Material testing for injection and transfer line absorbers

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Antonio Perillo Marcone
On behalf of the TCD section

October 2015
EN-STI-TCD

Outlines

Introduction to TCDI and TDIS and the related beam parameters

- *TDIS*
- *TCDI*
- *Material pre-selection*

Parameters involved in the selection of materials

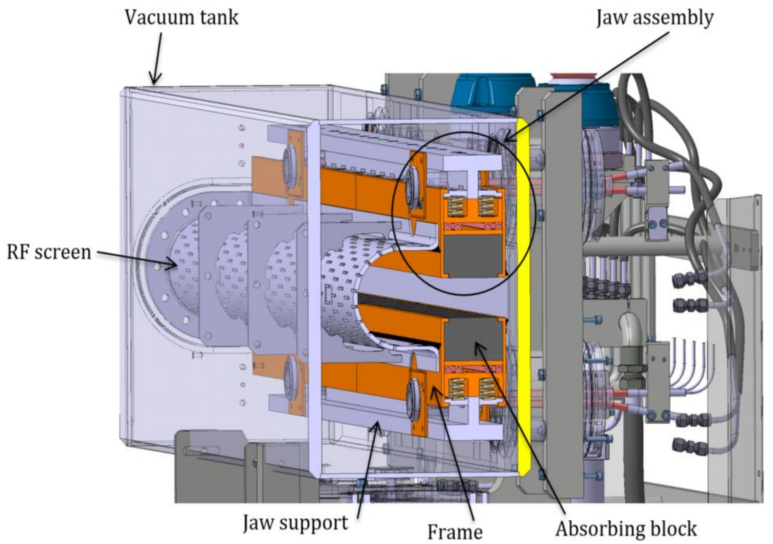
- *Mechanical / physical characteristics*
- *Machinability*
- *UHV compatibility*
- *Other parameters*
- *A dedicated test: HRM28*

Conclusion

TDIS (Target Dump Injection Segmented)

Beam parameters

Beam	Emittance x,y (um)	Beam size (σ) at front face (um)	Bunch Intensity (288 bunches)
Standard	2.0	410	2.3e11
BCMS	1.3	340	2.0e11

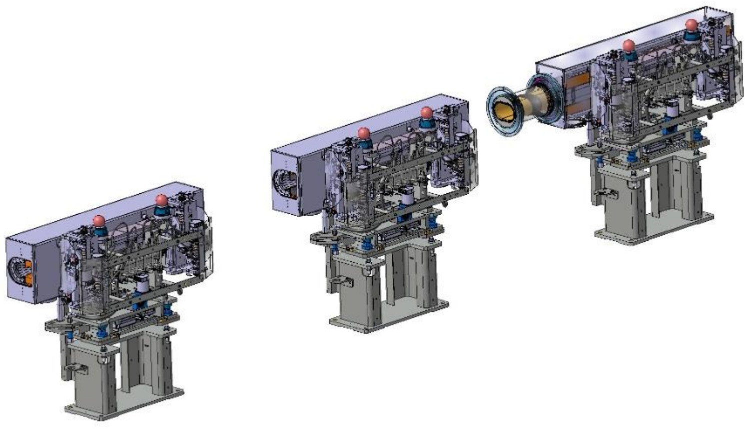


Main characteristics

- 3 modules of same length (1.7 m)
- First 2 modules of low-Z material
- Last module of Al and Cu

Requirements

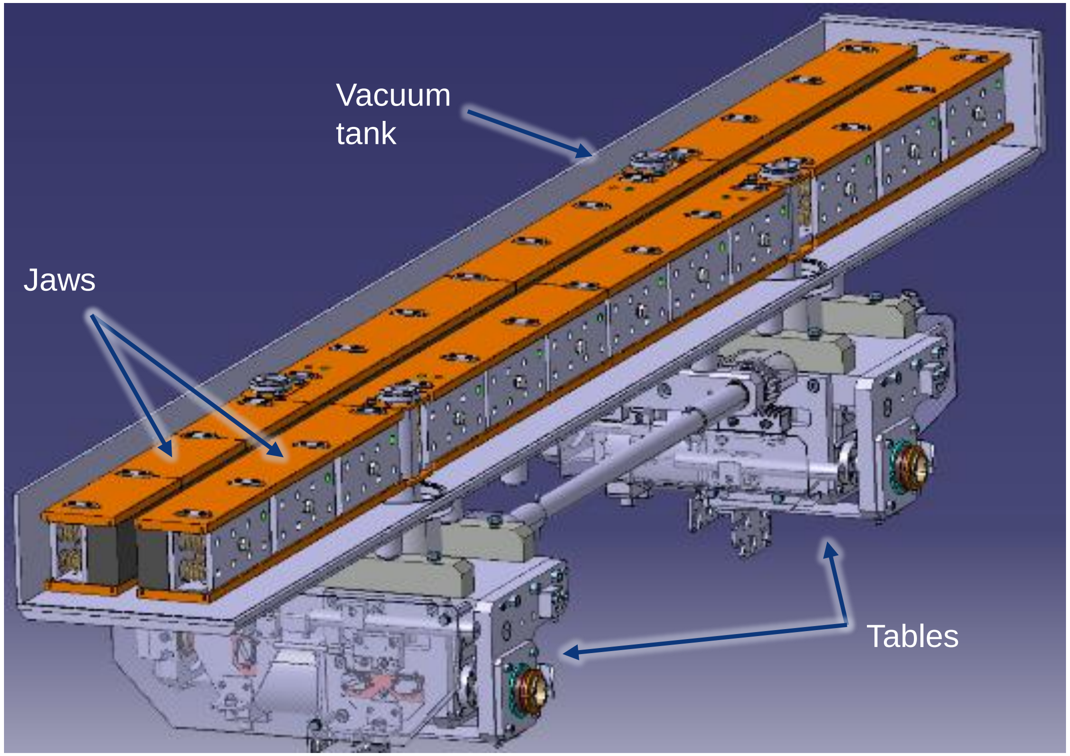
- Device in LHC (UHV) vacuum
- Impedance management
- Reliability
- Position accuracy
- Robust design



TCDI (Target Collimator Dump Injection)

Beam parameters

Beam	Emittance x,y (um)	Beam size (σ) at front face (um)	Bunch Intensity (288 bunches)
HL-LHC	2.08	X: 405 µm Y: 646 µm	2.3e11
BCMS	1.3	X: 320 µm Y: 511 µm	2.0e11



Main characteristics

- 12 longer collimators (2.1m jaws)
- Possible hybrid design:
  -->Use of graphite and 3D-CC

Requirements

- Installed in Ti2/Ti8 transfer lines (pressure range from 5.10^{-9} to 5.10^{-8} mbar)
- Reliability
- Position accuracy
- Robust design

Material selection

- Fluka simulations (energy density maps);
- Thermo-mechanical simulations (temperatures and stresses);
- Outgassing properties;
- Electrical conductivity;
- Supply availability, cost, lead times;
- Machinability, achievable tolerances, etc;
- Material property reliability, repeatability, spread;
- Behaviour under irradiation;
- Available data, previous experience/testing.

Mechanical and physical properties of materials

Mechanical and physical properties of materials

- High thermal shock resistance
  - Low Young's modulus
  - Low thermal expansion
  - High tensile strength
- Low density (lower energy density)
- High specific heat (lower ΔT for a given deposited energy)

		Graphite R550 SGL	Graphite 2123PT Mersen	3D C/C Safran Herakles			3D C/C A412N Mersen			2D C/C CX31 Toyo Tanso		
Density [g/cm3]	RT	1.83	1.84	1.7			1.8			1.61		
Tensile Strength [MPa]	RT	30 (Assumption)	35	145	186	17	60	60	25	98		
Compressive Strength MPa]	RT	130 (Average)	137	129	166	91	110			-		
Young's Modulus [GPa]	RT	10	11.4	36	47	9	15			23 (Flex Mod)		
CTE [10^{-6} 1/K]	RT	3.6	5.6	1.0	0.7	2.7	1.5	1.5	3.5	<1	<1	4.1
Specific Heat [J/Kg.K]	RT	650	-	730			-			600		
Applications		Electrodes and other general refractory applications		Shuttle Nozzles, airplane brakes			Fusion Reactor Protection Tiles			Heat Treatment Furnaces		

3D CC from Herakles: Sepcarb®

Sepcarb® is a composite of carbon fibers and a carbon matrix which bonds the fibers together and distributes the load evenly.

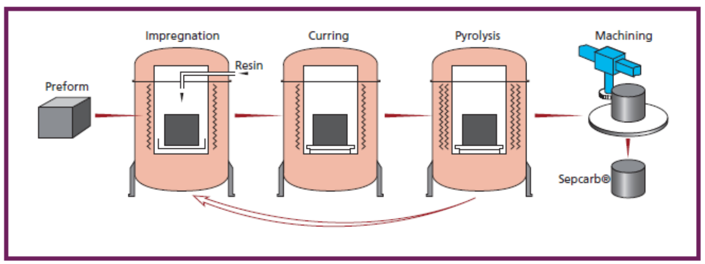
Both the carbon fibers and the carbon matrix are resistant to extremely high temperatures. (Stability of mechanical properties at temperatures up to 2700°C).

CARBON FIBERS

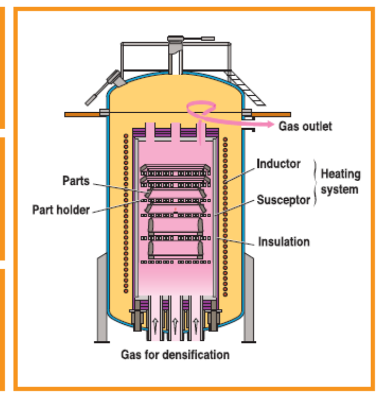
FIBER REINFORCEMENT (1D, 2D, 3D, 4D, ND ARCHITECTURE)

LIQUID ROUTE	GASEOUS ROUTE
IMPREGNATION POLYMERIZATION CARBONIZATION	INFILTRATION
MACHINING	MACHINING

SEPCARB®

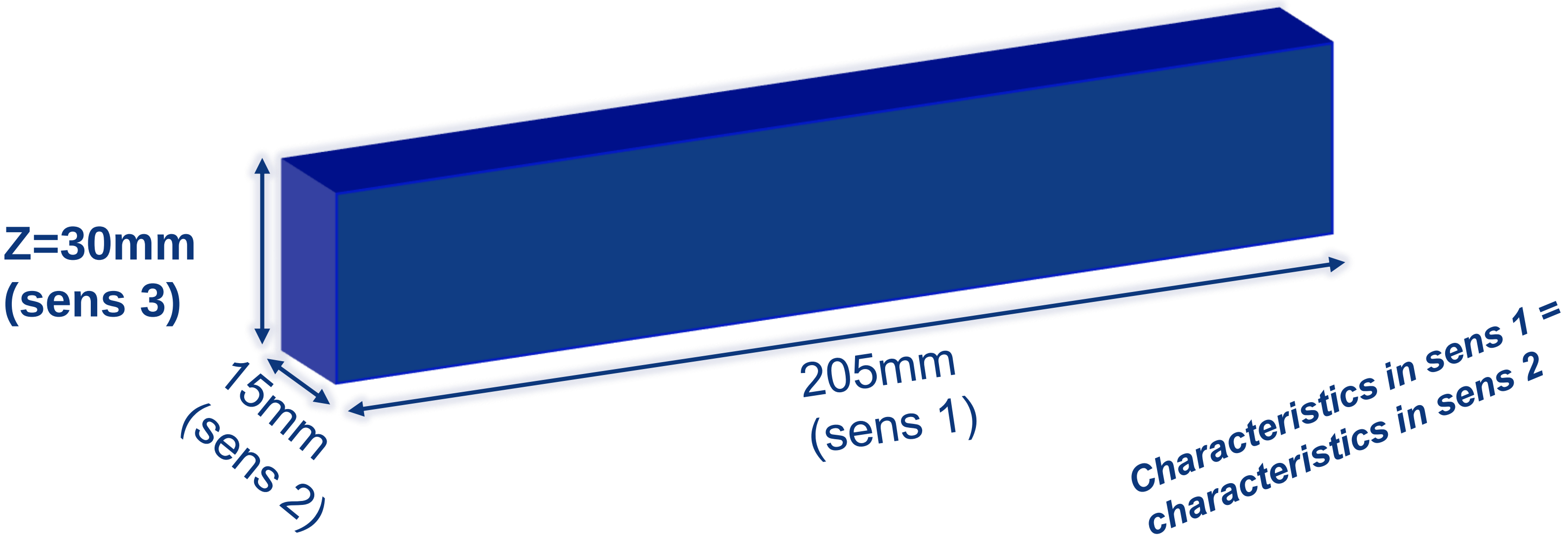


Liquid route densification process



Chemical Vapor Infiltration (CVI) process

Sepcarb® samples



Received state: seal coated (30µm thick).
Plan 205*15 = quasi isotropic characteristics in the plan (fiber orientation = 4*45°).

Material quality, spread of mechanical and physical properties

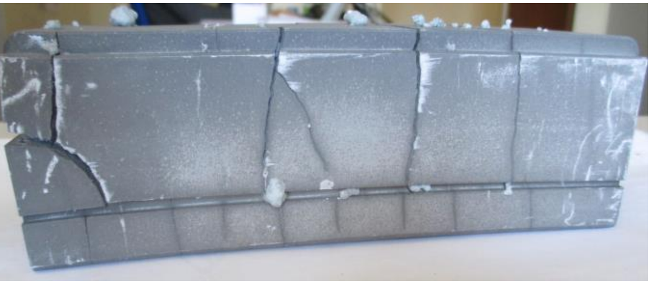
- Special attention to production process
  - Reproducible
  - Homogeneous
- Example – hBN recently purchased

From supplier's datasheet

Max. operating temp Air Inert Gas or Vacuum	°C	850 1150	850 1150

After thermal treatment @ 800ºC in vacuum – 20% failure

After thermal treatment @ 1000ºC in vacuum – 50% failure

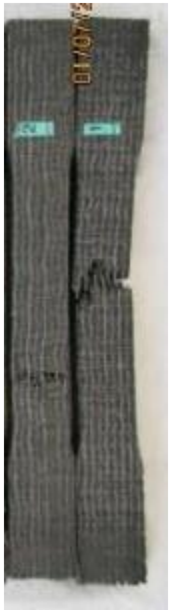


→ **Cross-checks of some properties is crucial!**

→ **Qualification of supplier is needed (need of representative testing/characterisation)!**

Mechanical tests on 3D CC [Herakles]

Tensile testing sens 1



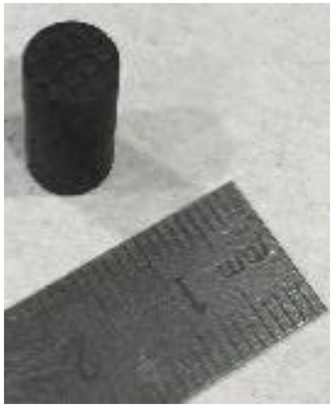
Standard used:

NF-EN-658-1
NF-EN-658-2
NF-EN-658-3
NF-EN-658-4

Reports on:

EDMS 1517185
EDMS 1524213

Compression tests sens 1&3



Courtesy: MME, M. Guinchard and A.Gerardin

Mechanical tests on 3D CC [Herakles]

Characteristics got by Safran			
Tensile Properties (5 samples, average density =1.75) Ambiant temp.	σ1t average = 161 Mpa (@ failure)	ε1t average = 0.51% (@ failure)	Et average = 37GPa (@ origin)
	Standard deviation = 16MPa	Standard deviation = 0.03%	Standard deviation = 2GPa
	σ1c average = 129 Mpa		

Characteristics got by CERN 2015			
Tensile Properties (8 samples, average density =1.82) Ambient temp.	σ1t average = 97 Mpa (@ failure)	ε1t average = 0.39% (@ failure)	Et average = 28.6GPa (@ origin)
	Standard deviation = 8.2MPa	Standard deviation = 0.05%	Standard deviation = 4.2GPa
Comp. Properties (3 samples, average density =1.82) Ambiant temp.	σ1c average = 138.4 Mpa (@ failure)	ε1c average = 0.3% (@ failure)	E1c average = 32.1GPa (@ origin)
	Standard deviation = 2.2MPa	Standard deviation = 0.1%	Standard deviation = 11GPa
Comp. Properties (3 samples, average density =1.82) Ambient temp.	σ3c average = 166.6 Mpa (@ failure)	ε3c average = 0.65% (@ failure)	E3c average = 10.1GPa (@ origin)
	Standard deviation = 7.6MPa	Standard deviation =0.03%	Standard deviation = 2.5GPa

- The results acquired display a satisfying consistency.
- According to the standards, no conclusions can be taken on the properties determined from the outcome of this experiment due to 50% of specimens being invalidated as failure occurred outside of their calibrated length .
- Therefore, comparison with Herakles results wouldn't be pertinent.
- Glued metallic tabs or autogripping jaws shall be used for further tests.

- The strain values were measured until the break of the strain gauge.
- The compression tests display a higher compressive strength in both directions compared to the supplier values from the wrapping process samples.
- Cern measurments are close to Safran's communicated values.

Thermal tests on 3D CC [Herakles]

CTE (dilatation), *dilatometer*.

Dilatation measurements dL/L0 (%)			
	1000ºC	1500ºC	1950ºC
Cern values, Sens 1 [Plane]	0.10	0.22	0.38
Herakles data, Sens 1 [Wrapp]	0.10	0.25	0.42
Cern values, Sens 3 [Plane]	0.30	0.56	0.86
Herakles data, Sens 3 [Wrapp]	0.26	0.50	0.84

Specific heat

Diferencial scanning calorimeter

Specific heat Cp (kJ/kg/K)			
	25ºC	250ºC	500ºC
Cern values, [Plane]	0.81 (50ºC)	1.29	1.66
Herakles data, [Wrapp]	0.73	1.3	1.67

Thermal diffusivity

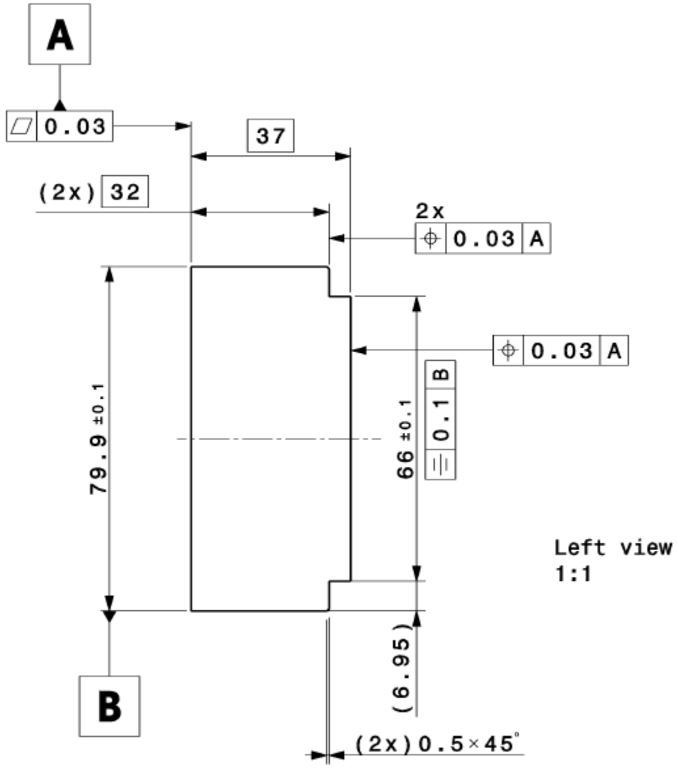
Laser flash

Thermal diffusivity α (mm^2/s)				
	25ºC	1000ºC	1500ºC	2200ºC
Cern values, Sens 1 [Plane]	61	18	15.5	13.9
Herakles data, Sens 1 [Wrapp]	49	14.5	12	11
Cern values, Sens 3 [Plane]	38.5	15.6	9.8	8.8
Herakles data, Sens 3 [Wrapp]	37	11	9	8

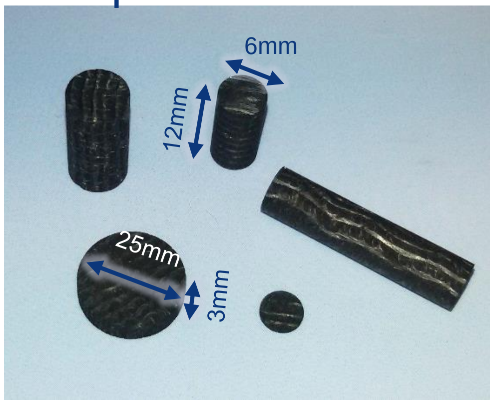
Courtesy: MME, M. Guinchard and A.Gerardin

Machining abilities

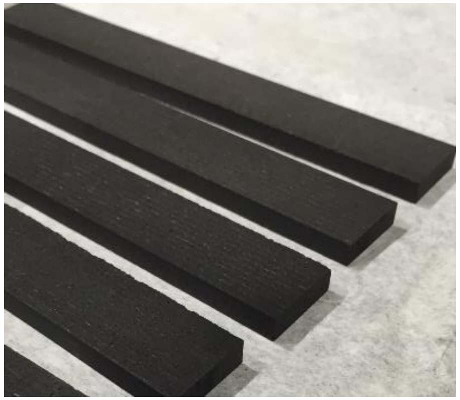
Machinability

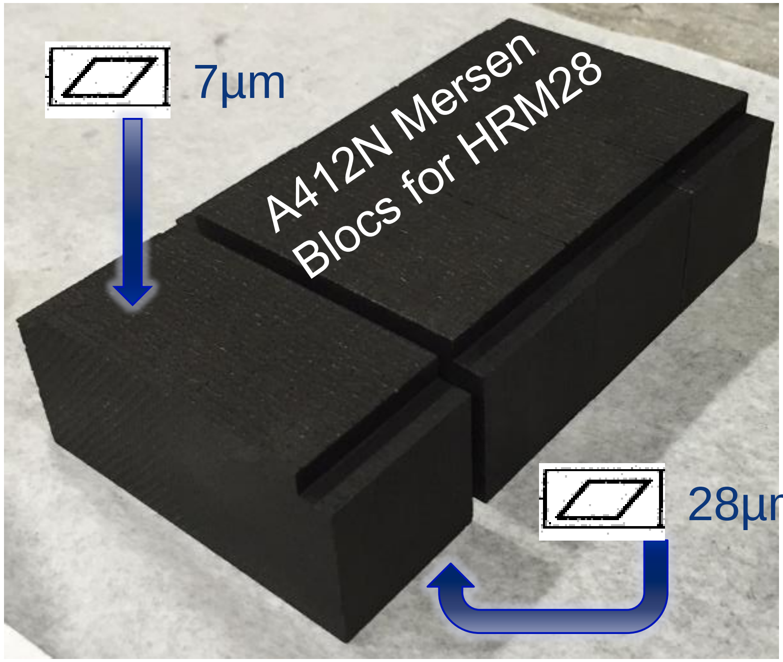


Sepcarb Herakles



A412N Mersen





- Production shape?
- Ability to produce precise parts
- High vacuum compatible machining
- Internal CERN machining or subcontracted *(Carbone system Meyzieux, France)*

Ultra-High Vacuum compatibility

Ultra-High Vacuum compatibility

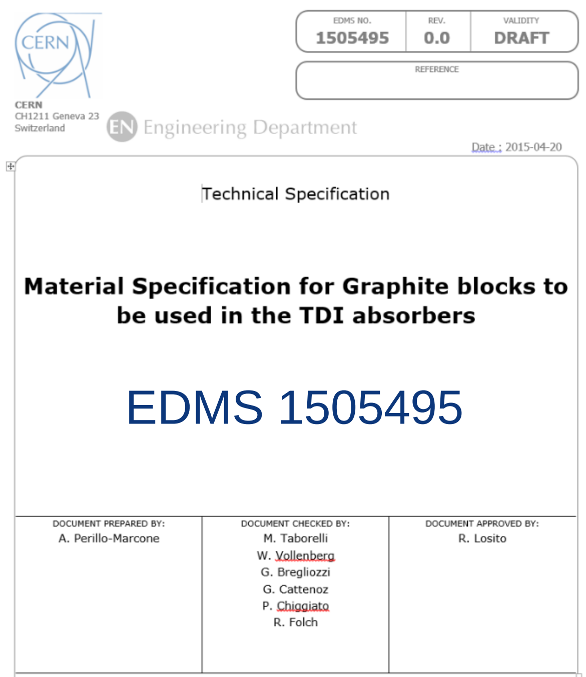
The maximum acceptable outgassing rate for collimators is 10^{-7}mbar.l/s.

<u>Supplier</u>

- Purification
- Machining (no lubricants)
- Handling (nitrile gloves, clean environment)
- Packaging (silk foil, aluminium foil, plastic bag)

<u>CERN</u>

- Outgassing tests
- Vacuum firing
- Handling (nitrile gloves, clean environment)
- Minimise exposition to air or other contaminants



EDMS NO.	REV.	VALIDITY
1505495	0.0	DRAFT

REFERENCE

CERN
CH1211 Geneva 23
Switzerland
Engineering Department

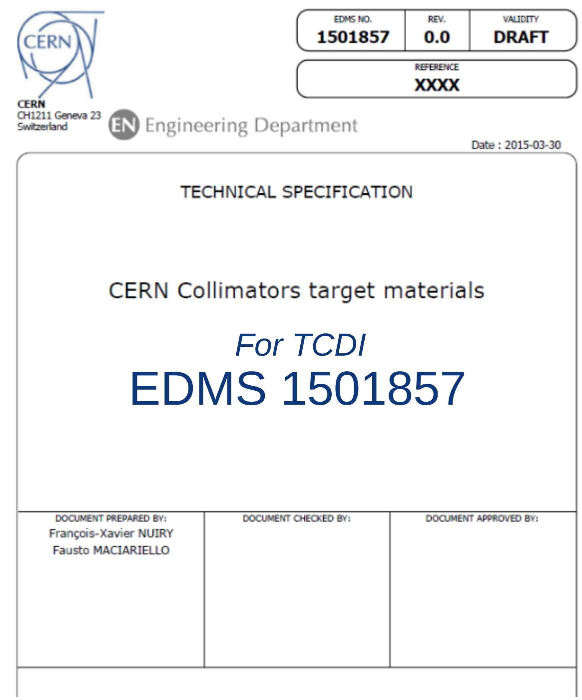
Date : 2015-04-20

Technical Specification

Material Specification for Graphite blocks to be used in the TDI absorbers

EDMS 1505495

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
A. Perillo-Marcone	M. Taborelli W. Vollenberg G. Bregliozzi G. Cattenoz P. Chiggiato R. Folch	R. Losito



EDMS NO.	REV.	VALIDITY
1501857	0.0	DRAFT

REFERENCE
XXXX

CERN
CH1211 Geneva 23
Switzerland
Engineering Department

Date : 2015-03-30

TECHNICAL SPECIFICATION

CERN Collimators target materials

For TCDI

EDMS 1501857

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
François-Xavier NUIRY Fausto MACIARIELLO		

Outgassing tests

Preliminary results
Under approval by TE/VSC

- **Herakles Sepcarb testing bloc:**

1. Machining at CERN: 0.2mm face off cut (dry and with clean tools and machines)
2. Cleaning at CERN laboratory b.102, solvent cleaning.
3. Thermal Treatment (under vacuum):
Temperature increase rate :200°/h
Temperature plateau: 950°C (start of the step)
Plateau duration: 6 hours
4. Cool down

Total outgassing rate after 10 hours of pumping:

5.8×10^{-7} mbar·l·s^{-1}

After bake out (250C, 50C/h, 24h plateau), total outgassing rate after 48h at RT:

5.5×10^{-9} mbar·l·s^{-1}

A first extrapolation would lead to a total outgassing rate for jaws made of 100% CC of: 2.8×10^{-7} mbar·l·s^{-1}

Promising results, but improvements still needed.

- **Graphite R7550P5D:**

- CERN vacuum procedures:
EDMS n°1437531 (before bake out);
EDMS n°1312756 (after bake out).

Total outgassing rate after 10 hours of pumping:

	Graphite 4550D	
	As received	After vacuum firing
Total outgassing rate [mbar·l·s^{-1}]	1.1×10^{-6}	2.9×10^{-6}

After bake out (300C, 15C/h, 48h plateau), total outgassing rate after 48h at RT:

	Graphite 4550D	
	As received	After vacuum firing
Total outgassing rate [mbar·l·s^{-1}]	1.8×10^{-8}	2.3×10^{-9}

Vacuum fired graphite outgassing rate contribution in one TDI instrument is about 7.0×10^{-9} mbar·l·s^{-1}.

Other aspects:

Impedance coatings

Radiation ageing

…

Other aspects

Coating: required for impedance management.

- Adhesion interlayer may be required (e.g. 1 um Ti)
- Cu layer to increase conductivity (the thicker the better)
- Risk of coating damage if grazing beam impact (the thinner the better…)
- Usually outgassing worsen by coating
- Low mechanical strength. Sensitive to scratching.
- If possible, one shall profit from past experience.

Radiation ageing.

- If required, once shall profit from past experience with:

CNGS target: Carbone Lorraine PT2020

NuMI target: ZXF-5Q POCO graphite

Dedicated test for TCDI and TDIS material selection:
HRM28

Motivations

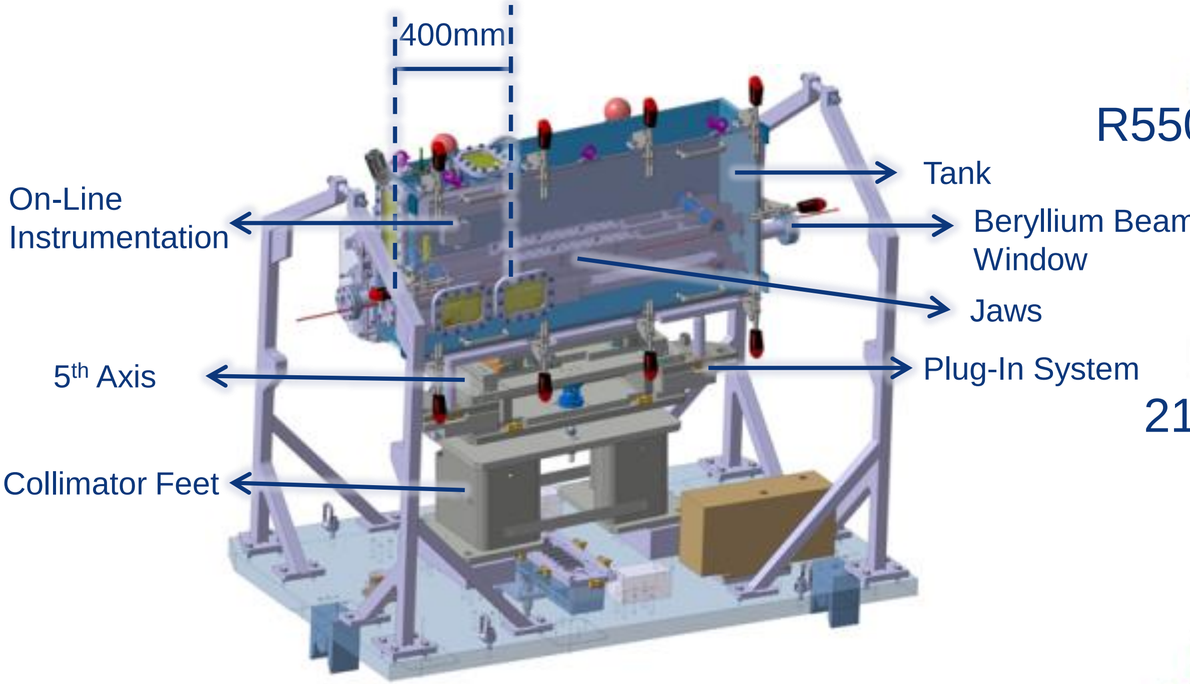
1. Assess the Integrity of Graphite for TCDIs and TDIs during Run 3. The goal is to reproduce the worst accidental scenario that the TCDI and the TDI can see during their life time.

Beam	Intensity	Sig X[mm] * Sig Y[mm]	Peak per Primary [GeV/cm^3]	Max Temperature [°C]	M-C Safety Factor*
Run 3 BCMS	5.76 E13	0.320*0.511	0.436	1450	0.8
HiRadMat	3.46 E13	0.313*0.313	0.663	1342	0.7

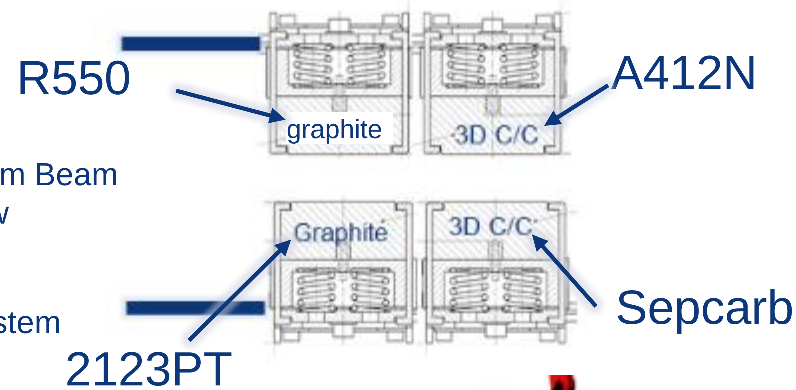
2. Test new promising materials for BIDs: 3D CC.

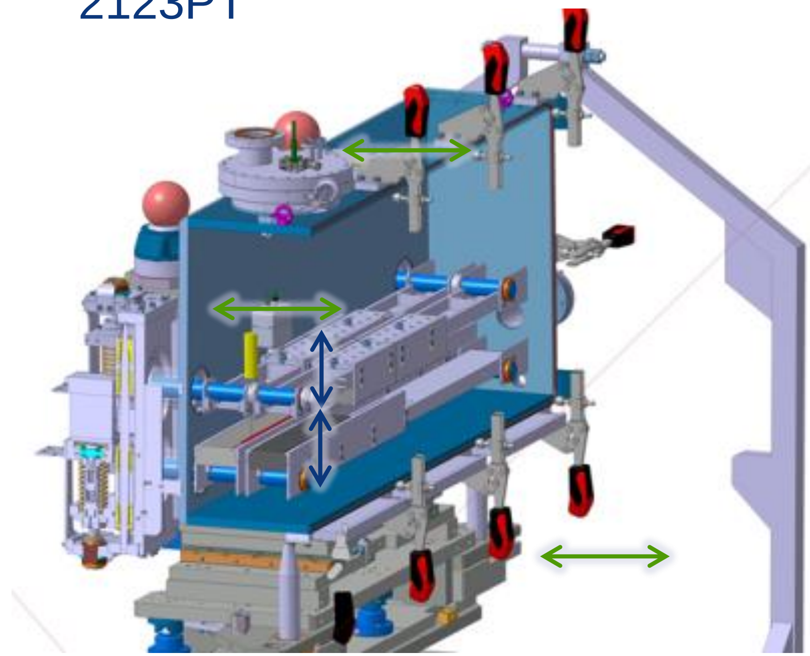
3. Benchmark simulations
   - Displacement measurements foreseen.

The Experimental set up



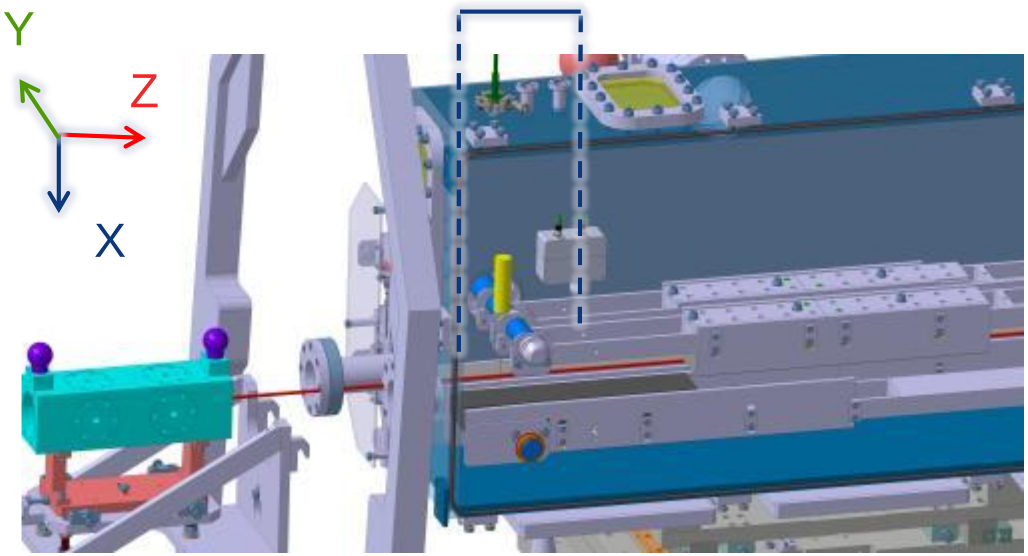
Active Part Materials:

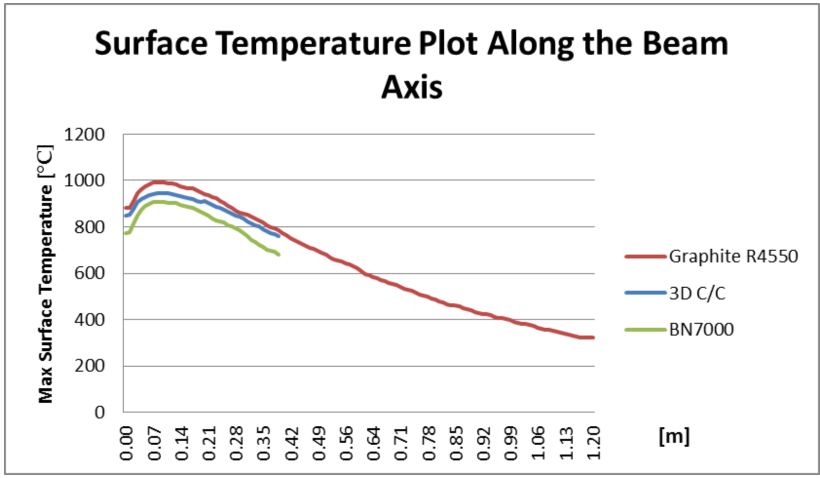


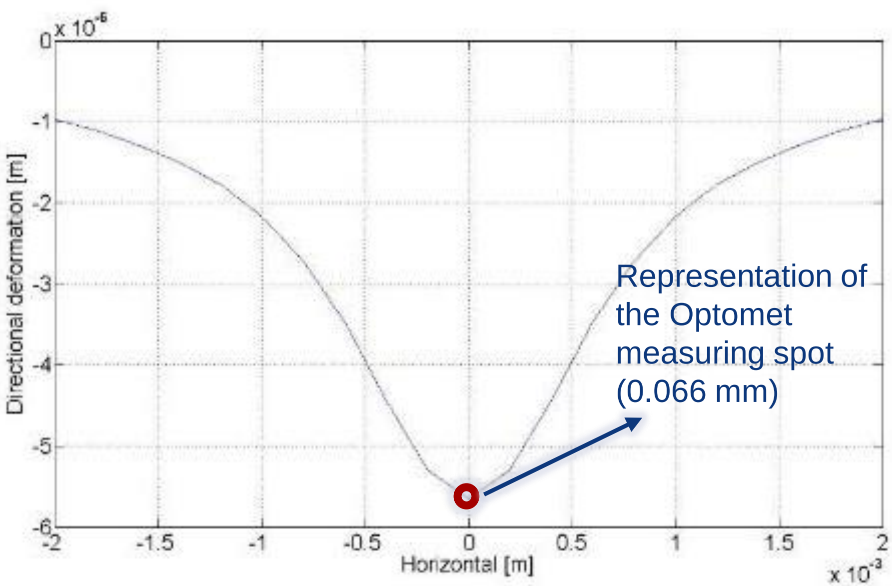


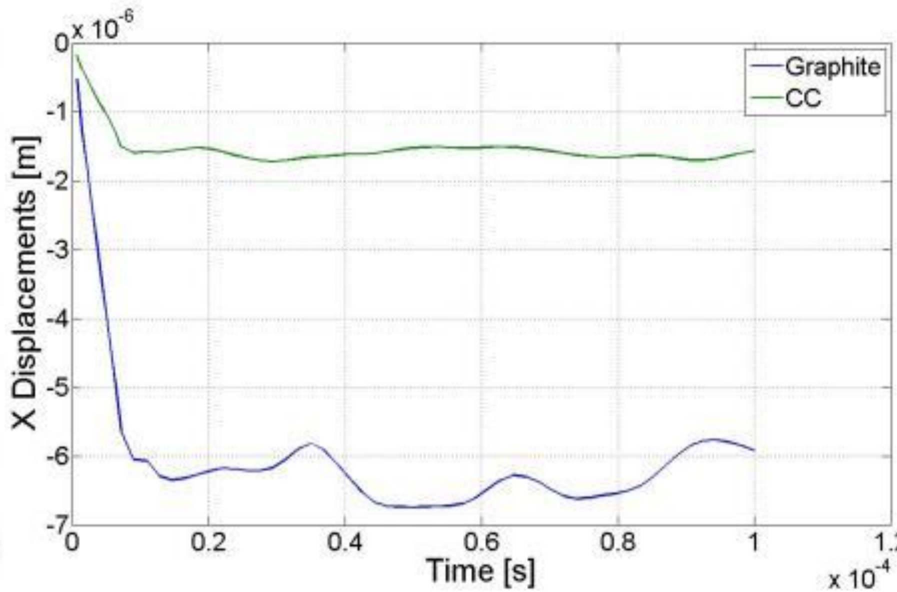
- Jaws stroke: standard collimator stroke.
- The upper jaws will begin at z=400mm.
- The lower jaws will begin at z=0 mm.
- Tank stroke (5th axis): +/- 60mm.

On-line instrumentation monitoring



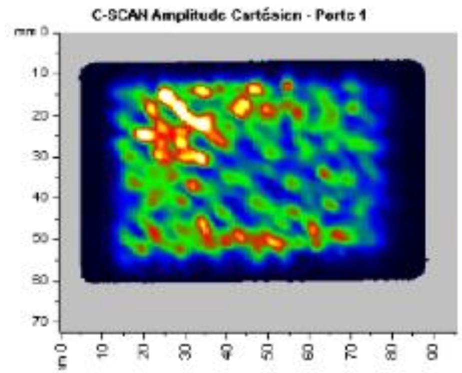




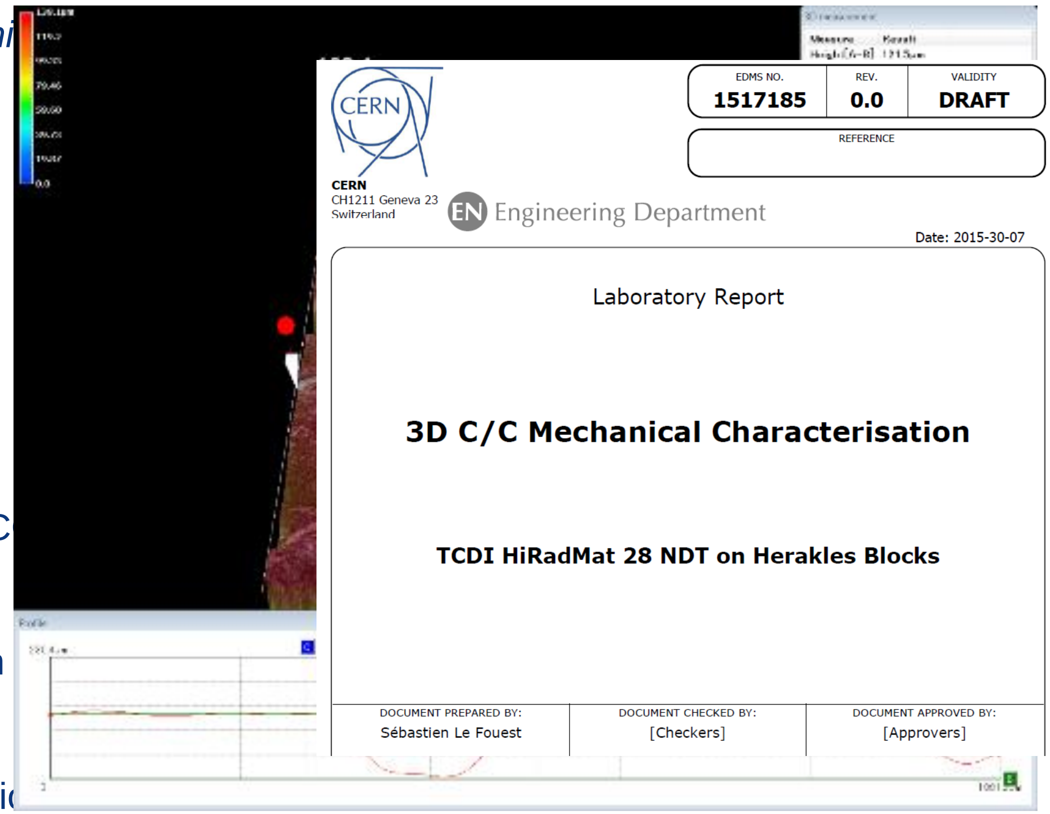


Pre/Post irradiation analysis

- Ultrasounds: Only for graphite.
Detectable defects:
1mm over 25mm thickness,
2mm over 50 mm thickness.



- Microscopy Inspection with *Keyence digital mi*
(CERN, MM lab) (on surface)


CERN
CH1211 Geneva 23
Switzerland

EN Engineering Department

EDMS NO.	REV.	VALIDITY
1517185	0.0	DRAFT

REFERENCE

Date: 2015-30-07

Laboratory Report

3D C/C Mechanical Characterisation

TCDI HiRadMat 28 NDT on Herakles Blocks

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
Sébastien Le Fouest	[Checkers]	[Approvers]

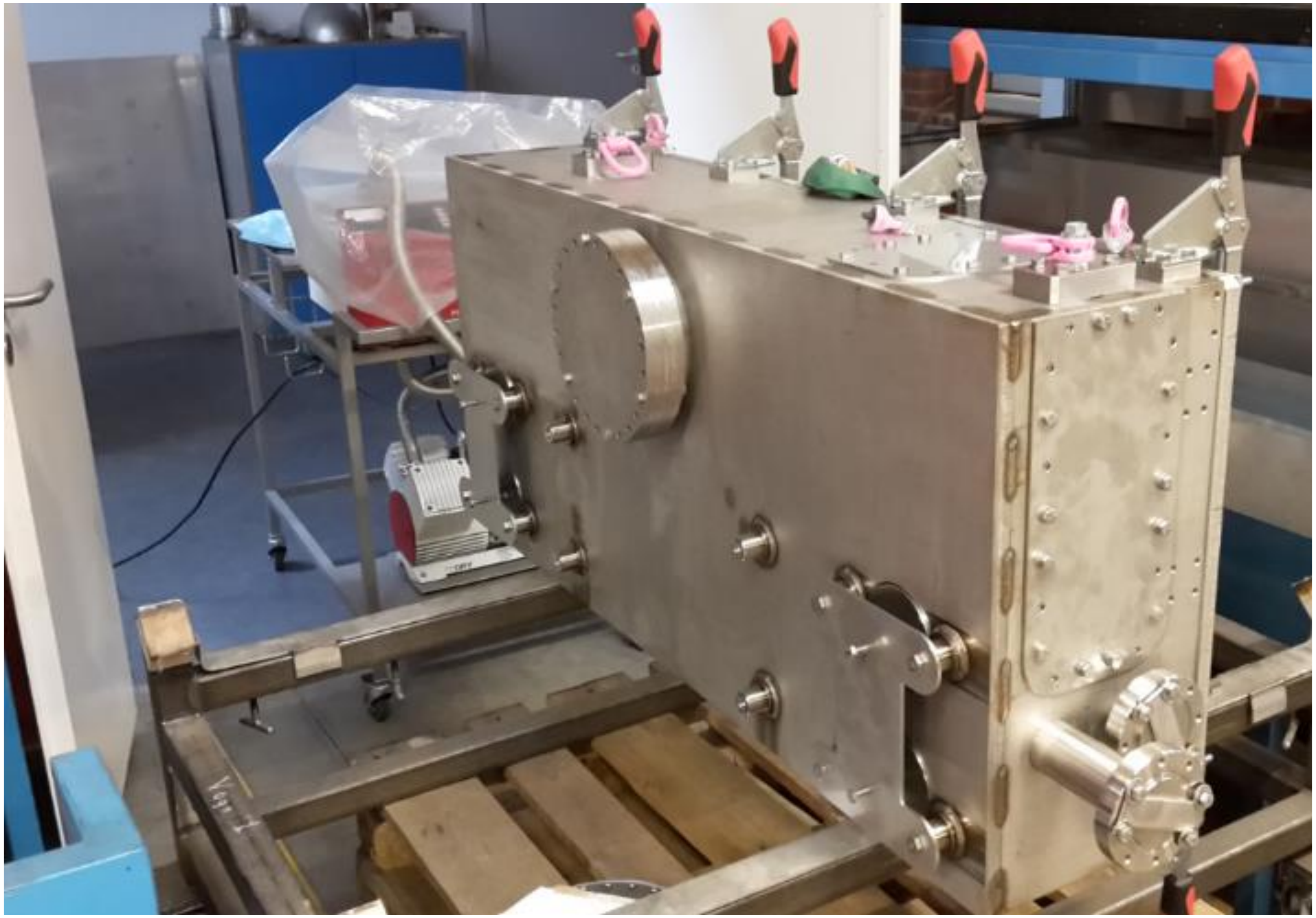
- Radiographic controls: not conclusive for 3DC

- Metrology Controls:
Pre irradiation metrology are already on-going on

- Micro tomography technique under investigati

Courtesy: MME, S. Sgobba

Tank



Conclusion

- Material characterisation for BIDs is wide: from material physical properties to vacuum compatibility, production, machining;
- Cross checking material properties is complex, requests time and money: Production process are controlled by quality assurances and regular visits to suppliers.

- HRM28 is part of the material selection for TCDI/TDIS. It aims at testing possible accidental scenarios, with the actual materials planned to be used (low Z);
- A particular attention is brought to the on-line instrumentation alignment as stress is expected to be very localised.

THANKS FOR YOUR ATTENTION!

CERN

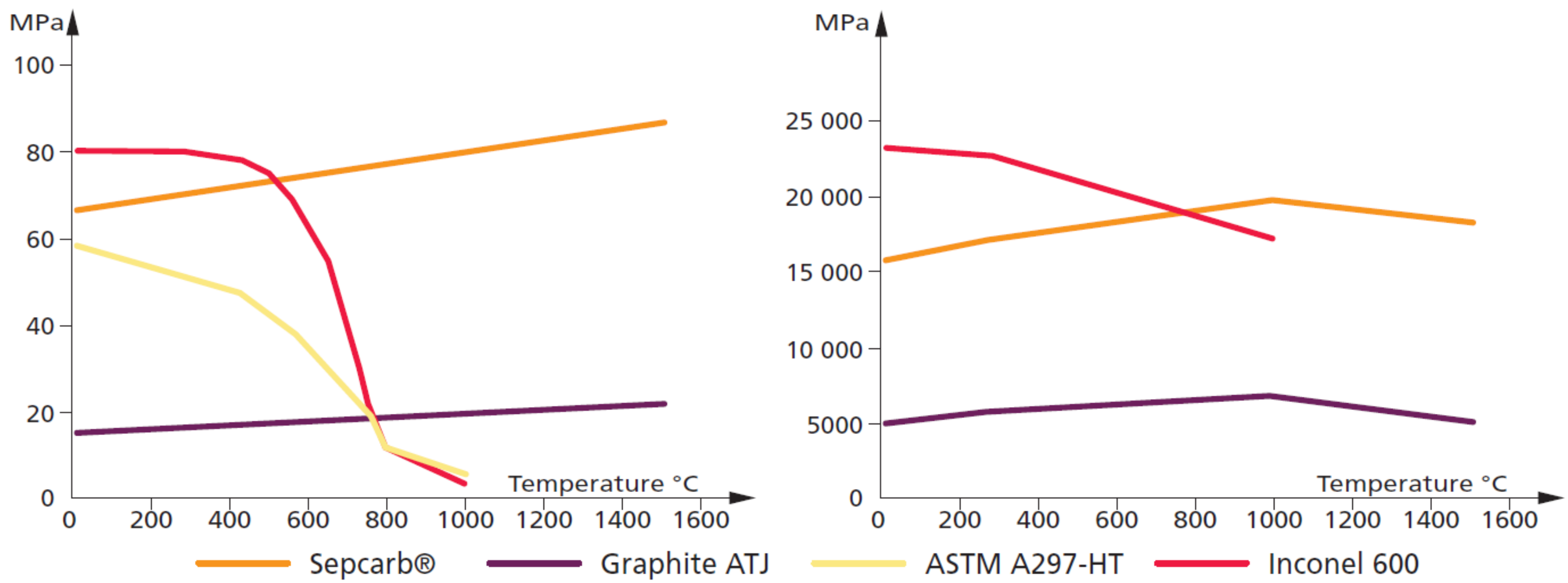
EN

ENGINEERING DEPARTMENT

General Sepcarb® characteristics

COMPARATIVE TABLE OF SPECIFIC ULTIMATE STRENGTH (ULTIMATE STRENGTH / DENSITY)

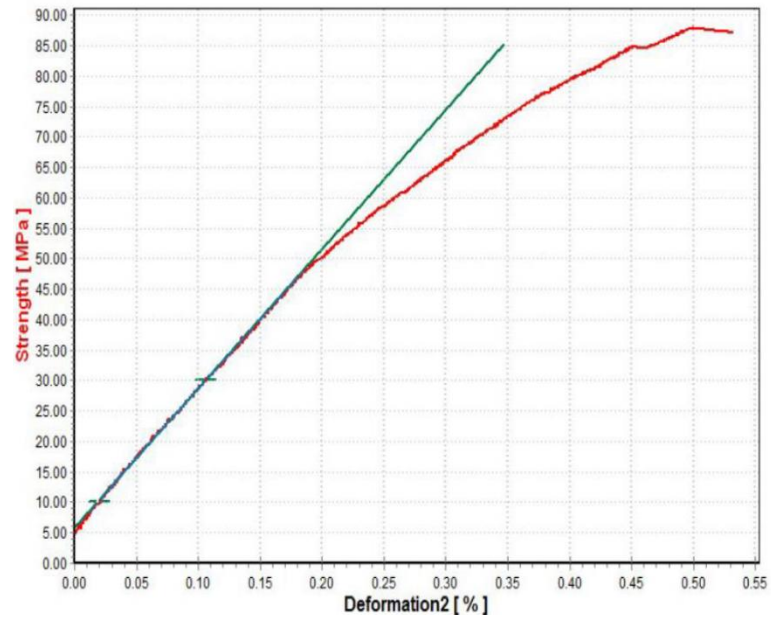
COMPARATIVE TABLE OF SPECIFIC YOUNG'S MODULUS (YOUNG'S MODULUS / DENSITY)



Density		1.5		
Temperature	°C	25	1000	1500
Tensile strength	σt,r (MPa)	100	120	120
	εt,r (%)	0.6	0.5	0.5
	Eo (GPa)	30	30	30
Interlaminar shear strength	T_r (MPa)	22	30	31
	V (%)	1.3	1.1	1.1
	G (GPA)	5	5	5
Thermal expansion	(%)		0.2	0.3
Heat capacity	($J.Kg^{-1}.K^{-1}$)	800	1900	2100

Mechanical tests on 3D CC [Herakles]

Tensile testing sens 1



Standard used:

NF-EN-658-1

NF-EN-658-2

NF-EN-658-3

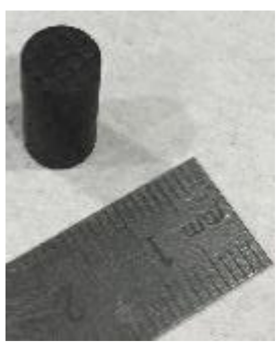
NF-EN-658-4

Reports on:

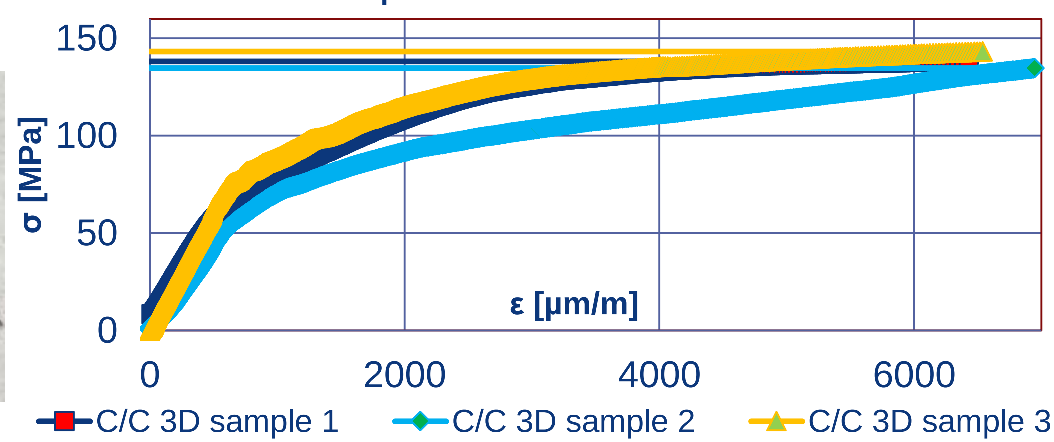
EDMS 1517185

EDMS 1524213

Compression tests sens 1&3



Carbon/Carbon 3D Direction 3
Compressive Stress vs Azimuthal Strain



Courtesy: MME, M. Guinchard and A.Gerardin

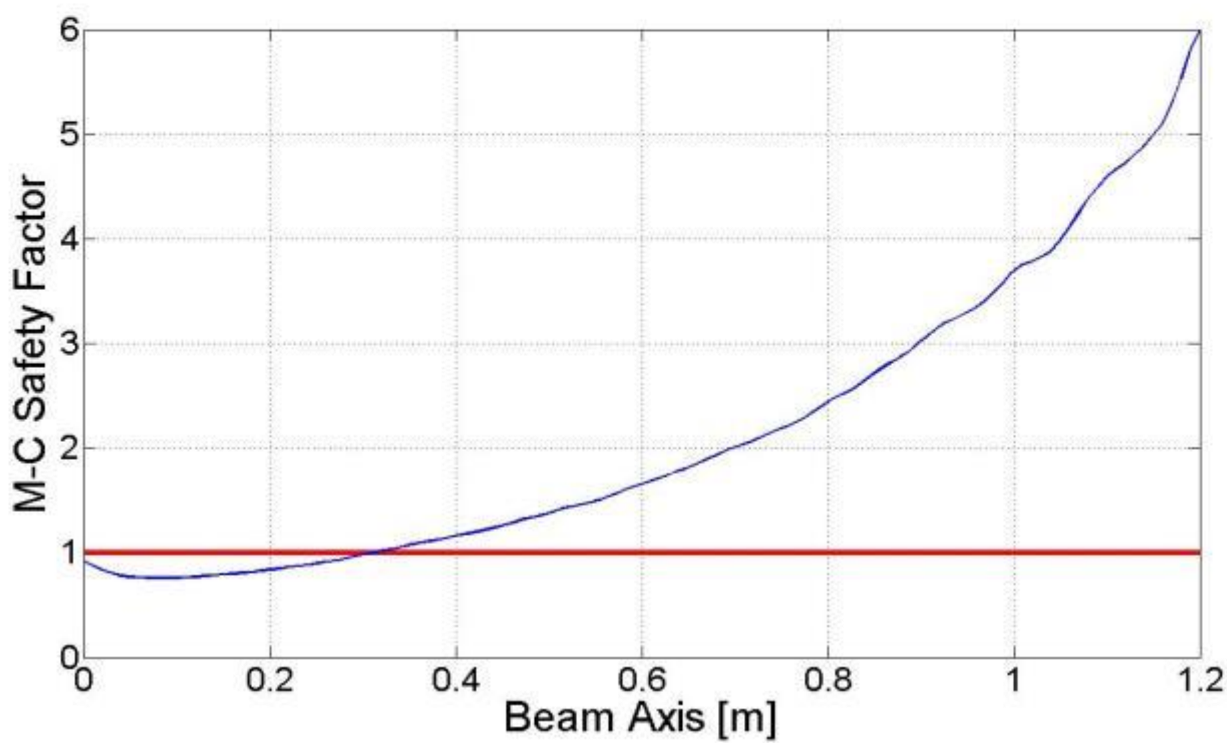
Failure Scenarios

1. Global deformation that makes the flatness larger than 100 μm.
2. Cracks on fragile materials (Graphite and BN) can be really dangerous and not acceptable. On 3D C/C “small” cracks (not affecting the surface flatness requirements and not affecting the block integrity) can be accepted due to its ductility.

- *Mohr-Coulomb safety factor should be larger than 1 as an indicator for the material survival (Criterion to be applied to fragile materials as graphite)

$$F_s = \left[\frac{\sigma_1}{\sigma_{Tensile\ limit}} + \frac{\sigma_3}{\sigma_{compressive\ limit}}\right]^{-1},$$

Mohr-Coulomb Safety Factor (SF) definition



Expected results are based on material static limits (displacement rate 0.02mm/s) while we are under dynamic load conditions (2000 mm/s)