I. We have simulated planar targets for NDCX I that indicate NDCX-I will begin to explore the two-phase boundary of metals in the Warm Dense Matter regime.

NDCX-I currently produces a 350 kV, 25 mA singly charged potassium ion beam with a pulse duration up to 10 μs [3]. Four solenoids provide beam confinement and impart a radial convergence towards a final, high field solenoid. A section of the beam, approximately 120 ns in length, can receive a time dependent voltage ramp that gives the tail a velocity increase relative to the head, that, in the absence of space charge effects, can compress the pulse to a duration of ~ 2 ns and a current of approximately 1.2 A. After the voltage tilt is imposed, the beam passes into a neutralized drift section where plasma is injected along the path of the beam. After the two meter drift, the beam passes through a final solenoid where it converges towards the target to a radius ($2^{1/2}$ rms) of 0.5 to 2 mm. Figure 1 shows results from HYDRA [8] simulations (by E.Henestroza) of the beam impinging on a 300 nm tin foil after 6 ns. As can be seen in the simulation, the temperature reaches approximately 0.24 eV. By using the prepulse to heat the material near (or to) the boiling point, and then depositing a short (~ 2 ns) pulse to super critically raise the temperature of the material, optimal use of the total pulse energy may be obtained and observations of the material expanding through the two-phase region may be achieved. A gold cone (cf [6]) to focus the beam will be employed to further enhance the beam intensity, as well as ensure that the beam is fully neutralized near the target. The ion energy of NDCX-I will be below the energy at the Bragg peak, but nevertheless will be relatively constant due to the pleateau in dE/dX with energy at that energy arising from contributions to nuclear scattering. Descriptions of the experiments planned on NDCX-I may be found in [6]). Part of the evolution of the expanding material will be through the two phase (vapor/liquid) regime, and the evolution of the droplets and bubbles in super heated metals is of practical interest [9]. The droplet evolution has been modeled using simple kinetic rate equations, that suggest that most droplets should persist in the outflowing expanding material. See e.g. [9, 10].

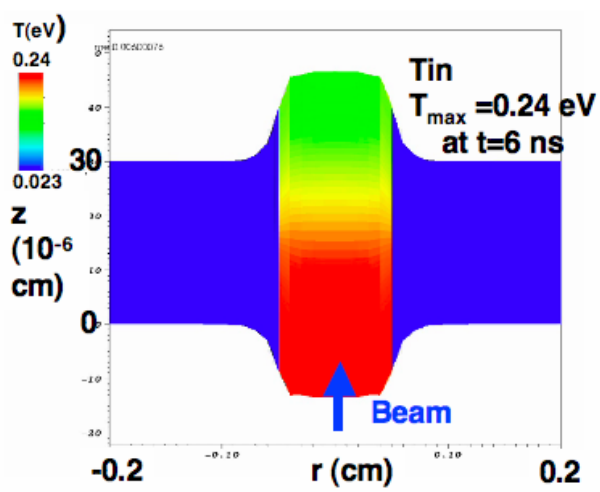

Figure 1. HYDRA simulation (by E. Henestroza) of NDCX I beam focused onto 300 nm Tin foil. Color indicates the temperature at points within the foil, 6 ns after the NDCX1

beam began bombarding the foil. Parameters used in the simulation: Ion energy 350 keV, ion species: K^+, spot radius 0.5 mm, central peak fluence of 0.1 J/cm^2 .

II. We have simulated a variety of novel target concepts for NDCX II, that demonstrate that NDCX II will be able to explore both the Warm Dense Matter egime with solid and foam planar targets, and higher temperatures and densities using spherical and cylindrical implosions of micron scale voids.

With the higher ion energy (~2.8 MeV), ion current (~30 A), longer range (~ 4 μm), and shorter pulse (~1 ns FWHM), NDCX II is being designed for experiments in the WDM regime, i.e. it will be able to access temperatures around the critical temperature of several metals (~ 1 eV), and densities at solid density and below. Simulations [11] of the NDCX-II beam impinging upon a solid or foam target of Al, have shown that pressures slightly less than one Mbar will be achieved in solids, and less in foams. To achieve even higher pressures and temperatures with the same ion beam, novel target configurations are being considered. One such technique utilizes voids in the the material to allow the pressure from heated walls surrounding the voids to compress the material between the expanding metallic walls. Planar voids, cylindrical holes and spherical holes are being considered. The highest temperatures and pressures so far achieved to date in the simulations using NDCX II parameters, occur when spherical bubbles (containing Ar gas) in solid Al are heated at 25 kJ/g/ns over a 1 ns pulse (corresponding to 35 J/cm^2). In figure 2, results from a simulation (by S. F. Ng) using the 1D DISH [12] code adapted to spherical coordinates [16] are displayed. The equation of state used in the simulation is QEOS [13]. In the simulations ~10 Mbar pressures were obtained in the center of bubble.

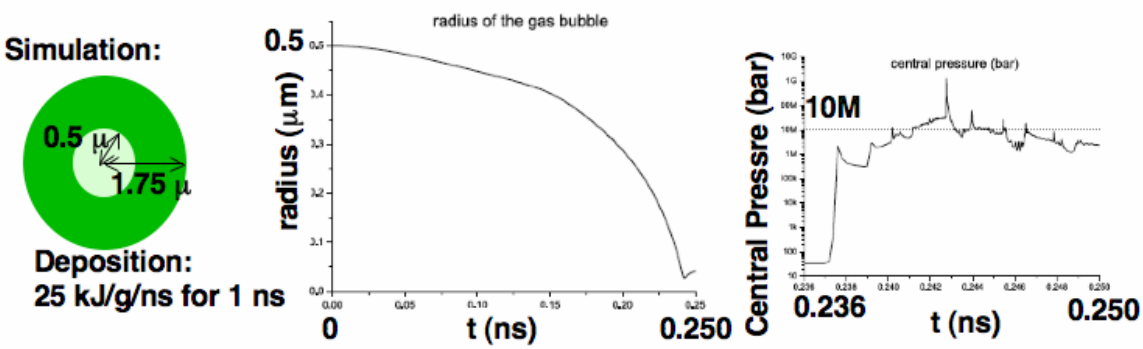

Figure 2. Simulation (by S.F. Ng) of a spherically imploding bubble in Al for NDCX II parameters.

Simulations in which the targets are planar with cylindrical holes parallel to the beam direction have also been carried out (by E. Henestroza) using HYDRA. The ion beam heats the walls of the cylinder, compressing the heated metal along the axis of the hole. For energy deposition of 10 J/cm^2 (a conservative estimate of NDCX II capabilities) onto 4 μ thick Sn foil, with a 6 μ diameter cylindrical hole, central temperatures of 2.6 eV and maximum pressures of 1.3 Mbar were achieved.

Another class of targets that is being consider for study on NDCX II are metallic foams. To understand the simple scaling of expansion rate, pressure and temperature evolution, and homogenization rate with foam parameters a model consisting of solid slabs and voids has been simulated. Figure 3 illustrates a typical simulation result (by A. Zylstra), from the DISH [12] code of a planar 30% Al foam consisting of 15 layers. The slabs were heated in 0.5 ns pulse, with a total energy deposition of 30 kJ/gm. The figure shows the initial evaporation of the slabs, followed by partial homogenization, and a macroscopic rarefaction wave propagating to the center of the slab. Foams are of interest because of their use in ICF targets as radiation converters and structural material, as well as the intrinsic physics.

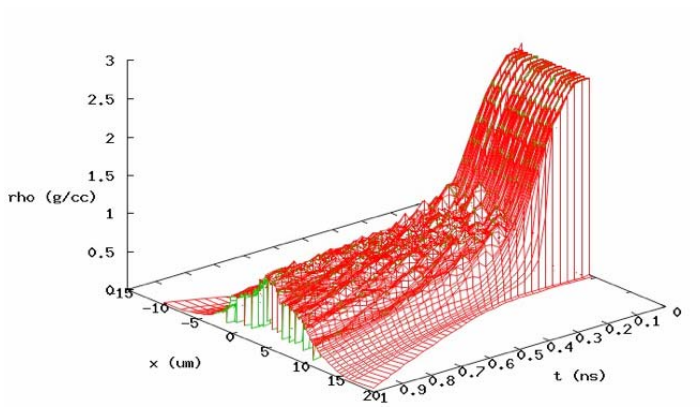

Figure 3. Evolution of the density (rho) of a 1D metallic foam, consisting of 15 solid layers interspersed with voids using the DISH code. (See text for simulation parameters).

III. We have simulated targets for NDCX-II that show that NDCX II will be able to directly test the use of energy ramping to optimize coupling in direct drive HIF targets

In addition to WDM studies described in section II, NDCX II will test the efficacy of energy ramping to increase coupling efficiency that is crucial for the direct drive target concepts discussed in section IV above. The concept for the experiment is to compare the target performance after two ion pulses heat a planar slab of material creating a shock wave, for which the velocity can be measured at the downstream face of the slab. By comparing the results when the second pulse has the same energy as the first, to those for the case when the second pulse has a higher energy than the first, the effect of energy ramp can be demonstrated. For either case, the first pulse of the ion beam deposits energy in one ion range R (where the target is envisioned to be have a thickness that is about three times the ion range). After one hydrodynamic time (R/c_s, where c_s is the sound speed) the ablation pressure wave has propagated a distance ~ R/c_s, and has raised the temperature from an initial temperature T_0 to a higher temperature T_1. Meanwhile if the second pulse is at the same ion energy, it is stopped in the outflowing plasma, and does not add any energy to the ablation pressure. However, if the second pulse has a sufficiently higher ion energy and hence larger range, the second pulse energy deposition can be right behind the ablation wave, adding to the pressure and temperature T_2 of the

wave, where $T_2 > T_1$. In an ion direct-drive target, a temporally ramping ion energy will lead to efficient coupling of the ion beam energy into ablation pressure, which ultimately leads to an efficient acceleration of the fuel layer in the target, and thus efficient coupling of ion energy into fuel kinetic energy. In a planar experiment on NDCX II, the coupling efficiency can be calculated by measuring the velocity of the material at the face of the target where the beam exits the slab, after the pressure wave has reached it. We have carried out simulations of these types experiments. Energies of up to 6 MeV are assumed, achieved by either increasing the number of induction cells in the accelerator, or by doubly ionizing the Li beam.

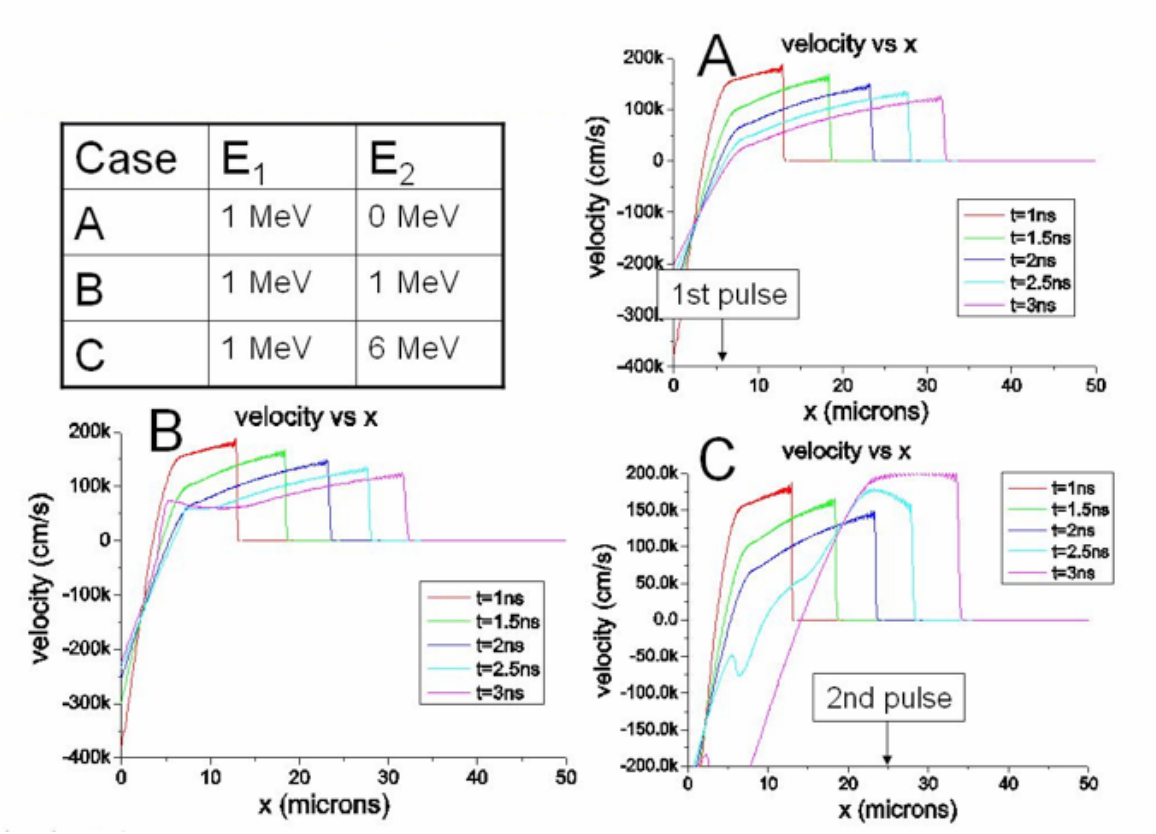

Figure 4. Simulations (by S. F. Ng) using the DISH code of the double-pulse experiment (see text below for explanation).

In Figure 4, an ion pulse of length one ns, and energy of 1 MeV impinges upon a 50 micron thick slab of solid Ar at $x = 0$, creating a weak shock wave that propagates to the right. A second pulse also of duration 1 ns impinges upon the slab at time t= 2 ns. Snapshots of the velocity profile within the slab are shown for three different cases A, B, and C, having second pulse ion energies of 0, 1, and 6 MeV respectively at five different times. As can be seen from the figure, the velocity of the shock wave is not changed if the second pulse has an ion energy of 1 MeV or is not there at all (0 MeV), (indicating weak coupling of the second pulse) but is greatly enhanced if the ion energy increases to 6 MeV energy, so that its increased range can keep pace with the shock front. Other simulations (not shown) indicate that a single 6 MeV pulse would produce material

velocities much less than the combination of a 1 MeV and a 6 MeV pulse. Other experimental concepts including the use of a ramped pulse instead of two separate pulses, and double pulses in metallic foams have been investigated [15] and are reported elsewhere.

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