

# Beam pipe developments

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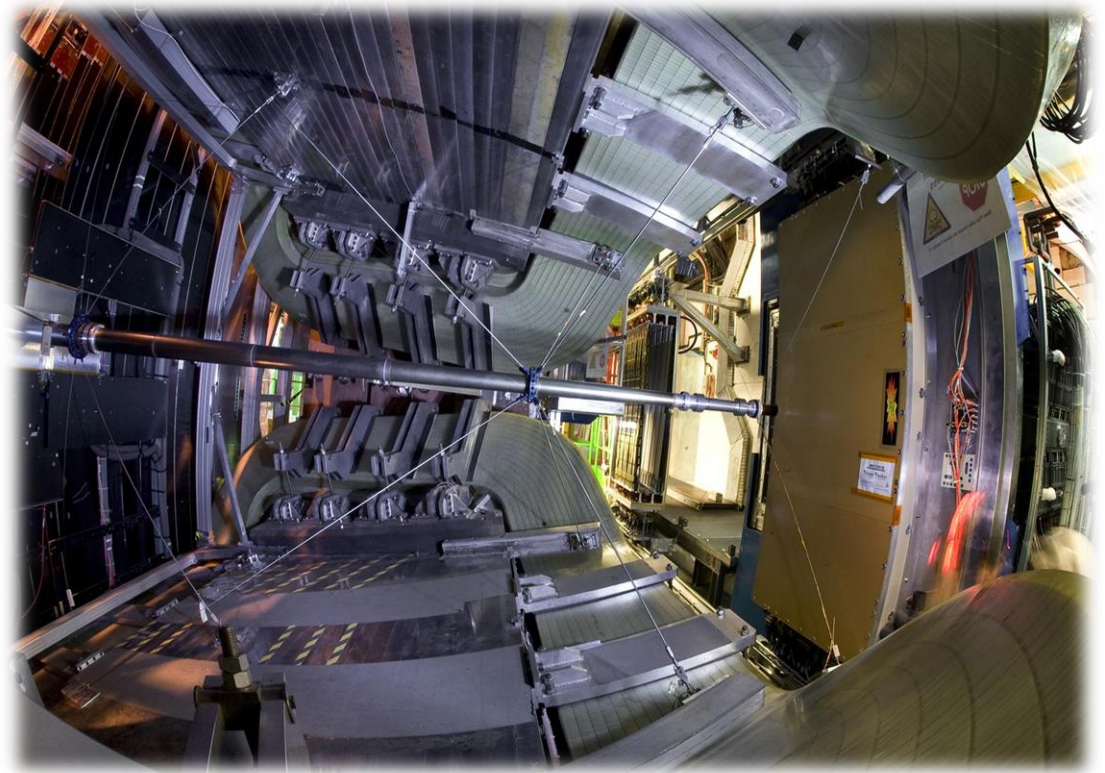
## Outline:

- Highly transparent vacuum chambers
  - Context and requirements
  - Present solutions
  - New material development
- Monte Carlo simulations for dynamic vacuum assessment
- 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:

thickness of the chamber

$$\frac{t}{X_0}$$

radiation length

Atomic weight

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

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:

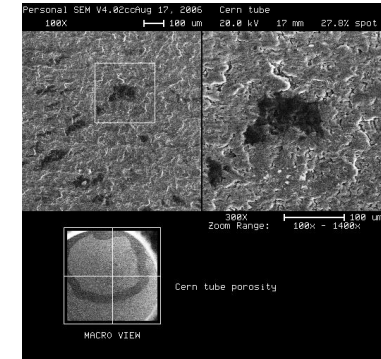
- Thickness: 0.8 mm to 2.6 mm
- Diameter: 43.4 to 260 mm
- Length: up to 7.3 m

### 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

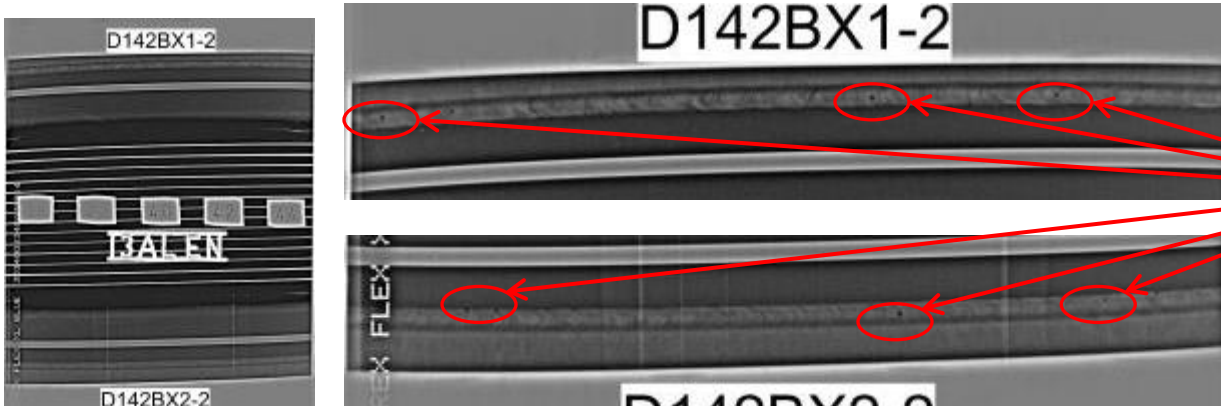
Two grades are used for our applications:

- 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

Porosities in EB welds between 2219 and 5083 for a bellows

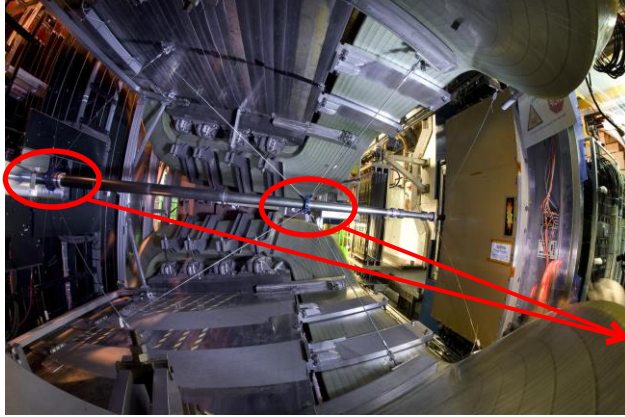
# LHC transparent vacuum chambers

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

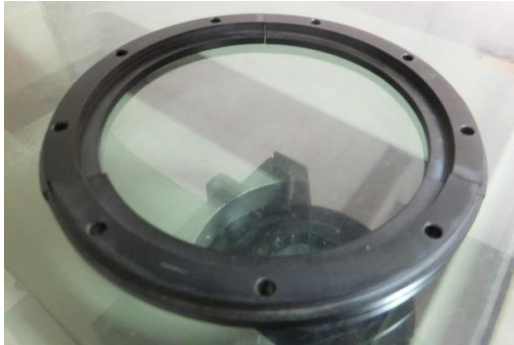
## Supporting system



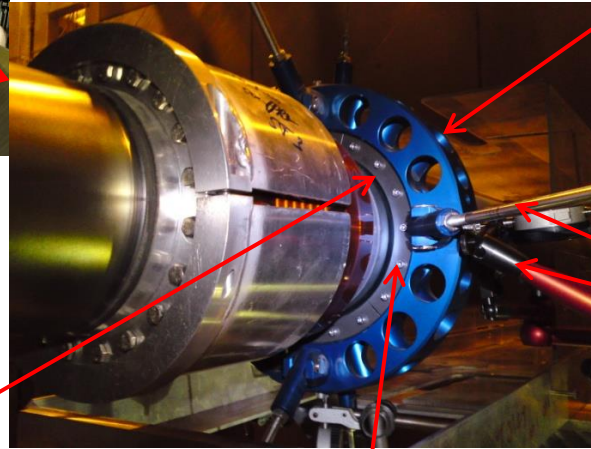
“old” support to new design



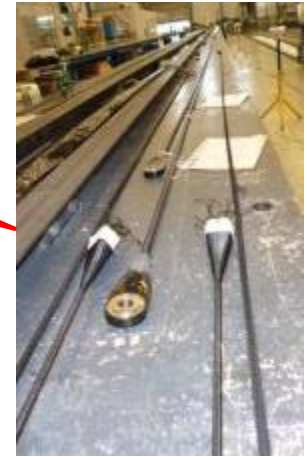
Aluminium to beryllium collar



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

## chambers

### Material choice

1 (IA)											18 (VIIIA)																
Hydrogen											Helium																
<sup>1</sup> H 1.00784 91.0%											<sup>4</sup> He 4.002602 8.9%																
2 (IIA)												13 (IIIA)	14 (IVA)	15 (VA)	16 (VIA)	17 (VIIA)											
Lithium		Beryllium												Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon								
<sup>7</sup> Li 6.941 1.86x10 <sup>-6</sup> %	<sup>9</sup> Be 9.012182 2.38x10 <sup>-6</sup> %											<sup>5</sup> B 10.811	<sup>6</sup> C 12.0107	<sup>7</sup> N 14.00674	<sup>8</sup> O 15.9994	<sup>9</sup> F 18.9984032	<sup>10</sup> Ne 20.1797										
Sodium		Magnesium												Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon								
<sup>11</sup> Na 22.989770 0.000187%	<sup>12</sup> Mg 24.3050											<sup>13</sup> Al 26.981538	<sup>14</sup> Si 28.0855	<sup>15</sup> P 30.973761	<sup>16</sup> S 32.066	<sup>17</sup> Cl 35.4527	<sup>18</sup> Ar 39.948										
Potassium		Calcium		Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton								
<sup>19</sup> K 39.0983	<sup>20</sup> Ca 40.078	<sup>21</sup> Sc 44.955910	<sup>22</sup> Ti 47.867	<sup>23</sup> V 50.9415	<sup>24</sup> Cr 51.9961	<sup>25</sup> Mn 54.938049	<sup>26</sup> Fe 55.845	<sup>27</sup> Co 58.933200	<sup>28</sup> Ni 58.6934	<sup>29</sup> Cu 63.546	<sup>30</sup> Zn 65.39	<sup>31</sup> Ga 69.723	<sup>32</sup> Ge 72.61	<sup>33</sup> As 74.92160	<sup>34</sup> Se 78.96	<sup>35</sup> Br 79.904	<sup>36</sup> Kr 83.80	<sup>37</sup> Rb 85.4678	<sup>38</sup> Kr 83.80								
Rubidium		Strontium		Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon								
<sup>37</sup> Rb 85.4678	<sup>38</sup> Sr 87.62	<sup>39</sup> Y 88.90585	<sup>40</sup> Zr 91.224	<sup>41</sup> Nb 92.90638	<sup>42</sup> Mo 95.94	<sup>43</sup> Tc [98]	<sup>44</sup> Ru 101.07	<sup>45</sup> Rh 102.90550	<sup>46</sup> Pd 106.42	<sup>47</sup> Ag 107.8682	<sup>48</sup> Cd 112.411	<sup>49</sup> In 114.818	<sup>50</sup> Sn 118.710	<sup>51</sup> Sb 121.760	<sup>52</sup> Te 127.60	<sup>53</sup> I 126.90447	<sup>54</sup> Xe 131.29	<sup>55</sup> Cs 132.90545	<sup>56</sup> Ba 137.327								
Cesium		Barium		Lanthanum	Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon								
<sup>55</sup> Cs 132.90545	<sup>56</sup> Ba 137.327	<sup>57</sup> La 138.9055	<sup>58</sup> Hf 178.49	<sup>59</sup> Ta 180.9479	<sup>60</sup> W 183.84	<sup>61</sup> Re 186.207	<sup>62</sup> Os 190.23	<sup>63</sup> Ir 192.217	<sup>64</sup> Pt 195.078	<sup>65</sup> Au 196.96655	<sup>66</sup> Hg 200.59	<sup>67</sup> Tl 204.3833	<sup>68</sup> Pb 208.98038	<sup>69</sup> Bi 208.98038	<sup>70</sup> Po [209]	<sup>71</sup> At [210]	<sup>72</sup> Rn [222]	<sup>73</sup> Fr [223]	<sup>74</sup> Ra [226]								
Francium		Radium		Actinium	Rutherfordium	Dubnium	Seaborgium	Bohrium	Hassium	Meitnerium	Element-110	Element-111	Element-112	Element-114	Element-116	Element-118											
<sup>87</sup> Fr [223]	<sup>88</sup> Ra [226]	<sup>89</sup> Ac [227]	<sup>90</sup> Rf [261]	<sup>91</sup> Db [262]	<sup>92</sup> Sg [266]	<sup>93</sup> Bh [264]	<sup>94</sup> Hs [269]	<sup>95</sup> Mt [268]	<sup>110</sup> 110 [271]	<sup>111</sup> 111 [272]	<sup>112</sup> 112 [277]	<sup>114</sup> 114 [289]	<sup>116</sup> 116 [289]	<sup>118</sup> 118 [293]													
† Lanthanides																											
Cerium		Praseodymium		Neodymium		Promethium		Samarium		Europium		Gadolinium		Terbium		Dysprosium		Holmium		Erbium		Thulium		Ytterbium		Lutetium	
<sup>58</sup> Ce 140.116	<sup>59</sup> Pr 140.90765	<sup>60</sup> Nd 144.24	<sup>61</sup> Pm [145]	<sup>62</sup> Sm 150.36	<sup>63</sup> Eu 151.964	<sup>64</sup> Gd 157.25	<sup>65</sup> Tb 158.92534	<sup>66</sup> Dy 162.50	<sup>67</sup> Ho 164.93032	<sup>68</sup> Er 167.26	<sup>69</sup> Tm 168.93421	<sup>70</sup> Yb 173.04	<sup>71</sup> Lu 174.967														
‡ Actinides																											
Thorium		Protactinium		Uranium		Neptunium		Plutonium		Americium		Curium		Berkelium		Californium		Einsteinium		Fermium		Mendelevium		Nobelium		Lawrencium	
<sup>90</sup> Th 232.0381	<sup>91</sup> Pa 231.03688	<sup>92</sup> U 238.02891	<sup>93</sup> Np 237	<sup>94</sup> Pu 244	<sup>95</sup> Am 243	<sup>96</sup> Cm 247	<sup>97</sup> Bk 247	<sup>98</sup> Cf [251]	<sup>99</sup> Es [252]	<sup>100</sup> Fm [257]	<sup>101</sup> Md [258]	<sup>102</sup> No [259]	<sup>103</sup> Lr [262]														

Melting Point (°C)  
Boiling Point (°C)  
Critical Point (°C)

Key to Table

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



# 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.

- Mechanical Stability (buckling):  $X_0 E^{1/3}$
- Temperature rise in steady state:  $X_0 \cdot \lambda \cdot T_f$
- Temperature rise in transient regime:  $X_0 \cdot \rho \cdot C \cdot T_f$
- Thermal fatigue:  $\frac{X_0 \cdot \rho \cdot C \cdot \sigma_y}{E \cdot \alpha}$

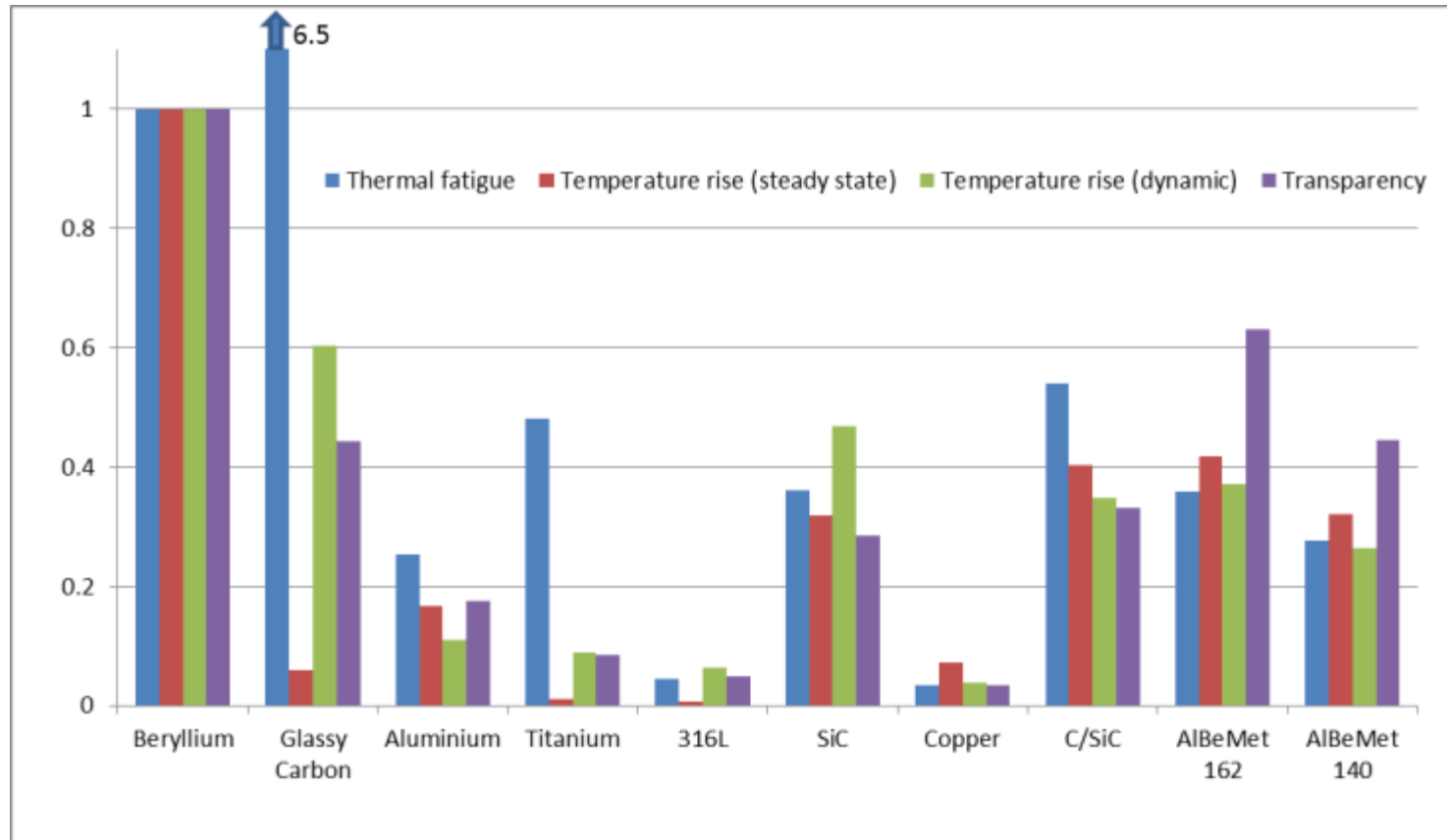
# New material development for transparent vacuum chambers

Figure of merit for thin vacuum chambers

	Radiation length [cm]	Young Modulus [Gpa]	$XOE^{1/3}$
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
Al <sub>2</sub> O <sub>3</sub>	7	390	51
AlLi	10-11	78	43
Al	9	70	37
Ti	3.7	113	18
316L	1.8	200	10.5

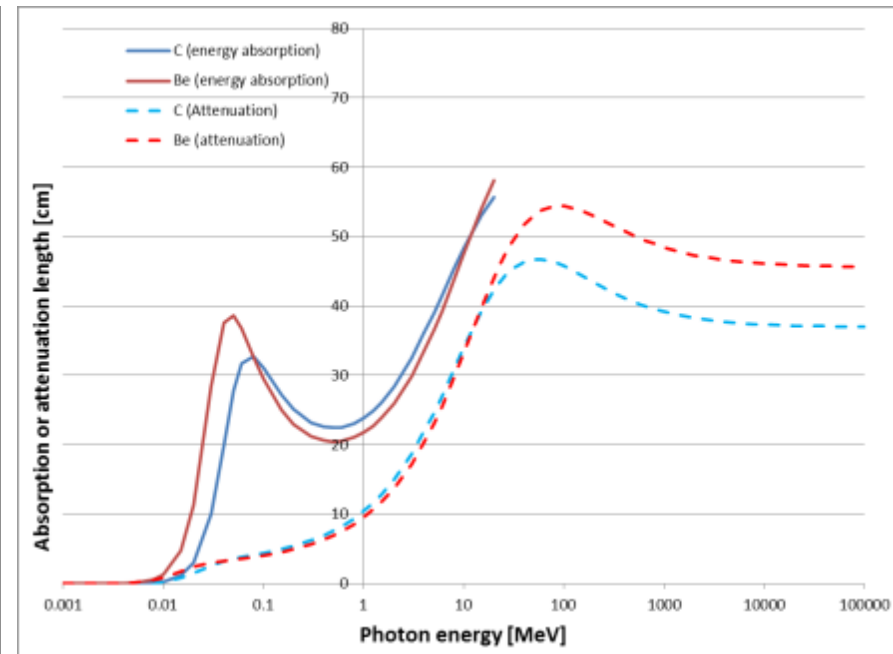
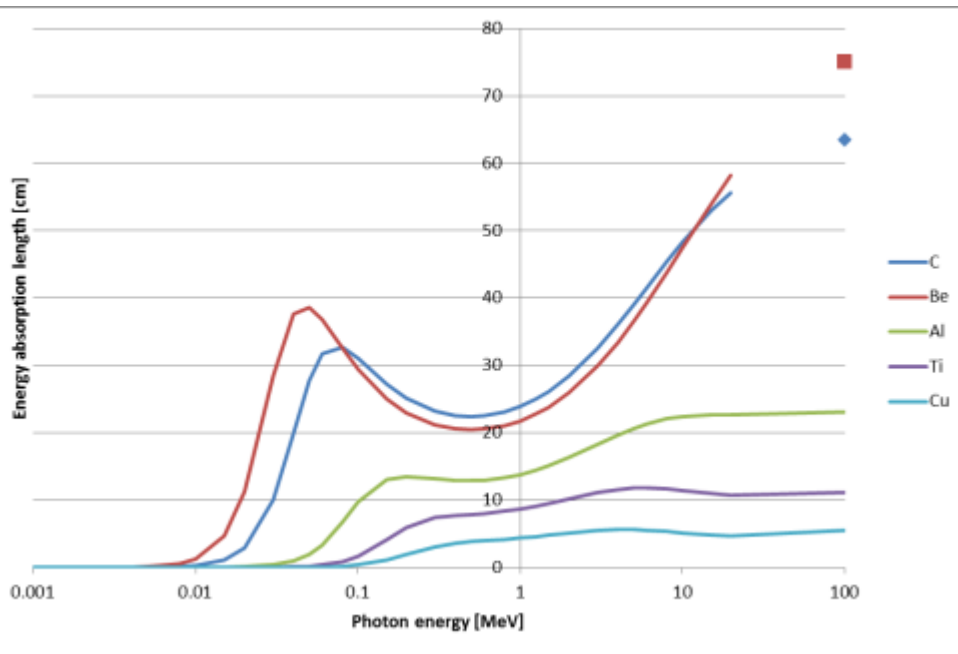
# New material development for transparent vacuum chambers

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



# New material development for transparent vacuum chambers

Photon absorption of different materials, compared to beryllium



# New material development for transparent vacuum chambers

Low Z material for beam pipe

Raw material

- Carbon (Glassy carbon)
- Al alloys
- SiC



Composite material

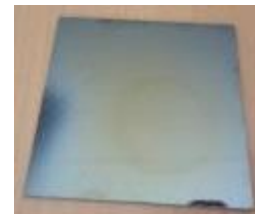
Carbon reinforcement:

- long fibers
- short fibers
- particulates



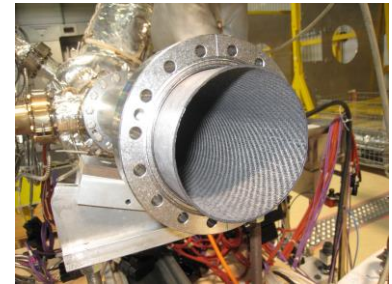
Matrix:

- 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

☺ 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
<b>H<sub>2</sub> Pumping Speed [l/s]</b>	310	530
<b>Sticking probability [-]</b>	5.9*10 <sup>-3</sup>	1*10 <sup>-2</sup>

Pumping speed with NEG coating



Internal C/C tube

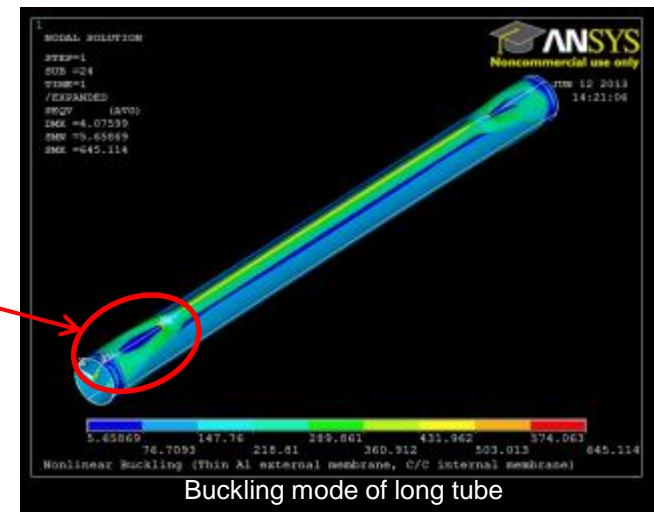
☹ Issue with the mechanical behaviour:

- Differential thermal expansion → buckling of the thin aluminium envelop

Strain  
concentration

→ Need to have significant envelop thickness

→ Either not reliable or not interesting



Buckling mode of long tube

# 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 :

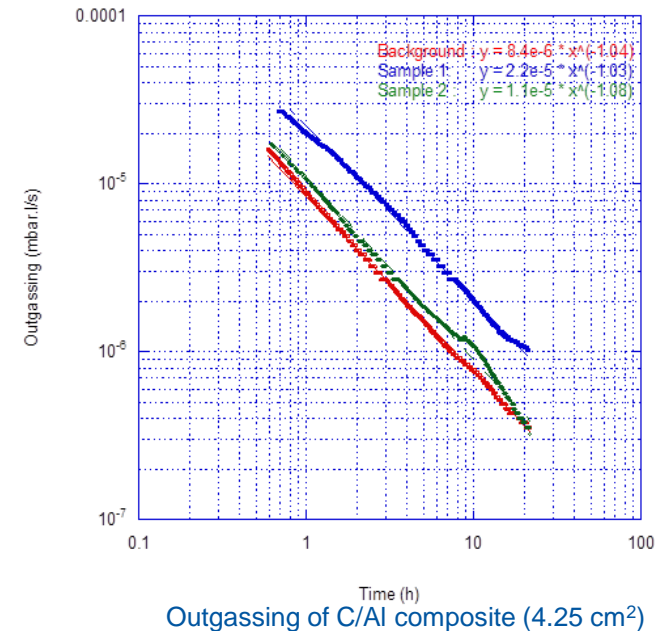
- Leak tightness
- Preliminary outgassing tests promising for unbaked sample

😐 Reliability with thermal cycles not assessed

😐 Compatibility C/Al: corrosion, cleaning

😞 Material not available at the industrial scale.

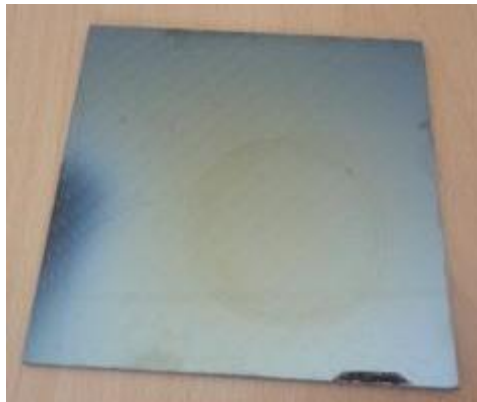
→ Tentative to find company to try short carbon fibers or graphen in aluminium matrix:  
not successful (yet).



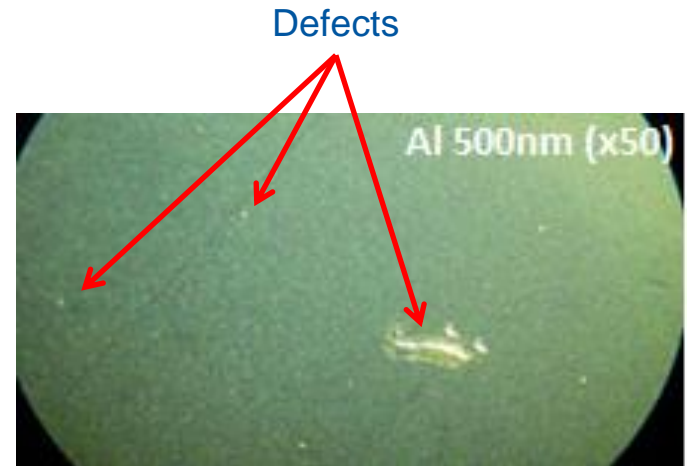


# New material development for transparent vacuum chambers – Carbon fiber reinforced epoxy + coating

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



Long carbon fibre epoxy resin with metallic coating



Surface observations

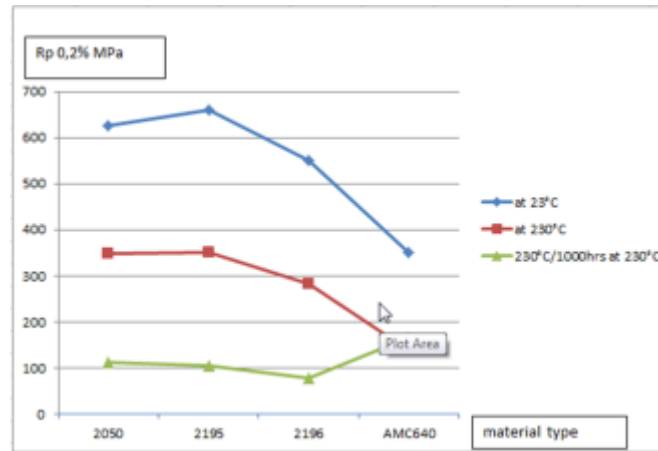
☹ Vacuum tests not successful due to pin holes

- 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

- Further tests on grades with Lithium
- Tests on ultra fine grain aluminium alloys

# New material development for transparent vacuum chambers – SiC

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



SiC plate sample

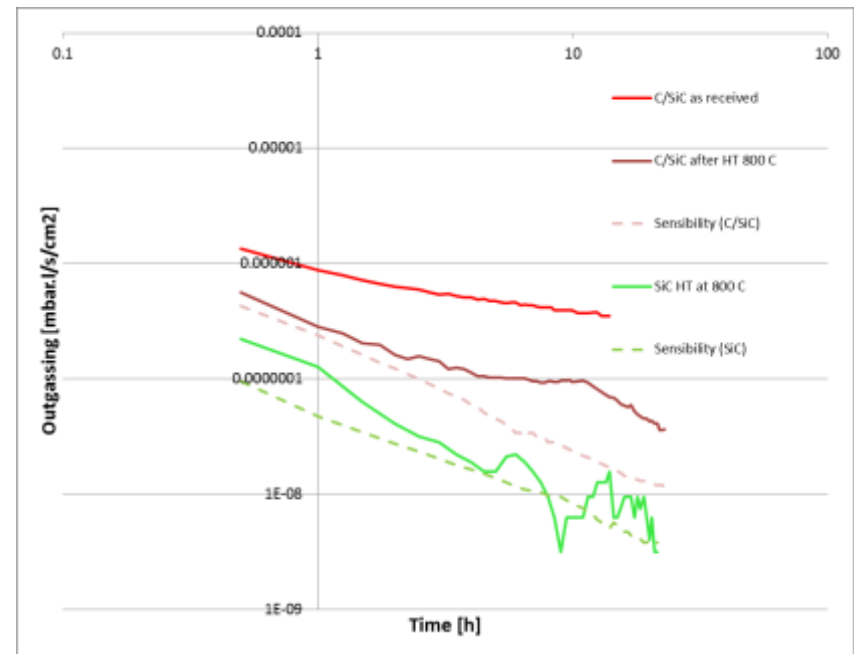


Small C/SiC plate sample (Cesic)

## 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 2200 °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:

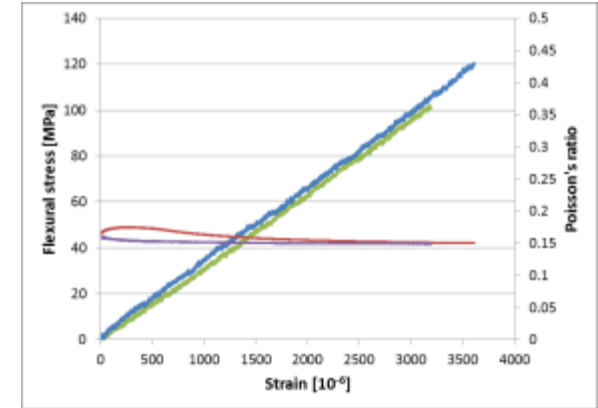
### Stiffness:

- 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



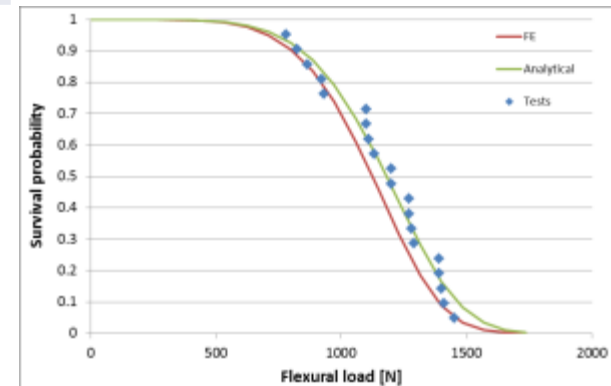
Elastic properties

### 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:

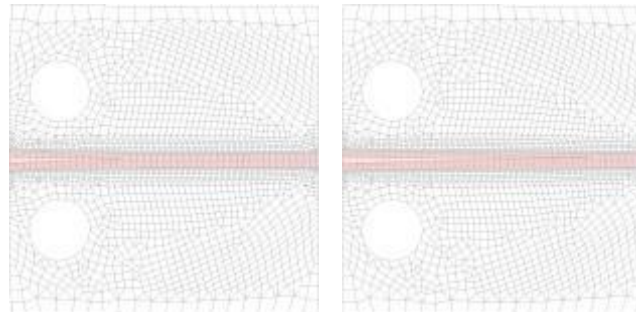
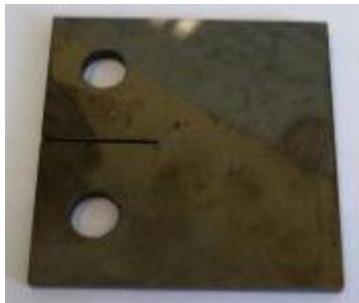
- Notched bar under 4 points bending test:



Notched bar

Sample	Groove depth [mm]	Force to failure [N]	Bending stress [MPa]	$K_{Ic}$ [MPa.m <sup>1/2</sup> ]
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

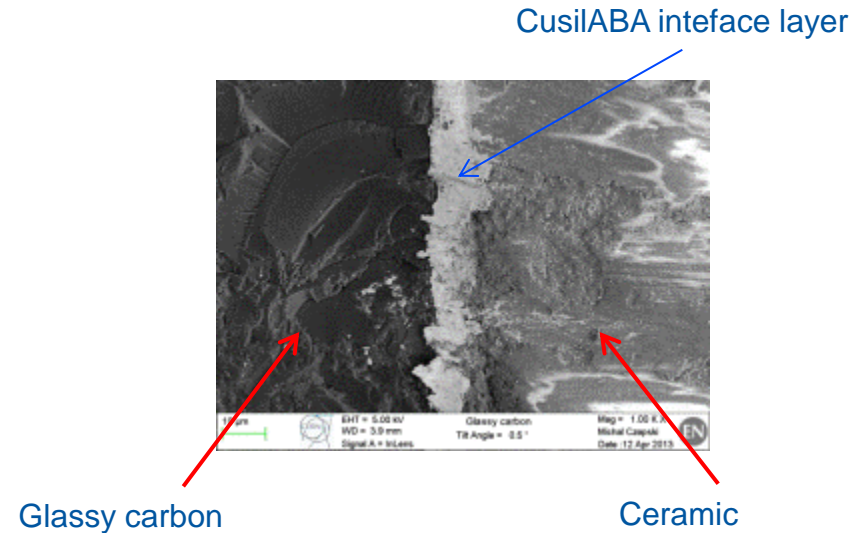
- Two methods will be used to determine the toughness: Maximum force for a given stress intensity factor or load decrease during crack propagation.
- Crack growth test is also foreseen

# 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



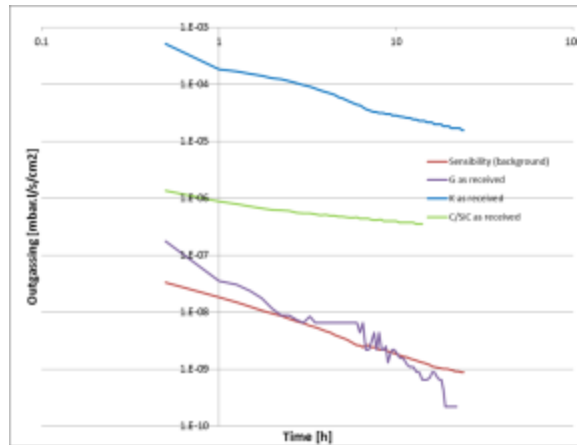
GC crucible soldered with a copper ring

# New material development for transparent vacuum chambers – Glassy carbon

## Outgassing rate:

### Unbaked material:

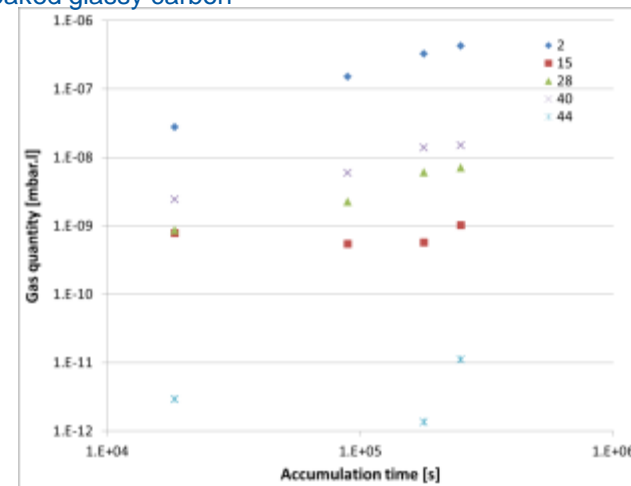
- Throughput method
- Grade K : high outgassing
- Grade G : low outgassing



Outgassing curve of unbaked glassy carbon

### Baked material:

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



Outgassing of baked glassy carbon

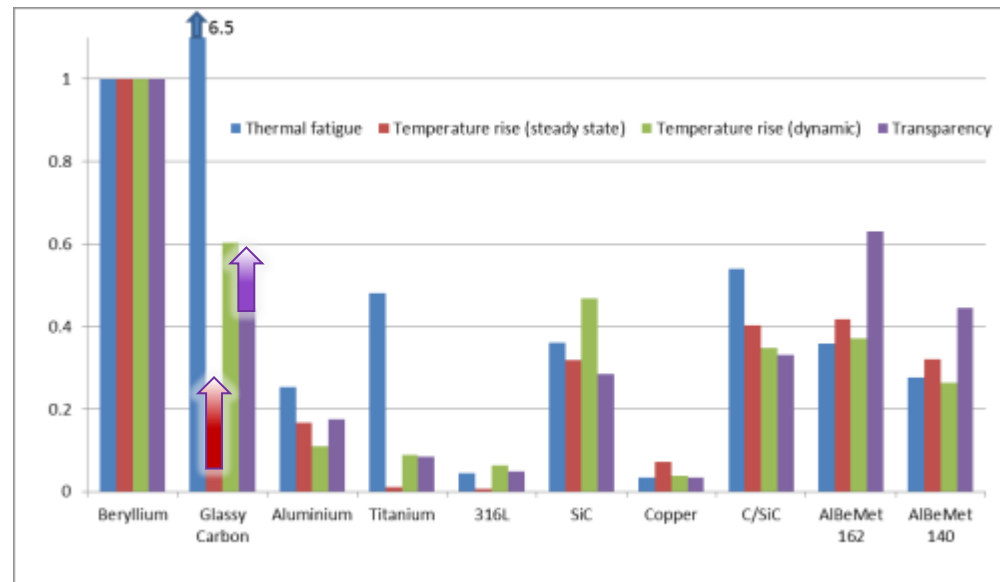


# New material development for transparent vacuum chambers – Glassy carbon

Possibility to improve the material properties:

Reinforcement with carbon nanotubes:

- mechanical properties ↑
- thermal conductivity ↑

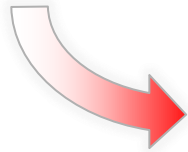


# Monte Carlo simulations for dynamic vacuum assessment

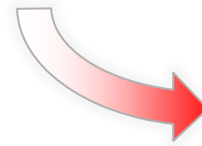
Courtesy M. Ady, R. Kersevan\*

A Monte Carlo software, SynRad+, is being developed by CERN VSC group.

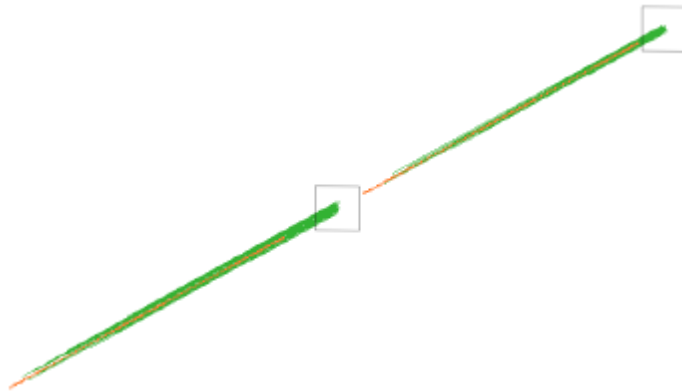
- Beam parameters: intensity, energy, emittance
- Lattice: Magnetic field distribution and  $\beta$  functions



→ Particle tracking (beam trajectory)  
→ Ray-tracing of generated photons



→ Synchrotron radiation power and flux fields  
→ Photon induced desorption



Geometry, beams and generated photons on SynRad's interface

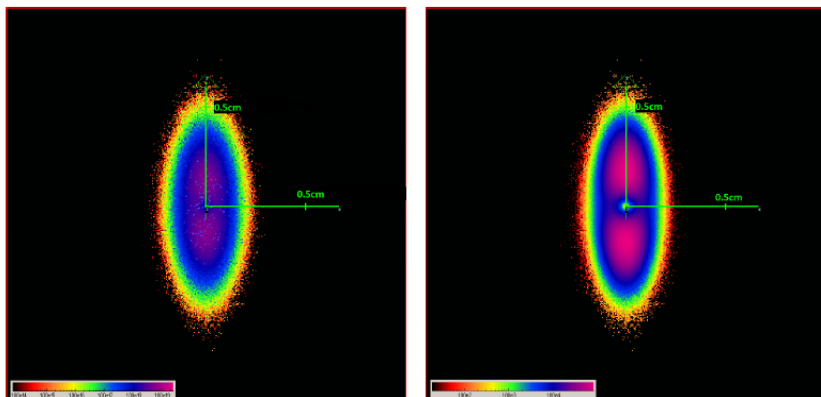
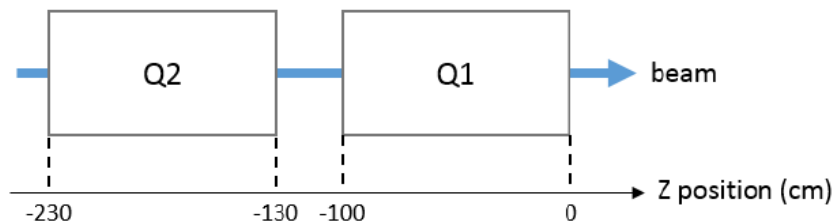
\*: CERN-ACC-NOTE-2013-0043

# Monte Carlo simulations for dynamic vacuum assessment

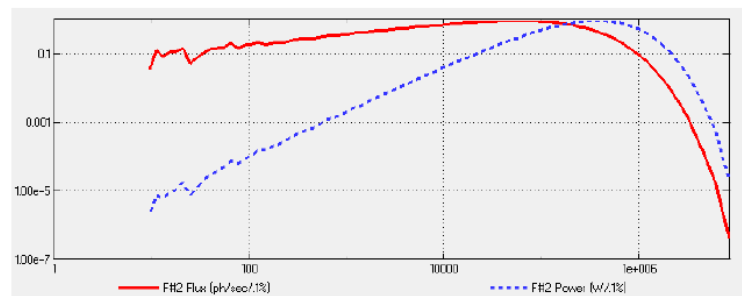
Courtesy M. Ady, R. Kersevan

## Application to LHeC interaction region:

First model: beam centred w.r.t magnetic axis



Flux and power distribution of SR of Q2



Normalized flux and power of Q2

Generated SR power:

Element	Power [W]		
	Analytic <sup>2</sup>	Geant4 <sup>3</sup>	SynRad+
Q1	4208.3	4231.8±92.7	4262.7±53
Q2	5131.9	5173.7±91.5	5190.3±66
Total	9340.2	9405.5±130.3	9453.0±120

$E_{c1} \sim 209$  keV

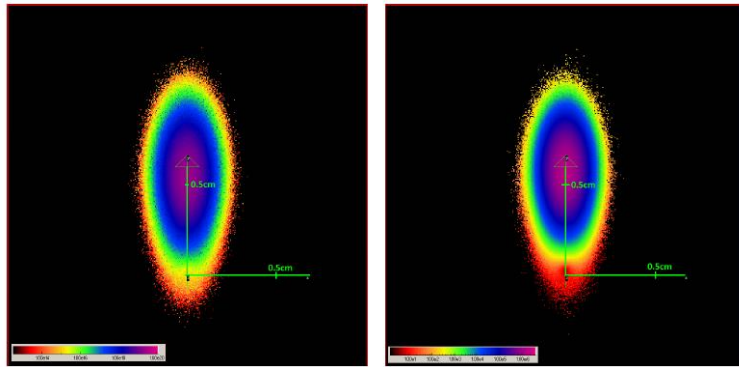
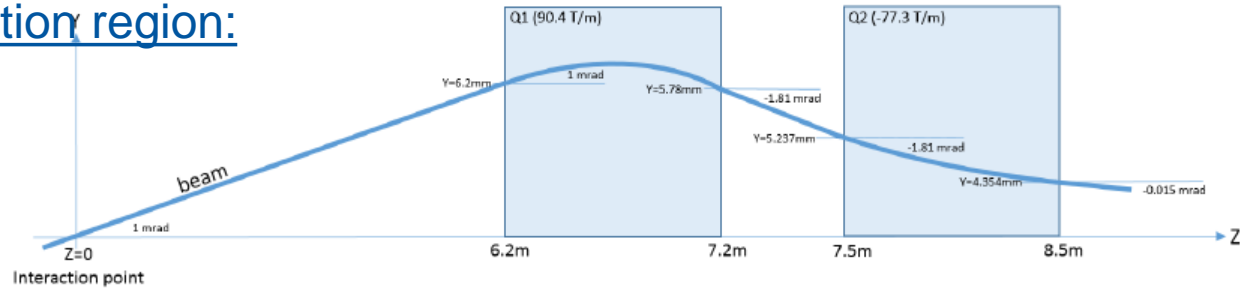
$E_{c2} \sim 220$  keV

# Monte Carlo simulations for dynamic vacuum assessment

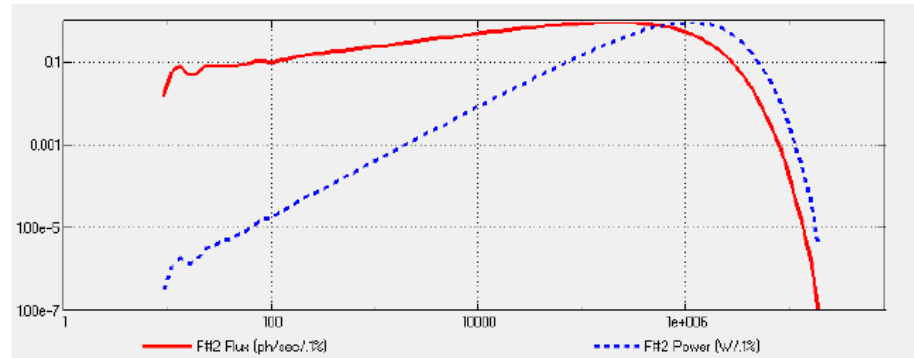
Courtesy M. Ady, R. Kersevan

## Application to LHeC interaction region:

Second model: beam off-axis



Flux and power distributions of SR of Q2



Normalized flux and power of Q2

Generated SR power:

Element	Power [kW]
Q1	148.79±0.09
Q2	64.21±0.04
Total	213.0±0.13

$E_{c1} \sim 1.4$  MeV

$E_{c2} \sim 880$  keV

# Beam pipe development

## 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
- Glassy carbon qualification and tests, if available, reinforcement with carbon nanotubes for structural applications

Monte Carlo simulation code, SynRad+, is available at CERN for synchrotron radiation flux and power distribution.

# Thanks for your attention

