Mach stem hysteresis: Experiments addressing a novel explanation of clumpy astrophysical jet emission

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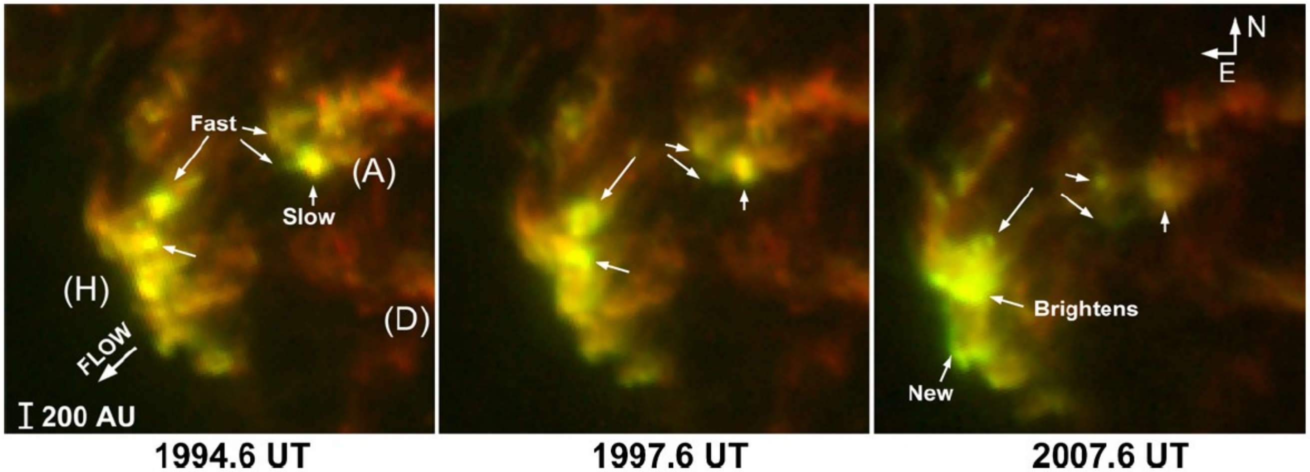
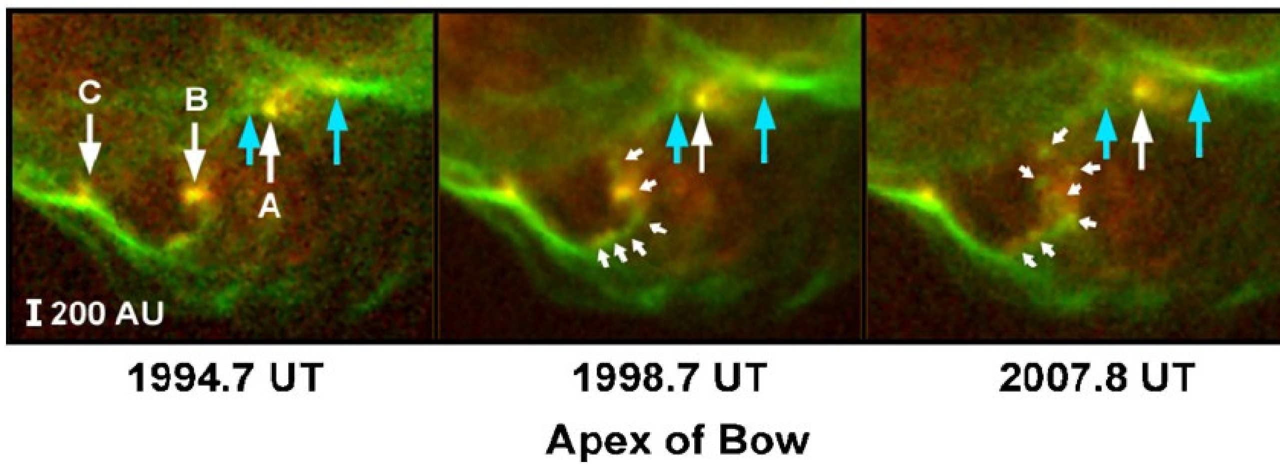
Can some emission features in Herbig-Haro objects be explained by mutual bow shock interaction?



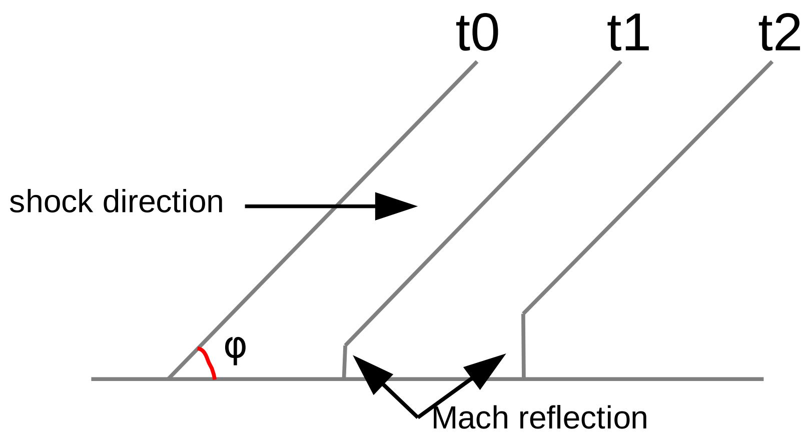
Left: emission features intuitively interpreted as distinct “knots” or clumps.

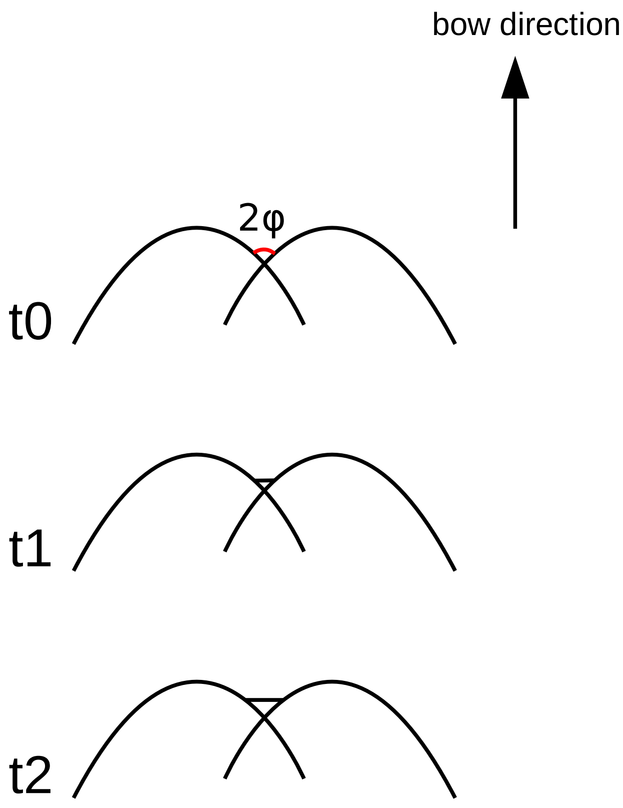
Right: emission features possibly tied into field of bow shocks?



Hartigan et al., ApJ, 2011

The physical mechanism of interest is Mach reflection.





Above: Planar Mach reflection.

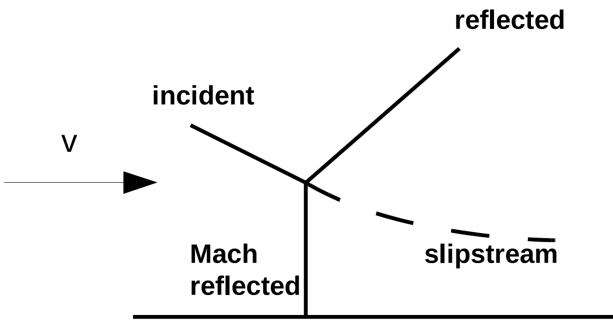
Right: An analogous case of two colliding bows.

Motivation: understanding Mach stem evolution

Basic shock theory (of e.g. Gabi Ben-Dor) indicates that the Mach stem will not form AND cannot survive when the included angle φ is below a critical value:

$$\phi_{cr} = \arcsin\left(\frac{1}{\gamma}\right)$$

We know that these astrophysical systems are in constant motion. Can we begin to answer the question of whether Mach stem formation and destruction timescales agree at all with observations?

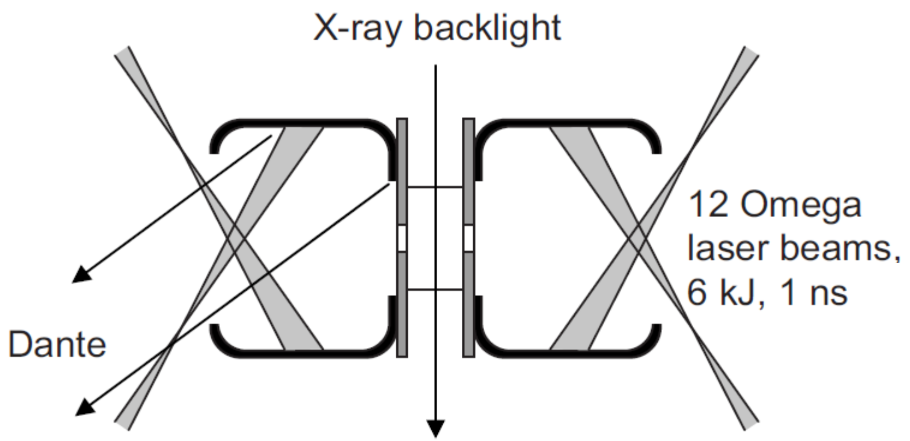


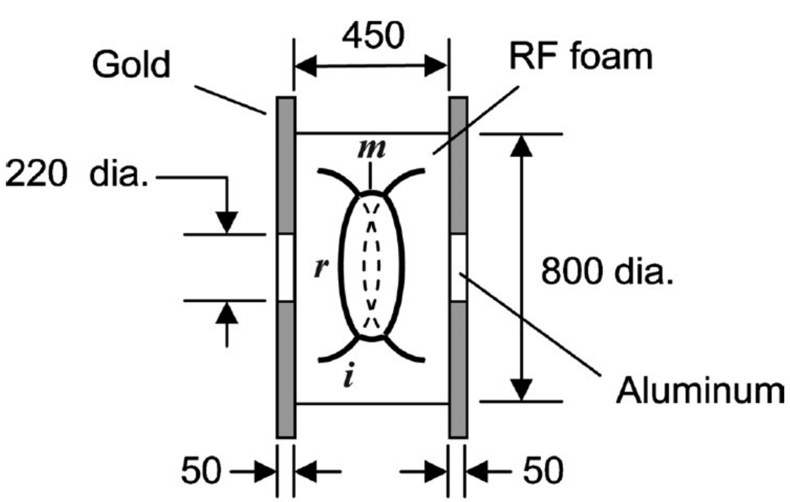
Simplified planar Mach reflection diagram (shock reference frame).

The key question for this specific project:

What can we learn about Mach stem growth *and destruction* in the warm dense plasma experimental regime, and how can we extrapolate this to the astrophysical regime?

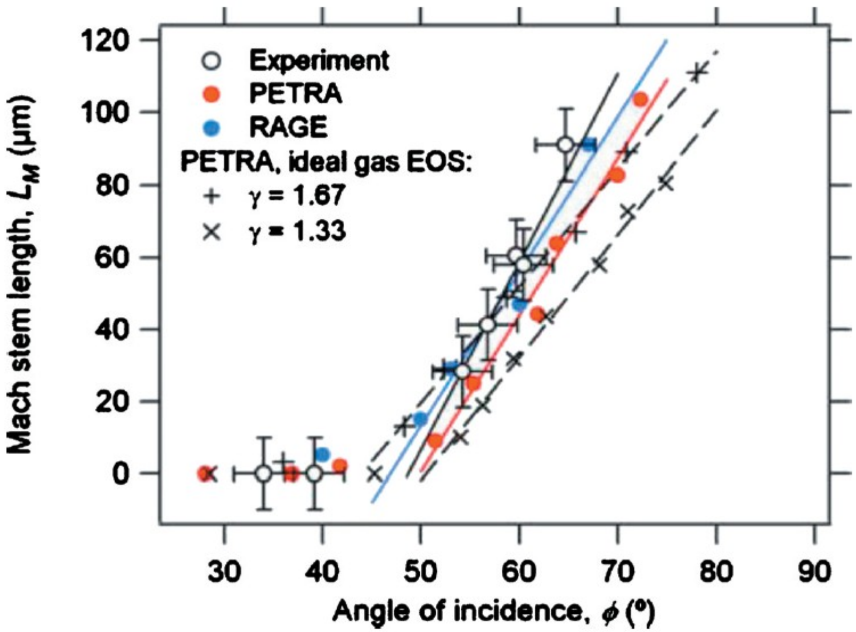
Previous related work: head-on colliding bows, looking at the experimental value of φ_{cr}.





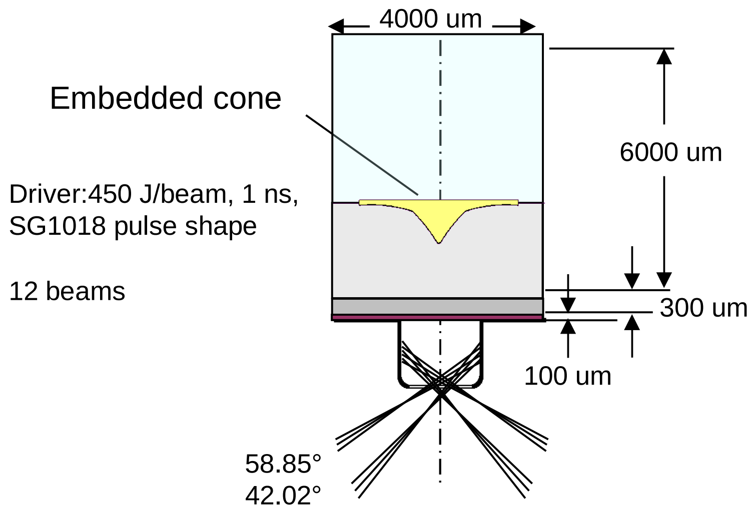
$\varphi_{cr,\ theory} \sim 35°$

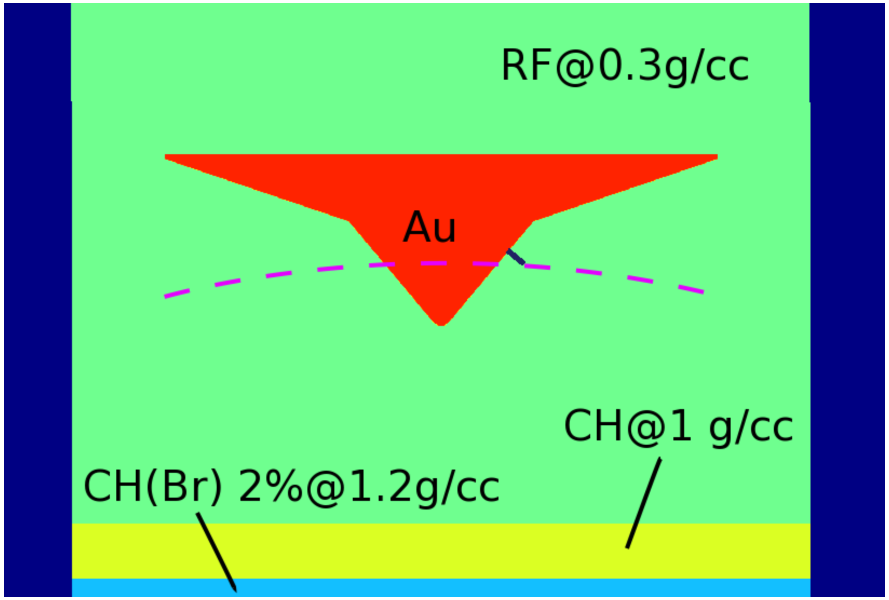
$\varphi_{cr,\ exp} \sim 48°$



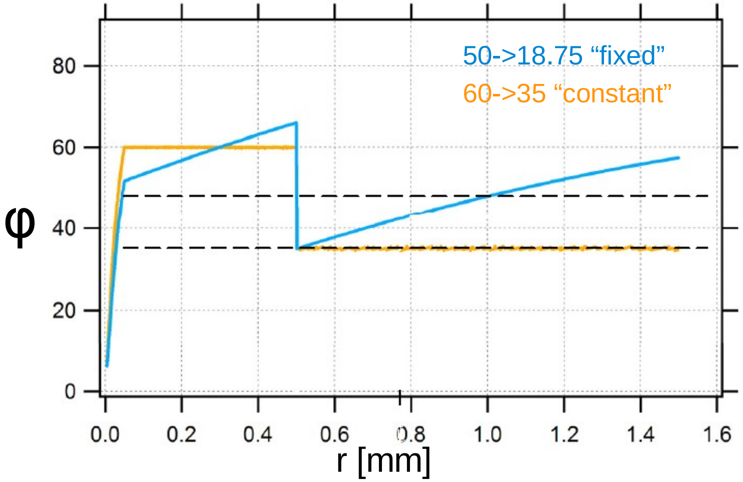
Foster et al., 2010

To date we have fielded 2 variations of a simplified design, based on RAGE simulation (next slide).





Example of RAGE initial geometry, showing the 50->18.75 cone, cropped. The bottom of the image is the top of the halfraum in reality; in simulation we employ a volumetric temperature source (Foster et al. 2002) below the bottom of the image.



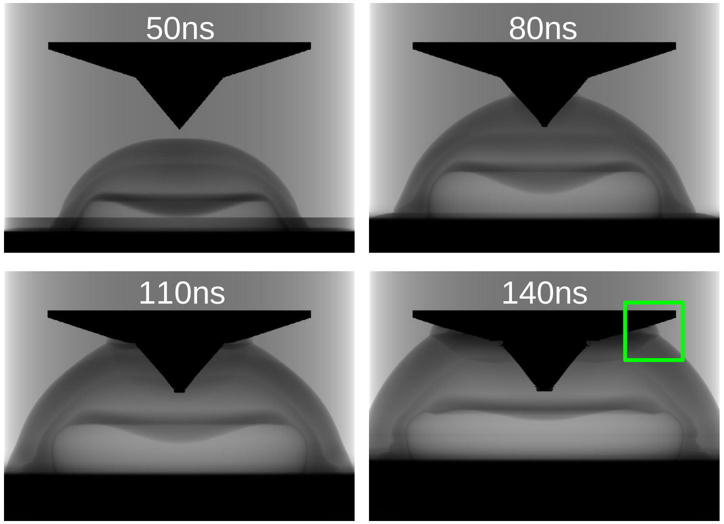
Why these cones? Because they allow a sweep of interesting φ.

Design work is carried out with the LANL code RAGE.

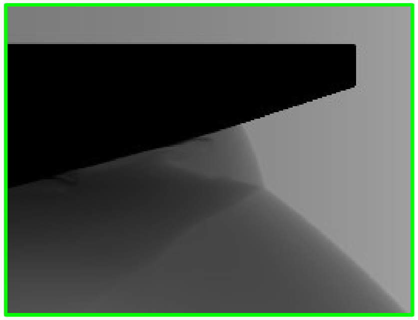
RAGE is a multidimensional, multiphysics AMR code with applications for laboratory experiments. It utilizes radiation diffusion and the SESAME EOS tables.

I employed RAGE in its cylindrically-symmetric capacity; typical resolutions were around 1µm and problem sizes around 64^3--256^3 (250,000--1.5 million) cells.

On the right, some example synthetic Ni backlighter images of a run.



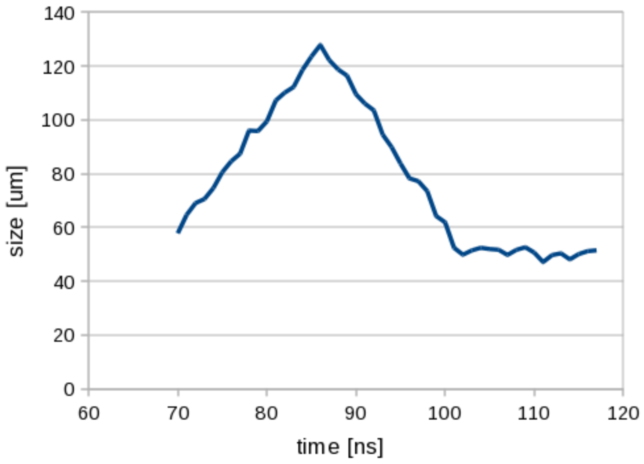
Synthetic Ni BL images of the straight-sided 50 to 18.75 degree cone design.

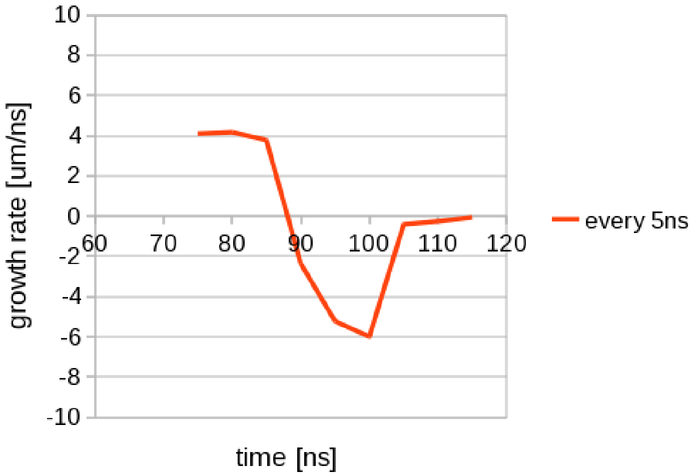


Zoom at 140 ns, Mach stem size=106um.

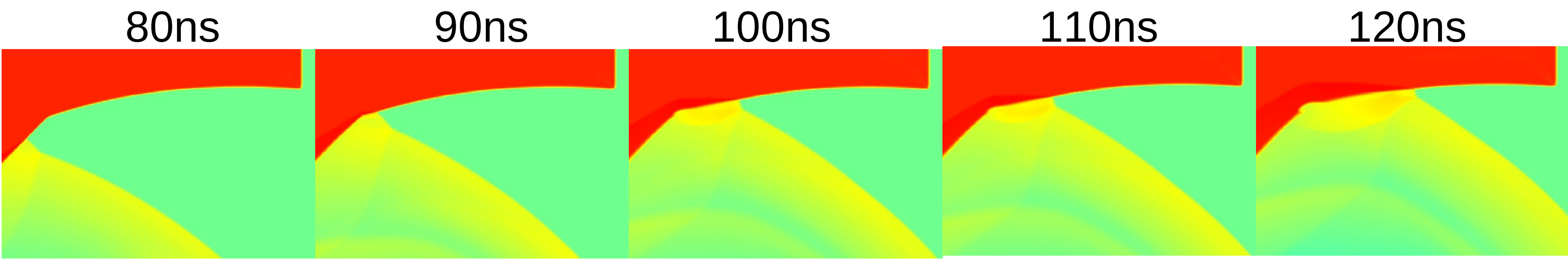
Simulation results suggest survivability below phi_cr for one of the cone designs.

60 to 35 degree constant-angle design.



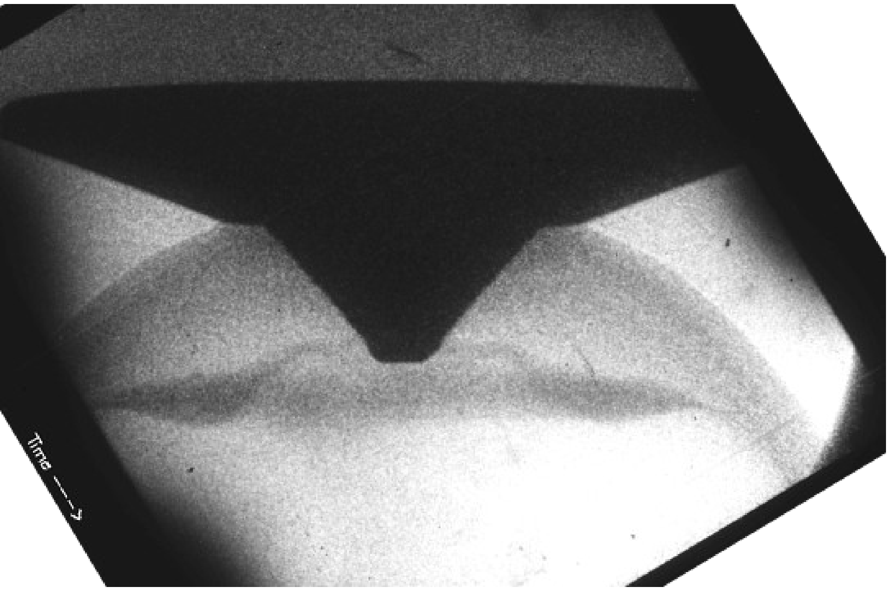


Merger happens at t=100ns.

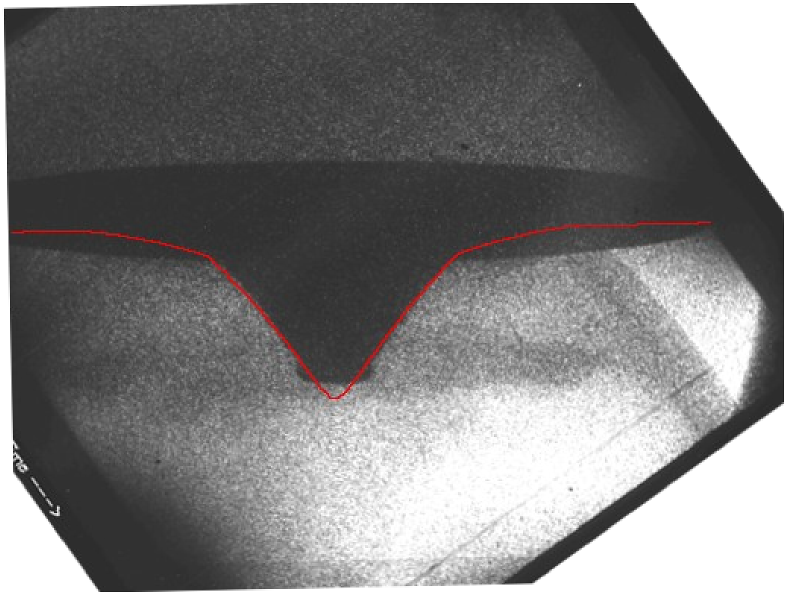


Mach stems merge

The present experimental campaign cannot yet answer our key questions definitively.



A 50->18.75 degree cone, at t=115ns. Calculated Mach stem size is of order 50--100um. Here it is ≲10--20um.



A 60->35 degree cone. Overlaid is the cone shape extracted from the preshot radiographs. Note the occlusion post-transition, owing to the cone's circular base.

We identified 3 issues:

1) We saw evidence of preheat in the cones, causing them to expand and correspondingly reduce the Mach stem sizes (left image, above).

2) Because of the extreme angle of the 60 to 35 degree cone after transition, line-of-sight occlusion due to target tilt basically eliminated any data after transition (right image, above).

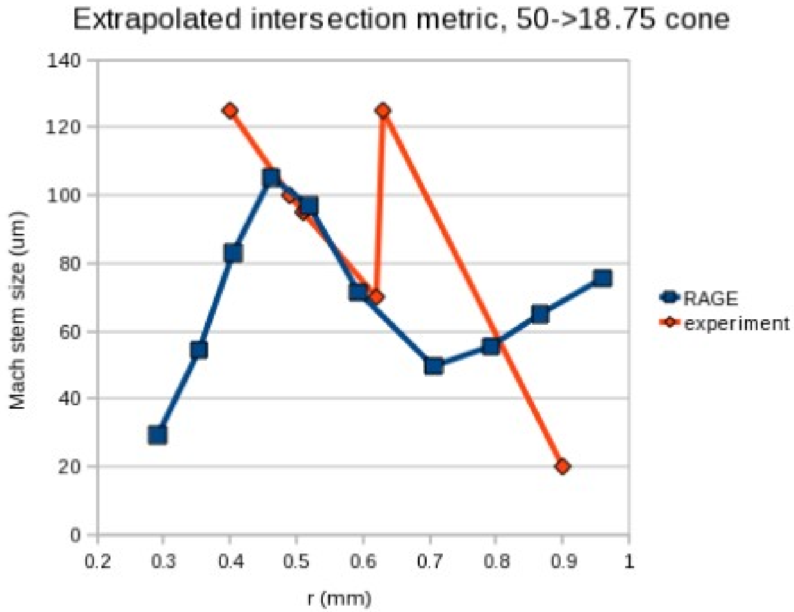
3) The 50 to 18.75 data (shown on next slide) show large scatter after transition.

September 2012 experiments will focus on obtaining additional time evolution data.

By going with a single design, we can maximize our sweep.

By using the straight-sided, 50 to 18.75 degree cone, we minimize line-of-sight occlusion which was present for the other design.

We also are updating our pusher design in the hopes of mitigating the unexpected preheat.



RAGE results show a smooth evolution through the transition point. Experimental data are very scattered.

(Note that the positive growth after transition is after the time when $\varphi > \varphi_{cr}$ again.)

Conclusion and Future work.

We are attempting to understand how Mach stems form and are destroyed in a warm dense plasma. On the one hand, this is continuing earlier efforts which found a critical angle differing from theory. On the other hand, it is laying the groundwork to evaluate whether Mach stems in astrophysical jets are a good candidate for certain emission features that do not well fit the usual interpretation.

Much more could be done in understanding Mach stem behavior in warm, dense plasmas.

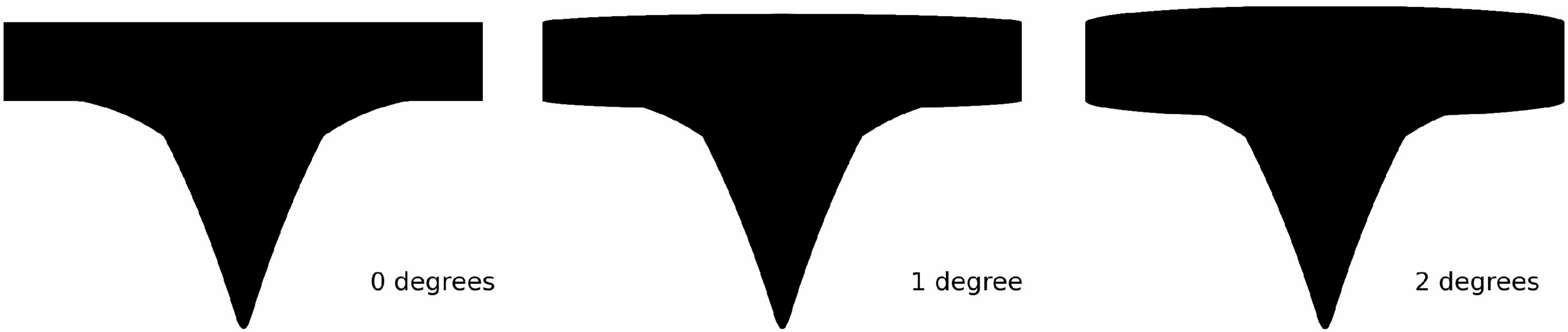
Much more still needs to be done in our present project in extrapolating to the astrophysical regime. One avenue is to either connect with the U. Rochester code AstroBEAR, or bring in the relevant astrophysical physics to RAGE.

Acknowledgments and my thanks.

Again, our team:

- **PI: Pat Hartigan (Rice), Experimental PI: John Foster (AWE), Paula Rosen (AWE), Bernie Wilde (LANL), Melissa Douglas (LANL), Reny Paguio (GA), Brent Blue (GA), Adam Frank (U. Rochester), David Martinez (LLNL), Dave Farley (LLNL), and myself.**

Thank you.


0 degrees
1 degree
2 degrees