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Effects induced by LHC high energy beam in copper structures

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ABSTRACT

This study is performed in order to estimate the damage on copper components due to the impact of a 7 TeV proton beam in the Large Hadron Collider. The case study represents an accidental case consequent to an abnormal release of the beam, in which eight bunches impact directly the copper. The energy delivered on the components is calculated by the FLUKA Team at CERN using their Monte-Carlo code for calculation of particle transport and interactions with matter. The energy maps are used by the authors as input for the structural simulations carried out via the FEM code LS-DYNA. The evolution of the phenomenon is quite similar to what might happen during an explosion. The impacted part of the component reaches extremely high values of pressure and temperature and undergoes changes of state. The sudden increase in pressure originates outgoing shockwaves that, travelling through the component, lead to a substantial density reduction in the impacted part. The energy delivered on the component is sufficient to severely damage the target.

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1. Introduction

The Large Hadron Collider (LHC) [1], built at the European Organization for Nuclear Research (CERN, Geneva), is installed in a circular tunnel with a circumference of almost 27 km situated across the border between Switzerland and France at an average depth of 100 m underground. In design condition, this machine provides the collision between two counter-rotating proton beams. Each proton beam will consist of 3×10^{14} protons at 7 TeV. The entire proton beam of the LHC is not continuous but is divided into 2808 bunches, each having 1.15×10^{11} protons.

The total energy stored in each beam at maximum energy is about 350 MJ, two orders of magnitude higher than the Tevatron or HERA. This large amount of energy (sufficient to melt 500 kg of copper) is potentially destructive for accelerator components having direct interaction with particles (e.g. the collimation system) in case of uncontrolled beam loss. The accident case, in which a fraction of the proton beam is directly lost on the collimator jaws, might happen with a low probability but, an assessment of possible structural damages is needed. An accurate prediction of the reliability and robustness is quite difficult, since beam-induced damage for high energy and high intensity occurs in a regime in which the possibility to perform experimental tests is limited. For this reason, it is of fundamental importance to develop reliable

methods and accurate models that could be efficiently applied to estimate the damage occurring during a beam impact.

When a particle beam interacts with a solid target the particles deposit their energy on the material. This provokes a dynamic response of the structure entailing thermal stress waves and thermally induced vibrations or even the failure of the component.

The evaluation of thermal loads on the material was performed by the FLUKA Team at CERN, using the statistical code FLUKA [2,3], based on the Monte-Carlo method.

In order to correctly simulate the thermo-mechanical response of the material it is necessary to take into account both the hydrodynamic behaviour, using a dedicated equation of state (EOS), and the deviatoric behaviour, using a dedicated strength material model. The numerical simulations are performed using the commercial code LS-DYNA [4]. LS-DYNA is a general purpose transient dynamic finite element program including an implicit and explicit solver with thermo-mechanical and highly non-linear capabilities. This code is often used to solve impact problems also for nuclear applications and particle accelerator technology [5–7]. For the simulations the chosen equation of state is a polynomial form, in which the coefficients are obtained fitting a multi-phase tabular equation of state, and the material model is the Johnson–Cook model.

2. Case study and numerical model

The main objective of this work is the understanding of the phenomenon evolution in order to predict the damage on a copper target (see Fig. 1) consequent to a high energy deposition. The case

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Fig. 1. Numerical model: cylindrical bar (10 mm of radius and 1 m of length) hit perpendicularly in the centre of one face. The dashed line identifies qualitatively the area hit by the beam in which the energy deposition is more significant.

study represents an accidental scenario in which eight proton bunches (the bunch length is 0.5 ns and the time between two successive bunches is 25 ns), generated in the LHC, impact against the structure: this is a possible accident case with an impact duration of about 200 ns. This study is performed on a simple cylindrical specimen (10 mm of radius and 1 m of length) hit perpendicularly in the centre of one face. The model represents the irradiated part of a bigger component: the radial external surface is not modelled as a free surface, so there is not any reflections to the boundary, simulating, in this way, the presence of other material.

The FEM analysis is performed on a 2D axisymmetric geometry with 50 elements in the axial direction (element/bin size of 20 cm) and 100 elements in the radial direction (element/bin size of 0.1 mm). The performed study of the mesh influence showed that these values are a good compromise between solution accuracy and computational costs [8]. The FEM solution is obtained in case of lagrangian and pure structural analysis solved with an explicit time integration method. The time step size is about 0.01 ns in order to correctly appreciate the bunch profile.

Dalocchio [9] carried out the study of a similar problem on the thermo-mechanical effects induced in solids by LHC high energy particles beams via both analytical and numerical approaches. The thermo-structural analysis was performed using the commercial code ANSYS. Also in this case, the starting point of the analysis was the energy map on the component calculated by the FLUKA Team at CERN. The energy was converted in a thermal power distribution and used as input for the solution of the thermal problem, from which the temperature distribution was calculated as function of space and time. The results of temperature analysis were used as nodal loads for the structural analysis, from which dynamic thermal stresses and displacements were evaluated. Finally, a quasi-static step was performed in order to calculate potential permanent deformations of the structure.

A similar approach was presented by Bennett et al. [6,10] in which the energy calculation, resulting from high-energy particles beam impact with a solid material, was performed using the MARS code. From the energy map the temperature rise was calculated and used in LS-DYNA (for explicit analyses) or ANSYS (for implicit analyses) codes to calculate the dynamic stresses in the target.

In these two approaches the calculation of the temperature from the energy map was performed without using an equation of state: the proportional factor between energy and temperature was the heat capacity at constant volume for the solid at room temperature. Besides, a linear equation of state was used to describe the pressure evolution, while, in this kind of problems, it is fundamental to correctly describe the pressure evolution using a more complex equation of state. In addition, it is important to underline that, since the energy levels involved are very high, the material could undergo changes of state, so the use of a multi-phase equation of state is needed in order to correctly evaluate the physical state of the matter.

In this sense there are the works proposed by Tahir et al. [11,12], in which the energy deposition was evaluated via the FLUKA code and then directly used as input in the hydrodynamic code BIG-2 in order to calculate pressure, temperature and density of the hit material for a simple 2D geometry (a cylindrical bar). To do this, a sophisticated three-phase equation of state was used. On the other hand, this approach did not present the deviatoric part of the stress that is indeed negligible in the part of the material closest to the impact zone, while it is by no means negligible in the remaining portion of material.

Ryazanov et al. [13] developed a work complementary to the work of Tahir et al. [11], in which both theoretical and numerical models were developed in order to describe the consequences in the materials of the LHC collimation system in case of multi-bunch 7 TeV proton beam impact. In more details, the study was for the estimation of physical and mechanical properties changes: the interaction between the material and the high energy beam produces the formation of a cascade of secondary fast particles that leads to the formation of shockwave and radiation damage in the material. In [13], as first approximation, only the shockwave formation was considered from a pure hydrodynamic point of view for a two-dimensional model representing a cylindrical geometry. The theoretical model took into account phenomena such as the ionization, the electronic excitation and the energy transfer from the excited electronic subsystem to the ionic one, due to the electron-phonon coupling. Besides, in [13], some preliminary numerical results of the distributions of density, pressure and temperature were also shown.

The purpose of this work is to analyze simultaneously both the deviatoric behaviour and the hydrodynamic one, using the FEM code LS-DYNA, in which there is the possibility to use an equation of state combined with the strength model of the materials.

In this sense a previous study was developed, see Le Blanc et al. [14], in which a coupled mechanical, thermal and electromagnetic simulation was performed. Le Blanc et al. performed studies on the material behaviour using High Pulsed Power technologies to realize compression test. The basic principle implies a strong current generating a magnetic pressure shockwave and a subsequent rise in temperature due to the Joule effect, which can locally melt or vapourise the material. The problem is quite different, but the approach can be similar: also in [14] the problem was linked with a rise in temperature that can produce phase transition in the material. The simulations were performed via LS-DYNA code, in which there is the possibility to implement a user-defined EOS. In [14] the three-phase equation of state GRAY, see Royce [15], was implemented and the input energy distribution came from the electromagnetic solver.

3. Beam energy loss: discussion

In general, in case of interaction between a high energy particle (protons) beam and a metallic material three main dynamic response regimes may occur, depending on several parameters,

mainly 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 speed of sound. 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 initiation of shockwaves, 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 become relevant. Besides, in the material close to the hit zone the encountered temperatures are very high and two possible situations can arise, see Royce [15]. If the energy deposition is very quick, such that the deposition time is shorter than the system hydrodynamic characteristic time, the material density remains near to the normal density (isochoric transformation). Nevertheless, the temperature and the pressure increase and reach very high value. Once the hydrodynamic rarefaction process starts, the material can expand reaching lower values of density and pressure. This same evolution is also in case of slow energy deposition process: the material reaches directly a condition characterized by low pressure and density because the hydrodynamic characteristic time is faster than the energy deposition rate.

In case of LHC, different thermal loads must be taken into account depending on the interaction condition. In normal situations, a continuous interaction (low energy values) provokes a constant energy-rate deposition over a long period (from some seconds up to few hours). In this case thermal stresses and deformations take place but no dynamic response can usually be observed. Otherwise, in case of abnormal beam impacts, energy is rapidly deposited in time-scales of the order of microseconds or nanoseconds. This loading condition typically entails a dynamic response of the structure. The resulting thermal stresses and deformations may affect the integrity or the proper functionality of the hit equipments. It is in this condition that an in-depth thermo-mechanical analysis is strongly necessary.

From a structural point of view the energy deposition induces a sudden non uniform temperature increase. In function of which part of material is investigated the behaviour is different. In the material part close to the beam, the pressure and temperature increase and the material can undergo phase changes (liquid, gas, vapour and plasma depending on the impact condition). The material response in this condition can be correctly described using an equation of state that is able to describe the hydrodynamic behaviour, while the deviatoric stress is totally negligible. On the other hand, the remaining part of the material is characterized by high values of thermal-induced plastic strain in a very short time (high strain-rates), so the complete description of the material response implies also the definition of a constitutive strength material model.

As mentioned in the introduction, the evaluation of thermal loads on the hit material is performed by the FLUKA Team at CERN, using the statistical code, called FLUKA [2,3], based on the Monte-Carlo method. The FLUKA code calculates the map of the energy density absorption in the matter in function of the spatial coordinates. The value of energy (GeV/cm^3) is calculated for each bin (element mesh) in which the considered target is divided. The calculation takes into account a large number of primaries (70,000 for this case study) ensuring statistical errors not exceeding a few percents over the whole target component and much lower in the peak region, for the adopted scoring mesh and then the results are normalized to one ideal proton. This means that, sampling from

Fig. 2. Spatial distribution of the deposited specific energy (GJ/m^3) on copper cylindrical component.

a Gaussian distribution, adding all the contributions up, and dividing by the number of sampled particles, FLUKA result turns out to be representative of the whole distribution. Finally it is possible to rescale the FLUKA map by the real bunch intensity (1.15×10^{11} protons).

The FLUKA results are correct for the first bunch impacting against the pristine material. The next bunches encounters a material that presents differences in some chemical, physical and mechanical properties.

In this work, the authors use the provided FLUKA map as the starting point in the thermo-mechanical simulations under the hypothesis of isolated bunches. This means that the reactions generated by the first bunch are assumed to be finished before the arrival of the second bunch and so on. The assumption is reasonable since a relativistic particle takes about 3 ns to cover 1 m in vacuum. The particles decays generated for each primary collision are not yet spent in the time between two successive bunches (25 ns) but most of them are far enough (5–8 m) to no longer be considered. This is true excluding the low energy neutrons, the nuclear reactions products in case of fragmentation and any particles with a decay time of about nanosecond or microsecond.

Figs. 2 and 3 show the FLUKA map on the copper bar for a single bunch handled in order to be used as input in the structural calculation: the energy distribution (logarithmic scale), the energy vs. radius curves varying the axial coordinate and the energy vs. axial direction curves varying the radial coordinate are shown. The peak of the energy deposition is about $36 \text{ GJ}/\text{m}^3$ and occurs along the axis of symmetry ($r = 0 \text{ mm}$) at an axial coordinate $L_{\text{Emax}} = 16 \text{ cm}$.

4. Material requirements and modelling

Given the extreme loading conditions, the materials should have particular properties; see the report written by Schimdt et al. [16]. The ideal material used for this application and generally in nuclear applications (e.g. see [17,18]), should present good electrical and thermal conductivities, low ability to absorb elementary particles, low coefficient of thermal expansion and, finally, good mechanical properties, such as high stiffness, strength and shock resilience. Moreover, the performance issues are essentially and directly correlated to the material abilities to maintain these key properties also in more extreme conditions (i.e. accidental cases), in which they should also absorb the beam-induced shock.

Usually, in order to cope with all the requirements for the material, a composite approach is used. Some results of experimental irradiation studies performed on some materials were presented

Fig. 3. Distribution of the deposited specific energy on copper cylindrical component: energy vs. axial direction curves varying the radial coordinate (left) and energy vs. radius curves varying the axial coordinate (right).

by Schmidt et al. in the report [16]. These studies showed that carbon composite exhibits dramatic reduction of the stability of the thermal expansion coefficient in case of high level of radiation. Similar problems were found also in graphite, in which the radiation produces also the reduction of thermal and electrical conductivities. On the other hand, encouraging results in case of proton irradiation were obtained for copper, GLIDCOP® (alumina dispersion strengthened copper), Invar, Ti–6Al–4V alloy and AlBeMet. Currently, the research is oriented on metal–diamond materials, such as copper–diamond, molybdenum–diamond and silver–diamond, since these types of materials should satisfy all the above-mentioned requirements [19].

In this work the numerical analysis is performed on components in copper since it is at present employed as functional part of the LHC collimation system, as reported by Assmann [20].

4.1. Equation of state

In order to describe the hydrodynamic response of the material the use of an equation of state is required. An EOS is a constitutive relation between state variables and describes the state of the matter. Usually it expresses a thermodynamic variable (such as pressure P or internal energy E) as a function of two other independent variables (such as density ρ and temperature T). In general the equations of state can be divided into two categories: analytical EOS, such as Mie–Grüneisen and GRAY [15], and tabular EOS, such as SESAME [21].

A formulation widely used in FEM codes for the description of the constitutive relation $P(\rho, E)$ is the polynomial equation of state, which defines the pressure for compressed material ($\mu = \rho/\rho_0 - 1 > 0$, ρ_0 is the solid reference density) as

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (1)$$

and for expanded material ($\mu = \rho/\rho_0 - 1 < 0$) as

$$P = C_0 + C_1\mu + C_3\mu^3 + (C_4 + C_5\mu)E \quad (2)$$

in which the cold curve is approximated with at least a third order polynomial in the density (C_2 set equal to 0 if $\mu < 0$) and the thermal component at least with a second order polynomial in the density (C_6 set equal to zero if $\mu < 0$). Obviously, if all the coefficients are set equal to zero, except for C_1 , then the resultant EOS expresses the linear elastic pressure–volume relation in which C_1 represents the elastic bulk modulus, both in compression and expansion.

The GRAY equation of state was developed by Royce [15] in order to make reliable predictions in case of transient problems involving high energy densities. It expresses the pressure as function of the specific volume and the internal energy and describes the solid, liquid and vapour phases. Also the description of the

bi-phases zones in correspondence with phase transitions are included.

Another widely used equation of state form is the tabular one. For the construction of the tabular EOS several codes are developed and in general the EOS includes the description of both solid and fluid phases (liquid, vapour, gas and plasma).

In this work, the starting equation of state is the tabular form shown in Fig. 4, [22]. Since with LS-DYNA there is no possibility to use an EOS in this form, an interpolation of the tabular data, in accordance with the polynomial formulation (Eq. (1) and (2)), is performed locally for each element.

As mentioned in the introduction, since the FLUKA simulation results are used as input in the FEM numerical simulations, it is necessary to transfer the calculated energy deposition in the matter to the FEM model, through the equation of state. In more details, the calculated energy has to be included in the energy balance and the method depends on the specific FEM code.

In LS-DYNA, the balance energy equation is managed by the routine of the equation of state. For each element and at each time step, the update of the internal energy is based on the relation

$$E_{\text{NEW}} = E_{\text{OLD}} + \Delta E \quad (3)$$

$$\Delta E = \Delta E_{\text{dev}} + \Delta E_{\text{hydro}} + \Delta E_{\text{ext}}$$

which expresses the total internal energy as the sum of the internal energy evaluated at the previous time step and the increment correspondent to the actual time step. The internal energy increment is evaluated as the sum of the increments coming from both the mechanical work, consequent to the deformation process (divided into deviatoric and hydrostatic) and the external energy. Then, the evaluation of the temperature comes from the equation

$$T_{\text{NEW}} = \frac{E_{\text{NEW}}}{\rho_0 C_p} \quad (4)$$

in which the density ρ_0 and the heat capacity at constant pressure C_p refer to the initial condition of the material (solid state at the nominal density).

4.2. Material strength model

Since the energy distribution (and consequently also the pressure distribution) is not uniform on the hit component, the pressure gradients induce plasticity: the definition and the choice of the material strength model is of fundamental importance. The part of the component external to the impacted zone and that, after the end of the deposition phase, is still solid is subjected to plasticity. In order to provide a complete and comprehensive description of the problem, the material model should take into

Fig. 4. Tabular EOS of copper, Kerley [22]: pressure in function of density varying the temperature (left); internal energy in function of density varying the temperature (right).

account all the mechanical variables of interest for the stress flow evolution.

In the case study of this work, the material results to be heavily deformed in a very short time and in a very high temperature condition. In addition, the phenomenon has a strong thermo-structural coupling: the rise in temperature consequently modifies the mechanical material response. As a matter of fact, the material properties may depend strongly upon the local temperature and for these problems it becomes necessary to compute the temperature throughout the material. Usually, due to the rise in temperature, there is a modification (reduction) in the effect of the strain-rate on the flow stress, jointed with thermal softening effects (mechanical strength reduction). Besides, the process is characterized by the generation of a shock front that, travelling through the hit component, invests the solid part and implies a mass transport process with a significant density modification. Finally, given the high levels of pressure, also the pressure could influence the mechanical material response.

From these considerations it follows that the constitutive relation for the deviatoric behaviour of the material should consider as variables: the strain (both effective plastic and volumic strains), the strain-rate, the temperature and the pressure. In addition, it could be important to take into account the modification of the mechanical properties due to material irradiation. As a matter of fact, during the development of particles cascades in the irradiated material, defects, such as vacancies and interstitials, are produced. The consequence is the accumulation of radiation defects forming clusters of point defects, such as dislocation loops and vacancy voids, that lead to a significant degradation of physical mechanical material properties.

The purpose of this work is to provide a preliminary description of the phenomenon evolution. In this perspective a simplified approach is followed, taking into account only the effects of plastic strain, strain-rate and temperature on the flow stress. In this first approximation, the influence of pressure and density on the stress flow and the estimation of the reduction in the mechanical properties resulting from the material irradiation are neglected.

In this sense, in past decades several material models for the description of the elasto-visco-plastic behaviour were proposed. The Johnson–Cook (J–C) model [23] is purely empirical and it is one of the most widely used. Examples of semi-empirical models are the Steinberg–Cochran–Guinan–Lund (S–C–G–L) model [24], which was first developed for the description of high strain-rates behaviour and later extended to low strain-rates, and the Zerilli–Armstrong (Z–A) model [25], that is obtained on the basis of the dislocation mechanics theory and presents a different formulation for BCC and FCC materials. A more complex dislocation based model is the Mechanical Threshold Stress (MTS) model [26].

A problem related to most of these models is the availability in the scientific literature of the material parameters. In general these material models have been tested and calibrated with experiments on Hopkinson bars, Taylor cylinders and with high explosive shock or compression tests in a range of few tens of GPa for pressure and at least 10^5 s^{-1} for strain-rate. In case of high energy particle beam impact, the level of pressure expected is of the same order of magnitude of the energy deposited. The level of pressure could also exceed the hundreds of GPa and the strain-rates overcome the million per second. From these considerations, for future improvements of this work, an accurate and aimed material model calibration will be needed.

The material model used for the numerical simulations is the J–C model, which can predict the mechanical behaviour of the materials under different loading conditions. Besides, as mentioned before, it is one of the most used, so it is implemented in many FEM codes and is quite documented in literature for different materials. The J–C model expresses the stress flow as

$$\sigma_y = \left(A + B \epsilon_{pl}^n \right) \left(1 + C \ln \frac{\dot{\epsilon}_{pl}}{\dot{\epsilon}_0} \right) \left(1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right) \quad (5)$$

In which A is the elastic limit strength, B and n are the work hardening parameters, C and $\dot{\epsilon}_0$ express the strain-rate sensitivity and m describes the thermal softening. In more details, in the used formulation for the J–C model [4], $\dot{\epsilon}_0$ represents the quasi-static strain-rate threshold that, ideally, represents the highest strain-rate for which the strain-rate effects on the flow stress are negligible. Finally, the thermal effects are described, in function of the actual temperature T , the reference temperature T_r , at which there are no large thermal effects, and the melting temperature T_m , at which the material mechanical strength goes to zero and the material behaviour could be completely described even using a multi-phase equation of state. In this condition the material loses its shear strength and starts to behave like a fluid.

Probably the J–C model is too simple and quite inaccurate for the description of the material response in case of high energy particle beam impact. As a matter of fact, it is a multiplicative model, in which the effects of plastic strain, strain-rate and temperature are assumed to act independently. Besides, it neglects the influence of pressure and changes in volume on the flow stress and considers the shear modulus and the melting temperature constant, while they could be influenced by the density. Nevertheless, it can be used to obtain a first approximated solution that is the main issue of this work.

The J–C material model provides also a failure model (for the solid state, [27]) in which the strain at fracture is given by

Table 1
J–C parameters, copper [23,27].

Parameter	Value	Unit	Parameter	Value	Unit
ρ_0	8937.5	kg/m ³	T_{melt}	1356	K
G	4.6×10^{10}	Pa	T_{room}	300	K
ν	0.3406	–	C_p	383	J/(kg K)
A	9.00×10^7	Pa	P_{spall}	-1.2×10^9	Pa
B	2.92×10^8	Pa	D_1	0.54	–
n	0.31	–	D_2	4.89	–
C	0.025	–	D_3	–3.03	–
$\dot{\epsilon}_0$	1.00	s ^{–1}	D_4	0.014	–
m	1.09	–	D_5	1.15	–

$$\epsilon_f = (D_1 + D_2 e^{D_3 \sigma^*}) \left(1 + D_4 \ln \frac{\dot{\epsilon}_{\text{pl}}}{\dot{\epsilon}_0} \right) \left(1 + D_5 \left(\frac{T - T_r}{T_m - T_r} \right) \right) \quad (6)$$

in which D_1 , D_2 , D_3 , D_4 and D_5 are the failure parameters and σ^* is the ratio between the pressure and the effective stress. The material fracture occurs when the damage parameter

$$D = \sum \frac{\Delta \epsilon_{\text{pl}}}{\epsilon_f} \quad (7)$$

reaches the value of 1.

In addition, in this work, also a spall model for the description of the material failure under hydrostatic tensile loads is used [28]. The spallation is one of the modes of material failure: it is a process of internal failure of condensed matter that implies the nucleation, growth and coalescence of defects. This phenomenon, in general, occurs during high velocity impact and involves the generation of shockwaves in the hit material. When the incident shockwave reaches the material boundary, a reflected shockwave (with an opposite sign in case of free surface) is generated. The interaction of the two waves causes the formation of spall events that sometimes lead to the material fragmentation in which fragments of material are ejected from the body.

In case of high energy particle beam impact, the spallation could play an important role and possibly become the main cause of failure especially in case of impact near a free surface.

The spall model used in this work is a hydrostatic tension spall model, that limits the minimum pressure value and if spall is detected in an element of the numerical model the deviatoric stress and the pressure are set to zero. It is important to underline, that, in general, the spall criteria have been calibrated in experiments such as the flyer plate impact test, while it is difficult to find spall parameters for different materials to be used in case of more extreme loading conditions.

The input parameters for the J–C strength material model are summarized in Table 1. An erosion (deletion) criterion is added in order to preclude the possibility that elements in which the density gets too low values are subjected to negative pressure (physically impossible condition). This is useful to avoid excessive distortion of the numerical mesh. At each time step and for each element, the FEM solver performs the check of the erosion criterion condition: if both the pressure and the density become simultaneously lower than the corresponding imposed limits, then this element is deleted from the calculation. More precisely, the limit in terms of pressure is set equal to zero and the threshold in density is set equal to 8000 kg/m³.

5. Results and discussion

The numerical results on the component are shown in terms of pressure, density, temperature, Von Mises stress, plastic strain and particle velocity.

In this work, the bunch length is assumed equal to 0.5 ns while the time between two successive bunches equal to 25 ns. The

entire deposition phase is about 203.5 ns. The numerical simulations are performed until 1 μ s in order to have the possibility to evaluate the phenomenon evolution after the end of the impact phase. In Figs. 5–6, 9–10 the white area along the length axis represents the part of the component deleted from the calculation in accordance with the erosion criteria.

Figs. 5 and 6 report, respectively, the pressure and density evolutions at four different time steps: during the deposition phase (101.5 ns), at the end of the deposition phase (203.5 ns) and during the free phase (500 ns and 1000 ns). The results show that the energy delivered on the hit (central) part of the component acts as an explosive. During the deposition phase the pressure grows up and reaches a maximum value close to 50 GPa in the central part. Once no more bunches are delivered, the shockwave, generated in the impact zone, starts to travel from the hit zone to the external radial surface. The density evolution is strictly related to the pressure evolution in accordance with the EOS. The travelling shockwave produces a rarefaction in the material placed behind and a compression in the material placed ahead of it. The central part of the component corresponds to the zone in which there is the material rarefaction. This part of material could be subjected to sudden and continuous changes of phase. The remaining part of the component, that is mainly compressed, behaves similar to the solid state.

In Fig. 7 the pressure vs. time history curve is depicted for elements situated in different positions in the hit component: along the axis of symmetry at three different longitudinal coordinates (P1: $r = 0$ mm and $L = 5$ cm; P2: $r = 0$ mm and $L = 16$ cm; P3: $r = 0$ mm and $L = 50$ cm) and at two distances from the axis of symmetry for two axial coordinates (P4: $r = 2.5$ mm and $L = 20$ cm; P5: $r = 5$ mm and $L = 20$ cm; P6: $r = 2.5$ mm and $L = 50$ cm; P7: $r = 5$ mm and $L = 50$ cm). The diagrams show there is the growth in pressure followed by a sudden release in the part in which the highest values arises (P1–P3), while the other part of the component (P4–P7), that is quite far from the hit zone, is afterwards affected by a further increase in pressure (that could become greater respect to the one reached during the deposition phase) due to the crossing in the component of the shock front.

In Fig. 8 the pressure vs. radius curves at four different time steps (101.5 ns, 203.5 ns, 500 ns and 1000 ns) are depicted corresponding to two longitudinal coordinates (16 cm and 50 cm). The initial ($t = 0$) pressure evolutions follows the energy evolutions showed in Fig. 3. Observing the Fig. 8 it is possible to identify the radial position of the shock front that moves radially along the component reducing its intensity and investing the different part of the component at different times. The shock front is identified by the spatial pressure discontinuity which travels at a supersonic speed: after 1 μ s, the shock front covers about 5 mm of the component (i.e. the mean wave speed is about 5000 m/s, respect to 3940 m/s of the sound speed in copper).

In Fig. 9 there are the spatial distributions of temperature, Von Mises stress, plastic strain and particle velocity at the end of the deposition. The temperature is limited to the melting value (1356 K). In case of pure structural analysis, the temperature evaluation is performed in LS-DYNA by the material strength model routine that transforms the internal energy in temperature using as proportional factors the density and the specific heat capacity for solid at room temperature. This implies the temperature calculation does not take into account the modification of the specific heat capacity with the phase changes of the matter. So, the temperature evaluation is correct only in the solid part. At the end of the deposition about 4 mm of the component are not still solid. The Von Mises stress is zero in the part of material that overcomes the melting value. This means in the central part of the component, since the mechanical resistance of the material is defeated, the material behaviour could be treated completely as a pure hydrodynamic behaviour. On the other hand, for the material that remains

Fig. 5. Pressure distribution (GPa) on the copper cylindrical component at four different time steps: radius $0 \div 10$ mm ($\rightarrow$), length $0 \div 1$ m ($\uparrow$), the radial dimension is amplified.

Fig. 6. Density distribution (kg/dm³) on the copper cylindrical component at four different time steps: radius $0 \div 10$ mm ($\rightarrow$), length $0 \div 1$ m ($\uparrow$), the radial dimension is amplified.

Fig. 7. Pressure vs. time history: (left) for three elements situated along the symmetry axis (P1: $r = 0$ mm and $L = 5$ cm; P2: $r = 0$ mm and $L = 16$ cm; P3: $r = 0$ mm and $L = 50$ cm) and (right) for four elements situated respectively at P4: $r = 2.5$ mm and $L = 20$ cm; P5: $r = 5$ mm and $L = 20$ cm; P6: $r = 2.5$ mm and $L = 50$ cm; P7: $r = 5$ mm and $L = 50$ cm.

solid, the maximum value of Von Mises stress is reached just across the shock front, where there is a sharp and significant discontinuity in pressure and density. At the end of the deposition the plastically deformed part of the component is still limited. The shock front is in the molten area in which the maximum of the particle velocity is about 670 m/s, while in the solid part it overcomes the value of 100 m/s.

In Fig. 10 there are the spatial distributions of the same quantities after 1 μ s from the impact. The temperature is again limited to the melting value (1356 K) and the molten area stops to increase

since there is no longer any external energy intake in the system. The maximum of the Von Mises stress follows the shock front and reaches high values (about two times the yield strength of the material). A significant part of the component results to be heavily plastically deformed. The shock front propagates into the solid part of the component where the particle velocity exceeds the value of 400 m/s.

Observing the EOS in the pressure–energy plane varying the density (see Fig. 11) it is quite easy to follow the transformation in the material. Fig. 11 shows the evolution for the element in

Fig. 8. Pressure vs. radius curves at four different time steps corresponding to two different longitudinal coordinates (16 cm on the left and 50 cm on the right).

Fig. 9. Temperature, Von Mises stress, plastic strain and particle velocity distributions on the copper cylindrical component at the end of the deposition phase: radius $0 \div 10$ mm ($\rightarrow$), length $0 \div 1$ m ($\uparrow$), the radial dimension is amplified.

Fig. 10. Temperature, Von Mises stress, plastic strain and particle velocity distributions on the copper cylindrical component after $1 \mu\text{s}$ from the impact: radius $0 \div 10$ mm ($\rightarrow$), length $0 \div 1$ m ($\uparrow$), the radial dimension is amplified.

which there is the maximum of the deposited energy. During the bunch arrival (0.5 ns), there is a sudden increase in the internal energy with a negligible variation in the material density (isochoric transformation): consequently, the pressure increases. After the bunch impact (during the 25 ns of void separating two successive bunches, or at the end of the deposition), the material could expand (reaching lower value of pressure and density, case depicted in Fig. 11), or compress (reaching higher value of pressure and density) depending on the global redistribution of the stress on the component.

The energy deposition profile is strictly dependent on the material. In particular it depends on the density and the atomic number (Z number), since these affect the probability of the interaction between particles and material. The higher the atomic number (Z number) of the material the higher its energy density absorption over a shorter length. This implies that two materials subjected to the same impact condition, but with different Z number, experience different energy absorption. Furthermore, it means also that, if there is a density evolution during the simulation, it should be taken into account in order to recalculate the energy deposition

Fig. 11. Equation of state of copper: pressure vs. energy plane varying the density. The diagram represents the P - E - ρ evolution of the element in which there is the maximum of the energy deposition. The symbols represent the states P - ρ - E reached by the material. In particular, during the energy deposition phase, the symbols identify the material conditions after each bunch arrival and after 25 ns from its arrival. In the figure, E1 represents the energy deposited after the first bunch, E2 the total amount of energy after the arrival of the second bunch and so on.

on the material in these new conditions. About the last point, in this work, a preliminary approach was followed: the energy deposition on the material is calculated on the initial condition (density of the solid state) and then used during the entire multi-bunch impact simulation without any modifications.

In order to partially improve the quality of the results a sort of coupling between FLUKA and LS-DYNA codes might be useful. The most significant density variation is just in the zone in which, at the starting condition, there is the maximum of the energy deposition: after the density variation (reduction), this zone can no longer receive the same amount of energy as before. As future work, a coupling algorithm will be developed in collaboration with the CERN FLUKA Team. The procedure will mainly consist in stopping the FEM analysis before the arrival of the following bunch, extracting the FEM results in terms of density and using them as input to create a new FLUKA model. The new FLUKA model will have, in general, a non-constant density distribution on the component. Finally, starting from this model, a new FLUKA calculation will be performed and its results used as input for the next mechanical analysis. This loop will be performed for a number of times corresponding to the number of impacted bunches to simulate. This approach will be validated by experimental tests on simple geometry specimens that will be performed with the new HiRadMat facility, under development at CERN.

6. Conclusions

This study was performed in order to understand the material response in a metallic component consequently to the impact with a proton beam generated by the Large Hadron Collider (LHC) at CERN. The case study represents an accidental case in which, due to an abnormal beam loss, eight bunches at 7 TeV impact the target directly. The target was a cylindrical bar (10 mm of radius and 1 m of length) of copper. The map of the energy delivered on the component was used as input in the numerical simulation, that were carried out via the FEM code LS-DYNA.

In this kind of problems both the hydrodynamic and the deviatoric components of the stress are involved, but in different regions of the component. The hydrodynamic behaviour of the target was

described using a multi-phase equation of state, while the elastoplastic response was treated using the Johnson–Cook material model. The EOS used in the numerical simulations is a polynomial equation of state linear in energy. The coefficients are calculated fitting the multi-phase tabular EOS locally for each element of the numerical mesh.

The evolution of the phenomenon is quite similar to what might happen during an explosive scenario. The results showed that when eight bunches are delivered on the component, the material reaches extremely high values of pressure and temperature and changes in the matter state occur. The sudden increase in pressure launches outgoing shockwaves that, travelling through the component, lead to a substantial density reduction in the central part of the cylinder. The results also showed how the energy delivered on the component by eight bunches is sufficient to severely damage the target. A considerable part of the component is vapourized or molten and the solid remaining portion is heavily plastically deformed.

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