Hydrodynamic Calculations of 20-TeV Beam Interactions with the SSC Beam Dump
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Abstract
The 300μs, 400 MJ SSC proton beam must be contained when removed to the external beam dump. The current design for the SSC beam dump can tolerate the heat load produced if the beam is deflected into a raster scan over the face of the dump. If the high frequency deflecting magnet were to fail, the beam would scan a single strip across the dump face resulting in higher local energy deposition. This could vaporize some material and lead to high pressures.

Since the beam duration is comparable to the characteristic time of expected hydrodynamic motions, we have combined the static energy deposition capability of the MARS computer code with the two- and three-dimensional hydrodynamics of the MESA and SPHINX codes. EOS data suggest an energy deposition threshold of 15 kJ/g, below which hydrodynamic effects are minimal. Above this our 2D calculations show a hole boring rate of 7 cm/μs for the nominal beam, and pressures of a few kbar. Scanning the nominal beam faster than 0.08 cm/μs should minimize hydrodynamic effects. 3D calculations support this.

I. INTRODUCTION

Two- and three-dimensional hydrodynamic calculations using very high energy (TeV) particle deposition are required to understand the behavior of the SSC beam dump under abnormal beam aborts. The dump is currently designed as an 800 cm long, 160 cm square rectangular block of pressed graphite. The 20 TeV beam enters the dump about once a day through a 0.2 cm thick titanium window. The other faces are contained by an aluminum cooling vessel. For simplicity, our modeling approximated this structure as a graphite block. Normally the beam spot will be raster scanned across the beam dump face, keeping the temperature of the dump below 1300K. If the scanning magnets fail, a worst case scenario allows the beam spot to remain at a single location. A more realistic case has some linear spot motion across the face, due to the droop of the kicker magnet field.

We considered a limited set of beam characteristics: 20 TeV protons delivered in 290 microseconds at two fluxes, 4.5x10^17 and 1.0x10^19 protons/s. The first is the nominal SSC design, the second, a higher value we used to explore scaling effects. The SSC upgrade design has an intermediate fluence 3 times the nominal. Because of the long distance from the kicker magnet to the dump, the standard deviation of the beam’s transverse Gaussian profile has expanded to 0.2 cm.

Preliminary 2-D hydrodynamic calculations with mocked energy depositions led us to expect that the 400 MJ (energy equivalent to 100 kg of TNT), could have explosive consequences. The small spot size could also lead to boring a hole through solid material in the beam path. To study these phenomena and to guide mechanical designs for controlling these effects, we sought to create a 3D hydrodynamic code which correctly modeled energy deposition. We chose the MARS code for the nominal beam dump energy deposition code and both the Eulerian MESA and Lagrangian SPHINX hydrodynamics codes.

II. COMPUTER CODES

A. MESA
MESA is a two- and three-dimensional Eulerian hydrodynamics code. While originally developed for simulating the interactions of military projectiles with armor, it is easily adapted to other hydrodynamic applications. A variety of analytical and tabular equation-of-state, material strength, and fracture models is available to complement the hydrodynamics. The numerical hydrodynamics is divided into two phases. The first phase is Lagrangian; the second is an Eulerian advection. The Lagrangian phase is subcycled for increased computational efficiency. The Youngs interface reconstruction approach to solving the hydrodynamic time evolution equations. Later it was re-formulated in terms of interpolation theory, which was shown to better estimate the error scaling of the technique. Gradients that appear in the fluid equations are obtained via analytic differentiation of smooth interpolated functions, or kernels. Each kernel is a spherically symmetric function centered at the particle location and generally resembling a Gaussian in shape. The interpolation is accomplished by summing each equation or variable at any location over nearby known values at particle locations, each weighted by its own kernel weighting function. By appropriately modifying the normalization condition, the same code can easily switch between 1D, 2D, and 3D, spherical or cylindrical configurations. The computer code SPHINX is our implementation of MESA.

B. SPHINX
Smooth Particle Hydrodynamics (SPH) is a gridless Lagrangian computational technique in which “particles” represent mathematical points at which the fluid properties are known. SPH was first derived by Lucy as a Monte-Carlo approach to solving the hydrodynamic time evolution equations. Later it was re-formulated in terms of interpolation theory, which was shown to better estimate the error scaling of the technique. Gradients that appear in the fluid equations are obtained via analytic differentiation of smooth interpolated functions, or kernels. Each kernel is a spherically symmetric function centered at the particle location and generally resembling a Gaussian in shape. The interpolation is accomplished by summing each equation or variable at any location over nearby known values at particle locations, each weighted by its own kernel weighting function. By appropriately modifying the normalization condition, the same code can easily switch between 1D, 2D, and 3D, spherical or cylindrical configurations. The computer code SPHINX is our implementation of SPH.

C. MARS
MARS is a Monte Carlo program for inclusive simulation of three-dimensional hadronic and electromagnetic cascades in matter and of muon transport in radiation shielding, accelerator and detector components at energies up to 30 TeV.
It allows fast cascade simulation with modest memory requirements, providing the availability of complex geometries with composite materials, presence of magnetic fields, and a variety of scoring possibilities. To construct a cascade tree only a fixed number of particles from each vertex is chosen (four in MARS12), and in the simplest case each carries a statistical weight which is equal to the partial mean multiplicity of the particular event. Energy and momentum are conserved on the average over a number of collisions.

MARS is well suited for use with a 3-D hydrodynamics code. It was easily modified to allow arbitrary material densities, and runs quickly (five minutes of one CRAY YMP processor can give a meaningful calculation). Since MARS may be called hundreds of times in a calculation, speed was crucial. However MARS only needs be called by the hydrodynamic code when the distribution of mass has changed enough to change the energy deposition calculation. This time between MARS calculations we estimated as 0.2 times the maximum radial velocity in the deposition region. This time step control allowed us to reduce by factors of 2 to 10 the time spent in MARS calculations. Nevertheless an unoptimized 2D MESA/MARS calculation at nominal fluence required 12 CRAY YMP cpu hours to reach a time of 150 μs.

D. Equation of State

In order to perform hydrodynamic calculations we require the dependence of pressure and specific internal energy on a material’s temperature and density. The Sesame Equation-of-State (EOS) Library is a standardized, computer-based library which contains tables of thermodynamic properties for a wide range of materials over a wide range of physical regions (from ambient to astrophysical conditions). The library currently contains data for about 150 materials, including simple elements, compounds, metals, minerals, polymers, mixtures, etc. However for the beam dump application a new equation of state had to be created for compressed, porous, powdered graphite. An EOS for full density graphite was created using data from shock measurements at 1.948 g/cm³, a melt temperature of 4530K, and a vapor pressure of 0.01GPa at 4500K. These gave a critical temperature of 8204K, critical pressure of 0.1 GPa is assumed with a linear ramp in pressure as the porous graphite was assumed to be created for compressed, porous, powdered graphite. An EOS for full density graphite was created using data from shock measurements at 1.948 g/cm³, a melt temperature of 4530K, and a vapor pressure of 0.01GPa at 4500K. These gave a critical temperature of 8204K, critical pressure of 0.1 GPa is assumed with a linear ramp in pressure as the porous graphite of density 1.7 g/cm³ is crushed up to the 2.25 g/cm³ full density of graphite.

The resulting EOS displayed an important characteristic. Below a specific energy of 10 to 15 W/g, the pressure remained very low. Above this threshold the pressure rapidly increased to values above 1 GPa (10 kbar). This specific internal energy corresponds roughly to that needed for melt and evaporation. Above this energy deposition threshold substantial hydrodynamic effects will occur.

III. 2-D CALCULATIONS

Although we ultimately desire a 3-D calculational ability, we performed 2-D calculations to test the codes and study the consequences of the beam remaining stationary on the dump face. With the MESA/MARS code we modeled the beam dump as a 800 cm long, 4 cm radius graphite cylinder. We studied two beam fluences, 4.5x10¹⁷ (Figs. 1, 2, 3) and 1.0x10¹⁹ protons/s with σₓ = σᵧ = 0.2 cm. Figure 1 shows the temperature along the beam axis at 20, 60, and 150 μs. The curve at 20 μs shows the temperature rise from energy deposition in static, composite materials, presence of magnetic fields, and a variety of scoring possibilities. To construct a cascade tree only a fixed number of particles from each vertex is chosen (four in MARS12), and in the simplest case each carries a statistical weight which is equal to the partial mean multiplicity of the particular event. Energy and momentum are conserved on the average over a number of collisions.

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V. REFERENCES


VI. ACKNOWLEDGEMENTS

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Figure 1 Axial Temperature, 2D MESA at nominal fluence

Figure 2 Axial Density from 2D MESA at nominal fluence

Figure 3 Axial Pressure from 2D MESA at nominal fluence

Figure 4 Density from 2D SPHINX at high fluence

Figure 5 Density from 3D SPHINX at high fluence