Contribution to the Report being prepared as outcome of the External Review of LHC Collimation Project

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Material choice for the jaws (secondary collimators):

The collimator design consists of monolithic carbon-carbon composite or more precisely carbon fibre reinforced carbon composites (C/C) or graphite jaws (1200 mm long for secondary collimators) cooled by OFE Cu bars with embedded pipes clamped against the jaws. The heat sink is brazed to a stiff support bar made of Glidcop and clamping springs are mounted on the back to maintain low thermal contact resistance, while allowing for differential thermal expansion and minimise deformations. Cooling is provided by water (inlet temp. up to 27ºC) flowing at a speed <3 m/s. Accurate positioning of the jaws, in each collimator, is achieved by means of two motors.

The choice of the collimator material is not driven by the continuous losses during nominal operation but by the energy deposition in the collimator jaws during failure scenarios where a large fraction of the beam hits a small fraction of the collimator jaws. Heat deposition simulations for proton losses were performed with the FLUKA code for different scenarios and only C-based materials were found to satisfy the demanding LHC design criteria on robustness in case of failure scenarios. Beryllium is deemed to be very marginal from the mechanical stress point of view. Also, alternative design concepts, which rely on a thin film of Cu (few µm thick) deposited on C-based jaws, to minimize resistive impedance, are considered to be speculative at this stage, mainly because of the uncertainties of the lifetime of the thin film.

C-based materials have been extensively used in magnetic fusion research[1] and a large database exist (for a review see for example Ref. [1] and reference herein). Specific plasma-material interactions and technological issues associated with the development of robust C-based plasma-facing components for ITER and future fusion power reactors are dealt with elsewhere [2-6].

The C-based material currently considered for the jaws of LHC collimator are: 2D C/C composites (e.g., SGL C1001, Tatsuno AC150), isotropic graphite (e.g., SGL R4550). Because of intrinsic limitation in fabrication capability, the current length of jaws of the secondary collimators prevents the use of 3D C/C composites (e.g., SNECMA NB31). Based on considerations of strength and availability, and on calculated deformations under assumed design loads, only AC150 and R4550 are currently retained and are going to be further tested.

[1] Carbon has been the most favoured limiter/divertor material in magnetic fusion research since the early 80's. Carbon has allowed optimization of plasma performance - in combination with oxygen gettering techniques and enabled access to a large machine operational space. In addition C does not melt if overheated - it simply sublimes. During last years, many fusion devices have used more heat resistant C/C composites[1]. However, it is now recognized that C-based materials have substantial drawbacks for next-step burning plasma experiments, i.e., ITER and future reactors. On one hand, chemical erosion (Y ~ 0.1 C/D+), and ability to trap tritium in co-deposited layers provide operation and erosion lifetime concerns. On the other hand, the poor thermal and mechanical properties in a neutron environment (which had been known for many years from operating experience in fission reactor) prevent use of carbon in power producing fusion reactors. This has led to the consideration of alternatives, e.g., Be, and W which are used in ITER with the exception of the area near the strike-points where C is still retained.

Engineering and testing

The engineering concept is sound and robust and the accompanying testing program, part of which is in progress and part is planned, is well thought. The mechanical design allows for differential thermal expansion and minimise deformations. Results of thermo-mechanical analysis were presented on the basis of FLUKA input and assuming known properties data. It should be mentioned that the deformations and stresses of the jaws calculated by the Finite Element Method (FEM) code ANSYS strongly depend on assumed material properties, some of which are poorly characterised. Effect of radiations on material properties adds significant uncertainties on behaviour during normal and off-normal operation (see below). One should try to do some sensitivity thermo-mechanical analyses to better quantify the effects of variations resulting from changes of the thermal and mechanical properties of interest, within the range of uncertainties, and to determine the safety margins. In addition (see recommended work below) material properties have to be measured *in-house* and values provided by the manufacturer must be verified and confirmed prior to fabrication of the components.

The results reported on the heat test carried to investigate the heat transfer of the contact interface between graphite jaw and substrate were in good agreement with numerical predictions. The test must now continue and ensuing deformations should also be measured in addition to temperatures.

Based on available experience from fusion and pending upon results of functional and performance tests in SPS accelerator, it is recommended to manufacture collimator jaws out with C/C composites. Although, it is true that in general the scatter of the C/C composite physical and mechanical properties is larger than that of graphites and the quality of the C/C composites depends strongly on the grade of the materials, C/C are generally stronger and tougher than graphites, yet retain the excellent machinability exhibited by graphites. The presence of the fibres provides a better deformation stability and structural integrity. In general C/C composites have strength properties exceeding those of pyrolytic graphite by factors of 2-3. In addition, graphites (e.g., pyrolytic graphite) exhibit a worse resistance to thermal shocks and a tendency to delaminate under heat flux and large deformations/swelling is observed during irradiation. T

Possible surface degradation and production of erosion debris (e.g., dust) arising from erosion effects induced by energetic particle impact was not discussed. However, some attention must be given in further tests in the SPS accelerator to check whether these effects are observed. Abundant literature on the subjects of sputtering and chemical erosion of C-based materials is available in fusion (see for example [2]).

Effects of radiation:

It is well known that carbon suffer from radiation damage effects. A summary of radiation damage effects in graphite can be found in chapter 7 of Ref. [7]. Most of the properties of interest to the designer, change as a result of irradiation: induced changes in dimensions, thermal expansion coefficient, thermal conductivity and Young's modulus. In this case the use of the material is essentially a design problem, i.e., to utilize the properties to advantage and to accommodate the volume conserving dimensional changes for as long as possible._Issues would be: (1) damage by atomic displacements, and (2) products from nuclear transmutations (e.g., gas which may induce swelling). A lot is known about radiation damage in graphite (mainly by neutrons) because of its use as a moderator in fission reactors. This is now also true for some type of C/C composites, which are of interest in fusion [8-15]. For graphite, collisions produce interstitial carbon atoms, which migrate and agglomerate to form prismatic dislocation loops, or extra basal planes of graphite inserted between the original basal planes. This causes expansion of the lattice along the c-axis and contraction of the lattice perpendicular to the c-axis. In polycrystalline graphite this damage reduces mechanical strength and thermal conductivity. All of these effects have been well characterized and can be related to the amount of damage often characterized by the number of displacements per atom (dpa), although effects depend on the type of graphite and microstructure. The major difficulty here is the accuracy with which the displacement damage A and dA/dt can be calculated for the conditions of interest. An *ad-hoc* evaluation of the damage must be seriously carried out, and compared with theory. Only when this information is available, it will be possible to estimate the longevity of the collimator jaws.

Recommendations for further work

The following recommendations are made:

- A proper material properties characterisation program must be put in place to measure material properties (physical, thermal, mechanical) to check data provided by the manufacturer before procurement. This should be done for samples coming from different material batches. The critical properties to be considered include thermal conductivity properties, thermal expansion, Young's modulus, mechanical strength, coefficient of thermal expansion, etc.

- Pin down effects of radiation damage in graphite. Evaluate (by theory and possibly by experiments) damage i.e., dpa as a function of operation time and irradiation temperature, and products from nuclear transmutations (e.g., gas, which may induce swelling). This is issue is now recognised and a collaboration with experts from the Kurchatov Institute of Moscow has been initiated. Nevertheless it is recommend that a backup plan be developed and that also BLN and FNAL be consulted.

- It is also recommended to conduct further thermo-mechanical calculations of the collimator by reducing the length of the carbon part of a jaw of a factor of 2. Evaluate dimensional stability during normal operation and fault operation.

- Some attention must be given in further tests of jaws performance in the SPS accelerator to check whether macroscopic effects of sputtering and chemical erosion of the jaws are observed and they lead to the formation of visible debris.

- Cooling issues: the velocity of water in cooling circuits should be in the range of 1÷2m/s. If higher nominal velocities are required, particular attention should be paid to the risk of erosion-corrosion. Use of Glidcop instead of OFE copper would mitigate the problem.

- Evaluate shielding requirements to protect most sensitive components (e.g., cabling. motors).

- Develop detailed maintenance procedure for servicing and exchanging collimators.

- Quantify radiation effects on metal springs and motors and implication on operation and maintenance.

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