TDE simulations and limitations in case of severe N_2 pressure drops

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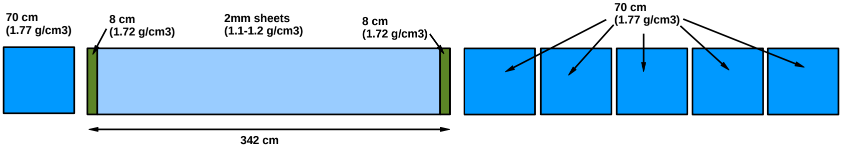
Introduction (1/2)

- Keeping the TDE graphite core under inert atmosphere (N_2) was implemented as a safety measure:
  - LHC Design Report: "... if **a massive air entry** were to occur in the **6 minutes** following **a high intensity dump**, the **graphite could burn** ..."
  - However, based on our present knowledge burning of graphite under these conditions **seems to be unlikely**
  - Existing **literature** is however **too scarce** to reliably conclude on the extent of graphite damage for LHC dumping conditions
  - EN/STI will conduct experimental studies to explore in more detail the behavior of graphite when being exposed to high temperatures in air (for short durations)
- As of now, we recommend to play safe (in the light of recent events):
  - We suggest to keep the peak temperature in the graphite core below 600°C if the N_2 pressure falls below 1.05 bar
  - This presentation derives **intensity limits** based on this assumption (for protons only, ions are not an issue despite their large ionizing energy loss before they interact)
  - The limitations will be revised depending on the outcome of above experiments

Introduction (2/2)

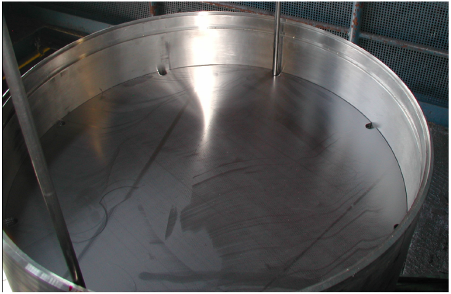
- First intensity limits have already been derived last year (at the time of the first N_2 pressure drop in Nov 2015)
  - See presentation of J. Uythoven LMC #242 (11/11/2015)
  - Due to the urgency of the situation in Nov 2015, these calculations included several simplified assumptions (e.g. only a small portion of the sweep was considered)
  - The present studies systematically investigate different beam energies/emittances and consider realistic dilution patterns based on measured MKB waveforms
- Accuracy of temperature estimates
  - We calculate temperature estimates in **adiabatic limit**, i.e. we neglect any heat transfer during the beam sweep across the dump front face
    - This slightly overestimates the peak temperatures (maybe by 10 %)
  - We do not have **temperature-dependent specific heat curves** for the graphite grades used in the dump
    - We use the specific heat curve for another grade, which could give rise to an over/underestimation of the actual temperature by maybe 10-15 %
    - STI plans to measure the specific heat of the grade used

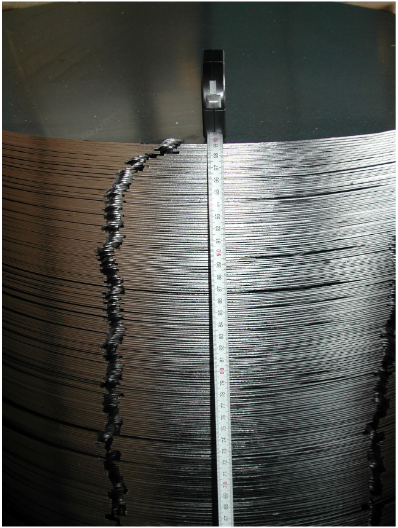
TDE Graphite core



- LHC dump core consisting of high- and low-density graphite absorbers
- Diameter of 70 cm and a total absorber length of ~7.6 m
- Low-density graphite absorber made of 2 mm thick, flexible graphite sheets
- Other absorber blocks consist of polycrystalline graphite
- 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

Low-density flexible graphite sheets





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Simulation Method

- FLUKA simulation of an entire beam dump with thousands of bunches impacting on TDE is not possible, especially at high beam energies.
- Solution:
  1. 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. **Conversion** of energy deposition **into temperature** increase as last step

Assumed Beam Parameters and Filling Schemes

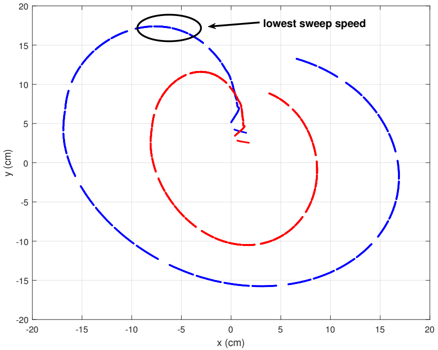
- Beam Parameter Settings (σ values for 7 TeV case):

	Emittance [μm rad]	σ_x [μm]	σ_y [μm]	**Intensity** [ppb]	**# bunches**
Standard	2.6	1330	1138	$1.3\text{x}10^{11}$	2748
BCMS	1.37	965	826	$1.3\text{x}10^{11}$	2448

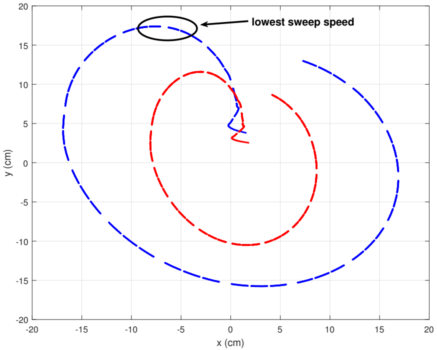
- Standard Beam train consists of 4 batches á 72 bunches (=288 bunches)
- BCMS Beam train consists of 3 batches á 48 bunches (=144 bunches)
- 900 ns gap between two consecutive trains, 225 ns gap between two batches
- Gaps in the filling schemes have an effect on the peak energy density and hence the temperature
- Only 3 BCMS batches per train considered as this is the max. number of batches for which sufficient protection is provided by the transfer line collimators (V. Kain, Chamonix 2014)

Sweep Patterns for Standard and BCMS beams

- Sweep path generated using measured MKB waveforms for a nominal dump occurring early 2015
- Sweep patterns derived by M. Fraser
- **Regular** sweep pattern in blue, sweep dumps with **2H+2V MKB erratic** in red
- 2H+2V MKB erratic rather unrealistic, included in the study for demonstration purpose



Sweep pattern for **Standard** beams.



Sweep pattern for **BCMS** beams.

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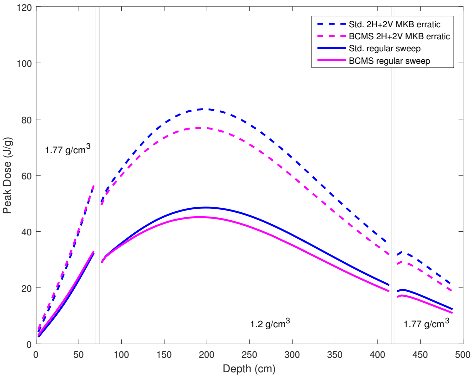
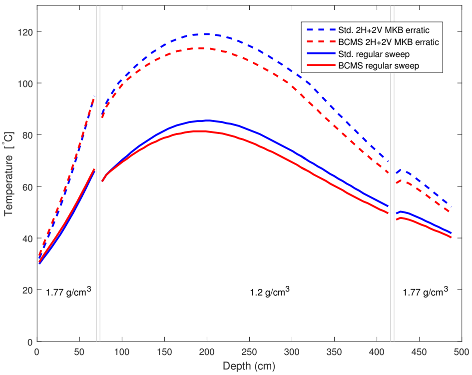
450 GeV: Longitudinal Distributions for Full Sweep Dumps

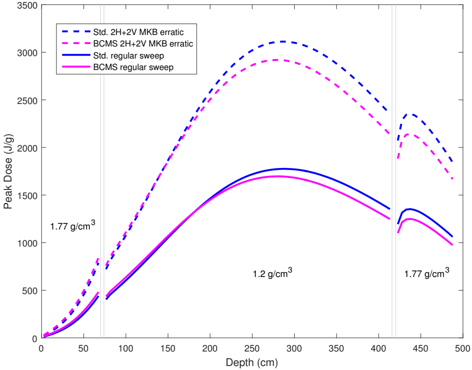


Peak dose distribution

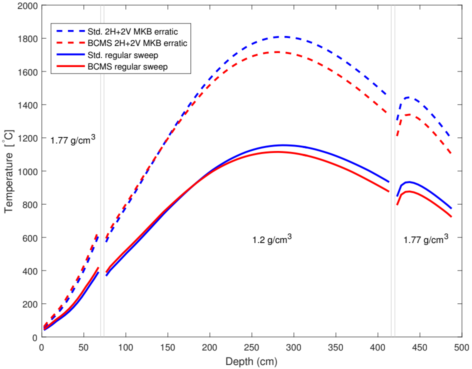


Peak temperature distribution

7 TeV: Longitudinal Distributions for Full Sweep Dumps



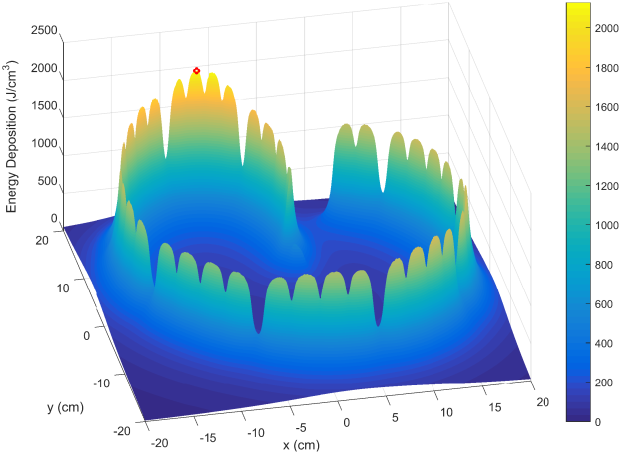
Peak dose distribution



Peak temperature distribution

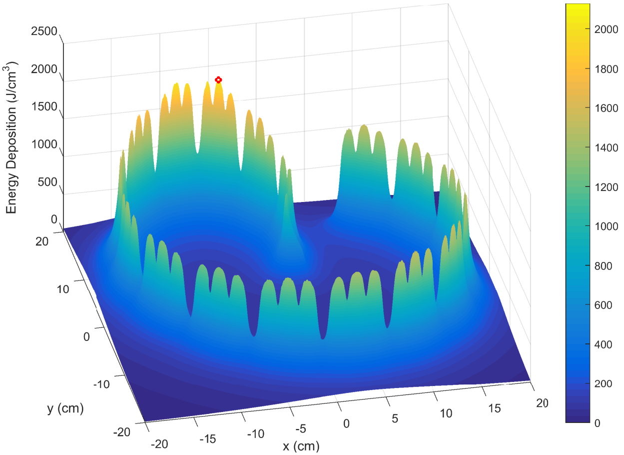
- Shower maximum observed at larger depth than for 450 GeV beams
- The **highest temperature occurs deep inside** the low-density graphite absorber segment, both longitudinally and radially

Transversal Energy Deposition at Longitudinal Peak 7 TeV Standard Beam Dump (Regular Sweep)



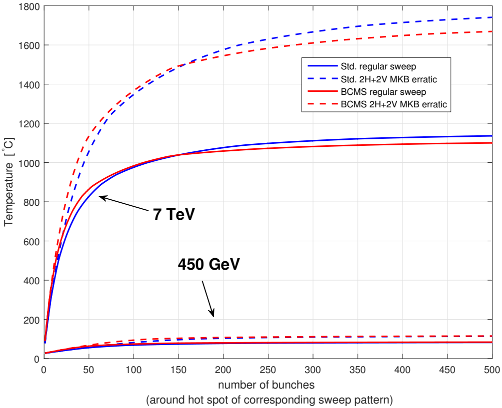
- Peak energy deposition of **2131 J/cm^3** (red circle) around the hotspot at a depth of 286 cm from the TDE front face
- Corresponding temperature increase of **1130°C**

Transversal Energy Deposition at Longitudinal Peak 7 TeV BCMS Beam Dump (Regular Sweep)



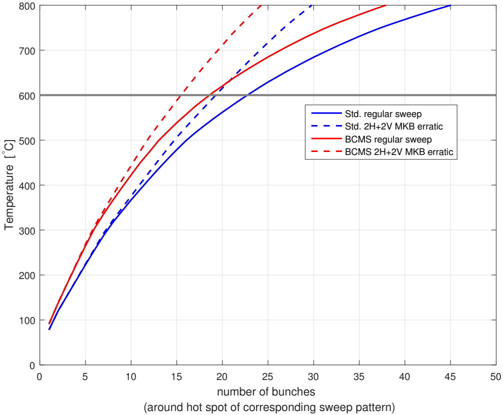
- Peak energy deposition of **2037 J/cm^3** (red circle) around the hotspot at a depth of 282 cm from the TDE front face
- Corresponding temperature increase of **1090°C**

Temperature vs. number of dumped bunches



- Peak temperature increase in the TDE depending on the number of dumped bunches.
- As shown before, dumps at 450 GeV safely remain below 600°C even for a full machine.

Dump limitation at 7 TeV



- Given a temperature constraint of 600°C beam dumps are limited to a **maximum of about 20 bunches** at a beam energy of **6.5 TeV**
- Beam dumps suffering from **2H+2V MKB failures don't impose much stronger restrictions** with respect of the maximal number of bunches allowed

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Summary & Conclusions

- As of now, we recommend to keep the peak temperature in the graphite core below 600°C if the N_2 pressure falls below 1.05 bar
- This implies that, at 6.5 TeV, the stored intensity shall be limited to max. 20 bunches with 1.3×10^{11} ppb
  - Here we assume that the **20 bunches** are **located at the most unfavorable position** in the dilution pattern
  - In principle, one could distribute several short trains (of 12 bunches) around the rings without exceeding 600°C, however then one needs to enforce several constraints on the allowed filling schemes (sufficient gaps between trains)
- For protons at **450 GeV**, no restrictions apply (neither for **ions** at all energies)
- The limitations will be revised depending on the outcome of experimental studies on graphite planned by EN/STI (tentatively throughout 2016)
  - The limit of 600°C is likely conservative even if the dump would be fully exposed to air
  - But safety comes first until we have experimental evidence that there is no risk to go to higher temperatures

Backup

- Calculation of a temperature increase based on the obtained distribution of the energy deposition
- Important: Taking into account the temperature dependency of the specific heat of graphite