PERMANENT DEFORMATION OF THE LHC COLLIMATOR JAWS INDUCED BY SHOCK BEAM IMPACT: AN ANALYTICAL AND NUMERICAL INTERPRETATION

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Abstract

Inspections carried out on jaws of the LHC collimator prototype, which underwent the 450 GeV robustness test in CERN TT40 extraction line, revealed no visible damage, except a permanent deformation of the jaw metal support of ~300 μm. An explanation of this phenomenon is proposed in this paper. The temperature increase on the metal support induced by the thermal shock, though limited to ~70ºC, led to a sudden expansion of the copper-based support which was partially prevented by the inertia of the material itself, thus generating compressive stresses exceeding the elastic limit of OFE-copper. An analytical assessment of the process, followed by a finite-element transient elasto-plastic analysis, is presented. Numerical results are in good agreement with measured data. In order to confirm this analysis, a special test on jaws from the series production, where OFE-copper has been replaced by Dispersion Strengthened Copper (Glidcop®), is scheduled for the second half of 2006.

INTRODUCTION

The design of the LHC collimators must comply with the very demanding specification entailed by the very high intensity beam handled in the accelerator.

On top of the extreme dimensional stability expected in normal operation conditions, functional requirements specify that, in the event of irregular proton losses (accident cases), the collimators must withstand, without any failure or permanent damage, the mechanical loads induced by the thermal shock, to protect the machine from the destructive effects of the beam [1].

The bulk of the complex Phase I collimation system in the two LHC cleaning insertions is essentially made up by primary and secondary collimators [2]: the most critical elements of both these objects are the collimating jaws, made of 2-dimensional Carbon/Carbon composites (C/C) [3]. These jaws were designed so as to survive the accident scenarios as defined by the functional specification [4]. One of the most critical cases is the injection error, which may lead to the impact on the C/C jaw of a full batch at 450 GeV (3.2×10^{13} protons over 7.2 μs), with transverse amplitudes up to 5-6 beam sigmas.

ROBUSTNESS TEST

In order to validate the collimator design, a robustness test was specially devised and carried out in the TT40 extraction line of CERN's SPS accelerator in autumn 2004 on a fully operational prototype of a secondary collimator (Figure 1), with the highest beam intensities then available at CERN [5].

Test Conditions

Each of the two prototype jaws were submitted to a series of impacts at 450 GeV in two different conditions: (1) with increasing beam intensities at fixed beam impact depth of 5mm from the jaw surface and (2) with beam impact depths from 1mm to 6mm at a beam intensity of 3.2×10^{13} protons. For material comparison, one of the jaws was in C/C (as for the series production), while the other was made of isotropic graphite.

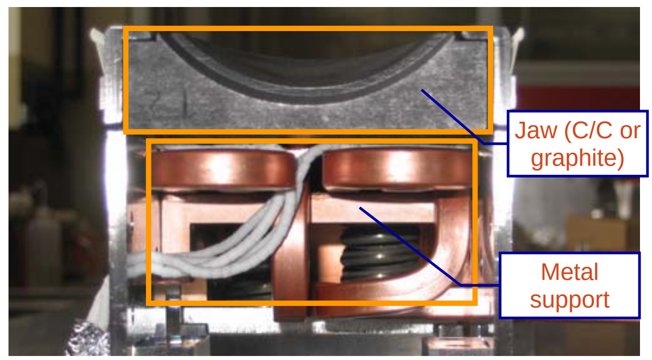

Figure 1 Front view of the collimator jaw assembly showing the carbon jaw and the metal support

Test results

Data acquisitions during the tests and preliminary visual inspections immediately after gave evidence of no permanent damage to the collimator jaws. More in-depth analyses, carried out on the disassembled prototype after it had attained safe levels of radiation, confirmed that no damage had occurred to the jaws, with their flatness remaining unaffected, in line with previous computations.

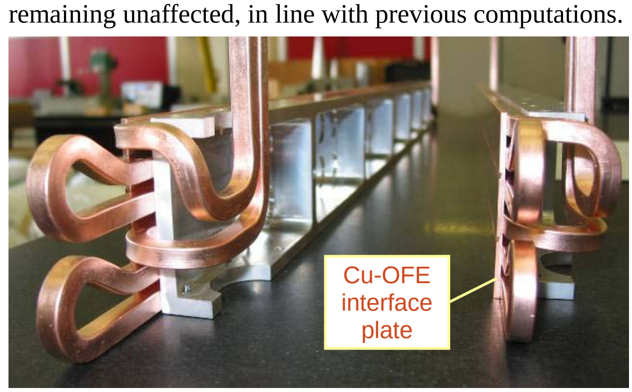

Figure 2: Collimator prototype metal supports (~1m long), showing the stainless steel support bar, the cooling pipes and the 3 mm-thick interface Cu-OFE plate

Yet, measurements performed on jaw assemblies and metal supports (Figure 2) revealed a permanent deformation of the metal support of up to 280 μm, with a well repeated pattern (maximum deflection is found toward that end of the support where highest temperatures are measured - Figure 3).

The metal support is a brazed sandwich structure, encompassing the main support bar, the cooling pipes and a 3mm-thick interface plate. In the robustness test prototype, the support bar was in stainless steel (as opposed to Dispersion Strengthened Copper - Glidcop® - for the series production), the cooling pipes and the interface plate were in OFE-Copper.

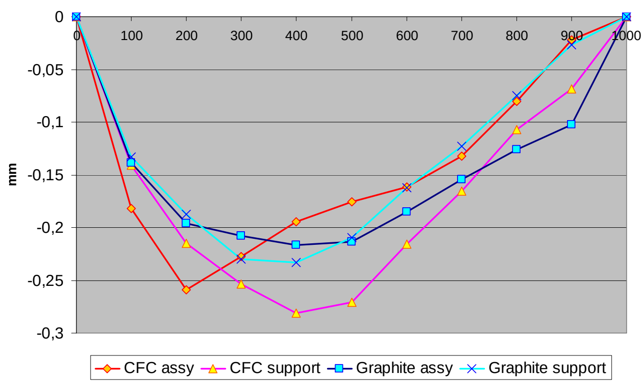

Figure 3: Permanent deformation of the jaw assemblies and metal supports as a function of the length (1000mm)

THERMO-MECHANICAL ANALYSIS

Analytical approach

An explanation of the permanent deflection can be conjectured on the basis of the thermo-mechanical phenomena occurring in solids in case of very fast heating. It is well known that, even if the structure is free to expand, when the heating process is shorter than the typical stress relaxation time (given by *L/c* where *L* is the typical dimension and *c* the speed of sound in the solid medium), stress waves arise as material inertia partially prevents the free thermal expansion (see e.g. [7], [8], [9]).

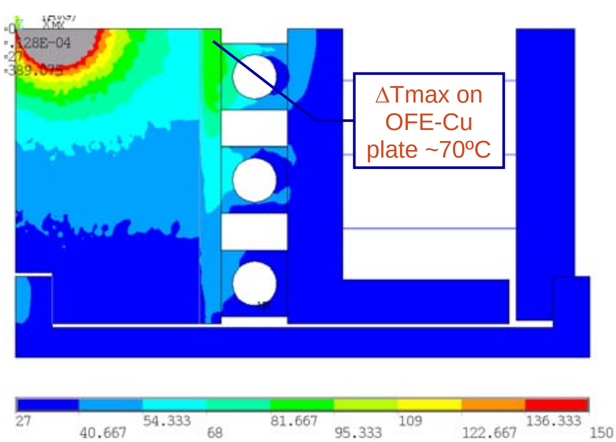

Figure 4: Temperature distribution after the thermal shock at the hottest cross-section of the jaw assembly

Thermal simulations of the injection error accident case [4], gave a maximum temperature increase at one end of the interface plate limited to roughly 70º C (Figure 4): based on previous explanation (thermal shock duration τ is 7.2 μs, speed of sound for copper is ~4500 m/s), we should expect that stress relaxation is no longer possible at more than ~35mm from one free end: from this point onward the behaviour can be reduced to that of a plate for which axial expansion is impossible (clamped plate). If we further assume that the temperature distribution does not change over the last 35 mm, we can easily obtain the linear elastic compressive thermal stress of a thin plate as:

$$\sigma_z^{lin} = -\frac{E\alpha\Delta T}{1-\nu} \cong -210\,MPa$$

Where E is the Young's modulus (117 GPa), α the coefficient of thermal expansion ($17\text{x}10^{-6}$ K^{-1}), ν the Poisson's ratio (0.345) for OFE-copper.

It can be immediately seen that the above stress magnitude is much larger than the proportional limit of annealed copper (50÷70 MPa – we assume here that tensile and compressive behaviours are symmetric): hence plastic strains will be present when stresses disappear. These residual strains, compressive in our case, are eccentric with respect to the neutral axis of the metal support and will lead to a permanent deflection sagged at the copper plate side, as in the prototype jaws.

Numerical analysis

The analytical method allows to qualitatively justify the permanent deflection and its shape; however it is practically impossible to quantitatively estimate the magnitude of the effect. To do so, it is necessary to resort to a complex Finite Element model, including the effects of temperature, contacts, time and plasticity (fast transient, coupled-field, elasto-plastic analysis). Two 3-d ANSYS® models of the metal support and of the whole jaw assembly were prepared, their energy distribution directly obtained from FLUKA simulations on a compatible 3-d model [10]; plasticity in metal parts was modelled both with bilinear and multilinear kinematic hardening. The numerical analyses took many weeks of CPU time, but allowed to obtain very interesting results.

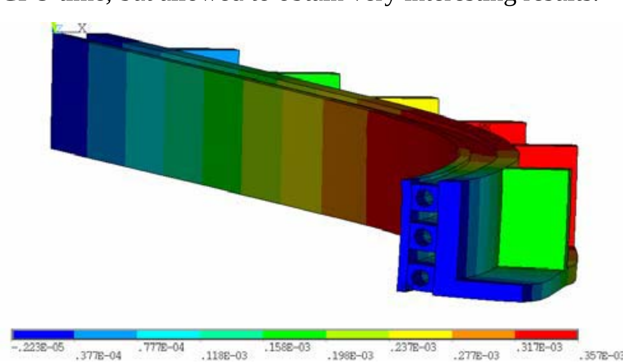

Figure 5 Residual deflection of the prototype metal support (maximum 357μm)

As anticipated by the analytical estimation, the largest residual plastic strains are found on the thin copper plate, their magnitude (up to 0.12%) and extension being compatible with the simplified approach. It is interesting to remark that the rest of the metal structure is only marginally affected by permanent strains and only for the copper pipes.

As shown in Figure 5, the calculated permanent deflection (357 μm) of the metal support is close to the measured values and matches well the actual deformed shape.

On the basis of these results, it was decided to modify the jaw assembly series design by changing the thin plate material from OFE-Copper to the higher yield strength Glidcop (proportional limit >200MPa): an updated model of the series jaw assembly (including Cu-Ni pipes and Glidcop support bar) gave a permanent deflection of 16 μm. This improvement is essentially due to the fact that plasticity is no longer attained on the thin plate and only occurs on a limited portion of the Cu-Ni pipes.

Another interesting outcome of the transient computations is the amplitude of the transverse oscillations occurring during the shock: as shown in Figure 7 the maximum deflection at the centre of the C/C jaw reaches up to 1.4 mm after ~12 ms; it is also worth noting that, during the transient, the ends of the jaw may depart from the support by as much as 1.3 mm.

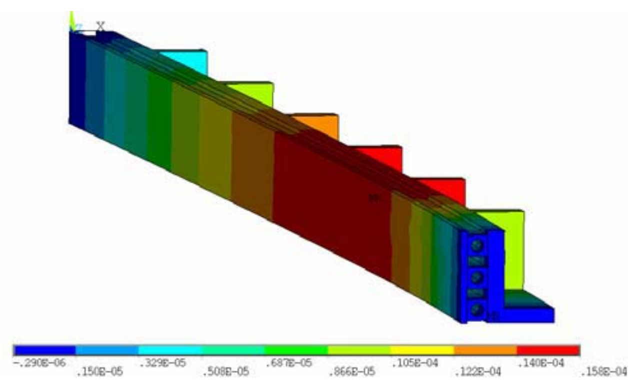

Figure 6 Residual deflection (maximum 16 μm) of the modified series metal support (Cu-Ni pipes, Glidcop support beam and thin plate)

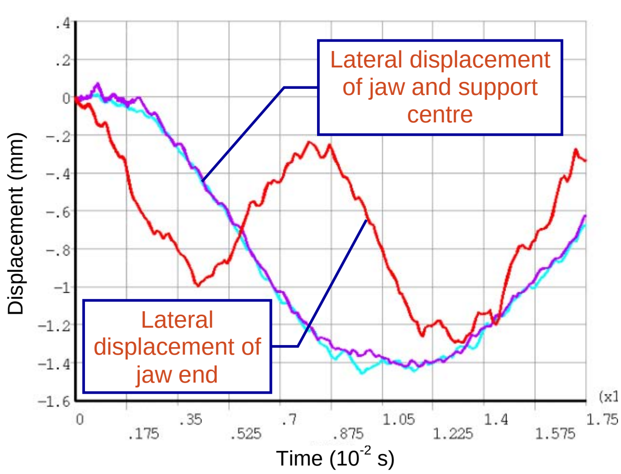

Figure 7 Time history of deflection of the centre and the ends of the C/C jaw for the series secondary collimator

CONCLUSIONS

After the robustness tests on a collimator prototype carried out in CERN's SPS accelerator, measurements confirmed that no damage had occurred to the carbon jaws; however a permanent deformation of almost 300 μm was found on their metal support. Analytical and numerical studies were launched to understand the issue. This phenomenon is most likely explained by the fact that compressive plastic strains were induced in the OFE-Copper plate of the support, which in turn provoked an unbalanced permanent deformation of the whole metal structure. Both analytical and numerical approaches confirmed this hypothesis: in particular, complex Finite Element simulations on a model of the prototype showed permanent deformations which compare well with the measured ones. Therefore, it was promptly decided to replace the OFE-copper with higher strength Dispersion Strengthened Copper (Glidcop®), obtaining calculated residual deflections (16 μm) within the admissible limits.

Nevertheless, given the complexity and difficulty of the numerical assessment and the importance of the topic, it has been decided to perform additional robustness tests on a series jaw assembly to confirm and validate this analysis. These tests will be carried out before the end of 2006.

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