SHOCK WAVE PROPAGATION NEAR 7 TEV PROTON BEAM IN LHC COLLIMATOR MATERIALS *

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Abstract

A theoretical model and numerical calculations are developed to estimate consequences of the impact of a 7 TeV proton beam on the physical-mechanical properties of materials used in the LHC, for example graphite used for collimators, and copper. Each 7 TeV proton beam consists of 2808 bunches with $1.1x10^{11}$ protons per bunch. In our calculations we assume a bunch length of 0.5 ns and a bunch spacing of 25 ns. The high energy stored in each bunch can produce a shock wave in these materials.

The theoretical model for the investigations of shock wave propagation in the collimator materials takes into account ionization, electronic excitation, and energy transfer from excited electronic subsystem of material to the ionic subsystem. The changes of some physical properties of the collimator materials during shock wave propagation are considered here. The deposited energy is calculated with FLUKA [1].

The first numerical results are presented here to show the possibilities of developed computer program and to test it in the calculations of microstructure changes in materials produced by shock wave propagation for different numbers of bunches for some deposited energy. This allows investigating the changes of density and internal pressure, temperature profiles in electronic and ionic subsystems of materials near the front of shock wave. This program will be used in the future for the understanding of behaviour of collimator materials used in LHC under 7 TeV proton beam in accident cases.

CALCULATIONS OF DEPOSITED ENERGY IN COLLIMATOR MATERIALS

The interaction of a 7 TeV proton beam with material results in a formation of secondary fast particles due to electromagnetic cascades and nuclear reactions of protons with target atoms. The slowing down of these secondary particles in materials leads to an accumulation of very high energy close to the beam and to formation shock wave and radiation damage. As a first step in this study, we consider here only a shock wave formation in the materials for some deposited energies. The study discussed here is considered to be complementary to the study presented in [2], and will in the future concentrate also on radiation damage. For understanding the effect of the beam irradiation on collimator materials of LHC, the deposited energy by the proton beam in electronic and ionic subsystems of these materials should be determined. For these calculations the FLUKA program [1] can be used. FLUKA is a Monte Carlo code to simulate transport and interaction of electromagnetic and hadronic particles in any target material in a wide energy interval.

Deposited energy due to energy losses of secondary charged particles is transferred initially to the electronic subsystem of the material and in the following due to electron-phonon coupling to the ionic subsystem. Due to these processes, the crystal lattice of the material will receive high energy producing shock waves. Here we consider the shock wave propagation in Cu and graphite.

The deposited energies per one proton in electronic subsystems of collimator materials for the cylindrical target geometry with 150 cm long (in X direction) and radial (in Y direction) used here in test calculations are presented in Fig.1 for copper and in Fig.2 for graphite. The beam impact is in the centre of target.

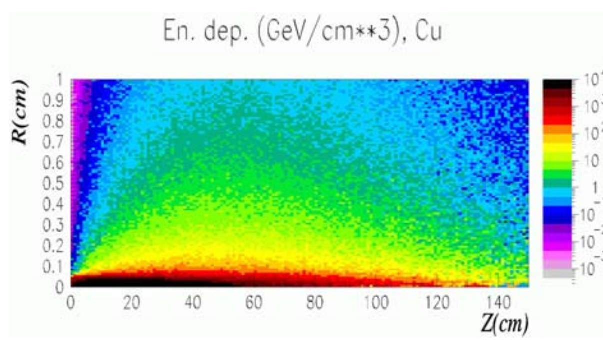

Fig.1 Energy deposition per one proton used in calculations for Cu as a function of the depth (Z) and the radial coordinate (*R*).

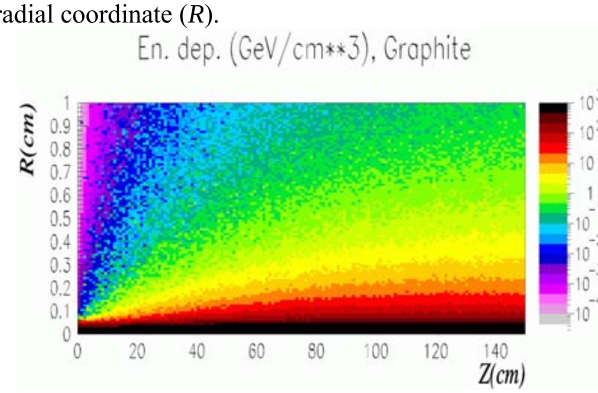

Fig.2. Energy deposition per one proton used in calculations for graphite as a function of the depth (Z) and the radial coordinate (*R*).

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THEORETICAL MODEL

The process of energy transfer from the excited electrons to target atoms takes place together with the processes of electronic and ionic thermal conductivities, therefore this process is characterised by the values of electronic and ionic thermal conductivities and the electron-phonon coupling. In the irradiated materials two thermal waves are formed in the electronic and ionic subsystems and the shock wave formation and propagation in collimator materials is determined by these two physical processes. The process of shock wave propagation has the some time dependence. Here we consider the shock wave propagation in hydrodynamic approximation taking into account the electronic and ionic properties of materials including the physical process of energy transfer from the electronic subsystem to the ionic one. The investigations of shock wave propagation are based on the self-consistent numerical calculations of a nonlinear system of equations for two-dimensional (cylindrical geometry) using the following conservation lows: density and momentum for moving target atoms, total energy of electronic and ionic subsystems taking into account the state equations for electrons and target ions. The results of numerical calculations for shock wave propagation near proton beam in Cu and graphite presented here are based on some deposited energies per one proton in electronic subsystems of these materials.

PHYSICAL PROPERTY CHANGE IN COLLIMATOR MATERIALS DURING SHOCK WAVE PROPAGATION

Numerical modelling of shock wave propagation in collimator materials allows obtaining the results for dynamical changes in real time scale of many physical values of materials such as electronic and ionic temperatures, changes of density and internal pressure (stress), velocities of atoms and sound velocity change in the front of propagated shock wave. These values are very important to predict the behaviour of collimator materials of LHC in accident cases.

Copper

Figure 3 shows the distribution of ionic temperature in Cu near one bunch of proton beam for the deposited energy per one proton presented in Fig.1 after 2.07 ns.

As it has been already pointed out in [2], we can see here that a reduction in the density of collimator materials can result in an increase of penetration depth of protons into the target.

Figures 4 and 5 show the density change and pressure in Cu: a) near one bunch after t = 2.07 ns and b) near 31 bunches (with bunch length 0.5 ns and bunch spacing 25 ns) after t = 812.9 ns of proton beam for the deposited energy per one proton presented in Fig.1 respectively.

Graphite

Figure 6 shows the distribution of ionic temperature in graphite near one bunch of proton beam for the deposited energy per one proton presented in Fig.2 after 0.25μs. Figure 7 shows the changes of internal pressure (stress) for different times during the shock wave propagation for the deposited energy per one proton presented in Fig.2.

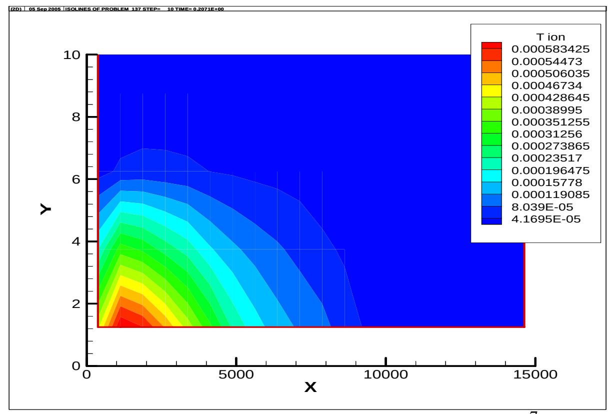

Fig.3. Distribution of ionic temperature (Tion $*10^7$, K) in Cu near one bunch of proton beam (at t = 2.07 ns).

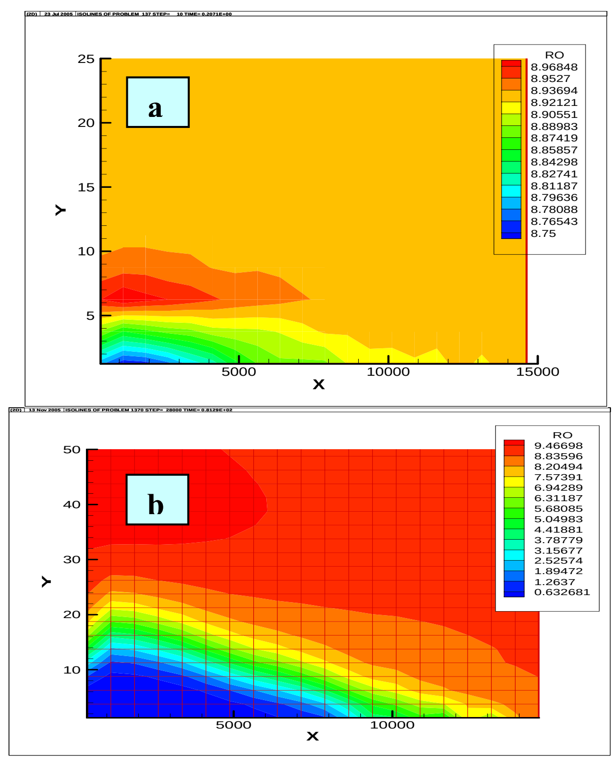

Fig.4. Distribution of density change (g/cm3) in Cu for different number of proton bunches with the deposited energy per one proton presented in Fig.1:a) for one bunch after t = 2.07 ns; b) for 31 bunches after t = 812.9 ns.

CONCLUSIONS

Theoretical models and computer tools are developed for investigations of shock wave propagations produced by 7 TeV proton beam in collimator materials: Cu and graphite taking into account electronic and ionic properties of materials, electronic excitation in materials induced by energy depositions and including time dependences of these processes.

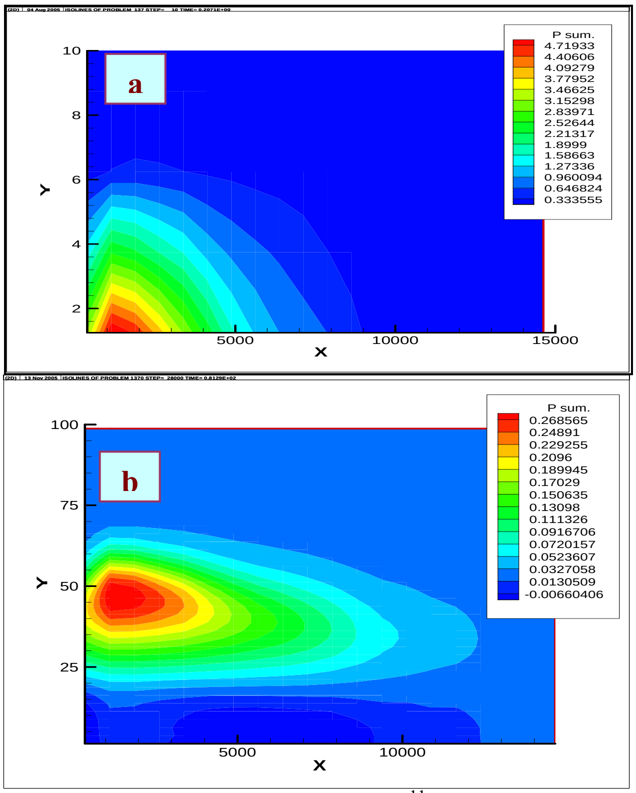

Fig.5. Distribution of pressure (x10^{11}, (erg/cm3)) in Cu for different number of proton bunches with the deposited energy per one proton presented in Fig.1:a) for one bunch after t = 2.07 ns; b) for 31 bunches after t = 812.9 ns.

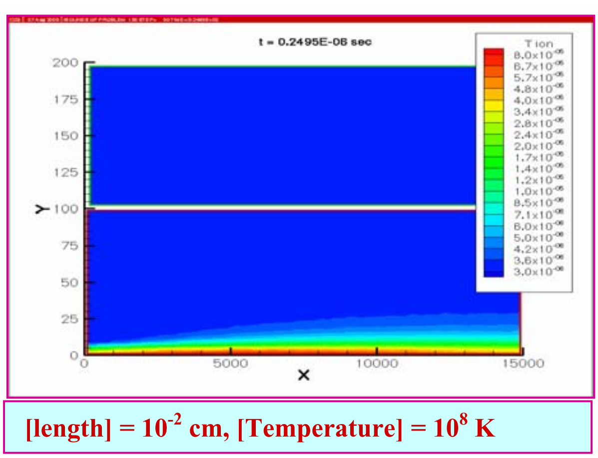

Fig.6. Distribution of ionic temperature (Tion *10^{8}, K) in graphite near one bunch of proton beam with the deposited energy per one proton presented in Fig.2 at t = 250 ns.

The calculations based on developed computer program allow to estimating in future such values as the changes of deformation and internal stress and other values that can characterize the behavior of collimator materials of LHC in accident cases under 7 TeV proton beam irradiation.

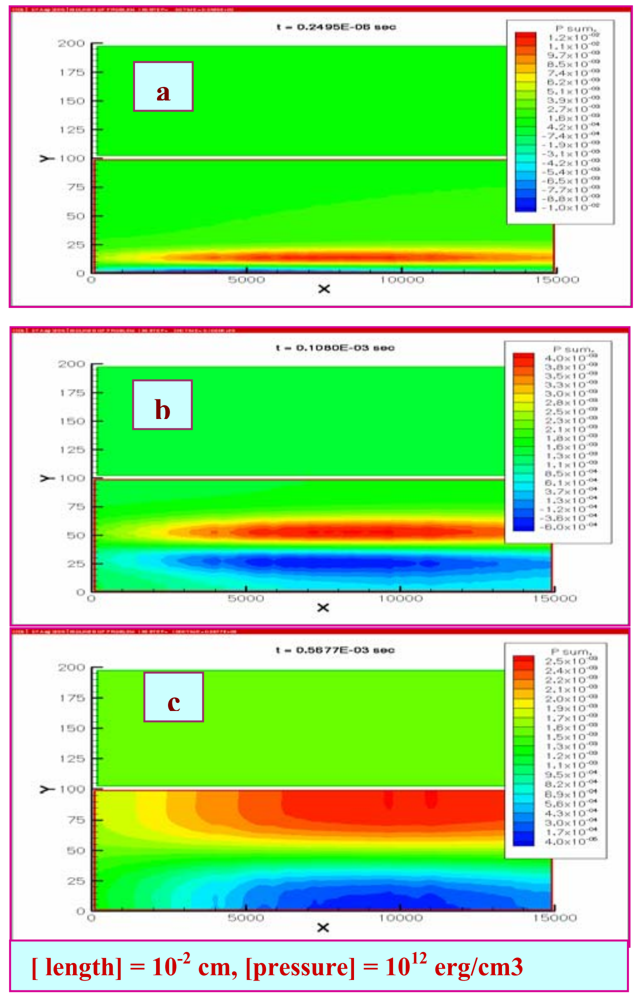

Fig.7. Distribution of pressure in graphite near one bunch of proton beam during shock wave propagation with the deposited energy per one proton presented in Fig.2 at different times: a) t = 0.25x10-6 s; b) t = 0.11x10-3 s; c) t = 0.57x10-3 s.

It is very important also in the future to consider the interference of shock waves from different bunches including reflection of shock waves at boundaries.

REFERENCES

[1] A.Fasso et al. The physics models of FLUKA: Status and recent development, CHEP 2003, LA Jolla, California, 2003
[2] N.A.Tahir et al. Journal of Appl. Phys., 97 (2005) 083532