Analyzing Proton Radiographs of Turbulent Transport in Magnetized HED Plasmas – Abstract

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Many laboratory experiments use magnetic fields to control high energy density (HED) plasmas, including studies of inertial fusion energy, magnetized shocks, and magnetic reconnection. Therefore, it is important to understand the coupling and behavior of magnetic fields and HED plasmas – especially turbulent or anomalous transport of plasma relative to the magnetic field. We present experiments at the OMEGA laser facility to study the interaction of a flowing plasma generated from the ablation of a CH target with an external magnetic field powered by MIFEDS. The plasma-field interaction was diagnosed with 2D proton radiography, which measures magnetic fields through the deflections of the protons. A mesh placed between the proton source and plasma served to break the proton beam into quantifiable beamlets. In this work we establish a system for analysis of this data, including algorithms to detect beamlet locations and automatically calculate their deflections from a reference image, which provides information about the evolution of the magnetic field.

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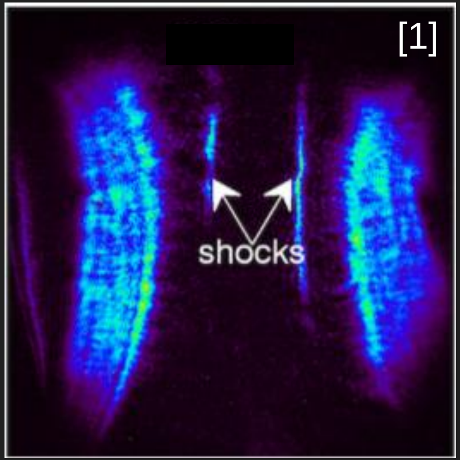
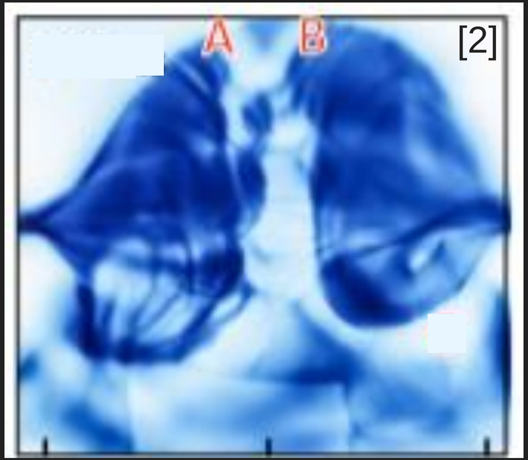
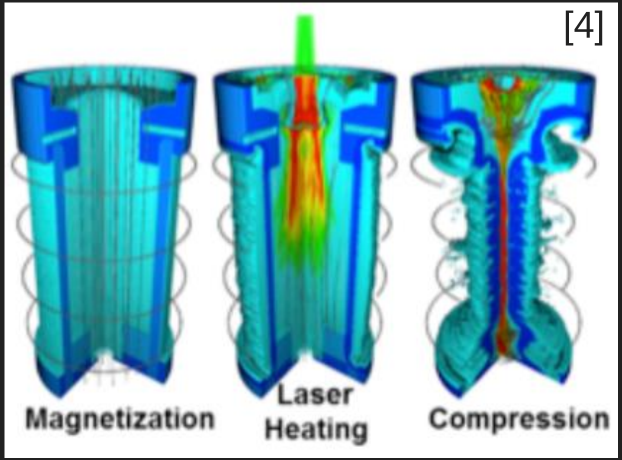
Applications of Magnetized HED Plasmas

Laboratory Astrophysical Experiments [1,2]
- Magnetic shocks
- Magnetic reconnection

Inertial Fusion
- Magnetic Liner Inertial Fusion (MagLIF) [3]







[1] D. B. Schaeffer, W. Fox, D. Haberberger, G. Fiksel, A. Bhattacharjee, D. H. Barnak, S. X. Hu, and K. Germaschewski, “Generation and evolution of high-mach-number laser driven magnetized collisionless shocks in the laboratory,” Phys. Rev. Lett. 119, 025001 (2017).
[2] G. Fiksel, W. Fox, A. Bhattacharjee, D. H. Barnak, P.-Y. Chang, K. Germaschewski, S. X. Hu, and P. M. Nilson, “Magnetic reconnection between colliding magnetized laser produced plasma plumes,” Phys. Rev. Lett. 113, 105003 (2014).
[3] S. A. Slutz, M. C. Herrmann, R. A. Vesey, A. B. Sefkow, D. B. Sinars, D. C. Rovang, K. J. Peterson, and M. E. Cuneo, “Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial fielda),” Physics of Plasmas 17, 056303 (2010).
[4] A. B. Sefkow, S. A. Slutz, J. M. Koning, M. M. Marinak, K. J. Peterson, D. B. Sinars, and R. A. Vesey, “Design of magnetized liner inertial fusion experiments using the z facility,” Physics of Plasmas 21, 072711 (2014).

Experiment at OMEGA

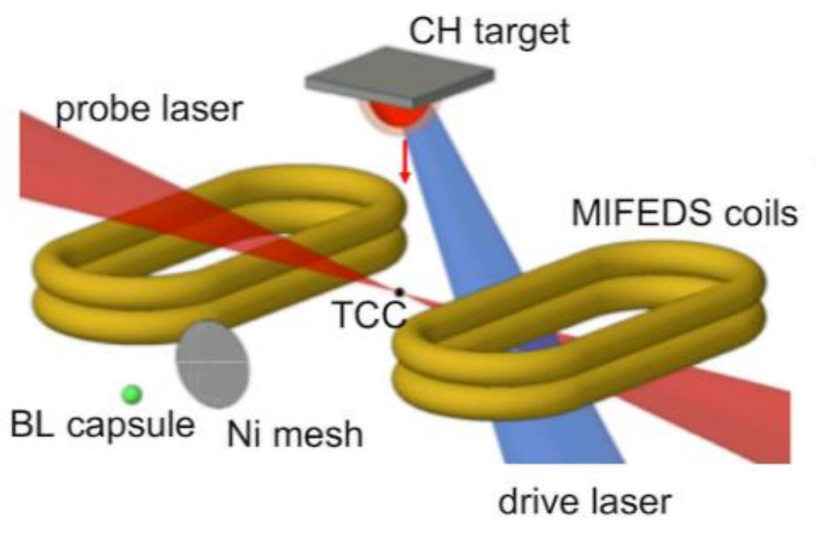
Purpose:
Observe anomalously-fast turbulent transport in magnetized HED plasmas and quantify the diffusion rate by measuring magnetic field and plasmas parameters

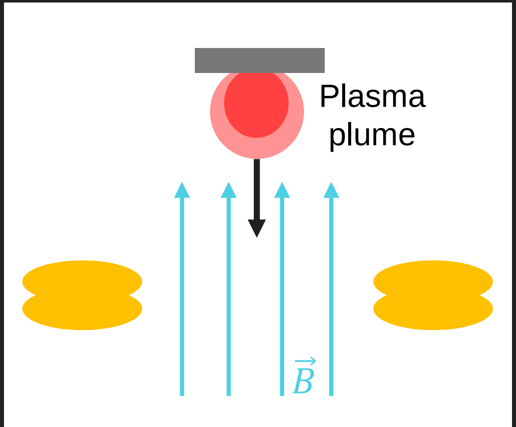
Diagnostics:

- Thomson Scattering – measure plasma parameters
- Proton Radiography – compare proton radiographs from different time points to see how magnetic field evolves with time

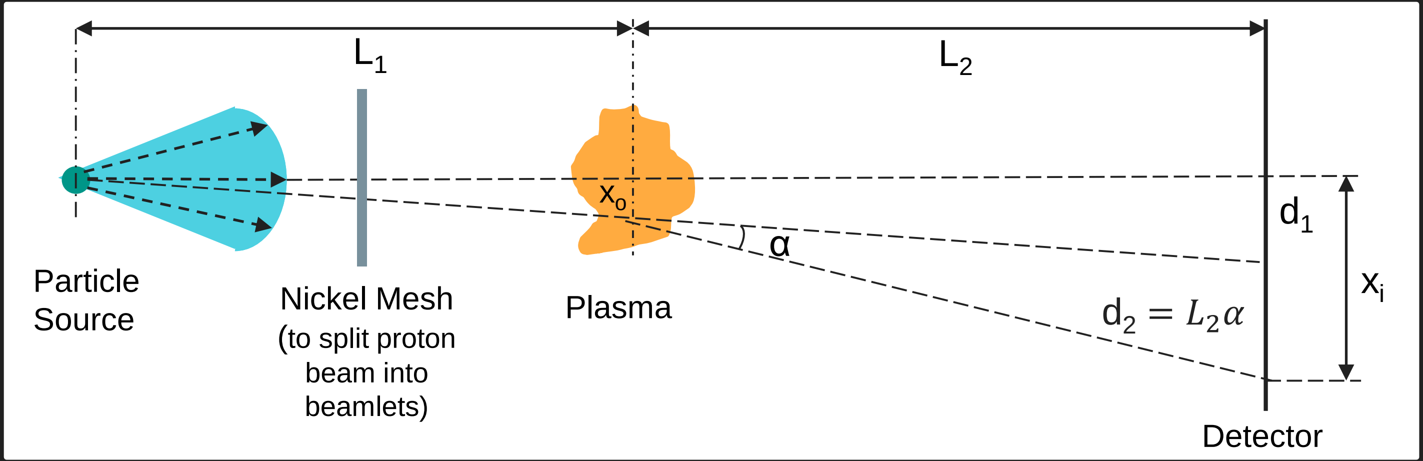
<u>**Scope of Summer Work:**</u>

Develop a system for analyzing proton radiography data to gather information about the magnetic field





Proton Radiography (P-RAD) used to measure magnetic fields in plasma



$$\Delta\alpha = \frac{q}{W}\int\left(\vec{E} + \vec{v}\times\vec{B}\right)\mathrm{d}l \longrightarrow \alpha = \frac{\mathrm{e}}{m_p v_p}\int \vec{B}\times \mathrm{d}\vec{l}$$

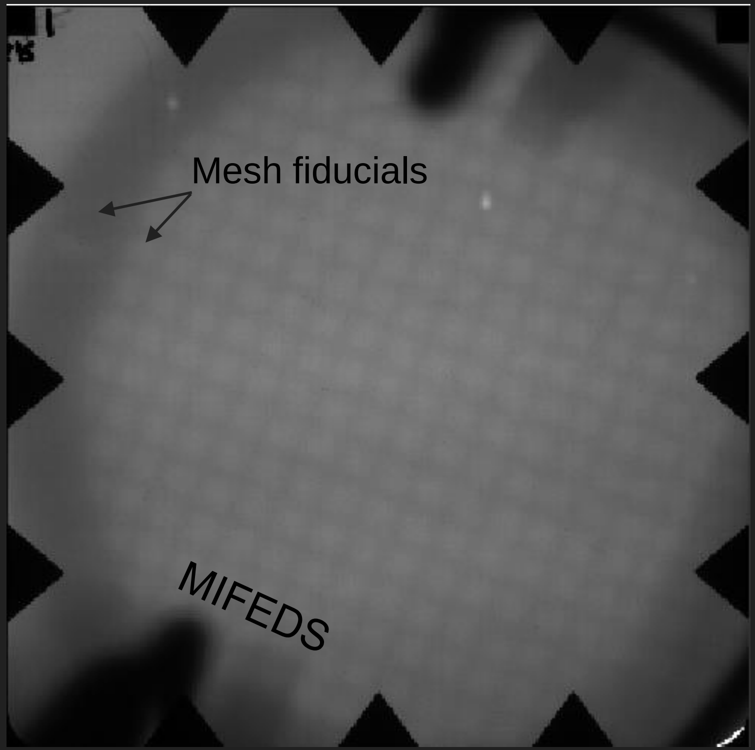
Define: $\beta = \frac{\mathrm{e}L_2}{M m_p v_p}$ and $\vec{\mathcal{B}} = \int \vec{B}\times \mathrm{d}\vec{l}$

$\boxed{x_i = x_o + \beta\vec{\mathcal{B}}}$ Final beamlet position on detector in terms of undeflected beamlet position[5]

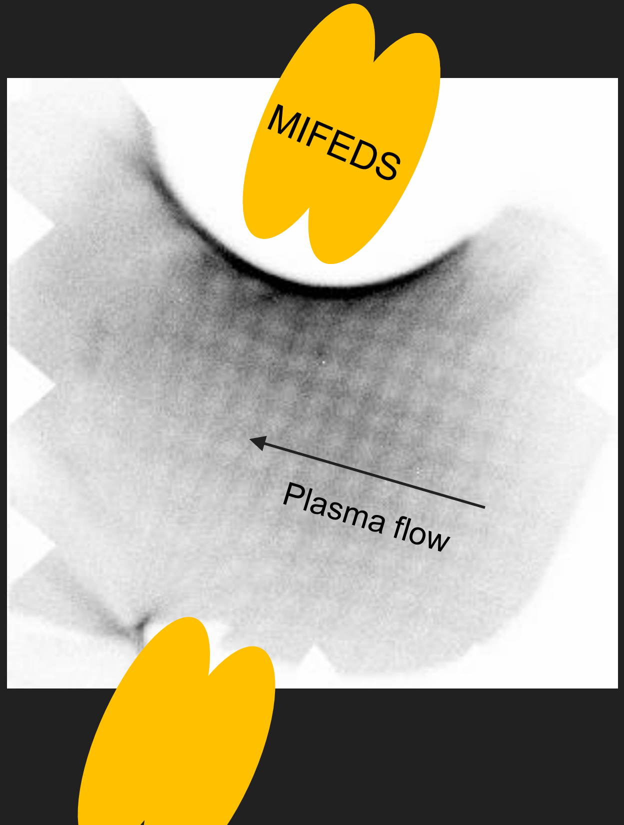
[5] N. L. Kugland, D. D. Ryutov, C. Plechaty, J. S. Ross, and H. S. Park, “Invited Article: Relation between electric and magnetic field structures and their proton-beam images,” Review of Scientific Instruments 83, 101301 (2012).

Proton Radiography Images

Image Plate (IP) – X-ray shadow of mesh



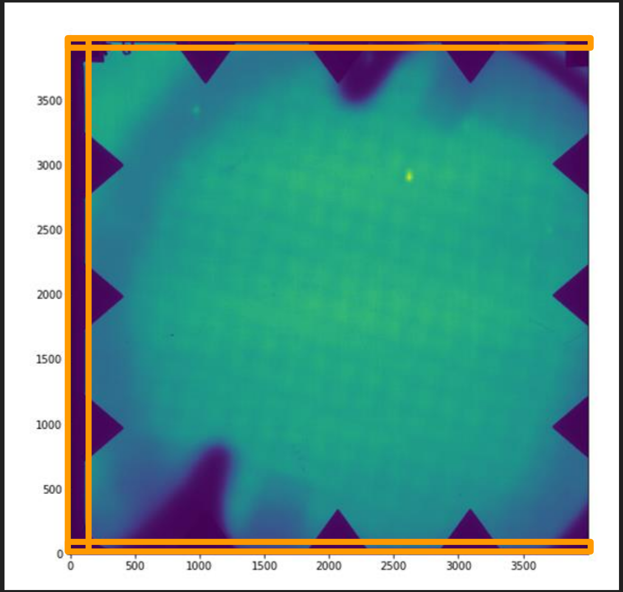
P-RAD (CR-39) – deflected protons



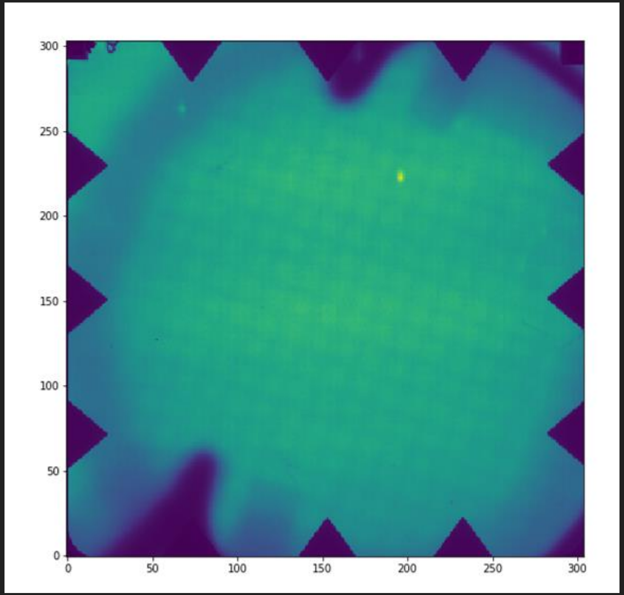
Step 1: Align P-RAD with IP image

Modifying IP:

Crop the excess near edges and resize to size of P-RAD



4000 x 4000



304x304

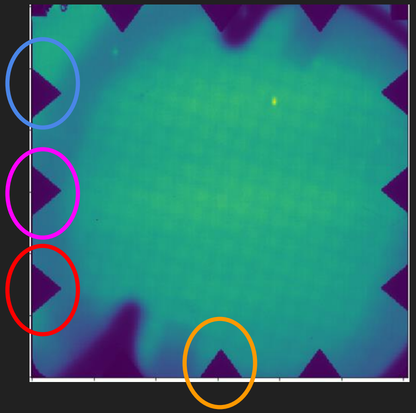
Step 1: Align P-RAD with IP image

Overlay IP and P-RAD:

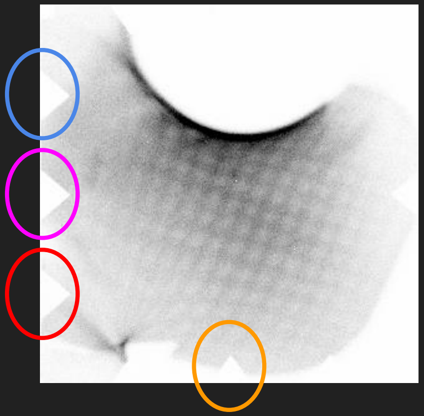
Check that teeth of frame overlap

- Rotate IP if necessary

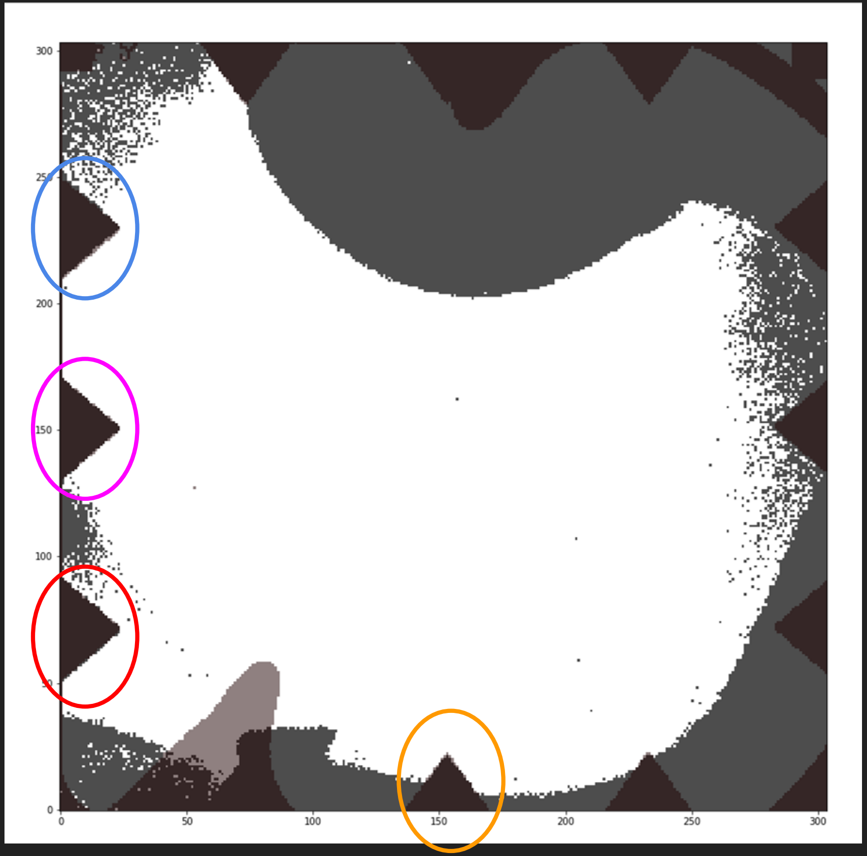
IP



P-RAD



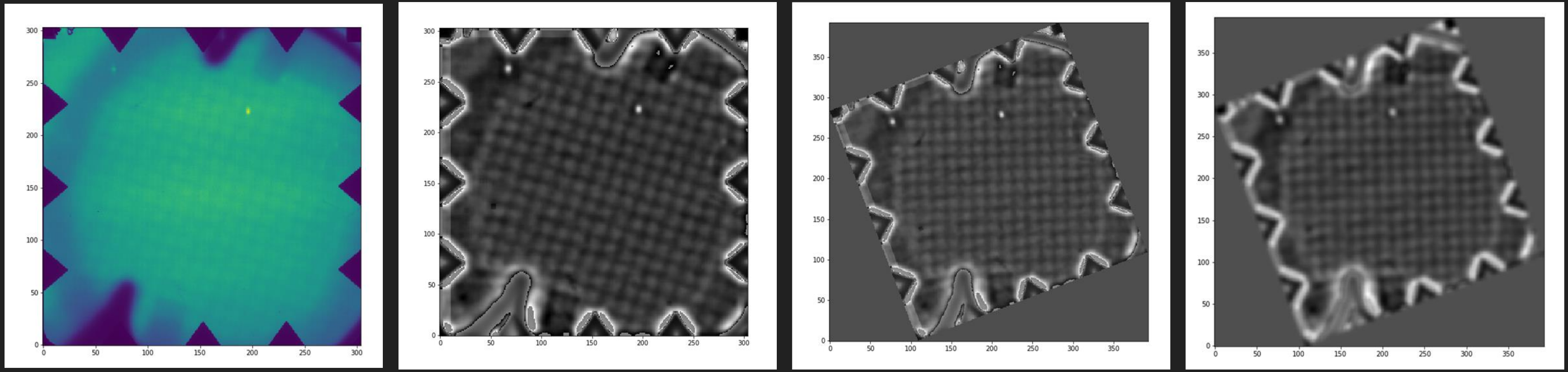
Overlapped



Step 2: Improve Contrast

IP:

- Rescale all pixel values to make mesh the area of largest contrast
- Rotate image so that rows are horizontal (parallel to x-axis)
- Apply smoothing filter to reduce noise



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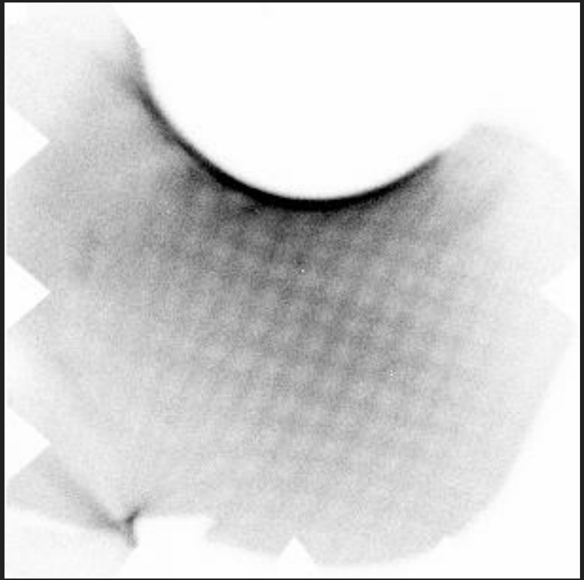
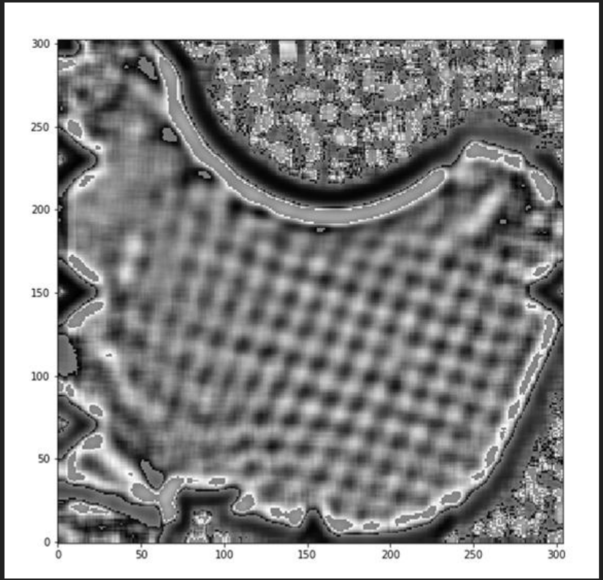
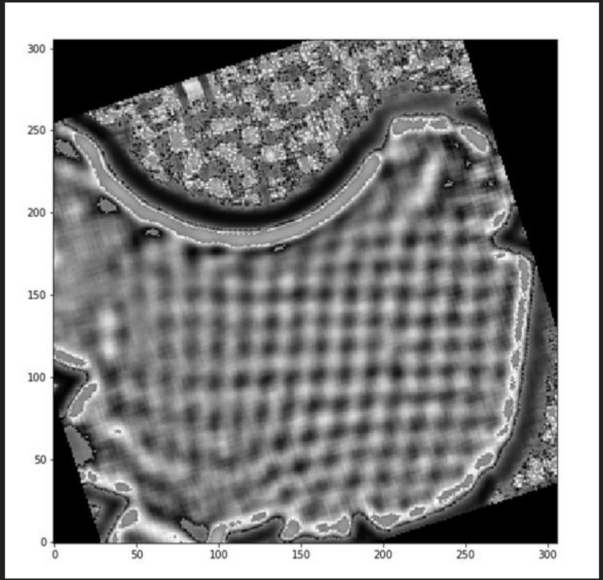






Step 3: Find Coordinates of Beamlets

IP: Find beamlet locations

<u>Automatic by row</u>

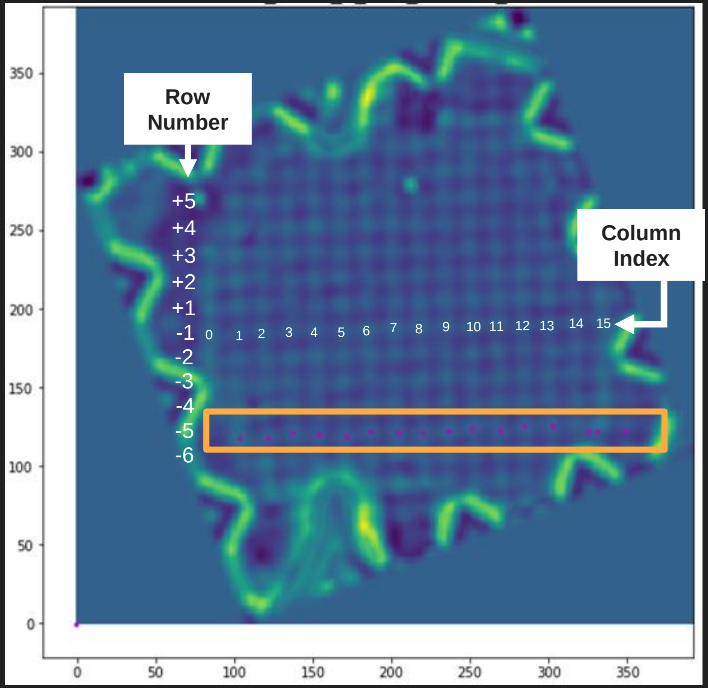
Python script using User Inputs
- Row start/end (in x and y)
- First beamlet row and column index
- Beamlet spacing parameter

Coordinates outputted to Excel file

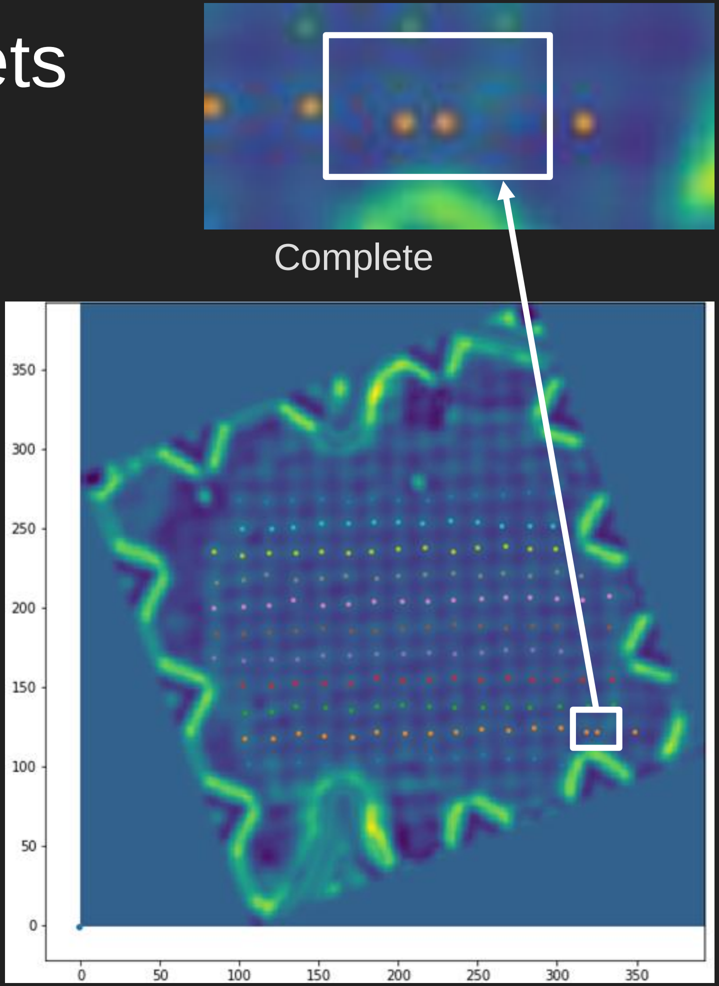
<u>Manual Corrections</u>

MATLAB script used to allow interactive, manual identification of beamlet centers

One Row



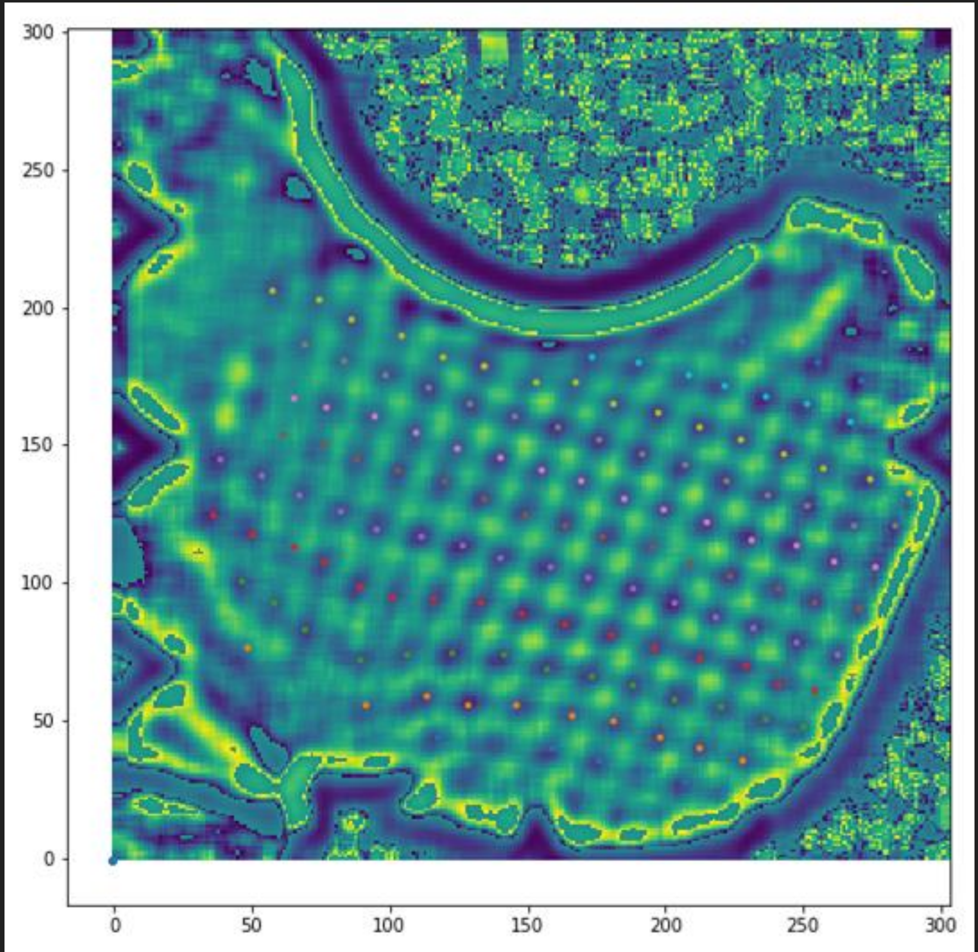
Complete



Step 3: Find Coordinates of Beamlets

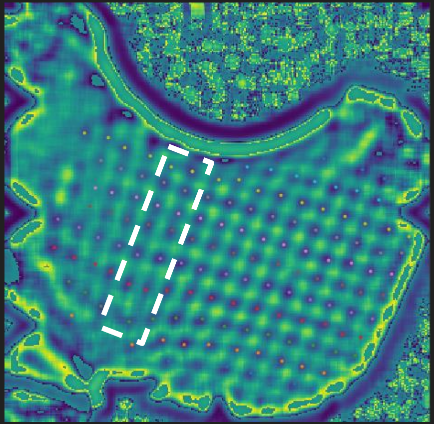
P-RAD:

Same Python and MATLAB scripts applied to find and transform beamlet locations on P-RAD

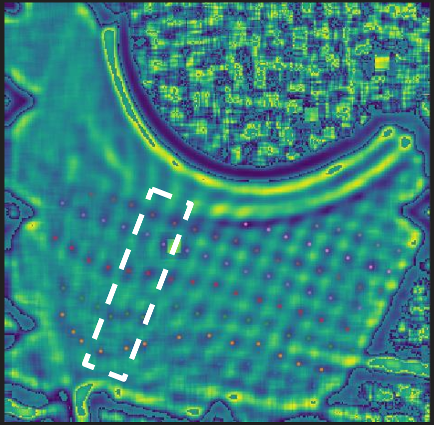


Step 4: Magnetic field profiles compared at two time points, showing significant evolution of profiles

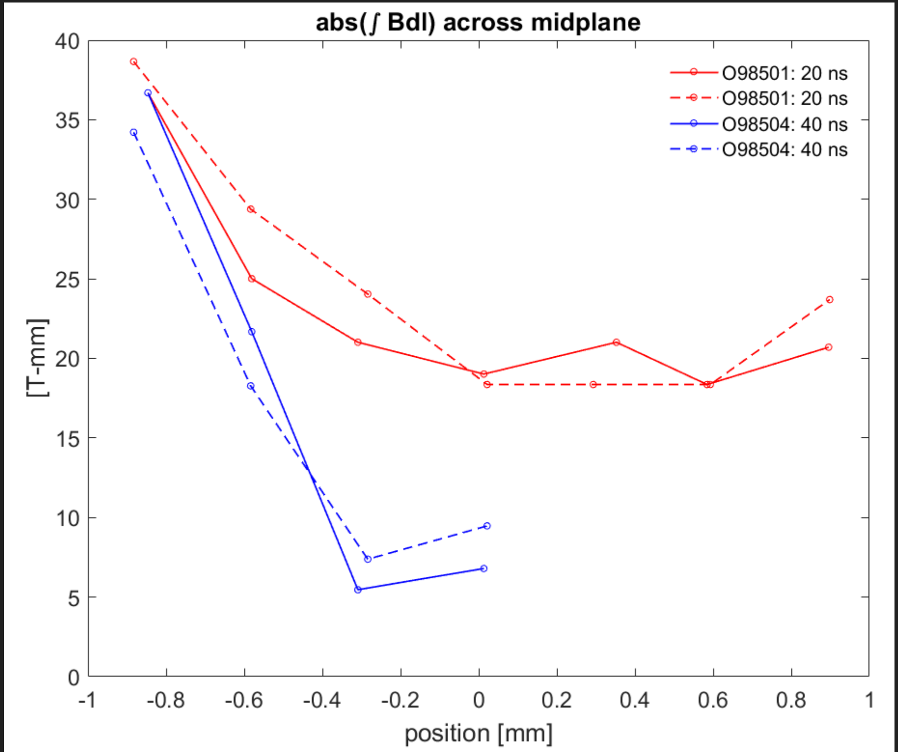
t = 20 ns



t = 40 ns



$$x_i = x_o + \beta\vec{B}$$



Conclusions and Next Steps

Conclusions:

- Proton radiography data can be processed semi-automatically to find beamlet locations and to calculate deflections
- The evolution of the magnetic field over time can be visualized

Next Steps:

- Apply process to analyze other shots from different time points, orientations, and for different energies of protons
- Compare magnetic field at different time points
    - Look at plasma parameters in order to analyze behavior of magnetic field and plasma over time

Thank You!

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