Laboratory Studies of Supersonic Magnetized Plasma Flows: Jets and Collisionless Shocks

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in collaboration with

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EPSRC
Engineering and Physical Sciences Research Council

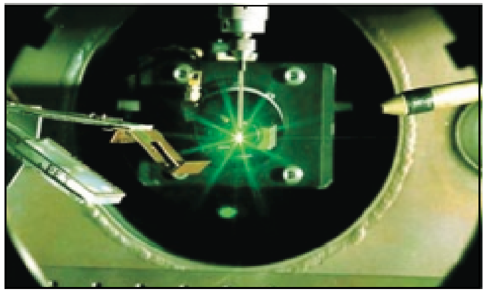
SCIENTIA IMPERII DECVS ET TVTAMEN

NNSA
National Nuclear Security Administration

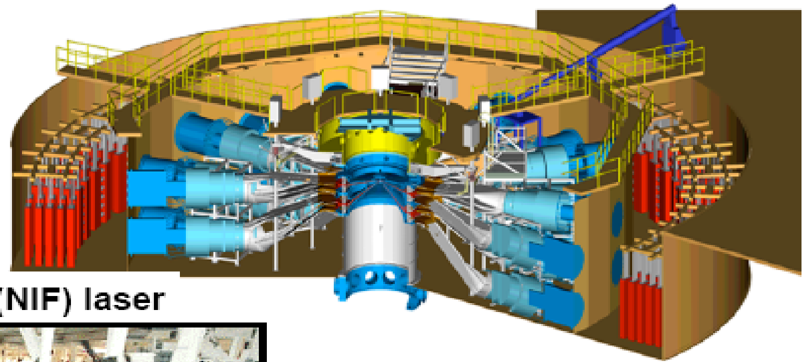
"Laboratory Astrophysics" on ICF facilities

Slide Courtesy Bruce Remington

Jupiter, Trident, Z-Beamlet, Vulcan, LULI, Gekko lasers

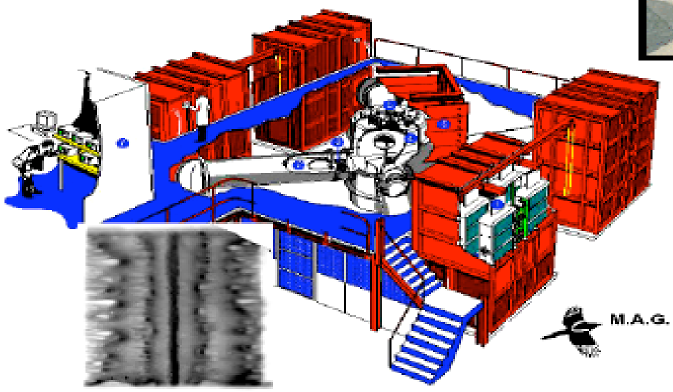


Z, ZR magnetic-pinch facility

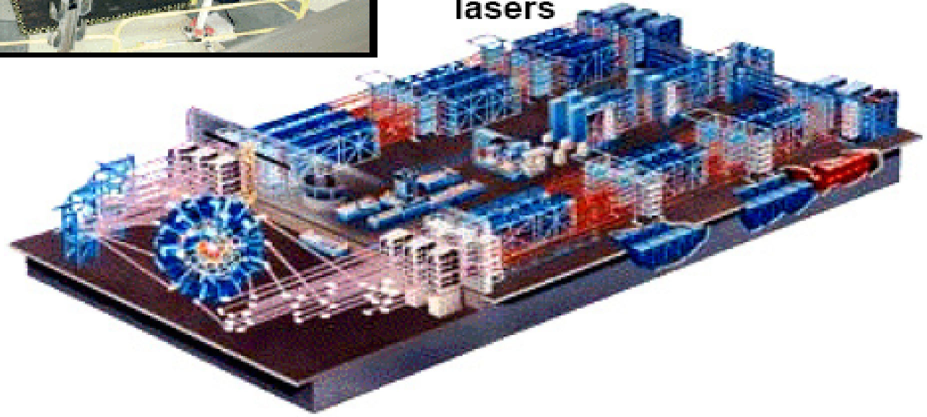


National Ignition Facility (NIF) laser

Magpie magnetic-pinch facility



Omega, EP lasers



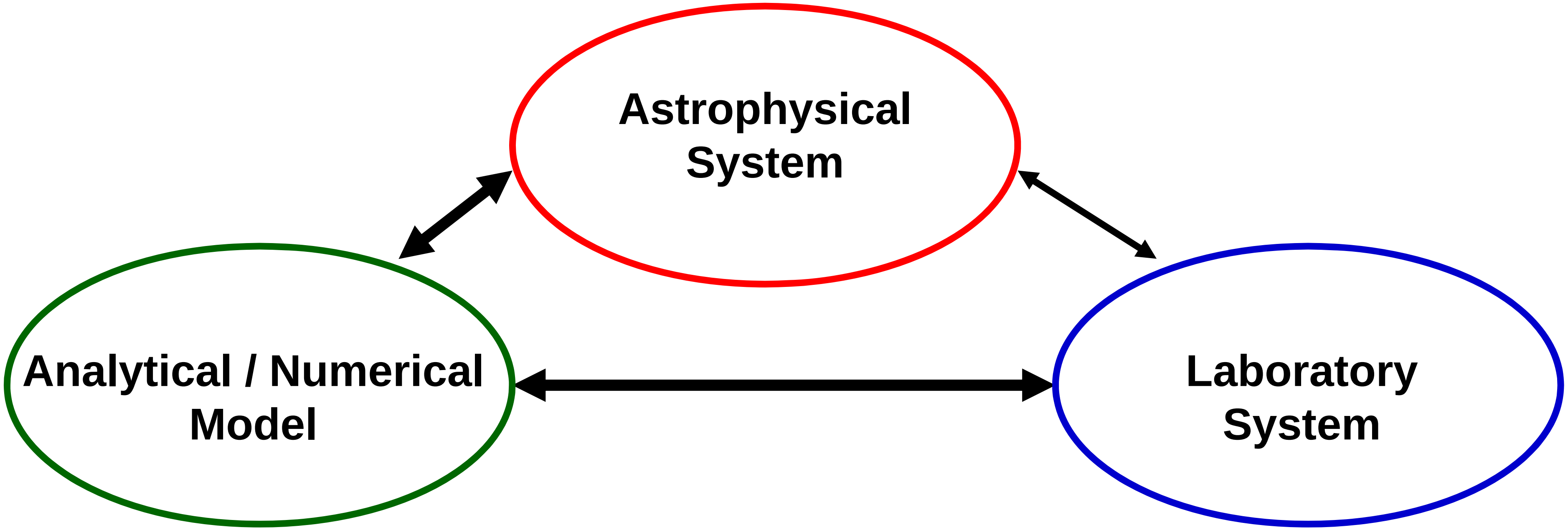
1. Create astrophysical conditions in the laboratory

Experiments providing data on properties of matter in extreme (astrophysical) conditions – e.g. opacity, EOS, ionization balance

2. Make a scaled "working" model of astrophysical phenomena

Modeling astrophysical dynamics in scaled laboratory experiments – e.g. shocks, instabilities, jets

Astrophysical Dynamics in Laboratory Experiments



Scaled representation of astrophysical plasma dynamics:

- **Laboratory and astrophysical phenomena are described by the same set of equations**
- **Dimensionless numbers and similarity transformations (Re, Mach, Re_M)**
- **Creating appropriate initial conditions (morphology)**

Experiments allowing quantitative measurements

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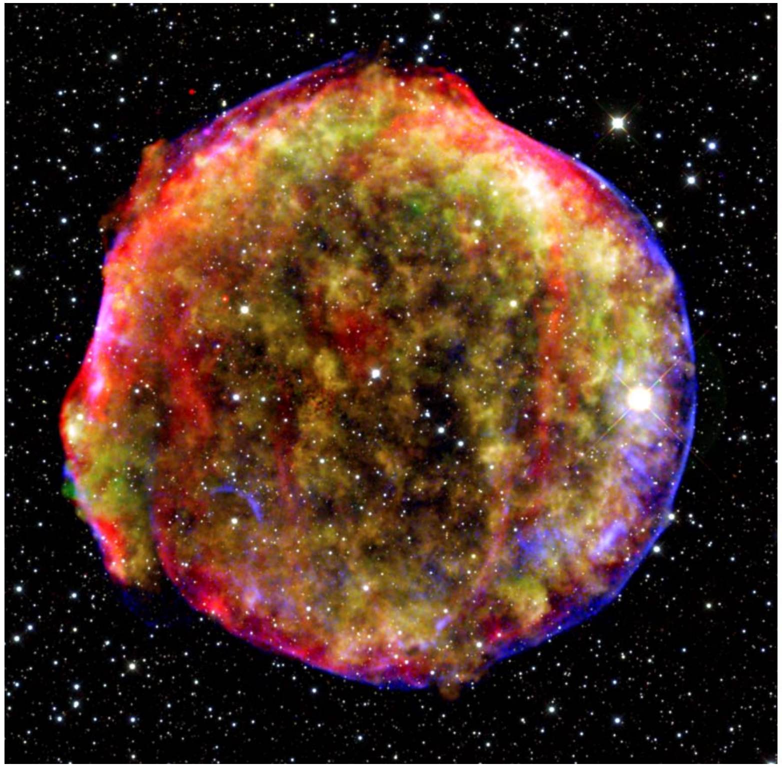
Remington, Drake, Ryutov, Rev. Mod Phys., 2006

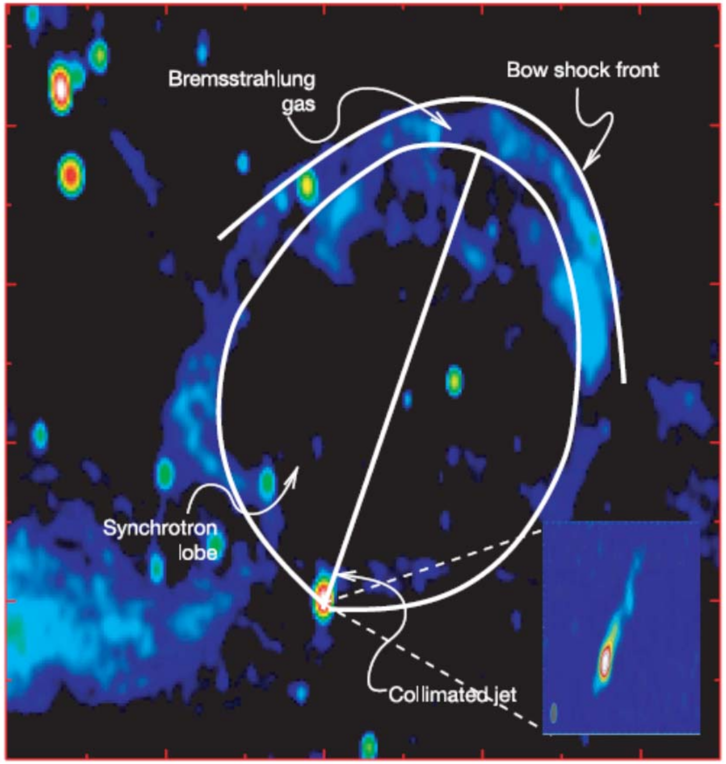
Magnetic fields play important role in many astrophysical phenomena

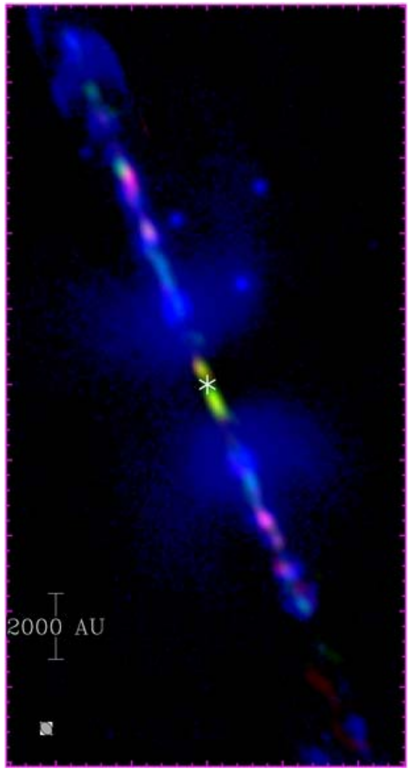
Cosmic ray acceleration in magnetized shocks

Astrophysical jets

Galactic **Protostellar**







Accretion discs, dynamos, magnetic reconnections, photoevaporated clouds

Magnetised HEDLA experiment

Supersonic magnetised plasma flow

$$M \equiv \frac{V_{flow}}{C_S} >> 1$$

Dynamically significant magnetic field

$$\beta \equiv \frac{nT}{B^2/8\pi} \approx 1 \quad \beta_{dyn} \equiv \frac{\rho V_{flow}^2}{B^2/8\pi} >> 1$$

Advection of magnetic field by the flow

$$\mathrm{Re}_M \equiv \frac{L \cdot V_{flow}}{D_M} >> 1$$

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

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

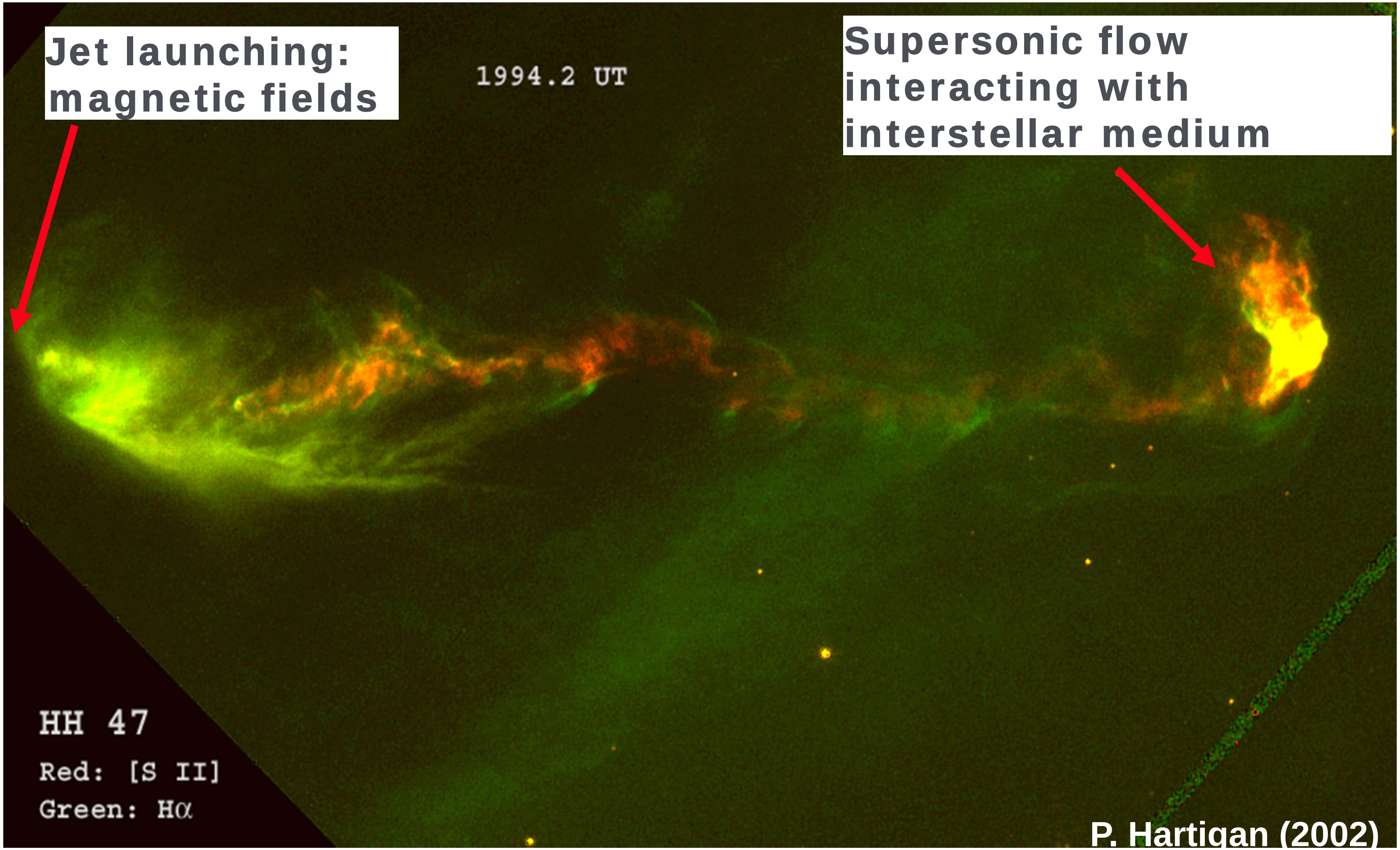
Increase *T* to increase Re_M

Increase *n* to retain large Re, Pe

Large *n·T* ➔ high energy density

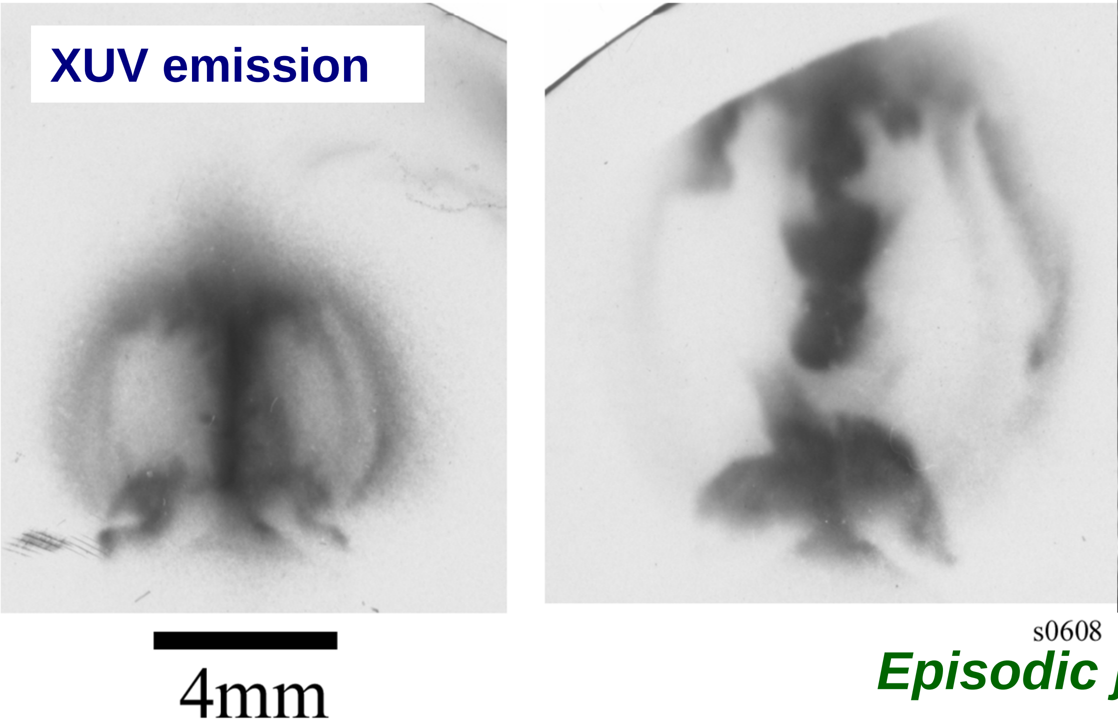
- **"1-D" initial configuration (negligible edge effects)**
- **Good diagnostic access**

“Movie” from HST observations of a proto-stellar jet

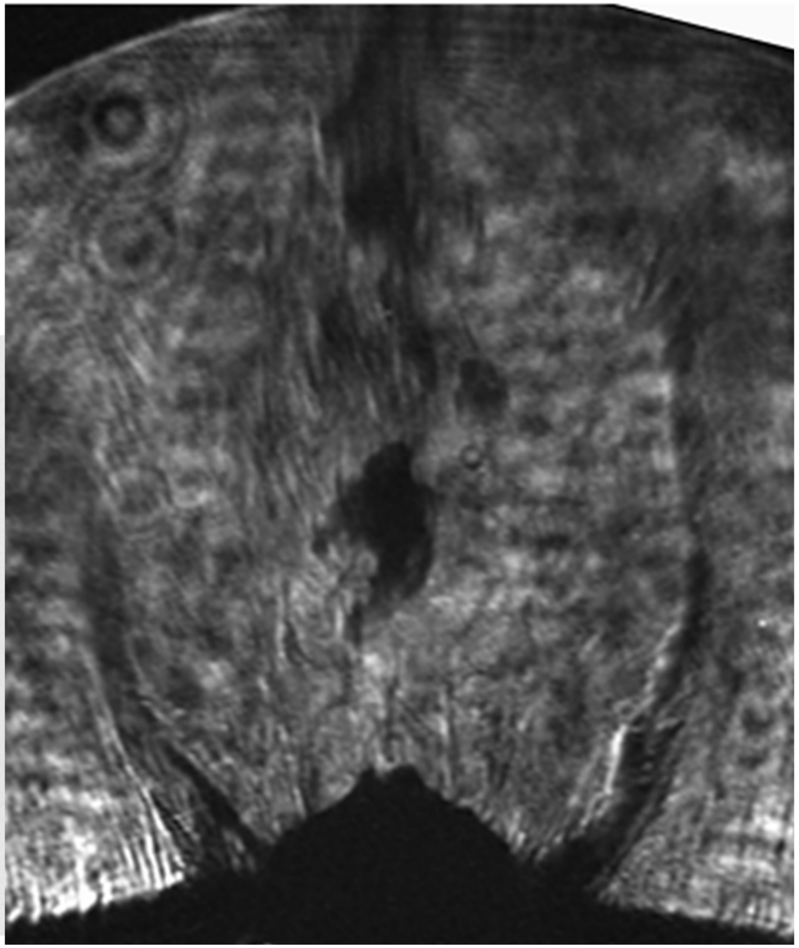


Magnetically driven jet: growth of 3-D structures

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



Laser shadowgraphy

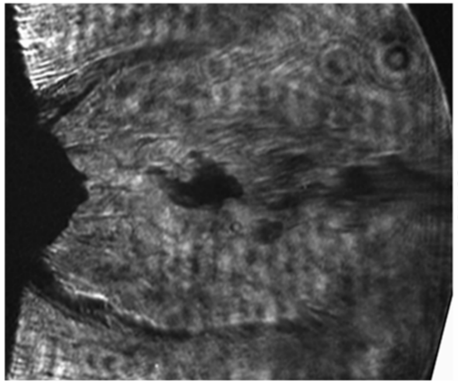


Episodic jets with repeatable eruptions

Ciardi, ApJL 2009; Suzuki-Vidal, PoP 2010

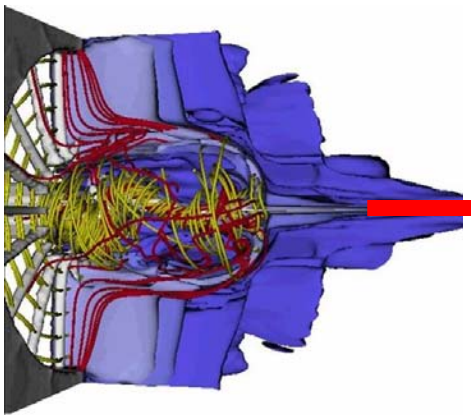
Jet propagation – input for astrophysical simulations

Experiment



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

3-D MHD simulation of the experiment



Scaling:

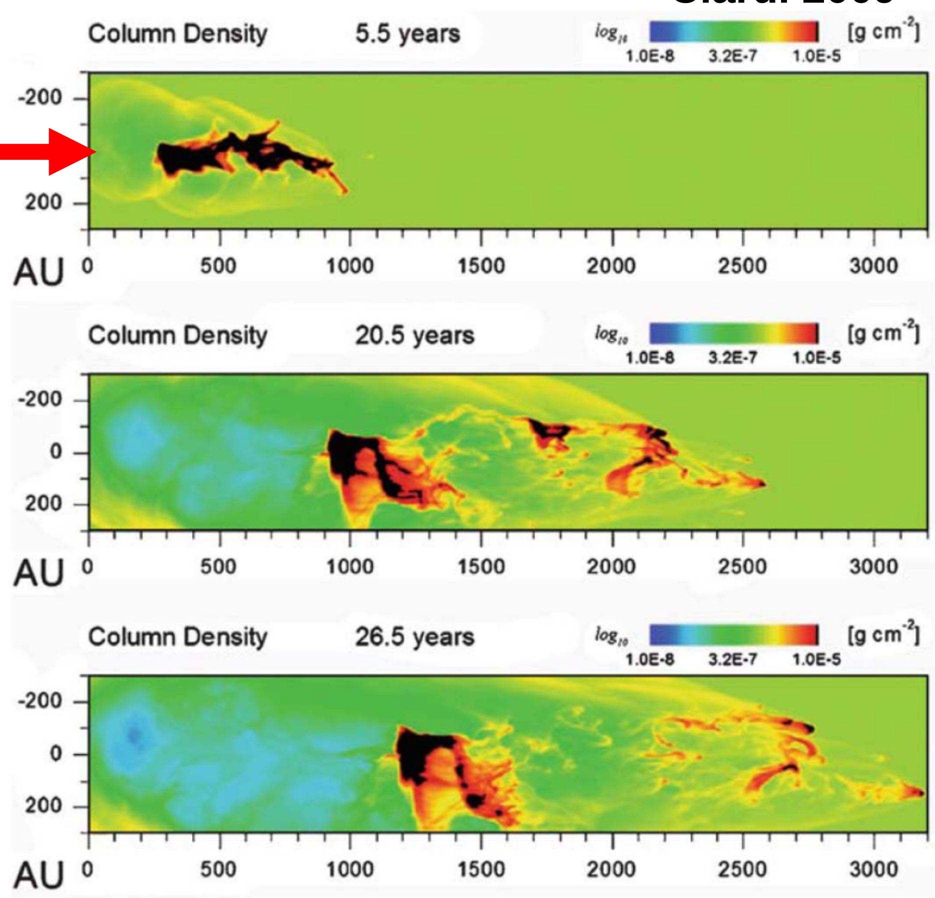
1mm ➔ 10 AU

200ns ➔ 10 years

1mg/cc ➔ 10^6 cm^{-3}

3-D simulation of astrophysical jet

Ciardi 2009



Need to compare with propagation of a “laminar” jet!

Outline

Motivation: develop experimental platform for quantitative studies of magnetised supersonic plasma flows

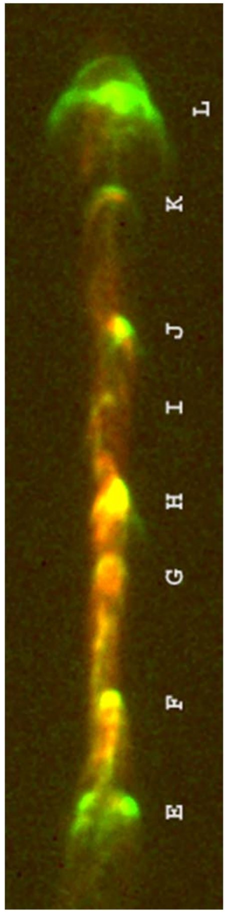
1. **Shocks in magnetised plasma flows:**
   - ***head-on collision of two laminar supersonic jets***
   - ***formation of reverse shock mediated by pile-up of magnetic field***
2. **Formation of differentially rotating plasma discs**

Common theme – dynamics of supersonic magnetised plasma flows

(MHD, compressibility, radiative cooling, ionisation balance…)

Internal shocks in YSO jets & colliding jets

Astrophysical jets: variability of velocity ➔ shocks

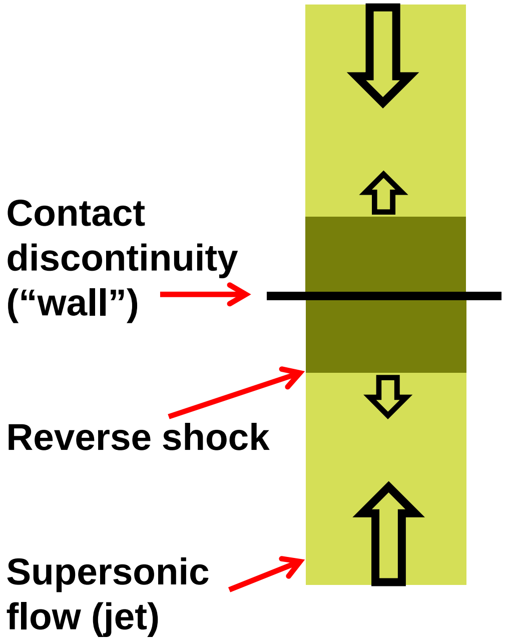


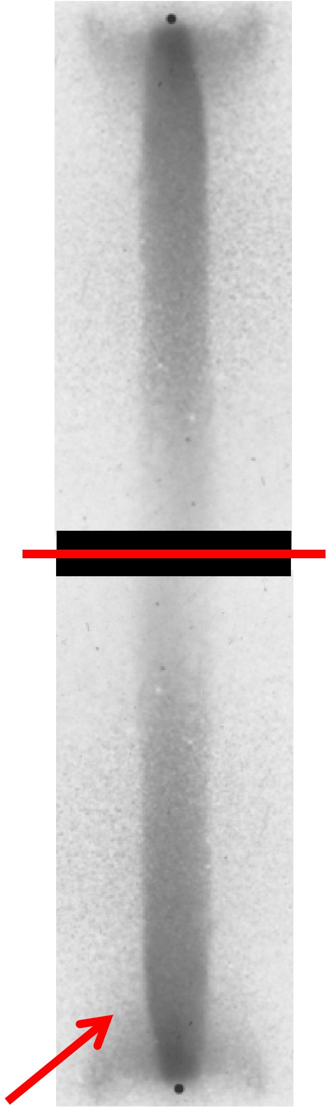
Collision of supersonic flows with entrained (toroidal?) magnetic field

Radiative cooling:

$$\tau_{cool} < \tau_{hydro}$$

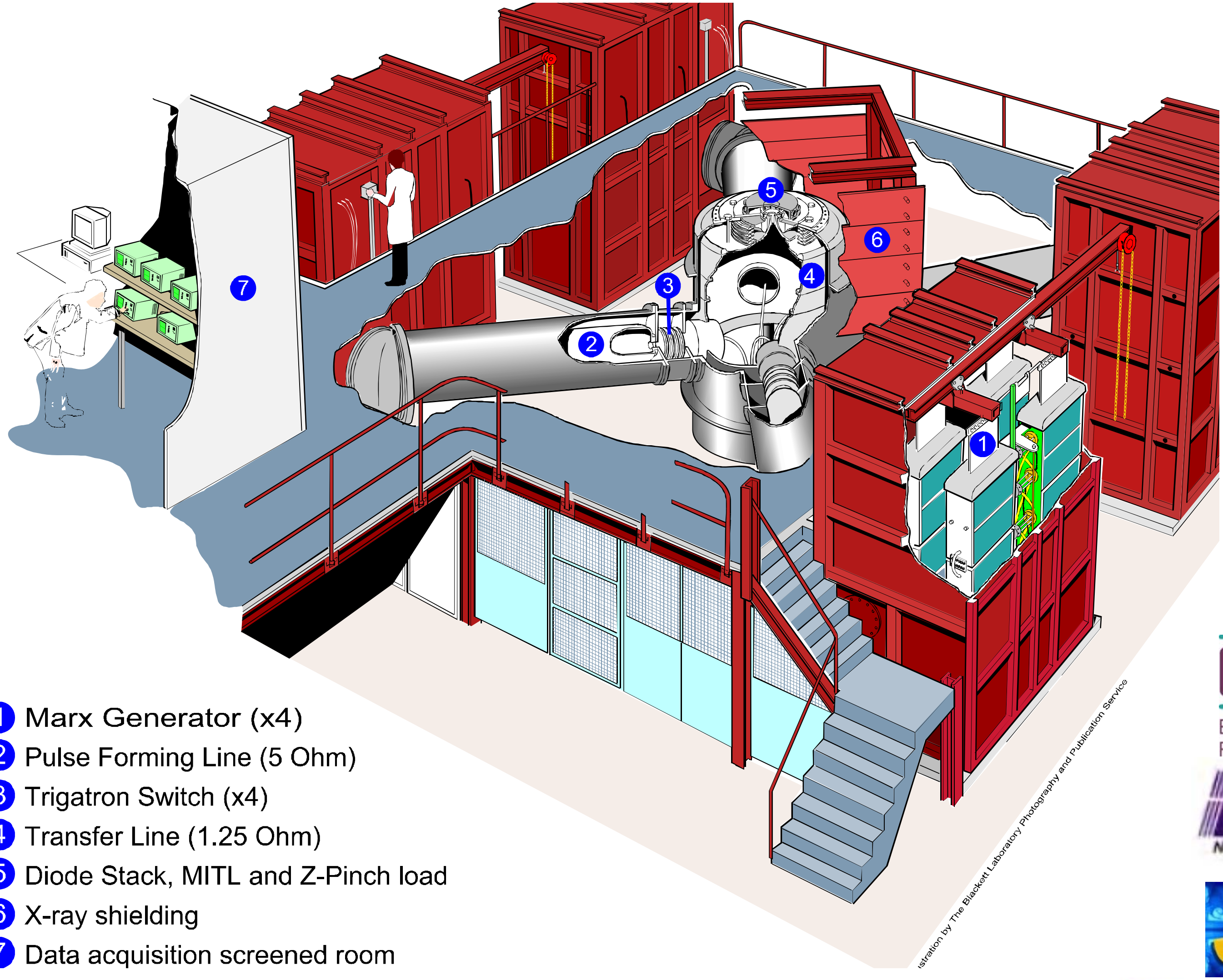
Experiment: reverse shocks in colliding jets





MAGPIE Z-pinch facility

1TW, 1.5MA, 250ns



~30kJ delivered to the load

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

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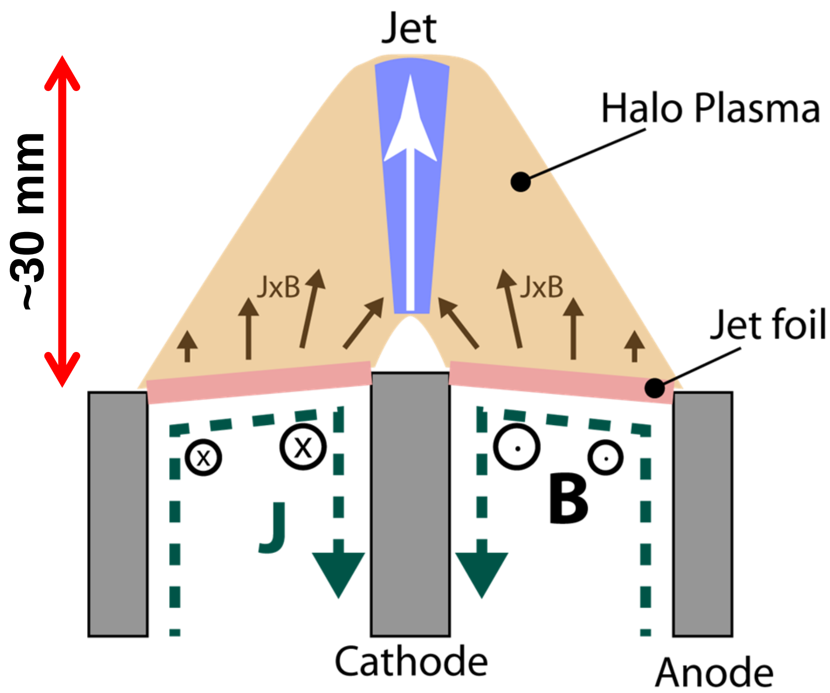
Formation of a laminar magnetically driven jet

Magnetically driven plasma jet



Radial foil z-pinch driven by 1.4MA, 250ns current pulse of MAGPIE pulsed power facility

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

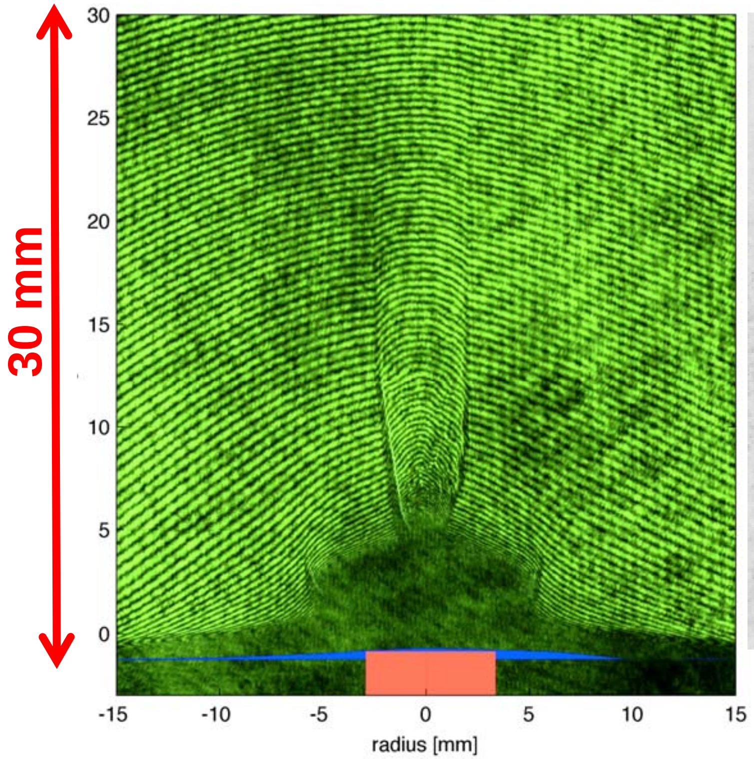
Azimuthal magnetic field is able to diffuse through the foil

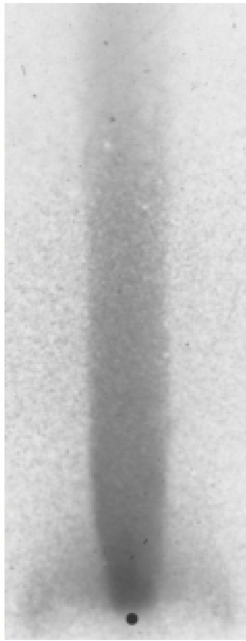
Jet is produced by ablation of the foil material ($j_r x B_\phi$)

Suzuki-Vidal et al., PoP, 2012

Interferometry: electron density distribution

Magnetically driven plasma jet





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

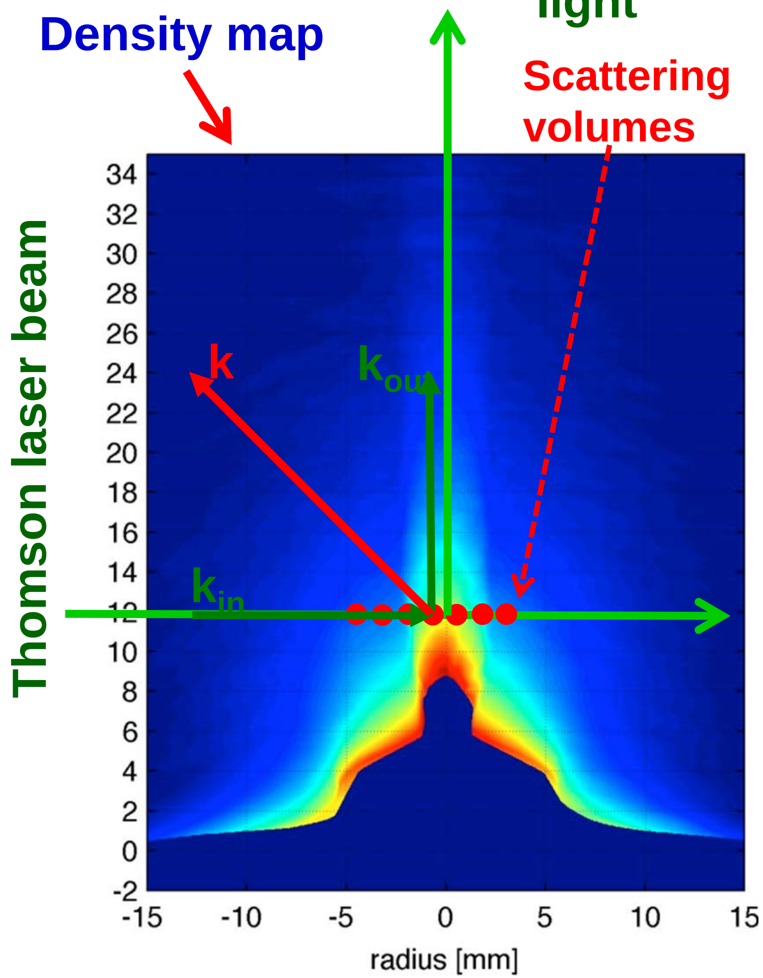
Azimuthal magnetic field is able to diffuse through the foil

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

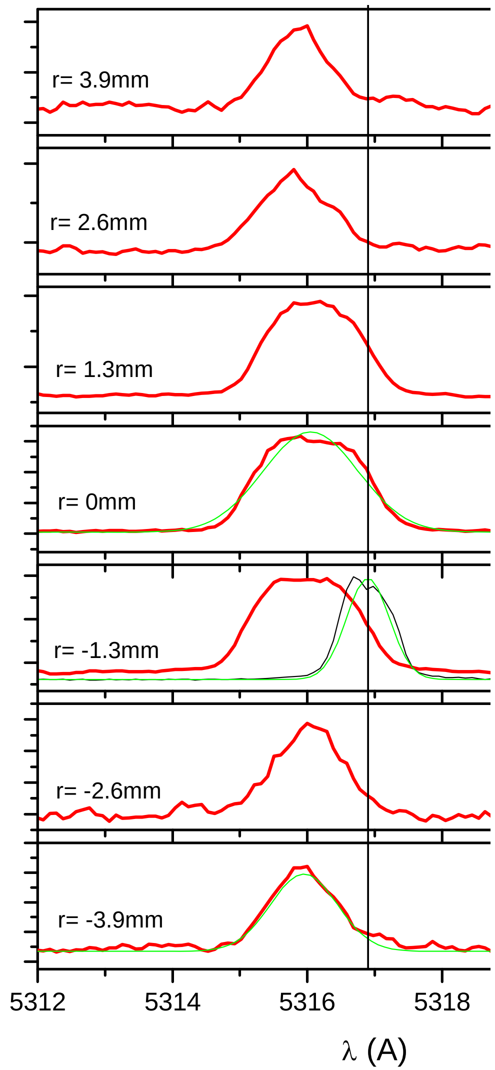
- **"laminar" flow for ~400ns**
- **Small opening angle (2^0 - 5^0) (internal Mach number 10-30?)**

Suzuki-Vidal et al., PoP, 2012

Thomson scattering: jet velocity and temperature



Blue-shifted spectrum, V_z from Doppler shift.



Jet is surrounded by lower density plasma moving with the same velocity (V_z~50km/s)

ZT_e ~60eV

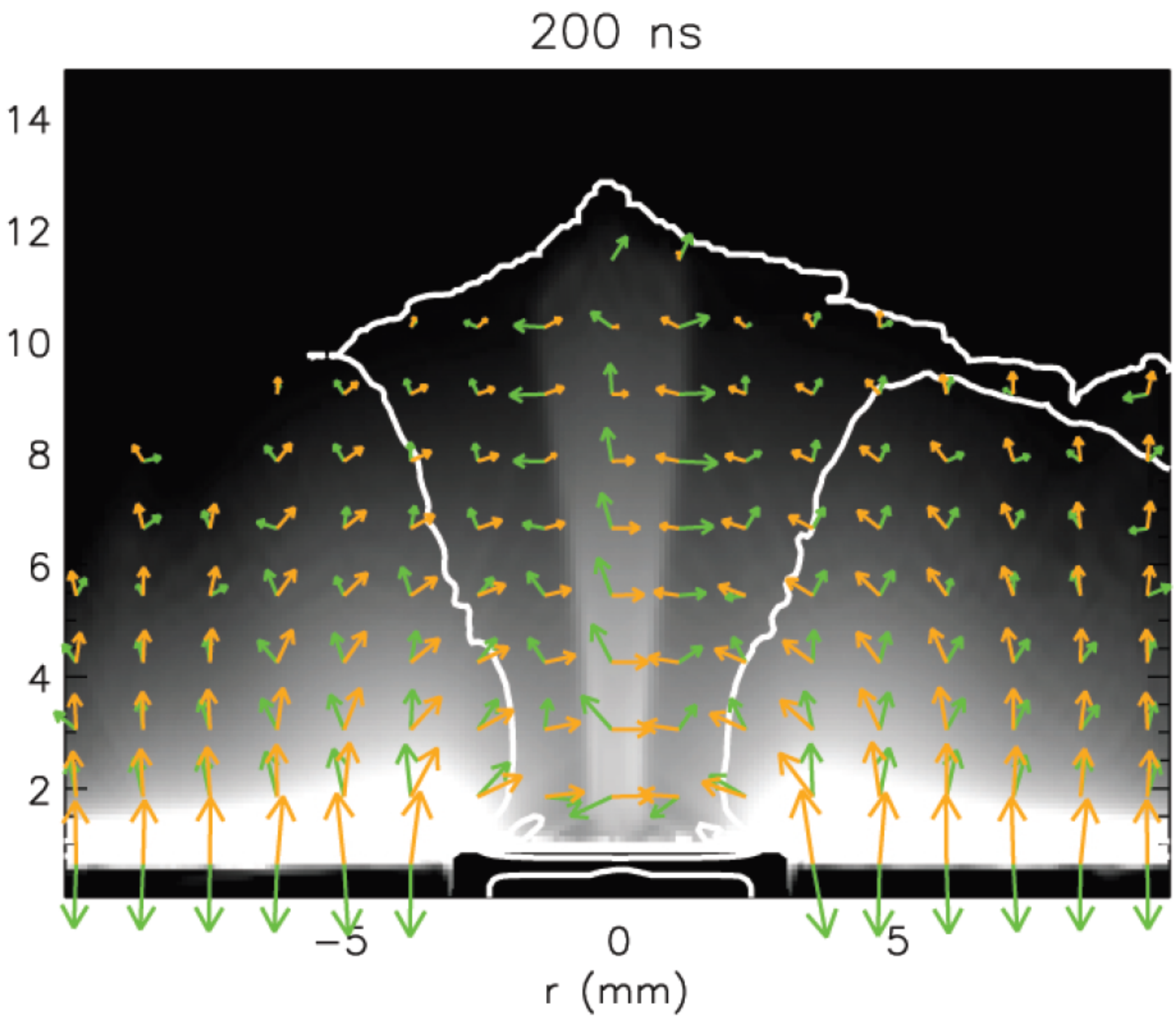
(T_e = 20eV , Z=3)

M ~3 – 4

Observed opening angle is 2-5^0, some collimating force is needed

Collimation of the jet is provided by magnetic fields

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



Toroidal magnetic field (B_φ) diffuses through the foil

"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

Thomson scattering measurements show inward flow with V_r~10km/s

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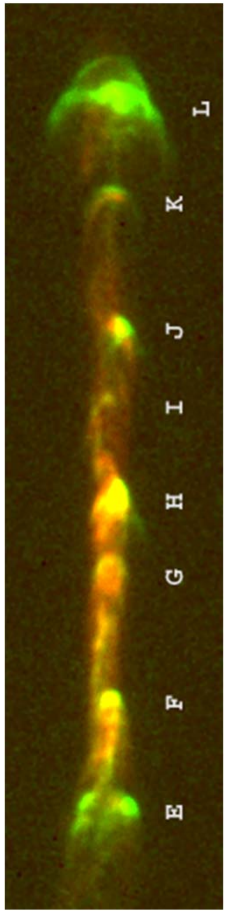
Internal shocks in YSO jets & colliding jets

Astrophysical jets: variability of velocity ➔ shocks

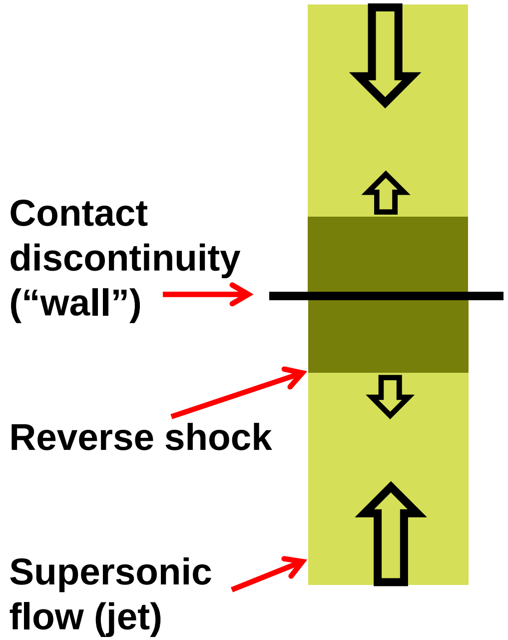


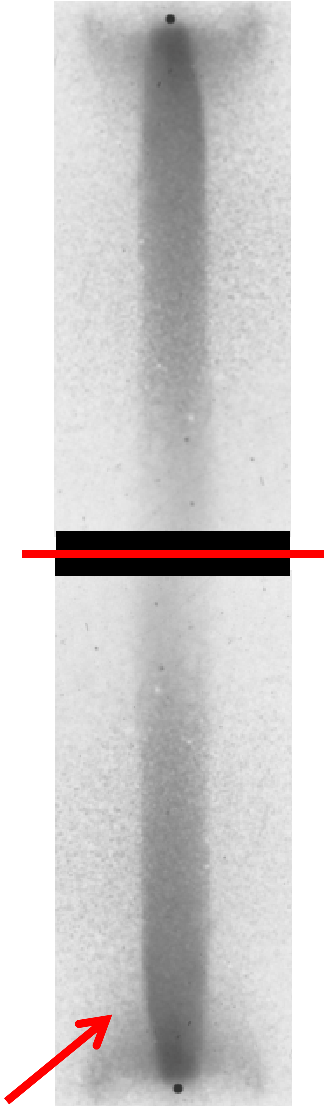
Collision of supersonic flows with entrained (toroidal?) magnetic field

Radiative cooling:

$$\tau_{rad} < \tau_{hydro}$$

Experiment: reverse shocks in colliding jets





Plasma jet from radial foil

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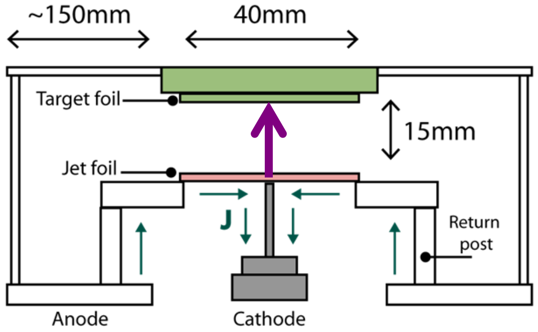
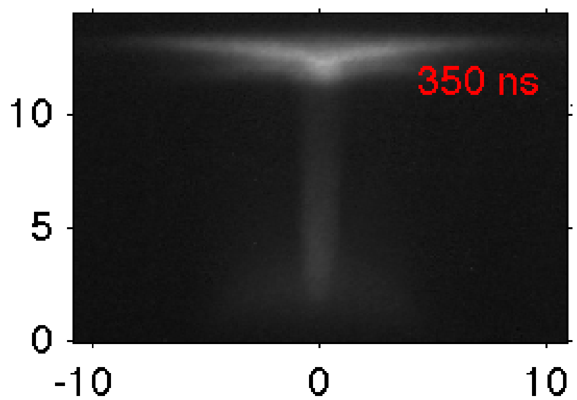
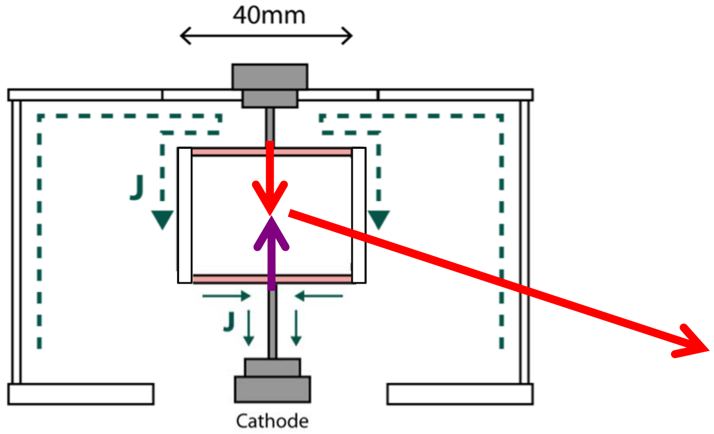
Set-up for colliding jet experiments

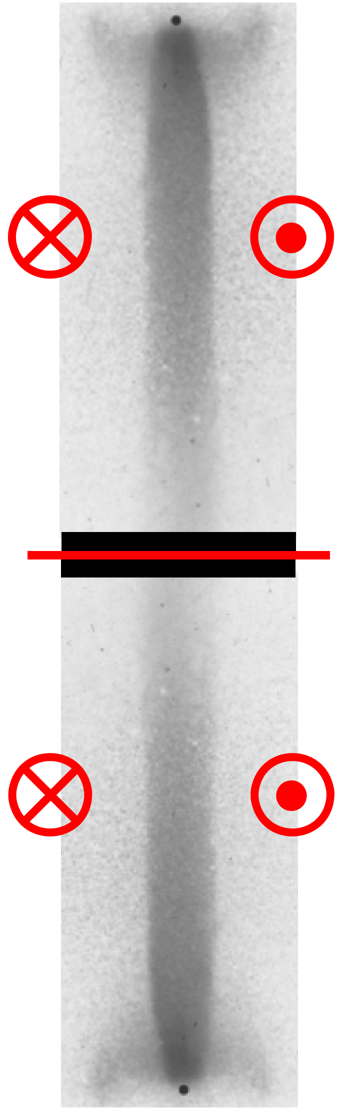
Jet – target collision





Colliding jets





Head-on collision of two radiatively cooled, supersonic (magnetized) jets

(the same orientation of B_θ in both jets)

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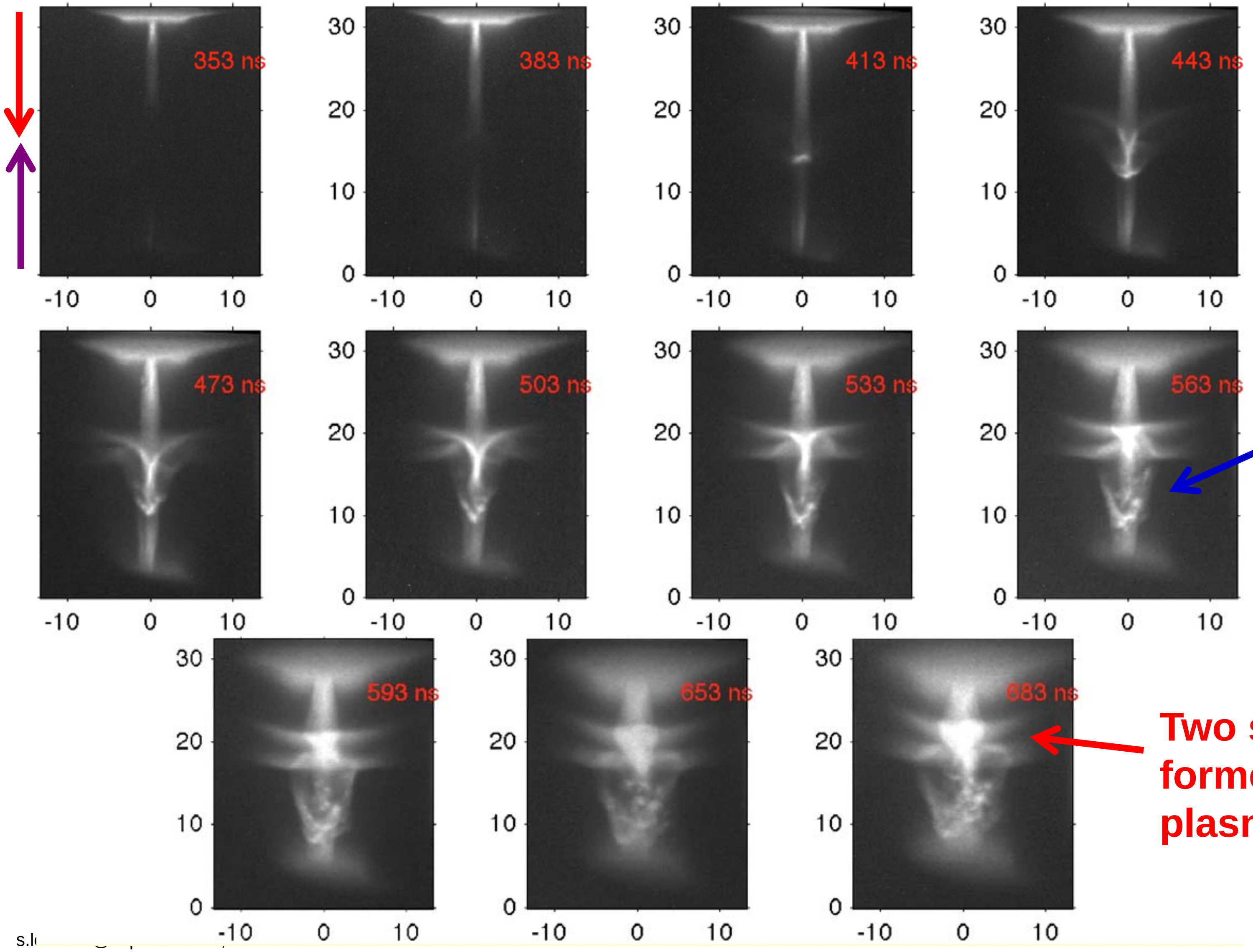
Colliding jets

Optical emission, 30ns inter-frame separation



"Stronger" jet from the top foil

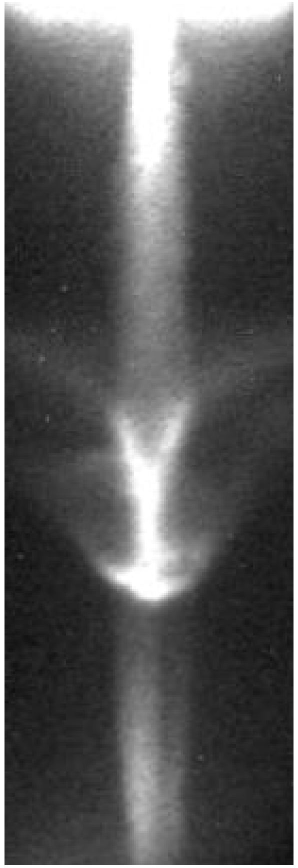
Bow-shock, developing clumpy structure (radiative cooling)

$$\chi_{cool} = \frac{\tau_{cool}}{\tau_{hydro}} \sim 10^{-2}$$

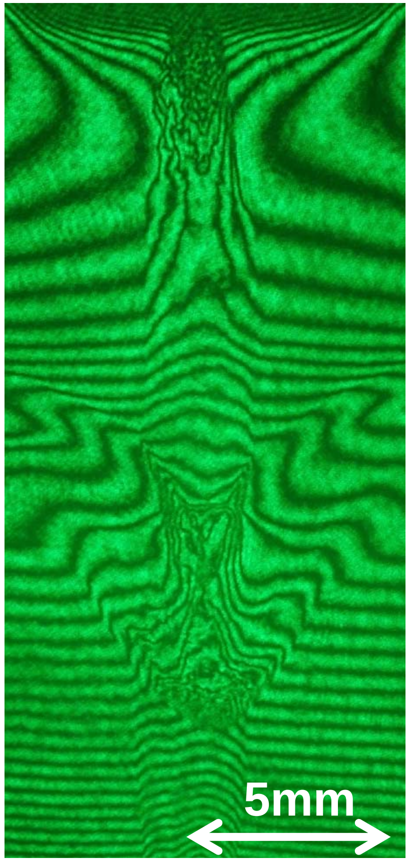
Two standing shocks formed in the halo plasma

Colliding jets: laser probing

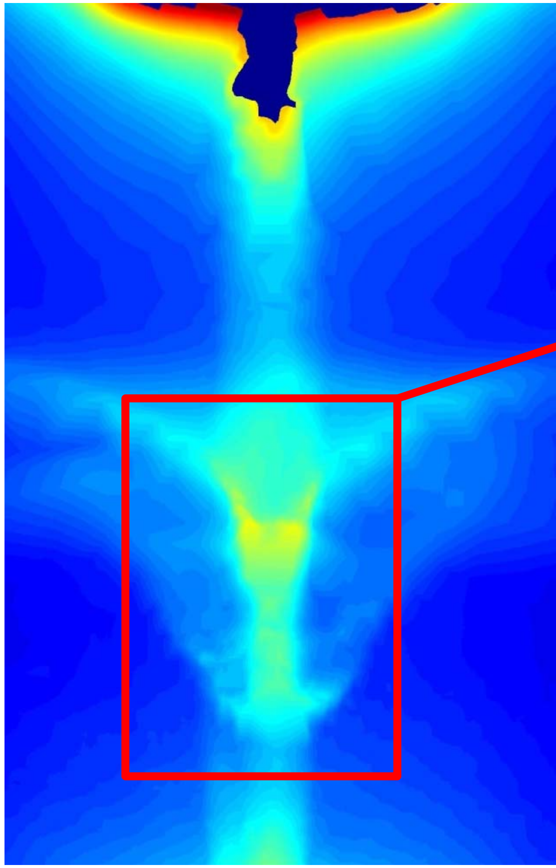
Emission



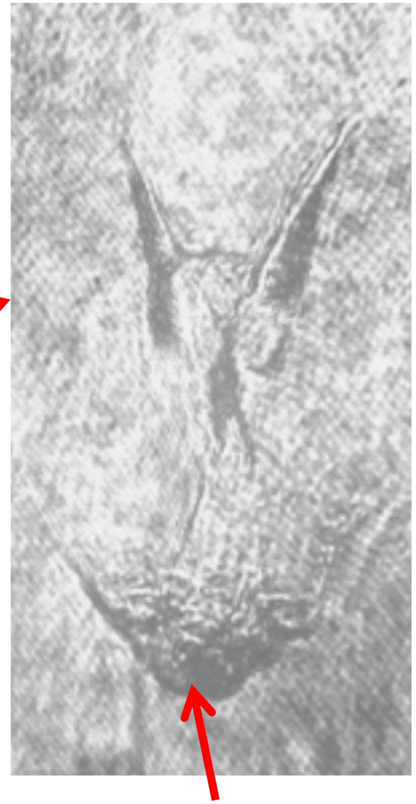
Interferometry ➔



n_e map



Schlieren (~dn/dr)



Small scale structures (0.1mm) in the bow-shock

Jet parameters:

V_{jet} ~ $1x10^7$cm/s n_e ~ $2x10^{18}$ cm^{-3}

t_{cool} ~ 1ns L_{cool} ~ 0.1mm

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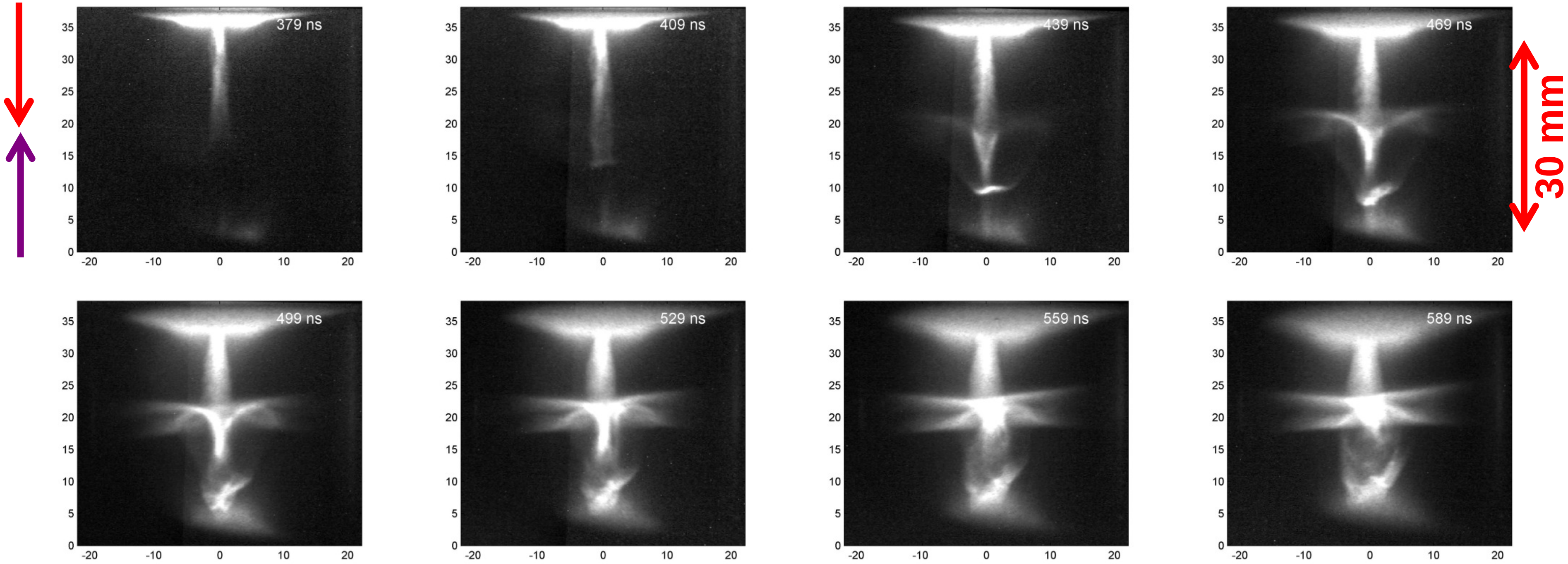
Colliding jets

Optical emission, 30ns inter-frame separation



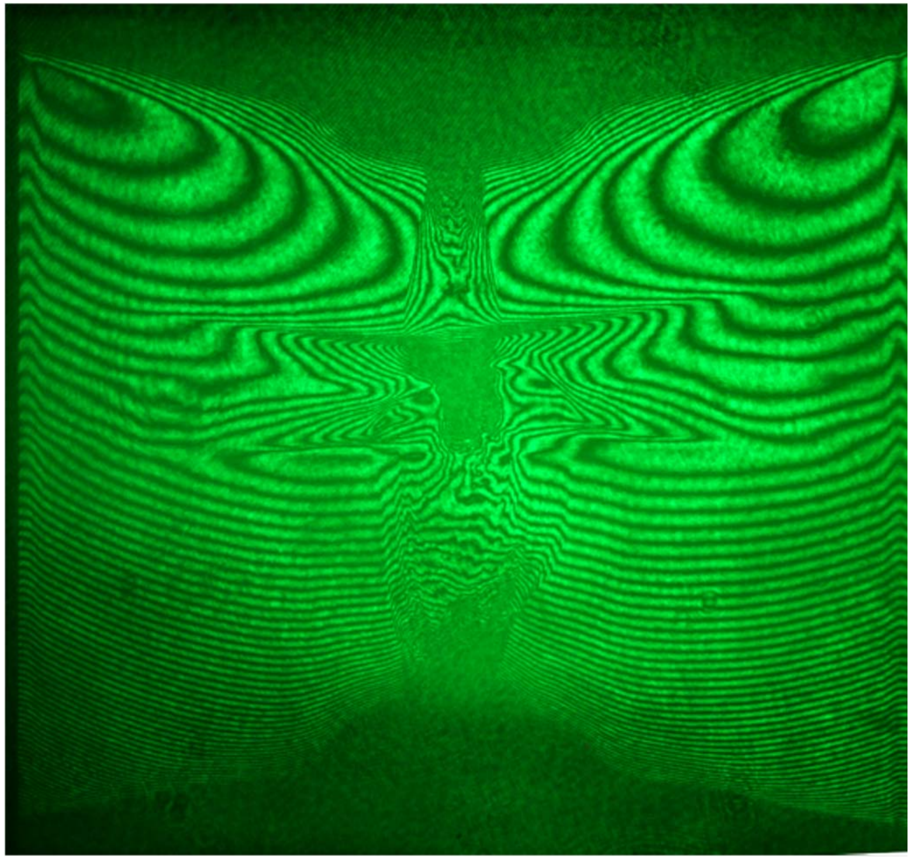
“stronger” jet from the top radial foil (“positive polarity”)

Formation of a bow-shock with a clumpy structure (strong radiative cooling)

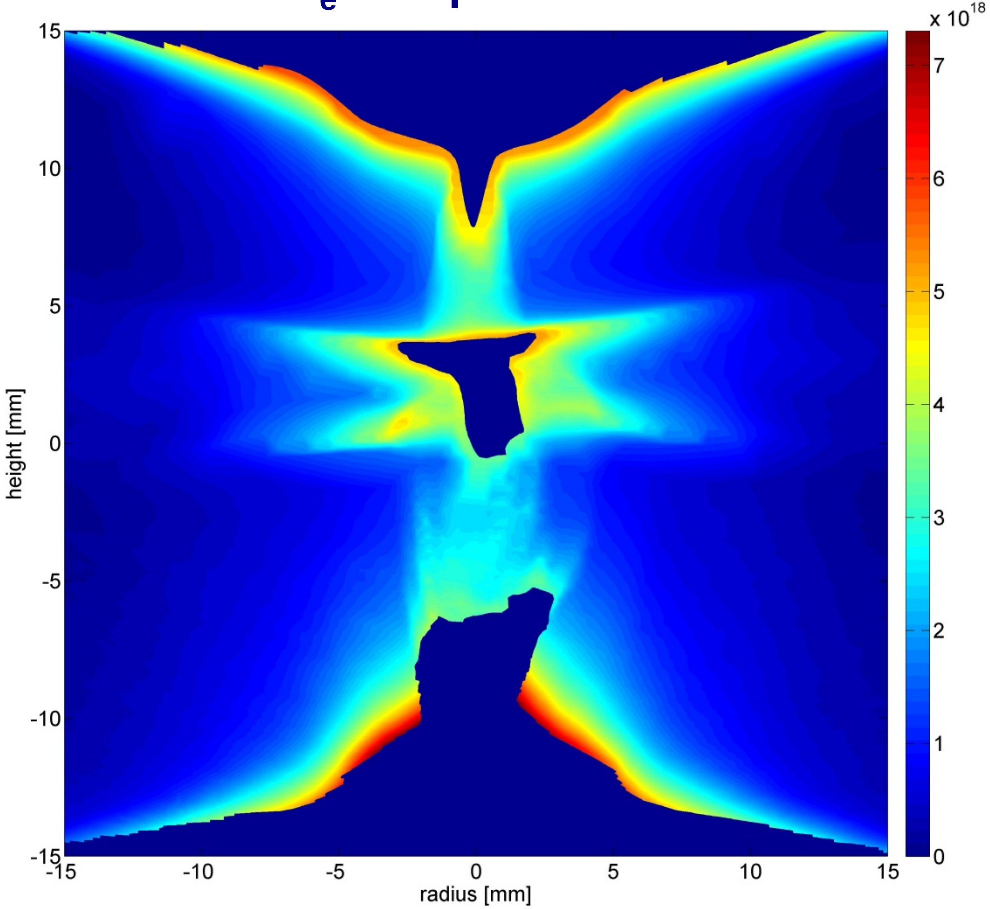
Formation of two standing shocks in the halo plasma

Colliding jets: interferometry

Interferometry



n_eL map



Formation of double-shock structure in the colliding "halo" plasma

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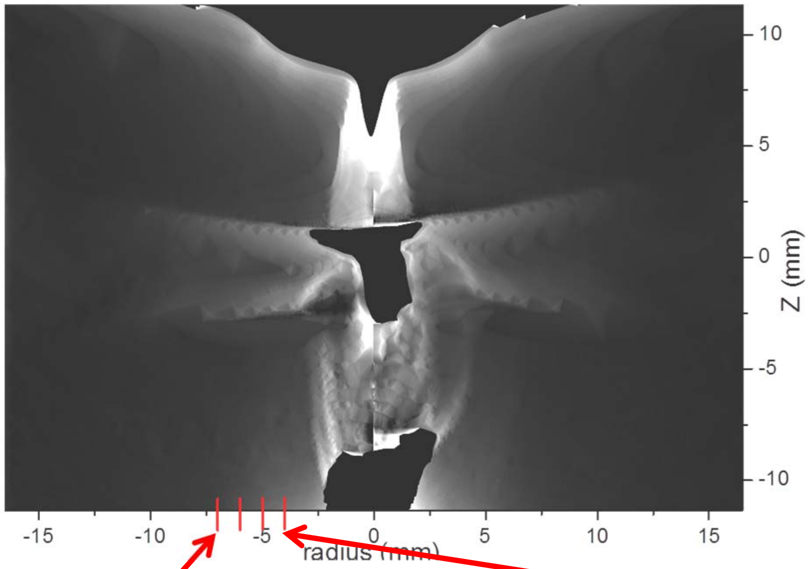
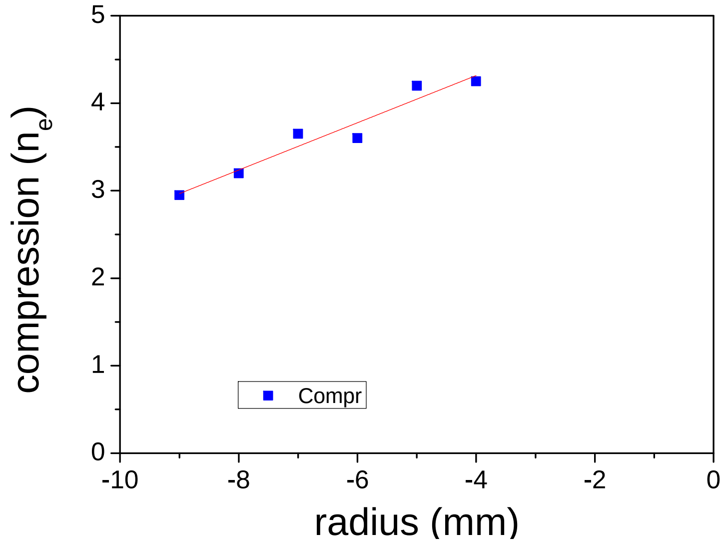
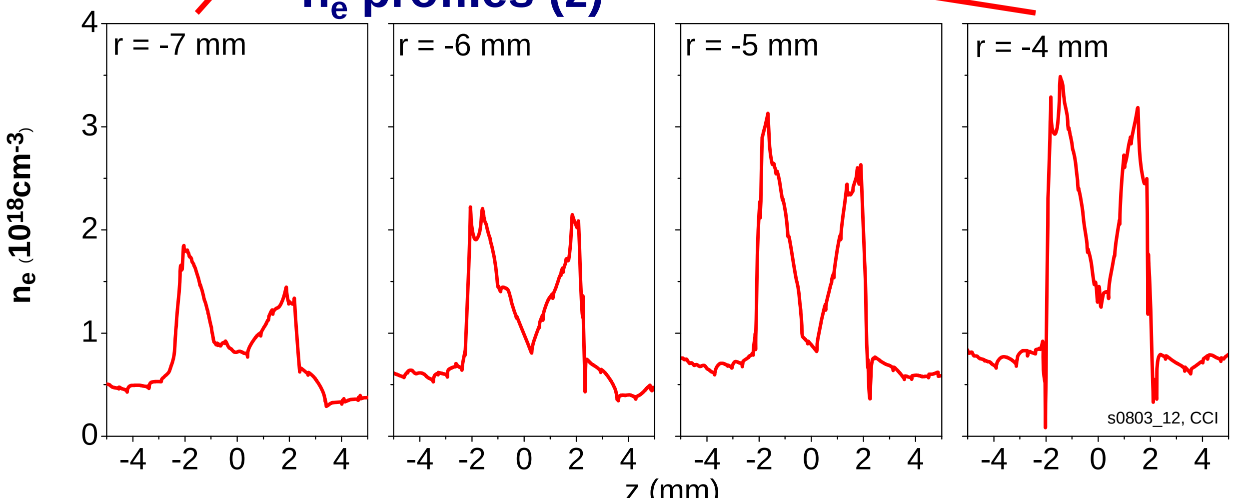
Colliding jets: density distribution

n_e map





n_e profiles (z)



Decrease of density after the shock?!

Magnetic field to balance flow ram pressure:

$$\frac{B^2}{8\pi} \sim \rho V^2$$

$$B \sim 70kG \quad (7T)$$

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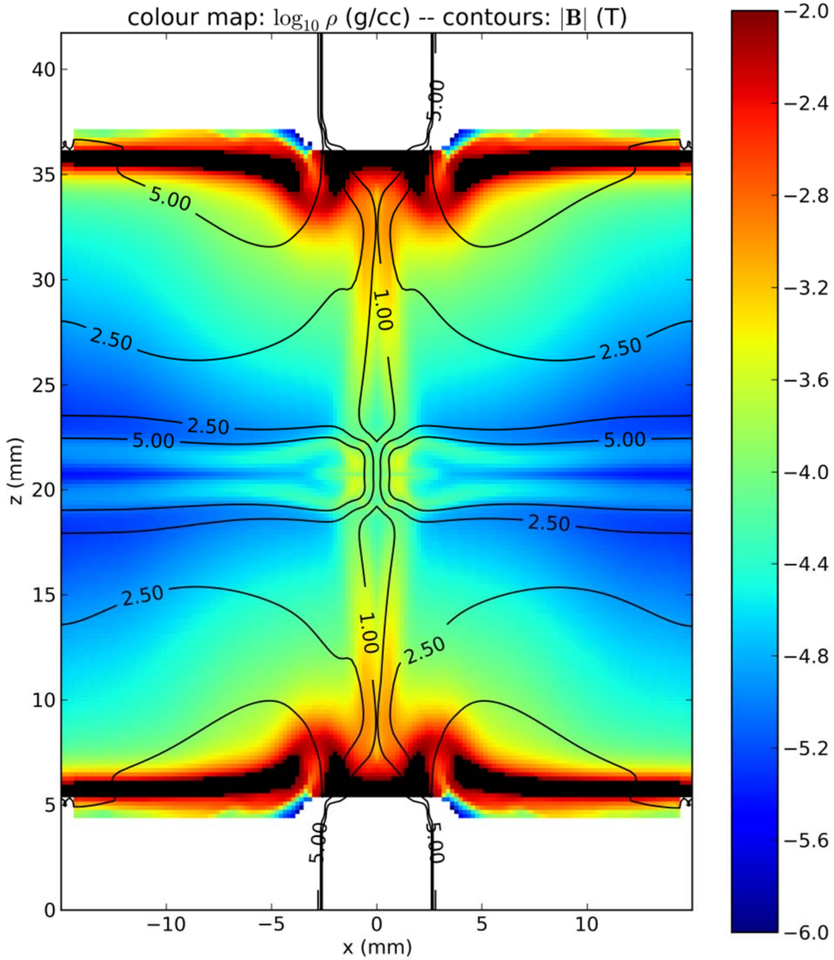
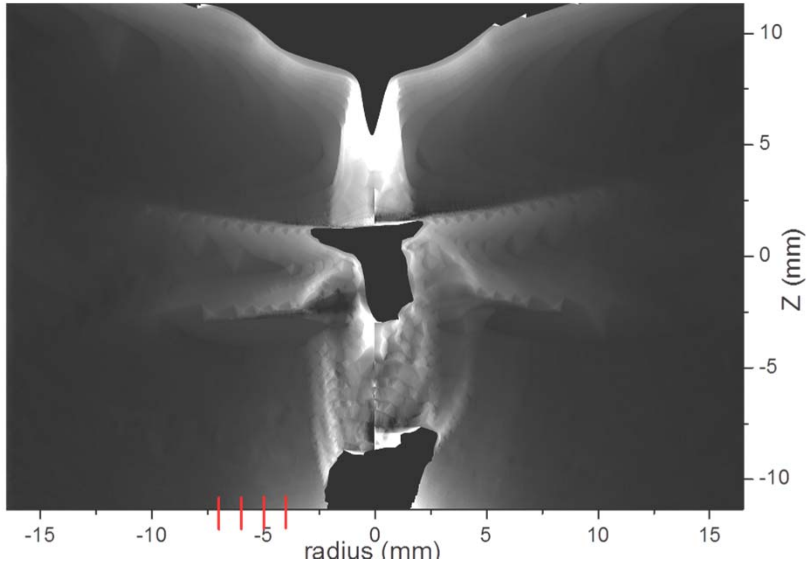
MHD simulations: shocks are supported by B-field

Density (g/cc) **[A. Ciardi, 2012]** **Density (cm^{-3})**



Hollow density profile



Accumulation (compression) of B_θ advected by the flow

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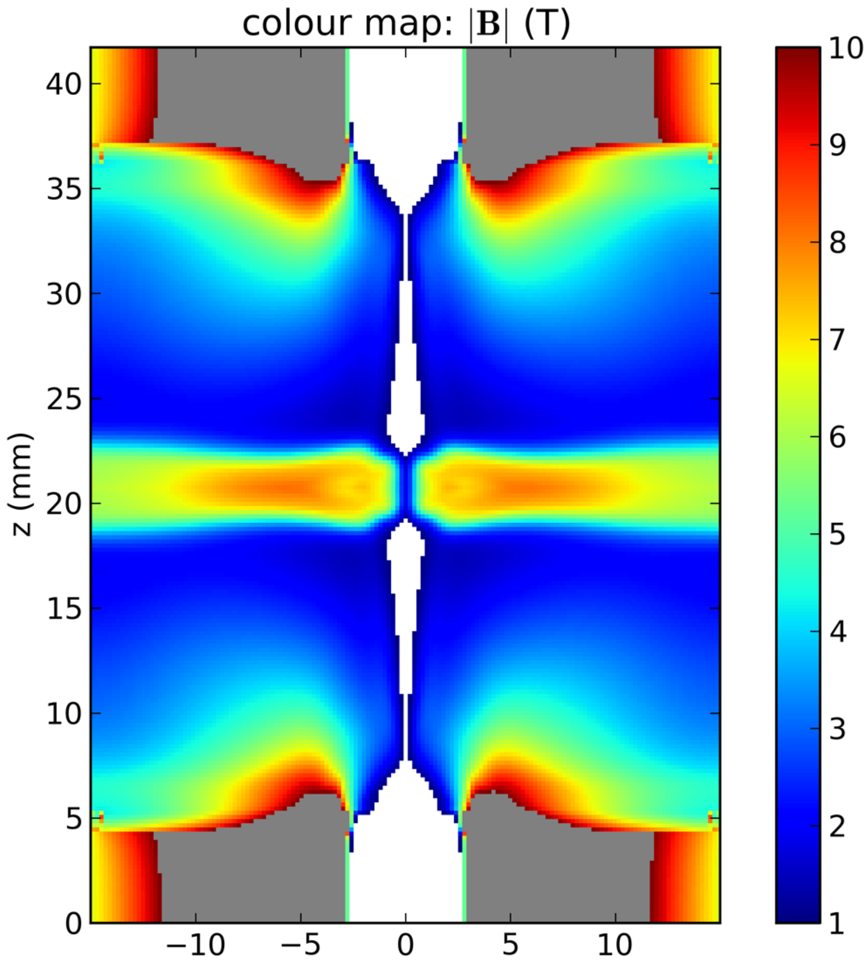
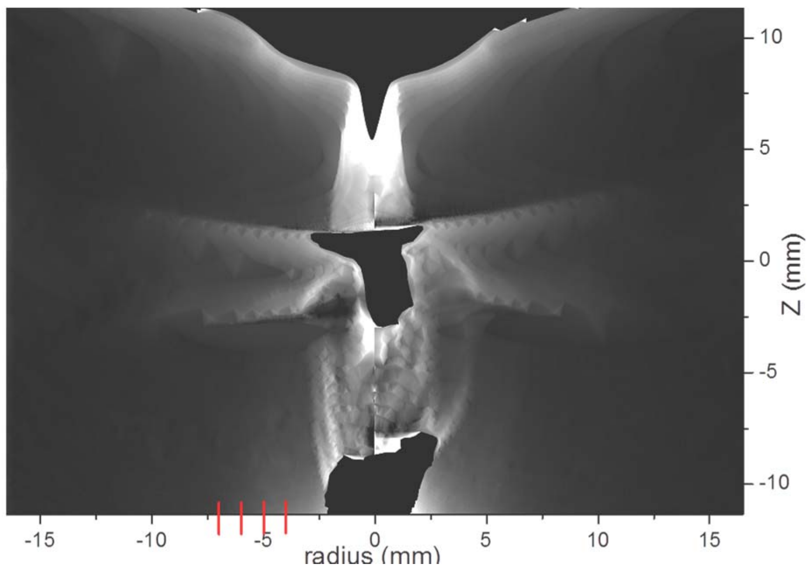
MHD simulations: shocks are supported by B-field

B_θ magnetic field (T) **[A. Ciardi, 2012]**



Density (cm^{-3})

Hollow density profile



Observed shocks are well reproduced by Laboratory MHD code

Simulations by astrophysical code are in progress

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Colliding jets summary

Development of small-scale instabilities near the axis, but absence of instabilities in the "stationary" shocks.

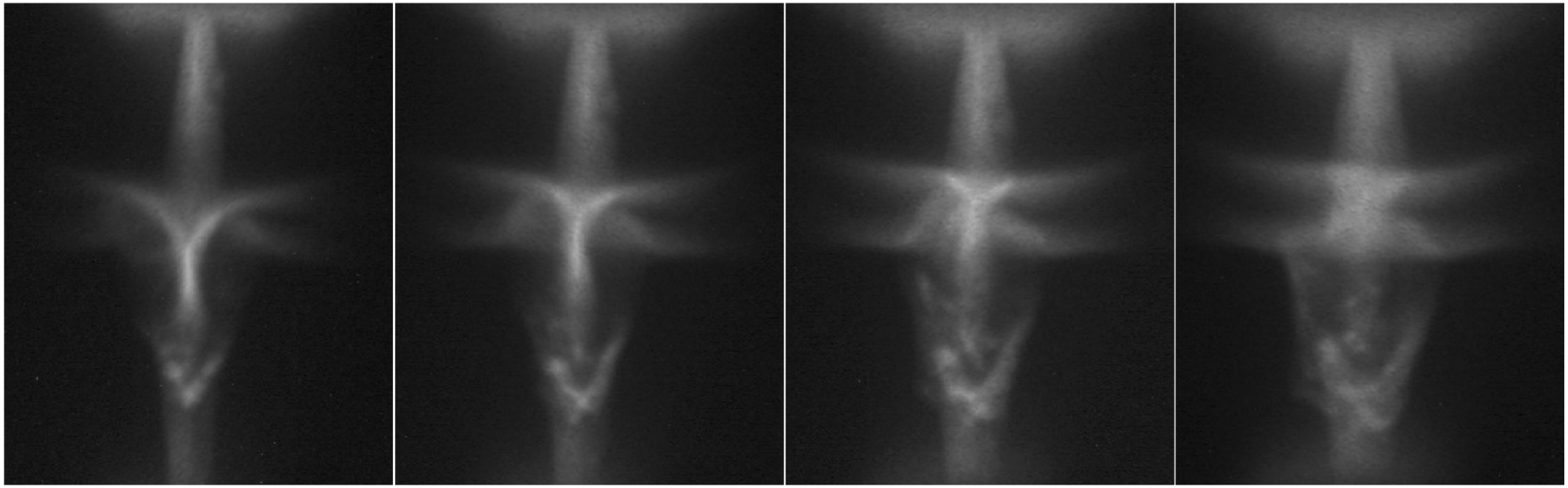
Suppression of cooling instabilities by B-field?

Magnetic fields play dynamically significant role

$$\chi_{cool} = \frac{\tau_{cool}}{\tau_{hydro}} \sim 10^{-2}$$

$$\mathrm{Re} = \frac{V_{jet} R_{jet}}{\nu} \approx 10^{5}$$

$$\mathrm{Re}_M = \frac{V_{jet} R_{jet}}{D_M} \approx 10 - 100$$



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Outline

Motivation: develop experimental platform for quantitative studies of magnetised supersonic plasma flows

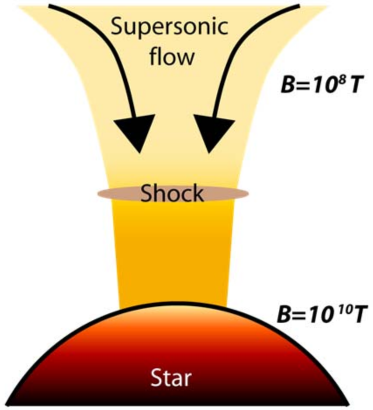
1. **Shocks in magnetised plasma flows:**
   - ***head-on collision of two supersonic jets***
   - ***formation of reverse shock mediated by pile-up of magnetic field***
2. **Formation of differentially rotating plasma discs**

Common theme – dynamics of supersonic magnetised plasma flows

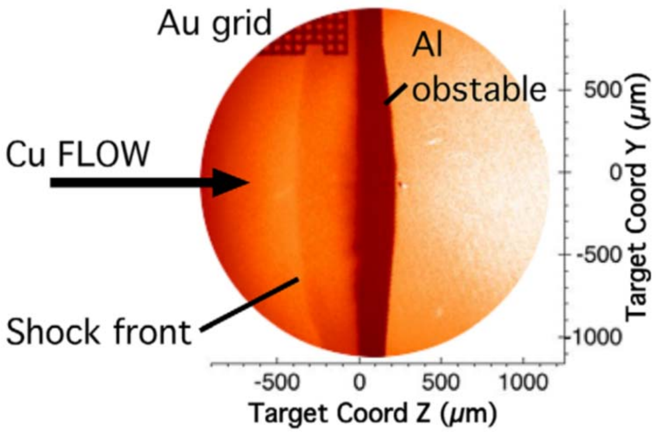
(MHD, compressibility, radiative cooling, ionisation balance…)

Shocks in supersonic plasma flows

Radiative accretion shocks



Krauland et al., PoP 2013

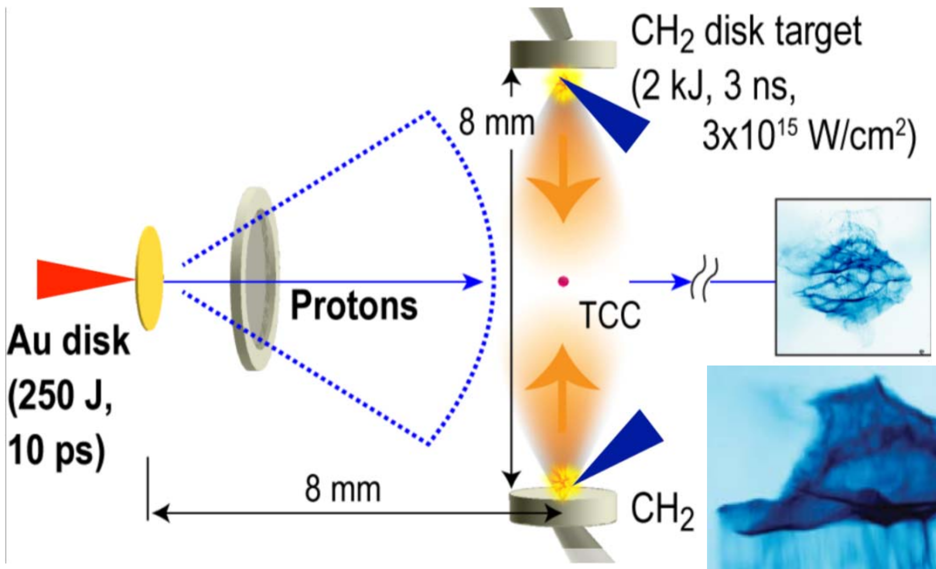


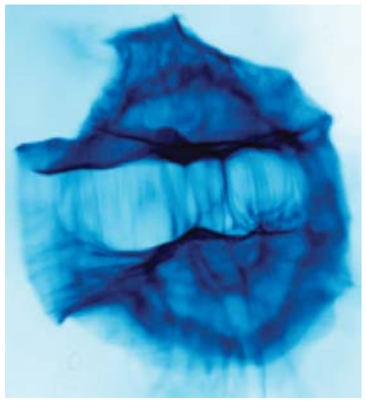
Collisionless shocks

Compression of pre-existing B-fields

Self-generated magnetic fields (e.g. Weibel instability)

Kugland et al., Nature Physics 2012





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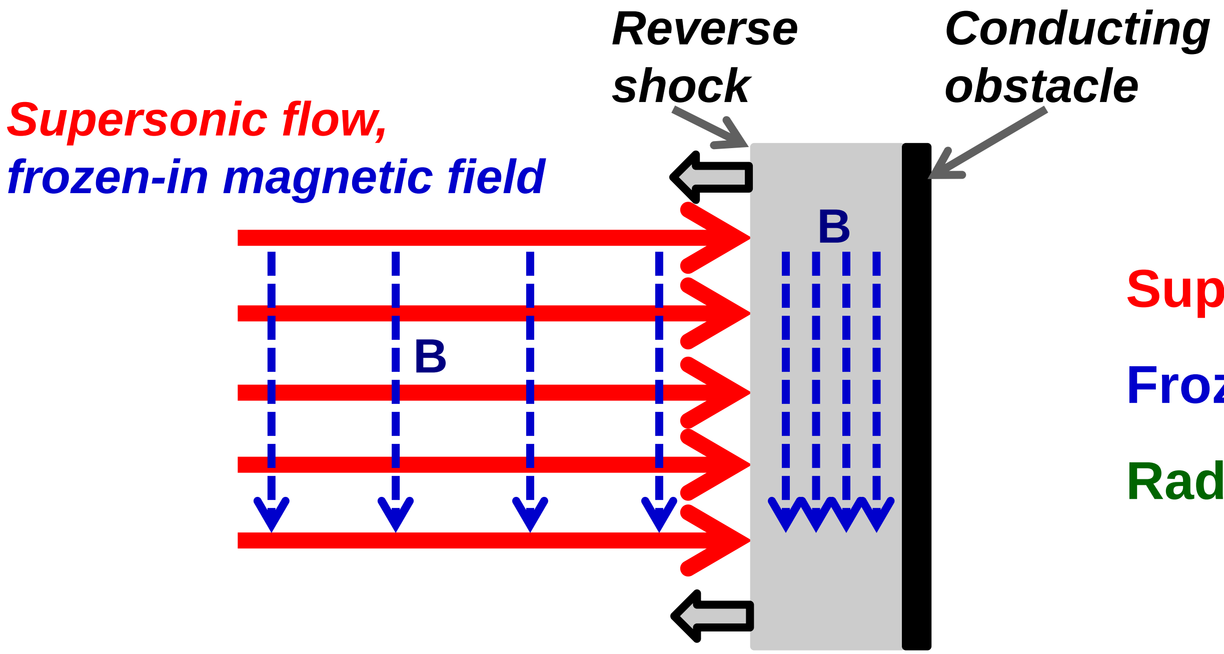
Reverse shock in supersonic plasma flow



Supersonic plasma flow

Frozen-in magnetic field

Radiative cooling

Planar 1-D geometry with good diagnostic access

Different orientation (and shape) of the obstacle

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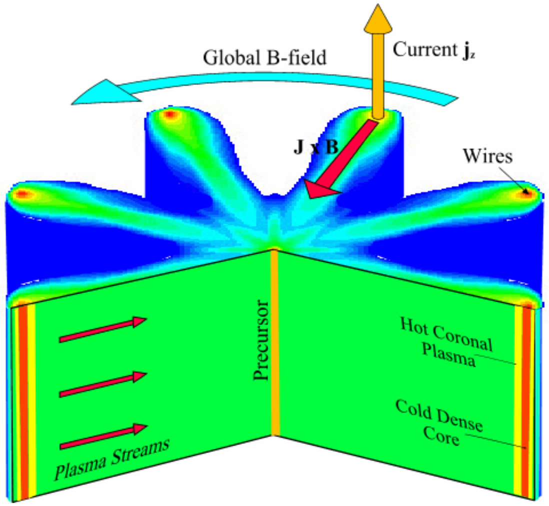
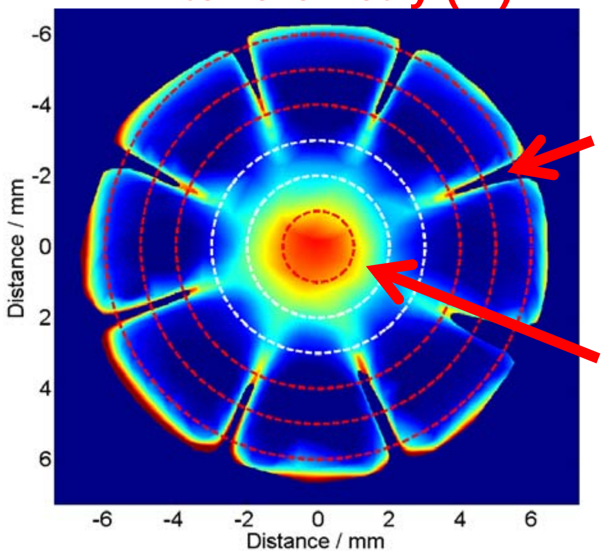
Supersonic plasma in wire array z-pinch

Wire array z-pinch



Interferometry (W)



Ablation streams

Plasma accumulating on axis

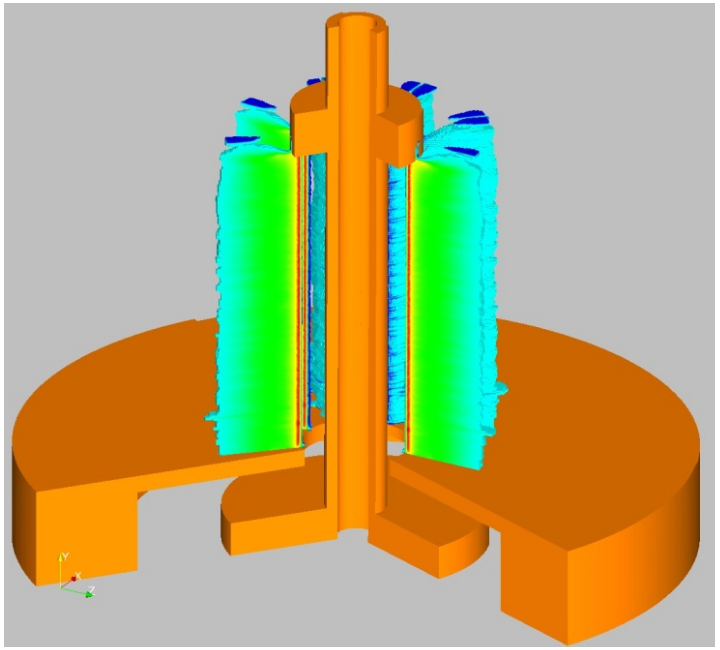
Ablation of wires + JxB force

⇩

Collimated plasma streams (M ~ 10) with advected magnetic field

V ~ 10^7cm/s (E_i ~ 1.5keV for Al)

Inverse wire array



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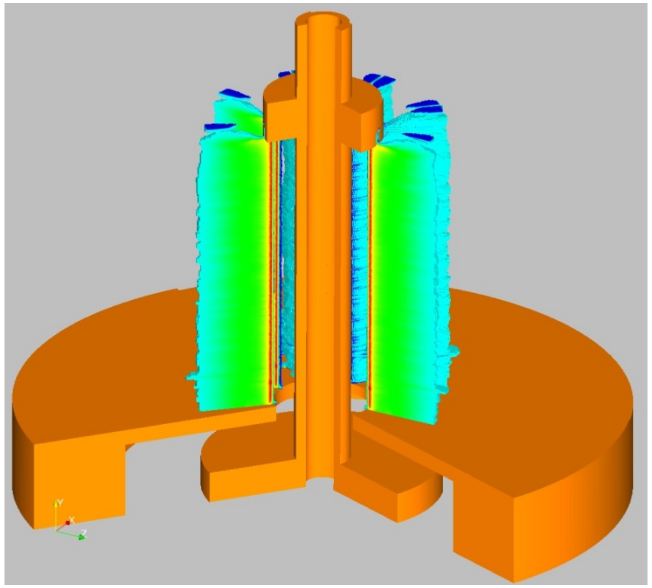
Z-pinch driven magnetized shock experiment

Plasma flow generated by ablation of wires in inverse wire array z-pinch



Al plasma:

$V_{flow} = 10^7$ cm/s

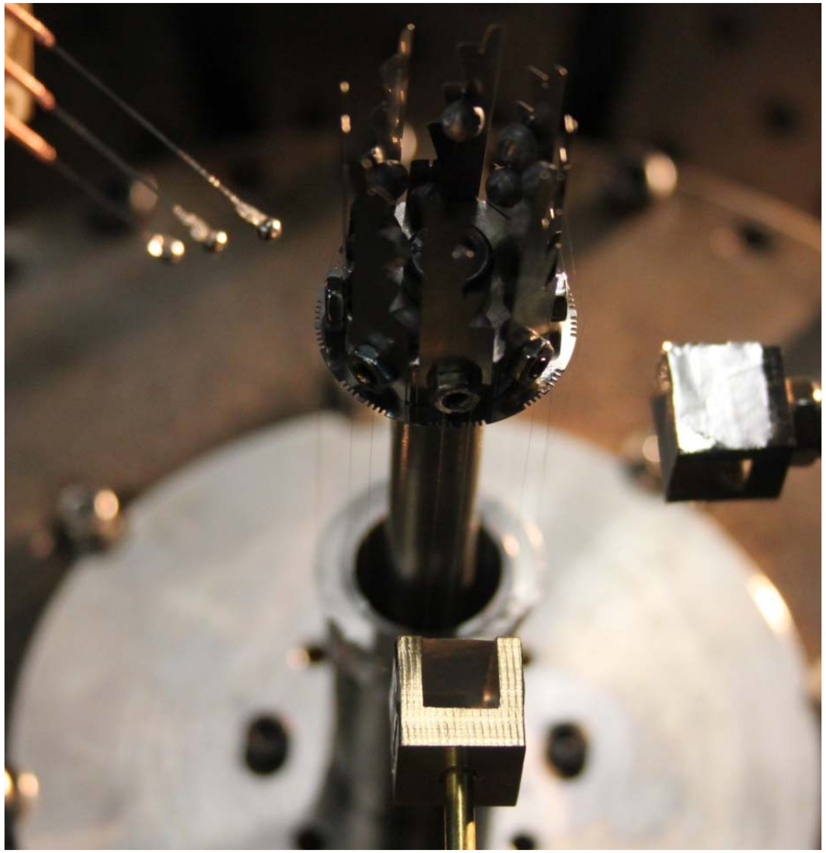
$n_e = 4\times10^{17}$ cm^{-3}

$B = 2\times10^4$ Gs

M_A, M_S ~ 6

$Re \sim 10^5$

$Re_M \sim 50$



Plasma flow with embedded magnetic field ($B(t) \sim \rho(t)^{1/2}$ ➔ $V_A \sim$ constant)

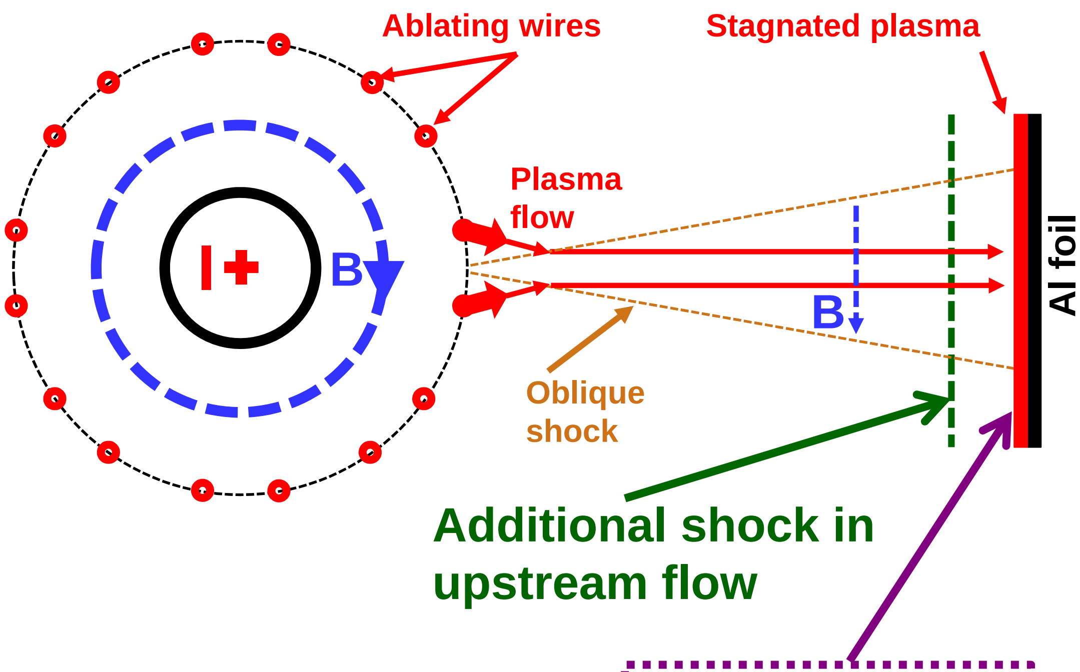
Propagation into field-free region

"Small" B field: $\beta_{dyn} = \frac{\rho V^2}{B^2/8\pi} \approx 40$

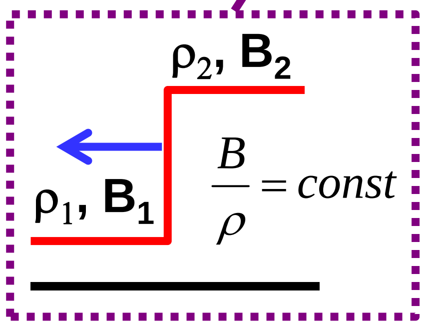
Collision with planar foil creates quasi one-dimensional shock

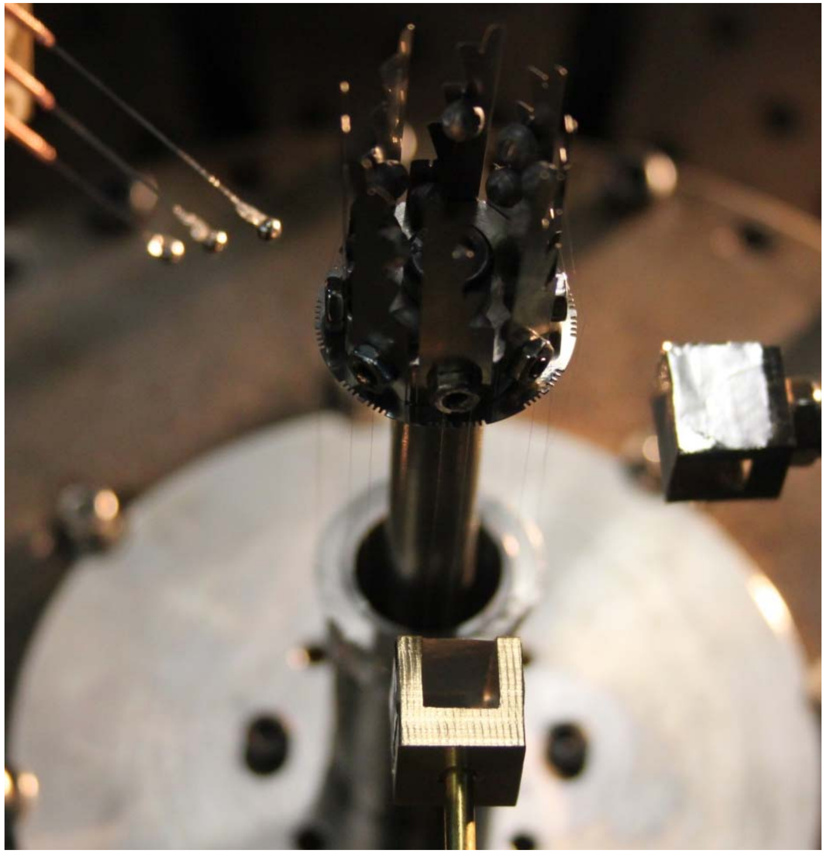
Shock formation – experimental set-up

Plasma flow generated by ablation of wires in inverse wire array z-pinch



Perpendicular shock: compression of magnetic field reduces density jump





Diagnostics:

End-on and side-on interferometry (n_e)

Inductive probes (B(t))

Thomson scattering (V_{flow} , T)

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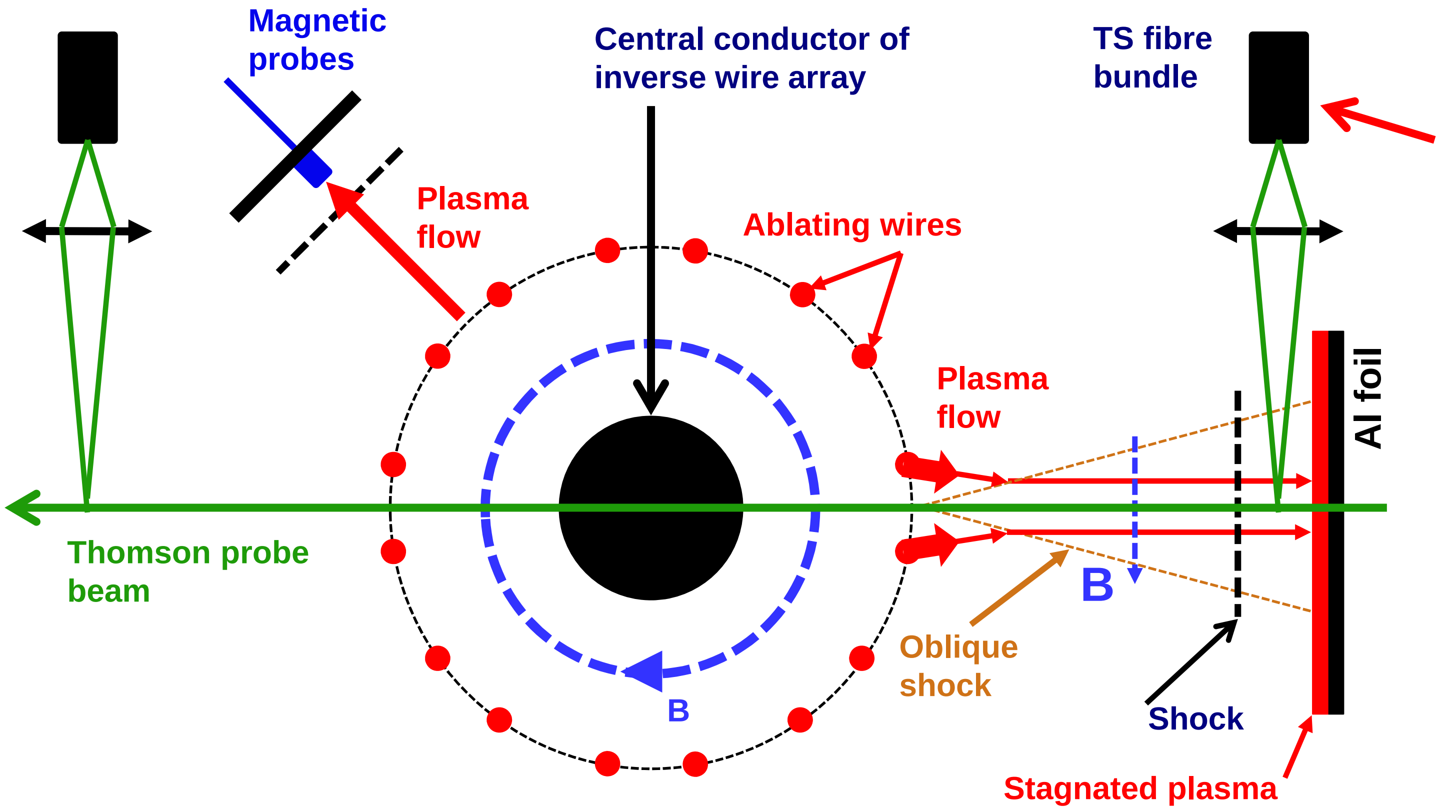
Thomson scattering and other diagnostics

Plasma flow generated by ablation of wires in inverse wire array z-pinch



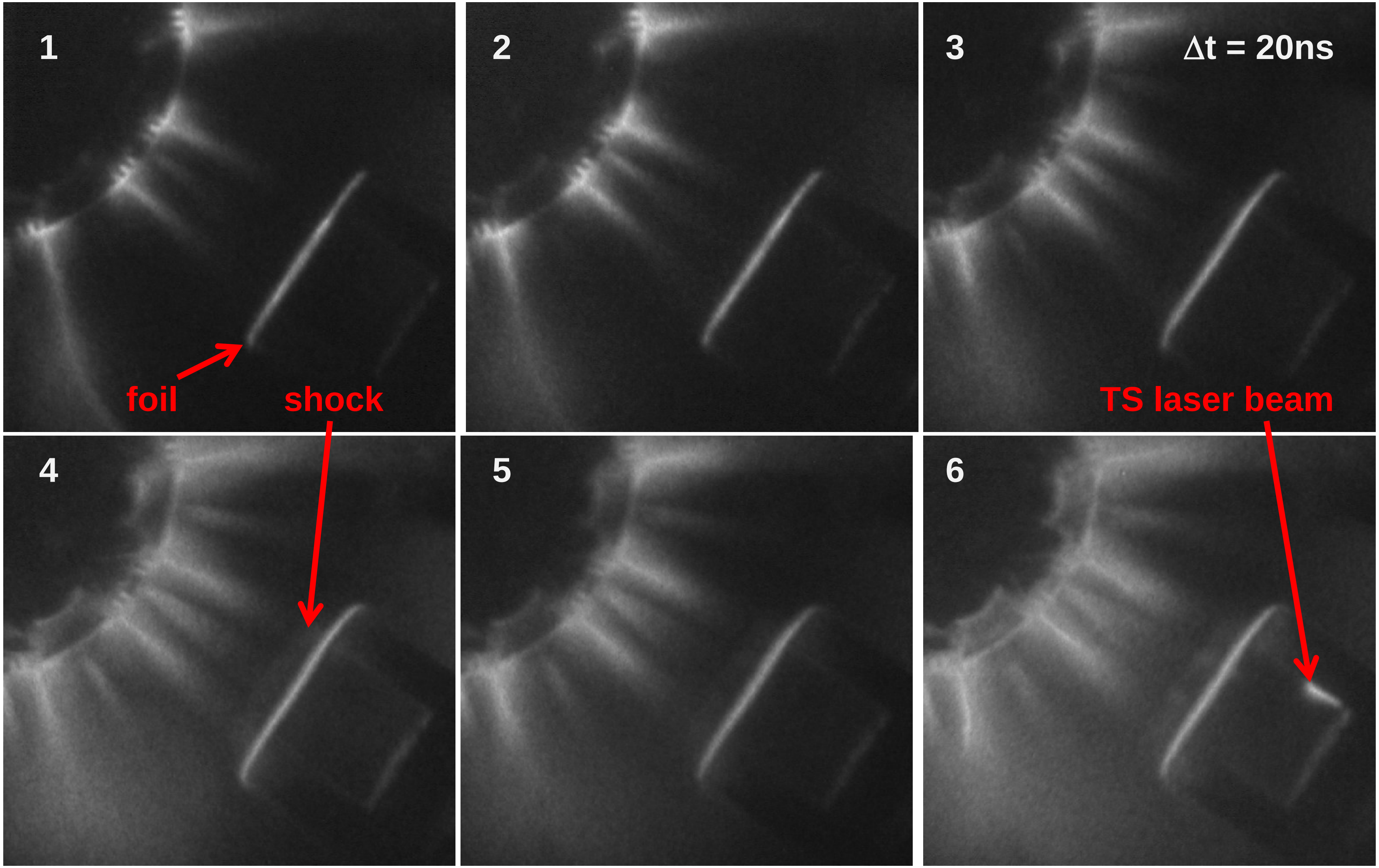
Thomson scattering spectrum (7 or 14 points along probing beam)

Flow velocity from Doppler shift of the ion feature

Probing of the shock in end-on and side-on directions

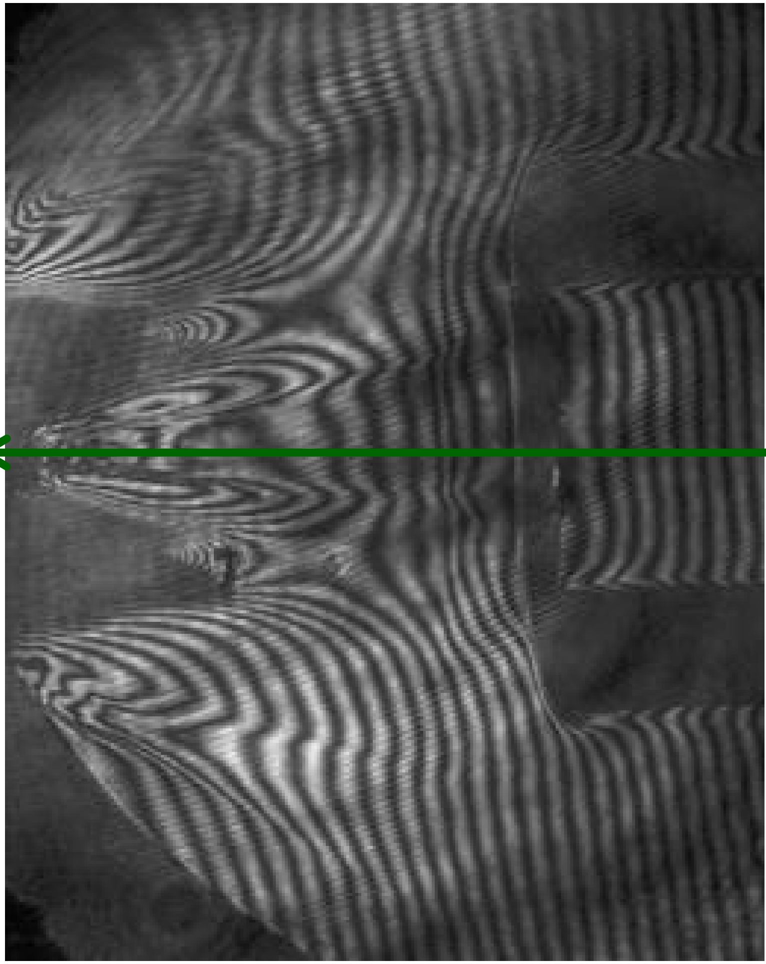
8 identical outflows – additional probing of undisturbed flow

Optical emission, end-on. Shock is seen from frame 4.

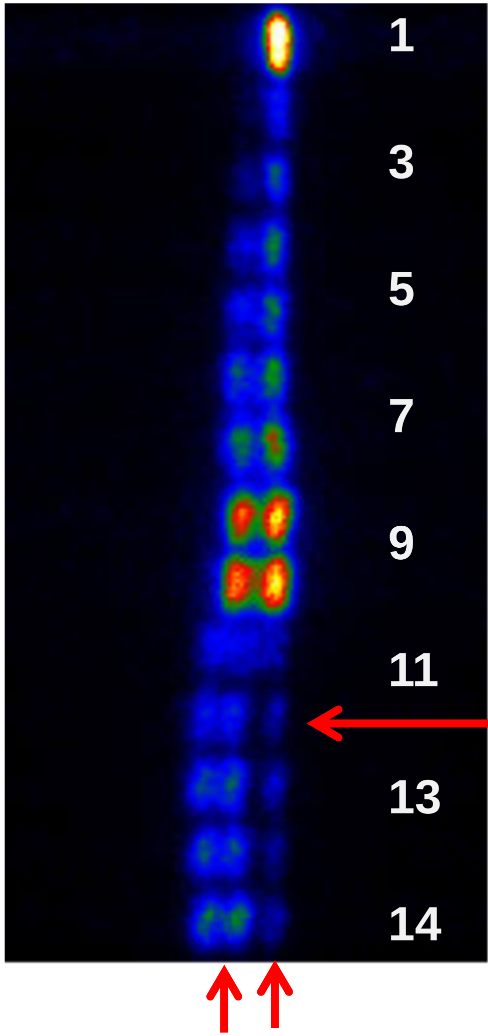


Density and flow velocity in the shock

End-on interferometry



Thomson scattering.



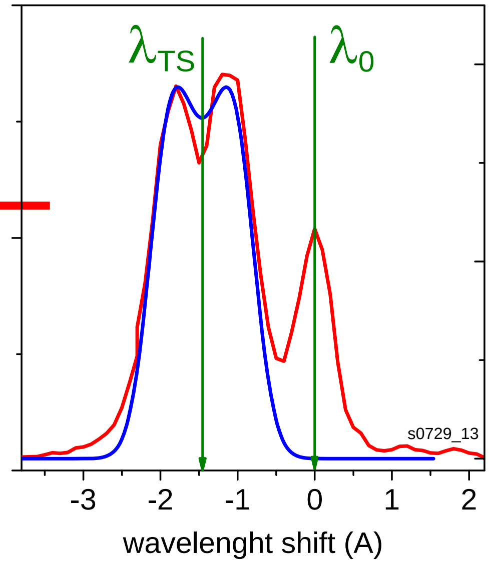
Doppler shift of the ion feature yields flow velocity

V_{flow} = 1x10^7 cm/s

Broadening gives ZT_e ~60eV

(T_e = 20eV , Z=3)

M_S = 6-7



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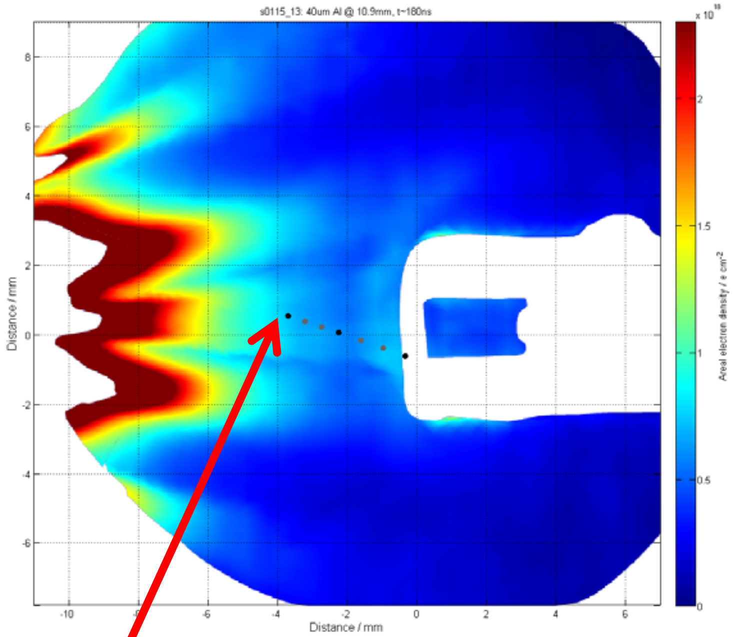
Density and flow velocity in the shock

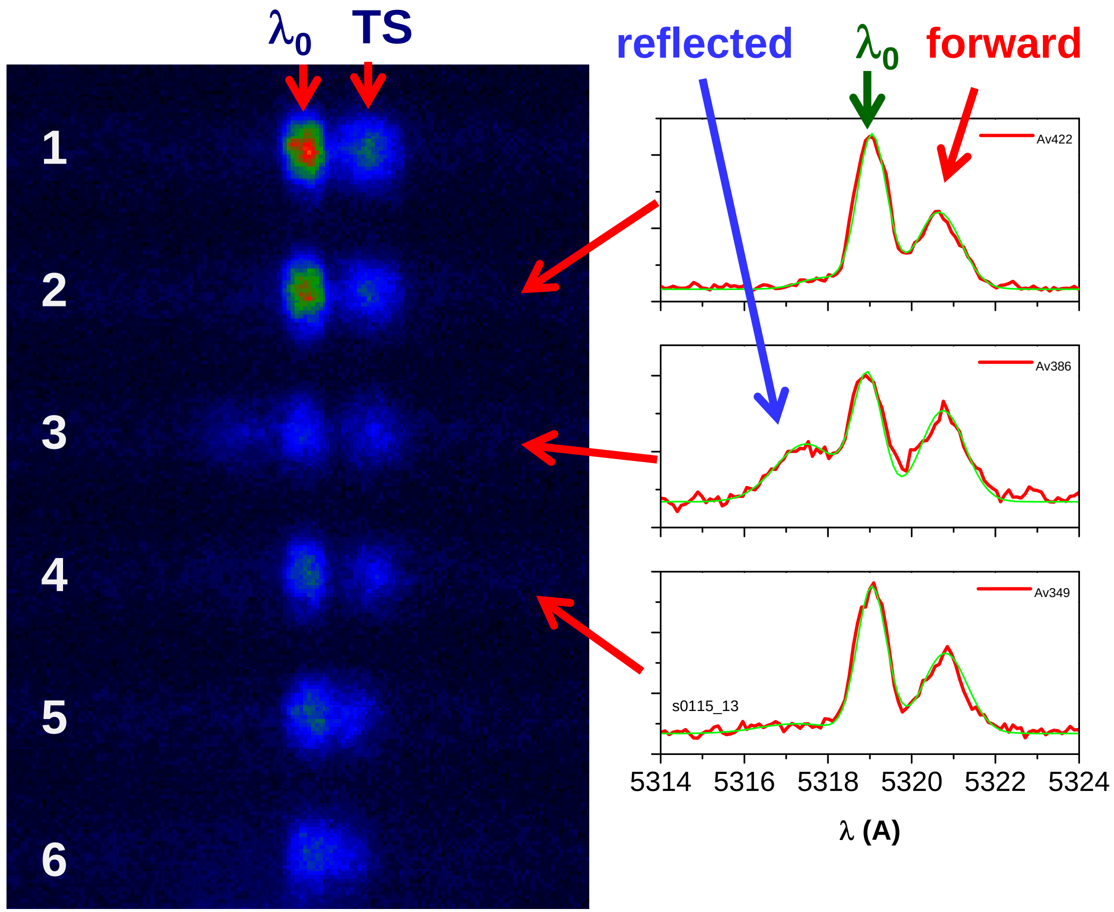
2-D map of electron density obtained from interferometry

Upstream $n_e = 4 \times 10^{17}$ cm^{-3}



Dots indicate positions of TS measurements (fibre 7 at foil)

Thomson scattering, Doppler shift of the ion feature yields flow velocity

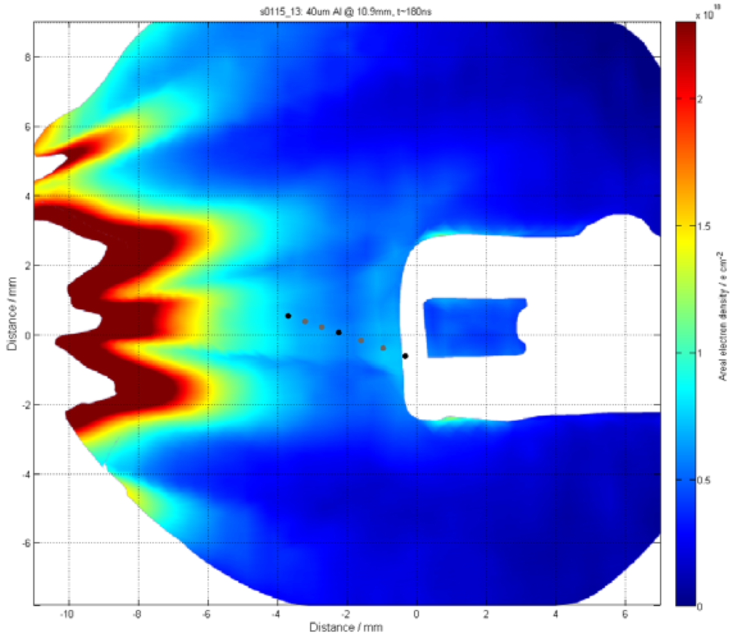


No temperature increase in downstream plasma (but reflected ions are “heated”)

Density and flow velocity in the shock

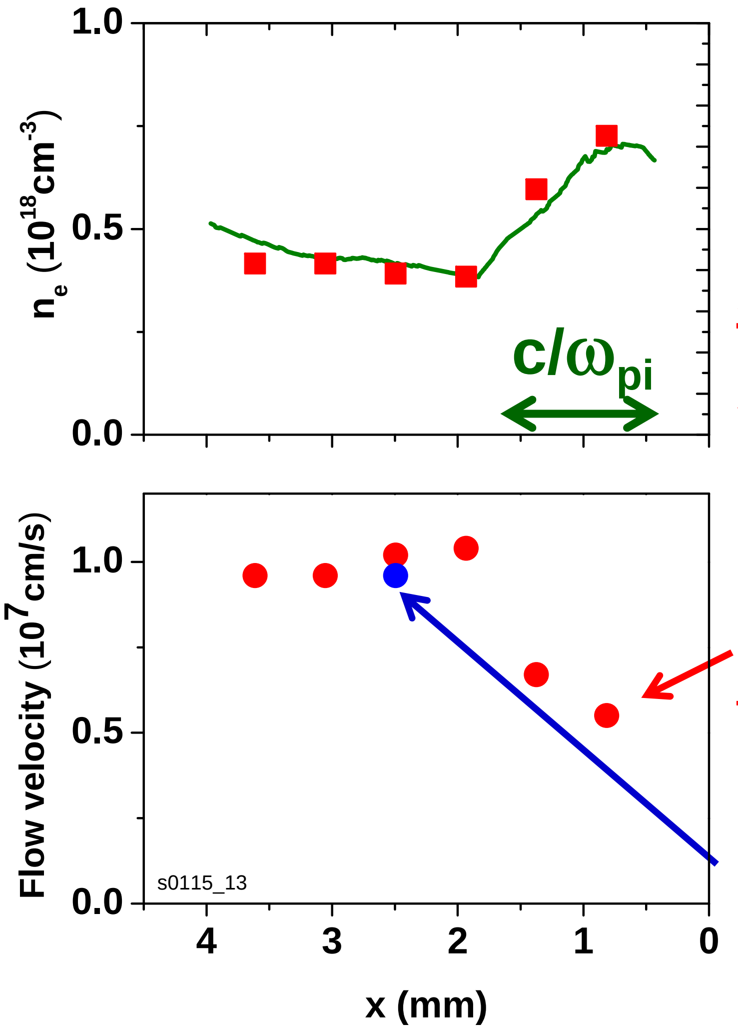
2-D map of electron density obtained from interferometry

Upstream $n_e = 4x10^{17}$ cm^{-3}



Deceleration and density increase start before stagnation of the flow at foil

Density and velocity profiles (180ns)



Density:

n_e interferometry

ρ (a.u.) ~$1/V_{flow}$ Thomson scattering

Flow velocity:

red shift – towards foil

blue shift – reflected ions

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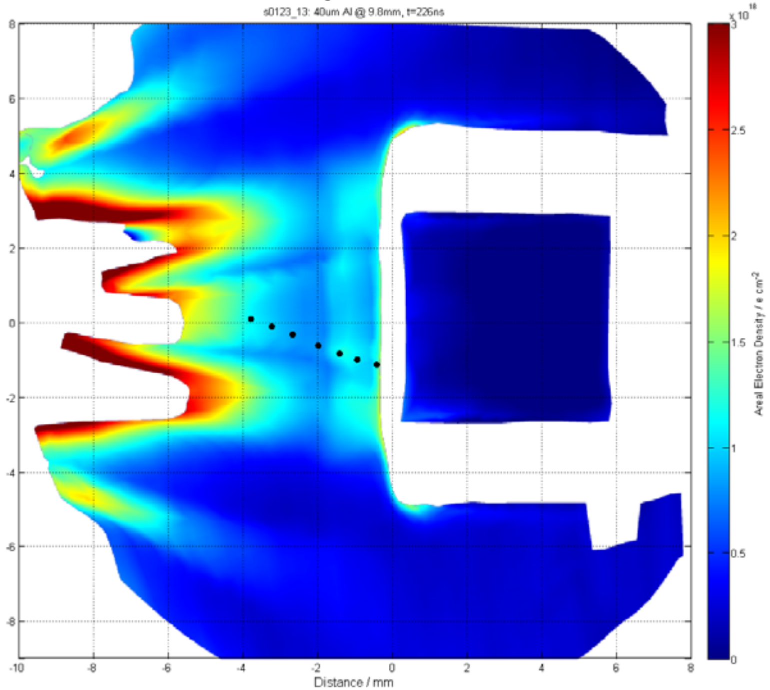
Density and flow velocity in the shock

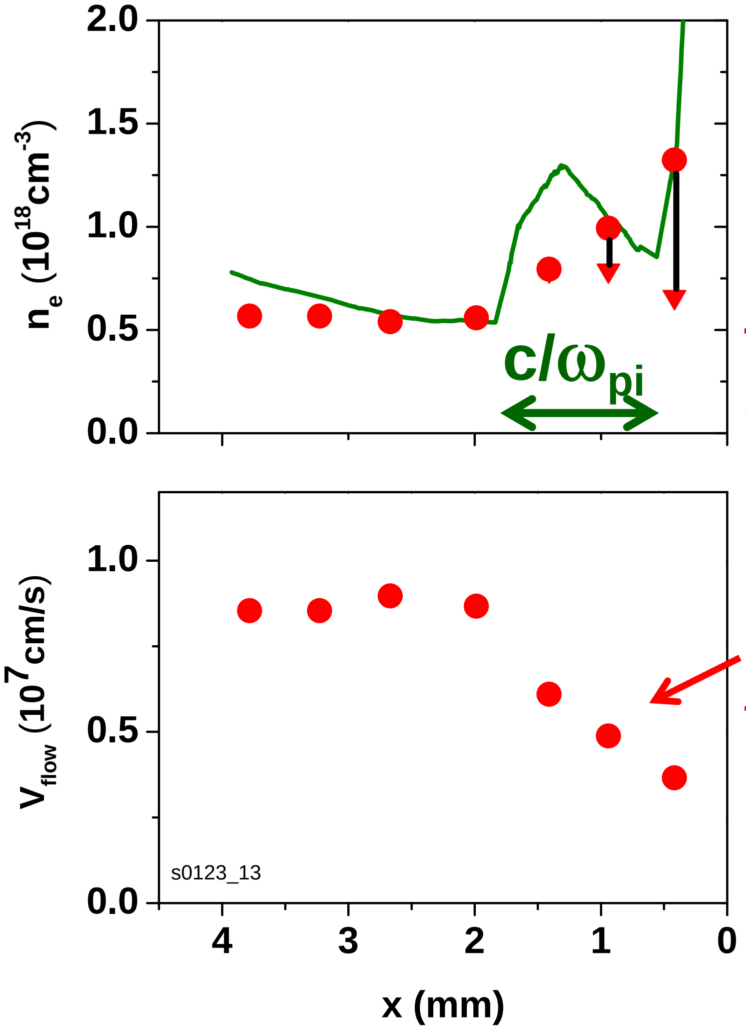
2-D map of electron density obtained from interferometry

Upstream $n_e = 5 \times 10^{17}$ cm^{-3}



Steepening of the "magnetic precursor" into a shock

Density and velocity profiles (225ns)



Density:

n_e interferometry

ρ (a.u.) ~$1/V_{flow}$ Thomson scattering

Flow velocity:

red shift – towards foil

no detectable reflected ions

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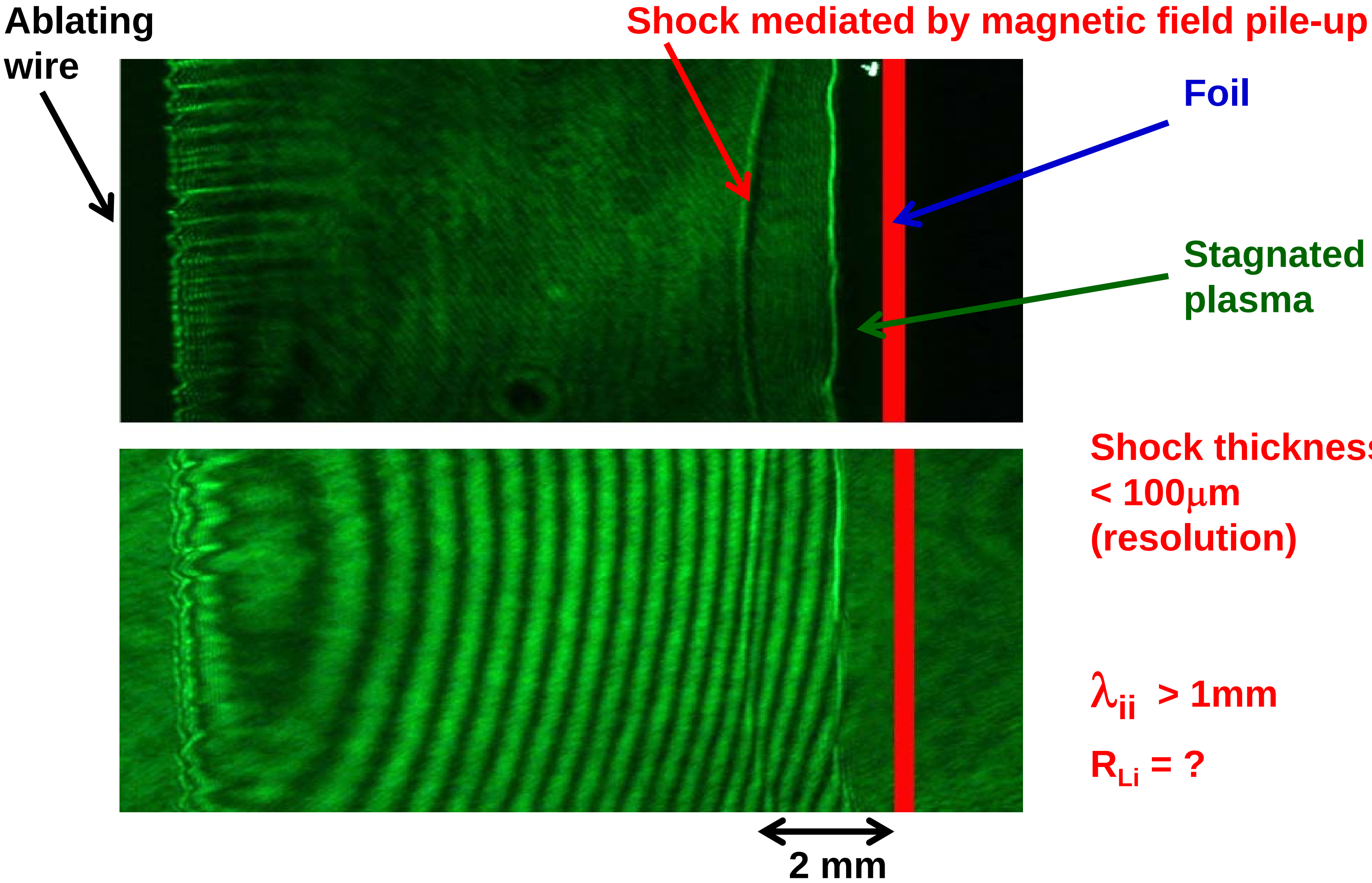
Shock formation – side-on laser probing



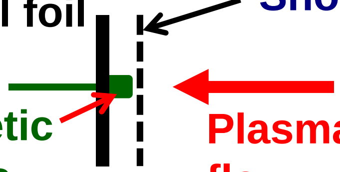
Shock thickness < 100μm (resolution)

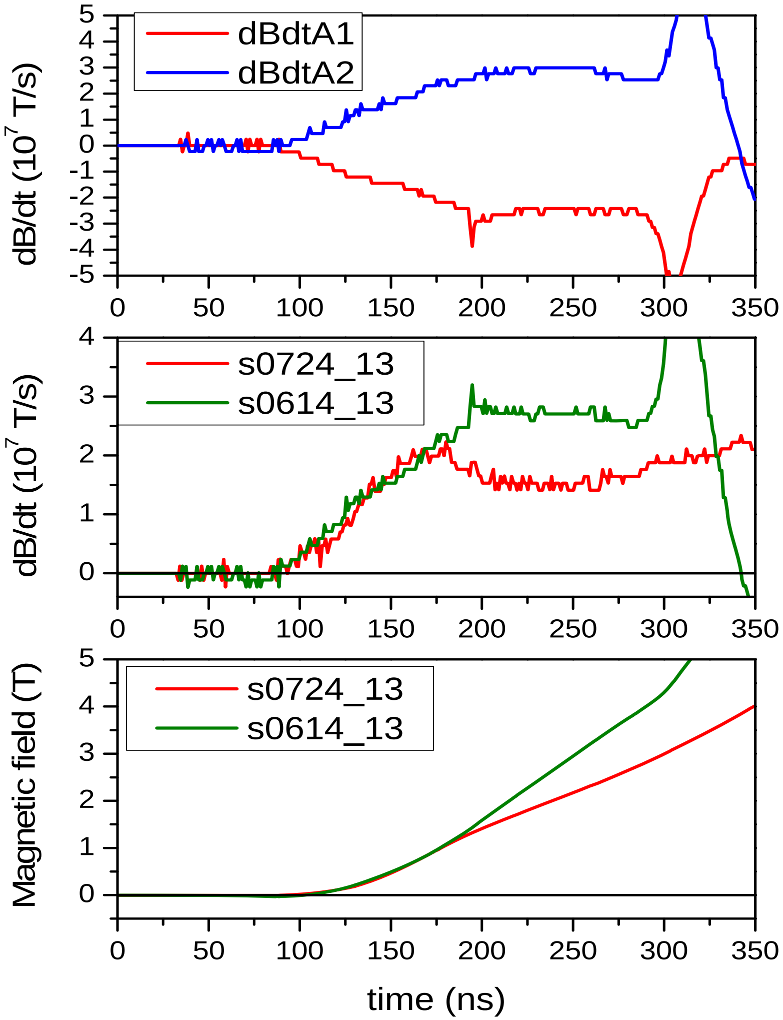
λ_{ii} > 1mm

R_{Li} = ?

Magnetic fields in the flow

Co-located pairs of oppositely winded inductive probes





Equal signals of opposite polarity – magnetic field

Probes:

8mm from the wires (2mm from the foil)

Faster growth of magnetic field with foil present

(from ~180ns, time of shock formation)

Start of magnetic field signal corresponds to plasma arrival – field is advected by the flow

(Re_M ~ 50)

M_A ~ 6

$$\rho_{L\_ion} \equiv \frac{V_{flow}}{\omega_{ci}} \approx 5mm$$

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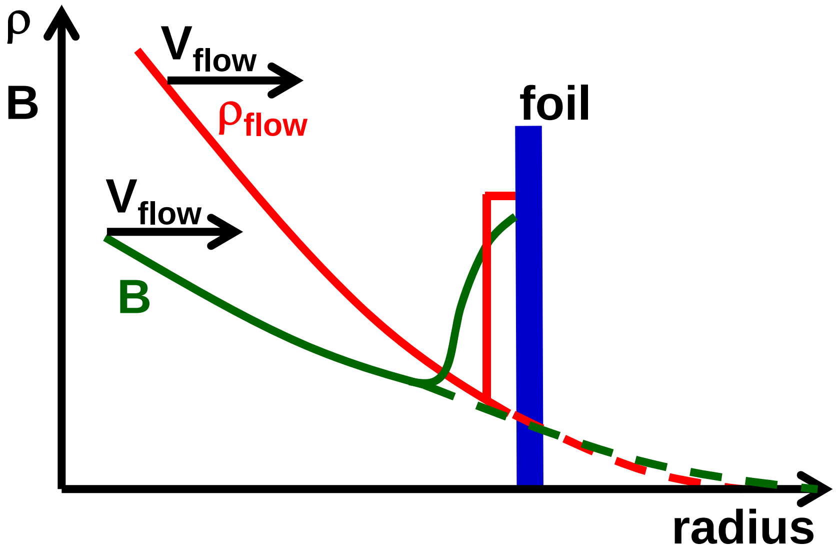
Interpretation of the shock formation (early time)

Reverse shock mediated by pile-up of frozen-in magnetic field



High Mach flow (M ~ 6)

Small (electron) density jump (x2)

Stagnated Al plasma accumulates at the foil, forming a thin layer expending with velocity <5 km/s, consistent with reverse shock in plasma with $\gamma < 1.1$

Diffusion of compressed magnetic field into upstream plasma

Magnetic field pressure decelerates electron fluid, but does not affect ion motion (large $\rho_{Li} = V_{flow} / \omega_{ci}$)

Build-up of electrostatic potential leading to deceleration of ions

Formation of a narrow shock at $x \sim c/\omega_{pi}$ with thickness $\Delta < 0.1\ c/\omega_{pi}$

Transient reflection of significant (~100%) fraction of the ions

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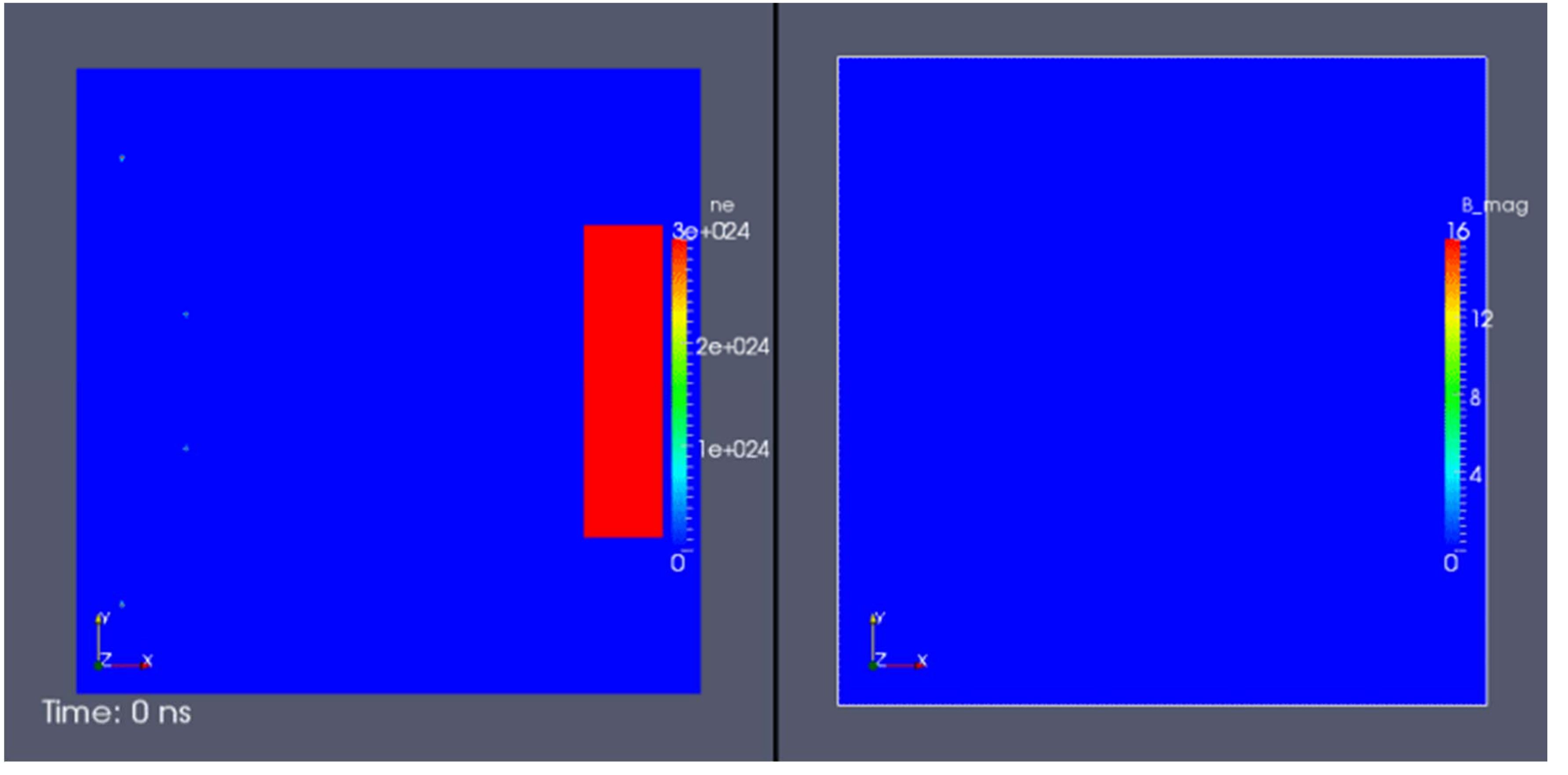
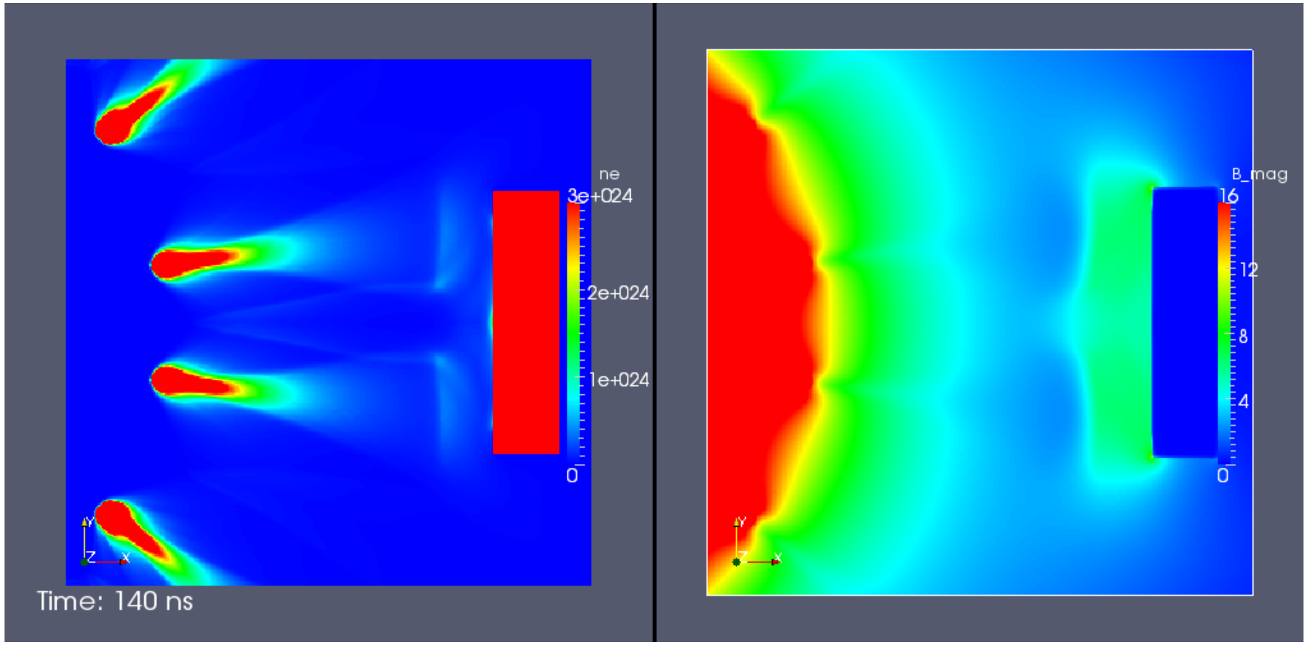
Resistive MHD simulations

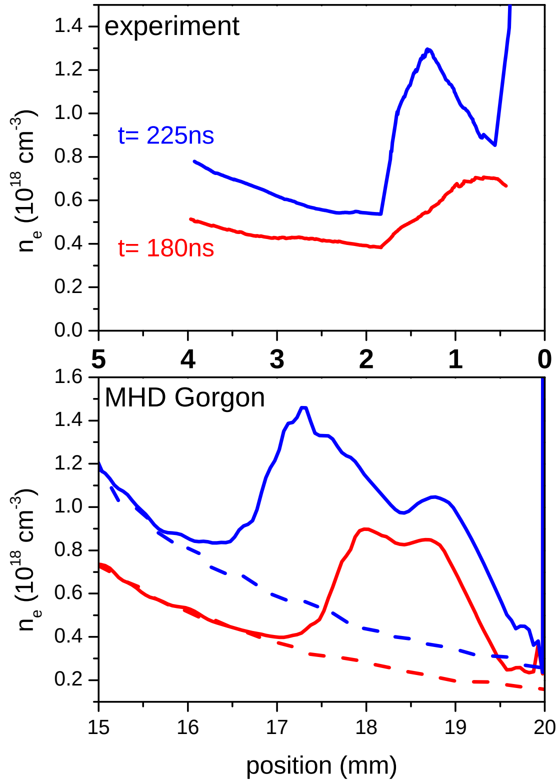
Pile-up of magnetic field in front of the obstacle, formation of shock



Resisitve MHD simulations

Pile-up of magnetic field in front of the obstacle, formation of shock





MHD simulations:

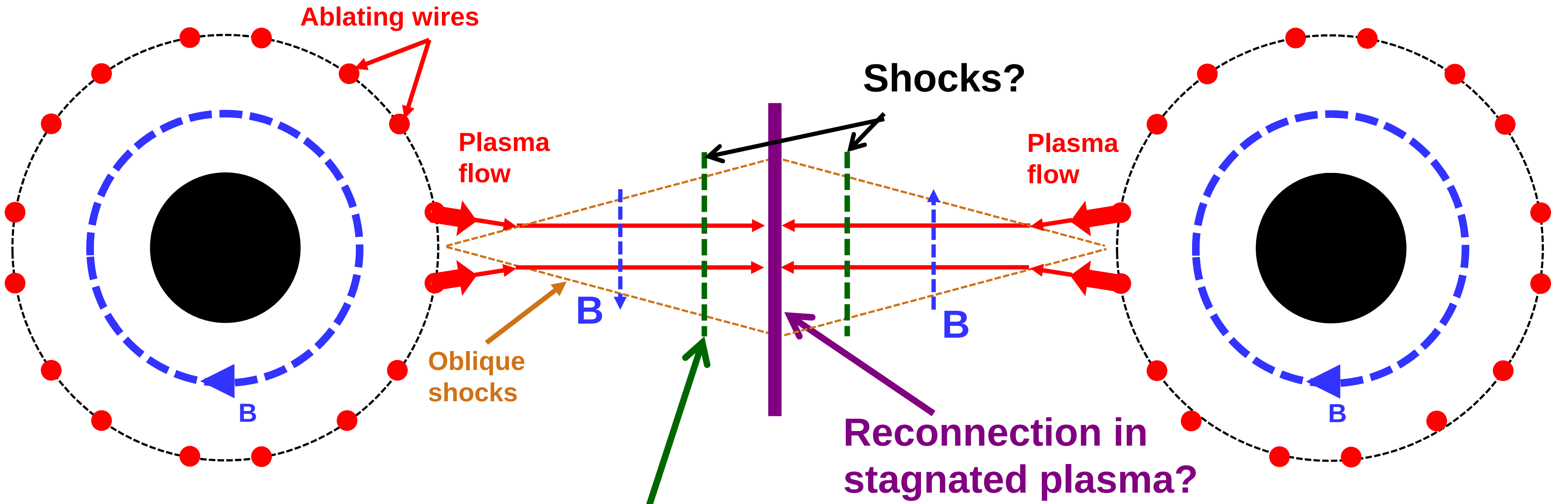
Faster motion of the reverse shock

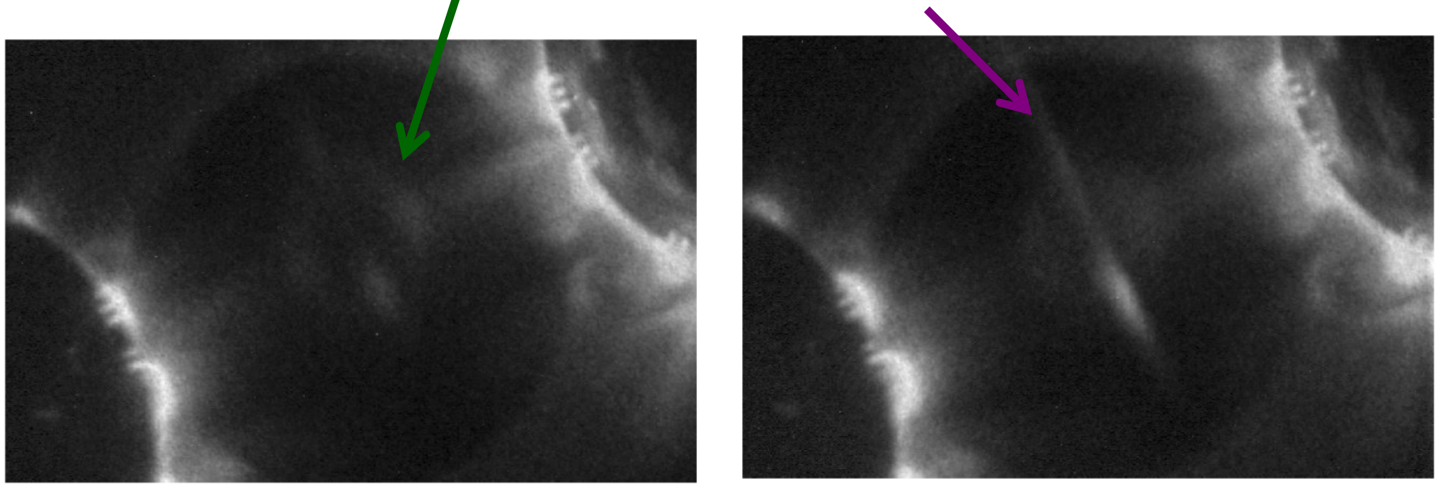
Larger magnetic field

Hybrid simulations are in progress to account for the large ion m.f.p. at early times

Future directions

Magnetic reconnections in counter-streaming magnetised flows?





Outline

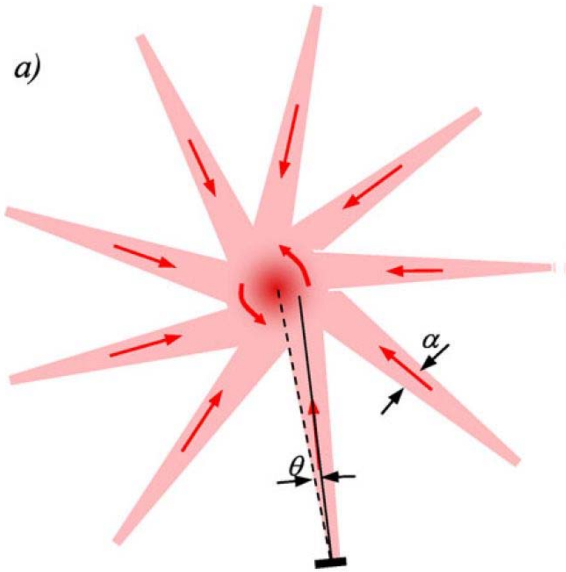
Motivation: develop experimental platform for quantitative studies of magnetised supersonic plasma flows

1. **Shocks in magnetised plasma flows:**
    - ***head-on collision of two supersonic jets***
    - ***formation of reverse shock mediated by pile-up of magnetic field***
2. **Formation of differentially rotating plasma discs**

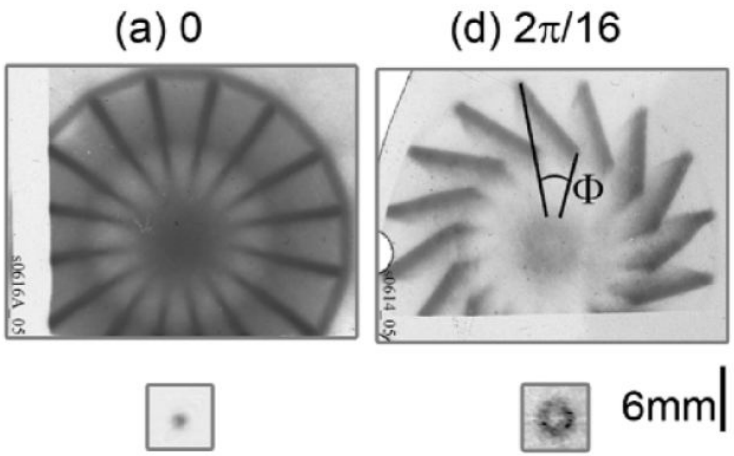
Common theme – dynamics of supersonic magnetised plasma flows

(MHD, compressibility, radiative cooling, ionisation balance…)

Rotating plasma in HEDP experiments



Ryutov, 2011



Ampleford et al, 2008

Hydrodynamic instabilities in differentially rotating plasma

- **Proposed laser driven experiment [Ryutov, ApSS 2011]:**
  - **rotating plasma disc is produced by off-axis collision of a number of laser driven jets**
- **This work:**
  - **converging plasma streams are formed in a wire array z-pinch (MHD simulations [Bocchi et al, ApJ 2012])**
- **Related z-pinch experiment:**
  - **Rotating jet from twisted conical wire array [Ampleford et al, PRL 2008]**

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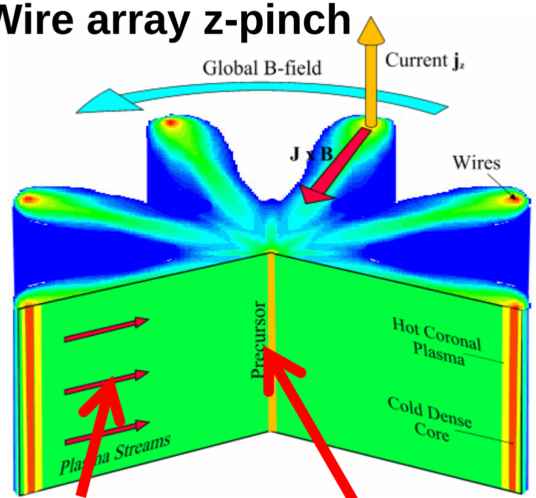
Experimental set-up

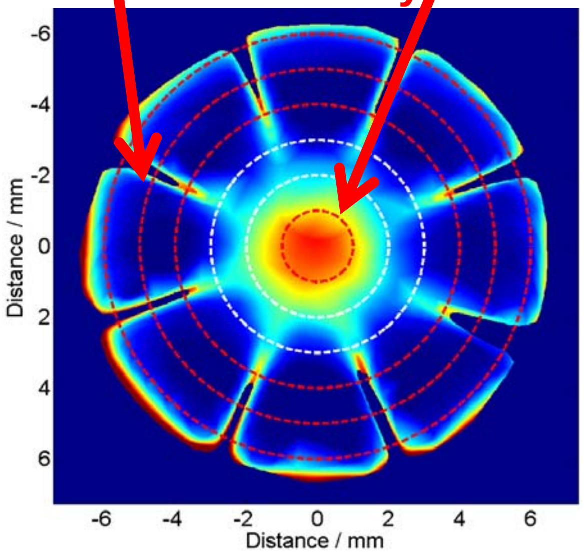
Wire array z-pinch



Ablation streams

Plasma accumulating on axis

Interferometry

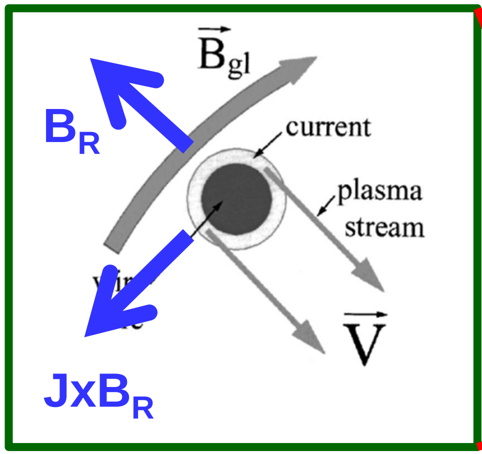


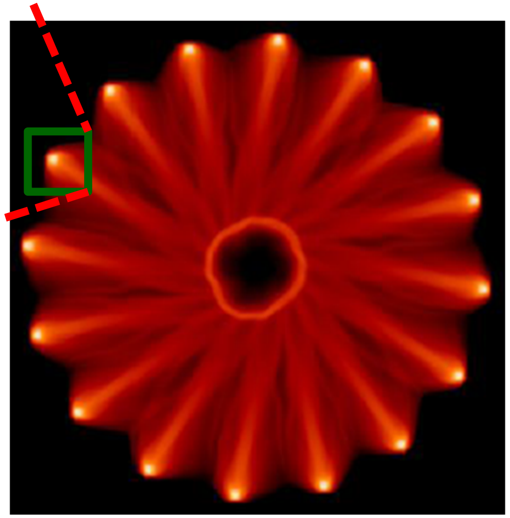
Ablation flow in wire array z-pinch

JxB force:

$J_z \times B_\theta \rightarrow V_r$

$J_z \times B_r \rightarrow V_\theta$

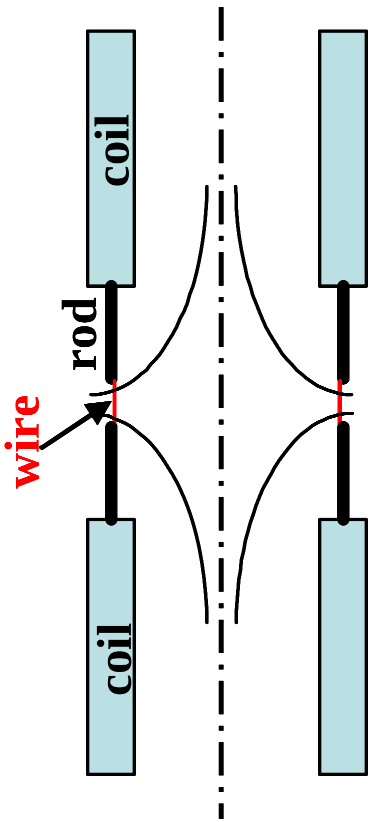




MHD simulations: Bocchi et al, ApJ 2013

Experimental set-up

Wire array z-pinch with additional coils to create B_r on wires



Ablation flow in wire array z-pinch

JxB force:

$J_z \times B_\theta \rightarrow V_r$

$J_z \times B_r \rightarrow V_\theta$

Rotation is introduced by B_r component of magnetic field from additional coils (cusp B-field configuration: N_{wire} , N_{turn})

Ablating wires and the coils are driven by the same current ➔ fixed in time "injection" angle $\theta \sim 5^0$ ($V_\theta / V_r \sim 1/10$)

<u>Diagnostics</u>:
Multi-frame XUV and optical imaging
End-on interferometry
Thomson scattering

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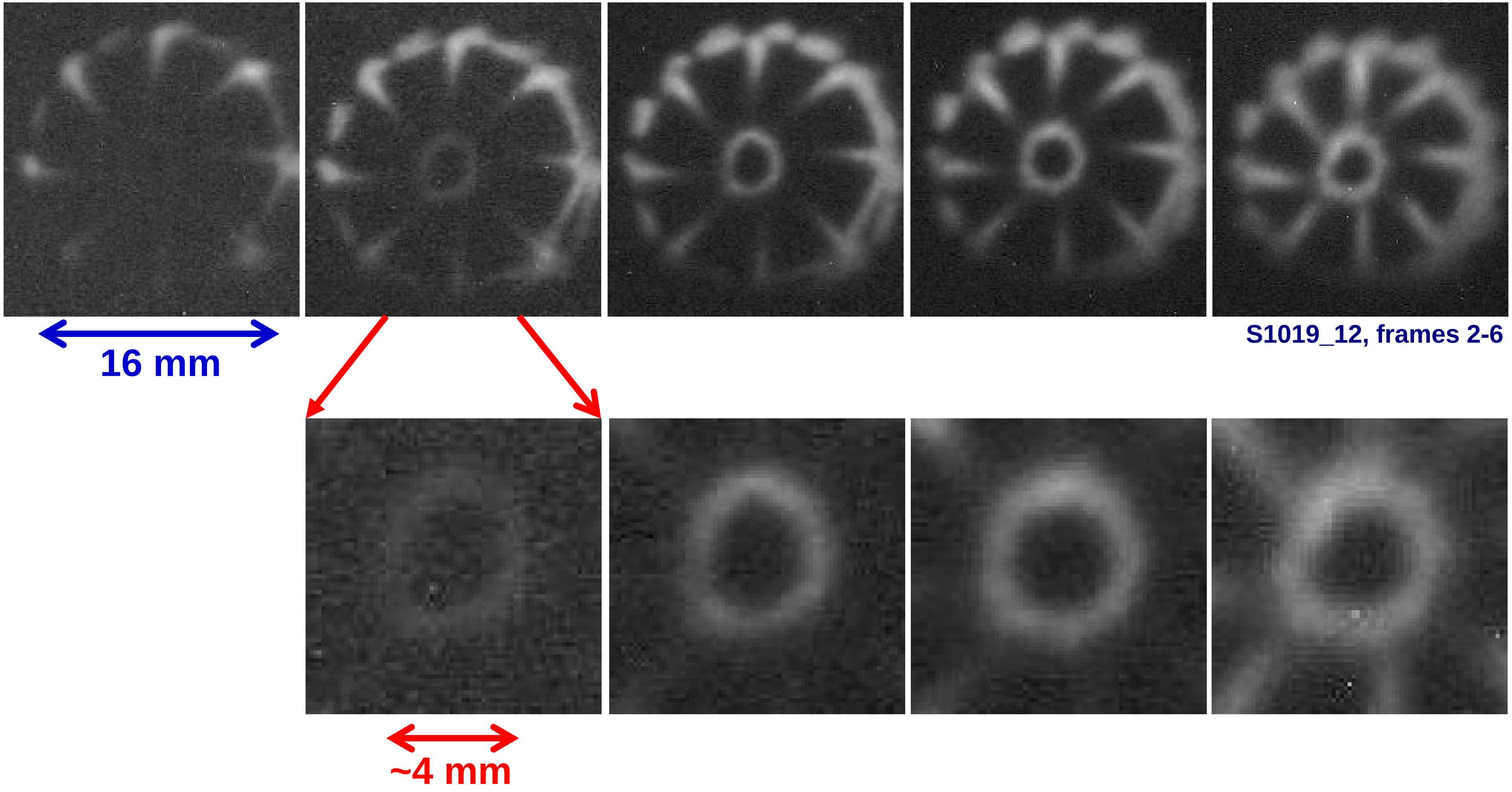
End-on images of rotating plasma (optical emission)

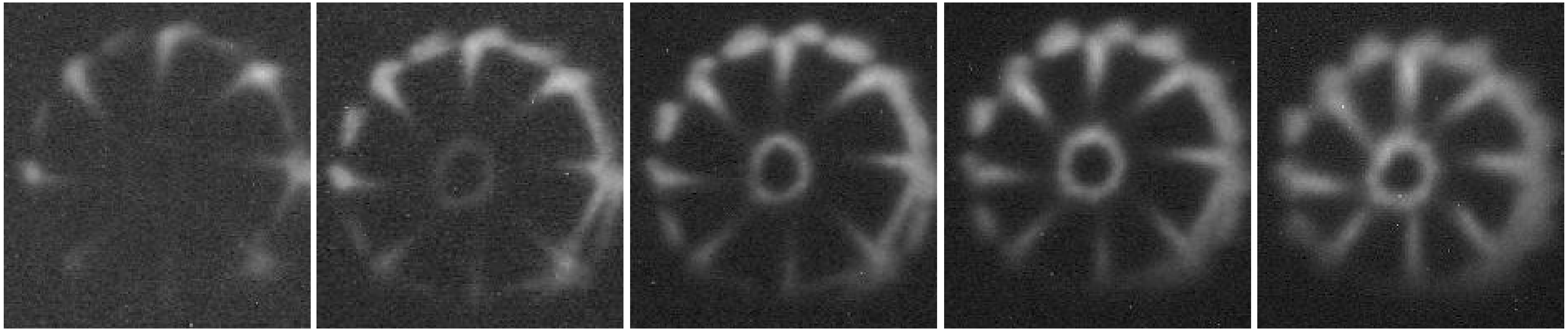
Optical framing camera: 20ns inter-frame time, 5ns gate **8x30μm Al wires**



B_r/B_θ ratio controls disc diameter

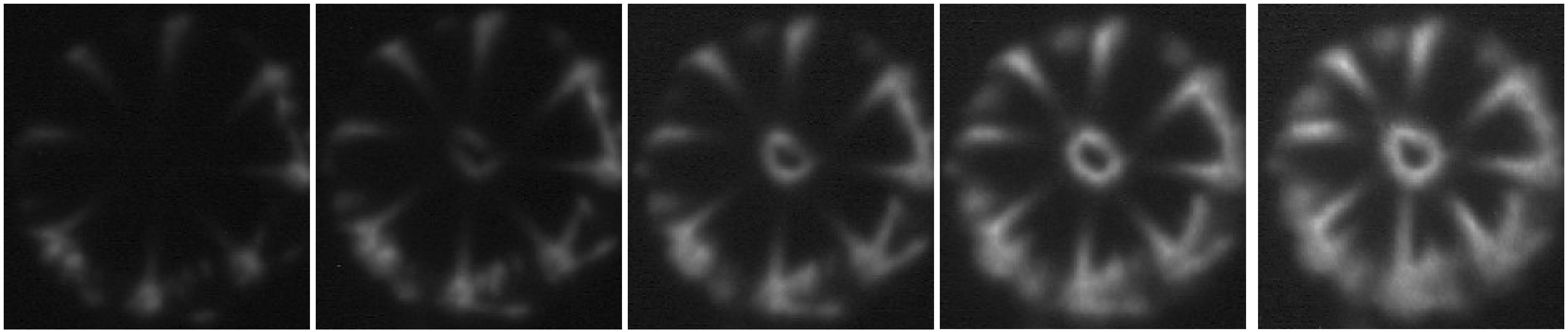
Optical framing camera: 20ns inter-frame time, 5ns gate. **8x30μm Al wires**

Cusp coil twist: 1/8



S1019_12, frames 2-6

Cusp coil twist: 1/16



S1023_12, frames 4-8

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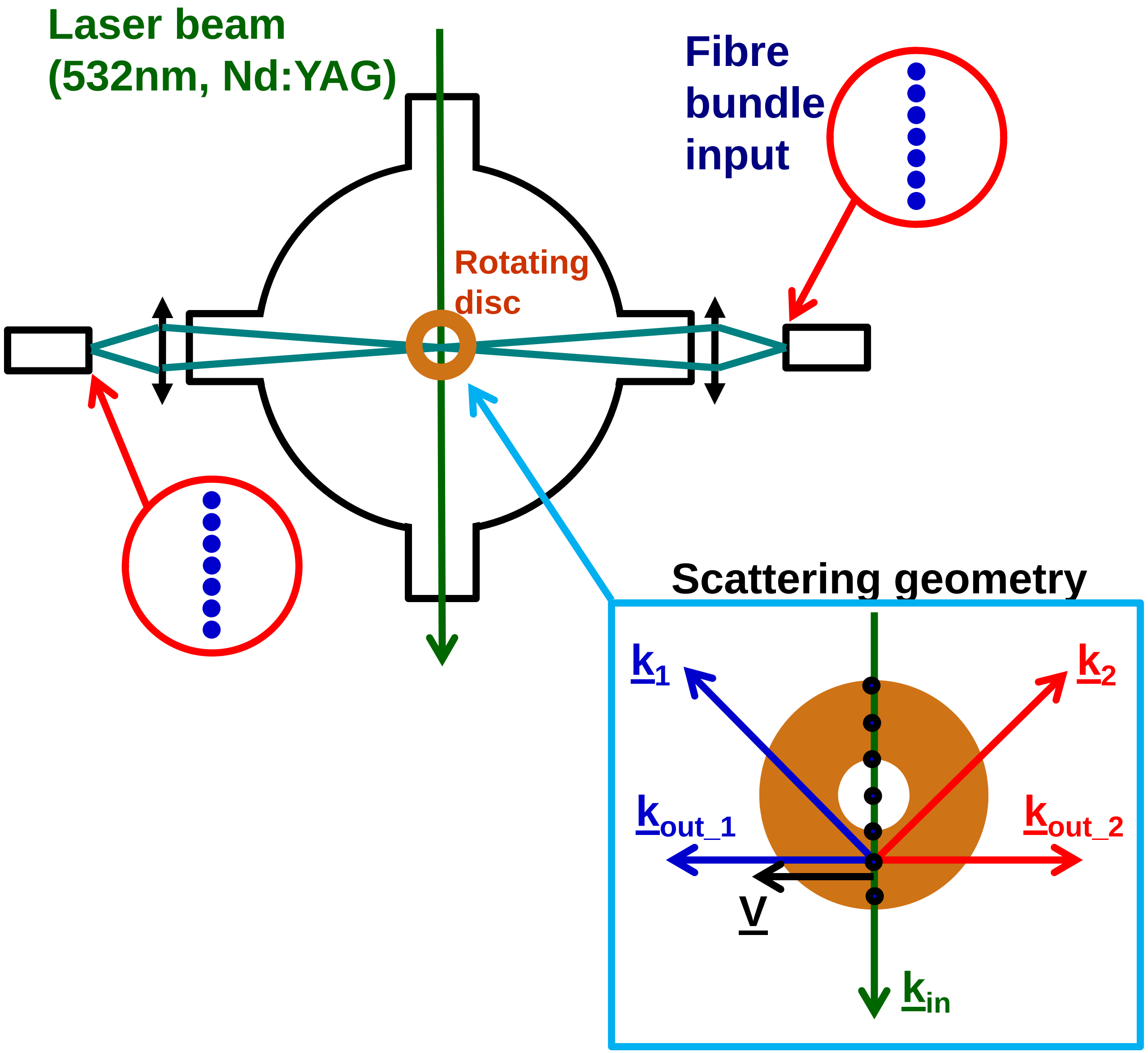
Thomson scattering set-up



Spatially resolved spectrum (7 points along probing beam)

(side-on observation allows measurements of velocity in r-θ plane)

Doppler shift of the ion feature (2 directions)

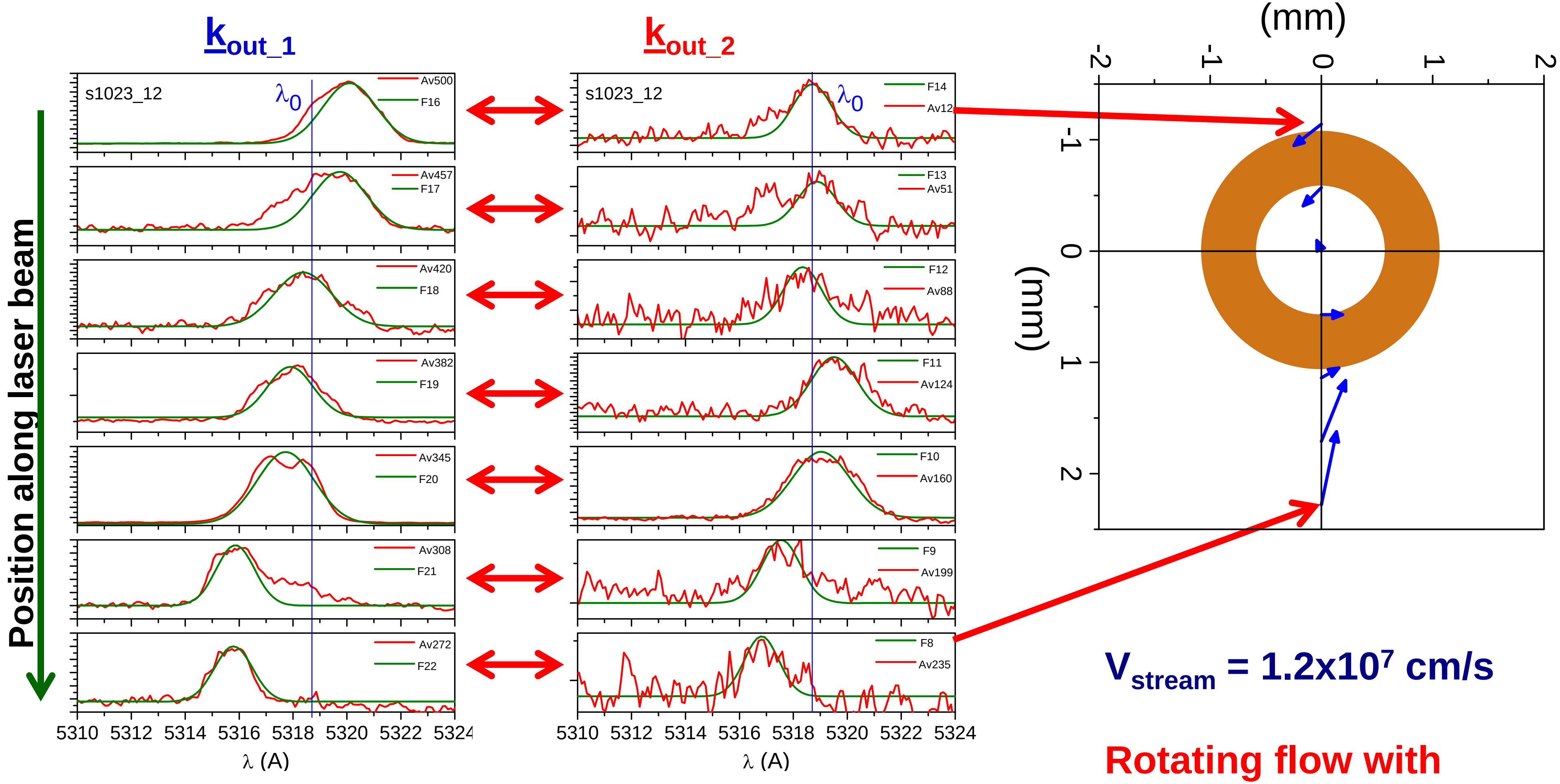
$\omega_{s1} = \omega_0 + \underline{k}_1 \cdot \underline{V} \rightarrow V_{k1}$

$\omega_{s2} = \omega_0 + \underline{k}_2 \cdot \underline{V} \rightarrow V_{k2}$

$\underline{k}_{1,2} = \underline{k}_{out\_1,2} - \underline{k}_{in}$

Velocity profile from Thomson scattering

TS spectra **Velocity vectors**



V_{stream} = 1.2x10^7 cm/s

Rotating flow with V_θ = (4-5)x10^6 cm/s

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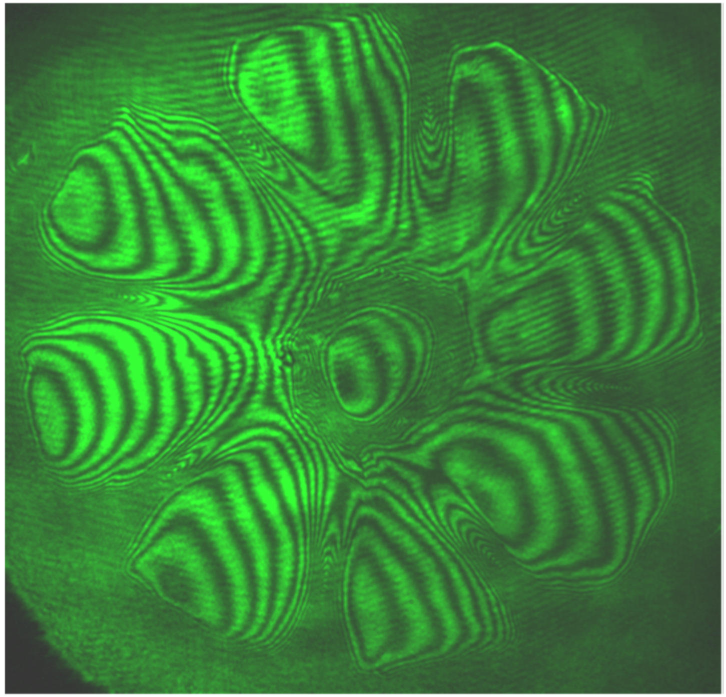
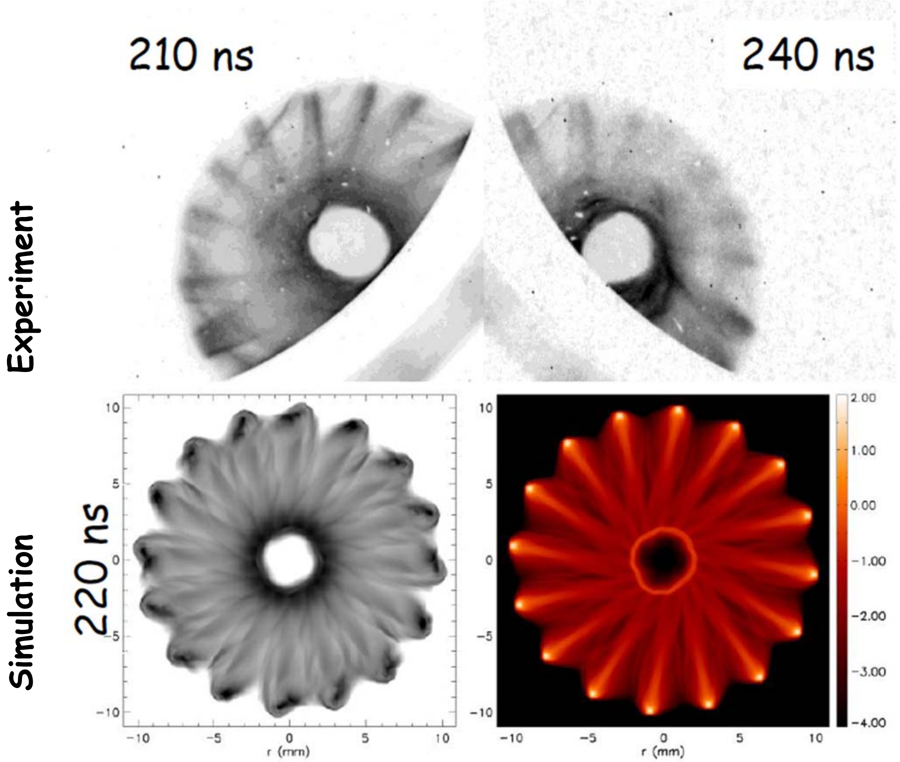
Rotating plasma disc summary

Rotating supersonic (M~3) plasma "disc" sustained for >150ns (~1 rotation)

High Reynolds number (Re ~5x10^5)

Magnetic Reynolds number exceeding unity (Re$_M$ ~10)





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Conclusions

Scaled laboratory experiments can be used as a tool complementary to numerical simulations of astrophysical processes:

- **Benchmarking 3-D codes under scalable conditions (Re, Re_M in experiments are at least comparable to numerical values)**
- **May prompt the emergence of new concepts (e.g. episodic jets)**

Supersonic plasma flows driven by pulsed power allow development of well-characterized Laboratory Astrophysics experiments

- **Dynamically significant embedded magnetic fields**
- **Steady, long duration, large spatial scale, good access for diagnostics**