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Title: Rapid heating of matter using high power lasers

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Rapid heating of matter using high power lasers

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4/12/2016

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Outline

1. **Motivation**

   - uniform & rapid heating of a target, opportunity to study warm dense matter, study of nuclear fusion reactions

2. **Rapid heating of matter with intense laser-driven ion beams**

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

4. **Nuclear fusion experiments using high power lasers**

   - Direct heating of deuterium spheres (radius~ 10 nm) with an intense laser pulse

5. **Conclusion**

Motivation

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

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

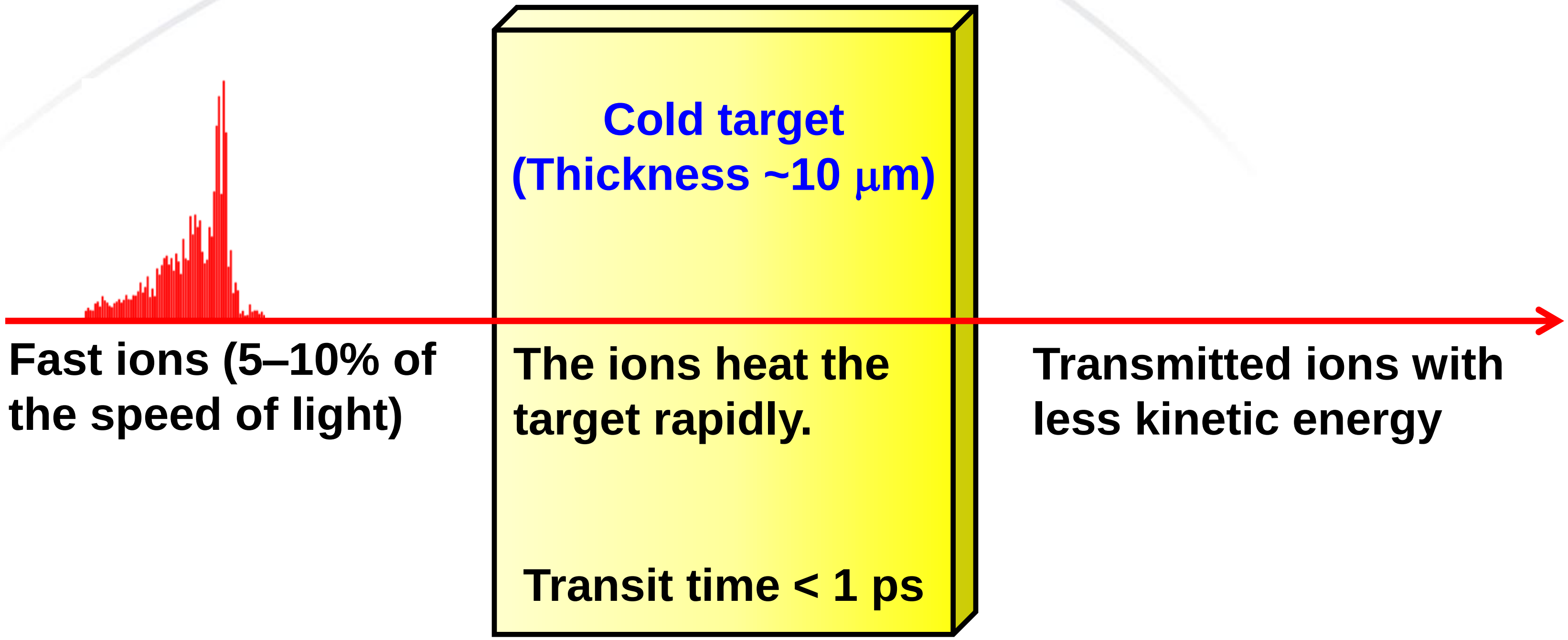
2. **Opportunity to study warm dense matter**

   - 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 nuclear fusion reactions using high power lasers**

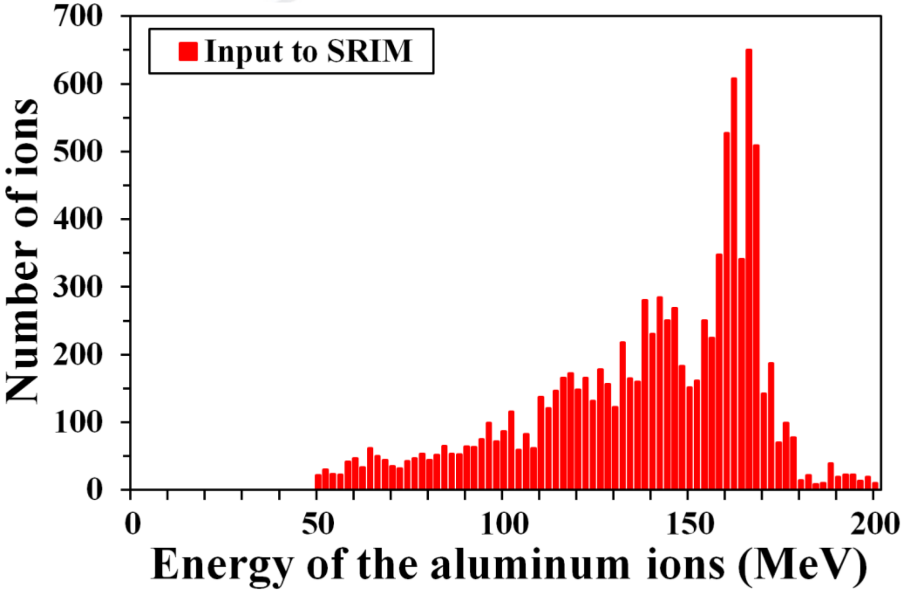
   - Measurement of the fusion cross-sections, a compact neutron source

Energetic ions can heat a target material very quickly

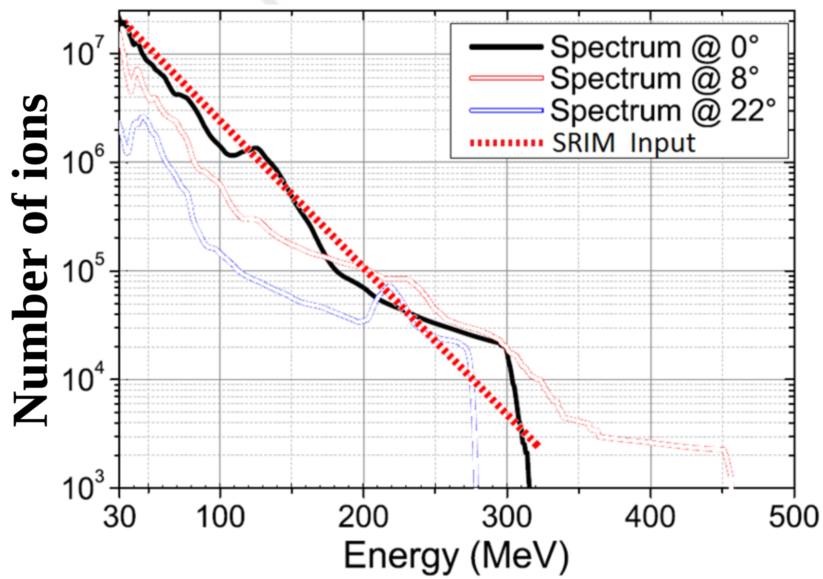


- Energetic ions incident on a target can transfer a significant amount of their kinetic energy to the target.
- This heating occurs so quickly (~ 20 ps) that the target does not have enough time to expand hydrodynamically during heating.

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

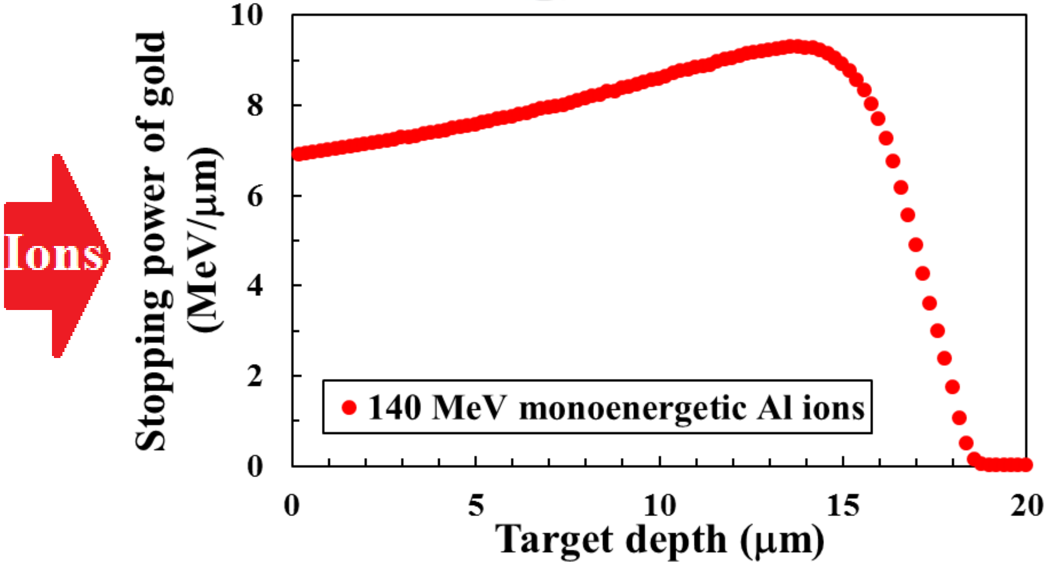
Measured ion energy spectra were used in a Monte Carlo simulation code (SRIM) to calculate the expected heating per atom.

* S. Palaniyappan *et al*., Nature Communications **6**, 10170 (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).

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).

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

< Example: EOS table for gold >

Target density →

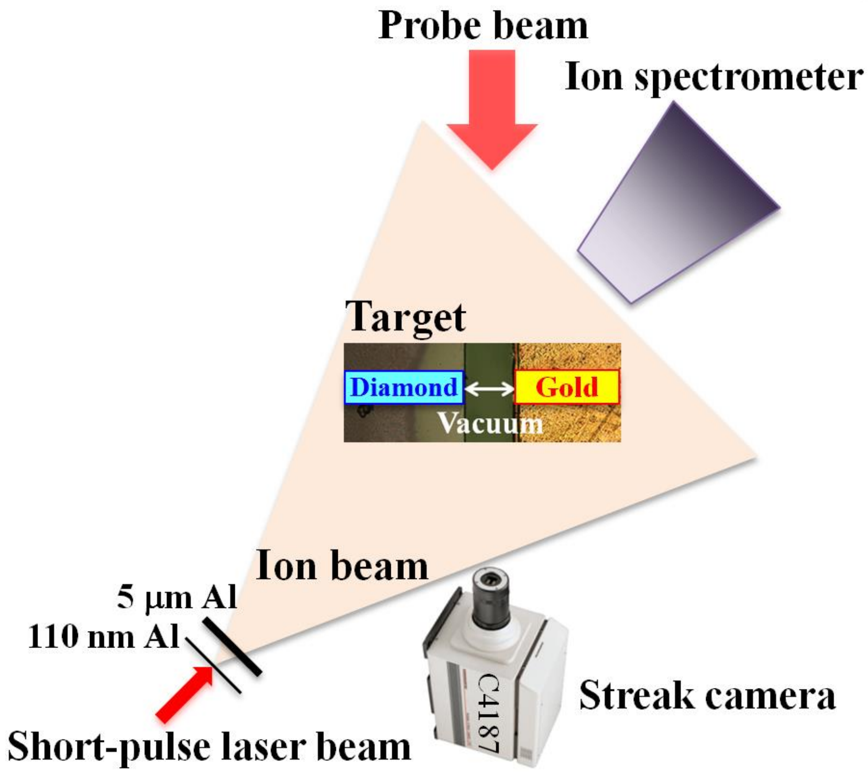
Heating per atom ↓

	…	…	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)

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

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

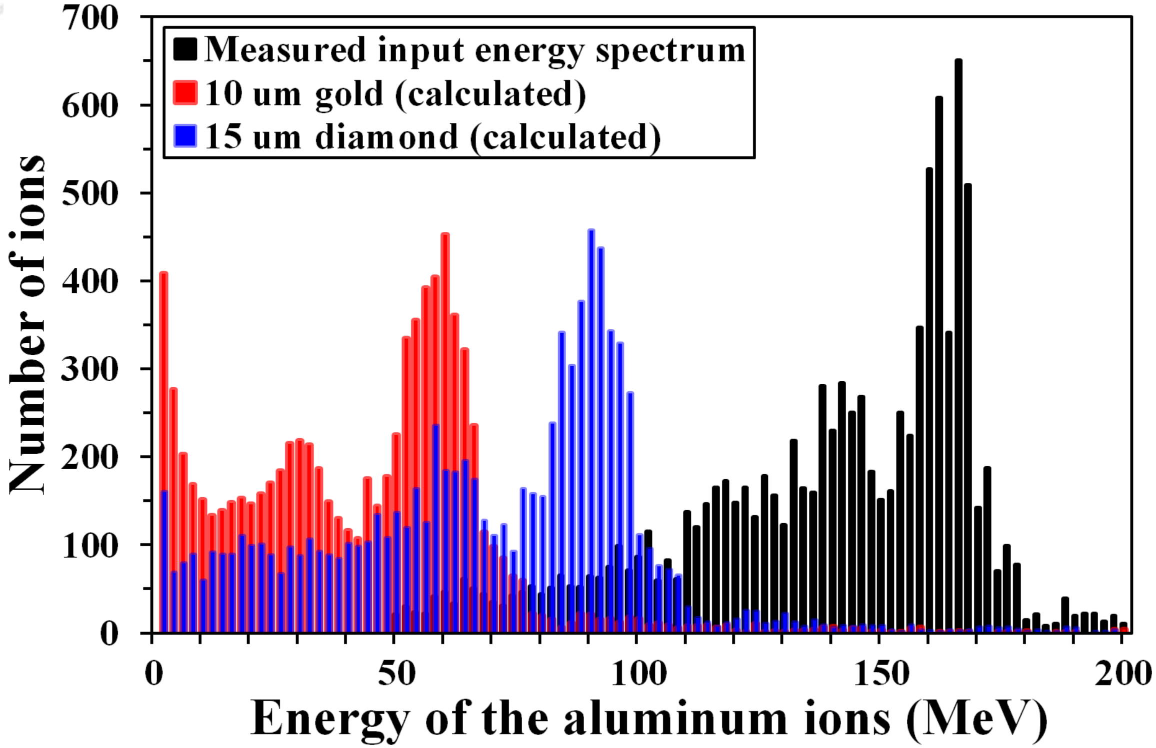


An optical streak camera detects the light not blocked by gold or diamond.

* S. Palaniyappan *et al*., Nature Communications **6**, 10170 (2015).

*** W. Bang *et al*., Scientific Reports **5**, 14318 (2015); W. Bang *et al*., Phys. Rev. E **92**, 063101 (2015).

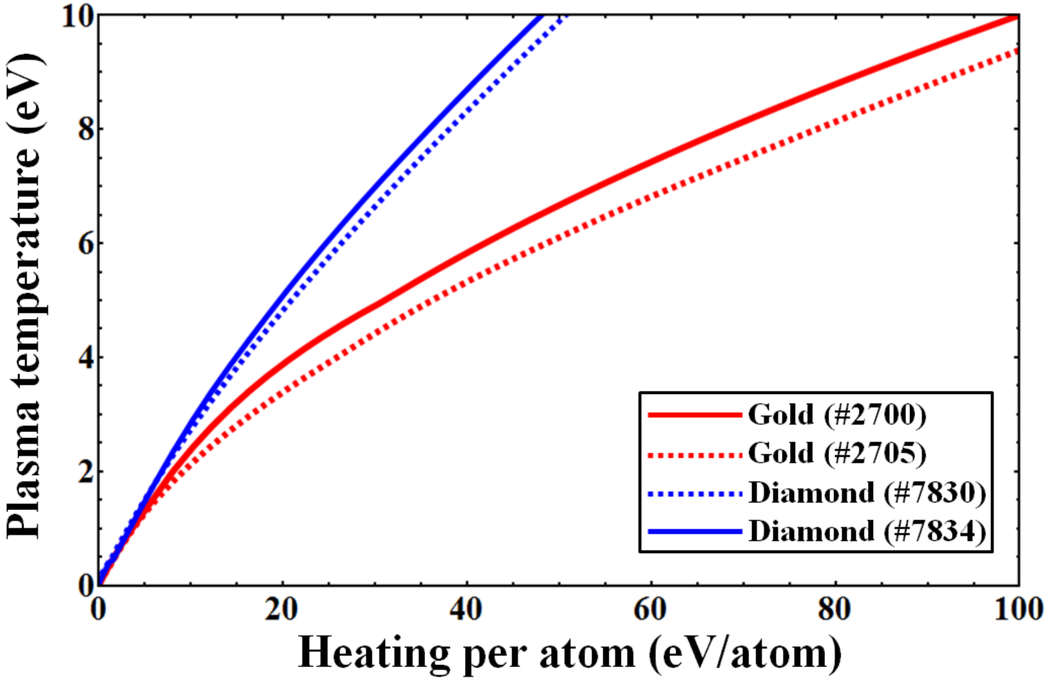
Energy deposition was calculated from the measured incident ion energy spectrum



The ion energy spectra after penetrating through a gold foil (red bars) or a diamond foil (blue bars) were calculated from the measured incident ion energy spectrum (black bars).

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

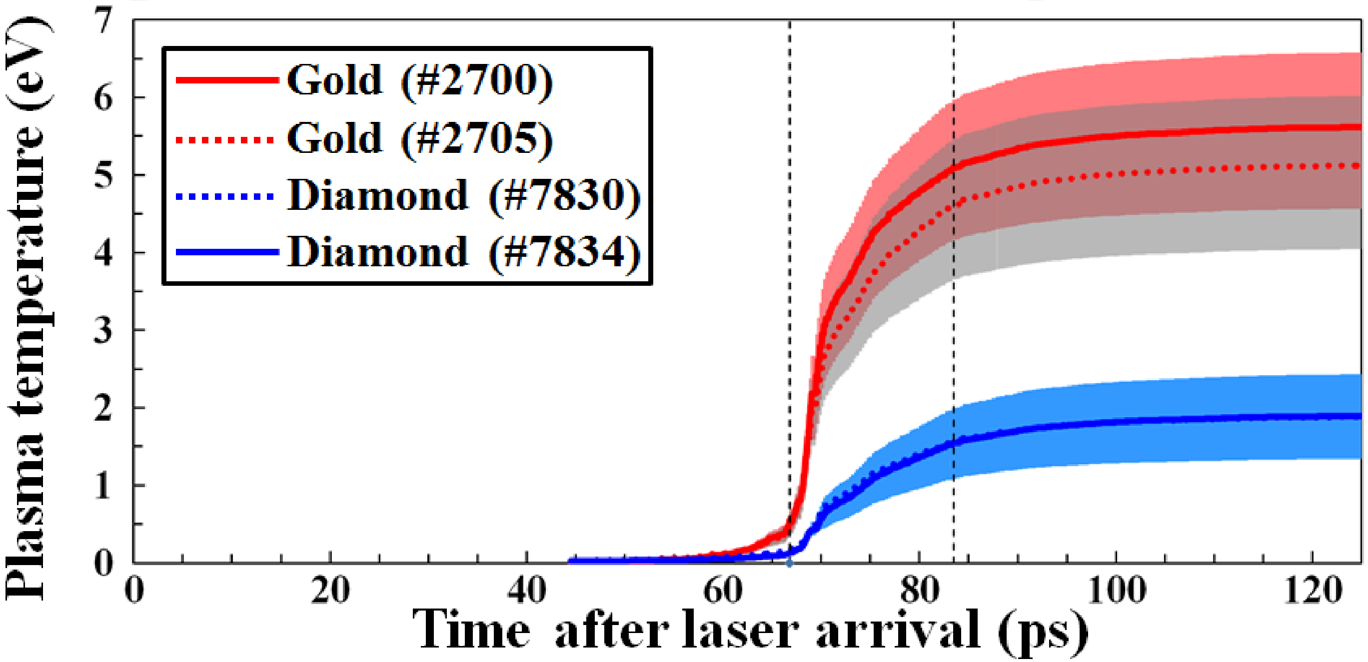
We use SESAME**** EOS tables to bound the expected target temperatures



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).

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

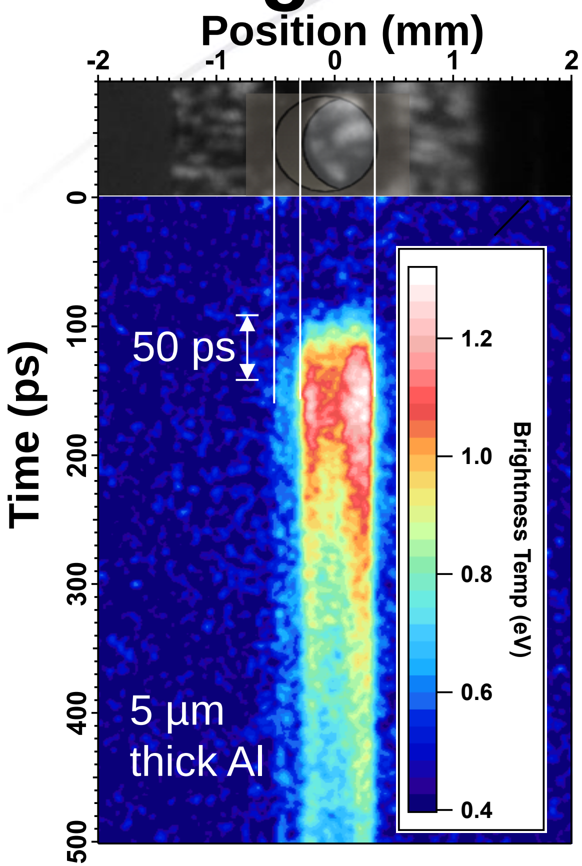


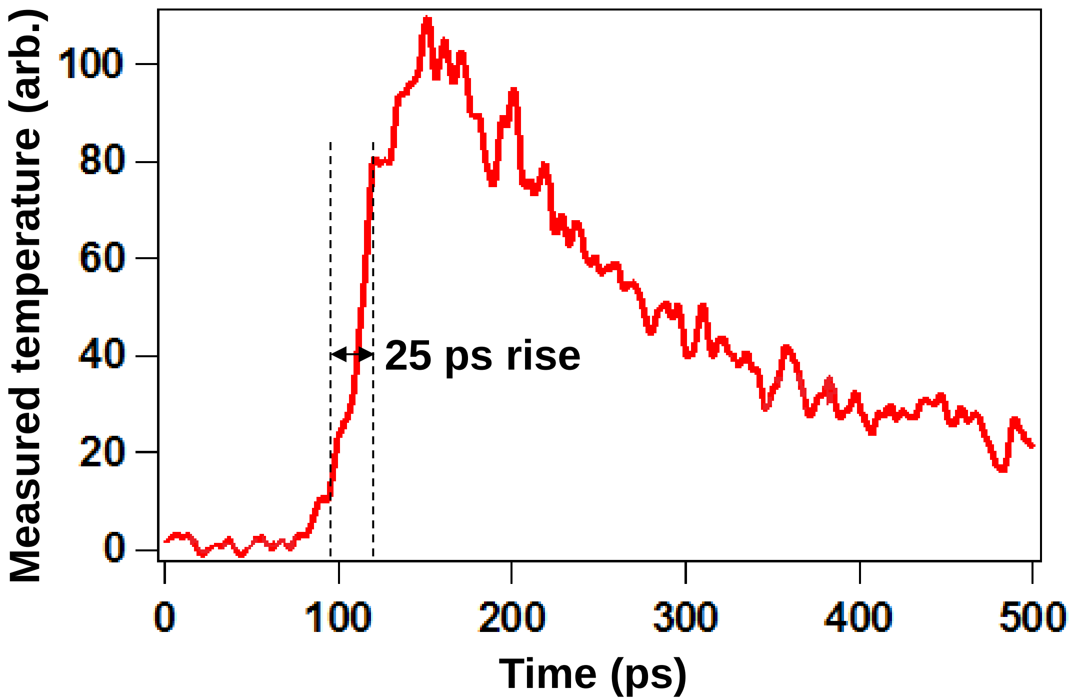
Ions with different kinetic energy arrive at the target at different times. (200 MeV Al ion at 63 ps, 50 MeV Al ion at 125 ps)

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

W. Bang *et al*., Scientific Reports **5**, 14318 (2015).

Temperature measurements show rapid heating of Al foils by the ion beam

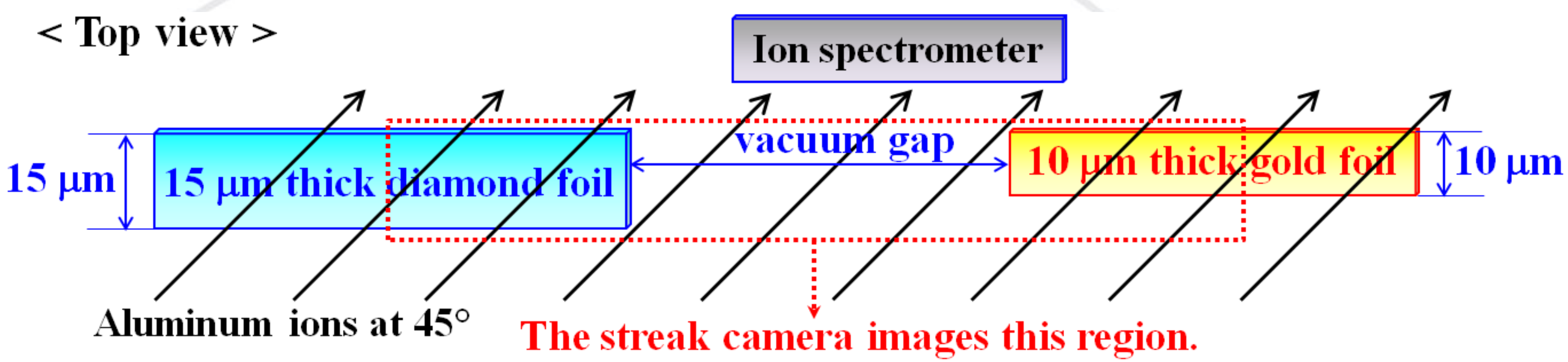


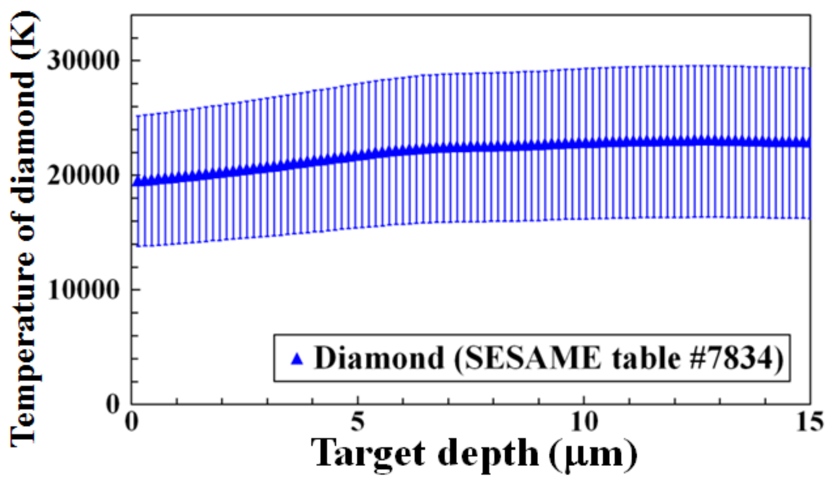


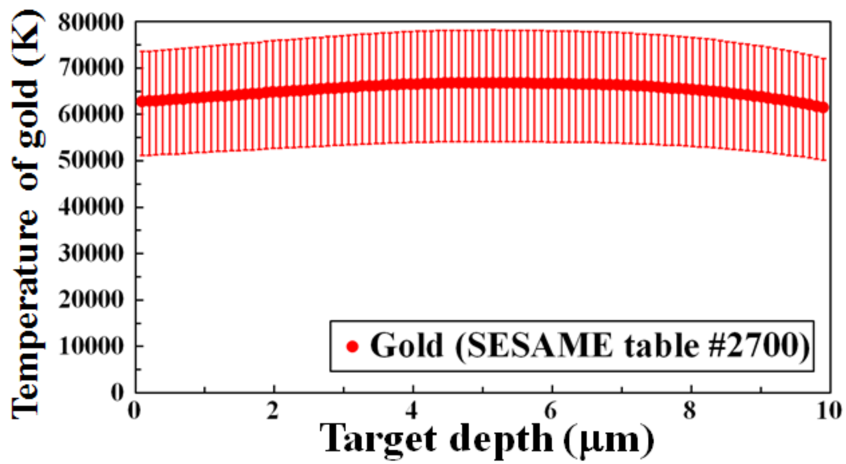
A streaked optical pyrometer (SOP) measured the surface temperature of an aluminum foil showing a rapid heating (25–50 ps).

G. Dyer *et al.*, Phys. Rev. E (in preparation).

The ion beam is expected to heat gold and diamond very uniformly



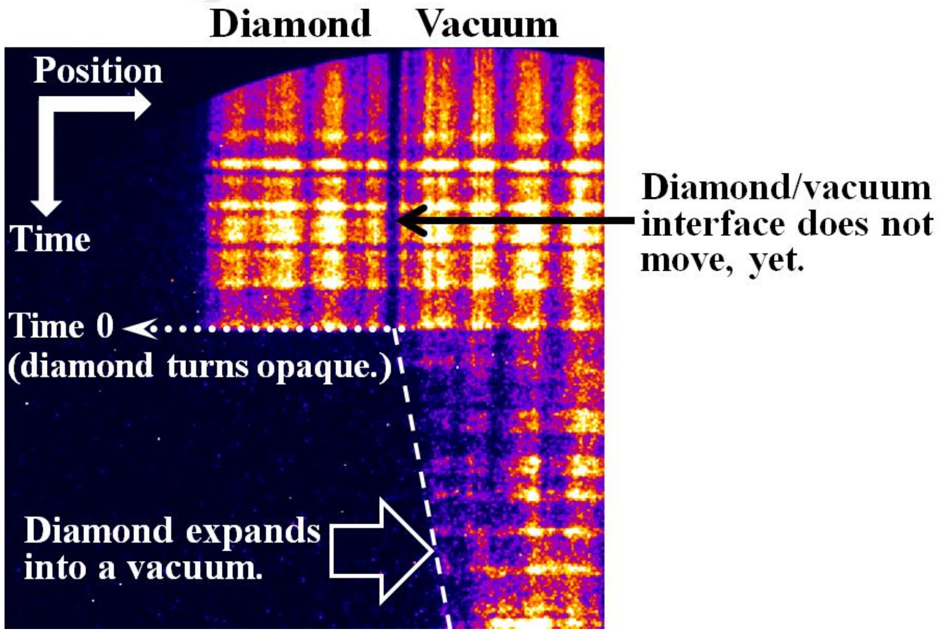




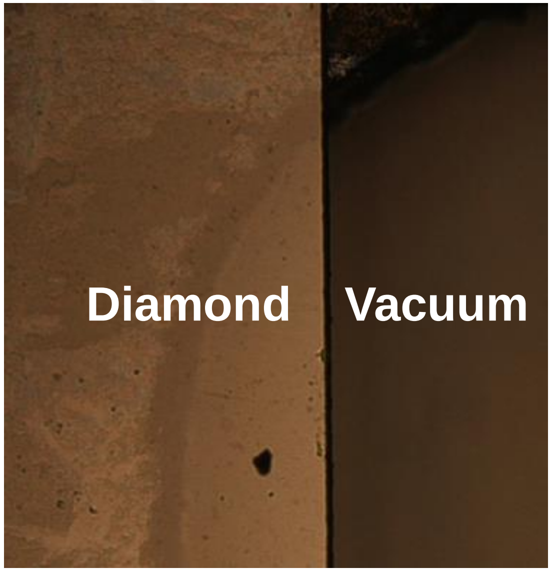
- **45° ion incidence angle owing to geometric constraints**

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

A streak camera visualized the expansion of diamond after heating



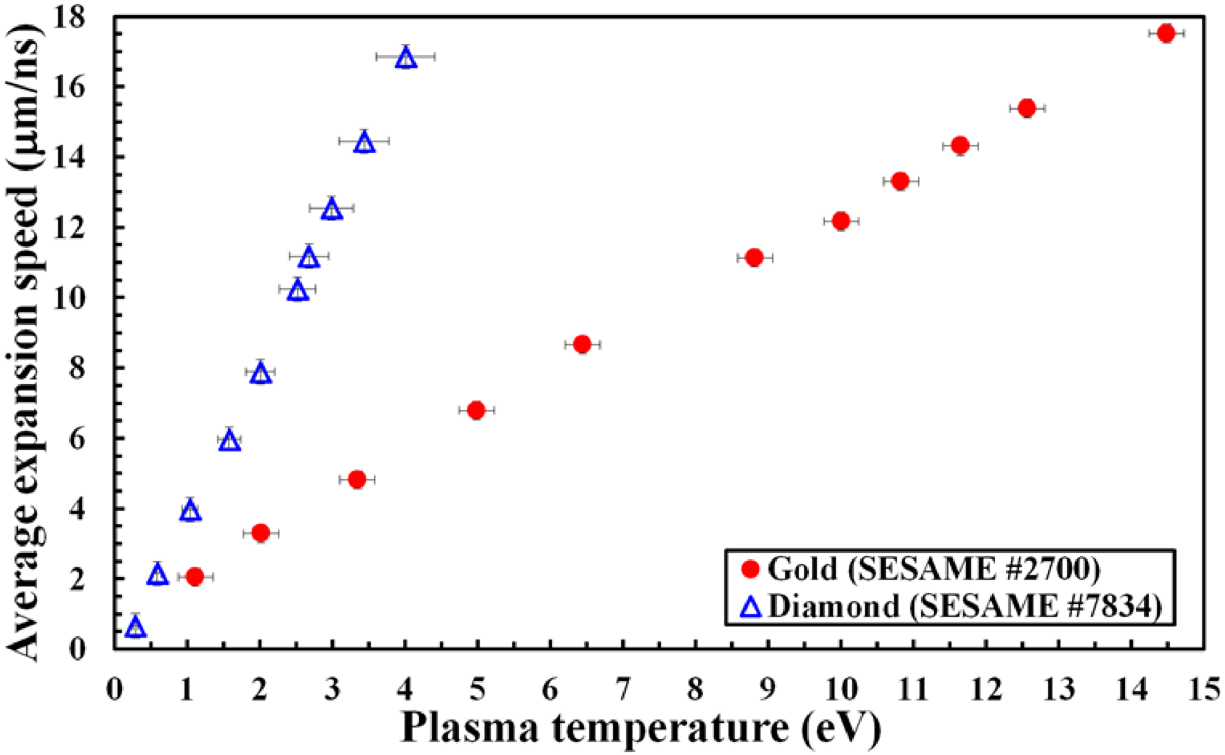
A streak camera image showing the expansion of diamond



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.

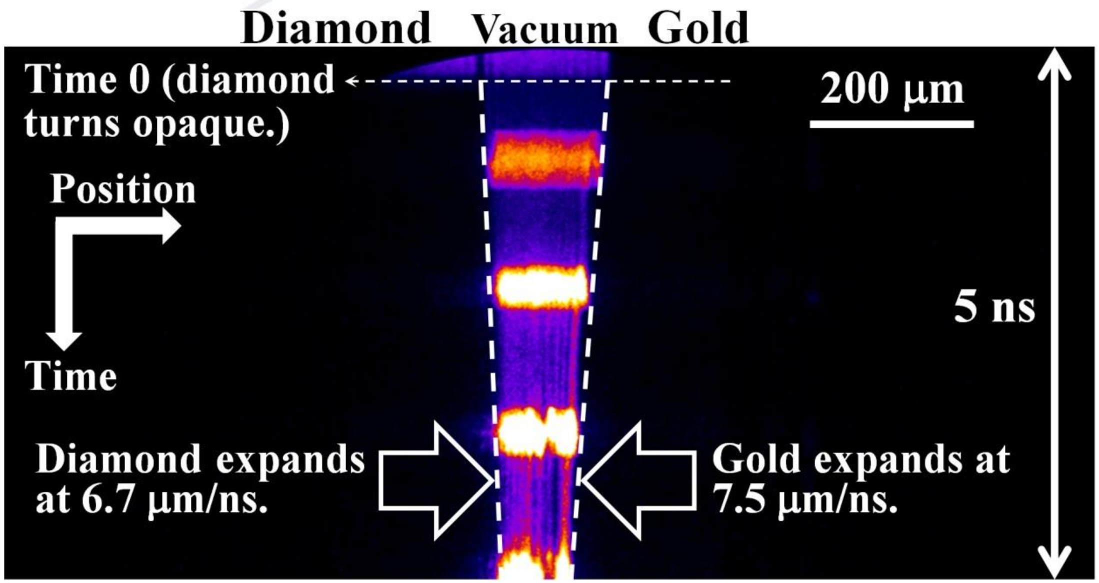
The expansion speed is determined by the initial target temperature



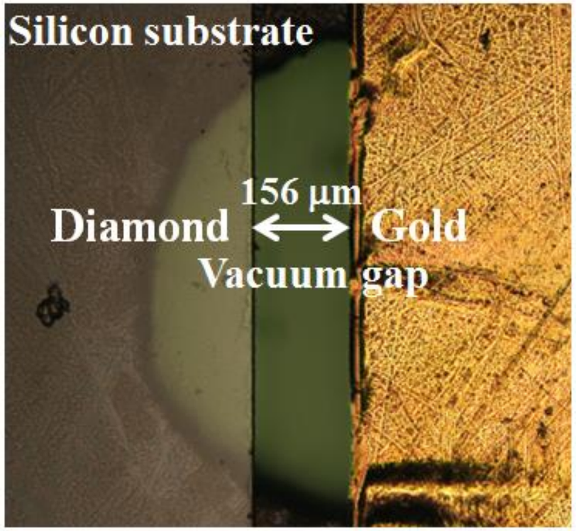
Computer simulations were used to determine the initial plasma temperature from the measured expansion speeds. (new technique)

W. Bang *et al*., Scientific Reports **5**, 14318 (2015).
W. Bang *et al*., Scientific Reports (submitted); LA-UR-16-21124 (2016).

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



A streak camera image showing the expansion of gold and diamond



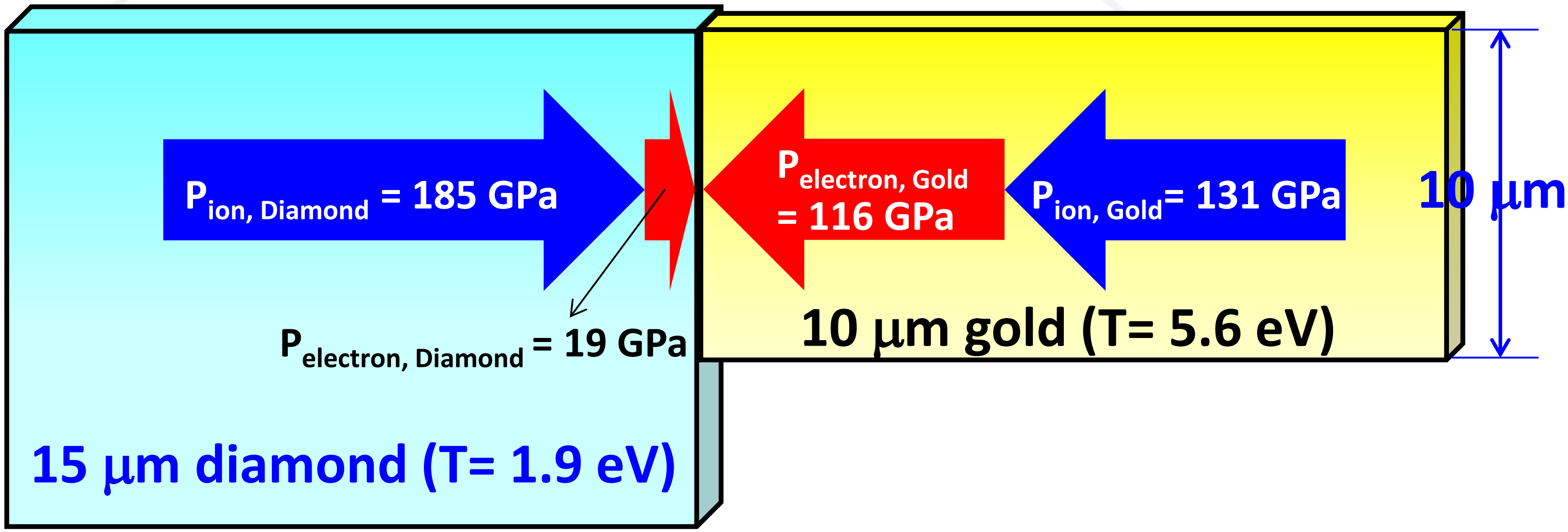
Picture of the target

- 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*., Scientific Reports **5**, 14318 (2015).

We want to record how the gold/diamond interface moves

< Top view >



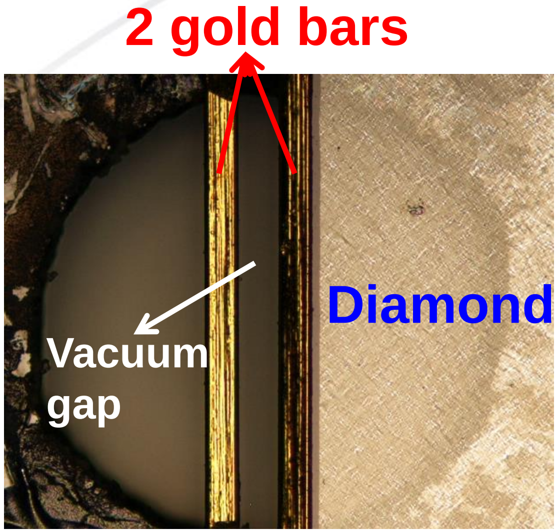
$$P_{electron,\ Diamond} \ll P_{electron,\ Gold}$$

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

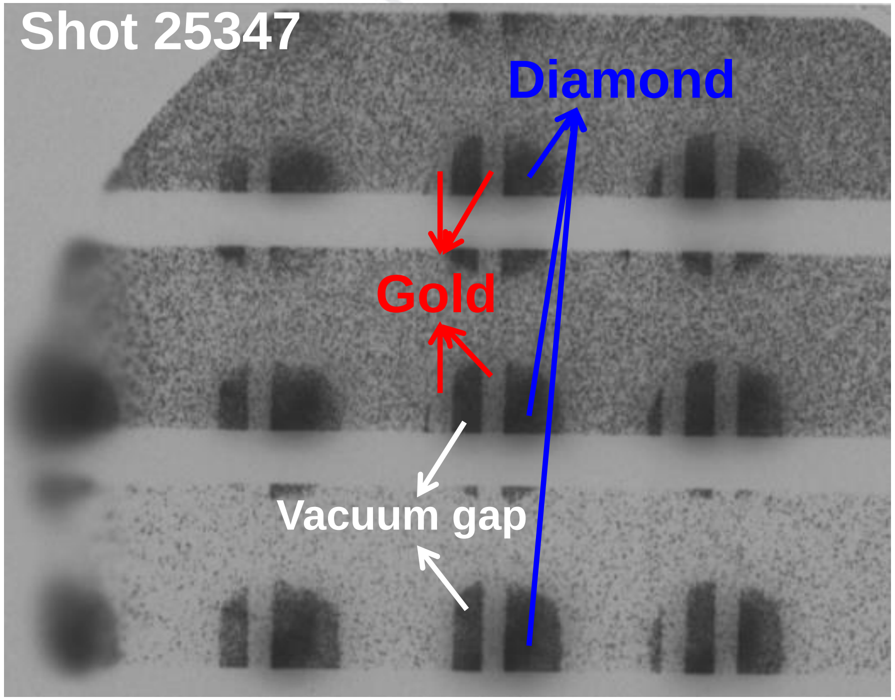
The total pressure of gold is 25% larger than that of diamond.

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

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

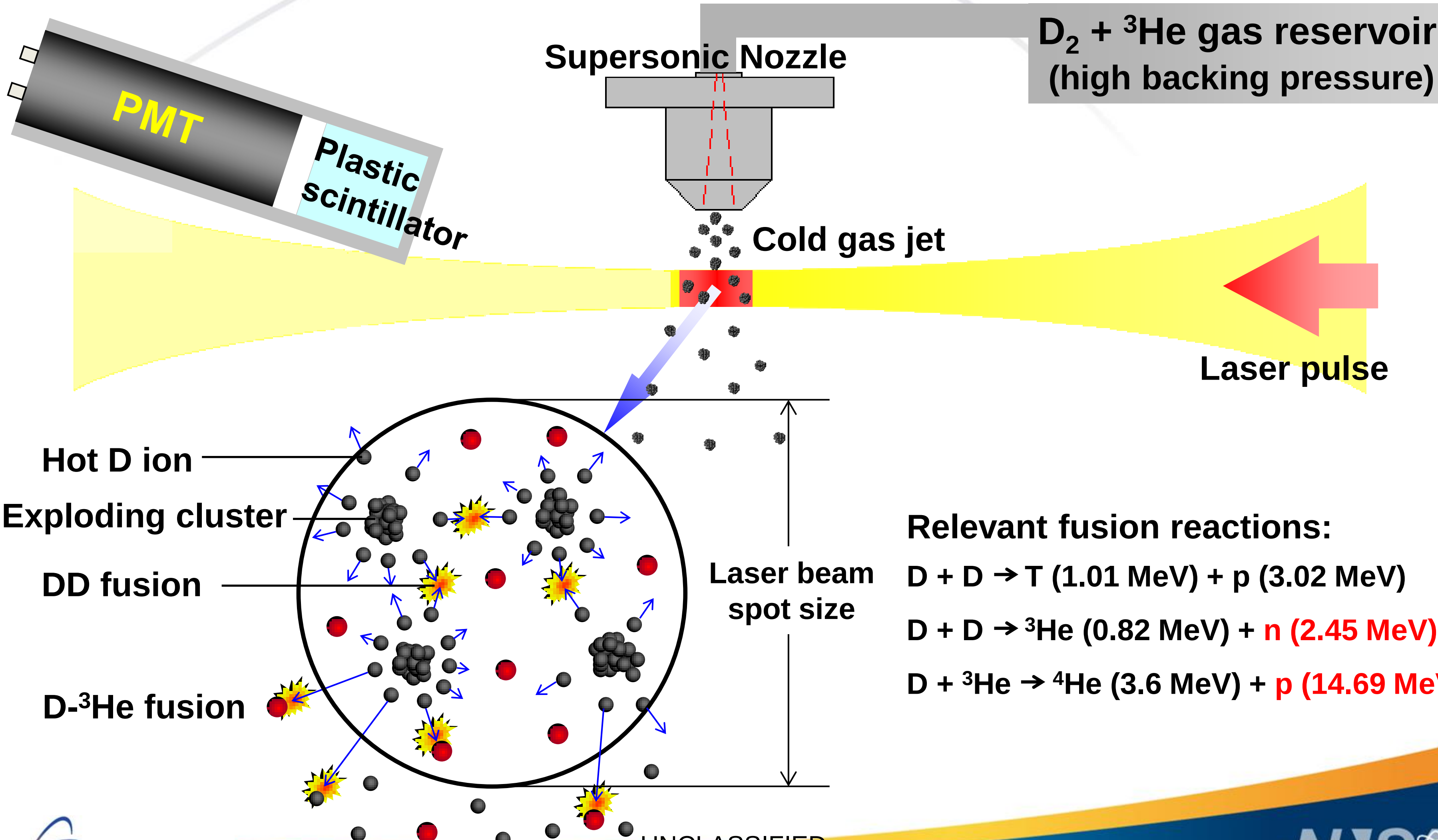


Target for this shot (picture by Miguel)



- 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 produce fusion plasmas by irradiating deuterium clusters with intense laser pulses



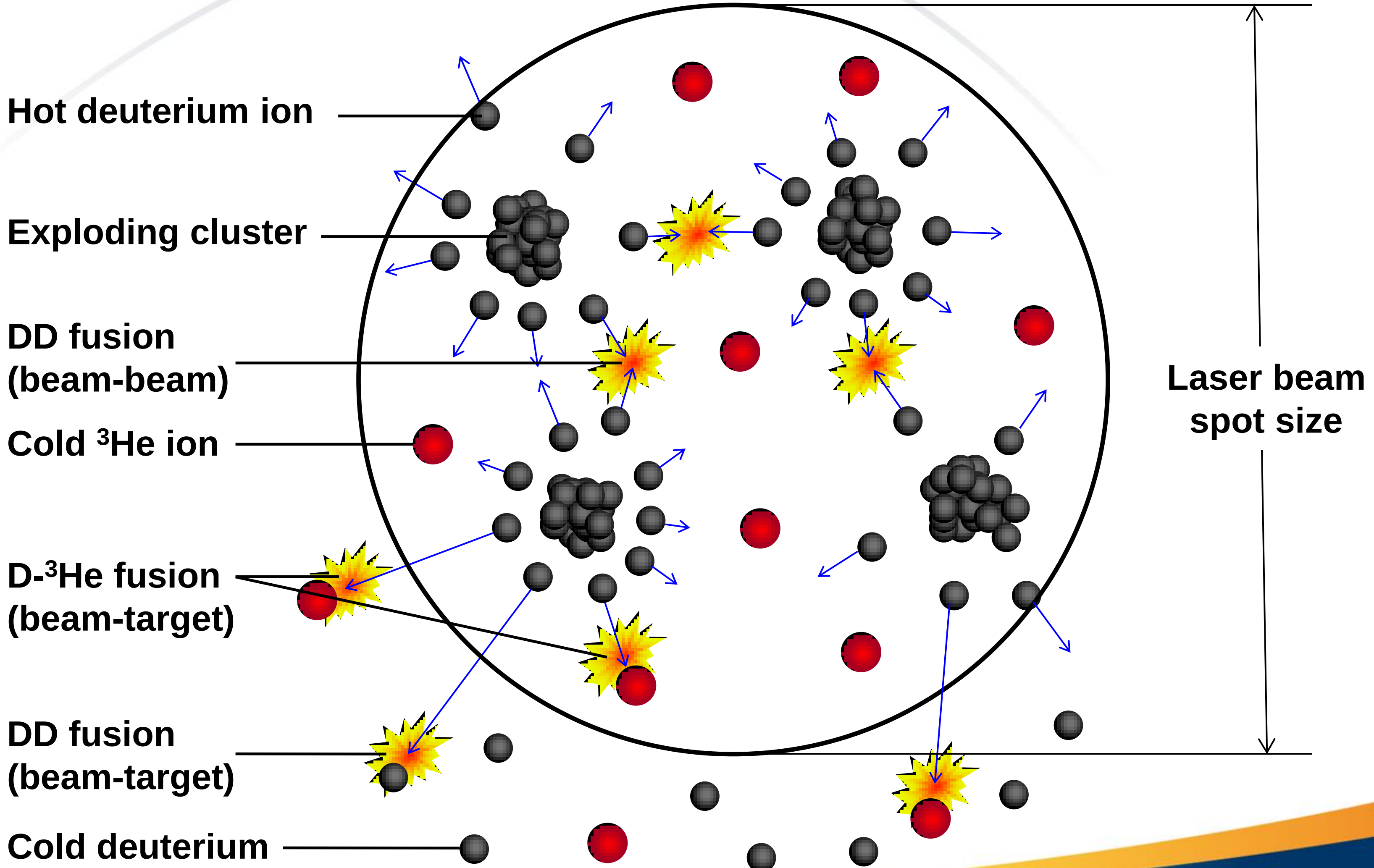
Relevant fusion reactions:

D + D → T (1.01 MeV) + p (3.02 MeV)

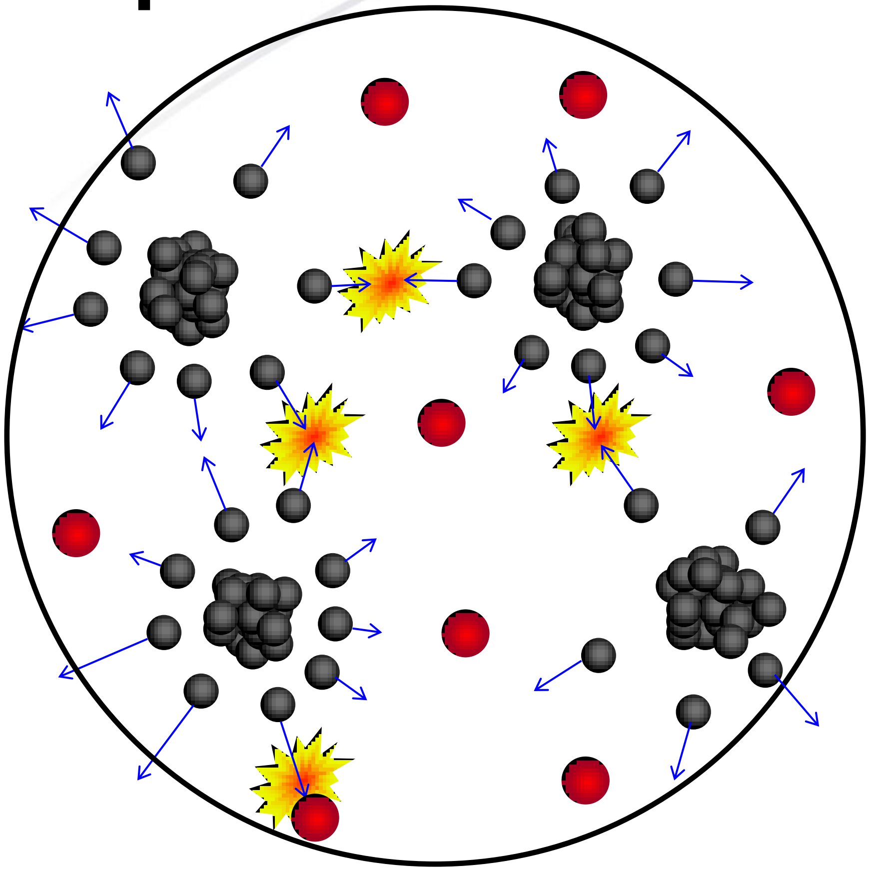
D + D → ^{3}He (0.82 MeV) + n (2.45 MeV)

D + ^{3}He → ^{4}He (3.6 MeV) + p (14.69 MeV)

Fusion occurs when energetic deuterium ions collide with other deuterium or ^{3}He ions



We add ^{3}He to determine the ion temperature responsible for the fusion reactions



$$Y_p = \int n_{^3He} n_D < \sigma_{D^3He} v >_{\frac{3}{5}kT} \, dV dt$$

$$Y_n = \frac{1}{2} \int n_D{}^2 < \sigma_{D(D,n)^3He} v >_{kT} \, dV dt$$

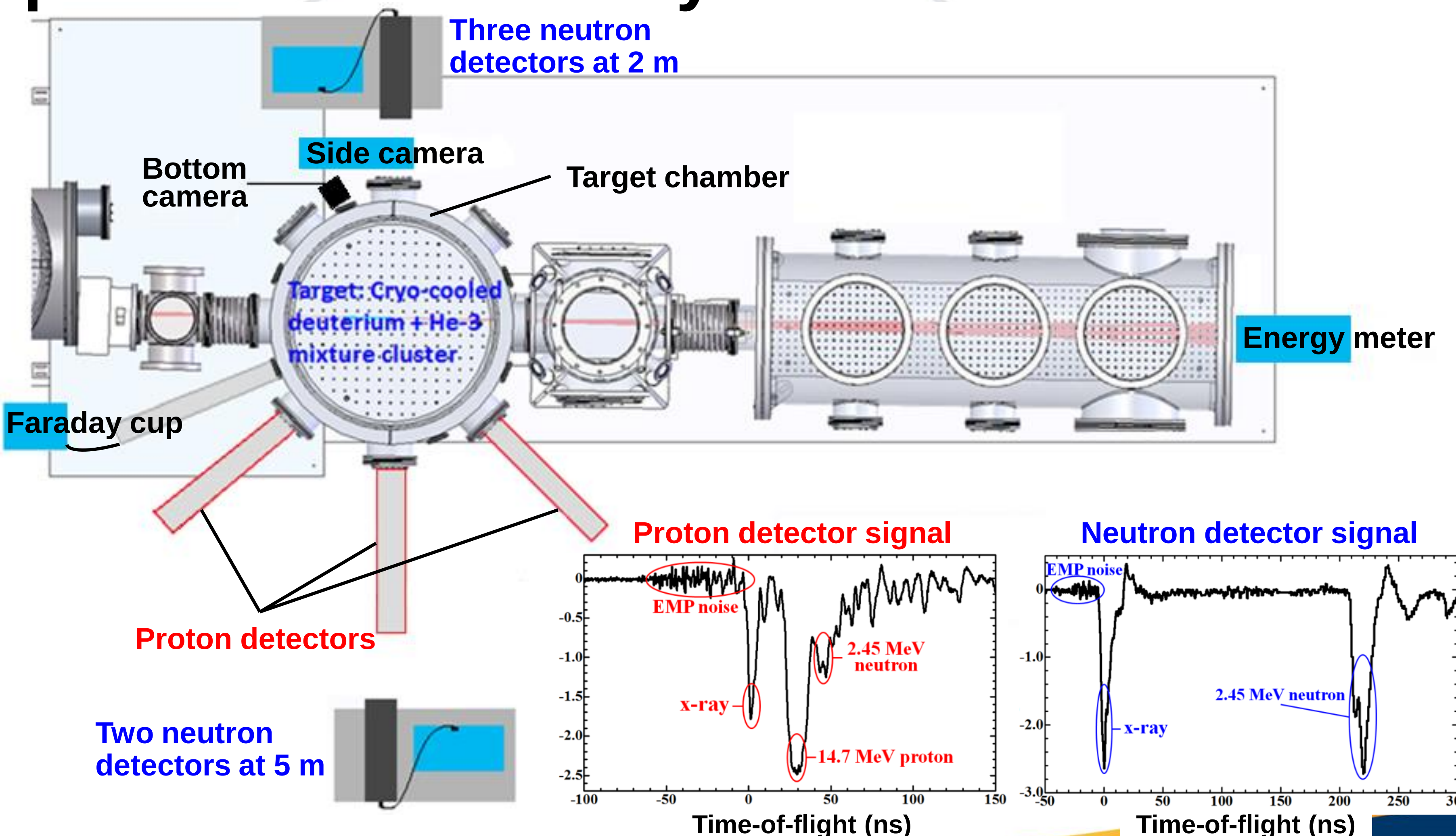
$$\frac{Y_p}{Y_n} \approx 2 \frac{n_{^3\mathrm{He}}}{n_D} \frac{\langle \sigma_{D^3\mathrm{He}} v \rangle_{(3/5)kT}}{\langle \sigma_{D(D,n)^3\mathrm{He}} v \rangle_{kT}}$$

Function of *kT*

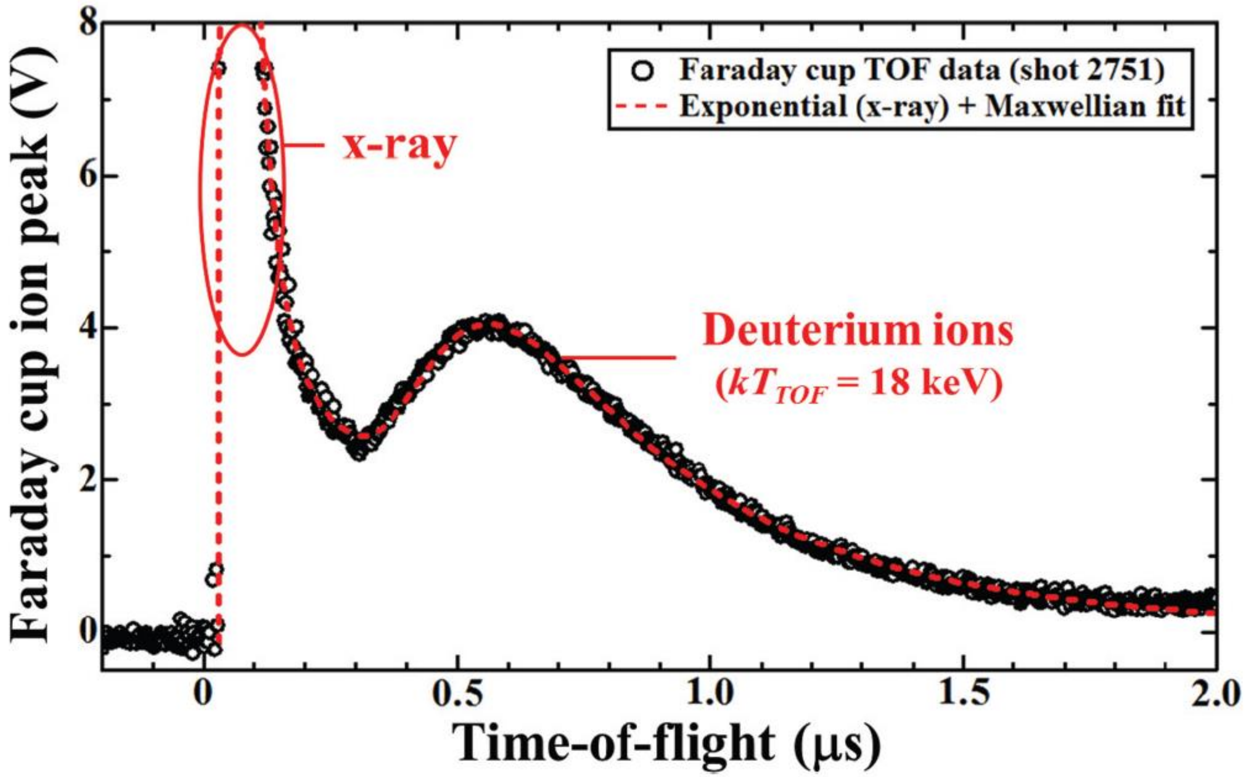
The ion temperature, *kT,* is determined by the measured ratio of fusion proton and neutron yields ($n_{^3He}/n_D$ is also measured experimentally).

W. Bang *et al*., Phys. Rev. Lett. **111**, 055002 (2013); M. Barbui *et al*., Phys. Rev. Lett. **111**, 082502 (2013).

Scintillation detectors measured the fusion proton and neutron yields



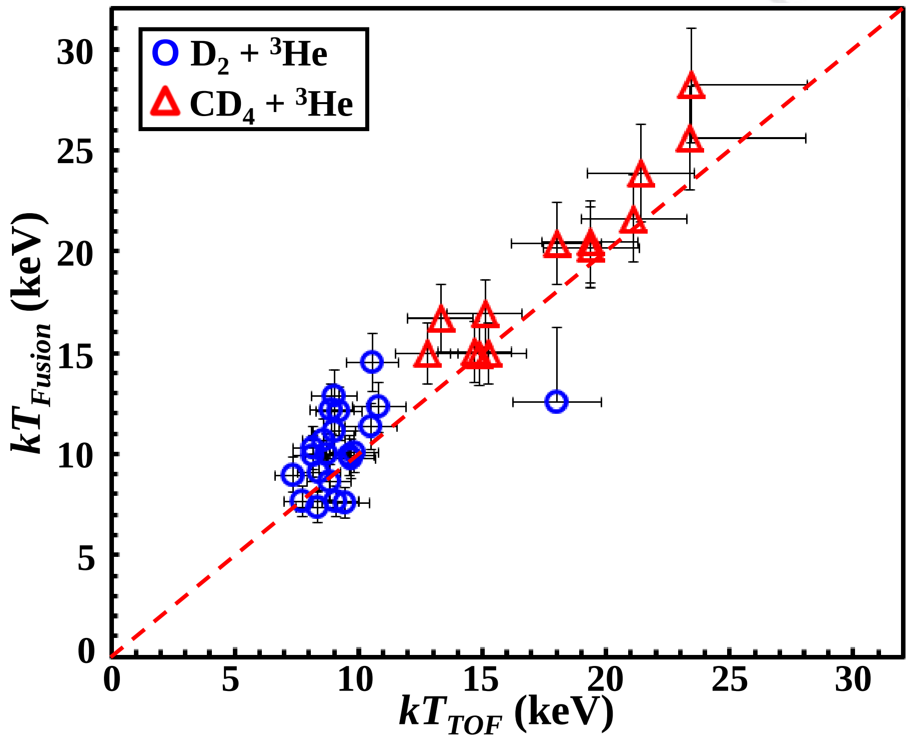
A Faraday cup provided the ion time-of-flight (TOF) measurements



An example of the ion TOF data along with an 18-keV Maxwellian fit and an exponentially rising and decaying curve accounting for the initial x-ray peak.

W. Bang *et al*., Phys. Rev. E **88**, 033108 (2013).

We measured the ion temperature at the time of fusion reactions



- **By adding ^{3}He, we successfully measured the ion temperature at the time of fusion reactions using the ratio of measured fusion yields.**
- **This agreed with the temperature measured from the ion time-of-flight.**

W. Bang *et al*., Phys. Rev. Lett. **111**, 055002 (2013); W. Bang *et al.*, Phys. Rev. E **90**, 063109 (2014);
W. Bang *et al*., Phys. Rev. E **88**, 033108 (2013).

Conclusion

- **We calculated the expected target temperatures using SESAME EOS tables.**

- **Intense laser-driven ion beams heated gold and diamond uniformly and rapidly.**

- **A streak camera imaged the expansion of warm dense gold and diamond.**

- **We produced deuterium fusion plasmas, and measured the ion temperature at the time of the fusion reactions.**

Final thoughts – Why should GIST care about laser-plasma experiments?

1. **A feasible route to nuclear fusion "ignition"**

   - There is an increasing interest in using lasers for nuclear fusion science.

   (NIF in the USA, LMJ in France, HiPER in the EU, ……)

2. **GIST has an excellent infrastructure for laser-plasma experiments**

   - Petawatt laser systems are already available at GIST.

   - A mJ-level Ti:Sapphire laser system is affordable.

3. **Exotic states of matter are achieved after heating**

   - Excellent tool for creating extreme states of matter (giant planetary cores are in warm dense matter state, which can be created effectively using lasers).

   - Fundamental knowledge about interaction between light and matter.

References

[1] **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).
[2] **Bang, W.** *et al.* Temperature measurements of fusion plasmas produced by petawatt laser-irradiated D_2-^{3}He or CD_4-^{3}He 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-^{3}He or CD_4-^{3}He 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).
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[6] Barbui, M. *et al.* Measurement of the plasma astrophysical *S* factor for the ^{3}He(d, p)^{4}He reaction in exploding molecular clusters. *Phys. Rev. Lett.* **111,** 082502 (2013).
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[8] **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).
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[10] **Bang, W.** *et al.* Linear dependence of surface expansion speed on initial plasma temperature in warm dense matter. *Scientific Reports* (submitted); LA-UR-16-21124 (2016).
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