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SIMULATION OF HYDRODYNAMIC TUNNELING CAUSED BY HIGH-ENERGY PROTON BEAM IN COPPER THROUGH COUPLING OF FLUKA AND AUTODYN

Y. Nie†, C. Fichera, F. Carra, A. Bertarelli, D. Wollmann, CERN, Geneva, Switzerland
L. Mettler, University of California, Berkeley, USA
R. Schmidt, TU Darmstadt, Darmstadt, Germany

Abstract

For machine protection of high-energy colliders, it is important to assess potential damages caused to accelerator components in case large number of bunches are lost at the same place. The numerical assessment requires an iterative execution of an energy-deposition code and a hydrodynamic code, since the hydrodynamic tunneling effect will likely play an important role in the beam-matter interactions. For proton accelerators at CERN and for the Future Circular Collider (FCC), case studies were performed, coupling FLUKA and BIG2. To compare different hydrocodes and not to rely only on BIG2, FLUKA and a commercial tool, Autodyn, have been used to perform these simulations. This paper reports a benchmarking study against a beam test performed at the HiRadMat (High-Radiation to Materials) facility using beams at 440 GeV from the Super Proton Synchrotron. Good agreement has been found between the simulation results and the test as well as previous simulations with FLUKA and BIG2, particularly in terms of penetration depth of the beam in copper. This makes the coupling of FLUKA and Autodyn an alternative solution to simulating the hydrodynamic tunneling. More case studies are planned for FCC and other high-beam-power accelerators.

MOTIVATION

In the Large Hadron Collider (LHC), the energy stored in one beam reaches 362 MJ, under nominal beam parameters, i.e. 2808 bunches at 7 TeV with a bunch intensity of 1.15×10^{11} [1]. This energy is already sufficient to melt 500 kg of copper. For the High Luminosity LHC (HL-LHC), the bunch intensity will increase to 2.2×10^{11}, doubling the energy stored in the beam [2]. Moreover, in the Future Circular Collider (FCC) study, an acceleration of the proton beams up to 50 TeV is proposed. The nominal number of bunches in one beam is 10400 and the bunch intensity is 1.0×10^{11}, leading to a beam energy of 8.3 GJ [3]. In these high-energy colliders, one of the worst-case failures is that the entire beam or a large fraction of it is lost at the same location [4]. Such accident could happen during injection and extraction, if for example the kickers or septum magnets deflect the beam by a wrong angle due to failures in the energy-tracking system or in the magnets themselves. Another possibility is that the beam is extracted towards the beam dump block without energy dilution due to a dilution kicker malfunction. In general, an accidental loss of the entire beam on a single spot is very unlikely, thanks to the reliable machine protection systems [5]. However, it is still important to perform studies to understand the severe consequences of the hydrodynamic tunneling effect [6-8], i.e. energy deposited by the head bunches produces an outgoing radial shock wave that reduces the density along and around the beam axis, and therefore the subsequent bunches and their secondary hadronic shower will penetrate deeper and deeper into the target.

Dedicated experiments performed at the High-Radiation to Materials (HiRadMat) facility with the Super Proton Synchrotron (SPS) beam of 440 GeV have confirmed the existence of the hydrodynamic tunneling [9-11] at high beam energies. To simulate this phenomenon, iterative coupling of two kinds of numerical codes is necessary. A Monte Carlo code such as FLUKA [12, 13], MARS [14] or Geant4 [15] calculates the energy deposition of the proton beam in the target material. A hydrodynamic code such as Autodyn [16], LS-Dyna [17, 18] or BIG2 [19] addresses the response of the material. Complex material constitutive models including equations of state (EOS), strength model and failure model are required, since the target will usually undergo phase transitions during the beam impact. In the past, most of the calculations were done by coupling FLUKA and BIG2. To compare different hydrocodes and in order not to rely on BIG2, FLUKA and a 2D / 3D commercial tool, Autodyn, have been coupled recently for such simulations. This is an alternative solution when other codes are unavailable or not suitable for certain cases, e.g., with BIG2 being a 2D code it is more difficult to calculate the case of non-round beams.

In this paper, we report a benchmarking study against the mentioned HiRadMat experiment. Our simulation results are in very good agreement with the results of the experiment, as well as with results from coupling FLUKA and BIG2. Other case studies will be addressed using the new methodology.

BEAM AND TARGET PARAMETERS

In the HiRadMat experiment of 2012, three copper targets were facially irradiated by three different beams from the SPS. Each target comprised 15 copper cylinders separated by a 1 cm gap between each other to allow for visual inspection after the beam test. Each cylinder had a radius of 4 cm and a length of 10 cm. In the experiments, the proton energy was 440 GeV, the bunch intensity 1.5×10^{11}, the bunch length 0.5 ns, and the used bunch

† yuancun.nie@cern.ch

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spacing was 50 ns. Target 1 was irradiated by a beam of 144 bunches with $\sigma_{x,y}$ = 2 mm. Two beams with the same rms beam size of $\sigma_{x,y}$ = 0.2 mm irradiated Targets 2 and 3, while the bunch numbers were 108 and 144 respectively. The protons were delivered in 3 or 4 packets (for 108 or 144 bunches), while the packets were spaced by 250 ns and each packet consisted of 36 bunches.

We chose the case of target 3 as a benchmarking study for the coupling of FLUKA and Autodyn, since the hydrodynamic tunneling is more visible than in target 1. The case of target 2 was covered automatically during the simulation when 108 bunches were delivered. In the simulations, as a simplification, an extended copper target with a radius of 4 cm and a total length of 150 cm was considered. The 1 cm gap was not taken into account, since the hydrodynamic effect is much stronger in the radial direction than in the axial direction.

SIMULATION METHOD AND RESULTS

The calculations were carried out under the axisymmetric condition in a cylindrical coordinate (r-φ-z) system since the beam was round. The workflow is as follows:

- An initial FLUKA simulation was performed under nominal density (8.94 g/cm^3) of solid copper. The locally deposited heat was estimated by multiplying the dose (per proton) by the total number of protons. The most impacted zone was thus predicted, within which the material was expected to undergo density changes later. For the present study, the zone was defined from $r = 0$ to 0.5 cm and from $z = 0$ to 100 cm, where the target was divided into 2500 fine regions. Each fine region had a radial size of $\Delta r = 0.1$ mm ($\sigma_{x,y}/2$) and a length of 2 cm. Each region was assigned later a density corresponding to the modified density distribution from Autodyn.
- The dose distribution was imported into Autodyn as internal energy load to calculate the mechanical responses of the target. Using the same FLUKA map, a certain number of bunches was successively simulated until the density decreased by 10-15%. The density distribution just before a subsequent bunch arrived at the target was then exported for the next FLUKA modeling iteration.
- Before executing a new FLUKA calculation, the target geometry was rebuilt by assigning densities to the fine regions based on the updated density map. This was the most crucial procedure. To do so, two steps of data processing were needed. Firstly, densities within one region were merged by means of averaging. When a mesh distortion due to material deformation was evident, a linear interpolation was applied to estimate the density at the desired location. Secondly, the merged densities were categorized into 100 predefined density levels ranging linearly from 0.1 to 10.0 g/cm^3.
- After this reconstruction of the target, a new FLUKA simulation was carried out to provide a modified energy deposition data to Autodyn.
- FLUKA and Autodyn were hence run iteratively until all the bunches had been delivered onto the target. From the Autodyn calculations, the state of the target during and after the beam impact are extracted, such as temperature, pressure and density.

Compared with the previous method, the general principle is similar, but our methodology has two main advantages. Firstly, predefined density levels are employed in all iterations instead of defining discrete density levels in each iteration. In this way, the simulation accuracy of FLUKA is not influenced, whereas data analysis and target modelling are simplified significantly, since for any new density level, a new material has to be defined in FLUKA. Secondly, we are able to assign one material to different regions, so that the number of regions could be up to 20000. In contrast to previous reports [20], one material could only be assigned to one region, which limited the total number of regions to be less than 700 due to the fact that FLUKA does not support more than 700 materials at once.

In FLUKA, a radial bin size of 0.05 mm ($\sigma_{x,y}/4$) and an axial bin size of 2 mm were adopted. In Autodyn, a tabular SESAME EOS and the empirical Johnson-Cook strength and failure model were used for copper. A Lagrangian mesh with a set of points attached to the material was employed taking advantage of its computational efficiency.

The beam pulse lengths are 5.8 and 7.8 μs for 108 and 144 bunches, respectively. The maximum density drop reached 13% after the first 12 bunches had been delivered. Therefore, 12 bunches were simulated within each iteration, and in total 12 iterations were executed.

The dose in units of GeV/(g p) along the target axis for bunches delivered at different times are shown in Fig. 1. At time $t = 0$ μs, when bunch 1 starts impacting on the target, the nominal density of solid copper was used in FLUKA. As shown in curve 1 of Fig. 1, the maximum dose is 3.8 GeV/(g p) around $z = 12$ cm. The dose distribution shown in curve 2 was calculated using the density data provided by Autodyn at $t = 2$ μs, just before bunch 37 arrived at the target. The broadened range of energy deposition indicates that the hadronic shower penetrates deeper into the target. The maximum dose has decreased to 2.6 GeV/(g p) due to the density reduction in the most heated area where the outgoing radial shock wave has been generated. At $t = 4$ μs, the range of dose is further broadened while a double peak behavior is observed with a maximum dose of about 1.8 GeV/(g p) as indicated in curve 3. The double peak behavior becomes much more visible in curve 4, at $t = 6$ μs. The second peak with a dose of 1.7 GeV/(g p) at $z = 45$ cm is even higher than the first one. The reason is that the density in the previously heated region has decreased so much that the shower passes through this region with very little energy loss and deposits more energy deeper into the target.

The temperature distribution along the target axis at $t =$ 1.8, 3.8, 5.8, 7.8, 10 and 20 μs is shown in Fig. 2. The large energy deposition results in strong heating of the target material during the beam impact as shown in curves

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1 to 4 of Fig. 2, where a maximum value of 7000 K is observed. Note that during the delivery of the beam, the maximum target pressure exceeds 3 GPa. In Fig. 2, there is a flat region on the right part of each curve around a temperature of 1360 K, corresponding to the melting of copper. This plateau moves deeper into the target due to the hydrodynamic process until curve 4. As shown in curve 3 of Fig. 2, the melting region lies between $z = 77$ and 83 cm after 108 bunches have been delivered (corresponding to target 2). This melting region ranges from $z = 89$ to 95 cm after 144 bunches (target 3) as can be seen in curve 4. Curves 5 and 6 in Fig. 2 indicate that the temperature decreases in the range of $z = 0 - 70$ cm due to the radial heat propagation, while it does not change after $z = 70$ cm on the simulation timescale. The melting front stops to penetrate deeper after the entire beam has deposited its energy in the target. A hole was generated in the target via melting and evaporation, as shown in Fig. 3.

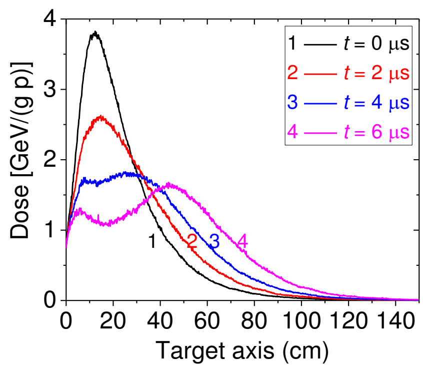

Figure 1: Dose along the target axis for bunches delivered at different times $t = 0, 2, 4$ and 6 μs.

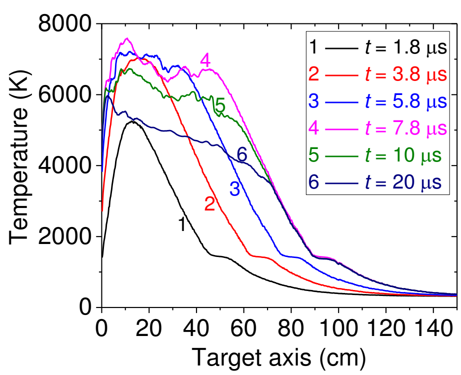

Figure 2: Temperature along the target axis at different times $t = 1.8, 3.8, 5.8, 7.8, 10$ and 20 μs.

RESULT COMPARISON

A comparison between the above simulations and those performed with FLUKA and BIG2 has been made, in terms of the accumulated specific energy and the evolution of target temperature, pressure and density. Differences of the order of 10% are acceptable, considering that different FLUKA binning, iteration steps, material constitutive models and meshes were used. For example, semi-empirical EOS, Prandtl-Reuss strength model and Eulerian mesh were used in the coupling of FLUKA and BIG2.

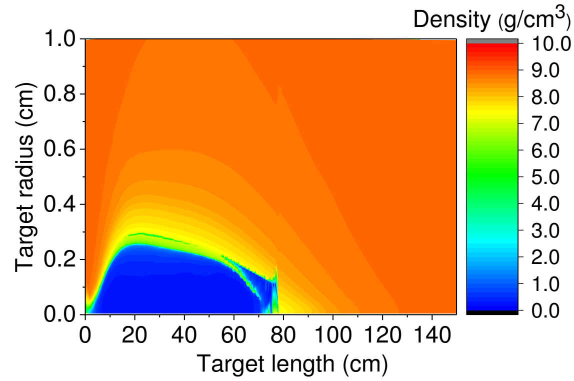

Figure 3: Two-dimensional distribution of the target density at t= 20 μs, 12.2 μs after the end of the beam impact.

Table 1 shows the good comparison of the molten length in targets 2 (108 bunches) and 3 (144 bunches) between simulations and measurements. For the coupling simulations, the axial ranges of the melting plateau are listed. In addition, the results of the static approximation (linear scaling of the initial FLUKA data without considering the density change) are listed as well. It can be concluded that our results agree very well with the experimental measurements and the simulation results performed using FLUKA and BIG2, with a difference of the order of only 10%. A significant lengthening of the damage distance can be seen compared to the static results.

Table 1: Comparison of Molten Depth in cm between Simulations and Measurements

Method	Target 2	Target 3
FLUKA (static)	63.5	67.5
Measurement	79.5	85
FLUKA and BIG2	74-81	85-92
FLUKA and Autodyn	77-83	89-95

CONCLUSIONS AND OUTLOOKS

Hydrodynamic tunneling is an important process to be considered when severe beam losses occur in particle accelerators. A new simulation method of the hydrodynamic tunneling caused by successive ultra-relativistic proton bunches impacting on an extended target has been developed with a new tool, coupling FLUKA and Autodyn instead of BIG2. The simulations have been benchmarked against a previous beam test performed at the HiRadMat facility.

The numerical method presented in this paper can be applied to many other case studies for machine protection of high-energy colliders, e.g., the beam impact on a graphite dump block without dilution, and the design of alternative beam dump principles for the FCC.

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