Radiatively Cooled Supersonic Jets and Shocks in Laboratory Plasma Experiments

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in collaboration with

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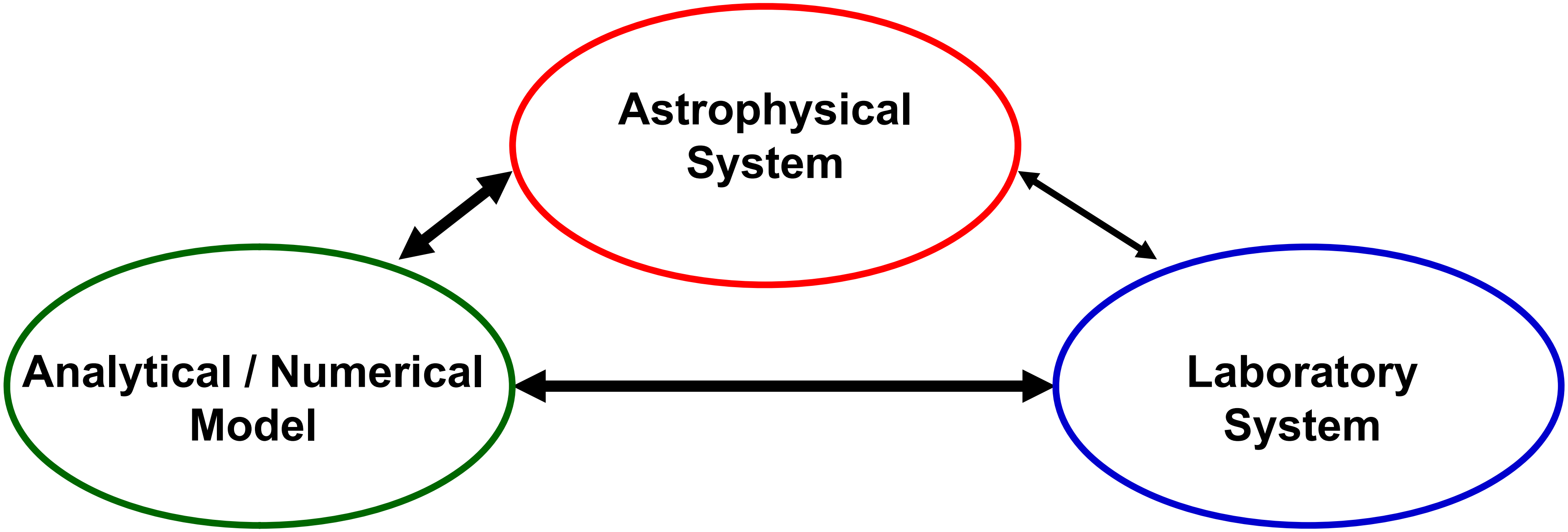
Astrophysical Dynamics in Laboratory



Scaled representation of astrophysical plasma dynamics:

- Laboratory and astrophysical phenomena are described by the same set of equations
- Dimensionless numbers and similarity transformations
- Creating appropriate initial conditions (morphology)
- Establish how long the similarity holds

Remington, Drake, Ryutob, Rev. Mod Phys., 2006

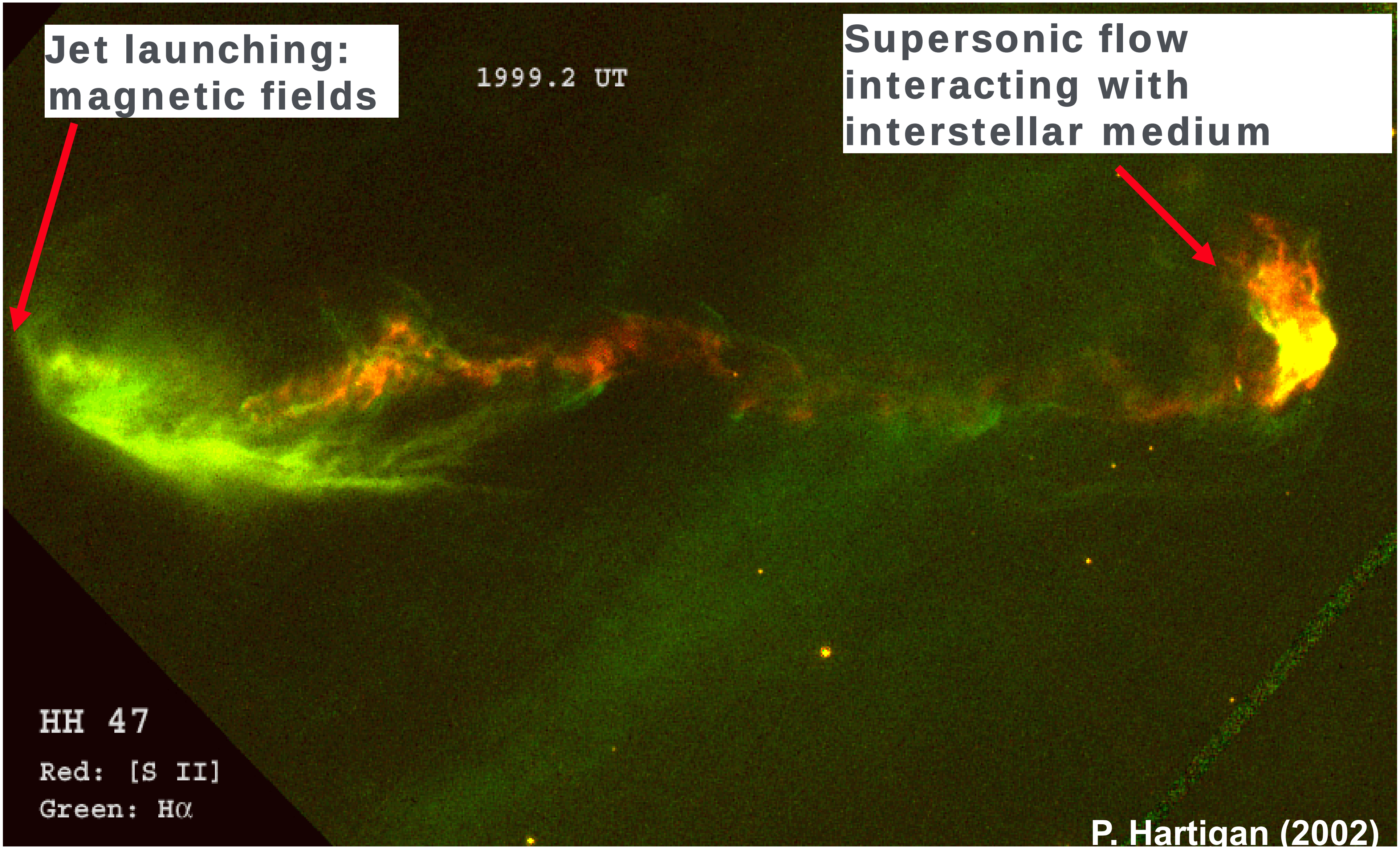
Outline

1. Laboratory modeling of jets from young stars
   - Jet launching – MHD jets
   - Jet-ambient interaction – effects of radiative cooling
2. Shocks in colliding plasma flows

Common theme – interaction of supersonic plasma flows

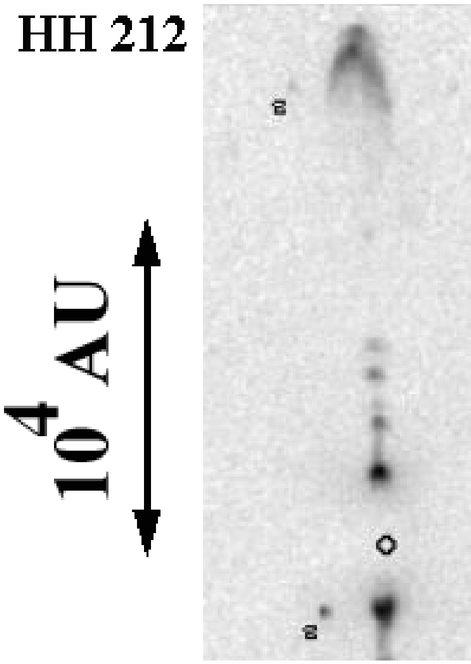
(compressibility, radiative cooling, ionisation balance, MHD)

"Movie" from HST observations of a proto-stellar jet



Scaling of laboratory jets

Space ← **similarity** → **Experiment**



"shape" & dimensionless parameters:

Mach number

M ~ 10 – 50

Density contrast: jet / ambient

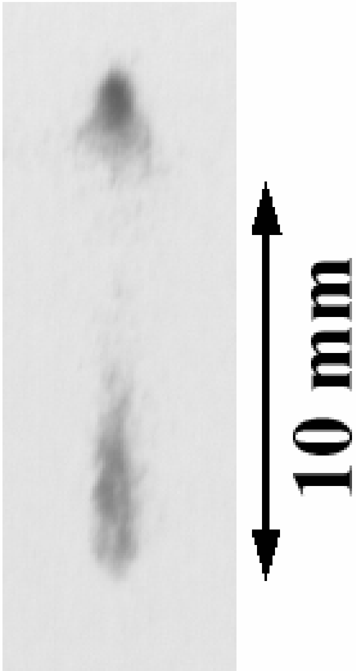
η ~ 1-10

Cooling parameter

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

Magnetic fields:

β ~ 1



$\lambda/R \ll 1$, $Re \gg 1$, $Re_M \gg 1$, $Pe \gg 1$

[1] D.D. Ryutov et al., Astrophys. J. 518, 821 (1999) and Astrophys. J., Suppl. 127, 465 (2000)

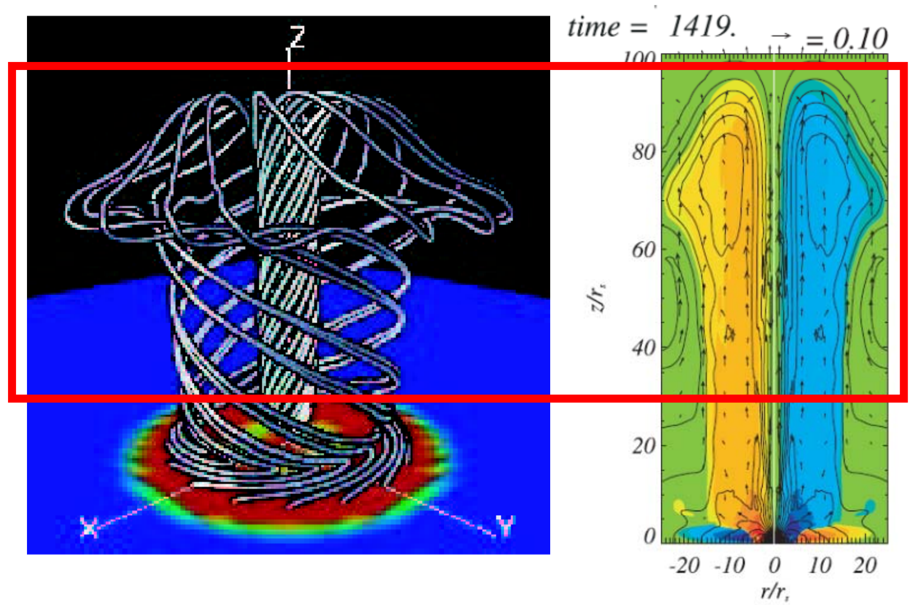
Jets launching - magnetic fields

Astrophysical models:

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

Launching and collimation of the outflow by the magnetic fields

Kato, 2004



Some unanswered questions:

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

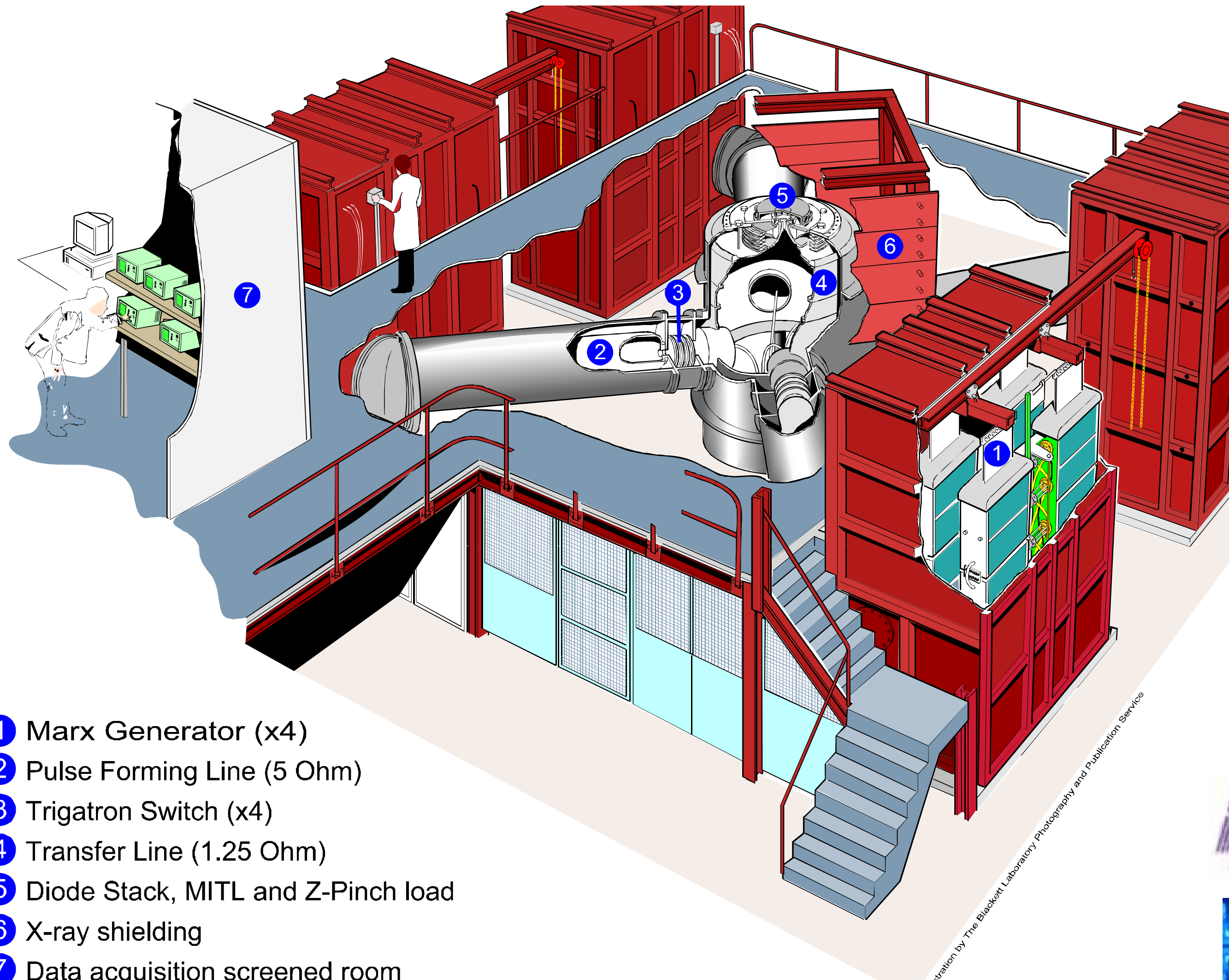
Models are steady-state, but observations show strong variability in both density and velocity.

Experiment:

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

MAGPIE Z-pinch facility

1TW, 1.5MA, 250ns



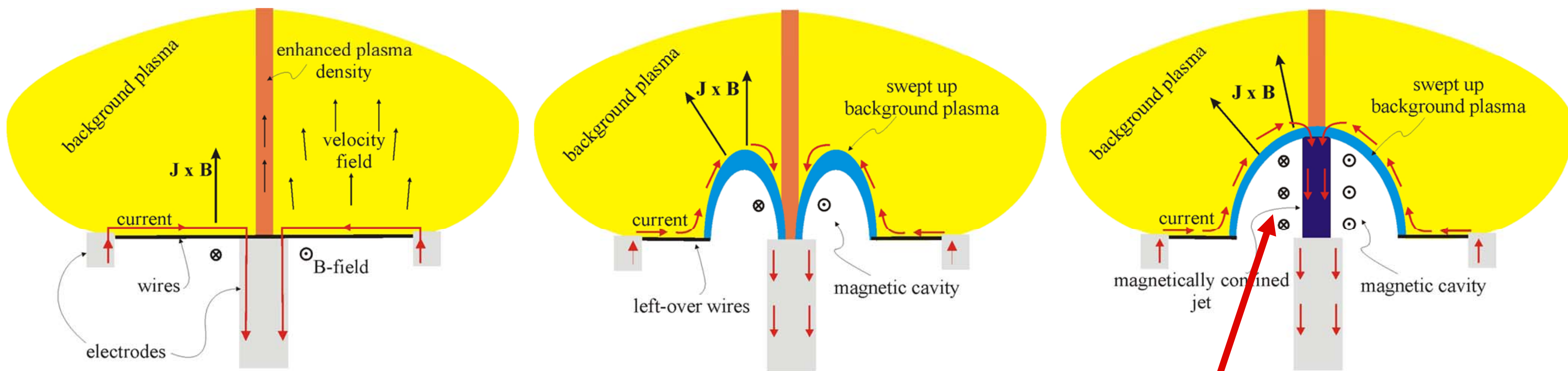
1. Marx Generator (x4)
2. Pulse Forming Line (5 Ohm)
3. Trigatron Switch (x4)
4. Transfer Line (1.25 Ohm)
5. Diode Stack, MITL and Z-Pinch load
6. X-ray shielding
7. Data acquisition screened room

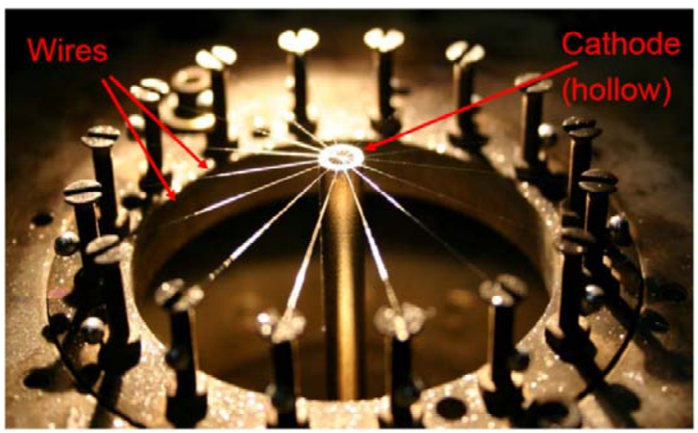
NNSA National Nuclear Security Administration

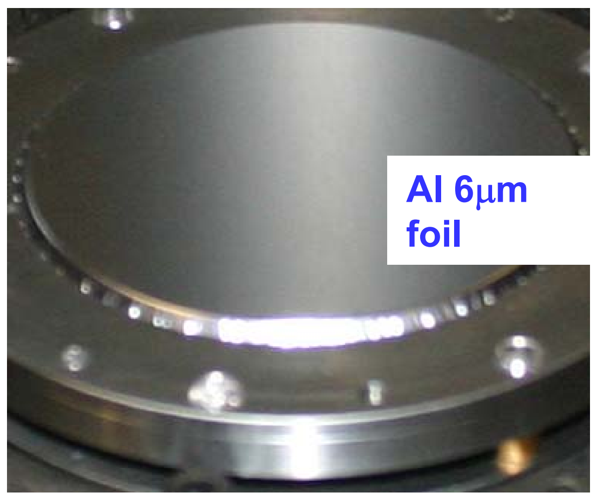
JeTseT

Sandia National Laboratories

Magnetically driven jets: schematic of the experiment





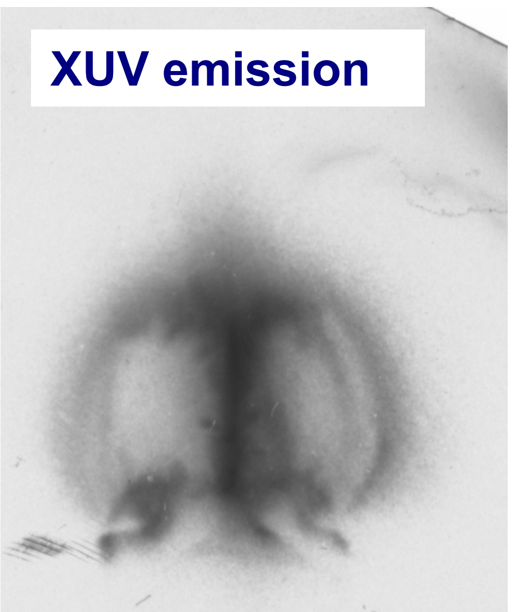


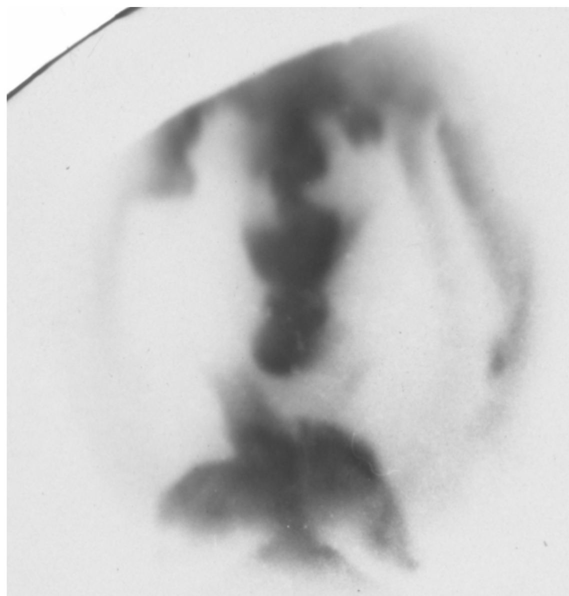
Magnetically confined jet on the axis of magnetic cavity expanding through ambient plasma

Lebedev et al, MNRAS (2005), Ciardi et al, ApJL (2009), Suzuki-Vidal et al, PoP (2010, 2012)

Magnetically driven jet – single episode

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

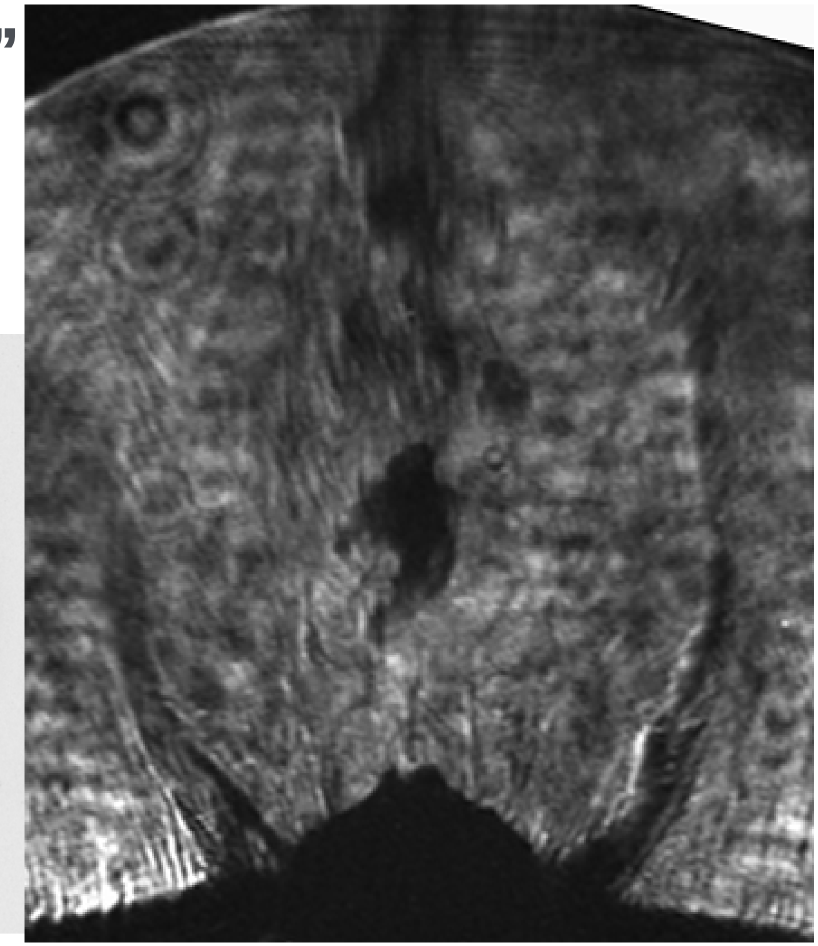




4mm

s0608

Laser shadowgraphy

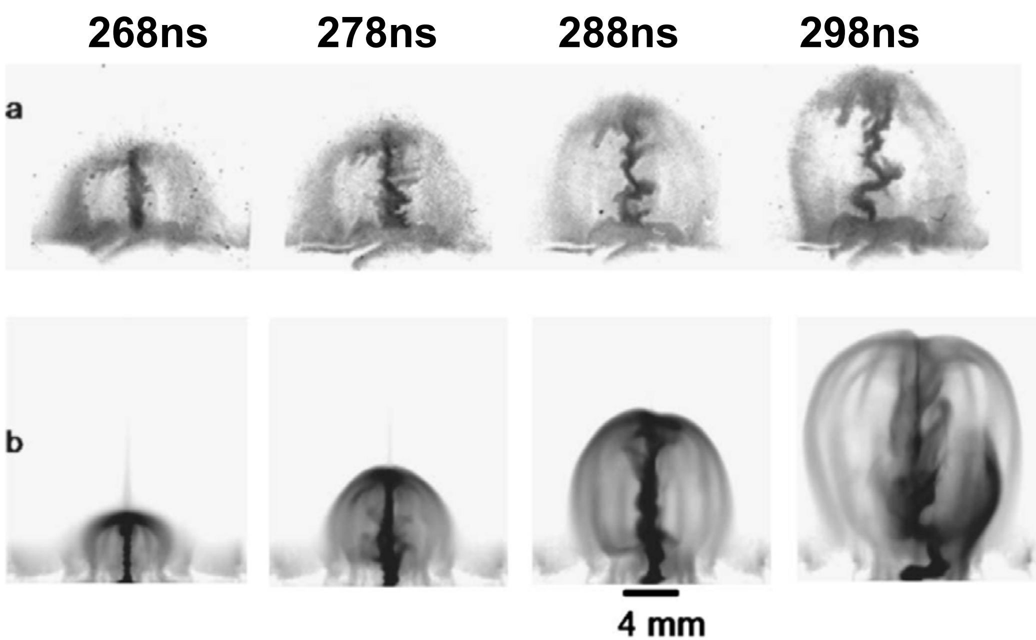


V~200km/s, β ~ 1

Dynamics of Magnetic Tower jets

Experiment versus 3-D MHD

Ciardi et al, PoP 2007



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

I ~ 1 MA, B ~ 100 T

Re > 10^4 , $\lambda/R \sim 10^{-5}$, Pe > 10

$\beta \sim 1$, $Re_M \sim 50\text{-}300$

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

Two temporal scales for outflow variability:

- fast – instability growth time (~1ns)
- slow – bubble growth time (~50ns)

<u>Instabilities do not destroy the jet but produce a clumpy outflow</u>

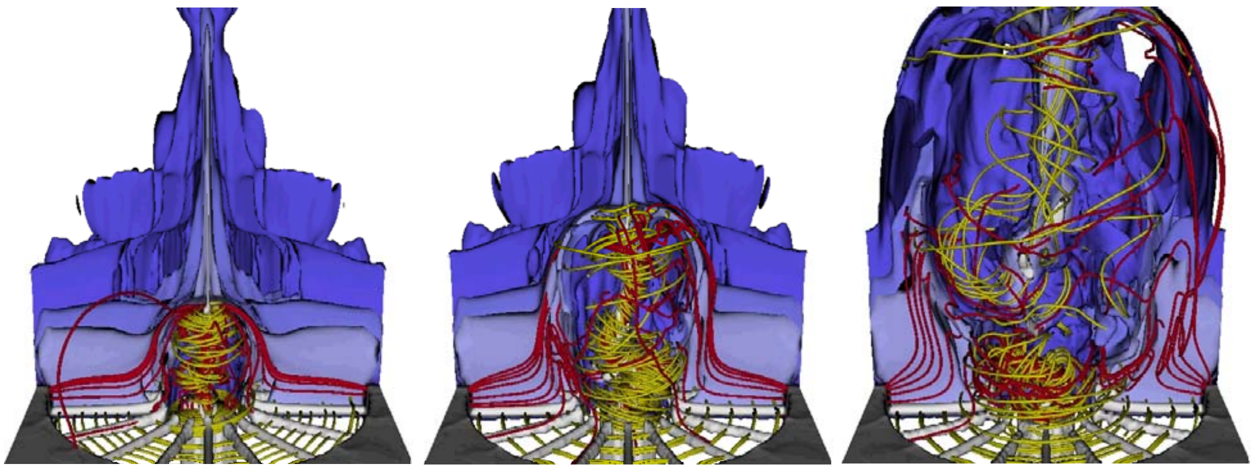
Magnetically driven jet – MHD simulations

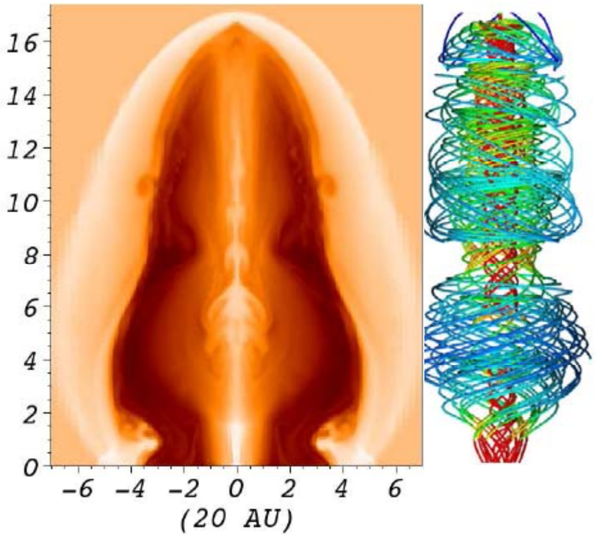
Simulations with laboratory code

Ciardi et al, PoP 2007

Astrophysical code

Huarte-Espinosa et al, 2012





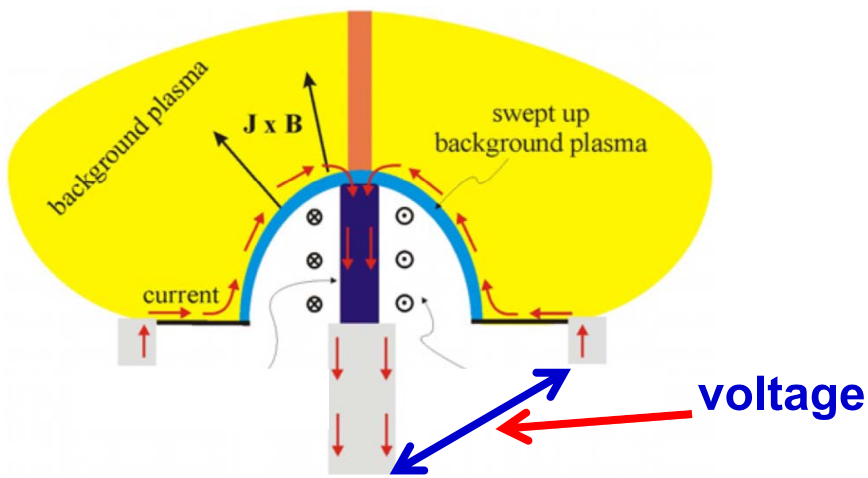
Magnetic cavity (β <<1) with dense jet on axis (β ~1)

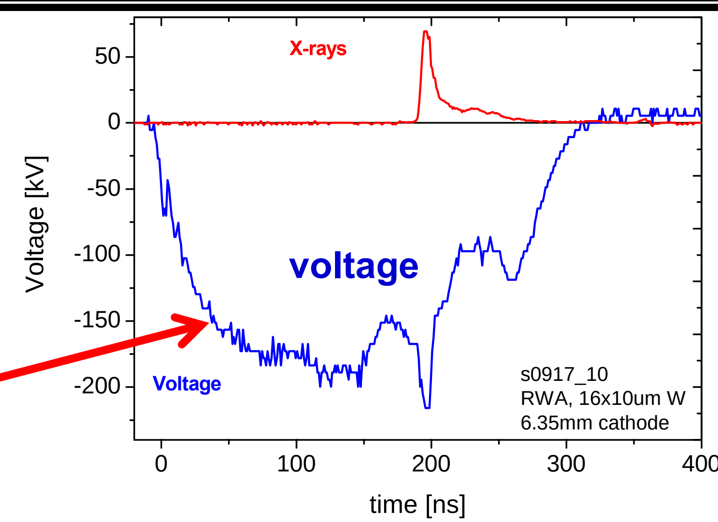
MHD instabilities, change of magnetic field topology ($B_\varphi \rightarrow B_z$, B_r)

Energy balance: Poynting flux, magnetic energy, kinetic energy, radiation.

Difference in how the mass and Poynting energy are injection

Non-MHD effects (fast particles)





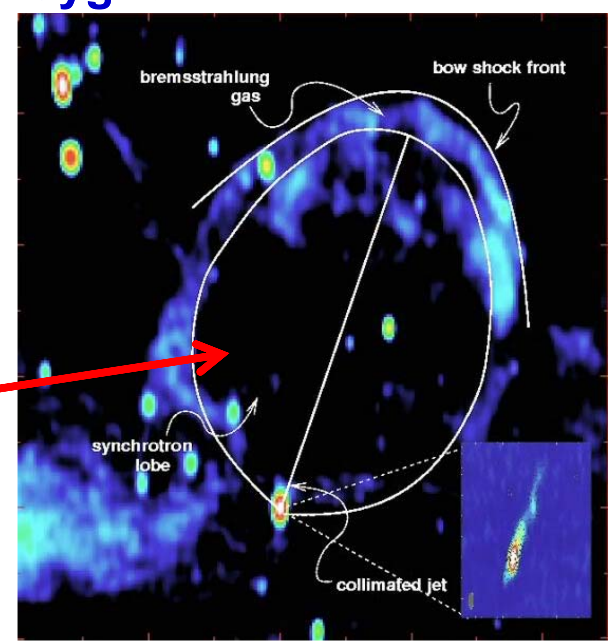
High voltage at the base of the jet at the time of the jet formation

Trapping of energetic particles in the magnetic cavity?

~ 200 keV protons, B ~ 0.5 MGs, ρ_L ~ 1mm

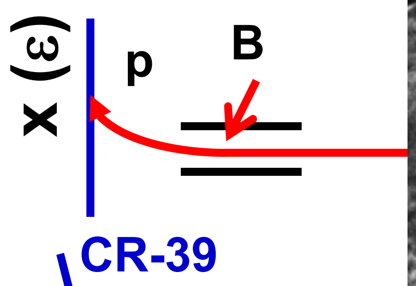
There is observational evidence of trapped particles in e.g. AGN jets (synchrotron radiation)

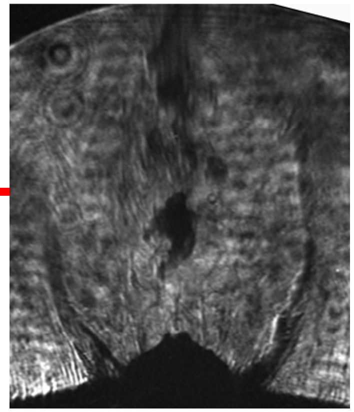
Cygnus X-1 **Gallo et al 2005**



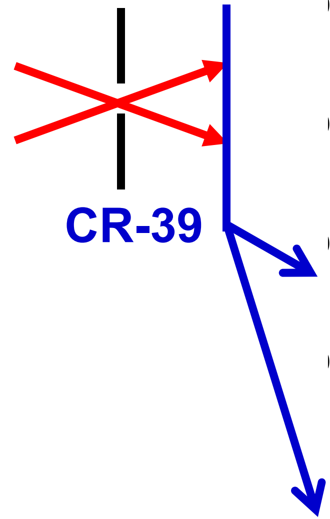
Trapped particles – proton emission images

Magnetic spectrometer

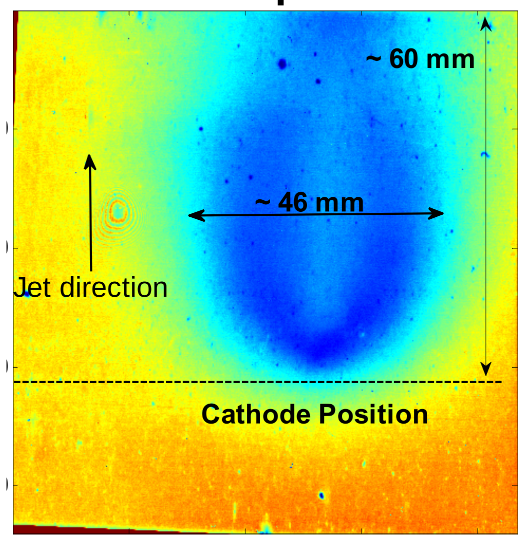




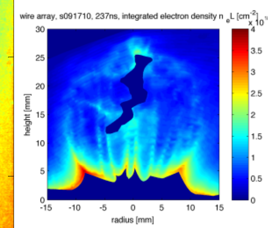
Proton pin-hole camera



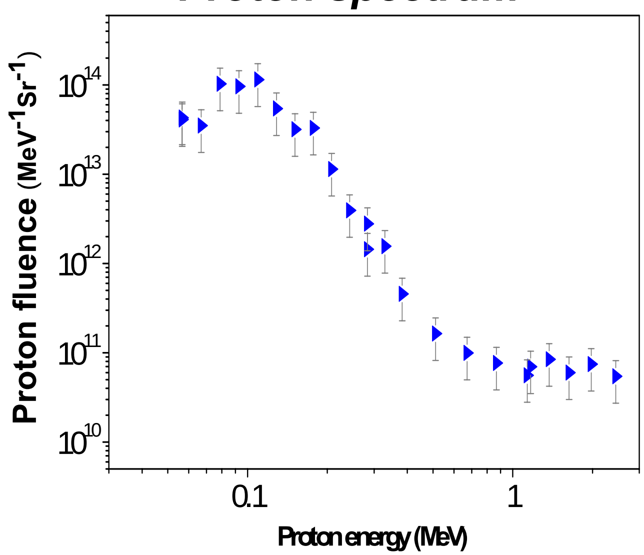
1 mm pinhole



Electron density map

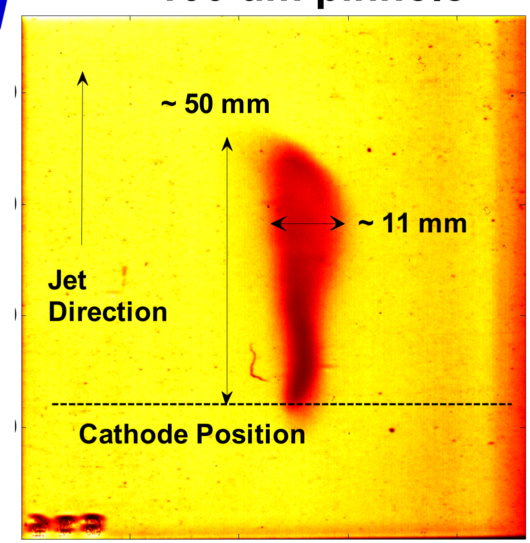


Proton spectrum



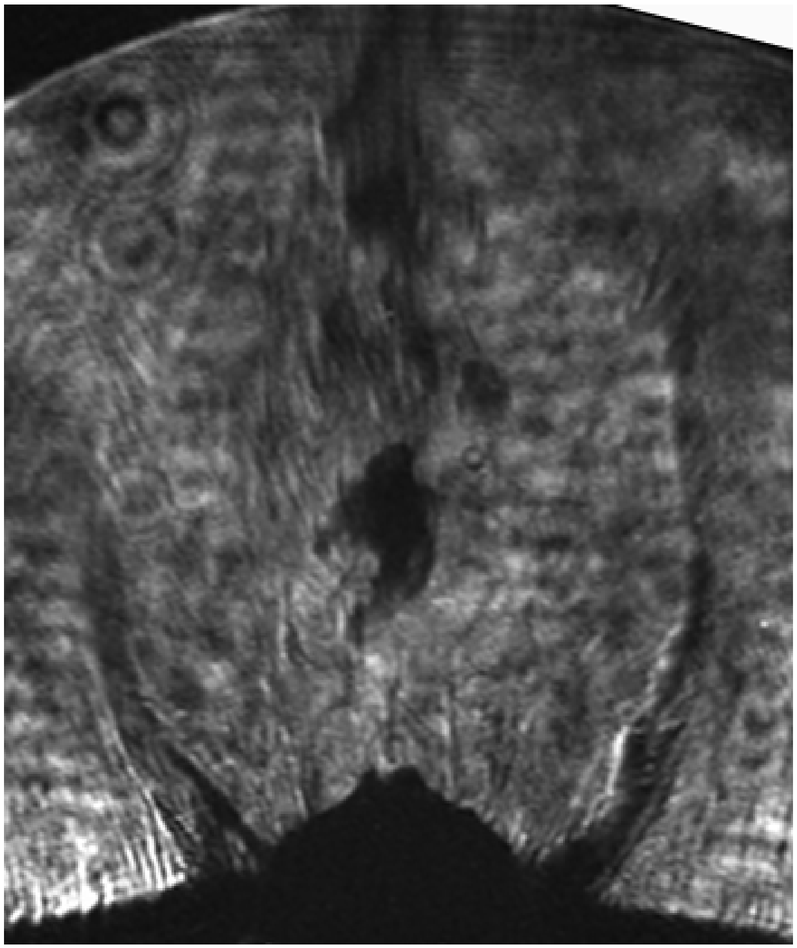
Presence of proton trapped in the magnetic cavity

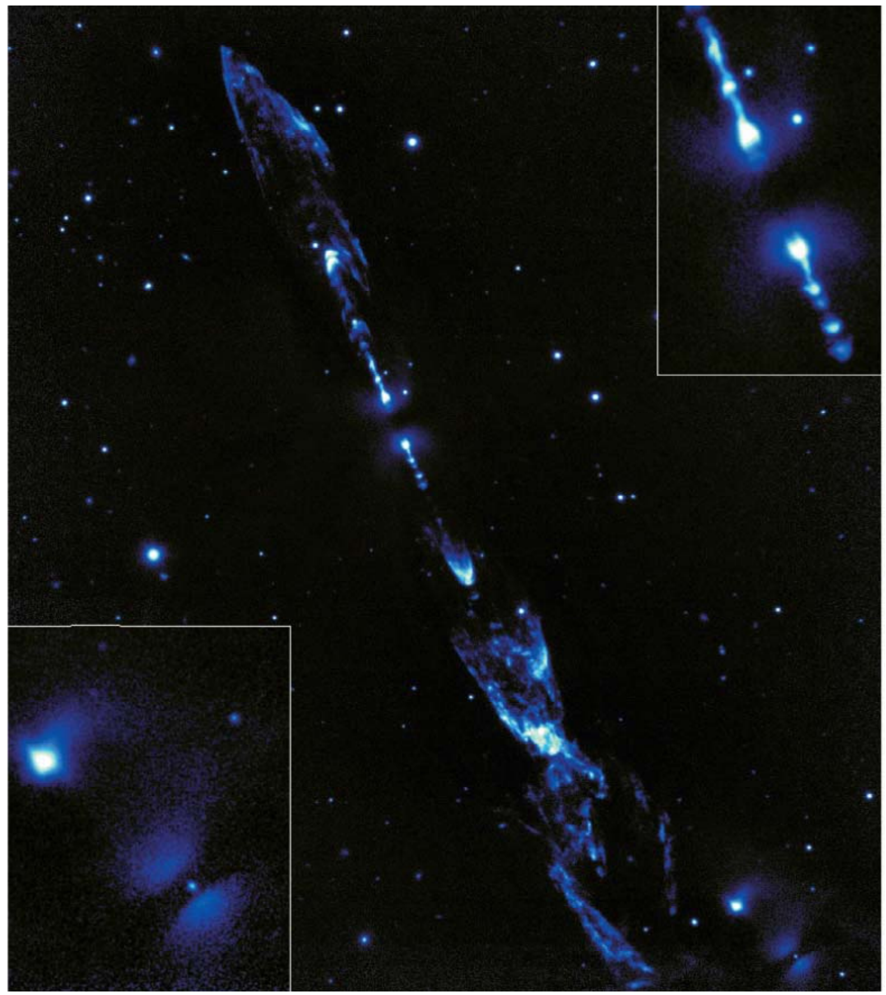
100 um pinhole



Magnetically driven jet – single episode

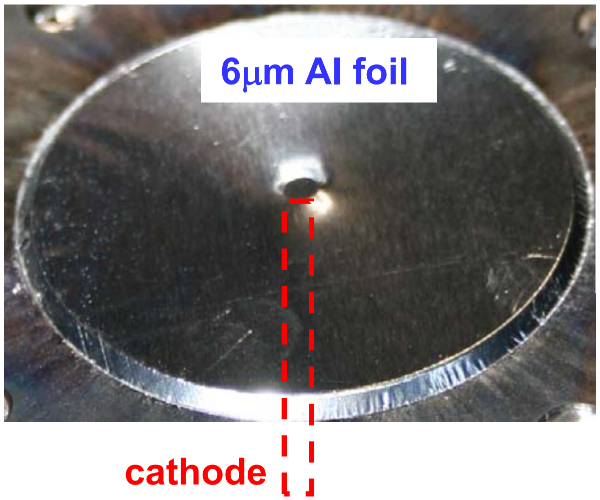
These experiments (and "magnetic tower" astrophysical models) produce a single jet episode

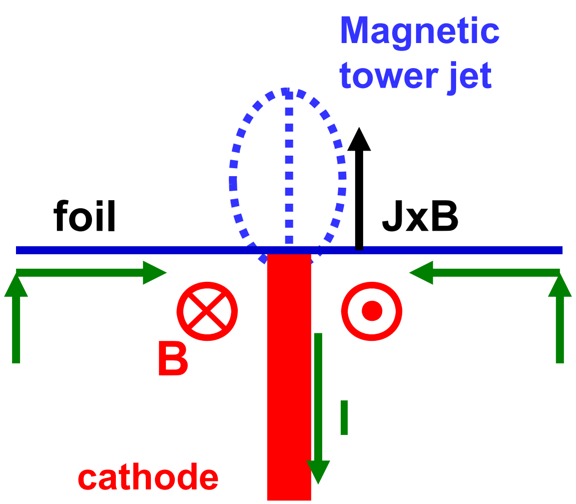


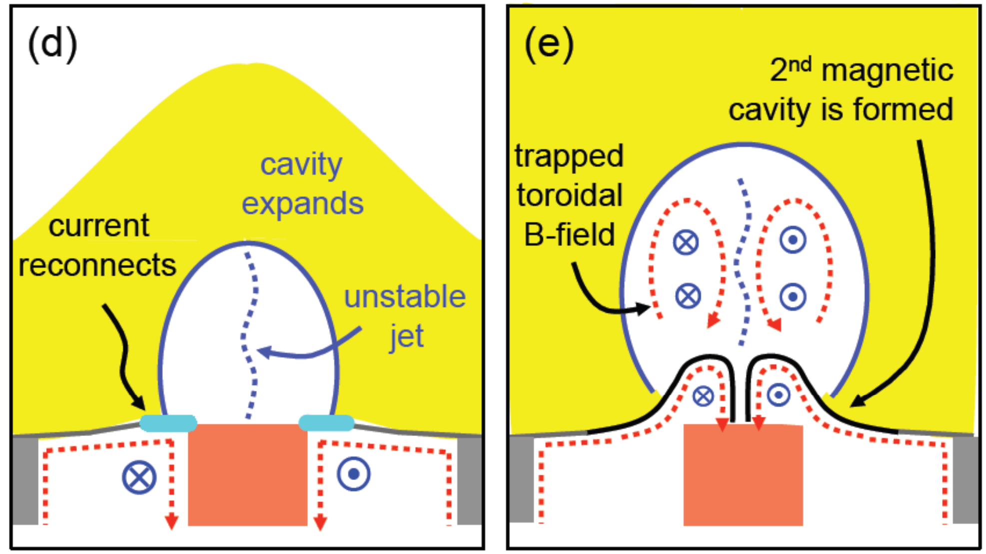


Episodic jets: schematic of the experiment

Foil instead of wire array







Plasma expanding from the electrodes close the gap and reconnects the current

The first magnetic cavity with trapped magnetic flux continue its expansion

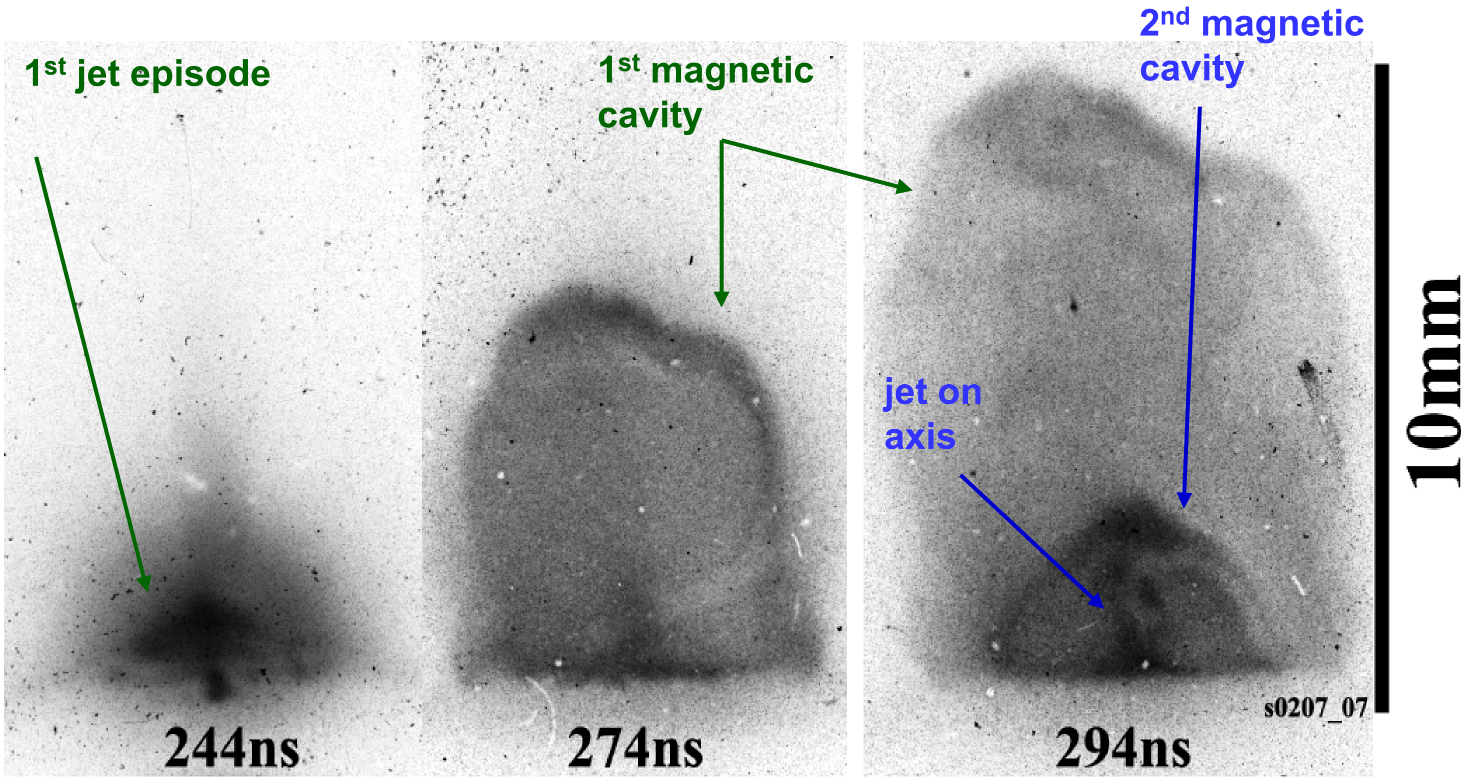
New episode of magnetically driven jet starts

Intrinsically time-dependent scenario with repeatable eruptions

Astrophysical jet simulations: Goodson et al. 1997, Romanova et al. 2005

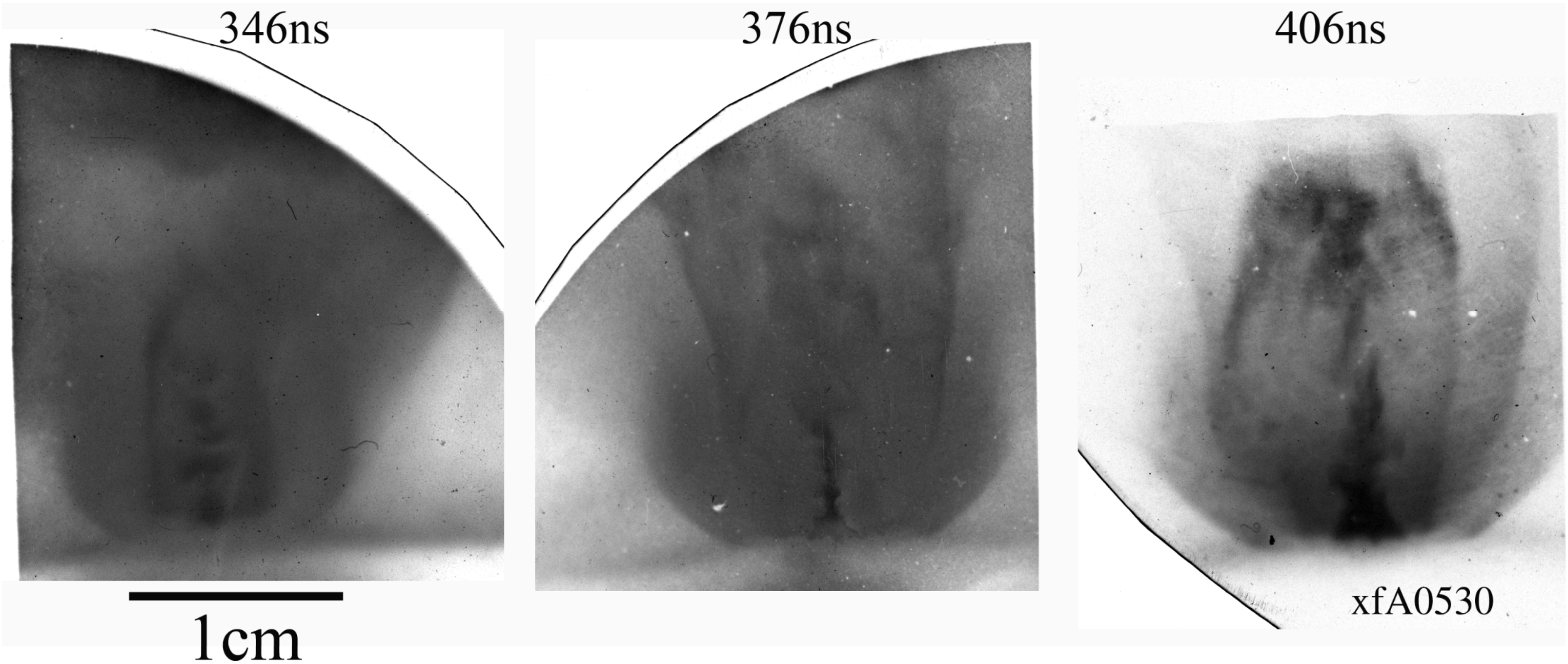
Episodic jets

XUV ($h\nu$ >30eV)



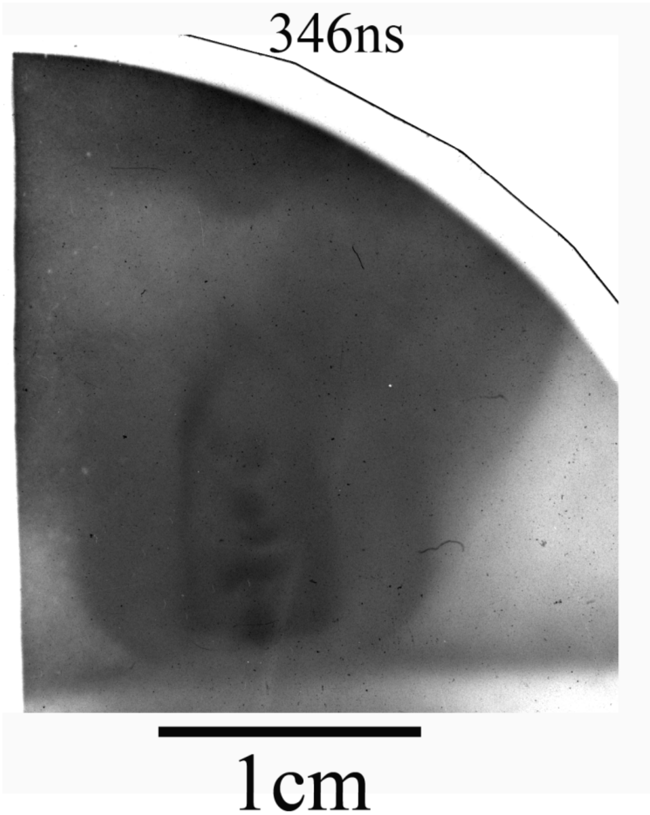
Reconnection of current at the base produces several magnetically driven bubbles

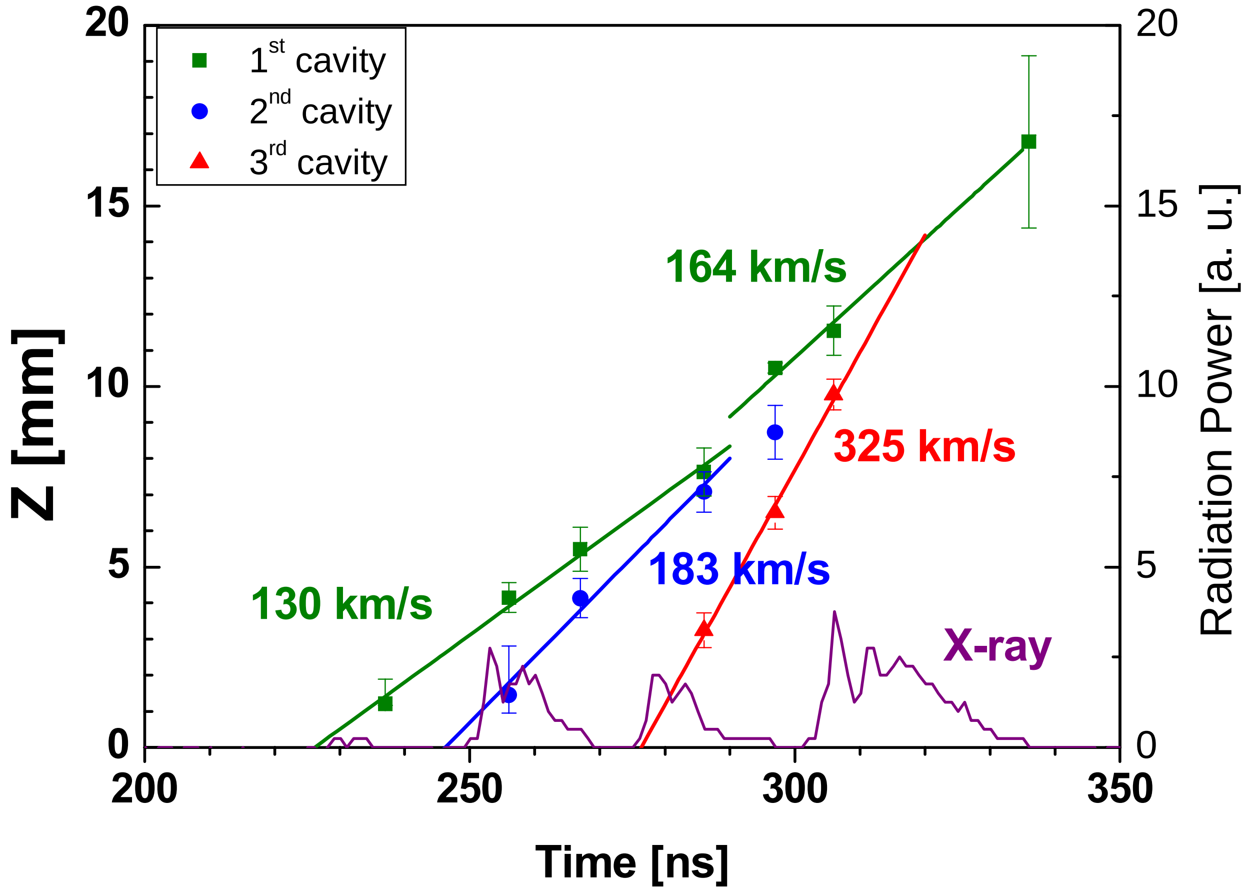
Episodic jets



Episodic formation of magnetic cavities with collimated clumpy jets on axis, embedded in the "old" outflow

Episodic jets

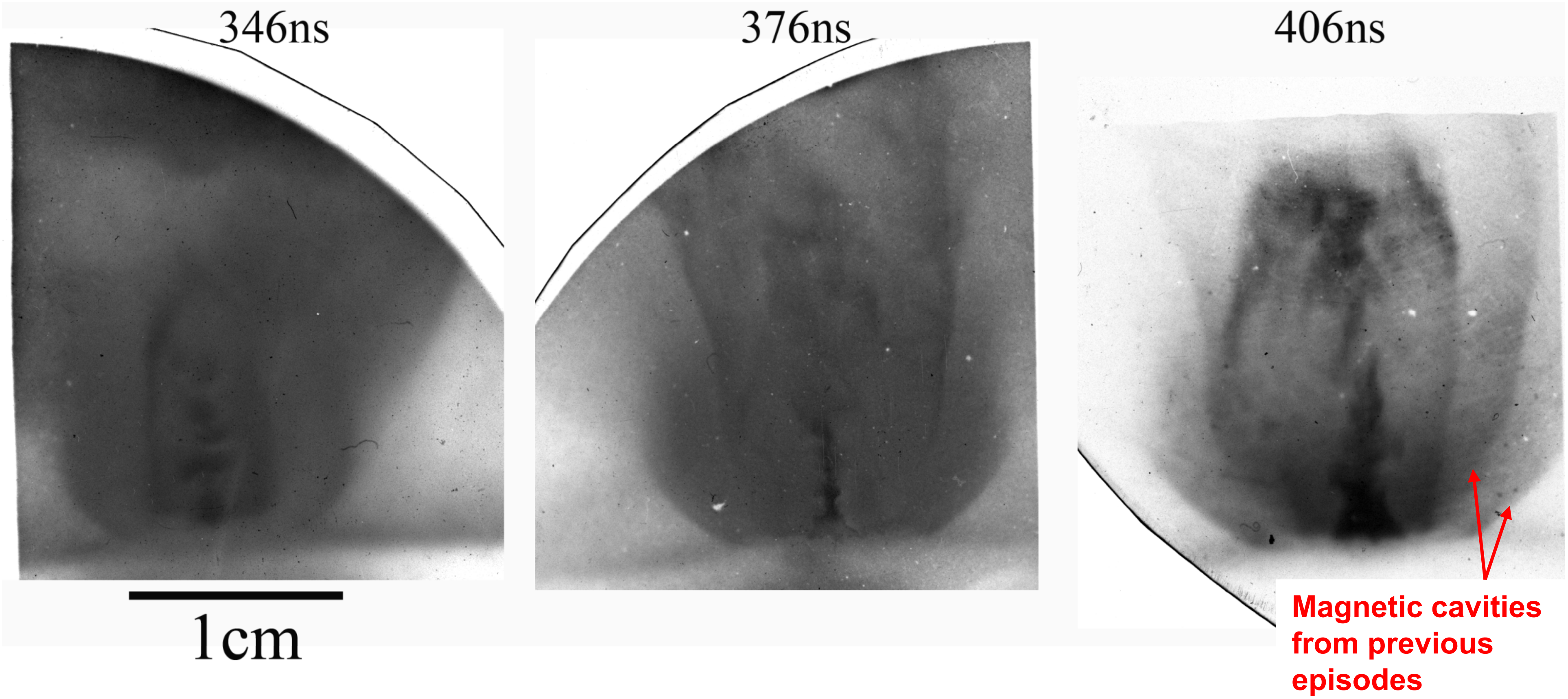




Subsequent magnetic cavities move faster

X-ray pulses, correlated with formation of each outflow episode

Episodic jets

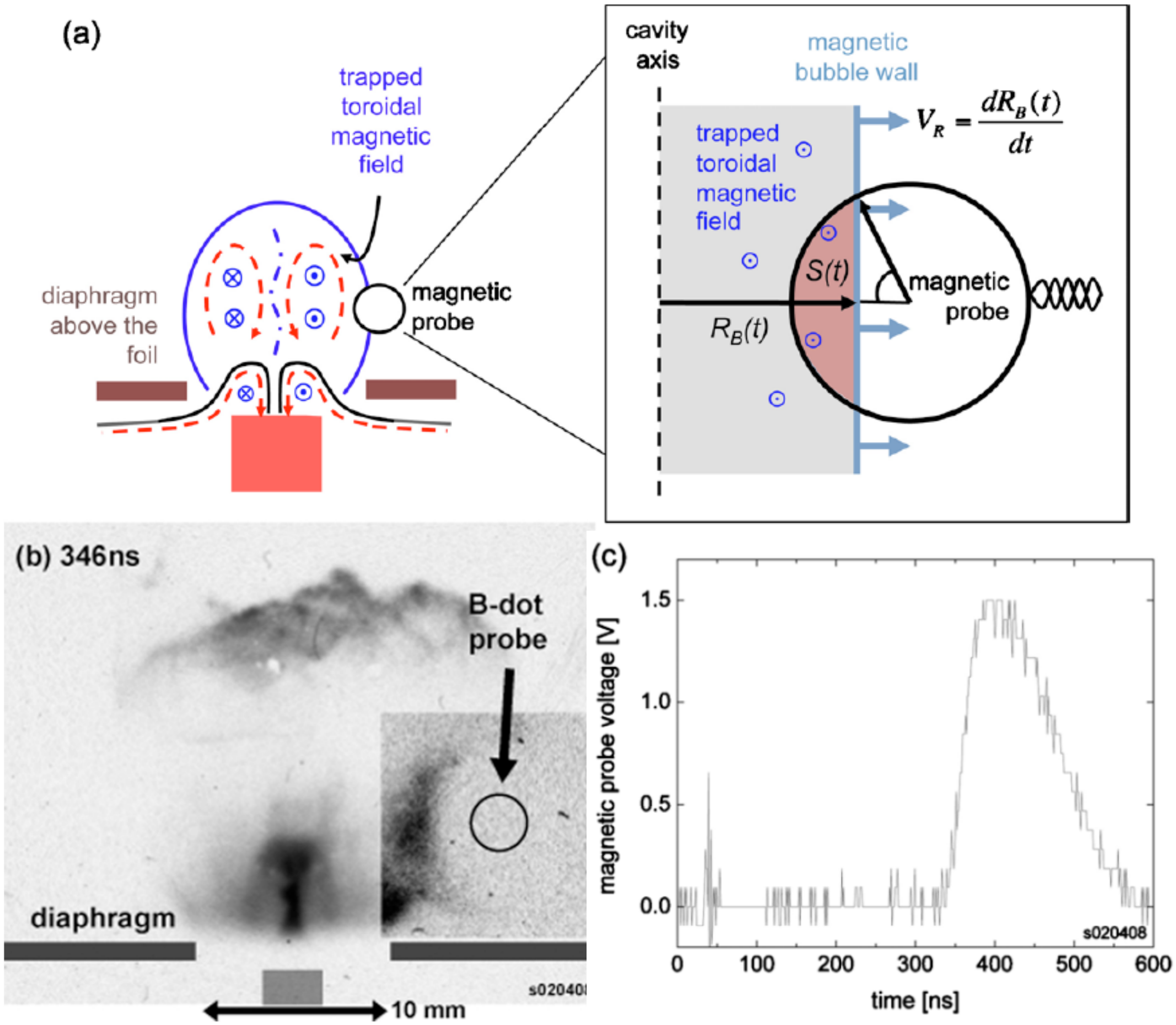


Reduced radial expansion of the subsequent magnetic cavities

Collimation by the trapped magnetic flux left from the earlier episodes?

Magnetically driven jet – trapped magnetic field

Suzuki-Vidal, PoP, 2010



Magnetic field is trapped in the expanding cavity

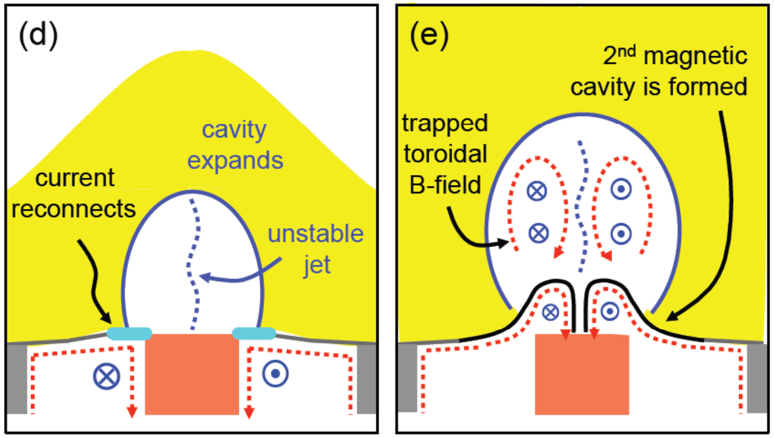
This is consistent with high magnetic Reynolds number,

$Re_M > 200$,

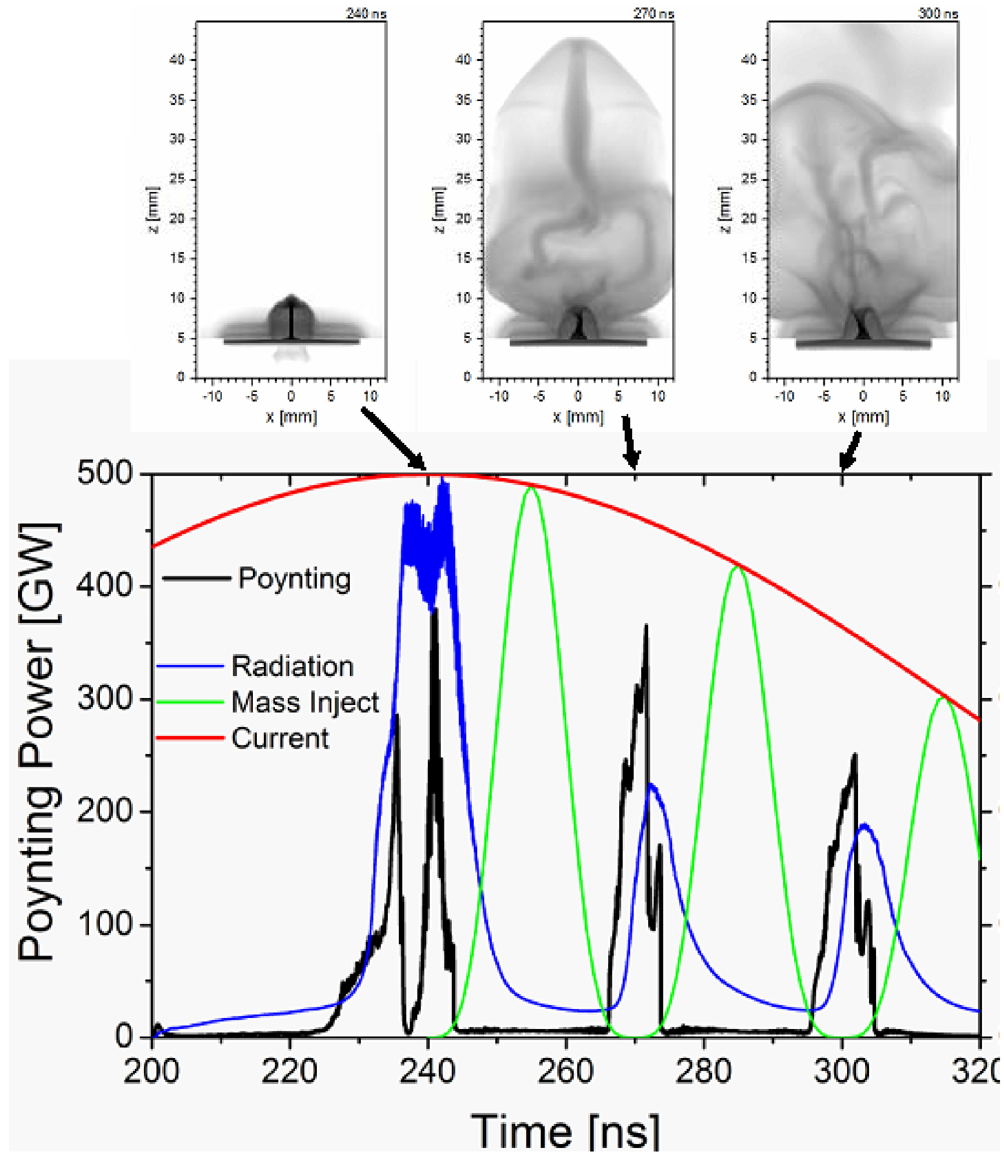
estimated from measured plasma temperature and flow velocity

MHD simulations of episodic jet eruptions

3-D resistive MHD simulations (Ciardi et al., ApJL, 2009)

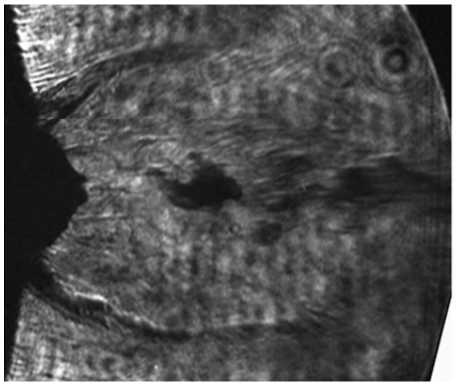


The reconnection of current is not simulated, instead mass is injected into the gap with dm/dt, proportional to the radiation power from the jet



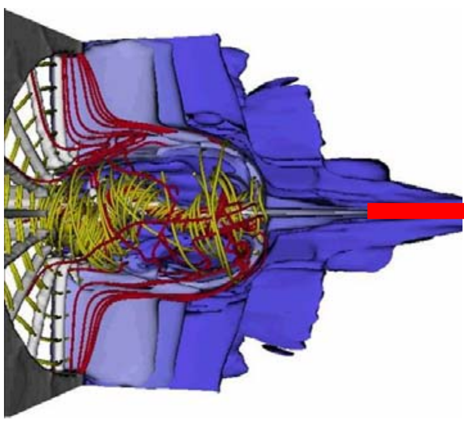
Jet propagation – input for astrophysical simulations

Experiment



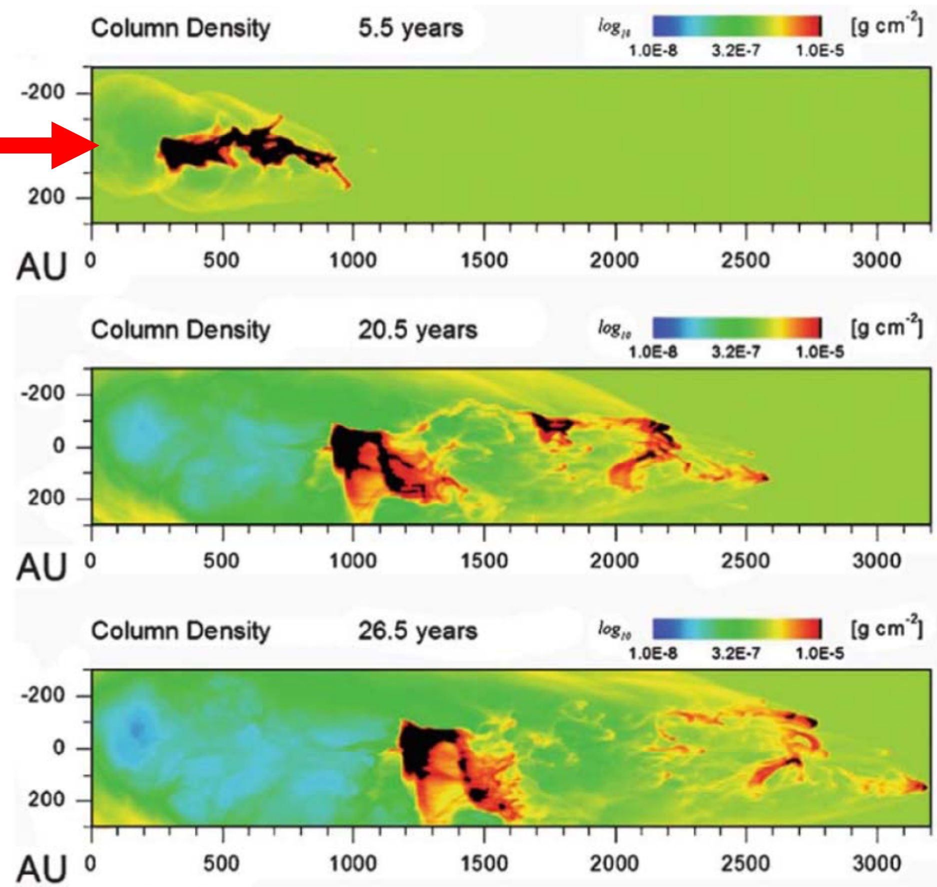
Simulation of the experiment is used as an input for astrophysical jet simulation

3-D MHD simulation of the experiment



3-D simulation of astrophysical jet

Ciardi 2009



Scaling:

1mm ➔ 10 AU

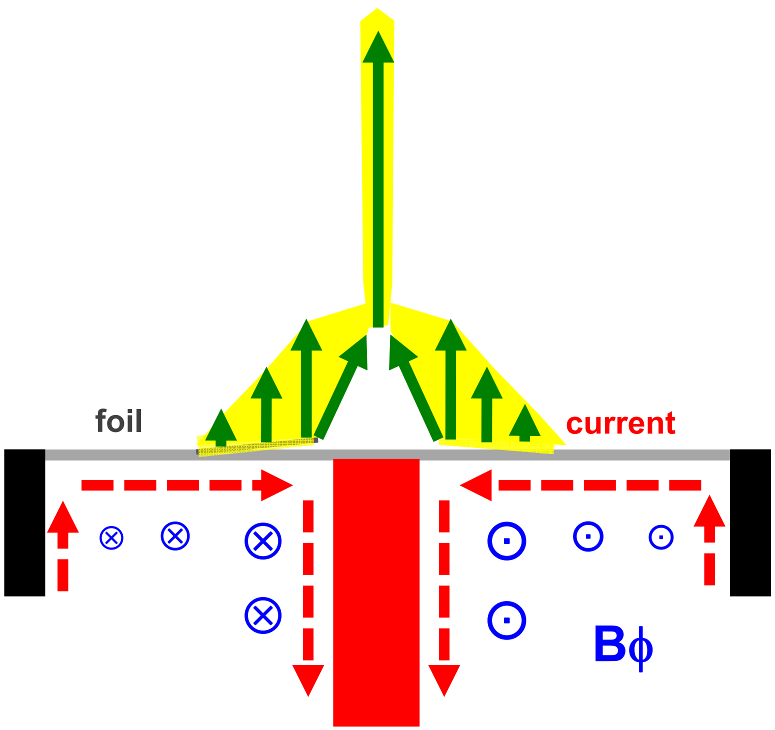
200ns ➔ 10 years

1mg/cc ➔ 10^6 cm^{-3}

Need to compare with propagation of a "laminar" jet!

Formation of a "laminar" jet: experimental set-up

"Hydrodynamic" jet



Radial foil z-pinch driven by 1.4MA, 250ns current pulse

15μm thick Al foil (~ skin depth)
6.3mm diameter cathode

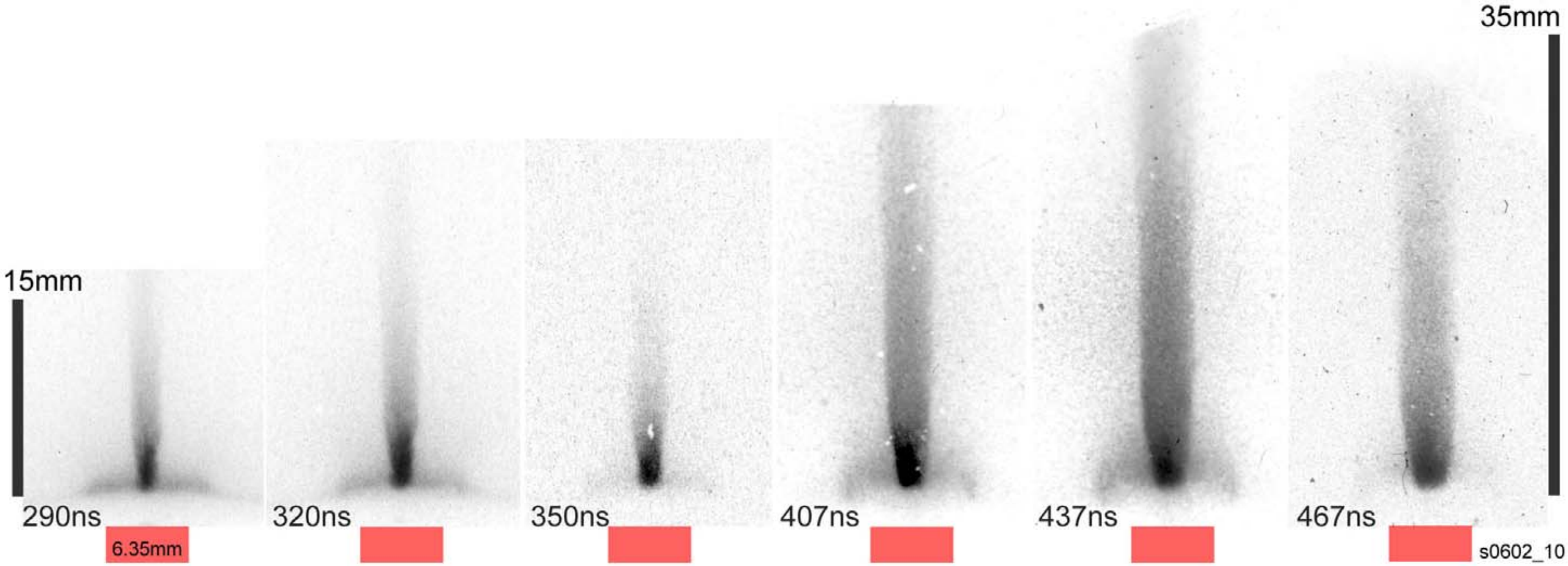
Azimuthal magnetic field is able to diffuse through the foil

Jet is produced by ablation of the foil material ($j_r x B_\phi$)

Ambient gas (e.g. He, Ar, Xe) can be added above the foil for jet-ambient interaction studies

Suzuki-Vidal et al., PoP, 2012

XUV images of jet propagating in vacuum



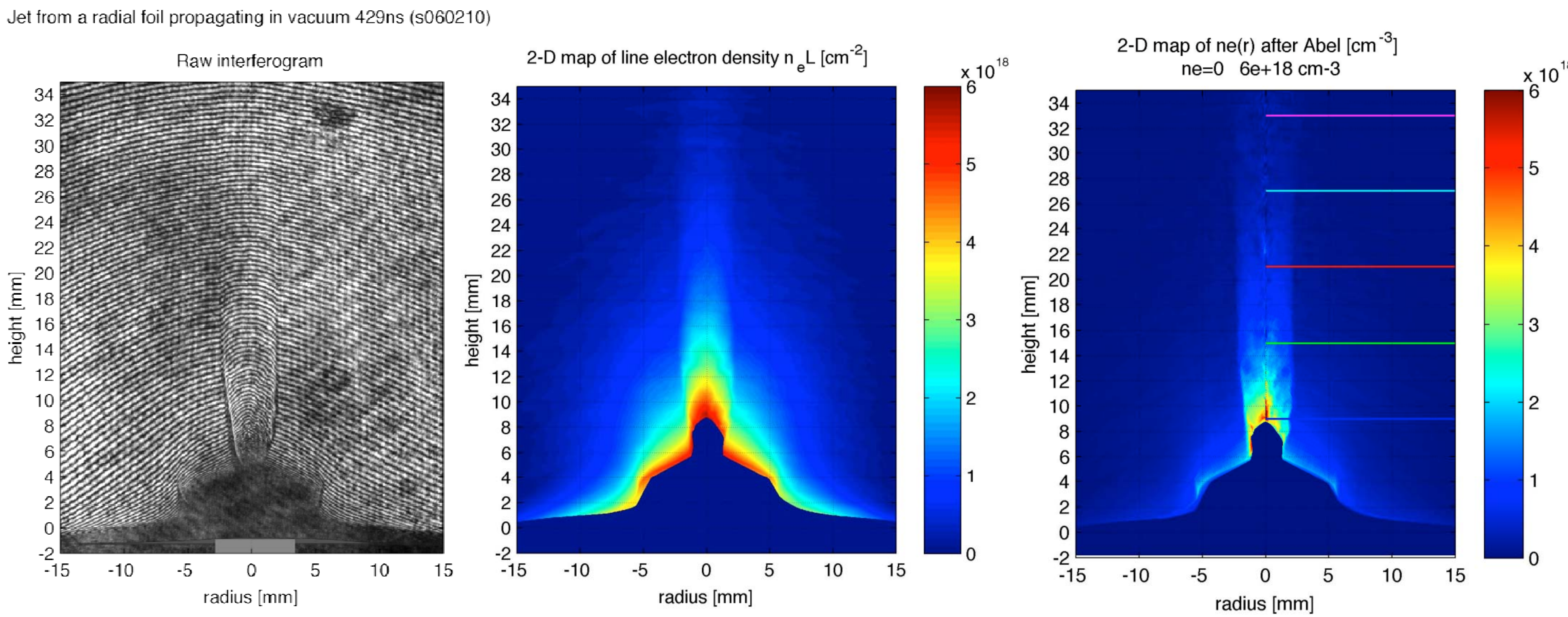
Highly collimated jet , plasma is flow supported for ~350ns

Length > 35mm, diameter 2mm – 4mm, aspect ratio ~20

Tip velocity ~100km/s. Radial expansion velocity ~5km/s

Opening angle 2 – 5 degrees (internal Mach number 10-30?)

Density distribution of the jet propagating in vacuum

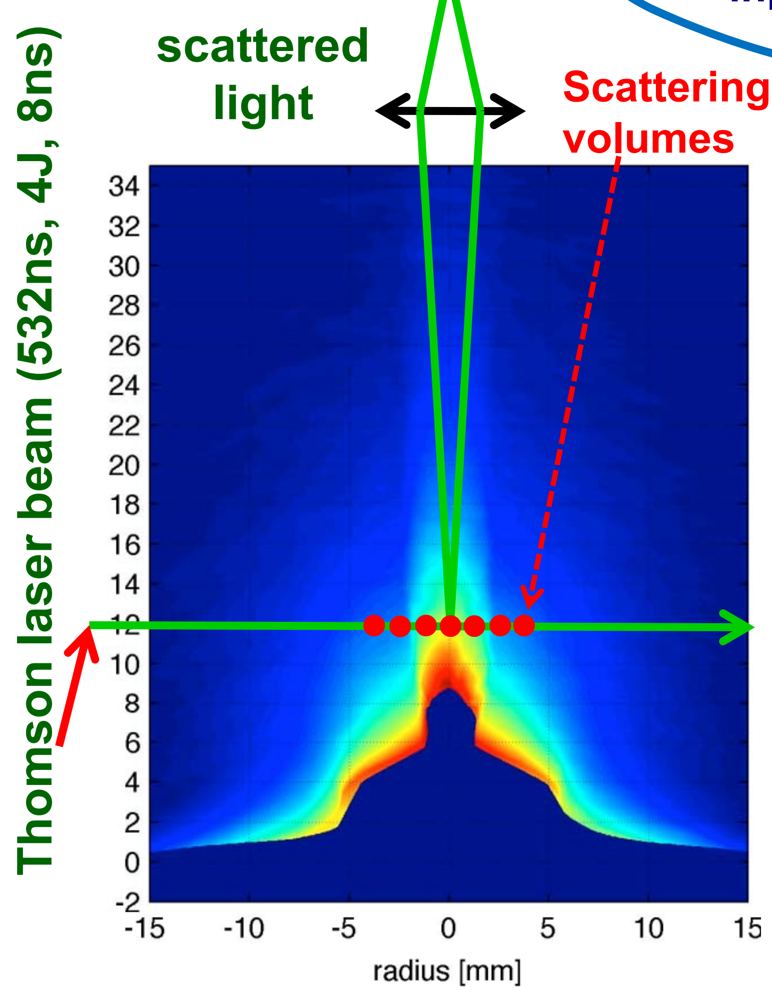


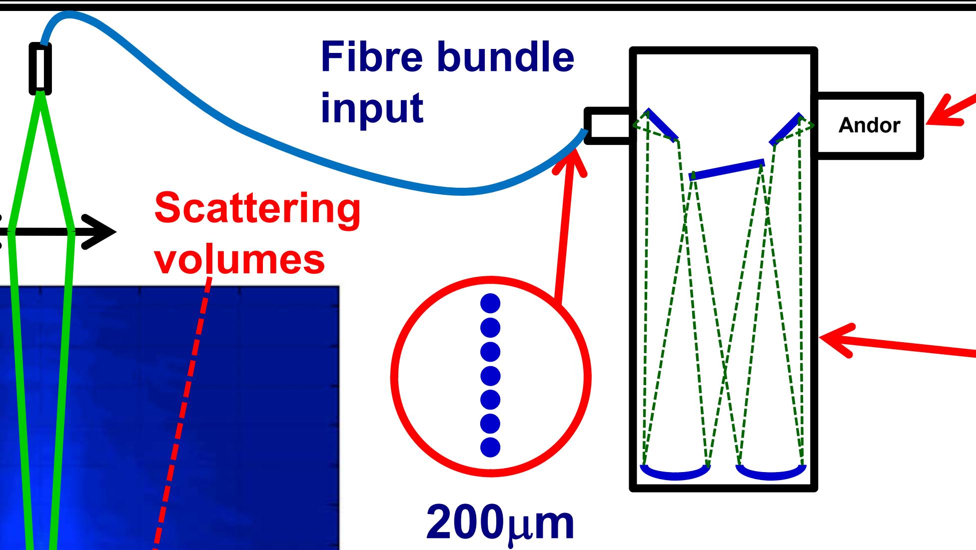
Shape / collimation of the jet are similar to observed in XUV emission

Electron density decreases with height from ~8x10^{18} cm^3 to ~5x10^{17} cm^3

The jet is surrounded by a lower density plasma (20-30% of the jet density)

Thomson scattering: jet velocity and temperature



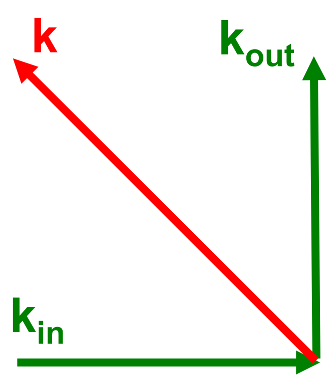


Gated (4ns) ICCD camera

0.5 m imaging spectrometer

grating 2400 l/mm

$\delta\lambda_{Gs}$ = 0.45 A



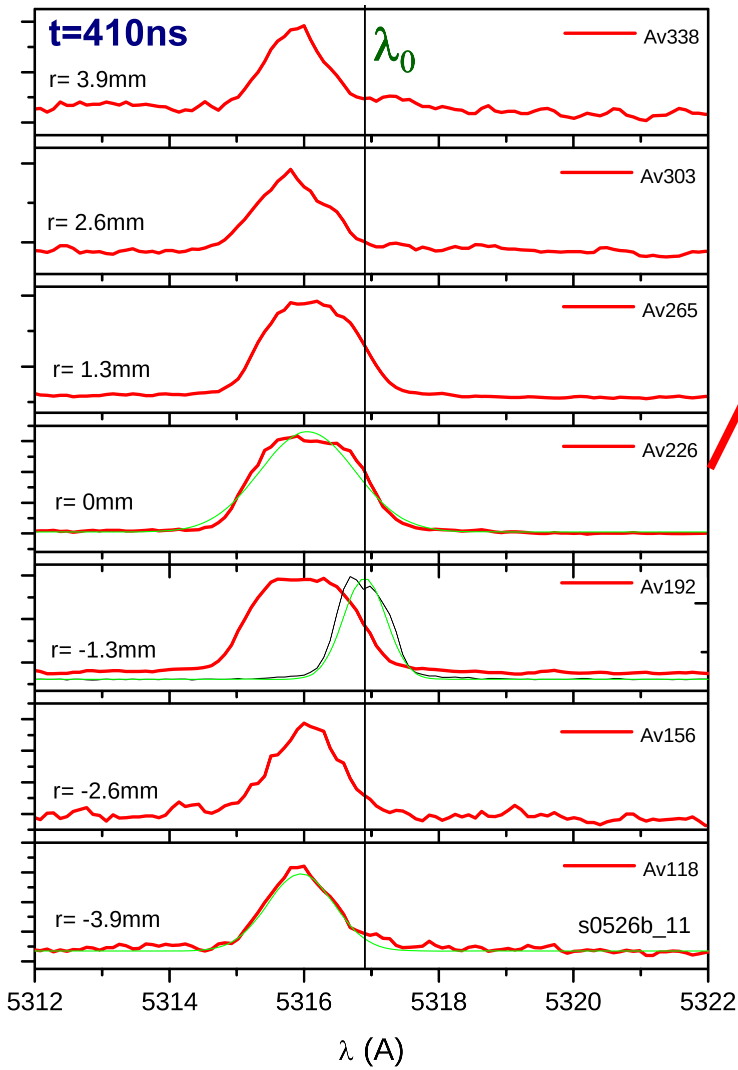
Doppler shift of the scattered light yields jet velocity V(r) or V(z)

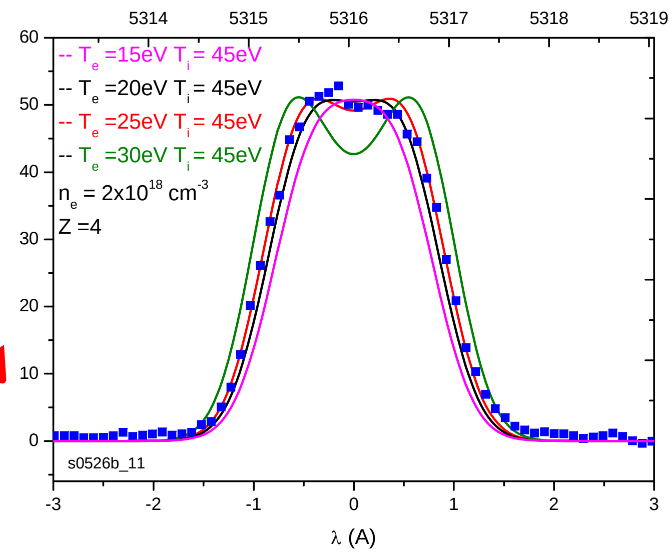
k and V at 45^0 (blue shifted spectrum, $\Delta\omega = kV/\sqrt{2}$)

($\delta\lambda$ = 1.77A for V_z =100km/s)

Thomson scattering: jet velocity and temperature

Blue-shifted spectrum





Flow velocity from Doppler shift

Te and Z from broadening

Flow velocity: 50-60km/s at z=12-20mm

(jet tip at z>35mm, V_{tip} ~100km/s)

T_e = 15-20eV (Z~4)

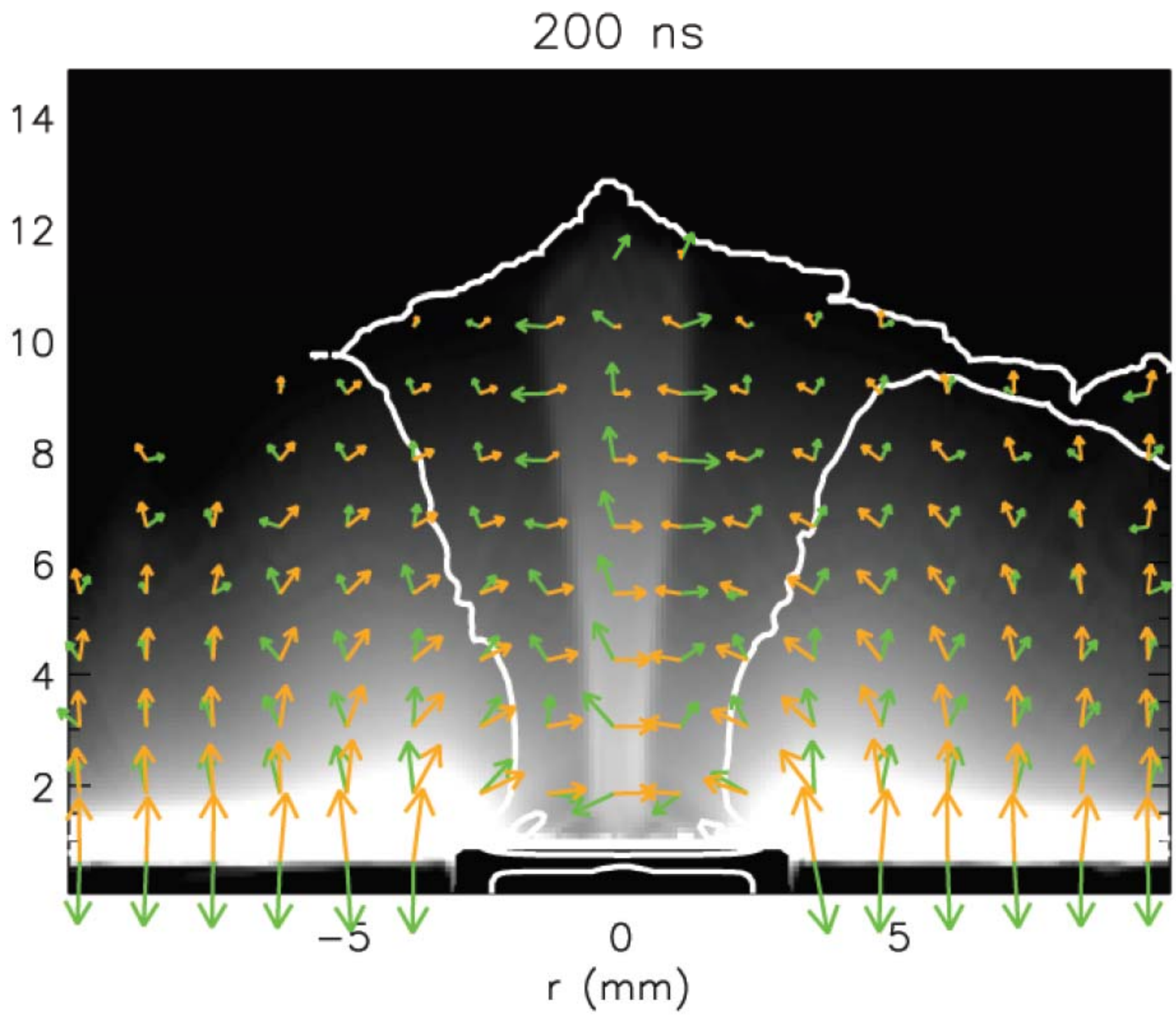
$C_s \sim 2\times10^6$ cm/s ➔ internal Mach # ~2.5-3

Opening angle of a free-expanding M=3 jet:

$\theta = \tan^{-1}(1/M) \sim 20^0$ >> 2-5^0 measured

Simulations of jet formation in vacuum

The experiment have been modeled using a 3D resistive MHD code GORGON



Toroidal magnetic field (B_φ) diffuses through the foil

1. $j_r x B_\varphi$ force provides axial acceleration of ablated plasma

2. "indirect" magnetic collimation:

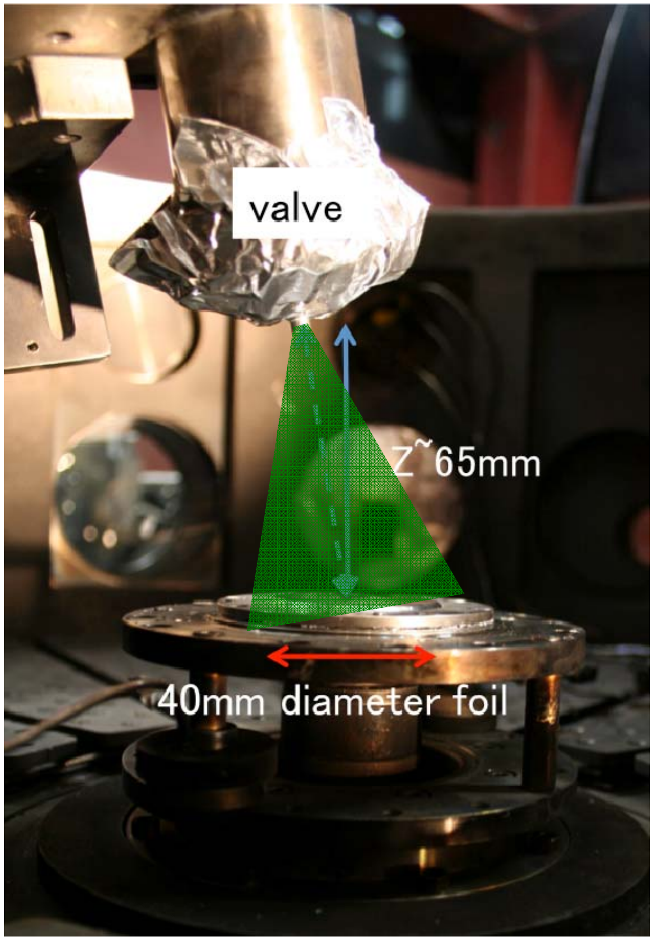
$j_z x B_\varphi$ force provides redirection of the flow (at $r > R_j$) towards the axis

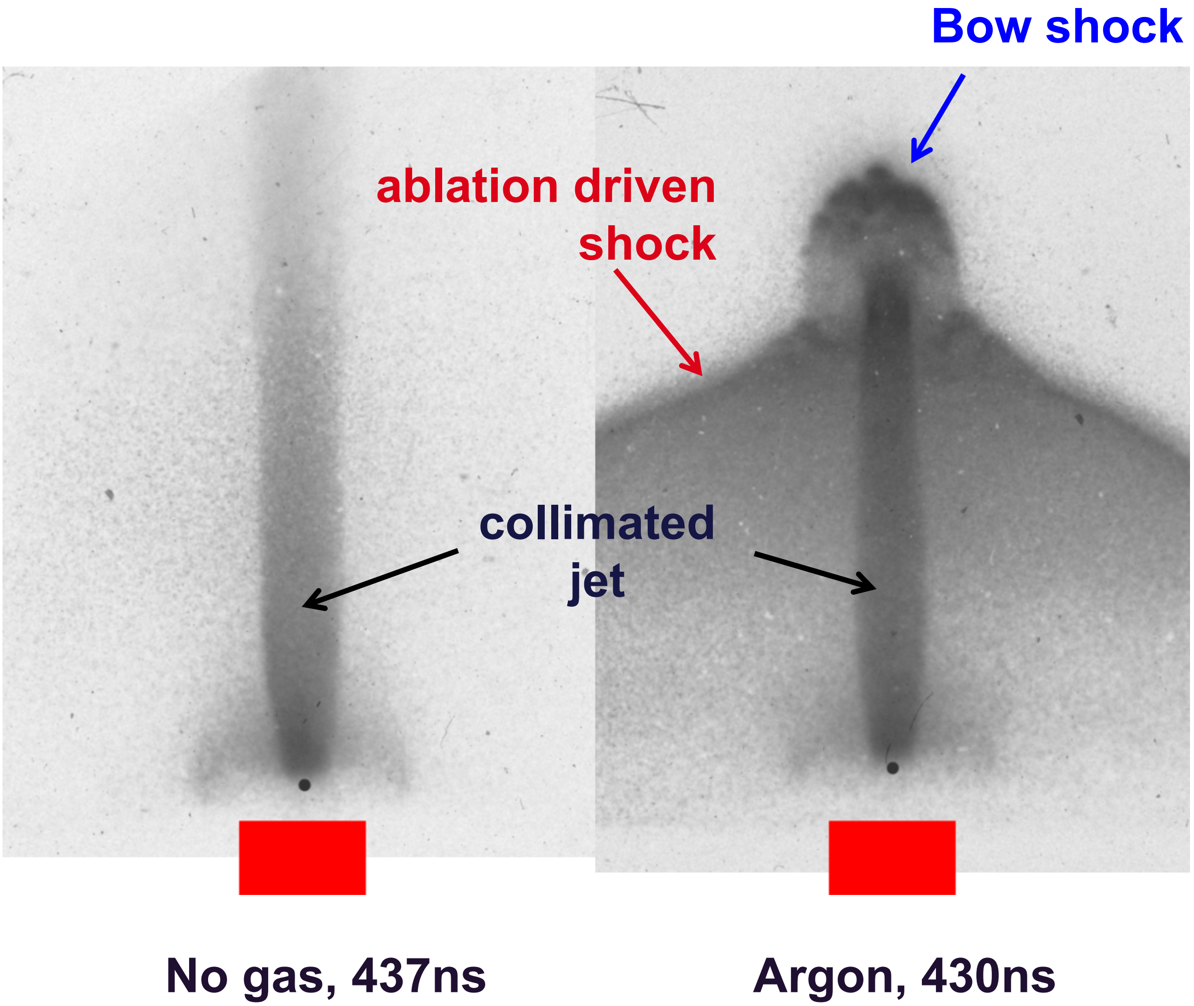
Ram pressure of the converging flow confines the dense jet

Jet-ambient interaction: experimental set-up

A neutral gas (Ar) is injected above the foil using a fast valve with a supersonic gas nozzle (*M. Krishnan et al. 2008*)

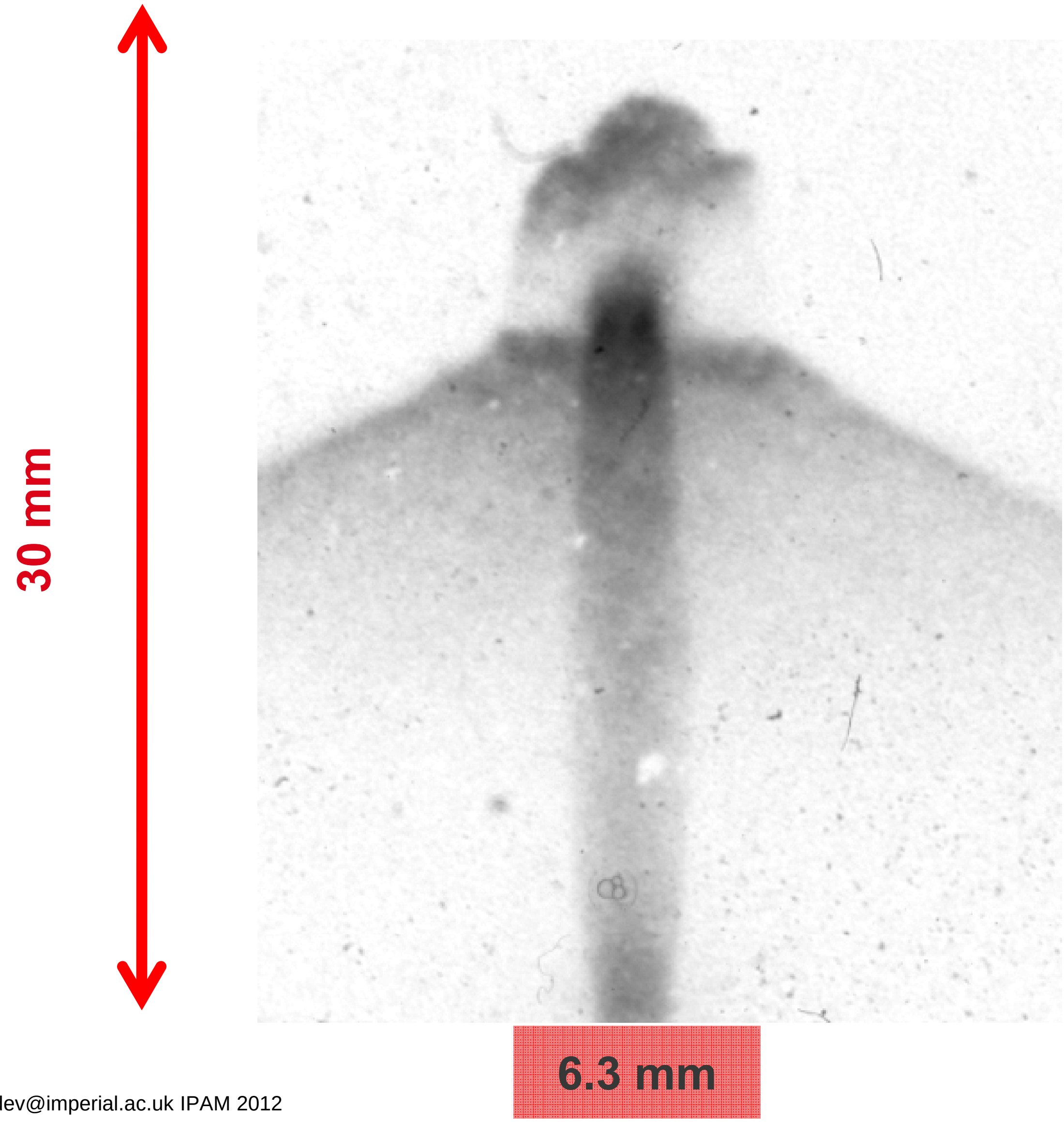
Argon number density at the foil $n \sim 10^{16}$-10^{17} cm^{-3}





Formation and evolution of the jet in argon ambient

XUV self-emission (E>30 eV)   Images from 115 to 440 ns



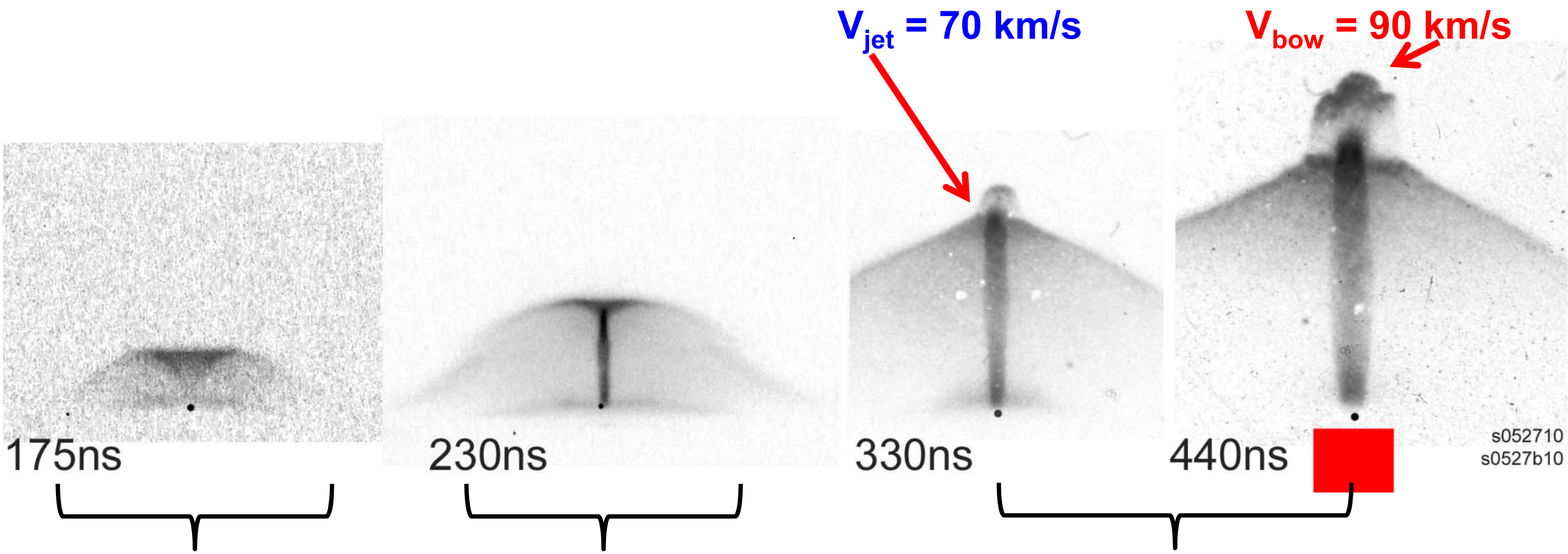
Presence of argon does not disrupt formation of a collimated jet

New features:

Ablation shock

Bow shock ahead of the jet

Formation and evolution of the jet in argon ambient



"Zippering" implosion (similar to a plasma focus)
Shock driven by material ablated from the foil

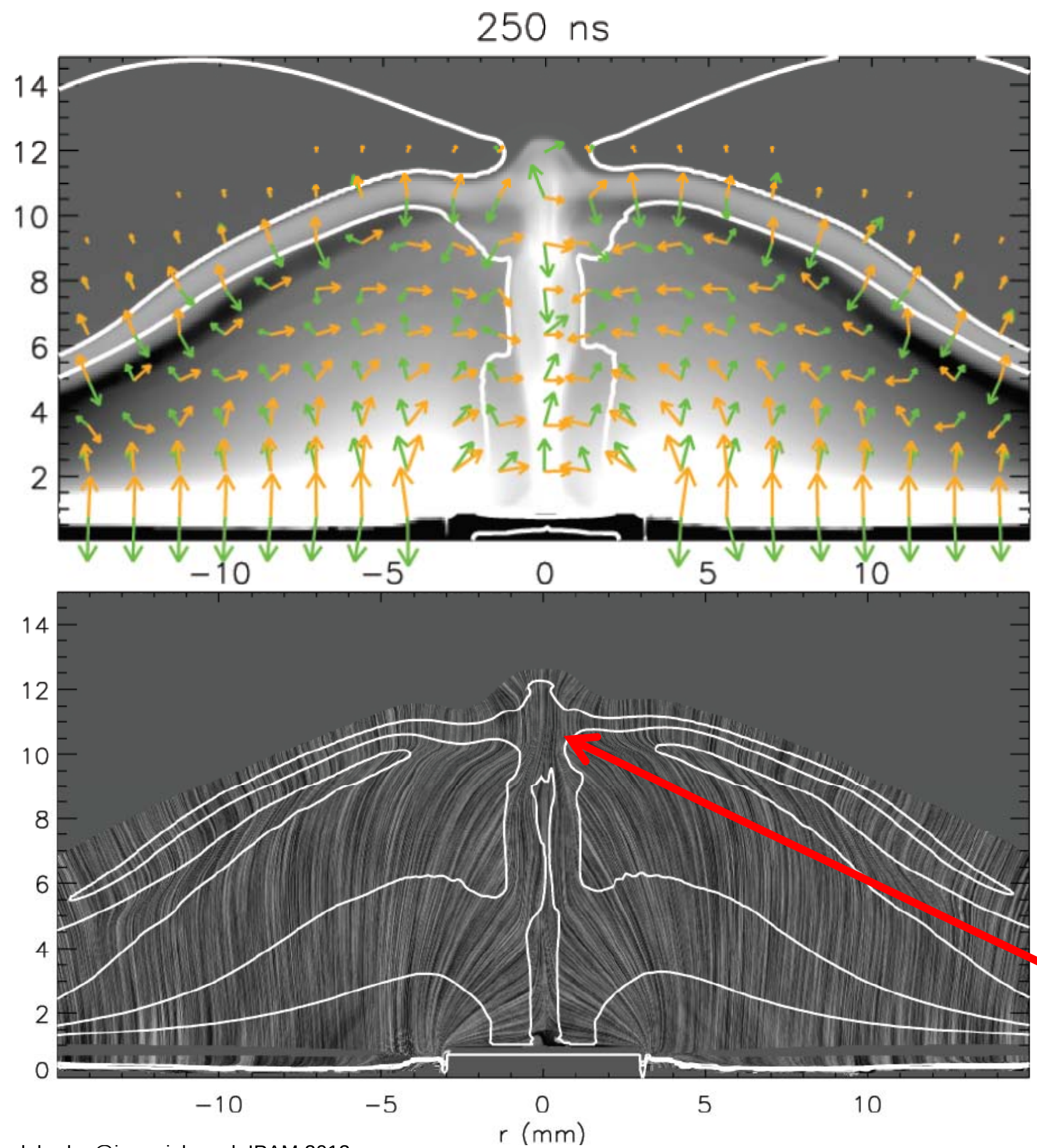
Minimum jet diameter

Tip of the jet is pinched

Bow shock ahead of jet

High level of emission at the tip of the jet and at the front of bow shock

3-D MHD simulations of jet propagating in argon



Force diagram:
orange = J x B, green = ∇P
white = iso-contours of plasma beta

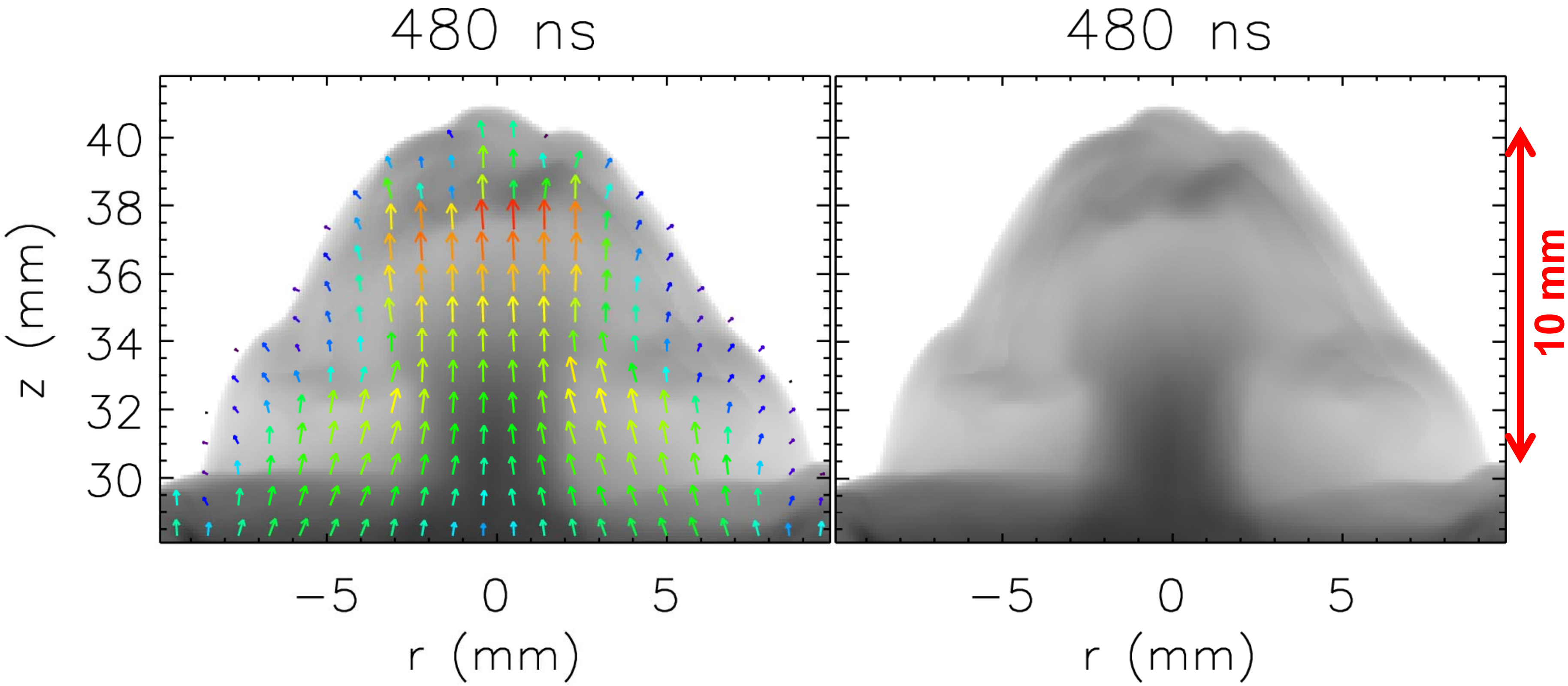
Presence of a magnetic field / current above the foil

(in progress, < 5-10% of the total current).

Flow velocity and iso-contours of current density

Nozzle-like configuration accelerating the flow into a "secondary" jet

"Secondary" jet in simulations



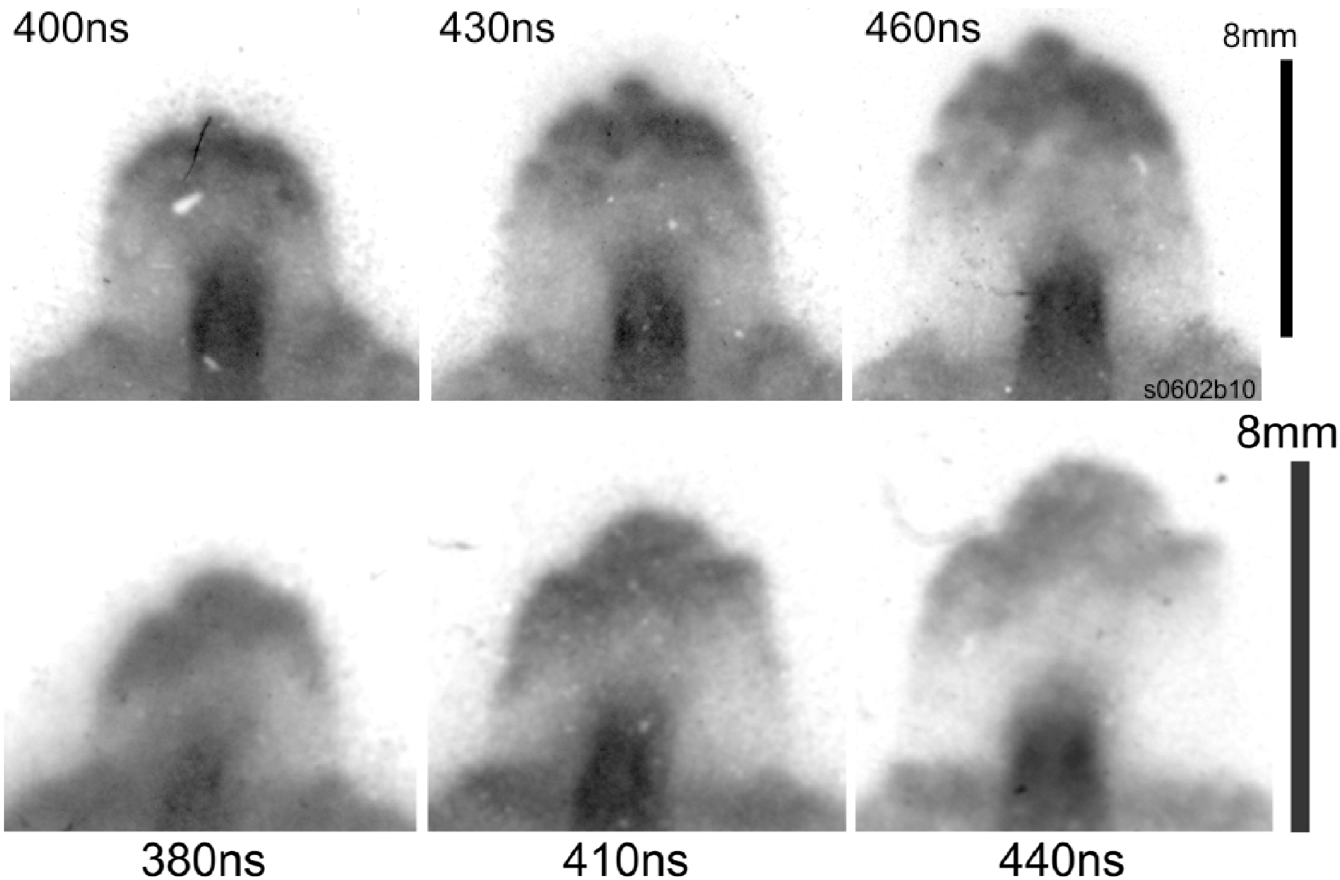
n_e~1-5x10^{18}cm^{-3}, T~20eV, ρ_{amb}~5x10^{-6}g/cc, ρ_{jet}~1-5x10^{-5}g/cc

τ_{cool}~1-3ns, l_{cool}~0.1-0.3mm - strong radiative cooling

Re ~1-4x10^5, Pe ~20-50, M ~ 5-8, $\eta = \rho_{jet}/\rho_{amb}$ ~ 2-10

Secondary jet interacting with ambient

XUV emission (E>30 eV), in the reference frame of the tip of the ablation shock



Jet parameters:

V_{jet}~$1x10^7$cm/s

n_e~$2\text{-}8x10^{18}$cm^{-3}

T~20eV

ρ_{amb}~$5x10^{-6}$g/cc

ρ_{jet}~$2\text{-}8x10^{-5}$g/cc

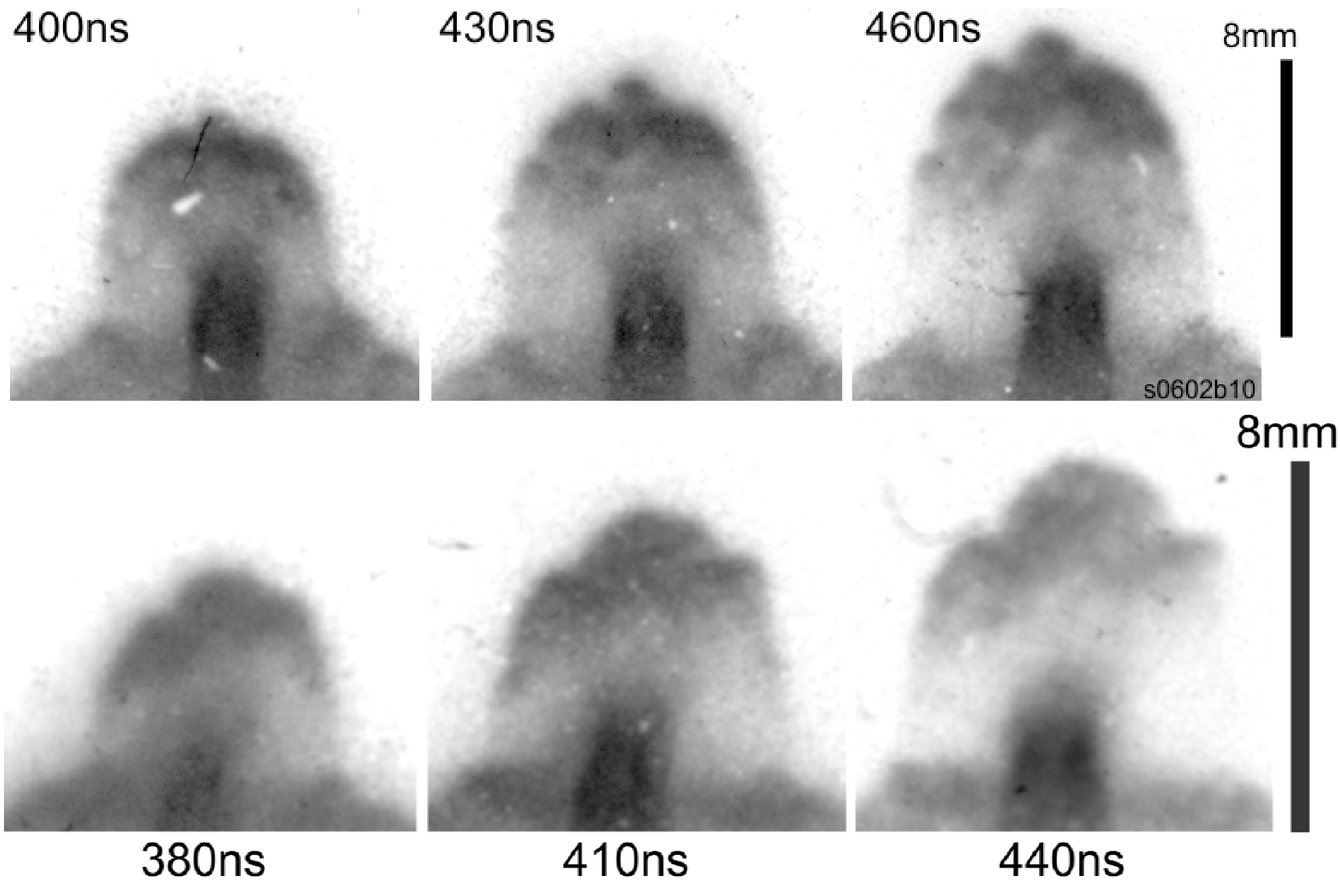
t_{cool}~1-3ns

L_{cool}~0.1-0.3mm

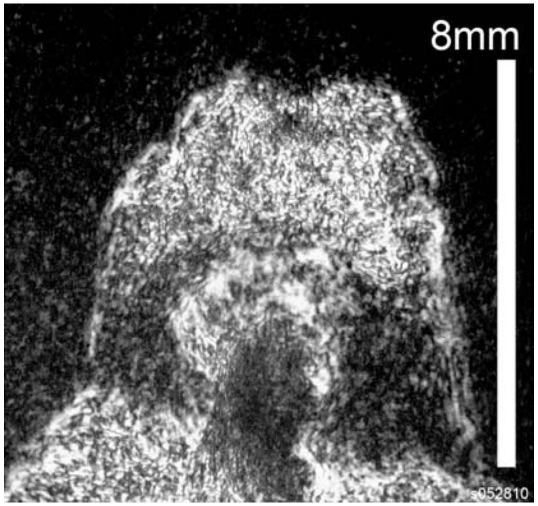
$$\chi \equiv \frac{\tau_{cool}}{R_j / V} \sim 10^{-3} \qquad \eta \equiv \frac{\rho_{jet}}{\rho_{amb}} \sim 5-15 \qquad \mathrm{Re} \sim (1-4)\cdot 10^5 \qquad Pe \sim 20-50 \qquad M \sim 5-8$$

Secondary jet interacting with ambient

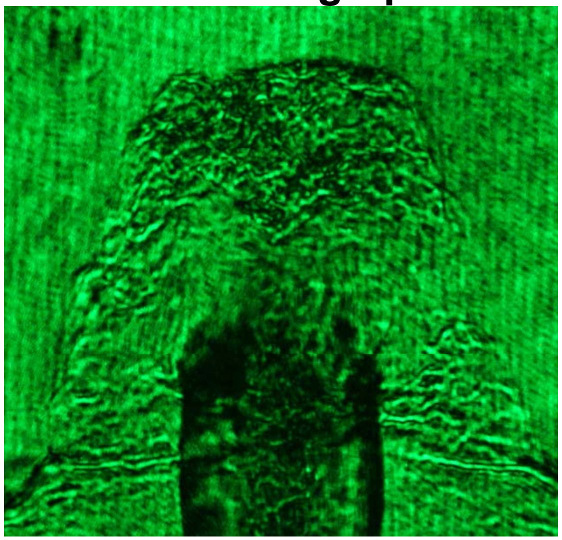
XUV emission (E>30 eV), in the reference frame of the tip of the ablation shock



Dark field schlieren



Shadowgraph

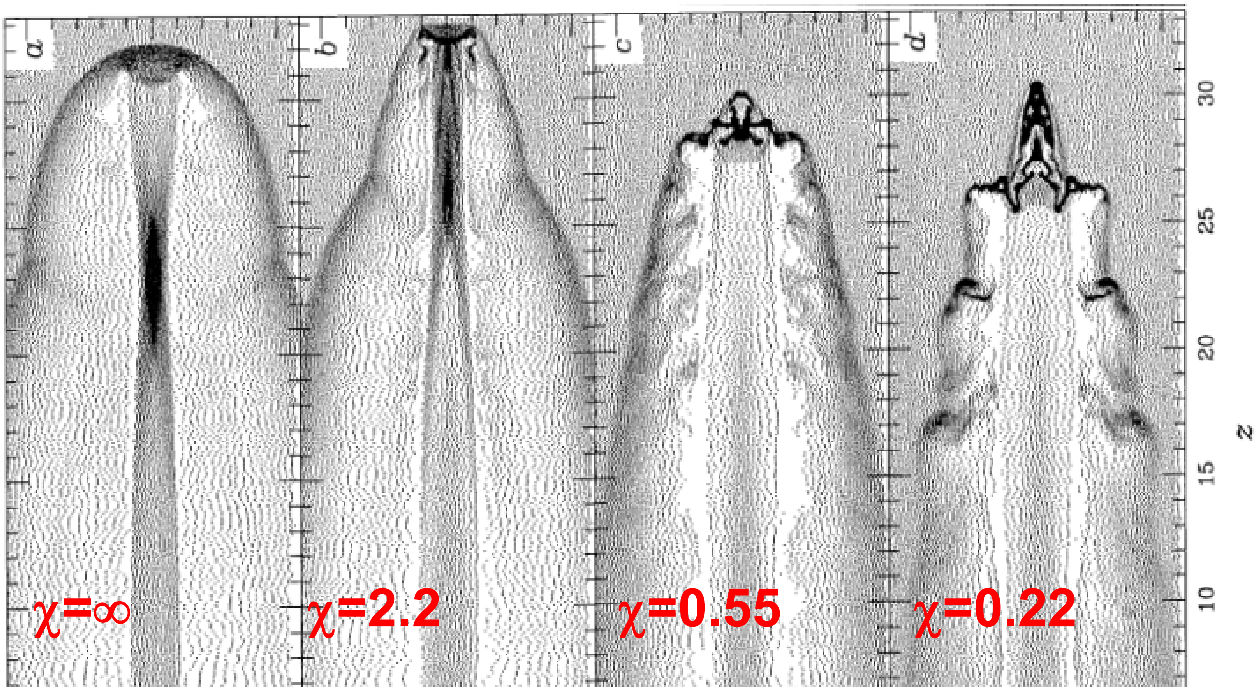


High compression in the shock due to radiative cooling

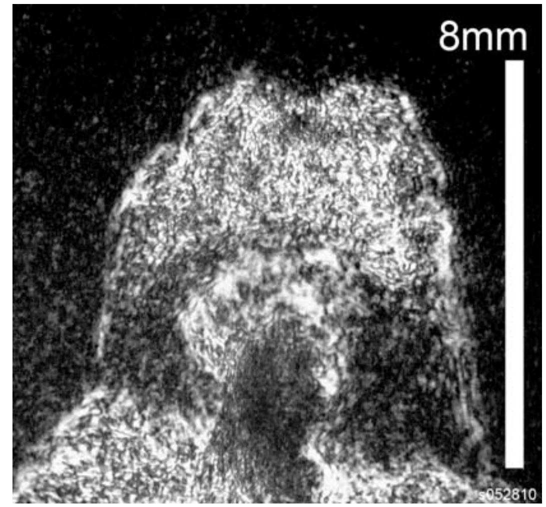
Formation of small scale structures in the bow-shock

Astrophysical jet – ambient interaction

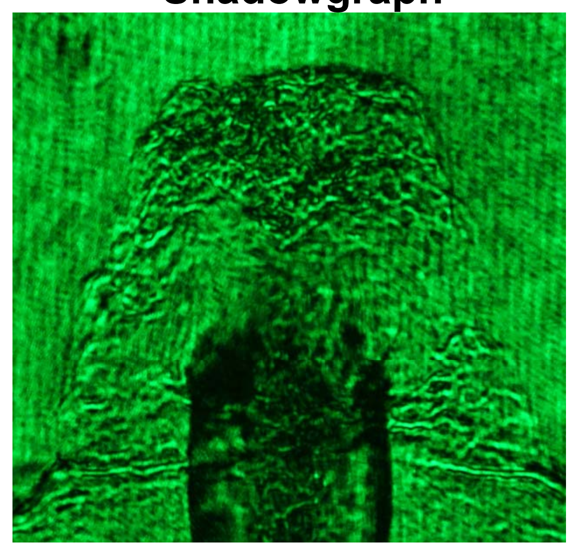
Simulations of astrophysical jets (Blondin et al., ApJ 1990)



Dark field schlieren



Shadowgraph



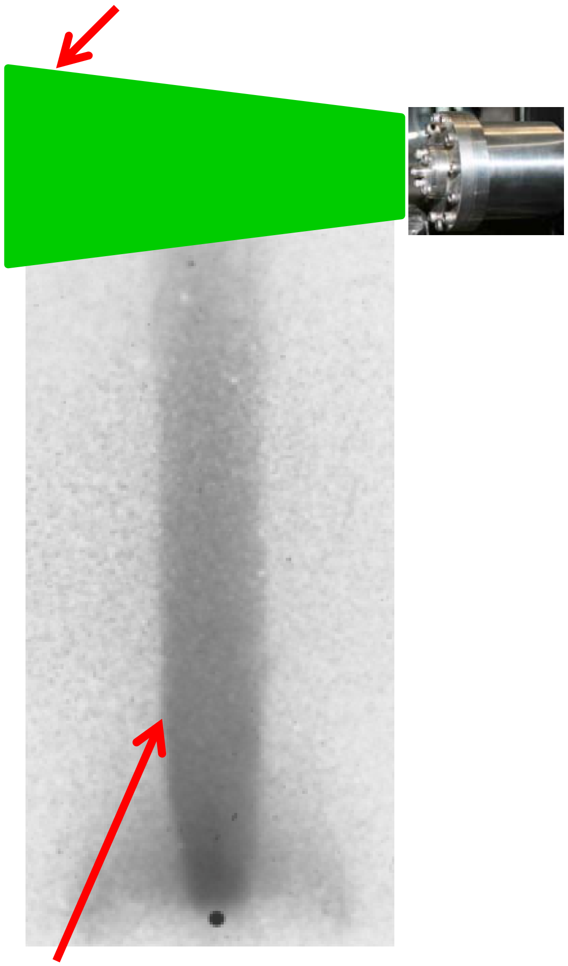
Cooling parameter $\chi=l_{cool}/r_{jet}$

In experiment $\chi=0.001$

Instability of a radiatively cooled shock?

Effect of radiative cooling on jet-ambient interaction

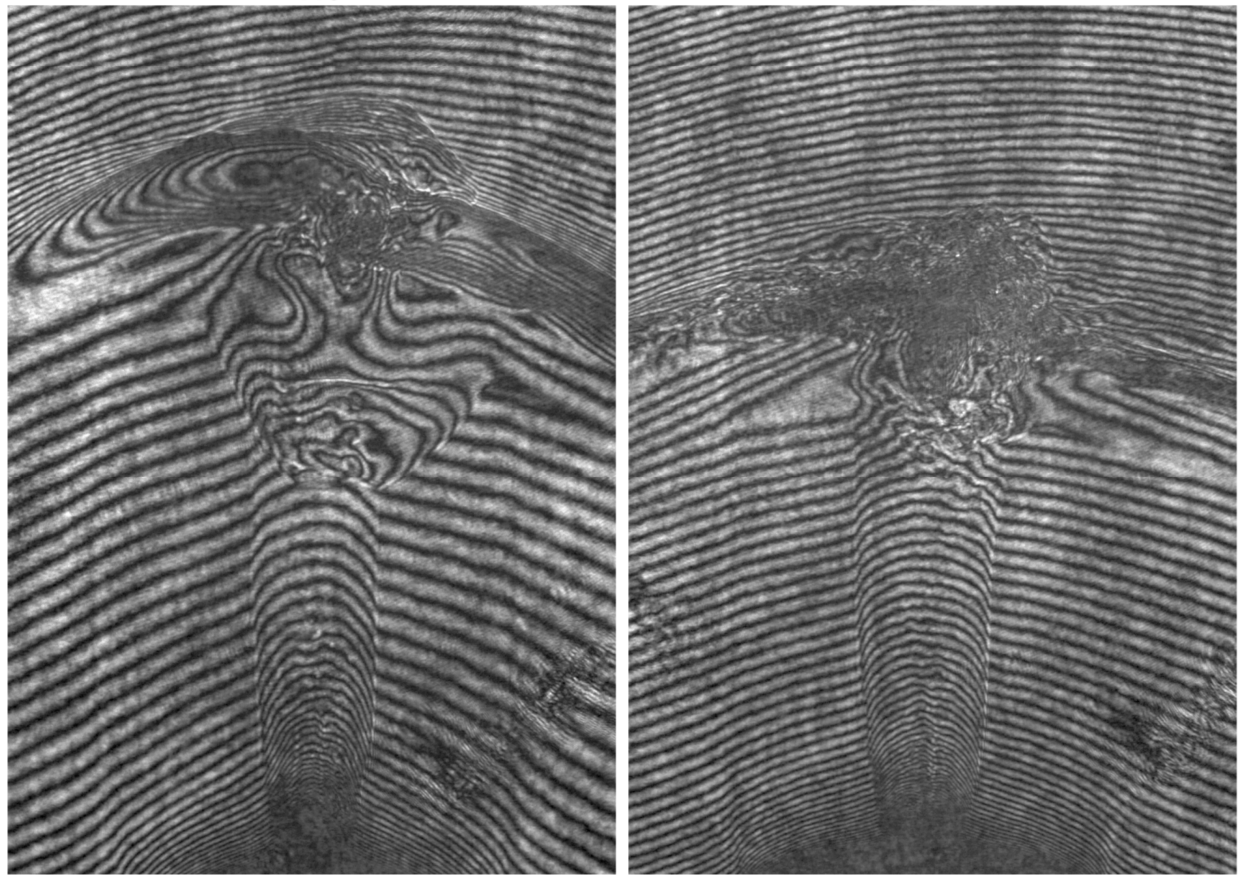
Localised gas cloud



Plasma jet from radial foil

The same density contrast, different cooling rates

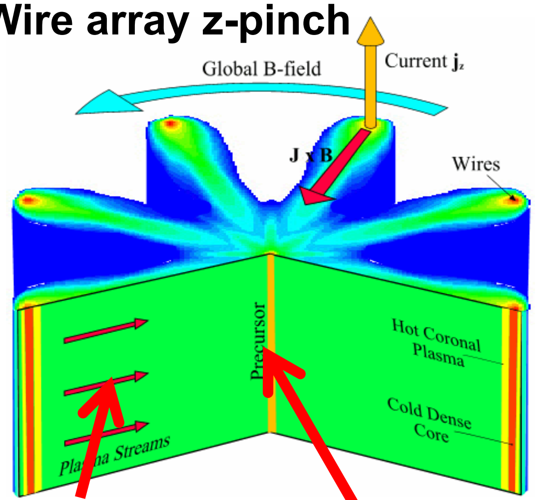
He Kr



Thinner shocks, appearance of small scale structures for gases with higher cooling rates

Colliding supersonic plasmas

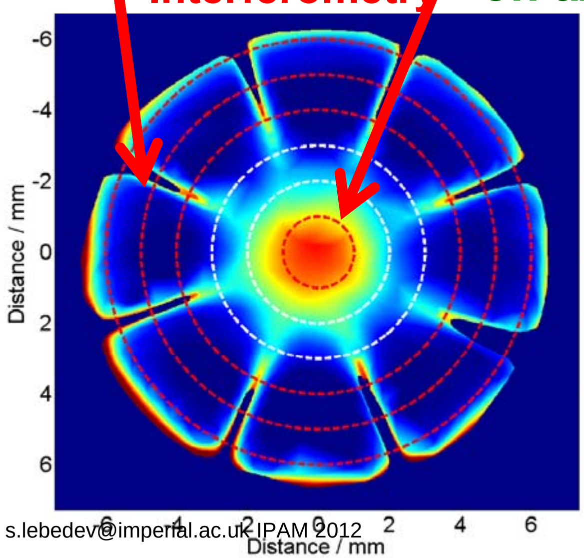
Wire array z-pinch



Ablation streams

Plasma accumulating on axis

Interferometry



Ablation of wires + JxB force

⇩

Collimated plasma streams (M > 10)

V ~ 10^7cm/s (E_{ki} ~ 10keV for W, ~2keV Al)

Harvey-Thompson et al., PRL 2012

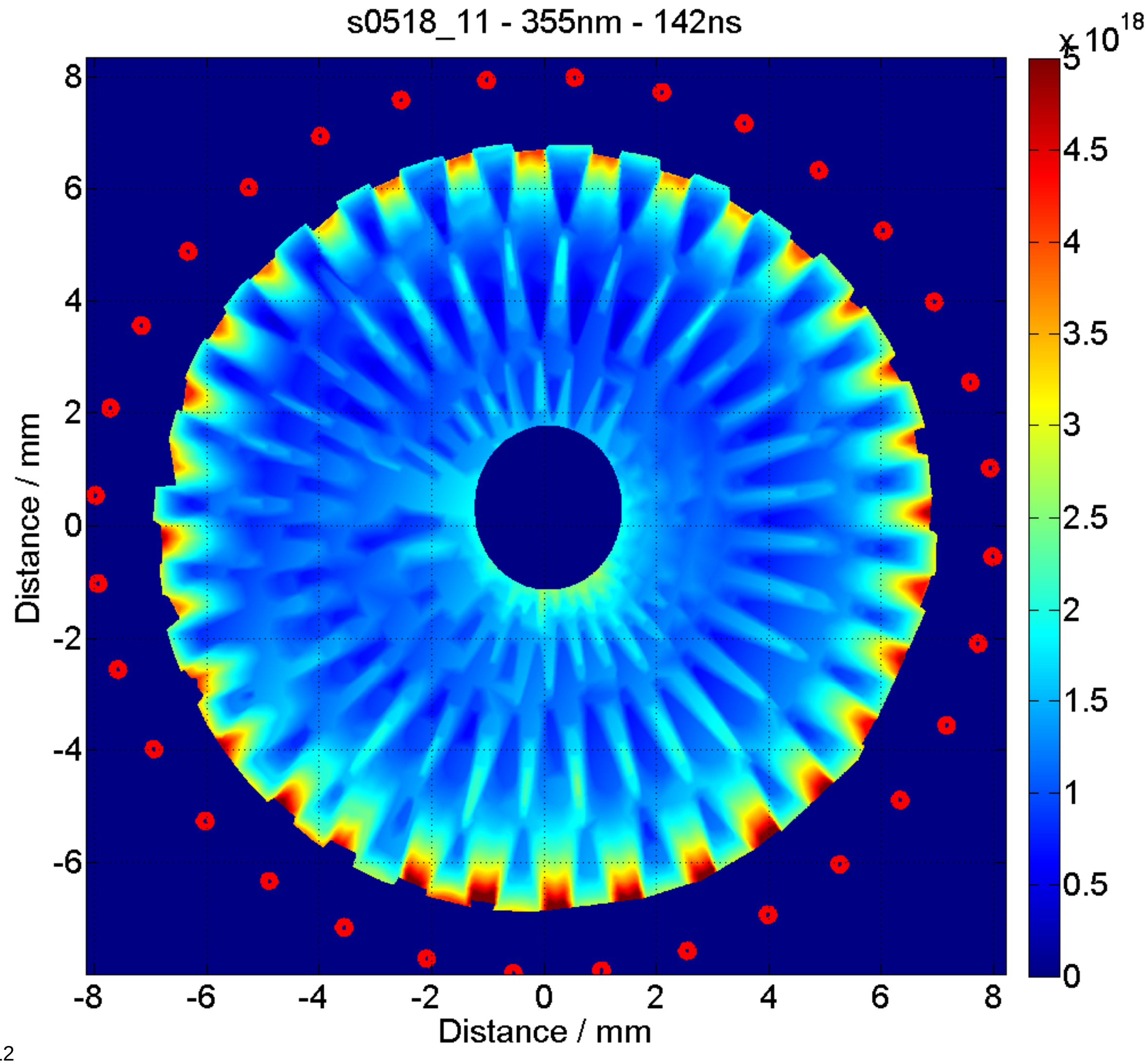
<u>Collision on axis:</u>

Large ion-ion m.f.p. (λ_{ii} ~ cm for W)

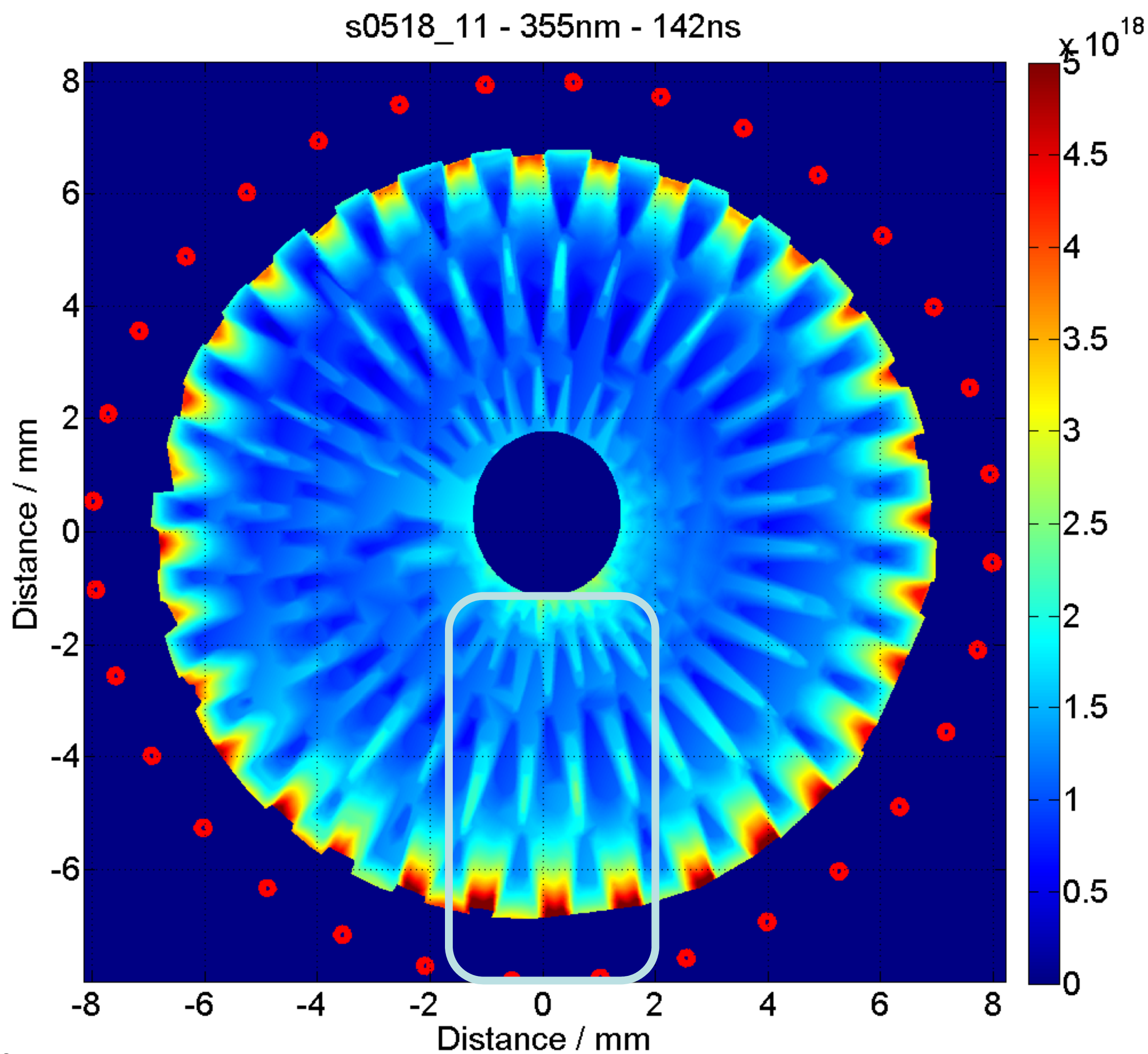
- Interpenetration of the streams
- Deceleration of the flow
- Thermalisation of ion kinetic energy:

V(r) ➔ T(r)

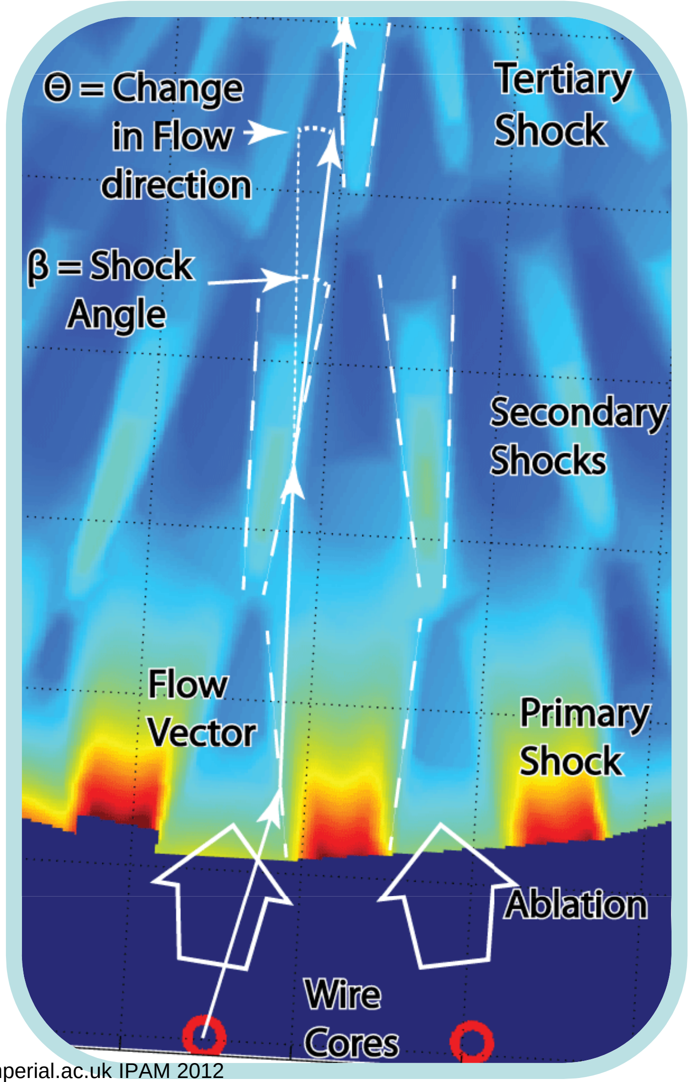
Shock structure in 32 Al wire array



Shock structure in 32 Al wire array



Shock structure in 32 Al wire array

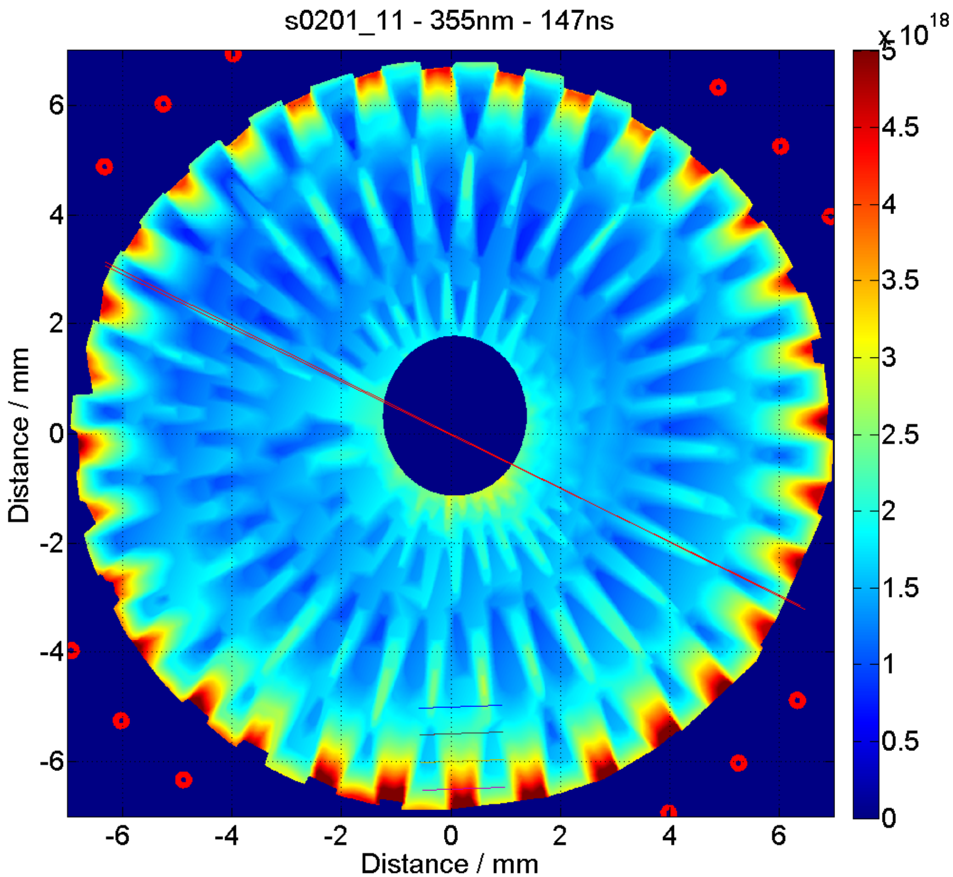


From the measurement of these structures we may estimate:

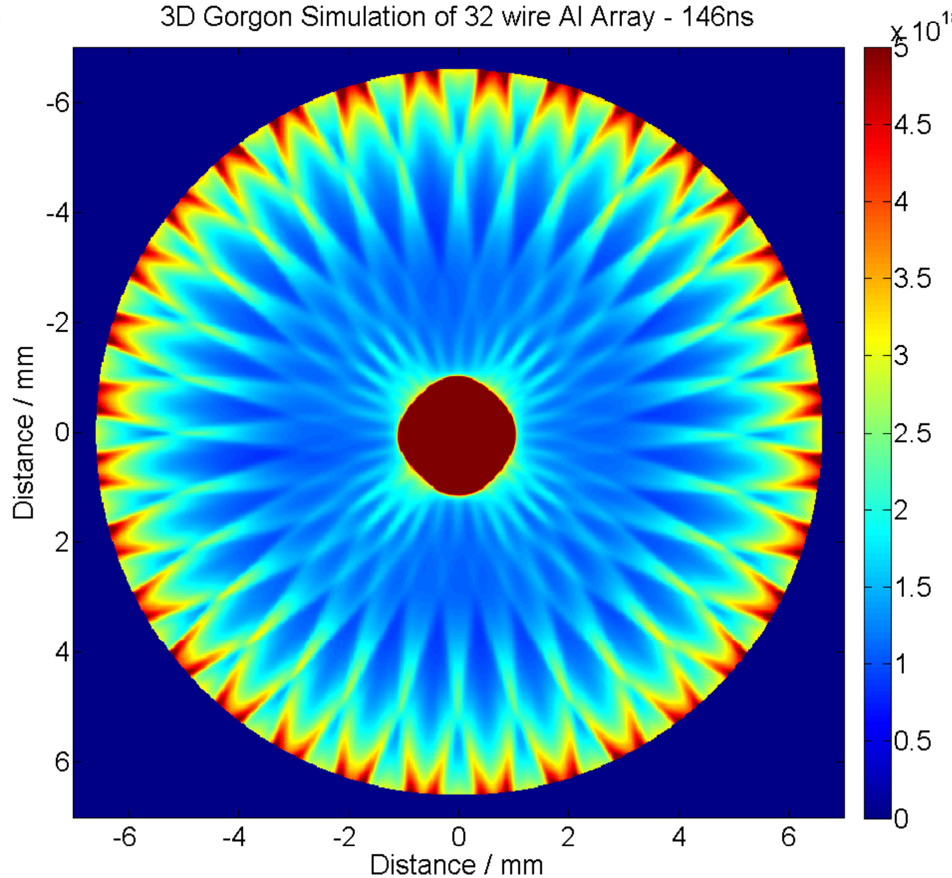
- **Mach Number** of primary shock region: $M \sim 8$
- **Density contrast** over shock : $\frac{\rho_2}{\rho_1} \sim 2$

Comparison with MHD simulations (32 Al wire array)

Aluminium plasma behaves as a fluid, and the dynamics are well described by an MHD model.



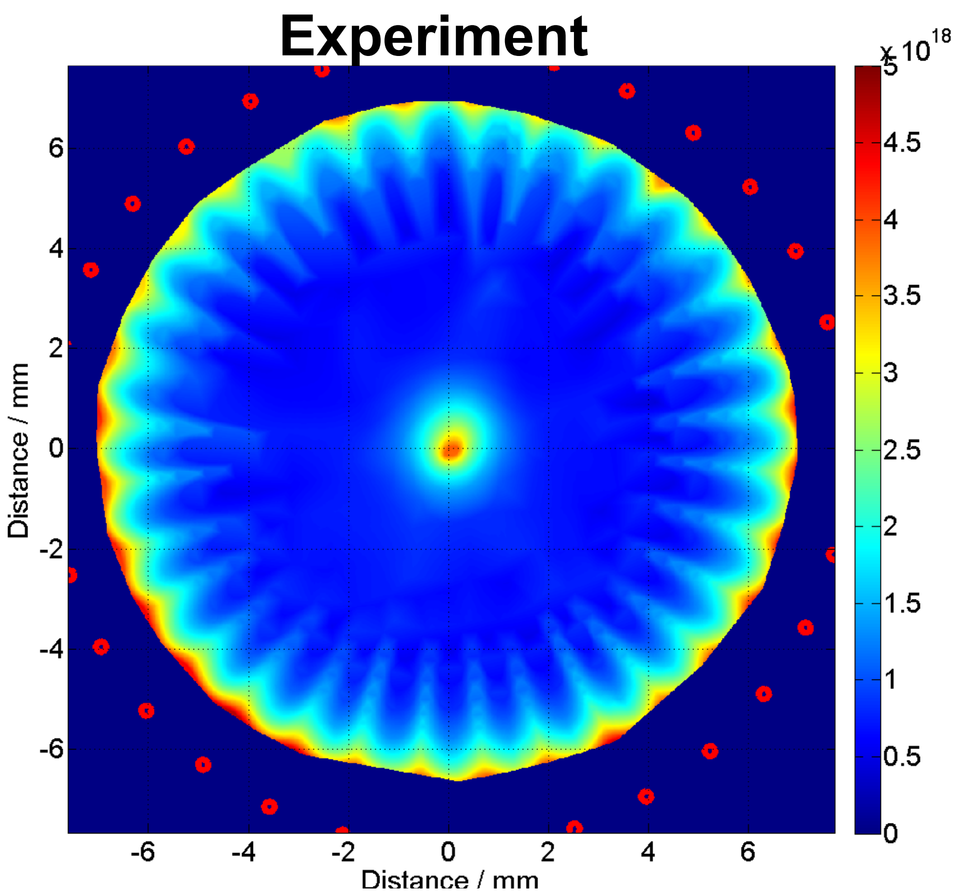
Experiment

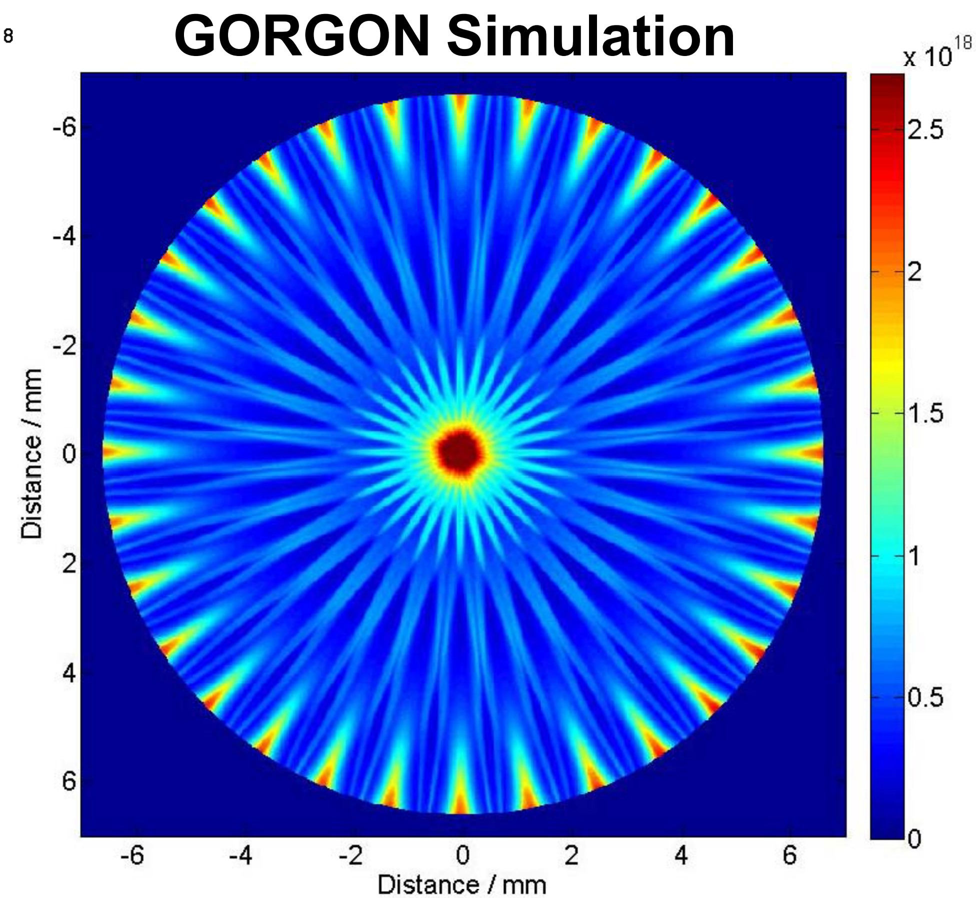


GORGON Simulation

Comparison with MHD simulations (32 W wire array)

Experiment does not show formation of shocks for Tungsten.



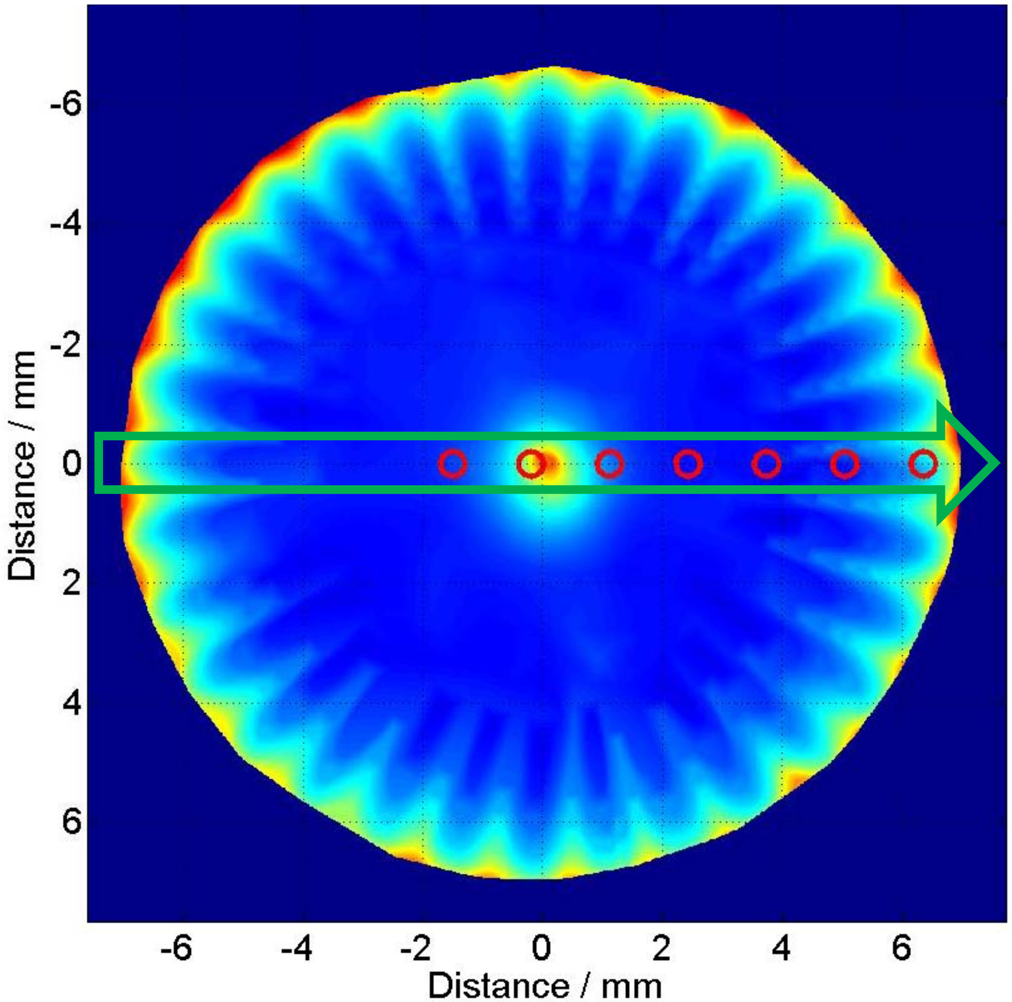


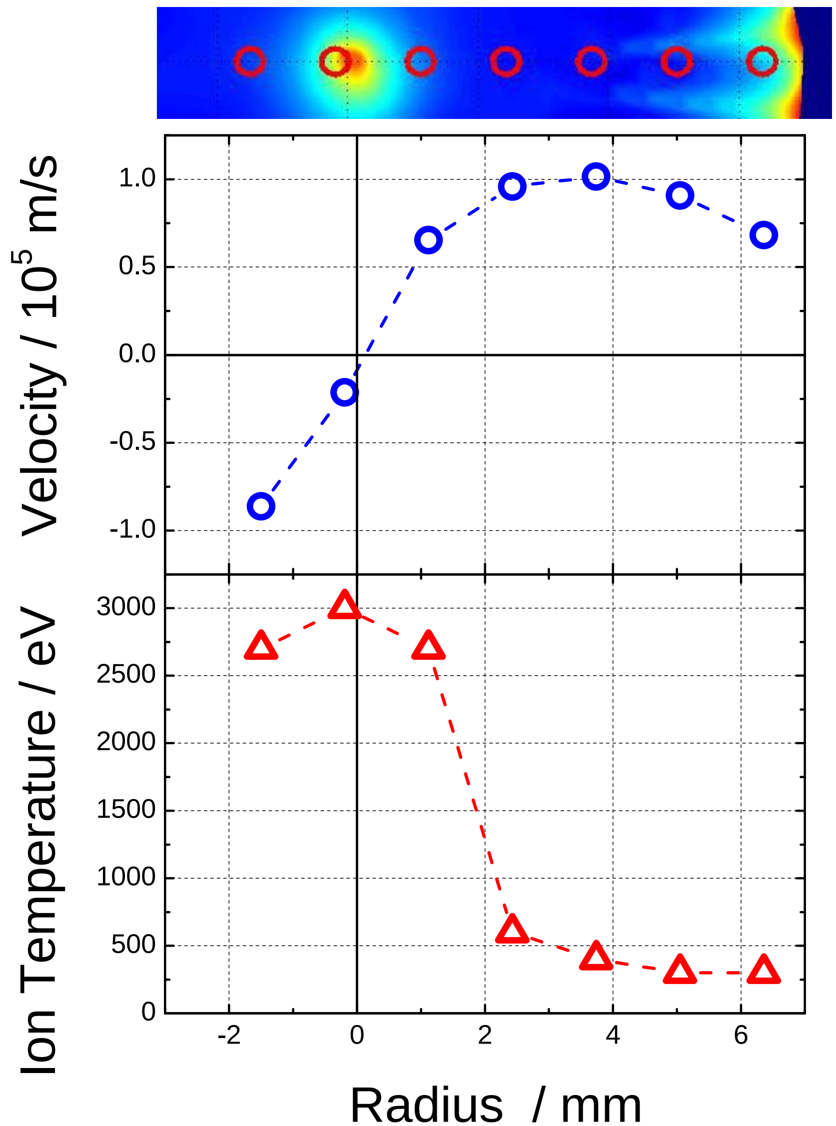
Different collisionalities for Al and W

$$\lambda_{\perp,i-i} \propto \frac{E_{kin}^2}{Z^4} \propto \frac{M_i^2}{Z^4}$$

Deceleration of the flow and heating of ions

Thomson scattered - end-on registration





s.lebedev@imperial.ac.uk IPAM 2012

“Collisional story” for tungsten

Energetic “slow” ion: E_{kin} ~10keV, T_e~10eV, $V_i << V_{Te}$

$$Z(T_e) \propto T_e^{0.5}$$

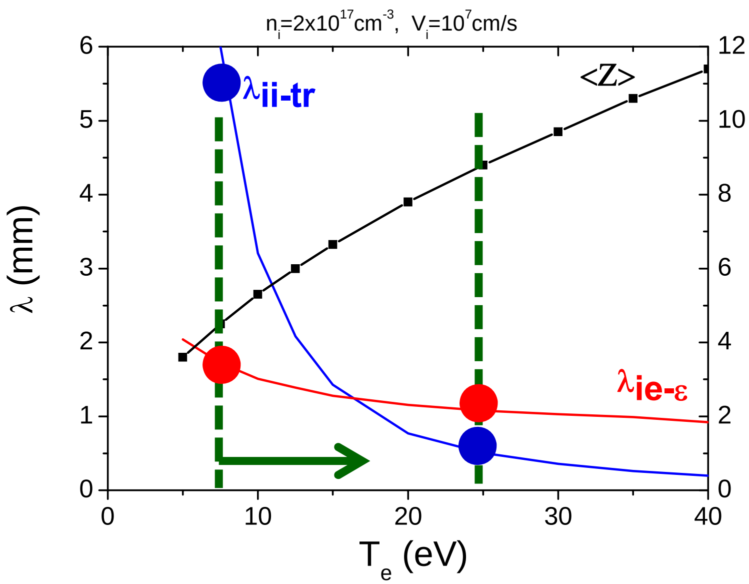
1. **Slowing down via ion-electron collisions (decrease of directed velocity without scattering)**

$$\lambda_{\varepsilon,i-e} \propto \frac{T_e^{3/2} V_i}{n_e [Z(T_e)]^2} \propto \frac{T_e^{1/2}}{n_e}$$

$$\lambda_{\perp,i-i} \propto \frac{E_{kin}^2}{n_i [Z(T_e)]^4} \propto \frac{1}{n_i T_e^2}$$

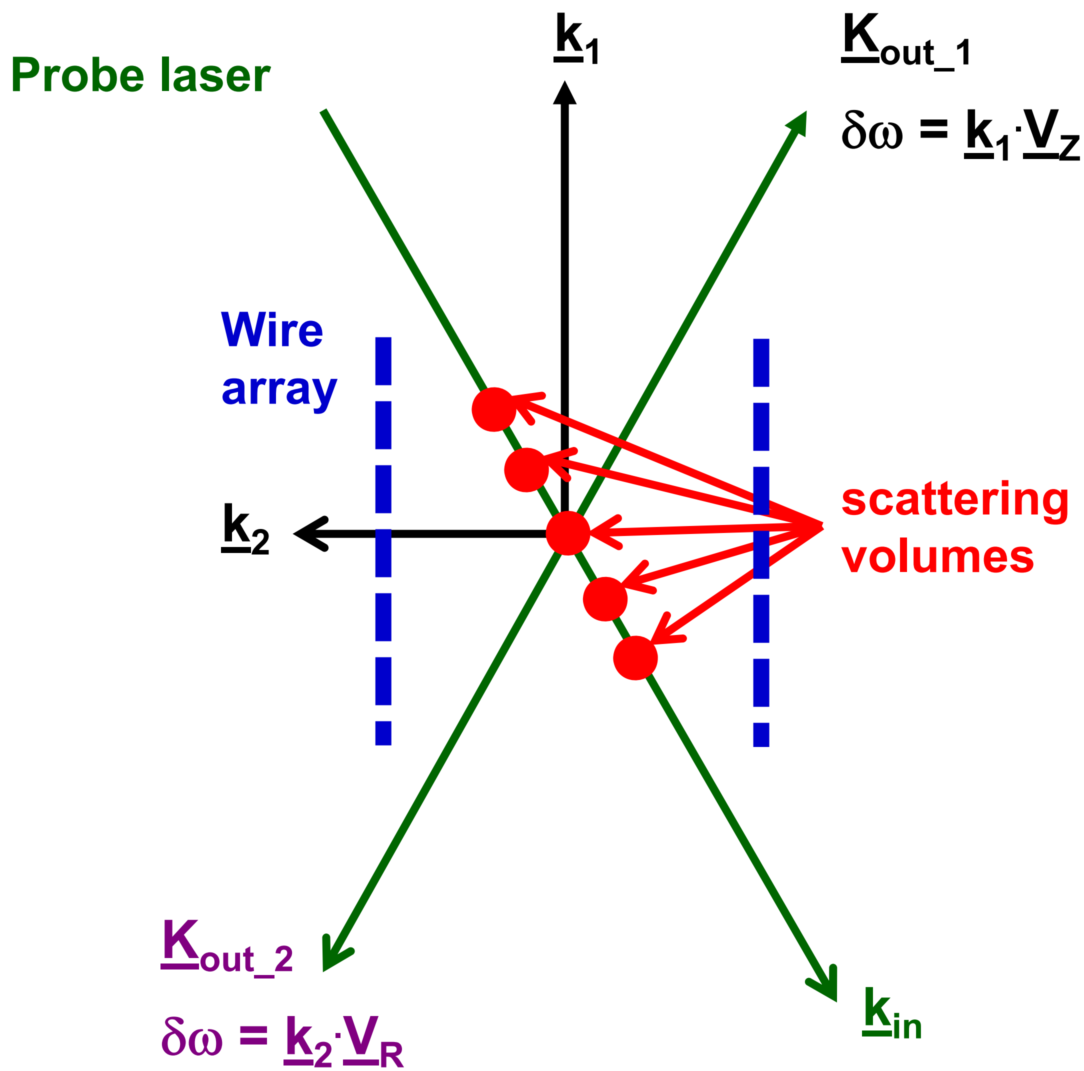
2. **Increase of electron temperature T_e leading to increase of <Z>**

3. **Rapid increase of ion-ion scattering leading to thermalisation of the kinetic energy**



Simulations by M. Sherlock et al, PoP 2004

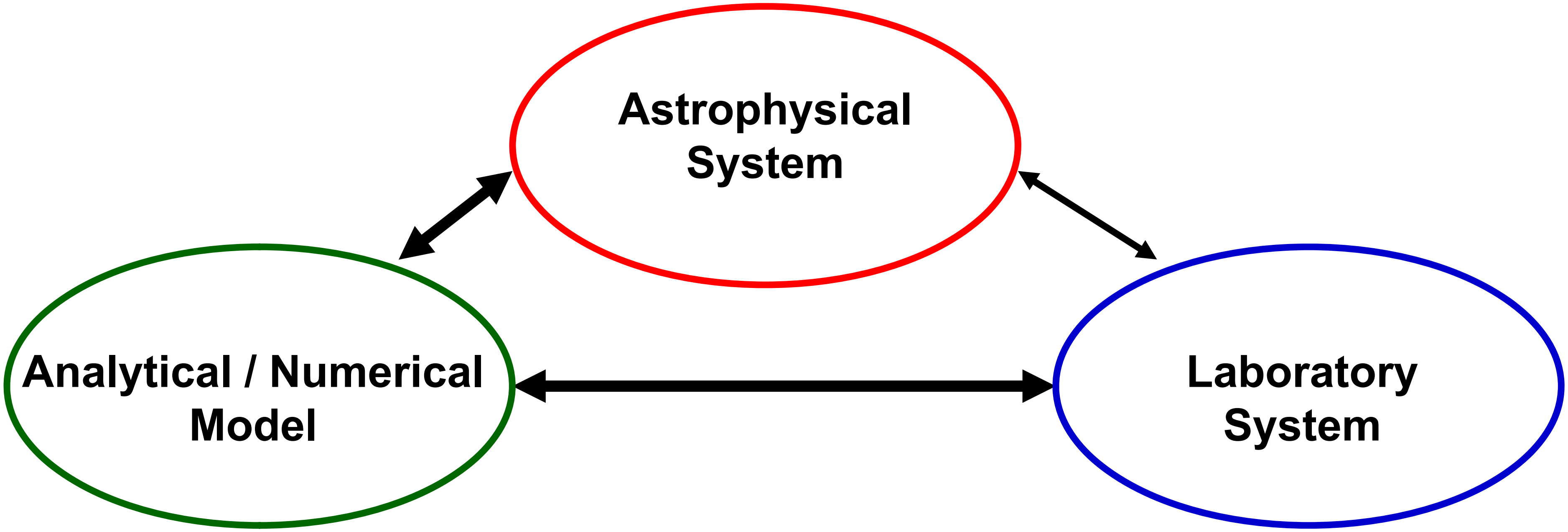
Future work



Separate changes in $V_{\parallel}$ and in $V_{\perp}$ (deceleration and scattering)

- **K_{out_1} – evolution of transverse velocity (V_z – from scattering)**
- **K_{out_2} – evolution of radial velocity (V_z – deceleration and scattering)**

Astrophysical Dynamics in Laboratory



Scaled representation of astrophysical plasma dynamics:

- Laboratory and astrophysical phenomena are described by the same set of equations
- Dimensionless numbers and similarity transformations
- Creating appropriate initial conditions (morphology)
- Establish how long the similarity holds

Remington, Drake, Ryutob, Rev. Mod Phys., 2006