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

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Collaborators

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Electron radiography based on the electron beams from a LPA could enable a flexible, portable, powerful diagnostic for the visualization of ultra-fast, ultra-thin dynamic processes

- **Prior electron radiography (eRad) experiments using linac-produced electron beams have demonstrated that eRad could fill the existing gap in radiographic capabilities**
- **Experiments on OMEGA EP demonstrated contact and projected eRad using the electron beam from a laser-plasma accelerator (LPA) with resolutions as low as 100 µm***
- **Experiments on the OMEGA EP laser have shown the potential capability of this platform to radiograph plasma-generated fields and penetrate materials that protons cannot**
- **Future work will seek to upgrade the platform to um-scale resolutions and to capitalize on this capability to help better understand driven targets and hohlraum physics**

* G. Bruhaug *et al*. Submitted to Scientific Reports

eRad is a potential path to fill the gap in visualizing fast, dynamic processes in the meso-scale range of materials from mg/cm^2 to several mg/cm^2*

- Today's workhorse radiographic probes can evaluate the following scales of areal density
  - The very thick (180 g/cm^2 using LANL's DARHT)
  - The intermediate (1-50 g/cm^2 using LANL's pRad LANCSE)
  - The very thin (< 0.001 g/cm^2 using Washington State's DCS)

Gap

- Prior eRad experiments using linac-produced electrons demonstrated the ability of eRad to visualize materials in the 0.01 g/cm^2** to several g/cm^2† range
  - These experiments showed that the gap between very thin and intermediate areal density capabilities is the one that eRad can potentially fill

Can LPA-based eRad driven by the lasers already associated with HED facilities also fill that gap?

* Merrill, F.E., "imaging with penetrating radiation for the study of small dynamic physical processes", Laser and Particle Beams, 2015
DARHT: Dual-Axis Radiographic Hydrodynamic Test Facility
DCS: Dynamic Compression Sector at Washington State
** 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).

In additional to filling the gap, charged particle (electron & proton) radiography has several advantages compared to classic radiography (neutrons & x/gamma rays)

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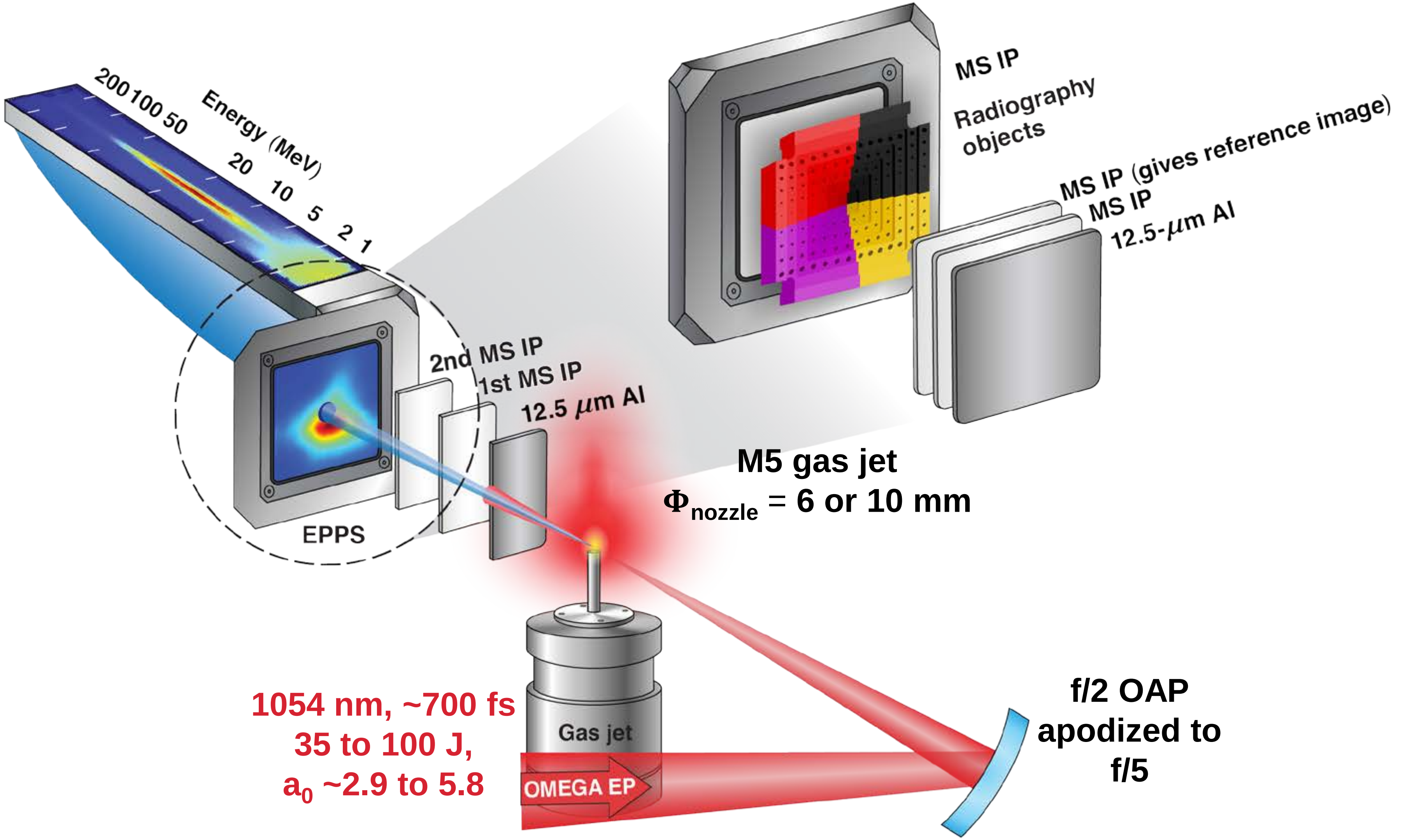
- Generation:
  - Typically cheap and efficient compared to neutrons and x/gamma rays
    - Electrons even more so than protons
  - Control over pulse length, depending on generation mechanism (fs to s)

- Utilization:
  - Extremely penetrative compared to x-rays
    - Able to penetrate high Z material and a wide variety of areal densities
  - Sensitive to magnetic and electric fields
    - Compared to protons, electrons are more penetrating for a given energy while providing more sensitivity to magnetic fields and less to electric fields*
  - Magnetic optics can be used to enhance the resolution and utilize distant focal planes
    - Also can be used to separate the image from the bremsstrahlung background caused by the probing electrons

* Merrill, F.E., "imaging with penetrating radiation for the study of small dynamic physical processes", Laser and Particle Beams, 2015

eRad experiments were performed on OMEGA EP using the LPA platform, which can produce electron beams with charges as high as 0.7 μC*



Materials:

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

*J.L. Shaw *et al*. Sci. Rep. 11, 7498 (2021).
G. Bruhaug *et al*. Submitted to Scientific Reports
EPPS: electron–positron–proton spectrometer
OAP: off-axis parabola
$a_0 = \frac{eE_0}{mc\omega_0} \propto \sqrt{I_0[W/cm^2]}$, I_0 = Peak laser intensity

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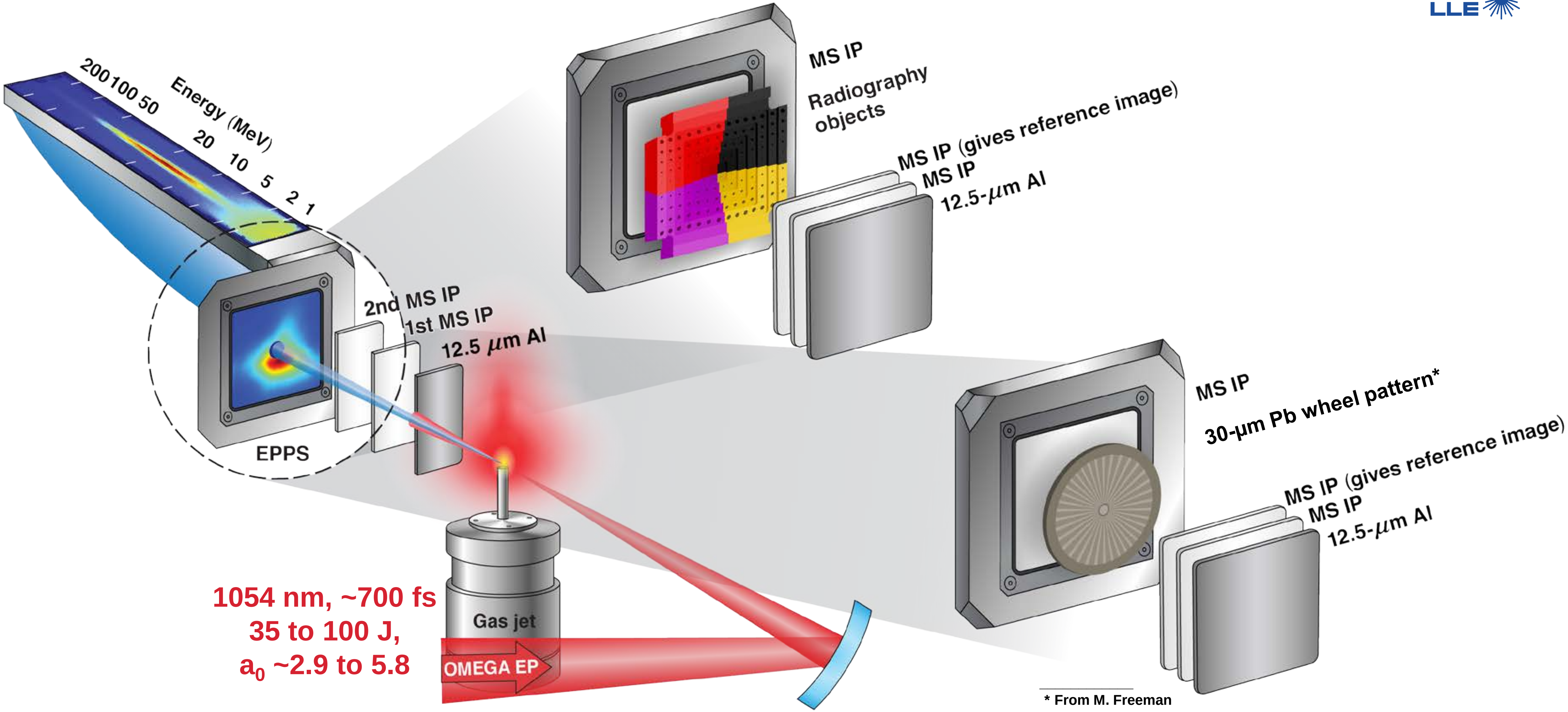
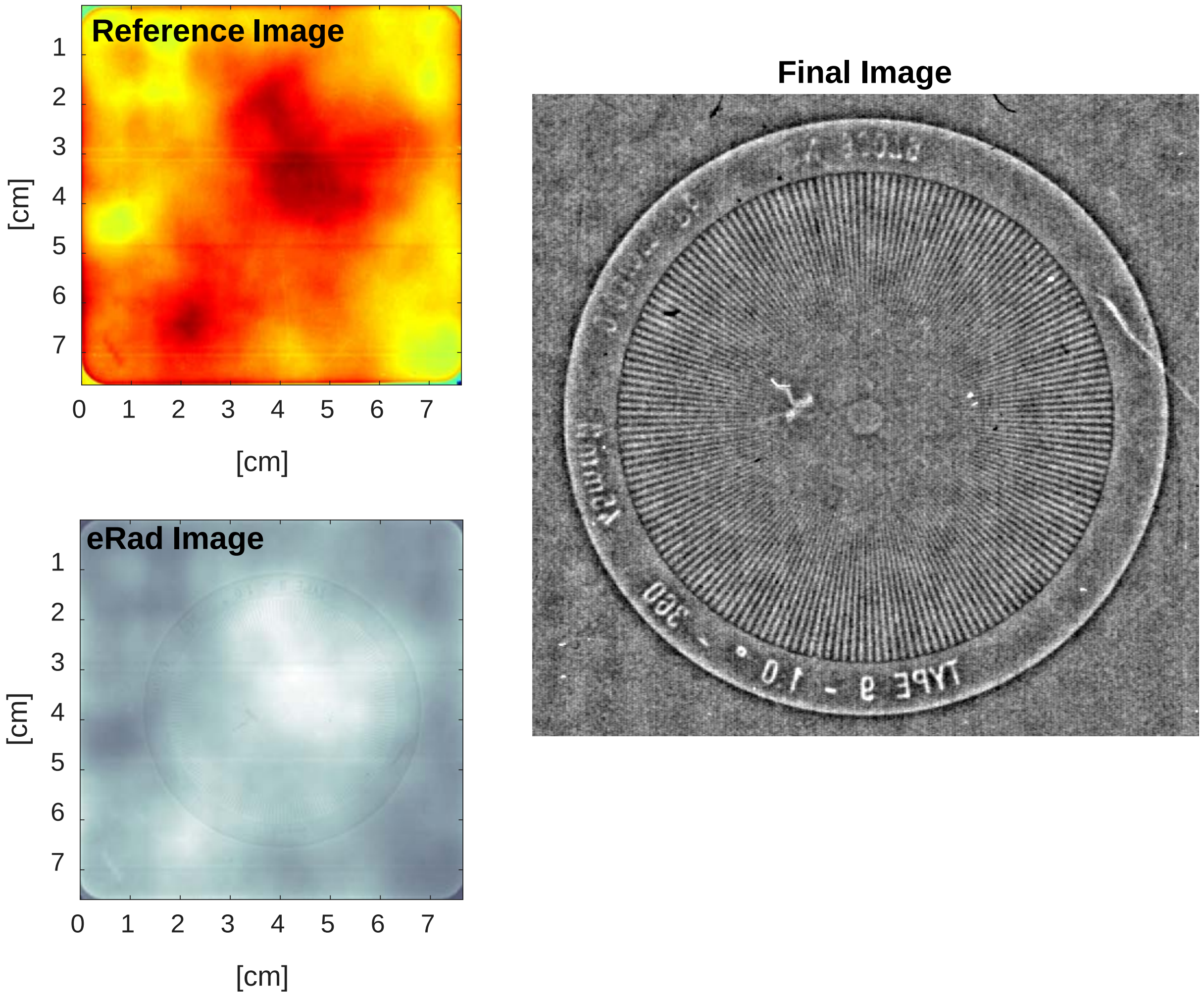
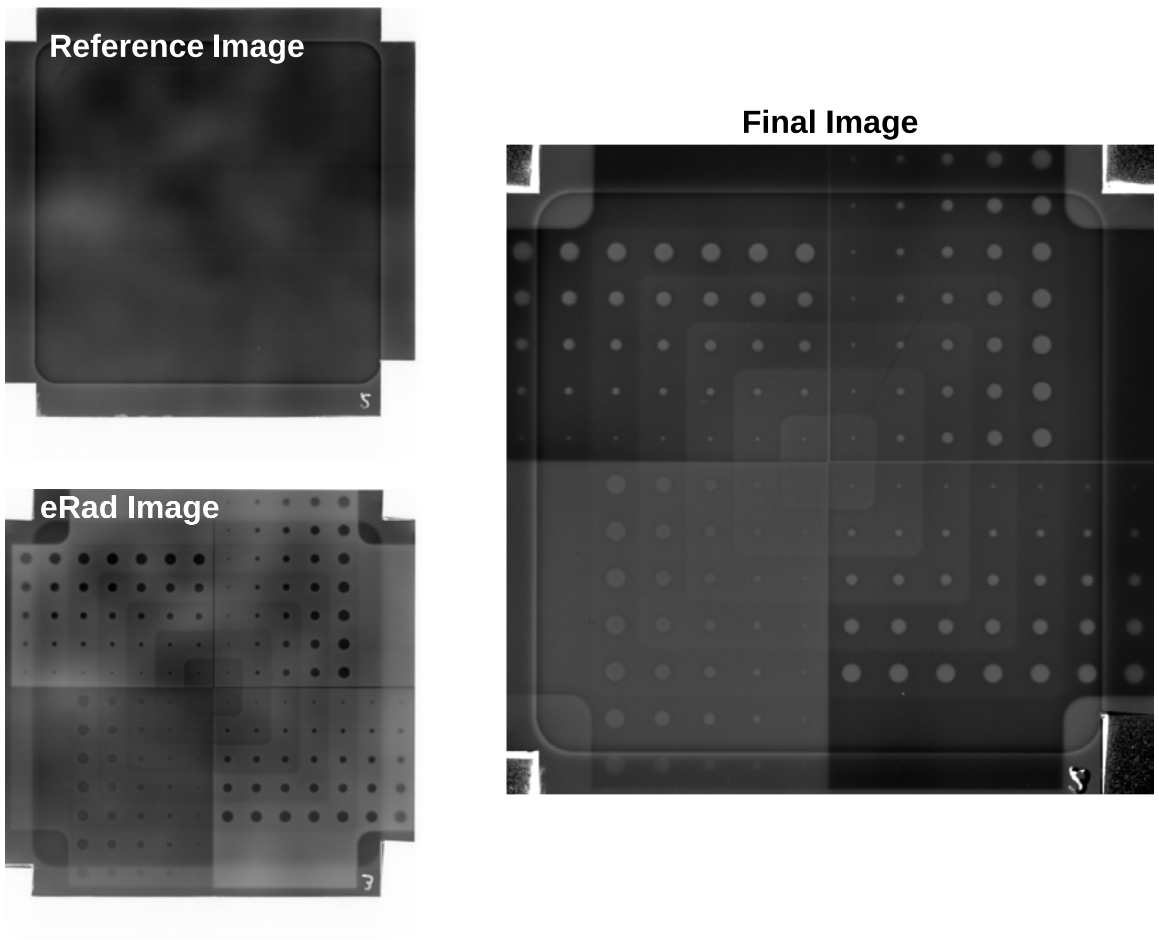


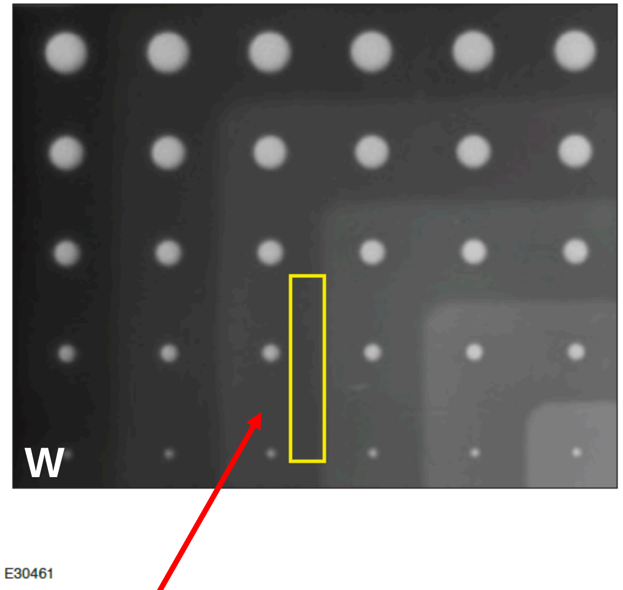
* From M. Freeman

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





Measured resolution is calculated by fitting an error function to the lineout across a step in material thickness*



Box lineout 10s of pixels wide

- **Measurements were taken for all steps and holes**
- **Error was determined by averaging multiple measurements**
- **Blur can be attributed to several factors**
  - Source size
  - Imaging system pixel size
  - Uncorrected Multiple Coulomb Scattering (MCS)
  - Bremsstrahlung broadening

* G. Bruhaug *et al*. Analysis methods for electron radiography based on laser-plasma accelerators, Proceedings of 2022 North American Particle Accelerator Conference

The measured resolution is compared to the theoretical resolution for charged particle radiography

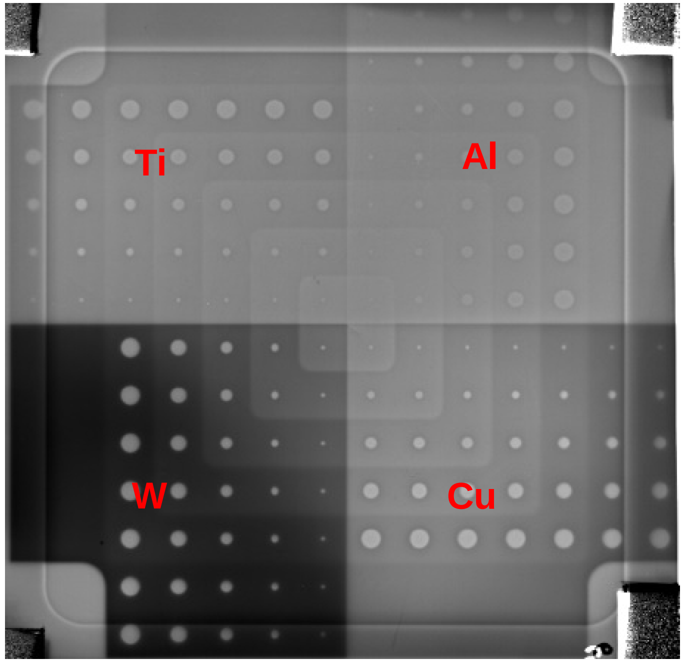
$$\text{Resolution} = \frac{1}{\text{Magnification}}\sqrt{\Delta s^2 + \Delta x^2 + \Delta p^2}$$

- Δs = Source Size
  - For targets less than a radiation length in thickness, the source size dominates
  - Typically ~ 30 um in our system
- Δx = Scattering
  - For targets on the order of a radiation length or more, the scattering Δx dominates
  - Approximately scales as target $Z^2 + Z$
- Δp = Imaging system pixel size
  - 25-100 um for image plates in our system
- Note that it does not account for bremsstrahlung blurring

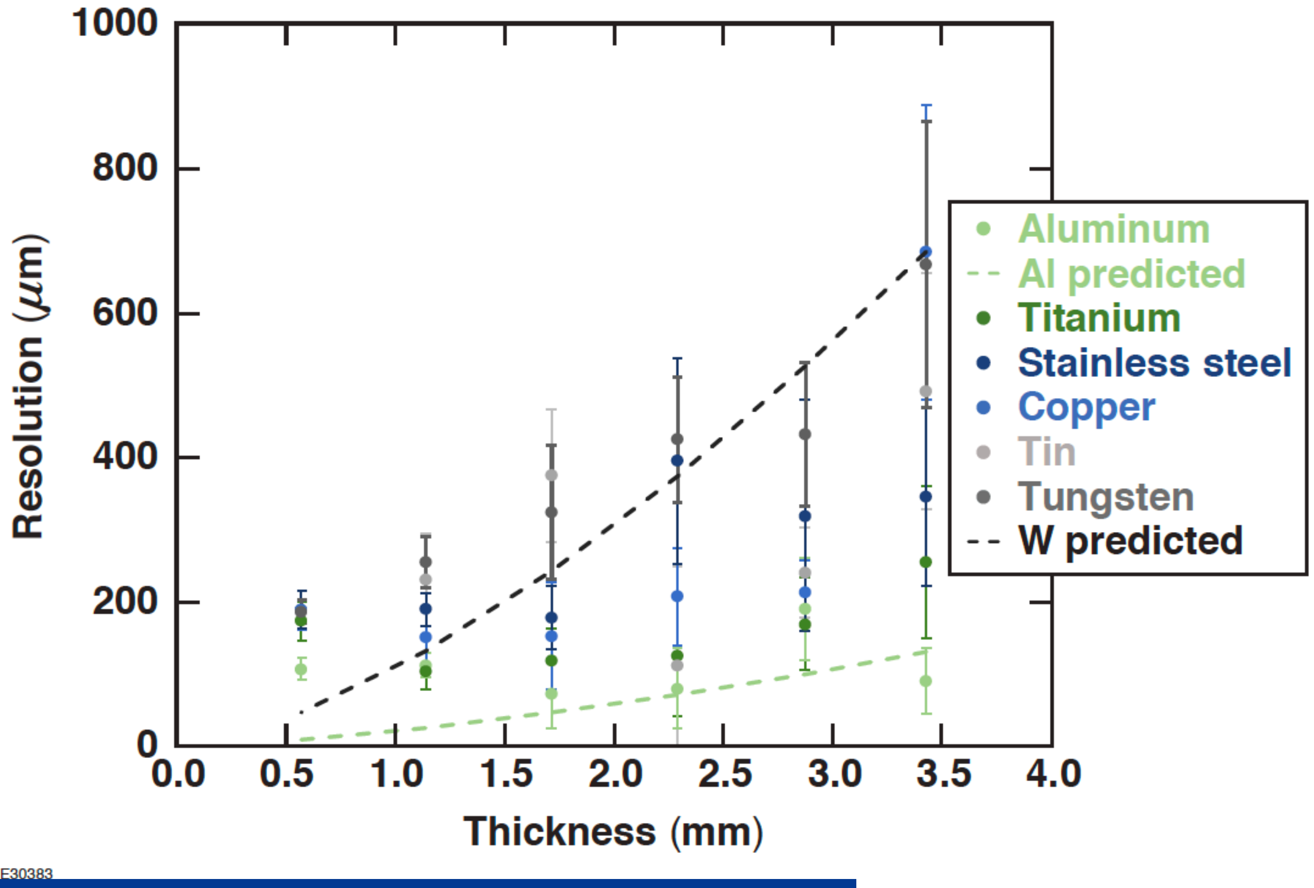
* G. Bruhaug *et al*. Submitted to Scientific Reports

The resolution in the contact eRad configuration degraded with increasing thickness and Z number of radiography target*

G. Bruhaug



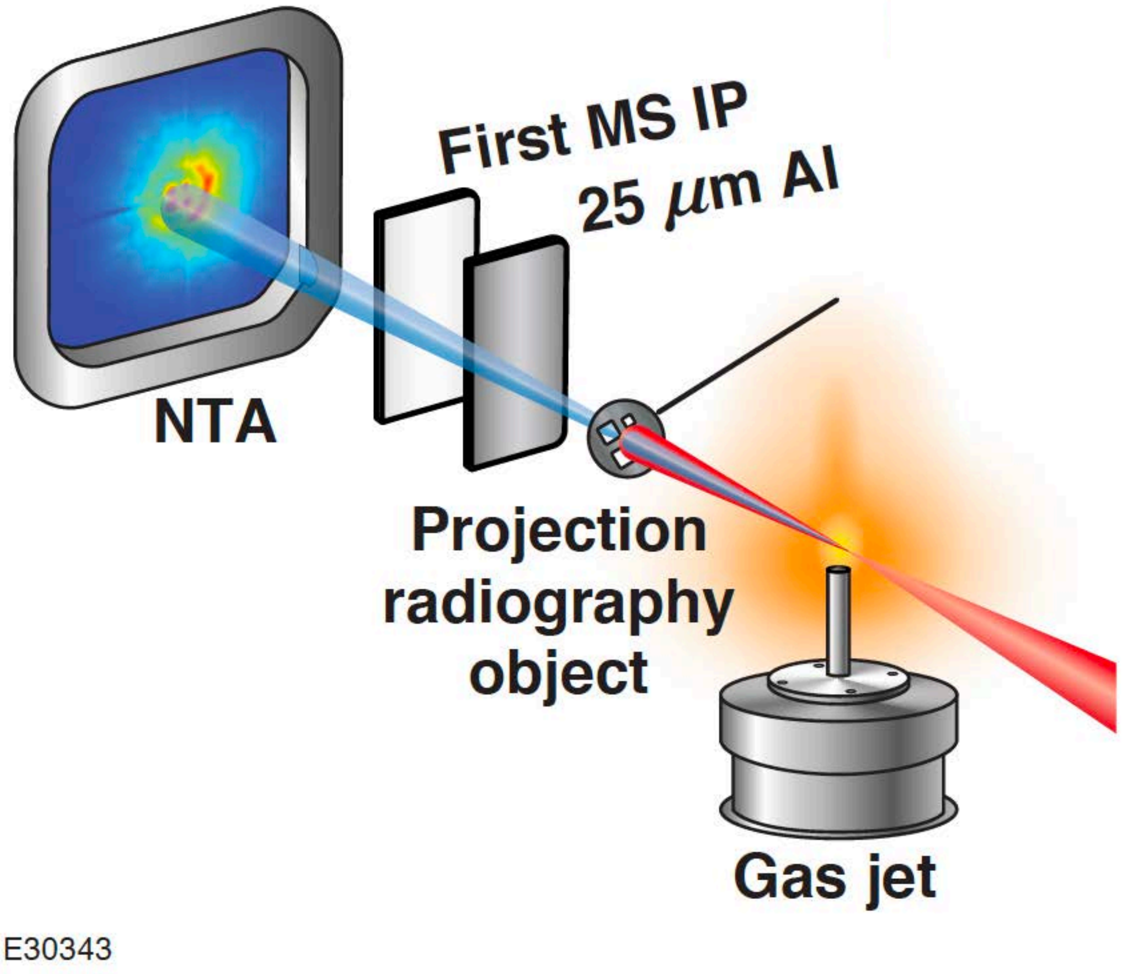
Shot 34030



Clear images seen even through 4 mm of tungsten

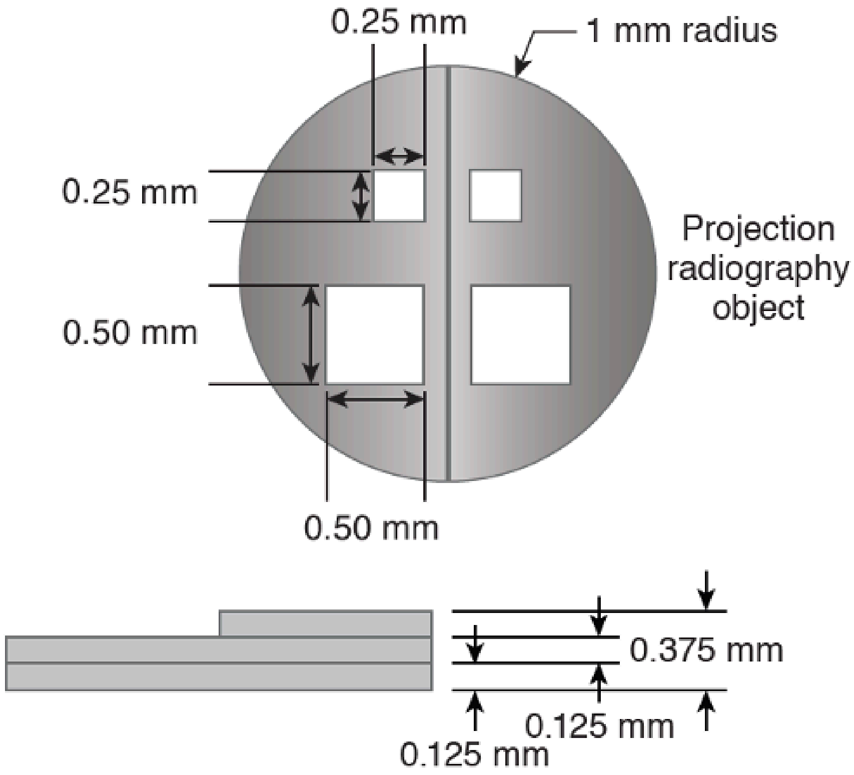
* G. Bruhaug *et al*. Submitted to Scientific Reports

The projected eRad studies required some modifications to the experimental setup



<u>Materials:</u>

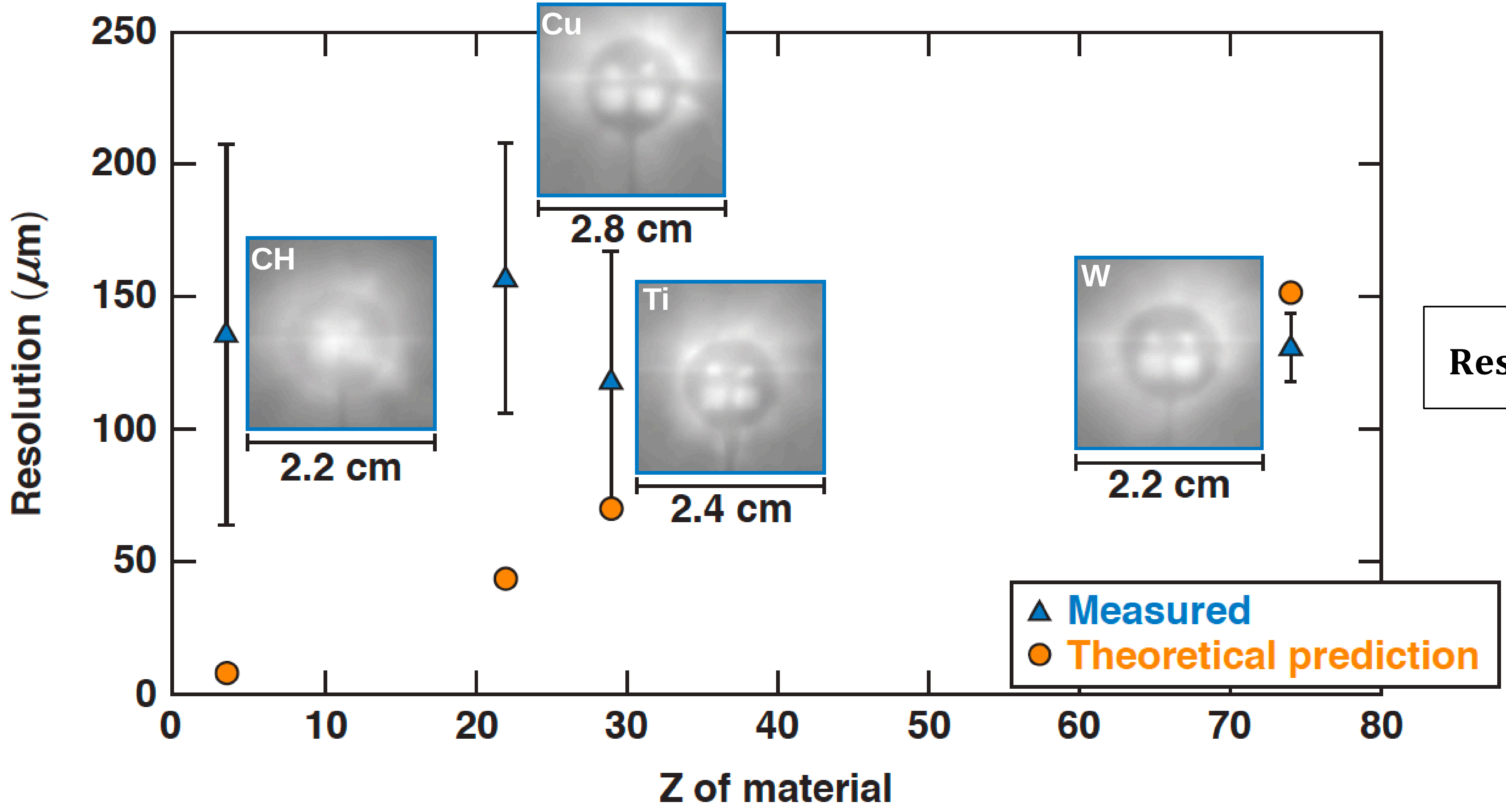
- **Polyimide (3 stacks)**
- **Cu**
- **Ti**
- **W**



* G. Bruhaug *et al*. Submitted to Scientific Reports

The resolution was insensitive to the Z number of the target material*

G. Bruhaug



$$\text{Resolution} = \frac{1}{M}\sqrt{\Delta s^2 + \Delta x^2 + \Delta p^2}$$

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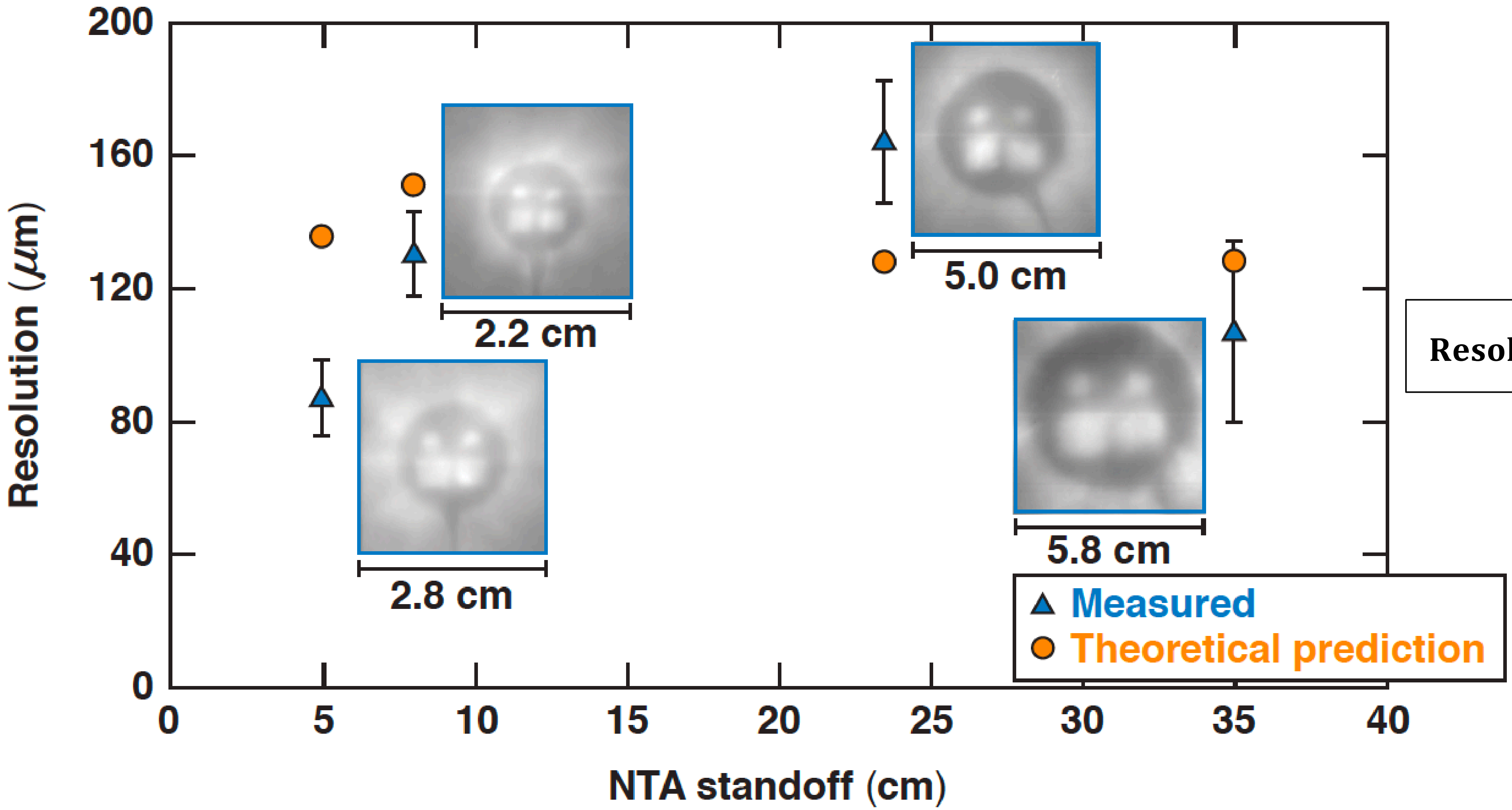
Possible reason is that bremsstrahlung blurring dominates the scatter in thin samples

*G. Bruhaug *et al*. Submitted to Scientific Reports

Results: Projected eRad

The resolution was also insensitive to the magnification of the target*

G. Bruhaug



$$\text{Resolution} = \frac{1}{M}\sqrt{\Delta s^2 + \Delta x^2 + \Delta p^2}$$

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Resolution is limited by scattering rather than source size, so magnetic optics required to improve resolution

*G. Bruhaug *et al*. Submitted to Scientific Reports

The measured diameters were ~1.5X smaller than expected based on projection calculations

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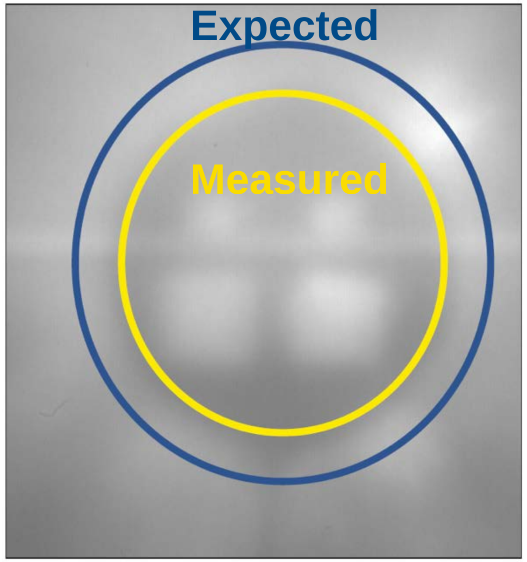

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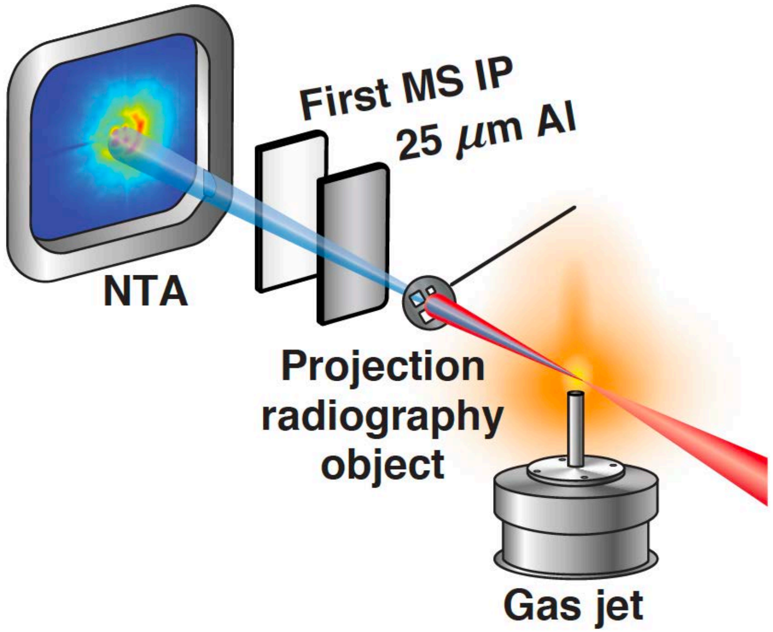


E30343

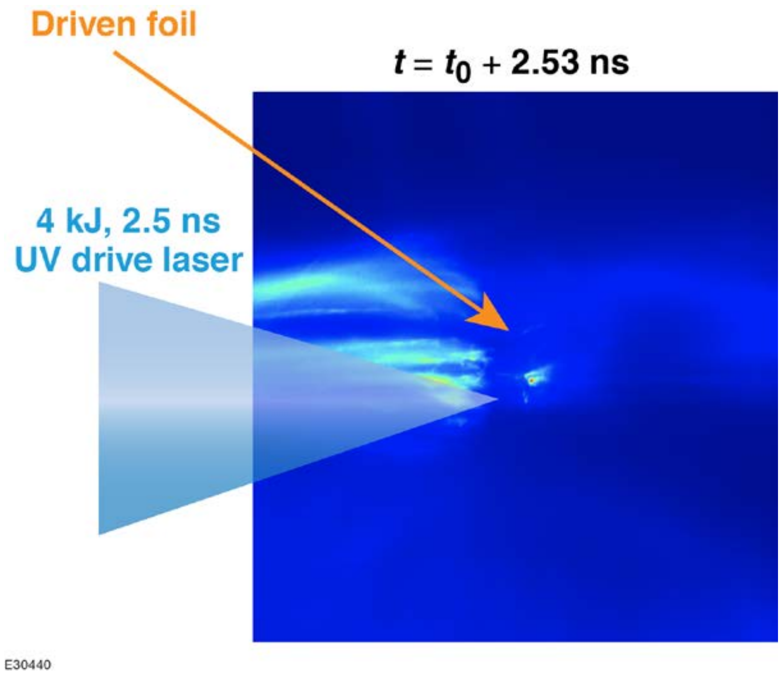
- An equation* was derived to determine the electric field needed to alter the images in this way
- ~1 GV/m found to fit both analytically and with Geant4 simulations*

Fields in laser-driven targets were already measured!

*G. Bruhaug *et al*. Submitted to Scientific Reports
**G4 Beamline 3.06." **T. Roberts, Muons Inc, 2018, [Online]. Available: http://www.muonsinternal.com/muons3/g4beamline/G4beamlineUsersGuide.pdf.

Future work for this eRad platform includes driven targets, hohlraum-relevant work, and the addition of magnetic optics

- We recently collected electron radiographs of foils driven by long pulse UV heater beams
  - Comparing that work to equivalent pRad experiments*
- In December, experiments will investigate magnetic field generation in metal foils
  - Seeking to further the understanding of the "drive deficit" issue in hohlraums†
- M. Freeman has designed a chicane and magnetic optic system for OMEGA EP
  - <10 um resolution predicted



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

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