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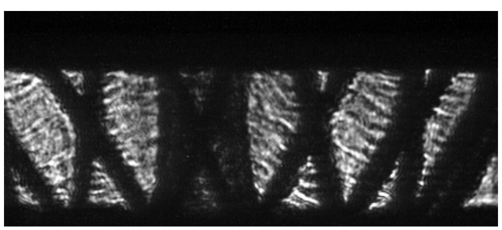
Supersonic radiatively cooled rotating flows and jets produced by wire array z-pinches



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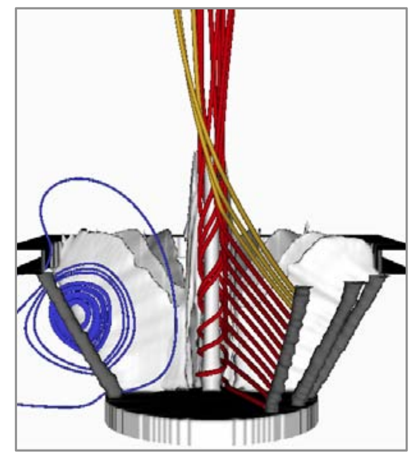

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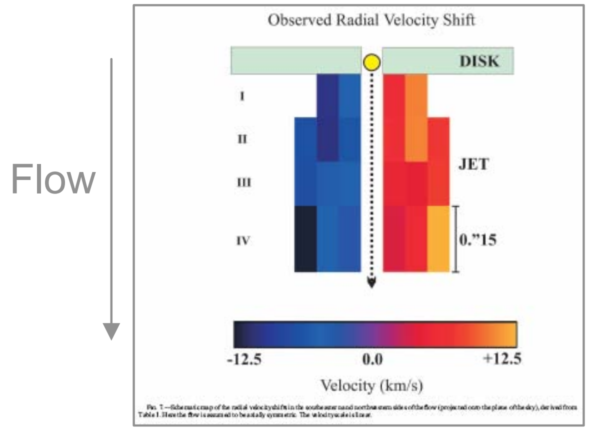
Motivation for modeling rotating jets

- Rotation is critical to the formation dynamics of stars
  - Extraction of angular momentum from accretion disk required to allow inflow of material
  - Observations indicate jets from young stars carry angular momentum

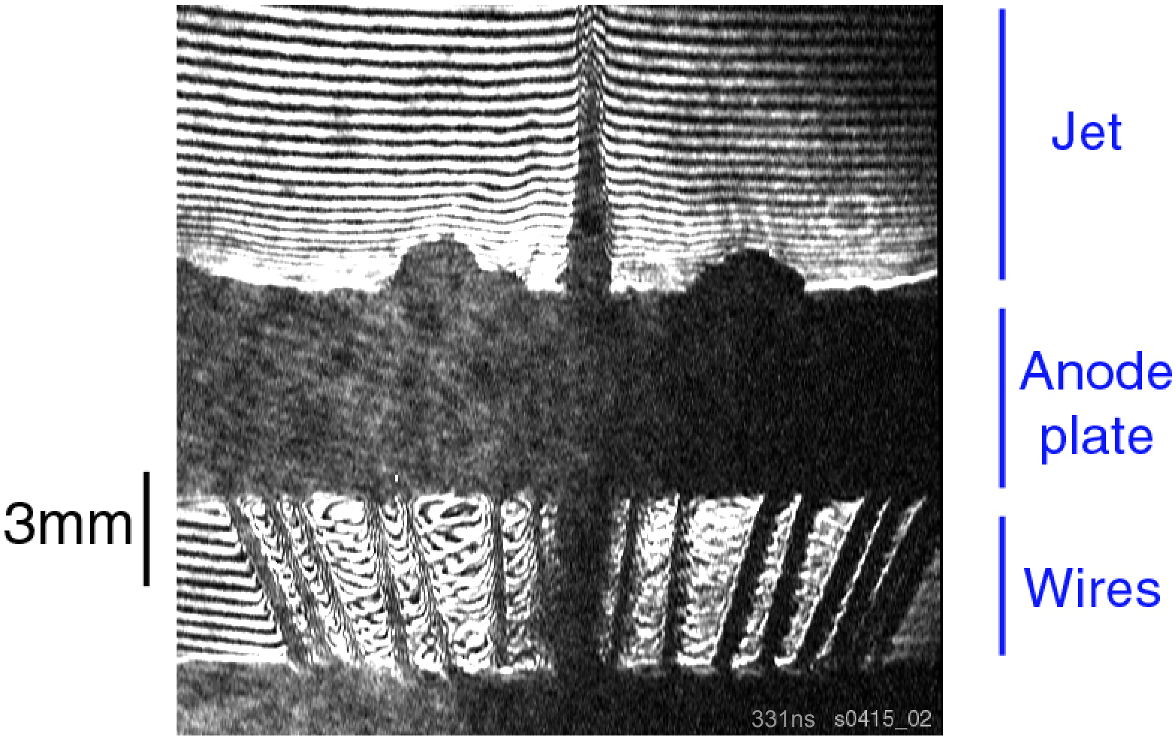
- Laboratory modeling of such astrophysical objects
  - can provide insight into the astrophysical system
  - can be used to benchmark codes

- Rotation also proposed as stabilizing mechanism for wire array Z-pinches

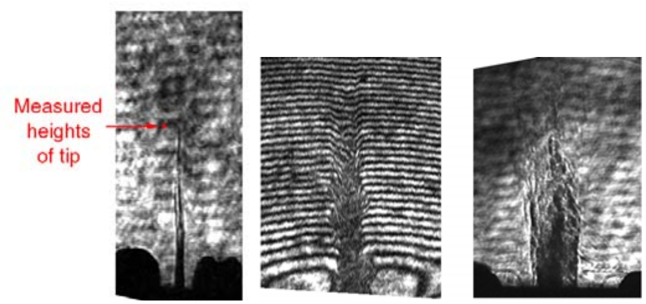


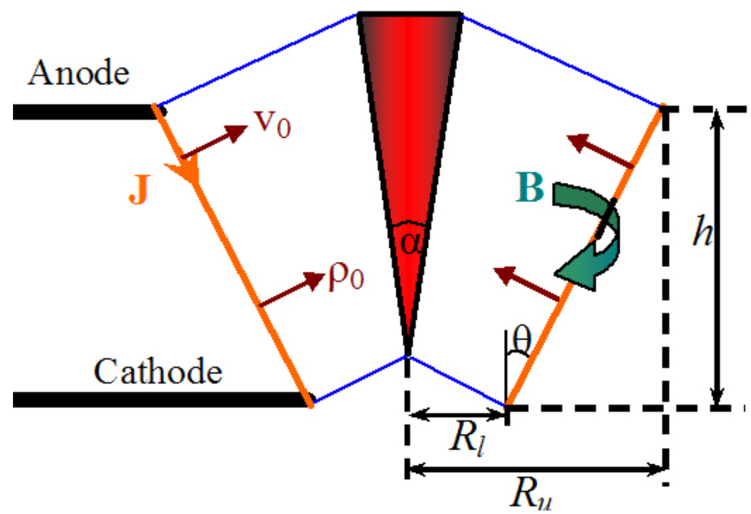
Bacciotti et al., ApJ 576,222 (2002)
Schematic of rotation velocities inferred from Doppler shift measurements near the base of the DG Tau jet

Jet production by conical wire array z-pinches



Effect of cooling: High Z → → Low Z





- Passing a large current (1MA, 240ns) through fine wires causes a steady flow of plasma from the wires, accelerated by the jxB force towards the array axis, and upwards (perpendicular to the wires).
- A standing shock forms on axis, which thermalizes the kinetic energy associated with the radial motion
- For high Z elements, radiative cooling ensures a highly supersonic collimated flow of plasma

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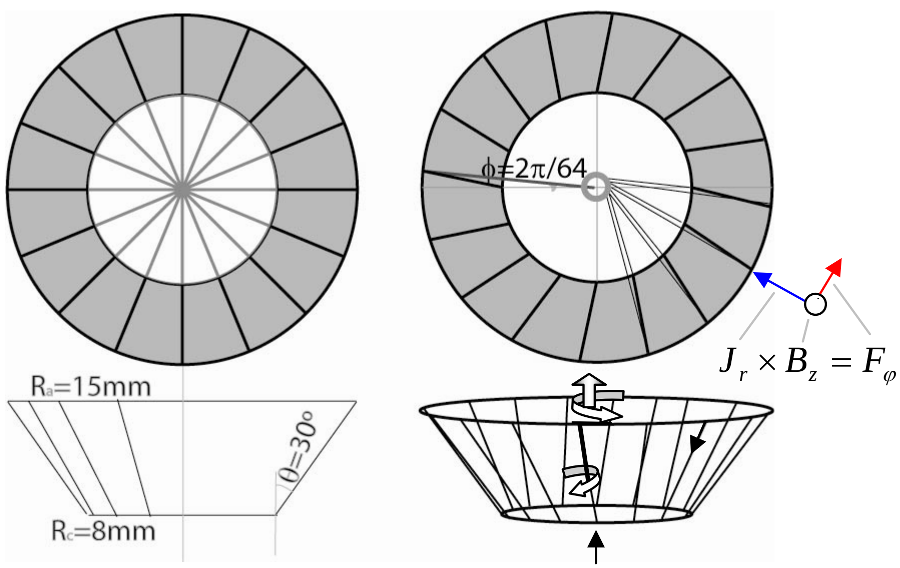
Introducing angular momentum into the system

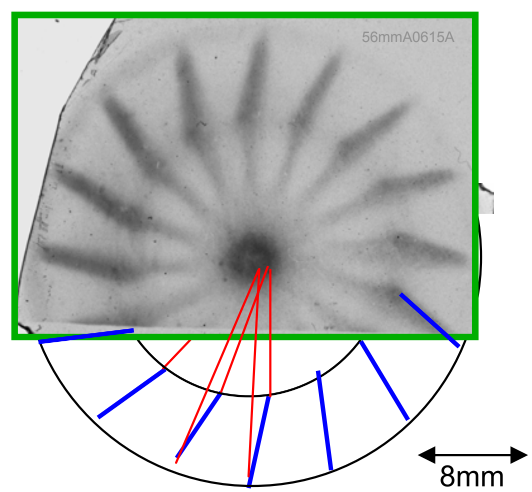
- Twisting the conical wire array introduces an axial magnetic field (B_z)
- Divergence of field leads to additional radial magnetic field

Experimental setup



Experimental data

XUV emission end-on to the array (hν>30eV)



Hollow conical shock

- Lorentz force now has additional azimuthal components
- Angular momentum should then be conserved in the:
  - precursor plasma streams
  - standing conical shock on the array axis
  - supersonic jet that is produced

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Conservation of angular momentum into the standing shock

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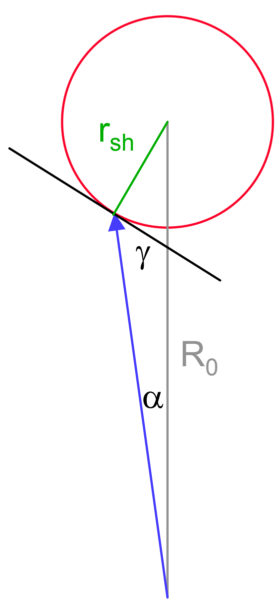
- If the converging flows collide on axis, we expect conservation of angular momentum.
- Can use force balance arguments to determine the diameter of the rotating column.

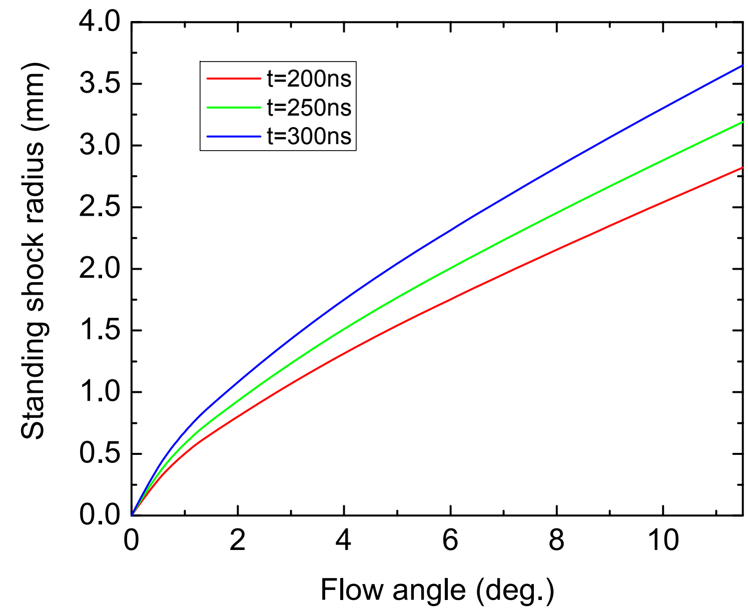


Standing shock radius is determined by the balance between the centrifugal force of the rotating shock and the kinetic pressure of the converging plasma acting on the surface of the shock:

$$m\frac{V_{rot}^2}{r_{sh}} = \frac{dm}{dt}V_{abl}\cos\beta\sin\gamma$$

Also conservation of the accumulated angular momentum (m is mass in the rotating shock):

$$mR_0V_{abl}\cos\beta\sin\alpha = mV_{rot}r_{sh}$$



Expect the diameter of the conical shock to be approximately proportional to the flow angle (and hence also to the angle of twist between the two electrodes)

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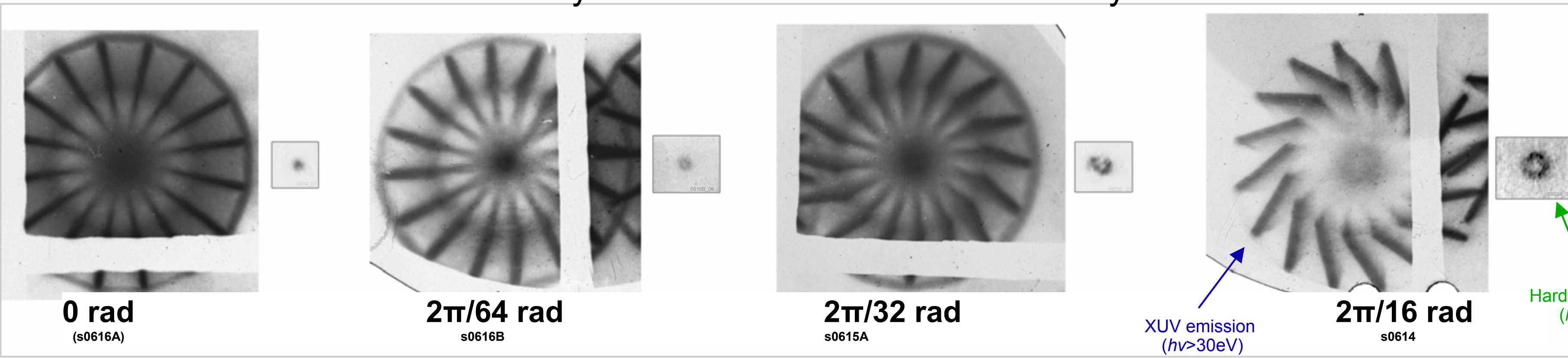
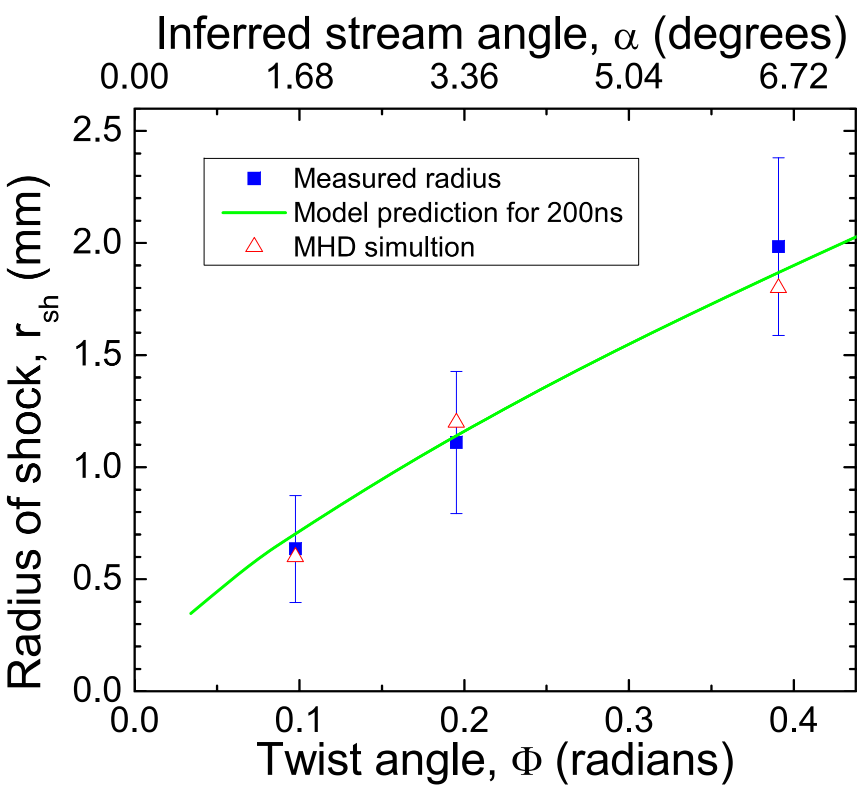
Conical shock becomes larger and more hollow as angular momentum of flows increases

XUV and soft x-ray emission from end-on to the array at ~210ns



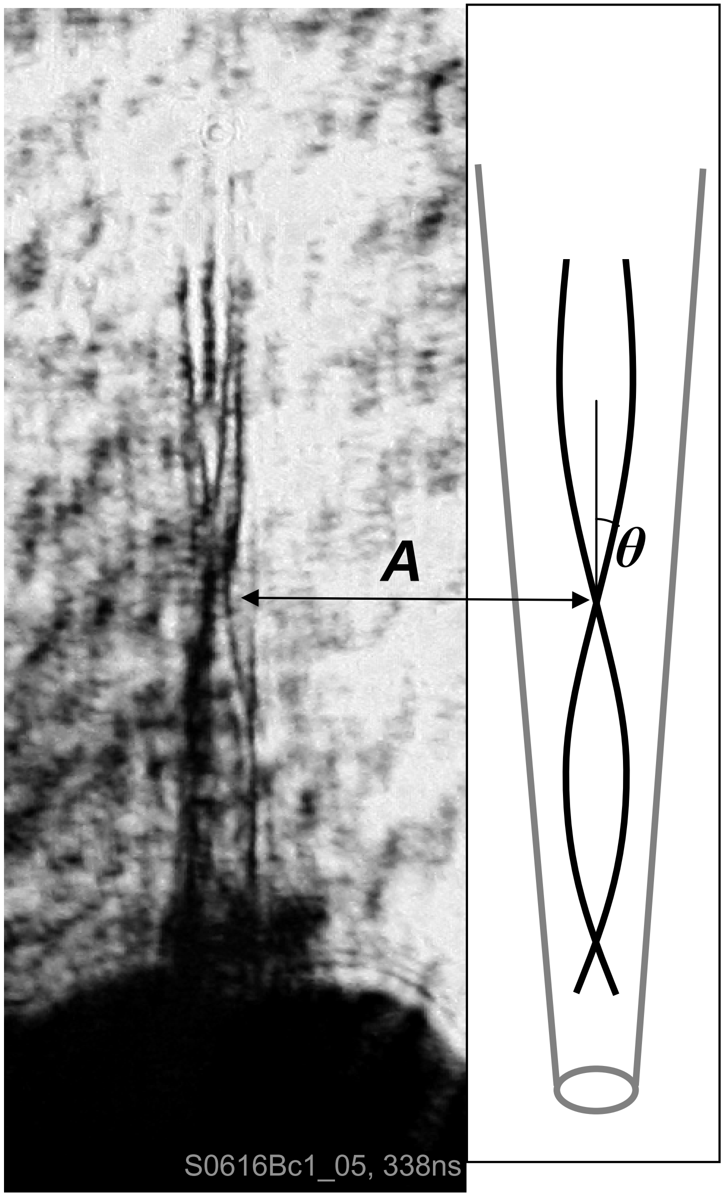


Experimental data indicates hollow conical shock

Comparison to model (normalized to one data point) shows good agreement

Inferred azimuthal velocity indicates that rotation is highly supersonic

Filaments show rotation within the jet



- Filamentary structure is present in the jet
- Filaments are likely to be tracking rotation of the jet as it propagates
  - From jet velocity $v_j \approx$ 200km/s determine an azimuthal velocity $v_{az} \approx$ 35km/s
- Ratio of azimuthal to axial velocity is

  $v_{az}/v_z = sin(10°) = 17\%$
- Angular momentum does not destroy the jet

Sufficiently large rate of rotation destroys the jet

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- Again, use twist angle of the array to control the magnitude of angular momentum within the system, and ultimately the jet:

Laser shadowgraphy imaging of the jet:

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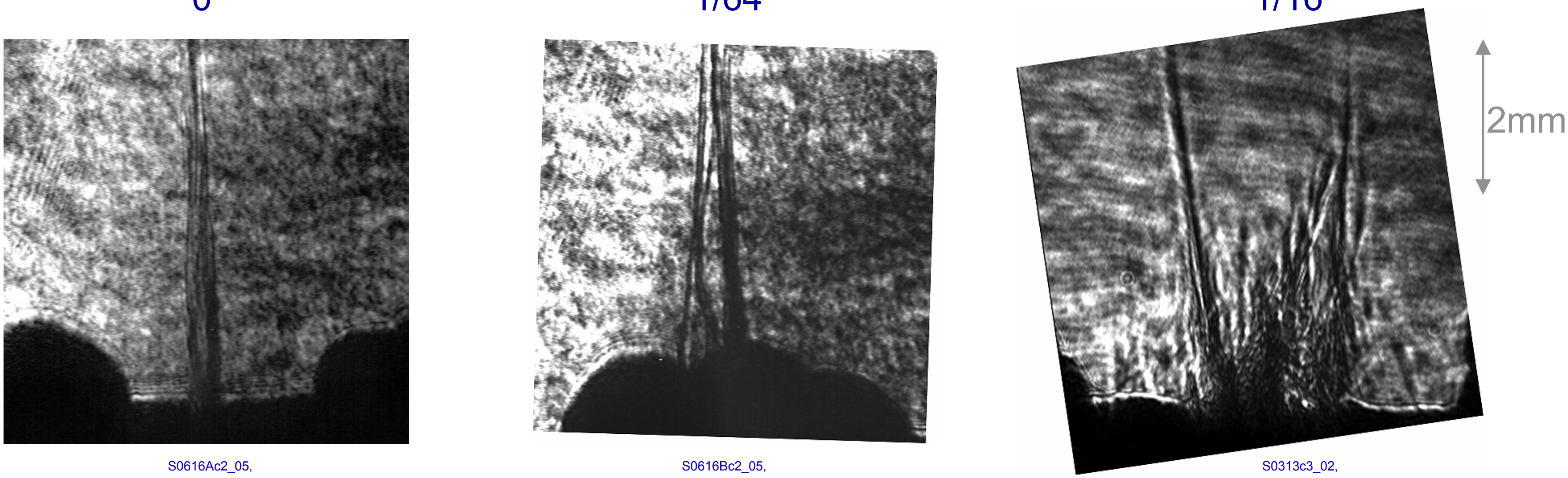

S0616Ac2_05, 316ns | S0616Bc2_05, 338ns | S0313c3_02, 337ns

- Reach a condition where angular momentum is sufficient to destroy the jet over a distance of a few jet radii

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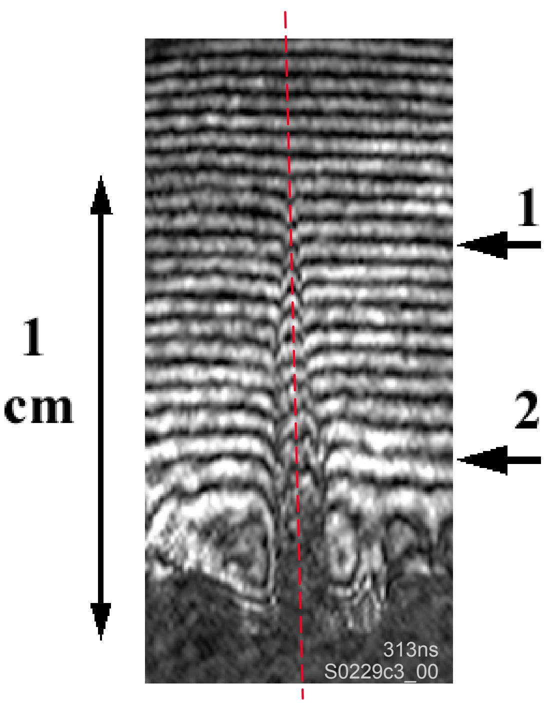
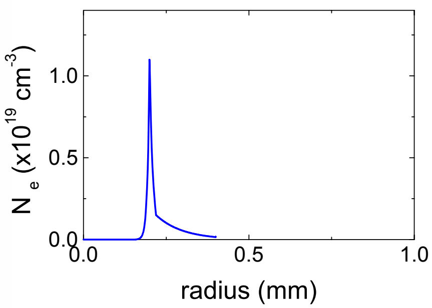
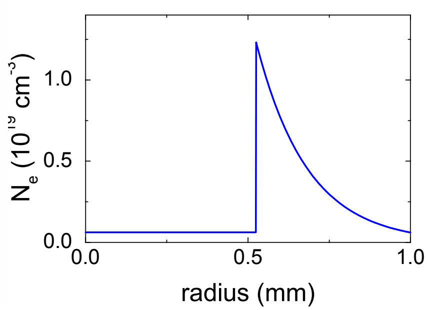
Mass distribution with in the rotating jet

- As for the conical shock, we expect the presence of angular momentum to produce a hollow density profile

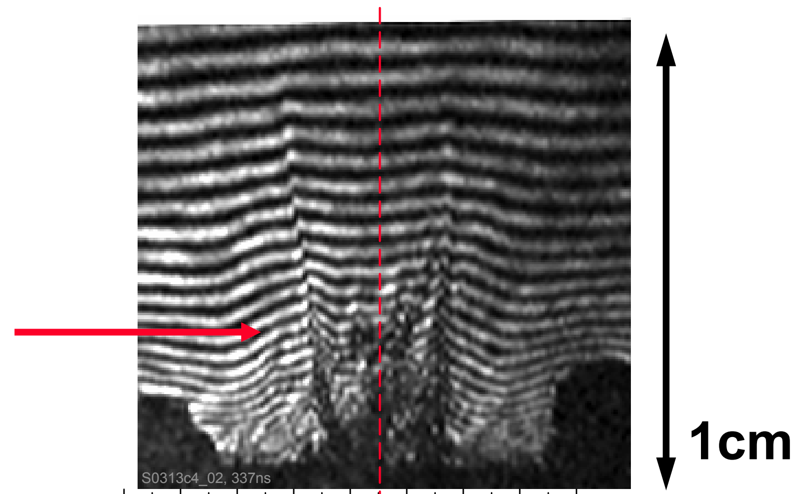
Small rotation rate

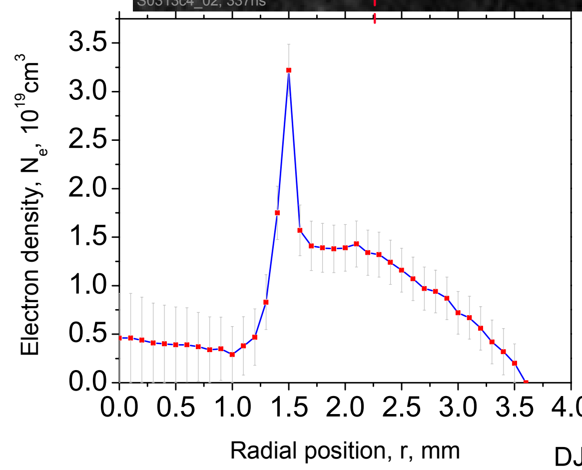




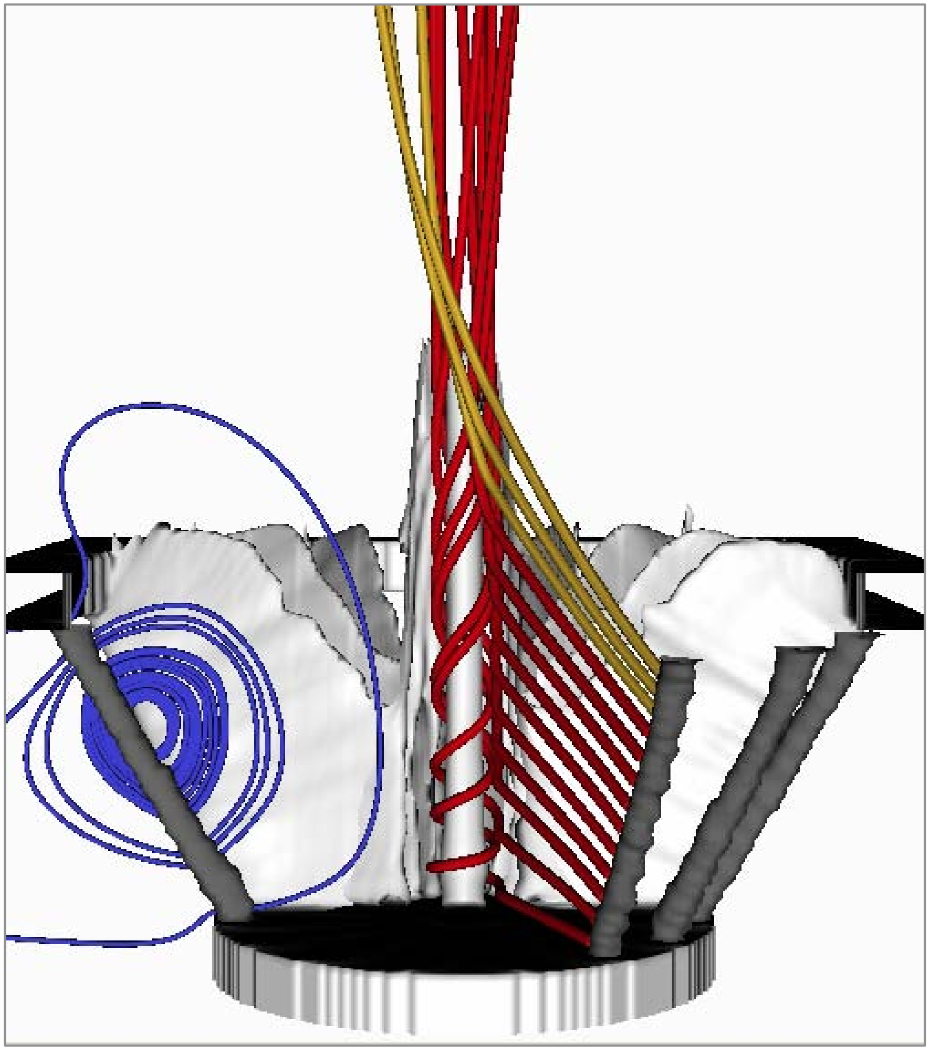


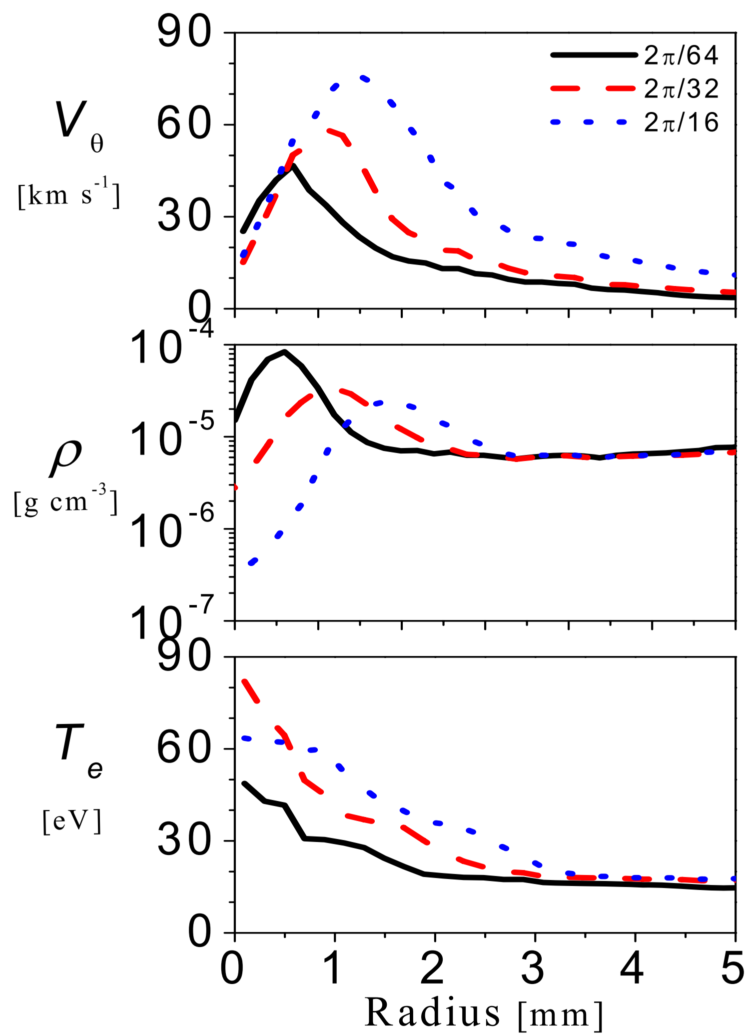
Larger rotation rate





Simulations show similar dynamics and can be used to recover physical parameters of the jet





How do you scale a rotating jet between the laboratory and astrophysics

- Standard similarity parameters for radiatively cooled jets can be met by conical wire array jets
  Lebedev et al. Astrophys. J. **616**, 988 (2004)
  - Conditions for hydrodynamics
  - Mach number
  - Density contrast
  - Cooling parameter
- Vector velocity is a key variable (Mach number in each direction).
- The ratio of azimuthal to axial velocity is appropriate parameter to describe rotation
- For experiments have v_{φ}/v_z~10%, which is similar to measurements of stellar jets
  Bacciotti et al., Astrophys. J. 576,222 (2002)
- Clearly more detailed analysis of mass and velocity distributions is required if we are attempt to describe the full angular momentum distribution within the jet

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Conclusions

- Produced rotating flows using a modification of the wire array z-pinch
- This angular momentum is introduced into a standing conical shock
  - increase in diameter
  - hollow density profile
- Angular momentum conserved when radiatively cooled jet is formed
- Rotation of the jet is made evident by discrete filaments
- MHD simulations