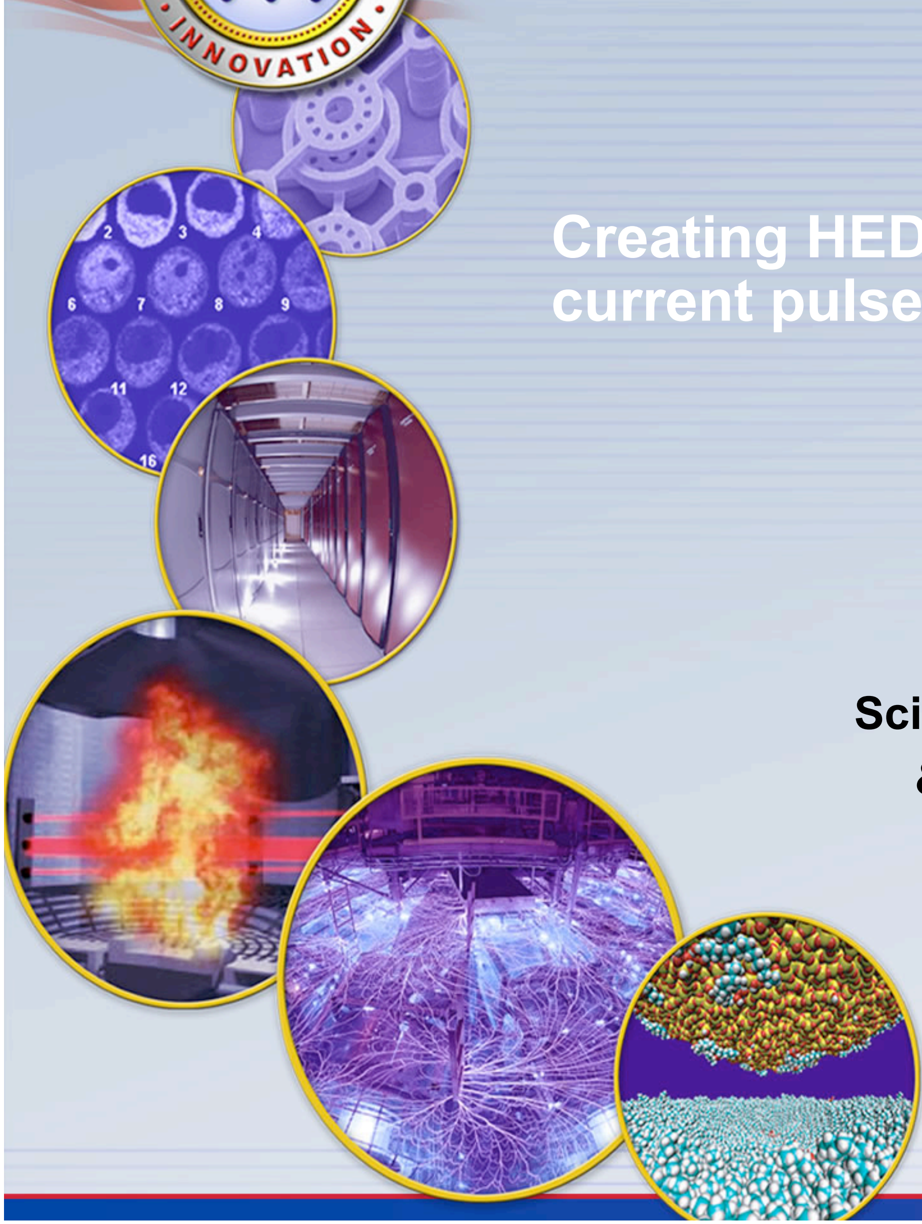

Creating HED jets and flows using high current pulsed power facilities

D.J. Ampleford

Presented at

Science with High-Power Lasers

& Pulsed Power Workshop

* Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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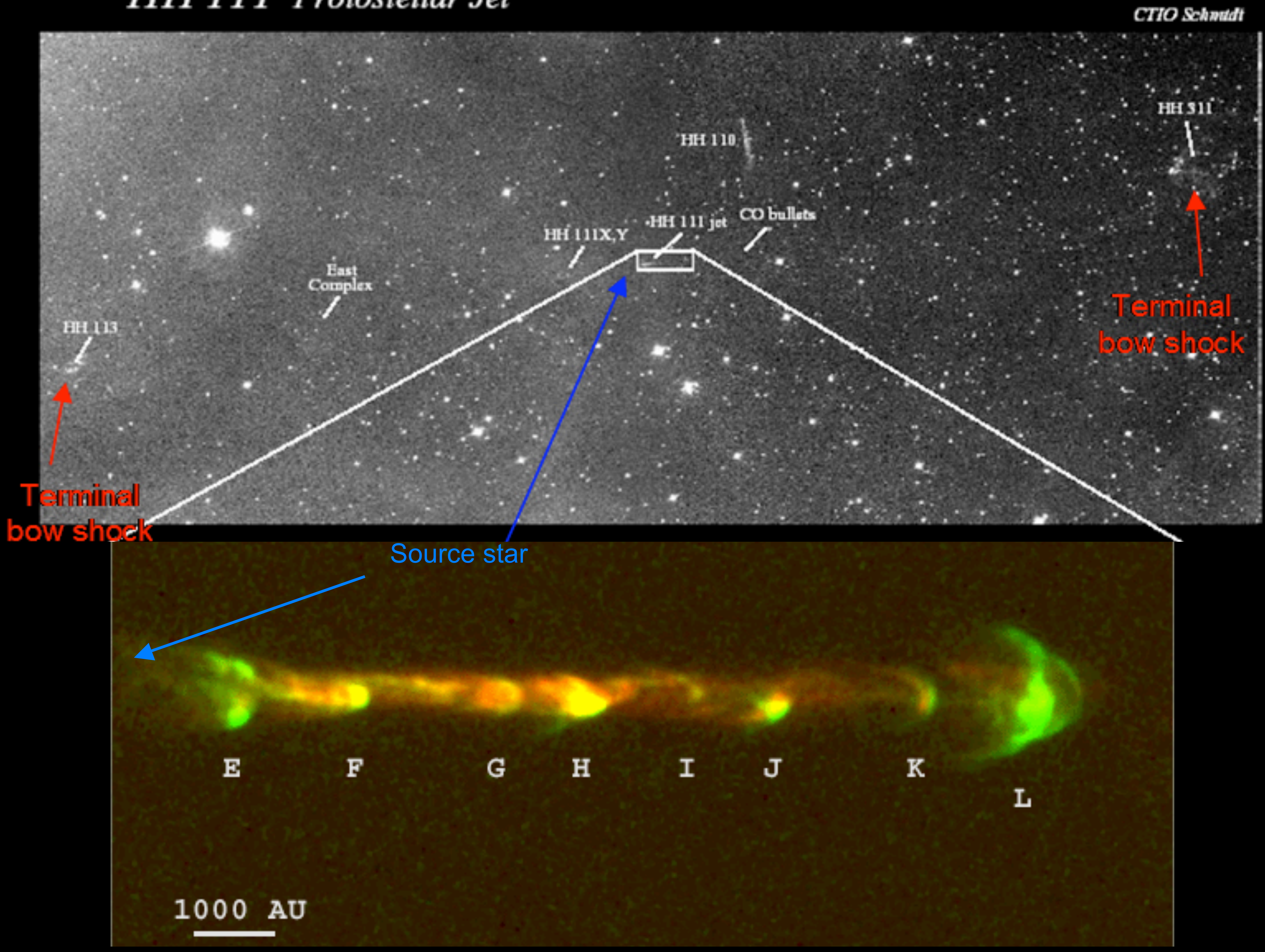
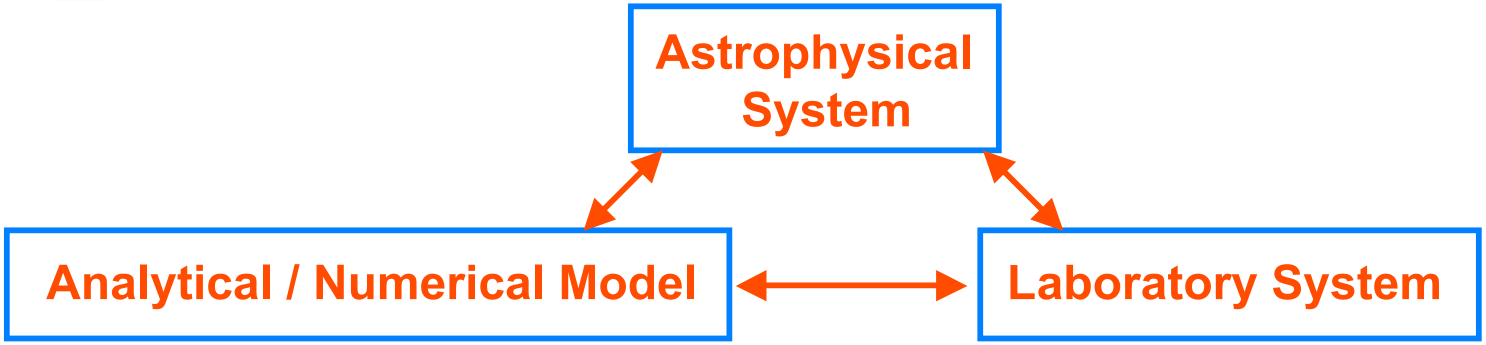
HH 111 Protostellar Jet



Top: Adapted from J. Bally et al., The Birth of Stars: Herbig-Haro Jets,Accretion and Proto-Planetary Disks. Science with the Hubble Space Telescope - II, page 491, 1996
Bottom: Animation courtesy of P. Hartigan (Rice)

Astrophysical dynamics in the Laboratory



Astrophysical System

Analytical / Numerical Model

Laboratory System

- Study subset of a problem, described by the same set of equations (e.g. MHD), which can be correctly scaled
- Control and vary initial conditions, follow the evolution
- Especially promising for studies of 3-D problems
- Scaling: difference in 15-20 orders of magnitude

Lebedev et al., DZP (2008)
Remington, Drake, Ryutov, Rev. Mod. Phys., (2006)

Simulations are the strongest connection between z-pinch jets and their astrophysical counterparts

- To date two codes have been used to make this connection
  - Gorgon (3D resisitive MHD code, developed at Imperial)
    - » Laboratory code used to model z-pinch implosions
      - Including MAGPIE, Z and Saturn, with circuit model
    - » Modified to cover astrophysical scales
  - AstroBEAR (3D MHD code with AMR, developed at Rochester)
    - » Astrophysical code adapted to model laboratory experiments

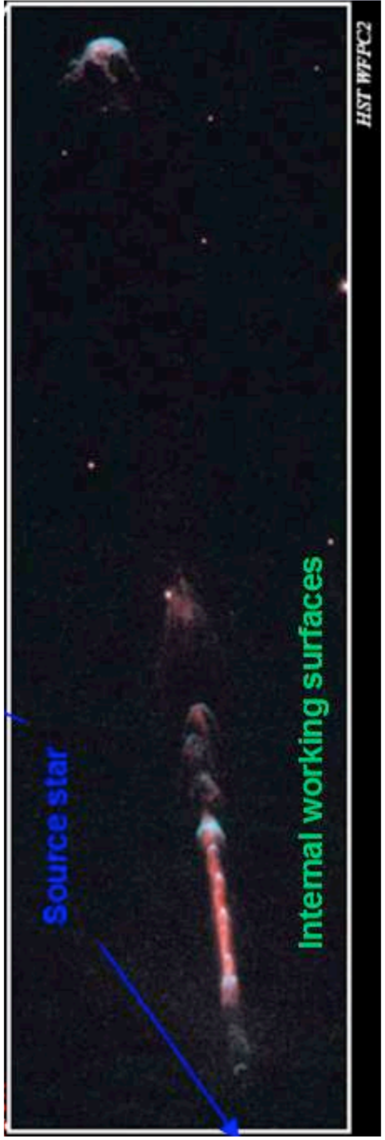
- 1MA experiments have already had impact on codes used by astrophysical community

- Well diagnosed experiments are the key to code benchmarking
  - Typical jet diameter is 100x ZBL backlighting resolution (20µm)!
  - Data can be used to benchmark both laboratory and astrophysical simulations
    - » Good publication route for validation of existing codes

A. Ciardi et al., Phys Plasmas 14, 056501 (2007)
A. Ciardi et al., Astrophys. J. 678, 968 (2008)
A. Frank et al., Astrophys & Sp. Science 298, 107 (2005)

Despite huge scales and low densities of astrophysical jets, lab experiments needed to model them are HED

- Protostellar jets typically
  - Are highly supersonic, predominantly due to radiative cooling
    - Ensure lab experiment is highly supersonic
    - Need to be characterized by high radiative cooling rate
      - cools over lengthscale ~ jet radius despite small radius
    - Astro jets are low Z element, however in lab need to go to dense high Z jets to model them
  - Propagate through the Interstellar Medium (ISM)
    - Need control of ambient medium in the laboratory
      - Uniform/non-uniform, Static/moving, Cooling rate of ambient medium, Ambient fields
  - Are magnetically launched, but propagation is independent of fields
    - Need control of significance of magnetic pressure to study specific regions
  - Have lengths ~10^{18} cm and aspect ratios (length/radius) 15-1000
    - Must have control over general flow configurations for specific problems
  - Have small scale structures
    - Re, Re_M & Pe » 1
    - 1MA experiments have large values, but not large enough



e.g. J.M. Blondin et al., Astrophys J. 360, 370 (1990)

Challenge for laboratory experiments is to achieve significantly larger Re, Pe & Re$_M$ than available at 1MA

- **For experiments translated from 1MA to 20MA we expect**
  - **Strong increase in density, ρ**

$$\rho \sim I^2$$
$$\rho_Z \sim 400\ \rho_{MAGPIE}$$

  - **Some increase in temperature T$_e$**

- **Length and velocity scales will be reasonable similar**
  - **Already shown similar on few different generators**

- **Should increase relevant dimensionless fluid parameters**

$$\mathrm{Re} \equiv \frac{V \cdot L}{\upsilon} \propto \frac{V \cdot L \cdot Z^4 \sqrt{A} \cdot n_i}{T^{5/2}} >> 1 \quad \uparrow$$

$$Pe \equiv \frac{V \cdot L}{\chi} \propto \frac{V \cdot L \cdot Z \cdot (Z+1) \cdot n_i}{T^{5/2}} >> 1 \quad \uparrow$$

$$\mathrm{Re}_M \equiv \frac{V \cdot L}{D_M} \propto \frac{V \cdot L \cdot T^{3/2}}{Z} >> 1 \quad \uparrow$$

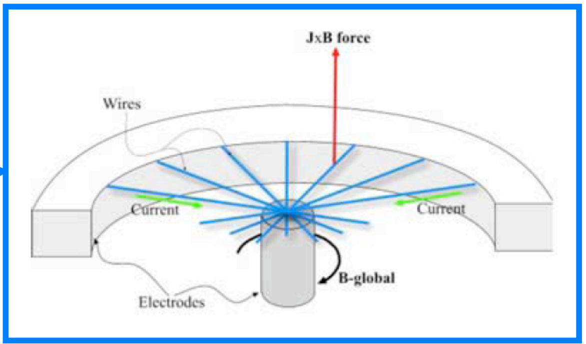
- **Z experiments should actually achieve values**
  - **Similar to stellar jets**
  - **Potentially higher than numerical Re, Re$_M$ and Pe achievable in typical simulations**

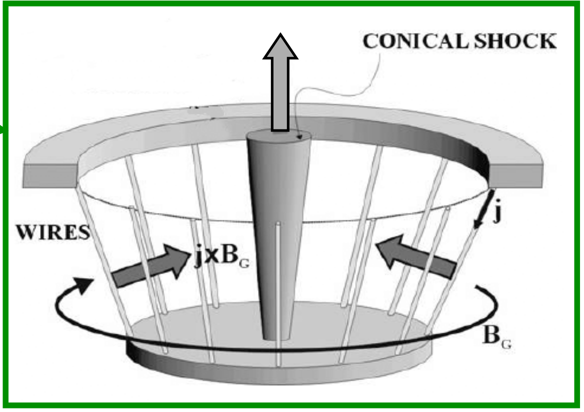
D.D. Ryutov et al., Astrophys J., 518, 821 (1999)
B.A. Remington et al., Rev Mod Phys. (2006)

Many aspects of jet formation and propagation can be explored on Z

- Jet formation (Radial wire arrays / foils)
  - Magnetic tower formation
  - Mechanisms for episodic formation
- Jet Propagation (Conical wire arrays)
  - Steady ablation flows create conical shock and jet
  - Ambient medium
  - Radiative cooling
  - Angular momentum
  - Velocity variations
- Critical question is what happens when two or more of these are present
  - Full 3D problems requiring very fine resolution
  - Experiments are good at being 3D and defining their own resolution

Exploration and *staging* experiments on many of these topics have begun on smaller generators such as
  - MAGPIE at Imperial College London (1-2MA, 250ns)
  - Saturn at Sandia (Org. 1300) (7MA, 40-150ns)





Detailed experiments at lower current levels allow the basic mechanisms to be well understood and models to be developed well in advance of performing experiments that utilize the full Z-machine

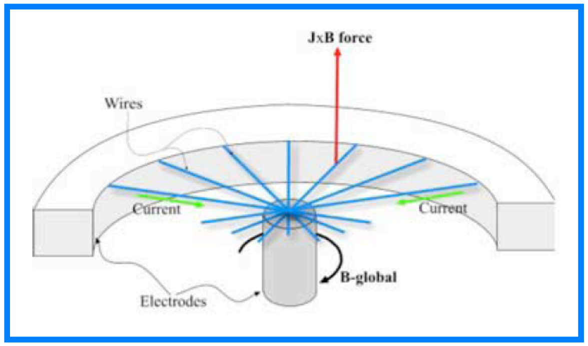
Will give overview of 1MA & 7MA experiments and discuss simulations demonstrating likely HED regimes achievable on Z

Radial wire arrays are an effective means to model magnetic launch in the laboratory

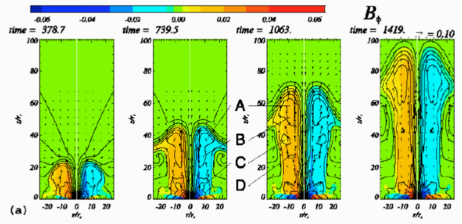
- **Magnetic tower formation is now accepted launching mechanism**
  - **Magnetic field tied into accretion disk**
  - **Rotation of disk leads to ‘twisted’ field**
  - **Toroidal component leads to axial magnetic pressure**

- **In the laboratory use a central cathode with radial wires**
  - **Does not capture mechanism for field generation**
  - **However, is good at determining dynamics due to field**

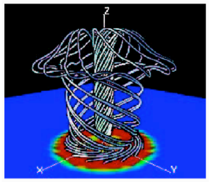
- **Radial wire arrays are first experiments to create a radiatively cooled jet by magnetic launch**
  - **V_{jet} ~ 150km/s**
  - **Can also adapt to include episodic nature of astro jets**



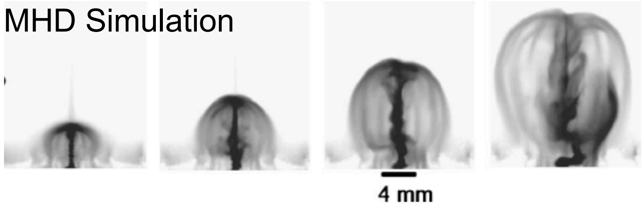
Map of the toroidal magnetic field



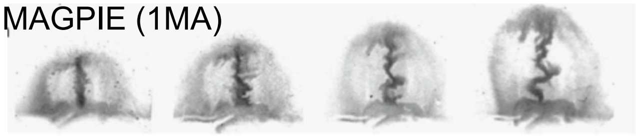
Kato, ApJ 2004



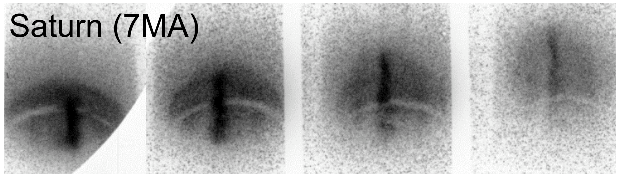
MHD Simulation

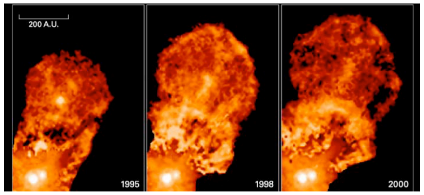


MAGPIE (1MA)



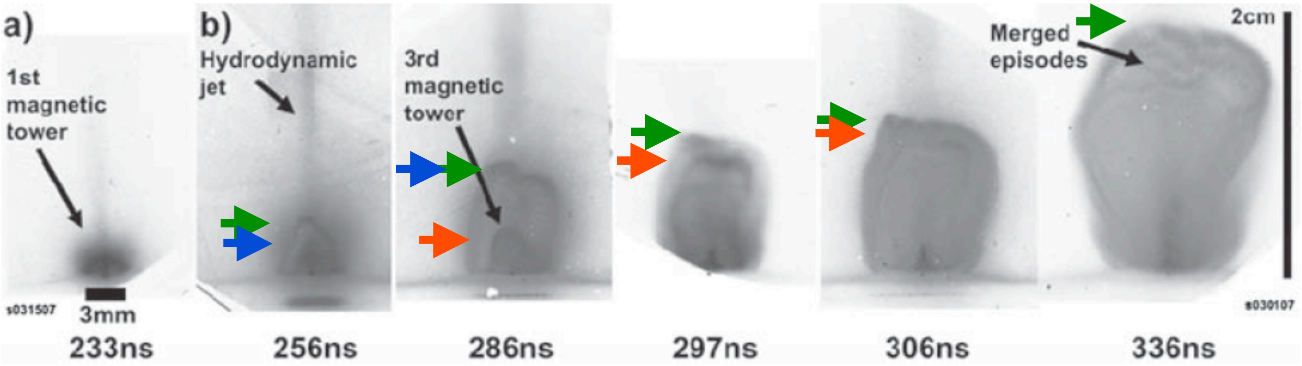
Saturn (7MA)

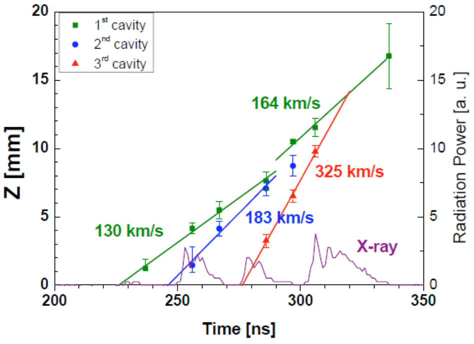




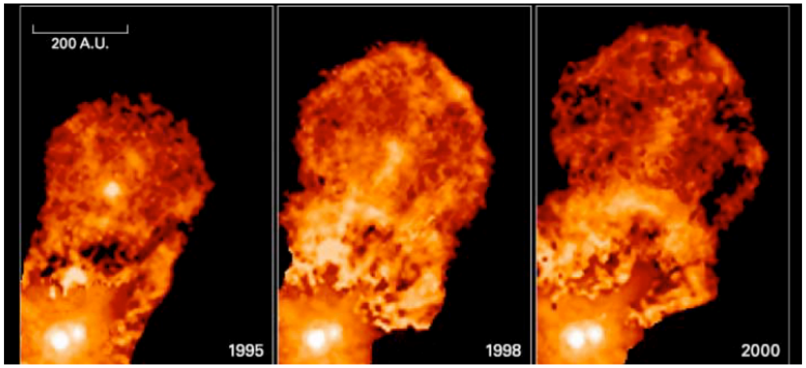
S.V. Lebedev et al., MNRAS 361, 97 (2005)
A. Ciardi et al., Phys Plasmas 14, 056501 (2007)

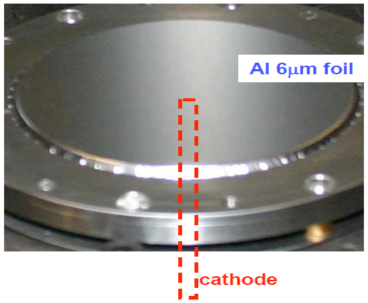
Episodic jet production can be achieved in the laboratory





- **By replacing wires with foil current restrike can occur**
- **Many jet episodes occur**
- **Episodes collide and significant structure observed**
- **Similar seen in stellar jets**



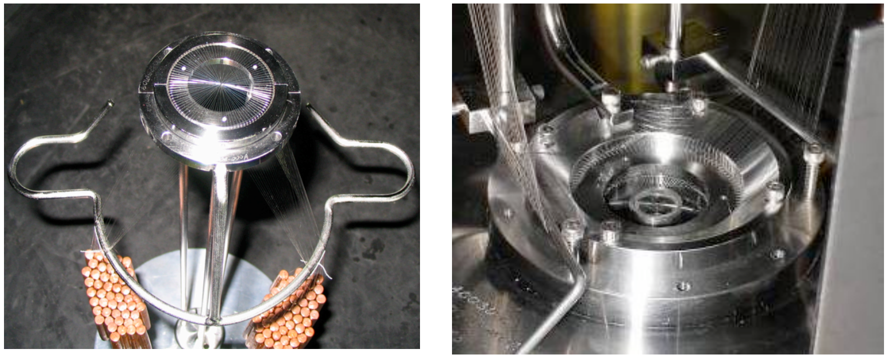


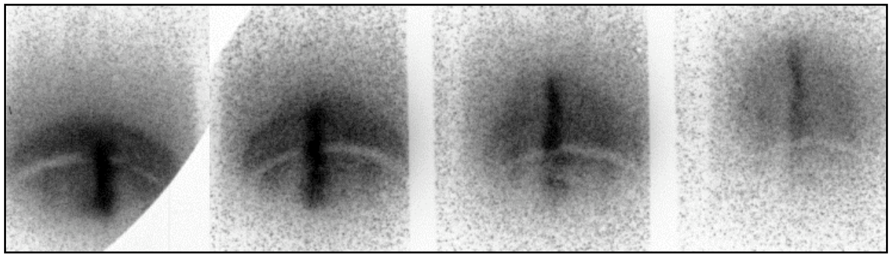
F. Suzuki-Vidal et al., Astrophys. Sp. Sci. 322, 19, (2009)

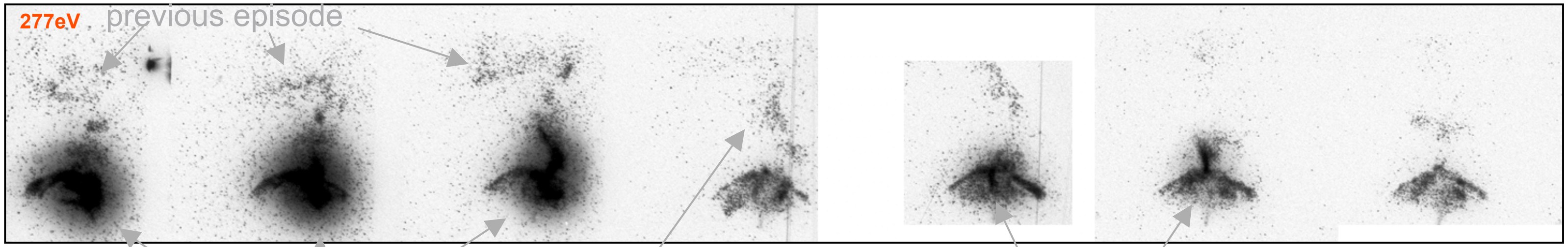
Experiments at higher current can enter different regimes

- **Experiments on SATURN can achieve higher jet densities and hence higher Reynolds numbers and ability to interact with solid targets**

- **Already experiments have demonstrated ability to form single and multi-episode jets**







Material from previous episode

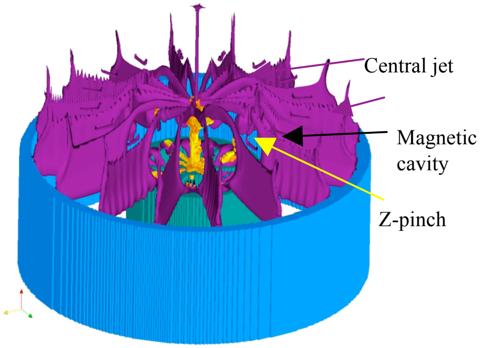
New jet grows over ~6ns

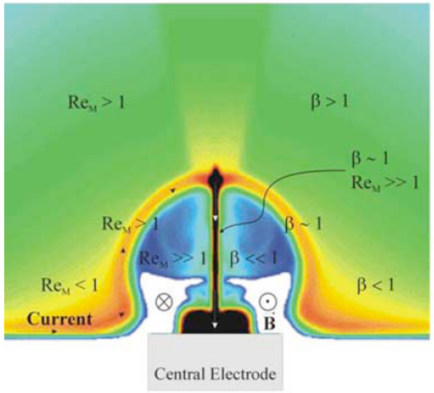
Material continues to propagate

Yet another jet starts to form

D.J. Ampleford et al., ICOPS 2008
Work funded under a Sandia LDRD (Project 117862)

Experiments on Z with radial arrays would allow significant progress





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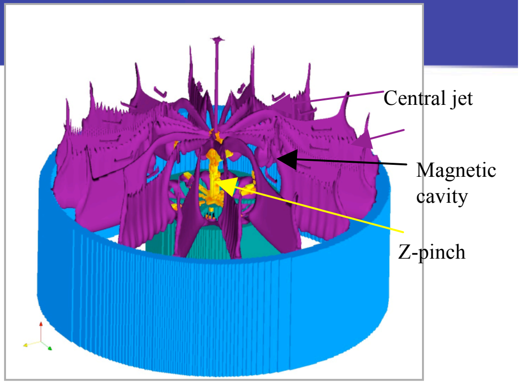
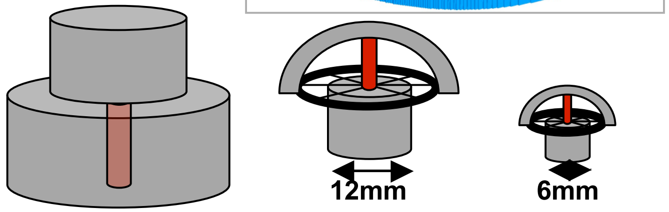
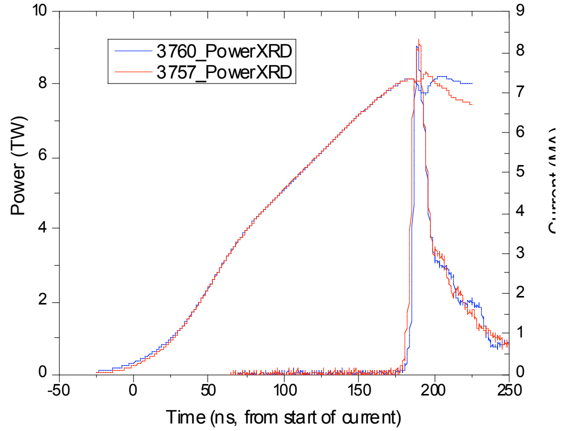
Independent of jet-physics, radial wire arrays open new options for HED



- **Radial arrays are an intense, compact x-ray source**
- **Experiments on Saturn have demonstrated power densities necessary to drive compact hohlraum (6mm diameter secondary) to ~90eV**



40mm Saturn array **Saturn Radial arrays**

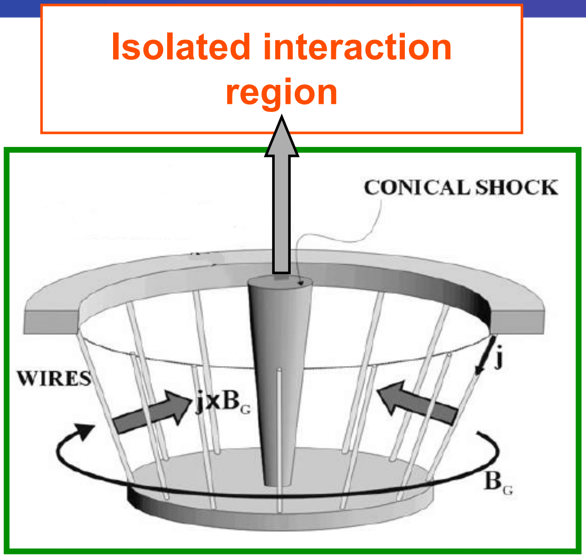


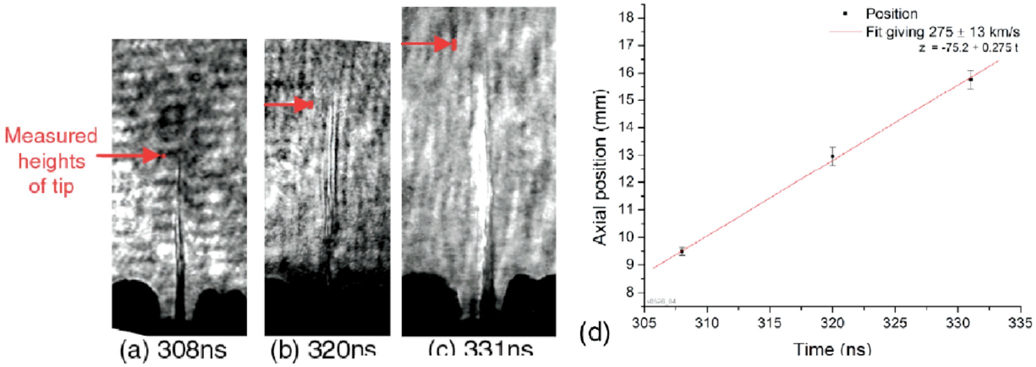
	Existing Cyl	Existing data		What if??
Cathode diameter (mm)	**Cyl. 40mm**	**12mm**	**6mm**	**6mm**
Pinch power (TW)	40	9.5	8.0	40
Area of Primary wall (cm^2)	53	4	1.6	1.6
Area of Sec. wall (cm^2)	25	3.3	1.4	1.4
Area of p-s aperture (cm^2)	12.6	1.1	0.3	0.3
T primary (eV)	61	80	95	140
T secondary (eV)	56	70	89	128

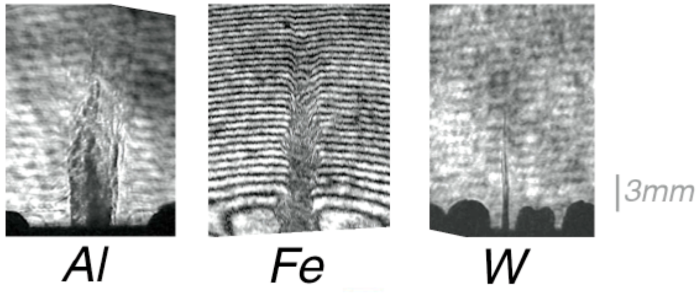
D.J. Ampleford et al., ICOPS 2008
Work funded under a Sandia LDRD (Project 117862)

Away from the jet launch region plasma β significantly smaller, and experiments can be designed to match

- **Conical wire arrays have been used to model ‘field free’ jets**
- **High mass wires are used such that they act as a plasma source but never move**
- **Conical shock is formed on axis which redirects flow**
  - **similar to earlier astrophysical jet formation theories**
  - **Steady-state formation (many τ_{char})**
- **Jets are highly supersonic (M≥30)**
- **Changing wire material demonstrates significance of cooling and hence M**
  - **Radiative cooling dominates YSO jets**
- **Very reliable, reproducible wire array setup for producing jets**
  - **Allows experiments on actual jet independent of formation**
  - **Fixed current path therefore no L-dot**


Isolated interaction region





S.V. Lebedev et al., Astrophys. J. 564, 119 (2002)
D.J. Ampleford et al., AIP Conf Proc 1088, 83 (2009)

Simulations can be use to estimate the regimes accessible on Z in long pulse

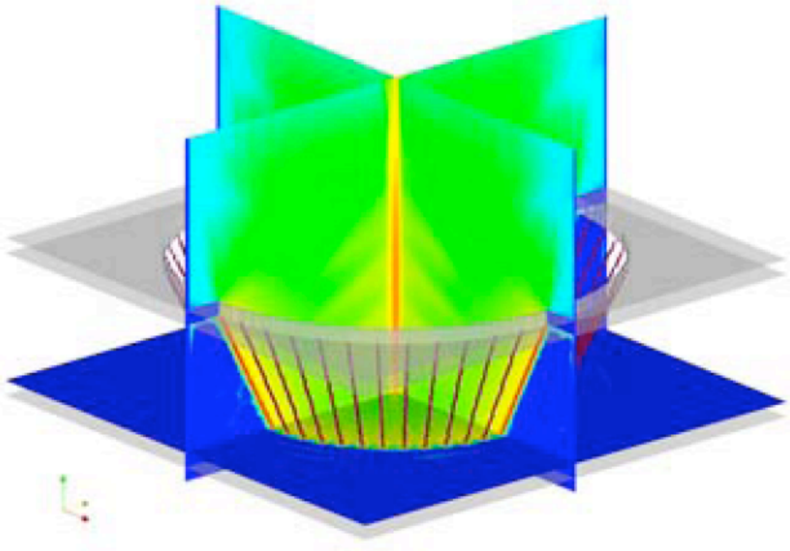


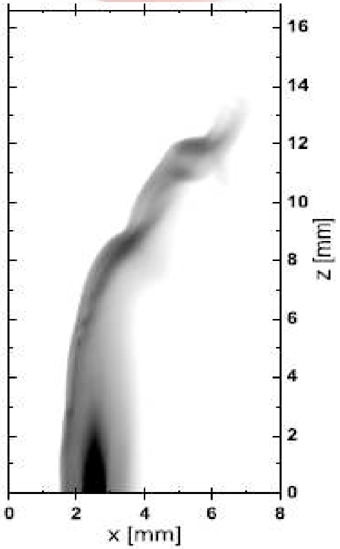
Fig.13 Initial calculation of a conical wire array configuration on Z using 48 tungsten wires in long pulse mode.

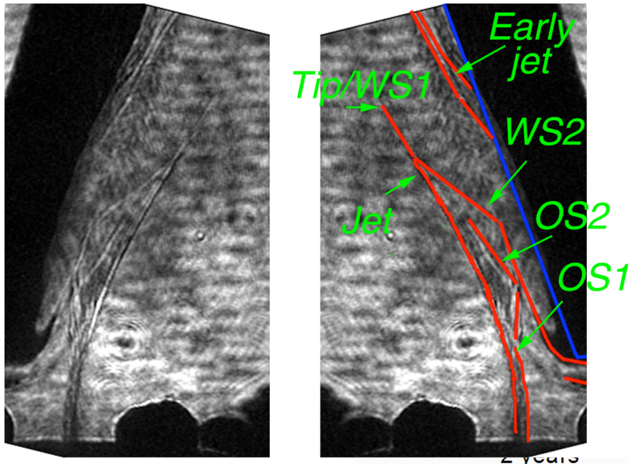
- Simulations indicate jets from conical arrays on Z would have
  - Kinetic pressure ~ 25Mbar,
  - Velocities ~ 50-150 cm/μs
  - Densities ~ 1000-100 mg/cm^3
- Densities well suited to introducing foam targets
  - Well diagnosed initial conditions
  - Targets can have controlled density perturbations
  - Spectroscopic dopants
- Current pulse shaping can be used to control jet density/velocity over time
- Z-beamlet laser affords opportunity to take multi-frame (or multi-color) high resolution backlighting

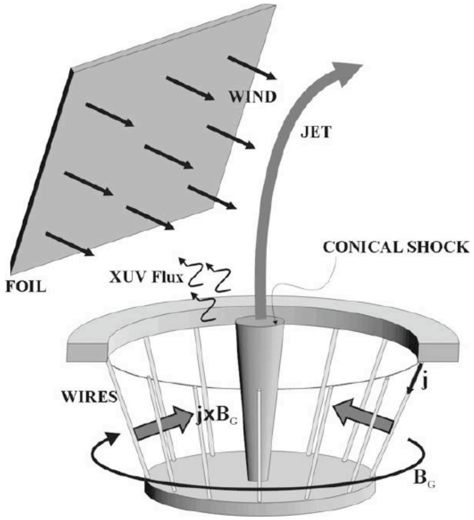
  Jet diameter >500μm
- Once basic jet is characterized, many interesting experiments can be designed

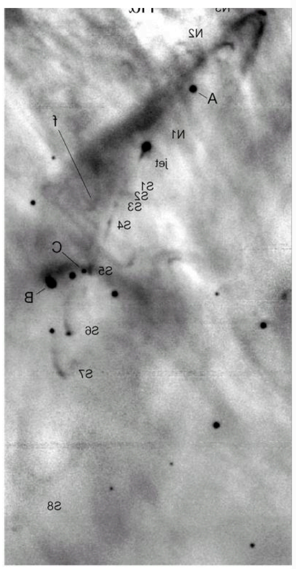
e.g. A. Frank, S.V. Lebedev et al., NNSA/OFES HEDLP proposal (2009)
A. Ciardi et al., Las. Part. Beams 20, 255 (2002)

MAGPIE experiments and MHD simulations demonstrate significant structure that needs to be explored further on Z







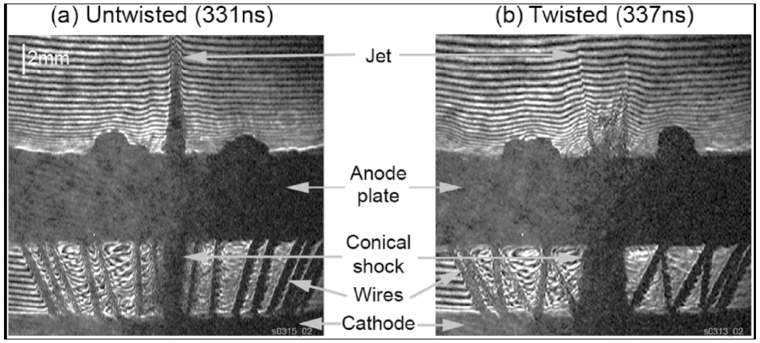


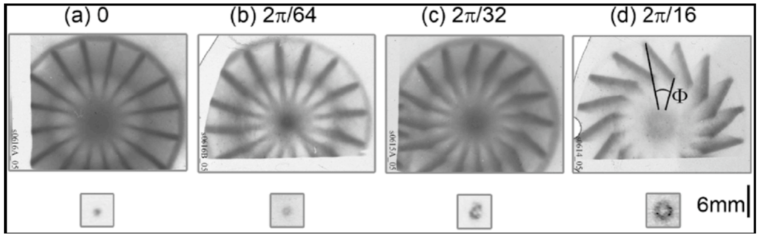
- Z experiments will achieve higher jet densities than MAGPIE
  - Allows foam targets to be introduced
- Hydro parameters will lead to more small scale structure
  - Previously inferred for astrophysical jets
  - ZBL backlighting has resolution to really probe this structure
- Use of foam allows
  - Strong control and diagnosis of initial conditions
    - Length of interaction
    - HH110 *bouncing* off cloud
  - Use of dopants for spectroscopic diagnosis

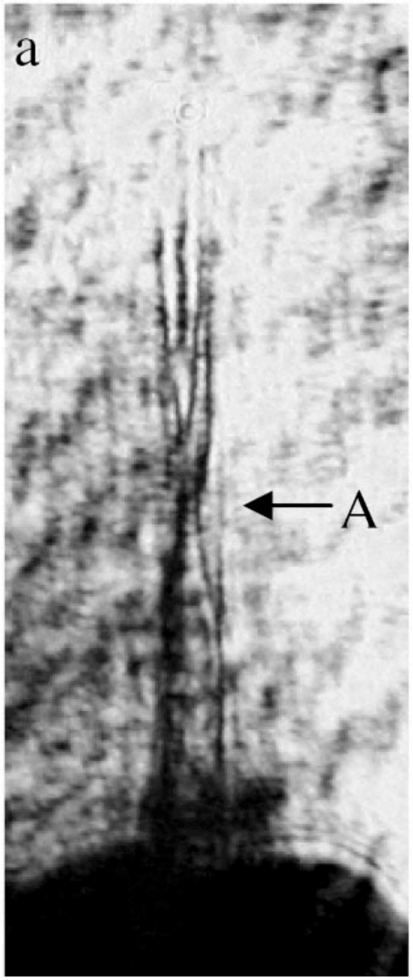
D.J. Ampleford et al., Astrophys & Sp. Science 307, 29 (2007)
A. Ciardi et al., Astrophys. J. 678, 968 (2008)

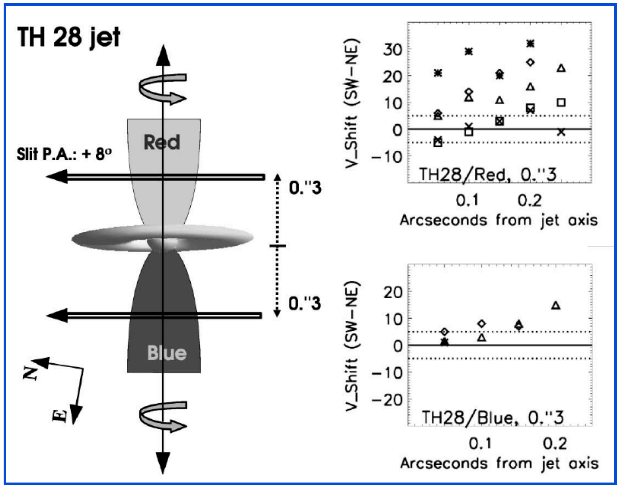
As if experiments weren’t hard enough to simulate

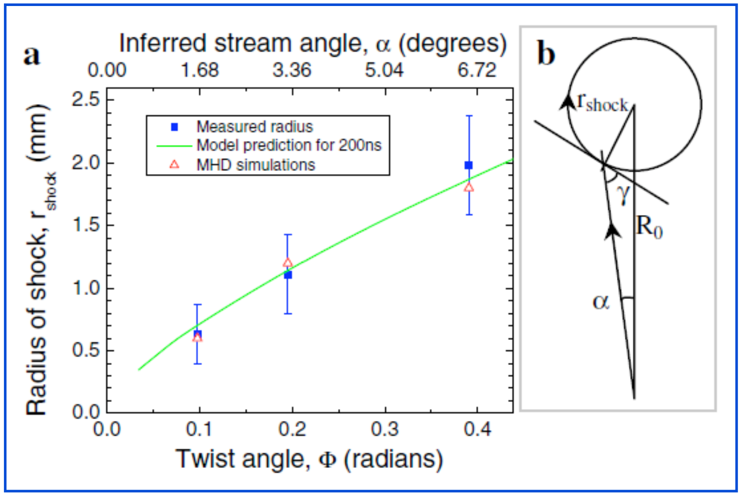
- **Rotation measured by Doppler shift for stellar jets**
- **Conical wire arrays can be adapted to create rotating jets**
- **Magnetic field near wires is perturbed by twisting array**
- **Non-zero angular momentum for entire system**
  - **Ablation flow**
  - **Shock**
  - **Jet**







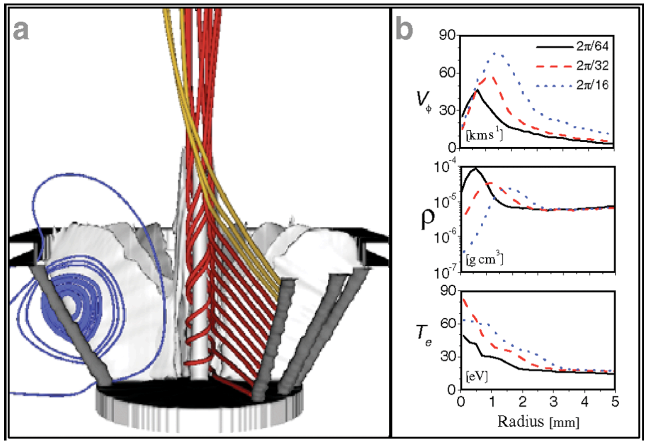


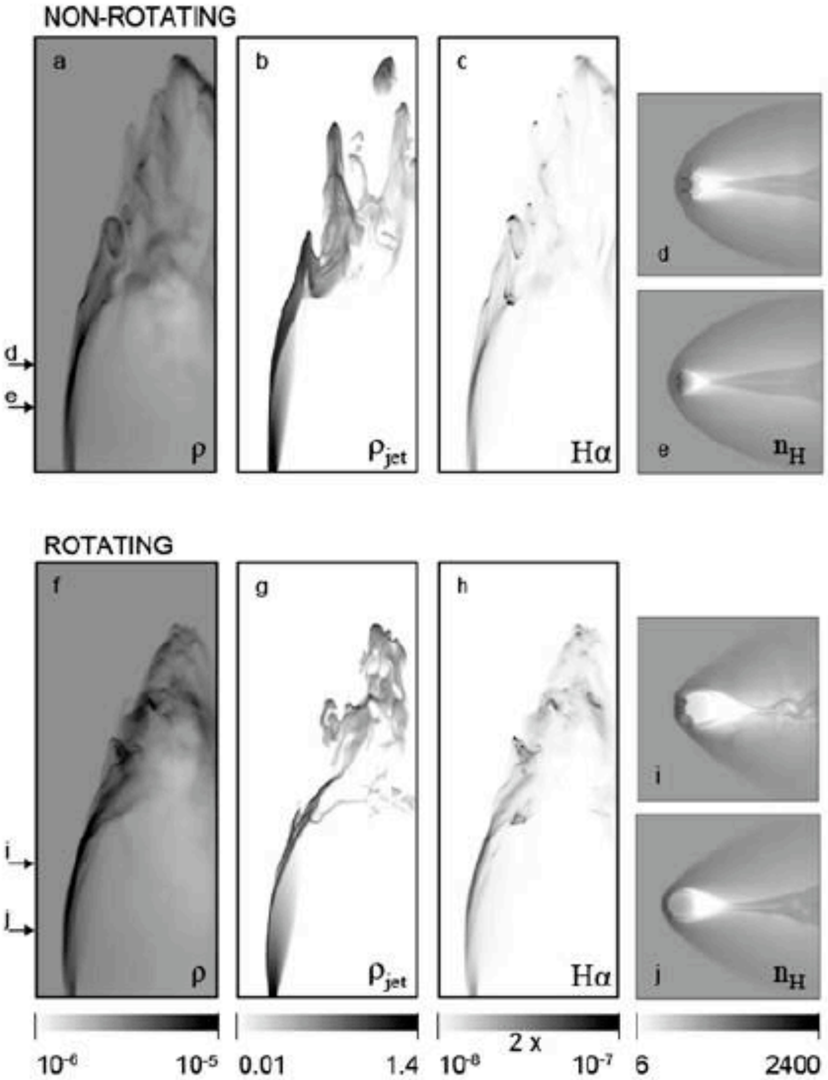


D.J. Ampleford et al., Phys Rev Lett 100, 035001 (2008)
D. Coffey et al., Rotation of YS jets, Astrophys.J. 604, 758 (2004)

Experiments can combine effects, which require high resolution, 3D simulations

- Highly diagnosed experiments can distinguish subtle differences found in simulations
- Good initial conditions to simulations which can then me extrapolated to new configurations for lab and astro
- Simulations should then be tested in further experiments



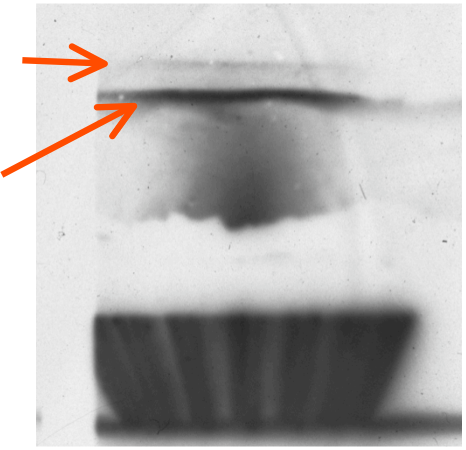


A. Ciardi et al., Astrophys. J. 678, 968 (2008)
D.J. Ampleford et al., Phys Rev Lett 100, 035001 (2008)

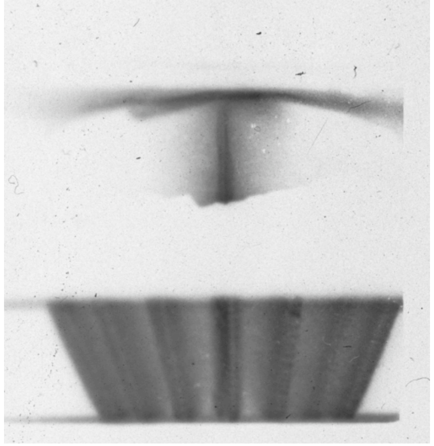
Fast jet produced by conical wire array can also be applied to dynamic materials work

Target foil

Ablated plasma gathering on buffer foil

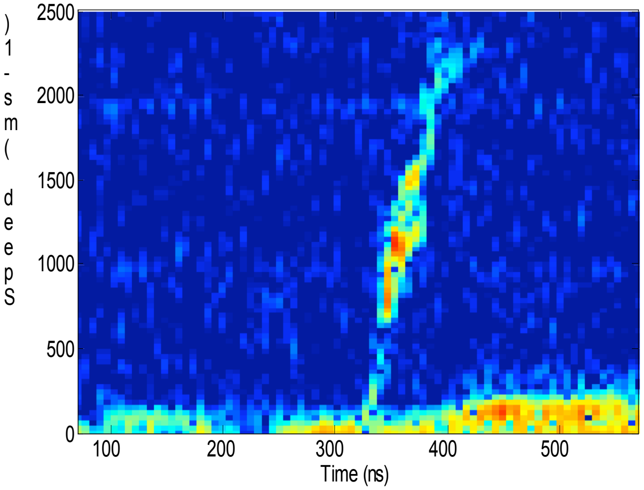


201ns



261ns

With buffer foil



Experiments utilize a buffer foil to minimize early-time ablated material impacting sample

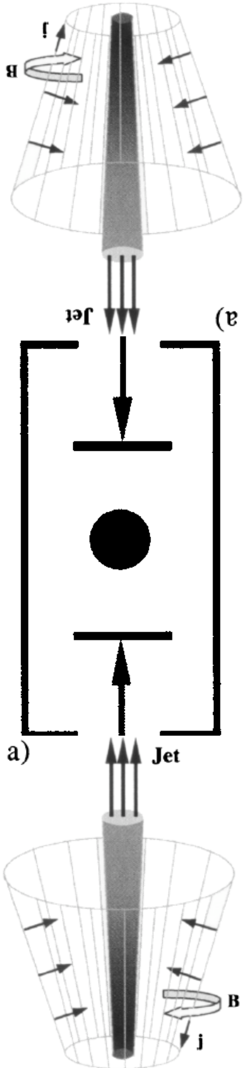
With buffer foil, no acceleration due to ablated plasma is observed

Rapid acceleration observed once jet arrived at foil

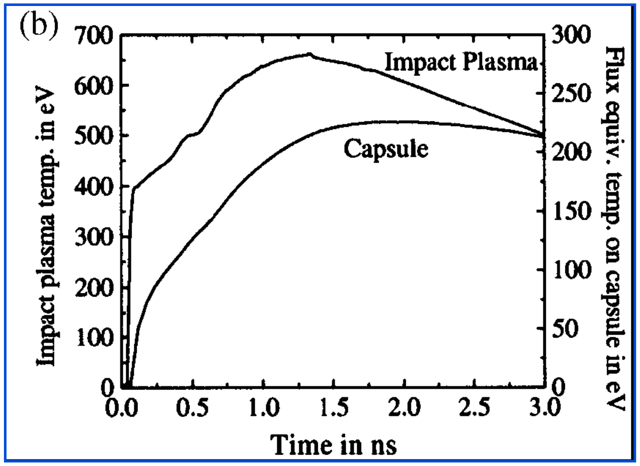
Acceleration ~ 40×10^{9} ms^{-2} corresponds to 14KBar

S.N. Bland et al., Int. Conf. HED, Austin, TX (2009)

Alternative use of such a jet on Z is to drive a NIF scale hohlraum by kinetic drive

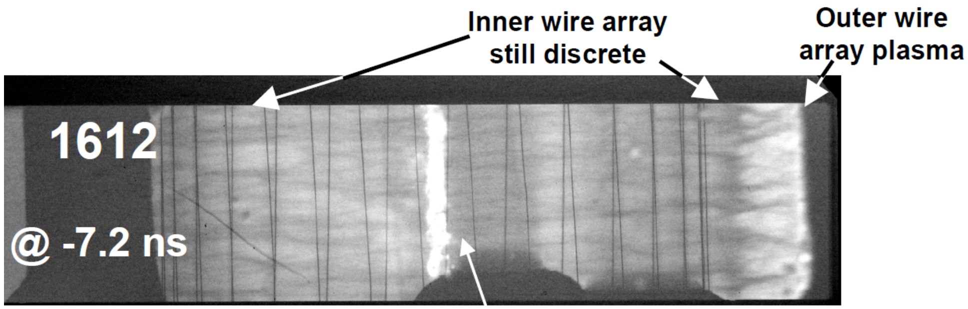


- **Kinetic drive from two jets can be thermalized on converter foils**
- **Simulations indicate each slug has**
  - **Velocity of 2x10^6 m/s**
  - **Kinetic energy 250 kJ**
  - **Density 43 kg/m^3**
- **Hohlraum is heated to ~225eV**

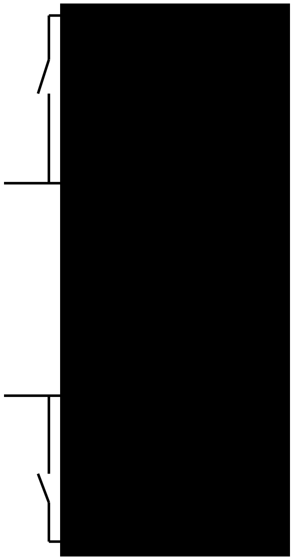


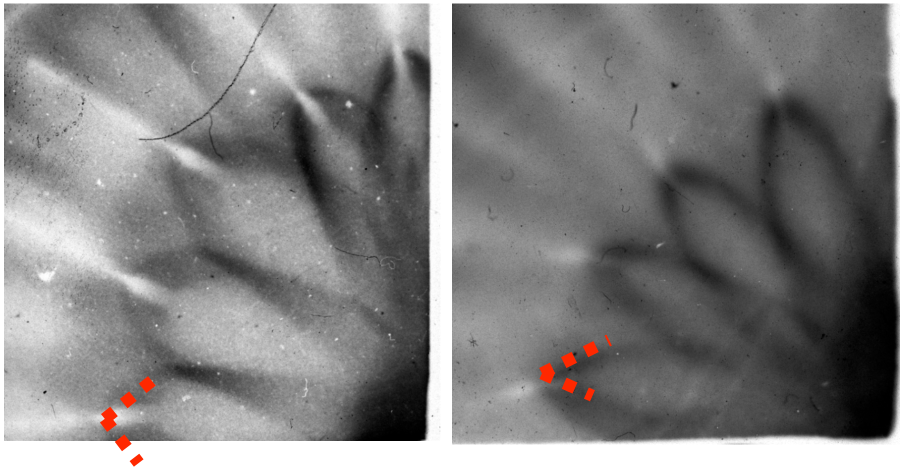
J.P. Chittenden, M. Dunne et al., Phys. Rev. Lett. 88, 235001 (2002)

Even flows in standard wire array configurations can have laboratory astrophysics applications

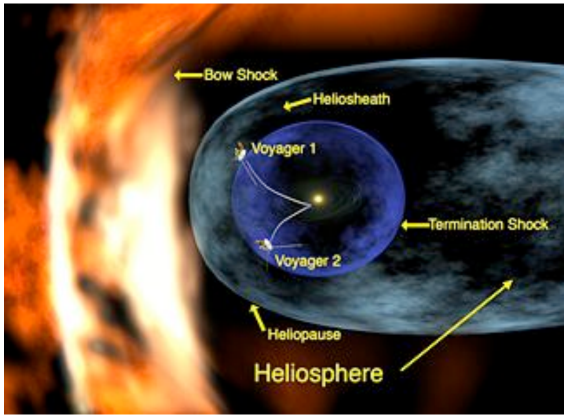


- Generally inner wires in nested array are quasi-current free
- Inner array wires act as obstructions to ablation flow
  - Presence of shocks has connection to interaction pulse in nested arrays
- Controlled current through inner wires
  - no current to ~1kA
  - notable effect on shock structures



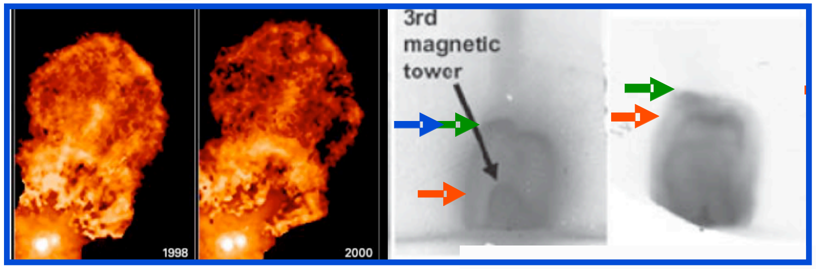


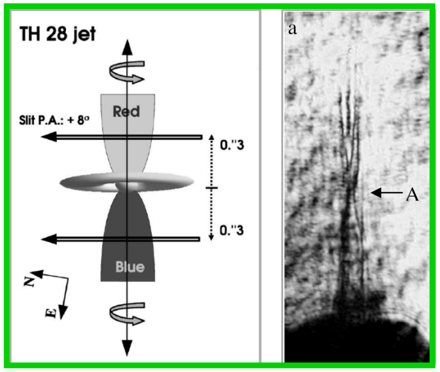
With field **Without field**

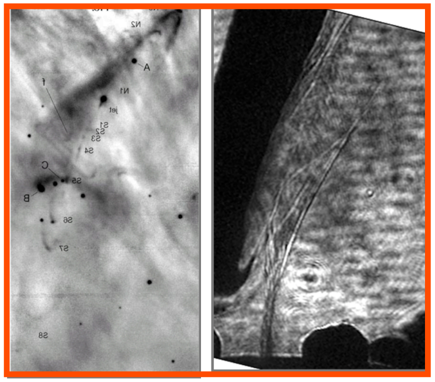


D.J. Ampleford et al., HEDLA (2008)
D.J. Ampleford et al., to be presented APS-DPP invited (2009)

Summary: Many valuable jet experiments can be performed on Z and then be embraced by astrophysical community







2 years

- Carefully designed experiments can have significant impact on astrophsyical community
- For example, previous experiments have demonstrated many features of astrophsyical jets, which fall broadly in the correct regime
  - Episodic jets
  - Rotating jets
  - Deflected jets
- Z experiments can take these established and understood techniques from lower current machines and take them into a more relevant parameter space
  - Better Re, Re_M and Pe
  - Better control of initial conditions
  - Better diagnosis of system
- Key to connecting 1MA, 7MA, 20MA experiments and nature is the of state of the art computer simulations and interactions with astrophsyical modelers and observers
- HEDLP proposal by A. Frank (Rochester) for jets on MAGPIE & Z was recently succesful using this approach
- There is some potential overlap between experiments for astrophysical and other applications (although design for a specific problem)

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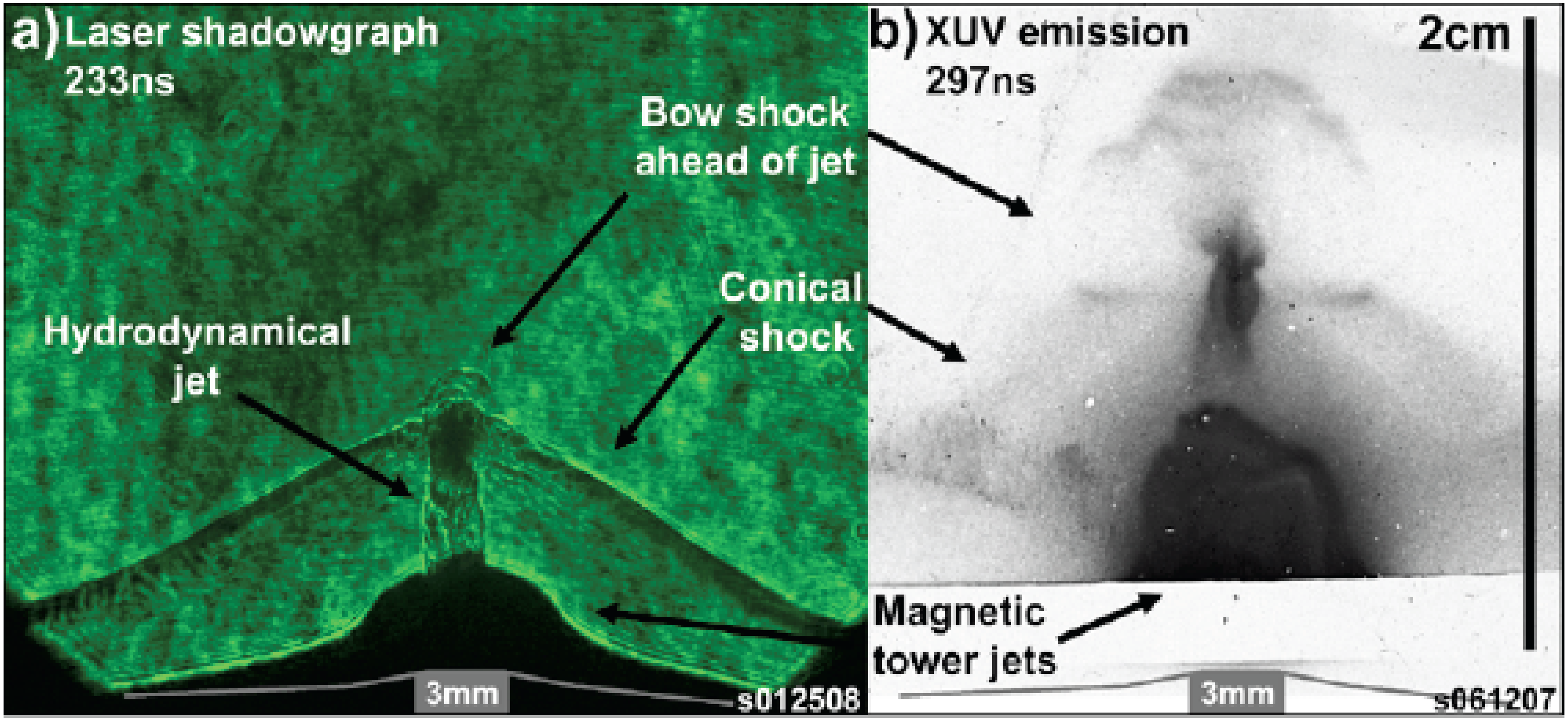
Highly diagnosed jet experiments provide a wealth of data to test our understanding and benchmark codes



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BACKUP

Dimensional and Dimensionless parameters relating our laboratory jets to those from Young Stellar Objects [2]. Experimental dimensionless parameters shown in bold are the ranges of values achievable by variations to the experiment configuration, as described in the text; however this is not necessarily a control independent of other parameters.

Parameter	**YSO jet (away from source)**	**Conical wire array Z-pinch jet**
General flow variables		
Length (cm)	3×10^{18}	2
Radius (cm)	1×10^{15}	0.1
Dynamical time scale	10^5 years	100ns
Electron temperature (eV)	1	10
Jet tip velocity (km/s)	~100	~200
Jet bulk velocity (km/s)	~100	~100
Azimuthal (rotation) velocity (km/s)	0 – 10	0-20
Jet Density (g/cm^3)	~ 10^{-22}	10^{-4}
Validity of fluid description [2]		
Localization parameter (mfp/r)	$<<10^{-6}$	$\leq 10^{-4}$
Reynolds Number (Re)	$>10^8$	10^5
Peclet number (Pe)	10^7	$2 – 2 \times 10^3$
Jet scaling parameters in 1D		
Mach number, M	>10	**10-30**
Density Contrast, η [5,6]	1 – 2	**~1 – >10^3**
Cooling parameter, χ [2]	0.1 – 10	**5-10**
Jet aspect ratio (Length/Radius)	15-1000	**3-20**
Parameters representing 3D effects		
Rotation fraction (v_φ/v_z) [3]	0 – 0.1	**0 – 0.2**
Wind velocity contrast [6]	0 – 0.2	**0 – 0.5**

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