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Title: Visualizing expanding warm dense matter heated uniformly by laser-driven ion beams

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Visualizing expanding warm dense matter heated uniformly by laser-driven ion beams

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12/7/2015

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Outline

1. **Motivation**
   - uniform & rapid heating of a target, study of warm dense matter

2. **How can we heat a target uniformly and rapidly?**
   - Ion source (Al 11+ vs. C 6+)
   - Heating per atom calculations
   - Expected temperatures of various targets (SESAME table)

3. **Visualization of the expanding warm dense gold and diamond**

4. **Ongoing works – observing the movement of the interface**
   - X-ray source (field of view, resolution)
   - Gated x-ray imager (GXI-X)

5. **Conclusion**

Motivation

1. **Uniform and rapid heating of targets beyond 10,000 K**

   - A laser-generated aluminum ion beam can heat the targets very uniformly and rapidly

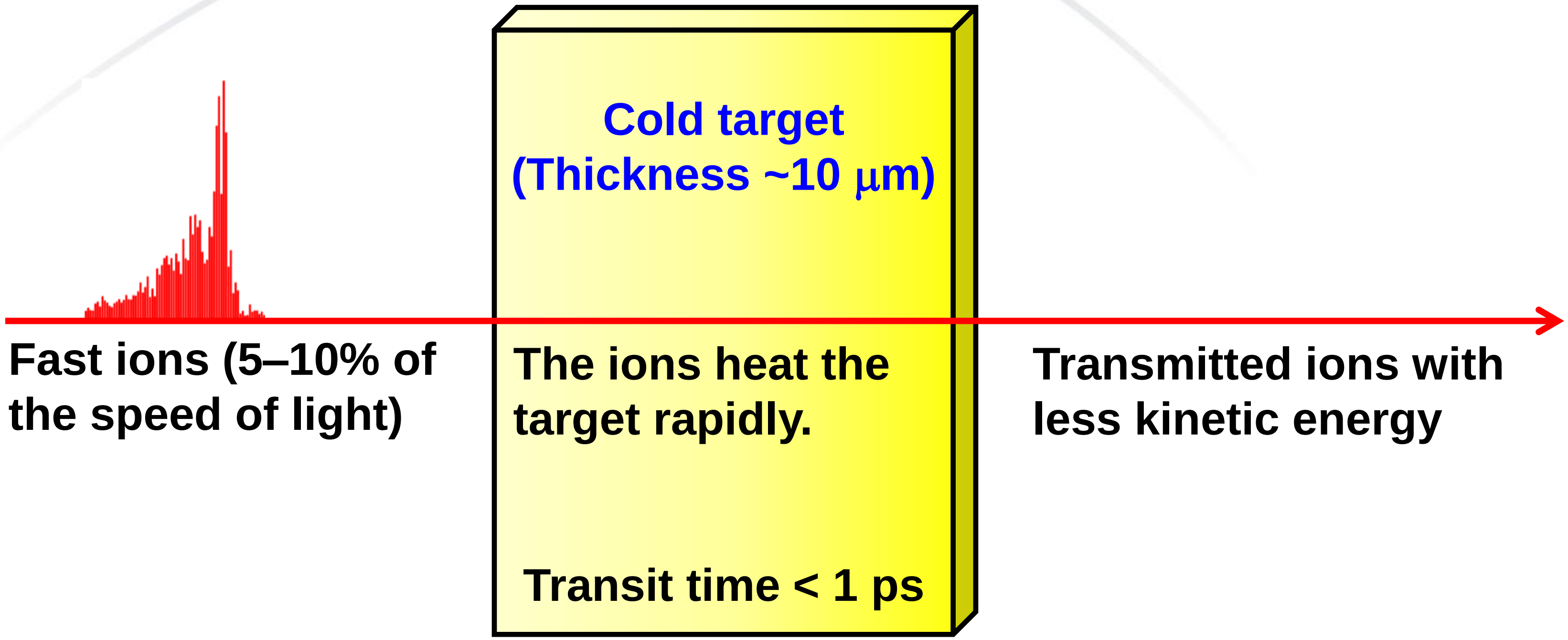
2. **Study of warm dense matter**

   - commonly found in astrophysics (e.g., in planetary cores) as well as in high energy density physics experiments, but its properties are not well known

3. **Study of mix at the interface between two different materials**

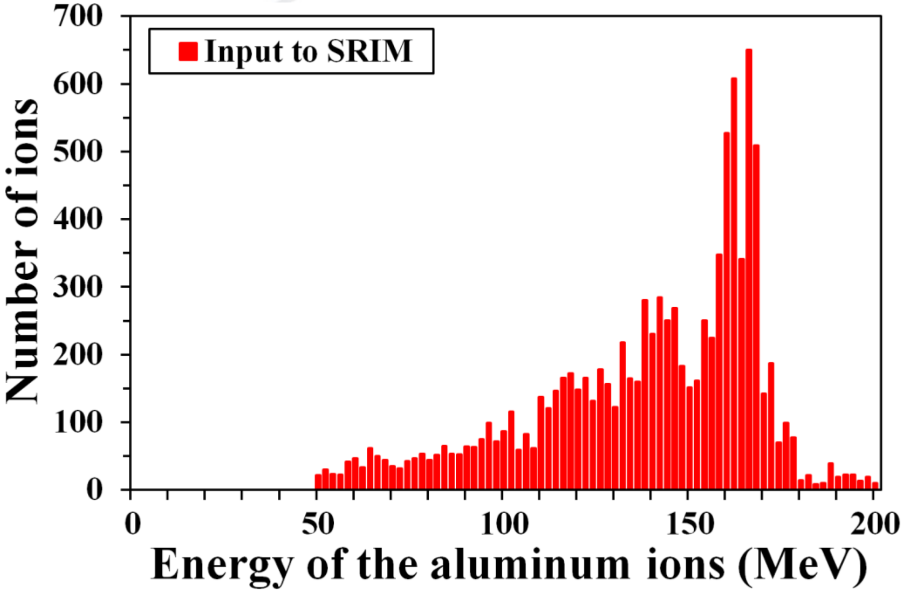
   - Probe the interface movement

Energetic ions can heat a target material very quickly

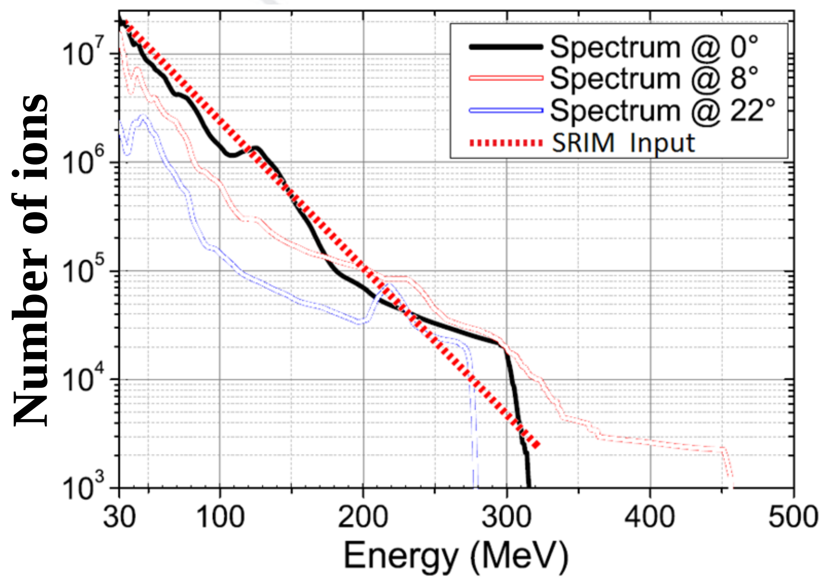


- Energetic ions incident on a target can transfer a significant amount of their kinetic energy to the target.
- This heating occurs so quickly (~ 20 ps) that the target does not have enough time to expand hydrodynamically during heating.

We considered several ion sources available on Trident for rapid heating



Aluminum ions*
Average energy: 140 MeV
(quasi-monoenergetic)



Carbon ions (1–320 MeV)
Average energy above 33 MeV = 65 MeV

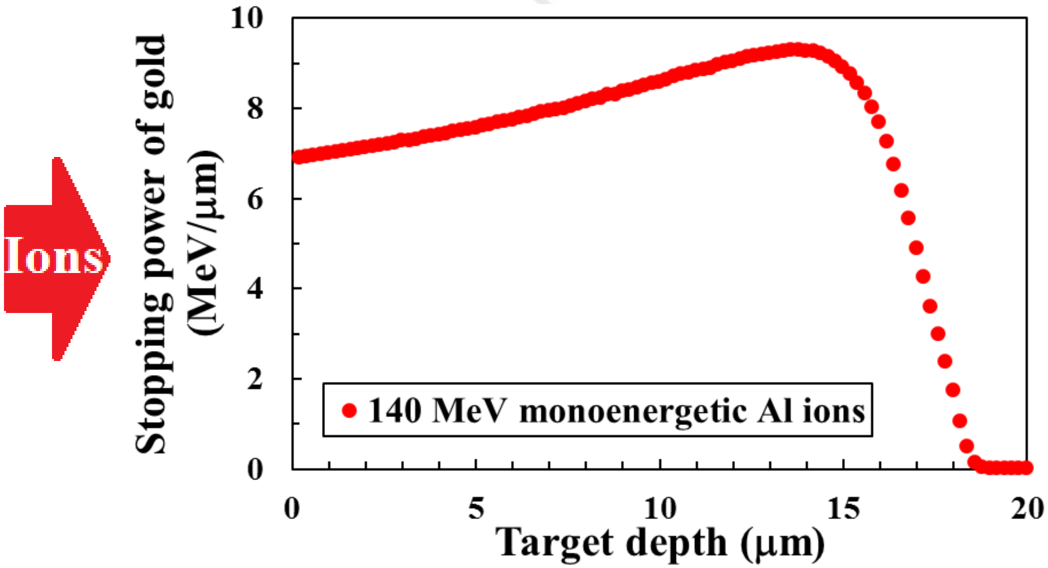
Measured ion energy spectra were used in a Monte Carlo simulation code (SRIM) to calculate the expected heating per atom.

* S. Palaniyappan *et al*., Nat. Commun. (accepted); arXiv:1506.07548 (2015).

SRIM** calculates how the ions deposit their kinetic energy into the target

< Example >

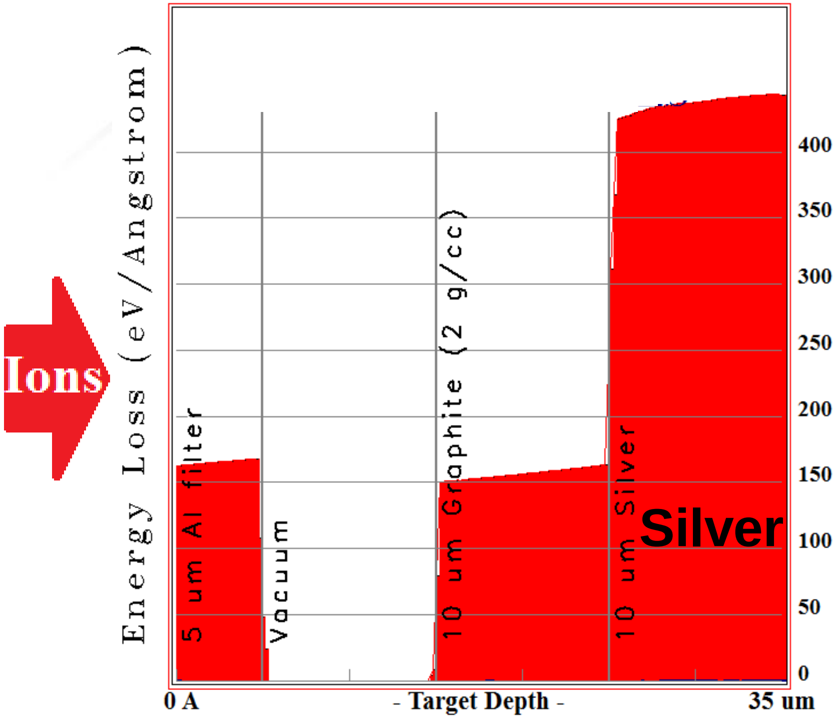
140 MeV Al ions incident on a 20 μm thick gold foil



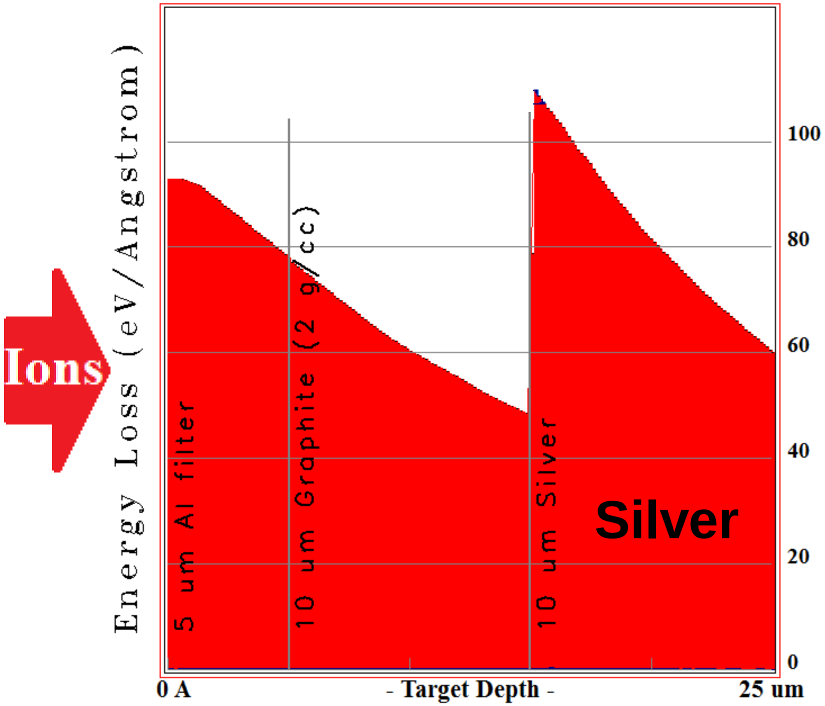
- **Stopping power (-dE/dx): Energy loss of the given charged particle (-dE) per unit path length (dx)**
- **SRIM calculates the stopping power of a target for the known incident charged particle, from which we estimate the ion kinetic energy deposition into the target.**

** J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon Press, New York,1996).
J. F. Ziegler *et al*., Nucl. Instrum. Methods Phys. Res. B 268, 1818 (2010).

Stopping powers of various target materials were calculated using SRIM



Aluminum ion beam



Carbon ion beam

Example target: 5 μm Al filter + 10 μm graphite + 10 μm silver

Aluminum ions heat the targets more uniformly.

We calculate the heating per atom using the ion fluence and the stopping power

< Example scenario >

10 Al ions IN
(K.E. = 140 MeV)

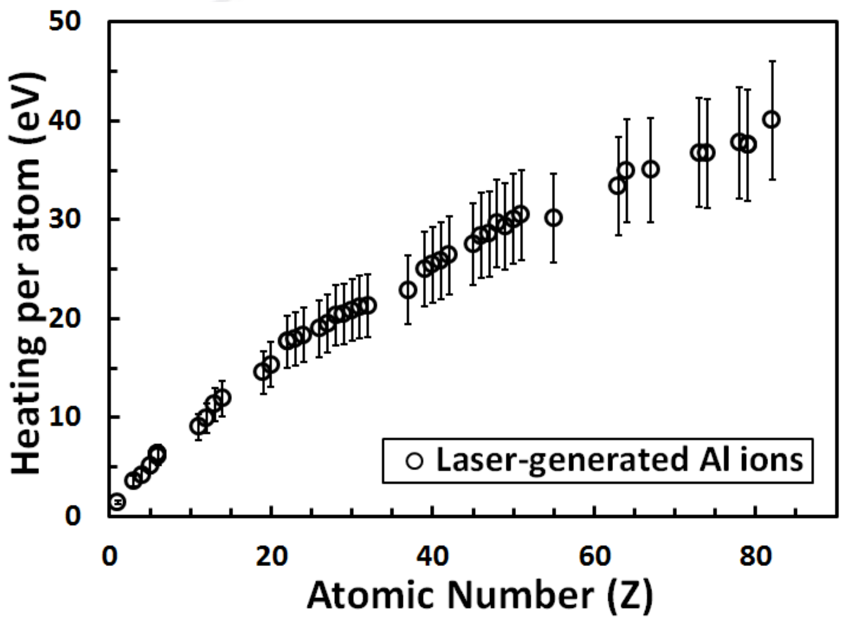
10 Al ions OUT
(K.E. = 100 MeV)

Total absorbed energy in the target = 10 ions × 40 MeV/ion
The number of target atoms = 10 million atoms

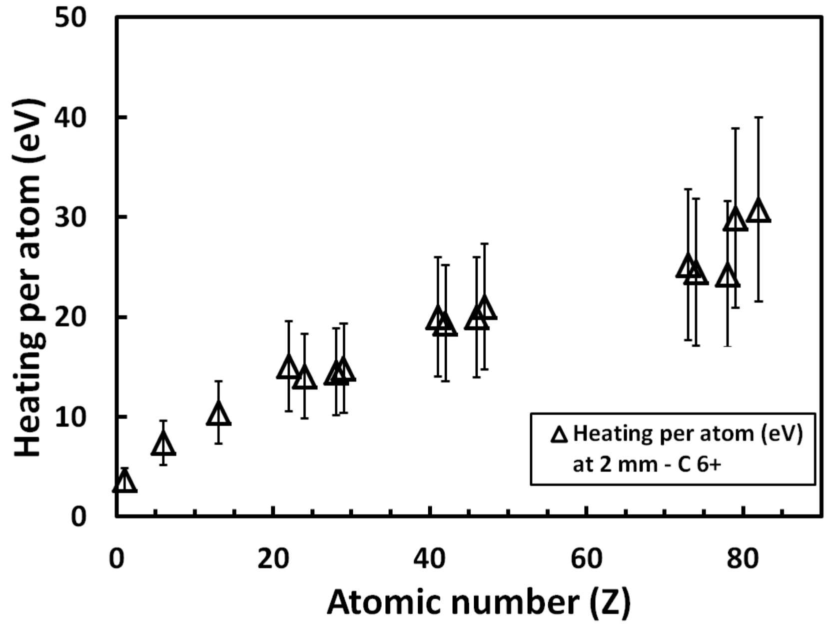
$$\textbf{Heating per atom} = \frac{10\ \text{ions} \times 40\ \text{MeV/ion}}{10\ \text{million atoms}} = 40\ \text{eV/atom}$$

W. Bang *et al*., Phys. Rev. E **92,** 063101 (2015).

We calculated the heating per atom for various target materials



Aluminum ion beam



Carbon ion beam

In general, the absorbed energy (heating) per atom increases with Z.

W. Bang *et al.*, Phys. Rev. E **92,** 063101 (2015).

An equation-of-state (EOS) table can be used to calculate the target temperature

< Example: EOS table for gold >

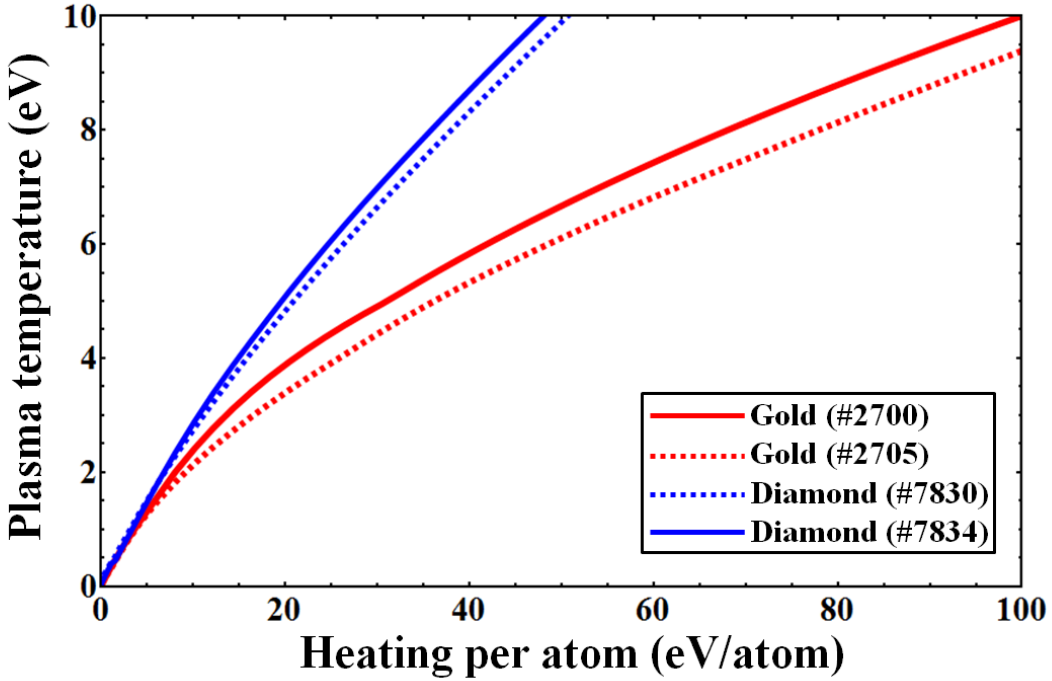
Target density →

Heating per atom ↓

	…	…	Solid density of gold (19.3 g/cc)	…
…			…	
…			…	
40 eV/atom			Temperature = 5.8 eV	
…			…	

Since the density of the target is close to the solid density and we have the heating per atom calculations, we can estimate the expected target temperatures immediately after heating.
(1 eV = 11,600 K)

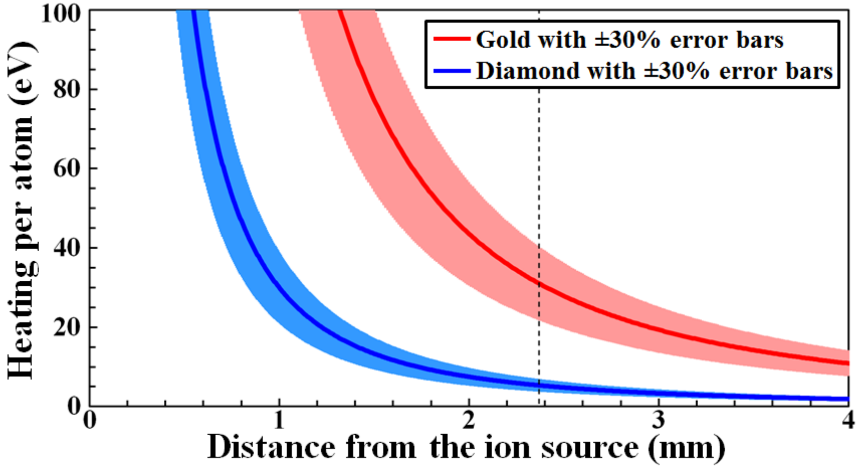
We use SESAME*** EOS tables to calculate the expected target temperatures

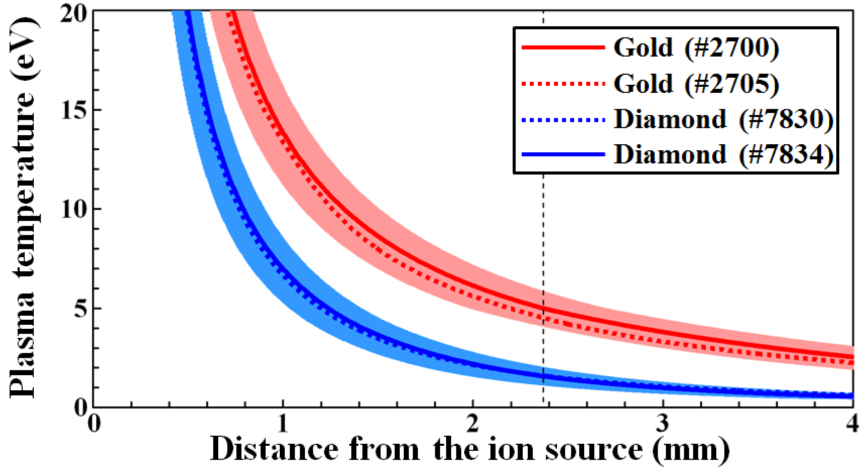


Using heating per atom calculations and SESAME equation-of-state (EOS) tables, we can estimate the expected temperatures of gold and diamond immediately after heating.

*** S. P. Lyon and J. D. Johnson, LA-UR-92-3407 (1992).
W. Bang *et al.*, Phys. Rev. E **92,** 063101 (2015).

At ~2 mm, the Al ion source is expected to heat diamond to 2 eV and gold to 6 eV

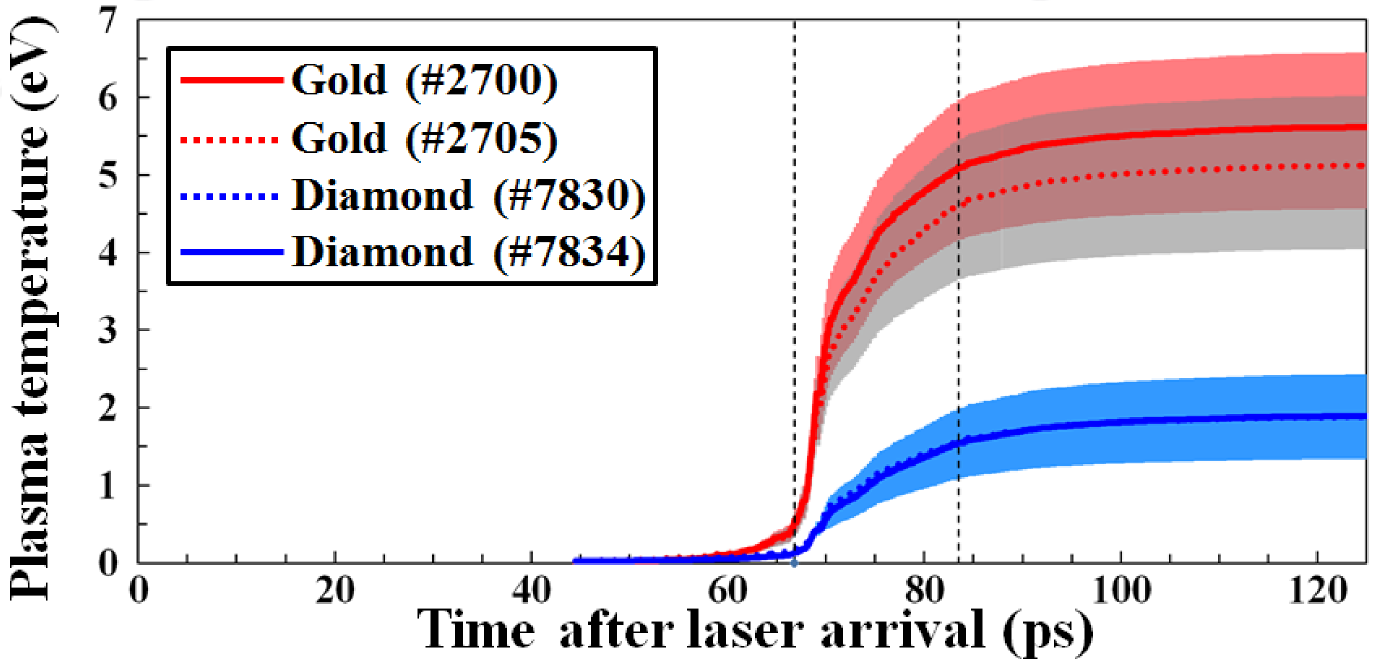




- **The plasma temperatures were calculated as a function of the source-to-target distance.**
- **Source-to-target distance = 2.37 mm**
- **Shot-to-shot fluctuation in the ion fluence = ±30%**
- **1 eV = 11,600 K**

W. Bang *et al*., Sci. Rep. **5**, 14318 (2015).

We expect rapid heating of both gold and diamond by the aluminum ion beam

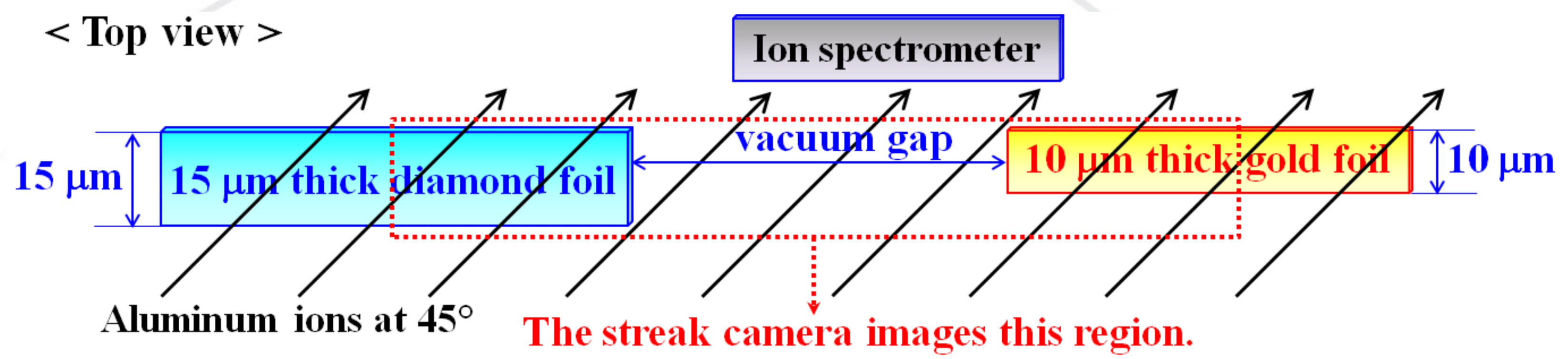


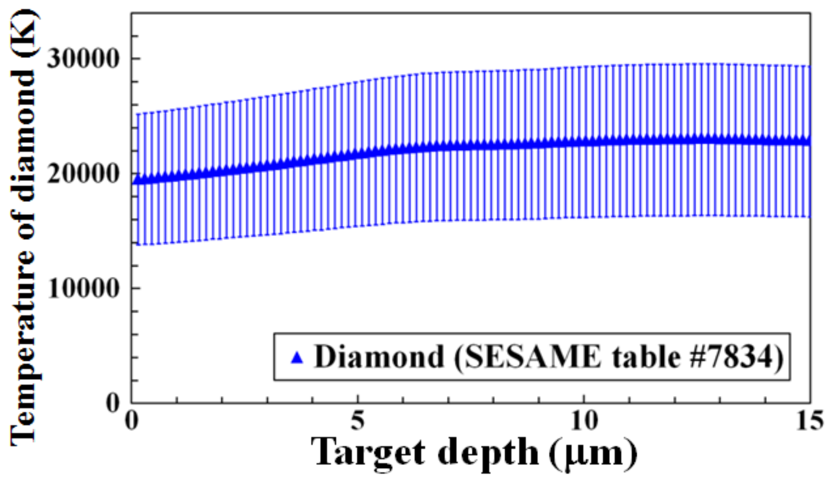
Ions with different kinetic energy arrive at the target at different times. (200 MeV Al ion at 63 ps, 50 MeV Al ion at 125 ps)

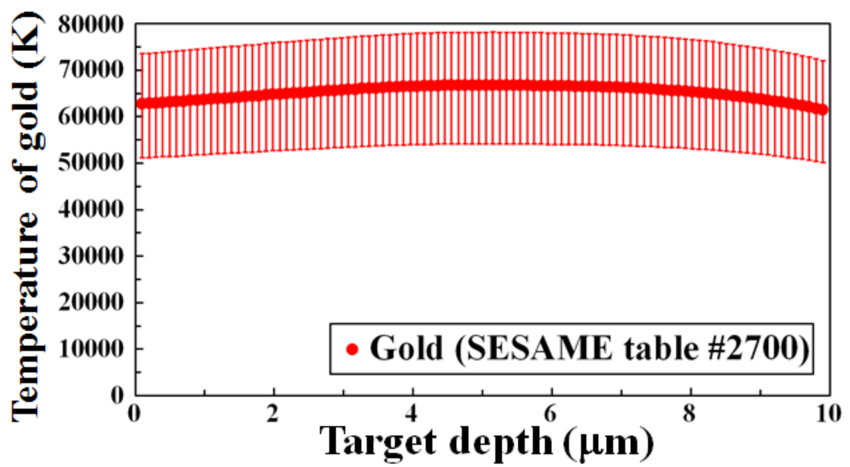
- **Gold (#2705): 17 ps rise time (10% to 90%)**
- **Diamond (#7834): 22 ps rise time**

W. Bang *et al.*, Sci. Rep. **5**, 14318 (2015).

The aluminum ions are expected to heat gold and diamond very uniformly



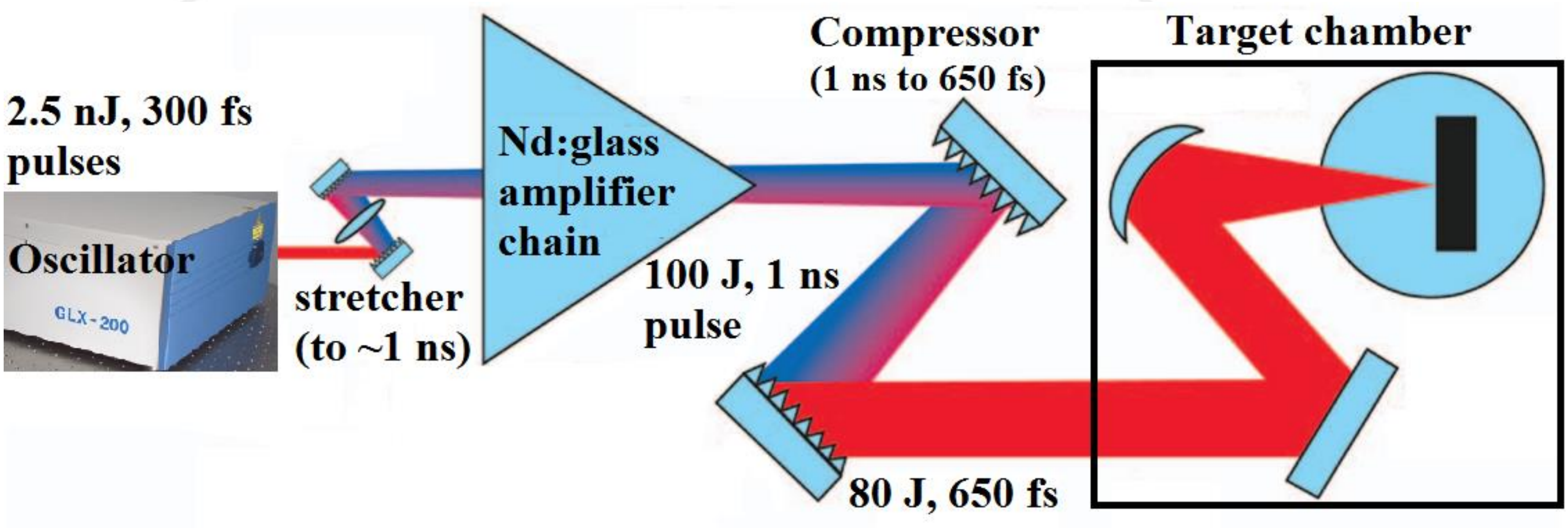




- **45° ion incidence angle owing to geometric constraints**

W. Bang *et al*., Phys. Rev. E **92,** 063101 (2015).

Trident laser delivers 80 J, 650 fs pulses to generate quasi-monoenergetic ion beams

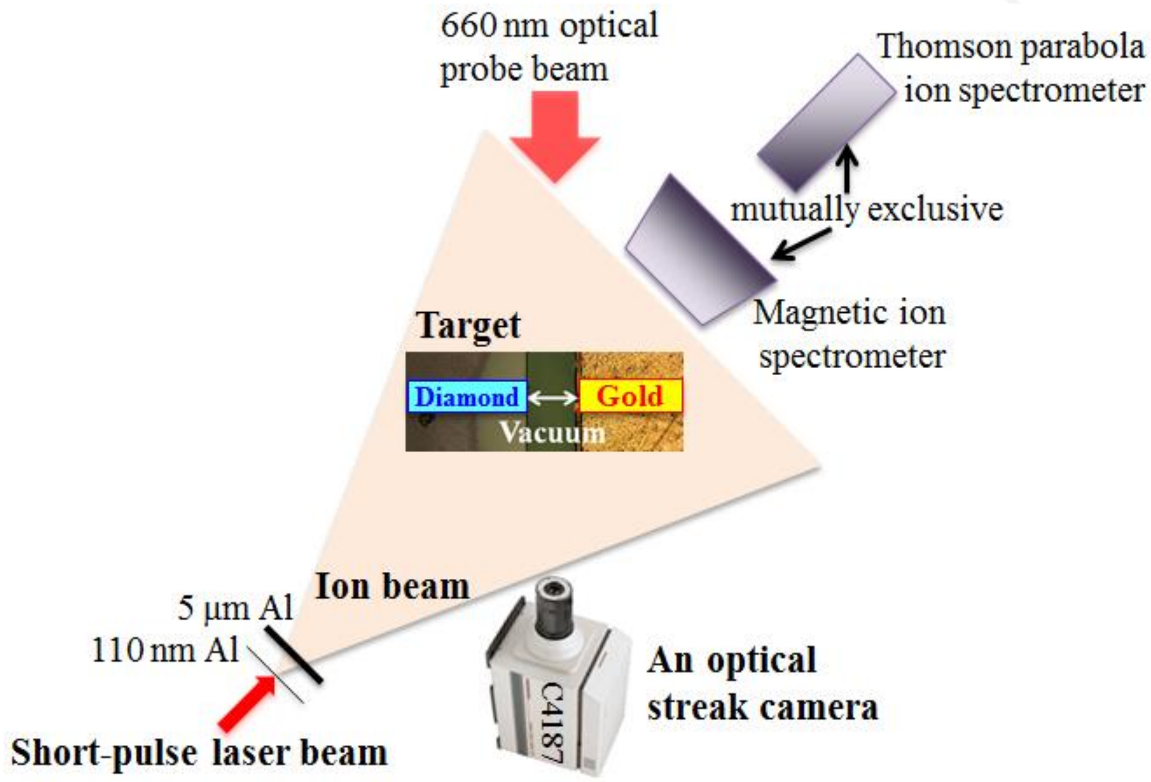


A focused laser beam (10 μm diameter) with a peak laser intensity of $2{\times}10^{20}$ W/cm^2 irradiates a thin (110 nm) aluminum foil, and produces a quasi-monoenergetic aluminum ion beam.
(repetition rate: 1 shot every 90 minutes)

Image taken & modified from S. H. Batha *et al*., Rev. Sci. Instrum. **79**, 10F305 (2008).

The aluminum ion beam heated both gold and diamond in a single shot

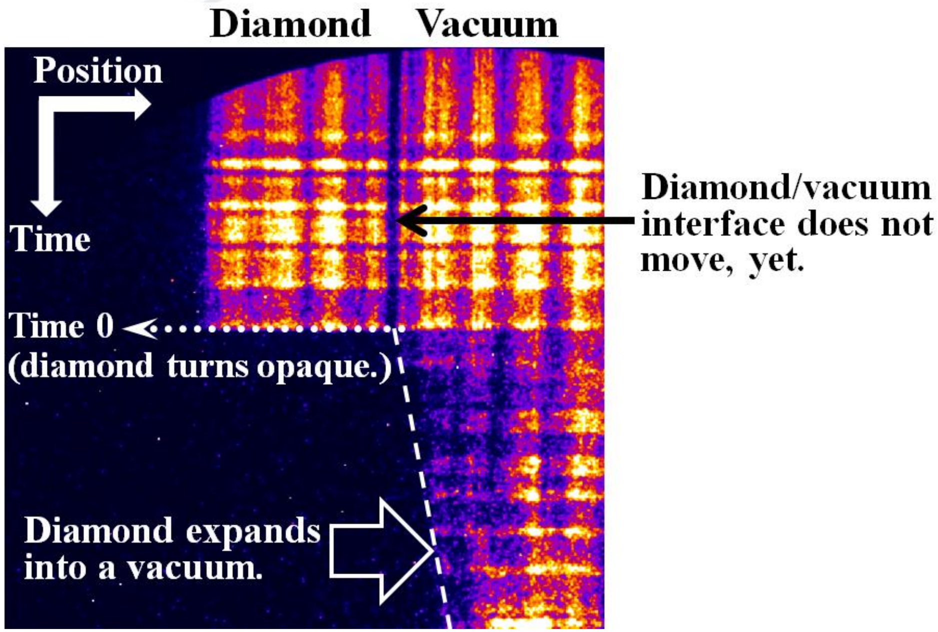
< Schematic layout of the experimental setup (not to scale) >



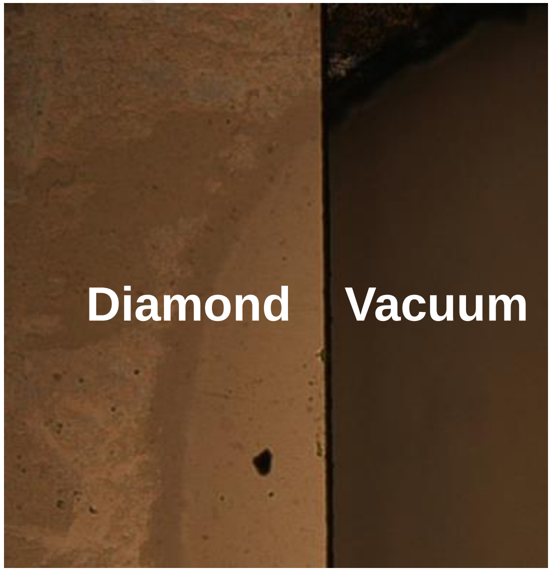
An optical streak camera detects the light not blocked by gold or diamond.

W. Bang *et al*., Sci. Rep. **5**, 14318 (2015).

Diamond turns opaque as it becomes a plasma upon heating



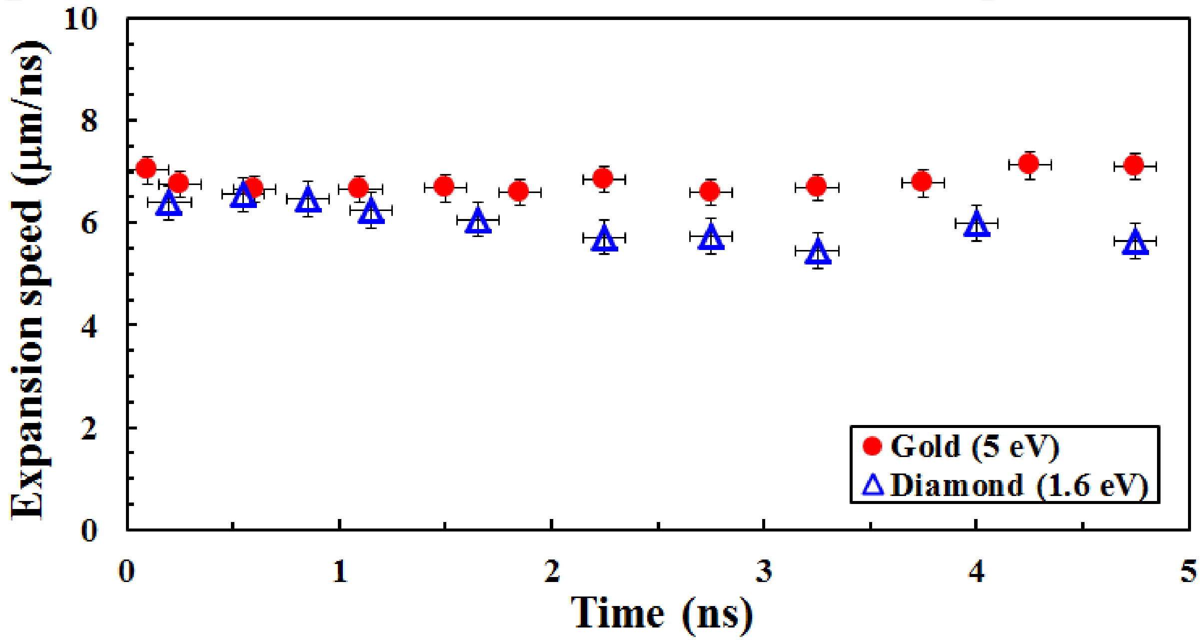
A streak camera image showing the expansion of diamond



Picture of the target

- A diamond foil transmits 70% of the probe light before heating.
- Diamond turns opaque immediately after heating, and starts expanding into vacuum.

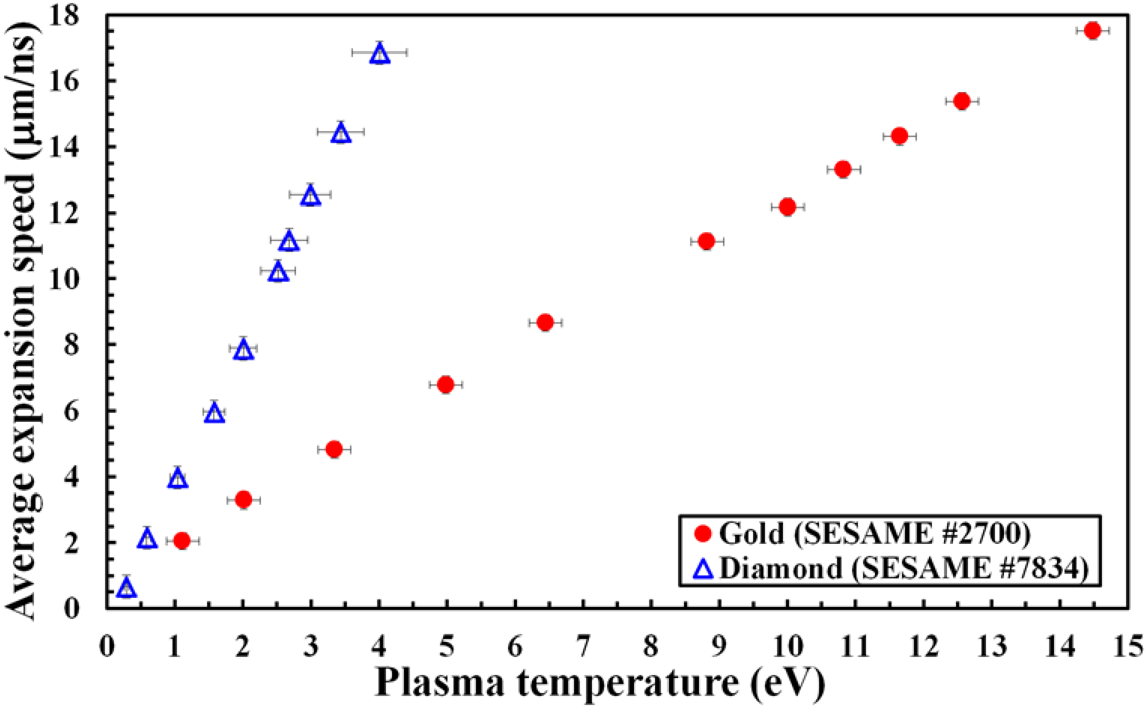
Computer simulations can predict the expansion speeds of gold and diamond



Two-dimensional RAGE radiation-hydrodynamic simulations indicate that the expansion speed of each material stays nearly constant during the first 5 ns after heating, consistent with a (work) free plasma expansion into vacuum.

W. Bang *et al*., Sci. Rep. **5**, 14318 (2015).

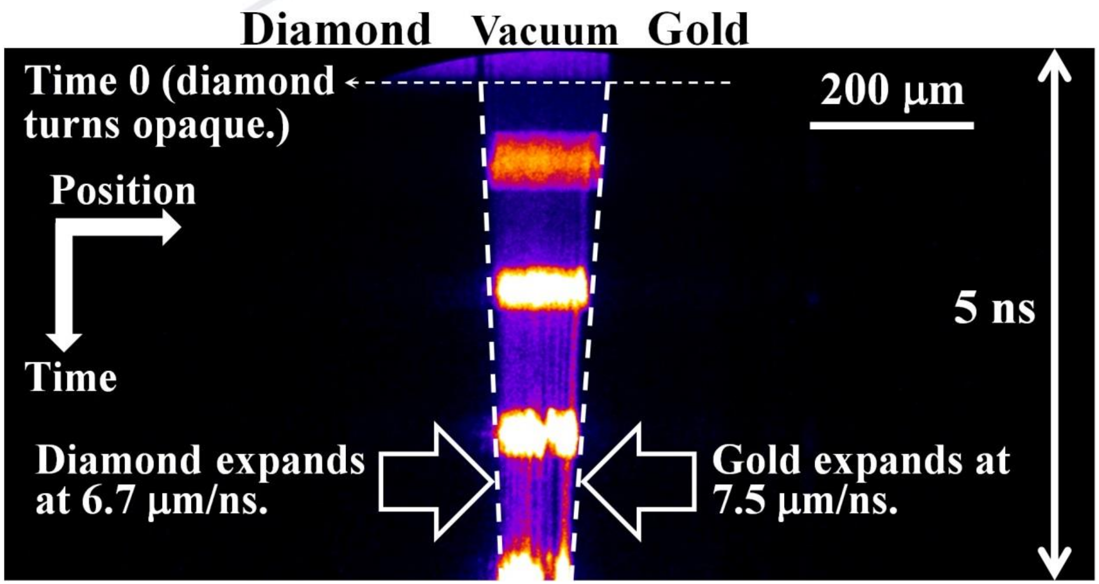
The expansion speed is mostly determined by the initial plasma temperature



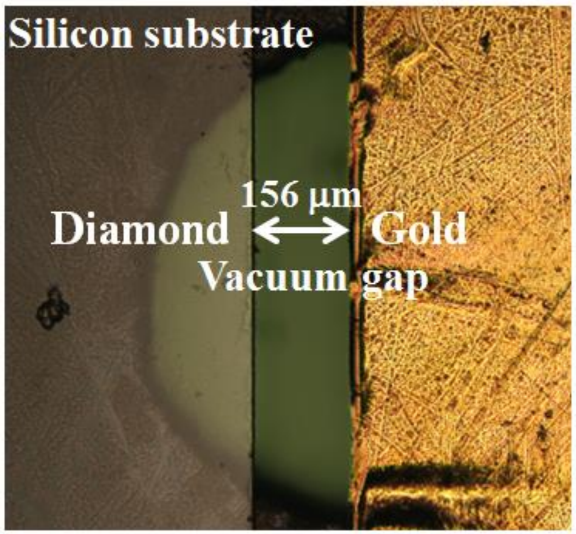
We observed a direct one-to-one relationship between the time-averaged expansion speed and the initial temperature of warm dense matter.

W. Bang *et al*., Sci. Rep. **5**, 14318 (2015).

We imaged the expansion of gold and diamond using an optical streak camera



A streak camera image showing the expansion of gold and diamond



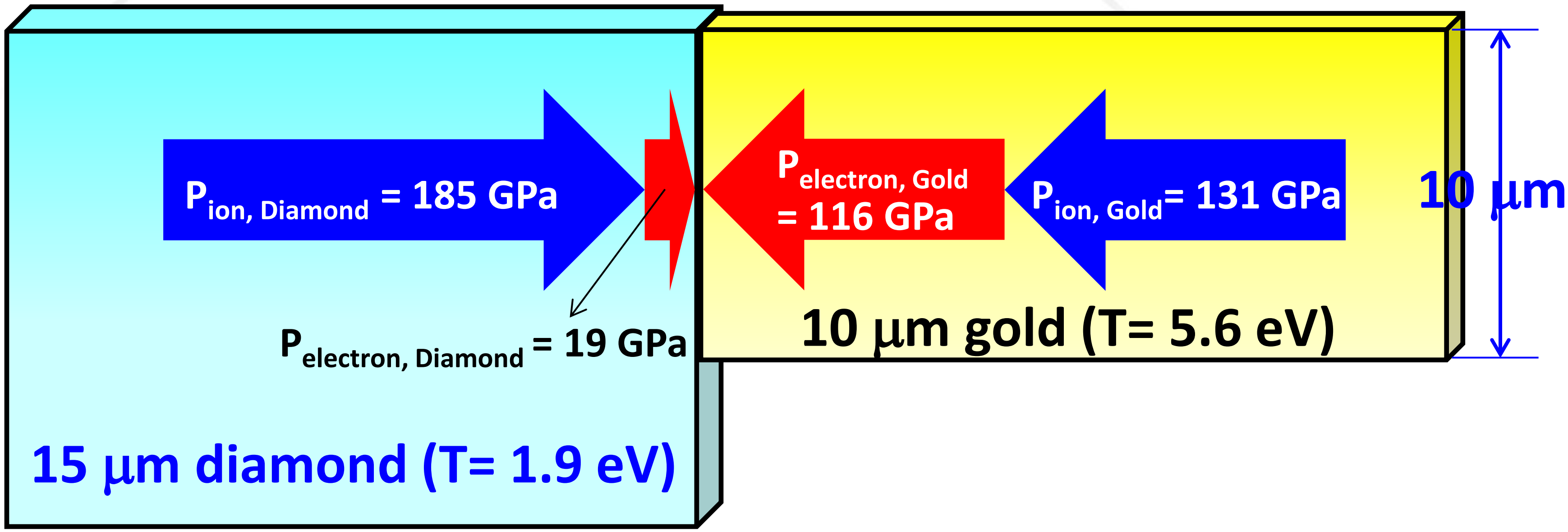
Picture of the target

- **The measured expansion speeds agree with those from RAGE hydrodynamic simulations using 5.5 eV gold and 1.7 eV diamond.**
- **An optical fiducial confirmed the calibration of the streak camera.**

W. Bang *et al*., Sci. Rep. **5**, 14318 (2015).

We want to record how the gold/diamond interface moves

< Top view >



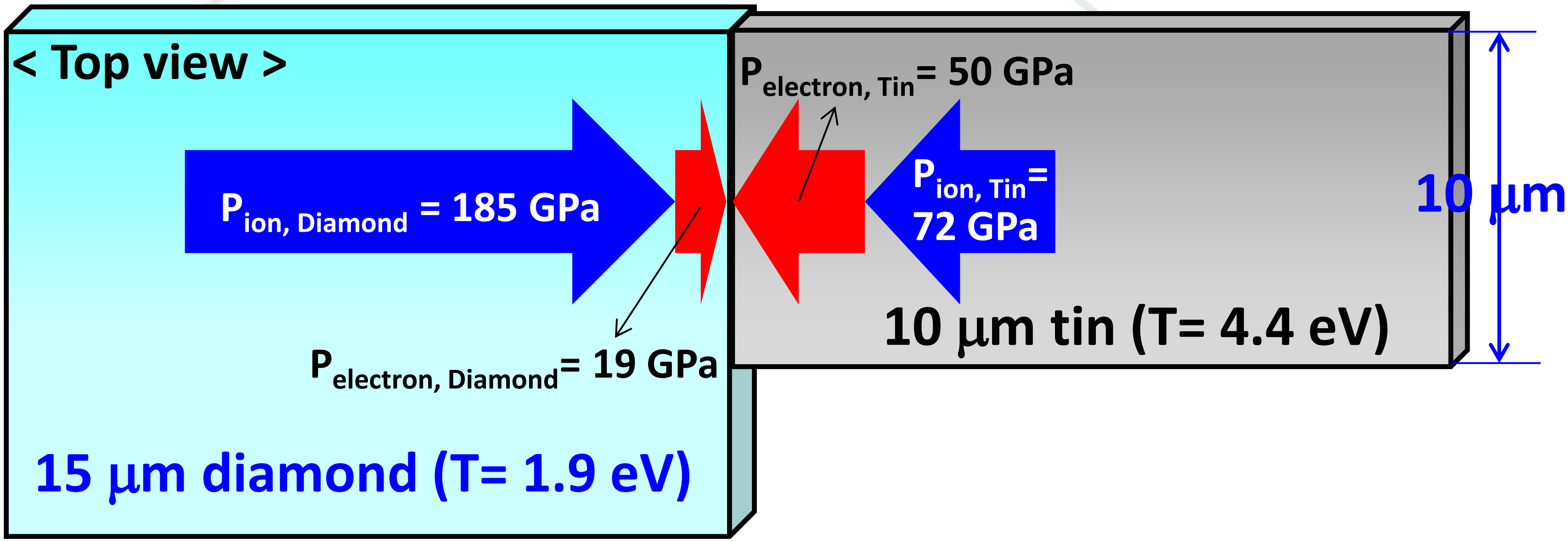
$$P_{electron, Diamond} \ll P_{electron, Gold}$$

$$P_{electron, Diamond} + P_{ion, Diamond} < P_{electron, Gold} + P_{ion, Gold}$$

The total pressure of gold is 25% larger than that of diamond.

The electron pressure of gold is much bigger than that of diamond.

Diamond + tin target could be also very interesting



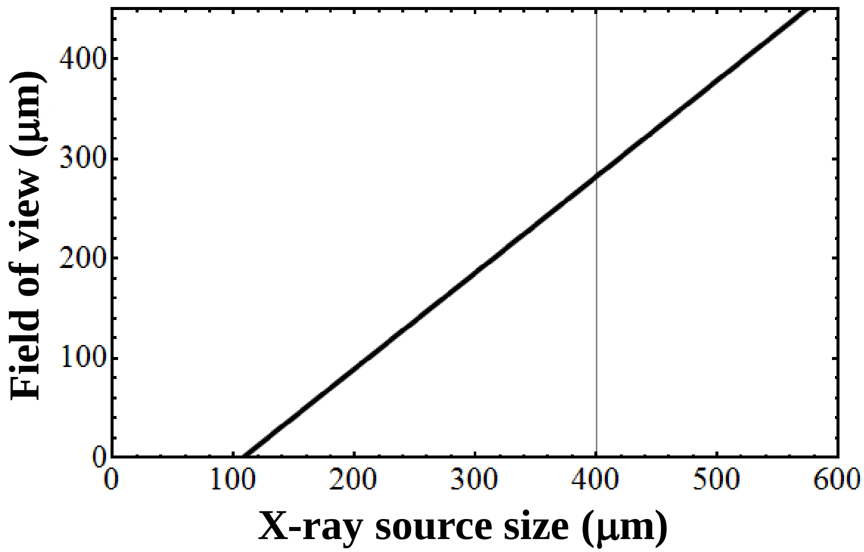
The total pressure of tin (=121 GPa) is smaller than that of diamond (=198 GPa).

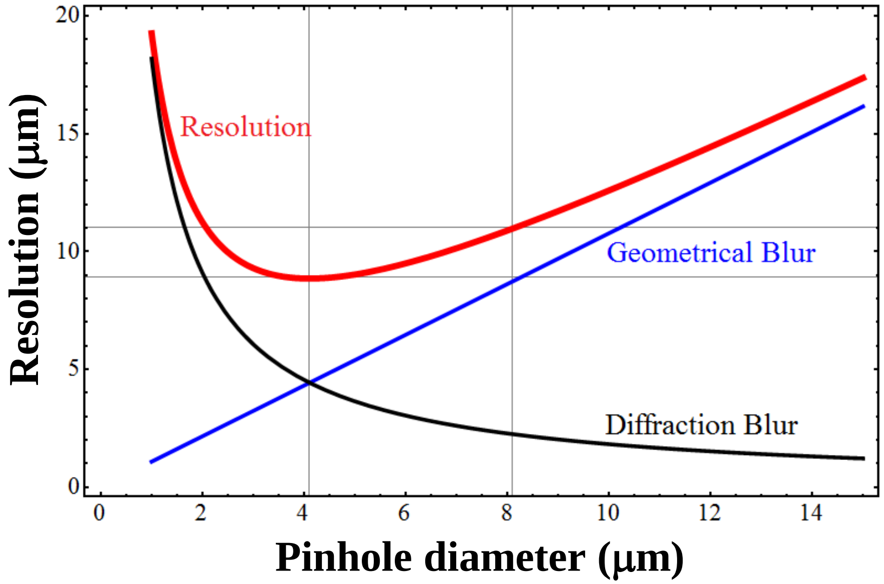
→ The interface is expected to move toward tin.

The electron pressure of tin, however, is bigger than that of diamond.

→ Would the interface move toward diamond?

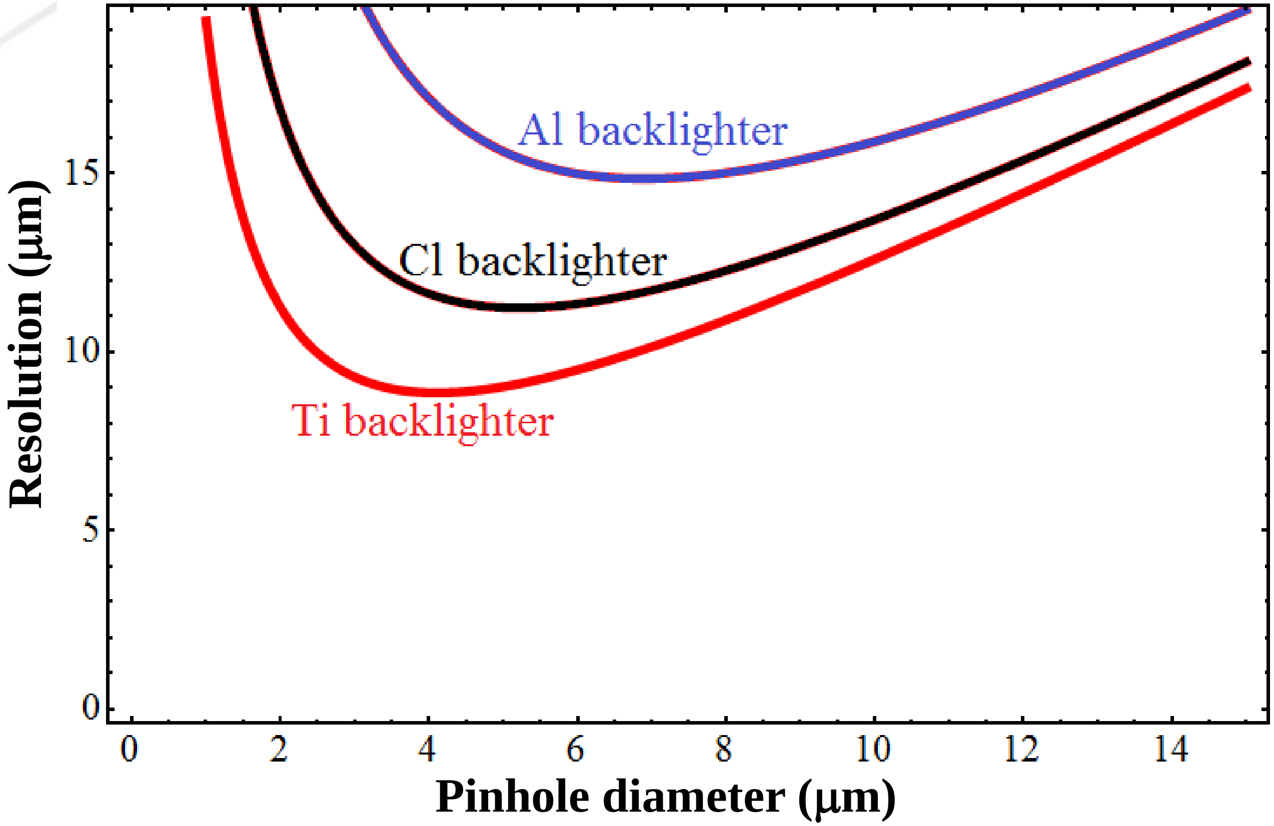
We use an x-ray pinhole camera to observe the motion of the interface





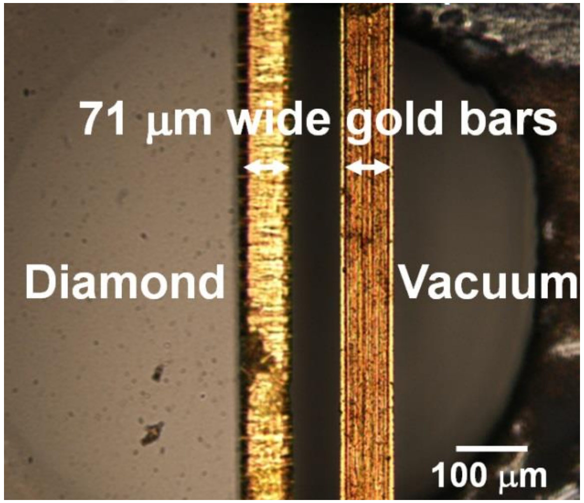
- **X-rays penetrate diamond and we can probe the movement of the gold/diamond interface.**
- **We calculated the required x-ray source size and the pinhole size for a sufficient field of view and resolution, respectively.**

We use Ti backlighter because the image resolution is 20–50% better

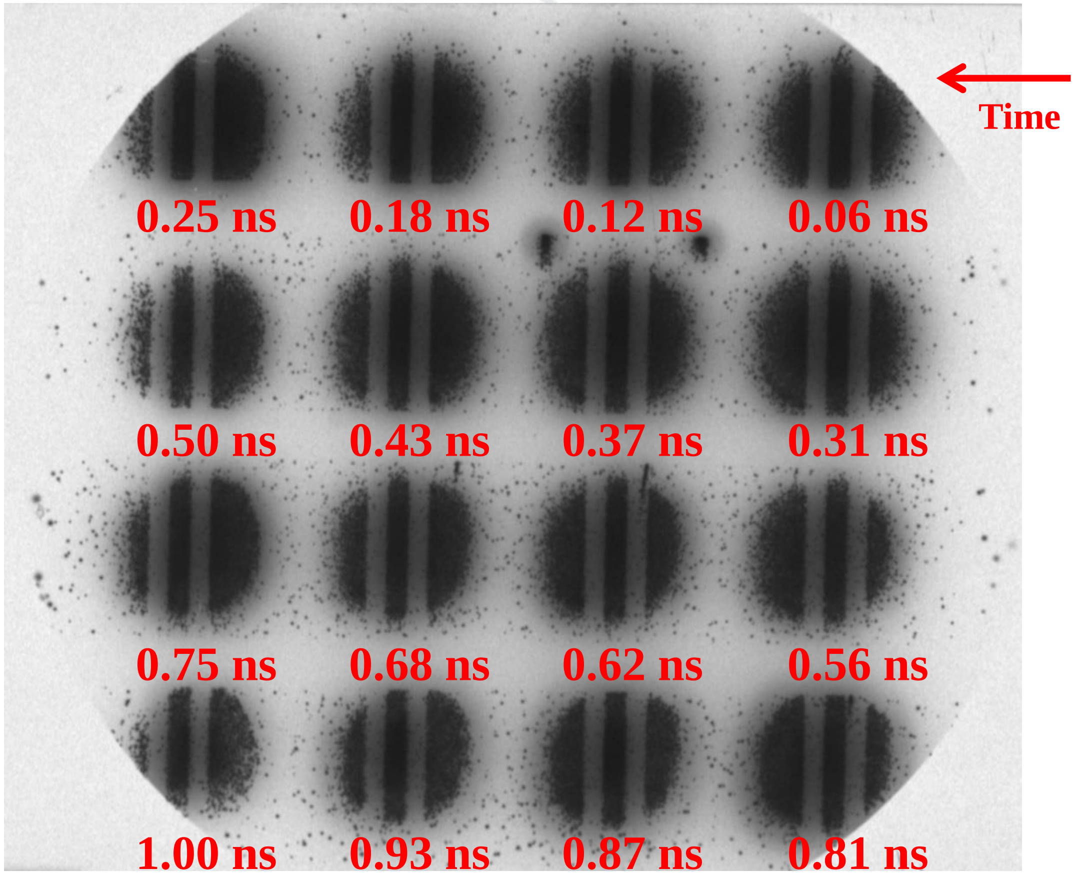


Sufficiently intense Ti backlighter has been commonly used on Trident.

GXI-X on trident can image the motion of the gold/diamond interface

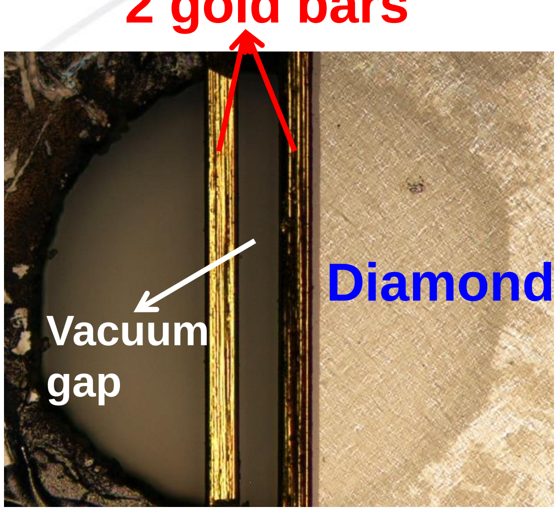


Proposed target geometry (microscope image)

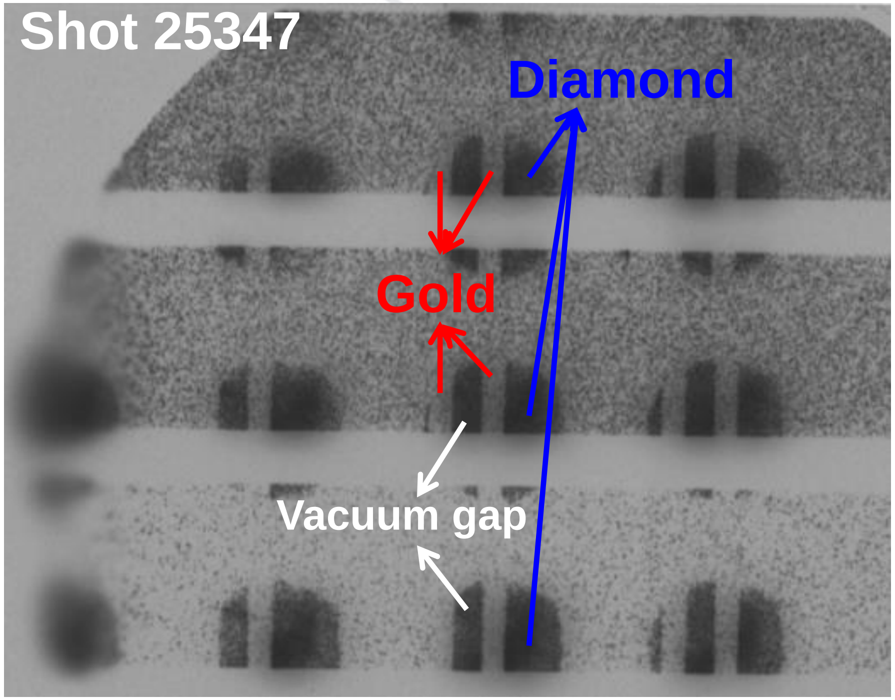


X-ray images of the unheated target at different times

We successfully acquired clear x-ray images of the heated target last month



Target for this shot
(picture by Miguel)



- Target = two gold bars (=opaque) + diamond foil (transparent)
- Analysis is underway.
- Comparison to theory prediction from multiple models (single fluid, plasma two-fluid, plasma kinetic) will be forthcoming.

We have worked on this project as a team

LDRD DR (XW9W)

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Co-investigators:

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E. L. Vold (XCP-2)
L. Yin (XCP-6)
J. Boettger (XCP-5)
C.-K. Huang (T-5)
T. Archuleta (P-24)
M. A. Santiago Cordoba (MST-7)
C. E. Hamilton (MST-7)

Conclusion

- **We calculated the expected heating per atom and temperatures of various target materials using a Monte Carlo simulation code and SESAME EOS tables.**

- **We used aluminum ion beams to heat gold and diamond uniformly and rapidly.**

- **A streak camera imaged the expansion of warm dense gold (5.5 eV) and diamond (1.7 eV).**

- **GXI-X recorded all 16 x-ray images of the unheated gold bar targets proving that it could image the motion of the gold/diamond interface of the proposed target.**

Backup slide (my works) References

[1] **Bang, W.** *et al.* Calibration of the neutron detectors for the cluster fusion experiment on the Texas Petawatt laser. *Rev. Sci. Instrum.* **83,** 063504 (2012).
[2] **Bang, W.** *et al.* Temperature measurements of fusion plasmas produced by petawatt laser-irradiated D_2-^3He or CD_4-^3He clustering gases. *Phys. Rev. Lett.* **111,** 055002 (2013).
[3] **Bang, W.** *et al.* Experimental study of fusion neutron and proton yields produced by petawatt-laser-irradiated D_2-^3He or CD_4-^3He clustering gases. *Phys. Rev. E* **88,** 033108 (2013).
[4] **Bang, W.** *et al.* Optimization of the neutron yield in fusion plasmas produced by Coulomb explosions of deuterium clusters irradiated by a petawatt laser. *Phys. Rev. E* **87,** 023106 (2013).
[5] **Bang, W.** *et al.* Optimum laser intensity for the production of energetic deuterium ions from laser-cluster interaction. *Phys. Plasmas* **20,** 093104 (2013).
[6] Barbui, M. *et al.* Measurement of the plasma astrophysical *S* factor for the $^3He(d, p)^4He$ reaction in exploding molecular clusters. *Phys. Rev. Lett.* **111,** 082502 (2013).
[7] **Bang, W.** *et al.* Characterization of deuterium clusters mixed with helium gas for an application in beam-target-fusion experiments. *Phys. Rev. E* **90,** 063109 (2014).
[8] **Bang, W.** Disassembly time of deuterium-cluster-fusion plasma irradiated by an intense laser pulse. *Phys. Rev. E* **92,** 013102 (2015).
[9] **Bang, W.** *et al.* Visualization of expanding warm dense gold and diamond heated rapidly by laser-generated ion beams. *Scientific Reports* **5,** 14318; doi:10.1038/srep14318 (2015).
[10] **Bang, W.** *et al.* Uniform heating of materials into the warm dense matter regime with laser-driven quasimonoenergetic ion beams. *Phys. Rev. E* **92,** 063101 (2015).