Summary of the ongoing Thermo-mechanical calculations for TCDS and TCDQ absorbers

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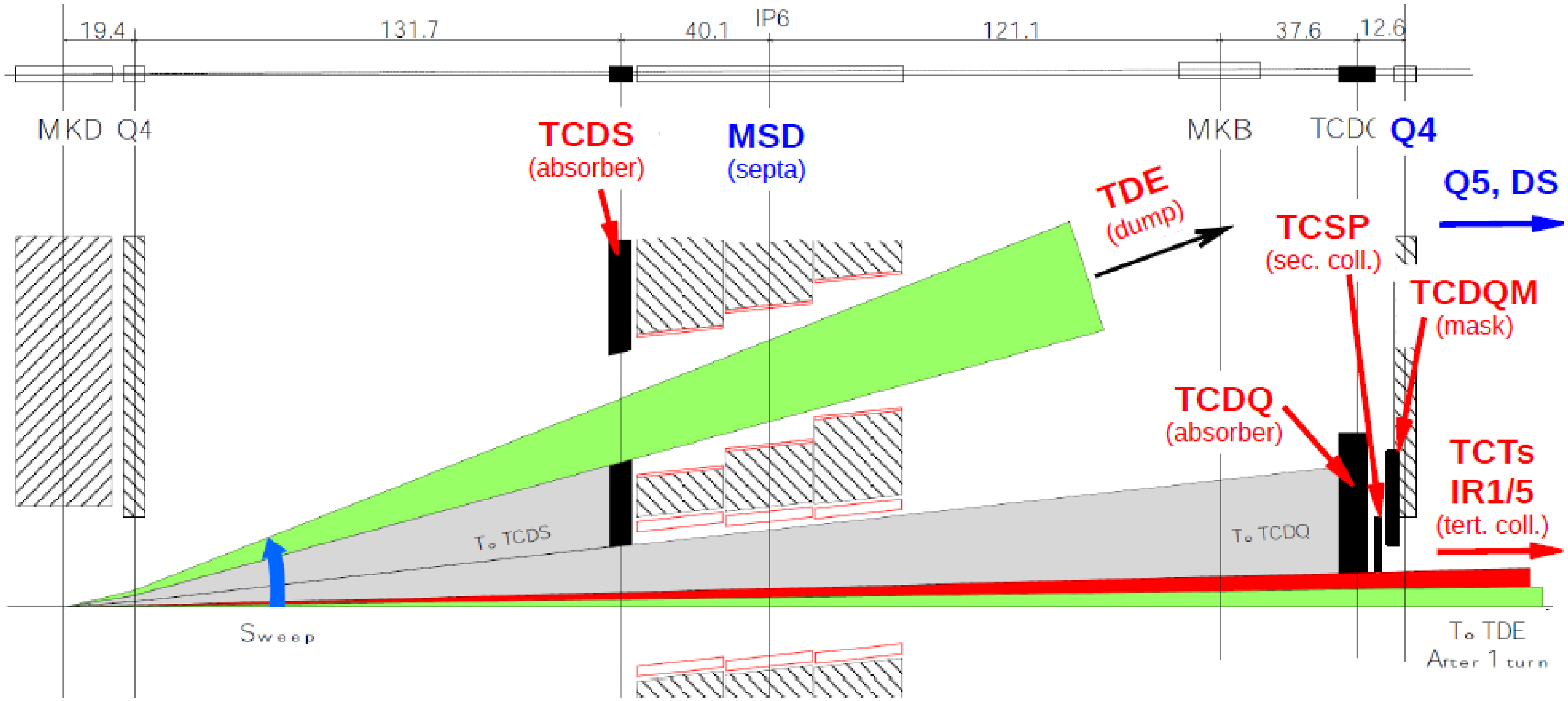
8th HL-LHC Collaboration meeting, CERN, Geneva, 18th of October 2018

Outlines

- TCDS / TCDQ description
- TCDQ context
- TCDQ Thermo-mechanical analyses
- TCDS context
- TCDS Summary of past thermo-mechanical analyses

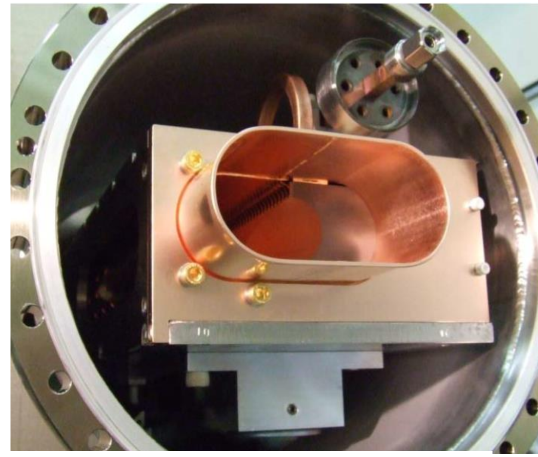
TCDS / TCDQ

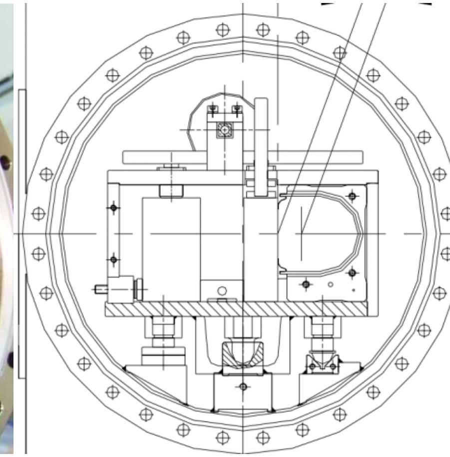


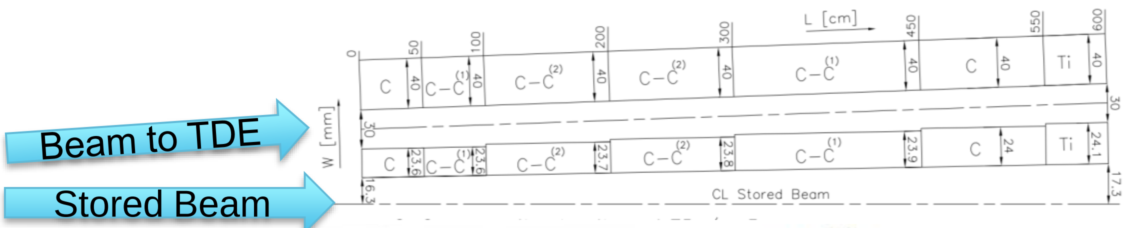
TCDS – A fixed diluter block installed immediately upstream of the MSD magnets(IR6)
TCDQ – A mobile diluter block to protect the Q4 magnets, (IR6)

→Asynchronous firing of MKD kickers would cause the beam to sweep over the septum walls

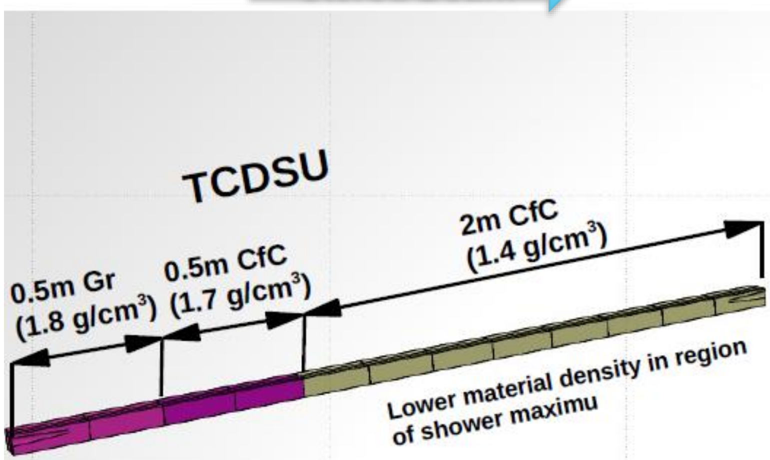
TCDS description *

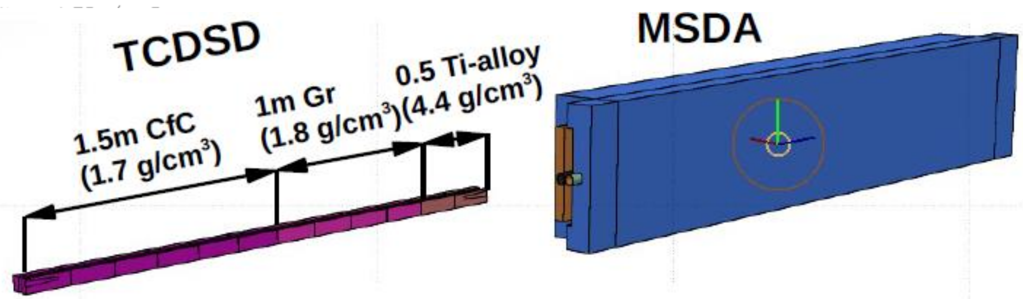






Two jaws
6 m long absorbers



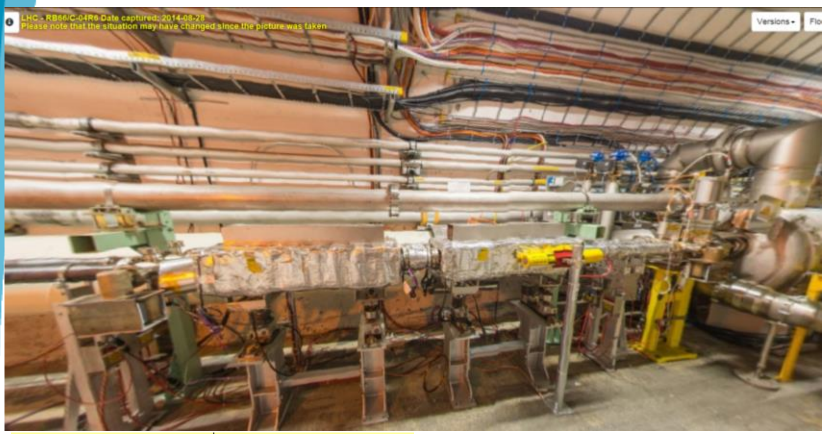


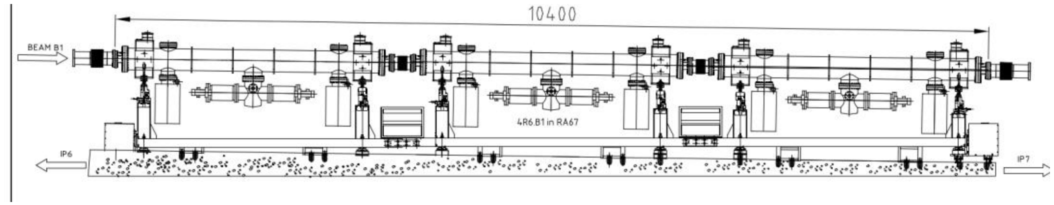
Cu coating of a few microns thickness is applied to the all graphite and C-C composite parts

*For more information→ W. Weterings, "TCDS diluter to protect MSD septum magnets," CERN EDMS document No. 393973, 2006.

TCDQ description

A 10.4 m long 3-tank system, on a mobile support girder, with 9 m absorber length installed at ~12.5 m in front of the Q4 magnet. Each tank consists of 12 absorber blocks, made of carbon fibre reinforced carbon (CFC), having a density of 1.75 or 1.4 g/cm3.

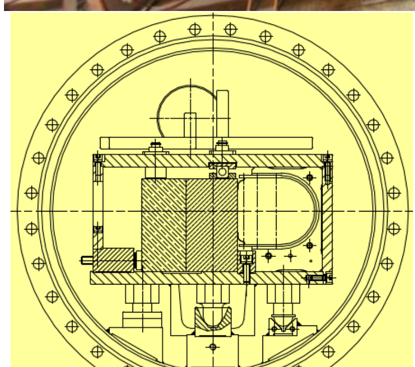




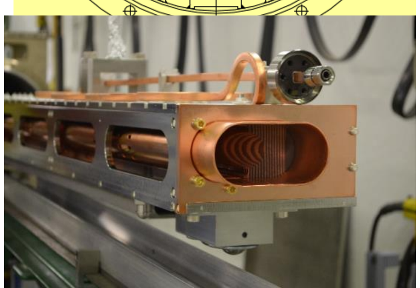
1	2	3	4	5	6	7	8	9	10	11	12		13	14	15	16	17	18	19	20	21	22	23	24		25	26	27	28	29	30	31	32	33	34	35	36
1.75				1.4									1.4								1.75					1.75											

→36 blocks of 250 mm of carbon composite (CFC) with different densities:

- 4 blocks of high density CFC (1.75 g/cm^3)
- 16 blocks of low density CFC (1.4 g/cm^3)
- 16 blocks of high density CFC (1.75 g/cm^3)



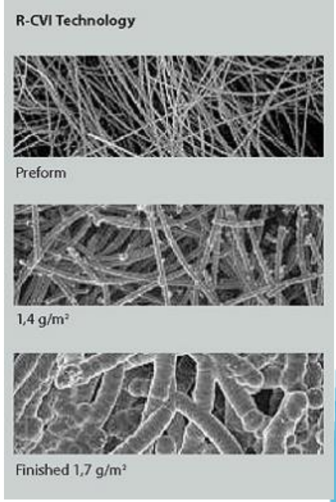
Cross-section of the proposed TCDQ structure showing the graphite (left) and CFC (right) absorber blocks

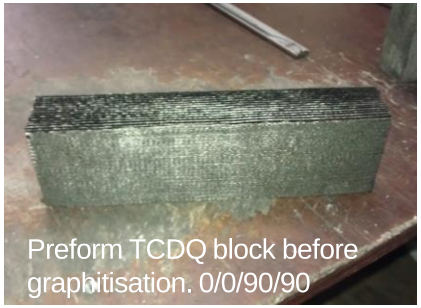


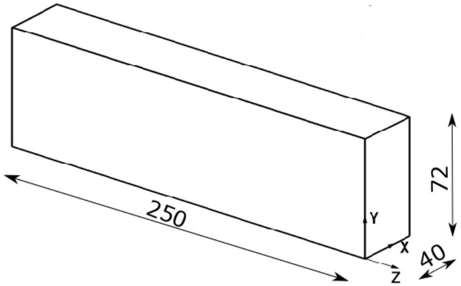
TCDS/Q Target Material Properties

CfC RNFF-SG (from CVT) is an orthotropic material. The fibers are in the y and z axes.

CfC RNFF-SG (at 22 C)		⊥(x)	∥(y)	∥(z)	⊥(x)	∥(y)	∥(z)
Density	g/cm3	1.4			1.75		
Tensile strength	MPa		84	61		84	61
Compresive strength	MPa	69.6	88.6	82.4	69.6	88.6	82.4
Compresive Young Modulus	GPa	2.8	10	10	2.8	10	10
Thermal conductivity	W/mK	91	110	110	91	110	110
3-point bending strength	MPa	170	190	190	170	190	190
3-point bending Young Modulus	GPa	38	40	40	38	40	40




Preform TCDQ block before graphitisation. 0/0/90/90



CFC:

- Fiber configuration 0/90°in the plane YZ (major strength in Y dir.)

Graphite TCDS	Density	Tensile strength	Compressive strength	Young Modulus
Graphite C2020	1,77 g/cm³	35 MPa	35 Mpa	10.7 GPa

➢ Simulations are very sensitive to material properties.

Main source: Luca Massidda, CRS4 – "Structural Analysis of the TCDS Collimator New Design" (EDMS 716298)

TCDS Titanium Material Properties

Properties (at RT)	Units	Ti6Al4V
Density	g/cm³	4,43
Yield Strength	MPa	925
Tensile Strength	MPa	1120
Young Modulus E	GPa	113,8
Thermal Conductivity	W/m·°C	7
Melting Point	°C	1604-1660
Specific Heat	J/kg·°C	513

All the properties modelled as a function of the temperature

The titanium was modeled as a plastic material.

Main source: MIL-HDBK-5J, DEPARTMENT OF DEFENSE HANDBOOK: METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES

TCDQ Energy deposition

Beam Parameters	HL-LHC25ns
Bunch Intensity	2.3E11
Number of bunches	56.8
Beam energy	7 TeV
Pulse length	950ns
Bunch spacing	25ns
Beam emittance	2.1 µm

Table 1. Beam parameter

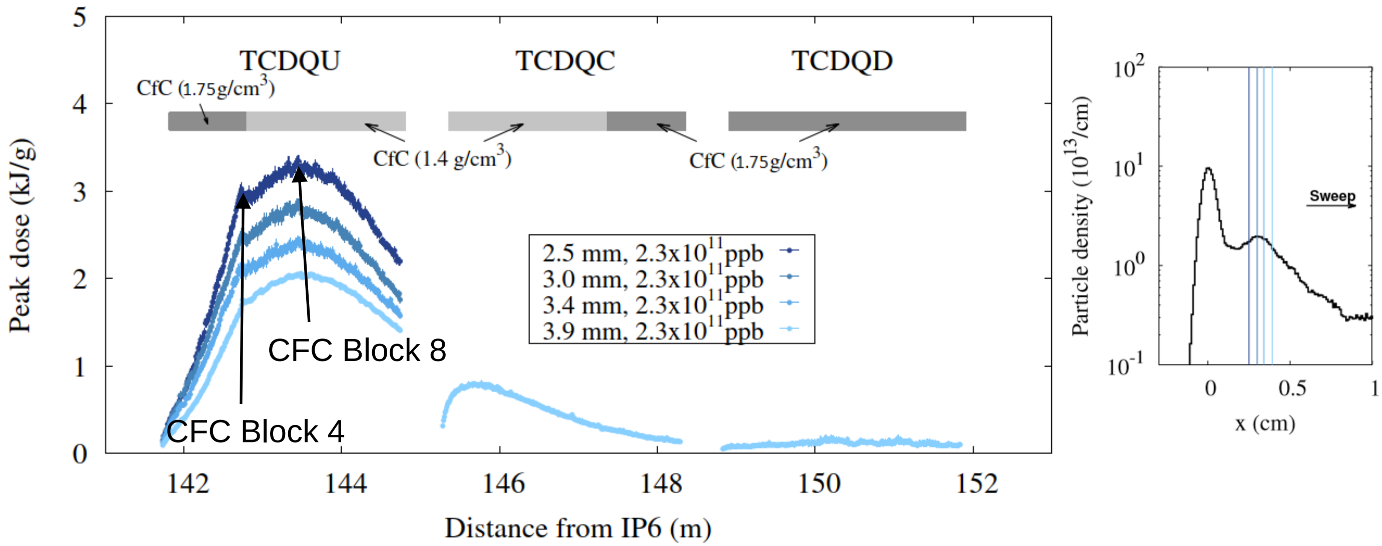


Fig. 1. Energy deposition distribution [2]. Courtesy of M. I Frankl.

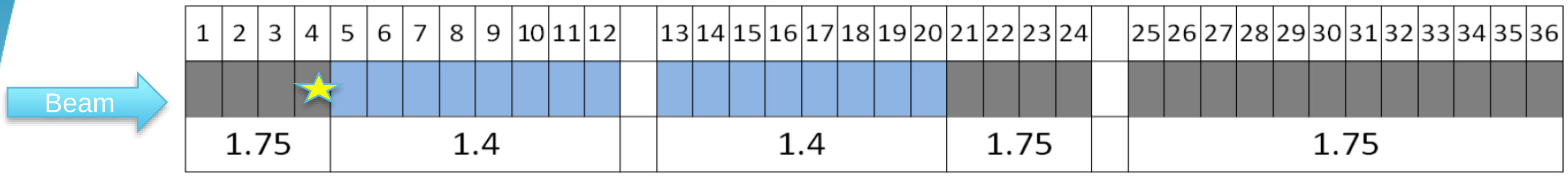
- The TCDQ gap affects the energy deposition.
- From the mechanical point of view, the 4th and 8th blocks (high and low density CFC blocks, respectively) are the most affected.

	1.4×10^{11}	1.7×10^{11}	2.0×10^{11}	2.3×10^{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)

Table 2. Peak doses as function of the gap and beam intensity [2]

[2] A. Lechner, C. Bracco, M. Calviani, S. Gilardoni, C. Di Paolo, M. Fraser, M. Frankl, B. Goddard, F.X Nuiry, A. Perillo Marcone, T. Polzin, C. Wiesner , *Run III limitations TCDQ, TCDS, TDE (related to beam impact)*, CERN indico
[3] A. Lechner, M. Atanasov, C. Bracco, J. Borburgh, M. Calviani, C. Di Paolo, M. Fraser, M. Frankl, B. Goddard, A. Perillo Marcone, C. Wiesner, W. Weterings , *Energy deposition and thermo-mechanical studies for IR6 protection devices and downstream magnets/septa*, CERN indico

TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap Block 4



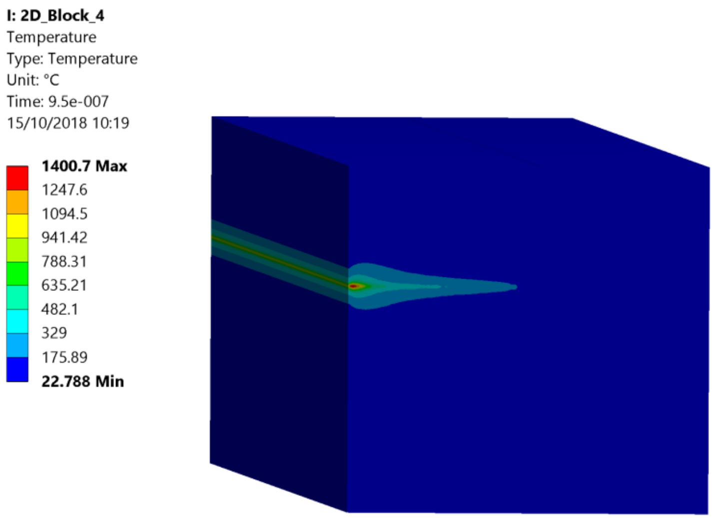


Fig. 1. Temperature distribution after the beam pulse

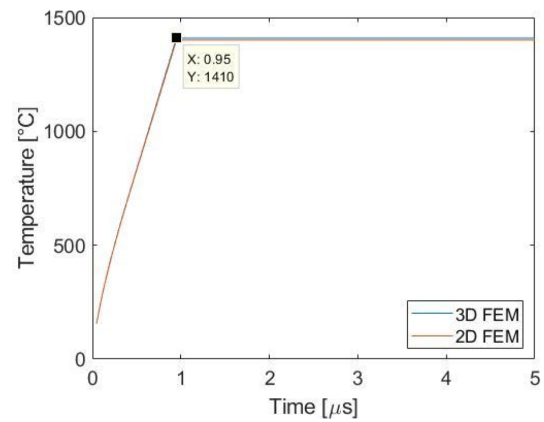


Fig. 2. Temperature evolution for the 2D and 3D FEM

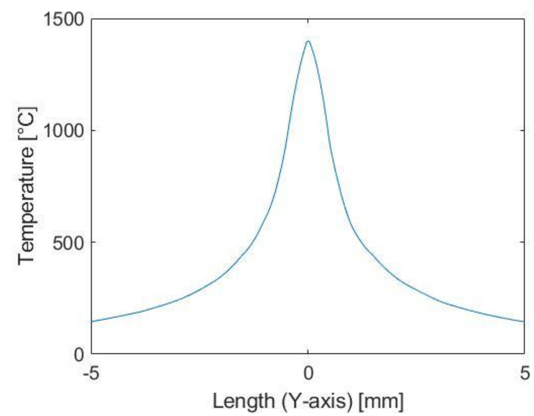
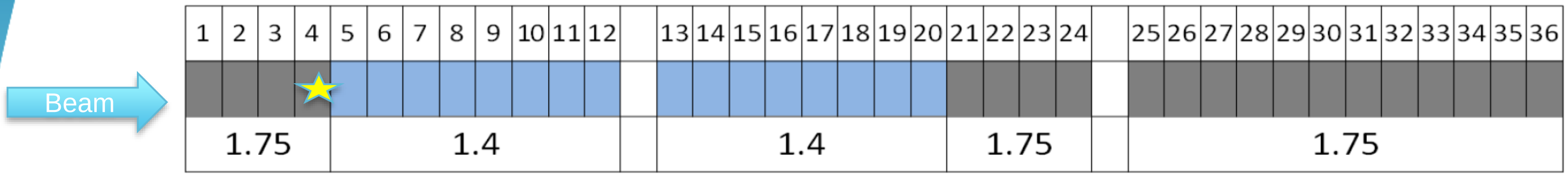


Fig. 3. Temperature distribution along the Y-axis at the temperature peak.

- Maximum temperature (1400°C) is expected to be acceptable. This temperature is reached after the beam pulse and is practically constant during the first 5 μs.

TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap Block 4



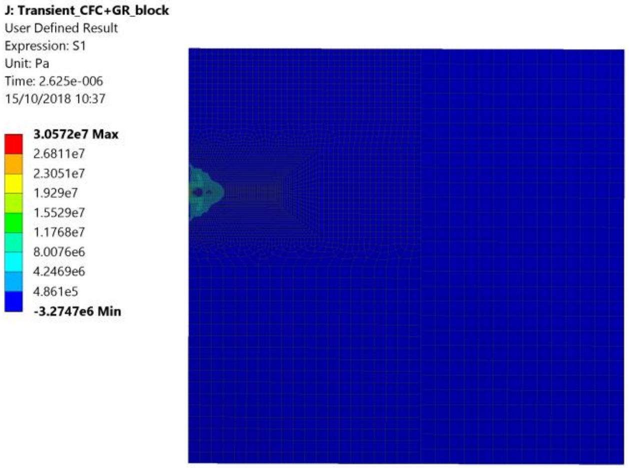


Fig.1. Maximum principal stress distribution for internal plane

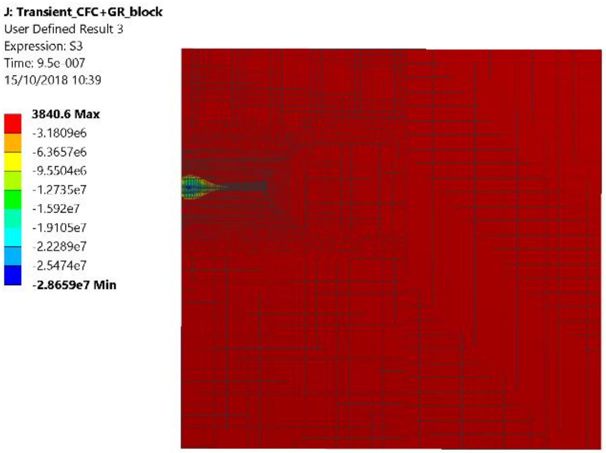


Fig. 2. Minimum principal stress distribution for internal plane

TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap Block 8

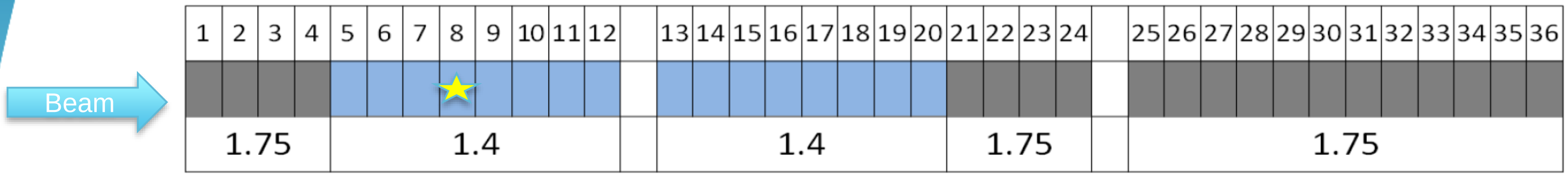
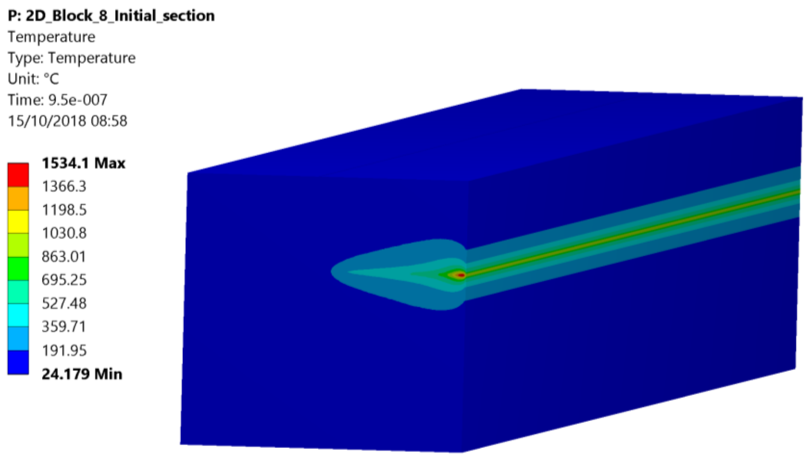


Fig. 1. Temperature distribution after the beam pulse



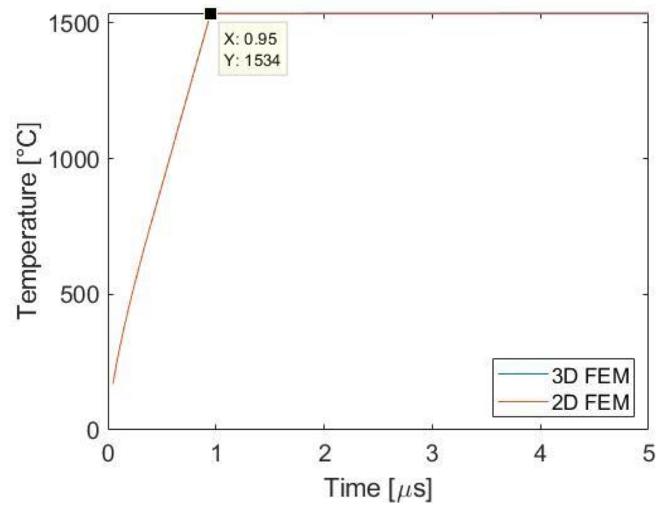


Fig. 2. temporal temperature evolution for the 2D and 3D FEM

- Maximum temperature (1536 °C) is expected to be acceptable. This temperature is reached after the beam pulse and is practically constant during the first 5 μs

TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap Block 8

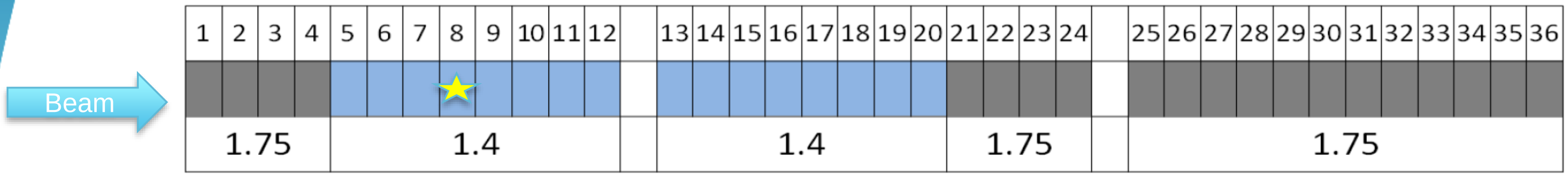


Fig. 1. Maximum principal stress distribution 3D

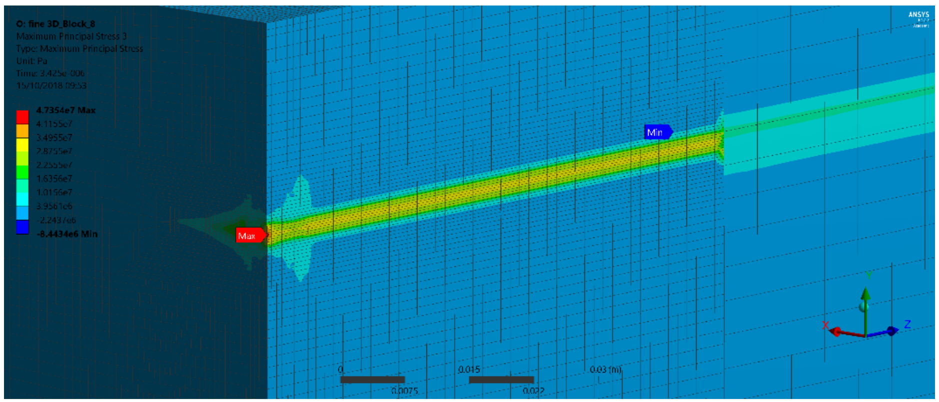


Fig. 2. Maximum principal stress over time

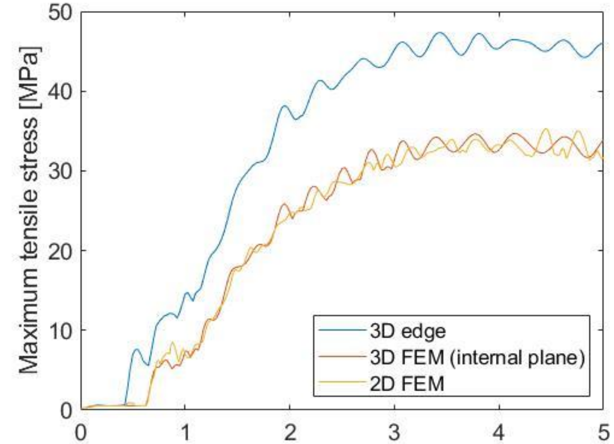


Fig. 3. Minimum principal stress distribution 3D

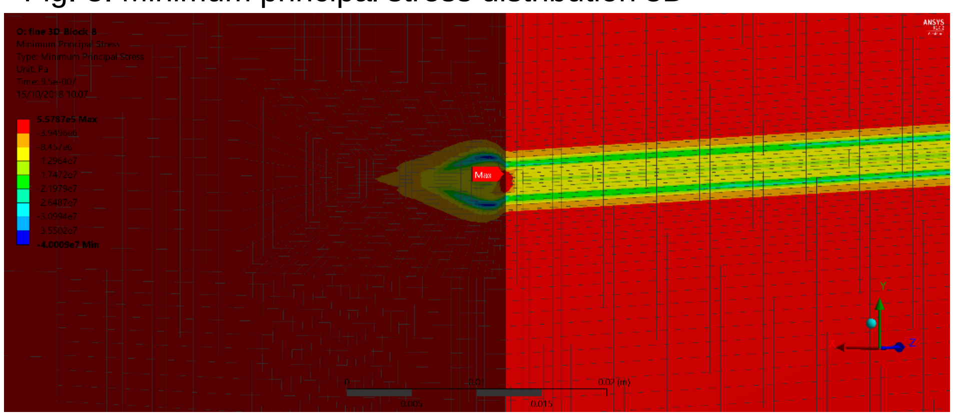
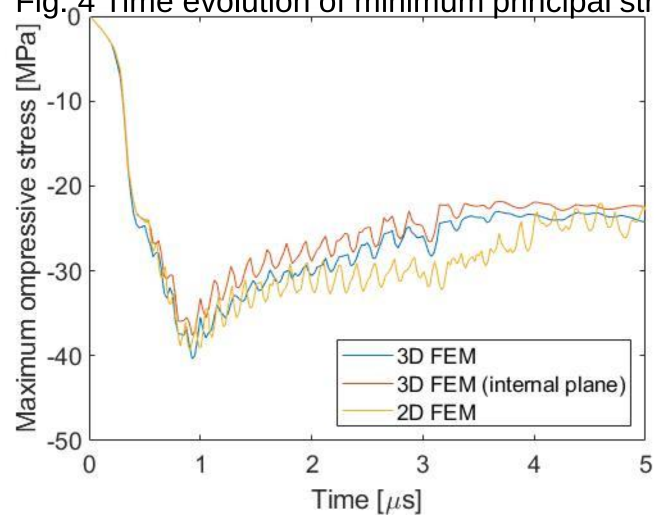
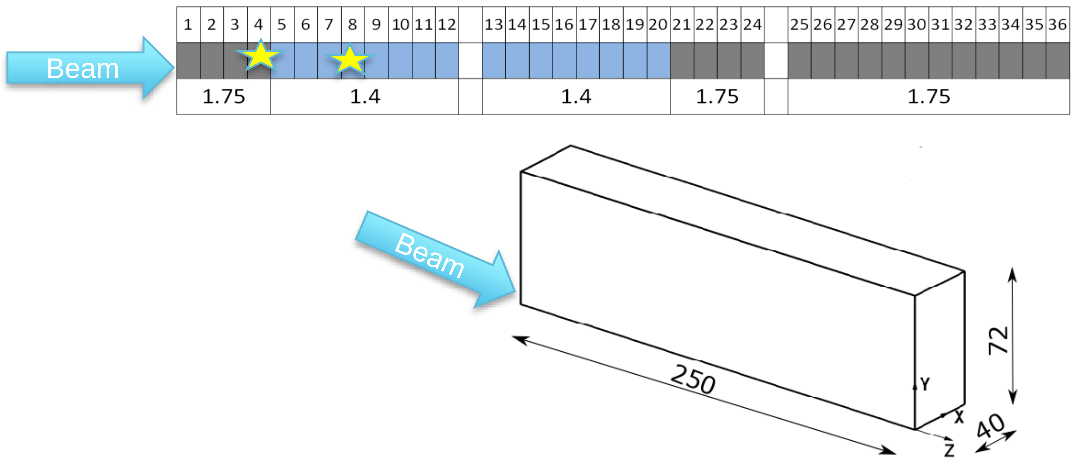


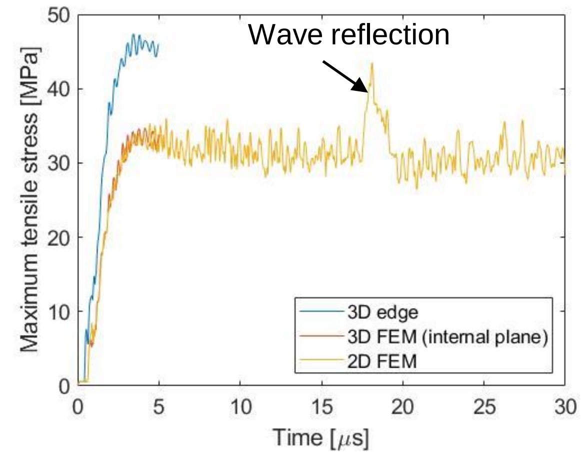
Fig. 4 Time evolution of minimum principal stress



TCDQ results for 1.7×10[11] ppb and 2.5 mm gap
TCDQ results for 2.3×10[11] ppb and 2.5 mm gap

Blocks 4 and 8





	Bunch intensity 1.7e11		Bunch intensity 2.3e11	
	CFC 4th block	CFC 8th block	CFC 4th block	CFC 8th block
	2D FEM			
Max. Temp [°C]	1401	1534	1837	2018 ⚠
Max. Princp. Stress [Mpa]	31 Y-dir	35 Y-dir	41 Y-dir	42 / 58 (wave reflection), Y-dir
Min. Princp. Stress [Mpa]	-29	-39	-38	-48
Tensile Stress [MPa]	Sx:8.7 Sy: 31	Sx:9 Sy: 35	Sx:10 Sy: 41	Sx:10 Sy: 42
Compressive stress [Mpa]	Sx: -19 Sy: -24	Sx: -21 Sy: -39	Sx: -24 Sy: -35	Sx: -28 Sy: -48
Compressive strength [Mpa]	-69.6 (X-dir) -88.6 (Y-dir) -82.4 (Z-dir)			
Tensile strength [Mpa]	≈ 40 (X-dir) 84 (Y-dir) 61 (Z-dir)			
Safety factor (based on stress)	2.5	2.4	1.90	1.45 ⚠

TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap
TCDQ results for 2.3×10^{11} ppb and 2.5 mm gap
Blocks 4 and 8

- Typical CFC materials experience non linear behavior
- A better way to post process the results consist in checking the **thermal strain (temperature imposed problem)**
- **The material strain at failure is unknown**
- **A strain at failure <u>estimate</u> is proposed based on the young's modulus at RT and the max tensile and compression strength**

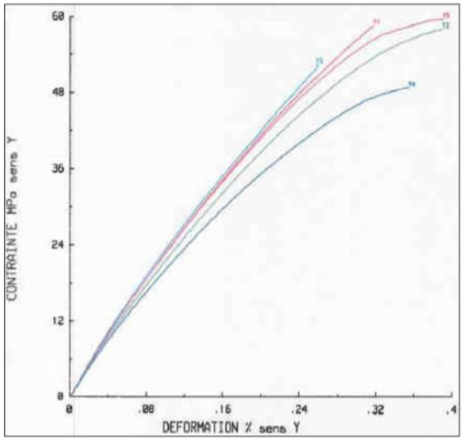


Fig. 1. Typical stress / strain curves for Carbon carbon composite

	Estimated strain at failure	
	CFC 4th block	CFC 8th block
Ultimate Compr. Strain	≈ -25e-3(X-dir) -8.9e-3(Y-dir) -8.2e-3(Z-dir)	
Ultimate Tens. Strain	≈ 14e-3(X-dir) 8.4 e-3(Y-dir) 8.2e-3(Z-dir)	

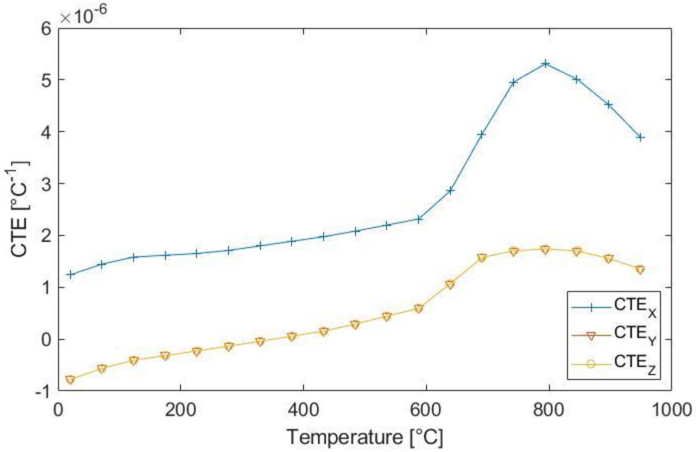
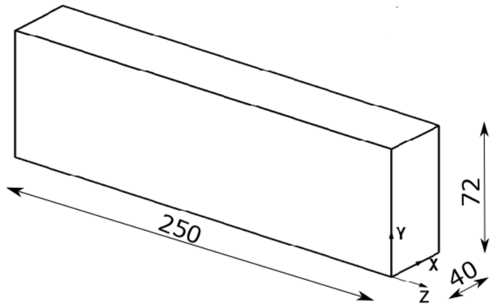
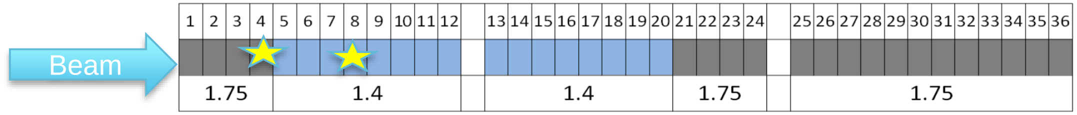


Fig. 2. Coefficient of thermal expansion of CFC.



TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap
TCDQ results for 2.3×10^{11} ppb and 2.5 mm gap

} Blocks 4 and 8



	Bunch intensity 1.7e11		Bunch intensity 2.3e11	
	CFC 4th block	**CFC 8th block**	**CFC 4th block**	**CFC 8th block**
	2D FEM			
Max. Temp [°C]	1401	1534	1837	2018 ⚠
Max. Princp. Strain [-]	3.8e-3 mainly Y-dir	4.4e-3 mainly Y-dir	4.5e-3 Y-dir	5.9e-3 Y-dir
Min. Princp. Strain [-]	-4.8e-3 XY-dir	-5.1e-3 XY-dir	-6.1-e-3 XY-dir	-6.8-e-3 XY-dir
Ultimate Compr. Strain	≈ -25e-3(X-dir) -8.9e-3(Y-dir) -8.2e-3(Z-dir)			
Ultimate Tens. Strain	≈ 14e-3(X-dir) 8.4 e-3(Y-dir) 8.2e-3(Z-dir)			
Safety factor (based on strain)	1.8	1.7	1.45 ⚠	1.3 ⚠

- The material production process temperature shall allow to confirm if > 2000°C on the CfC is acceptable.
- Considering that strains are estimates, the safety margin shall be considered small
- Several impacts shall not be sent to the TCDQ
- **To confirm / precise the results, one could launch new material characterization aiming at determine:**

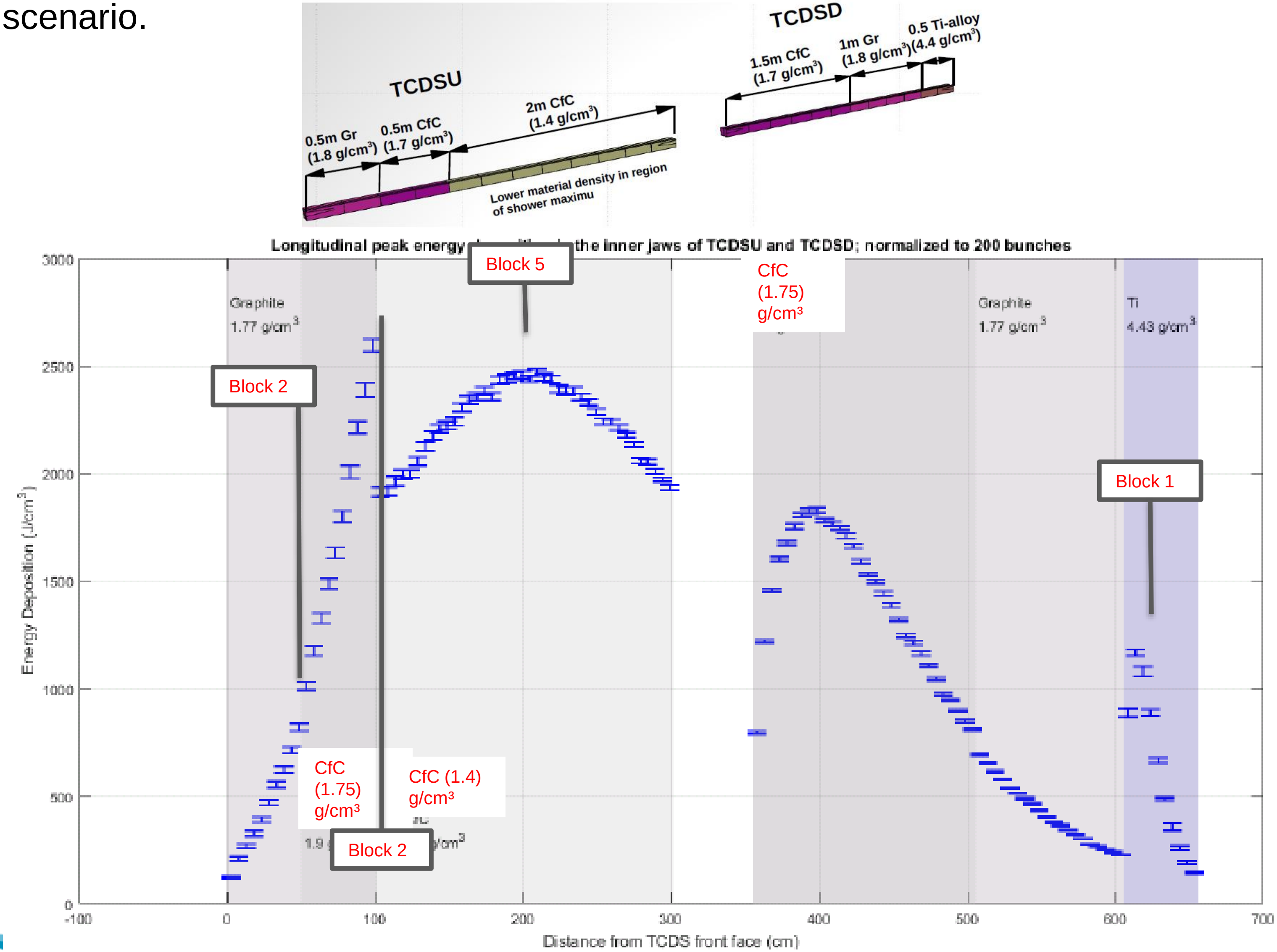
→ **The ultimate strain at RT and up to at least 1500°C**

→ **The strain rate effect on the ultimate strain (at RT and up to at least 1500°C)**

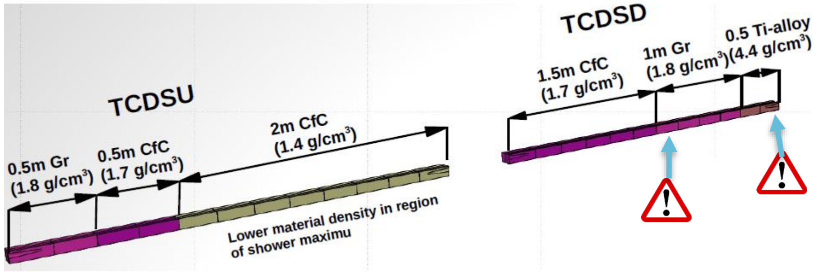
- *Material available.*
- *Demanding work but very helpful to confirm the equipment ability to survive HL-LHC beam.*

TCDS Energy deposition

The analyses were performed with the HL-LHC Std 25ns Beam that represent the worst case scenario.



TCDS thermal and structural results



TCDS (low Z)			
Material	C-C 1.75	C-C 1.4	Graphite C2020 (block 19)
Max. Temp. [°C]	798	1141	396
Max. Comp. Stress. [MPa]	**23**	**27**	**33**
Comp. Strength	70	70	35
Max. Tens. Stress. [MPa]	**18**	**51**	**38** ⚠
Tensile Strength	61	84	35

Risk of failure caused by the high stresses and elevated temperature generated in the Block 19 of graphite.

TCDS (Ti6Al4V)			
	Area at Max T	Area at Max stress	Area at Max plastic strain
Temp. [°C]	**568**	**164**	**255** ⚠
Eq. Stress [MPa]	**308**	**711**	**601**
Yield Strength	248	628	529
Tensile Strength	358	734	645

The titanium block experiences a plastic deformation (1.2%) on a part of the surface in the middle plan. Although the material still have elongation before reaching the necking point (UTS at about 10% of the equivalent strain), material integrity cannot be guaranteed for several shots.
An optimal design shall prevent any permanent deformation of the material.

Preliminary conclusions I

→The material properties available does not allow to formally conclude about the TCDS / TCDQ target survival for HL-LHC beams.

→The same material properties are considered for both CfC, whereas the mechanical characteristics are expected to vary with different densities (experience on 3D CC).

→The key missing data are:
- The ultimate strain, because it's a temperature imposed problem;
- Ideally the Stress / Strain curves at different temperatures and high strain rates.

Preliminary conclusions II

With today's available material data, conclusions are:

TCDQ

- Simulations output for 1.7×10^{11} ppb and 2.5 mm gap → Targets integrity is expected to be kept, to be confirm with ultimate strain comparison.
- Simulations output for 2.3×10^{11} ppb and 2.5 mm gap → High temperature and high strain may lead to material failure.

TCDS

- A high risk of failure caused by the high stresses and elevated temperature generated in the Block 19 of graphite is expected.
- The titanium block experiences plastic deformation and very high temperature. An optimal design shall prevent any permanent deformation of the material. The block will deform after one impact and potentially break after several impacts.

The complete assembly flatness / geometry could be also affected by a beam impact, as observed on the TDE and recent HRMT experiments.

→Vessels absolute position could be measured after each impact (following ALARA's principle)?

→Interferometers could be eventually installed on the tank / absorber girders ?

Thanks for your attention