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Thermo-mechanical modelling of high energy particle beam impacts

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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 LHC in a single beam is equivalent to about 80 kg of TNT explosive, stored in a transverse beam area 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 occurs in a regime where practical experience does not exist. This study is performed in order to estimate the damage on a copper component due to the impact with a 7 TeV proton beam generated by LHC. 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 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. Different numerical models are realized trying to obtain the simplest model able to correctly describe the material response without affecting the goodness of the results.

Introduction

Particle accelerators [1] act as microscopes for such a complex research; these large machines accelerate charged elementary particles (electrons, protons or ionized atoms) to high kinetic energies. A high energy particle beam can be brought into collision against a fixed target or against another beam and from this encounter a multitude of short life sub-atomic particles is originated. The investigation of matter in these extreme conditions can be compared with the status of the universe in the first moments after the so-called 'Big Bang'. The higher the energy of the colliding beams and the event rate, the wider the spectrum of the generable sub-atomic particles. It is in this perspective that the project of building the Large Hadron Collider (LHC) [2] at the European Organization for Nuclear Research (CERN, Geneva) was approved.

The LHC [3] 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. Each proton beam consists of 3×10^{14} protons at 7 TeV, so when the protons collide the collision energy is 14 TeV. Under nominal operating conditions, 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 μ s.

The total energy stored in each beam at maximum energy is about 350 MJ, two orders of magnitude beyond the achievements in the Tevatron or HERA [4]. 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 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 practical experience does not exist.

When a particle beam interacts with a solid target the particles deposit their energy on the hit material. So they provoke a dynamic response of the structure entailing thermal stress waves and thermally induced vibrations or even the failure of the component. The pressure and temperature increase and the materials could arrive at its melting temperature or vaporize. The remaining part of the material is characterized by high values of plastic strain, strain-rate and temperature.

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 [5]. 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 [6], based on the Monte-Carlo method. FLUKA returns an energy map on a particular geometry 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.

As mentioned before, the material involved 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.

State of art

Before describing the implemented methods, of course, a short discussion about the approaches developed by other research centres is presented. As a matter of fact, in literature different approaches to solve similar problems can be found.

In [7] the study of the thermo-mechanical effects induced in solids by high energy particles beams is carried out via two different approaches: an analytical method and a numerical one. Regarding of the numerical approach, the thermo-structural analysis is performed using the commercial code ANSYS. The starting point of the analysis is the energy map on the component calculated using FLUKA code, which is converted in a thermal power distribution used as input for the solution of the thermal problem, so the temperature distribution is calculated as function of space and time. The results of temperature analysis are used as nodal loads for the structural analysis, so dynamic thermal stresses and displacements are evaluated. Finally, a quasi-static step is performed in order to calculate potential permanent deformations of the structure.

A similar approach is carried out in [8, 9], in which the energy calculation on the material resulting from high energy particles beam impact with a solid material is performed via MARS code [10]. From the energy map the temperature rise is calculated and used in LS-DYNA (for an explicit analysis) or ANSYS (for an implicit analysis) code to calculate the dynamic stresses in the target.

It is important to note that in these two approaches the calculation of the temperature from the energy map is performed without using an equation of state, but simply considering the transformation in a solid material and using as conversion factor the heat capacity at constant volume for the solid.

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 an equation of state is needed in order to correctly evaluate the state of the material.

In this sense there are [11, 12], in which the energy deposition is evaluated via FLUKA code and the energy is directly used as input in the hydrodynamic code BIG-2 in order to calculate pressure, temperature and density of the hit material. To do this a sophisticated three-phase equation of state is used. On the other hand, the approach developed in [11, 12] is not presented the deviatoric part of the stress that is indeed negligible in the part of the material closest to the beam impact point, while it is by no means negligible in the remaining portion of material.

The purpose of this study is to analyze simultaneously the two aspects: the deviatoric behaviour and the hydrodynamic one, using the FEM code LS-DYNA in which there is the possibility to insert an equation of state. In this sense a previous study is developed in [13], in which a coupled mechanical, thermal and electromagnetic simulation is performed. So, the problem is quite different, but the approach can be similar. In fact, also in [13] the problem is linked with a rise in temperature that can melt or vaporize a portion of material. The difference is the cause of the heating: the temperature does not rise due to the impact of a high energy

particle beam, but due to the Joule effect induced in material by a current. The simulations are performed via LS-DYNA code in which there is the possibility to implement an user-defined EOS. In [13] the three-phase equation of state GRAY is implemented and the input energy distribution comes from the electromagnetic solver.

Interaction between a particle beam and a solid target

As mentioned in the introduction, the energy stored in LHC is unprecedented and potentially destructive for the accelerator equipments having direct interaction with high energy particles. High energetic beams may interact with several components present in particle accelerators, so it is of primary importance to predict the extension of the possible damage.

Different thermal loads must be taken into account depending on the interaction condition. In normal situations, a continuous interaction provokes a constant energy-rate deposition over a long period (from some second 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 load 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. From this it is clear that an in-depth thermo-mechanical analysis is strongly necessary.

Fig. 1.1 Pressure distribution in case of impact between the high energy beam and a solid target (a); damage on a metal target due to the impact (b).

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 (see Figure 1.1).

In the material part closest to the beam, the pressure and temperature increase and the materials 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.

Equation of State and material model

As mentioned before, in order to completely describe the response of a material hit by a high energy particle beam both a strength material model and an equation of state are needed.

In the literature there are many material models that keep into account strain-rate and temperature influences on mechanical behaviour. Elasto-plastic models such those proposed by Johnson-Cook [14] and Cowper-Symonds [15] are the most used. In general in FEM codes there are also more complex models, such as Zerilli-Armstrong, but they request the identification of a larger set of parameters.

The material model chosen in these analyses is Johnson-Cook material model implemented in LS-DYNA code [5] and widely discussed in [16, 17, 18]. It is a purely empirical model that allows to take into account the effect of plastic strain, strain-rate and temperature. This model expresses the flow stress as

$$\sigma_y = \left(A + B \varepsilon_p^n \right) \left(1 + C \ln \dot{\varepsilon}^* \right) \left(1 - T^{*m} \right) \quad (1.1)$$

where A , B and n are the material strain hardening constants, C is the strain-rate parameter, m is the temperature sensitivity, ε_p is the effective plastic strain, $\dot{\varepsilon}^*$ is the effective total strain rate normalized by quasi-static threshold rate ($\dot{\varepsilon}_0$) and defined as

$$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \quad (1.2)$$

and finally T^{*m} is the homologous temperature defined by the relation

$$T^* = \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \quad (1.3)$$

in which T_{room} and T_{melt} are the reference temperature and the melt temperature, respectively. It can be notice that the Johnson-Cook model, in contrast with other model like the Steinberg-Lund model, does not include in its formulation the influence of the pressure on the flow stress.

Since the Johnson-Cook model is a multiplicative model (see equation 1.1) it considers the effects of strain, strain-rate and temperature independent, even if in the experimental dynamic tests the conversion of mechanical work into heat couples them and make them difficult separable. It is also important to note that when the temperature reaches the value of the melting temperature the mechanical strength of the material becomes zero. This means that the material loses its shear resistance and starts to be considered like a fluid.

The model is widely used in LS-DYNA calculations because it takes into account also the effect of the thermal softening, due to heat conversion of plastic work occurring at high strain-rate deformations. In fact, in this case the thermal diffusion can be neglected and the temperature rise can be evaluated under adiabatic assumption. Under this hypothesis and the further assumption of uniform stress the temperature can analytically computed as a function of plastic work as

$$T = T_{\text{room}} + \frac{\beta}{\rho \cdot C_p} \cdot \int_0^{\varepsilon_p} \sigma(\varepsilon, \dot{\varepsilon}, T) \cdot d\varepsilon \quad (1.4)$$

where ρ is the material density, C_p is the specific heat at constant pressure and β is the Taylor-Quinney coefficient [19, 20] that represents the portion of plastic work converted into heat (for metals about 0.9).

In LS-DYNA the Johnson-Cook material model includes also a fracture model in which the strain at fracture is given by

$$\varepsilon_f = \left(D_1 + D_2 e^{D_3 \sigma^*} \right) \left(1 + D_4 \ln \dot{\varepsilon}^* \right) \left(1 + D_5 T^* \right) \quad (1.5)$$

where 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

$$D = \sum \frac{\Delta \varepsilon_p}{\varepsilon_f} \quad (1.6)$$

reaches the value of 1. Besides the J-C material implemented in LS-DYNA offers also a spall model to represent the failure under hydrostatic tensile loads.

The other fundamental aspect to consider is the implementation of an equation of state to simulate the hydrodynamic material behaviour. 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) in function of two other independent state variables (such as density and internal energy).

In general the equations of state can be divided into two categories: analytical EOS and tabular EOS.

In LS-DYNA [5] the equations of state for metals are in general partitioned into two terms: a cold pressure and a thermal pressure (see equation (1.7)). The first terms $P_C(\mu)$ is a function of the density and is hypothetically evaluated along a 0 K isotherm, while the second one $P_T(\mu, E)$ depends on both the density and the internal energy per unit volume of the system

$$P(\mu, E) = P_C(\mu) + P_T(\mu, E) \quad (1.7)$$

where $\mu = \rho/\rho_0 - 1$. It is clear that for a compressed material $\mu > 0$, for an expanded material $\mu < 0$ and if no load is applied to the material $\mu = 0$. More precisely the EOS implemented have the general form

$$P(\mu, E) = A(\mu) + B(\mu)E \quad (1.8)$$

so the pressure is a general function of the density but linearly depending by the energy per unit volume.

An example of analytical equation of state implemented in LS-DYNA is the Mie-Grüneisen EOS, that is able to describe the behaviour of a solid material. It defines the pressure for compressed materials as

$$P = \frac{\rho_0 C_0^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2} \right) \mu - \frac{a}{2} \mu^2 \right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{1 + \mu} - S_3 \frac{\mu^3}{(1 + \mu)^2} \right]^2} + (\gamma_0 + a\mu)E \quad (1.9)$$

and for expanded materials as

$$P = \rho_0 C_0^2 \mu + (\gamma_0 + a\mu)E \quad (1.10)$$

where ρ_0 is the initial density, C_0 the sound speed, γ_0 the Grüneisen parameter that defines the effect on the atoms vibration consequent to the change in energy (or temperature), S_i are the coefficients of the polynomial that defines the shock wave velocity as function of particle velocity and a is the first volume correction to γ_0 .

Another possible form of an equation of state is the tabular form. For the construction of the tabular EOS several codes are developed, an example is EOSPro code [21]. In this particular case the EOS includes solid and fluid phases and the dependent variable (i.e. pressure or internal energy) is defined as function of independent variables (temperature and density), as shown in Figure 1.2.

Fig. 1.2 Tabular EOS of copper: internal energy and pressure in function of temperature and density [22]

Case study

In the present work the case study is the impact of 8 bunches at 7 TeV on a cylindrical copper bar that is 1 m long and 5 mm radius. The case study represents an abnormal situation in which the beam impacts directly against the solid target perpendicular to the base of the cylinder.

The energy deposition on the hit material is calculated by FLUKA code on the same geometry for a solid copper target. FLUKA provides the distribution on a 2D axisymmetric model counting 1000 elements both in radial and axial direction for the interaction with a single proton. In Figure 1.3 the specific energy deposition due to the impact with one bunch is plotted in function of the longitudinal coordinate at different radial positions and in function of the longitudinal coordinate at different transverse positions. As mentioned before, in each bunch there are 1.11×10^{11} protons and each bunch is 0.5 ns long and the time between two consecutive bunches is 25 ns so the total duration of the impact is about 179 ns.

Fig. 1.3 Energy deposition: (a) longitudinal distribution for different radii; (b) radial distribution for different longitudinal positions

FEM model

The model used in this simulation is a 2D axisymmetric model with the same geometry on which the FLUKA calculation is performed. It is chosen a 2D axisymmetric model because in LS-DYNA the complexity to realize 2D or 3D models is the same. Besides, in this way the comparison with the results obtained in [12] with the hydrocode BIG-2 is easier.

The energy distribution per unit bunch calculated by FLUKA code and deposited on the component is shown in Figure 1.4.

Fig. 1.4 FLUKA energy distribution (GJ/m³) for a single bunch (a); numerical model (b)

Four types of mesh are analyzed in order to investigate the influence of the spatial discretization on the results. The comparison is performed on the starting case in which the material is considered to remain solid, so the Mie-Grüneisen EOS is used for the pressure, energy and density calculations, and the energy deposition is approximated as an initial condition. The models that are simulated present the following elements densities: 25×25 , 50×50 , 100×100 and 200×200 elements in the radial and longitudinal directions. In Figure 1.5 the comparison is performed in terms of pressure history variable for two elements and Figures 1.6 and 1.7, re-

spectively, show the results in terms of pressure and density at the end of deposition. Obviously, there are some differences in the solutions due mainly to the FEM accuracy and the precision in the allocation of the FLUKA distribution in the numerical model.

Fig. 1.5 Comparison in terms of pressure (GPa) in two different nodes varying the mesh densities: (a) $r=0$ mm, $l=200$ mm; (b) $r=1.2$ mm, $l=400$ mm

Fig. 1.6 Comparison of the result obtained with different mesh densities in terms of pressure (GPa) at the end of deposition (179 ns)

Fig. 1.7 Comparison of the result obtained with different mesh densities in terms of density (kg/dm^3) at the end of deposition (179 ns)

The material model used in the simulations is the Johnson-Cook material model [5], and the input parameters are summarized in the Table 1.1.

Table 1.1 J-C parameters

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
E	1.11×10^{11}	Pa	C_p	383	J/(kg K)
ν	0.3406	-	$P_{\text{cut-off}}$	1×10^1	Pa
A	9.00×10^7	Pa	D_1	0.54	-
B	2.92×10^8	Pa	D_2	4.89	-
n	0.31	-	D_3	-3.03	-
C	0.025	-	D_4	0.014	-
$\dot{\epsilon}_0$	1.00	s^{-1}	D_5	1.15	-
m	1.09	-			

In LS-DYNA code there isn't the possibility to use a tabular equation of state in the same form of that is calculated in [22]. To solve this problem, the code offers the possibility to implement an user-defined EOS. In this work a standard polynomial EOS is used to fit the tabular data to evaluate a simplified approach

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (1.11)$$

The multi-phase EOS for copper is well described in [22] and represented in Figure 1.2 and 1.8.a. In order to obtain the correct interpolation with the equation 1.11 a new plot is created drawing the function $P=P(E)$ for each density (see Figure 1.8.b).

The relation between P and E for a fixed ρ could be approximate with a generic function in E . Since the standard formulation (see equation 1.11) is linear with the energy the approximation will be more or less coarse depending on the energy range considered.

Table 1.2 EOS parameters (solid phase)

C_0 (Pa)	C_1 (Pa)	C_2 (Pa)	C_3 (Pa)	C_4 (-)	C_5 (-)	C_6 (-)
2.079×10^7	1.377×10^{11}	1.256×10^{11}	1.454×10^{11}	1.940	0.585	1.125

Fig. 1.8 Copper EOS in the region of interest: (a) P - ρ as function of temperature; (b) P - E as function of density

Below there is the description of the interpolation methods used to get the polynomial coefficients to set as numerical simulation inputs.

The first set of simulations is performed assigning to all elements the parameters extracted from the interpolation of the solid phase data (see Figure 1.9.a) and presented in the Table 1.2. In this case the region of interest, for what concerns the interpolation, is limited between 9000 and 12000 kg/m³ in density and 5 and 1360 K in temperature. As it could be expected interpolation is good in high density and low energy range which includes the solid matter behaviour, while in the other parts it is very coarse. Obviously, the consequence in the simulations results will be the pressure overestimation in the elements that will reach low density and/or high energy values.

In order to check the method of procedure for the solid coefficients the comparison with the Mie-Grüneisen equation of state is performed and the results obtained with this two formulations are equivalent.

Fig. 1.9 Results of polynomial interpolation: (a) solid phase; (b) entire tabular data

Then a second set of simulations is performed using the parameters extracted considering the whole region of interest. In this case the density is between 4000 and 12000 kg/m³ and the temperature is between 5 and 27000 K. The fit is carried out in two phases. First, the curve $P-\mu$ at 5 K is interpolated to obtain the coefficients of the cold curve $P_C(\mu)$ (see expression 1.11). Then the coefficients for the $P_T(\mu, E)$ are get fitting with a second-order polynomial the slopes calculated from the linear interpolation in energy on the tabular data. The results in term of pressure in function of density varying the energy is shown in Figure 1.9.b. Comparing this with the Figure 1.8.a, it is clear that the approximation is quite good except for the phase transition. The parameters are summarized in the Table 1.3.

Table 1.3 EOS parameters (entire tabular data)

C_0 (Pa)	C_1 (Pa)	C_2 (Pa)	C_3 (Pa)	C_4 (-)	C_5 (-)	C_6 (-)
-2.176×10^8	1.113×10^{11}	3.019×10^{11}	2.088×10^{11}	1.076	1.667	-0.039

In Figures 1.10 and 1.11 there are the results obtained with the two different sets of parameters at two different time steps. The simulations are performed on the 50×50 elements mesh under the assumption that the energy deposition can be approximated as an initial condition.

As mentioned before, the use of the equation of state obtained fitting the solid phase data respect to the equation of state related to the entire tabular data produces a great pressure overestimation. In fact, for example, for a fixed time the pressure obtained in the first case is approximately twice the pressure in the second one. Besides, you can see that for a fixed time the pressure and density profiles get deeper in the component in the radial direction with the solid interpolation: this is due to the difference of the shock-wave speed, consequent to the variation in the bulk modulus.

Fig. 1.10 Pressure and density evolutions obtained for the simulations performed using for the EOS definition the parameters extracted fitting the solid phase tabular data

Fig. 1.11 Pressure and density evolutions obtained for the simulations performed using for the EOS definition the parameters extracted fitting the entire tabular data

Energy deposition method

The energy deposition is simulated by using three different methods:

- the energy stored in 8 bunches is applied to the component as an initial condition;
- the time-energy profile is a 204 ns ramp (constant power);
- the time-energy profile is the sequence of the 8 bunches: each of them is 0.5 ns constant power and 25 ns void.

The way to reproduce an energy deposition in LS-DYNA is defining for each element (or for all the elements in which the energy level to be deposited falls within a certain range) a specific equation of state with the corresponding deposition time-history.

in Figure 1.12 the comparison between the different deposition methods is focalized on the pressure time history in two different elements. The comparison is carried out for a 50×50 elements mesh with the EOS coefficients obtained from the fit of the entire tabular equation of state. In Figure 1.13 there is the comparison in term of pressure at three different time steps for the extreme cases (initial condition and bunches profile). As it can be seen, if the energy is transferred to the material as an initial condition it produces an overestimation of the pressure, while if the correct bunches profile is used the pressure level reached is lower because the material has the time (25 ns of void) to expand and reduce its pressure.

Fig. 1.12 Comparison of the pressure time history in two elements for the different load cases: (a) $r=0.55$ mm, $l=250$ mm; (b) $r=3.85$ mm, $l=250$ mm

From the Figure 1.12 it is clear that the ramp and the bunches profiles generally produce the same results except for the deposition duration (about 179 ns). In fact, during the deposition, there are some diversities due to the different deposition methods, but in both cases the maximum energy level reached is the same and so the material behaviour after the end of deposition is quite similar.

Fig. 1.13 Comparison in terms of pressure (GPa) at three different time steps in case of energy deposition as initial condition (on the left) and with the bunches profile (on the right)

Results discussion

In this section the attention is focused on the results of the numerical simulation performed with 50×50 elements mesh, the EOS coefficients obtained fitting the entire tabular EOS data with the polynomial formulation and the bunches deposition profile. This configuration appears to be a model sufficiently adequate and representative of the evolution of the phenomenon. Figure 1.14 shows the results in terms of pressure, density and Von Mises stress at different time steps.

Fig. 1.14 Numerical results: pressure, density and Von Mises stress at four different time steps during the phenomenon evolution

Regarding the pressure, the energy deposition delivered after the impact of 8 bunches produces a very high level of pressure: a maximum value of 46.9 GPa at the end of deposition phase while the maximum value reached at a radius of 5 mm is about 17.2 GPa (after 1.05 μ s).

The impact generates the outgoing of shock waves that travelling the component produces a density reduction in the central part of the cylinder. It is highlighted by Von Mises stress distribution that over than 50% of the target is melted

(in this part the temperature exceeds the melting value so the stress flow calculation goes to zero). The remaining portion of the material is heavily plastically deformed consequent to the stress wave propagation.

In order to verify the likelihood of the solution it is compared (see Figure 1.15) with the results obtained in [12], in which the simulations are performed via a 2D hydrodynamic code BIG-2, which is developed to solve this kind of problems. Besides, in [12] a more accurate tabular equation of state is used to describe the hydrodynamic response of the material. The comparison is done using the same scale of values for the view and it represents the end of deposition phase. As you can see the comparison is quite good and the differences may be due to the simplifications made in this work and well discussed before.

Fig. 1.15 Results comparison between 2D hydrocode BIG-2 [12] and LS-DYNA simulations: pressure, density and temperature at the end of deposition phase

Conclusions

This study is performed in order to estimate the damage on a copper component due to the impact with a 7 TeV 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 is calculated using the FLUKA code and then used as input in the numerical simulation, that are carried out via the FEM code LS-DYNA. Different numerical models are realized trying to obtain the simplest model able to correctly describe the material response without affecting the goodness of the results. The most suitable, in terms of accuracy of the results and

computational speed, is found to be the model with 50×50 elements mesh, the EOS coefficients obtained fitting the entire tabular EOS data with the polynomial formulation and the bunches deposition profile. This configuration appears to be a model sufficiently adequate and representative of the evolution of the phenomenon.

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 is described using a polynomial equation of state obtained fitting a tabular EOS data, while the elasto-plasticity response is treated using the Johnson-Cook material model.

The material closed to the beam heated region reaches high value of pressure (46.9 GPa after the irradiation of 8 bunches) and can melt or vaporize. In this part the simulation indicates a reduction in density (until 4500 kg/m^3) due to the radial shock waves travel. When the pressure shock wave reaches the radius of 5 mm about the 50% of the component is damaged. The remaining portion of the material is subjected to high stress, plastic deformation, strain-rate and temperature even it is still solid.

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