Final Scientific Report on:

Magnetized Shock Physics and Convergent Flows

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Summary

The objective of this project was to study magnetized shocks in plasmas using the Omega Laser Facility to drive a solid foil into a magnetized gas, which would be preionized by the x-rays from the laser-solid interaction. The MIFEDS (magneto-inertial fusion electrical discharge system) provided the magnetic field.

Magnetized shocks are of interest in magneto-inertial fusion, such as MagLIF [1] and magnetized spherical implosions with both direct [2] and indirect drive [3], space physics, heliophysics, and astrophysics [4]. In magneto-inertial fusion the shocks of interest are collisional and perpendicular to the magnetic field lines, since the magnetic field needs to be compressed. In space, the shocks of interest are typically collisionless, due to the low plasma density, and both perpendicular and parallel to the magnetic field. The marginally collisionless regime between these is also of interest in both laboratory, fusion, and space plasmas, but has barely been investigated.

In the experiments, collisionality is controlled by varying the gas density and the orientation of the applied magnetic field can be varied. We did not carry out experiments on parallel, collisionless shocks because their formation length is too great for them to be generated on the Omega Laser Facility [5]. However, in collaboration with UCLA we designed a quasi-parallel, collisionless shock experiment for the NIF that should allow the first observation of shock formation in this regime. The experiment was accepted by the NIF Discovery Science program and should be executed in the first quarter of 2024. During the course of the project we executed 5 shot days on OMEGA EP, one using a gas cell and the rest a gas jet, and one cylindrical shot day on OMEGA. In addition, we collaborated on four shot days led by either LLNL, Princeton, or UCLA that adopted our platform developments.

The shots obtained, which were fewer than expected for the number of shot days due to technical issues on the facility, allowed us to refine the platform, but did not provide sufficient data to reach clear conclusions for a publication. However, we have two shot days scheduled on OMEGA in 2024 that we expect will significantly expand our data set on perpendicular collisional and collisionless shocks, using Thomson scattering (not available on EP).

We made considerable progress with PIC simulations of collisionless shocks, demonstrating that perpendicular shock formation is possible on Omega [6] and that quasi-parallel shock formation and ion acceleration is possible on the NIF.

During the course of the project we developed a new algorithm for the direct inversion of proton probing and shadowgraphy images [7], an algorithm to analyze Thomson scattering data for non-Maxwellian distributions [8], two new AFR (angular filter refractometry) masks [9], built hardware for a new proton probing geometry on EP, and improved understanding of the gas jet system. These diagnostic improvements will be applied to our future shock experiments.

Planar, perpendicular shock experiments on EP

The final setup for shock experiments on EP using the gas jet system is shown in figure 1. The first experiment with a gas jet placed the piston foil on a separate target positioner, but the foil was moved by the gas jet, even when placed outside the nominal cone angle of the jet, so a more robust mounting system attached to the field coils was developed.

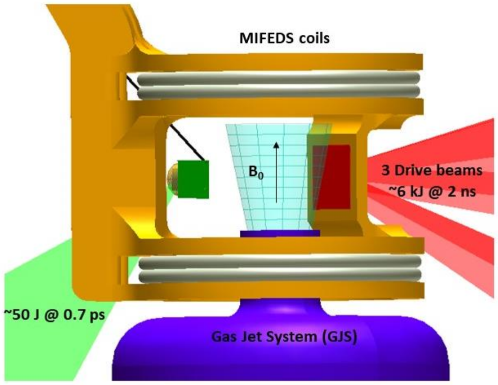


Figure 1: final setup for magnetized, perpendicular shock experiments on EP using a gas jet. Collisionality is varied by adjusting the gas pressure and the magnetic field can be adjusted. The proton source using the EP short pulse beam is shown. In separate shots the 4ω probe is used for shadowgraphy along the same line of sight.

A summary of data collected with proton probing and 4ω shadowgraphy is given in figure 2. Clear qualitative changes can be seen with gas density and magnetic field, but further analysis, comparisons with simulations, and repeat shots are required to draw any firm conclusions on the physics behind these changes.

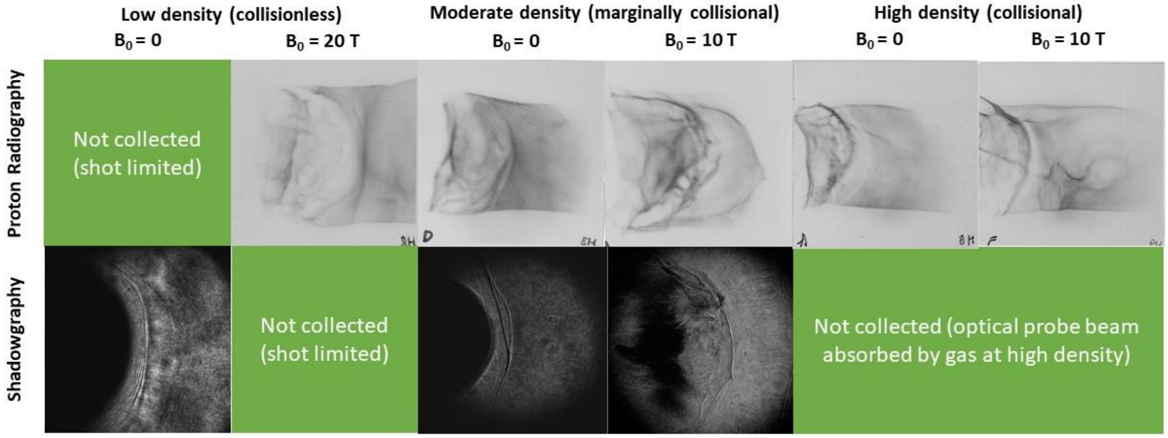


Figure 2: summary of the proton probing and shadowgraphy data collected on the EP gas jet experiments, timed to have the shock near the center of the field of view, which includes data from 8 separate shots. The hydrogen gas density was varied from about 2.5×10^{18} cm^{-3} up to 3.5×10^{19} cm^{-3}.

An experiment using a tube filled with hydrogen and neon in place of the gas jet was carried out to allow use of the time and space resolved VSG spectrometer, looking at neon lines. Use of framing cameras with the gas jet was not permitted due to the risk of damage caused by gas entering the high voltage system. Inexplicably, no shock structure was observed in the proton probing on this experiment. We believe that the tube interfered with the shock propagation in a manner not predicted by our initial hydrocode simulations. We have since worked with the facility to permit the use of a framing camera in certain cases on gas jet experiments, and plan to obtain VSG data in future shock experiments using the gas jet.

Cylindrical convergent flows on OMEGA

We carried out a magnetized cylindrical experiment on OMEGA, probing with D-^{3}He fusion protons along the axis using a reference mesh, as illustrated in figure 3. The radial component of the magnetic field, which is proportional to the axial component, rotates the mesh of protons [10,11]. For this experiment, we used an empty cylinder. An axial magnetic field is still compressed in vacuum, and the compressed magnetic field is expected to generate a shock in the compressing plasma.

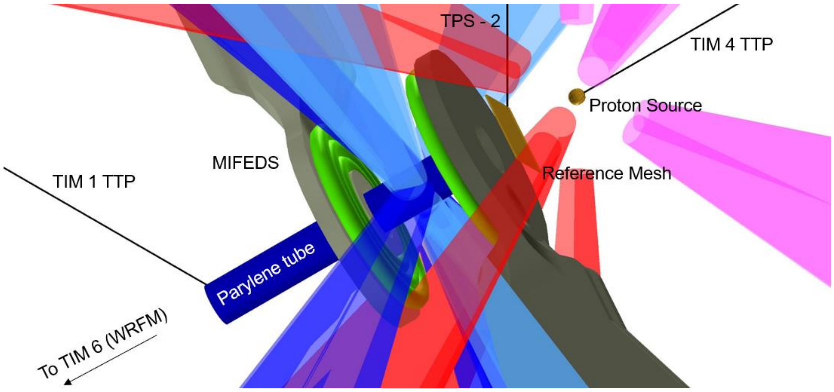
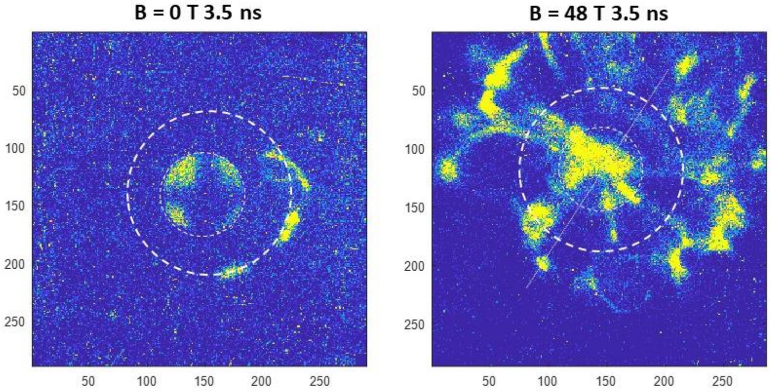


Figure 3: setup for the magnetized cylindrical experiment on OMEGA, note that the sample laser beams driving the proton source have been terminated short of the target in this illustration so as not to obscure it. The 40 beams, 20 for compression, 20 for the proton source, delivered 390 J each in a 1.5 ns square-shaped pulse.

Sample proton radiographs at the greatest compression that could be resolved, with and without a magnetic field, are shown in figure 4. The radiographs indicate that the compression becomes significantly non-uniform in the presence of a magnetic field, indicative of an instability. Possible instability mechanisms in the compression of an axial magnetic field by a plasma are currently being studied.


B = 0 T 3.5 ns

B = 48 T 3.5 ns

Figure 4: sample proton radiographs at 3.5 ns, 2 ns after the end of the laser pulse, with and without an applied axial magnetic field. The outer circle indicates the original cylinder position and the inner circle is 350 μm in diameter. The diagonal line indicates what may be a rotated mesh line.

PIC simulations

We have carried out a wide range of PIC simulations of magnetized, collisionless shocks for magnetic fields, densities and velocities achievable with available laser systems. We have used hydrodynamic simulations of the laser-foil interactions to determine the achievable piston velocities. The majority of the PIC simulations have used a reflecting wall boundary with the plasma flowing towards it to generate the shock, but we have also verified that a dense plasma flowing into the lower density plasma generates very similar shocks. In addition, we have carried out simplified simulations with counterstreaming ions to elucidate the mechanisms of collisionless shock formation and ion-electron energy exchange.

The first series of PIC simulations considered perpendicular shocks for parameters achievable on EP, and these results are published [6].

We then turned our attention to quasi-parallel shock formation on the NIF, which is the only system with sufficient energy to drive a piston for long enough to form a parallel, collisionless shock in the laboratory [5]. Magnetized, parallel shocks are believed to be the most efficient particle accelerators, so are of particular interest in astrophysics. Based on the simulations, we decided to use an angle of 30° in order to drive a shock with physics very similar to a purely parallel (0°) shock but with a shorter formation time. Figure 5 illustrates the experimental setup and PIC results for the ion spectra. These results formed part of a successful NIF Discovery Science proposal submitted in 2021, led by Derek Schaeffer (UCLA), which should be executed in the first quarter of 2024. A paper describing the PIC simulations is in preparation.

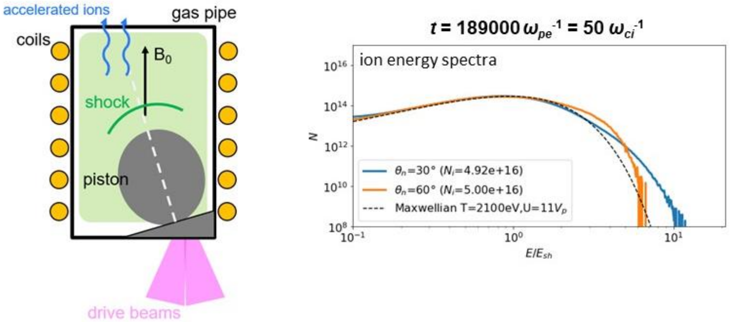


Figure 5: sketch of the NIF experiment to study quasi-parallel, magnetized collisionless shocks (left) and PIC simulation results (right) for the ion spectra at the end of the drive. An ion spectrometer is being built for this experiment.

The simulations for the NIF experiment revealed efficient, collisionless ion-electron energy exchange and thermalization. We are currently carrying out simplified simulations with counterstreaming ions to elucidate the physics of collisionless energy exchange, and analyzing the multi-fluid plasma dispersion function to identify candidate instabilities. We expect to write a paper on this work in the near future.

Diagnostic and hardware development

Our gas jet experiments rely on optical and proton probing diagnostics, and in 2024 we will carry out gas jet experiments on OMEGA with Thomson scattering. As a result, we have made a number of important developments in these areas not originally envisioned in the proposal.

Proton probing and shadowgraphy images both show intensity modulations caused by deflection of rays (protons or a laser beam) in a plasma. The images can be directly inverted to obtain a line-integrated transverse Lorentz force for protons, a line-integrated transverse refractive index gradient for shadowgraphy, under the constraints of minimum deflection and no trajectory crossing. We developed a new algorithm for direct inversion that works for arbitrarily large intensity modulations and with shadows from solid objects in the images, which has been published and is publicly available [7].

In order to be able to carry out proton probing along the same axis as the 4ω probe, we had a new NTA (near target arm) built for EP to support the detector pack in the correct position.

The 4ω probe on EP also includes angular filter refractometry (AFR), which uses a circular mask at the image plane to block direct rays and provide a series of bands giving the angular deflection at the target. AFR can be used to infer the electron density profile for a monotonic profile, but is not suited to shocks. Furthermore, the sharp edges of the bands cause diffraction artifacts. We designed new AFR filters with a sinusoidal profile to suppress the diffraction lines, and a filter with varying spacing, which used in conjunction with the regularly spaced filter can break the degeneracy for non-monotonic profiles. The new filters have been tested and a paper submitted to Review of Scientific Instruments [9].

The analysis of Thomson scattering spectra typically assumes a Maxwellian distribution for the electrons and ions, but this is not expected to be a good approximation for collisionless shocks. Therefore, we developed an open-source Thomson scattering analysis routine that can recover non-Maxwellian distributions [8]. We have applied these techniques to PIC simulations for our upcoming OMEGA shot days, as illustrated in figure 6.

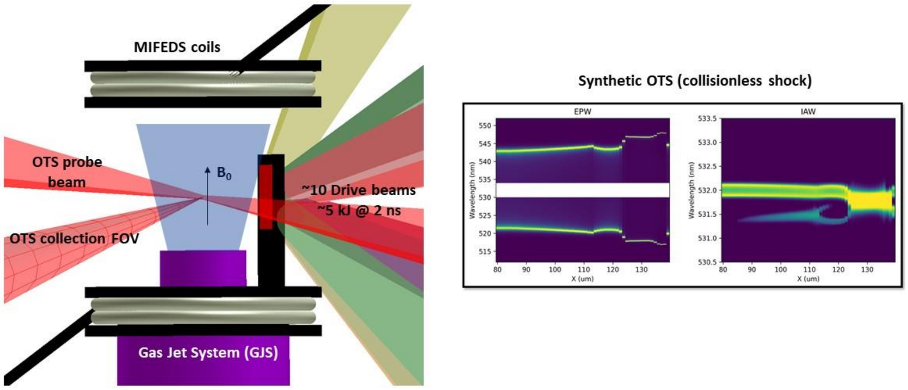


Figure 6: setup for the two upcoming OMEGA shot days using Thomson scattering (left) and synthetic Thomson scattering spectra (right) obtained from PIC simulation results.

Our experiments revealed that the cone of high pressure on the recently developed high-pressure gas jet system is wider than predicted by the existing gas jet model. We have started a program of extensive hydrodynamic simulations and offline experiments to characterize the existing gas jets nozzles and to design new ones with more desirable density profiles. Initial simulation results confirm our observations on the actual high-pressure cone angle.

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