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NUMERICAL SIMULATIONS OF TUNGSTEN TARGETS HIT BY LHC PROTON BEAM

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Abstract. The unprecedented energy intensities of modern hadron accelerators yield special problems with the materials that are placed close to or into the high intensity beams. The energy stored in a single beam of LHC particle accelerator is equivalent to about 80 kg of TNT explosive, stored in a transverse beam area with a typical value of 0.2 mm×0.2 mm. The materials placed close to the beam are used at, or even beyond, their damage limits. However, it is very difficult to predict structural efficiency and robustness accurately: beam-induced damage for high energy and high intensity occurs in a regime where practical experience does not exist. The interaction between high energy particle beams and metals induces a sudden non uniform temperature increase. This provokes a dynamic response of the structure entailing thermal stress waves and thermally induced vibrations or even the failure of the component. This study is performed in order to estimate the damage on a tungsten component due to the impact with a proton beam generated by LHC. The solved problems represent some accidental cases consequent to an abnormal release of the beam: the energy delivered on the components is calculated using the FLUKA code and then used as input in the numerical simulations, that are carried out via the FEM code LS-DYNA.

1 INTRODUCTION

The LHC [1,2] is a circular accelerator with a 26.659 km circumference situated at the border between Switzerland and France at an average depth of 100 m underground. This machine mainly provides the collision between two counter-circulating proton beams. At the design operating condition, each proton beam consists of 3×10^{14} protons at 7 TeV, so when the protons collide the collision energy is 14 TeV. The beam has 2808 bunches each having 1.11×10^{11} protons. The bunch length is 0.5 ns and the time between two successive bunches is 25 ns, so the duration of the entire beam is about 72 μs.

The total energy stored in each beam at maximum energy is about 350 MJ: this is enough energy to melt 500 kg of copper. This large amount of energy is potentially destructive for

accelerator equipments having direct interaction with particles (e.g. the collimation system) in case of uncontrolled beam loss, so everything is done to ensure that this never happens. Besides, it is important to know what will be the damage in case of the LHC malfunction. It is in this perspective that a thermo-mechanical analysis becomes relevant. However, it is very difficult to predict structural efficiency and robustness accurately: beam-induced damage for high energy and high intensity occurs in a regime where, nowadays, practical experience does not exist. For now the importance of developing a reliable multidisciplinary methods (physics, hydrodynamics and structural engineering are involved) and accurate models that could be efficiently applied to estimate the damage occurring during an impact is therefore evident.

The interaction between high energy particle beams and solids can be considered from a structural point of view as an energy deposition inducing a sudden non uniform temperature increase. In function of which part of material is investigated the behaviour is different (Figure 1). In the material part closest to the beam, the pressure and temperature increase and the material could arrive at its melting temperature or vaporize. The material response in this condition is correctly described only using an equation of state that is able to describe the hydrodynamic behaviour, while in this portion of material the deviatoric stress is totally negligible. On the other hand, the remaining part of the material is characterized by high values of plastic strain, strain-rate and temperature, so the response is related with the strength material model used.

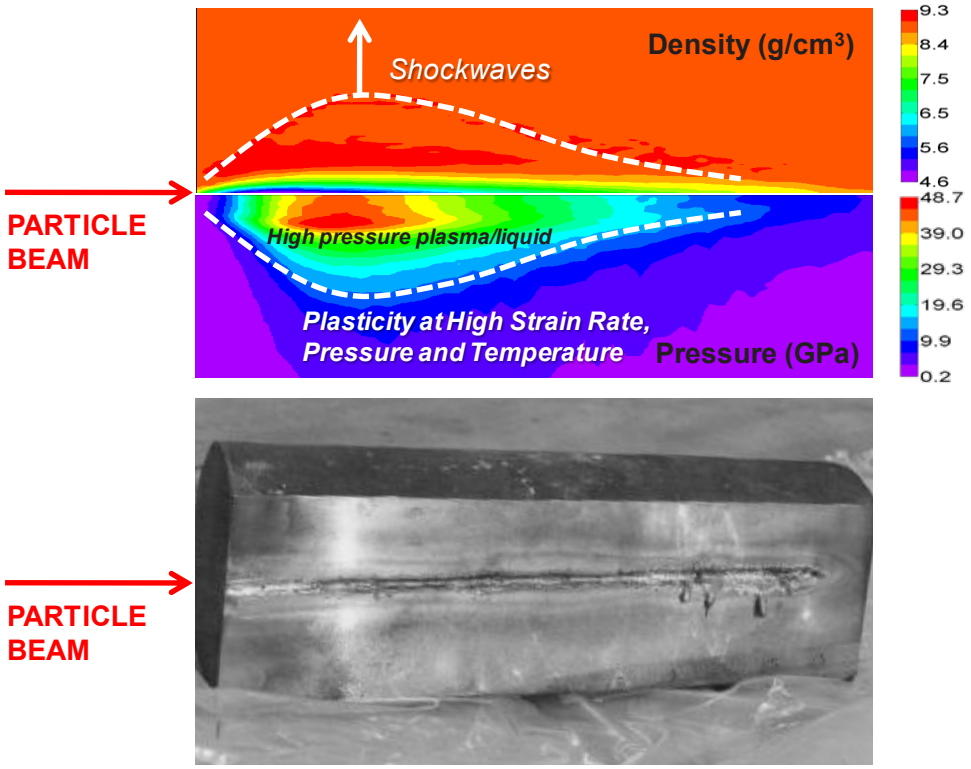

Figure 1: high energy particle beam impact effects on a metal structure

From these considerations it is clear what is the complexity of the problem: in order to correctly simulate the thermo-mechanical response of the hit material it is needed to take into

account both the hydrodynamic behaviour using a dedicated equation of state (EOS) and the deviatoric behaviour using a dedicated material model.

The numerical simulations are performed using the commercial FEM code LS-DYNA [3]. For the simulations the chosen equation of state is a polynomial EOS, in which the coefficients are obtained fitting a three-phase tabular equation of state, and the material model is the Johnson–Cook model.

The evaluation of thermal loads on the hit material is performed using a statistical code, called FLUKA [4], based on the Monte-Carlo method.

As mentioned before, the material involves in such high energy and high intensity impacts operates under extreme conditions, in which the possibility to perform experimental tests is limited. For this reason the importance of developing a reliable methods and accurate models that could be efficiently applied to estimate the damage occurring during an impact is therefore evident.

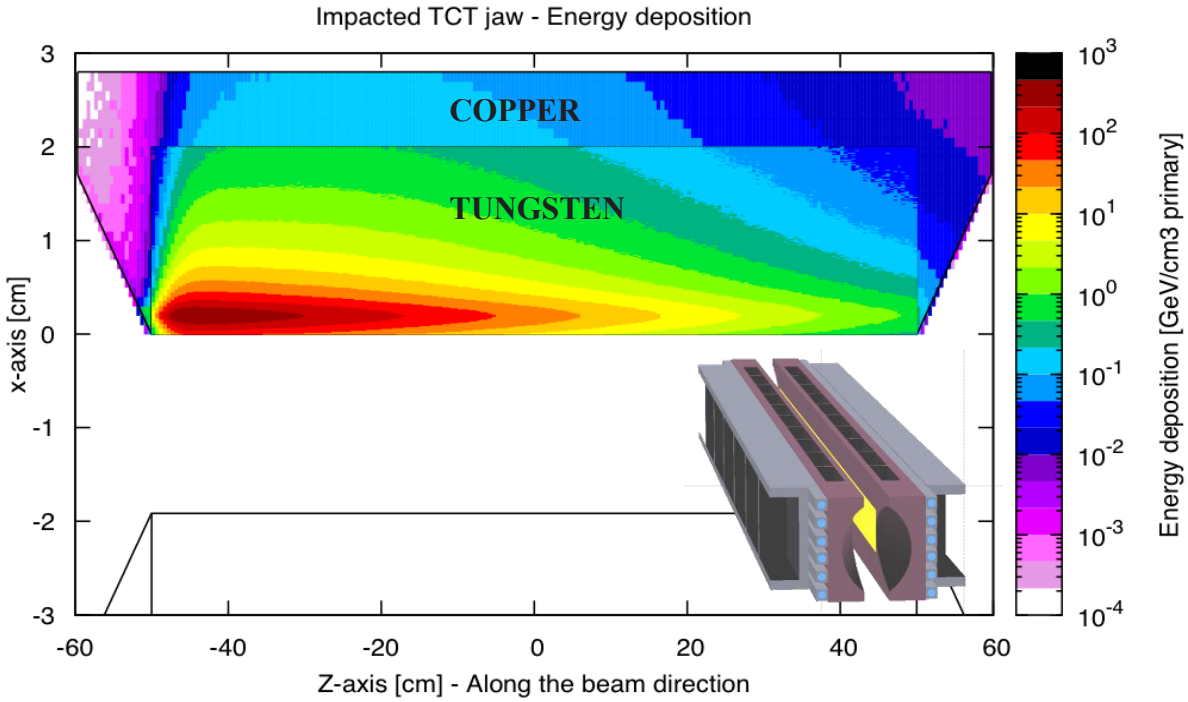

Figure 2: energy distribution (GeV/cm^3) on a tungsten/copper component (TCT collimators jaw) for a single proton at 5 TeV

In case of interaction between a high energy particle (protons) beam and a metallic material three main dynamic response regimes may occur, depending on the deposited energy, the energy density, the interaction duration and the material strength. The first possibility is the case in which the induced stress waves and the vibrations remain in the elastic domain. In this case the deposited energy density is low, the changes in density are negligible and the stress waves travel in the material at the sound speed. On the other hand, for medium energy levels, the stress waves are generated in the plastic domain. This implies the velocity of the waves is lower than the elastic domain speed and there are permanent deformations in the

component also once the load is over. The last case implies that a large amount of energy is delivered on the component. In the matter there is the dawn of shock waves, in which there is a nearly discontinuous change in the characteristic of the medium (pressure, temperature and density). The discontinuity moves with a supersonic velocity and this makes the mass transport phenomenon to be relevant.

In order to correctly simulate the effects of the high energy particle interaction with a solid target, it is necessary to calculate the energy deposition on the component delivered during the impact duration. In this work the calculation is done from the physicists at CERN via the statistical code FLUKA [4]. FLUKA is a fully integrated package for the calculation of particle transport and interaction with the matter, based on the Monte-Carlo analysis with many applications in high energy experimental physics and engineering. The FLUKA result (Figure 2) is the energy map on the same geometry on which the mechanical simulation is performed taking into account all the particles in the cascade generated by the interaction between the proton beam and the target. Finally the FLUKA results are used as input for thermo-structural studies.

2. HYDRODINAMIC AND VISCOPLASTIC BEHAVIOUR

2.1 Equation of state

An equation of state (EOS) is a constitutive relation between state variables and describes the state of the matter. Usually it expresses a thermodynamic variable (such as pressure or internal energy) in function of two other independent state variables (such as density and temperature).

In this work a tabular multi-phase equation of state [5] is used. In particular, solid, liquid, vapour, gas and plasma region are taken into account. In Figure 3 the P-ρ (varying T) and P-E (varying ρ) planes for tungsten are depicted.

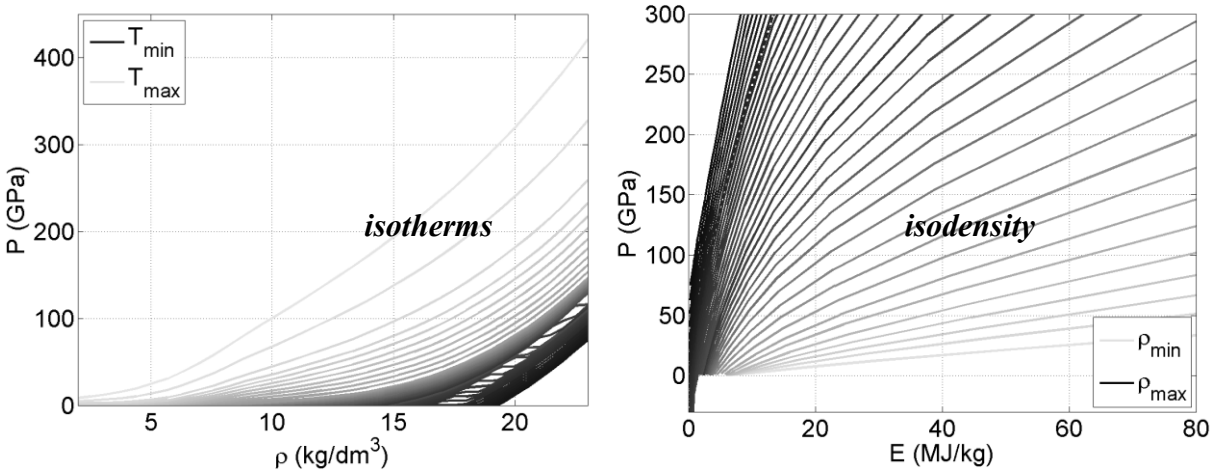

Figure 3: Equation of state for tungsten in the P-ρ (left) and P-E (right) planes for tungsten

Once the energy for the impact of a proton bunch is known, it is possible to understand the consequent material behaviour considering the EOS in the *P-E* plane varying the density (Figure 3). The arrival of the bunch pulse, obviously, modified the precedent matter condition: in particular, there is an increment in the energy of the medium. Since the impact is quite short, it can be considered as an isochoric transformation, so the jump in energy is done along the density curve characteristic of the previous state. This implies a new value in pressure univocally identified from the new energy and density conditions. The global result is that instantaneously the material reaches a different (greater) pressure. This, together with the fact that for this problem different parts of the component are not in the same condition, a shock front is generated: the elements with a high level of pressure rapidly expand into the elements with a low level.

2.2 Material model

In past decades a lot of material models for the description of the visco-plasticity in metals are proposed. The Johnson-Cook (J-C) model [6] is a purely empirical model; an example of semi-empirical model is the Steinberg-Cochran-Guinan-Lund model, which was first (S-G) developed for the description of high strain-rates behaviour [7], and after (S-L) extended to low strain-rates [8].

A first set of simulations is carried out with the J-C [6] model because also if it very simple it is able to predict the mechanical behaviour of the materials under different loading conditions. Besides, it is one of the most used material model, so it is implemented in many FEM codes and it is quite easy to find the values of J-C parameters for different materials. Nevertheless, the J-C model is quite inaccurate to describe the material behaviour in case of high pressure conditions and extremely high strain-rates. The J-C values are usually obtained in a range of strain-rate lower than 10^5 s^{-1} and could overestimate the strain-rate sensitivity for strain-rate $\geq 10^5$ s^{-1}. As a matter of fact, it neglects the influence of the pressure and changes in volume on the flow stress and it considers the melting temperature as a constant, while the solid-liquid transition is influenced by the density.

In this work, a more suitable model is used: the S-G material model [7] in which the strength material characterization is controlled by the equations

$$\begin{aligned} \sigma_y &= \sigma_A \, G/G_0 \\ \sigma_A &= \sigma_0 \left[1 + \beta\left(\varepsilon_{pl,i} + \varepsilon_{pl}\right)\right]^n \leq \sigma_{\max} \\ G/G_0 &= \left[1 + bPv^{1/3} - h\left(T - 300\right)\right] \\ T_m &= T_{m0} \exp\left[2a\left(1 - v\right)\right] v^{-2\left(\gamma_0 - a - 1/3\right)} \end{aligned} \tag{1}$$

in which both the flow stress and the shear modulus are function of temperature, strain and also pressure, v is the relative volume, b and n are the work-hardening parameters and $\varepsilon_{pl,i}$ is the initial equivalent plastic strain, normally equal to zero. The subscript 0 refers to the condition in which T=300 K, P=0 and ε=0, the reference state. b and h are proportional to the derivative of the yield stress respect to the pressure and to the derivative of the shear modulus respect to the temperature, respectively. As in the J-C model, if the temperature overcomes

the melting temperature then the material strength goes to zero, but differently from the J-C model, the melting temperature is not constant but is a density function. The S-G model is strain-rate independent, according to the fact that for strain-rates greater than 10^5 s^{-1} the rapid decrease of rate dependent effects with increasing dynamic stress may be explained by the increase in temperature with increasing stress [7]. This assumption is reasonable in case of FCC material, but could be inaccurate in case of BCC materials [8].

4. BENCHMARKING

The numerical simulations are performed via the commercial code LS-DYNA. The validation of the numerical results is performed on a simplified geometry: a cylindrical bar (radius of 10 mm and length of 1 m) facially irradiated by 8 bunches at 7 TeV (σ_r= 0.088 mm), each of them having 1.11×10^{11} protons. A lagrangian 2D axis-symmetric model is used with an explicit time integration (time step magnitude 0.01 ns). A non reflection boundary condition is applied at the external radius.

The response of a cylindrical structures subjected to a beam impact in the centre was investigated in different works for different materials [9,10]. For this reason, the results of similar simulations are easily comprehensible.

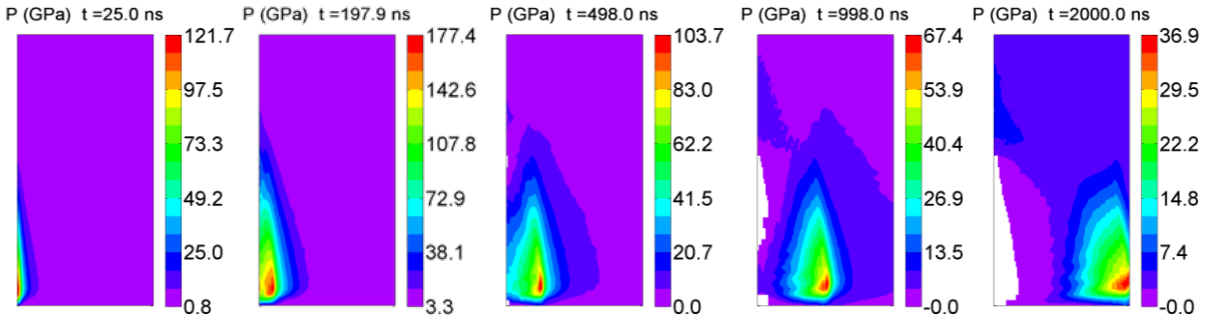

Figure 4: pressure evolution for tungsten components: radius (→), length (↑)

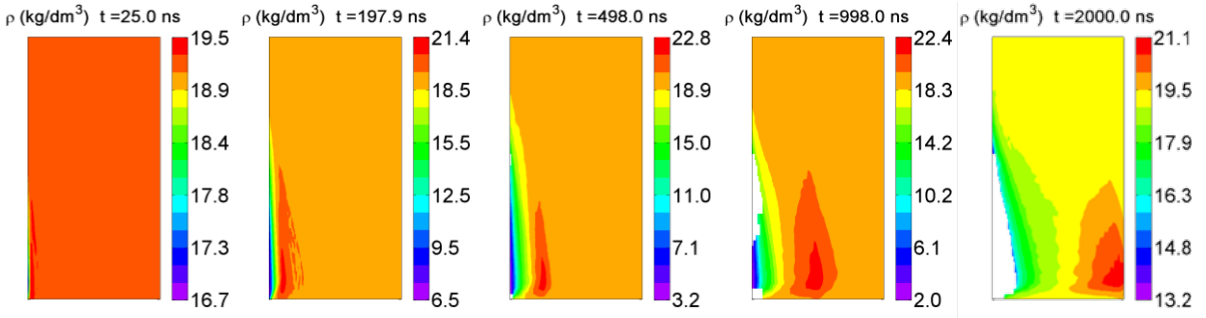

Figure 5: density evolution for tungsten component: radius (→), length (↑)

The results in terms of pressure, that are substantially independent from the chosen strength material model since the level of deposed energy is order of magnitude greater than plastic work, are reported in Figure 4.

A radial shock wave generated in the central/impact zone travels from the hit zone to the face. The levels of pressure reached at the end of the deposition (~200 ns) are very high. Since

the intensity level of the beam is the same used for the other materials [9,10], the difference in the pressure levels is essentially due to the difference in density: the greater the density the higher the energy absorption.

Figure 5, shows the density evolution: there is a rarefaction behind and a compression ahead the shock wave front. Due to the strong reduction in density, the material becomes gas and it is removed from the model.

In the centre the Von Mises stress (Figure 6) is zero because the temperature overcomes the melting value. In the remaining part of the component high levels of stress (~2 σ_0) are reached.

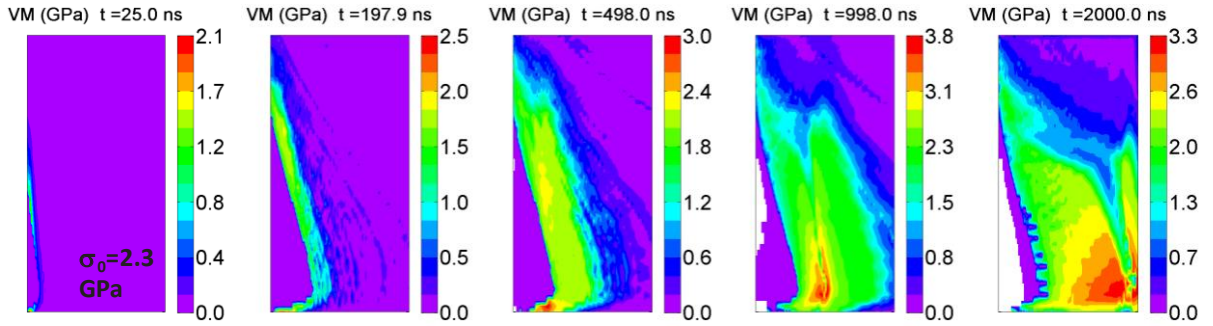

Figure 6: Von Mises stress evolution for tungsten component: radius (→), length (↑)

In Figure 7, an overview of the results is reported. The pressure and the density at the end of the deposition act as a pump (or similarly an explosive) which produces a dynamic deformation of the material ahead the shock front. In the remaining part of the component high levels of strain-rate (over 10^5 s^{-1}) and plastic strain (over 10%) are reached.

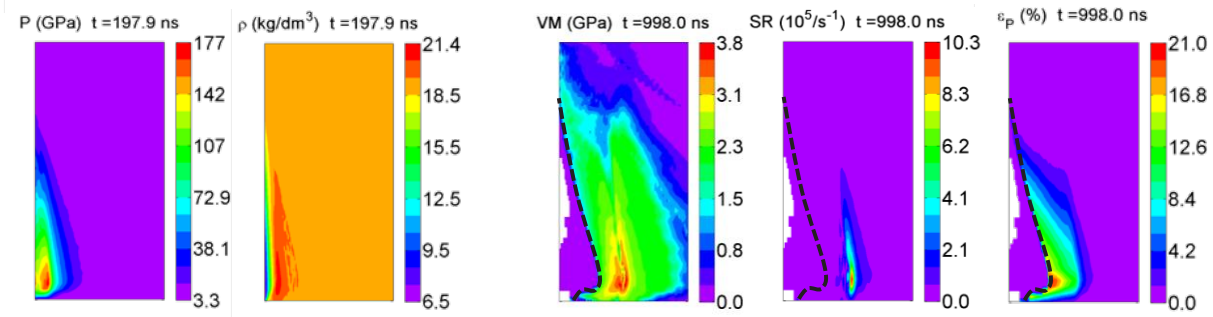

Figure 7: pressure and density distribution at the end of the deposition (left) and Von Mises, strain-rate and plastic strain at about 1 μs after the impact (right) for tungsten (bottom) component: radius (→), length (↑)

5. THREE-DIMENSIONAL REAL STRUCTURE

The method is finally applied to simulate the beam impact against a real complex geometry: the Target Collimator Tertiary (TCT) of LHC [11].

The lagrangian 3D numerical model (Figure 8) represents a simplified structure respect to the original one, but it considers the presence of two different material parts and the contact between the different model components. Substantially, the structure is a parallelepiped with

an internal part made by tungsten (the hit part) and an external C-section in copper. The simulation provides the impact of 8 bunches each having 1.13×10^{11} protons at 5 TeV (σ_x= 0.3 mm and σ_y= 0.19 mm).

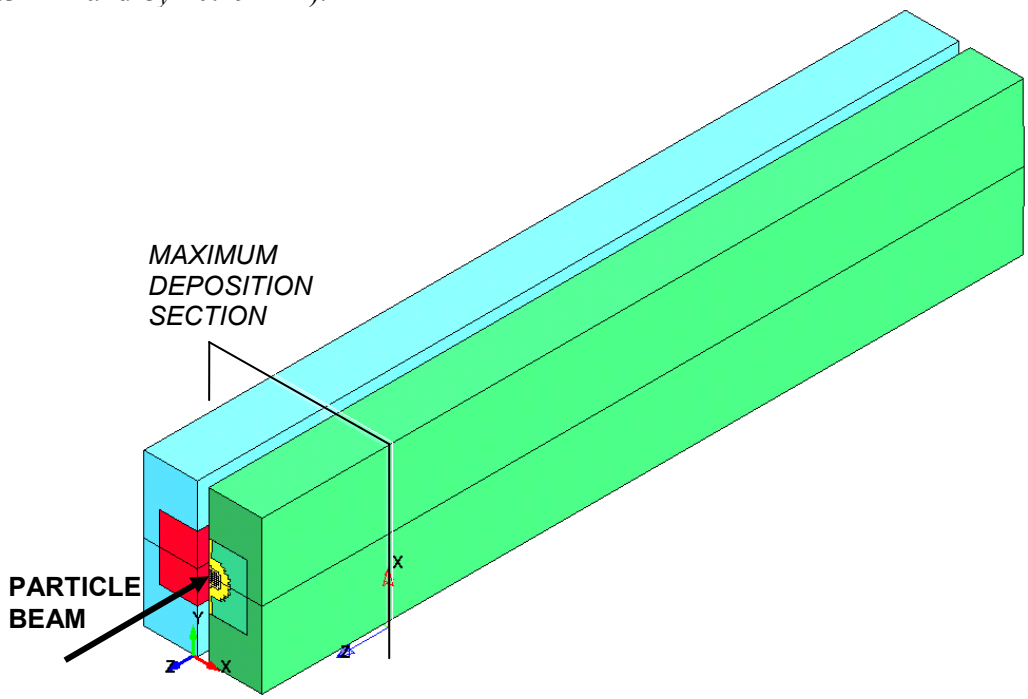

Figure 8. 3D view of the simplified TCT

In Figures 9-12 some simulation results on the model section of maximum deposition energy (Figure 8) are shown.

During the deposition phase (0÷182 ns) the pressure evolution is quite similar to the 2D cylindrical case. The reached level (156 GPa) is lower due to the different beam intensity and size. Once the deposition is finished a shock wave is generated and moves from the tungsten region to the copper part. Differently from 2D, in which the beam hits the centre of the structure, in this case the material is hit near a free surface. For this reason it can't create a wide zone of rarefaction because the pressure wave reaches in a short time the component free surface and is reflected: due to this the material is projected toward the other TCT jaw at high velocity (Figure 10) and consequently the other jaw may be damaged. The high level of particle speed in the material is a proof of shockwaves phenomena.

Since the significant difference in impedance between the two materials, the shock wave is in part reflected at the interface with the potential spallation of tungsten (P_{cutoff}=-900 MPa) and the reduction of the pressure level transmitted to copper.

In Figure 11 the results in terms of temperature are reported: the temperature is limited for a better understanding to the normal melting temperature (4520 K) since in the hit zone it could reach several thousand of K (plasma condition).

The level of stress is over 3 GPa in the tungsten part, that results heavy deformed after the beam impact. In the melted part of the component the Von Mises stress is zero and the behaviour is purely hydrostatic. On the other hand it reaches the maximum value behind the shock wave profile.

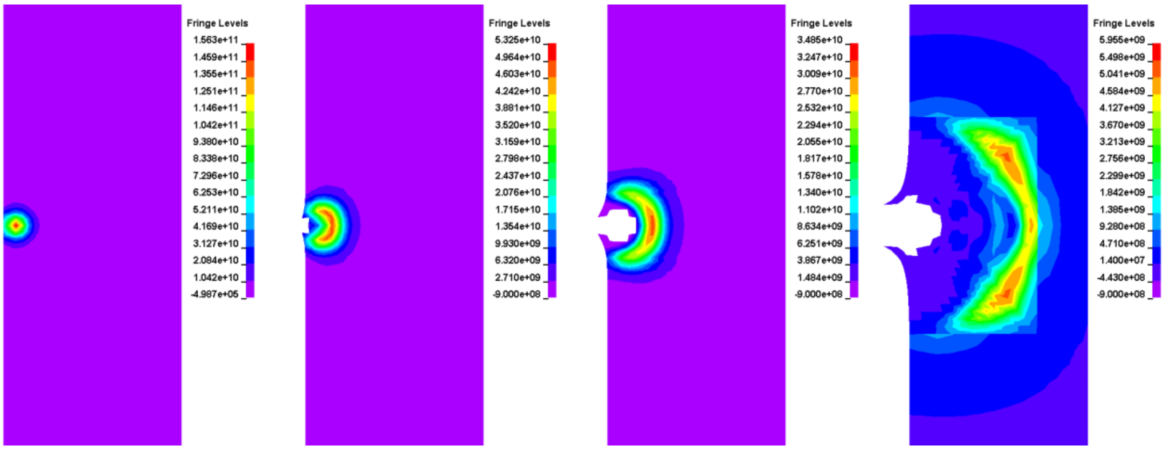

Figure 9. simulation results at: 182 ns (end of deposition), 600 ns, 1.2 μs, 4 μs, Pressure (Pa)

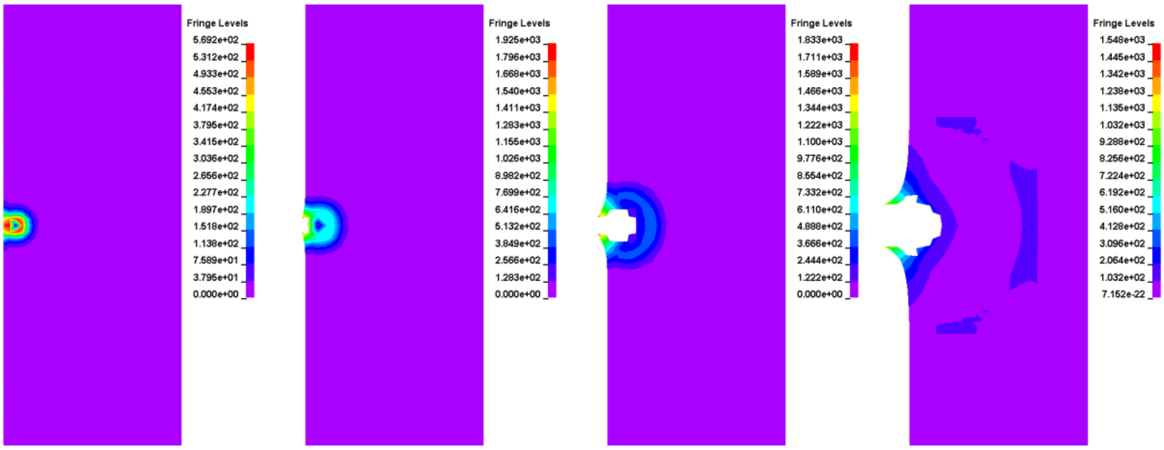

Figure 10. simulation results at: 182 ns (end of deposition), 600 ns, 1.2 μs, 4 μs, resultant velocity (m/s)

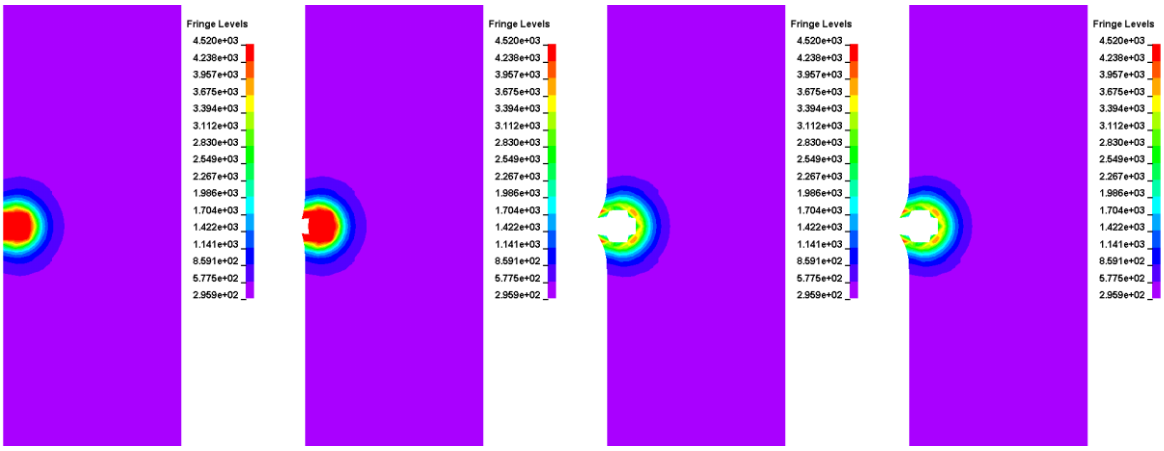

Figure 11. simulation results at: 182 ns (end of deposition), 600 ns, 1.2 μs, 4 μs, Temperature (K)

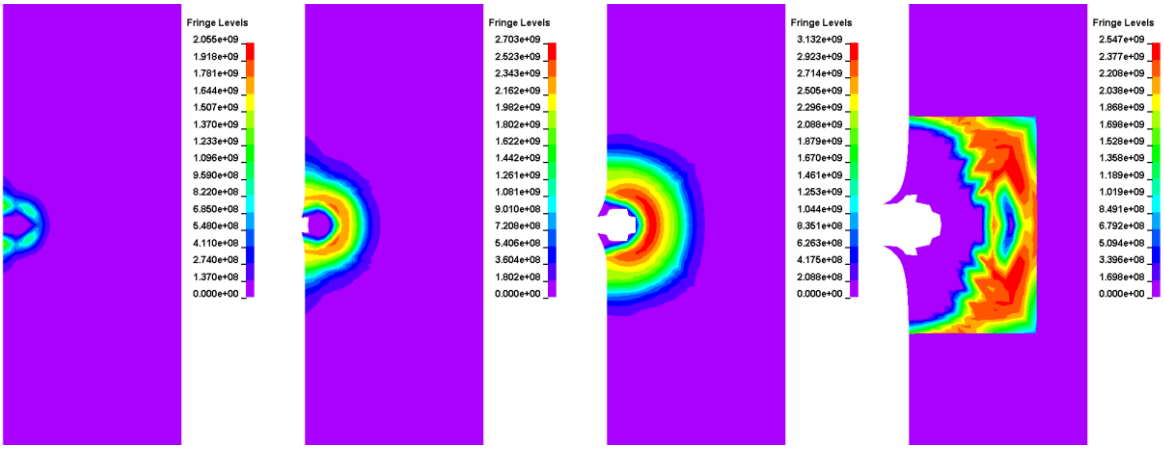

Figure 12. simulation results at: 182 ns (end of deposition), 600 ns, 1.2 μs, 4 μs, Von Mises Stress (Pa)

CONCLUSIONS

This study was performed in order to estimate the damage on a metal component due to the impact with a proton beam generated by the Large Hadron Collider (LHC) at CERN. The case study represents an accidental case consequent to an abnormal release of the beam, in which 8 bunches irradiate the target directly. The energy delivered on the component was calculated using the FLUKA code and then used as input in the numerical simulation, that were carried out via the FEM code LS-DYNA.

In this kind of problems both the hydrostatic and the deviatoric components are involved, but in different regions of the hit component. The hydrostatic behaviour of the target was described using a multi-phase equation of state, while the elasto-plasticity response was treated using Steinberg-Guinan material model.

In the first part, the validation of the numerical procedure on a simple geometry) and constitutive material models was presented. In particular, the high energy particle (7 TeV) impact was examined on a facially irradiated cylindrical bar: the beam hits the component directly on the centre of the basis. Then the final step was the study of the impact on a real structure with an energy beam of 5 TeV (the next target in the energy value of LHC beam).

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