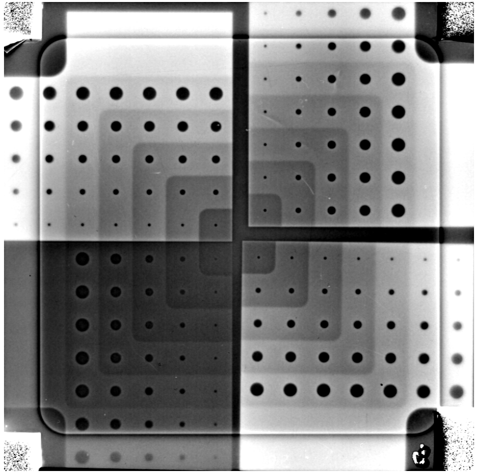
Laser-Plasma-Accelerator–Driven Electron Radiography on the OMEGA EP Laser



Gerrit Bruhaug
University of Rochester
Laboratory for Laser Energetics

NAPAC 2022
08/09/2022

Summary

Electron radiography based on laser generated electron beams provides a flexible and powerful diagnostic for HED facilities

- **Electron radiography fills a capability gap in High Energy Density (HED) science between protons and x-rays in both penetrative capability and sensitivity to fields**
- **Current HED facilities already posses the required lasers to generate effective electron beams for electron radiography using laser-plasma acceleration (LPA)**
- **Preliminary experiments on the OMEGA-EP laser have shown the potential capability of this platform to radiography plasma generated fields and penetrate materials that protons can not match**
- **Upcoming experiments will seek to capitalize on this capability to help better understand hohlraum dynamics at the National Ignition Facility**
- **Further platform development will allow for micron scale resolutions to be reached to support HED and direct drive ICF research**

Collaborators

J. L. Shaw, H. Rinderknecht, M.S. Wei J.R. Rygg, G.W. Collins

University of Rochester, Laboratory for Laser Energetics

M. Freeman, F. Merrill, L.P. Neukirch, and C. Wilde

Los Alamos National Laboratory

C. A. Walsh, E. Tubman

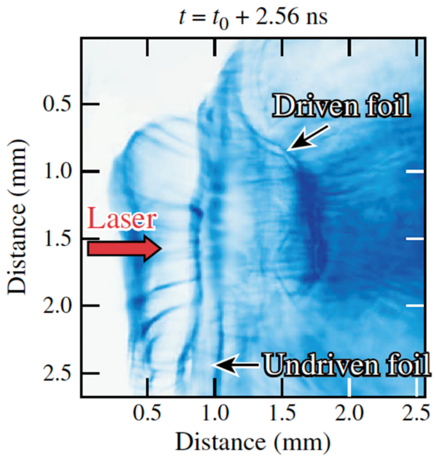
Lawrence Livermore National Laboratory

National Nuclear Security Administration

Motivation

Proton radiography was the original charged particle radiography performed

- **The first done with proton LINACs**
  - These are km scale machines
- **Later developments added magnetic optics and improved the resolution**
- **Laser driven proton radiography is now a mature technique for ICF/HED experiments**[**]



TNSA proton radiography of laser driven foil[*]

A. M. Koehler, *et al.* *Science* **160**, 303 (1968):

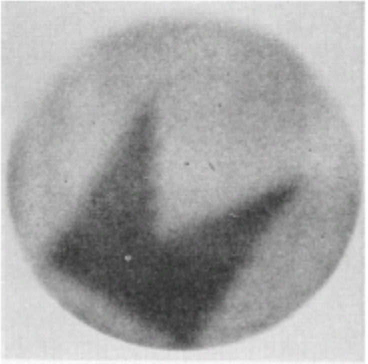


Fig. 1. Proton radiograph of aluminum absorber 7 cm in diameter and 18 g/cm² thick, with an additional thickness of 0.035-g/cm² aluminum foil, cut in the shape of a pennant, inserted at a depth of 9 g/cm². The addition of 0.2 percent to the total thickness produces a substantially darker area on the film.

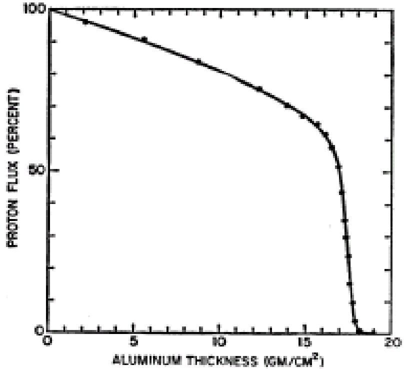


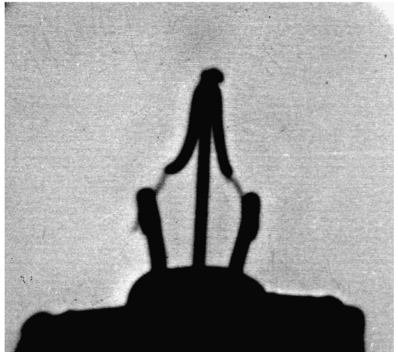
Fig. 2. Proton flux as a function of depth in aluminum. The steeply falling portion of the curve near 18 g/cm² is used to obtain the high contrast of Fig. 1.

Original LINAC derived proton radiograph

*Gao L., et al, "Magnetic field generation by Rayleigh-taylor instability in laser-driven planar plastic targets", PRL, 2012
**A. B. Zylstra *et al.*, "Using high-intensity laser-generated energetic protons to radiograph directly driven implosions," *Rev. Sci. Instrum.*, vol. 83, no. 1, 2012, doi: 10.1063/1.3680110.

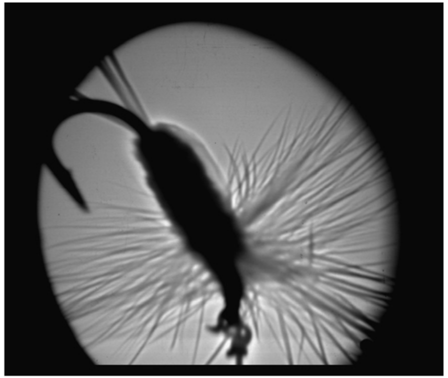
In 2007, Merrill *et al* conducted first electron radiography (eRad) experiments with 30 MeV electrons*

- **Work was motivated by:**
  - Desire to do both static ✓ and dynamic x measurements
  - Wanted to probe 0.01 – 1 g/cm^2 areal densities ✓
  - Wanted to demonstrate spatial resolutions of 100 um or better ✓
- **RF LINAC produced electron beams from 5-32 MeV**
- **First tests of magnetic optics for eRad**



Tungsten light bulb filament

Fly fishing fly

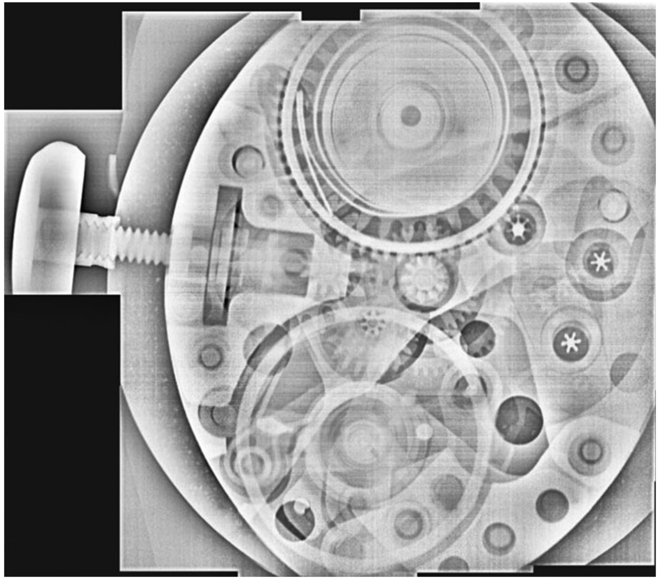


eRad proved to be useful for thin, small objects across the range of material Z numbers

* F. Merrill *et al.*, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 261 (1-2), 382 (2007).

eRad holds a lot of promise as a radiography technique

- **Electron beams are easier to generate than protons****
  - 1 GeV electrons can be generated in ~1 cm via laser-plasma techniques or in ~10 meters with RF accelerators
  - 1 GeV protons require km scale RF accelerators and no mature laser techniques exist*
- **Electrons are more penetrating for a given energy while providing more sensitivity to B-fields and less to E-fields compared to protons***
  - 20 MeV protons are stopped by ~2 mm of aluminum†
  - 20 MeV electrons penetrate 3+ cm of aluminum†
- **However, Bremsstrahlung adds new imaging complexity and further motivates the use of magnetic optics****



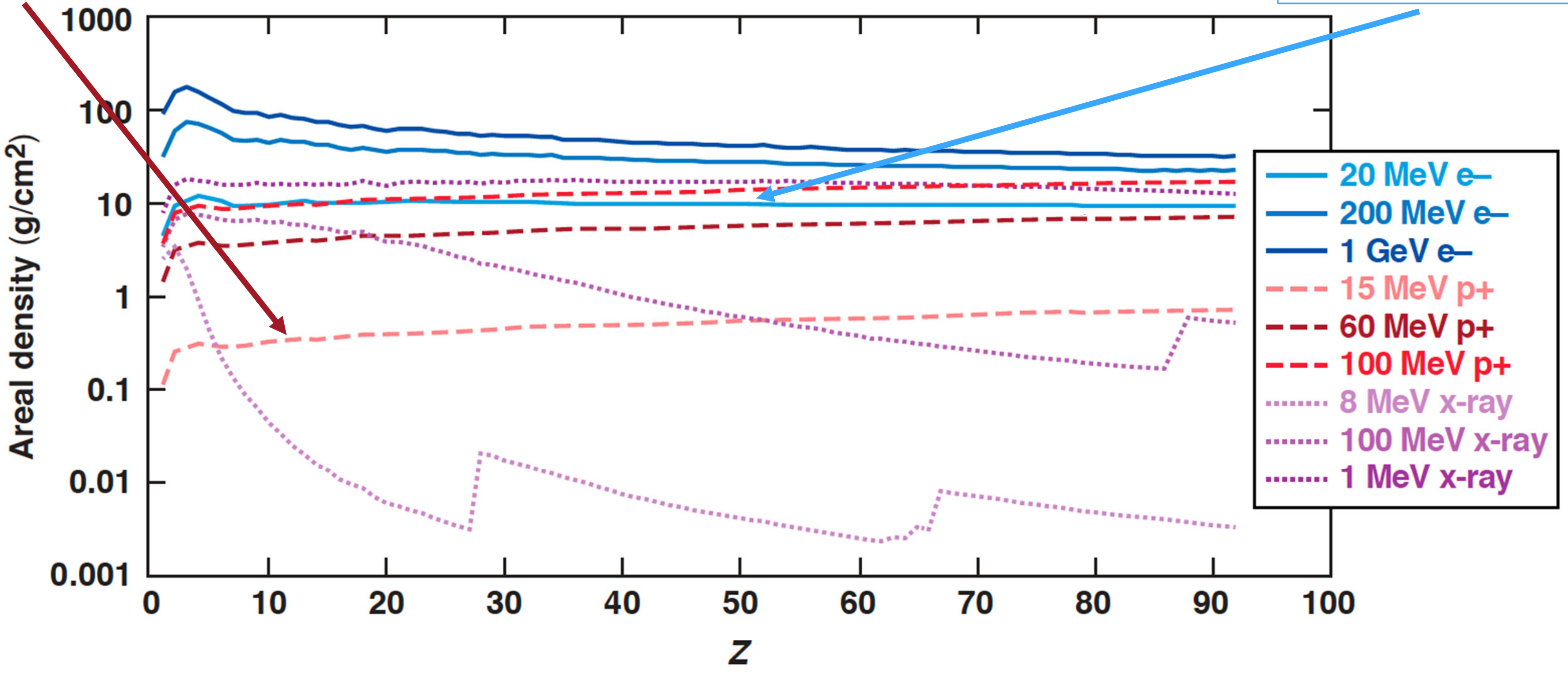
14 GeV eRad of pocket watch**

* Merrill, F.E., "imaging with penetrating radiation for the study of small dynamic physical processes", Laser and Particle Beams, 2015
** Merrill, F.E., "Demonstration of transmission high energy electron microscopy", AIP Conference Proceedings 2272 (2020)
†M. Berger, J. S. Coursey, and M. A. Zucker, "ESTAR, PSTAR, and ASTAR:Computing Programs for Calculating Stopping-Power and Range Tables for Electrons, Protons and Helium Ions.," 2005. http://physics.nist.gov/Star (accessed Apr. 01, 2022).

Electrons that can be generated right now are highly penetrative

Typical laser-proton

Typical laser- electron

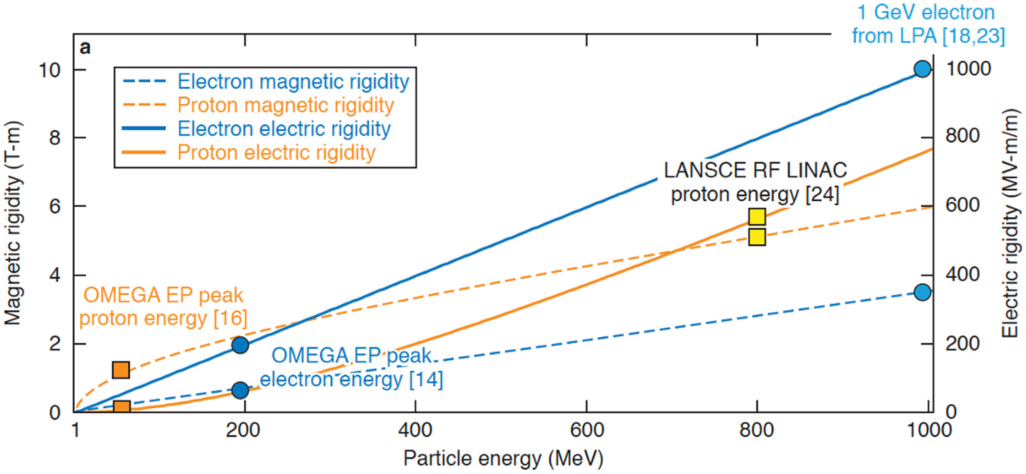


E30473

* M. Berger, J. S. Coursey, and M. A. Zucker, "ESTAR, PSTAR, and ASTAR:Computing Programs for Calculating Stopping-Power and Range Tables for Electrons, Protons and Helium Ions.," 2005. http://physics.nist.gov/Star (accessed Apr. 01, 2022).

The difference in electromagnetic field sensitivity is key to the utility of eRad

- **The lower magnetic rigidity makes electrons more sensitive to magnetic fields for a given energy***
  - Makes magnetic optics easier and allows the probing of weaker magnetic fields in experiments
- **We also define a term, “electric rigidity” to look at the sensitivity to electric fields**
  - Relativistic electrons are *far* less sensitive to electric fields
  - This provides a sharp contrast to protons and will help prevent mistaken claims of strong magnetic fields**



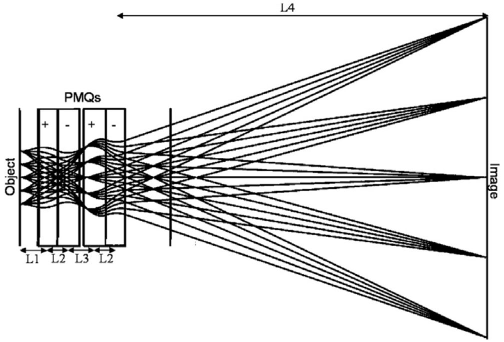
$$B\rho = \frac{p}{q}$$

$$E\rho = \frac{T\beta^2}{q}$$

*Lee S., et al, *Accelerator Physics Second Edition*, World Scientific, 2004
**Peebles, J.L. et al, “Axial proton probing of magnetic and electric fields inside laser-driven coils”, Physics of Plasma 27, 063109 (2020), https://doi.org/10.1063/1.5134786

Adding magnetic optics can dramatically increase the resolution capability

- **Prior experiments using the 14-GeV electrons from the SLAC LINAC demonstrated the ability of e-Rad to visualize materials in the < 0.1 g cm^{-2}** to several g cm^{-2} † with a spatial resolution down to 8.8 um**
- **Theoretically resolution can be as low as 0.06 um with proper beam and magnetic optic matching†**
- **Magnetic optics for electron beams are far smaller than for proton beams**
  - LANSCE magnetic optics for protons are many meters in length
  - Electron radiography optics are typically no bigger than 1 meter
- **The higher deflection angles of electrons with matter also make imaging of thin or low density objects easier than with LINAC derived protons**
  - Several mg/cm^2 areal density objects can be resolved with electrons, which is not possible with current LINAC proton probes



30-MeV ×5.9 magnifying electron lens

Electron radiography

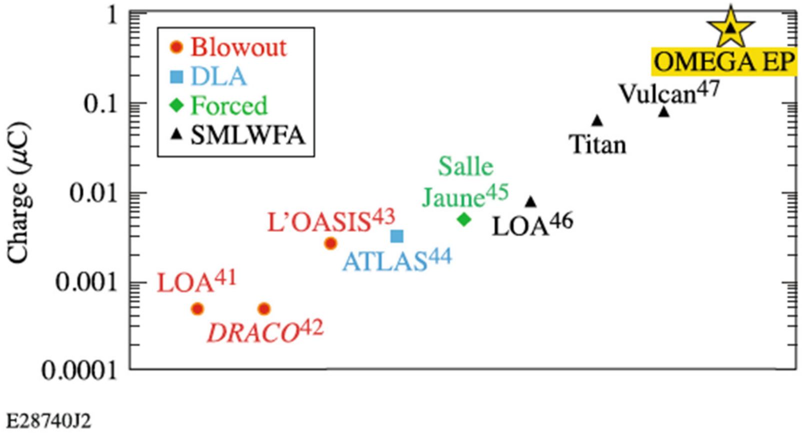
Frank Merrill [a,*], Frank Harmon [b], Alan Hunt [b], Fesseha Mariam [a], Kevin Morley [a], Christopher Morris [a], Alexander Saunders [a], Cynthia Schwartz [a]

[a] Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87544, United States
[b] Idaho Accelerator Center, Idaho State University, Pocatello, ID 83201, United States

* Slide material courtesy M. Freeman and J. Shaw
** F. Merrill *et al.*, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 261 (1-2), 382 (2007).
† F. E. Merrill *et al.*, Applied Physics Letters 112 (14), 144103 (2018).
‡ W Schumaker *et al.*, Physical review letters 110 (1), 015003 (2013).

Large laser facilities already have the drivers needed for generating electron beams

- **High intensity (>10^{18} W/cm^2), short pulse (≤1 ps) lasers are ideal for laser-plasma electron beam generation**
  - Electron pulses are on the order of the laser pulse, and thus much faster than many processes of interest
  - Multiple facilities now available: OMEGA-EP, NIF-ARC, Z-Petawatt
- **Laser generated electron beams are often not ideal sources for radiography due to the high energy spread and large emittance of the beam**
  - These beams can be tuned via collimators and chicanes, but at the cost of electron number
- **Recently using OMEGA-EP* we have generated record setting electron bunch charges**
  - This provides a beam that can be selectively tuned without losing SNR

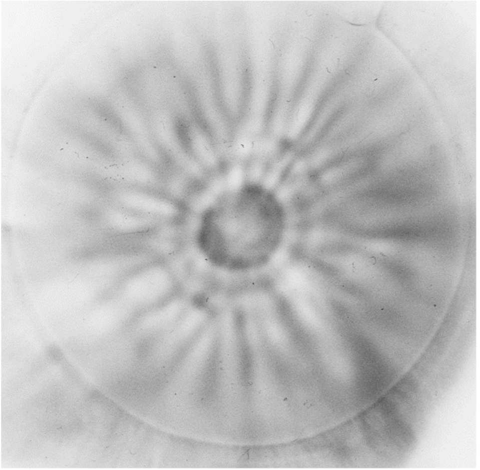


Comparison of laser driver vs electron beam bunch charge*

* Shaw J., et al, "Microcoulomb (0.7+/- 0.4/0.2 uC) laser plasma accelerator on OMEGA-EP

Electron beam radiography will allow for the probing of fields in HED environments that were previously unreachable with traditional proton probes

- **Magnetic field generation in laser-ablation of targets***
  - eRad can easily penetrate dense, high Z targets like hohlraums while laser driven protons struggle
  - Understanding the Bierman battery in these environments is important for indirect drive*†
  - This has been done at small scale facilities before**
- **Shock fields inside of thick targets**
  - Proton probes have previous had great success in low density targets†
  - eRad will be able to radiograph mm-scale, high density HED targets and provide field information
  - This will constrain plasma conditions in the target
- **Provides an important contrast to protons for similar experiments as well**
  - The inversion of electric and magnetic rigidity compared to protons provides a strong contrast in the images
  - eRad prevents strong electric fields from being mistaken for strong magnetic fields††



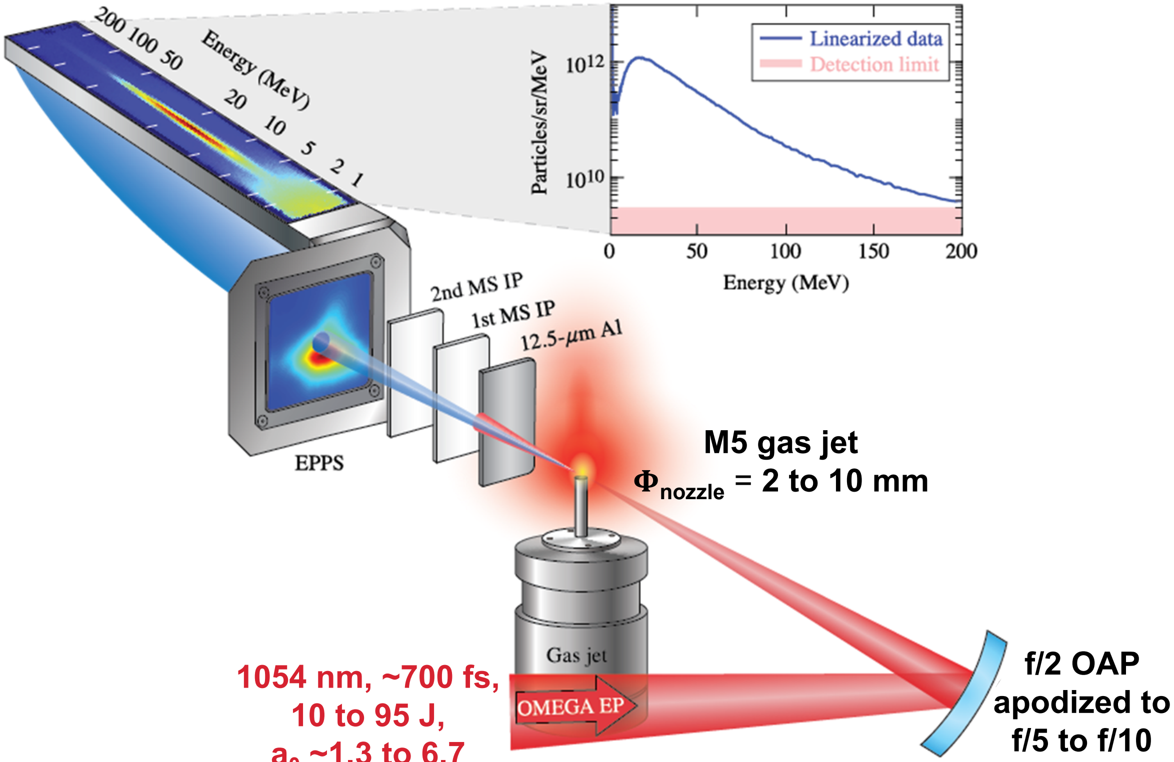
pRad of magnetic fields in laser driven foil*†

*P. T. Campbell *et al.*, "Magnetic Signatures of Radiation-Driven Double Ablation Fronts," *Phys. Rev. Lett.*, vol. 125, no. 14, p. 145001, 2020, doi: 10.1103/PhysRevLett.125.145001.
** W. Schumaker *et al.*, "Ultrafast electron radiography of magnetic fields in high-intensity laser-solid interactions," *Phys. Rev. Lett.*, vol. 110, no. 1, 2013, doi: 10.1103/PhysRevLett.110.015003.
† R. Hua *et al.*, "Self-Generated Magnetic and Electric Fields at a Mach-6 Shock Front in a Low Density Helium Gas by Dual-Angle Proton Radiography," *Phys. Rev. Lett.*, vol. 123, no. 21, p. 215001, 2019, doi: 10.1103/PhysRevLett.123.215001.
††J. L. Peebles, J. R. Davies, D. H. Barnak, T. Cracium, M. J. Bonino, and R. Betti, "Axial proton probing of magnetic and electric fields inside laser-driven coils," *Phys. Plasmas*, vol. 27, no. 6, 2020, doi: 10.1063/1.5134786.
*†Personal communication with C. Walsh

Experiments

The OMEGA-EP LPA electron beam is a high-charge, polychromatic beam

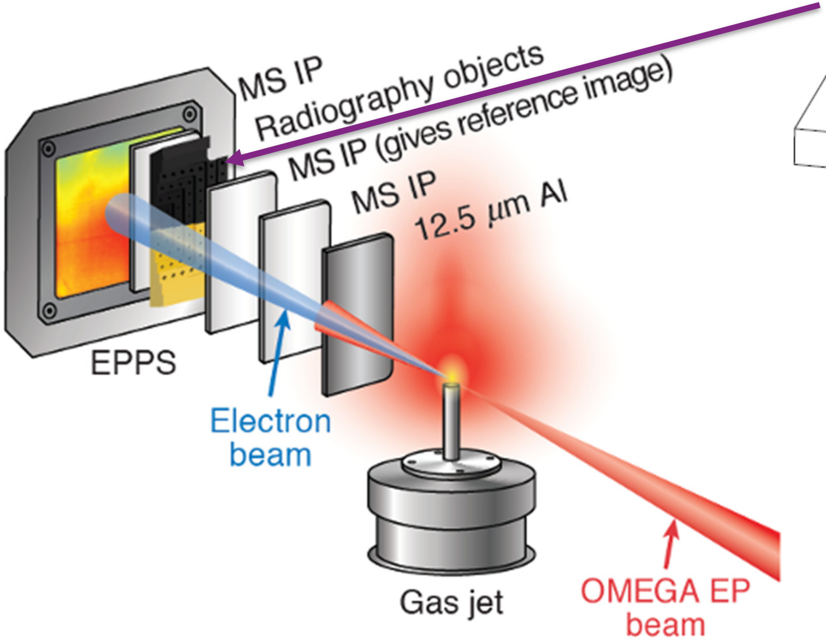
700 nC, 700 fs electron pulse

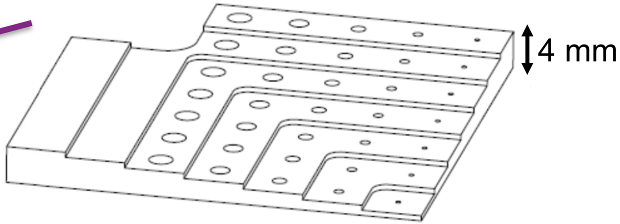


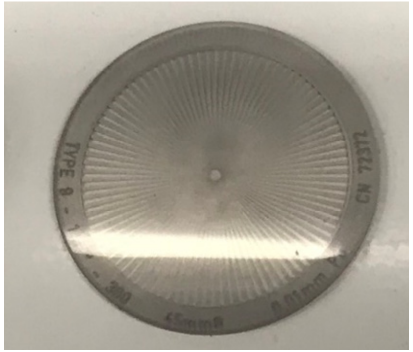
EPPS: electron–positron–proton spectrometer
OAP: off-axis parabola

* Slide material courtesy J. Shaw

The first eRad experiments were performed with objects placed directly onto an image plate (IP) stack in January of 2021







30-μm Pb wheel pattern*

Materials:

- Cu
- Al
- Ti
- W
- Sn
- S. Steel

* From M. Freeman

eRad resolution is driven by source size and scattering in the material

- **For targets less than a radiation length in thickness, source size dominates the resolution** Δs

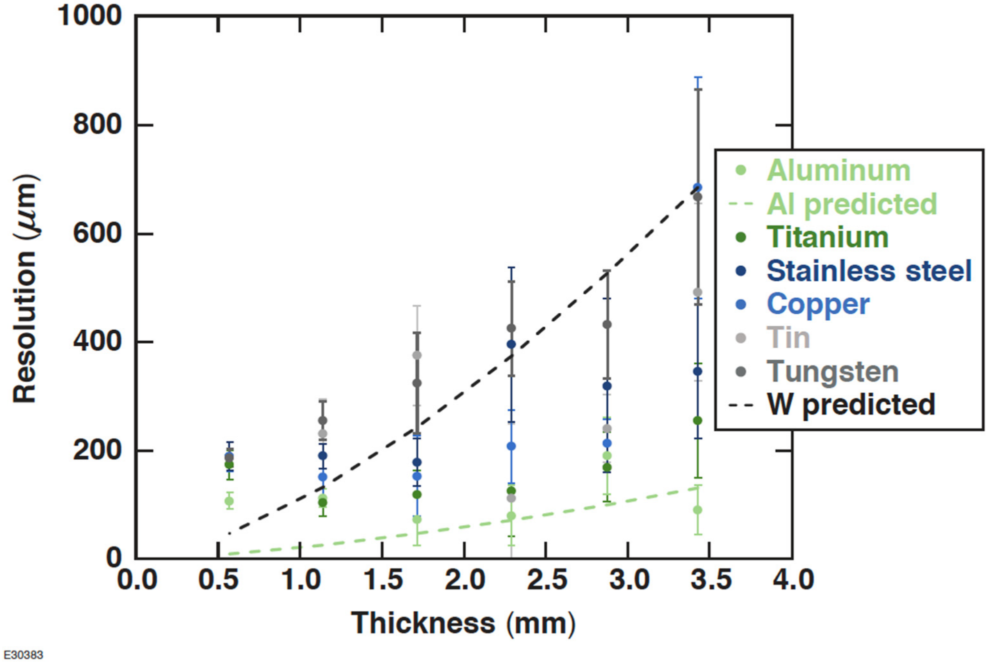
- **Targets on the order of a radiation length or more have resolution dominated by scattering** Δx
  - Goes roughly as target $Z^2 + Z$

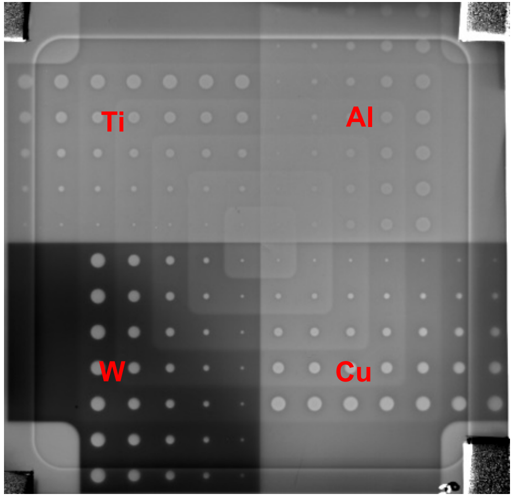
- **Imaging system pixel size (25-100 μm for image plates) also plays a role** Δp

$$Reslution = \frac{1}{Magnification}\sqrt{\Delta s^2 + \Delta x^2 + \Delta p^2}$$

* F. Merrill *et al.*, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 261 (1-2), 382 (2007).
**S. Power, S. A. Calculations, and A. P. Source, "Stopping Power and Scattering Angle Calculations," 1991.

The results were very encouraging and showed the potential of this platform





Shot 34030

Clear images seen even through 4 mm of tungsten

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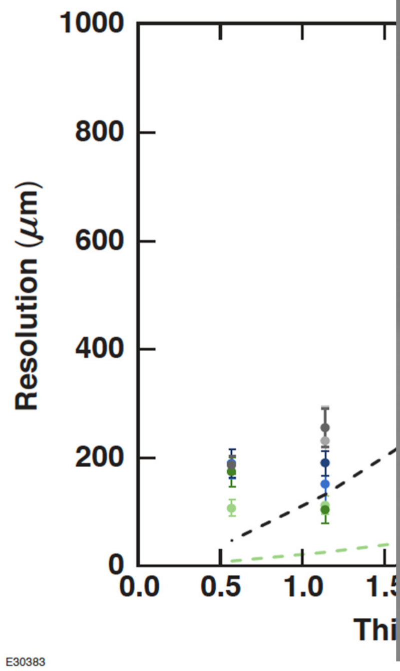

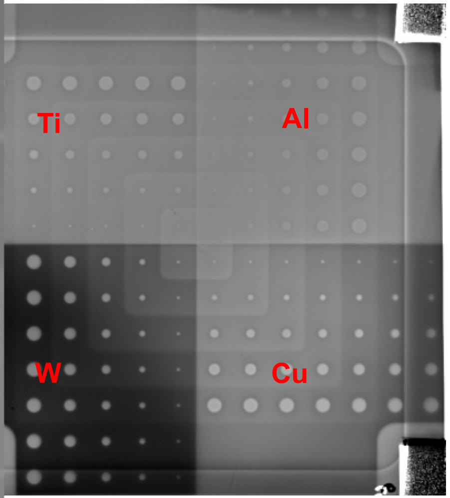

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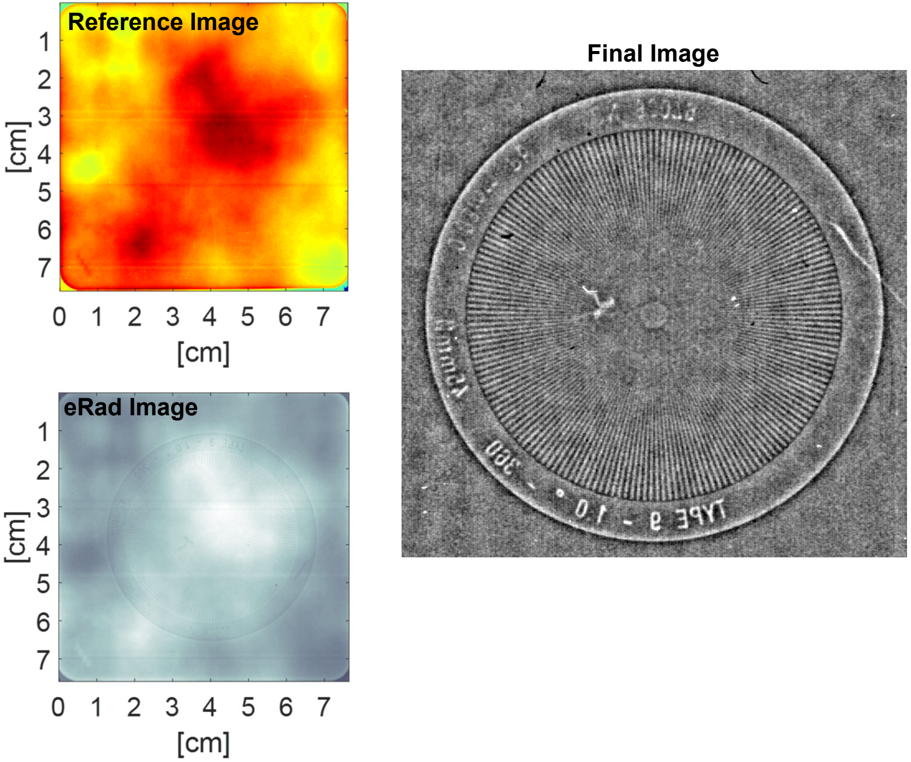
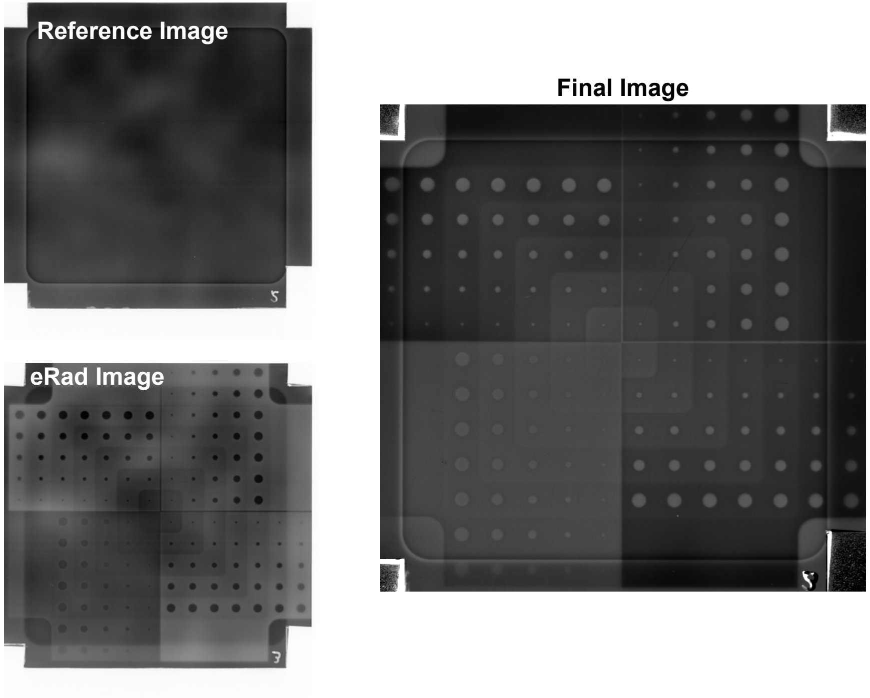
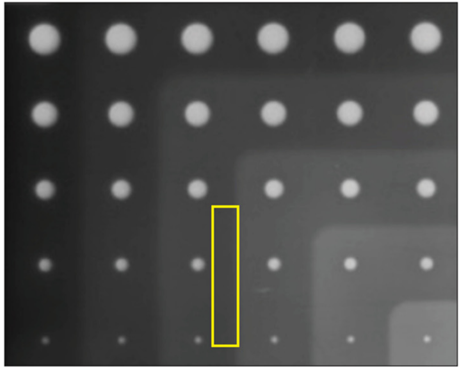
The structure from the electron beam can be flattened with a reference image

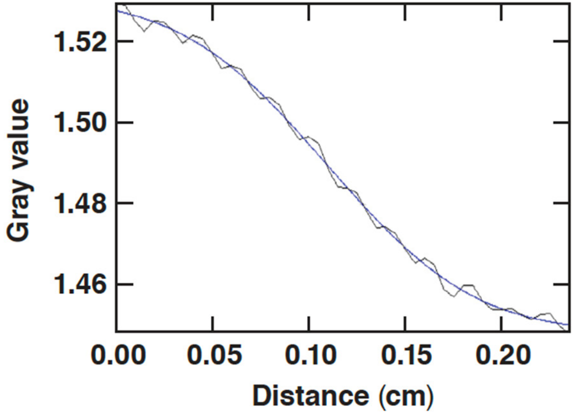




Resolution were measured over both edges and steps in the materials

- **Measurements were repeated for all steps and holes**
- **Error was determined by averaging multiple measurements**
- **Blur can be attributed to several factors**
  - Uncorrected Multiple Coulomb Scattering (MCS)
  - Bremsstrahlung broadening
  - Image plate pixel size (25-100 μm)
  - Source size blur (~30 μm)





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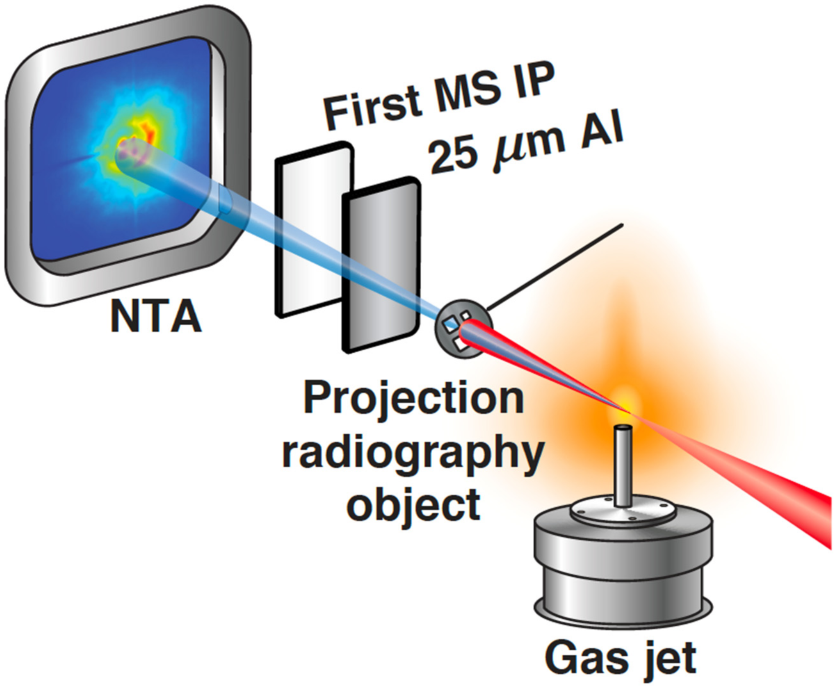
Resolution measurement on tungsten radiography object

Later experiments in 2021 tested projection radiography of static targets



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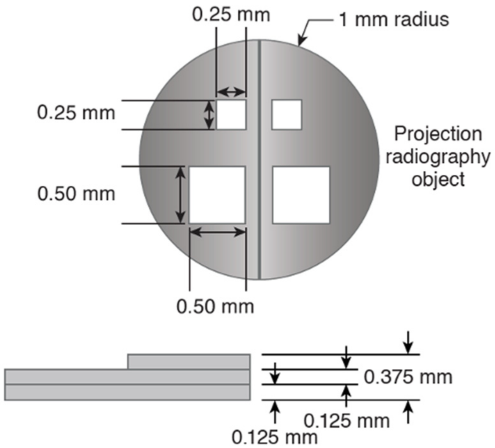
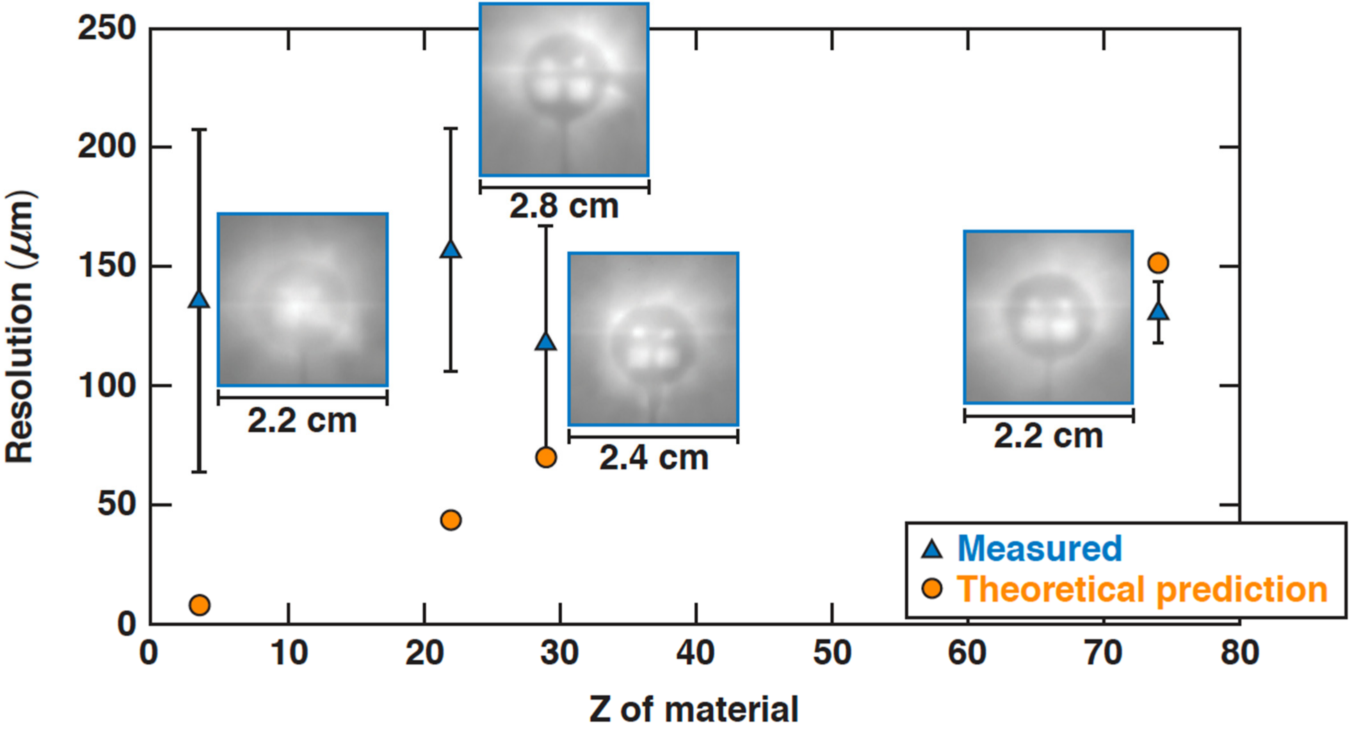
4 materials tested and NTA distance varied

- Polyimide (3 stacks)
- Cu
- Ti
- W



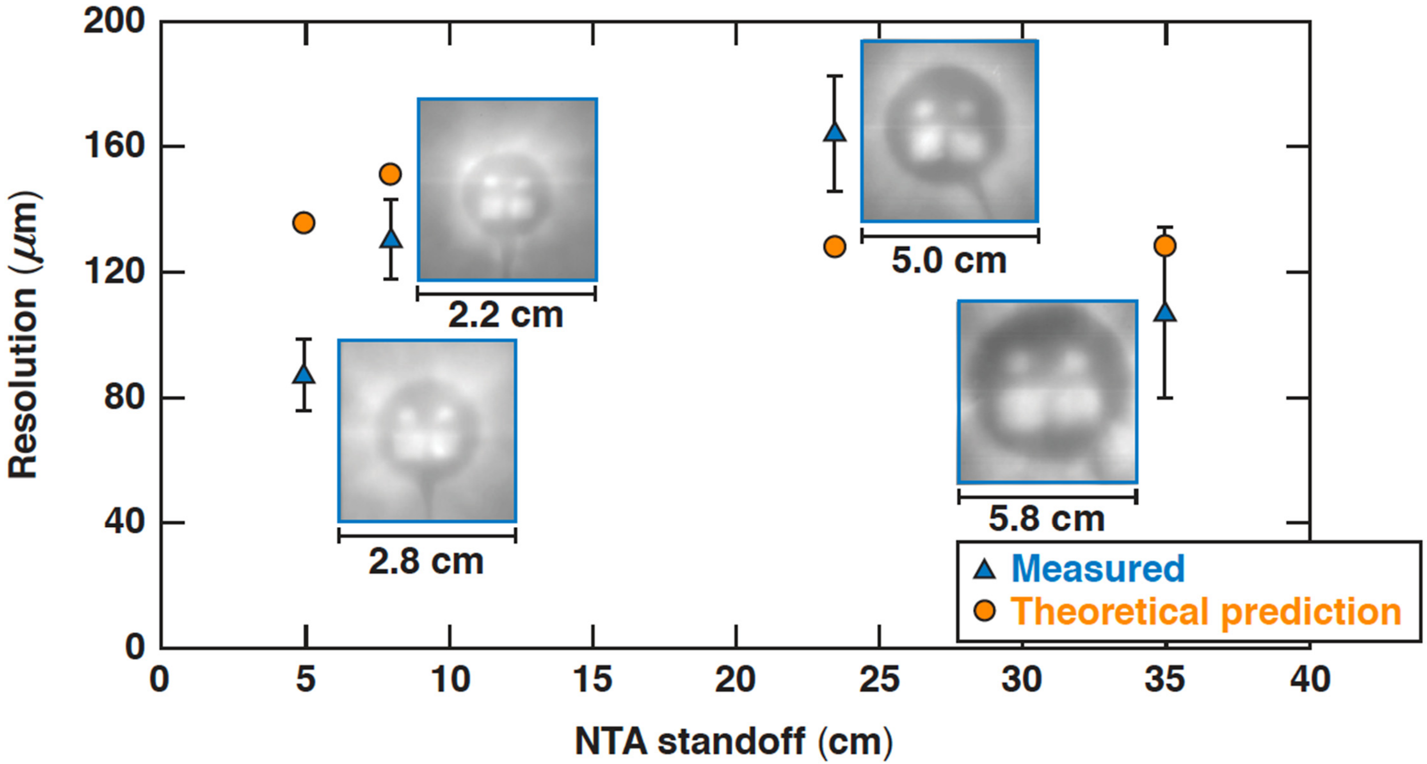
Without magnetic optics or collimation the resolution remained unchanged no matter the Z number of the target material



E30338

*S. Power, S. A. Calculations, and A. P. Source, "Stopping Power and Scattering Angle Calculations," 1991.

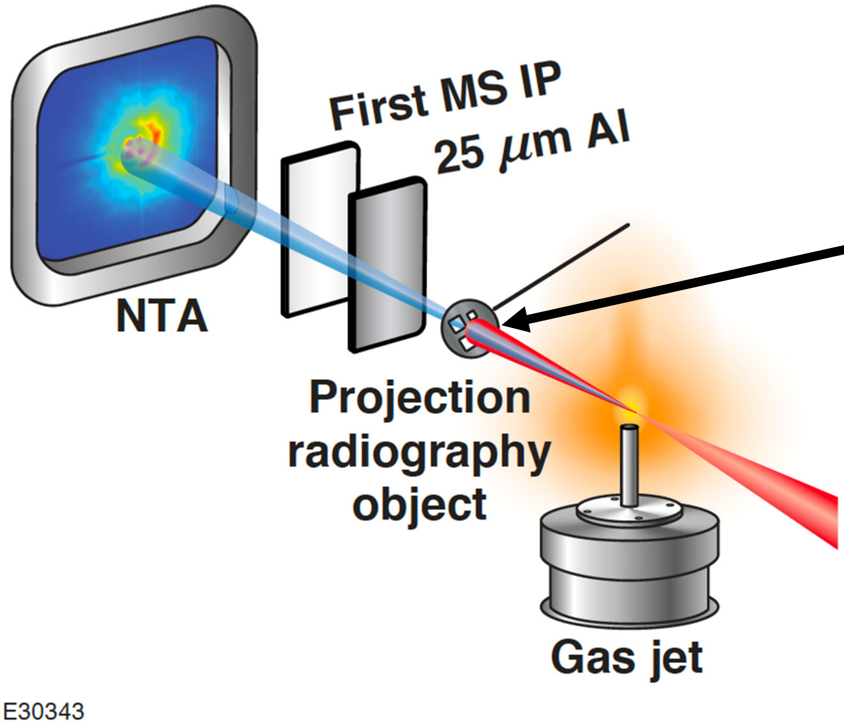
Without magnetic optics or collimation the resolution remained almost unchanged no matter the magnification of the target



E30339

*S. Power, S. A. Calculations, and A. P. Source, "Stopping Power and Scattering Angle Calculations," 1991.

It was noticed that the measured diameters did not match expectations



Laser hits the target!

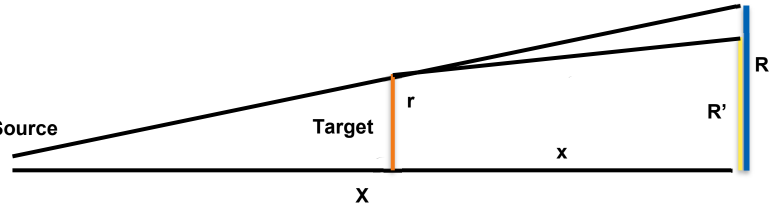
25-100 J, ~10^{15} W/cm^2 laser that is ~100 fsec ahead of electron beam

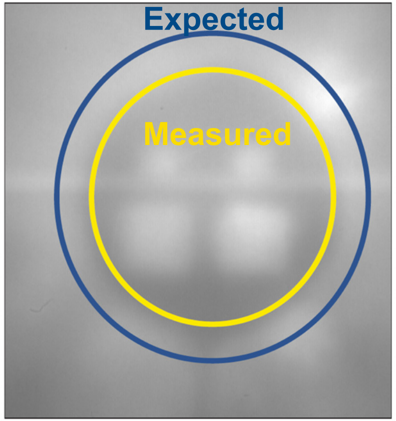
It was noticed that the measured diameters did not match expectations

- **All images were a factor of ~1.5X smaller than expected based just on simple radiography math**

- **An equation was derived to determine the electric field needed to alter the images in this way**
  - ~1 GV/m found to fit both analytically and with Geant4 simulations*
  - This is the expected field in laser plasmas at those intensities**

$$E\left({}^{GV}\!/_{m}\right) = \frac{R - R'}{10^9\sqrt{(R' - r)^2 + x^2}}\sqrt{1 - \left(\frac{X}{\sqrt{R^2 + X^2}}\right)^2}\,\frac{T}{q\rho}\,\frac{\gamma + 1}{\gamma}$$





E30463J1

Fields in laser driven targets were already measured!

*G4 Beamline 3.06." **T. Roberts, Muons Inc, 2018, [Online]. Available: http://www.muonsinternal.com/muons3/g4beamline/G4beamlineUsersGuide.pdf.

**J. L. Dubois *et al.*, "Target charging in short-pulse-laser-plasma experiments," *Phys. Rev. E - Stat. Nonlinear, Soft Matter Phys.*, vol. 89, no. 1, pp. 1–15, 2014, doi: 10.1103/PhysRevE.89.013102

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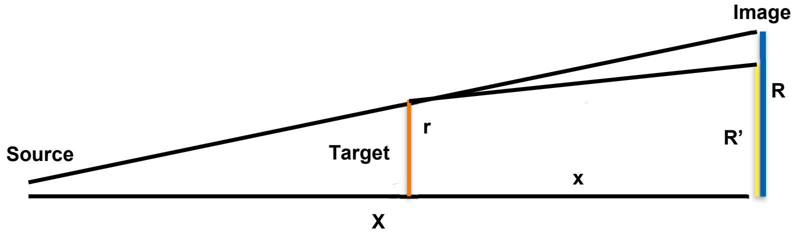
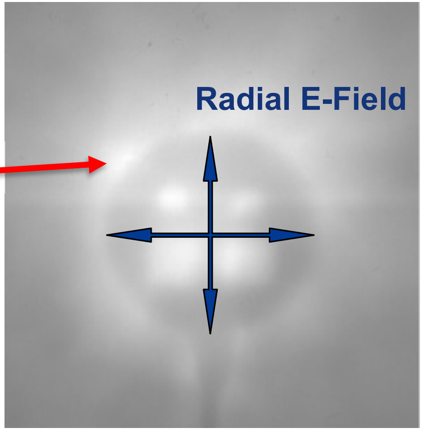


Laser produced plasma



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Laser-plasma E-fields have never been measured with electron beams before

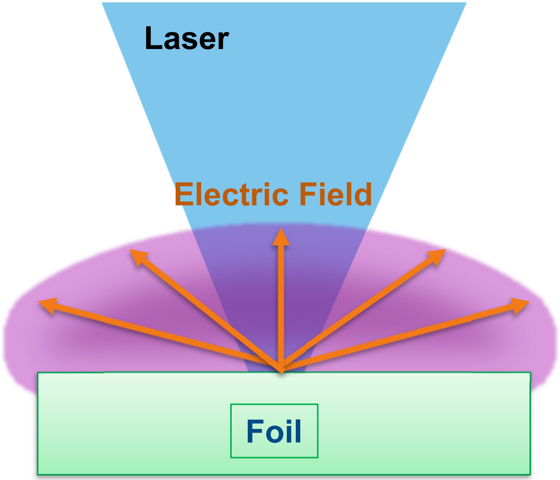
- **Plasma electric fields are driven by plasma pressure gradients**

$$\boxed{E \approx -\nabla P/en_e}$$

- **Plasma magnetic fields are driven by temperature and density gradients**

$$\boxed{\mathbf{B} \approx -\nabla n_e \times \nabla T_e/en_e}$$

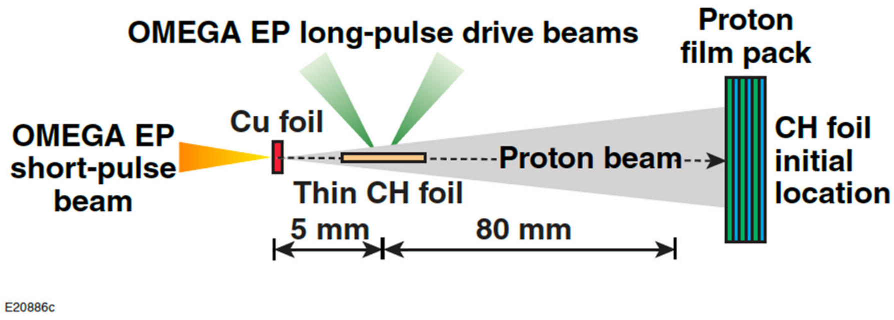
- **The lack of rotation in the image indicates a lack of large scale magnetic fields**



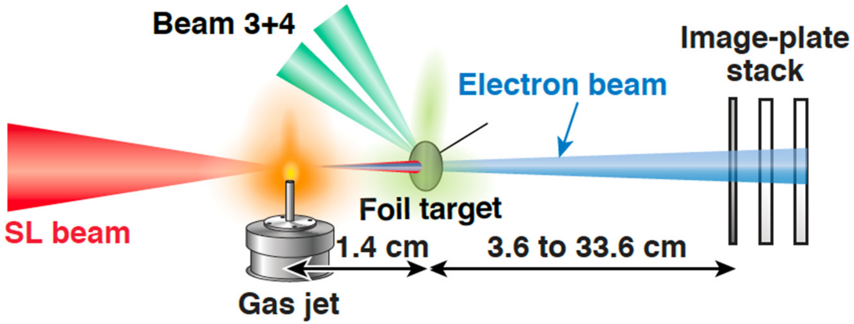
* J. L. Dubois *et al.*, "Target charging in short-pulse-laser-plasma experiments," *Phys. Rev. E - Stat. Nonlinear, Soft Matter Phys.*, vol. 89, no. 1, pp. 1–15, 2014, doi: 10.1103/PhysRevE.89.013102
**C.K. Li, *et al.* "Proton radiography of dynamic electric and magnetic fields in laser-produced high energy density plasmas", *Physics of Plasmas*,16, 056304, (2009), https://doi.org/10.1063/1.3096781

These results were then extended to intentional laser driven targets in early 2022

- The goal was to copy a previous proton radiography experiment
- 25 um plastic foils driven with 100 ps – 2.5 ns "long" pulse lasers



Schematic TNSA proton radiography of driven CH foil*

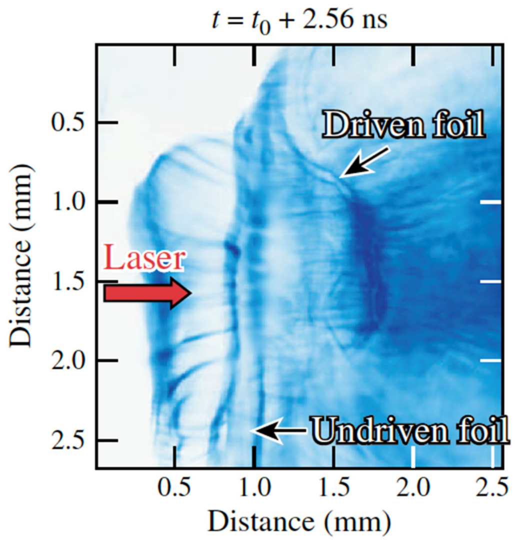


Schematic of of eRad of driven CH foil

* Gao L., et al, "Magnetic field generation by Rayleigh-taylor instability in laser-driven planar plastic targets", PRL, 2012

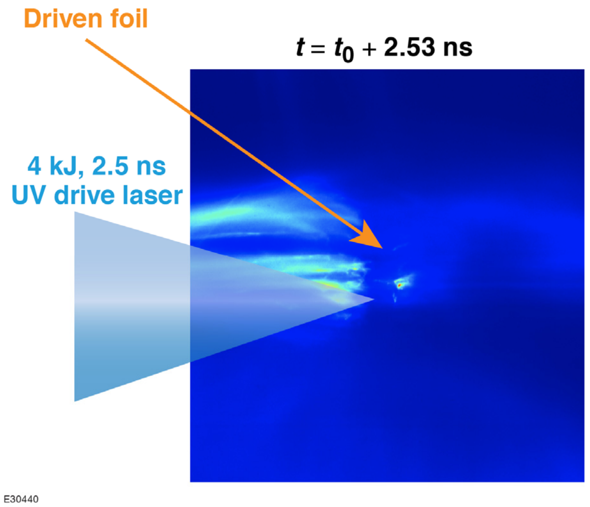
The laser driven results provide an interesting contrast to similar proton radiographs of driven targets

- Similar looking results, although more "streaming" from laser side
- pRad estimates were ~100 Tesla fields and eRad estimates are also ~100 Tesla fields!



13 MeV protons*

Similar field measurements!



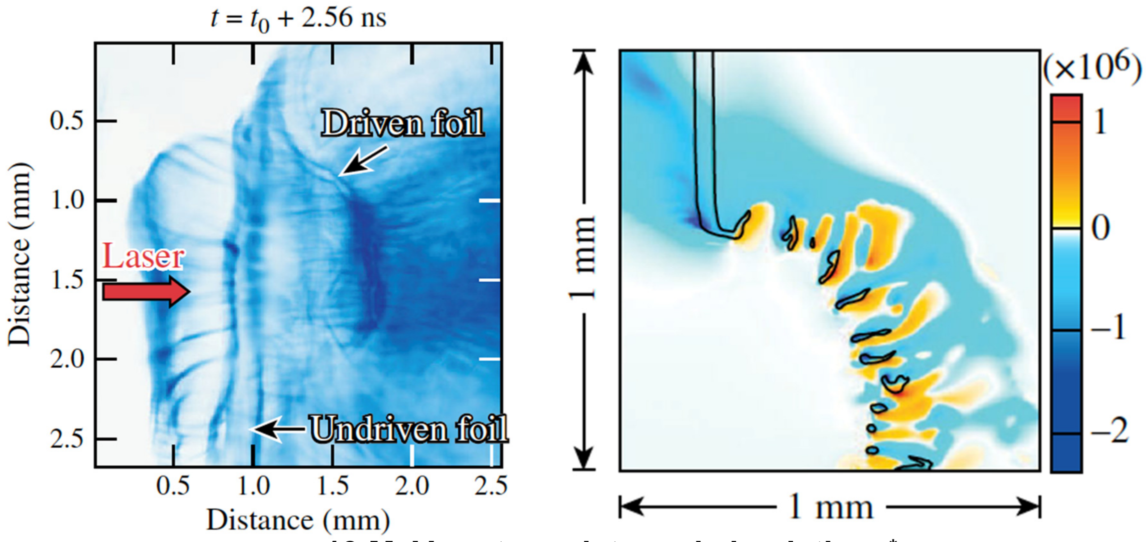
Relativistic Electrons

* Gao L., et al, "Magnetic field generation by Rayleigh-taylor instability in laser-driven planar plastic targets", PRL, 2012

The magnetic fields are focused in the ”streamers”

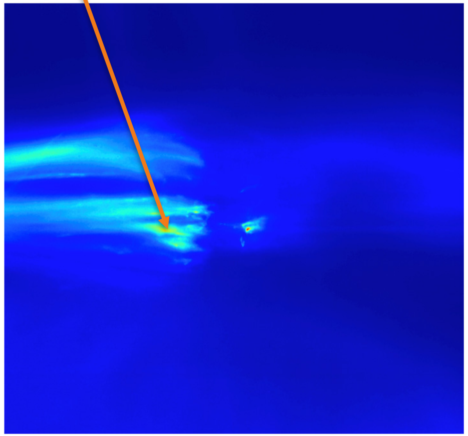
- **This is due to the Nerst effect where fields are driven by temperature and density gradients**

$$\mathbf{B} \approx -\nabla n_e \times \nabla T_e / e n_e$$



13 MeV protons data and simulations[*]

Streaming plasma focusing the beam



Relativistic electrons

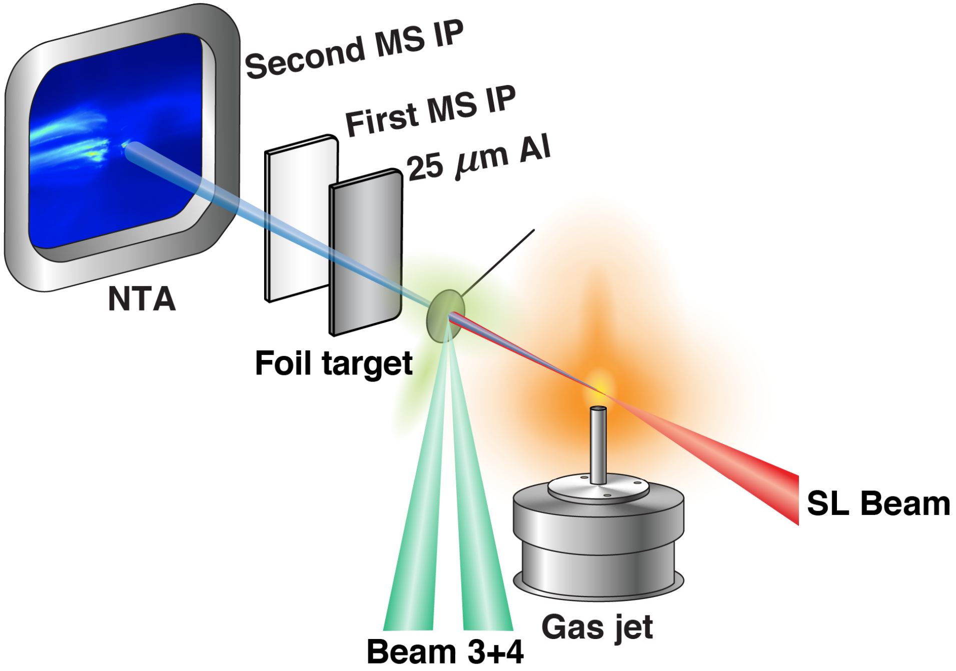
Gao L., et al, “Magnetic field generation by Rayleigh-taylor instability in laser-driven planar plastic targets”, PRL, 2012

[**]C.K. Li, *et al.* “Proton radiography of dynamic electric and magnetic fields in laser-produced high energy density plasmas”, *Physics of Plasmas*,16, 056304, (2009), https://doi.org/10.1063/1.3096781

Future Work

The OMEGA EP eRad source will be used to test hohlraum physics in Dec 2022

- **Experiments will then be undertaken to better understand magnetic field generation in metal foils****
  - Applicable to hohlraum physics and the “drive deficit” issue†
  - Protons can’t penetrate the gold walls, but electrons can easily punch through and retain field data
  - Side and face on experiments will be undertaken

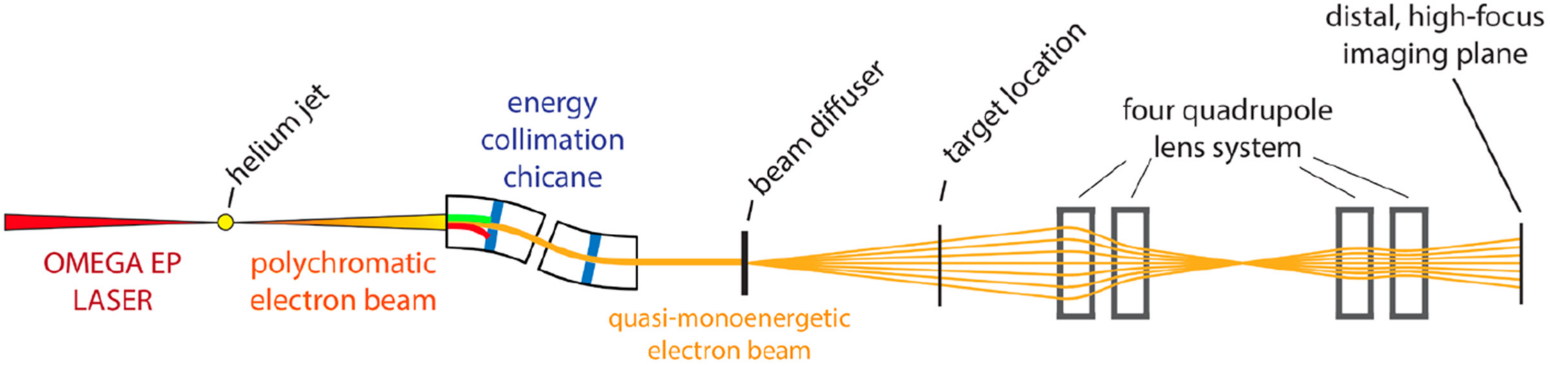


E29039a

†Personal communication with C. Walsh

A magnetic optics system is being developed for OMEGA-EP

- M. Freeman and a team from LANL has designed a chicane and magnetic optic system for OMEGA-EP
- <10 um resolution predicted, may be able to push that further with a refined design
- Good results may motivate future HED/ICF facilities to add an RF LINAC or specific laser for eRad



Chicane and magnetic optic design for OMEGA-EP

* Image courtesy of M. Freeman

We have developed a robust eRad capability using OMEGA-EP

- **Electron radiography fills a capability gap between protons and x-rays in both penetrative capability and sensitivity to fields**
- **OMEGA-EP eRad has shown the ability to radiograph a wide variety of targets and target conditions**
- **Upcoming experiments will utilize eRad to answer pressing indirect drive questions**
- **Future advancements will improve eRad resolution and motivate the addition of eRad to other facilities**

Thank you for your attention!

Questions?

gbru@lle.rochester.edu