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# Unexplained Structures in

# Laser Ablation of Solids

An Experiment, a Model, Some History,  
a Theory and Another Experiment

J. R. Davies, M. Fajardo, R. Bendoyro, K. Li

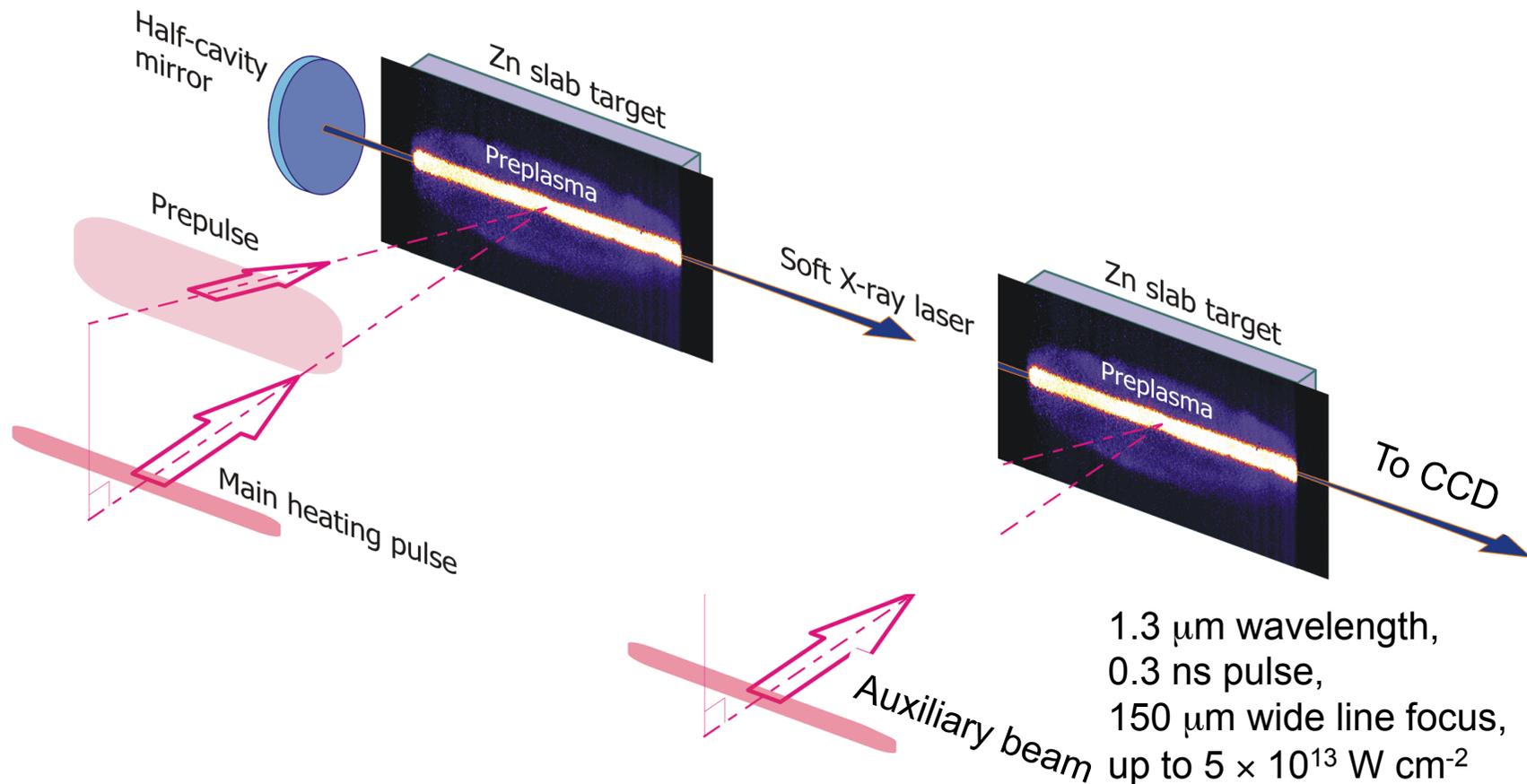
*GoLP, Instituto de Plasmas e Fusão Nuclear - Laboratório Associado,  
Instituto Superior Técnico, Portugal*

M. Kozlová, T. Mocek, J. Polan, B. Rus, D. Margarone,  
J. Nejd, M. Sawicka *et al.*

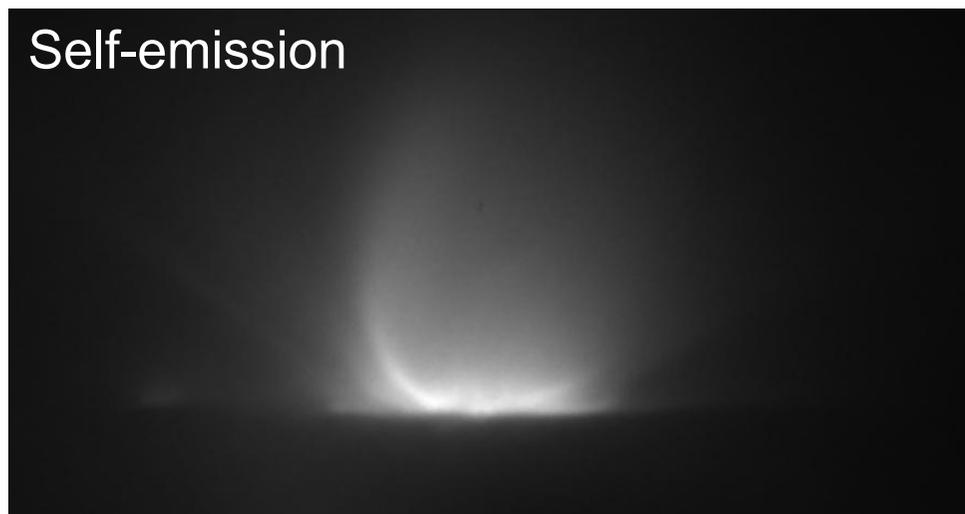
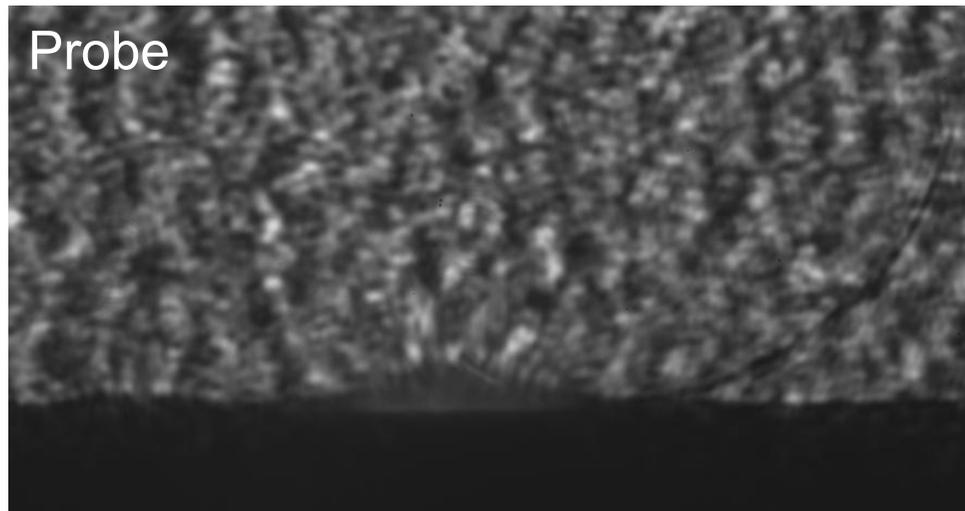
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# An Experiment

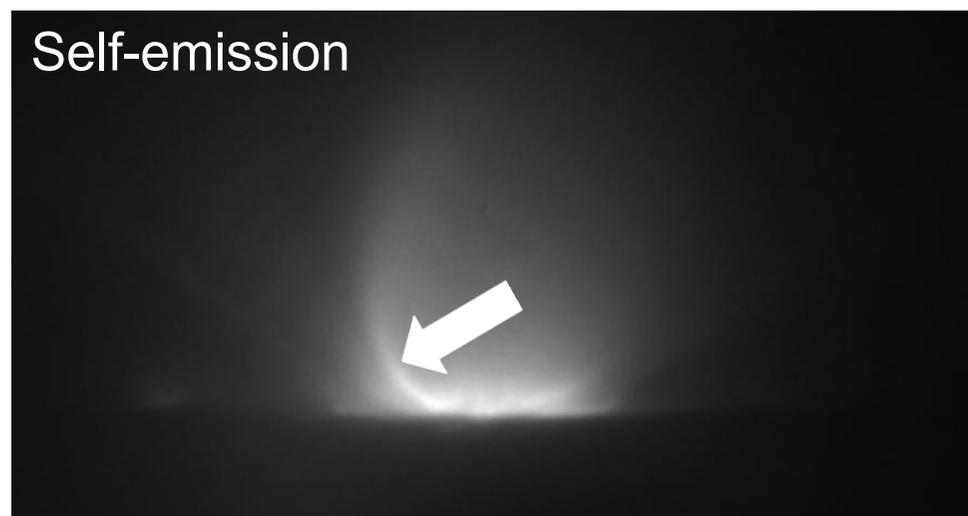
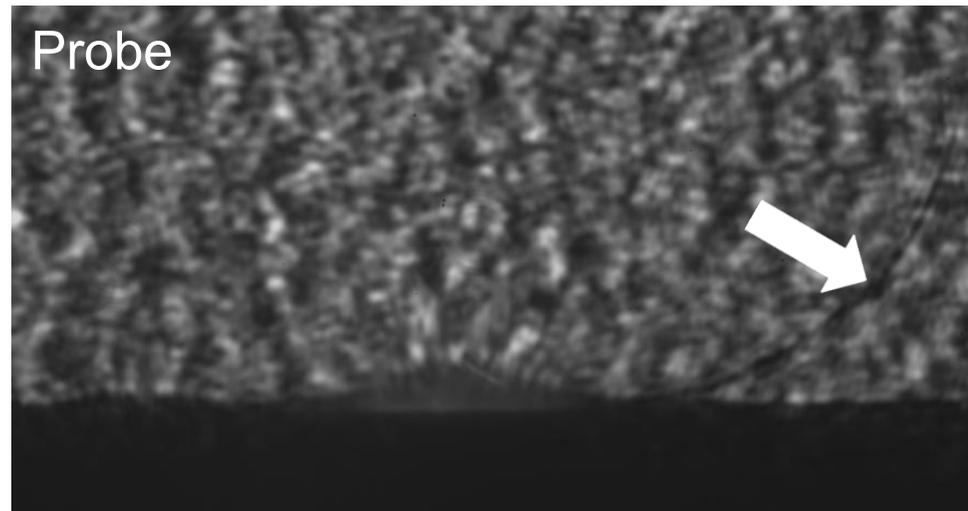
- PALS 2006; using an XUV laser to study plasma formation for an XUV laser



# Two Pictures



# It's Horny!



# Have been seen before on PERUN...

Rus *et al.* Phys. Rev. A **56** 4229 (1997)

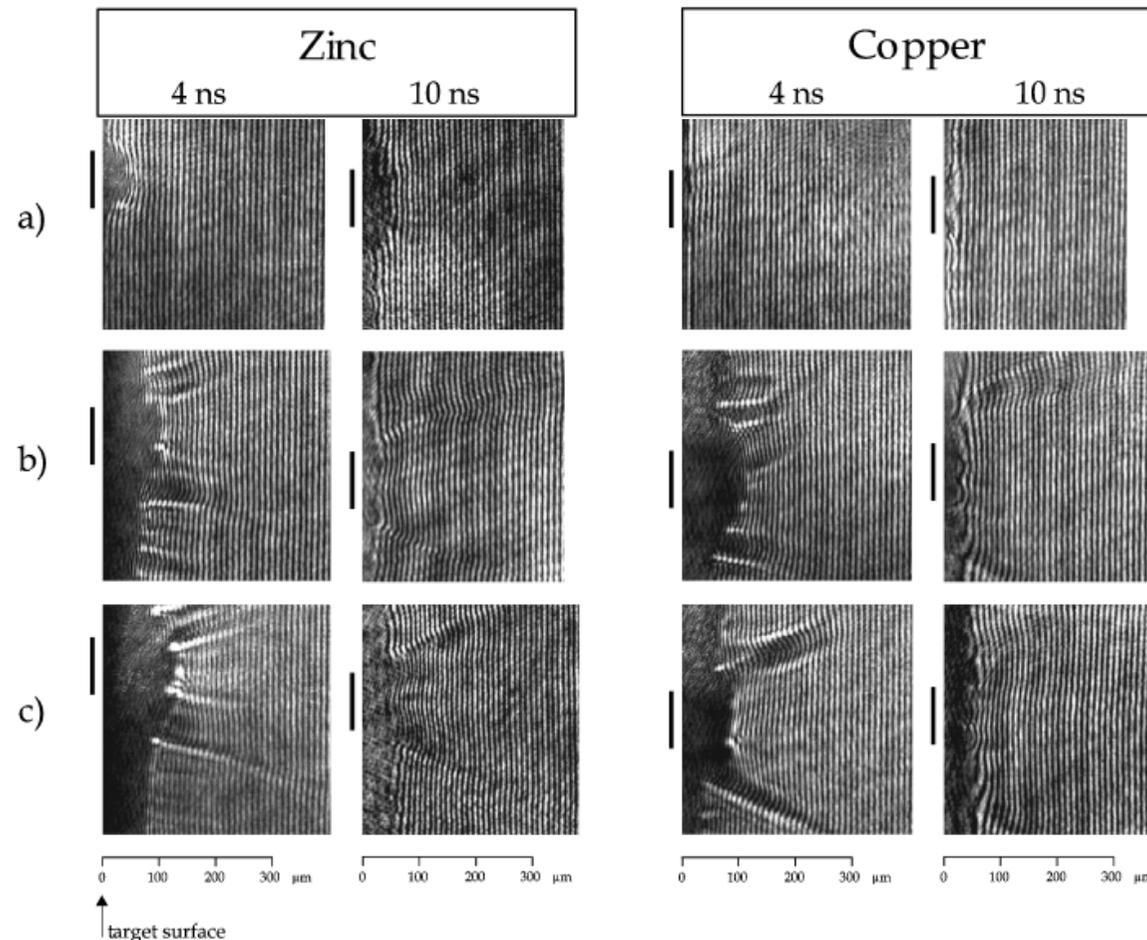


FIG. 2. Typical interferometric patterns obtained in  $t=4$  ns and  $t=10$  ns for plasmas generated by (a)  $10^{10}$ , (b)  $5 \times 10^{10}$ , and (c)  $10^{11}$   $\text{W cm}^{-2}$ . The vertical bar labels the width ( $=100 \mu\text{m}$ ) and the position of the laser impact for each shot. The left end of the records corresponds to the target surface, with an accuracy of  $\pm 5 \mu\text{m}$ . Access to higher electron densities near the target is hampered by refraction of the probe beam.

## ...and before that in China

Xu *et al.* Phys. Rev. A **39** 808 (1989)

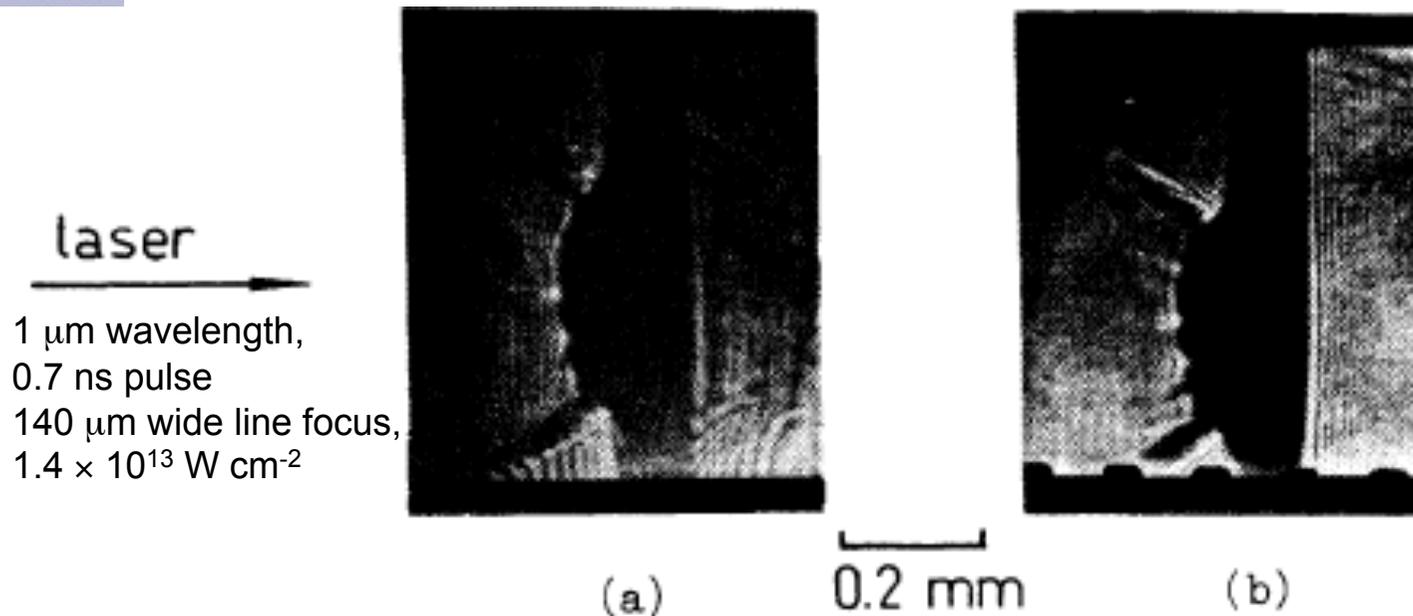


FIG. 9. (a) Interferogram and (b) shadowgram showing the relatively large-scale plasma-jet-like structure are recorded simultaneously by two-frame photography at  $\Delta t = 2.9$  ns. The target is a 100- $\mu\text{m}$ -thick Al foil and is irradiated by a line-focused laser light (with a horizontal focal line) at an irradiance of  $1.4 \times 10^{13} \text{ W/cm}^2$ . The probing beam is parallel to the focal line. Note that the plasma jets shown in the figure are similar in appearance to “tips of oxhorns.”

## Why?

- Is it due to a magnetic field?
  - ↪ The magnetic field you get around laser produced plasma jets from  $\nabla n \times \nabla kT$
- Does the magnetic field cause the jets to attract one another giving the curvature?

## A Model

- MH2D (A. R. Bell); 2D Eulerian, resistive MHD code

$$\Leftrightarrow \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0,$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \rho \mathbf{v} \mathbf{v} = -\nabla \left( P + \frac{B^2}{2\mu_0} \right),$$

$$\frac{\partial U}{\partial t} + \nabla \cdot U \mathbf{v} = S - P \nabla \cdot \mathbf{v} + \frac{\nabla \times \mathbf{B}}{\mu_0} \cdot \mathbf{E} + \nabla \cdot \kappa \nabla T,$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot \mathbf{B} \mathbf{v} = -\nabla \times \mathbf{E},$$

$$\mathbf{E} = -\frac{Am_p \nabla P}{Z\rho} + \frac{\eta}{\mu_0} \nabla \times \mathbf{B},$$

- ↔ Ideal gas equation of state
- ↔ Cylindrical geometry (r-z), so had to convert to Cartesian geometry (x-z) to model an infinite, symmetric line focus



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# Results

- Initial result: No Horns



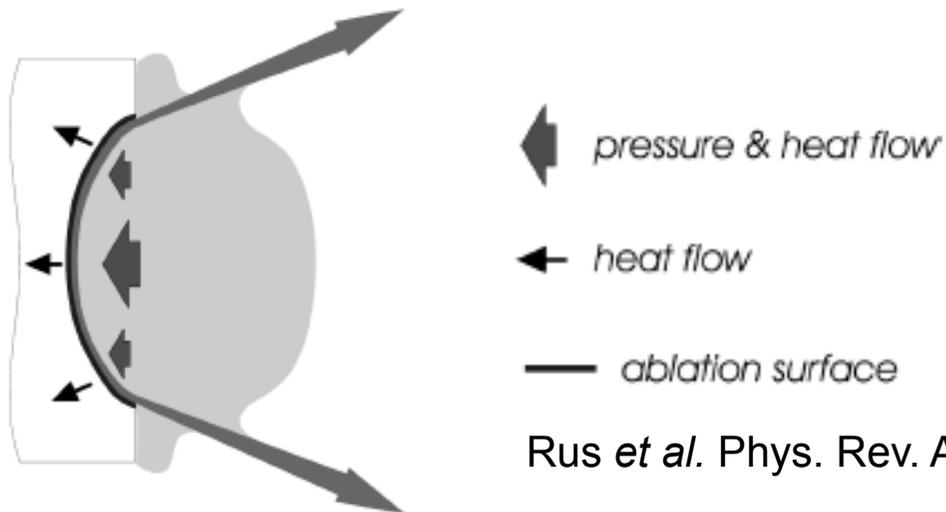
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## Results

- Initial result: No Horns
- Bumpy laser profile: No Horns

## Results

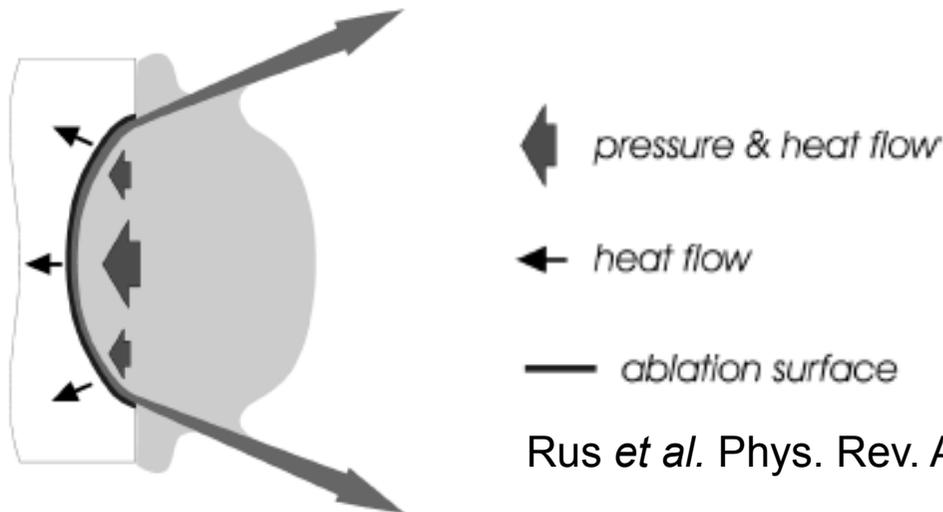
- Initial result: No Horns
- Bumpy laser profile: No Horns
- Curve the target: No Horns



Rus *et al.* Phys. Rev. A **56** 4229 (1997)

## Results

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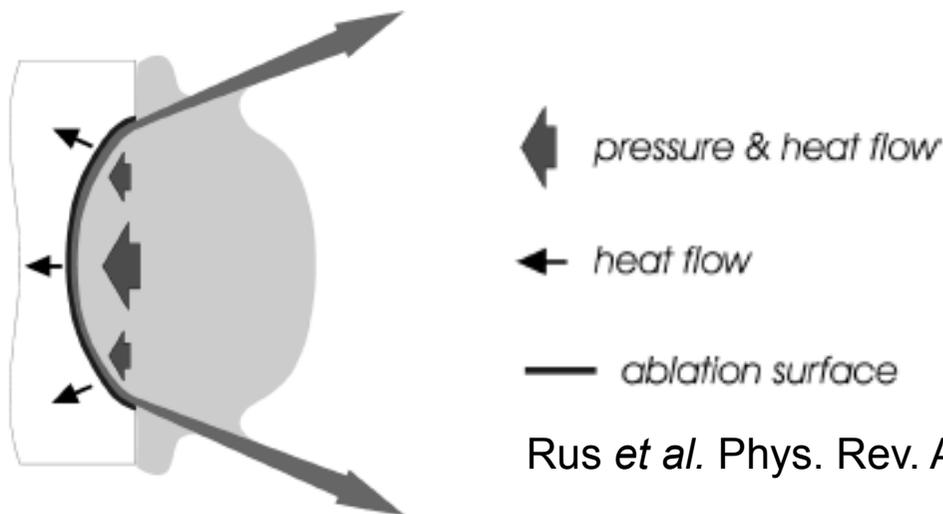


Rus *et al.* Phys. Rev. A **56** 4229 (1997)

- Put them in by hand: No Horns shortly afterwards

## Results

- Initial result: No Horns
- Bumpy laser profile: No Horns
- Curve the target: No Horns



Rus *et al.* Phys. Rev. A **56** 4229 (1997)

- Put them in by hand: No Horns shortly afterwards
- The magnetic field had no effect on the plasma jet(s)

# A PRL on Magnetic Field

Li *et al.* Phys. Rev. Lett. **99** 015001 (2007)

- Measured the magnetic field using 14.7 MeV protons from D-<sup>3</sup>He fusion on Omega and saw fine scale structure after the pulse that they could not explain

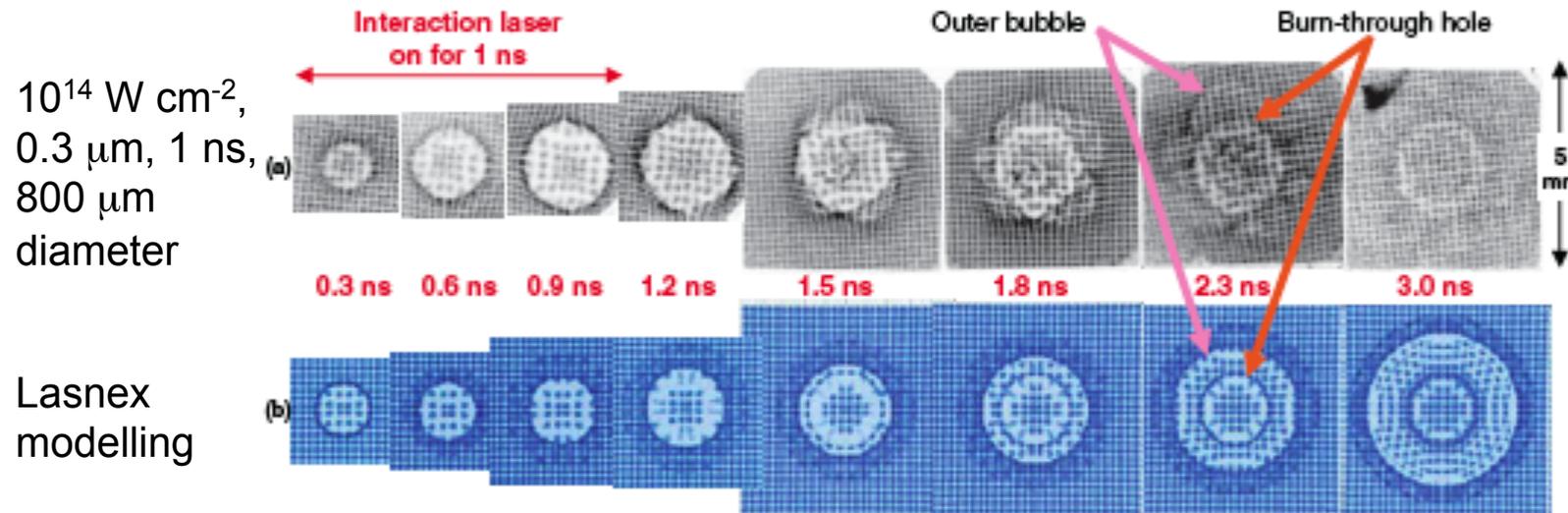
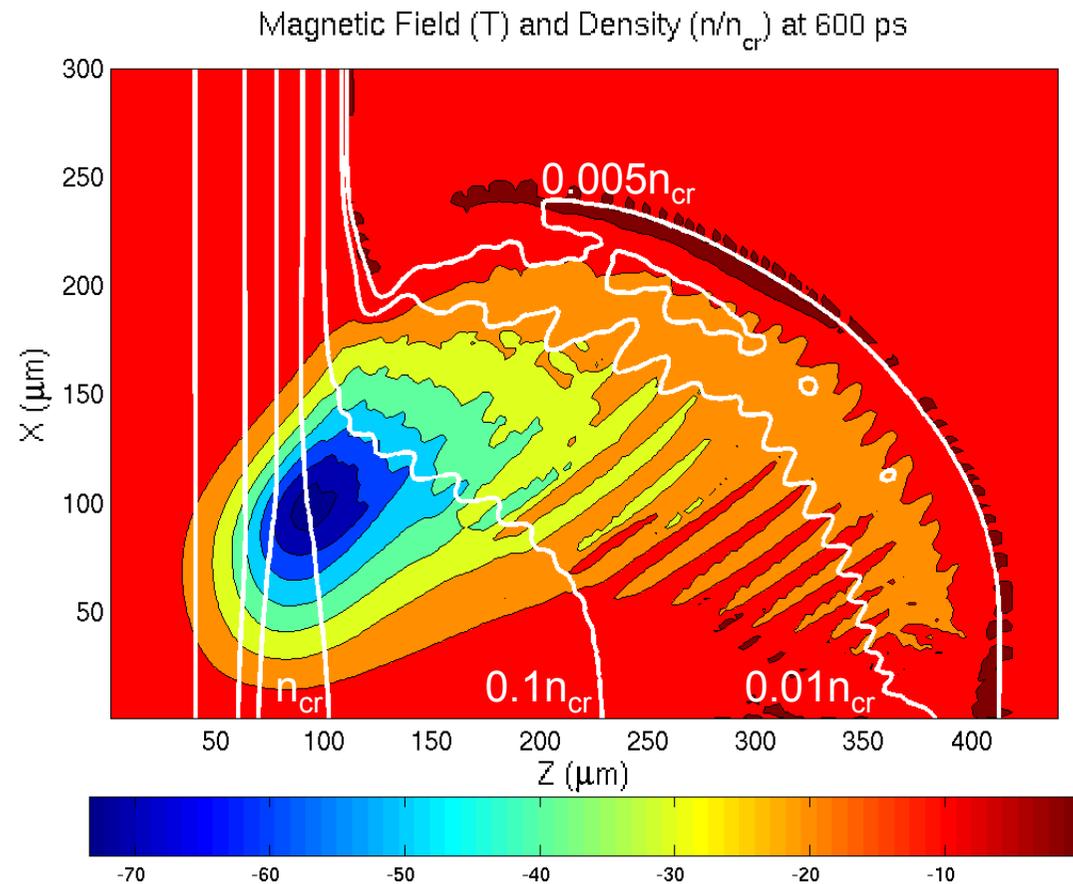


FIG. 2 (color). (a) Measured D<sup>3</sup>He proton images showing the evolution of  $B$  fields. (b) Corresponding images simulated by LASNEX + LSP. Arrows point to the image features corresponding to fields at the outer bubble boundary and at the laser burnthrough hole shown in Fig. 3(b).

# All My MH2D Runs Had This Feature!



- In magnetic field, density and flow velocity below the critical density, but *not temperature*

## Some History

- Such fine scale structure has long been reported in experiments
  - ↪ Seen after or towards the end of the pulse
  - ↪ Seen in the density but not the temperature (detected in probing not emission)
  - ↪ Look like hairs pointing predominantly in the direction of the plasma expansion
  - ↪ Can rule out laser filamentation
- A number of theories have been proposed
- It has never been possible to unambiguously identify the mechanism in any experiment



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# The Experiments

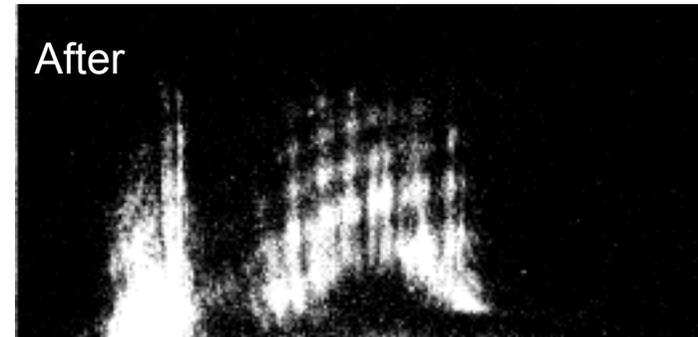
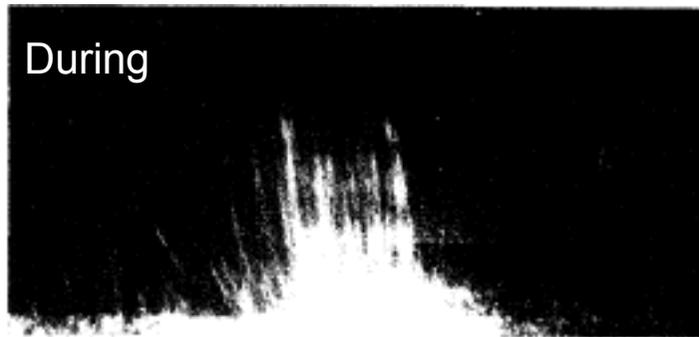
# 1978

➤ Grek *et al.* Phys. Rev. Lett. **41** 1811

10.6  $\mu\text{m}$  wavelength, 10-12 J in 1.2-1.7 ns, 100  $\mu\text{m}$  diameter spot,  $10^{14}$  W  $\text{cm}^{-2}$

Polyethylene target

2 ns ruby laser probe



1mm

# 1981

- **Willi's Hairs: Willi *et al.* IEEE J. Quant. Elec. 17 1909**  
1  $\mu\text{m}$  wavelength, 4 beams, 1.5 ns,  $2 \times 10^{13} \text{ W cm}^{-2}$ , Gold coated glass  
0.62  $\mu\text{m}$  wavelength, 50 ps probe



2 nsec

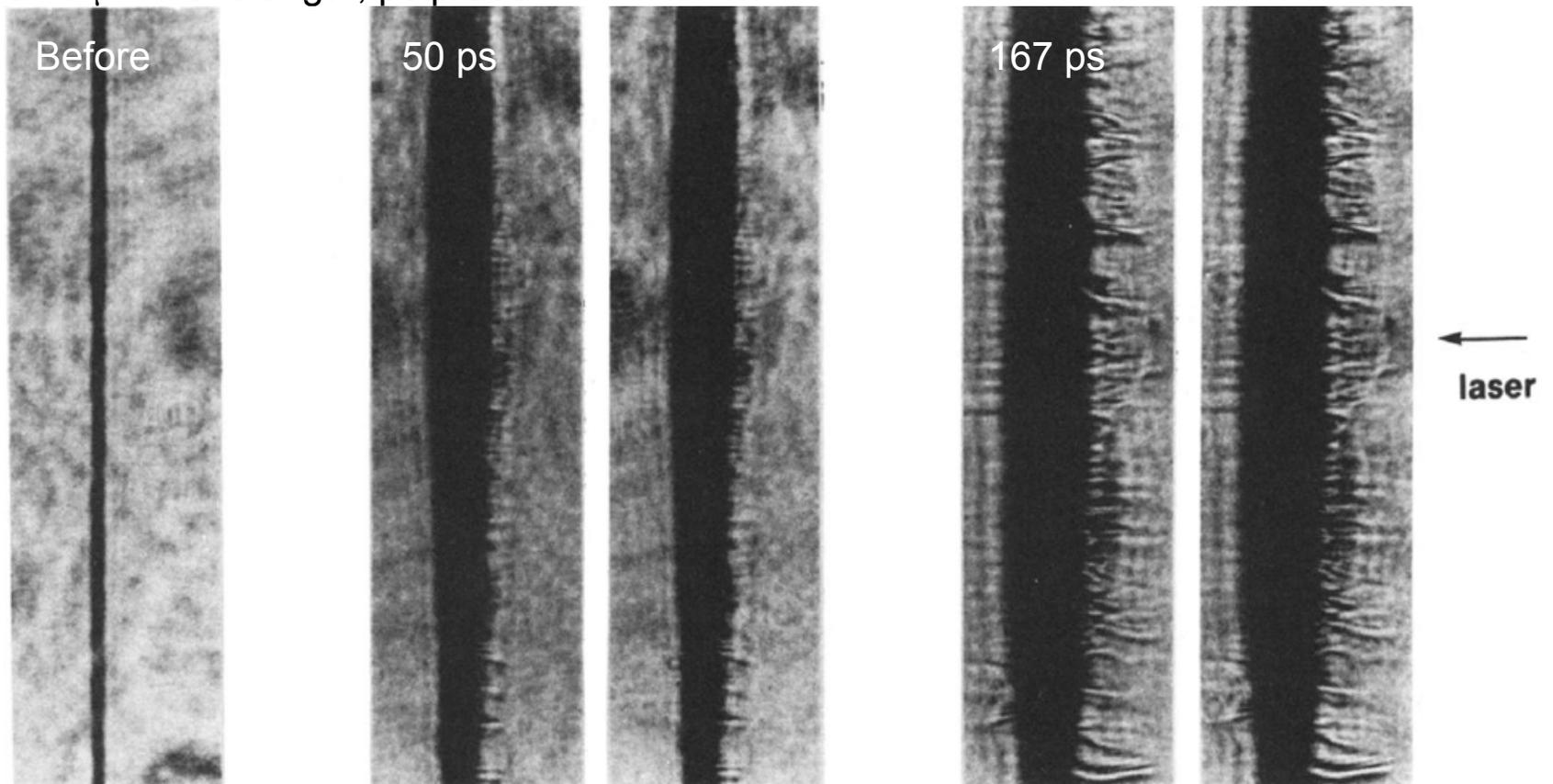
200  $\mu\text{m}$

3 nsec

# 1985

➤ Burgess *et al.* Phys. Rev. A **32** 2899

1  $\mu\text{m}$  wavelength, 30 ps pulse, 30  $\mu\text{m}$  wide line focus,  $10^{14}$  W  $\text{cm}^{-2}$ , 10  $\mu\text{m}$  C fibre  
0.26  $\mu\text{m}$  wavelength, ps probe



# 1989

➤ “Oxhorns” Xu *et al.* Phys. Rev. A **39** 808

1  $\mu\text{m}$  wavelength, 0.7 ns pulse, 140  $\mu\text{m}$  wide line focus,  $3.5 \times 10^{13} \text{ W cm}^{-2}$ , Al foil  
0.63  $\mu\text{m}$  wavelength, 50 ps probe

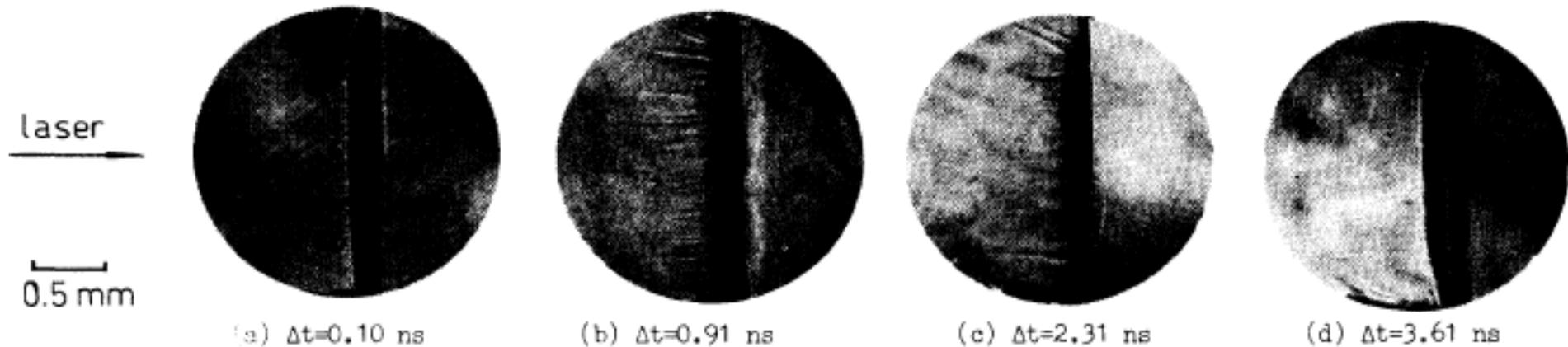


FIG. 7. Sequence of shadowgrams showing plasma jets and their time evolution. The 100- $\mu\text{m}$ -thick Al planar foil target is irradiated by a line-focused laser light at an irradiance of  $3.5 \times 10^{13} \text{ W/cm}^2$ . The probing beams are orthogonal to the 2-mm-long focal line.

# 1989

➤ Gabl *et al.* Phys. Rev. Lett. **63** 2737

0.5  $\mu\text{m}$  wavelength, 1 ns pulse, 500  $\mu\text{m}$  diameter spot,  $10^{14}$  W  $\text{cm}^{-2}$ , Gold disk  
0.27  $\mu\text{m}$  wavelength, 20 ps probe

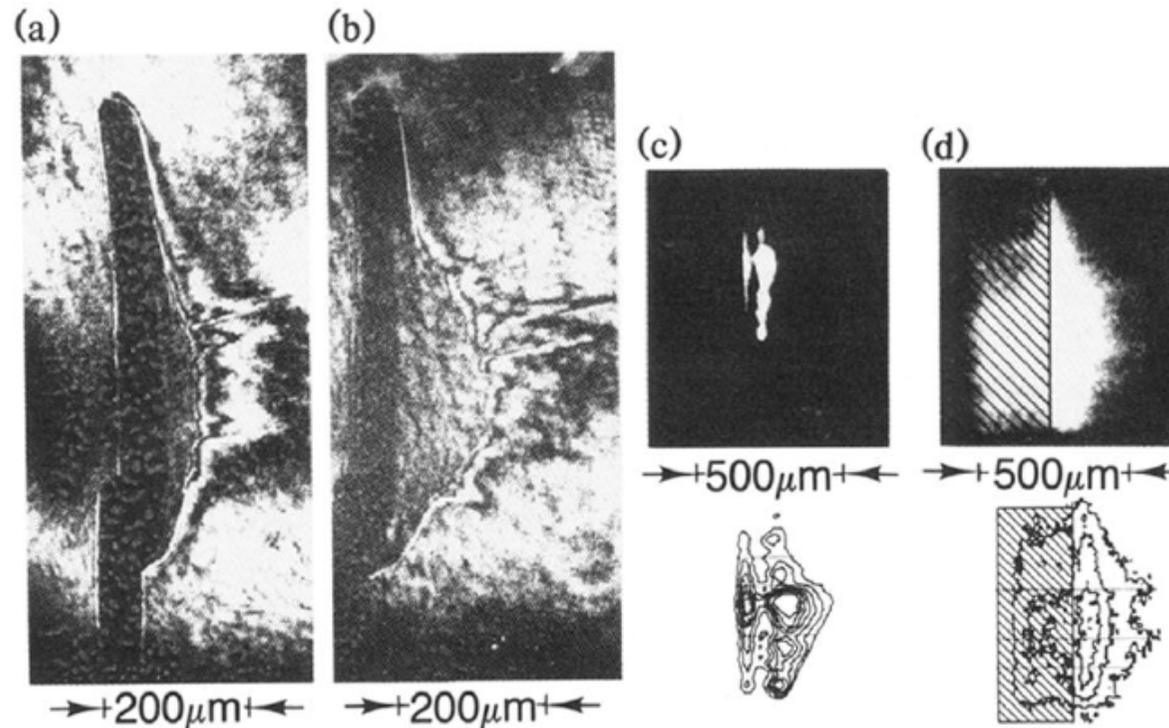


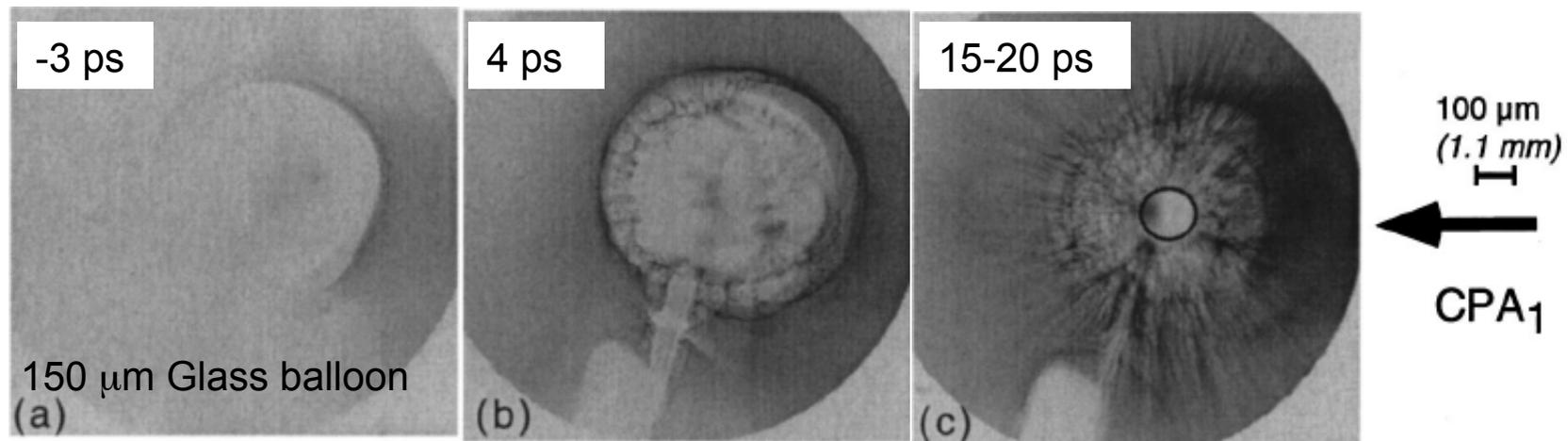
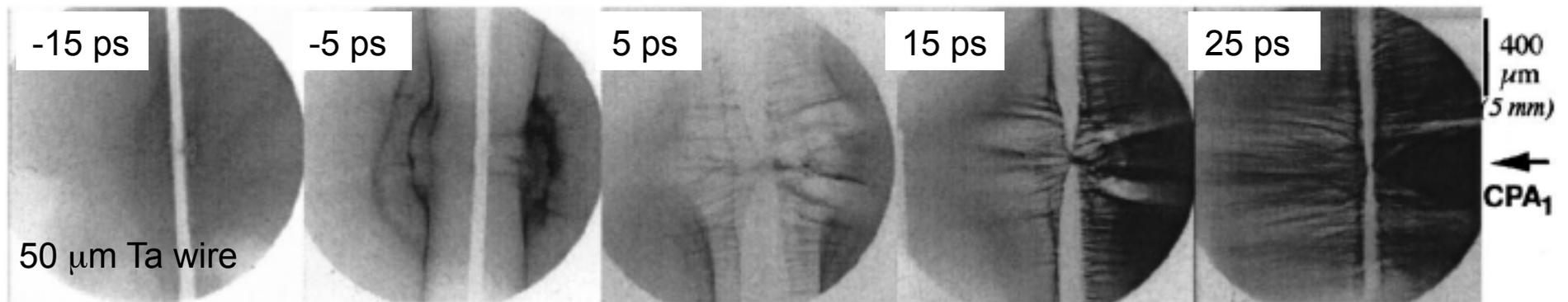
FIG. 3. Jetting is observed with a 3000- $\mu\text{m}$  offset on the divergent side of best focus for a picket laser pulse. Interferograms taken at (a) 320 and (b) 720 ps show a number of small jets. (c) The *M*-band and (d) soft-x-ray emission indicates that the jets are cool.

2002

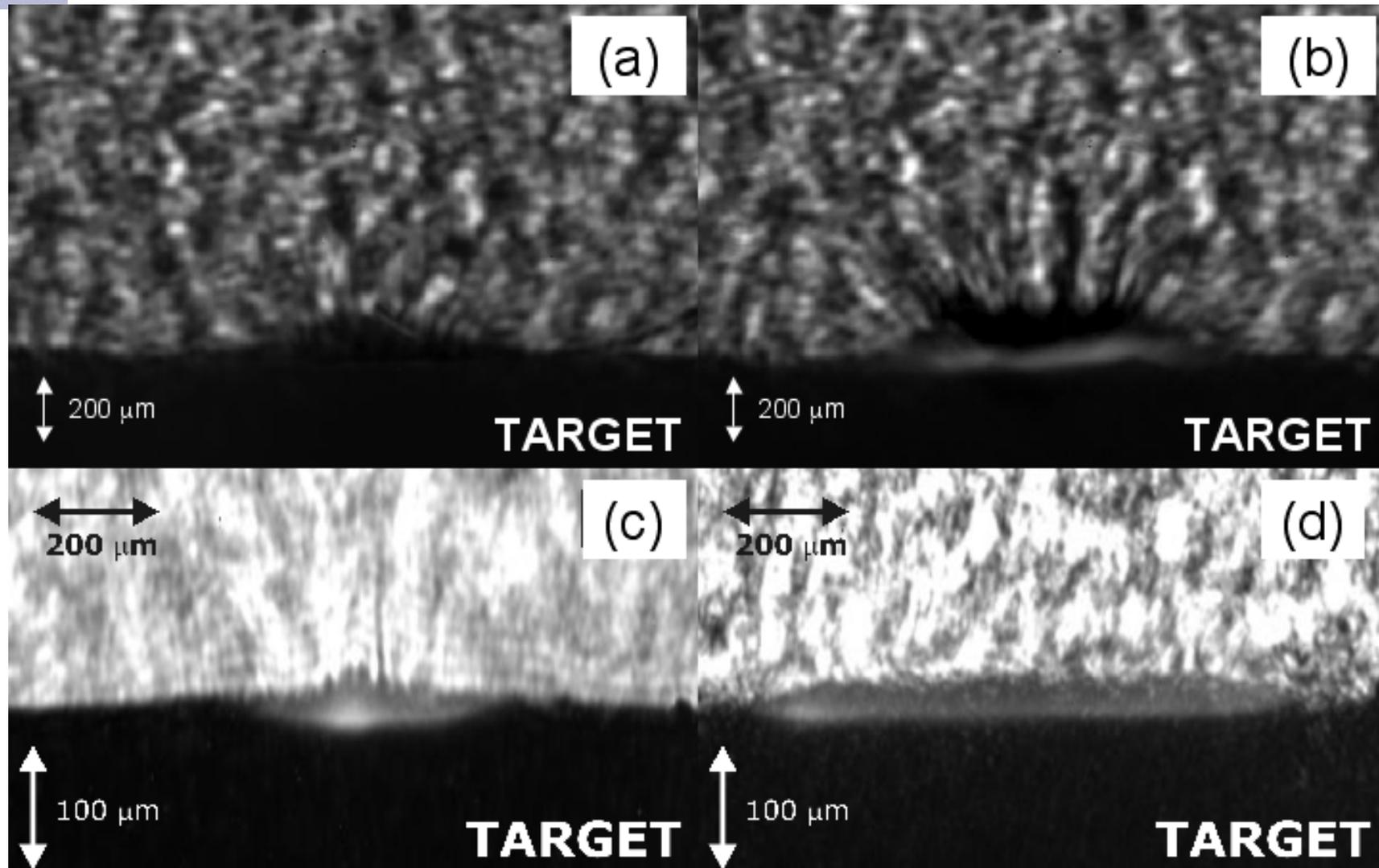
➤ Borghesi *et al.* Phys. Plasma **9** 2214

1  $\mu\text{m}$  wavelength, 1 ps, 20 J pulse,  $10^{19} \text{ W cm}^{-2}$

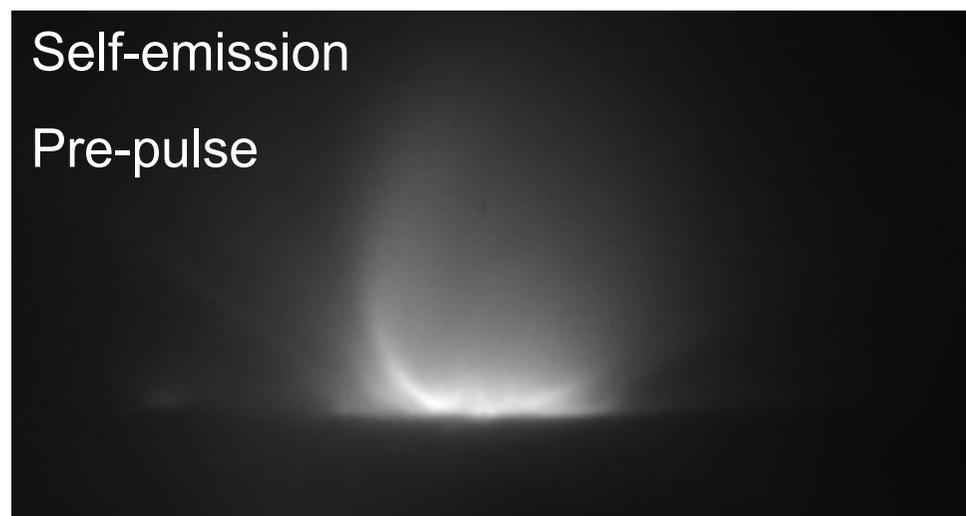
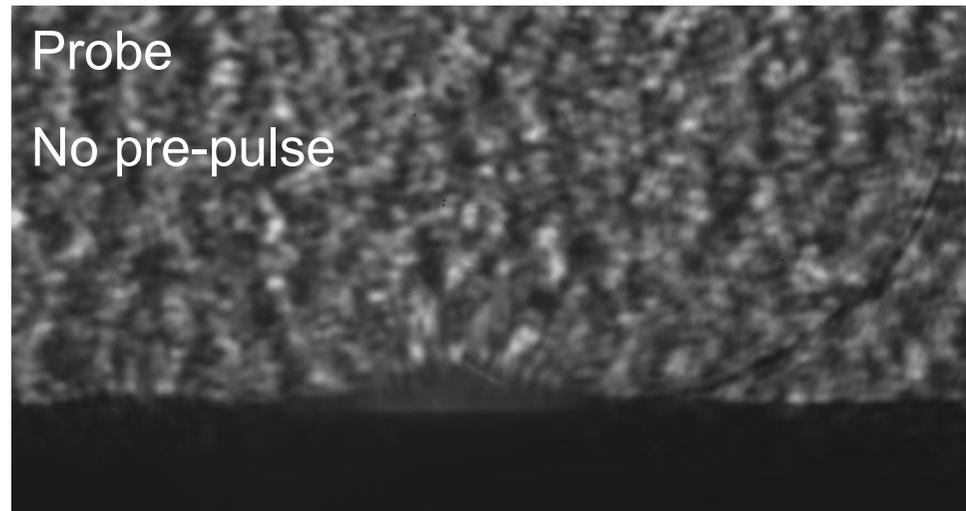
6 - 7 MeV proton probe (electric field)



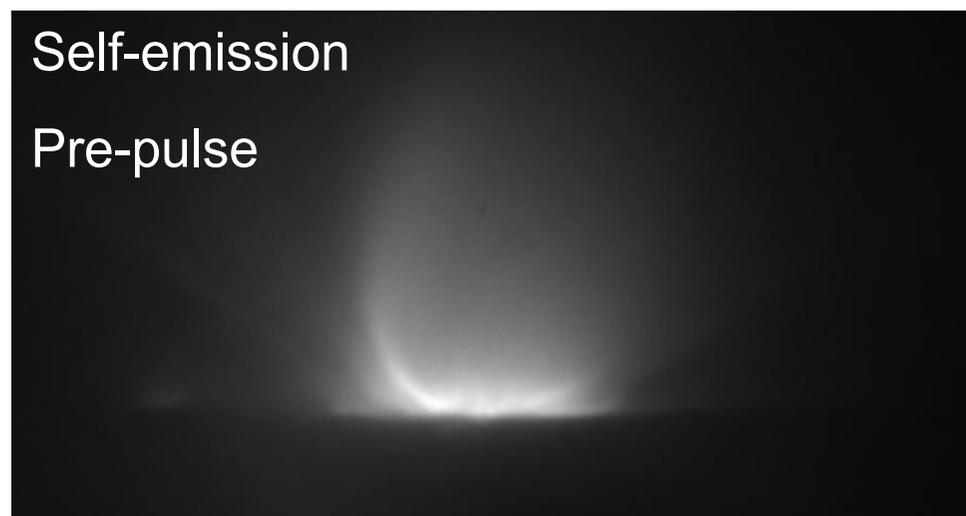
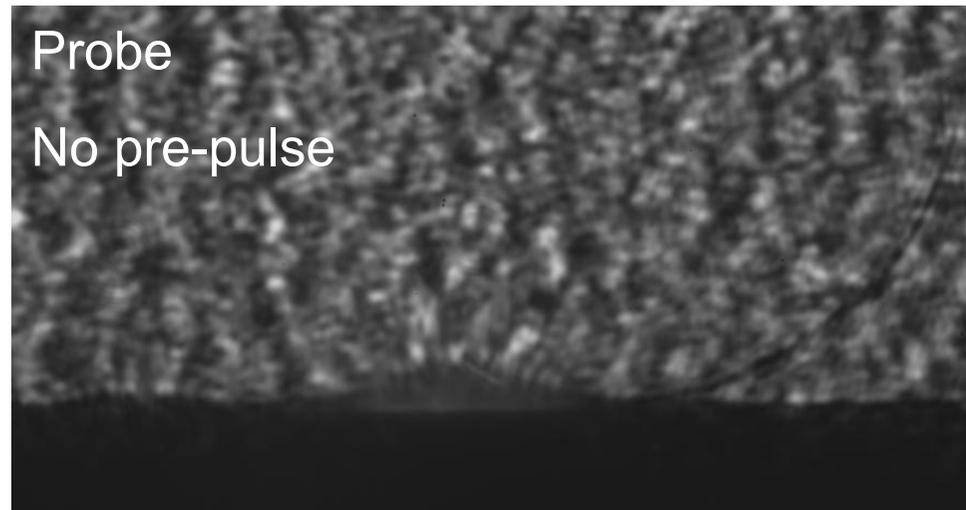
# PALS 2006



# We Were Looking at the Wrong Results

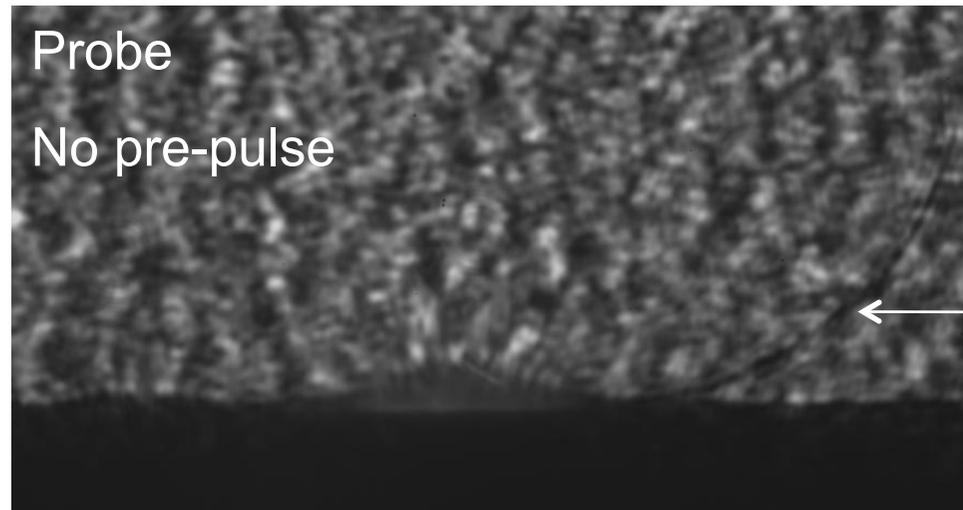


# We Were Looking at the Wrong Results

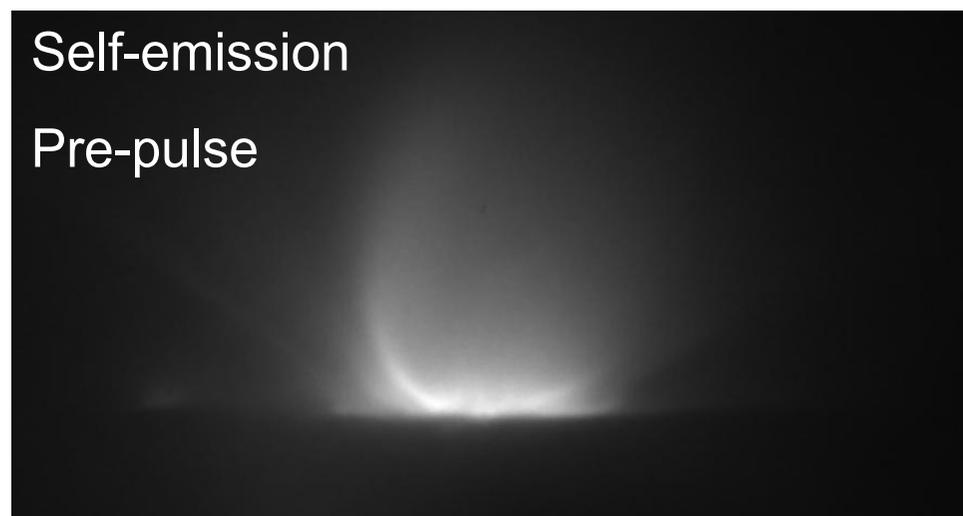


“Horns” only  
appeared in the  
emission with a  
pre-pulse

# We Were Looking at the Wrong Results



Only seen on  
this shot  
Edge of the  
plasma?



“Horns” only  
appeared in the  
emission with a  
pre-pulse

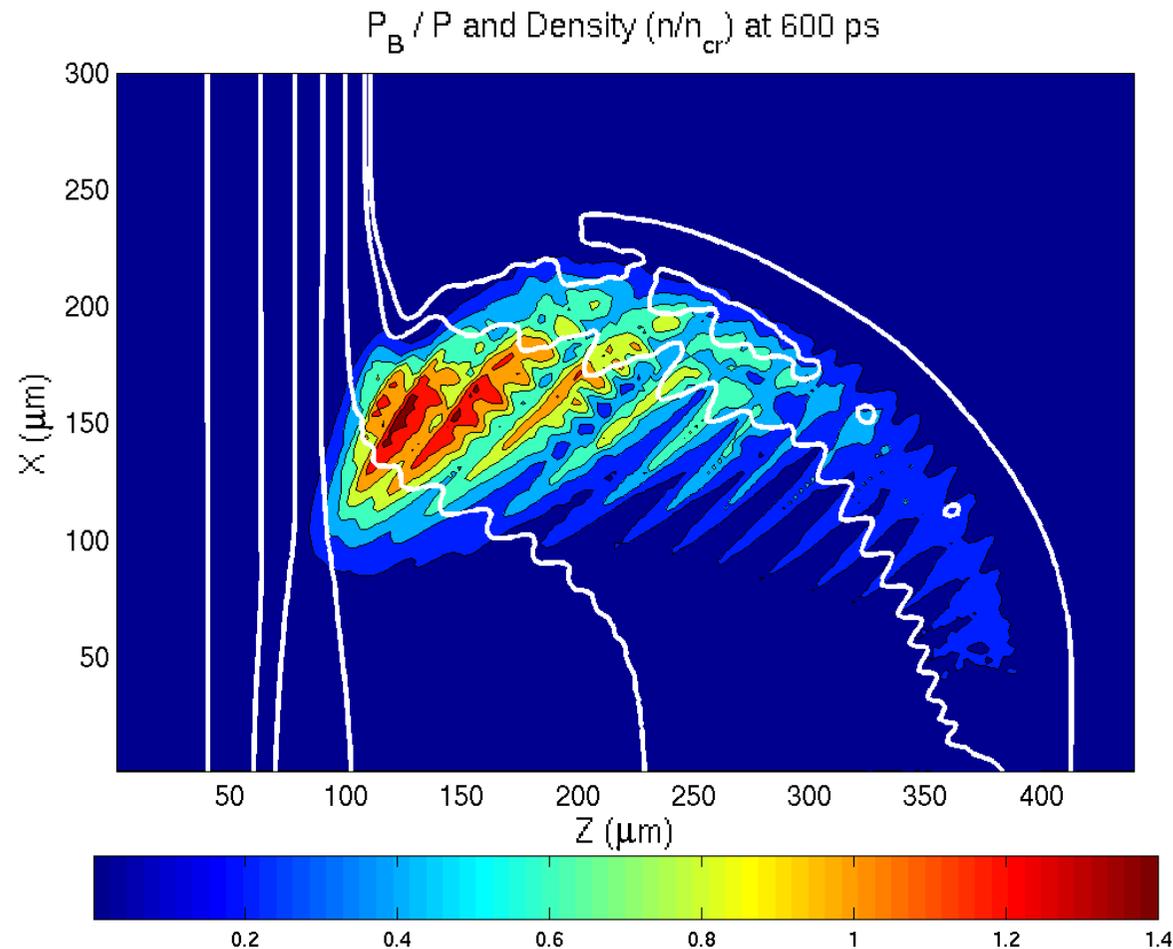
# The Theories

- The magneto-thermal instability 1974
  - ↪ Tidman and Shanny, Phys. Fluids **17** 1207
  - ↪ Hotspots generate a magnetic field that inhibits the heat flow
- The electro-thermal instability 1974
  - ↪ Haines, J. Plasma Phys. **12** 1
  - ↪ Hotspots lead to a lower resistivity ( $\eta$ ), which leads to a higher current ( $j$ ), which leads to greater heating ( $\eta j^2$ )
- The radiation cooling instability 1981
  - ↪ Evans, J Phys. D **14** L173
  - ↪ An increase in density leads to an increase in radiation that lowers the pressure leading to an increase in density
- The Weibel instability 1985
  - ↪ Epperlein, Plasma Phys. Control. Fusion **27** 1027
  - ↪ Strong heat flow between the critical and ablation surfaces

## What is New?

- The experiment probed to well above the critical density; others were limited to underdense plasma
- The fine scale structure is only present in the underdense plasma (and not in the emission)
  - ↪ Rules out the magneto-thermal, the electro-thermal and Weibel instabilities (should also produce hot filaments)
- The fine scale structure is visible before the end of the laser pulse
  - ↪ Rules out the radiation cooling instability because of the increase in inverse bremsstrahlung heating with density
- The MH2D results reproduce these features
- Why?

# Caused by Magnetic Field



- No such effect without the magnetic field

# Why is it Limited to Underdense Plasma?

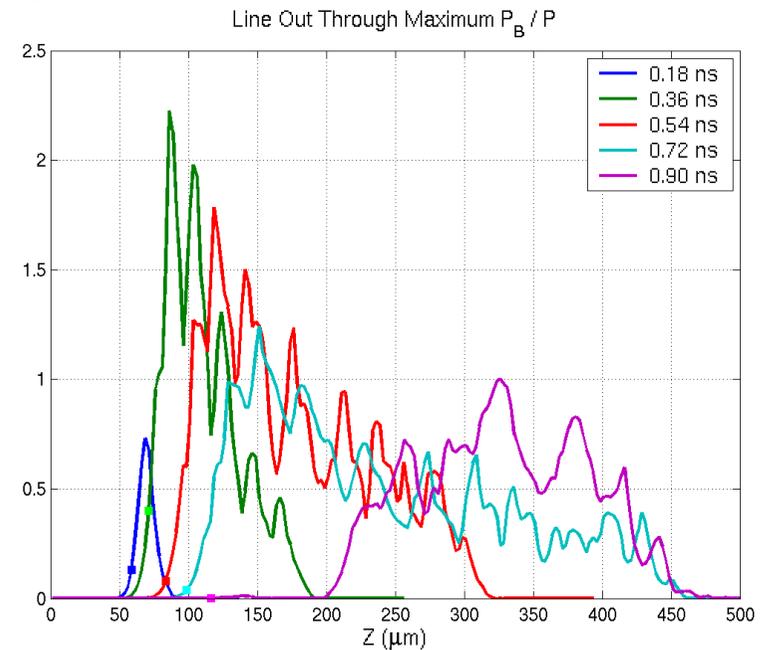
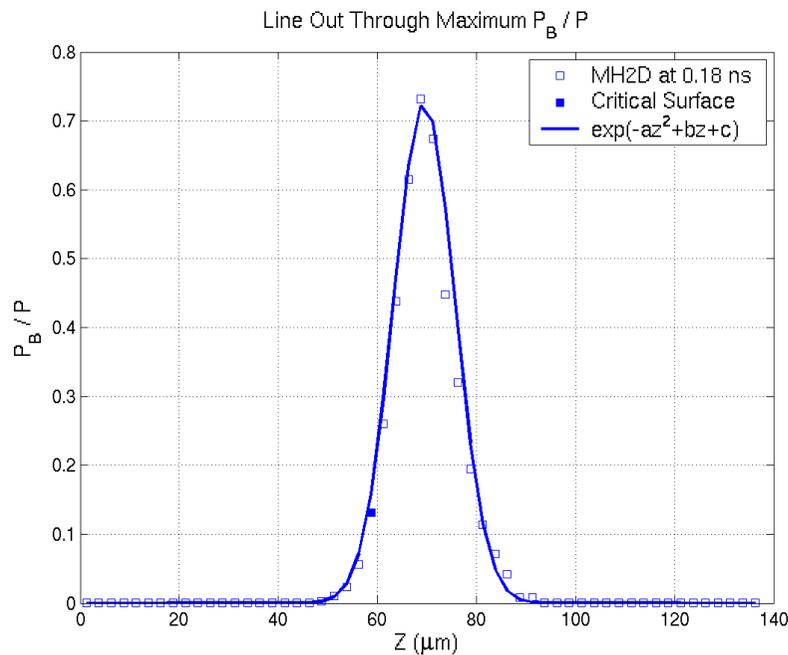
- Magnetic field saturates<sup>1</sup> with  $P_B < P/2$ , but it diffuses into lower density, lower pressure plasma

- ↪ Diffusion from a point leads to a Gaussian  $\exp(-z^2/L_D^2)$

- ↪ Pressure tends to fall exponentially  $\exp(-z/L_p)$

- ↪ Therefore  $P_B/P \propto \exp(-2z^2/L_D^2 + z/L_p)$

<sup>1</sup>Haines PRL 78  
254 (1997)





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# What is the Mechanism?



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# A Theory

## Starting Point

- The essential equations from MH2D are

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \rho \mathbf{v} \mathbf{v} = -\nabla \left( \frac{Z \rho k_B T}{A m_p} + \frac{B^2}{2 \mu_0} \right)$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot \mathbf{B} \mathbf{v} = \frac{\nabla k_B T \times \nabla \rho}{\rho e} - \nabla \times \frac{\eta}{\mu_0} \nabla \times \mathbf{B}$$

- ↪ There were no significant temperature fluctuations so the magnetic field must come from density fluctuations perpendicular to a temperature gradient
- ↪ The square of the magnetic field appears in the equation of motion so for it to appear in a linear theory there must be an initial magnetic field

# The Simplest Possible Model

- Initial 1D system ( $x$ ) with a constant temperature gradient ( $T'$ ) and a constant magnetic field perpendicular to it ( $y$ ) that satisfies the fluid equations

$$\Rightarrow \rho(x,t), v_x(x,t), T', B_y, \eta(x,t)$$

- Apply a small, fractional perturbation in the density perpendicular to the temperature gradient and the magnetic field ( $z$ ) that leads to a perpendicular velocity and a perturbation in the magnetic field

$$\Rightarrow \rho(x,t)[1 + \rho_1 \exp(i\omega t - ikz)]$$

$$v_{z1} \exp(i\omega t - ikz)$$

$$B_y(x,t) + B_{y1} \exp(i\omega t - ikz)$$

- Linearize and eliminate the perturbed variables

# The Dispersion Relation

$$\omega^3 - i \frac{\eta}{\mu_0} k^2 \omega^2 - c_s^2 k^2 \omega + i \frac{\eta}{\mu_0} c_s^2 k^4 + \Omega^3 = 0$$

↪ Where the characteristic frequency is

$$\Omega = \left( \frac{B k_B T'}{\mu_0 e \rho} \right)^{1/3} k$$

↪ The instability will occur once a magnetic field has grown and preferentially at low densities and fine scales (large  $k$ )

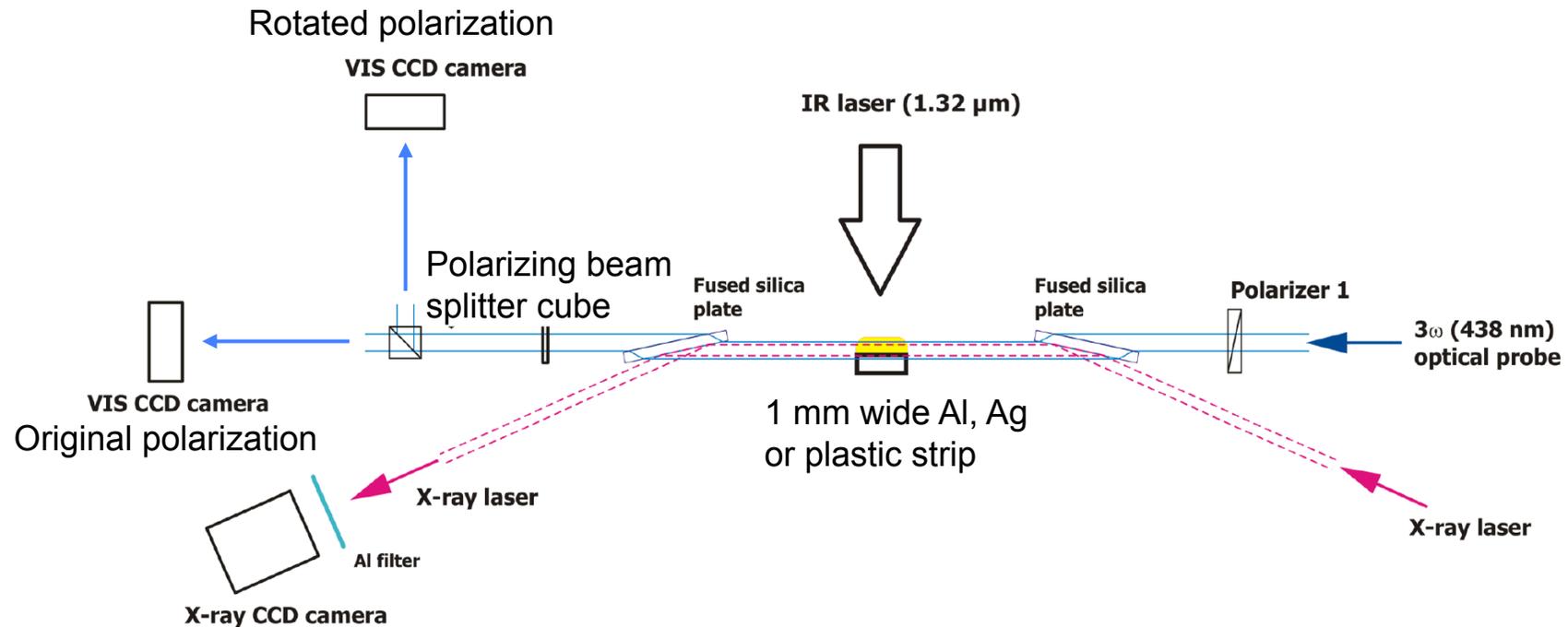
↪ *Always unstable* for a non-zero resistivity

# A Note on the Wavenumber Dependence

- The growth rate always increases with wavenumber
- Unphysical because there can be no modes with wave numbers  $k > 1/\lambda_D$ 
  - ↪ A well-known failure of the quasi-neutral approximation
  - ↪ In MH2D the wavenumber is limited by the grid spacing which has probably led to it being dismissed as a numerical instability in the past
  - ↪ In Lagrangian codes it will be suppressed by the stretching of the grid at low densities
- Neither MH2D nor the theory can predict the width of the filaments that should be observed in experiments
- Can we unambiguously attribute the experimental results to this mechanism?

## Another Experiment

- Measure the magnetic field using Faraday rotation of a 3<sup>rd</sup> harmonic probe combined with the XUV probe



- PALS Set/Oct 2009 financed by LaserLab

## Results

- Could not measure the magnetic field because the silica plate limited the collection angle so refraction limited the optical probe to too low a density
- Got good shadowgrams and XUV images of horns
- Found that the horns appear earlier and are more pronounced with higher  $Z$  targets
  - ↪ Is it the radiation cooling instability?
- Removed the silica plates and put a larger, shorter focal length lens in the chamber on the last day...

## Some Pictures

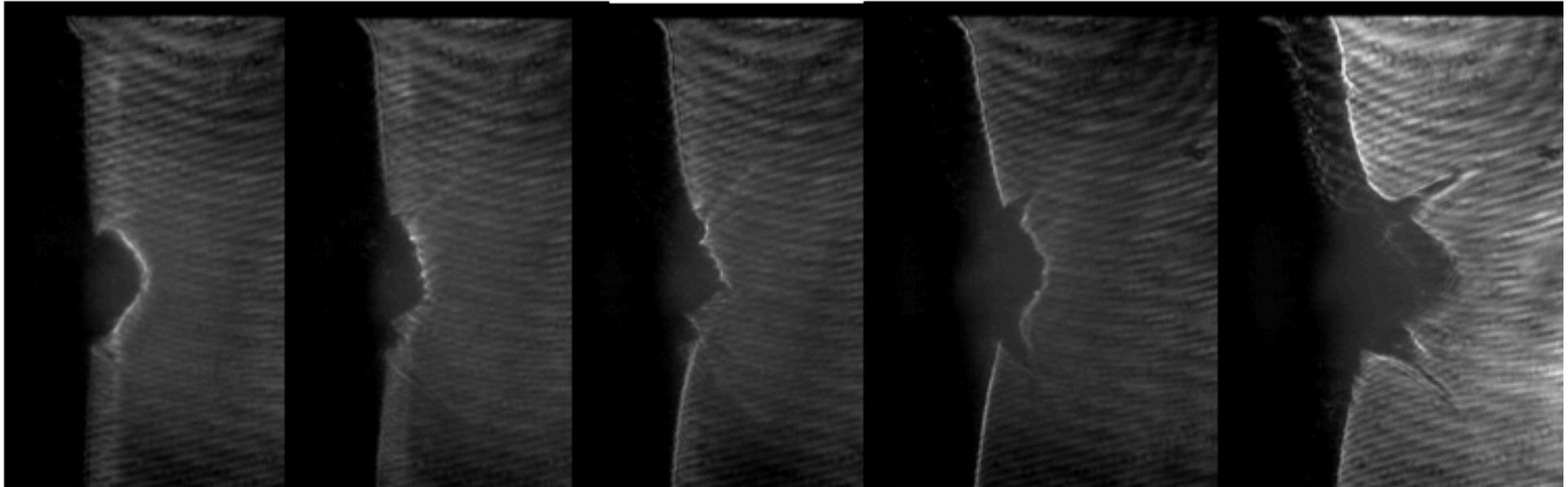
0.3 ns

0.9 ns

1.5 ns

3.0 ns

6.0 ns



# Some Pictures

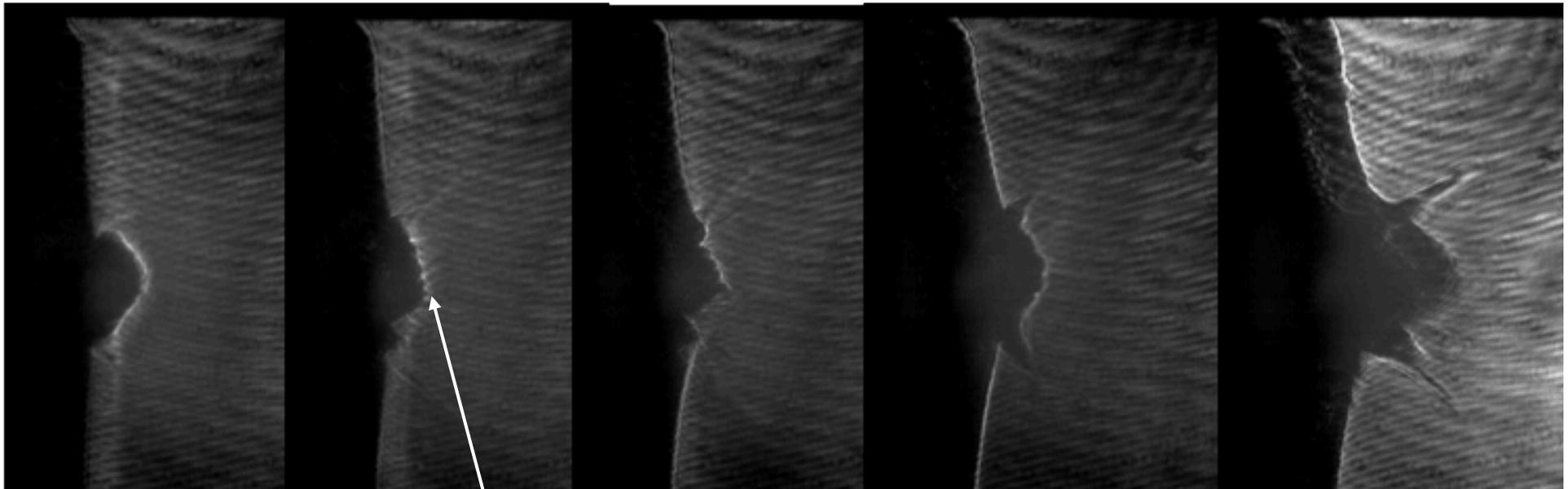
0.3 ns

0.9 ns

1.5 ns

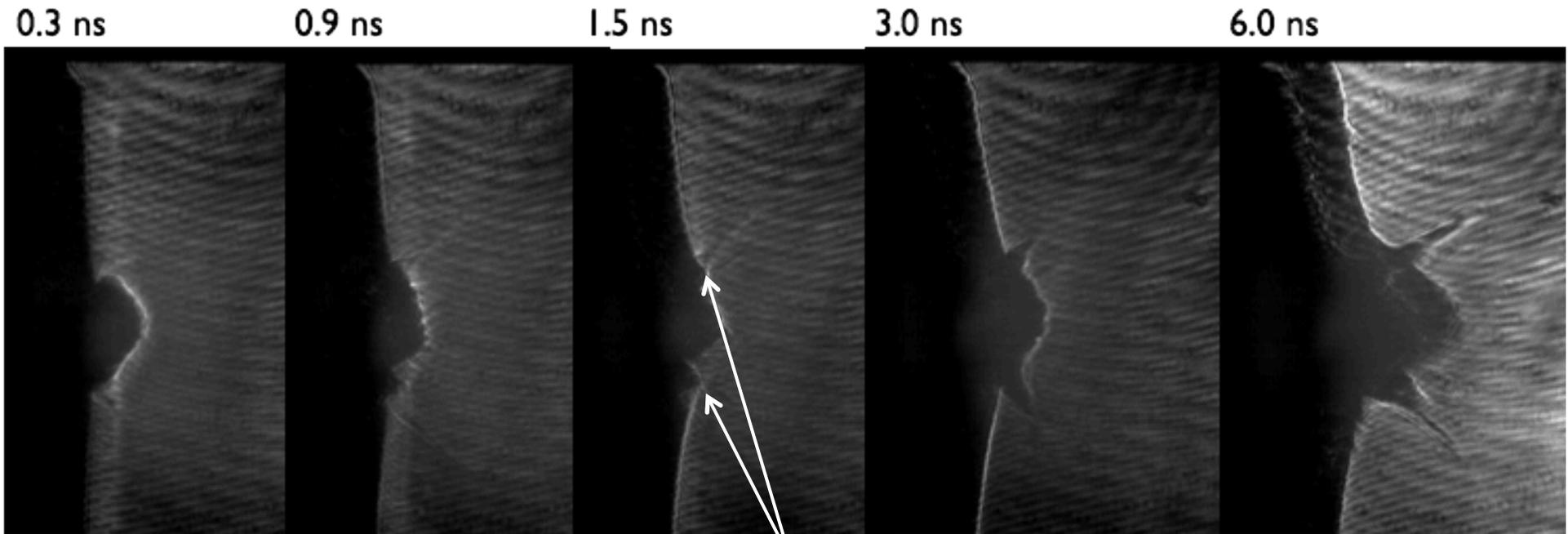
3.0 ns

6.0 ns



Small scale structure

## Some Pictures



Horns emerging

# Some Pictures

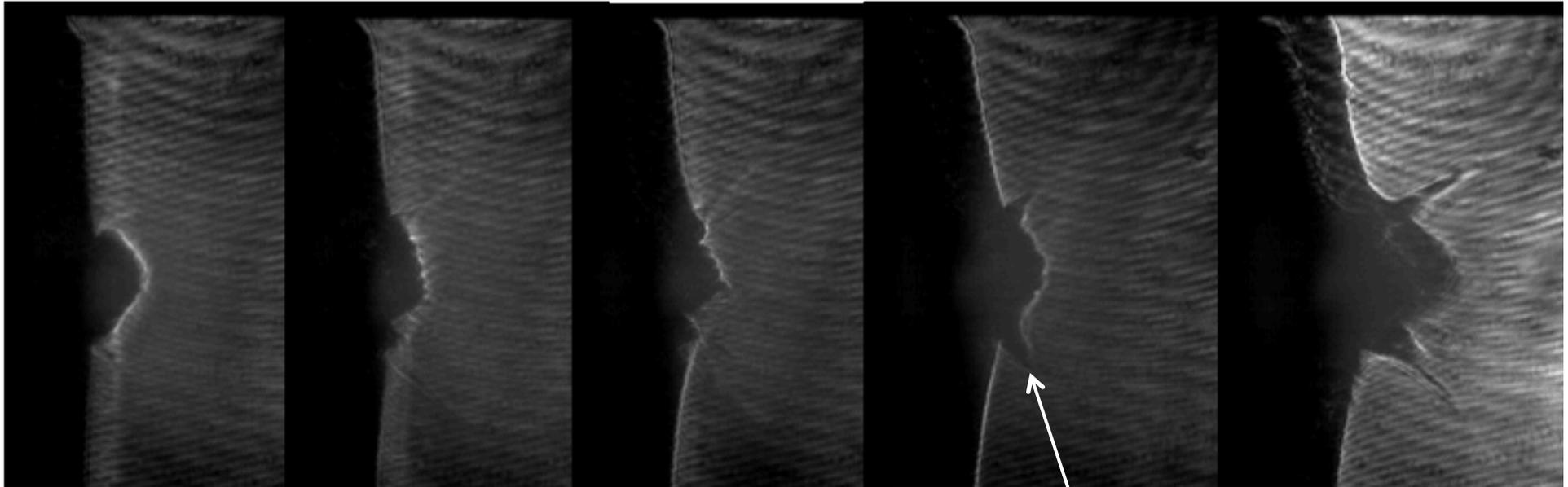
0.3 ns

0.9 ns

1.5 ns

3.0 ns

6.0 ns



Horns

# Some Pictures

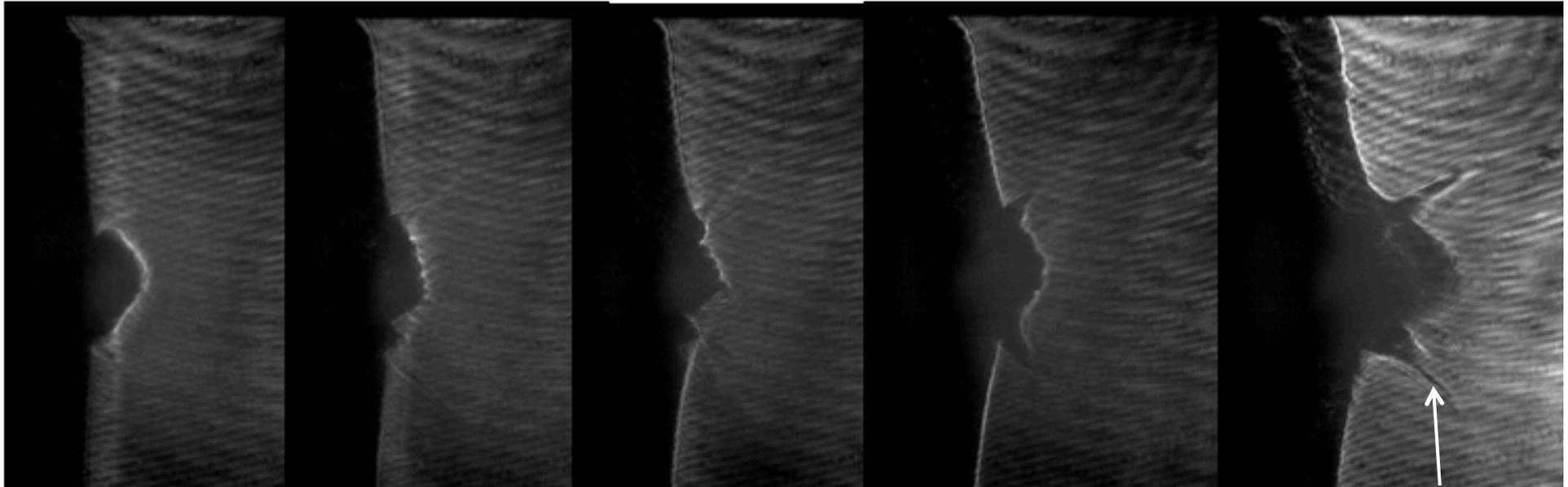
0.3 ns

0.9 ns

1.5 ns

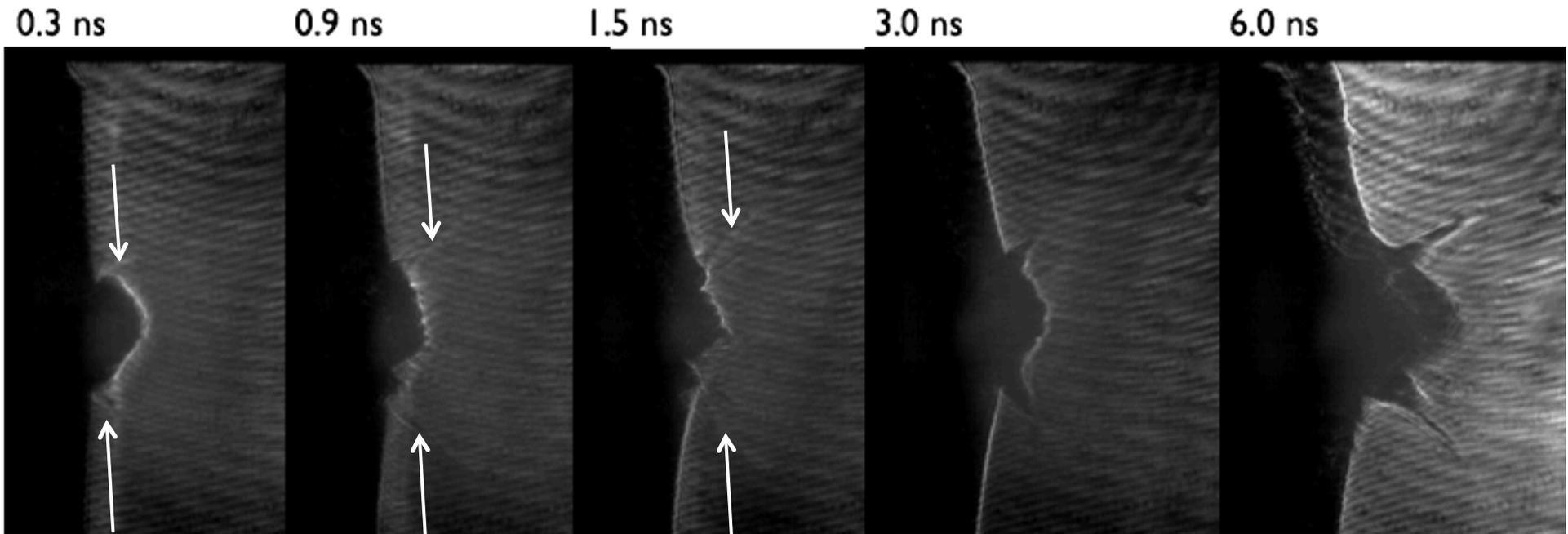
3.0 ns

6.0 ns



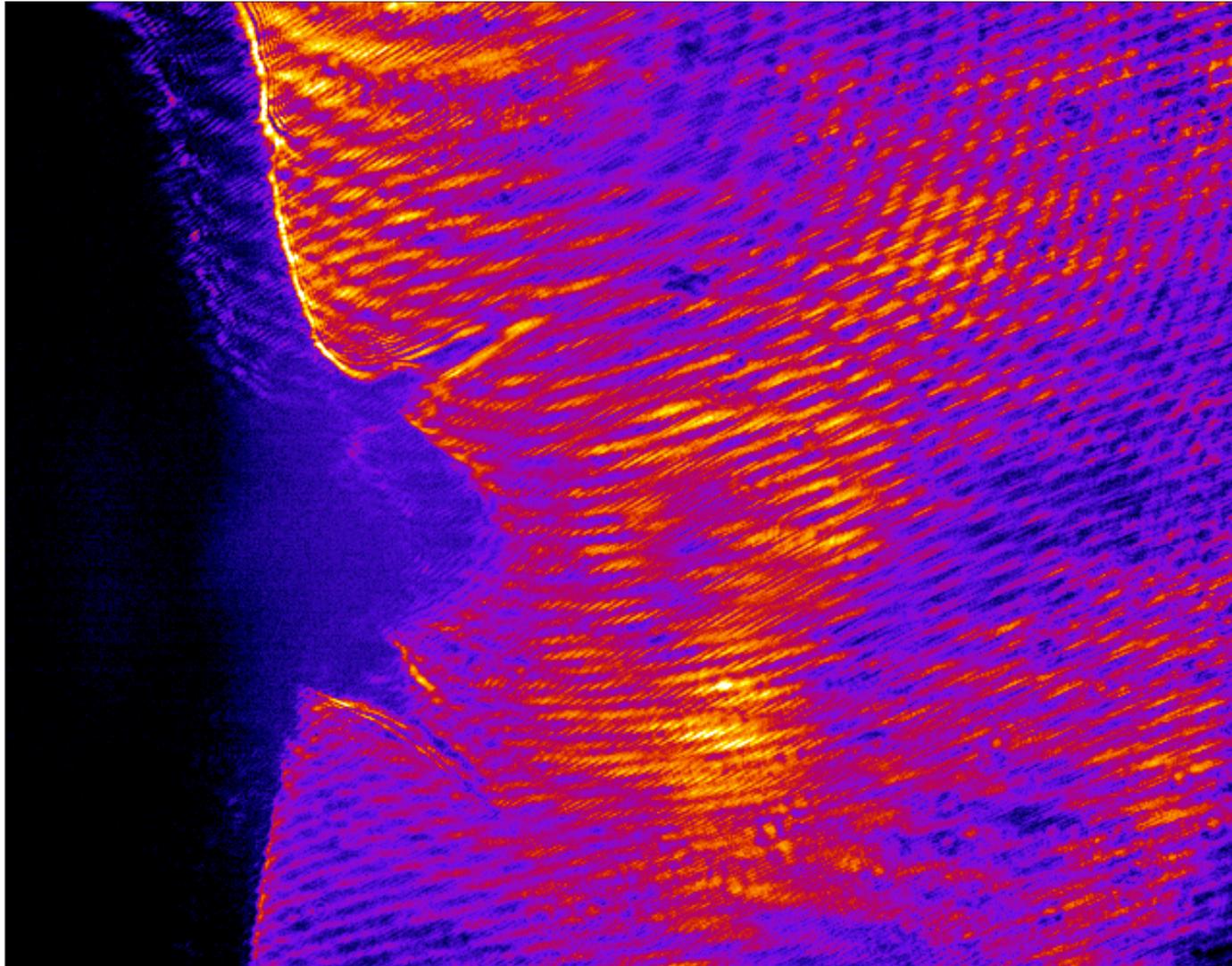
Well horny!

## Some Pictures

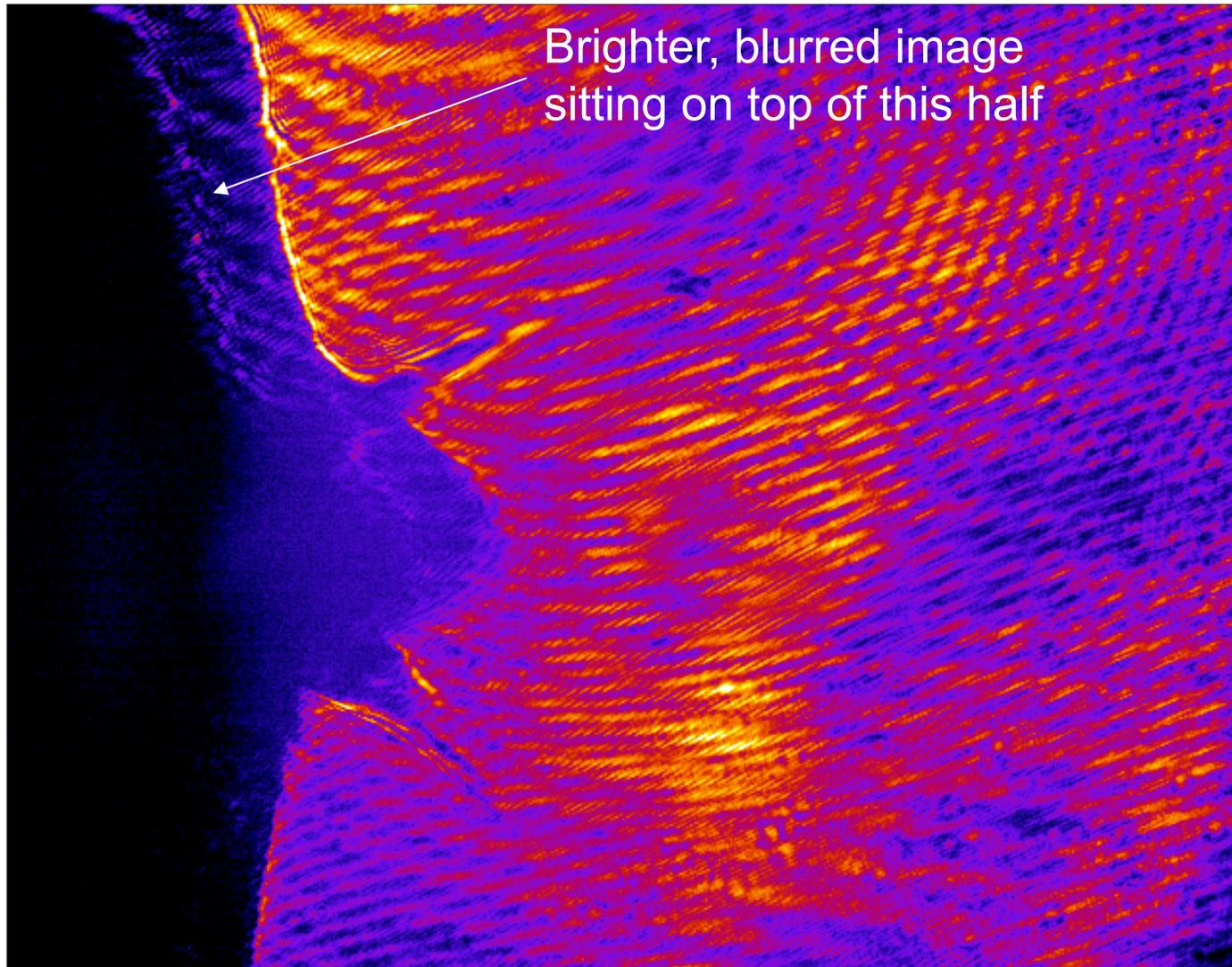


Thin curved line similar to the 2006 experiment

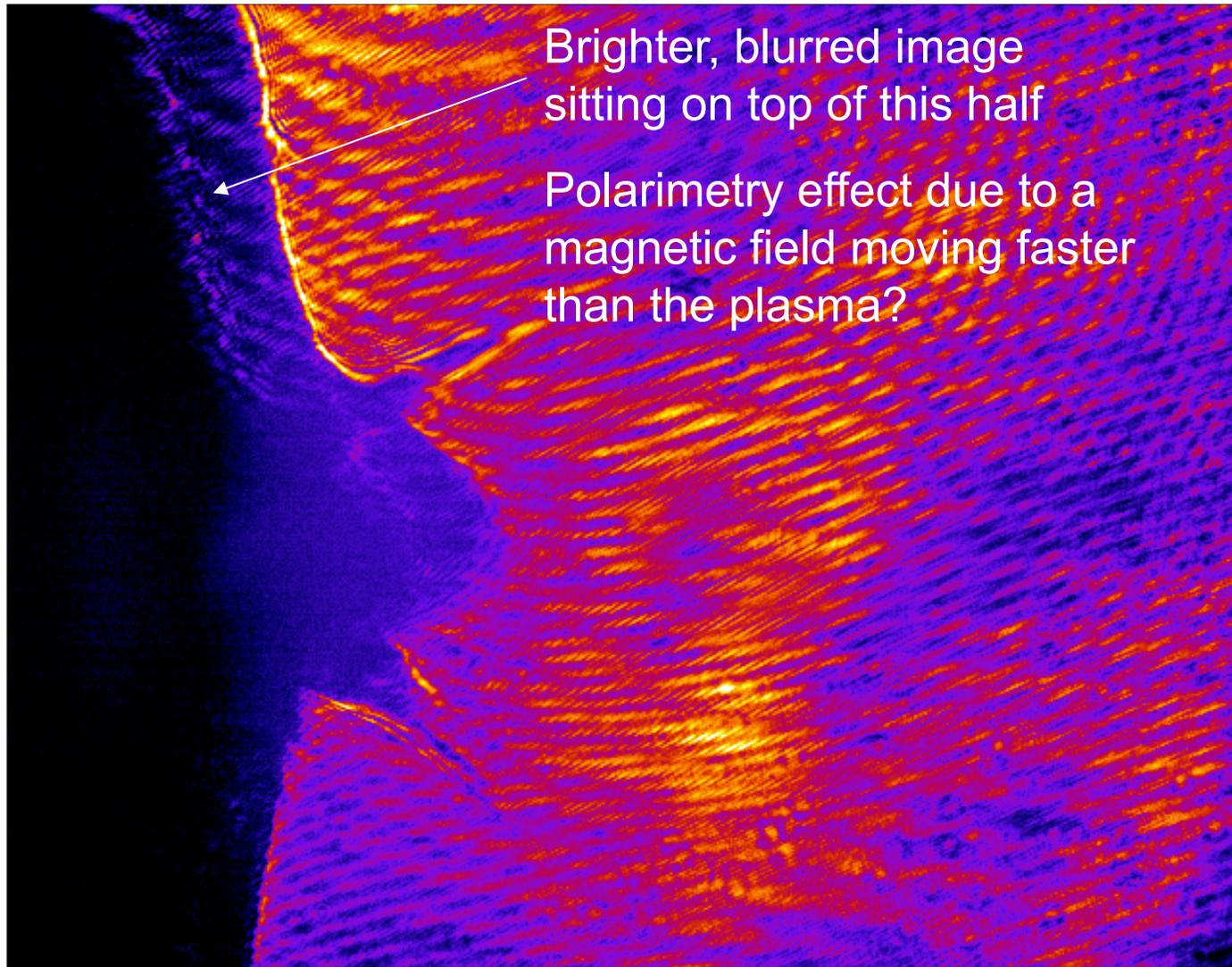
# Some Pictures



## Some Pictures



## Some Pictures



## Post Script

- The first experiment, the model and the theory have been published
- “Filamented plasmas in laser ablation of solids”
  - ↪ J. R. Davies, M. Fajardo, M. Kozlová, T. Mocek, J. Polan and B. Rus
  - ↪ Plasma Phys. Control. Fusion **51** 035013 (2009)
- Identified as a paper of particular interest by the referees
- Featured in “PPCF Highlights of 2009”

## Conclusions

- Magnetic field can explain fine scale structure that appears in the density but not the temperature in underdense plasma
  - ↪ May not be the explanation for all of the observations
  - ↪ To measure the magnetic field at PALS need a large collection angle and a gated imager
- The formation of large scale, horn-like structures is still unexplained
  - ↪ Due to physics not included in MH2D and most hydro codes
  - ↪ Interface effects, equation of state, radiation?
    - ↪ Working on the radiation cooling instability
- With better diagnostics we get better insights into the physics

