Challenge:

Using lab experiments
to understand jet:

(1)launching/acceleration

(2) propagation/termination

Paul Bellan
Caltech

3 existing types of lab jet experiments

All exploit technology developed for another purpose

1. Caltech MHD driven jet experiments
   - Derived from spheromak technology
2. Imperial College and Z facility MHD wire-array experiments
   - Derived from Z-pinch technology
3. Laser hydro experiments (HEDP, not MHD)
   - Derived from inertial fusion experiments

Jets are launched by magnetic fields

Astrophysical models:

Differential rotation in accretion disc leading to generation of toroidal magnetic field

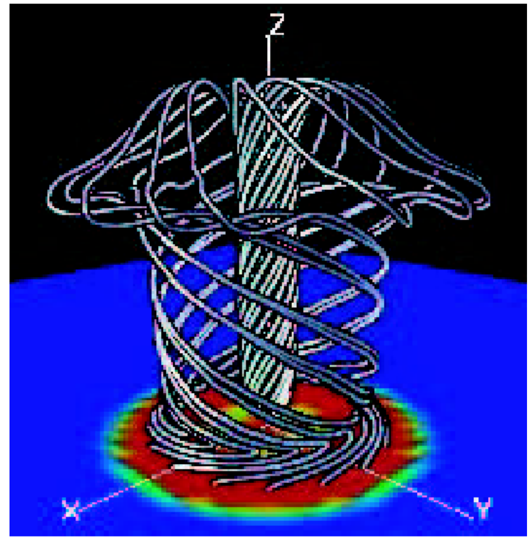
Collimation of the outflow by the magnetic field

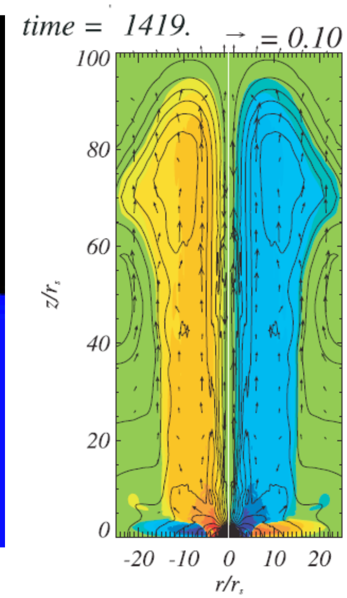
Some unanswered questions:

Why the jets are stable and not destroyed by MHD instabilities?

Models are steady-state, but observations show strong variability in both density and velocity.

Kato, 2004

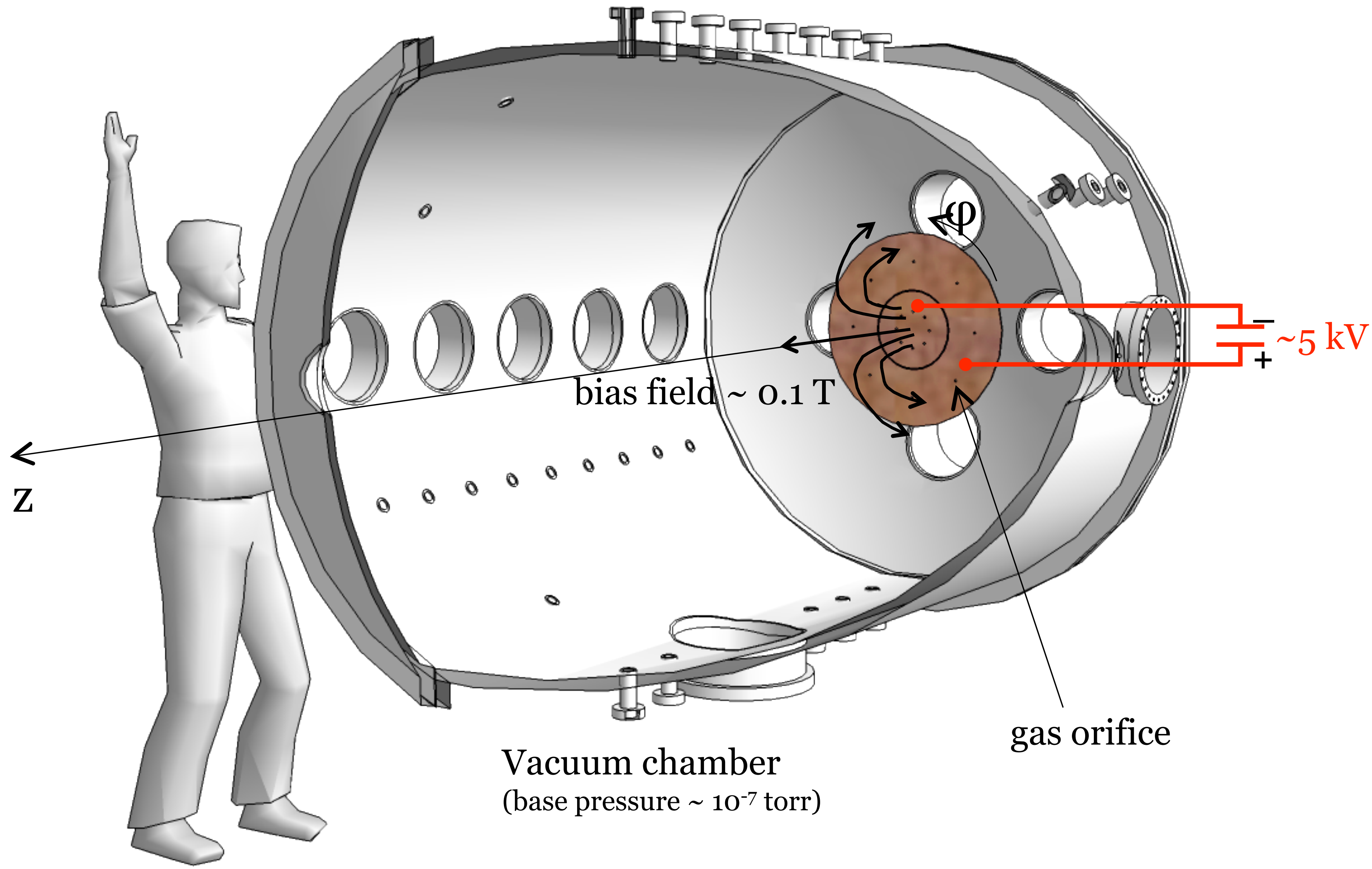




Experiment:

simulating part of the problem, the dynamics of an outflow driven by toroidal magnetic field

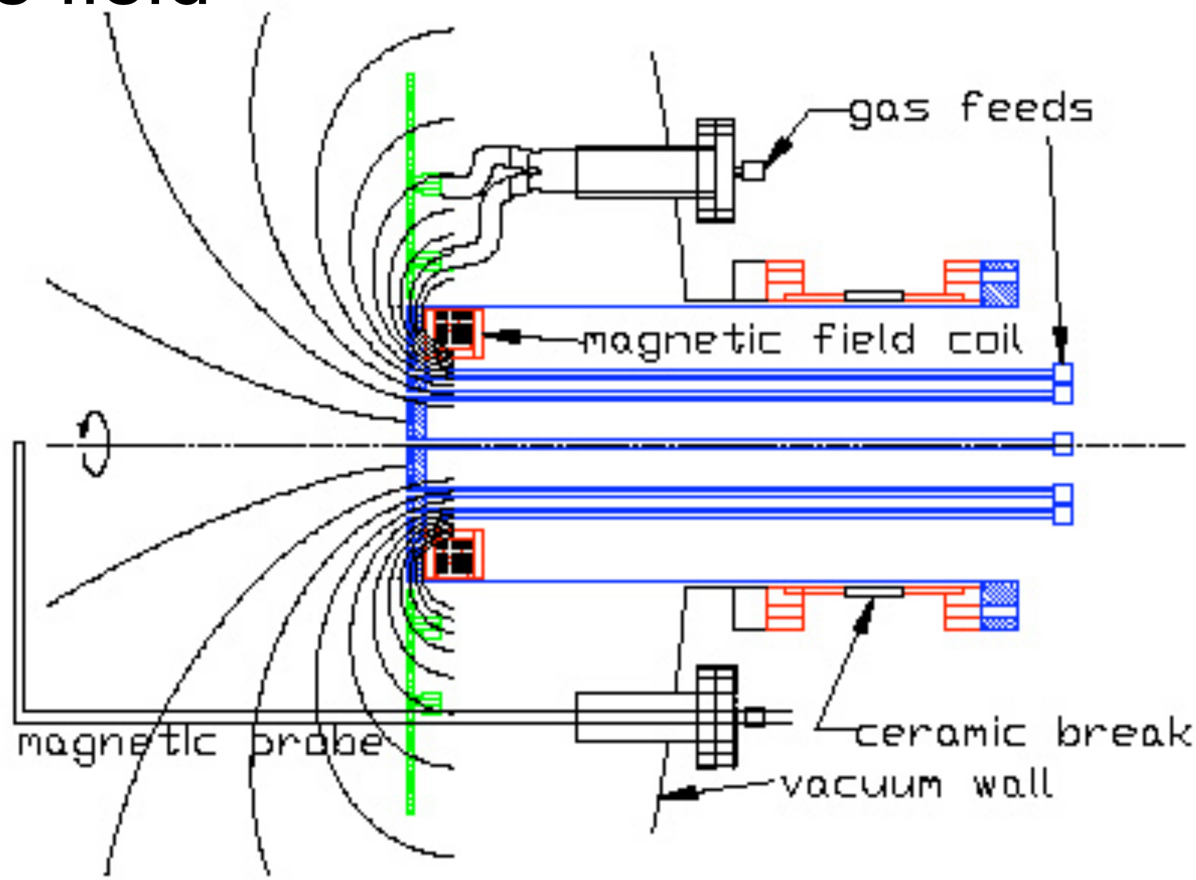
MHD jets: Spheromak technology



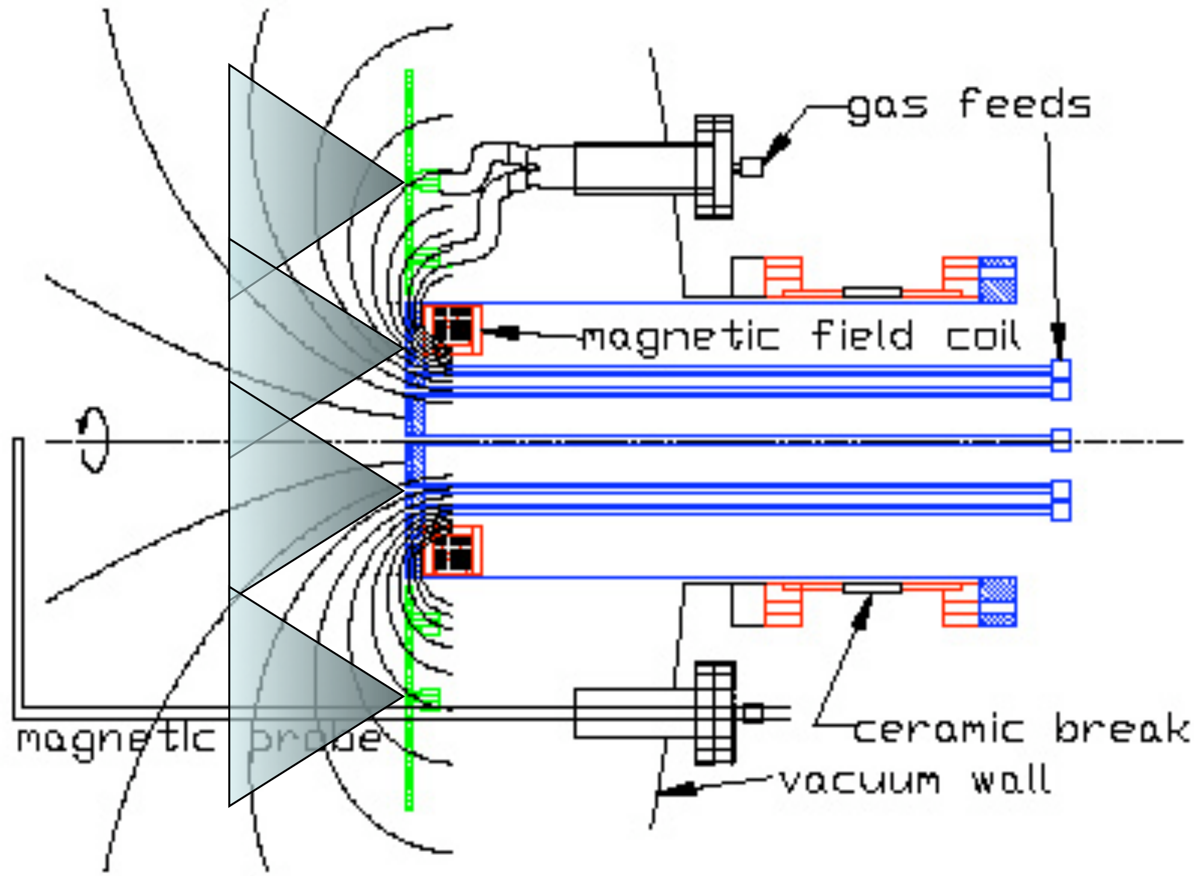
Sequence

Bias field

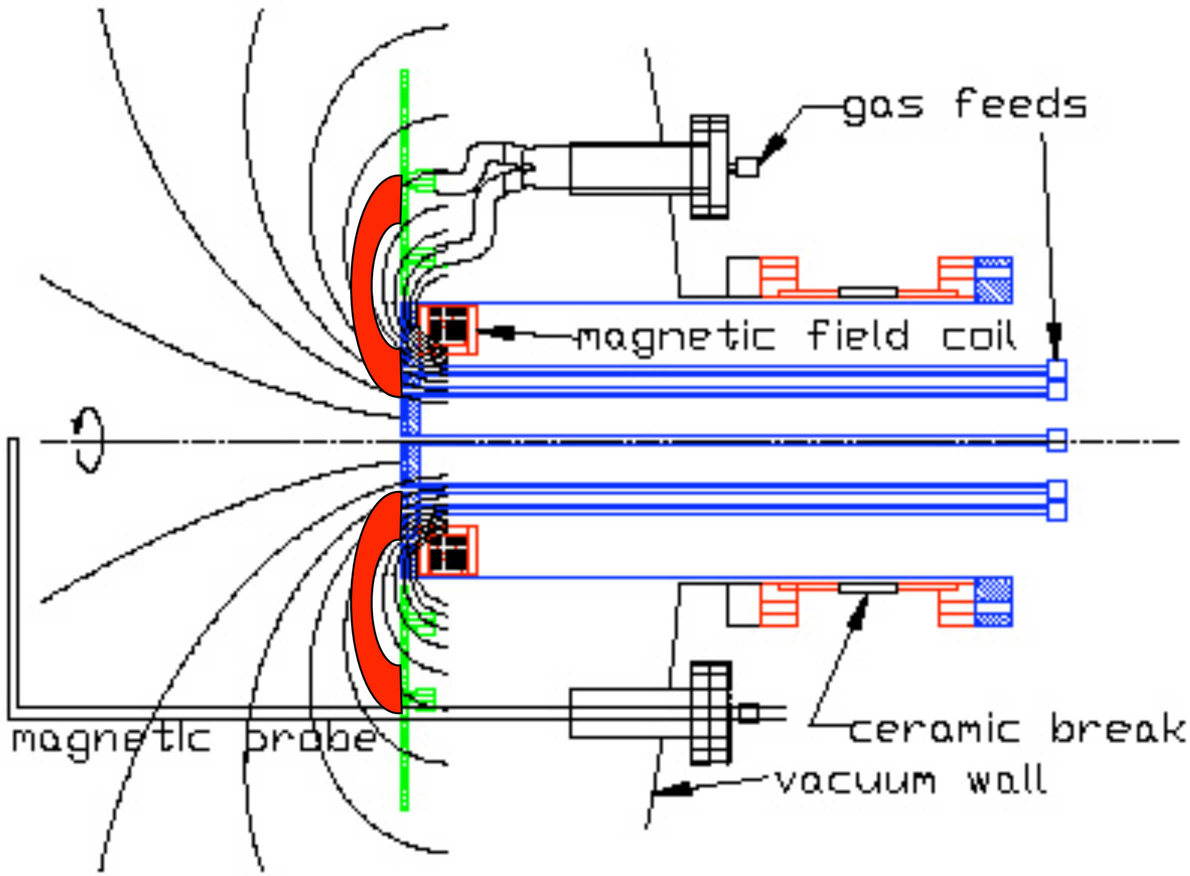
high vacuum

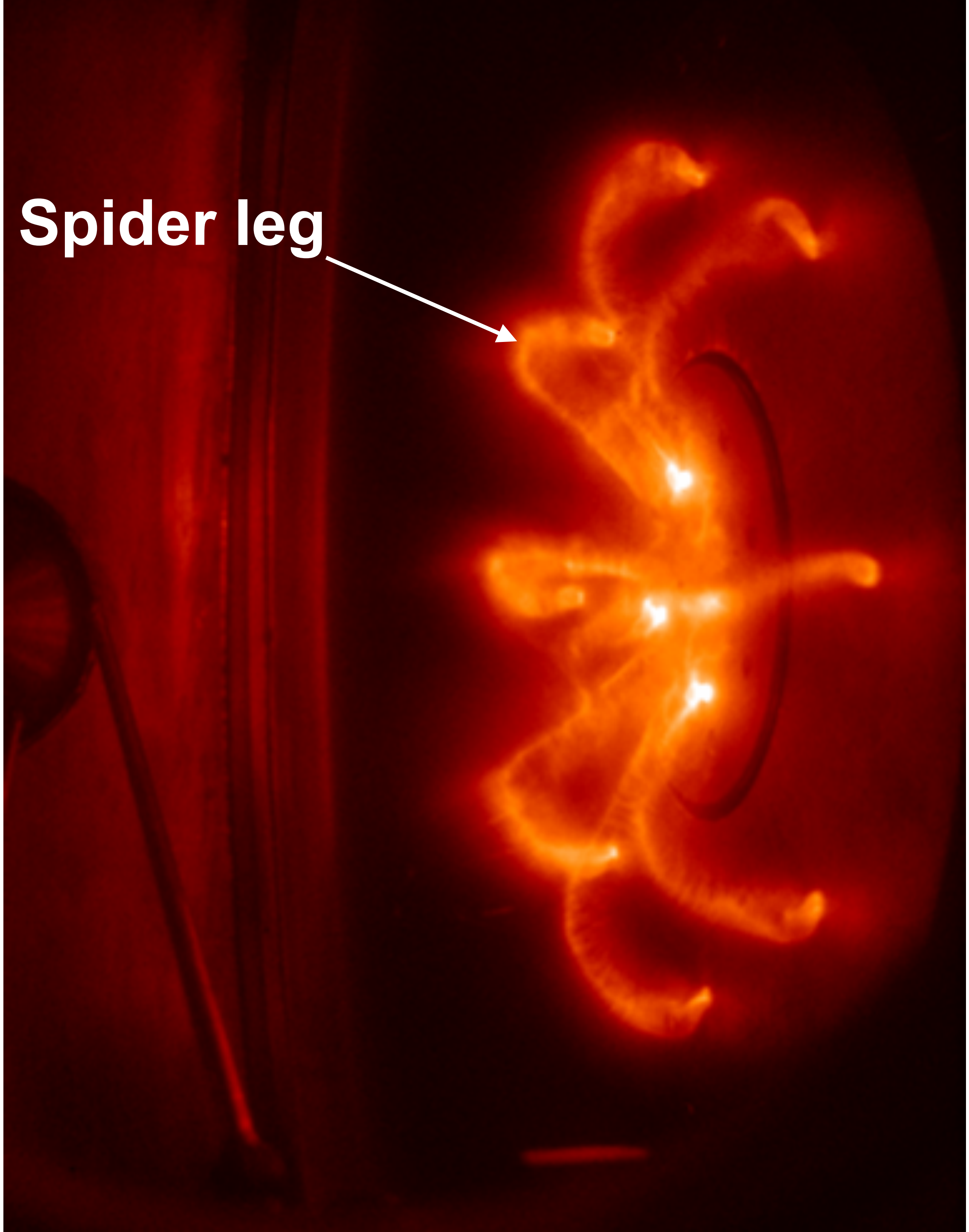


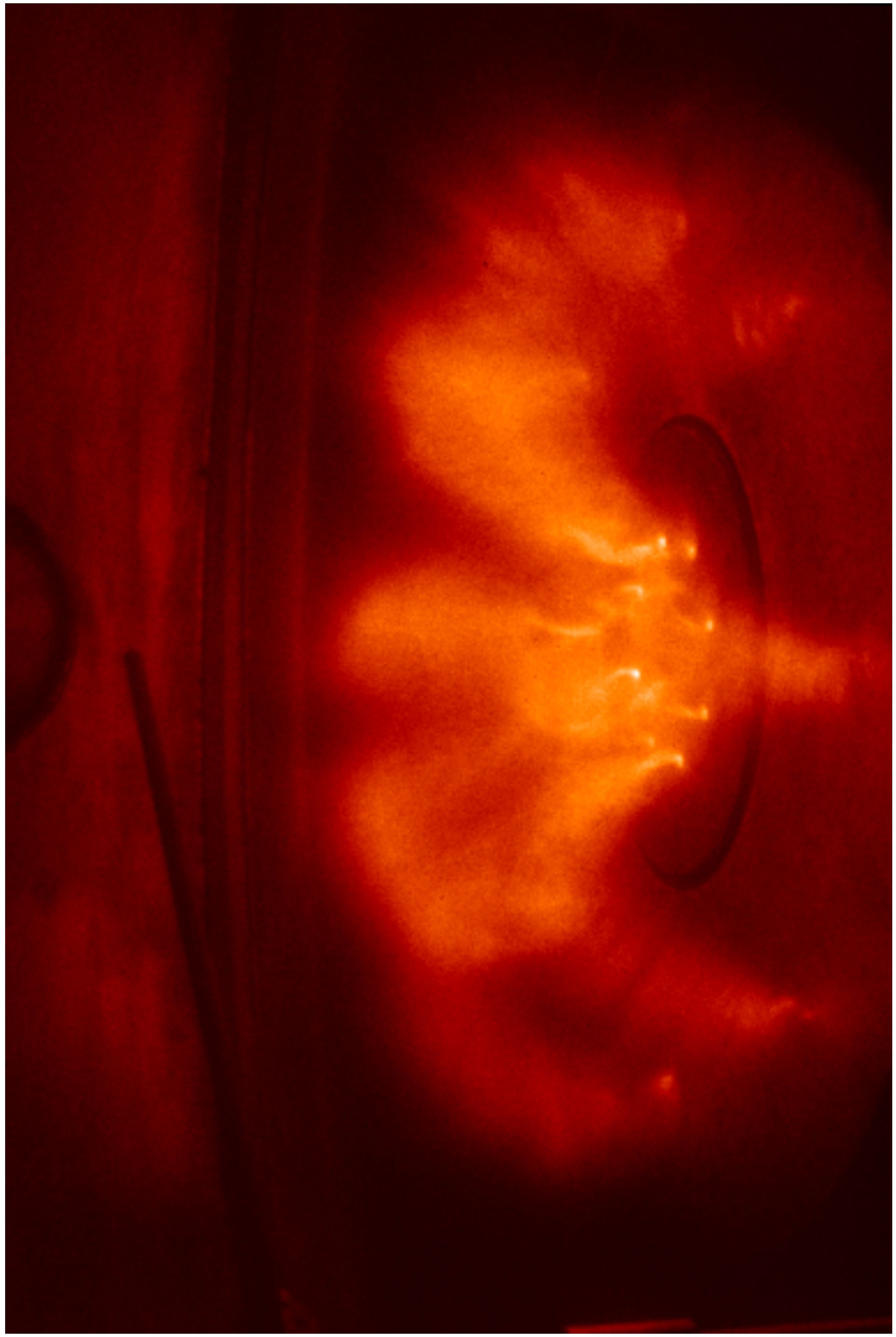
Puff in neutral gas

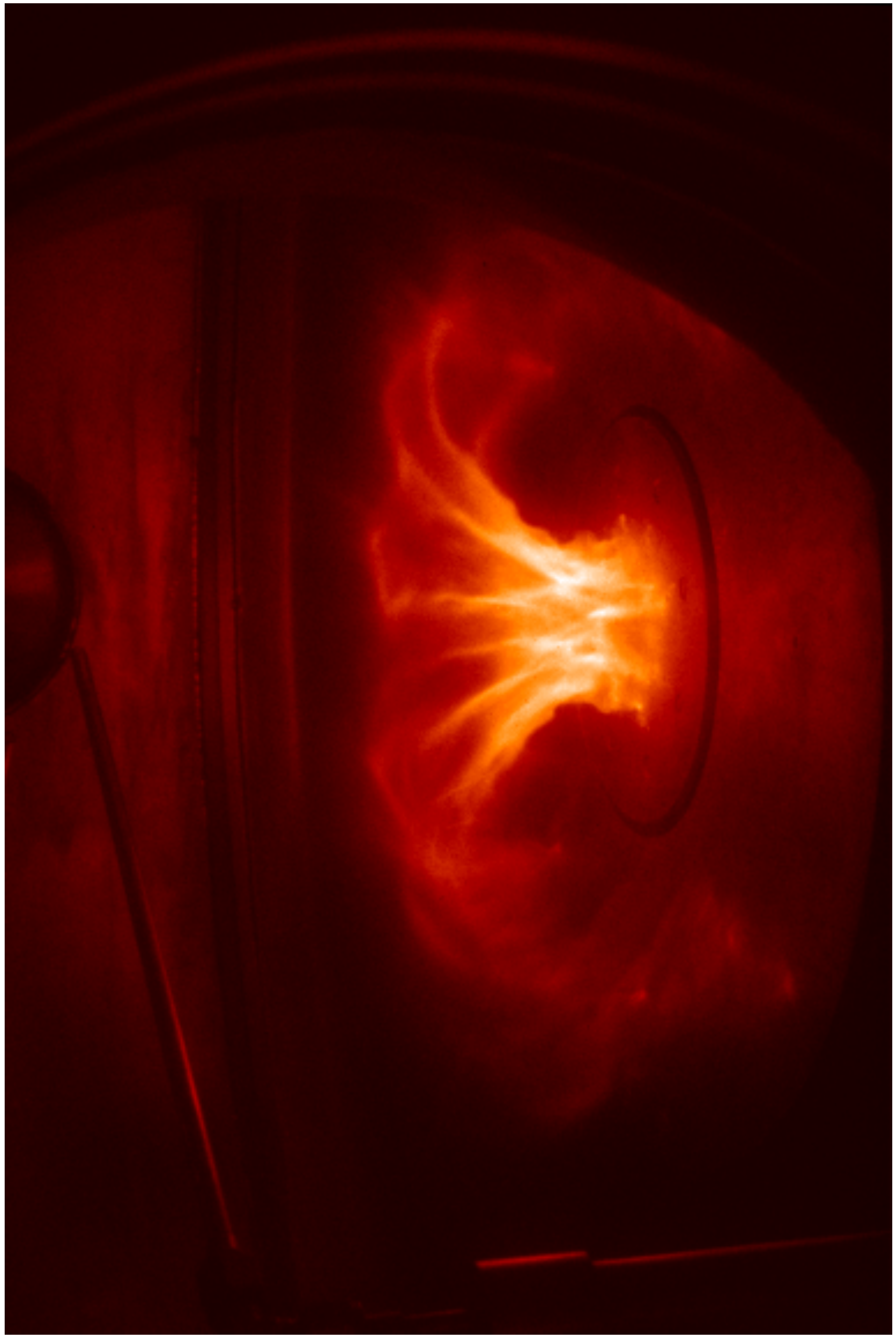


Breakdown, “spider leg formation”




Spider leg



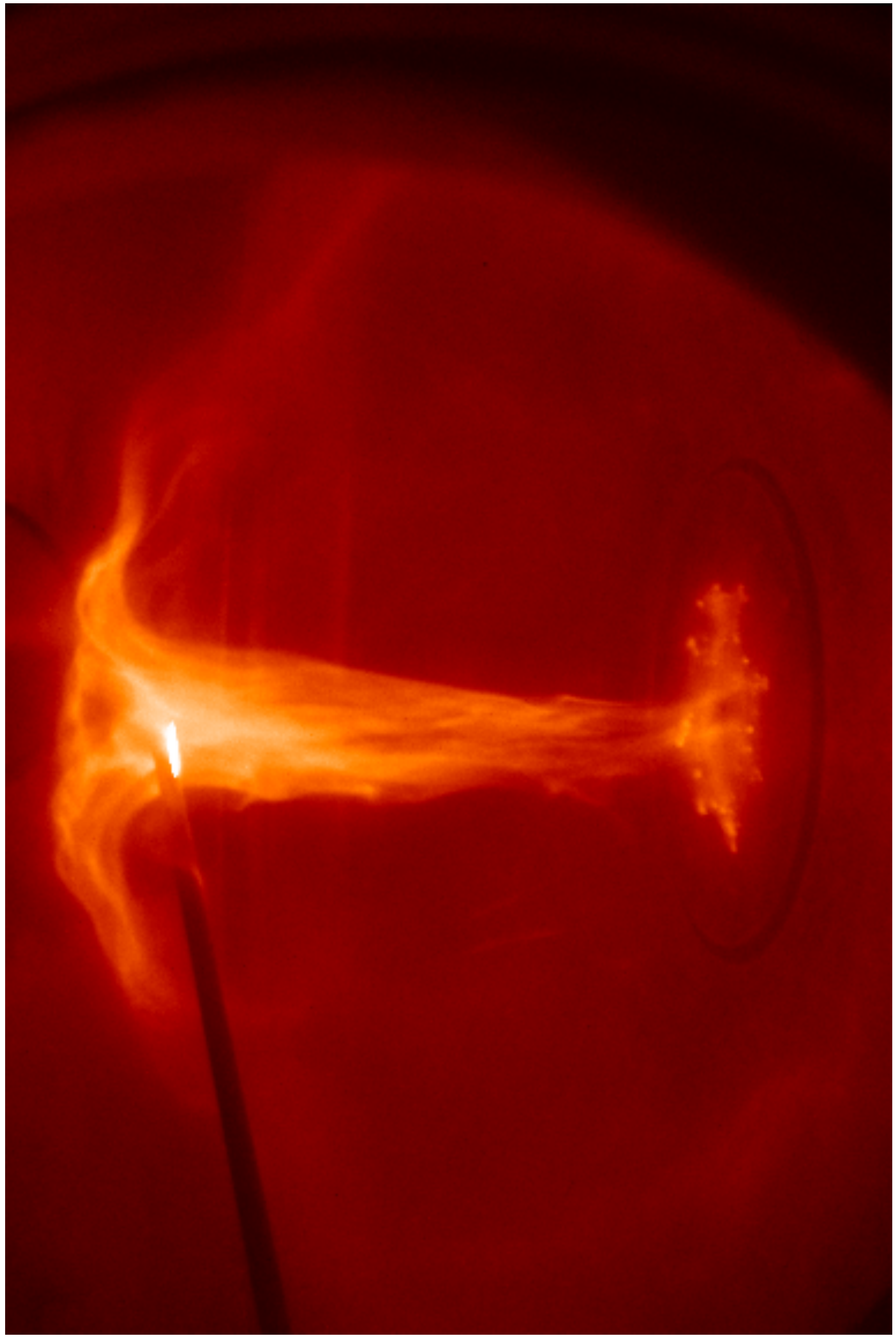


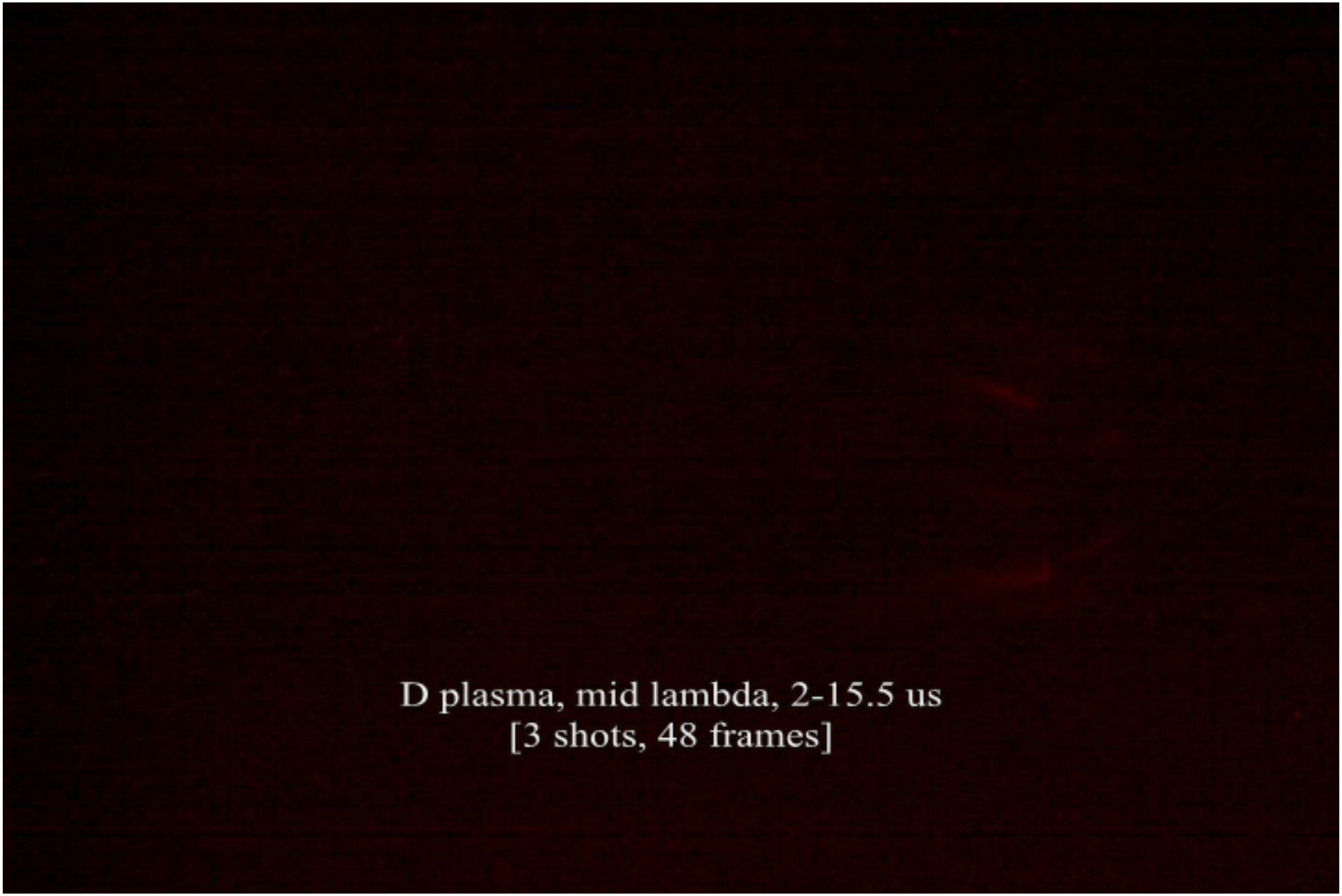
Nominal

I=150 kA

V=2 kV

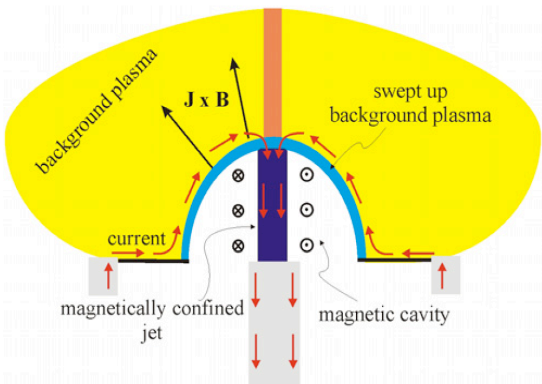
T=1-10 μs

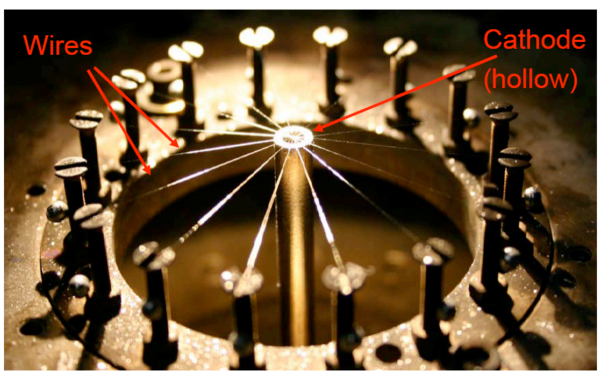



D plasma, mid lambda, 2-15.5 us
[3 shots, 48 frames]

MHD jets: Z pinch technology

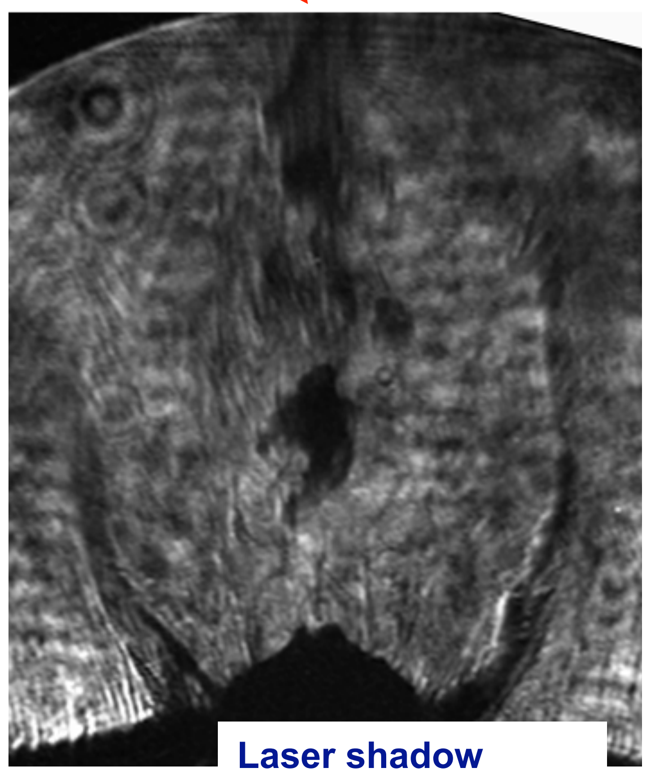
1.5MA, 250ns MAGPIE facility, Imperial College

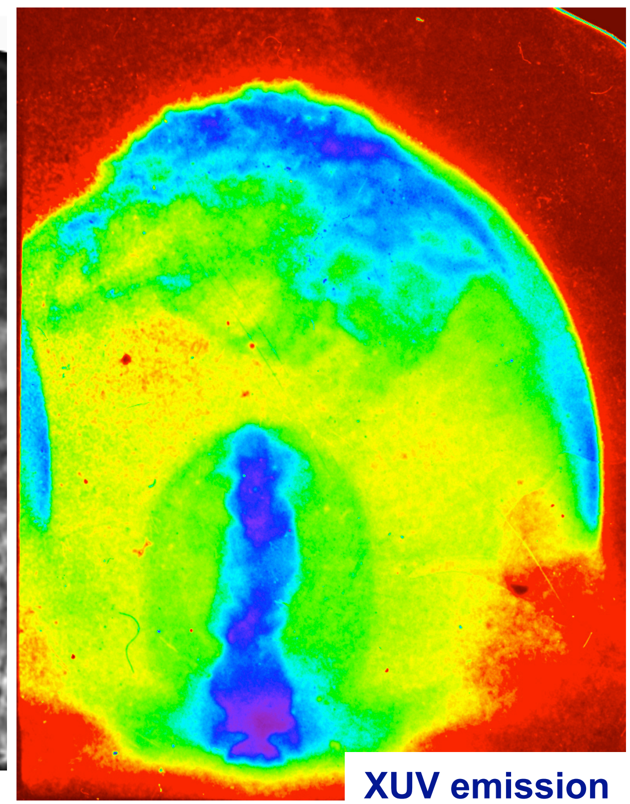




Instabilities produce "clumps" in the jet, but do not destroy collimation

Formation of episodic jets





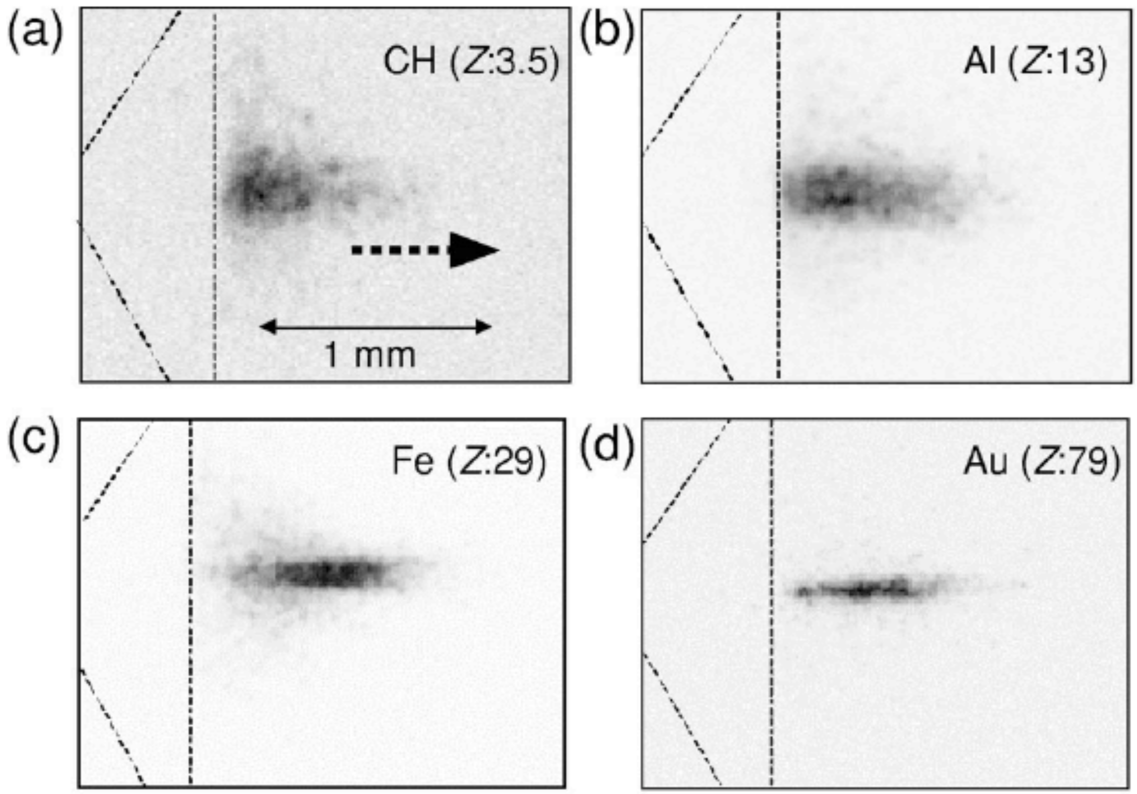
$n_i \sim 10^{19}$ cm^{-3}, T ~ 200 eV

Re > 10^4 , $\beta \sim 1$, $Re_M \sim 50$-300

Lebedev et al, MNRAS (2005), Ciardi et al., ApJL (2009)

Laser HEDP technology

Radiatively cooled jets:
Gekko-12 laser (Shigemori et al., 2000)



High Mach number (~20)
No dynamically significant magnetic field

Jet launching/acceleration: basic demonstration challenge

- Launching and acceleration is observed,
  - Only modest comparison between models and observations so far
  - Successes:
    - Ciardi MHD simulations of Imperial College jets,
    - Kumar/Bellan verification of predicted jet velocity dependence on magnetic force

- Theory proposes that jet extends through various regimes (sub-Alfvenic, super-Alfvenic, Poynting, hydro)

- Typical lab experiment does not yet have enough resolution to distinguish such regimes

Jet launching/acceleration: diagnostic challenge

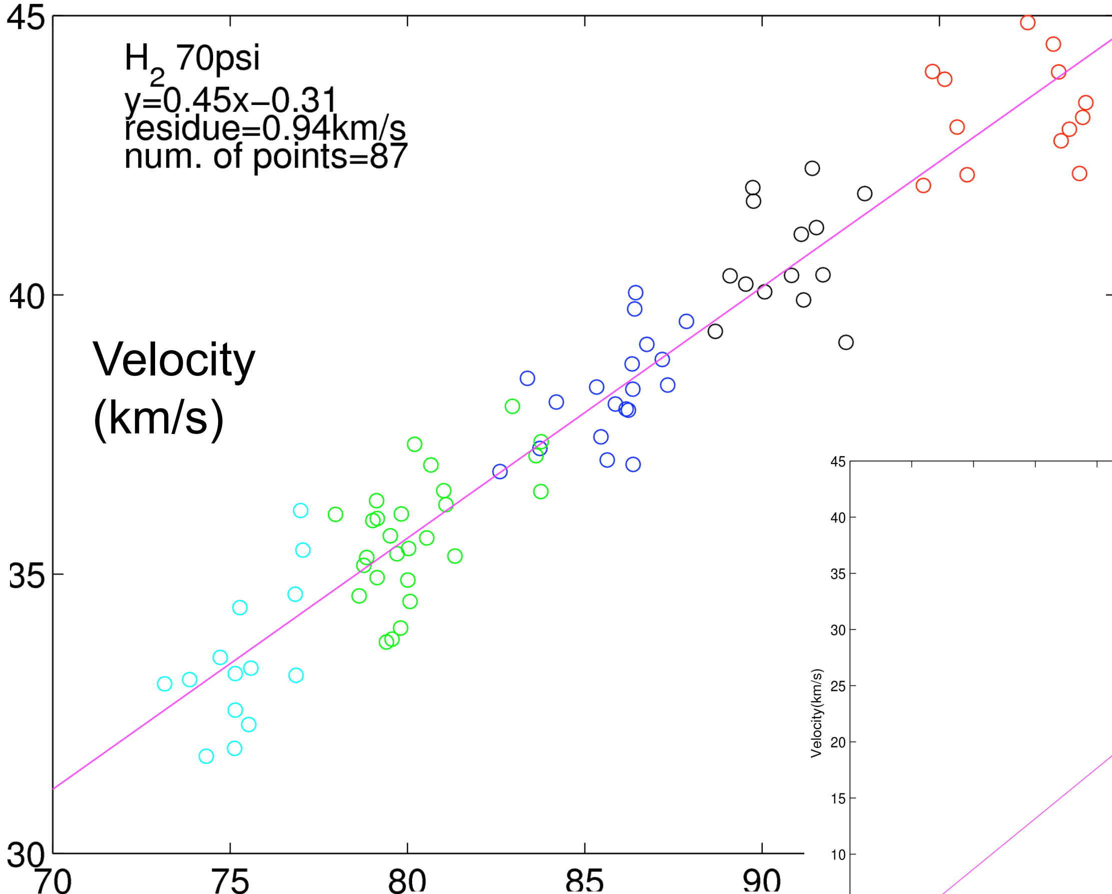
- Diagnostics
  - In principle, can measure everything in lab expt
  - In practice, many measurements are difficult, expensive
- Ideally would like to measure all parameters 3D spatially resolved and temporally resolved
- To date:
  - Caltech expt has 60 channels of in situ magnetic measurement, 12 spectroscopy channels for density (Stark), velocity (Doppler), high speed movies
  - Imperial has one channel of magnetic measurement, ? for density, X-ray radiography imaging
  - Laser HEDP experiments have mainly radiography imaging
- No experiment yet has COMPLETE 3D spatial and temporal resolution measurements
- Need improved diagnostics and new diagnostic technologies

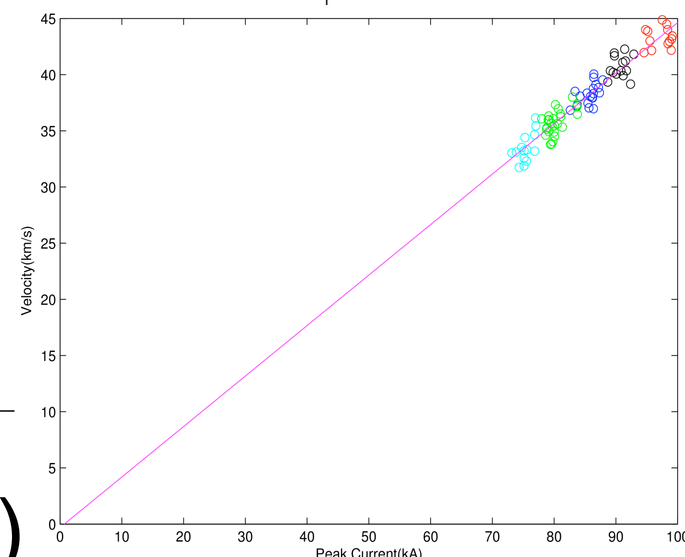
Jet launching/acceleration: interpretation/scaling challenge

- Determine how the Lorentz force converts electrical power into directed flow
- Determine where acceleration takes place , detailed mechanism(s)
- Quantitative scaling, dependence on voltage, current, field topology, mass source morphology
- Regimes: low mass density with high velocity, high mass density with low velocity, collimation

hydrogen plasma velocity v. gun current

Velocity (km/s)





Peak current (kA)

Jet launching/acceleration: episodic/intermittent challenge

- Why are some jets intermittant, bursty?
- Is this due to intermittent source?
- Imperial College experiments have observed episodic jets
- Need to understand what causes this

Jet launching/acceleration: angular momentum challenge

- Observations/theory suggest launching/acceleration results from *angular momentum* of rotating accretion disk producing magnetic forces that launch jets

- MHD Lab experiments produce similar magnetic forces and launch jets

- Rotating jets have been launched at Imperial College by shaping of wire source

- Need to make more of a connection between lab experiments and angular momentum mechanism

Once jet has been launched/accelerated,
the next questions are

1. why is jet so stable,
2. how does jet interact with ambient surroundings
3. how is the jet terminated

Lab experiments can address these issues

Jet propagation/termination: collimation challenge

- Observed jets are highly collimated: why?
  - Caltech, Imperial College experiments show similar collimation
  - Axial flux compression model involving axially non-uniform jet velocity has been proposed to explain this (Caltech)
    - Preliminary supporting evidence observed
    - Need to explore more, see if relevant

Jet propagation/termination: stability challenge

- Observed jets are stable: why?
  - would expect kink, Kelvin-Helmoltz, or other instability to destroy structure with such large length/radius ratio
- Caltech experiment shows clear kinking at critical length, why not same in observed jets?
- What can be done to stabilize Caltech jet?
  - Finding out may explain why observed jets are so stable

Jet propagation/termination: ambient medium

- Observed jets may have cocoon of ambient matter
  - Imperial College jets have similar cocoon
  - Shock interface observed, can be investigated
- Side wind of ambient matter observed to deflect actual jet
  - Similar deflection observed in Imperial College experiments
- Need to have more controlled interactions with cocoon
- Cocoon may stabilize against kink, need to investigate

Jet propagation/termination: internal shocks, knots

- Observed jets often show knots, internal shocks
  - believed associated with episodic launching
  - Shock: fast jet catches up with earlier slow jet

- Can this be duplicated and studied in lab?
  - Some evidence in Imperial College episodic jet experiments

Jet propagation/termination: super-, sub sonic/Alfvenic

- Models predict critical behavior when jet transitions from super- to sub-sonic, super- to sub-Alfvenic

- Can these transitions and associated critical behavior be produced and resolved in lab experiments?

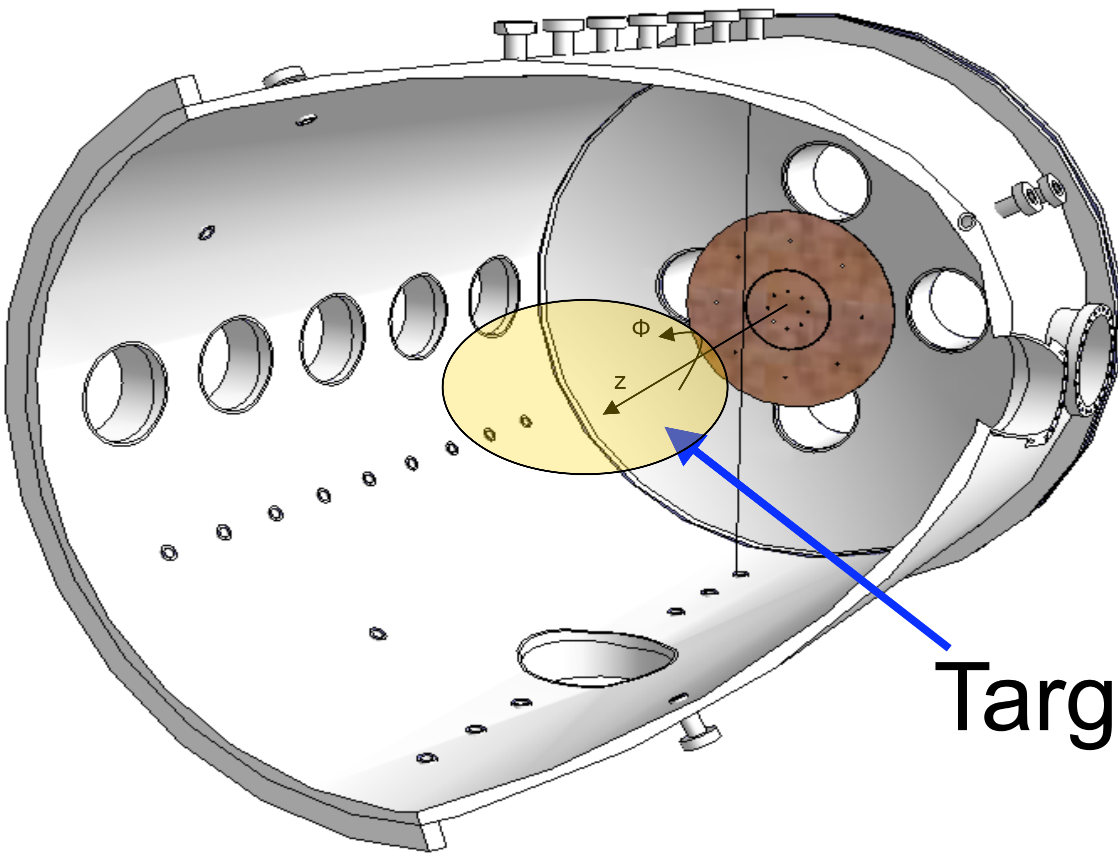
Jet propagation/termination: extreme parameters

- Lab experiments to date have been non-relativistic
- Are relativistic experiments feasible?
  - Perhaps mildly relativistic would be first step
- Rather than increase force, reduce mass density
- Make faster lab jets
  - Existing lab jet velocity < 100 km/s (i.e., $\sim 10^{-3}$ c)
    - Can lab jet velocity be increased by two or three orders of magnitude?
    - Need new technologies

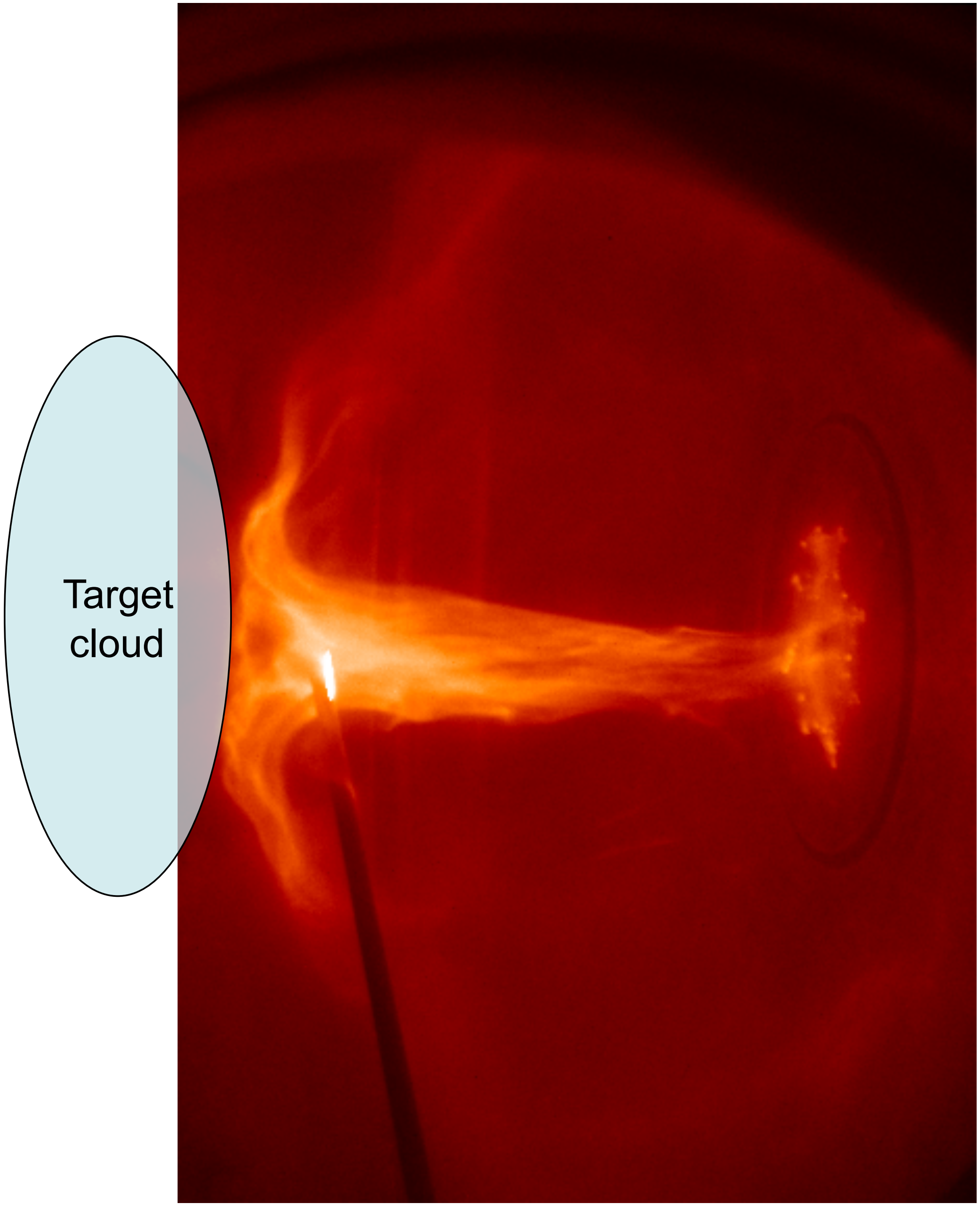
Jet propagation/termination: impacting target cloud, plume

- Observed jets often impact molecular cloud, resulting in broad plume, termination of jet
- What happens to magnetic field, helicity, velocity in this impact
- Caltech jet arranged to impact target cloud
  - Observe pile-up, concentration of jet flux
    - Amplification of jet internal magnetic field observed when it hits heavy target
    - Shocks observed when heavy jet hits light target

Magnetic flux compression when jet impacts target cloud



Target cloud


Target
cloud

Hydrogen jet impacting Argon target cloud

Hydrogen jet, No target cloud

Magnetic flux compression

Plots of |B| v. time at sequence of axial distances along jet