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Effects of high-energy intense multi-bunches proton beam on materials

M. Scapin [a,*], L. Peroni [a], V. Boccone [b,1], F. Cerutti [b]

[a] Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy
[b] CERN, EN-STI-EET, CERN, CH-1211 Geneva 23, Switzerland

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ABSTRACT

The prediction of material response in case of interaction with successive high energy proton bunches requires new tools and multidisciplinary approaches. The impact leads the propagation of shock-waves, which travels through the hit component causing a substantial density reduction and the appearance of tunneling effect along the beam direction. For taking into account this effect, an automatic procedure, consisting in coupling FLUKA Monte-Carlo and FE LS-DYNA codes, is developed. The case study consists of the accidental loss of 60 bunches of one of the 7 TeV proton beams of the Large Hadron Collider (CERN) on a tungsten collimator.

1. Introduction

The Large Hadron Collider (LHC) [1] is the most powerful particle accelerator in the world. It was built by the European Organization for Nuclear Research (CERN, Geneva) and 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. The LHC can accelerate and collide two protons (or Pb ions) beams to a nominal energy of 7 TeV/c (2.76 TeV/u for Pb ions). The LHC beams are segmented in train of bunches with 25 ns spacing. The nominal LHC beam is composed by 2808 bunches, each with 1.15×10^{11} protons. In this case each beam carries a total energy of about 350 MJ, two orders of magnitude higher than the other large accelerator machines like Tevatron or HERA.

The involved amount of energy is sufficient to melt 500 kg of copper, and is potentially destructive for any accelerator components having direct interaction with the beam (e.g. the collimation system) in case of uncontrolled beam loss. For this reason, it is needed to provide a realistic assessment of possible structural damage of the components in case they are interested by a partial or total accidental beam loss. An accurate prediction of the reliability and robustness is quite difficult, since beam-induced damages for high energy and intensity occur in a regime in which the possibility to perform experimental tests is limited. For this reason, it is of fundamental importance to develop detailed procedures, reliable methods and accurate models that could be efficiently applied to estimate the damage occurring during a beam impact.

The evaluation of thermal loads on the material is performed using the energy deposition maps, obtained by the FLUKA particle transport and interaction Monte-Carlo code [2,3]), as input for a thermo-mechanical analysis. In order to correctly simulate the response of the material it is necessary to take into account both the hydrodynamic behavior, using a dedicated Equation Of State (EOS), and the deviatoric behavior, using a dedicated strength material model. The numerical simulations are performed using the LS-DYNA [4] commercial code. LS-DYNA is a general purpose transient dynamic finite element program including an implicit and explicit solver with non-linear thermo-mechanical capabilities. This code is often used to solve impact problems also for nuclear applications and particle accelerator technology (see e.g. [5–7]). For the simulations, the chosen equation of state is a polynomial form, in which the coefficients are obtained fitting a multiphase tabular equation of state, and the material model is the Steinberg–Guinan (S–G) model.

The inelastic interaction of a High Energy (HE) particle of the beam with the target atomic nuclei initiates a shower of secondary particles. The energy deposited in the material produce a dynamic response of the structure entailing thermal stress waves and thermally induced vibrations or even the failure of the component. The evolution of the phenomenon is quite similar to what might

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* Corresponding author. Tel.: +39 011 090 3540.
E-mail addresses: martina.scapin@polito.it (M. Scapin), boccone@cern.ch (V. Boccone), francesco.cerutti@cern.ch (F. Cerutti).
URLs: http://www.polito.it (M. Scapin), http://www.cern.ch (V. Boccone), http://www.dpnc.unige.ch (F. Cerutti).

[1] On leave for Université de Genève, Département de Physique Nucléaire et Corpusculaire, 24 Quai Ernest-Ansermet, CH-1211 Genève 4, Switzerland.

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happen during an explosion. The regions where the energy deposition is dominant can reach extremely high values of pressure and temperature and might undergo changes of state. The sudden increase in pressure originates outgoing shock-waves that, travelling through the component, lead to a substantial density reduction in the interested part, thus leading to the appearance of tunneling effect mostly along the beam direction that changes the mechanical properties of the impacted material and *de facto* reduces the effectiveness of its shielding properties. This effect becomes more and more significant increasing the intensity of the beam that can be done by increasing the number of particles per each bunch or by increasing the number of bunches. In the case examined in this work, the authors change the number of bunches and fix the bunch population to the nominal LHC beam (1.15×10^{11} protons per bunch).

The energy deposition maps strongly depend on the material density therefore, when a significant reduction in density occurs during the FEM simulation, the FLUKA calculation performed at the beginning is no longer reliable and must be repeated using the updated density map. This aspect is fundamental for the correct evaluation of the consequences caused on the material hit by several HE proton beam bunches.

For this purpose, in this work a new methodology developed for the realization of the soft coupling between FLUKA and LS-DYNA is presented. The procedure involves the iterative execution of both codes independently under the assumption that the energy is instantaneously deposited by the proton beam ignoring any thermo-mechanical variation of the target during the FLUKA calculation and alike ignoring any energy absorption during the mechanical analysis.

The procedure starts with the calculation of the energy deposition map in the material at equilibrium that corresponds to the first bunch of the train. This distribution is used as an input for the LS-DYNA simulation that generates, in turn, an evolved density map that is passed to FLUKA. As the evolution of the material is slow compared to the bunch spacing (25 ns) and width (1 ns), the frequency of the FLUKA calculation can be adapted to the effective variation of the material density profiles with the successive bunches. The process can be iterated as long as the thermodynamic conditions are in the range where information available on the material models is reliable. In order to achieve a suitable spatial resolution of the FLUKA simulation the authors implement a voxel (3D pixel) model of the material, where the density of each voxel can be changed independently. Consequently, a 3D model is used also for FEM analysis.

In the next section the authors briefly review the state-of-the-art in this field and report on similar approaches performed by other groups. Moreover, the influence of the density on the energy absorption in the matter is discussed giving also the reasons that are at the basis of the development of the coupling procedure. Its step-by-step description is presented in Section 3 together with the results, compared with the ones obtained in the same case study for a non-coupled analysis. Conclusions are summarized in Section 4.

2. Response of a material impacted by an intense HE particle beam: background

Several studies were performed with the main goal of understanding the response of a solid (or liquid) material at equilibrium suddenly impacted by an intense HE particle beam (proton, ions or electrons). Many of the recent works deal with the same case study here presented as they were motivated in the context of the LHC collimation project [8] and aimed at the analysis of the consequences of intense HE beam losses on different materials [9–15]. Although with different methodologies, all these works address the problem of a facially irradiated cylindrical target. In this loading condition, the material pressure and temperature in the hit zone grow up reaching very high values and generating an outgoing radial shock-wave.

The case study analyzed in [9,12] represents a potential accidental case, in which 8 proton bunches at 7 TeV/c impact directly at the center of one basis of a copper cylinder. The numerical investigation was a Lagrangian explicit 2-D axis-symmetric analysis performed in LS-DYNA. In those works a first preliminary study was performed in which the influence of the mesh and EOS was investigated. In [12] an assessment on the damages induced by the beam was performed and finally in [9] a more sophisticated study was carried out. In both cases the analyses were intended to obtain preliminary results useful to understand the evolution of the phenomenon. In [13,14] the analysis was performed on tungsten both in 2D and 3D cases. The 3D case regards the impact on the tungsten inset of the tertiary collimator (Target Collimator Tertiary, TCT) jaw. Eight LHC proton bunches at an intermediate energy of 5 TeV/c were assumed to hit parallel to the tungsten surface with an impact parameter of 2 mm. The same case was also analyzed using the FE code AUTODYN, as reported in [15].

As for the present work, also in [9,12–14] a thermo-mechanical simulation was done, taking into account both hydrodynamic and deviatoric behavior of the material, with a multi-phase EOS and with a dedicated elastic-visco-plastic strength model, respectively. The input for the FEM analyses was the 2D axis-symmetric distribution of deposited energy by FLUKA, which was considered unchanged during all the duration of the simulation. The authors identified this as the weak point of the work. As a matter of fact, although a significant reduction in density was found, this was not taken into account in the FLUKA calculation.

Several studies by Tahir and co-authors (see e.g. [9,10]) were also trying to assess the problem of simulating HE beam impacts for LHC related applications for different materials (carbon, copper and tungsten), target dimensions and beam parameters (particle energy, beam dimensions, number of bunches, beam intensity, etc.). Their method involved the generation of a unique initial energy deposition map with FLUKA while the material response was numerically simulated via the BIG-2 simulation code [16]. In the authors' opinion their approach has some limitations. First BIG-2 is only a two-dimensional code with a pure hydrodynamic solver, second the evolution of the point-wise density fluctuations (increase or decrease) was taken in account only approximately, by scaling the energy map with the local density variation obtained along the axis of the cylindrical target. This type of approach, as opposed to the one here developed, neglected the strong relationship that links the point-wise density variation with the shock-waves generation and transport.

In a recent work Tahir et al. [17] described a procedure (using the above mentioned codes) to better evaluate the density variation effect on the energy deposition in matter by modifying the local material density in the target core ($r_{\text{core}} \sim r_{\text{beam}}$) according to the values obtained by the BIG2 code. The two codes are then run iteratively. To save computational time a FLUKA calculation is only performed every time the density changes of about 20–30%. Unfortunately, no more details on the technical aspects of the procedure (size and shape of the elements, errors on the energy deposition, etc.) are presented.

In the present work, a similar approach is applied for the soft coupling between FLUKA and LS-DYNA codes. A detailed description of the procedure is reported, with the aim to highlight its advantages. First of all, this method can be applied to simulate both hydrodynamic and thermo-mechanical responses in case of 3D structures. Moreover, it allows to take into account the effects of the localized change in density for each element of the numerical mesh.