Energy deposition and thermo-mechanical studies for IR6 protection devices and downstream magnets/septa

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On behalf of HL-LHC WP14

6th HL-LHC Collaboration Meeting

November 15th, 2016

Introduction

IR6 protection absorbers/LHC dump:

- Have been designed for **LHC ultimate beams** (1.7×10^{11} ppb, 3.5 μm·rad), i.e. for a smaller brightness and a smaller bunch intensity wrt HL beams

Scope of this talk:

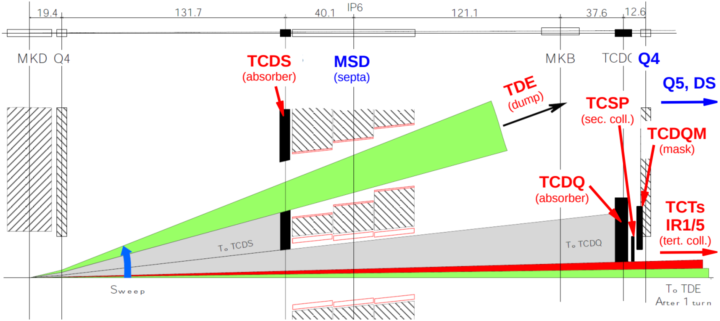
- Assessment of the **energy deposition** in
  - → IR6 protection devices
  - → IR6 magnets and septa

  for HL beam parameters and HL optics (**HLLHCV1.2**)
- Give a first indication if we expect possible issues with
  - → present absorber materials ⇒ **thermo-mechanical studies**
  - → the protection of equipment

  in case of extraction failures

Note: This presentation includes some minor updates of the thermo-mechanical studies with respect to my recent talk at the 19th HL-LHC TCC Meeting (27th Oct 2016): a longer time interval was simulated to fully assess all dynamic effects and some stresses were found a bit higher than reported in the TCC Meeting, however without any effect on the main conclusions.

Protection devices/dumps and failure scenarios



- Single MKD module prefire:
  - **TCDS** → **MSDs** ⇒ *this talk*
  - **TCDQ**+*TCDQM* → **Q4, Q5,** *DS magnets* ⇒ *this talk*
  - **TCTs** → **IR1/5 triplet,D1** (studied by WP5+WP10) ⇒ *A. Tsinganis (this afternoon)*

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

- Dilution (MKB) failure:
  - **TDE core** and **TDE windows** ⇒ *M.I. Frankl (this session)*

(equipment in *italic* still to be studied)

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 (*M. Fraser*)

Contents

TCDQ → Q4, Q5

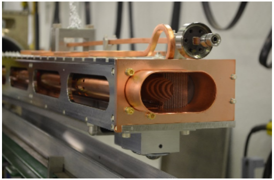
TCDS → MSDs

Conclusions

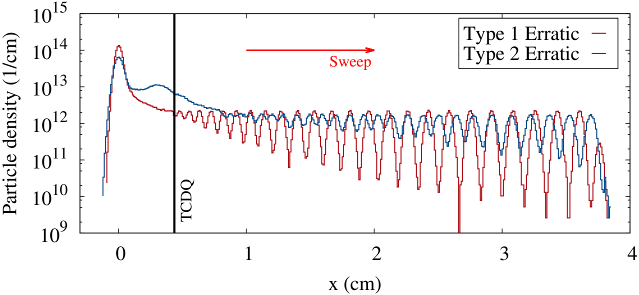
Backup

Some remarks on the TCDQ

- Was **upgraded in LS1** (2→3 modules, Gr→CfC)
- Upgrade studies (FLUKA+ANSYS) considered HL beam parameters
- However, **“new” MKD erratics observed in 2015**: particle density on TCDQ can be 2× higher than assumed for LS1 upgrade studies → needed to be cross-checked



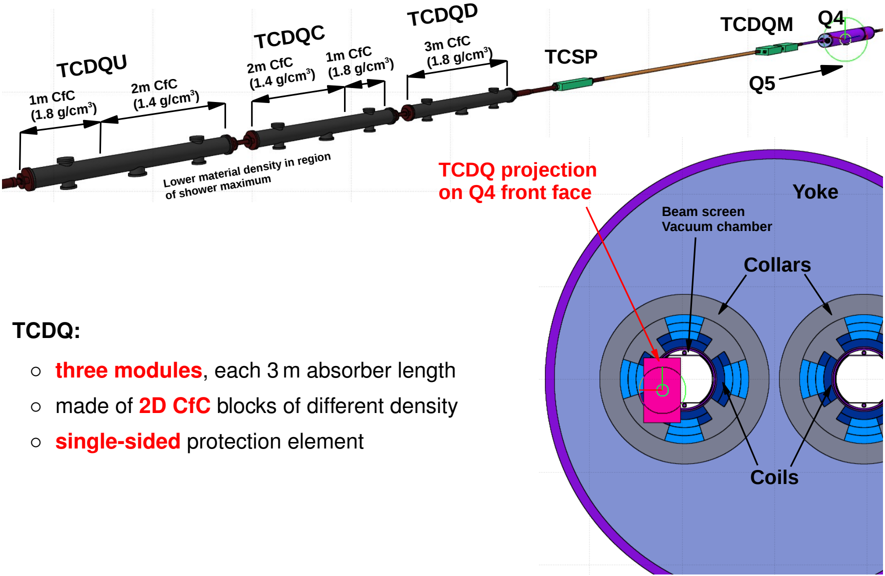
Particle distribution by M. Fraser



→ *all studies were carried out for a Type 2 erratic (worst case)*

→ *assumed TCDQ half gap = 8.1σ (includes 0.5σ misalignment)*

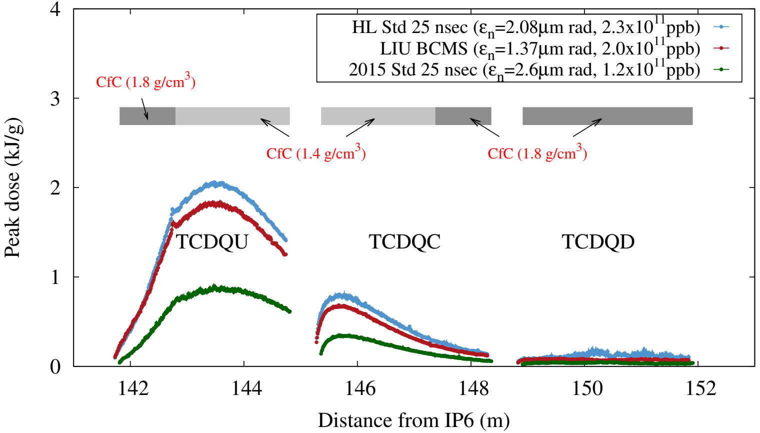
TCDQ+Q4/Q5 model for energy deposition simulations



- **TCDQ:**
  - **three modules**, each 3 m absorber length
  - made of **2D CfC** blocks of different density
  - **single-sided** protection element

Peak dose in TCDQ for a Type 2 MKD erratic

M. Frankl

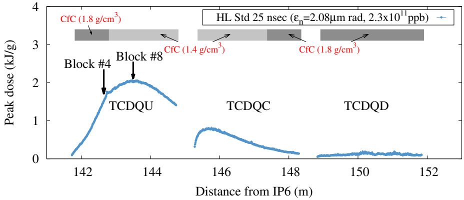


- <u>HL-LHC std:</u> peak dose in low-density blocks: **2.1 kJ/g**
- <u>LIU BCMS</u>: peak dose in low-density blocks: **1.8 kJ/g**

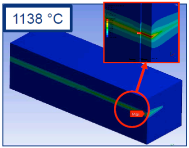
Peak temp. and stresses in TCDQ (HL-LHC std 25 ns)

C. Di Paolo

- Thermal and structural analysis for blocks with the **highest peak load** (for both CfC grades)



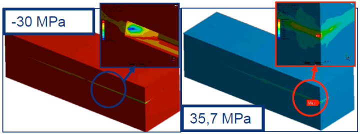
BLOCK 4 CfC 1.75 g/cm³



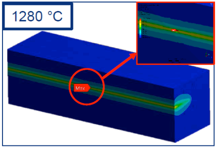
Linear elastic material model

Temperatures profiles at the peak after one pulse

Highest Compressive Stress **Highest Tensile Stress**



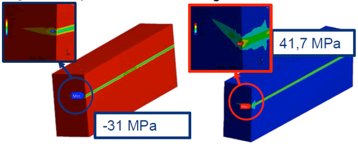
BLOCK 8 CfC 1.4 g/cm³



Linear elastic material model

Temperatures profiles at the peak after one pulse

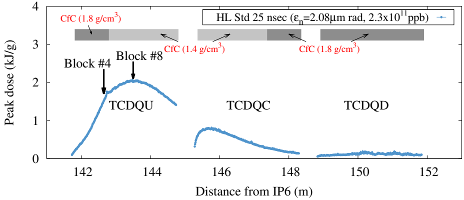
Highest Compressive Stress **Highest Tensile Stress**



Peak temp. and stresses in TCDQ (HL-LHC std 25 ns)

C. Di Paolo

- Thermal and structural analysis for blocks with the **highest peak load** (for both CfC grades)

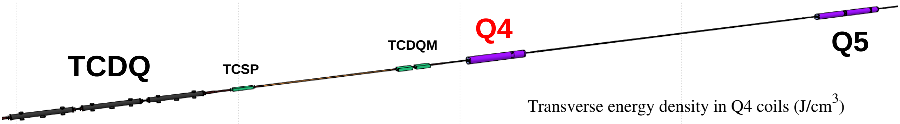


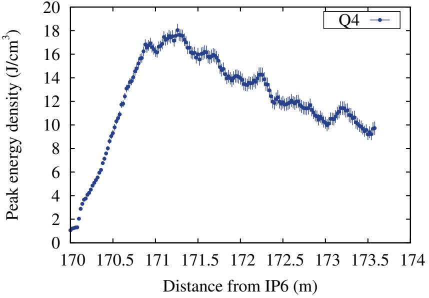
Material	C-C 1.75	C-C 1.4
Max. Temp. [°C]	1138	1280
Min. Princ. [MPa]	**-30**	**-31**
Compr. Strength	69.6	69.6
Max. Princ. [MPa]	**36**	**42**
Tensile Strength	61	61

→ *Tensile and compressive principal stresses are below the strength limits*

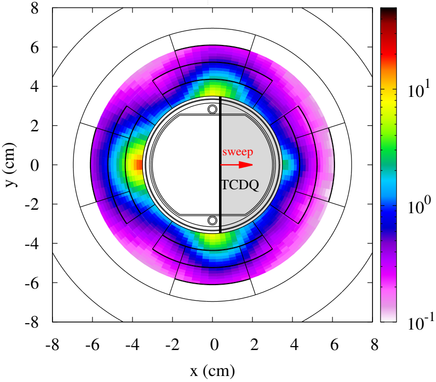
→ *A reduction of TCDQ half gap would require a revalidation of the block robustness*

Peak energy density in Q4 coils (HL-LHC std 25 ns)





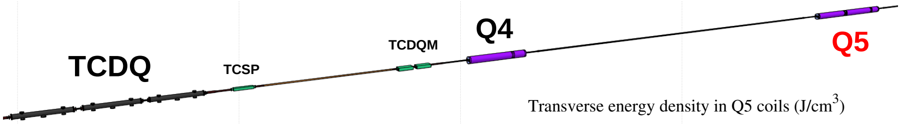
Transverse energy density in Q4 coils (J/cm^3)

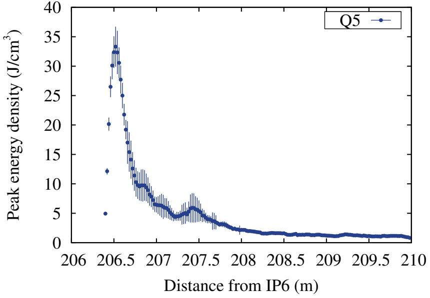


- Predicted peak energy density in Q4 coils: ∼17 J/cm^3

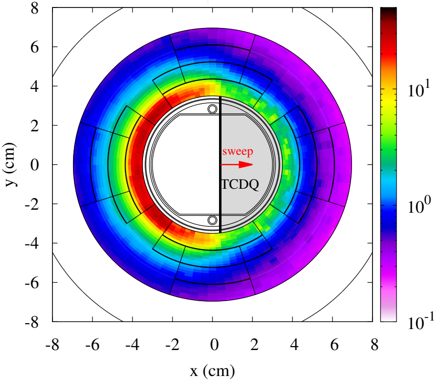
M. Frankl

Peak energy density in Q5 coils (HL-LHC std 25 ns)





Transverse energy density in Q5 coils (J/cm^3)



- Predicted peak energy density in Q5 coils: ∼30–35 J/cm^3 (statistics still to be improved)

M. Frankl

Remarks on the energy density in superconducting coils

- **Model calculations:**
  - → **Should account for a sufficient margin** (at least a factor 3 below damage limit)
- **Main issue: the damage limit of NbTi coils for ultra-fast losses is not exactly known**
  - → During the design of LHC protection devices a value of **$\sim$87 J/cm^3** was assumed, which however has to be revised
  - → **HiRadMat test** on SC cables carried out by colleagues from TE/MPE in Sep 2016 (at room temperature), another test planned at cryogenic temperatures
    → *talk of D. Wollmann et al. this afternoon*
  - → *Depending on HiRadMat outcome, an improved protection might need to be considered also for the Q5 in IR6*

Contents

TCDQ → Q4, Q5

TCDS → MSDs

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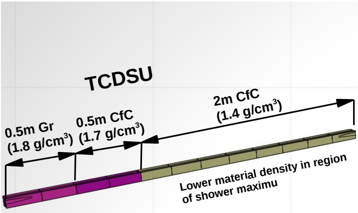
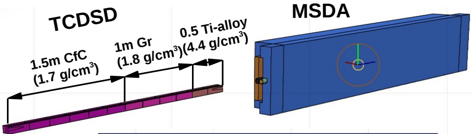
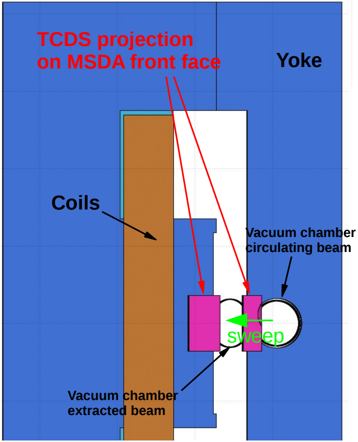
Backup

TCDS+MSD model for energy deposition simulations



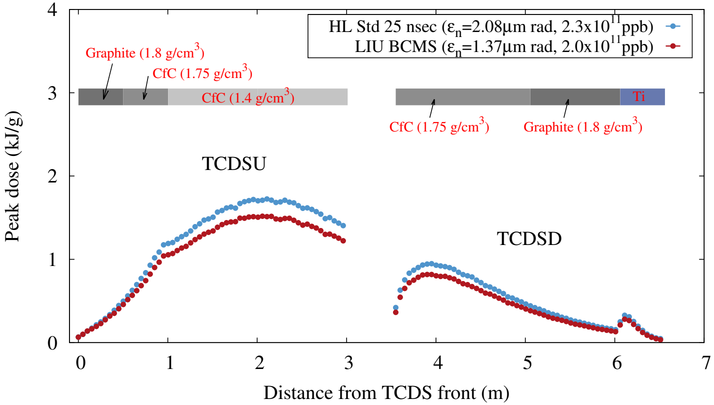




- **Existing TCDS:**
  - **2 modules**, each with 3 m absorber length
  - made of **Graphite/2D CfC blocks** of different density + **Ti-alloy block** at the downstream end
  - each module has two jaws (one directly impacted in case of an asynch. beam dump)
- **HL upgrade (baseline):**
  - 2 → 3 modules (a la TCDQ)

Peak dose in TCDS for a Type 2 MKD erratic

M. Frankl

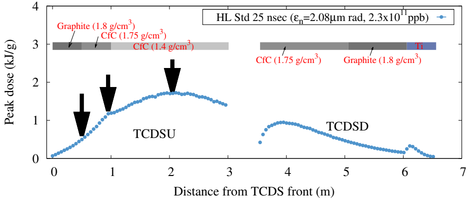


- HL-LHC std: max. energy density in low-density blocks: **1.7 kJ/g**
- LIU BCMS: max. energy density in low-density blocks: **1.5 kJ/g**

Peak temp. and stresses in TCDS (HL-LHC std 25 ns)

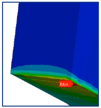
C. Di Paolo

- Thermal and structural analysis for blocks with the **highest peak load** (for all materials)



BLOCK 2 Graphite C2020

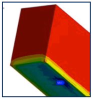
Linear elastic material model



Temperatures profiles at the peak after one pulse

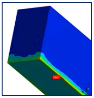
397°C

Highest Compressive Stress



-20 MPa

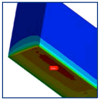
Highest Tensile Stress



27 MPa

BLOCK 2 CfC 1.75 g/cm³

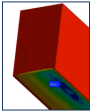
Linear elastic material model



Temperatures profiles at the peak after one pulse

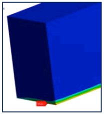
798°C

Highest Compressive Stress



-23 MPa

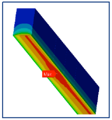
Highest Tensile Stress



18 MPa

BLOCK 5 CfC 1.4 g/cm³

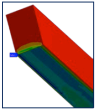
Linear elastic material model



Temperatures profiles at the peak after one pulse

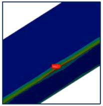
1141°C

Highest Compressive Stress



-27 MPa

Highest Tensile Stress



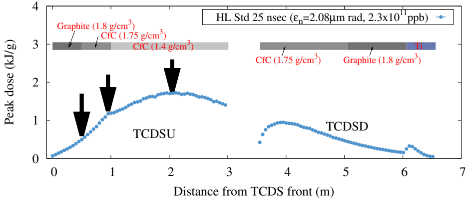
51 MPa

The maximum tensile stress is in the y direction

Peak temp. and stresses in TCDS (HL-LHC std 25 ns)

C. Di Paolo

- Thermal and structural analysis for blocks with the **highest peak load** (for all materials)



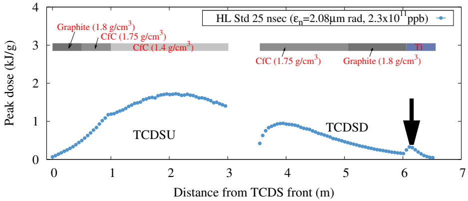
Material	C-C 1.75	C-C 1.4	Graphite
Max. Temp. [°C]	798	1141	396
Min. Princ. [MPa]	**-23**	**-27**	**-20**
Compr. Strength	69.6	69.6	35
Max. Princ. [MPa]	**18**	**51**	**27**
Tensile Strength	61	84 (y)	35

→ *Tensile and compressive principal stresses are below the strength limits*

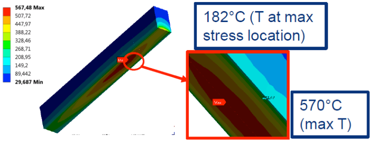
Peak temp. and stresses in TCDS (HL-LHC std 25 ns)

C. Di Paolo

- Thermal and structural analysis for blocks with the **highest peak load** (for all materials)



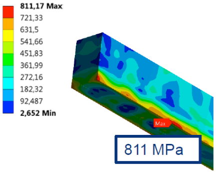
Temperature profiles at the peak after one pulse [°C]



182°C (T at max stress location)

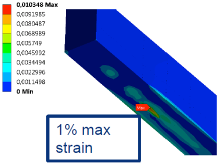
570°C (max T)

Equivalent stress (Von Mises) [MPa]



811 MPa

Equivalent plastic strain [m/m]



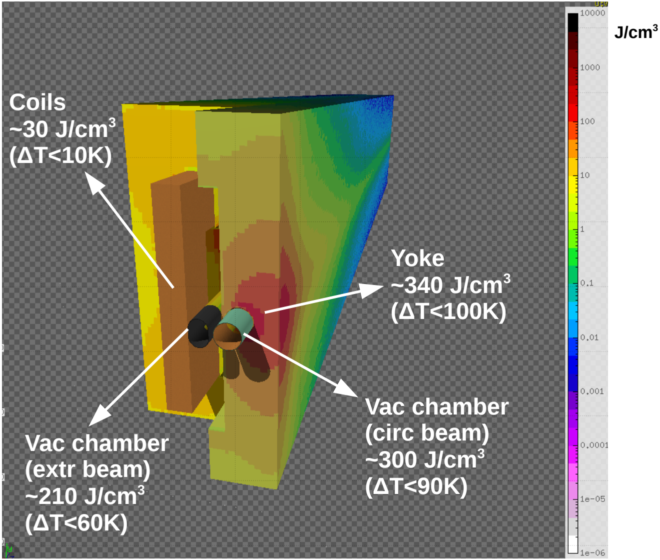
1% max strain

	Area at Max T	Area at Max stress
Temp. [°C]	568	182
Eq. Stress [MPa]	**413**	**811**
Yield Strength	**409**	**670**
Tensile Strength	520	830

→ *Ti block expected to plastify*

→ *However, plastic strain is only 1% (no risk to fracture)*

Energy deposition in first MSD for a Type 2 MKD erratic



Coils
~30 J/cm^3
(ΔT<10K)

Yoke
~340 J/cm^3
(ΔT<100K)

Vac chamber
(extr beam)
~210 J/cm^3
(ΔT<60K)

Vac chamber
(circ beam)
~300 J/cm^3
(ΔT<90K)

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Conclusions

Backup

Conclusions

- **TCDQ → Q4, Q5, *DS***
  - **CfC in TCDQ sufficiently robust** for HL beams even for the worst known MKD erratic
  - **Improved protection of Q5** might be necessary - pending outcome of TE/MPE HiRadMat test
  - Assumed TCDQ half gap = 8.6σ(-0.5σ margin) → change in settings or optics **needs reevaluation** of the material robustness and magnet protection
  - Next steps: energy deposition studies for **DS magnets**
- **TCDS → MSDs**
  - **Graphite/CfCs in TCDS sufficiently robust** for HL beams, but **Ti-alloy** expected to **plastify** (a priori acceptable)
  - HL baseline is to **add one more TCDS module** to enhance the MSD protection → this will also relax the load on the Ti block
  - Next steps: study in more detail the load on the MSDs, in particular extend energy deposition studies for downstream **MSDs**

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Backup

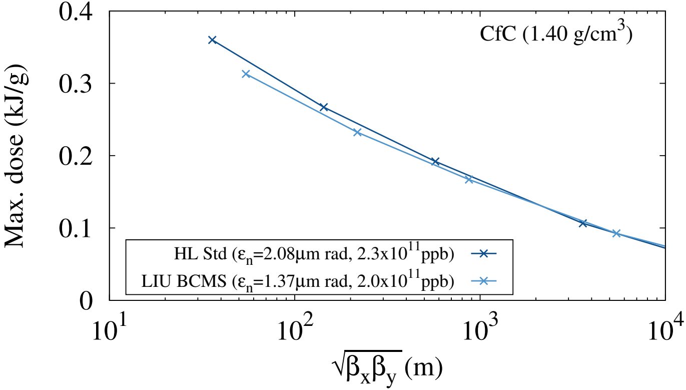
Considered optics and β-functions

- 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