DEVELOPMENT OF GLASSY CARBON BLADE FOR LHC FAST VACUUM VALVE

P. Coly, C. Garion, CERN, Geneva, Switzerland

Abstract

An unexpected gas inrush in a vacuum chamber leads to the development of a fast pressure wave. It carries small particles that can compromise functionality of sensitive machine systems such as the RF cavities or kickers. In the LHC machine, it has been proposed to protect this sensitive equipment by the installation of fast vacuum valves. The main requirements for the fast valves and in particular for the blade are: fast closure in the 20 ms range, high transparency and melting temperature in case of closure with beam in, dust free material to not contaminate sensitive adjacent elements, and last but not least vacuum compatibility and adequate leak tightness across the blade. In this paper, different designs based on a vitreous carbon blade are presented and a solution is proposed. The main reasons for this material choice are given. The mechanical study of the blade behaviour under dynamic forces is shown.

INTRODUCTION

Problem

During an unexpected gas inrush in a vacuum chamber, a pressure wave develops with a velocity of ~ 1000 m/s for room temperature system [1-5] or 35 m/s for a cold system [6]. This value is based on observations done during the 3-4 incident. The pressure wave carries small particles [7] that can compromise the functioning of sensitive machine systems such as the RF cavities or kickers.

It has been proposed to protect these elements by the installation of fast vacuum valves in these areas. The main requirements for the fast valves and in particular for the shutter are:

- Fast closure in the 20 ms range;
- Transparency and high fusion temperature in case of closure with beam;
- Dust free to not contaminate sensitive adjacent elements;
- Vacuum compatibility and leak tightness (in the range 1 mbar.l/s).

Pendulum type fast valves have been developed for the LEP for which titanium material has been used for the blade.

Material choice

Given the transparency requirement for the shutter, few options have been considered:

- Beryllium;
- Carbon fiber reinforced carbon matrix composite ;
- Amorphous carbon.

Several criteria have been drawn up and a ranking have been done (Table 1).

Table 1: Material choice

	Beryllium	C/C composite	Glassy carbon
Transparency	1	2	2
Temperature of fusion	3	1	1
Dust	1	3	1
Leak tightness	1	3	1
Mechanical strength	1	2	2
Fracture toughness	2	1	3
Hazard risk	3	1	1
Cost	3	1	2
Availability	3	1	1
Total	18	15	14

If all criteria are equally pondered, it turns out that glassy carbon fulfils all main criteria and is a good candidate. Moreover, beryllium represents a risk in case of an unexpected closure of the valve that could induce the sublimation of beryllium.

The glassy or vitreous carbon is a pure carbon material obtained by high temperature pyrolysis of thermosetting resins such as phenolic resin, furan resin. The physical properties include low density, chemical inertness, thermal stability, isotropic behaviour [8]. The main mechanical properties of glassy carbon are presented in Table 2 [8, 9].

Table 2: Mechanical properties of glassy carbon

Young modulus [GPa]	35
Poisson's ratio	0.15
Density	1.42
Dilatation coefficient [10^{-6}/K]	3.5-2.6
Yield stress [MPa]	260 (bending)
Fracture toughness [MPa.m$^{1/2}$]	1.17

DESIGN OF THE GLASSY CARBON BLADE

The blade in a fast shutter is subjected to large dynamic forces that occur during the acceleration and deceleration phases. For an in-plane rotation movement, dynamic specific forces read:

$$\vec{f} = \rho\omega^2 R\overrightarrow{e_r} - \rho\frac{d\omega}{dt}R\overrightarrow{e_\theta} \qquad (1)$$

where ρ stands for the specific mass, R is the distance between the considered point and the rotation center. ω denotes the rotation speed.

The present design is the result of a few iterations. Because of the brittle behaviour of the glassy carbon, stress concentrations (holes or local contact for example) have to be avoided. The actuator motion induces also large contact pressure on the blade. Therefore, it cannot be done in one piece with glassy carbon and an intermediate piece in hard material has to be used. Titanium due its lightness and good mechanical properties has been chosen. Two alternatives have been considered.

The first one is based on a small titanium piece with large carbon based. The interface was done by a dovetail connection (Fig. 1) for which the geometry has been optimised to minimize dynamic stresses.

Figure 1: Dovetail connection between the glassy carbon blade and the titanium support.

A Finite Element analysis has been carried out to estimate the mechanical behaviour and then the limitation during the acceleration and deceleration phases. A 2D model has been used with a plane stress assumption. The nodal forces are obtained by integration over an element. Conservative dynamic motion parameters have been used considering a rotation of 90 ° in 20 ms and that the acceleration and deceleration phases last 0.1 ms. The blade is subjected to a bending moment and a stress concentration is observed in the curvatures (Fig. 2.)

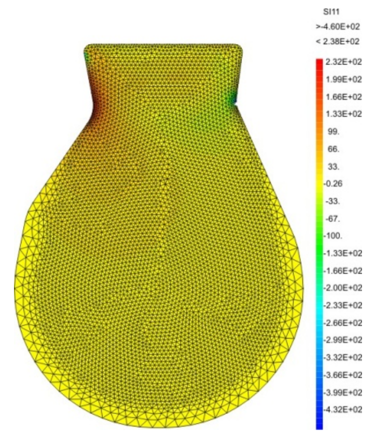

Figure 2: Principal stress field in deceleration for the dovetail geometry.

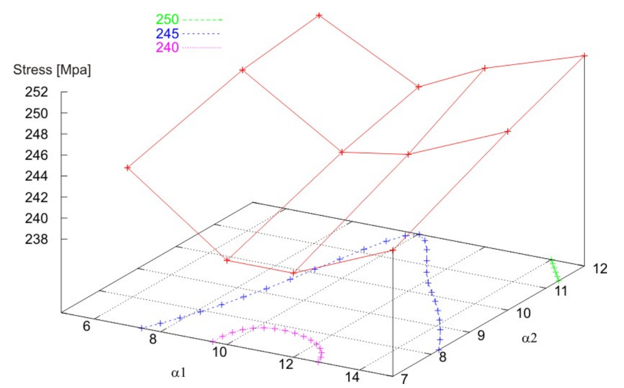

Figure 3: Influence of the dovetail geometry on stress concentration.

Despite this optimisation, the tensile stresses are in the range of 240 MPa (Fig. 3). This would not provide any margin with respect to the yield stress. Considering the fracture toughness of the glassy carbon [4] and a stress intensity factor for a lateral crack, of length a, in a half infinite sheet subjected to a stress σ_∞, given by eq. 2, a crack with a length in the order of 10 µm would be critical.

$$K_I = 1.122\sigma_\infty\sqrt{\pi a} \qquad (2)$$

Therefore a local bounding, that has to be done by brazing to be vacuum compatible, is mandatory to have acceptable dynamic stresses (Fig. 4).

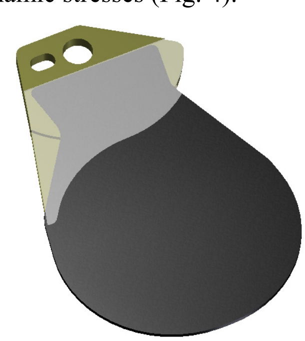

Figure 4: Dovetail connection between the glassy carbon blade and the titanium support.

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Several tests of vacuum brazing of the glassy carbon with other materials (titanium grade 2, molybdenum) have been carried out [10]. It turns out that on one hand the brazing itself on glassy carbon is successful, a good wet ability and adherence have been observed. On the other hand, the thermal contraction discrepancy between the glassy carbon and metals induces large thermal stresses during the cool down and leads often to a crack in the glassy carbon bulk (Fig. 5). This make process is very delicate and not reliable enough, especially with this geometry that induces high shear stresses.

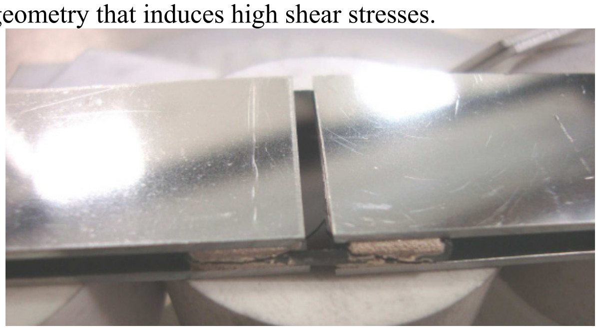

Figure 5: Brazing test of glassy carbon on metals.

The second solution is based on a carbon disc of large diameter to reduce as much as possible the contact pressure induced by the dynamic forces (Fig. 6). In this configuration, the blade is guided on both sides by the valve body. The thickness of the disc and its support is 2 mm.

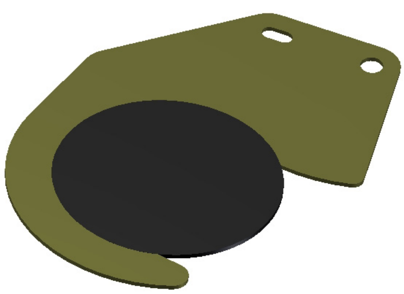

Figure 6: Solution based on a disc in glassy carbon

A non linear finite element analysis has been carried out. It takes into account contact elements between the disc and its support and large displacements. As a comparison the same dynamic motion parameters have been used as for the first solution. Fig. 7 represents the principal stress field.

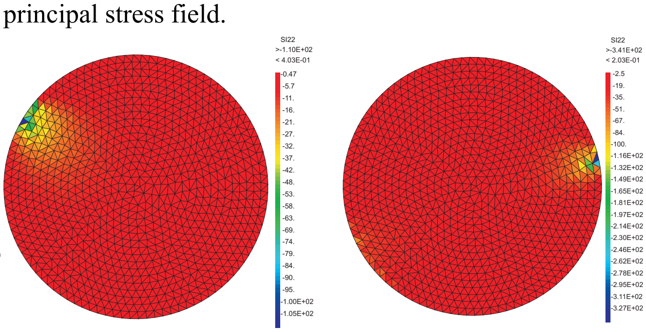

Figure 7: Principal stress field in the disc during the acceleration and deceleration phases.

It is worth to point out that the principal stresses on the disc are mainly in compression, which is much more favourable for brittle material. It turns out that this configuration is more favourable for the use of glassy carbon for fast shutter. This solution will be tested on a real fast vacuum valve.

CONCLUSION

In this paper, the design of a fast shutters blade to be used in the LHC vacuum system has been presented. Such a valve is required to protect sensitive systems against rapid gas inrush and debris propagation. The present retained technical solution is based on a glassy carbon disc trapped in a titanium support. This solution leads to compressive stresses that are convenient for a brittle material, during acceleration and deceleration phases. A test program, based on a valve available on the market, is foreseen to validate the present development:

- Outgassing tests to check the vacuum compatibility of the glassy carbon;
- Leak rate measurement in closed position;
- Mechanical strength with differential pressure of 1 bar (static or dynamic);
- Measurement of the dynamic motion parameters on the valve;
- Optimisation and validation of the design;
- Fatigue tests to estimate the reliability of the solution.

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