Enabling the Realisation of Proton Tomography

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Proton radiography is a widely-fielded diagnostic used to measure magnetic structures in plasma. The deflection of protons with multi-MeV kinetic energy by the magnetic fields is used to infer the path-integrated field strength, but extracting three-dimensional information has proven to be challenging. In this Letter, a new method for production of multiple spatially independent proton beams from a single laser-irradiated foil target is proposed. It is shown, via two-dimensional particle-in-cell simulations, that the irradiation of a ‘laser’ foil, connected by conductive wires to several secondary ‘beam’ foil targets, provides proton beams with the excellent fidelity required for proton probing. This novel target geometry allows for flexible positioning and direction of a number of ‘beam’ foils, thereby greatly improving the prospects of three-dimensional tomographic reconstruction of magnetic fields for high energy density physics studies which benefit from the largest possible number of view angles.

The proton radiography diagnostic allows probing of transient and quasi-static magnetic field structures in plasmas[1,2]. It has been used to image magnetic fields in laboratory analogues of astrophysical collisionless shocks[3,4], the Weibel instability in interpenetrating plasma flows[5], stochastic magnetic fields amplified by the turbulent dynamo mechanism[6] and fields involved in laser-driven magnetic reconnection[8,9]. In the higher-density physics regime, proton radiography has been used to probe plasma fields in imploding inertial fusion capsules in both direct-drive[10,12] and indirect-drive laser-hohlraum[13,15] configurations, and in studies of laser channeling physics relevant to fast ignition[16]. Proton-radiographic magnetic field measurements have also been used to validate a Faraday rotation-based magnetic field diagnostic at OMEGA[17].

An example of the path-integrated fields experienced by a proton beam probing a laser channel at 20° incidence is shown in Fig. 1 along with a synthetic radiograph produced using proton deflections corresponding to those fields. Kugland et al.[18] presented an early detailed theoretical treatment of proton radiography, followed by proposed inversion techniques by Kasim et al.[19] and Bott et al.[20] which detailed algorithms for quantitative recovery of path-integrated magnetic field values, and Kasim et al.[21] addressed uncertainties in the initial source profile used as input to these algorithms. Chen et al.[22] investigated machine learning-powered recovery of parametrised field structures from a proton radiograph, and proposed that imaging from several lines of sight could improve the fidelity of such three-dimensional reconstructions. While most proton radiography experiments to date use only one line of sight, Li et al.[23] have used unusual experimental geometry to probe similar interactions both side-on and face-on in a single shot, and more recently Tubman et al.[9] used two proton probes separated by 45° to assist in separating electric and magnetic field contributions to proton deflection. In this Letter’s companion article[24], we present the first thorough exploration of this idea, elucidating the capabilities and limitations of the approach we term proton tomography. Most significantly we derive two new techniques which can drastically improve the performance of the standard filtered back-projection algorithm under conditions expected to be typical for proton tomography.

The first is derived by considering the form of the two-dimensional Fourier transform in polar coordinates, and exploiting filtered back-projection to perform integer-order Hankel transforms. It is shown to be a form of interpolation in the angular variable of the tomographic data domain, which can therefore also be applied to enhance the results of other tomographic inversion algorithms as well as filtered back-projection. This interpolation is shown to radically improve reconstruction quality in the limit of a very small number of probe directions, improving the potential for proton radiography to be implemented practically.

Our second proposed technique is a sampling strategy which improves the efficiency of sampling highly prolate or oblate functions. Many plasma structures which carry distinctive magnetic field signatures commonly probed with proton radiography are highly elongated. Examples include laser-plasma channels, which have been studied using proton radiography by Spiers et al.[10] and laboratory analogues to astrophysical relativistic jets such as those studied by Li et al.[20]. Our derived method allows the user an additional degree of freedom in designing tomographic experiments which can be used to optimise
Simultaneous proton beams—more than the number used pulse beamlets would make available up to sixteen simultaneous proton beams per short pulse could be implemented at a single short pulse. For example, a version driving four wire-foil components from a single laser interaction. This method is easily extended to drive more wire-foil components from a single laser-foil interaction. A simplified version of this target geometry which enables production of several proton beams with independently controllable pointing from a single laser-foil interaction. A simplified version of this target geometry is validated in two-dimensional particle-in-cell simulations, producing two independent proton beams from a single laser interaction. This method is easily extended to drive more wire-foil components from a single short pulse. For example, a version driving four proton beams per short pulse could be implemented at a system such as the National Ignition Facility’s Advanced Radiographic Capability (NIF-ARC), whose four short pulse beamlets would make available up to sixteen simultaneous proton beams—more than the number used to produce the results of Figure 2—which would greatly improve the ability of experimenters to diagnose complicated three-dimensional field structures within the target.

The proposed scheme consists of connecting several metal foils by conductive wires. When a laser pulse is incident on the primary, ‘laser’ foil, electrons are heated rapidly and expand beyond the boundaries of the foil. In the classical target-normal sheath mechanism the resulting space-charge imbalance induces the titular sheath field, which then accelerates protons present in hydrocarbon impurities on the target surface to multi-MeV energies. In the scheme proposed here, the space charge imbalance in the laser foil sets up a pseudo-return current of electrons streaming down the wires from the secondary foils to the primary. This in turn leads to positive charging of the secondary foils, expelling the relatively light hydrogen ions while the gold ions respond far more slowly.

Two-dimensional particle-in-cell simulations were run using the code Smilei. The target was initialised with density profile given by the ‘test’ target geometry rendered in Fig. 3 and was composed of gold ions, electrons and a smaller density of hydrogen ion impurities. Protons were initialised using two separate species definitions: the first in the laser foil and wires, and the second in the two beam foils. This allowed protons from the beam foils to be distinguished in diagnostics and also allowed them to be modelled using a higher particle-per-cell count than in the rest of the simulation, in order to improve the statistical properties of the measured ion spectra. Additional simulations were run using only the laser foil and no wires or beam foils, and protons accelerated from this foil in the laser forward direction were measured to enable comparison of the spectra produced by ‘plain’ target-normal sheath acceleration to the spectra of ions accelerated from the beam foils in the full simulation set-up.

Figure 4 illustrates the proposed use of this new target geometry in schematic form. This includes four beam foil arrangements from a single laser foil rather than two, with wires covering larger distances than would be practical to simulate in a particle-in-cell framework. In Figure 5 the proton number spectrum as a function of kinetic energy is shown for both a single foil, i.e. the ‘classical’ TNSA arrangement, and for ions accelerated from secondary foils in our proposed set-up. The spectra have very similar form in each case, indicating that the proton beams produced by secondary beam foils connected by conducting wires to the primary laser foil are likely to be similarly suitable for radiographic applications.

The novel target construction presented in this Letter has been shown to allow more flexible design of proton radiography diagnostics, by enabling a single laser pulse to produce several independently pointed proton beams. This has been validated using two-dimensional particle-
FIG. 2. Three-dimensional renderings of a magnetic field structure representing laser-formed channel in plasma, as shown in this Letter’s companion article [24] (a) and reconstructions from nine projections of the $B_z$ component (b-e). In c) and e), our aspect ratio compensation method is employed to improve the sampling of the very elongated function. In d) and e), Fourier series interpolation is used to improve the smoothness of the reconstruction by removing artefacts arising from the sparse angular sampling rate. It is clear that in this regime - sparse sampling of an elongated function - only the combination of both enhancements results in a good reconstruction of the original function. Further testing has shown that the method is not highly sensitive to the precise aspect ratio used in the compensation, with ratios of 20:1 and 5:1 showing similar performance to the 10:1 compensation shown here. All functions are rendered as isosurfaces calculated at $\pm 1 \text{kT}$, with the positive isosurface shown in red and the negative in blue.

FIG. 3. Three-dimensional rendering of the proposed target geometry, as tested in particle-in-cell simulations. A 10 $\mu$m-thick gold foil (the ‘laser’ foil) is attached by 10 $\mu$m diameter wires to two smaller ‘beam’ foils of the same thickness. The ‘laser’ foil is struck from the rear by a short, high-contrast laser pulse and protons present as impurities in the ‘beam’ foils are diagnosed when they leave the simulation box.

in-cell simulations, which showed that the spectrum of protons accelerated from these ‘secondary’ foils agrees well with that of ions accelerated from the ‘primary’ foil in the absence of additional components. We have argued

that this target design is feasible for fielding on large laser systems featuring short-pulse capabilities, such as NIF-ARC, OMEGA EP and LMJ-PETAL. In the first of these cases, the Advanced Radiographic Capability at the NIF consists of four beamlets which may be pointed independently, and we envision using each of these four beamlets to drive one primary and four secondary foils [29, 30]. This provides sixteen proton beams with similar properties. This is in greater than the number of projections shown in Figure 2 to produce a good reconstruc-
FIG. 5. a) Spectra of ions accelerated from the laser foil in a ‘classical’ TNSA configuration and for ions accelerated from the beam foils in the proposed scheme. The former records proton energies as they leave the simulation through the positive x boundary, the latter through the y-boundaries. This reflects the different foil orientation in the two configurations. b) Proton energy-transverse position phase space of protons accelerated from one beam foil. c) Transverse profile of the protons accelerated from the beam foil. Proton energies extracted from simulations have been rescaled by a common factor of 10% in order to better reflect the known properties of TNSA-accelerated protons [28].

Motion of a laser-driven magnetic field structure when both the Fourier interpolation and aspect ratio compensation schemes derived in the companion article [24] are used, though both are necessary for good reconstruction quality. This new proposed experimental capability represents a major step towards the realisation of fully three-dimensional magnetic field reconstruction in laser-plasma experiments.

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