CERN

# Highly transparent vacuum chambers

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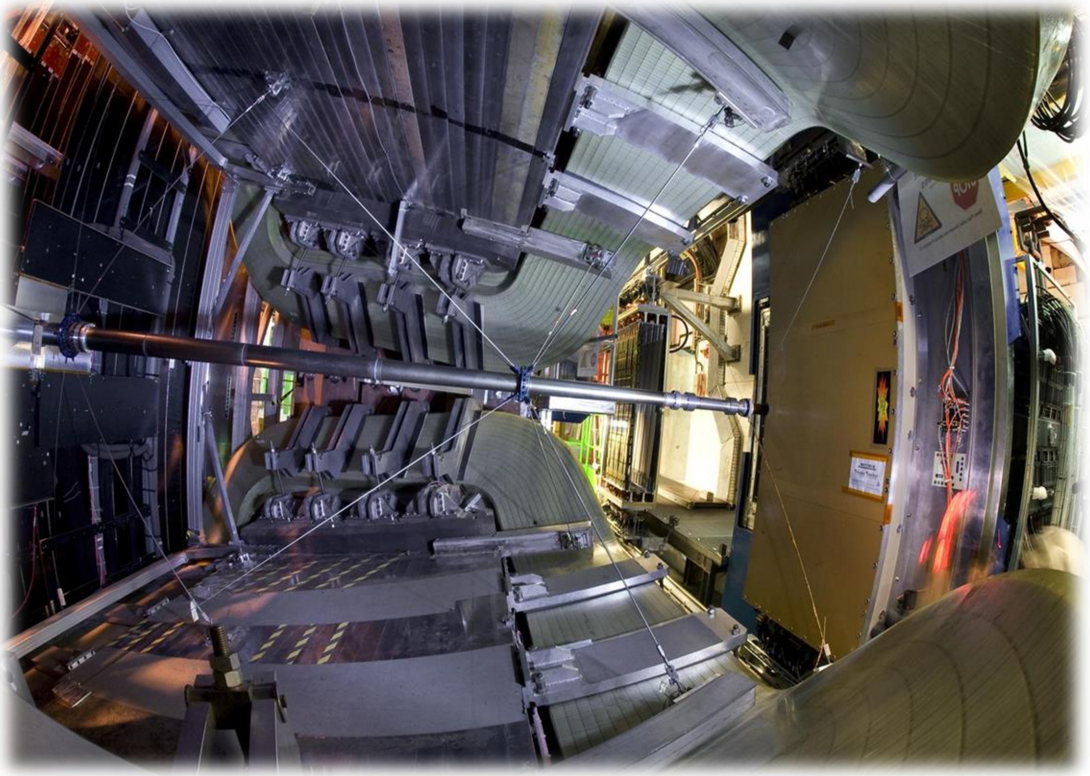
Outline:

- Context
- Present solutions
- New material development
  - Alternative to beryllium
  - Figure of merit
  - Type of material
  - Status of different alternatives
- Conclusion and next steps

# Highly transparent vacuum chambers

In high energy physics detectors, transparent vacuum systems are required to:

- Reduce the interaction of particles with the matter,
- Reduce the activation of the materials,
- Reduce the background to the experiments.



# Highly transparent vacuum chambers

Main requirements are:

- Vacuum compatibility (leak tightness, low outgassing and permeation),
- Temperature resistance (in the range 230 C)
- Mechanical stiffness and strength

Transparency of the chamber is defined as: $\frac{t}{X_0}$

thickness of the chamber

radiation length

$$X_0[cm] \sim \frac{1}{\rho} \frac{716.4\,A}{Z(Z+1)ln\left(\frac{287}{\sqrt{Z}}\right)}$$

Atomic weight

density

Atomic number

# Present solutions for transparent vacuum chambers

## Beryllium

Beryllium is used for vacuum chambers in the experimental area due to its transparency and stiffness.

Range of geometry:

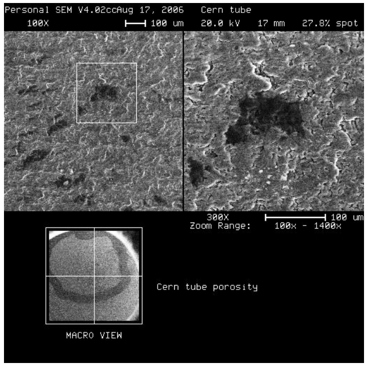
- Thickness: 0.8 mm to 2.6 mm
- Diameter: 34.4 to 260 mm
- Length: up to 7.3 m

Main drawbacks:

- Brittle
- Toxicity
- A few suppliers, cost

Technical difficulties:

- Material porosity thin walled vacuum chambers (0.8 mm);




- Welding: cracks in welded joints

# Present solutions for transparent vacuum chambers

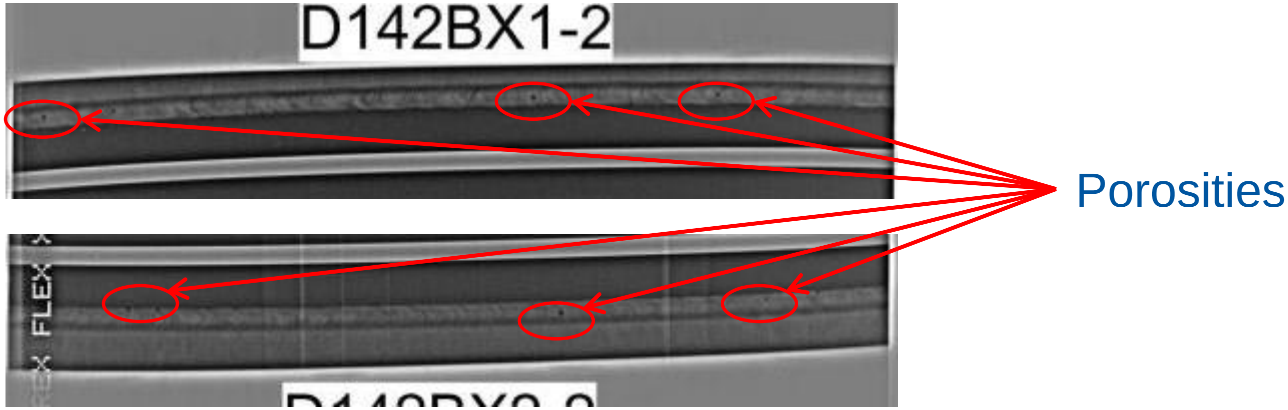
## Aluminum alloys

Two grades are used for our applications:

- 2219 for the vacuum chambers, thickness down to 1 mm
- 5083 for the bellows expansion joints, thickness 0.3 mm, internal diameter ~ 60 mm

Aluminium bellows

Issues: welds, deformation after bake out


Porosities in EB welds between 2219 and 5083 for a bellows

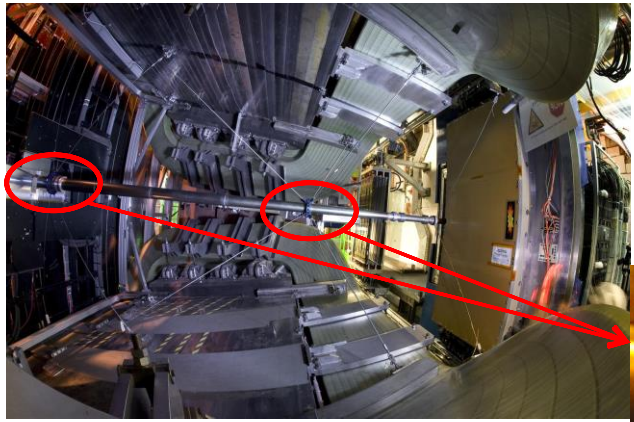
# LHC transparent vacuum chambers

## Characteristics: pre-LS1, (post-LS1), (post-LS2)

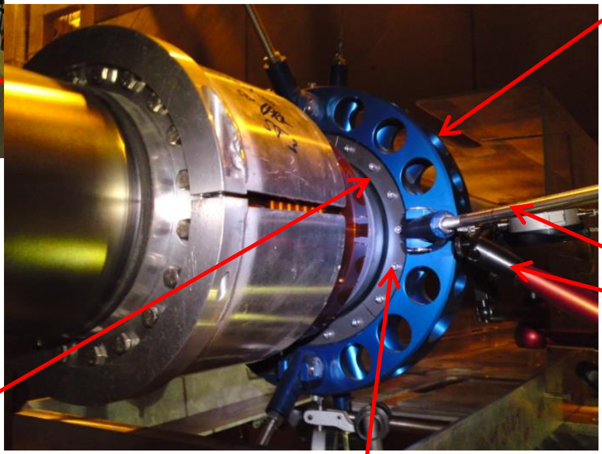
| Type | Feature | ATLAS | CMS | LHCb | ALICE |
|---|---|---|---|---|---|
| Central | Materials | Be/Al | Be/st.st (Be/Al) | Be/Al | Be/st.st (Be/Al) |
| | Length (m) | 7.3 | 6.2 | 1.85 | 4.82 (5.50) |
| | Int. dia (mm) | 58 (47) | 58 (43.4) | 50-260 | 58 (34.4) |
| | Wall (mm) | 0.8 | 0.8 | 1.0 | 0.8 |
| | Configuration | Cyl | Cone/Cyl/Cone | Cone (UX85/3) | Cyl (Cone/cyl/cone) |
| Forward | Materials | St.st (Al) | St.st (Al) | Be | Cu/St St |
| | Length (m) | 4.2-5.35 | 1.65-7.6 | 3.7-6.05 | 5.0-6.9 |
| | Int. dia (mm) | 60 – 120 | 55.1-318 | 50-260 | 60-506 |
| | Wall (mm) | 1 – 2.2 | 1.2-2.8 | 1.0-2.6 | 1.5-2.8 |
| | Configuration | Cyl | Cone/cyl | cone | Cyl/cone |

# Present solutions for transparent vacuum chambers

## Supporting system



“old” support to new design



**Aluminium to beryllium collar**

**PBI (Celazole) interface pieces (can be used during bake out)**

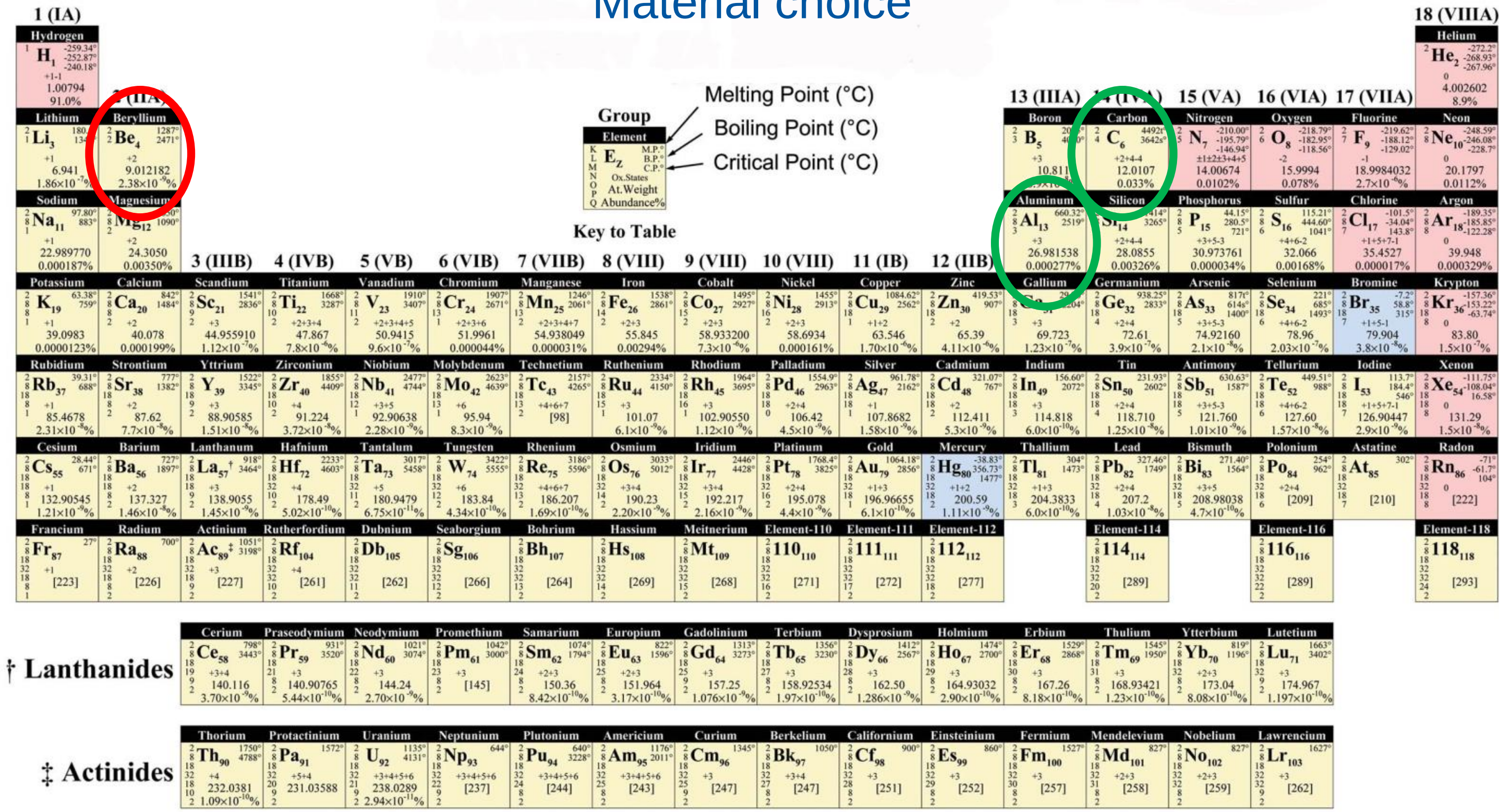
**Stainless steel to titanium screws**

**Stainless steel to CFRE or aramid fibres (Technora) wires**

All polymeric materials have been tested and qualified under radioactive environment.

# New material development for transparent vacuum chambers

## Material choice




Transparency is related to: $X_0[cm] \sim \frac{1}{\rho} \frac{716.4\,A}{Z(Z+1)\ln\left(\frac{287}{\sqrt{Z}}\right)}$

# New material development for transparent vacuum chambers – Figures of merit

Several figures of merit, characterizing the material, can be used depending on the final application.

- Temperature rise in transient regime: $X_0.\rho.C.T_f$

- Thermal fatigue: $\frac{X_0.\rho.C.\sigma_y}{E.\alpha}$

- Temperature rise in steady state: $X_0.\lambda.T_f$

- Mechanical Stability (buckling): $X_0 E^{1/3}$

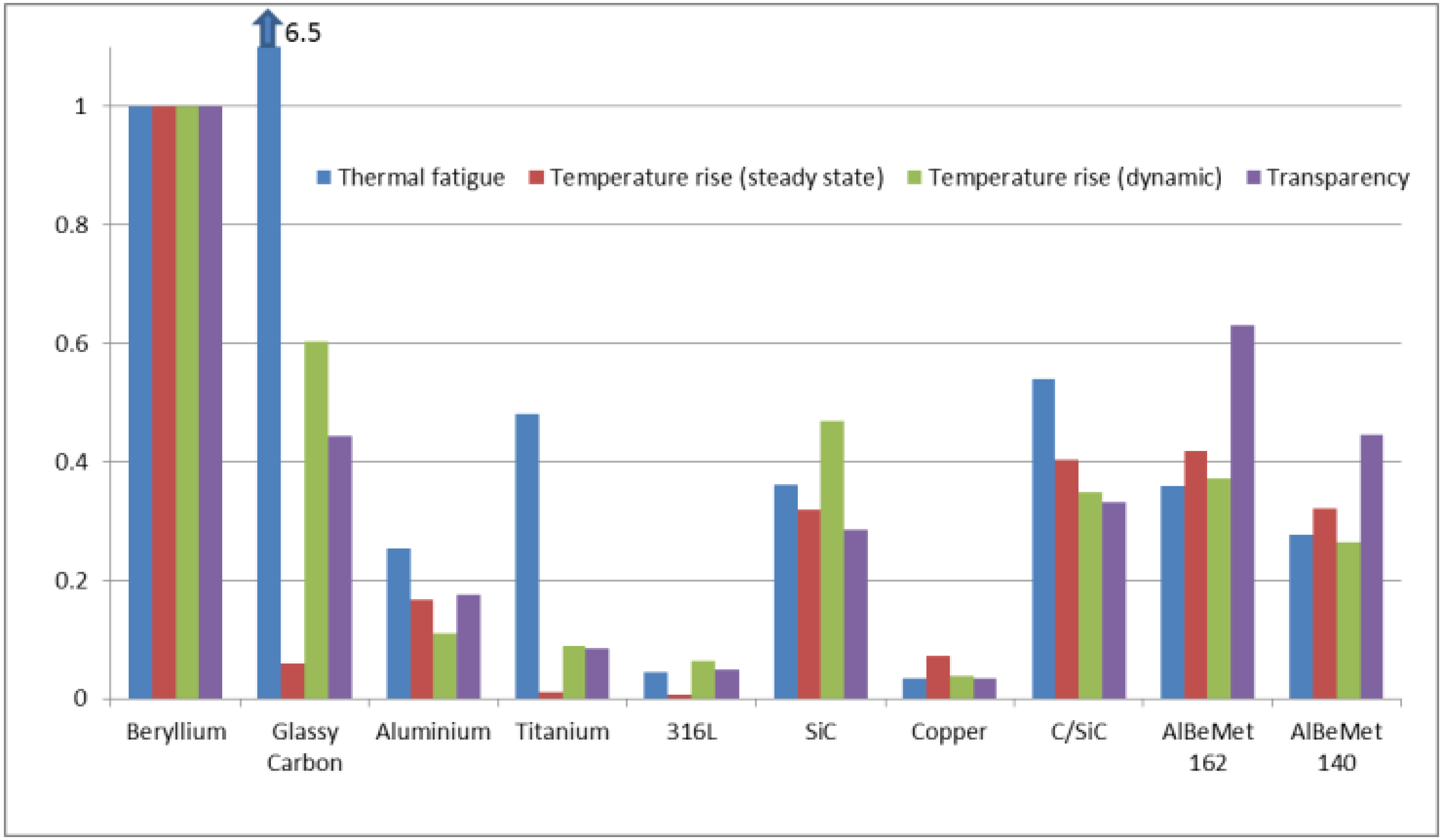
# New material development for transparent vacuum chambers

## Figure of merit for thin vacuum chambers

| | Radiation length [cm] | Young Modulus [Gpa] | $X0E^{1/3}$ |
|---|---|---|---|
| Beryllium | 35 | 290 | 230 |
| Epoxy | 30-36 | | |
| CFRE | 30 | ~ 200 | 175 |
| Carbon | 29 | 35 (GC) | 95 |
| Carbon/Al (60/40) | 17 | 120 (short fibers, randomly oriented) | 84 |
| SiC | 8 | 450 | 61.3 |
| Al2O3 | 7 | 390 | 51 |
| AlLi | 10-11 | 78 | 43 |
| Al | 9 | 70 | 37 |
| Ti | 3.7 | 113 | 18 |
| 316L | 1.8 | 200 | 10.5 |

# New material development for transparent vacuum chambers

Figure of merit of different materials, normalized w.r.t. beryllium



# New material development for transparent vacuum chambers

## Low Z material for beam pipe

### Raw material

- Carbon (Glassy carbon)
- Al alloys
- SiC

As a back-up solution and for very thin chamber

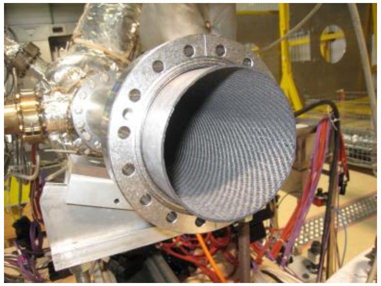
### Composite material

Carbon reinforcement:
- long fibers
- short fibers
- particulates

Matrix:
- Aluminium
- Epoxy + coating

### Structural composite

- C/C + liner
- Sandwich/ Honeycomb composite



**C/C tube and titanium tube set-up**

# New material development for transparent vacuum chambers – Structural composite

## Case of an external  thin leak tight aluminium envelop with internal C/C reinforcement

Internal C/C tube

### ☺ Good vacuum performance:

- Outgassing rate ~ 10-12 mbar.l.s-1.cm-2 after bakeout
- Compatible with NEG coating

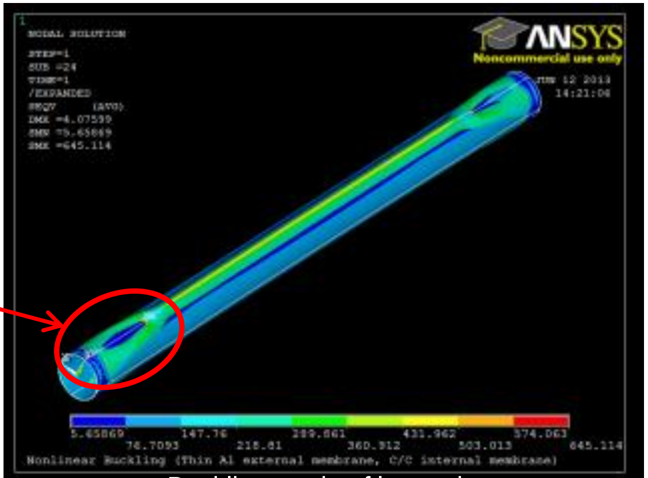
| | Activation 200 ◦C for 24h | Activation 250 ◦C for 6h |
|---|---|---|
| **$H_2$ Pumping Speed [l/s]** | 310 | 530 |
| **Sticking probability [-]** | $5.9*10^{-3}$ | $1*10^{-2}$ |

Pumping speed with NEG coating

### ☹ Issue with the mechanical behaviour:

- Differential thermal expansion → buckling of the thin aluminium envelop

Strain concentration




Buckling mode of long tube

→ Need to have significant envelop thickness
→ Either not reliable or not interesting

# New material development for transparent vacuum chambers – Carbon fiber reinforced aluminum

Material obtained by aluminium infiltration of a carbon perform.
Tests on samples from Thales Alenia Space and Dresden University.


Tube and plates of long carbon fibres in aluminium matrix

☺ Vacuum tests :

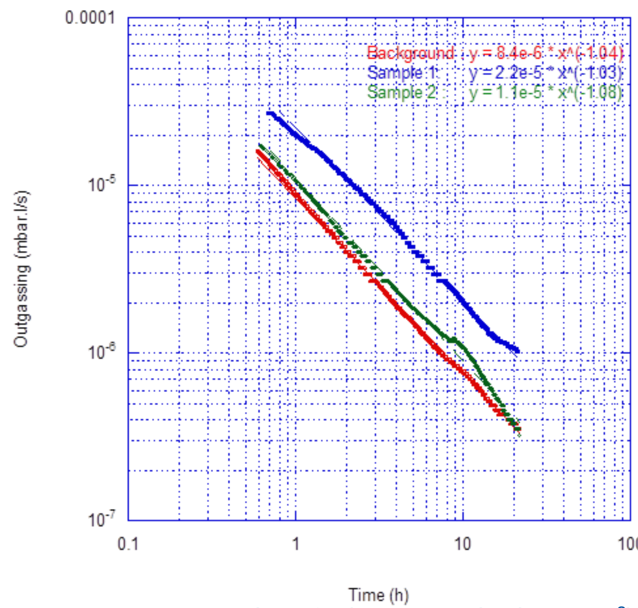
- Leak tightness
- Preliminary outgassing tests promising for unbaked sample

😐 Reliability with thermal cycles not assessed

😐 Compatibility C/Al: corrosion, cleaning

☹ Material not available at the industrial scale.

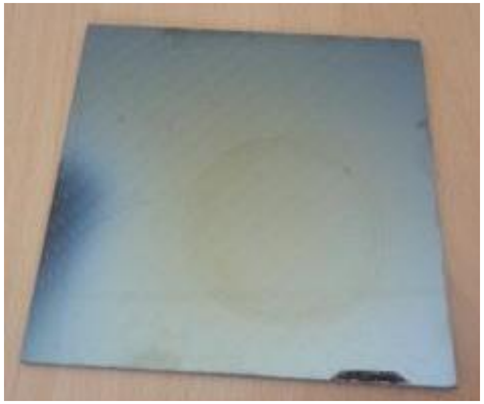
→ Tentative to find company to try short carbon fibers or graphen in aluminium matrix: not successful (yet).




Outgassing of C/Al composite (4.25 $cm^2$)

# New material development for transparent vacuum chambers – Carbon fiber reinforced epoxy + coating

Long carbon fibres reinforced epoxy resin
Aluminium sputtering coating (up to ~500 nm),



Long carbon fibre epoxy resin with metallic coating

Defects


Surface observations

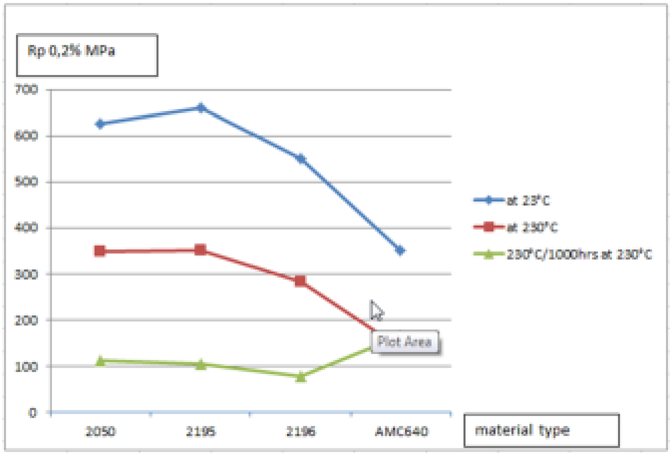
☹ Vacuum tests not successful due to pin holes

→ Try to coat in several steps with intermediate cleaning
→ Other coating process (ionic liquid)

# New material development for transparent vacuum chambers – Aluminum alloys

## New grades with Lithium being qualified: 2050, 2195:

- ☺ Transparency
- ☺ Stiffness
- ☺ Weld ability
- ☺ Promising strength




Strength of different aluminium alloys

## Thin walled manufacturing:

- Conventional machining
- Chemical machining

→ Are grades in 5XXX series with Lithium available?

→ Tests on ultra fine grain aluminium alloys in the near future

# New material development for transparent vacuum chambers – SiC

Carbon-fiber reinforced silicon carbide or silicon carbide ceramic are considered:

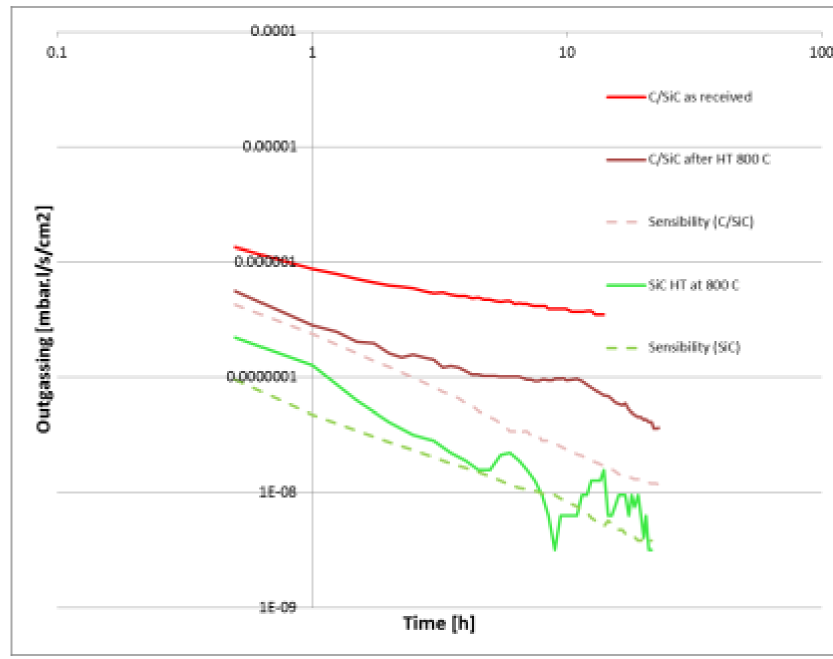

SiC plate sample

Small C/SiC plate sample (Cesic)

## Preliminary results:

☺ SiC and C/SiC are both leak tight
☺ Low outgassing rate for unbaked SiC
☺ Higher outgassing for C/SiC

→ C/SiC improvement?
→ Vacuum tests for baked samples
→ Manufacturing of thin wall




Outgassing curve of SiC materials

# New material development for transparent vacuum chambers – Glassy carbon

## Glassy carbon (GC):

- Obtained by the pyrolysis at high temperature of a highly reticulated resin.
- Two grades have been considered. Grade K is obtained after a heat treatment at 1000 °C whereas 3000 °C is used for the grade G.
- Chemical analyses have been done by EDS. The material is composed of around 98 % (weight) of carbon and 2% of oxygen.

Glassy carbon tube

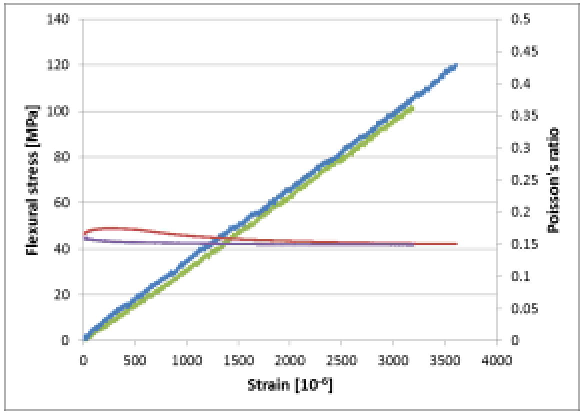
# New material development for transparent vacuum chambers – Glassy carbon

## Mechanical properties:

Stiffness:
- 4 points bending tests on plates equipped with strain gauges
- Young modulus and Poisson's ratio

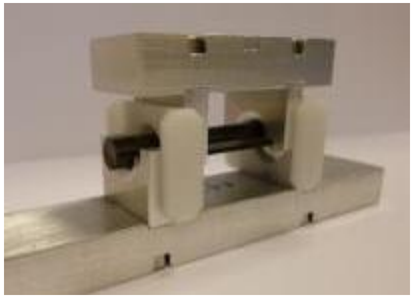
4 points bending test on plates

| | Young Modulus [GPa] | Poisson's Coefficient |
|---|---|---|
| Grade G | 32.4 ±0.8 | 0.155 |
| Grade K | 32.5 ±1 | 0.17 |

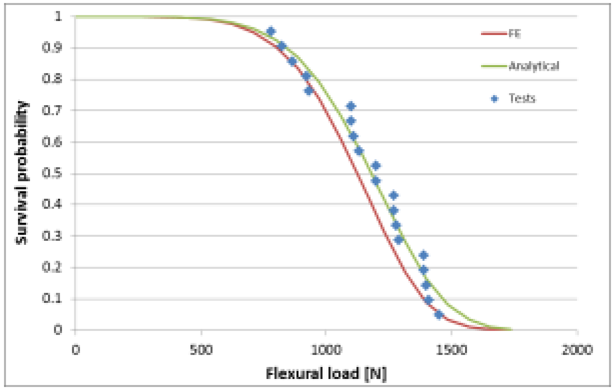



Elastic properties

Strength:
- 4 points bending tests on bars (avoid chips during cutting)
- Compression tests
- Weibull's distribution



4 points bending test on rods




Survival probability for the bending test

| | Average strength [MPa] | Standard deviation [MPa} | Weibull shape parameter | Weibull scale parameter [Mpa] |
|---|---|---|---|---|
| Flexure | 206 | 37 | 5.6-6.3 | 375-416 |
| Compression | 1012 | 73 | 13.5-14.6 | 1587-1644 |

# New material development for transparent vacuum chambers – Glassy carbon

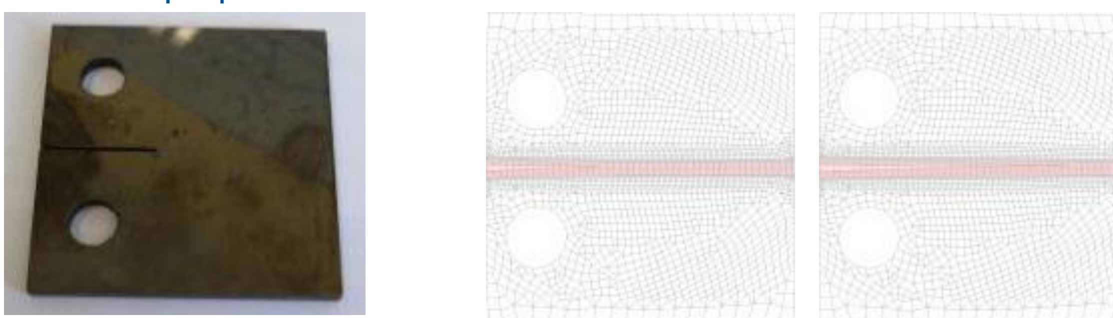
Fracture toughness:

- Notched bar under 4 points bending test:

Notched bar

| Sample | Groove depth [mm] | Force to failure [N] | Bending stress [MPa] | $K_{Ic}$ [$MPa.m^{1/2}$] |
|---|---|---|---|---|
| 1 | 0.04 | 697 | 123 | 7.8 |
| 2 | 0.023 | 973 | 172 | 6.3 |
| 3 | 0.049 | 964 | 170 | 13.1 |

- CT specimen: test in preparation



CT specimen and crack propagation simulation

→ Two methods will be used to determine the toughness: Maximum force for a given stress intensity factor or load decrease during crack propagation.

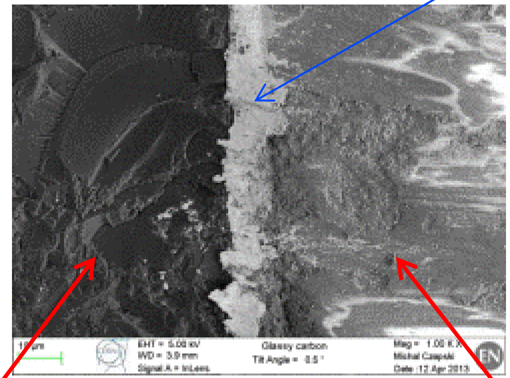
→ Crack growth test is also foreseen

# New material development for transparent vacuum chambers – Glassy carbon

## Transition to metallic parts:

### Soldering with intermediate ceramic part:

- Compatible thermal expansion
- Higher mechanical strength




### Preliminary tests on crucible:

- No failure
- Initial gaps to be adjusted to have a good flow of the solder

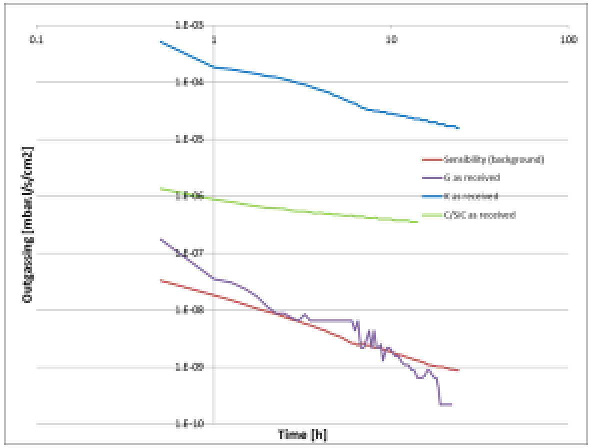
GC crucible soldered with a copper ring

# New material development for transparent vacuum chambers – Glassy carbon

## Outgassing rate:

### Unbaked material:

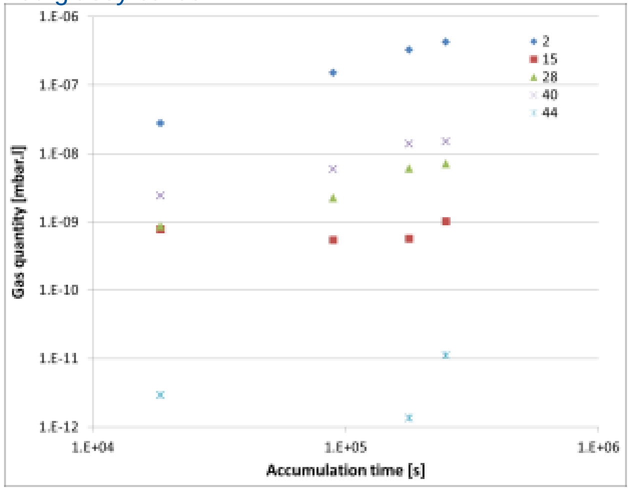
- Throughput method
- Grade K : high outgassing
- Grade G : low outgassing




Outgassing curve of unbaked glassy carbon

### Baked material:

- Gas accumulation method
- Grade G : outgassing rate of 1.5E-13 mbar l $s^{-1}$ $cm^{-2}$

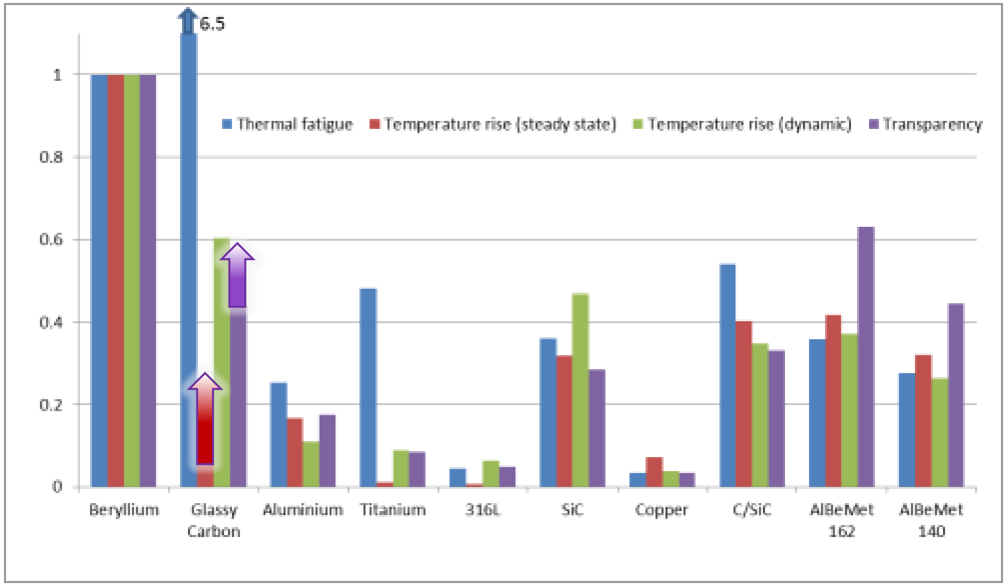



Outgassing of baked glassy carbon

# New material development for transparent vacuum chambers – Glassy carbon

Possibility to improvement the material properties:

Reinforcement with carbon nanotubes:
- mechanical properties ↑
- thermal conductivity ↑



# Highly transparent vacuum chambers

## Conclusion

Highly transparent vacuum chambers are required in high energy physics domain.

Beryllium and aluminium are two materials presently used for vacuum chambers.

Materials, alternative to beryllium, are studied for transparent vacuum chambers and require some studies and development:

- Aluminium characterisation and thin wall manufacturing
- Coating of polymer or composites
- SiC characterisation
- Glassy carbon qualification and tests, if available, reinforcement with carbon nanotubes for structural applications

## Thanks for your attention

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