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 extracted 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 0.2cm 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 consider a limited set of beam characteristics: 20 TeV protons delivered in 290 microseconds at two fluences, 4.5×10^{17} and 1.0×10^{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[1] energy deposition code and both the Eulerian MESA[2] and Lagrangian SPHINX[3] hydrodynamics codes.

II.COMPUTER CODES

A. MESA

MESA is a two- and three-dimensional Eulerian hydrodynamics code[2]. 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[4], which assures that materials are advected in the correct order, is a powerful feature of MESA. It minimizes the numerical diffusion characteristic of Eulerian codes. This interface treatment allows fewer computational cells to be used for the same numerical accuracy than earlier codes because it handles the mixed material cells at material interfaces so effectively. This feature is particularly important in 3-D simulations with relatively coarse meshes.

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[5] as a Monte-Carlo approach to solving the hydrodynamic time evolution equations. Later it was reformulated 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[1] 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.

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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 beam spot radius (1 σ) divided by 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/cm^3, a melt temperature of 4530K, and a vapor pressure of 0.01GPa at 4500K. These gave a critical temperature of 8204K, critical pressure of 2.04 GPa, and a critical density of 1.00 g/cm^3. A threshold crush pressure of 0.1 GPa is assumed with a linear ramp in pressure as the porous graphite of density 1.71 g/cm^3 is crushed up to the 2.25 g/cm^3 full density of graphite.

The resulting EOS displayed an important characteristic. Below a specific energy of 10 to 15 kJ/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, 4.5x10^{17}(Figs. 1,2,3) and 1.0x10^{19} protons/s with $\sigma_x = \sigma_y = 0.2$ 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, homogeneous material. Material at the peak energy deposition, 210 cm, has just vaporized. By 60 μs vaporization extends from 90 to 500 cm; by 150 μs to the end of the dump. Figure 2 at 60 μs shows why. Density on axis has been reduced allowing the beam to propagate farther into the dump. Figure 3 shows the pressure causing this expansion away from the beam axis. Peak pressures of 1 to 2 kbar are present not only at this time, but throughout the problem. Figure 4 shows the density variation with radius and length at 20 μs in a SPHINX/MARS calculation of a 2 cm radius cylinder at high fluence. The teardrop shape to the low density hole is qualitatively similar to the MESA/MARS calculation. Because SPHINX had not incorporated the Sesame EOS, results differ quantitatively.Temperature is approximately uniform within the low density region, the pressure somewhat less so. The MESA/MARS calculation at the nominal intensity gives temperatures of about 4500 K and pressures of 1-2 kbar. Although some of the graphite has been vaporized, the dump might be designed to contain these pressures. At the high fluence the temperatures are about 11000 K and peak pressures, 30-35 kbar. The existence of an EOS threshold suggested we should get little motion before 15μs in the nominal case and 0.7 μs for the high fluence. This was observed in the calculations.

These calculations show the SSC beam first depositing its energy into cold material, which as it evaporates creates pressures opening an axial density hole which expands outward. Because the density is low on axis, the beam penetrates farther into the dump, heating new material, and boring a hole through the dump. At the nominal fluence the penetration rate is about 7 cm/μs; at high fluence, 70 cm/μs. Since the beam strikes the dump for 290 microseconds, these rates are unacceptable.

IV. 3-D CALCULATIONS

The beam is not planned to dwell in one spot, but rather to perform a raster scan across the dump face. By moving the beam deposition into fresh, cold material, the deposition in any one location should be below the threshold for hydrodynamic effects. By integrating the lateral distribution of beam energy deposition over radius at the position of peak deposition and applying the hydrodynamic threshold, we obtain a minimum scanning speed. Below this speed hydrodynamic effects occur. For our nominal SSC beam on graphite this speed is 0.08 cm/μs; for high fluence, 1.7 cm/μs.

So far we have performed only one calculation, with SPHINX, to test three dimensional effects. Figure 5 shows density after 20 μs with the beam ($\sigma_x = \sigma_y = 0.2$ cm) sweeping in the z direction at 0.1cm /μs from 0 to 2 cm at high fluence (well below the minimum scanning speed). The dump is simulated by a graphite cylinder 2.0 cm in radius and 400 cm long. As expected the beam creates a hole between 120 and 400 cm and an asymmetrical expansion. Temperatures are reduced by a factor of 0.75 compared to the non-moving beam calculation.

V. REFERENCES

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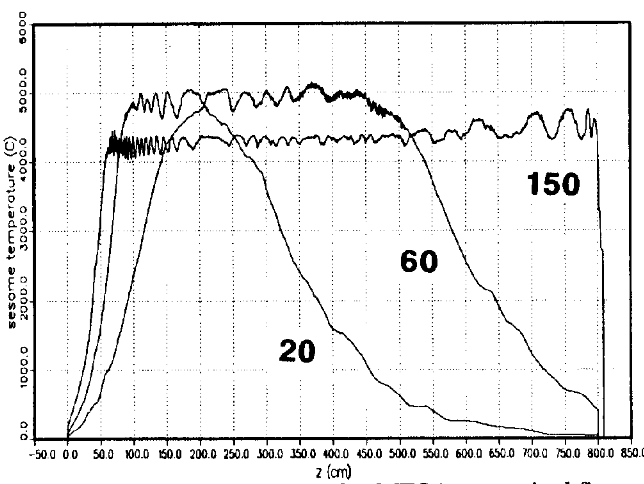

Figure 1 Axial Temperature, 2D MESA at nominal fluence

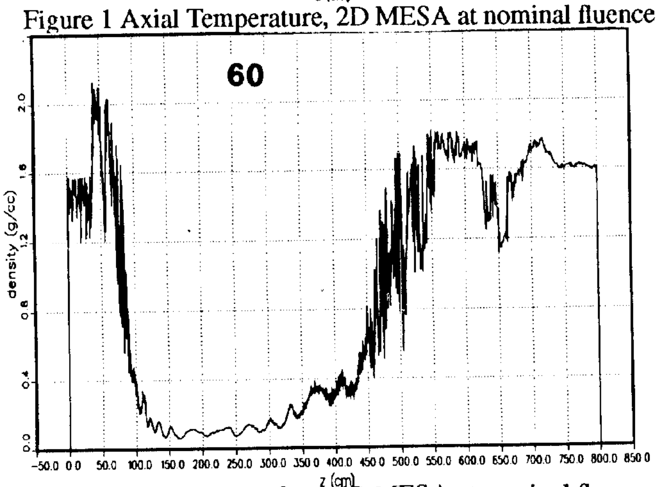

Figure2 Axial Density from 2D MESA at nominal fluence

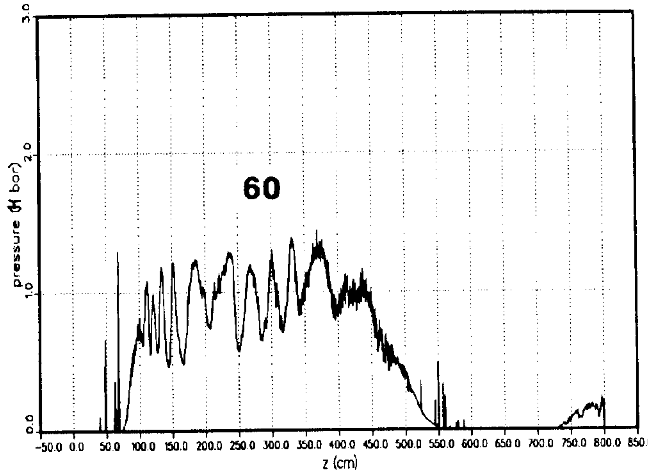

Figure 3 Axial Pressure from 2D MESA at nominal fluence

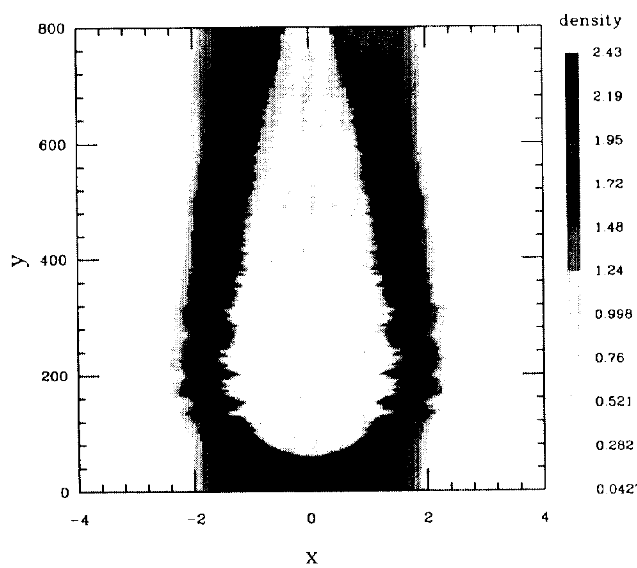

Figure 4 Density from 2D SPHINX at high fluence

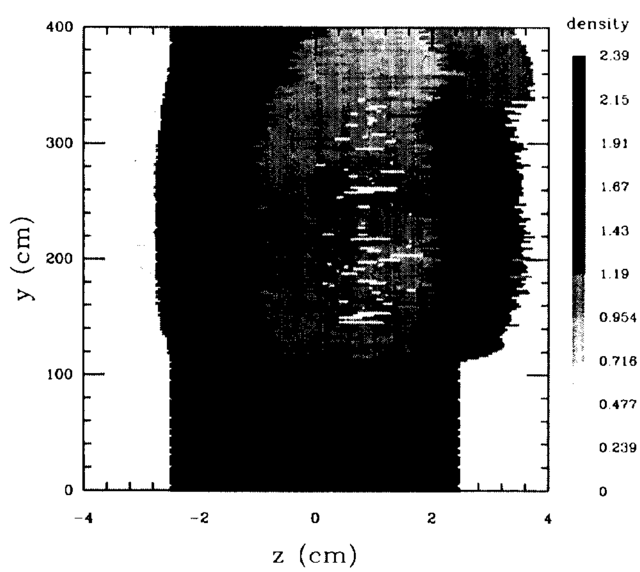

Figure 5 Density from 3D SPHINX at high fluence