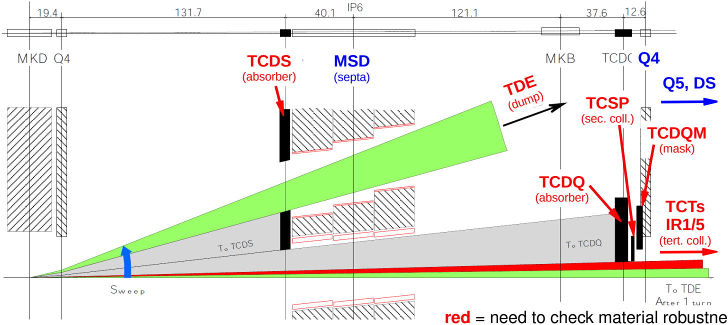
Protection devices/dumps and failure scenarios



red = need to check material robustness
blue = need to check if sufficiently protected

- Single MKD module prefire:
  - TCDS → MSDs
  - TCDQ+TCDQM → Q4, Q5, DS magnets
  - TCTs → IR1/5 triplet, D1 (studied by WP5+WP10)
- Dilution (MKB) failure:
  - **TDE core** and **TDE windows**, covered by this presentation

Assumed beam and optics parameters

- **Beam parameters:**
  - Assumed the **same normalized emittance** and **bunch intensity** as for
    → **LIU** protection/dump upgrades in **SPS/TLs** and
    → **HL-LHC WP14** protection upgrades in the **LHC injection regions**

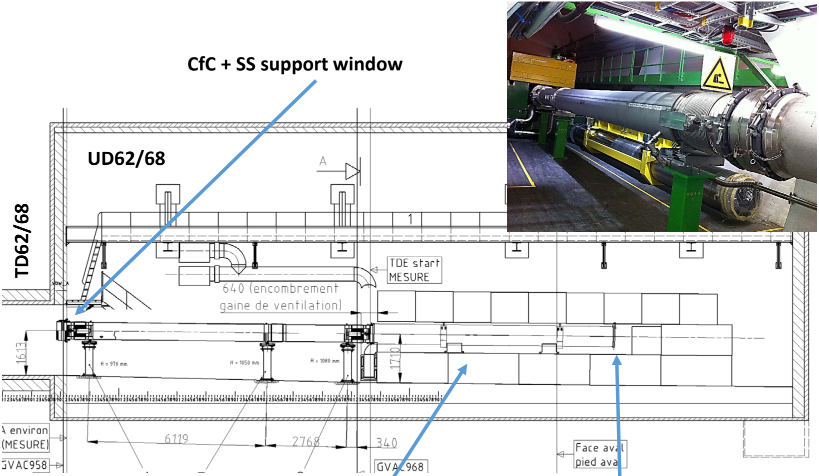
Beam	$\epsilon^n_{x,y}$	I_b
HL Std 25 nsec	2.08 μm·rad	2.3×10^{11}
LIU BCMS	1.37 μm·rad	2.0×10^{11} (*)

  - This is a cautious approach, i.e. no emittance growth and no intensity loss in ramp

- **Optics:**
  - All studies carried out for optics version **HLLHCV1.2**
  - For each device, **selected the worst case** from flat/flat HV/round optics

TDE location

CfC + SS support window



UD62/68

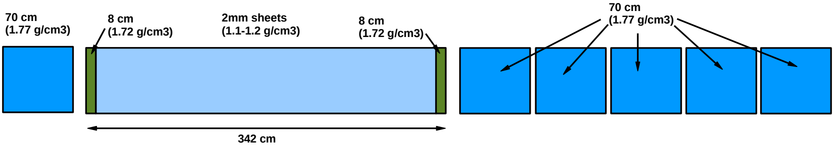
TD62/68

TDE graphite core

TDE Ti window

Material composition of the TDE core

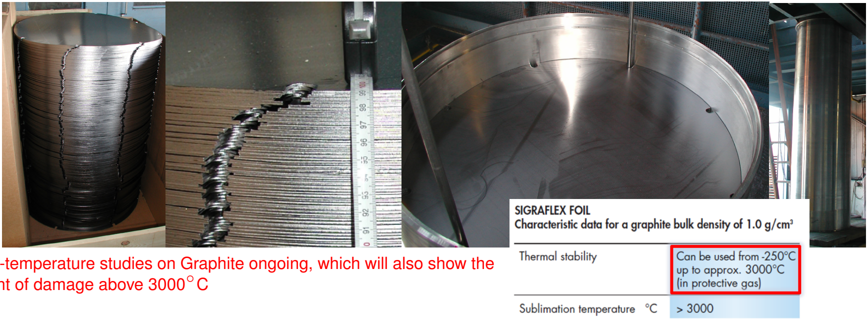
Segmented TDE layout:



- LHC dump core consisting of high- and low-density graphite absorbers
- **Diameter** of **70 cm** and a total absorber **length** of **∼7.6 m**
- **High-density** absorber blocks consist of **polycrystalline graphite**
- Graphite segments are shrink-fitted into a **12 mm** thick **stainless steel jacket**

Material composition of the TDE core

Low-density flexible Graphite sheets:



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

High-temperature studies on Graphite ongoing, which will also show the extent of damage above 3000°C

- **Low-density** graphite absorber made of **2 mm** thick, flexible **graphite sheets**
- Graphite segments are shrink-fitted into a **12 mm** thick **stainless steel jacket**
- Presence of **outgassing groves**, also providing passage for the N_2 along the core

Material composition of the TDE windows

Upstream window: → *exposed to swept proton bunches*

- Located ∼**10 m upstream** of TDE core
- **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*

- Located ∼**13 cm downstream** of last high-density core segment

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

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Beam sweep pattern

- **Bunch positions** at front face:

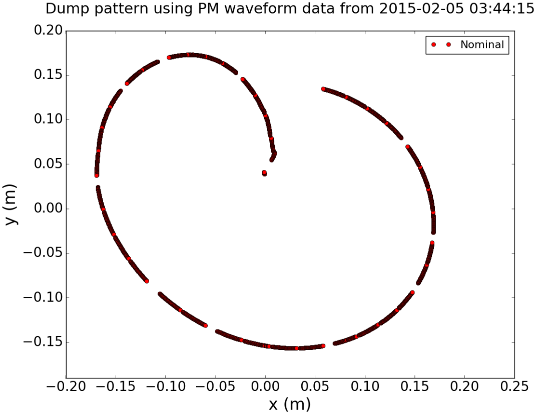
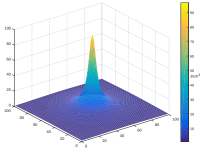


Figure courtesy of C. Wiesner

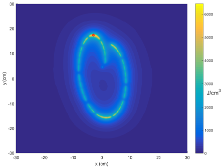
- Typical 'e' shape as effect of **6 horizontal** and **4 vertical dilution kickers** (MKBs)
- **Gaps** in the pattern as consequence of the **LHC filling scheme**

Simulation Method

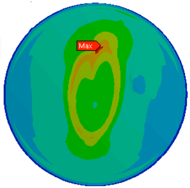
Single Bunch:



Superposition:



Temperature/Stress Analysis:



- **FLUKA** simulation of an **entire beam dump** with thousands of bunches impacting on TDE is **not feasible**, especially at high beam energies.
- Solution:
    1. **FLUKA** simulation of only **one bunch** and scoring of the energy deposition within the TDE
    2. Based on the results for one bunch, calculation of the **superimposed energy deposition** from all bunches in a beam dump **by means of an external tool**
    3. Energy deposition as base for **temperature** and **stress** calculations (ANSYS)

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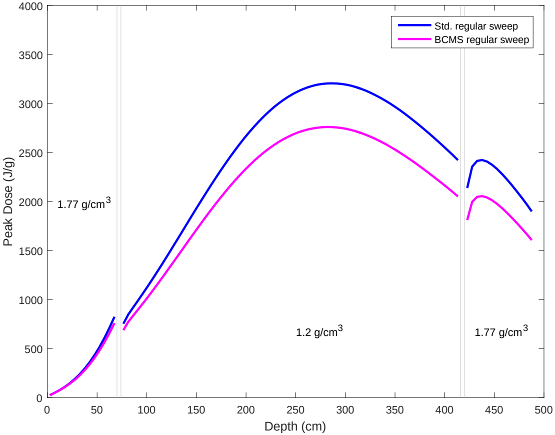
Peak dose in the TDE core (HL-LHC std 25 ns vs. BCMS)



Peak dose higher for HL-LHC std 25 ns beams:

- **Higher bunch intensity** of Std beams
- **Different LHC filling schemes** for Std and BCMS beams → sweep pattern for BCMS with a less concentrated superposition of the beam energy

Assumptions for a (realistic) worst case dilution failure

Bunch positions at front face:

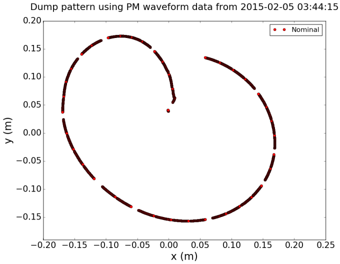
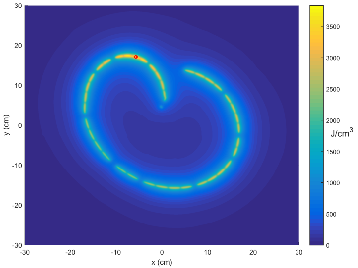


Figure courtesy of C. Wiesner

Transverse energy density in core (3 m depth):



- **Peak energy density/temperature in TDE core and windows:**
  - Depends on minimum sweep speed along sweep path
  - After about 15 μs when the vertical dilution changes direction
  - Hence **failure of H kickers more critical**
- **Realistic worst case scenario:**
  - A failure (erratic or missing kick) can affect two MKBs in the same tank
  - Hence we assume as worst case that **2H kickers provide no kick** (6V+4H → 6V+2H)

Assumptions for a (realistic) worst case dilution failure

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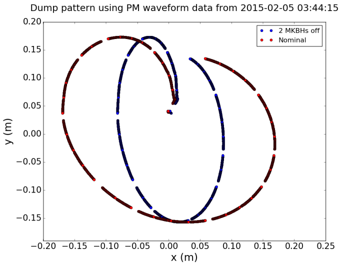

Figure courtesy of C. Wiesner

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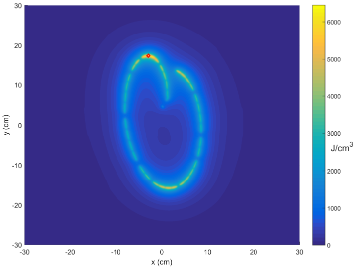

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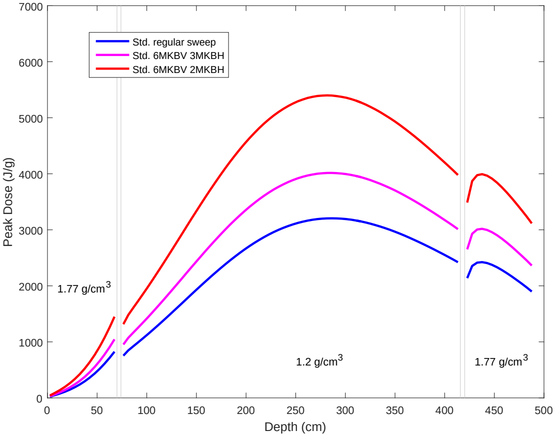
Peak dose in the TDE core (HL-LHC std 25 ns)



- Regular sweep → peak dose $\sim$ **3 kJ/g**
- 1 MKBH missing → peak dose rising to $\sim$ **4 kJ/g**
- 2 MKBH missing → peak dose rising to $>$ **5 kJ/g**

Peak temp. in the TDE core/windows (HL-LHC std 25 ns)

E. Lopez-Sola

Component	**Regular sweep Maximum temperature**	**1H Kicker failure Maximum temperature**	**2H Kicker failure Maximum temperature**
Dump core	1920°C	2150°C	2810°C ⚠
Titanium window	170°C	200°C	250°C
CFC window	43°C	46°C	68°C
Stainless steel foil	48°C	63°C	75°C

- The temperatures in the **dump core** are **very high in all cases**
  - In the case of 2H kicker failure scenario **close to sublimation temperature**
  - **Stresses** in the beam direction **negligible** for a **single Graphite 2 mm plate**, but plates are compressed against each other

    → they cannot be considered as individual thin plates

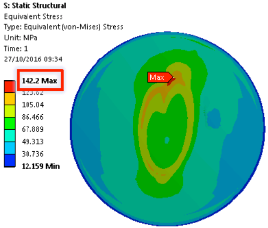
    → **need for a structural analysis of the full low-density segment**

Stresses in the TDE windows (HL-LHC std 25 ns)

E. Lopez-Sola

- Titanium downstream window – Structural analysis

Case	Max temperature	Max Von Mises eq. Stress	Minimum yield strength	Safety factor
Regular sweep	170°C	113 MPa	180 MPa	1.6
1H Kicker failure	200°C	124 MPa	150 MPa	1.2!
2H Kicker failure	250°C	142 MPa	130 MPa	0.9 ⚠



➡ The titanium window would not survive the 2H kicker failure scenario

- Stainless steel foil – Structural analysis

Case	Max temperature	Maximum VM eq. stress	Safety factor
Regular sweep	48°C	65 MPa	2.6
1H Kicker failure	63°C	125 MPa	1.4
2H Kicker failure	75°C	140 MPa	1.2 ⚠

Very low safety factor for the kicker failure cases

(Stainless steel 316L Minimum Yield strength = **170 MPa**)

Contents

Conclusions

- **TDE core**
  - ○ Very high temperatures reached in the low density graphite
  - ○ For the 2H kicker failure scenario, **almost at max. service temp.** (∼3000°C)
- **TDE windows**
  - ○ Upstream window: **very high stresses in stainless steel foil** for 1H and 2H kicker failure case
  - ○ Downstream Ti window: **high risk for 2H kicker failure case** (max stress $>$ min yield strength), very high stresses even for regular sweep

Long-term strategy for TDE

M. Calviani

- **Current TDE** shows **limitation** and **critical points** (operation)
- **Ongoing studies** on **graphite behavior** at high temperature
- Long-term strategy being assessed:
  - 2017-2020:
    - → **Complete** the **beam impact scenario studies**, including dynamical and thermal analyses, plus detailed material studies and R&D
    - → Study & propose an **engineering design** capable of **overcoming** the operational **limitations** for HL-LHC beams while **increasing reliability** and **dump monitoring** (compatible with UD installation and transport)
  - ∼2018/9: **Decision point** on the need to produce new dump cores
  - 2020-2024: **Detailed engineering design** and **construction** of new cores to be installed in LS3

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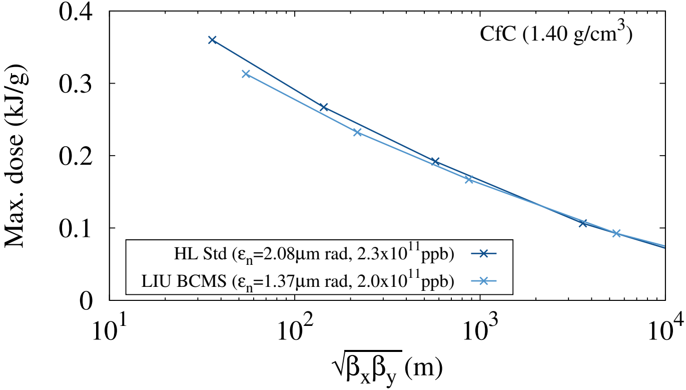
Considered optics and β-functions

- All studies presented here were carried out for HLLHCV1.2
- Selected the worst case for each device from flat/flat HV/round optics

Device	**Optics**	β_x	β_y	$\sqrt{\beta_x\beta_y}$	**Remark**
TCDQ	HLLHCV1.2	497 m	167 m	288 m	flat, end of squeeze, B1
	Run 2 (2015)	484 m	161 m	279 m	collision, B1
TCDS	HLLHCV1.2	168 m	174 m	171 m	flat HV, squeeze step 20, B2
	Run 2 (2015)	155 m	231 m	189 m	collision, B1
TDE	HLLHCV1.2	5052 m	3714 m	4331 m	round, end of squeeze, B2
	Run 2 (2015)	5076 m	3713 m	4341 m	collision, B2

M. Fraser

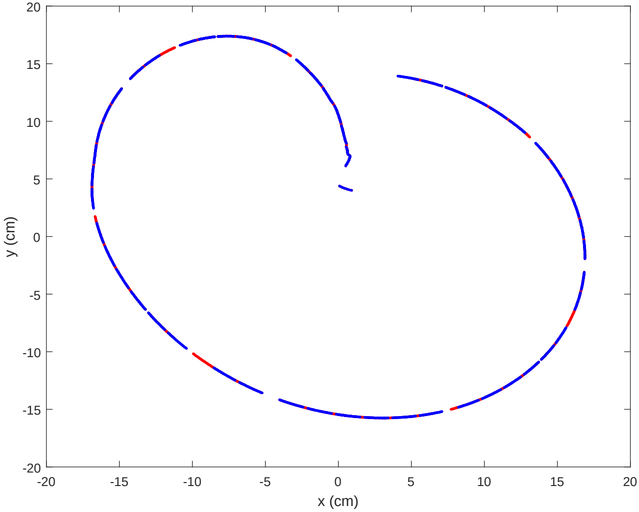
Single 7 TeV bunch: max energy density in CfC vs $\sqrt{\beta_x \beta_y}$



- A certain change of β and hence of the transverse bunch size might be digestable (yet there are other constraints for β)
- Note: the beam is swept across the TCDS/TCDQ/TDE front face

  → the peak energy density also strongly depends on the distance between neighbouring bunches in the sweep

Beam Sweeps: HL-LHC std 25 ns vs. BCMS



- **HL-LHC std 25 ns**: 2748 bunches
- **BCMS**: 2604 bunches