Laboratory modelling of astrophysics jets

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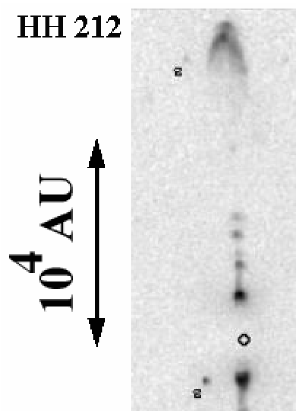
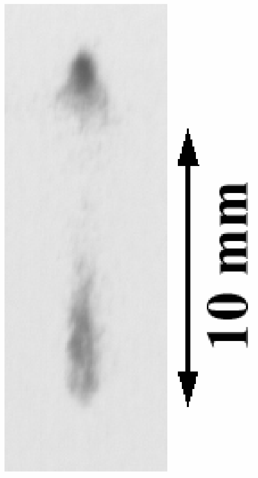
Plasma jets in astrophysics and in laboratory experiments

Motivation: to produce in laboratory experiments plasma jet with

Space ← **similar** → **Experiment**





dimensionless parameters:

"shape"

Mach number

Propagation of jets

M ~ 10 – 50

Density contrast: jet / ambient

η ~ 10

Cooling parameter

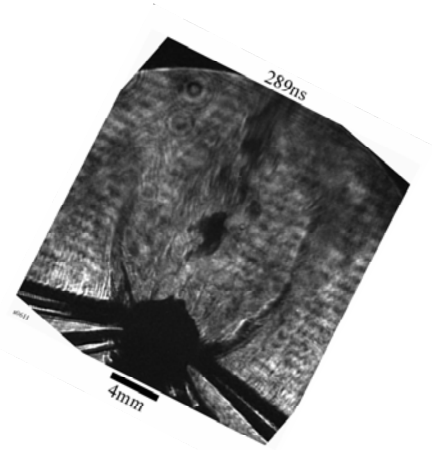
$$\chi \equiv \frac{\tau_{cool}}{R_j / V} \sim 0.1 - 10$$

Launching mechanism

Magnetic fields:

β ~ 1

XZ Tauri



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Outline

Wire array Z-pinch as a source of supersonic, radiatively cooled laboratory plasma jets

1. **Magnetic tower jets driven by toroidal magnetic filed**

2. **Cylindrically converging flows, shocks and rotating jets**

Jet launching mechanism - “Magnetic Tower” Jets

Differential rotation in accretion disc with poloidal magnetic field

Twisting leads to generation of toroidal magnetic field

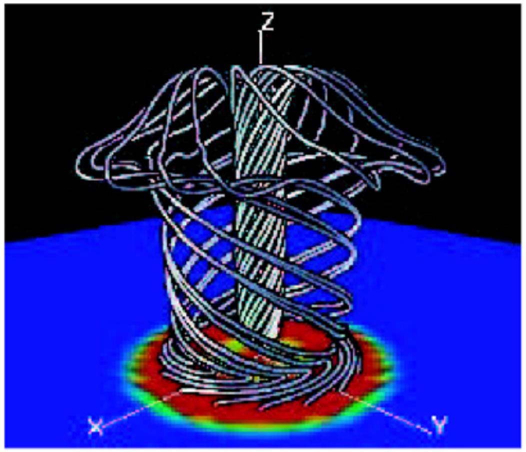
Formation of a magnetic cavity collimated by external pressure

Lynden-Bell

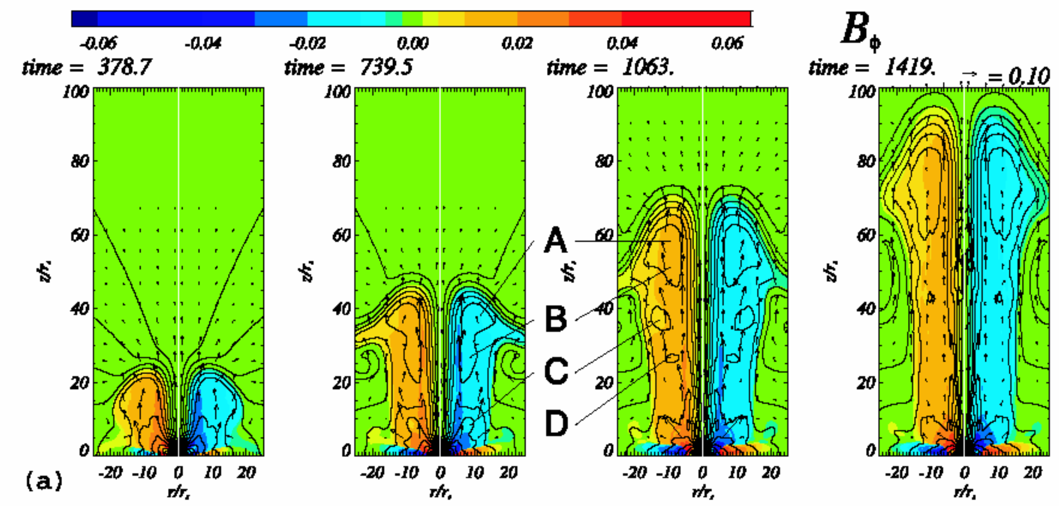
Lovelace

Kato

Magnetic field lines [Kato, ApJ 2004]



Map of toroidal magnetic field



Experiment – dynamics of magnetic bubble driven by toroidal magnetic field

Jet launching mechanism - "Magnetic Tower" Jets

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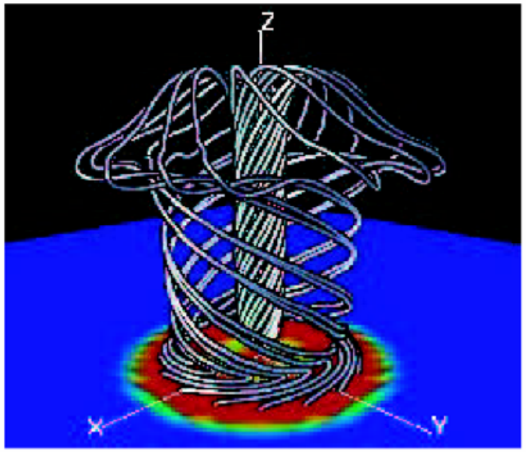
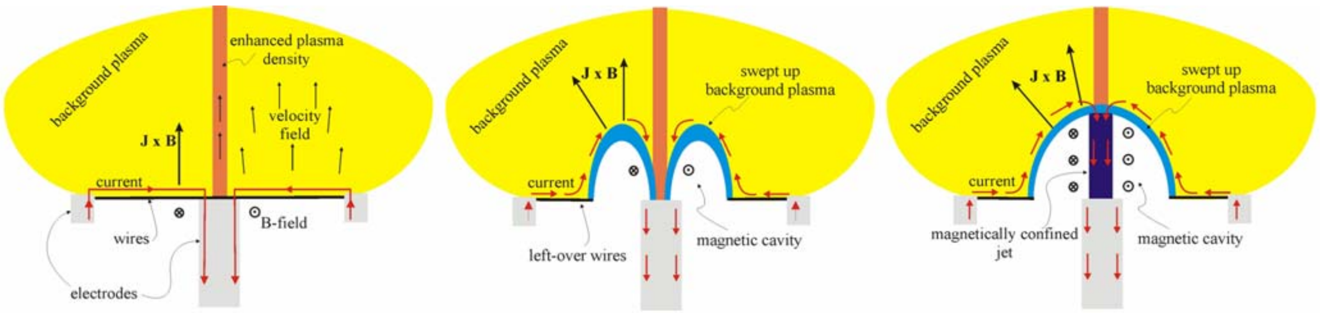


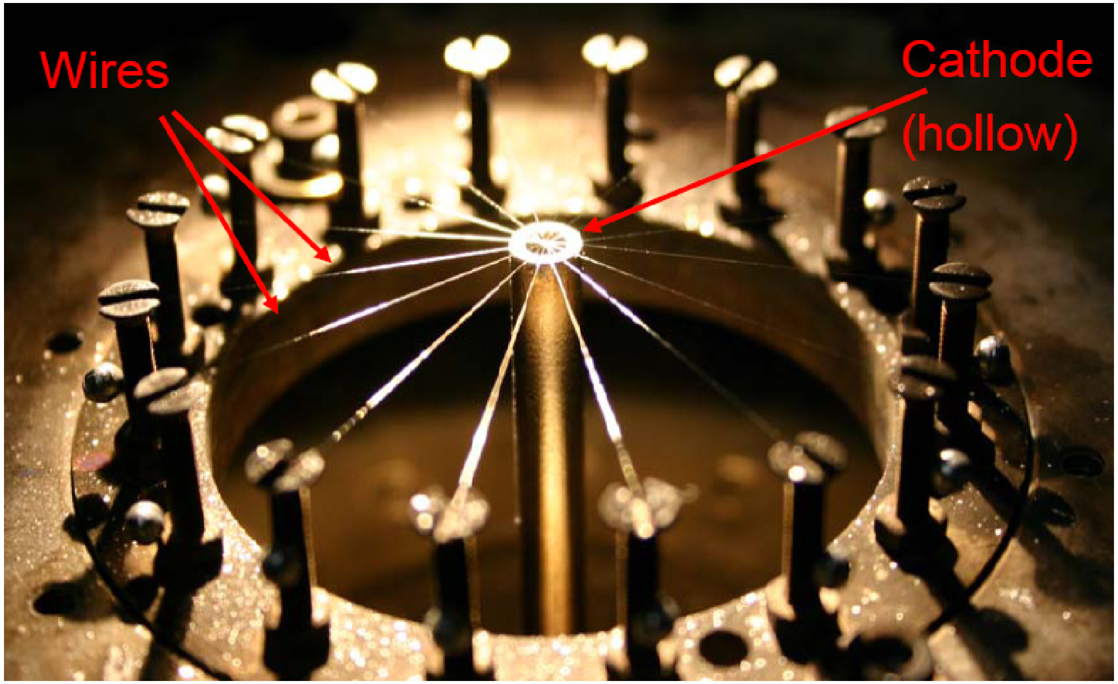
Possible experimental realisation

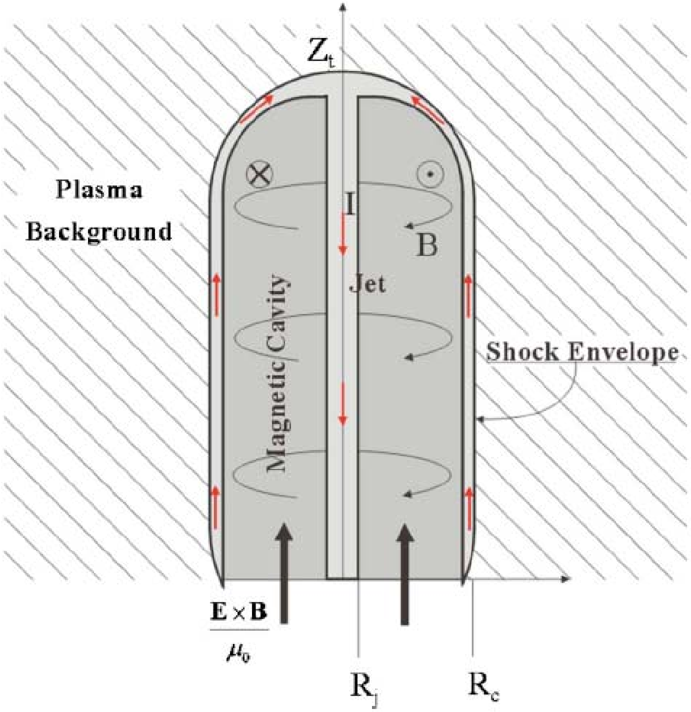


Experiment – dynamics of magnetic bubble driven by toroidal magnetic field

Schematic of the experiment

16 x 13μm W wires driven by 1MA, 250ns current pulse (~1 MG toroidal magnetic field)

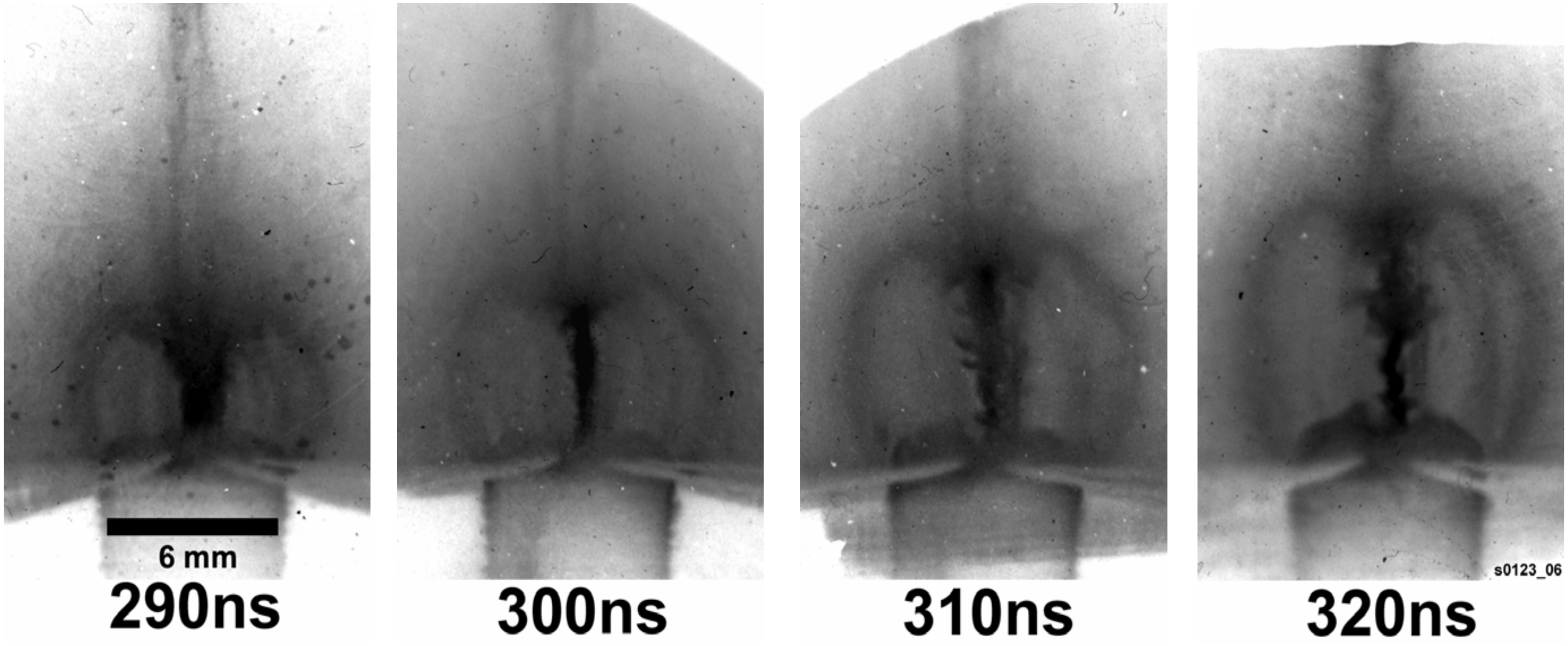




Evolution of the jet

W

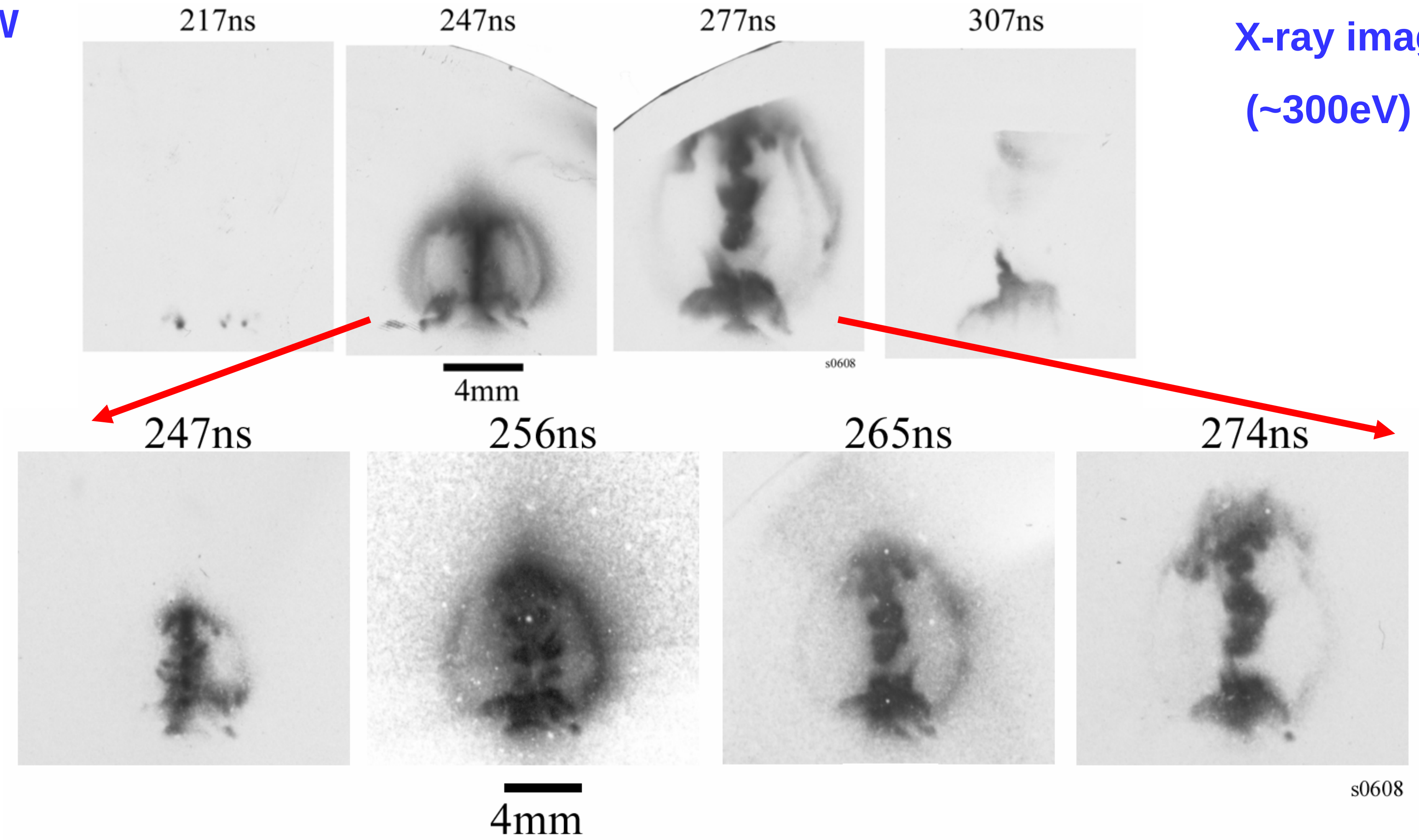
XUV emission



The jet demonstrates MHD instabilities typical for Laboratory plasmas (Z-pinch) but they do not destroy the jet

Evolution of the jet

W



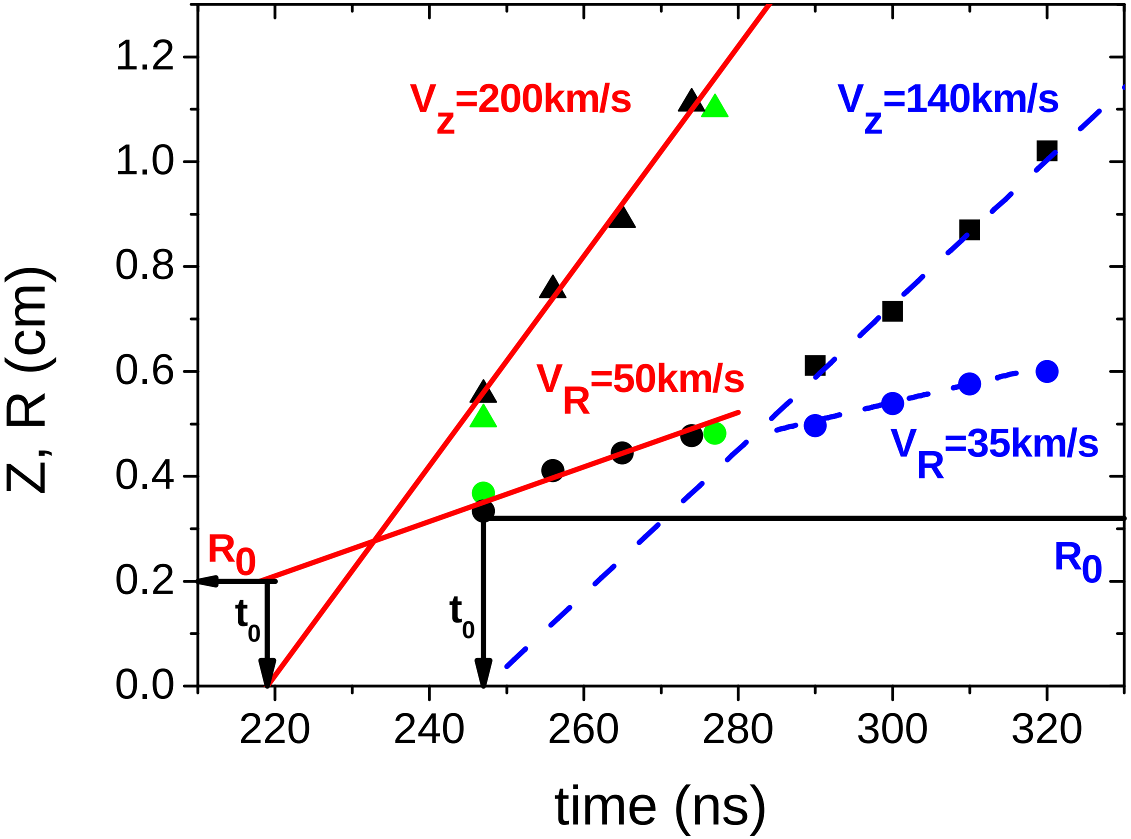
X-ray images

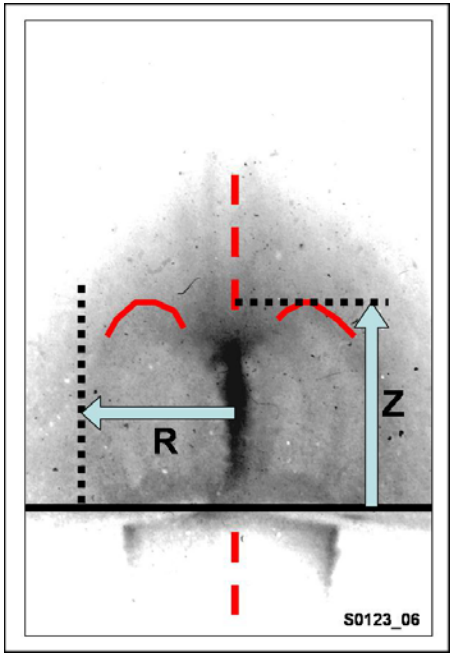
(~300eV)

The jet demonstrates MHD instabilities typical for Laboratory plasmas (Z-pinch) but they do not destroy the jet

Expansion can be controlled

Velocity of the emitting boundary





Electrode (or wire) diameter controls the duration of the ablation phase and thus the time of the magnetic bubble formation and the ambient density distribution.

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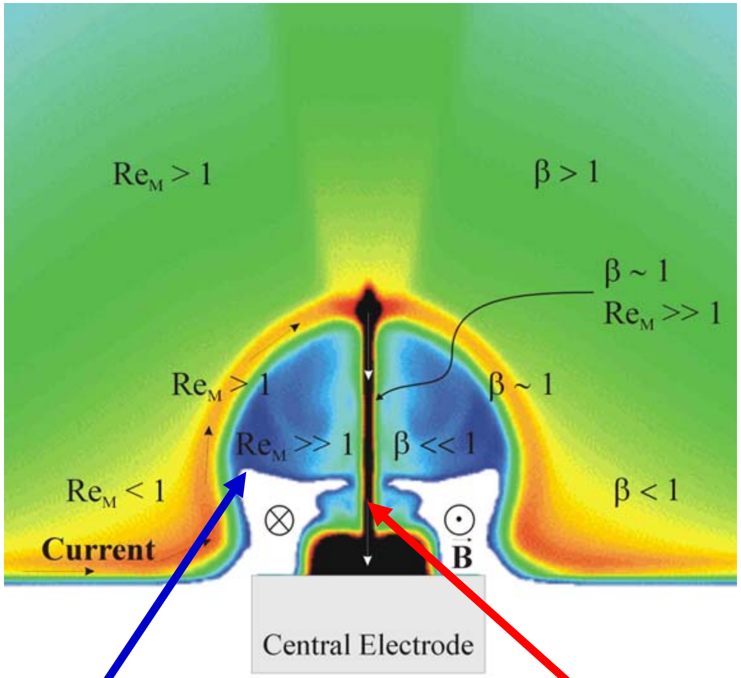
Structure of the "magnetic tower"

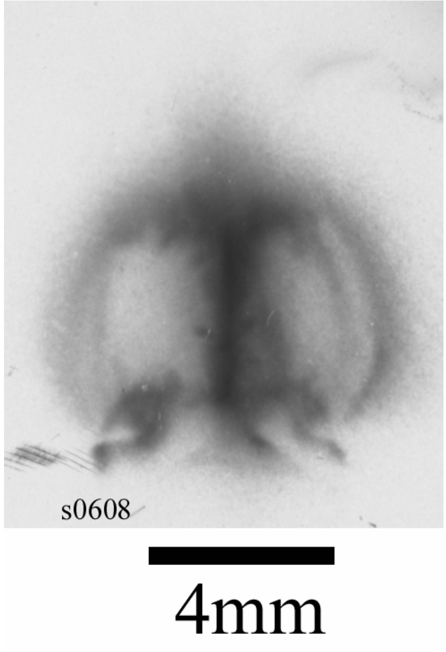
Dimensionless parameters from 2-D MHD simulations



Expanding magnetic bubble

Jet pinched by the toroidal magnetic field

Experiment: X-ray emission (~300eV)



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

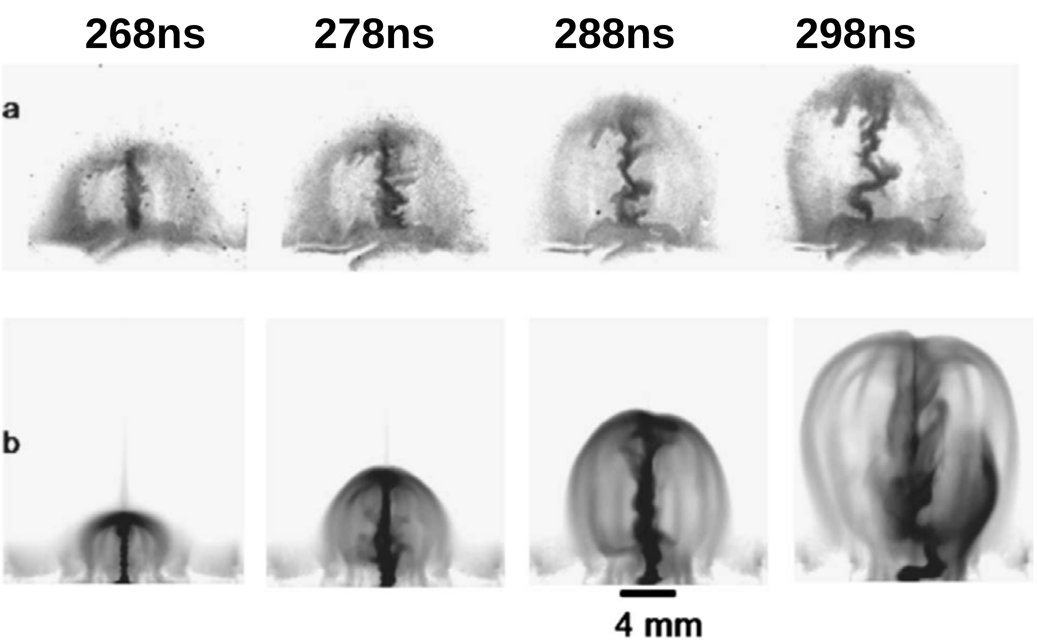
I ~ 1 MA, B ~ 100 T

Re > 10^4 , λ/R ~10^{-5} , Pe > 10

$\beta \sim 1$, Re_M ~50

Magnetic Tower jets in laboratory experiments

Experiment versus 3-D MHD



Jet driven by the pressure of the toroidal magnetic field

Collimation of the central jet by the hoop stress

Collimation of the magnetic bubble by the ambient medium

Instabilities do not destroy the jet but lead to variability of the flow

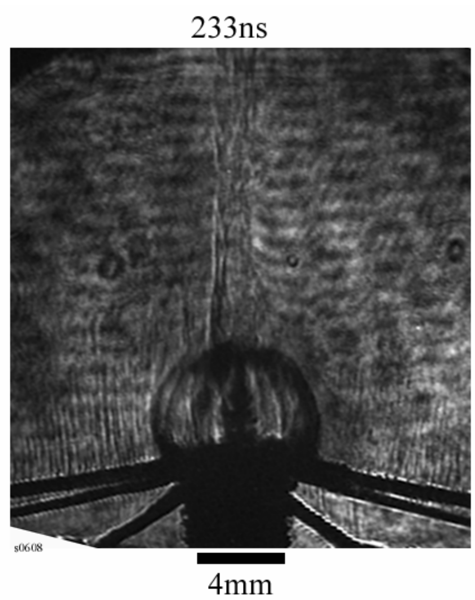
Variability of the jet emission

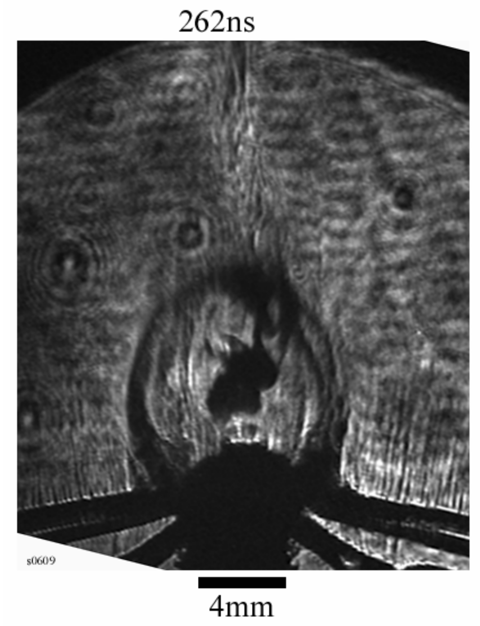
Two temporal scales for outflow variability:

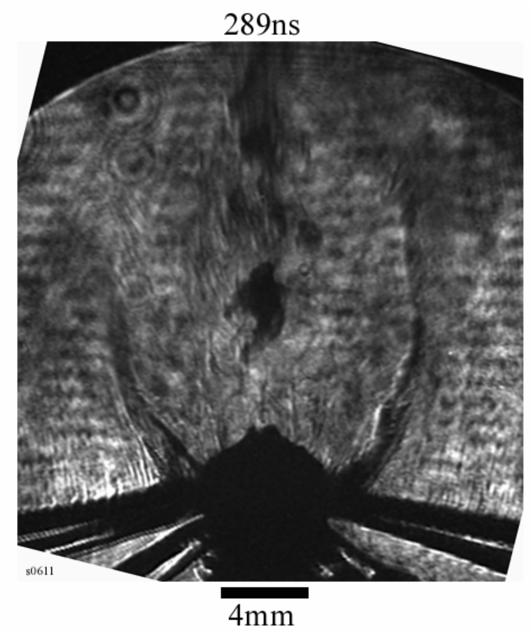
- fast – instability growth time
- slow – bubble growth time

Expansion of the “magnetic cavity”

Laser probing (shadow)



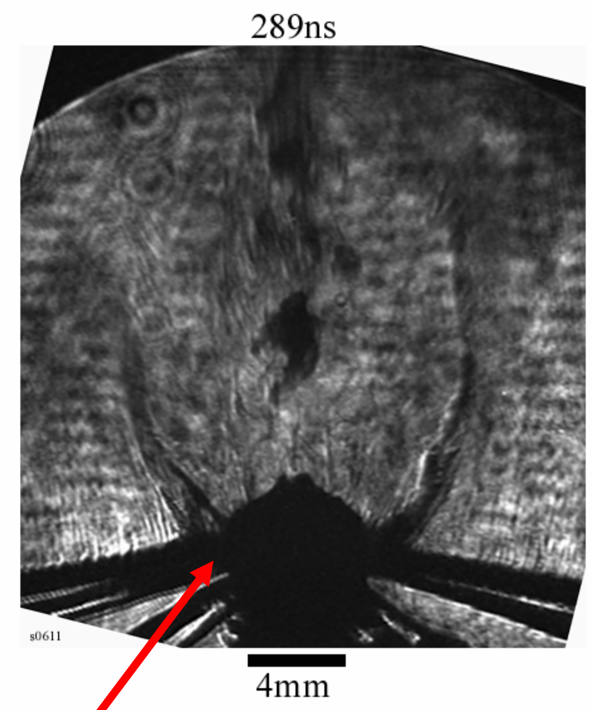




Expansion of the bubble is driven by the magnetic pressure ($B_{toroidal}$)

Expansion velocities: V_Z ~ 200 km/s, V_R ~ 50 km/s

MHD jet - summary



"Magnetic bubble" breaks when it reaches the region of too low ambient density

Jet is detached from the source

Clumps in the jet are result of MHD instabilities (assisted by radiative cooling)

$Re_M > 1 \Rightarrow B_{toroidal}$ could be trapped in the jet (need to measure)

<u>**What could happens next?**</u>

New material to reconnect the current through initial path (accretion?)

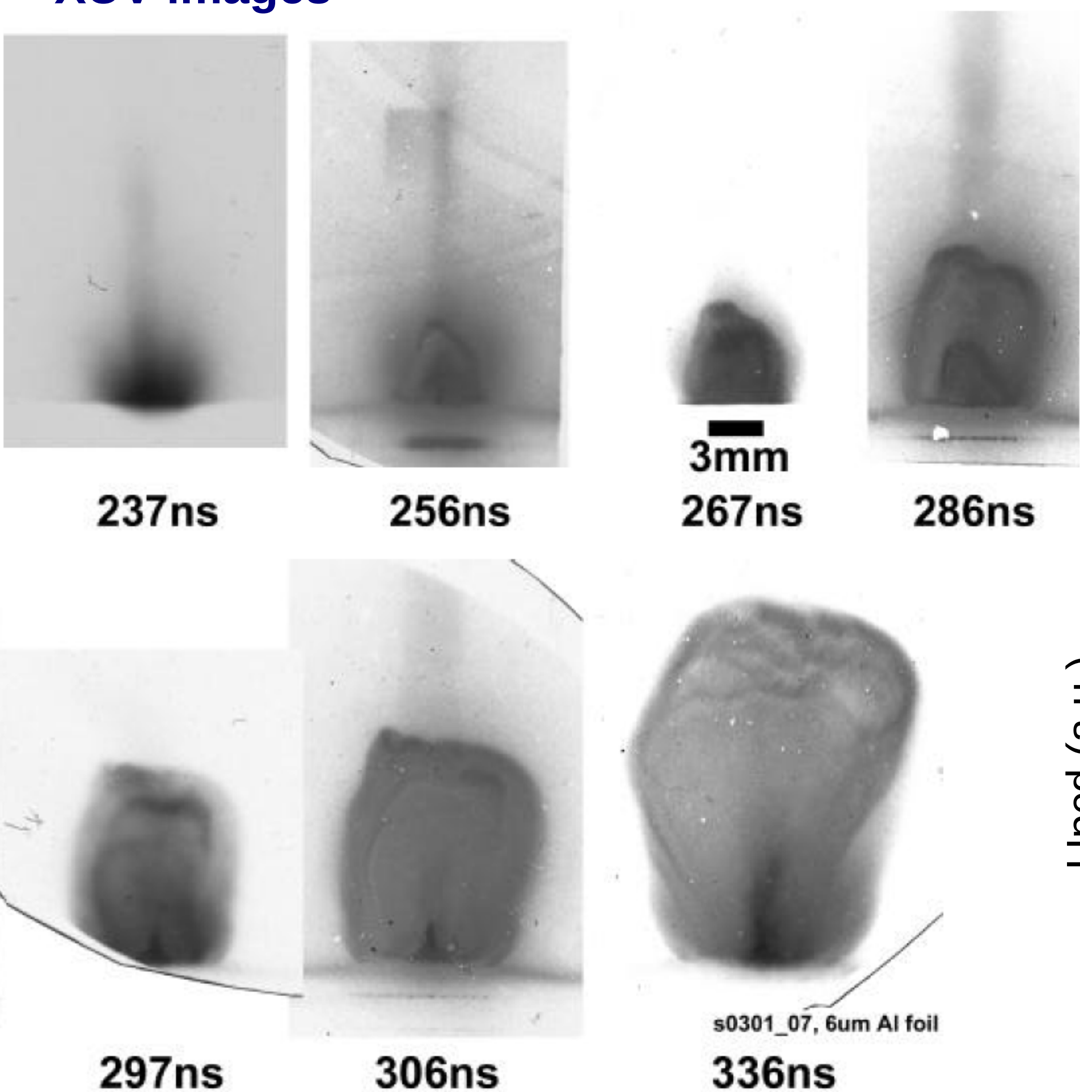
Formation of new magnetic bubble (twisting of B_p)

This is intrinsically time-dependent scenario with repeatable eruptions

Next jet episode in the experiments?

Episodic magnetic tower jet

XUV images

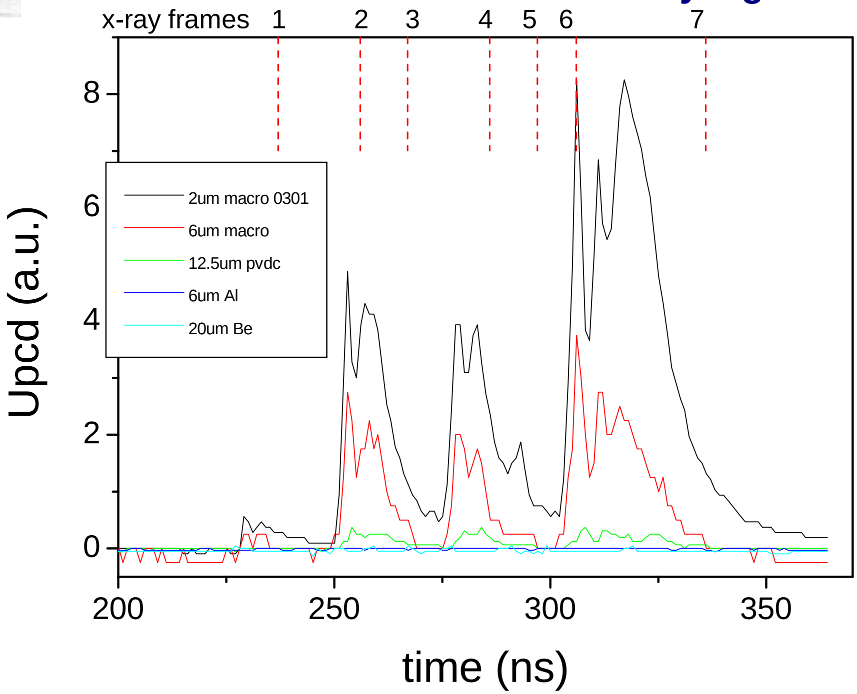


Radial foil instead of radial array

Reconnection of current at the base produces several magnetically driven bubbles

Subsequent magnetic bubbles move faster and collide with produced earlier

X-ray signals



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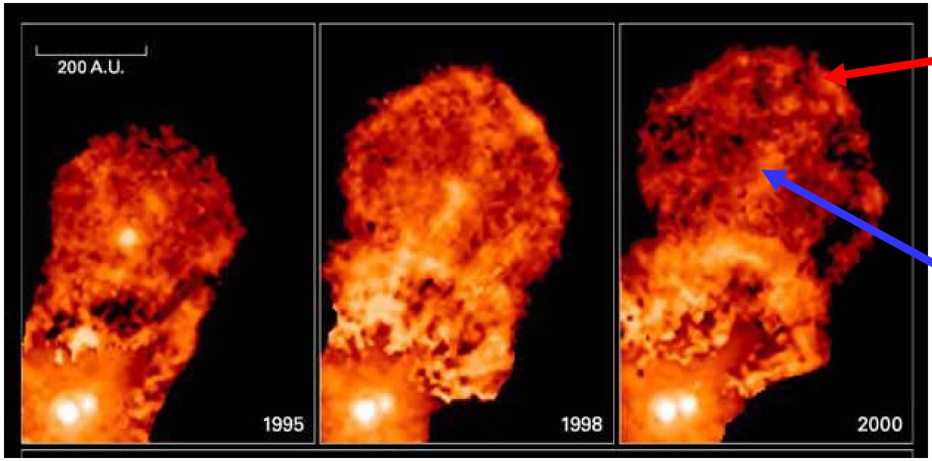
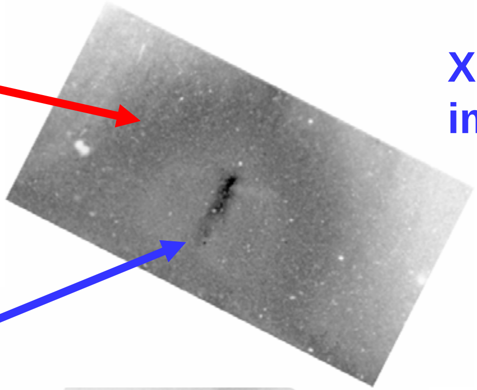
Analogy with astrophysical objects: is this more than just a similar look?

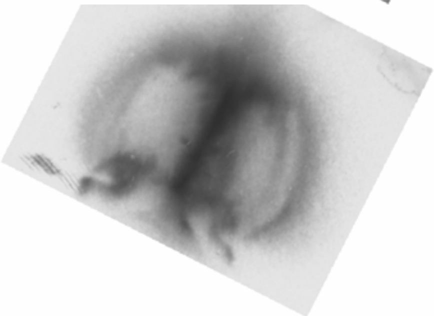
XZ Tauri



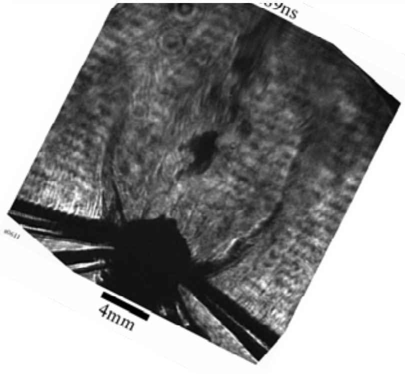
Experiment



XUV image

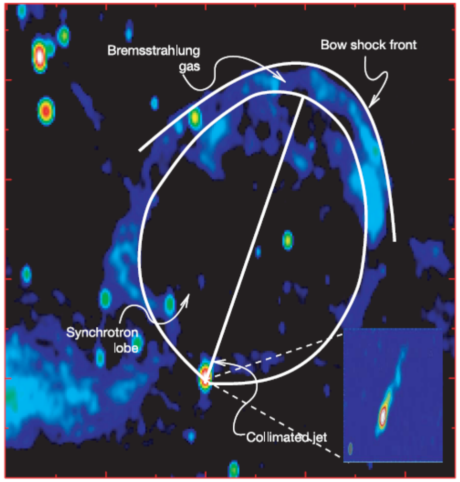


X-ray image



Laser shadow

Cygnus X-1

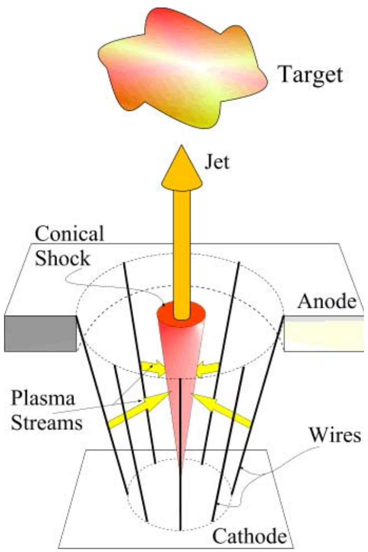


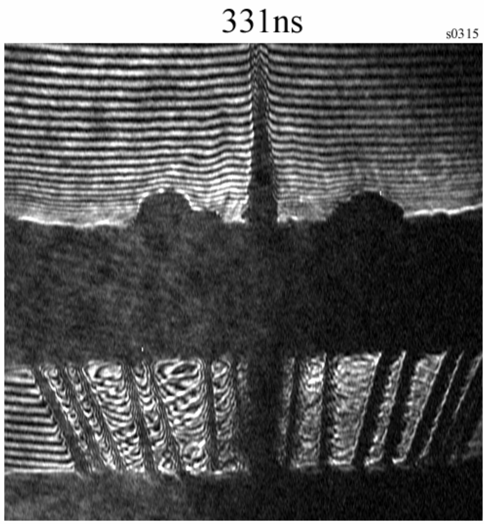
Similarities:

Hot collimated jet (x-ray in experiment, optical in observations)

surrounded by a lower temperature bubble (XUV in experiment, IR in observations)

Plasma jet in conical wire array Z-pinch



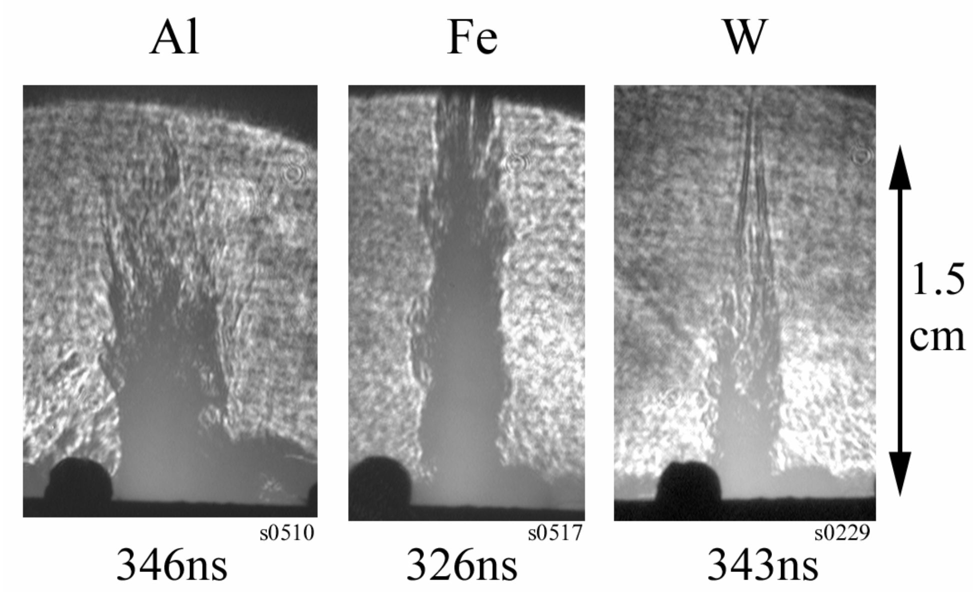


Lebedev et al., ApJ 2002

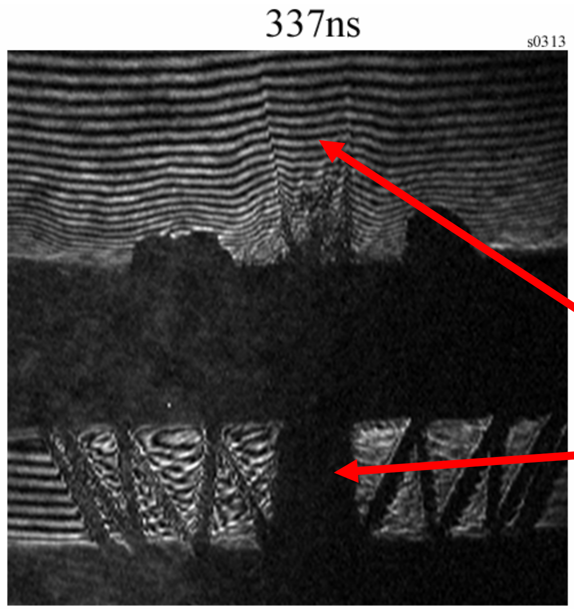
- **Converging plasma flow is re-directed by a standing conical shock**
- **Radiatively cooled jet with M >20**
- **Jet velocity ~ 200km/s**
- **Electron density 10^{18}-10^{19} cm^{-3}**

$\lambda/R < 10^{-4}$ Re > 10^4 Pe > 10-50

Radiative cooling affects jet collimation



Jets with angular momentum in conical arrays



Twisted conical arrays:

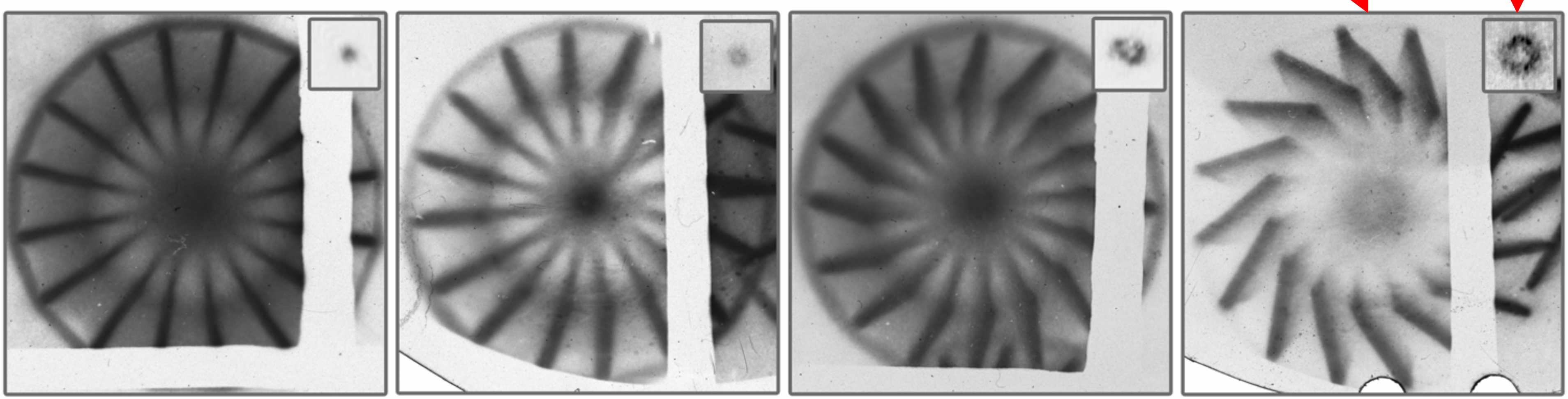
$$V_\varphi \propto j_r B_z$$

B_z magnetic field

converging flow with azimuthal velocity

Hollow standing shock and rotating jet

XUV X-ray



$\vartheta = 0$ $\vartheta = 2\pi/64$ $\vartheta = 2\pi/32$ $\vartheta = 2\pi/16$

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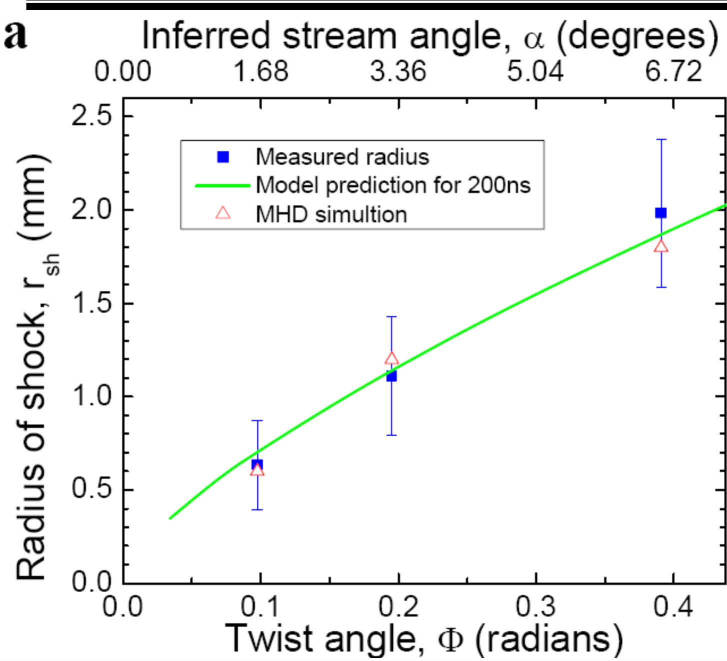
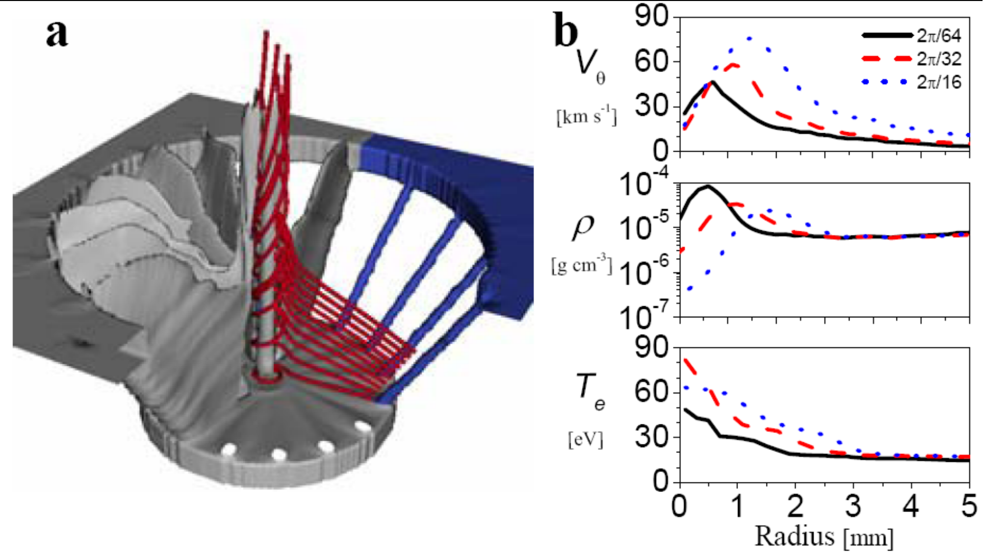
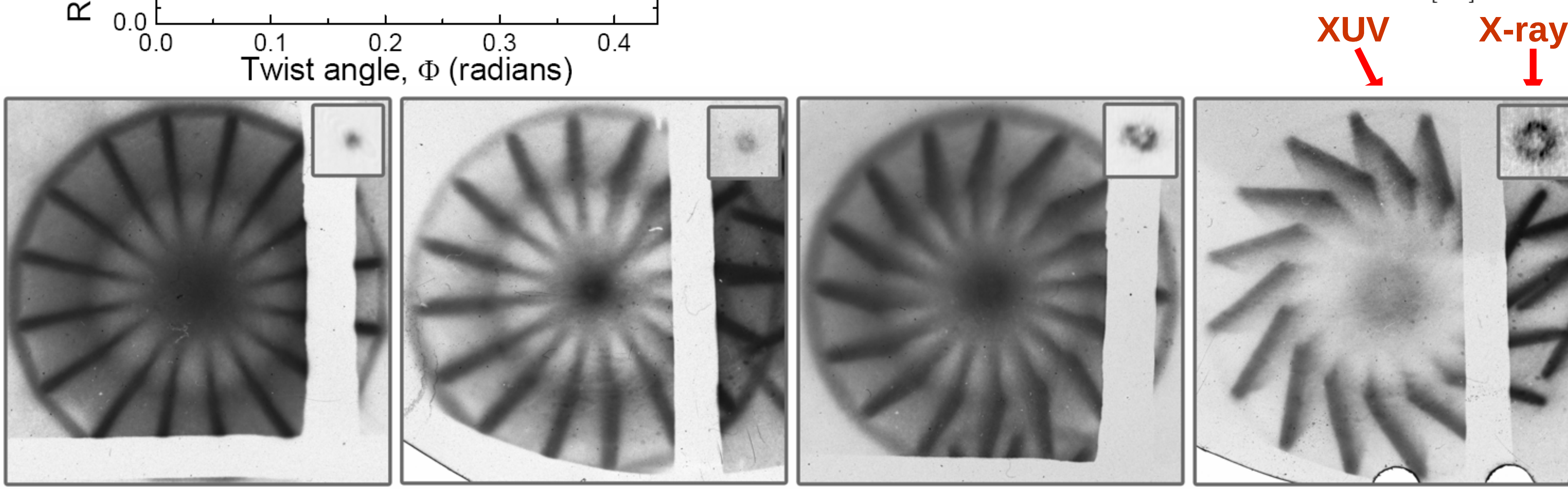
Jets with angular momentum in conical arrays







ϑ = 0 ϑ = 2π/64 ϑ = 2π/32 ϑ = 2π/16

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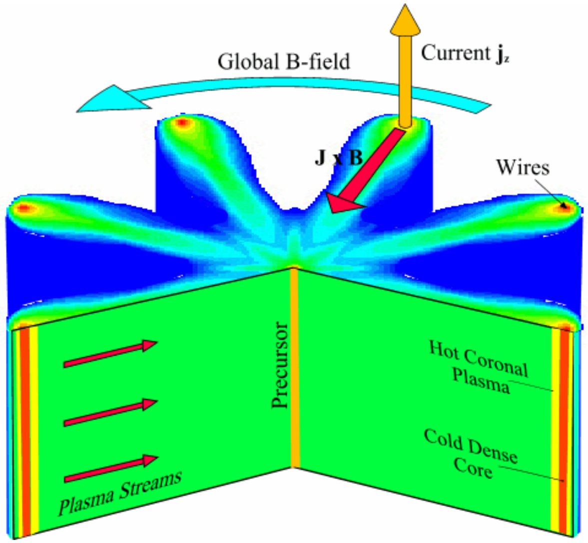
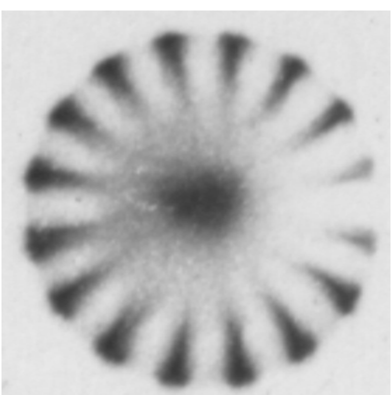
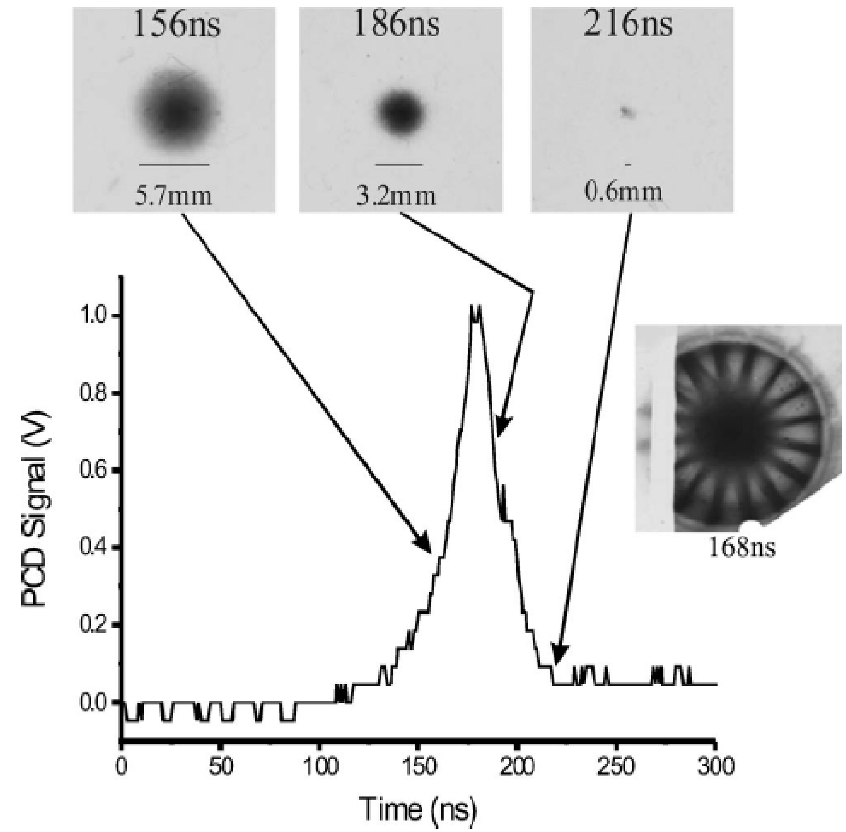
Precursor plasma flow in wire array Z-pinches





Onset of collisionality and formation of standing radiatively cooled shock

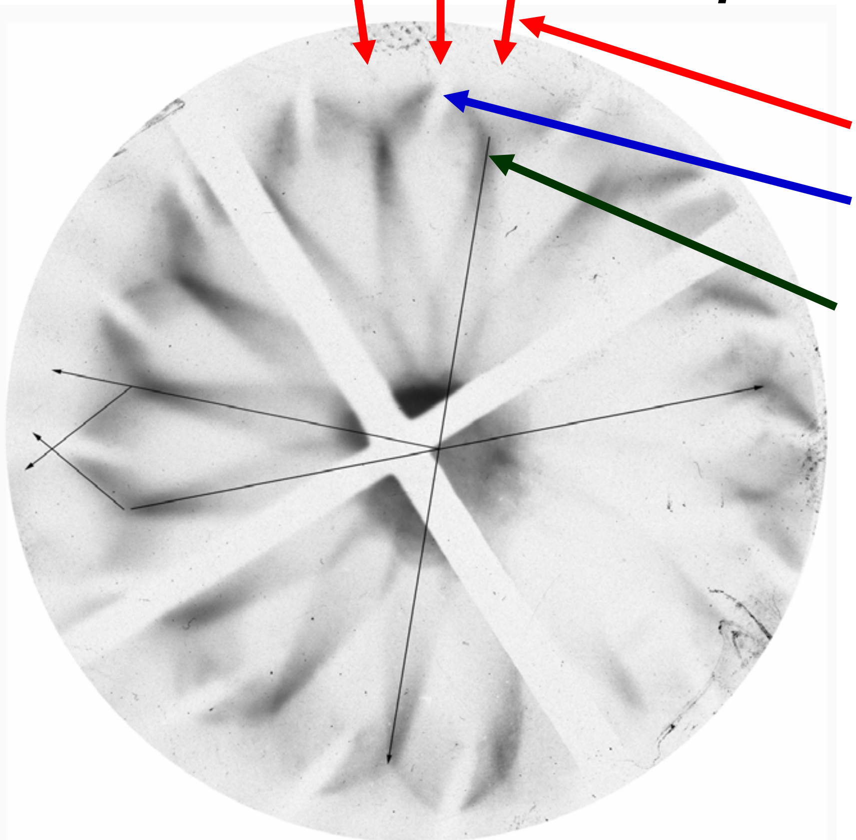


Plasma flow:

V ~ 150 km/s,
Mach number ~5

Formation of shocks in converging flow

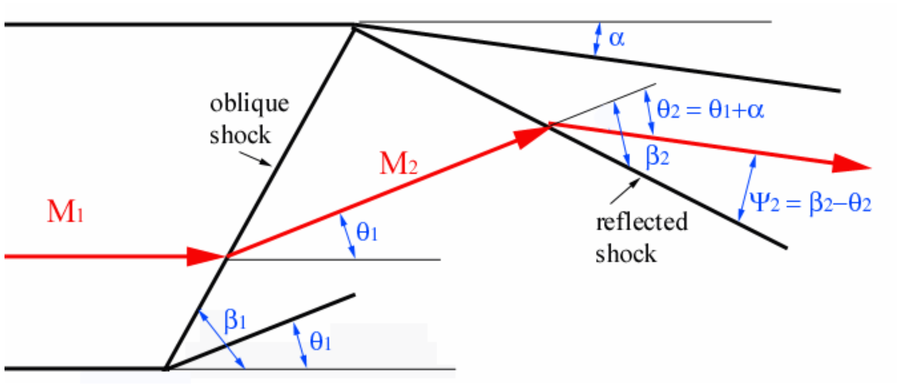
Test problem for hydro codes with radiative cooling



Cylindrically converging plasma flow

Small obstacles produce bow shocks

Collision of these oblique shocks produces reflected shocks

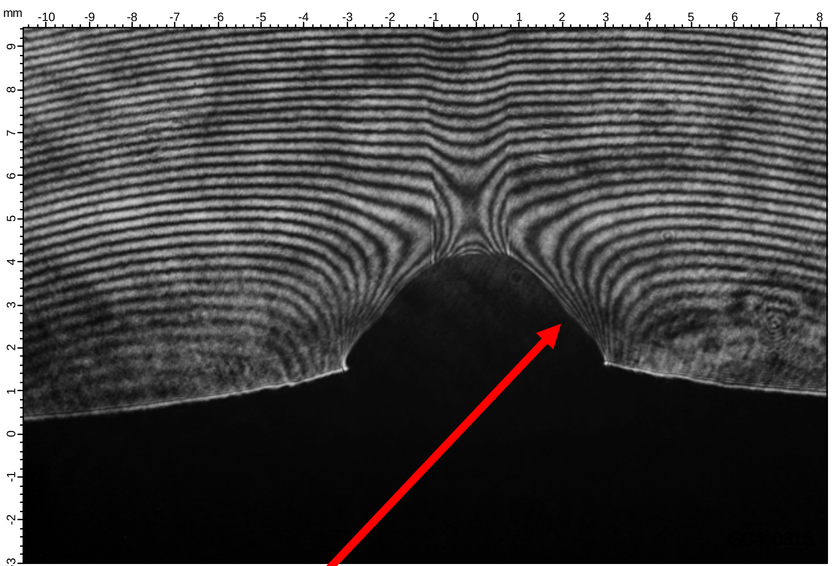


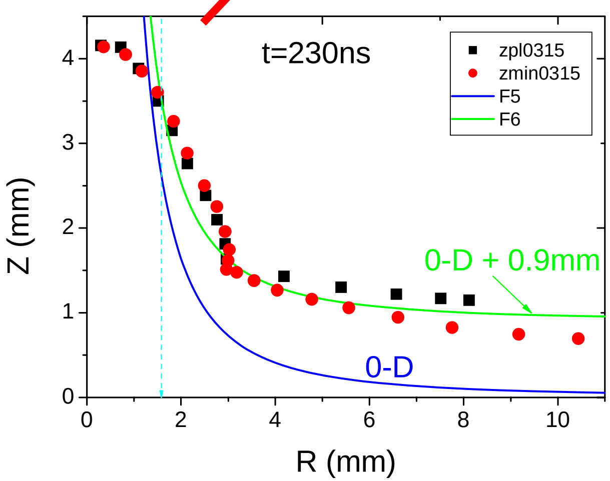
Shock geometry corresponds to M_1 ~ 10, γ ~ 1.1

Addition of magnetic fields (B_θ or B_z) is possible

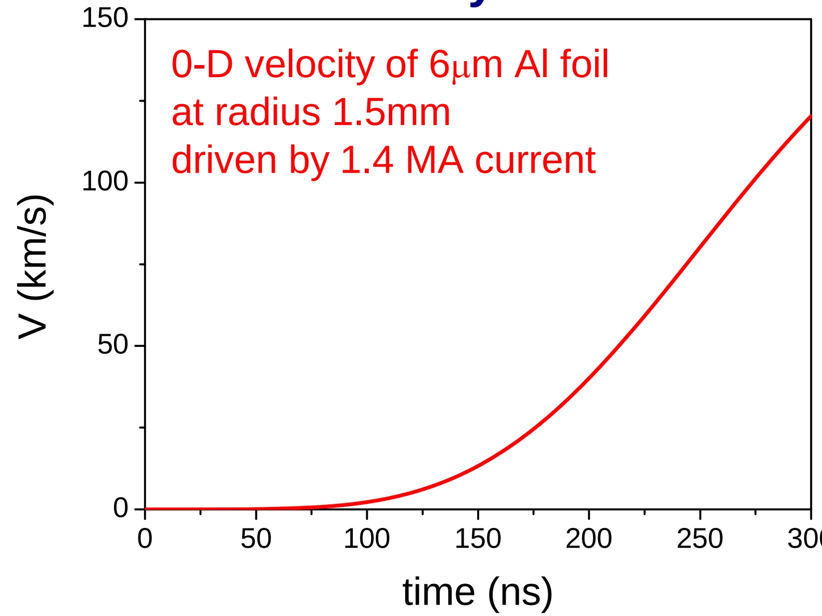
Radial foil Z-pinch can drive shocks in gas targets

Boundary of the bubble moves as expected from 0-D model





0-D velocity of the foil



Axial motion of the radial foil can be used to drive ~100km/s shocks in high Z (e.g. Xe) gas targets

Summary

Wire array Z-pinches provide natural way for introducing dynamically significant magnetic fields into laboratory plasma jet experiments. The dimensionless parameters of these jets are in astrophysically relevant regime (Re, Re_M, M, β, χ).

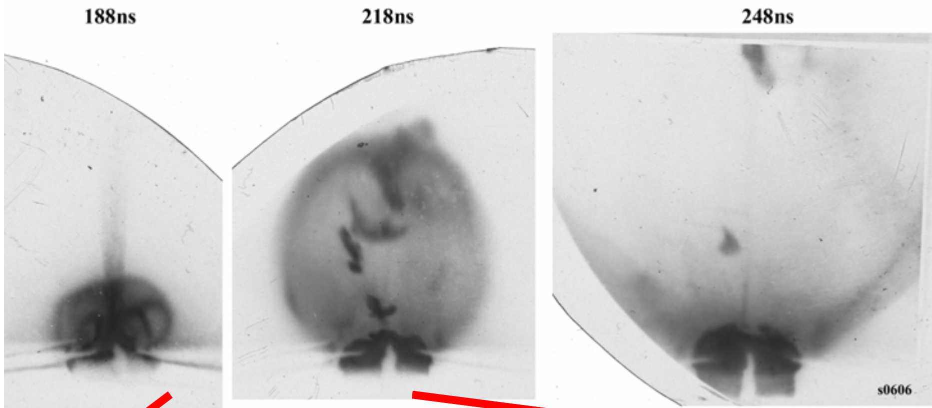
<u>Interface with astrophysics:</u>

in Europe: JETSET network (10 university groups, mostly astro)

in USA: A. Frank (Rochester) and R. Lovelace (Cornell)

Evolution of the jet with a smaller cooling rate

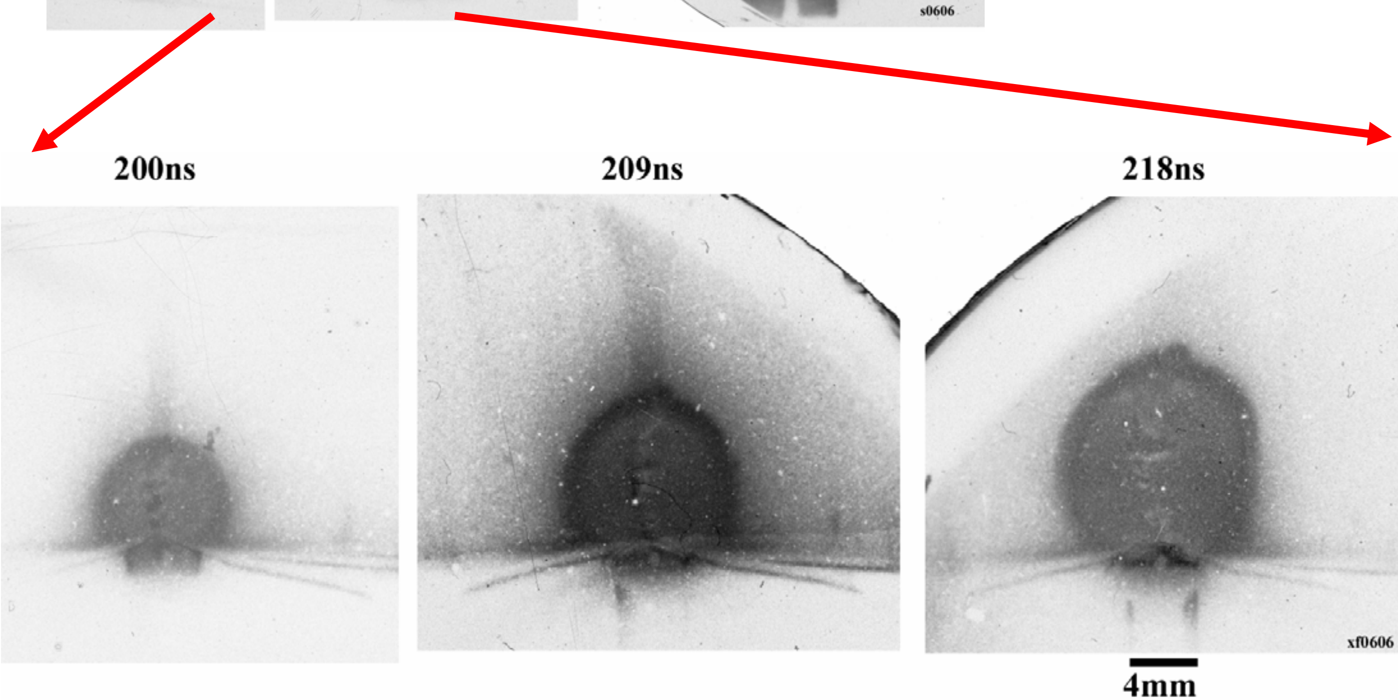
Al



Different material (Al), smaller cooling rate

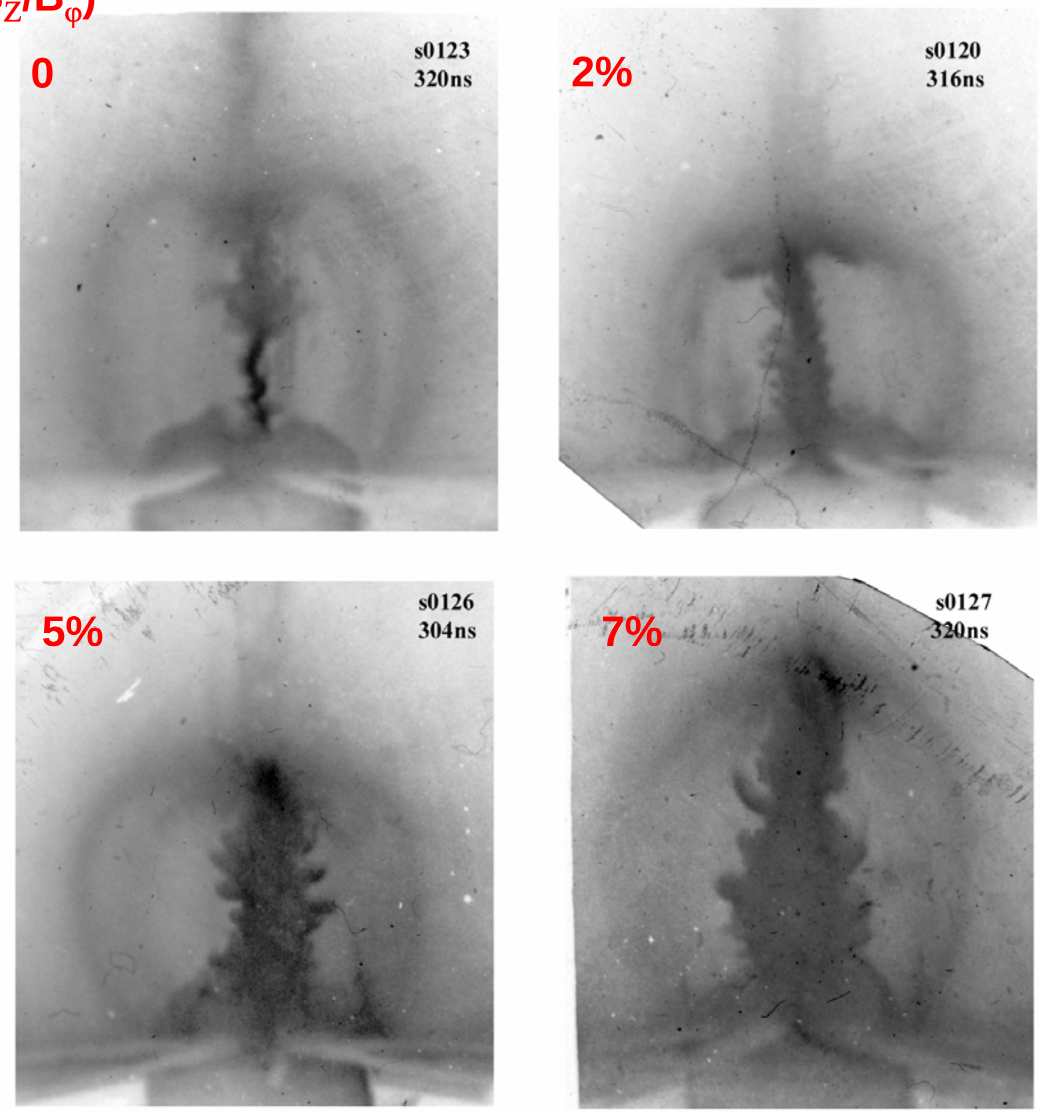
Similar dynamics of the magnetic bubble

More unstable central jet



Effect of poloidal magnetic field on the jet

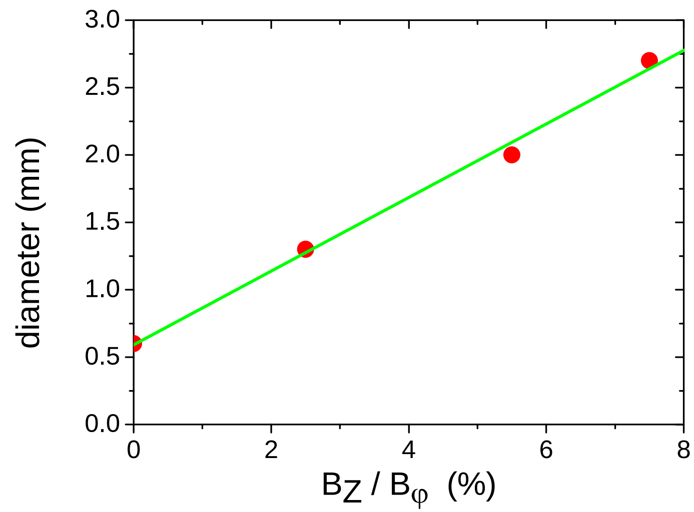
(B_Z/B_φ)



"Vacuum" B_z is relatively small

No influence of B_Z on the bubble evolution

Increase of central jet diameter could be due compression of the B_z magnetic flux or presence of angular momentum



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