V International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2013
S. Idelsohn, M. Papadrakakis and B. Schrefler (Eds)

A LS-DYNA/FLUKA COUPLING FOR THE NUMERICAL SIMULATION OF HIGH ENERGY PARTICLE BEAM INTERACTION WITH MATTER

MARTINA SCAPIN[*], LORENZO PERONI[*], VITTORIO BOCCONE[†,♦] AND FRANCESCO CERUTTI[†]

[*] Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129 Turin, Italy
e-mail: martina.scapin@polito.it, web page: http://www.polito.it

[†] CERN, EN-STI-EET
CERN, CH-1211 Geneva 23, Switzerland
Email: francesco.cerutti@cern.ch - Web page: http://www.cern.ch

[♦] on leave for Université de Genève,
Département de Physique Nucléaire et Corpusculaire
24 Quai Ernest-Ansermet, CH-1211 Genève 4, Switzerland
Email: boccone@cern.ch - Web page: http://dpnc.unige.ch

Key words: high energy deposition, cylindrical shock-wave, density variation, FLUKA, LS-DYNA.

Abstract. The interaction between intense high-energy particle beams and materials provokes a sudden non-uniform temperature increase. This induces a dynamic response of the structure entailing the generation of shock-waves, which start to travel in the component producing a strong reduction in density in the impacted zone. FLUKA is a numerical tool for the calculation of the energy delivered in matter based on the Monte-Carlo method. LS-DYNA is a non-linear FE explicit code, which can use as input for the thermo-mechanical analysis the results from FLUKA code.

In this work a soft-coupling method between the two codes is developed and applied for the numerical simulation of an accidental impact of a multi-bunch 7 TeV proton beam of LHC on a metallic collimator insert. The FLUKA model was obtained using a voxel structure approach, while the FEM simulation was a 3D Lagrangian analysis. The FLUKA energy distribution, calculated on the initial geometry, is updated in accordance with the density modification during the simulation. As a matter of fact, the next bunches will impact against a lower mass target and can penetrate more in depth in the material.

These effects were evaluated with an iterative soft-coupling of the two codes, performed in Matlab. The number of the primary protons that need to be simulated determines the precision of the FLUKA results. The first FLUKA simulation, performed with an unmodified material, is followed by the first FEM mechanical analysis. At this point, at each step, the algorithm: takes as input the density map resulting from the FEM calculations, re-defines the regions

with different density in the target material, using the voxel structure and then runs a new FLUKA calculation which will be used as input for the next step FEM analysis (and so on).
The first results confirm that the density reduction in the maximum deposition area provokes a reduction in the particle beam/matter interaction with a reduction of deposited energy and a sort of tunnelling effect. In more details, the peak of the energy deposition moves into the component along the direction of the beam. The comparison with the uncoupled case shows that also the pressure is affected: the maximum value decreases since the shockwave penetrates more into the material. The results also show that to be able to appreciate the difference between coupled and uncoupled analysis, it is necessary to obtain a quite significant density reduction: this occurs when the shockwaves has the time to travel radially away from the hit zone producing a significant rarefaction.

1 INTRODUCTION

Large Hadron Collider (LHC) is the most powerful particle accelerator in the world and can accelerate two proton or ion beams up to an energy of 7 TeV/c and 2.76 TeV/u respectively [1]. The LHC was built by the European Organization for Nuclear Research (CERN) in a circular 27 km long tunnel about 100 meters underground the border between France and Switzerland. 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 other large accelerator machine like Tevatron or HERA. This large amount of energy, sufficient to melt 500 kg of copper, 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 a fraction of the full beam is lost on them. 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 reliable methods and accurate models that could be efficiently applied to estimate the damage occurring during a beam impact.

When a High Energy (HE) 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 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 fact that the amount of energy absorbed by the matter is strongly density dependent implies that if a significant reduction in density occurs, this aspect has to be considered in order to correctly evaluate the consequences caused on the material hit by several high energy proton beam bunches. The main consequence is the generation of a tunneling, which implies that the proton beam penetrates more in depth in the hit target. Obviously, the effects become more and more appreciable and significant increasing the number of bunches considered impacting against the target. The main objective of this work is

to describe a methodology to be applied for taking into account for this phenomenon.

The evaluation of thermal loads on the material is performed using the energy deposition maps obtained by FLUKA (a particle physics MonteCarlo simulation package, [2, 3]) as input for a thermo-mechanical analysis, performed using the commercial code LS-DYNA [4], which is a general purpose transient dynamic finite element program including an implicit and explicit solver with thermo-mechanical and highly non-linear capabilities.

Several studies were performed with the main goal of understanding the phenomenon evolution in case of energy deposition in the matter consequent to the impact of a high energy particle beam and a solid component. Recently Tahir et al. [5] described a procedure for taking into account the influence of the density variation of the material on the overall energy deposition of the impinging. Their method involves the coupling between the FLUKA and the hydrodynamic BIG2 code. The energy maps calculated by FLUKA code is used in the BIG2 code to study the corresponding thermodynamic and the hydrodynamic response of the target that leads to a reduction in the density. The modified density distribution is used in FLUKA to calculate new energy loss distribution and the two codes are thus run iteratively. A FLUKA simulation is performed every time the density along the target axis changes of about 15-20%. Unfortunately, no more details on the technical aspects of the procedure are presented.

2 NUMERICAL MODELS

The amount of energy deposited in a material by a high energy proton beam, as well as the penetration or stop lengths, is strongly affected by the density of the material itself.

The density influences the probability of the interaction between particles and matter, playing a key role in the calculation of the proton energy loss in case of impact against a target. This implies that two materials subjected to the same impact condition, but with different Z numbers, experience different energy absorption. In particular, higher the atomic number (Z number) of the material, then higher its energy absorption. Besides, it means also that, for the same material, if there is a density modification, it should be taken into account in order to recalculate the energy deposition on the material in these new conditions.

To take in account those effects, a soft coupling between FLUKA [2, 3] and FE code LS-DYNA [4] is developed, in collaboration between Politecnico di Torino and FLUKA Team at CERN. The routine is implemented in Matlab and automatically, runs FLUKA and LS-DYNA on a Linux platform (Fedora14).

The method is applied to simulate the beam impact against a tungsten geometry, which represents a parallelepiped of 21×35×1000 mm. The mesh is such that 21×35×200 elements are used, so the elements dimensions are 1×1×5 mm. The same discretization is used both for FE and FLUKA models. For the FLUKA calculations a voxel-based method [6] is used to build the model, while for the thermo-mechanical simulation in LS-DYNA Lagrangian 3D solid elements with one integration point are used. The scheme of the LS-DYNA model is reported in Fig. 1.

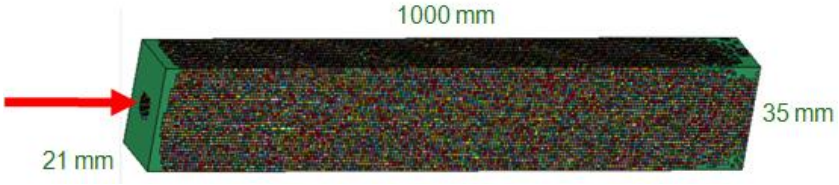

Figure 1: 3D numerical model (for the LS-DYNA calculation) of a parallelepiped made in tungsten used for the simulation of a multi-bunch impact. (x,y,z): 21x35x1000 mm

The FLUKA calculation is performed for a proton bunch at 7 TeV. The beam dimensions are taken from the realistic Tertiary Collimator (TCT) accidental scenario (left of the IR5) interaction region, where the full width at half maximum of the beam are 0.12 cm and 0.076 cm along the x and y axis, respectively. For each step, a total of about 20000-30000 primaries are simulated. The time required for the simulation is reduced by splitting the CPU-demanding tasks over about 30-40 CPU cores.

In order to correctly simulate the thermo-mechanical 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. For these simulations the chosen equation of state is a polynomial form, in which the coefficients are obtained fitting a multi-phase tabular equation of state taken from the SESAME library [7], and the material model is the Steinberg-Guinan (S-G) model [8].

3 PROCEDURE DESCRIPTION

The methodology developed for the soft coupling between the two codes implies that, first of all, a sufficient number of primaries, needed to achieve a good precision on the energy deposition and beam size and intensity are defined. Then, the first FLUKA calculation is run, considering that the entire target is solid. As next step, the first FE mechanical analysis is run. At this point the iterative procedure starts and will terminate when the desired number of bunches impact against the target. Each iteration contains the total duration of a bunch pulse: the deposition phase (0.5 ns) and the successive free phase (25 ns). In this work the impact of a maximum number of 60 bunches is simulated. At each iteration, the coupling algorithm:

- takes as input the density map resulting from the FE calculation and defines discrete density levels: each level corresponds to an independent FLUKA material;
- defines, using a voxel structure, the regions with different density in the target block and associates to each voxel the corresponding material with the correct density;
- stores the energy deposition for each voxel, and runs the new FLUKA simulation;
- takes as input the energy map resulting from FLUKA calculation and defines discrete energy levels;
- generates the new FE model, associating to each FE element the corresponding energy and interpolating the SESAME EOS for getting the polynomial coefficients for each element (see e.g. [9, 10]);
- restarts the mechanical LS-DYNA simulation for the next bunch;

• analyzes the results in order to get the density map for the construction of the new FLUKA model.

The update of the FLUKA map can be performed at each bunch, but preliminary studies suggested that updating every 5 bunches is sufficient to obtain stable results.

4 RESULTS

In Figs. 2-4, some results of the numerical analysis are reported in the *x*-*z* section of the target. In more details, the results are in terms of energy calculated by FLUKA, pressure and density maps, corresponding to the bunches number 1, 10, 20, 30, 40, 50 and 60. The results are shown for the end time of each simulation (after the free phase in which there is not the deposition, 25 ns).

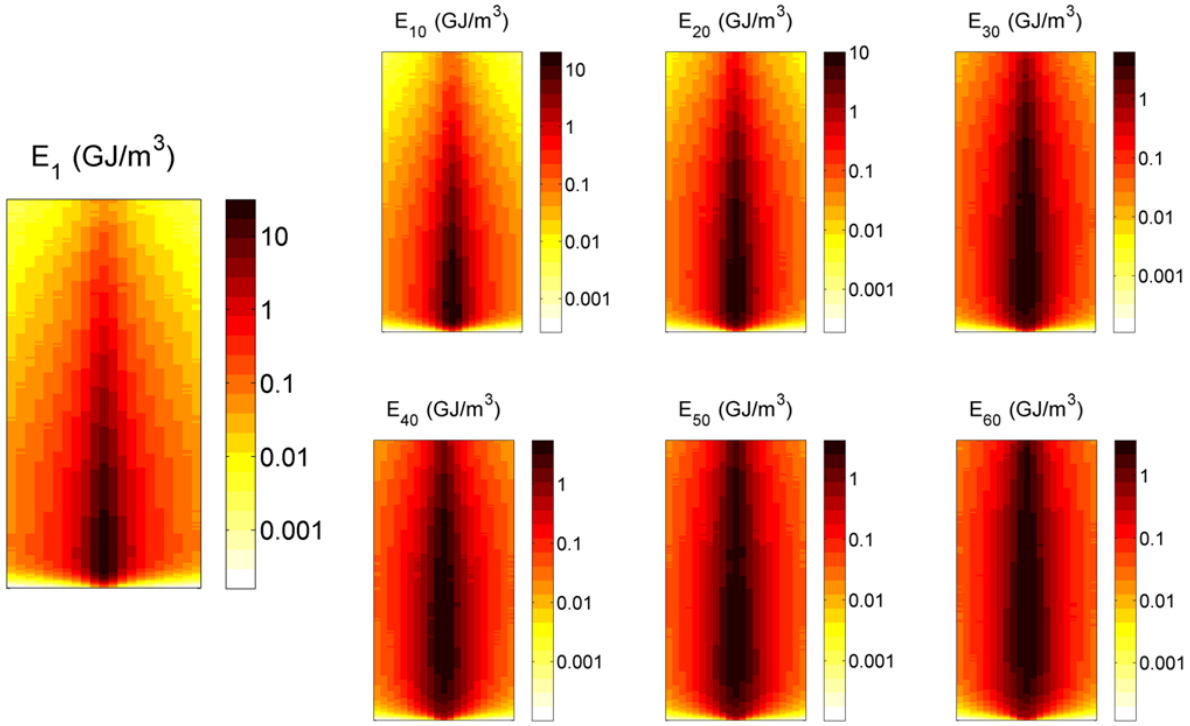

Figure 2: Energy distribution on the tungsten target in the *z* (↑)-*x* (→) section corresponding to the maximum energy deposition in the *y* direction: results for the bunches number 1, 20, 30, 30, 40, 50 and 60 after the free phase (the *x* dimension is amplified)

Looking the results of Fig. 2, it is possible to notice that the energy distribution on the target changes, both in values and shape, during the deposition phase. This is a direct consequence of the density variation, reported in Fig. 3. As a matter of fact, the material, in which a great amount of energy is deposited, is subjected to a significant density reduction during the free expansion phase, in which the shock-wave propagates. This implies that the material becomes more transparent to the particles of the next bunch and the shower generated by the interactions of the bunch itself with the material. This provokes the so called tunnelling effect. The consequences of this are that the proton beam penetrates more in depth

in the material in the axial (z) direction (beam direction) and the energy is more diluted over the target.

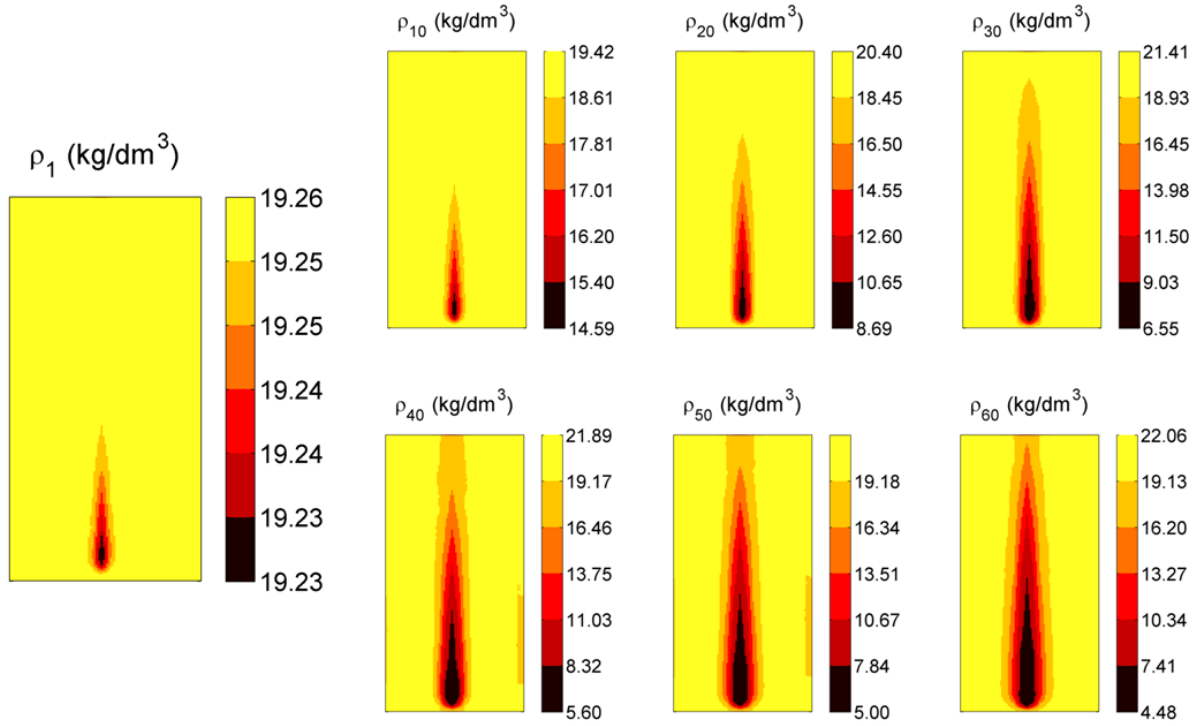

Figure 3: Density distribution on the tungsten target in the z (↑)-x (→) section corresponding to the maximum energy deposition in the y direction: results for the bunches number 1, 20, 30, 30, 40, 50 and 60 after the free phase (the x dimension is amplified)

The results in terms of density emphasize the tunnelling: the density modification involves higher longitudinal coordinates increasing the number of bunches. After 60 bunches the total length of the target experiences a reduction in density in the zone around the beam axis.

The results in terms of pressure (Fig. 4) show that the maximum of pressure remains more or less in the same longitudinal position with respect of the first bunch, but the pressure wave starts to travel in the x direction. Since the pressure wave generated is cylindrical (due to the shape of the energy deposition), the same happens also in the y direction. The fact that the energy deposited by the following bunches is lower and more widespread, with respect to that calculated for the first bunch impacting the solid material, implies that the pressure increment, consequent to the next bunches, is reduced in the zone, in which the first bunch deposited a great amount of energy. On the other hand it should increase in the part of the target, in which there is an increment in density.

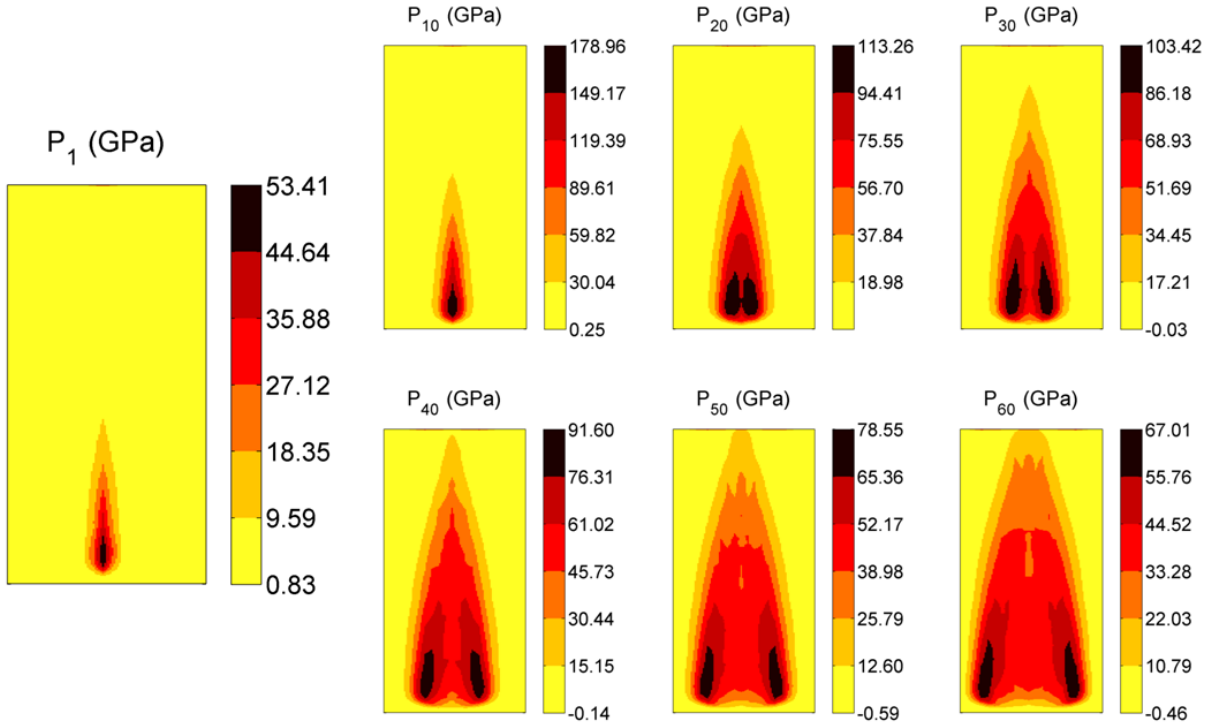

Figure 4: Pressure distribution on the tungsten target in the z (↑)-x (→) section corresponding to the maximum energy deposition in the y direction: results for the bunches number 1, 20, 30, 30, 40, 50 and 60 after the free phase (the x dimension is amplified)

5 CONCLUSIONS

In this work a new methodology is applied for the numerical simulations of the multi-bunch impact of the LHC beam on a solid tungsten target. The idea was to realize a soft coupling between the FLUKA code, used for the evaluation of the thermal load on the target, and the FE code LS-DYNA, used for evaluating the thermo-mechanical response. The routine for the coupling was developed in Matlab and iteratively runs the two codes on the same Linux platform.

The main objective was to build a reliable numerical tool for predicting the consequences on the target of the tunnelling effect, produced by the propagation of the cylindrical shock-wave, generated by the impact. The shock-wave propagation leads to a substantial density reduction in the impacted part of the target, which has to be taken into account due to the fact that the amount of energy absorbed by the matter is strongly density dependent. The update of the FLUKA calculation is performed every 5 bunches, to which corresponds a significant density reduction.

The results obtained showed that the procedure is able to describe evolution of the tunnelling effects. As a matter of fact, the energy distribution over the target changes, both in values and shape, during the deposition phase: the material, in which a great amount of energy is deposited, is subjected to a significant density reduction and becomes more transparent to

the next proton bunch, reducing the amount of absorbed energy. The consequences are that the proton beam penetrates deeper in the material in beam axis direction and the energy is more diluted over the target.

REFERENCES

[1] Petterson TS, Lefèvre P. *The Large Hadron Collider: conceptual design*. CERN Desktop Publishing Service, Geneve (1995)

[2] Battistoni G, Muraro S, Sala PR, Cerutti F, Ferrari A, Roesler S, Fasso` A and Ranft J, *The FLUKA code: Description and benchmarking*. Proceedings of the Hadronic Shower Simulation Workshop (2006), Fermilab 6--8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)

[3] Fasso A, Ferrari A, Ranft J and Sala PR *FLUKA: A Multi-Particle Transport Code*. CERN-2005-10, INFN/TC_05/11, SLAC-R-773 (2005)

[4] Gladman B et al *LS-DYNA® Keyword User's Manua*l – Volume I – Version 971. LSTC (2007)

[5] N.A. Tahir et al. *Impact of high energy high intensity proton beams on targets: Case study for Super Proton Synchrotron and Large Hadron Collide*r. Physical Review special topics – Accelerators and beams, 15 (2012)

[6] *Voxel and medical applications*, 7th FLUKA course (2008)

[7] Kerley, G.I., *Equations of State for Be, Ni, W, and AU*, SANDIA REPORT SAND 2003-3784 (2003)

[8] Steinberg, D.J., Cochran, S.G. and Guinan, M.W., *A constitutive model for metals applicable at high-strain rate*. Journal of Applied Physics, 51:1498 (1980).

[9] Scapin M., Peroni L. and Dallocchio A., *Effects induced by LHC high energy beam in copper structures,* Journal of Nuclear Material 420: 463-472 (2012).

[10] Scapin, M., Peroni, L., Dallocchio, A., Bertarelli, A, *Shock loads induced on metal structures by LHC proton beams: Modelling of thermo-mechanical effects,* Applied Mechanics and Materials, vol. 82, pp. 338-343 (2011).