CERN

Beam pipe developments

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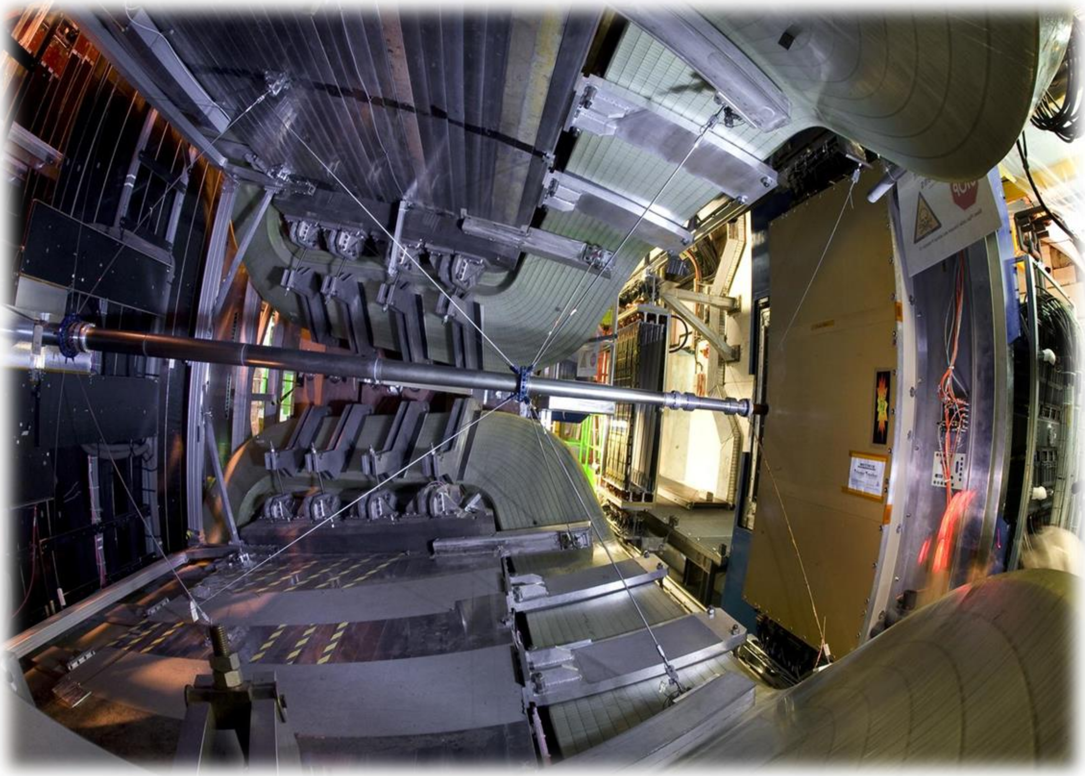
Outline:

- 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: $\frac{t}{X_0}$

thickness of the chamber (t)

radiation length (X_0)

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

Atomic weight (A)

density (ρ)

Atomic number (Z)

Present solutions for transparent vacuum chambers

Beryllium

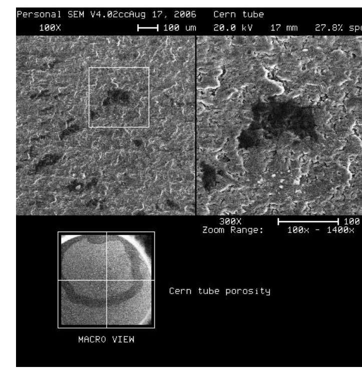
Beryllium is used for vacuum chambers in the experimental area due to its transparency and stiffness.

Range of geometry:

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

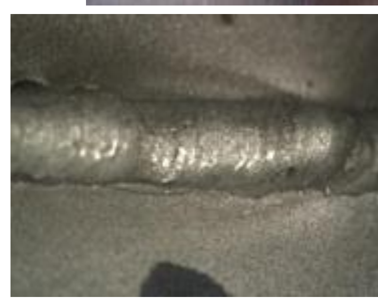
Main drawbacks:

- 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

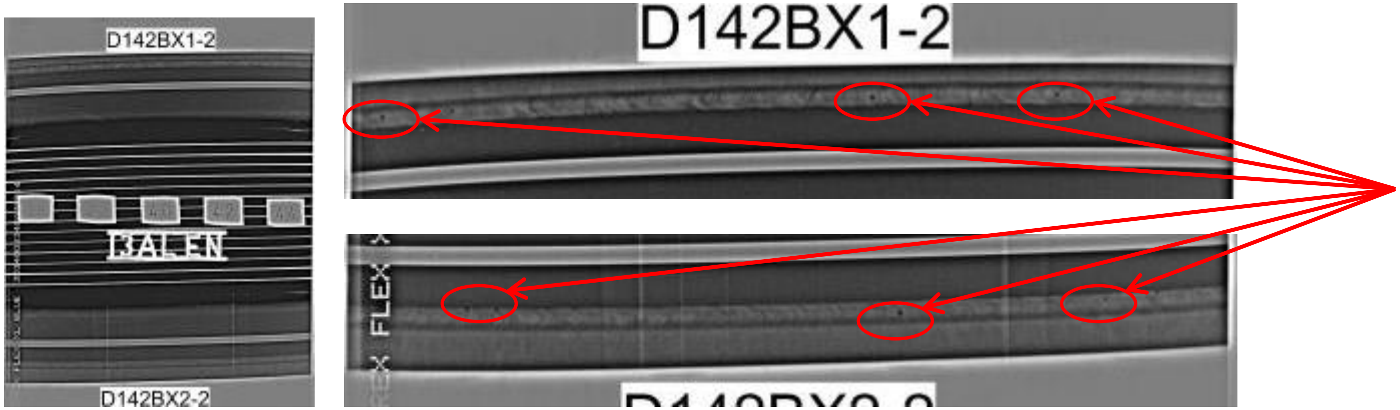
Aluminum alloys

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 in EB welds between 2219 and 5083 for a bellows

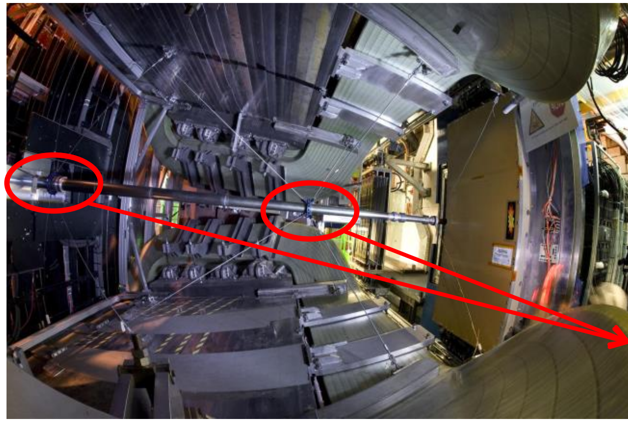
LHC transparent vacuum chambers

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

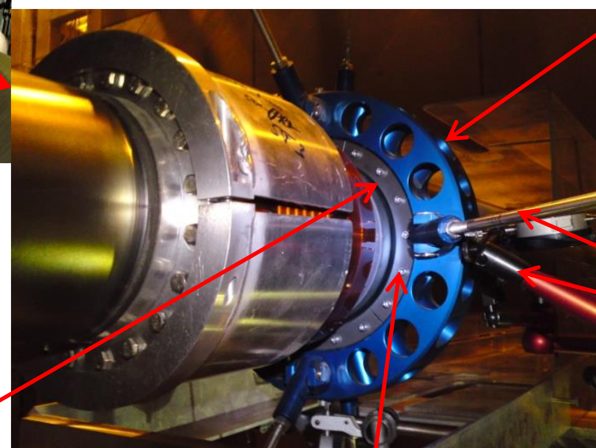
Type	Feature	ATLAS	CMS	LHCb	ALICE
Central	Materials	Be/Al	Be/st.st (Be/Al)	Be/Al	Be/st.st (Be/Al)
	Length (m)	7.3	6.2	1.85	4.82 (5.50)
	Int. dia (mm)	58 (47)	58 (43.4)	50-260	58 (34.4)
	Wall (mm)	0.8	0.8	1.0	0.8
	Configuration	Cyl	Cone/Cyl/Cone	Cone (UX85/3)	Cyl (Cone/cyl/cone)
Forward	Materials	St.st (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)

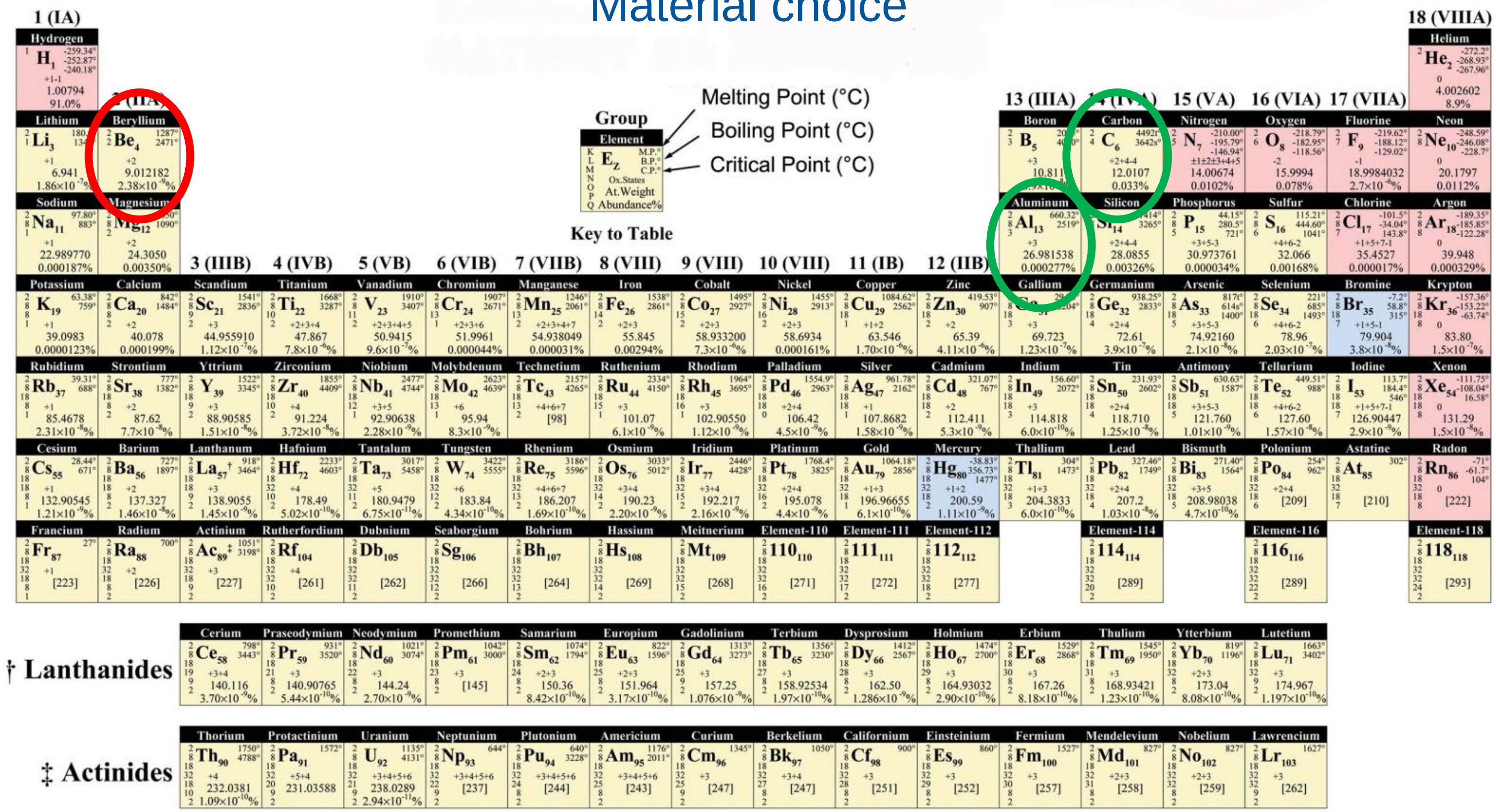
Stainless steel to titanium screws

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.

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

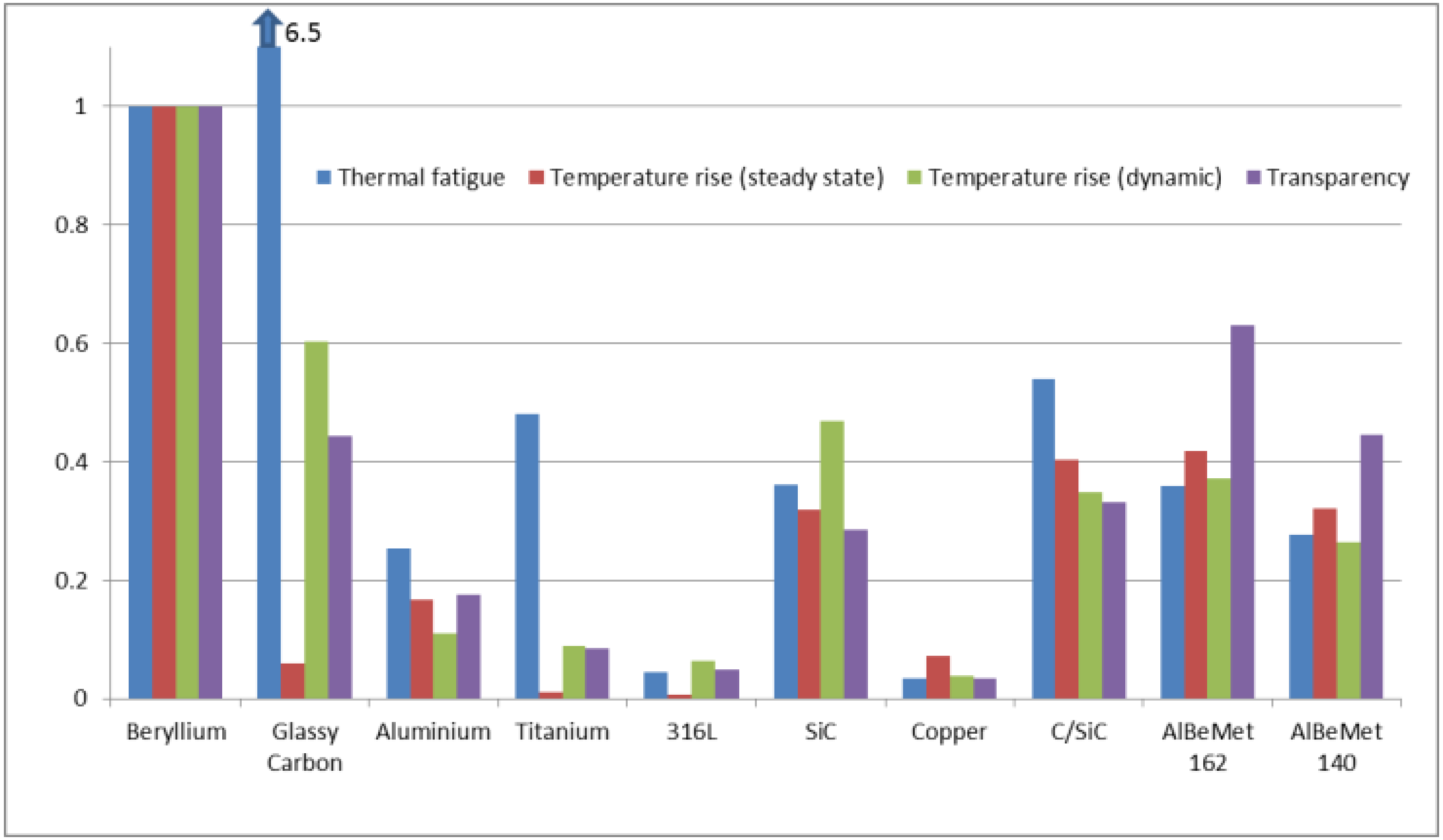
New material development for transparent vacuum chambers

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

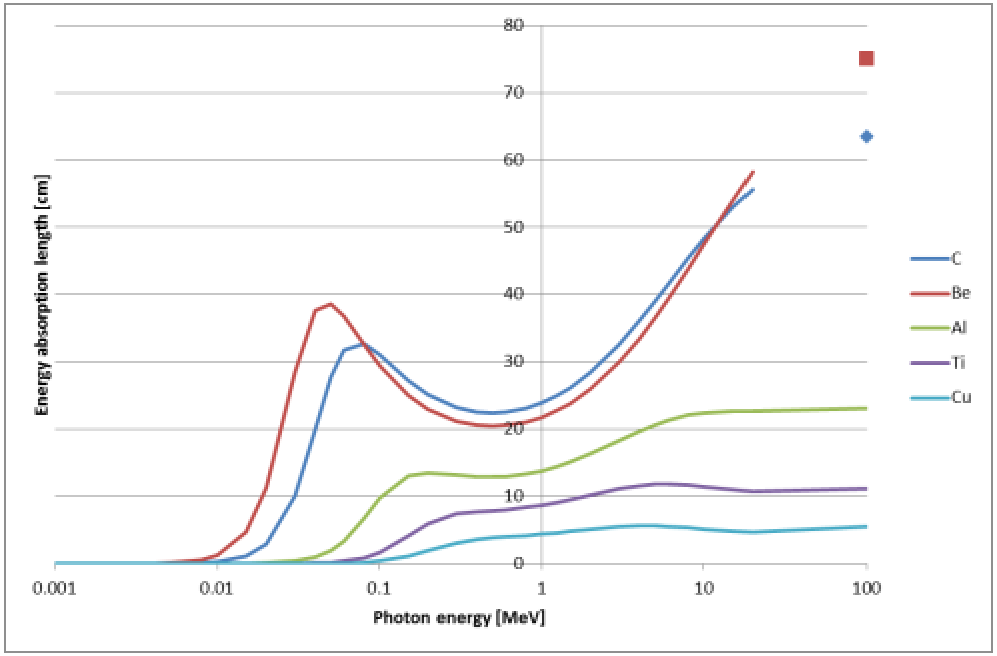
New material development for transparent vacuum chambers

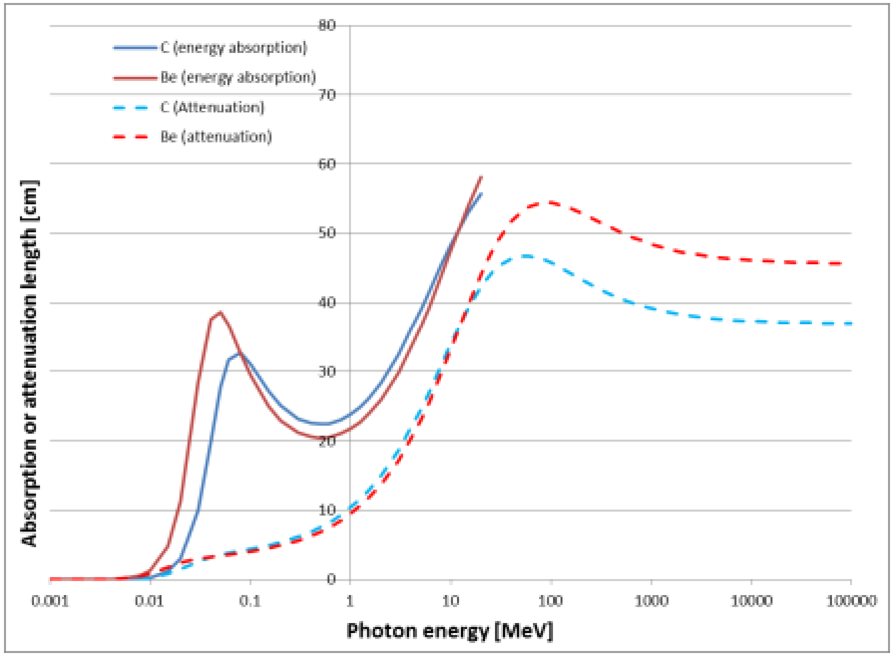
Figure of merit of different materials, normalized w.r.t. beryllium



New material development for transparent vacuum chambers

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:

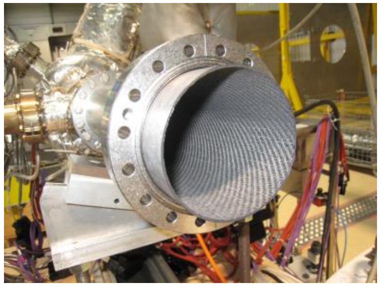
- long fibers
- short fibers
- particulates

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

Internal C/C tube

☺ Good vacuum performance:

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

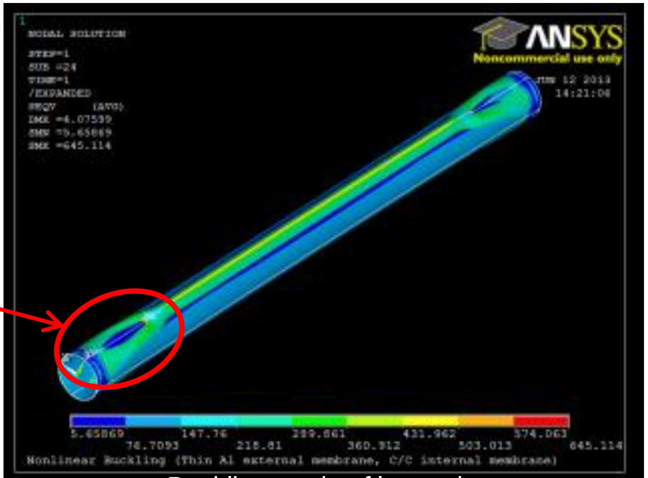
	Activation 200 ◦C for 24h	Activation 250 ◦C for 6h
H_2 Pumping Speed [l/s]	310	530
Sticking probability [-]	$5.9*10^{-3}$	$1*10^{-2}$

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

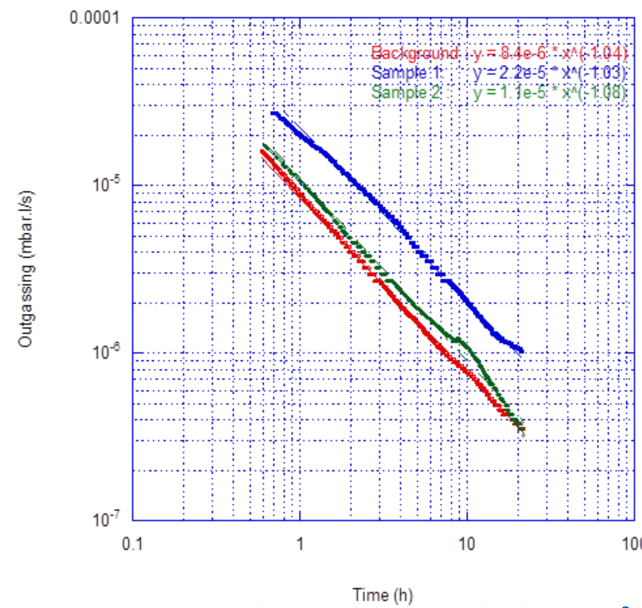
☺ Vacuum tests :

- 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.

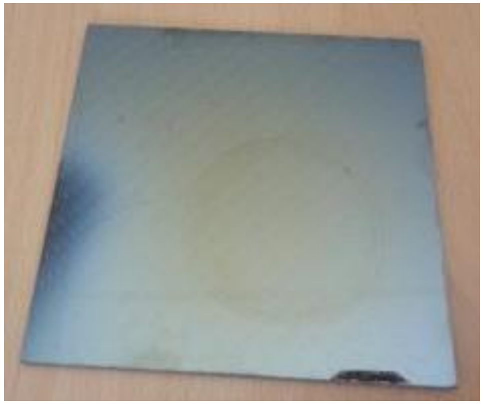


Outgassing of C/Al composite (4.25 cm^2)

→ 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

Defects

Surface observations

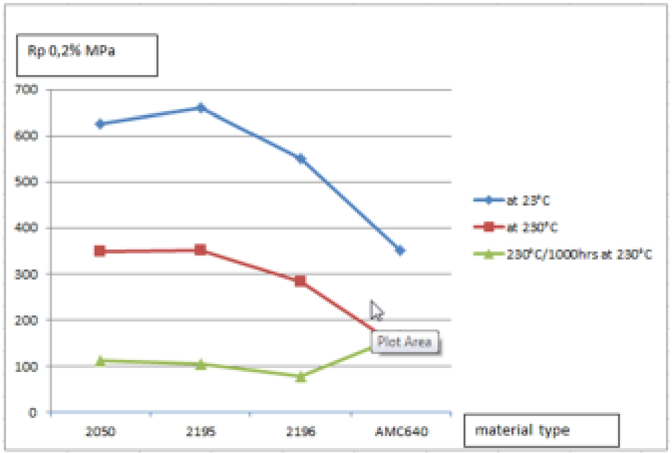
☹ Vacuum tests not successful due to pin holes

→ 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

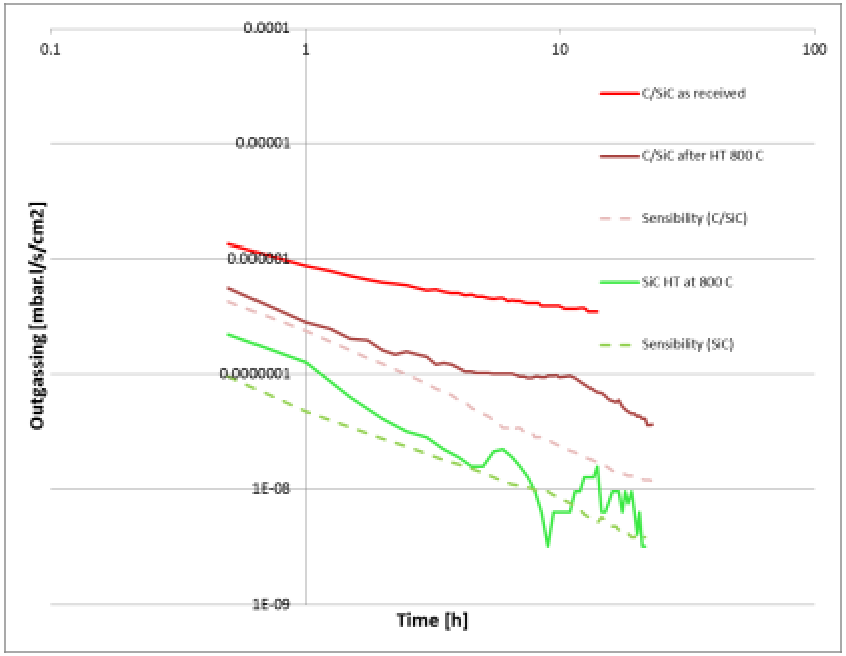
→ Further tests on grades with Lithium
→ Tests on ultra fine grain aluminium alloys

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)



Outgassing curve of SiC materials

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

New material development for transparent vacuum chambers – Glassy carbon

Glassy carbon (GC):

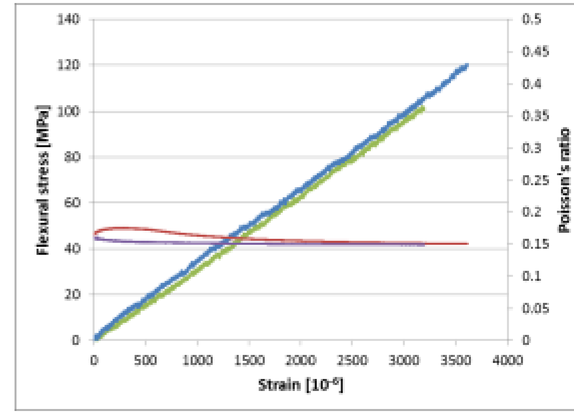
- Obtained by the pyrolysis at high temperature of a highly reticulated resin.
- Two grades have been considered. Grade K is obtained after a heat treatment at 1000 °C whereas 2200 °C is used for the grade G.
- Chemical analyses have been done by EDS. The material is composed of around 98 % (weight) of carbon and 2% of oxygen.

Glassy carbon tube

New material development for transparent vacuum chambers – Glassy carbon

Mechanical properties:

4 points bending test on plates



Elastic properties

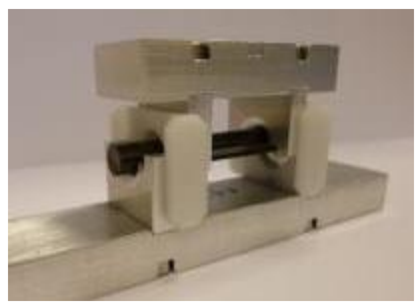
Stiffness:

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

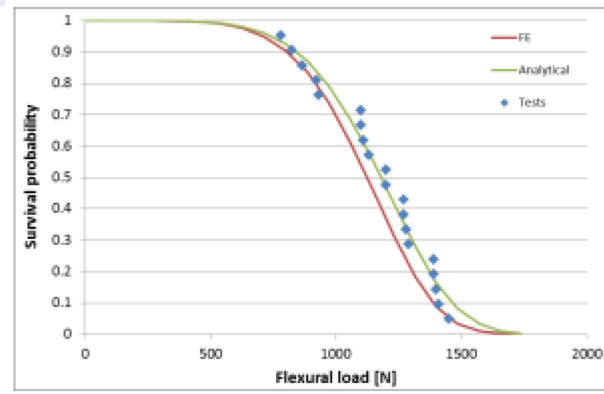
	Young Modulus [GPa]	Poisson's Coefficient
Grade G	32.4 ±0.8	0.155
Grade K	32.5 ±1	0.17

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

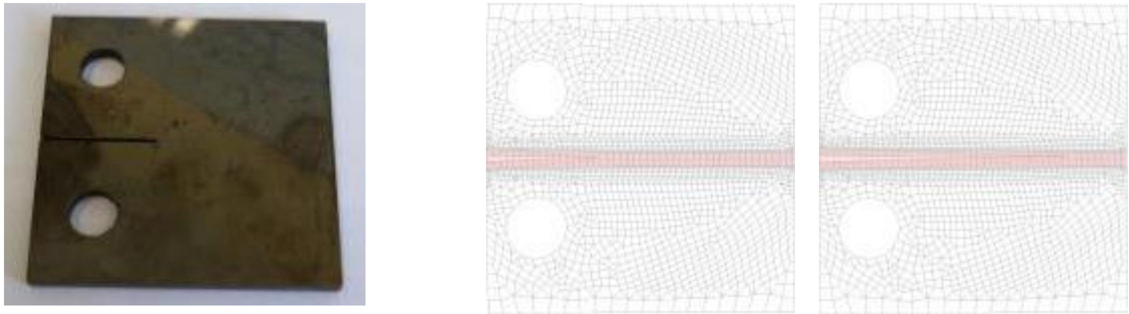
Fracture toughness:

- 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



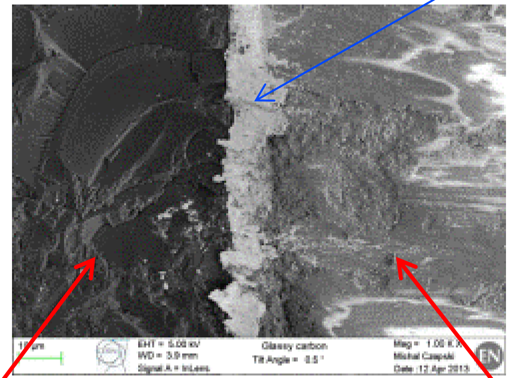
CT specimen and crack propagation simulation

→ 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

GC crucible soldered with a copper ring

Preliminary tests on crucible:

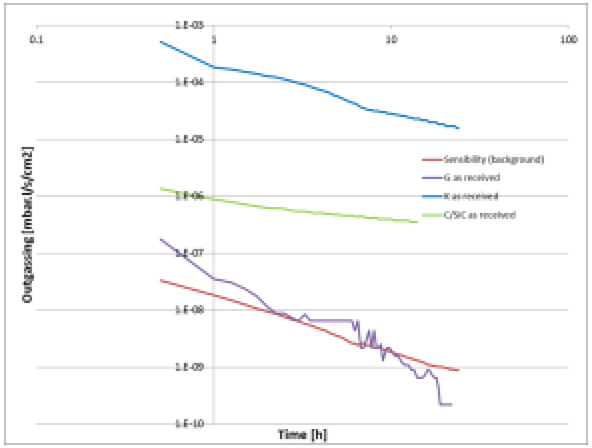
- No failure
- Initial gaps to be adjusted to have a good flow of the solder

New material development for transparent vacuum chambers – Glassy carbon

Outgassing rate:

Unbaked material:

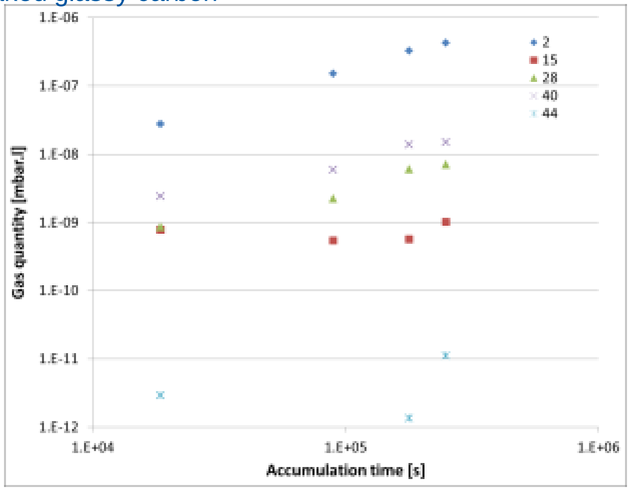
- Throughput method
- Grade K : high outgassing
- Grade G : low outgassing



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}



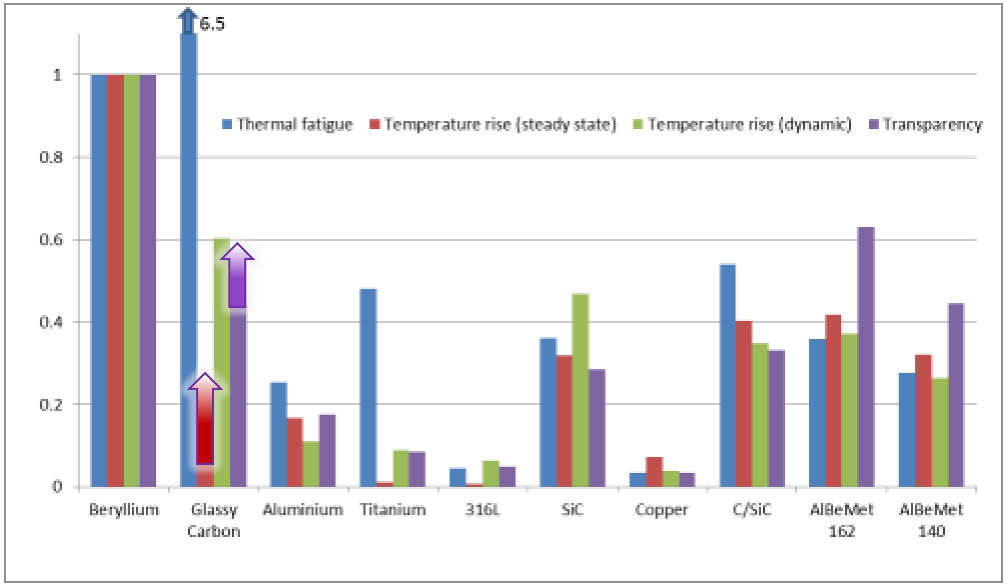
Outgassing of baked glassy carbon

New material development for transparent vacuum chambers – Glassy carbon

Possibility to improvement the material properties:

Reinforcement with carbon nanotubes:

- mechanical properties ↑
- thermal conductivity ↑



Monte Carlo simulations for dynamic vacuum assessment

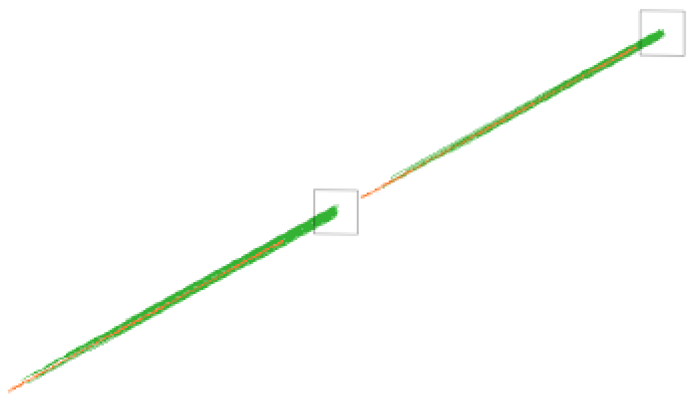
Courtesy M. Ady, R. Kersevan*

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

- Beam parameters: intensity, energy, emittance
- Lattice: Magnetic field distribution and β 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

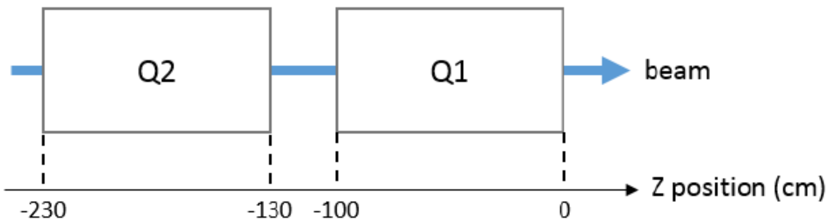
*: CERN-ACC-NOTE-2013-0043

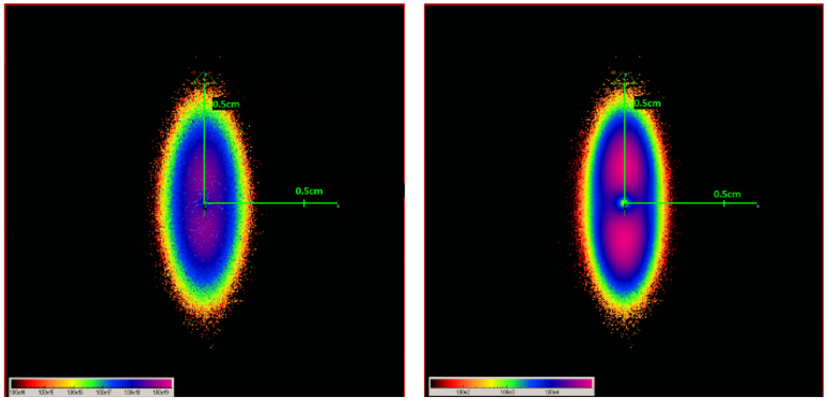
Monte Carlo simulations for dynamic vacuum assessment

Courtesy M. Ady, R. Kersevan

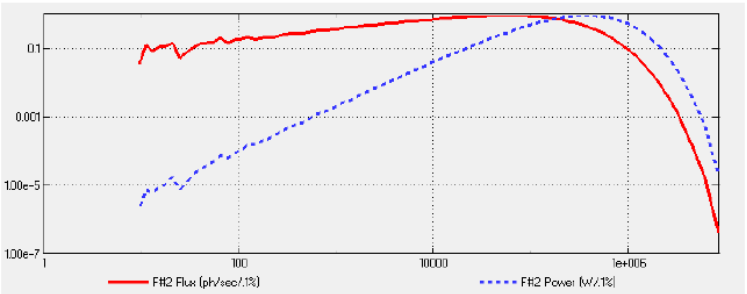
Application to LHeC interaction region:

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 [2]	Geant4 [3]	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} ~ 209 keV

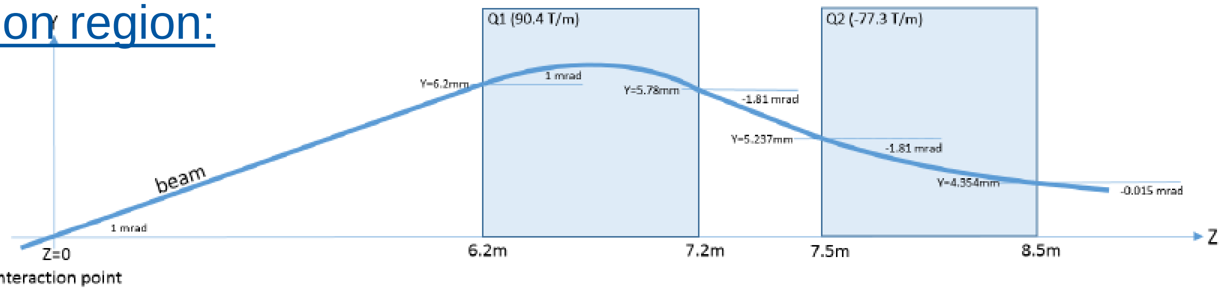
E_{c2} ~ 220 keV

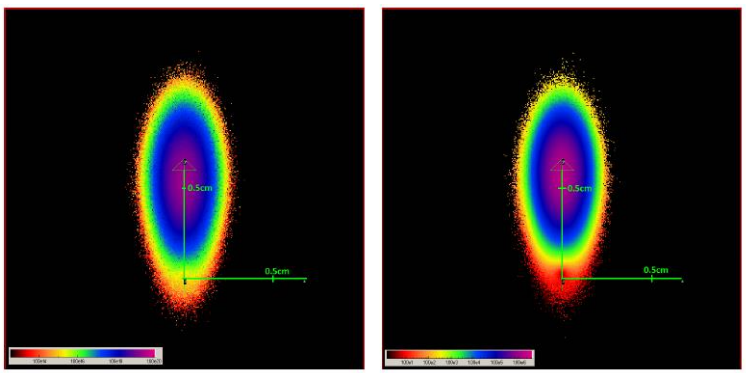
Monte Carlo simulations for dynamic vacuum assessment

Courtesy M. Ady, R. Kersevan

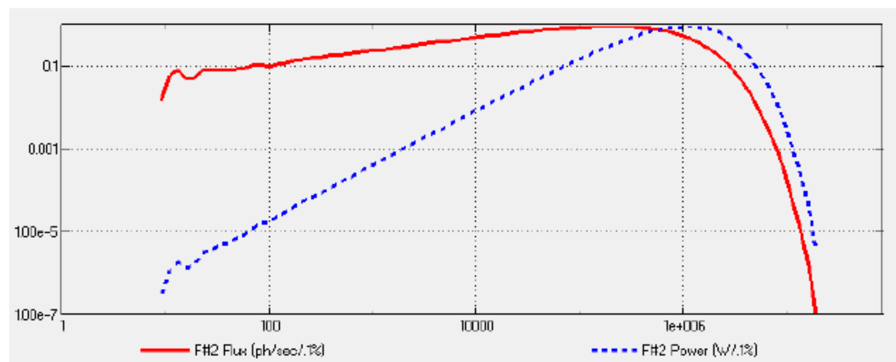
Application to LHeC interaction region:

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} ~ 1.4 MeV
E_{c2} ~ 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 synchroton radiation flux and power distribution.

Thanks for your attention

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