TCDS/TCDQ for Run III and HL-LHC
Summary of the ongoing Thermo-mechanical calculations
3/03/2020 WP14 meeting

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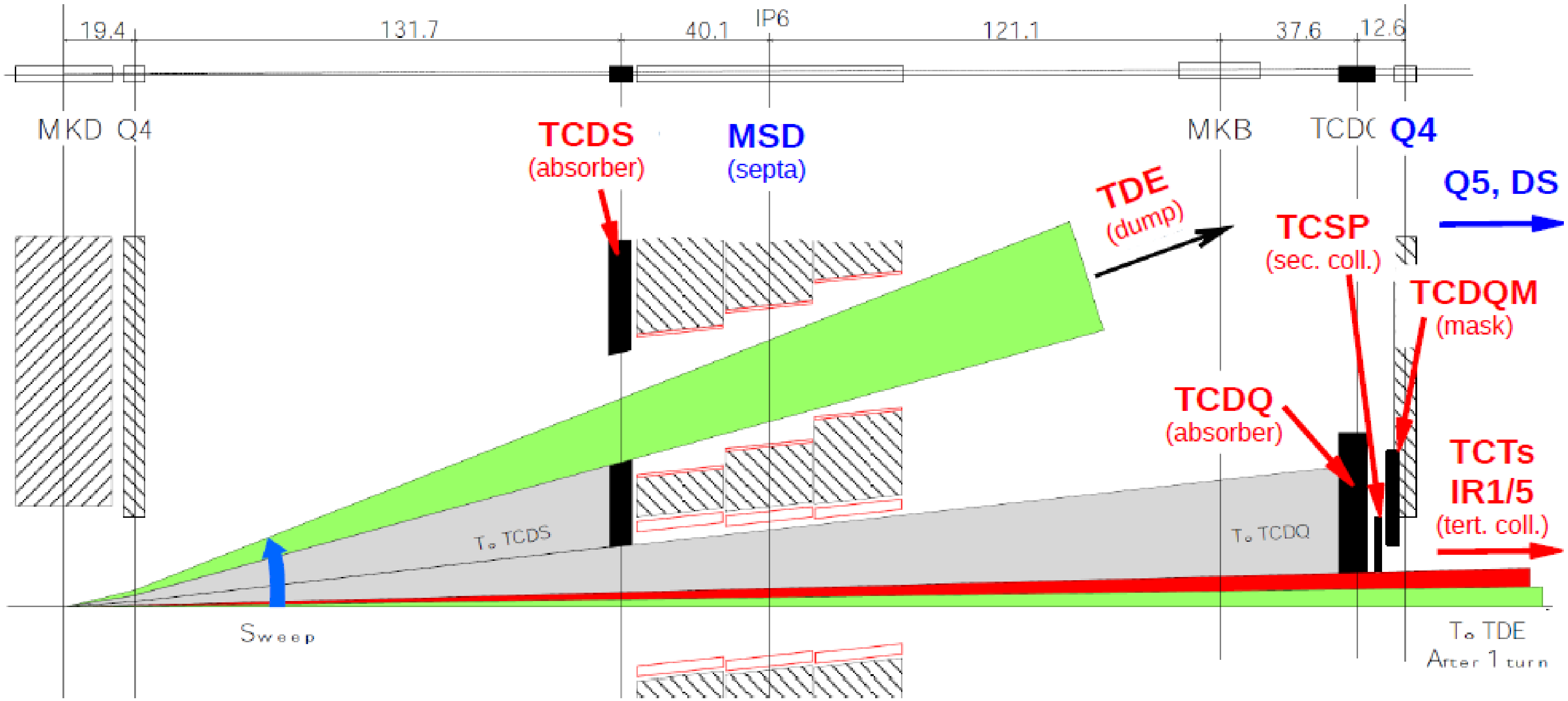
Outlines

- TCDS description and materials
- TCDS context and thermo-mechanical analyses
- TCDS Summary

- TCDQ description
- TCDQ context and thermo-mechanical analyses
- TCDQ Summary

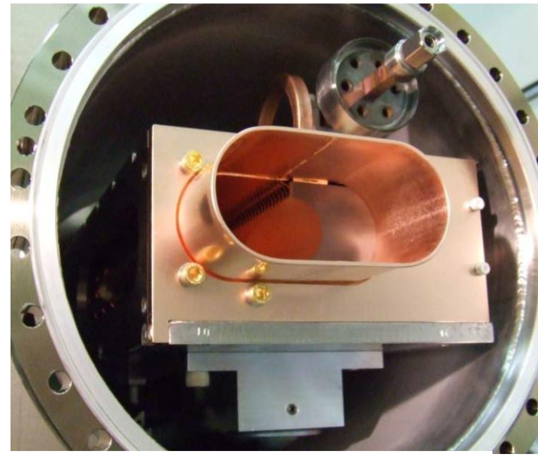
TCDS / TCDQ

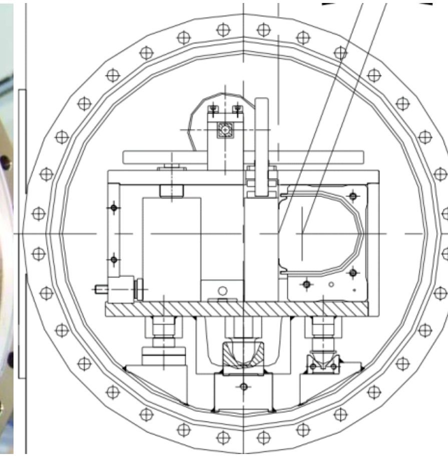


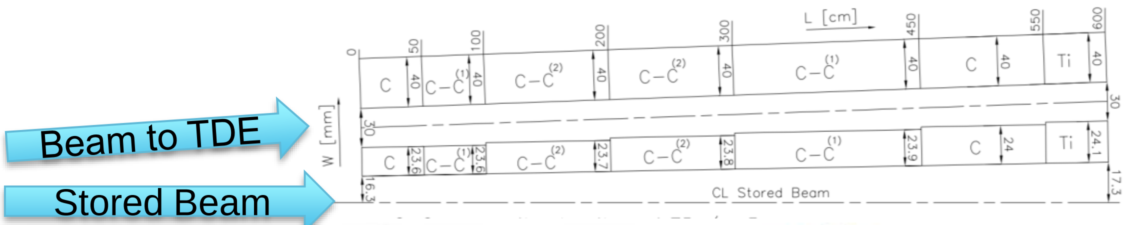
TCDS – A fixed diluter block installed immediately upstream of the MSD magnets(IR6)
TCDQ – A mobile diluter block to protect the Q4 magnets, (IR6)

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

TCDS description *

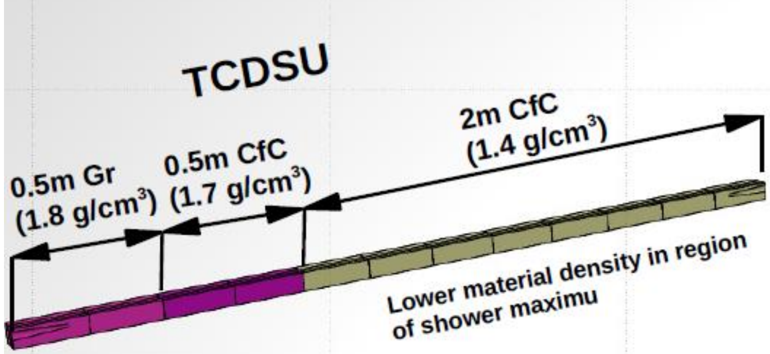


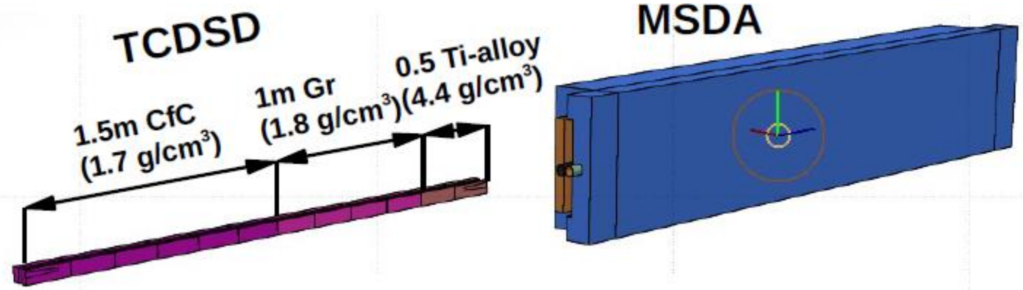




Two jaws

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.

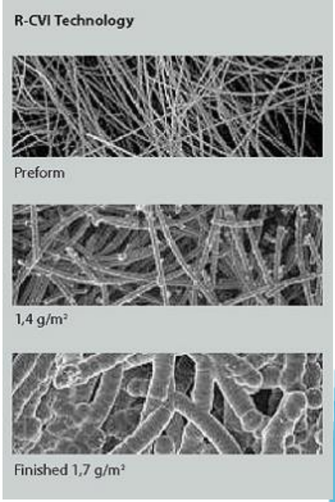
TCDS/Q Target Material Properties

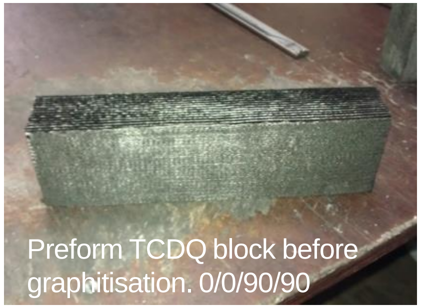
CfC RNFF-SG/SAG (from CVT) is an orthotropic material. The fibers are in the y and z axes (+ small fibers in X).

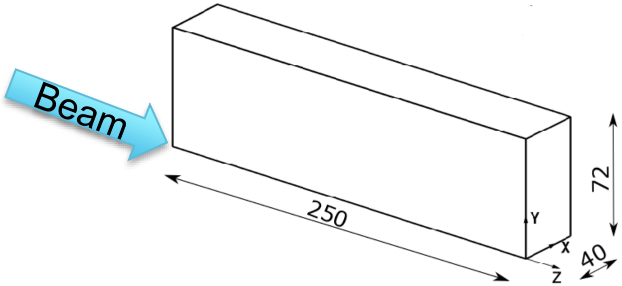
Rapid-CVI Needled Fiber Fabric

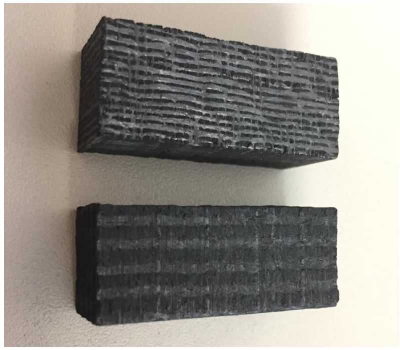
CfC RNFF-SG (at 22 C)		⊥(x)	∥(y)	∥(z)	⊥(x)	∥(y)	∥(z)
Density	g/cm3	1.4			1.75		
Tensile strength	MPa					84	61
Compresive strength	MPa				69.6	88.6	82.4
Compresive Young Modulus	GPa				2.8	10	10
Thermal conductivity	W/mK				91	110	110
3-point bending strength	MPa				170	190	190
3-point bending Young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

NOT Known, assumption: taking data from 1.75 g/cc grade




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





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, especially the young's modulus and the CTE.

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

Some material considerations

- Typical CFC materials experience non linear behavior

  → Data not available

- A way to post process the results consist in checking the thermal strain (temperature imposed problem)

  → Strain at failure not available

- Coefficient of thermal expansion varying a lot from one sample to another one

  → Measurements done dependent with the layer thickness

- Material behavior at high strain rate?

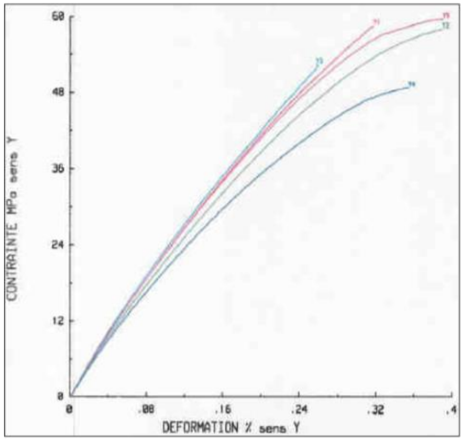


Fig. 1. Typical stress / strain curves for Carbon carbon composite

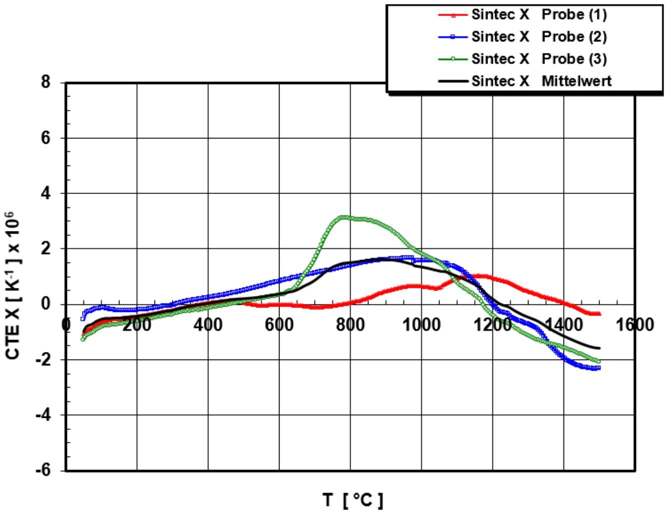
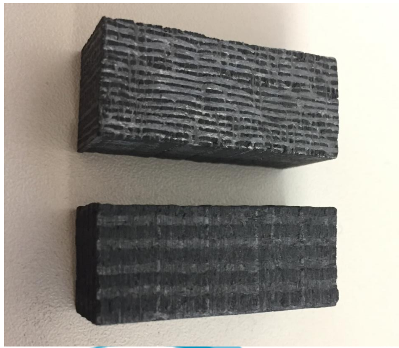
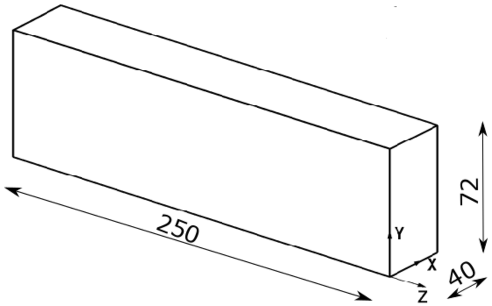


Fig. 2. Coefficient of thermal expansion of CFC.





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. (Multilinear kinematic hardening)

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

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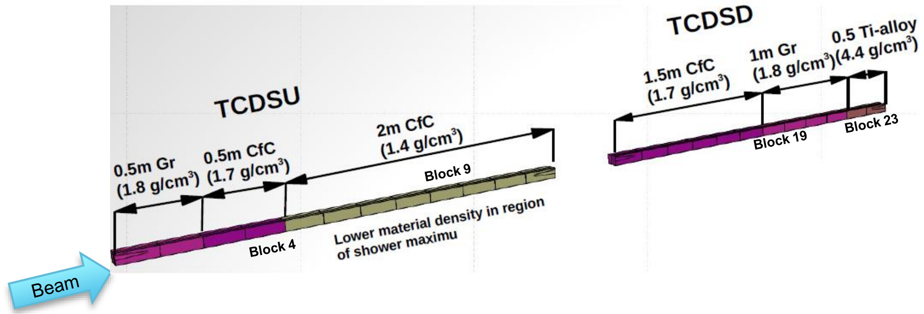
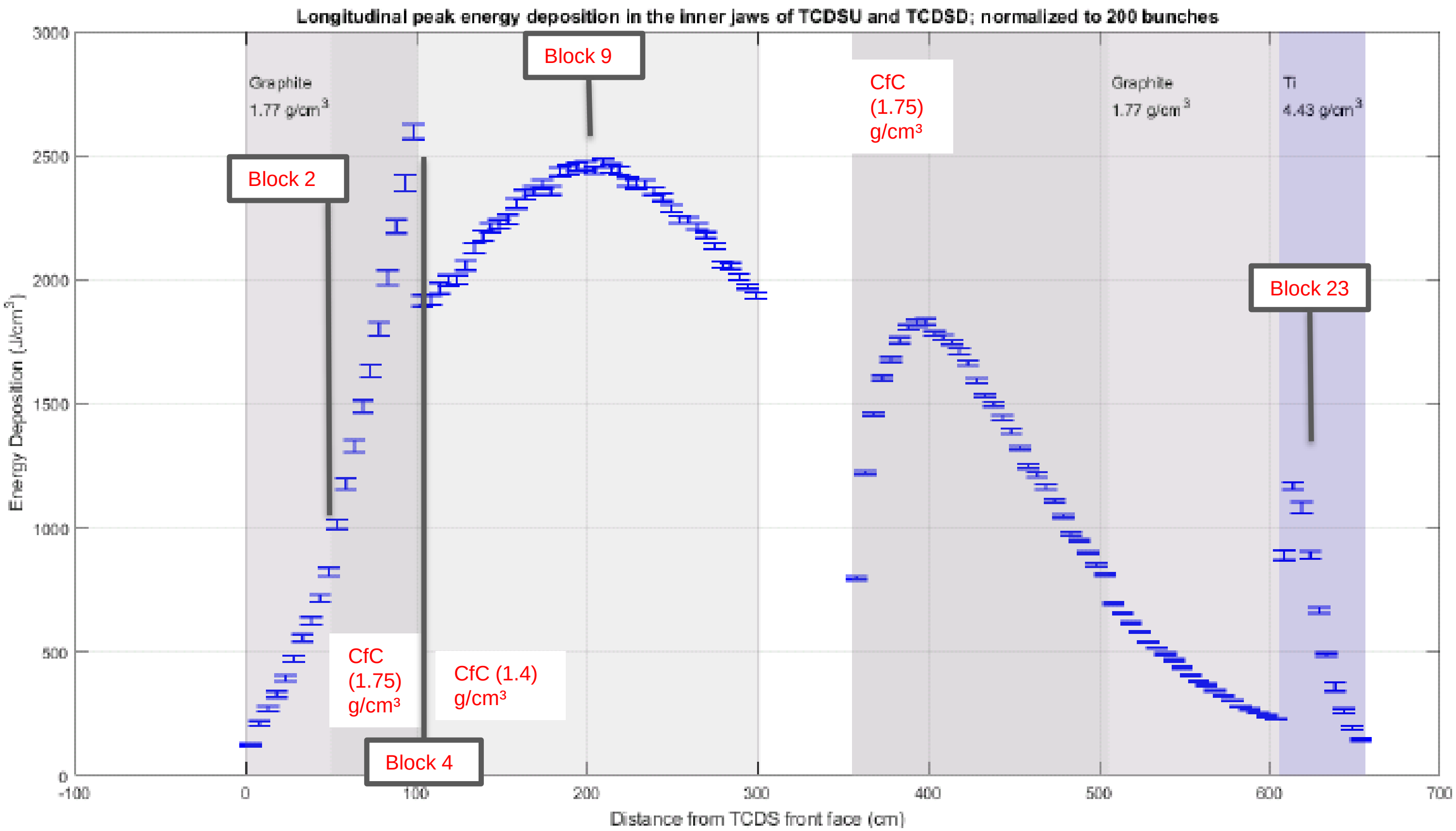
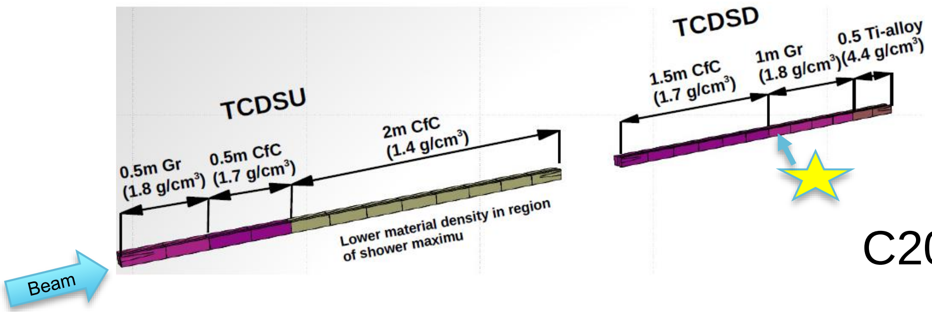
TCDS Energy deposition (single MKD module pre-fire)

Parameters	HL-LHC25ns
Bunch intensity	**2.3e11**
Number of bunches	**65**
Total pulse intensity	**1.5e13**
Beam energy	**7 TeV**
Pulse length	**1.1 µs**
Beam emittance	**2.1 µm**





TCDS thermal and structural results



Graphite
C2020 (block 19)

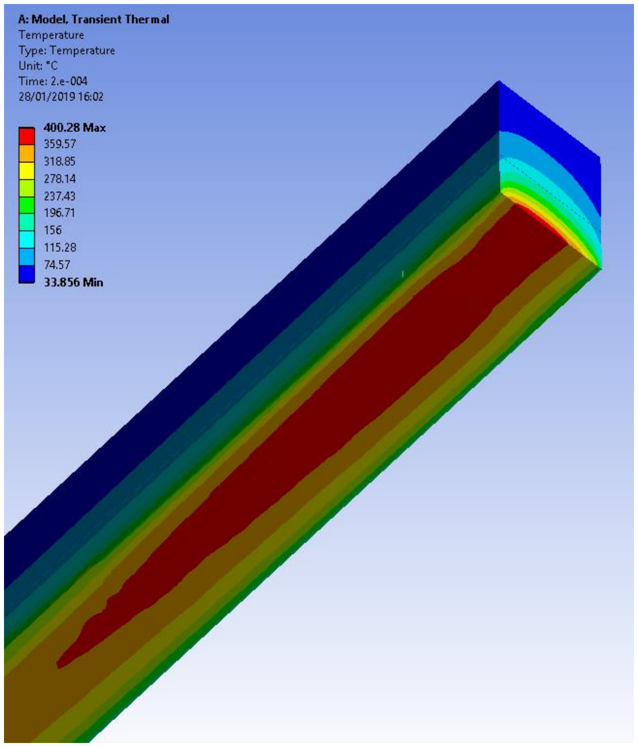


Fig. 1. Temperature distribution after the beam pulse

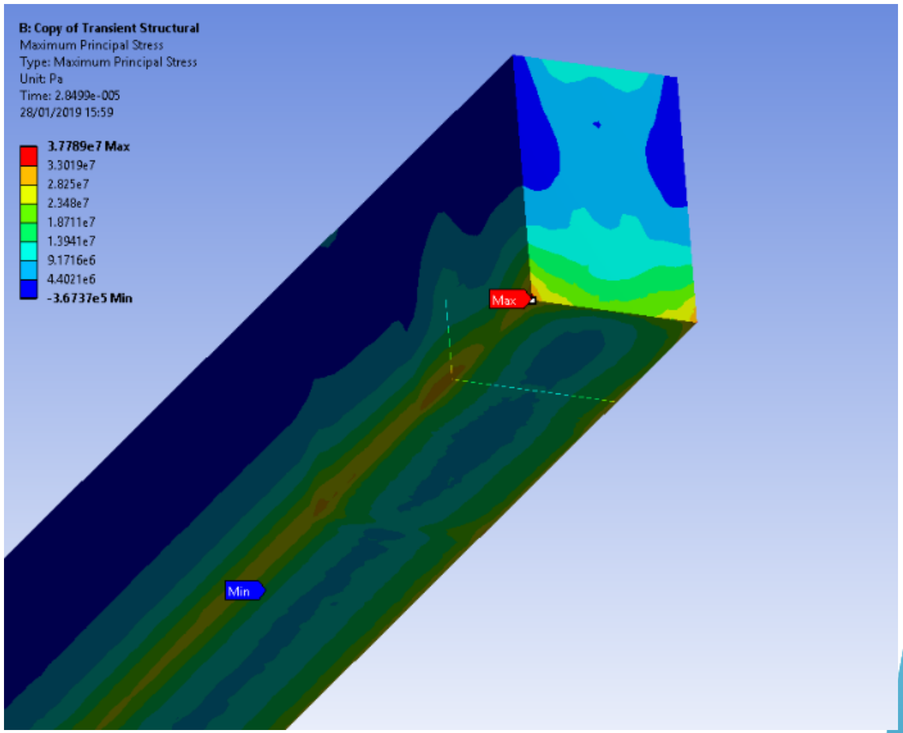
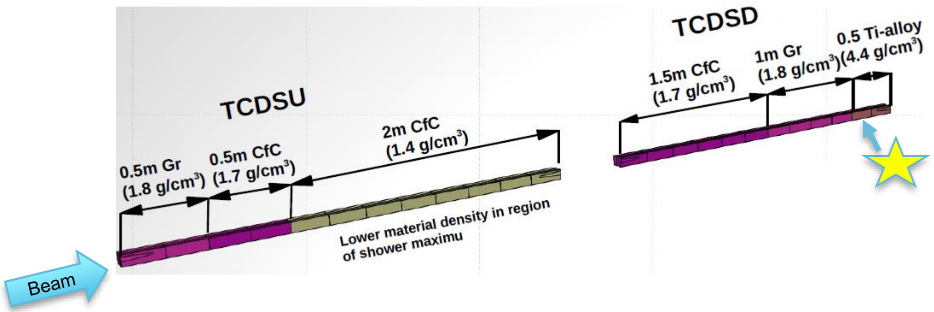


Fig. 2. Maximium principal stress after the beam pulse

TCDS thermal and structural results



(Ti6Al4V), block 23

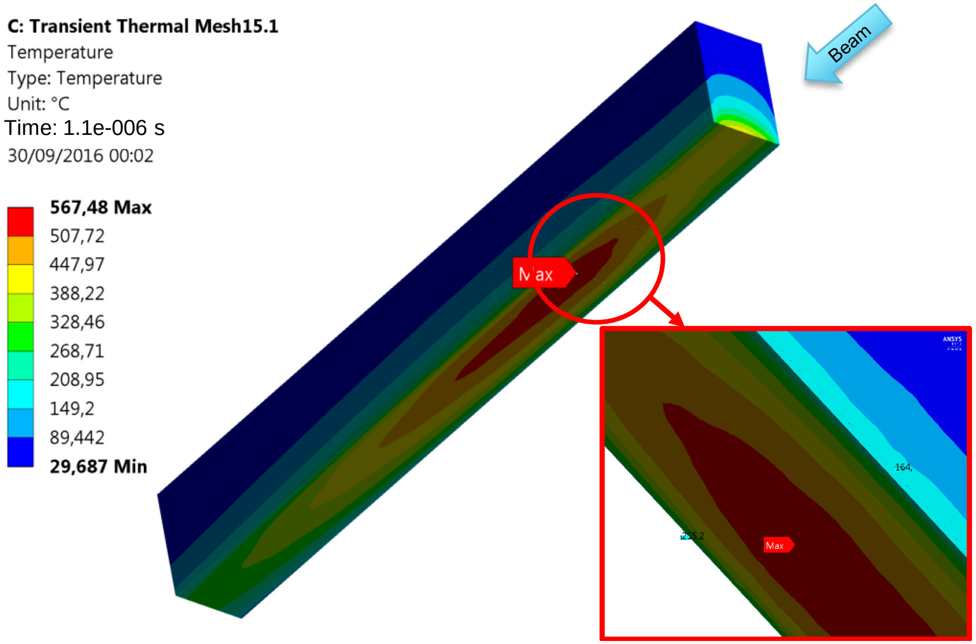


Fig. 1. Temperature distribution at the end of the beam pulse

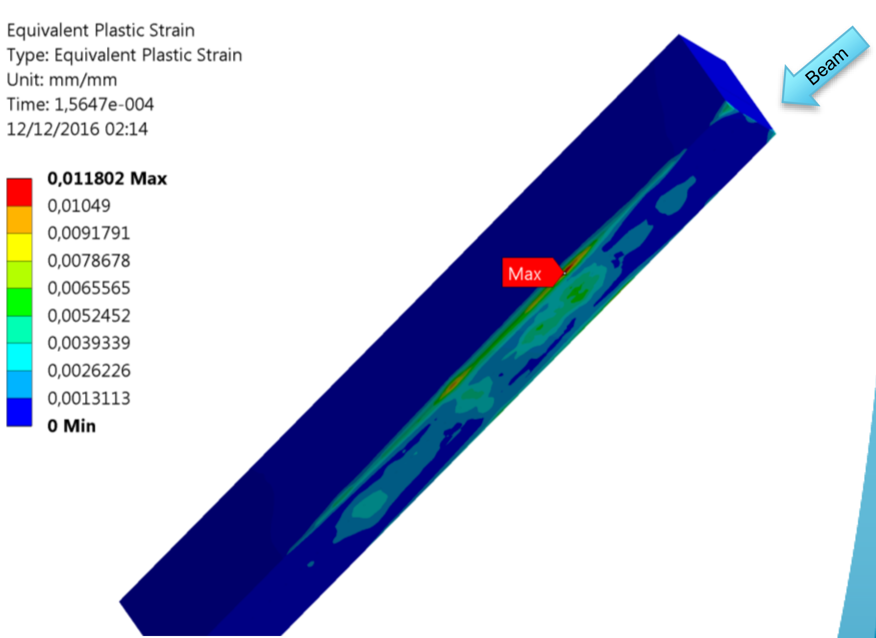
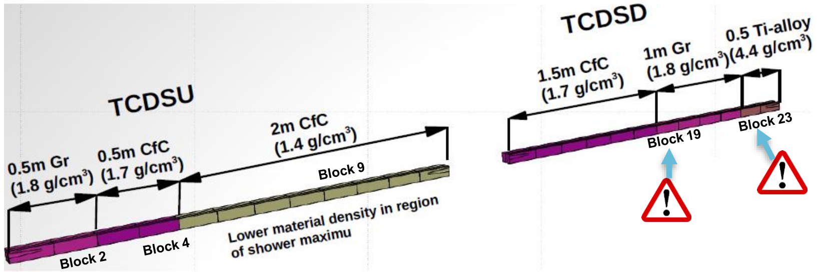


Fig. 2. equivalent plastic strain after the beam pulse

TCDS thermal and structural results

Preliminary results, pending new simulations and material characterization



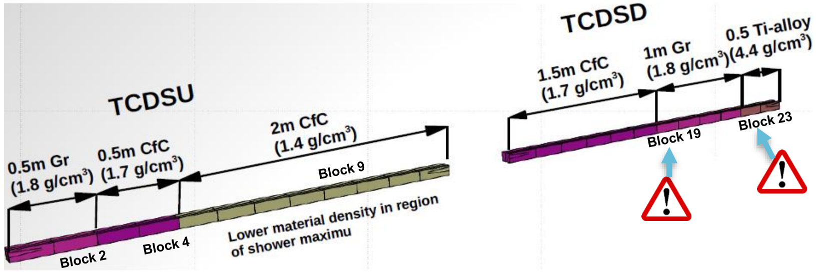
TCDS (low Z)				
Material	Graphite C2020 (block 2)	Block **4** C-C 1.7	Block **9** C-C 1.4	Graphite C2020 (block 19)
Max. Temp. [°C]	396	798	1141	402
Max. Comp. Stress. [MPa]	**-20**	**-23**	**-27**	**-33**
Comp. Strength	-35	-70	-70	-35
Max. Tens. Stress. [MPa]	**29**	**18**	**51**	**38**
Tensile Strength	35	61	84	35

TCDS (Ti6Al4V), block 23	
	Area at Max plastic strain
Temp. [°C]	**255**
Eq. Stress [MPa]	**601**
Yield Strength	529
Tensile Strength	645

The titanium block experiences a plastic deformation (1.2%) on part of the surface.

For block 9 → **Material properties are not known. Values written are assumptions based on 1.7 g/cc grade**

TCDS preliminary conclusions



- A 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.

→It is suggested **to launch a new simulations campaign** searching for optimizing the material distribution:

a. Substituting at least blocks 19 and 20 with 2D CFC (1.7 g/cc);
b. Checking the Titanium blocks need for MSDA protection / or slicing it;
c. Substituting the Titanium blocks with another material;

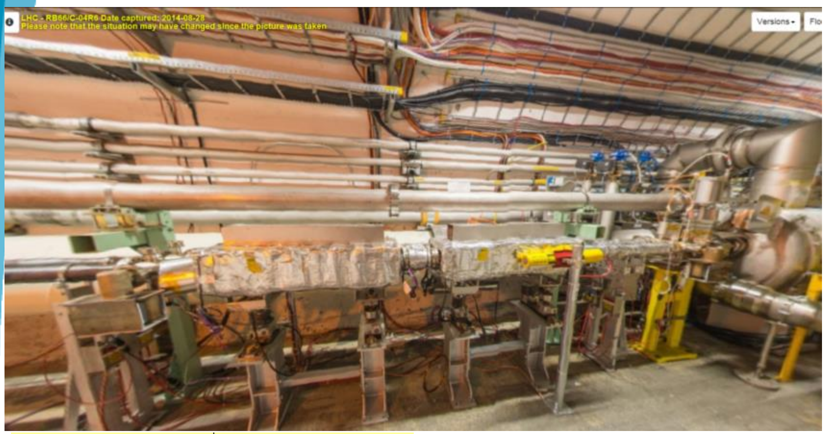
→The 2D CFC seems to be strong enough **although the key material properties (ultimate strain /strength at high temperature…) are not available.**

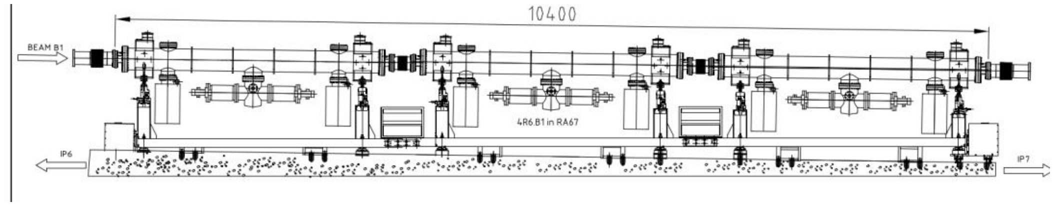
Material characterization is needed

TCDQ

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/cm^3.

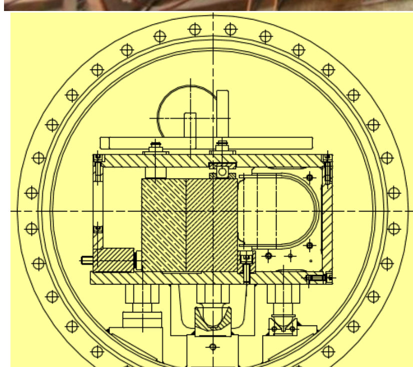




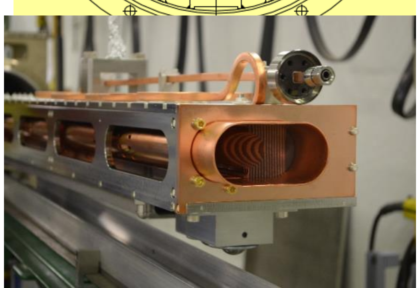
1	2	3	4	5	6	7	8	9	10	11	12		13	14	15	16	17	18	19	20	21	22	23	24		25	26	27	28	29	30	31	32	33	34	35	36
1.75				1.4									1.4								1.75					1.75											

→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 TCDQ structure showing the graphite (left) and CFC (right) absorber blocks



TCDQ Energy deposition

Beam Parameters	HL-LHC25ns
Bunch Intensity	2.3E11
Number of bunches	50
Beam energy	7 TeV
Pulse length	950ns
Beam emittance	2.1 µm

Table 1. Beam parameter

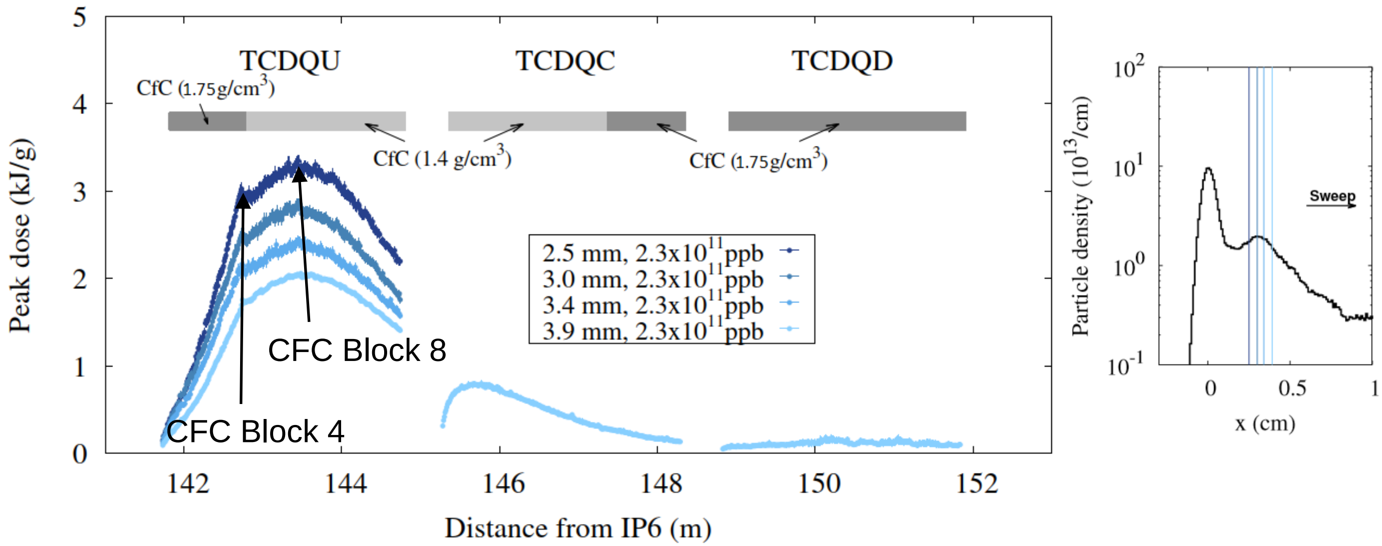


Fig. 1. Energy deposition distribution [2]. Courtesy of M. I Frankl.

- 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

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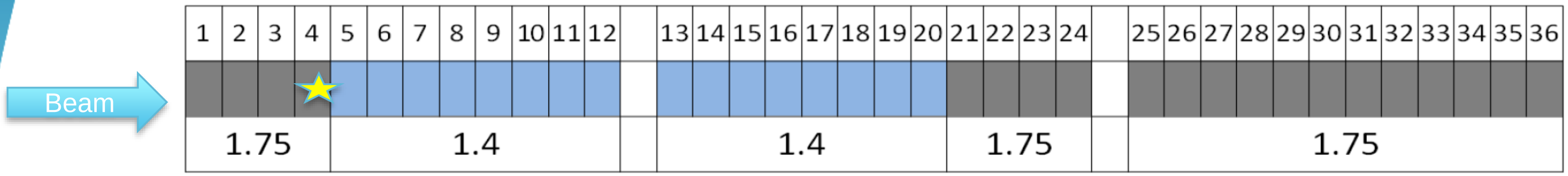
TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap Block 4



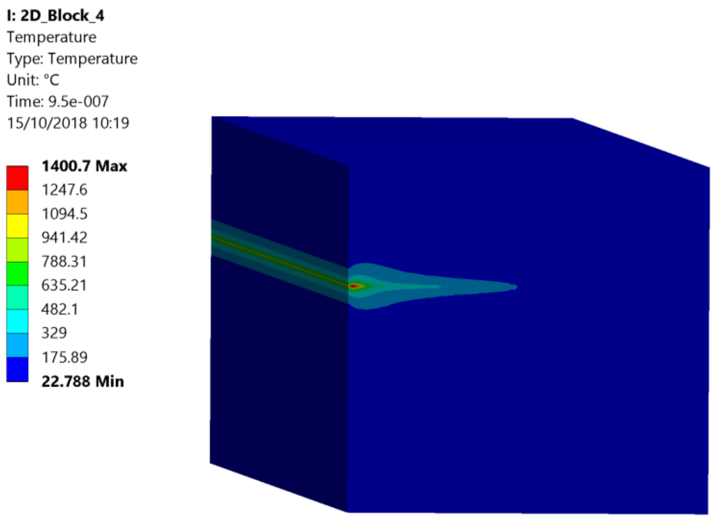


Fig. 1. Temperature distribution after the beam pulse

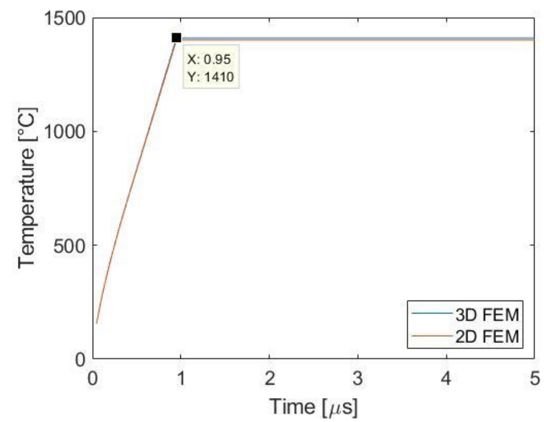


Fig. 2. Temperature evolution for the 2D and 3D FEM

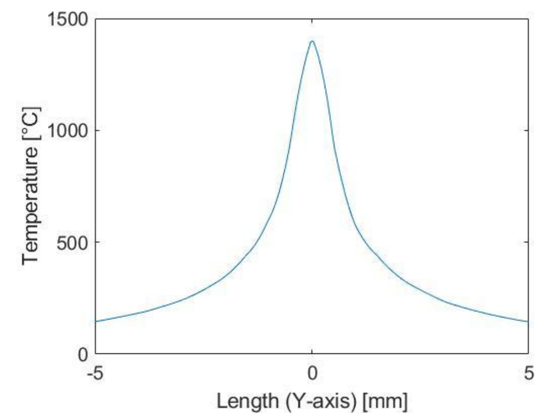


Fig. 3. Temperature distribution along the Y-axis at the temperature peak.

- 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 8

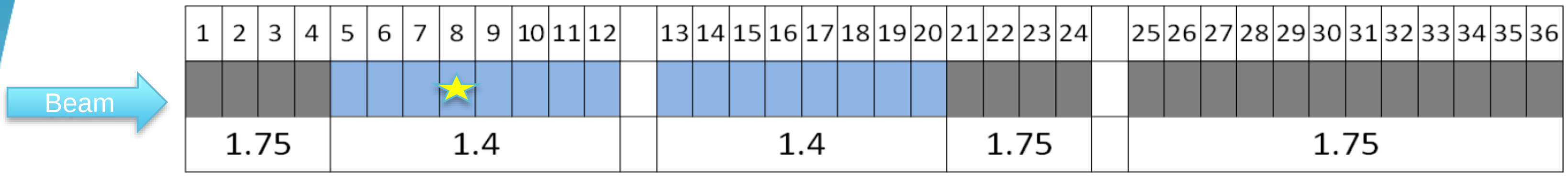
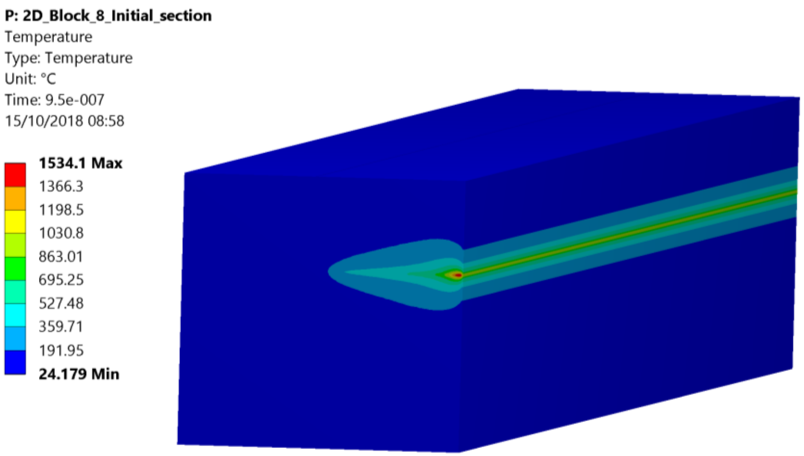


Fig. 1. Temperature distribution after the beam pulse



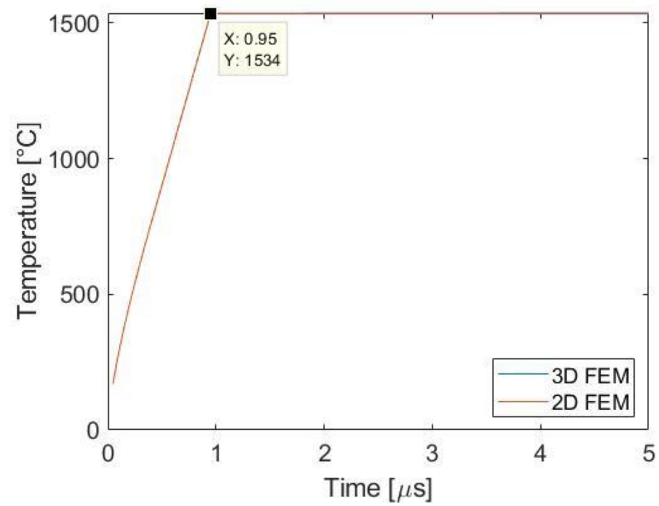


Fig. 2. temporal temperature evolution for the 2D and 3D FEM

- 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

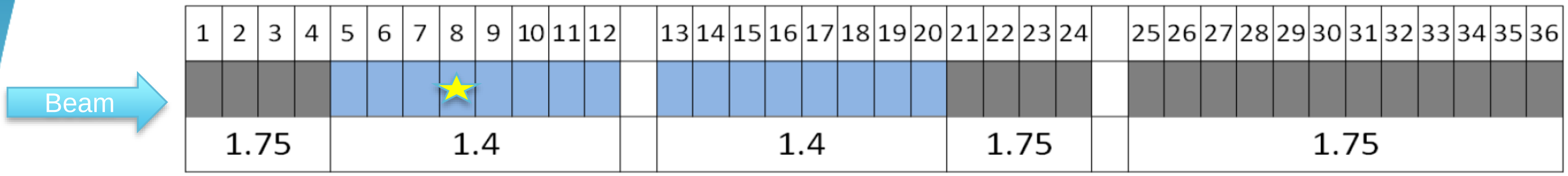


Fig. 1. Maximum principal stress distribution 3D

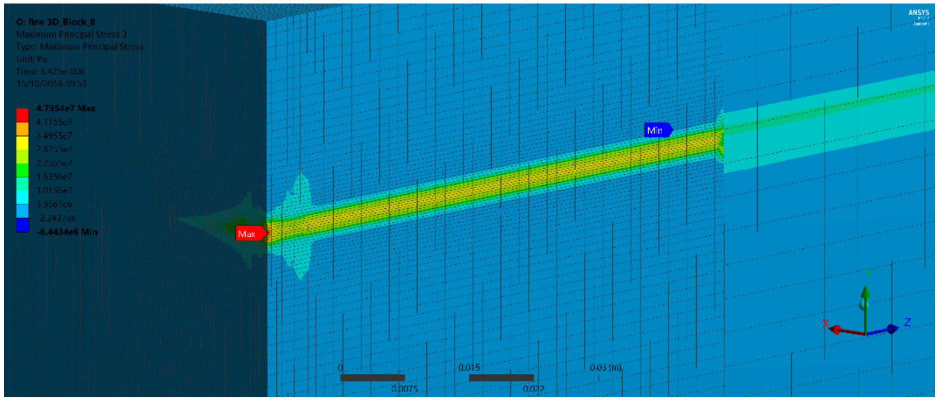


Fig. 2. Maximum principal stress over time

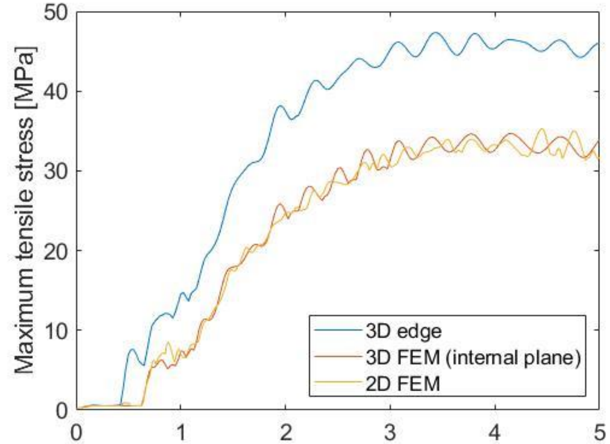


Fig. 3. Minimum principal stress distribution 3D

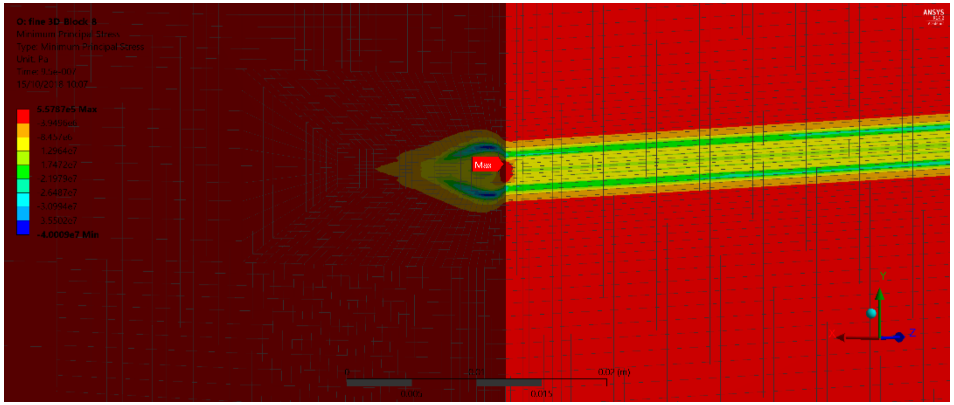
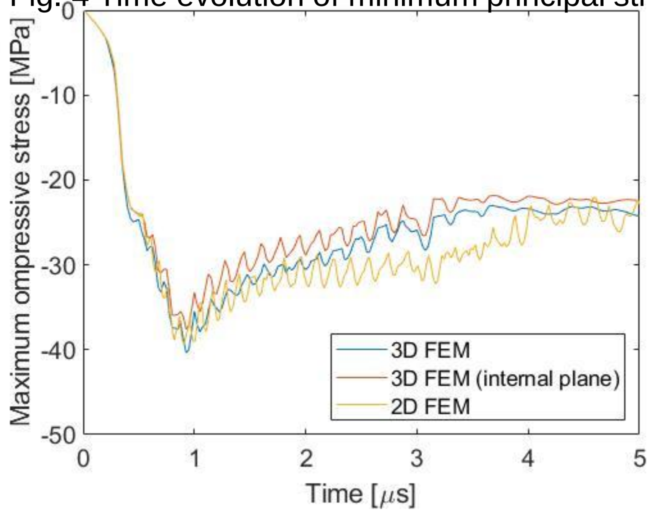


Fig. 4 Time evolution of minimum principal stress



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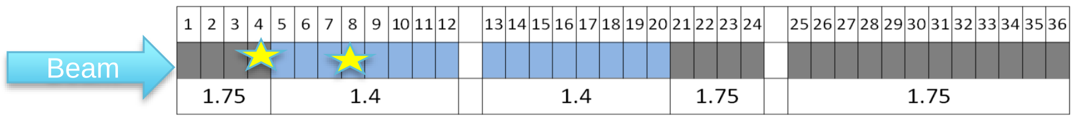
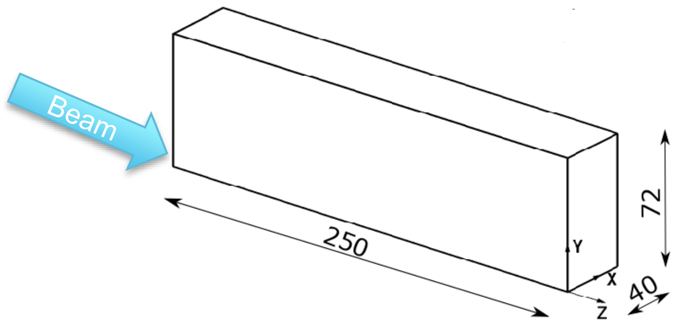
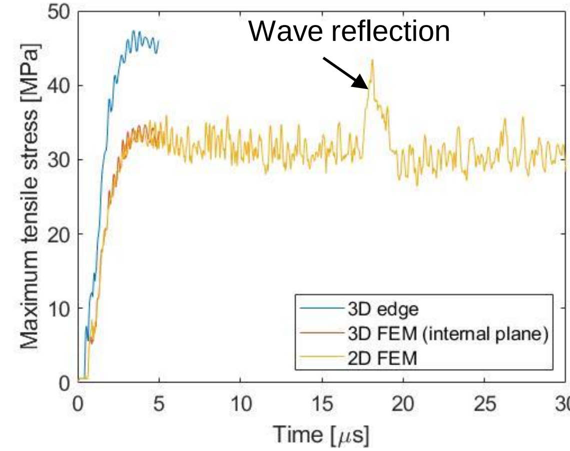
TCDQ results for 1.7×10^{11} ppb and 2.5 mm gap
TCDQ results for 2.3×10^{11} ppb and 2.5 mm gap

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]	31/33(wave refl.) Y-dir	35/43(wave refl.) Y-dir	41/44(wave refl.) Y-dir	42 / 58 (wave reflection), Y-dir
Min. Princp. Stress [Mpa]	-29 Y-dir	-39 Y-dir	-38 Y-dir	-48 Y-dir
Compressive strength [Mpa]	-69.6 (X-dir) -88.6 (Y-dir) -82.4 (Z-dir)	Not known	-69.6 (X-dir) -88.6 (Y-dir) -82.4 (Z-dir)	Not known
Tensile strength [Mpa]	? (X-dir) 84 (Y-dir) 61 (Z-dir)	Not known	? (X-dir) 84 (Y-dir) 61 (Z-dir)	Not known
Safety factor (based on stress)	**2.5**	**2.4***	**1.90** ⚠	**1.45*** ⚠

*Considering strength of 1.75 g/cc grade

Results highly dependent on the CTE

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Preliminary conclusions I

TCDS

- **New simulation campaign** shall be launched with new material distribution for TCDS

TCDQ

- Simulations output for 2.0×10^{11} ppb and 2.0 mm gap, and 1.7×10^{11} ppb and 2.5 mm gap:

→ Targets integrity is expected to be kept, but impossible to commit due to lack of material data.

- Simulations output for 2.3×10^{11} ppb and 2.5 mm gap → High temperature and high strain may lead to material failure.

Preliminary conclusions II

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

→MATERIAL CHARACTERISATION NEEDED:

- Material properties for RNFF-sg (1.4 g/cc);

- For all:

- Ideally the Stress / Strain curves at different temperatures (up to 1500 C);

- High strain rates strength of the material (at high temperature too);

- CTE cross check with suitable sample size.

→This work will request resources and funding

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

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 ?

HiLumi HL-LHC PROJECT

Preliminary conclusions III

3D CC HiRadMat impact testing (2016/2017/2018)

Peak energy deposition achieved:
6.1 kJ / cc

TCDQ Accidental impact: 2.3×10^{11} ppb and 2.5 mm gap

Peak energy deposition Expected:
5.8 kJ / cc

Transversal energy deposition gradient to be compared (could be worst for HiRadMat)

If confirmed →
Materials tested at HiRadMat 28 could be potential candidates for TCDQ.

Material characterisation possibilities at CERN

- CTE: samples: cubes → 6*6*6 mm^3
- Specific heat: samples: any kind of geometry
- Thermal diffusivity: samples: Cylinders → Ø12.7 mm * 6 mm (H)
- Compression samples: Cylinders → Ø8 mm * 15 mm (H)

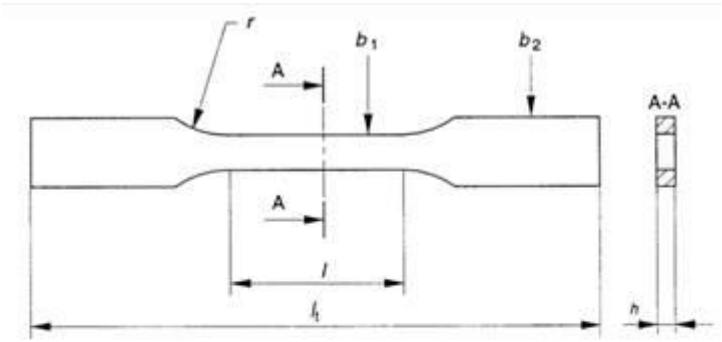
- Traction samples (maxi 700°C):

+ some ongoing test with IET

Table 1

Dimensions in millimetres

l_t, total length	≥ 100	±0,5
l, calibrated length	≥ 40	±0,2
h, thickness	≥ 3	±0,2
b_2, width	≥ 10	±0,2
b_1, width in the calibrated length	≥ 8	±0,2
r, Blend radius	≥ 30	±2
Plan parallelism of machined parts	0,05	—



	Samples	Directions	Cost per Test [CHF]	Cost per Test Type [CHF]
CTE	3	3	600	5400
Diffusivity	3	3	600	5400
Specific Heat	3	1	300	900
Overall Cost				11700

HiLumi HL-LHC PROJECT

Thanks for your attention

Material considerations

- Typical CFC materials experience non linear behavior
- A way to post process the results consist in checking the **thermal strain (temperature imposed problem)**

  → Strain at failure not available

- **A strain at failure <u>estimate</u> is proposed based on the young's modulus at RT and the max tensile and compression strength**

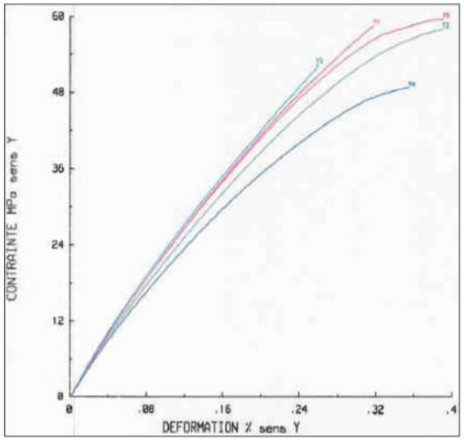


Fig. 1. Typical stress / strain curves for Carbon carbon composite

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

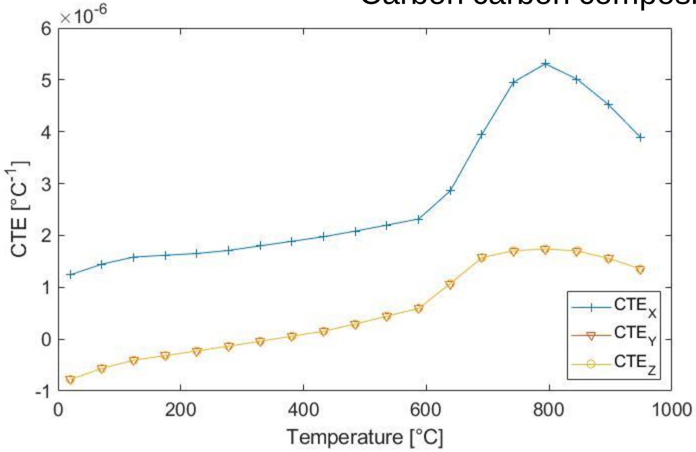
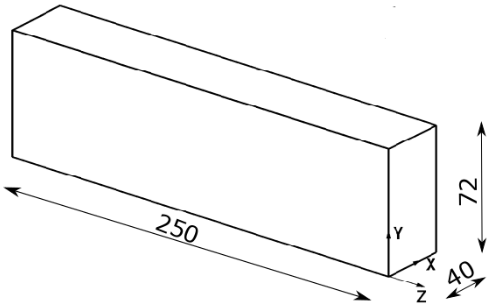
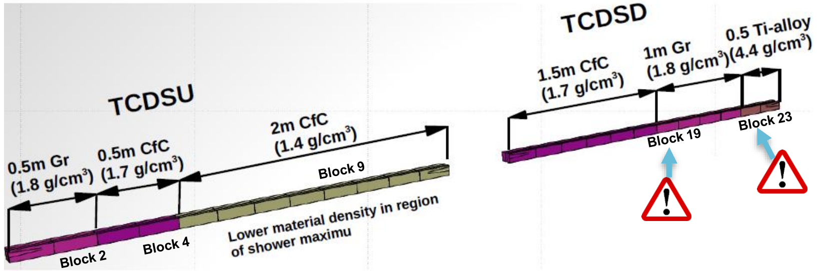


Fig. 2. Coefficient of thermal expansion of CFC.



TCDS thermal and structural results

Preliminary results, pending new simulations and material characterization



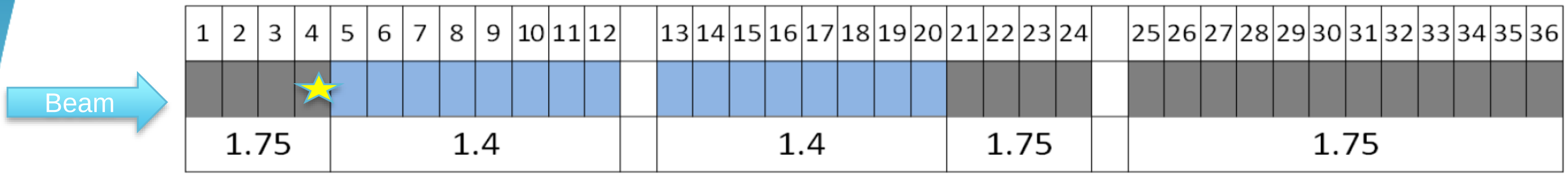
TCDS (low Z)				
Material	Graphite C2020 (block 2)	Block **4** C-C 1.7	Block **9** C-C 1.4	Graphite C2020 (block 19)
Max. Temp. [°C]	396	798	1141	402
Max. Comp. Stress. [MPa]	**-20**	**-23**	**-27**	**-33**
Comp. Strength	-35	-70	-70	-35
Max. Tens. Stress. [MPa]	**29**	**18**	**51**	**38**
Tensile Strength	35	61	84	35

TCDS (Ti6Al4V), block 23			
	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

For block 9 → **Material properties are not known. Values written are assumptions based on 1.7 g/cc grade**

The titanium block experiences a plastic deformation (1.2%) on 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.

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



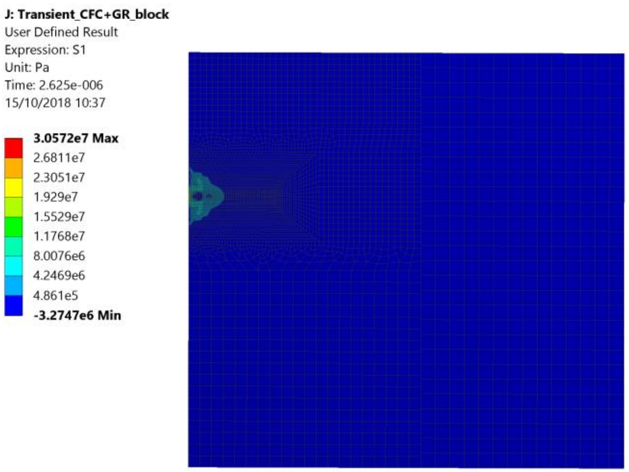


Fig.1. Maximum principal stress distribution for internal plane

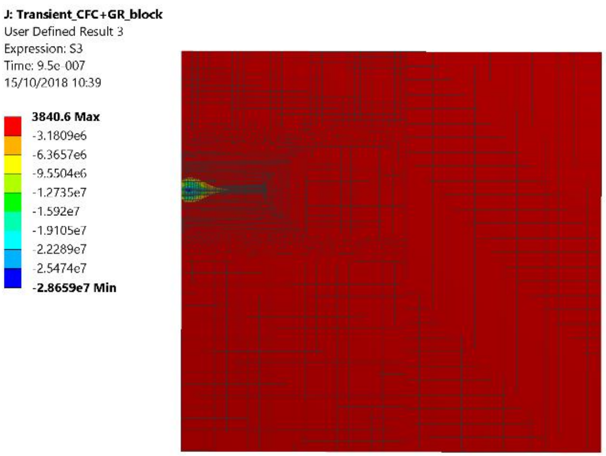
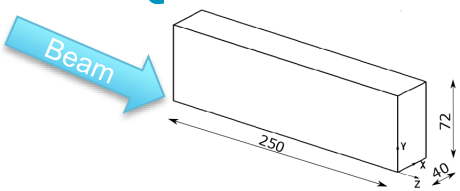
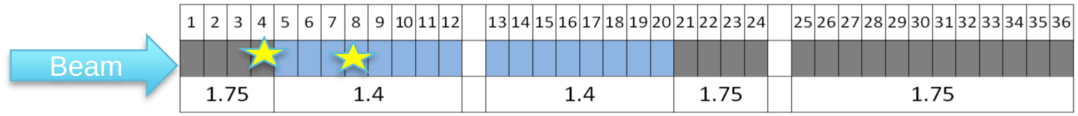


Fig. 2. Minimum principal stress distribution for internal plane

TCDQ results for 1.8×10^{11} ppb and 2.0 mm gap
TCDQ results for 2.3×10^{11} ppb and 2.5 mm gap } Blocks 4 and 8





	Bunch intensity 1.8e11		Bunch intensity 2.3e11	
	CFC 4th block	CFC 8th block	CFC 4th block	CFC 8th block
	2D FEM			
Max. Temp [°C]	1636	1775	1837	2018 ⚠
Max. Strain [-]	4.9e-3 X-dir	5.3e-3 X-dir	5.8e-3 X-dir	6.4e-3 X-dir
Min. Strain [-]	-4.6e-3 X-dir	-4.4e-3 X-dir	-4.6-e-3 X-dir	-4.8-e-3 Y-dir
Ultimate Compr. Strain	= ? (X-dir) -8.9e-3(Y-dir) -8.2e-3(Z-dir)			
Ultimate Tens. Strain	= ? (X-dir) 8.4 e-3(Y-dir) 6.1e-3(Z-dir)			
Safety factor (based on strain)	**Not known (lack of mat data in X direction)**			**1.8 (Y), warning X-dir**

- The material production process temperature is 1500°C. → small permanent deformation of blocks can happen
- Considering that ultimate strains are estimates, the safety margin shall be considered small
- **To confirm / precise the results, one could launch new material characterization aiming at determine:**

→ Material properties for RNFF-sg (1.4 g/cc);

→ 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)

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

SUMMARY: 2.5 mm GAP 2.3e11 BI

	Bunch intensity 2.3e11	
	CFC 4th block	**CFC 8th block**
	2D FEM	
Max. Temp [°C]	1837	**2018**
Max. Princp. Stress [Mpa]	28.8/28.8(wave refl.)	31.0 / 39.0 (wave refl.)
Min. Princp. Stress [Mpa]	-35.7	-48.6
Max. Stress [MPa]	*Sx=20.2* ; Sy=28.8 ; **Sz=24.7**	*Sx=22.8* ; Sy=39. ; Sz=26.3
Min. Stress [MPa]	Sx=-17.7 ; Sy=-35.7 ; Sz=-23.5	Sx=-19.4 ; **Sy=-48.6** ; Sz=-26.1
Tensile strength [Mpa]	X-dir≈ - Y-dir= 84 Z-dir=61	
Compressive strength [Mpa]	X-dir= -69.6 Y-dir= -88.6 Z-dir=-82.4	
Safety factor (based on stress)	2.5 (Z), warning X-dir	1.8 (Y), warning X-dir

Based on stress

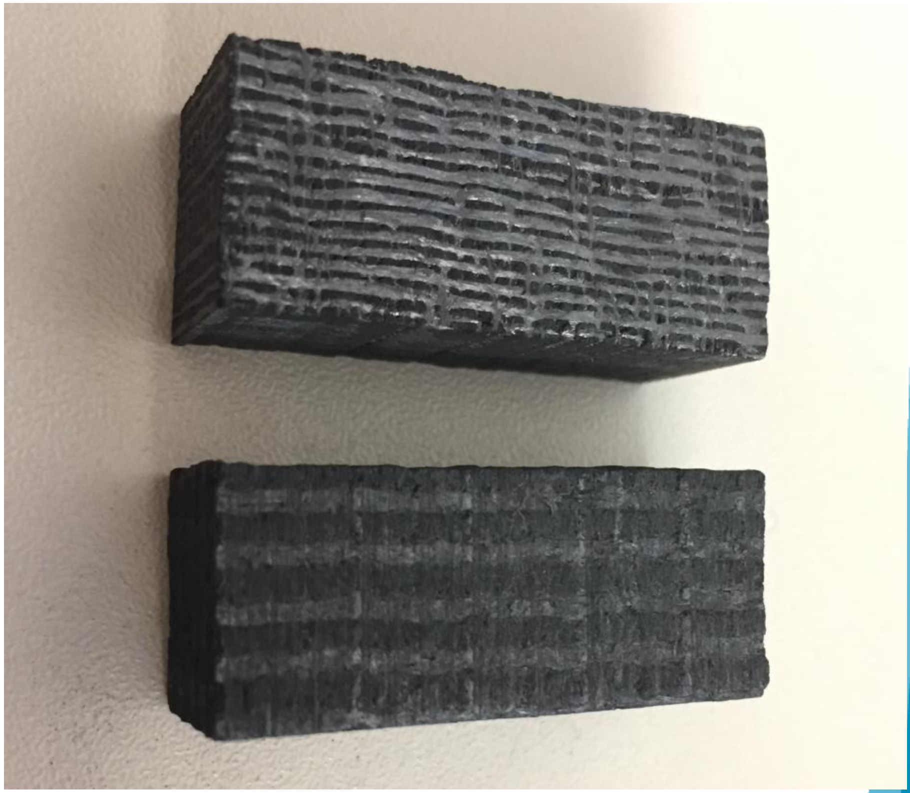
	Bunch intensity 2.3e11	
	CFC 4th block	**CFC 8th block**
	2D FEM	
Max. Temp [°C]	1837	**2018**
Max. Princp. Strain [-]	5.8e-3	6.4e-3
Min. Princp. Strain []	-4.6e-3	-4.8e-3
Max. Strain [MPa]	*STx=5.7e-3* ; **STy=3.0e-3**	STx=6.4e-3; STy=3.9e-3
Min. Strain [MPa]	STx=-4.6e-3 ; STy=-3.0e-3	STx=-4.4e-3; **STy=-4.8e-3**
Ultimate tensile strain []	X-dir≈- ; Y-dir= 8.4e-3; Z-dir= 6.1e-3	
Ultimate compressive Strain []	X-dir= -24.8e-3; Ydir= -8.9e-3; Z-dir= -8.2e-3	
Safety factor (based on stress)	2.8 (Y), warning X-dir	1.9 (Y), warning X-dir

Based on strain

Carbon Carbon composite costs

Ariane Group
3D CC Sepcarb Novoltex (2018) / Naxeco (2016)

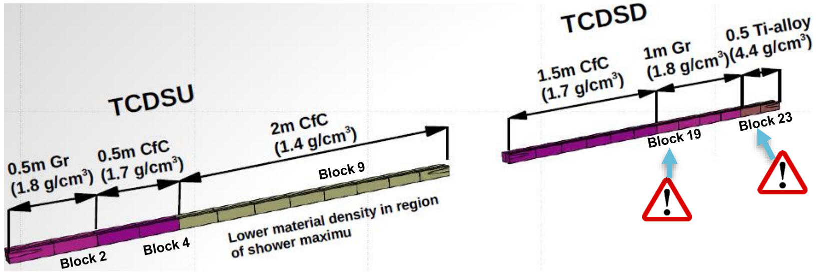
3300 € / block (80 x 37 x 170 mm^3)
1 year of procurement time
Up to 200 mm thick in direction 3



CVT
RNFF-sag

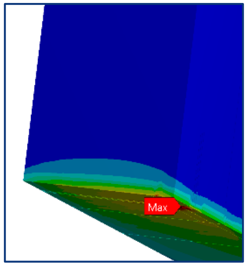
1300 € / block (in 2012)
(40 x 72 x 250 mm^3)
1 year of procurement time

TCDS detailed results



BLOCK 2 Graphite C2020

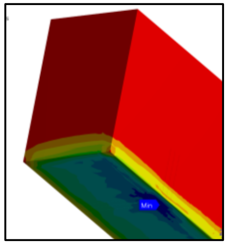
Linear elastic material model



Temperatures profiles at the peak after one pulse

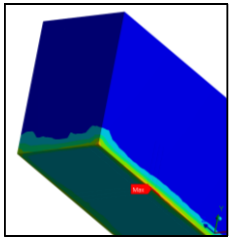
397°C

Highest Compressive Stress



-20 MPa

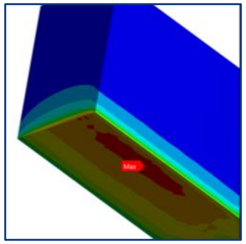
Highest Tensile Stress



27 MPa

BLOCK 4 CfC 1.7g/cm³

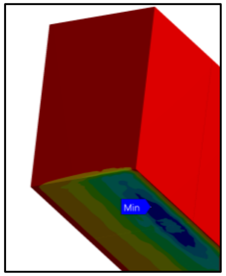
Linear elastic material model



Temperatures profiles at the peak after one pulse

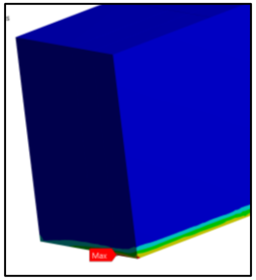
798°C

Highest Compressive Stress



-23 MPa

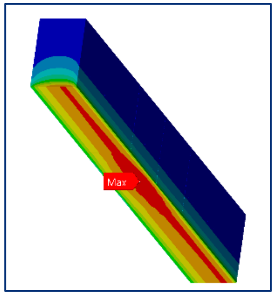
Highest Tensile Stress



18 MPa

BLOCK 9 CfC 1.4 g/cm³

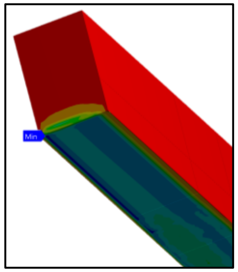
Linear elastic material model



Temperatures profiles at the peak after one pulse

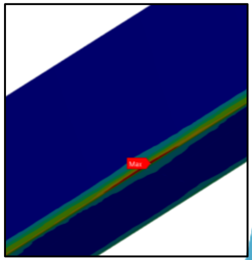
1141°C

Highest Compressive Stress



-27 MPa

Highest Tensile Stress



51 MPa

The maximum tensile stress is in the y direction

COMPARATIVE: 3DCC NOVALTEX vs CFC 1.75 g/cm3

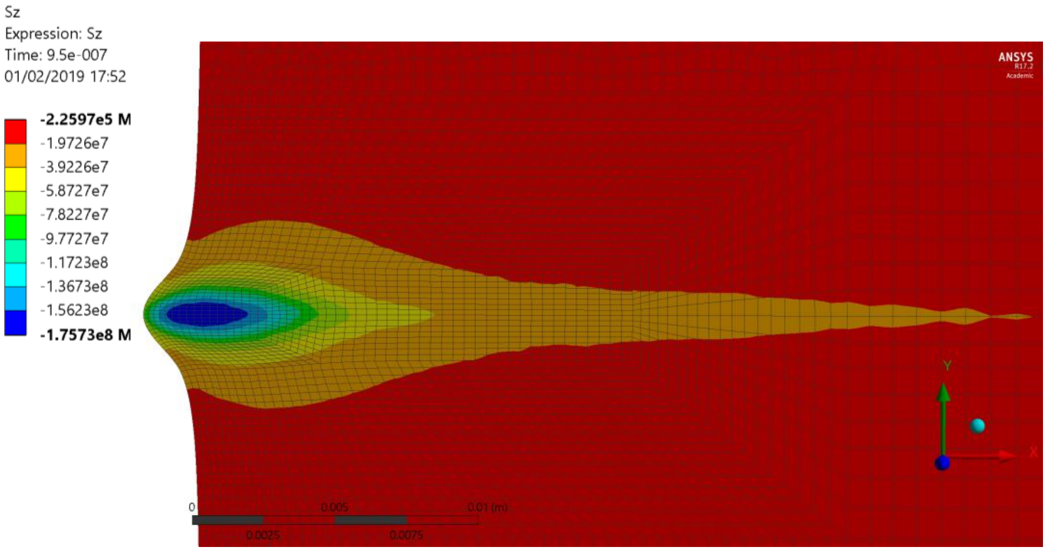


Fig. 1 Stress in beam direction for 3DCC (2.5 mm gap and 2.3e11 BI)

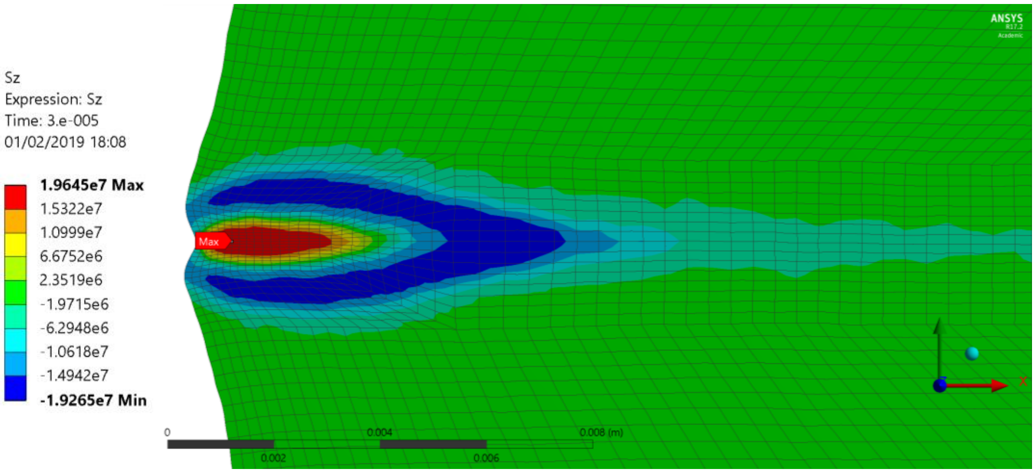


Fig. 2 Stress in beam direction for CFC (2.5 mm gap and 2.3e11 BI)

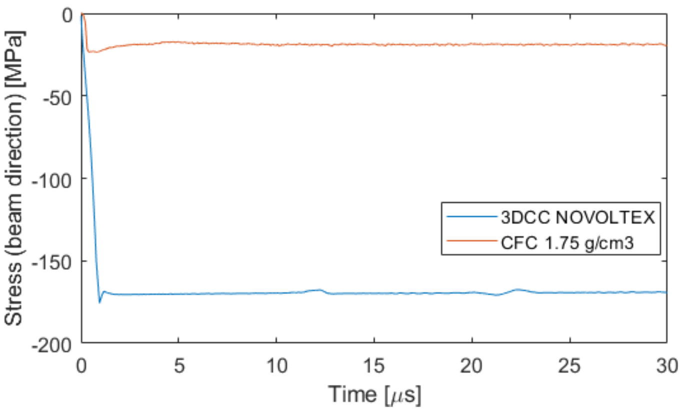


Fig. 3 Stress evolution on the beam direction for a block of 3DCC novoltex and a block of CFC 1.7 gr/cm3 assuming a gap of 2.5 mm and a bunch intensity of 2.3 e11 p.

- A comparative between a block of 3DCC novoltex and CFC has been carried out.
- Numerical simulations show that CFC has a lower stress level due to its lower stiffness.