Pulsed Power High Energy Density Science research at Imperial College

Simon Bland

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Magical electronics tech: S. Parker

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&
part of AMPLIFI Prosperity Partnership with EPSRC / First Light Fusion

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With thanks to our many collaborations - and apologies to those I have missed!

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P^3 UCSD — S. Bott-Suzuki

Massachusetts Institute of Technology — J. Hare

UR LLE — R.B. Spielman

UNIVERSITÉ DE PAU ET DES PAYS DE L'ADOUR — A. Gusev

R. Curry, G.C. Frye-Mason, A. Sarracino, E. Yu

D. Hammer, B. Kusse, E.S. Lavine and A. Rososhek — CORNELL UNIVERSITY FOUNDED A.D. 1865

R. Mancini, T. White

B. Lukic and A. Rack — ESRF

L. S. Caballero Bendixsen, J. Read, C. Dobranszki, H. Doyle, E .Escauriza, J. Skidmore, L.S.Caballero-Bendixsen, F. Suzuki-Vidal — first light

D. Sterbentz, W. Schill, J. Belof

Capabilities include

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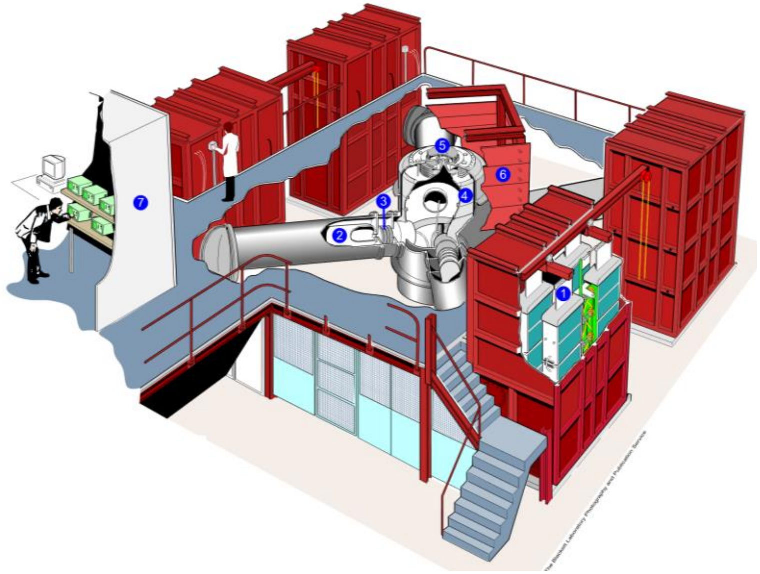

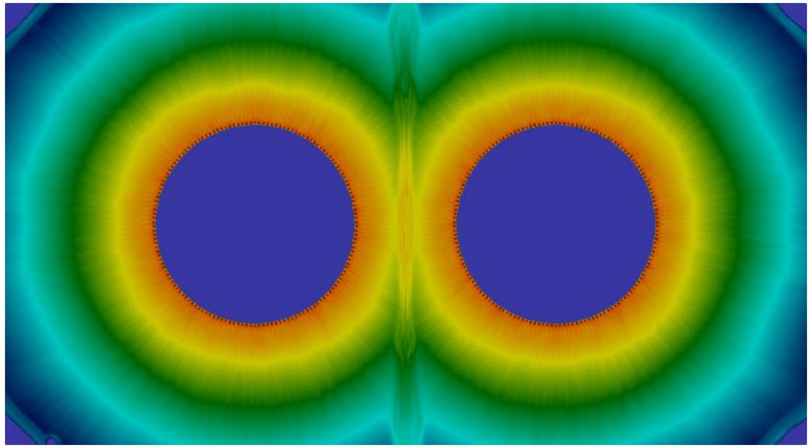

MAGPIE 1.4MA, 2.4MV, 240ns

Typically used to drive plasma loads

High impedance enables excellent diagnostic access – ‘open load’

Laser probing, Thomson scattering, high speed imaging, XUV and hard X-ray imaging, Spectrometry (optical to X-ray), X-ray power and yield

MACH 0.5 to 1.5MA, 80kV, 400ns

Dry system – no oil, water or SF_6

ICE, Flyers, Exploding wires and Convergent/shaped shockwaves

Diagnostics include laser shadowgraph, interferometry, multipoint velocimetry, line VISAR

Gorgon RMHD

3D Cartesian, Cylindrical & Spherical geometry with mesh refinement

2 temperature, EoS, Multi-group Radiation, Magnetised Heat Flow, Strength, Burn, extended MHD

New Platforms; Precise Measurements; Cutting Edge Simulations

Highlights from the last 2 years….

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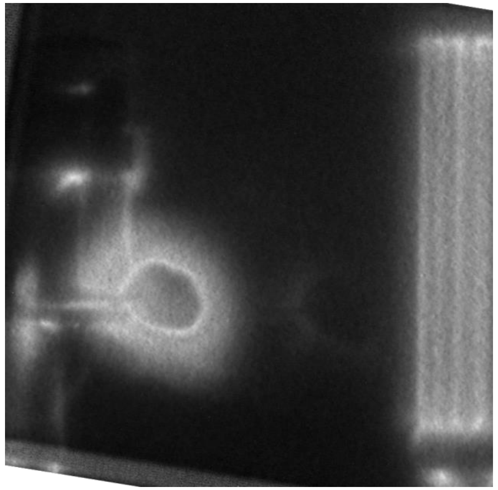
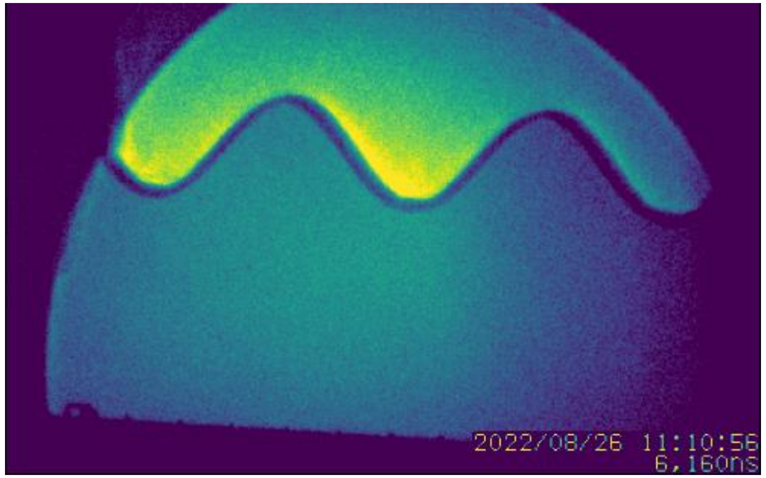
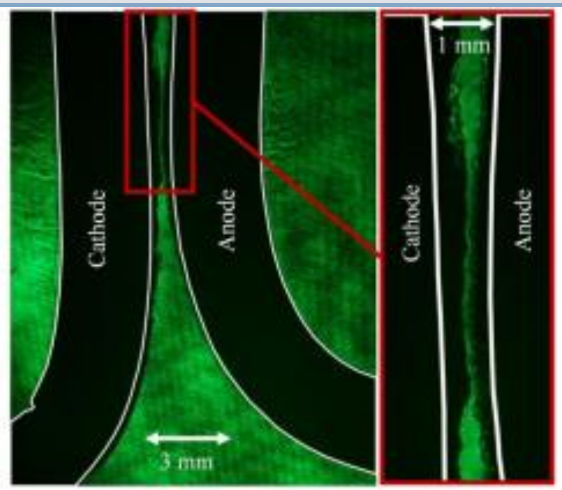


Magnetised plasma flows and (collisionless) shocks

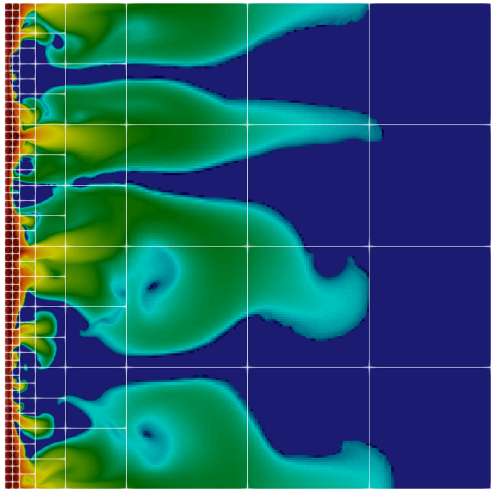


Hydrodynamic instabilities and methods to mitigate them

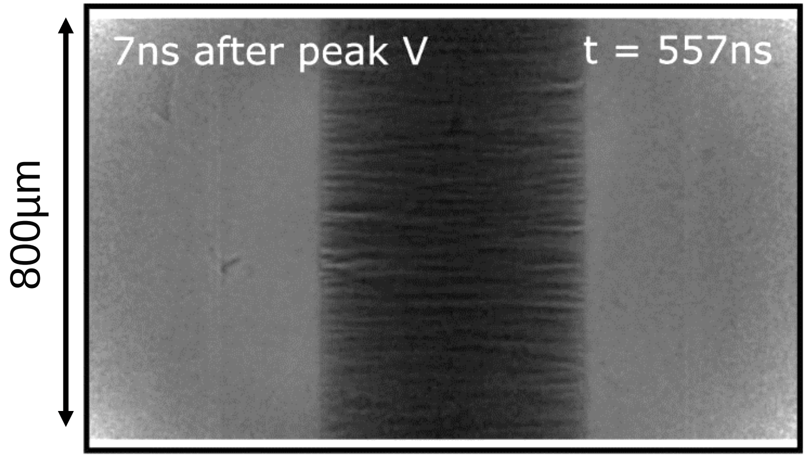
Turbulence - and effect on laser propagation



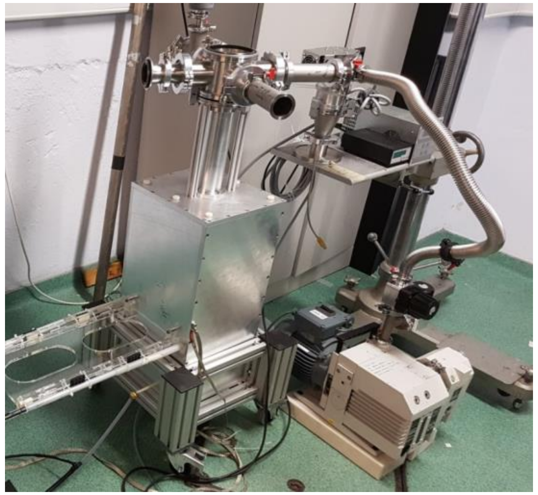
Power flow and damage to electrodes



Quantitative RMHD simulations



New diagnostics for HEDP experiments



New pulsed power technology

1. Radiatively driven ablation and shocks

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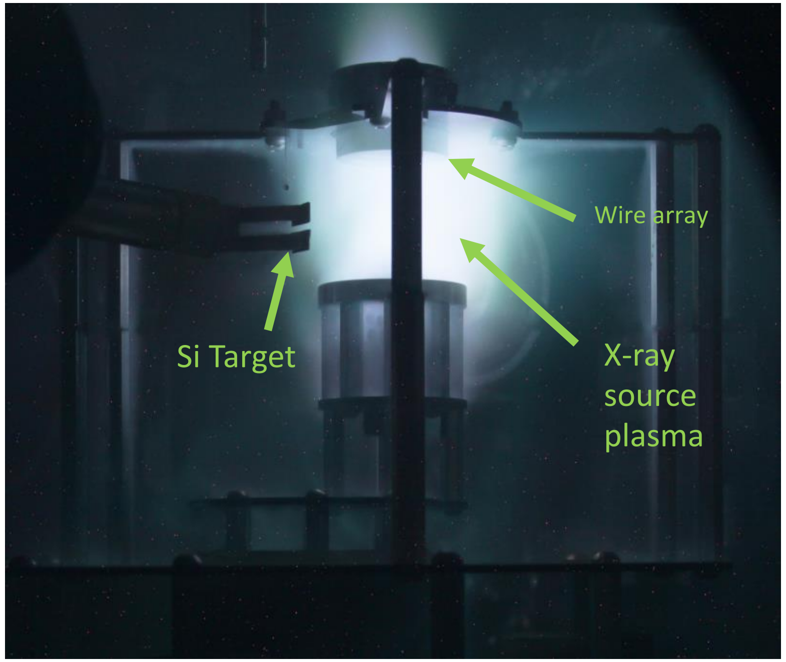
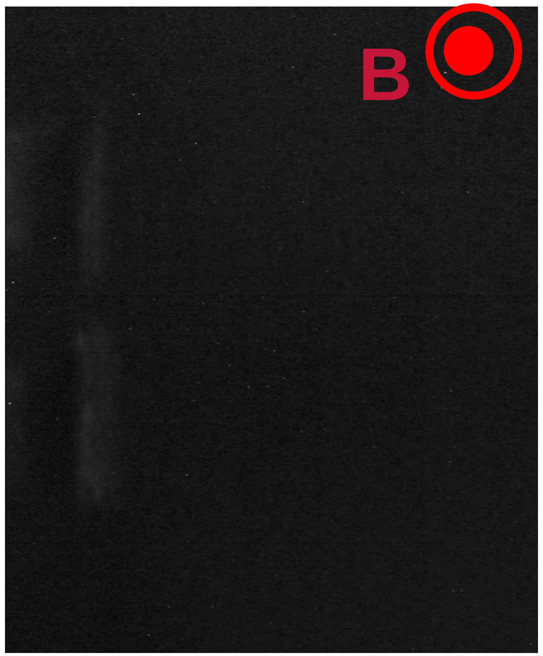
Soft X-ray radiation pulse from imploding array used to ablate targets and drive (magneto) hydrodynamic experiments.

Main pulse ~ 400J/cm^2 over 25ns, up to ~10GW/cm^2

Parameters of x-ray driven flow [1]	
Velocity, u	≈ 50 km/s
Electron density, n_e	~1e18 cm^{-3}
Average ionization, $\bar{Z}$	5
Mass density, ρ	≈ 9×10^{-3} kg m^{-3}
Mach number	~2
Temperature	≈ 15 eV





Targets can be arranged to align with ambient field from pinch or at an angle to it; or field can be separated from targets (targets outside current return)

1. Radiatively driven ablation and shocks

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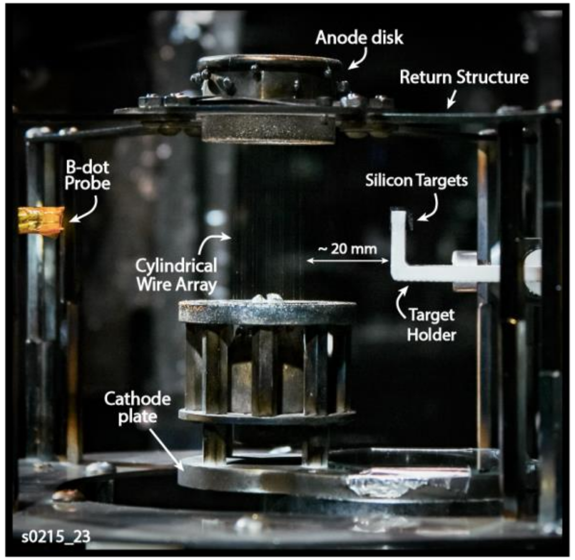

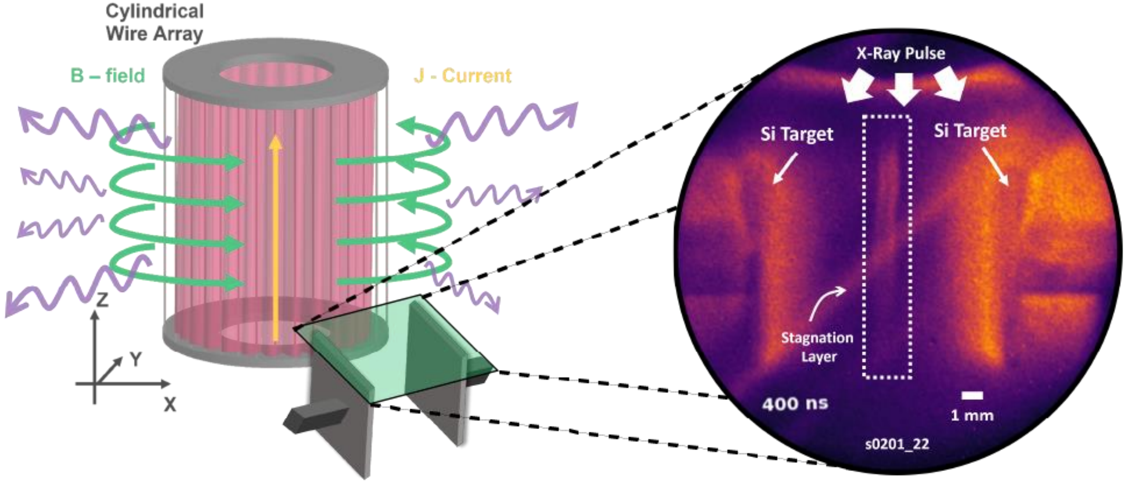

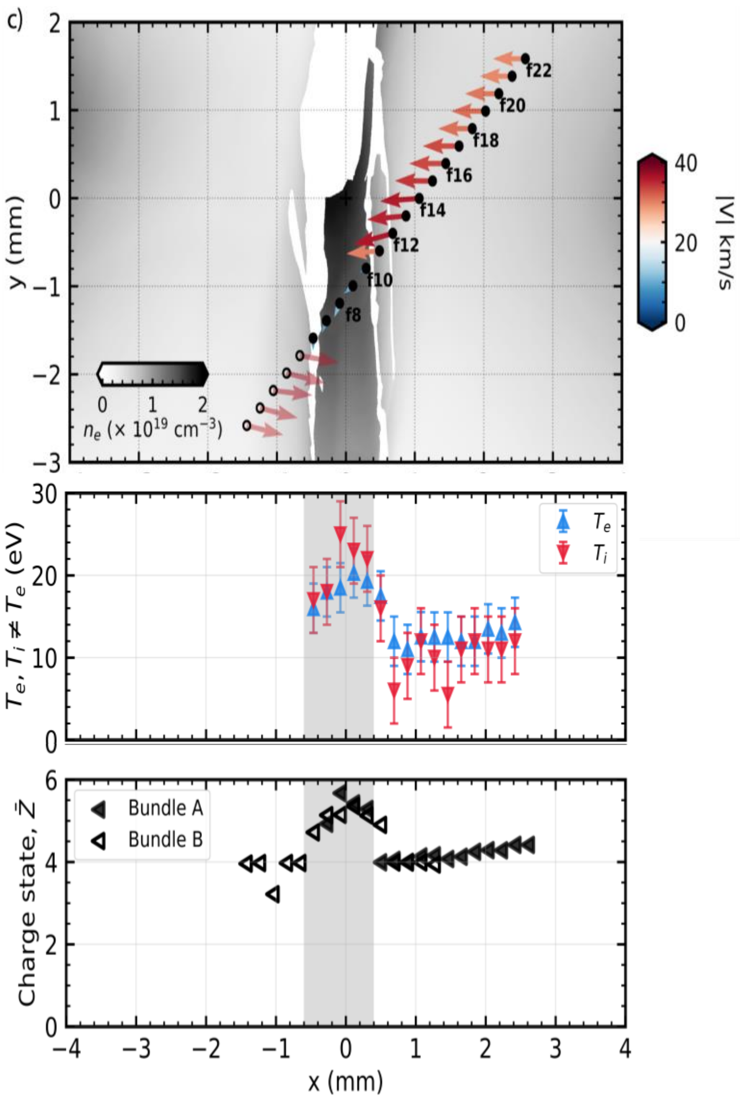

Can explore boundary-free accretion shocks from the collision of counter-streaming plasma flows (with and without ambient B-field)

Above / right has field parallel to flows

Comparisons with 1-D reverse shock model show agreement only for γ ≤ 1.2, suggesting the importance of ionization and radiative cooling effects

Quantity	Symbol	Measured	$\gamma = 5/3$	$\gamma = 1.2$	$\gamma = 1.1$
Density ratio	$R = \rho_2/\rho_1$	4 ± 0.5	2.8	4.3	4.7
Electron density ratio	$R_{n_e} = RZ_2/Z_1$	5 ± 0.5	3.5	5.4	5.9
Velocity ratio	u_1/u_2	0.2 ± 0.04	0.4	0.23	0.2
Pressure ratio	P_2/P_1	5 ± 1.5	7.5	6	6
Shock velocity (km/s)	v_s	-7	-20.5	-11	-10
Postshock temperature (eV)	T_2	18 ± 3	25	20	20

1. Radiatively driven flows into dipole fields

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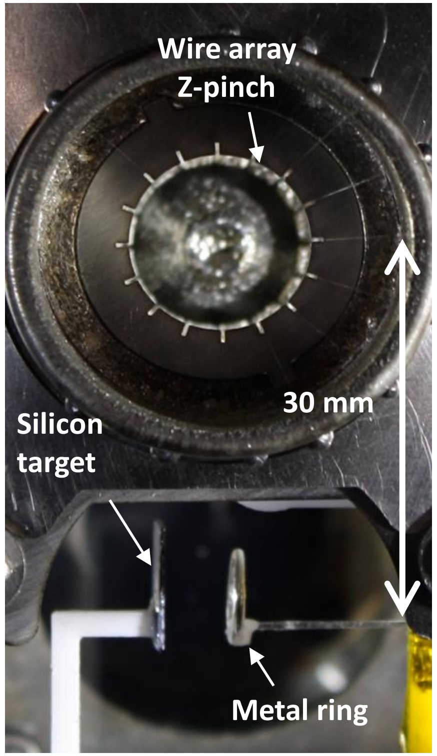
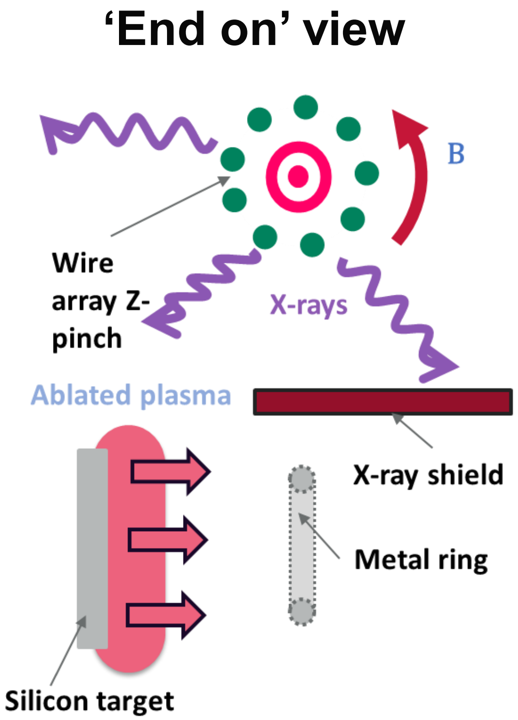
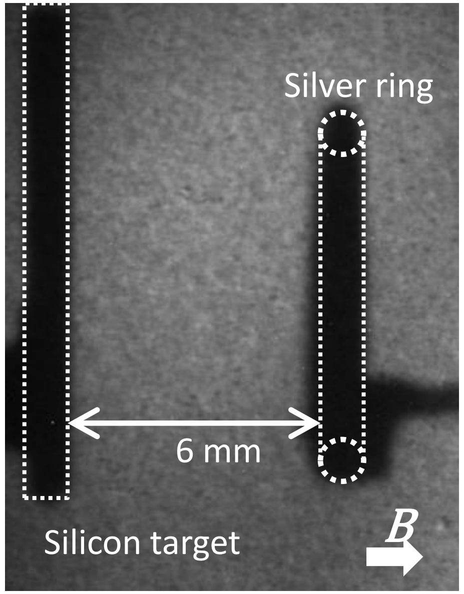
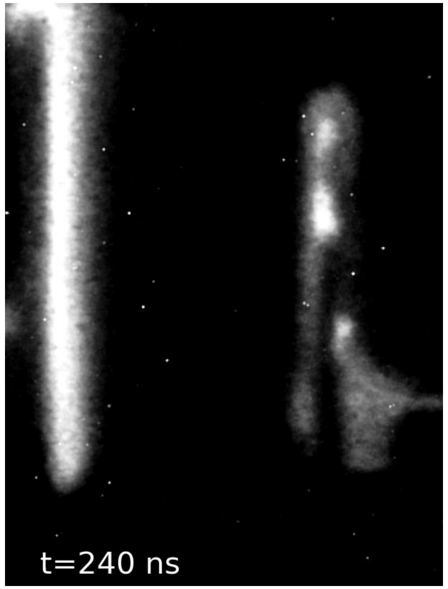
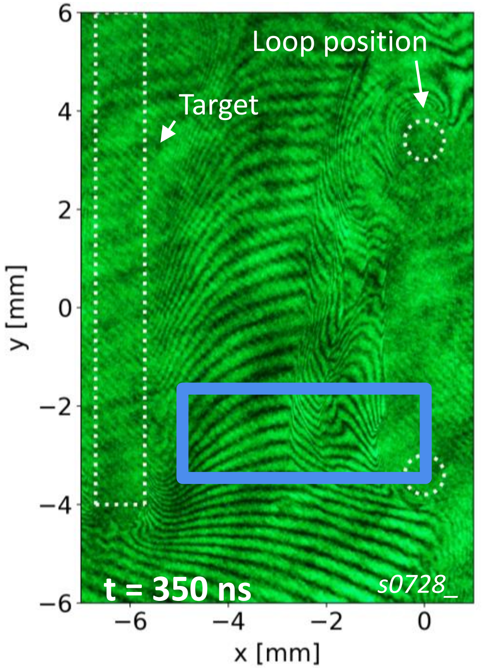
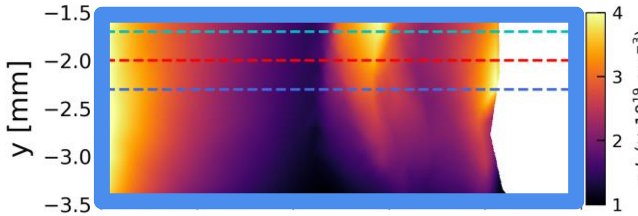


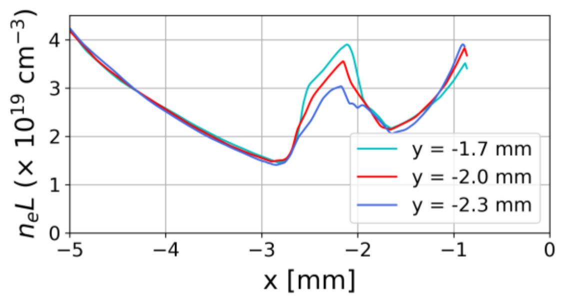










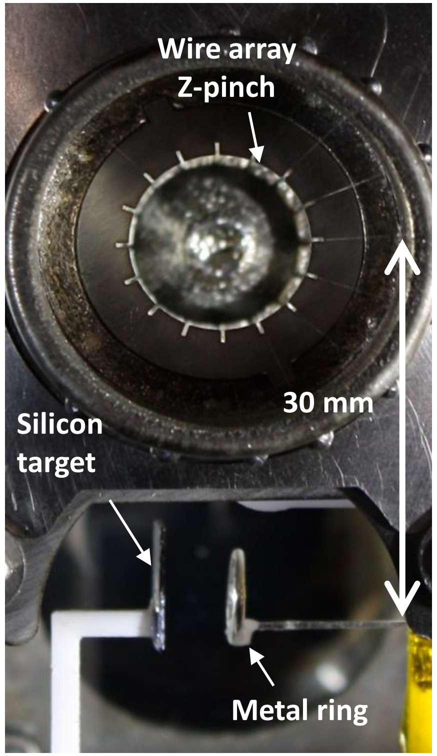


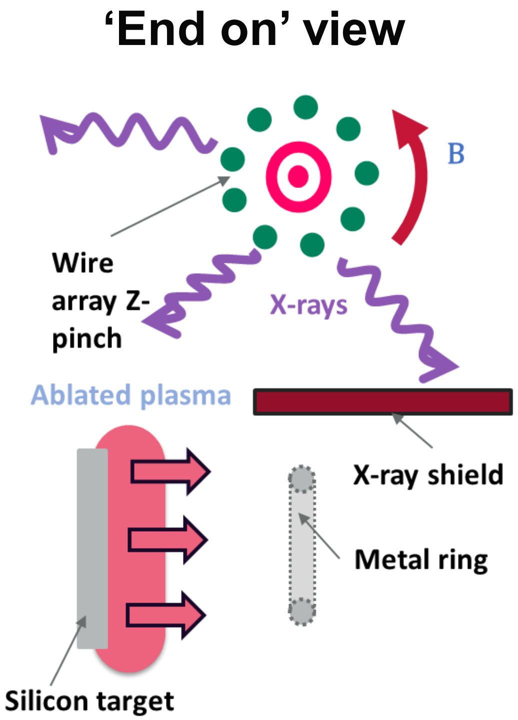
Results show formation of a stand-off shock when a plasma flow collides with a conducting ring => implies magnetic field is induced.

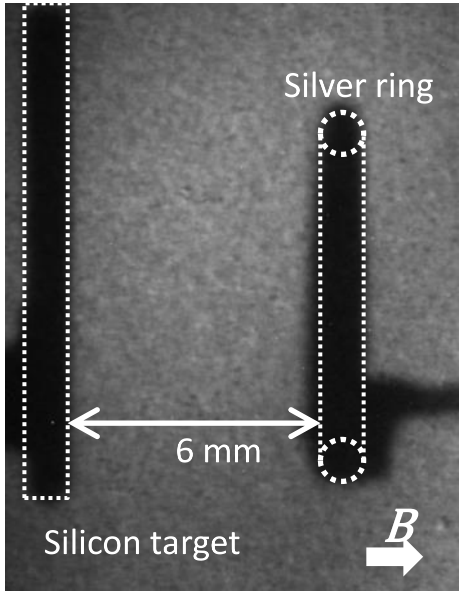
Assuming pressure balance at shock: $\rho u^2 = \frac{B_\perp^2}{2\mu_0}$ => magnetic field ≈ **4.9 T**

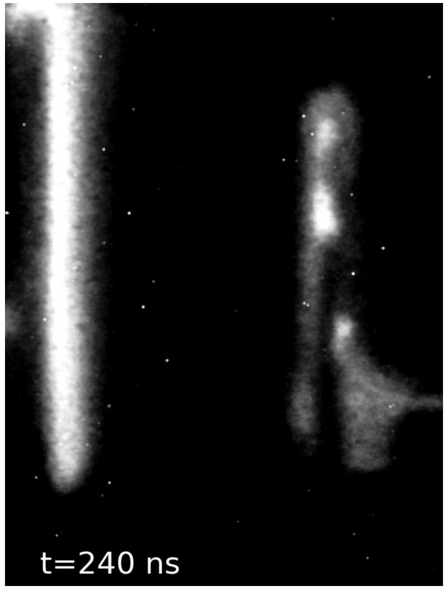
Experiments can be with / without ambient field

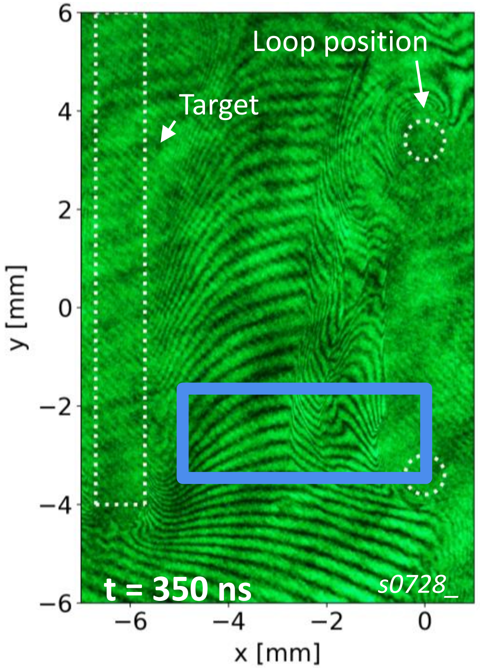
1. Radiatively driven flows into dipole fields











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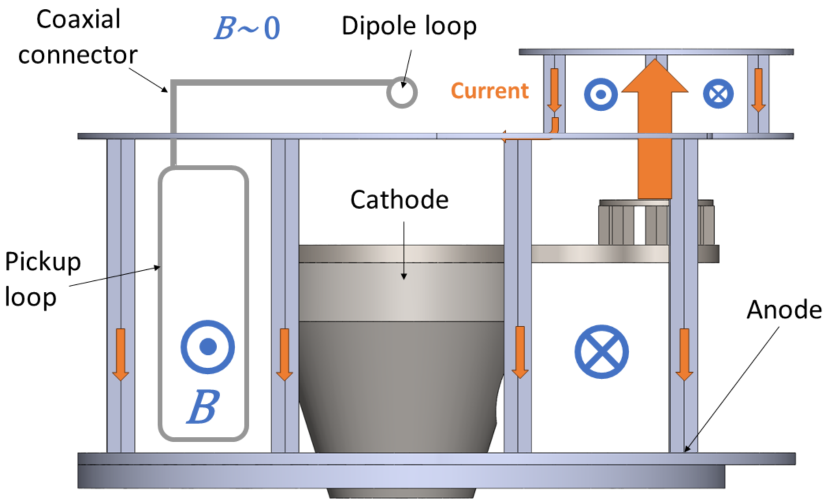
Experiments can be with / without ambient field

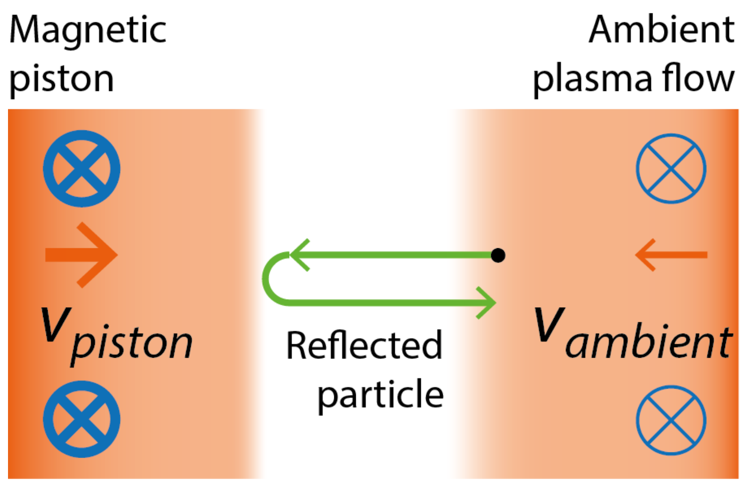
Instead of a closed ring, dipole field can be generated (and better controlled) using a pickup loop placed in the return structure.

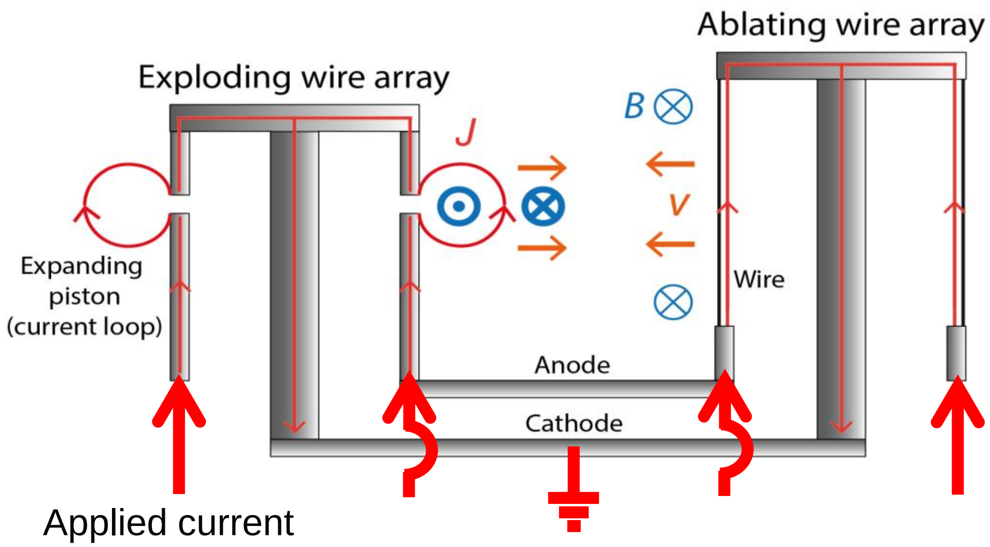


2. A pulsed-power collisionless shock platform

Colliding plasmas, we are starting to explore creating collisionless shocks

1. Piston sweeps up magnetized ambient plasma, facilitating reflection of upstream ions
2. Large velocity difference: reflected particles are "collisionless" w.r.t. upstream (mean free path ∝ V^4)





Exploding array
- thin, short wire array for rapid ejection of current loop / piston

Ablation array
- thick wires for ablation of counter-streaming ambient

2. A pulsed-power collisionless shock platform

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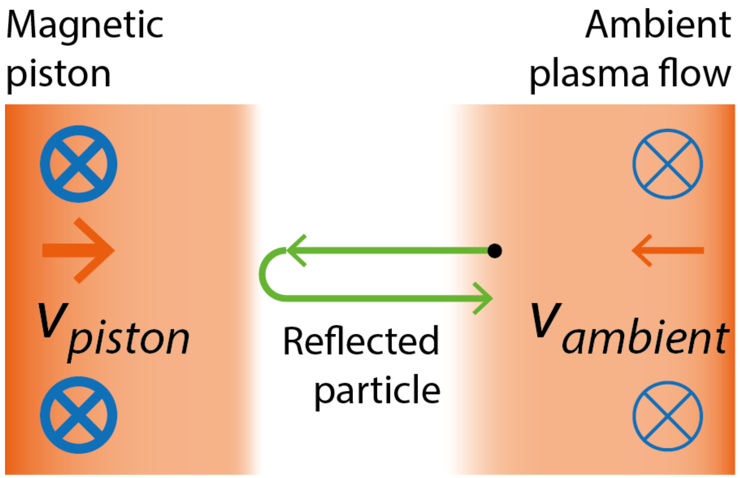
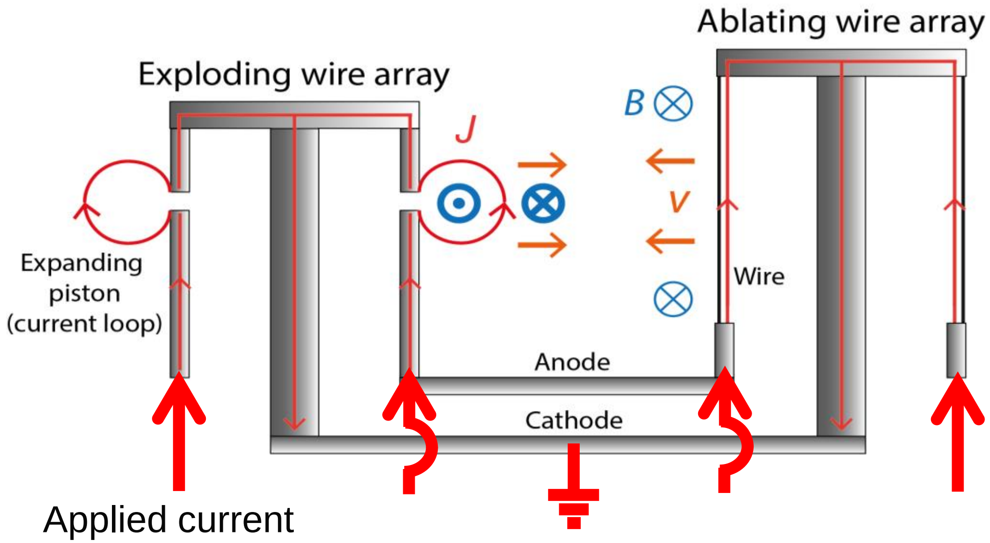


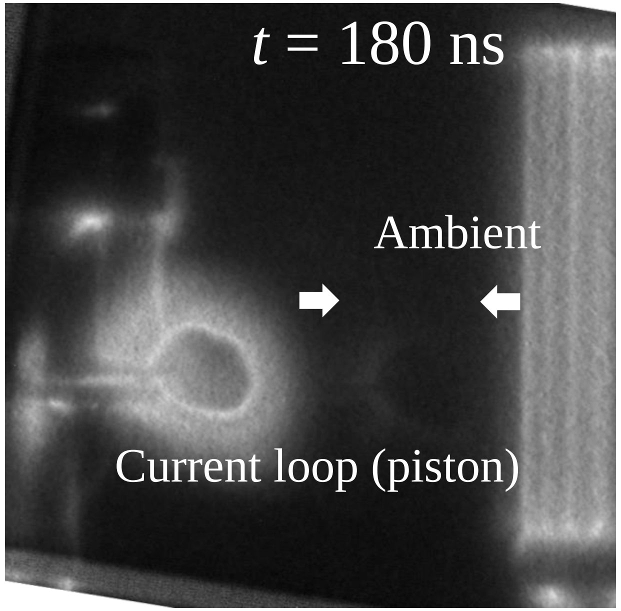


Exploding array
- thin, short wire array for rapid ejection of current loop / piston

Ablation array
- thick wires for ablation of counter-streaming ambient

Relative velocity piston to ambient ≤ 335 km/s → $\lambda_{ii,ref}/L_{system} = 100$

But no reflected ions yet seen via Thompson scattering –heavier piston



3. Synchrotron radiography of ETI

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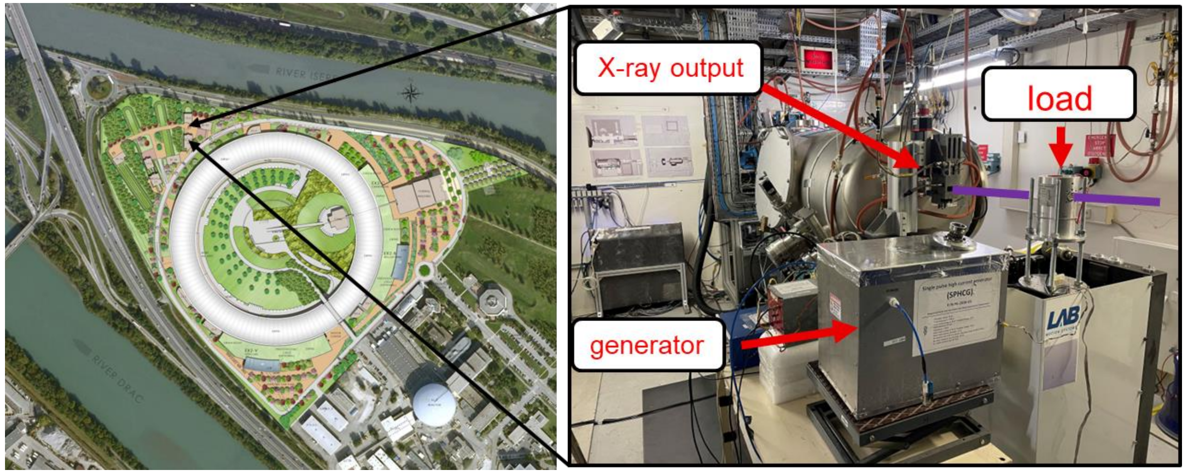

ESRF synchrotron now has 2 pulsed power systems

i) original ~30kA in ~1000ns

ii) new ~100kA in ~500ns

256 frames of radiography 20-50 keV, 176ns apart

Typically used for wire in water / insulator expts

New x10 mag imaging with 3µm resolutions

3. Synchrotron radiography of ETI

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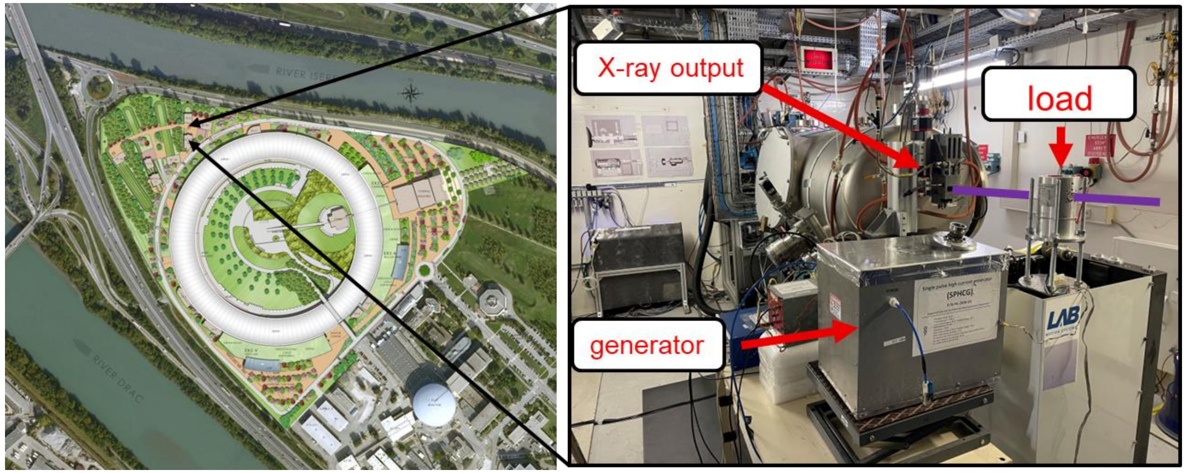

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256 frames of radiography 20-50 keV, 176ns apart

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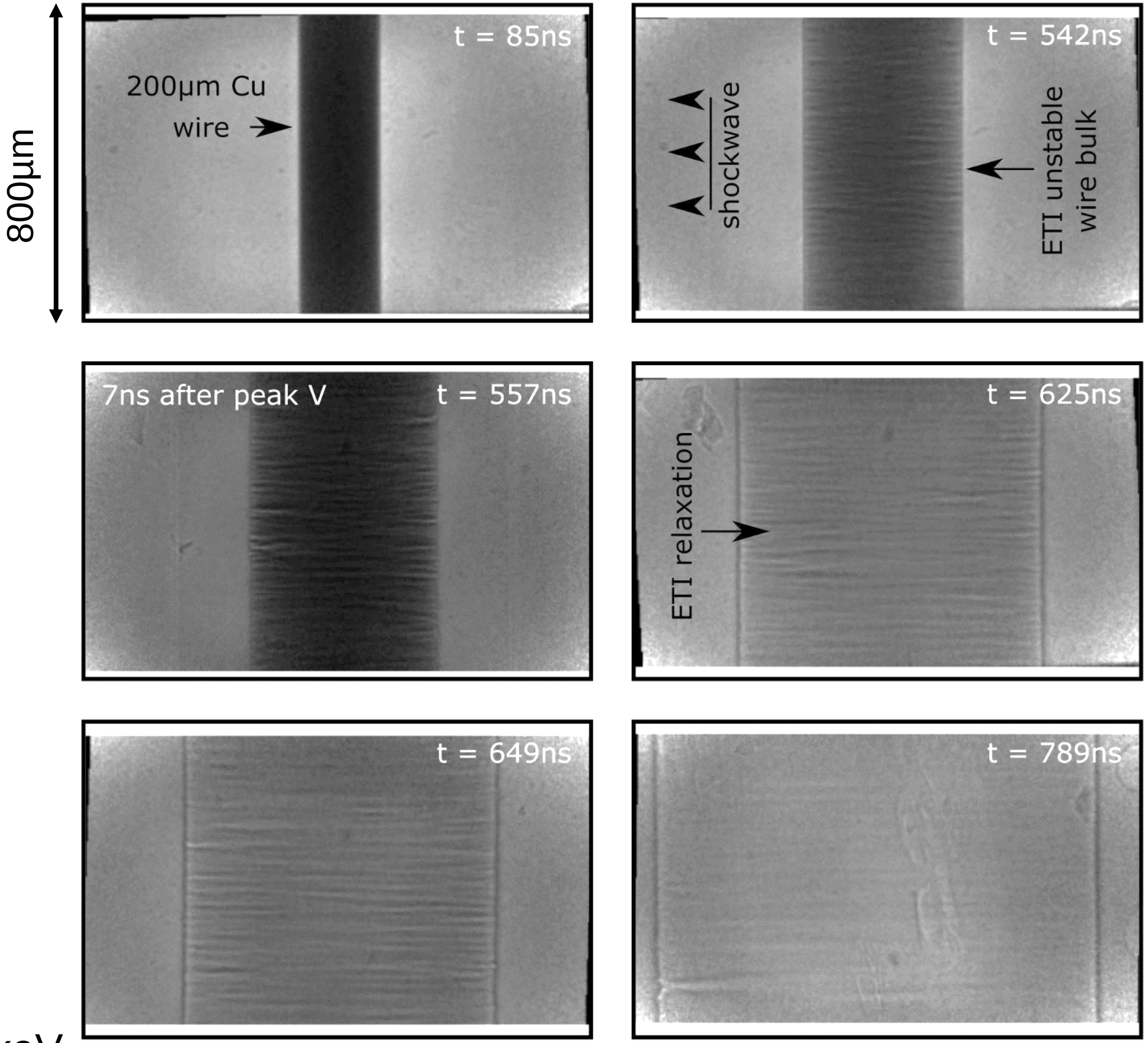
New x10 mag imaging with 3µm resolutions

Ideal for measurements of ETI instability, showing growth up to peak voltage / then relaxation after current pulse



1 of 3 wires in water 20-30keV

3. Synchrotron radiography of RMI

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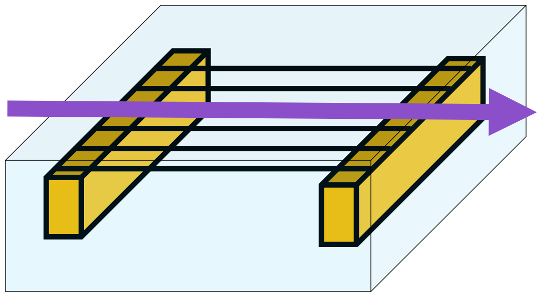
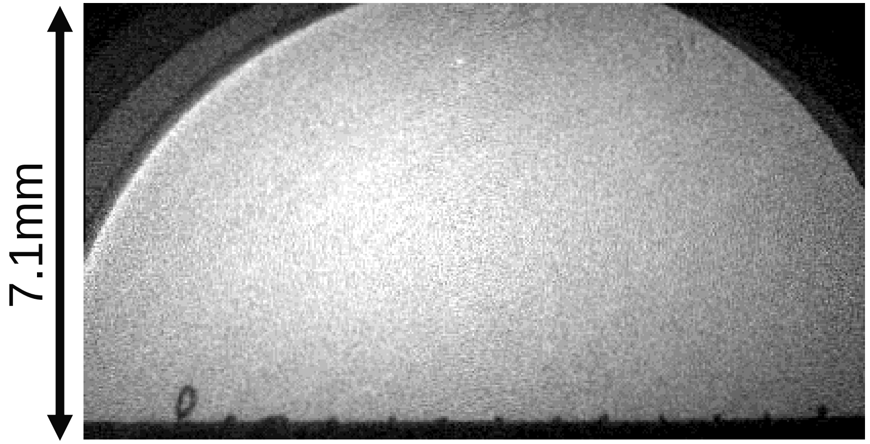
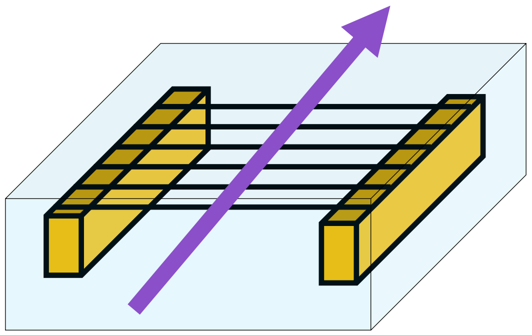
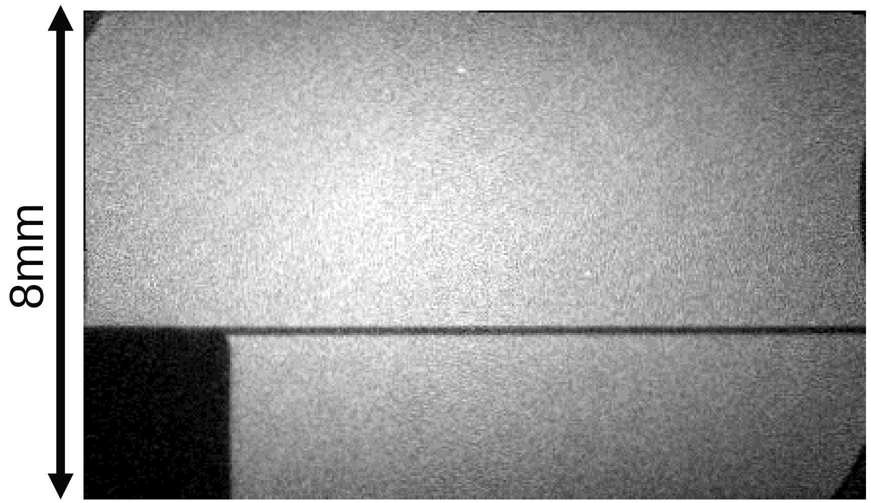
Planar arrays produce planar shockwaves in water

- Current splits resistively between wires – all explode together
- Shockwaves merge to produce planar shock
- Radiography enables quantitative density estimates of shocked water ~ 1.07g/cc
- shock speed $u_s = 2.2 \pm 0.05$ km/s ($M{\sim}1.5$)
- RH conditions, shock pressure ~ 330 MPa





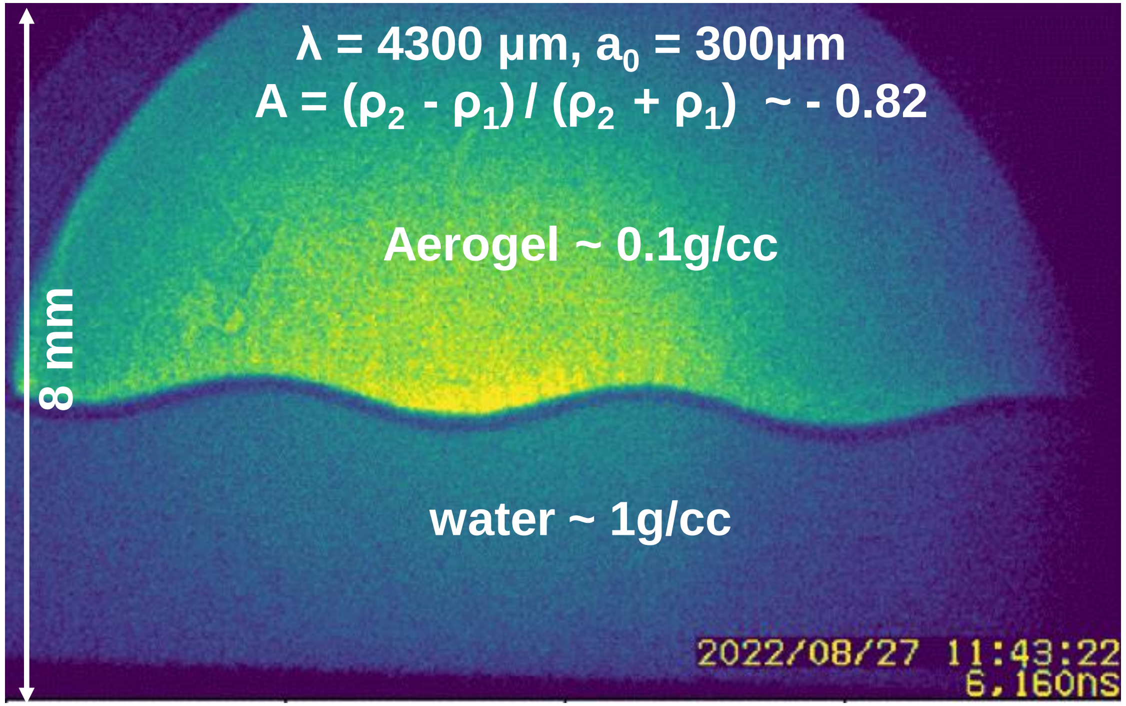




X-ray imaging 13x75µm Cu array in water driven by ~35kA

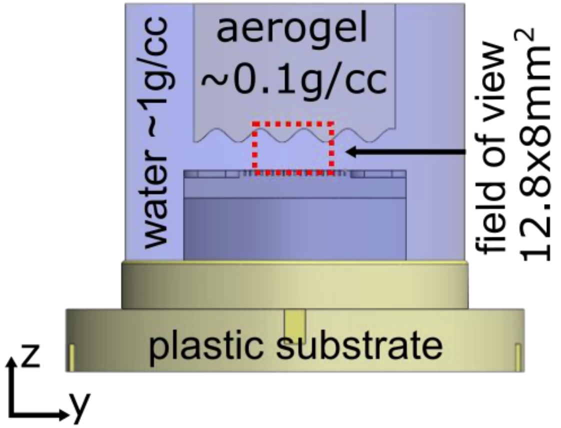
Can we use the shock itself as a driver for hydrodynamic instability studies?

3. Synchrotron radiography of RMI



False colour X-ray image

Y-Z plane view



3. Synchrotron radiography of RMI

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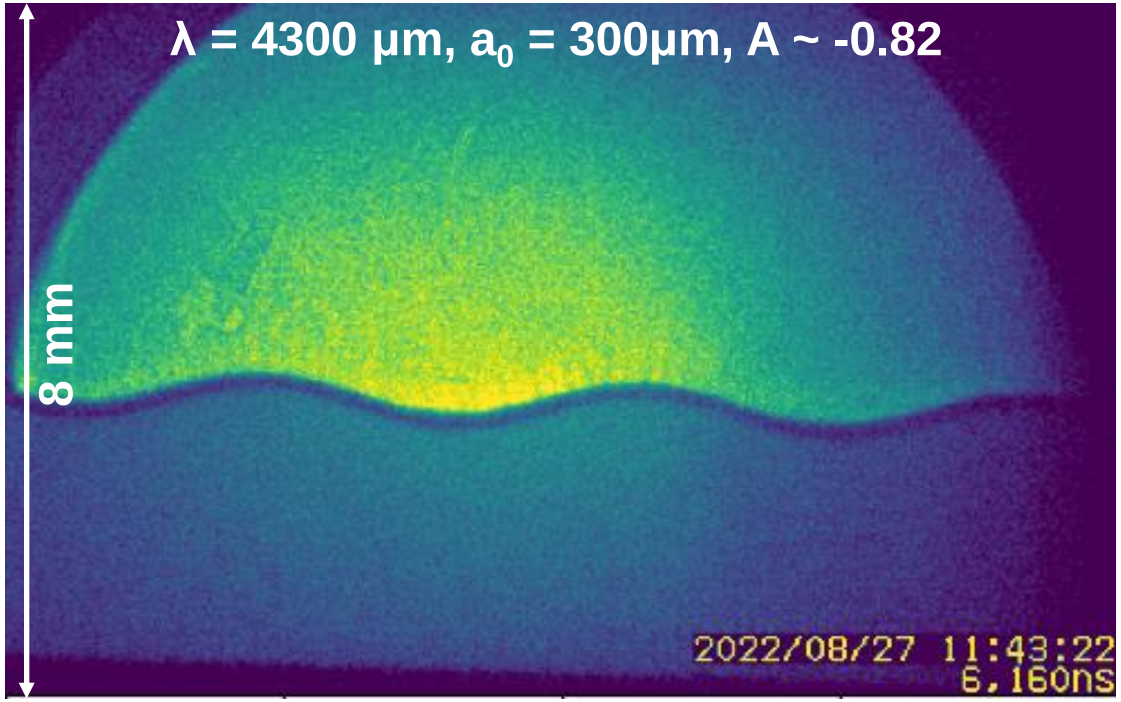
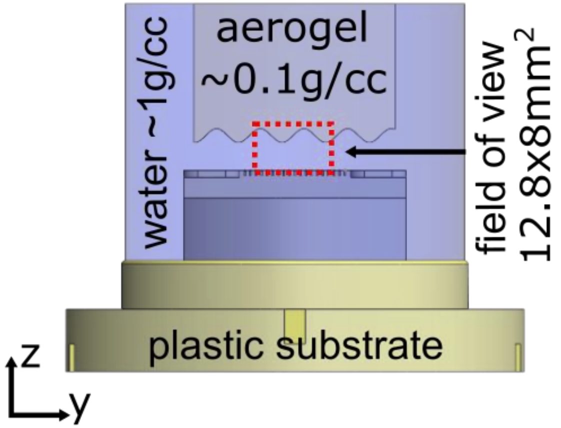
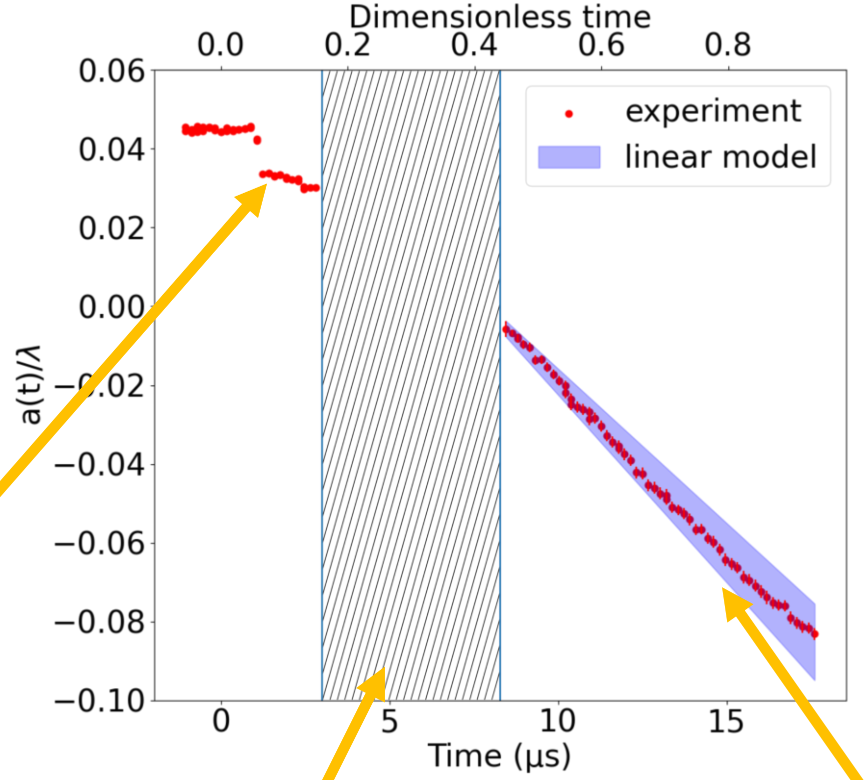


Y-Z plane view





Compression – usually under-resolved; $a_0/\lambda = 0.045 \rightarrow 0.034$ in 350 ns
timescale ~ interface amplitude / shock speed

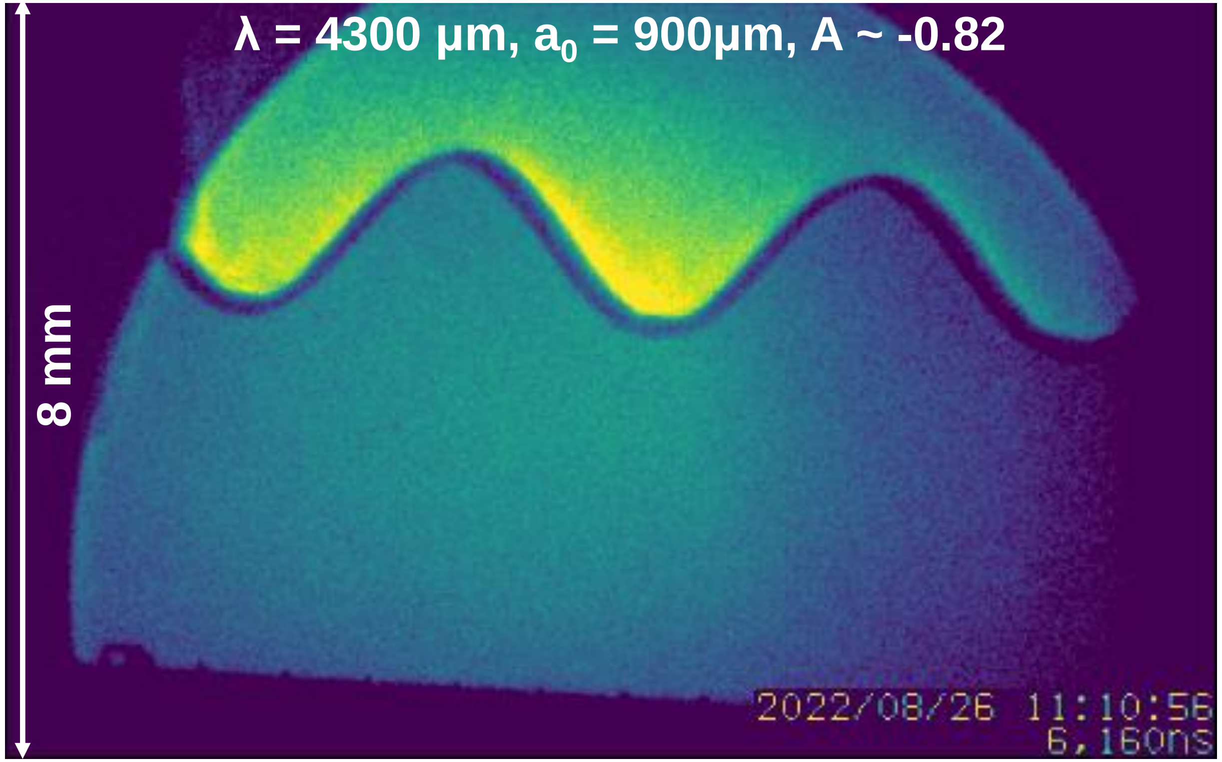
Acceleration – small amplitude behaviour; lasts until dimensionless time ~

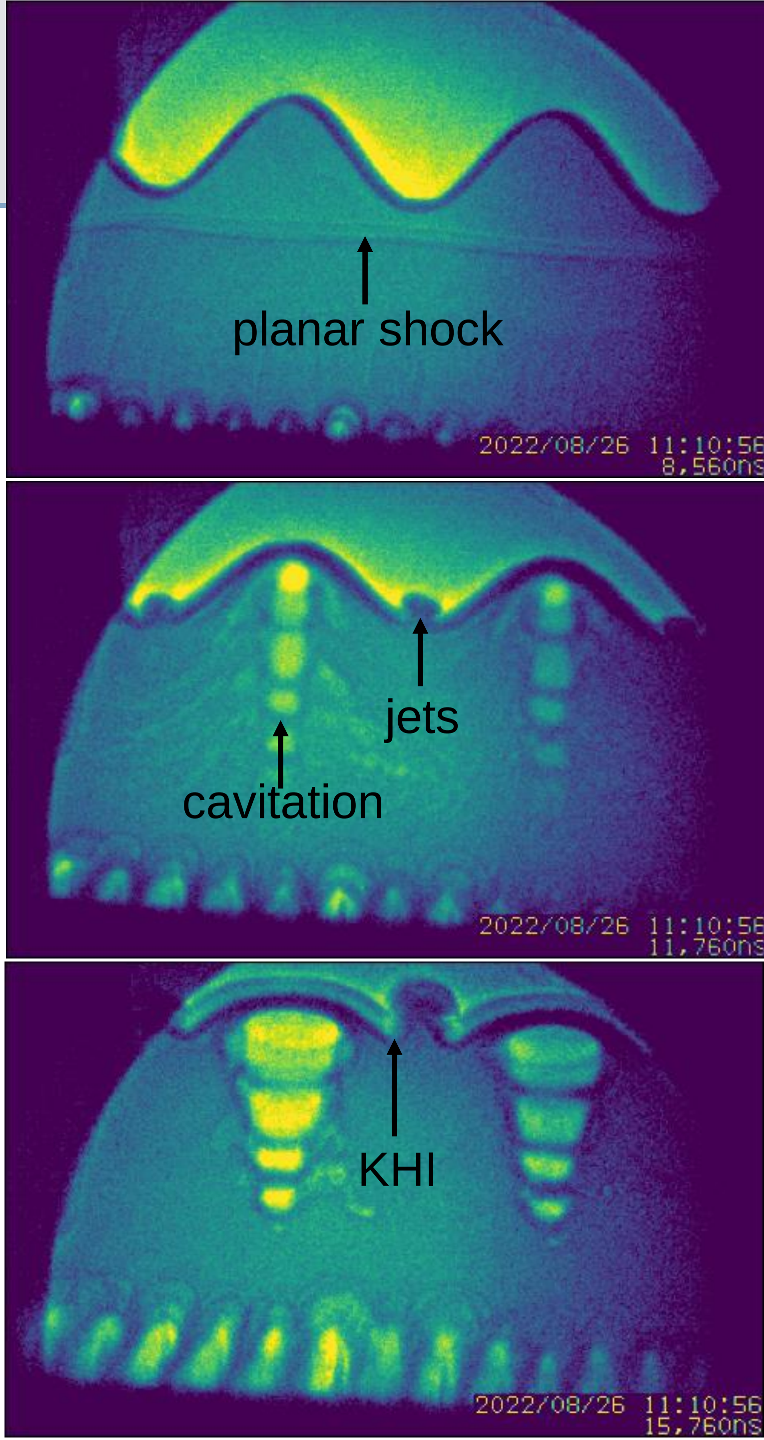
$$\left(\frac{\lambda_0^2}{2\pi a_0 A \Delta u}\right)^{-1} t$$

Linear phase – lasts while $a_0/\lambda < 1$, follows Richtmyer's impulsive theory

$$\frac{da(t)}{dt} = \frac{2\pi}{\lambda_0} A \Delta u a_0$$

3. Synchrotron radiography of RMI





t=8.5μs → planar shock reaches interface

t=11.7μs → jets are ejected from the troughs

t=9.2μs → a rarefaction waves reflects from the interface

t=15.8μs → jets develop Kelvin-Helmholtz-like shape

3. Synchrotron radiography – suppression of RMI

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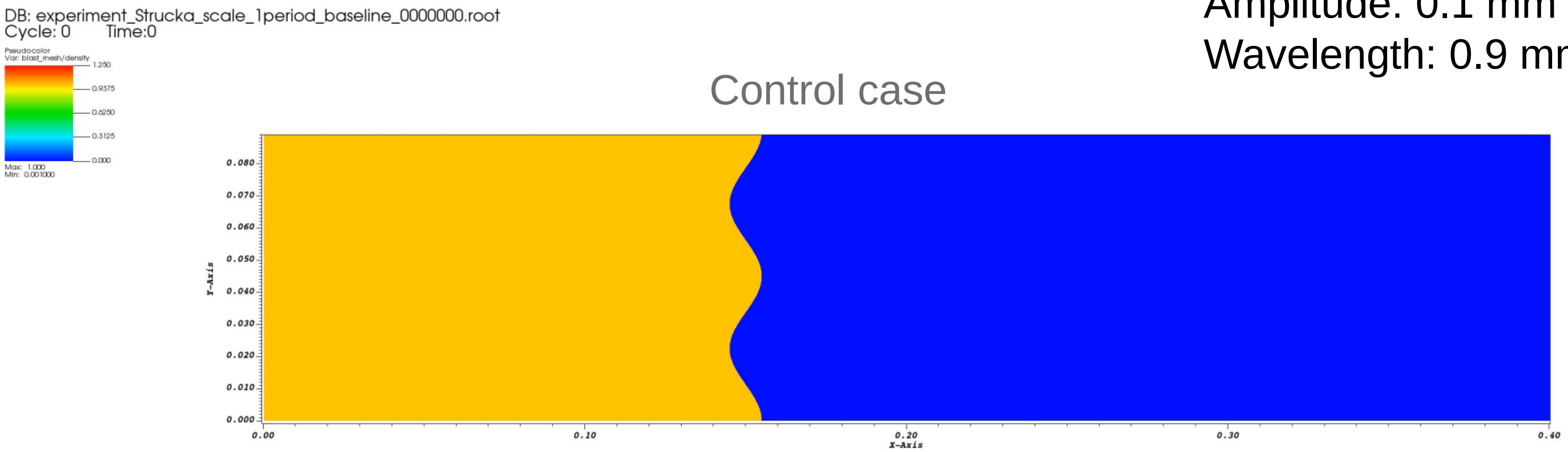
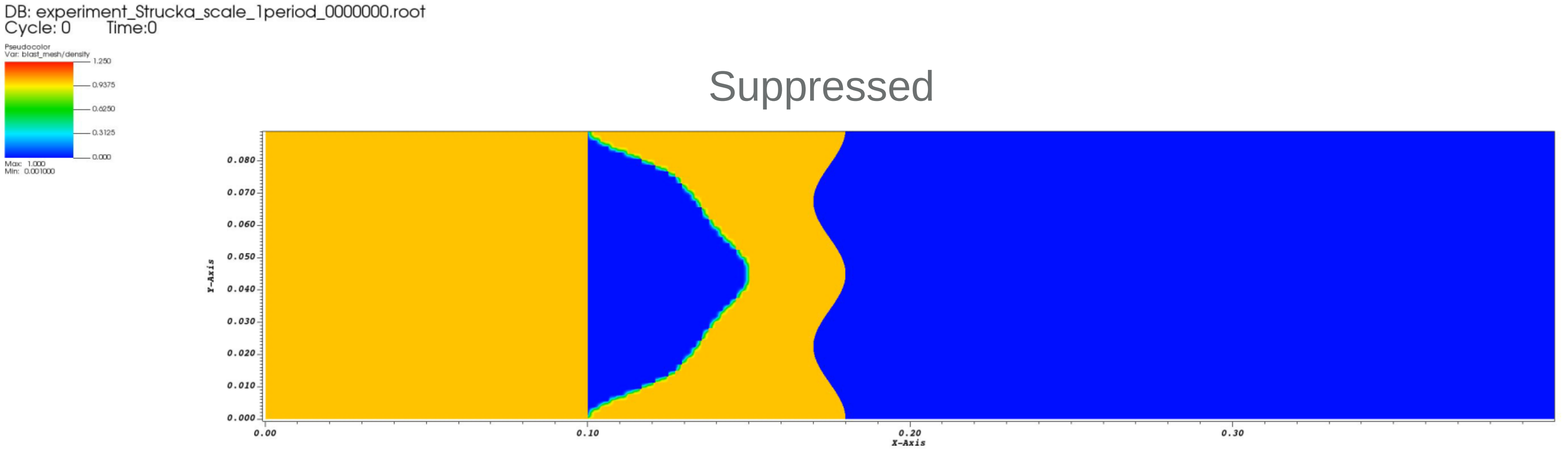
Amplitude: 0.1 mm (100 µm)
Wavelength: 0.9 mm (900 µm)

Control case



Suppressed



with D. Sterbentz, W. Schill, J. Belof of LLNL

3. Synchrotron radiography – suppression of RMI

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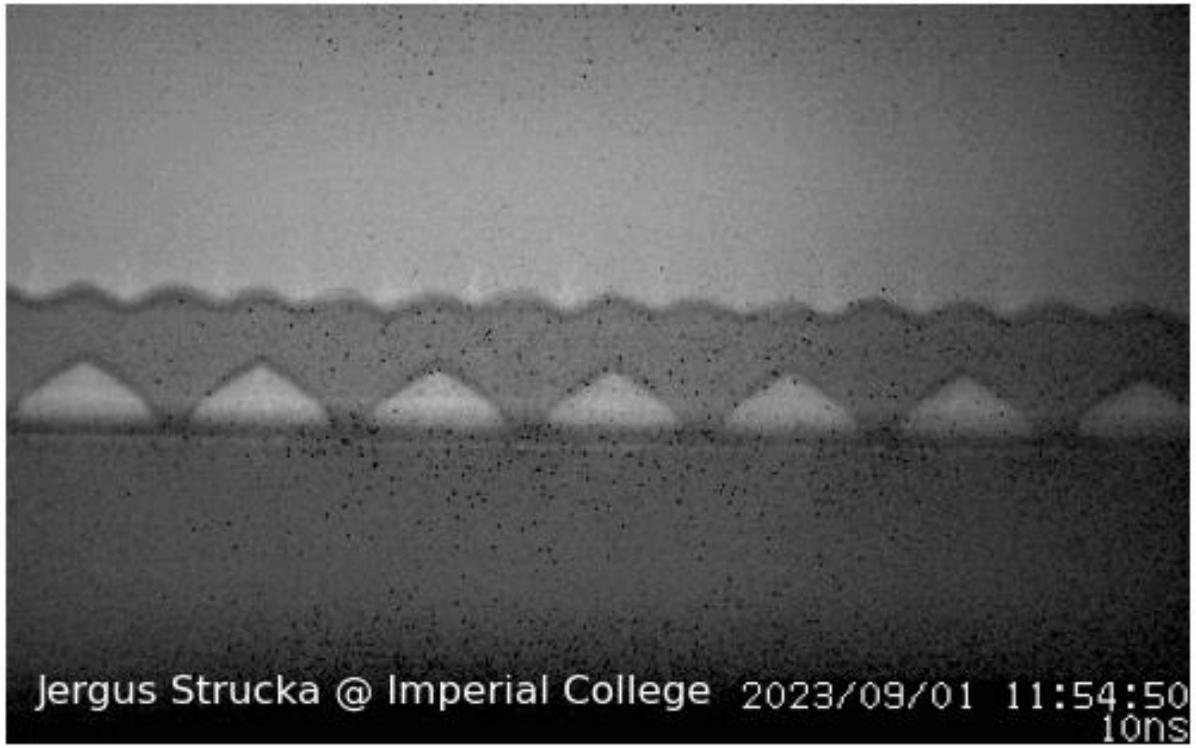
Control



Suppressed

λ ~ 900 µm, 10% gelatine – Y ~ 0.05 MPa
Target uniformly driven by a planar shockwave.
Interframe time ~176ns
Resolution ~ 32um

with D. Sterbentz, W. Schill, J. Belof of LLNL

3. Synchrotron radiography – suppression of RMI

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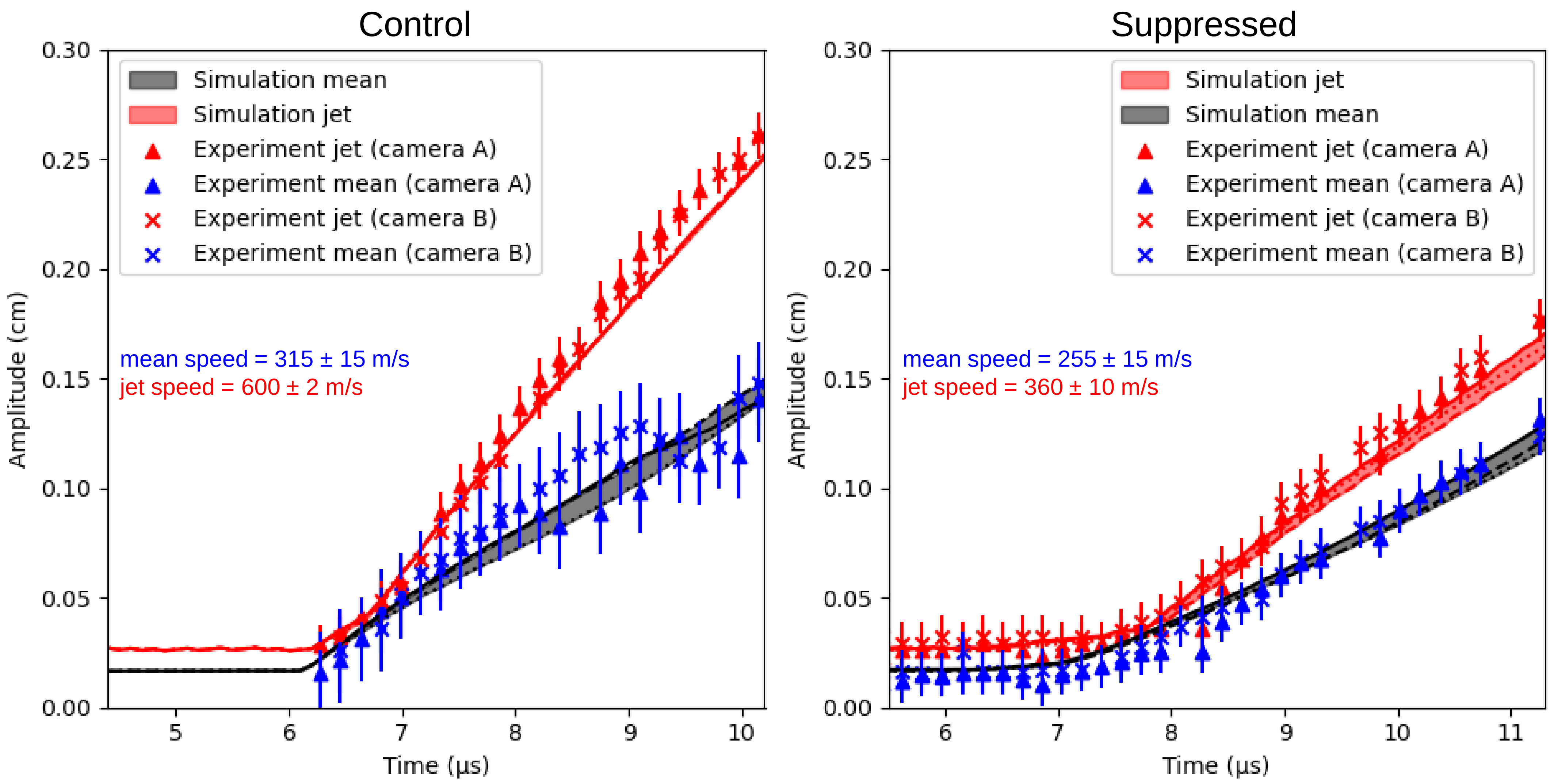
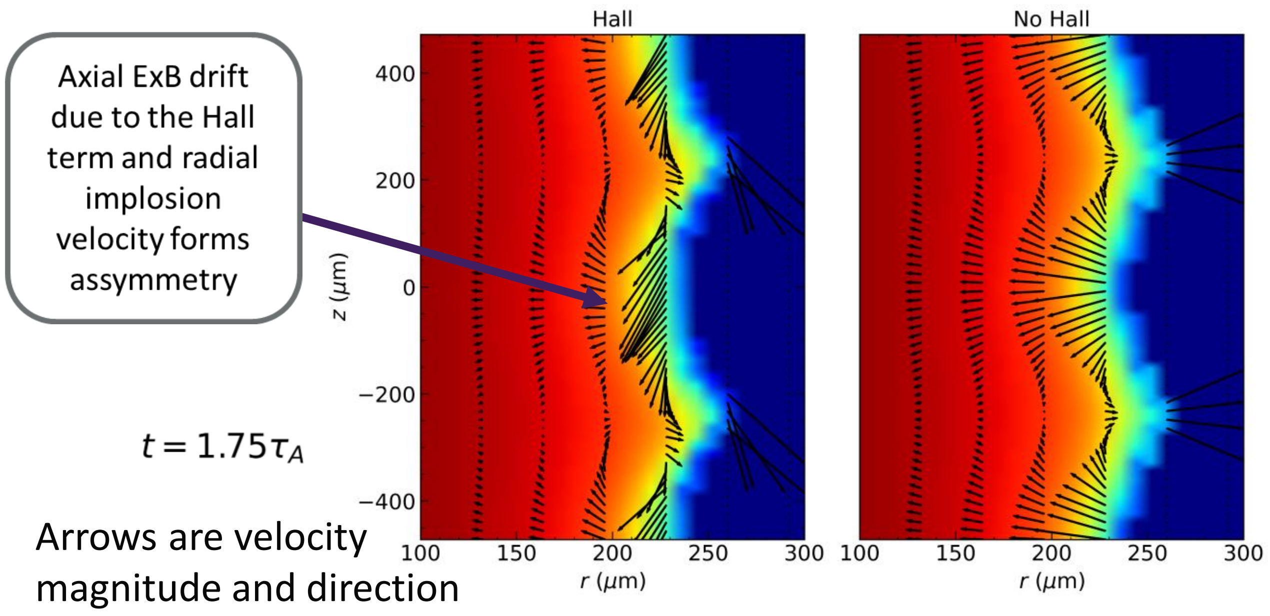
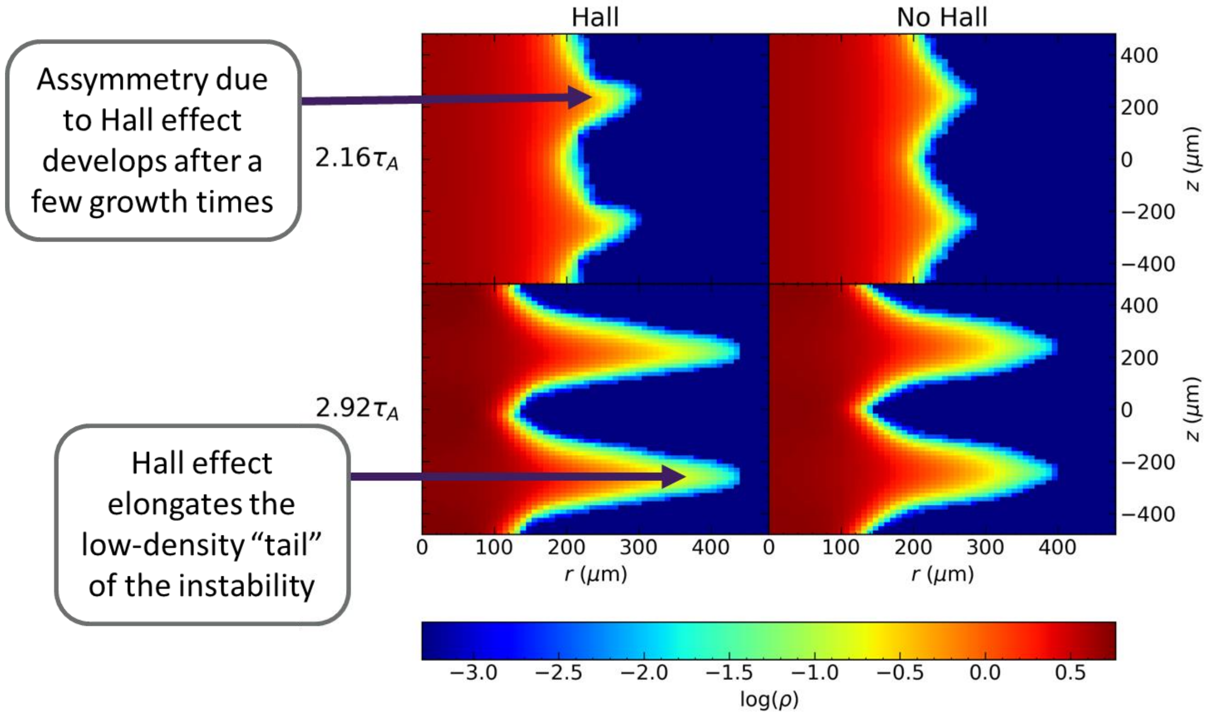


Note: Suppression not due to compression by shockwave - Jet speed / mean speed = 1.9 (control); 1.4 (suppressed)

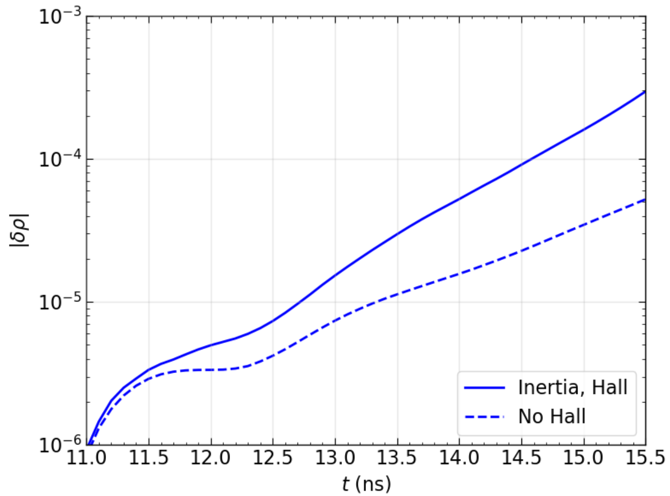
4. Improvements to Gorgon RMHD code - Hall





A new Hall solver has been implemented in the Gorgon code and used to study m=0 instabilities:

- Uses a semi-implicit time-stepping scheme, then rigorously tested against a suite of theoretical problems
- Growth rate of the instability increases due to the Hall effect - including Hall in liner/z-pinch simulations could be important



4. Improvements to Gorgon – Mesh refinement

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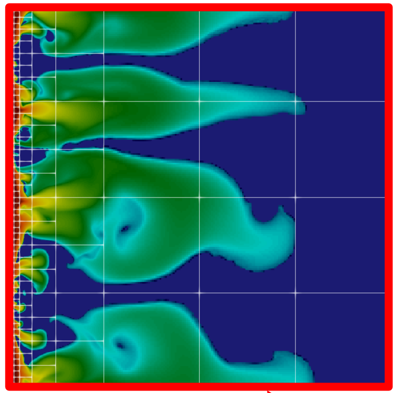
A static mesh refinement capability with has been implemented with

- block-structured refinement strategy
- arbitrary number of refinement levels
- flexible splitting
- novel transfer algorithm for MHD variables

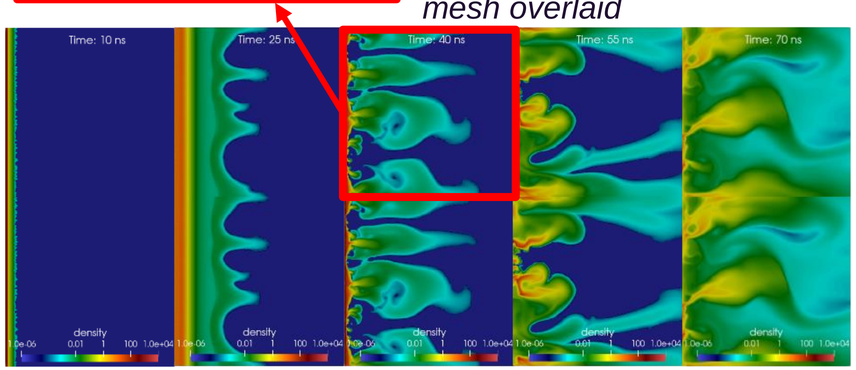
See poster by Niki Chaturvedi

1. Single wires



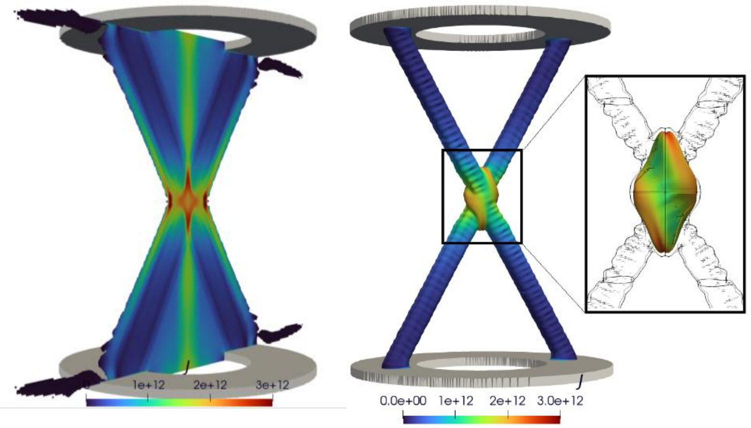
Simulated in 2D using 1 μm resolution on axis.
Captures $m = 0$ growth from possible ETI seed

Density contours with mesh overlaid



2. X-pinches

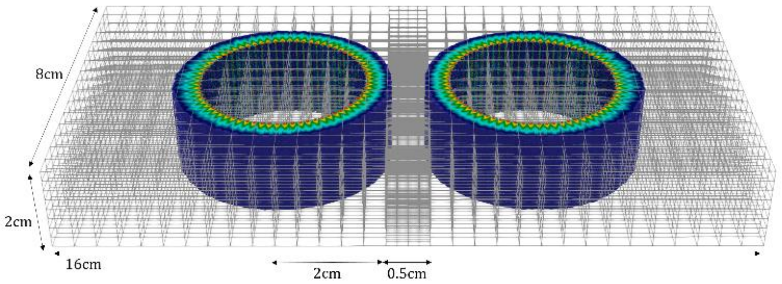
Simulated in 3D using 2 μm resolution, shows dynamics of crossing point.

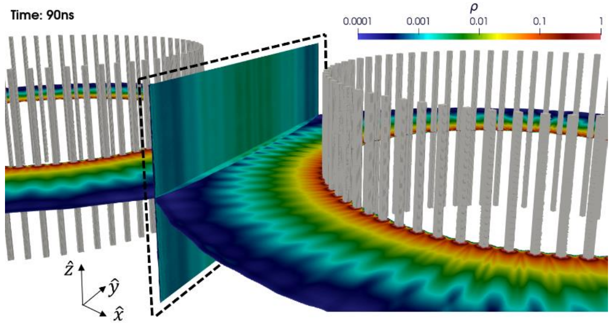


Current density contours for (left) $\rho > \rho_{vac}$ (right) $\rho > 100\ kg/m^3$

3. MARZ Magnetic Reconnection on Z)

Radiative cooling of layer requires resolving 50 μm plasmoid dynamics on a 16 cm domain





Density contours of ablation streams

Summary ?

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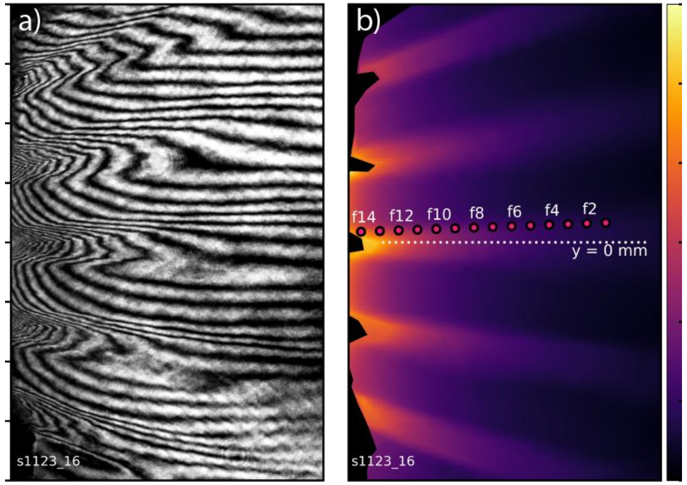

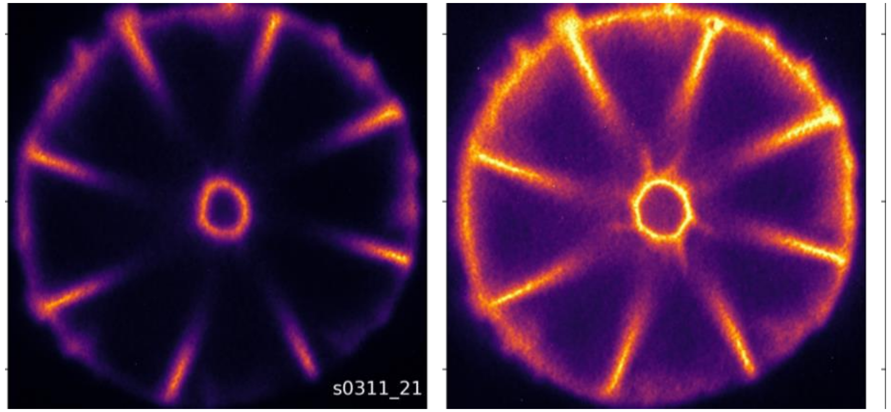

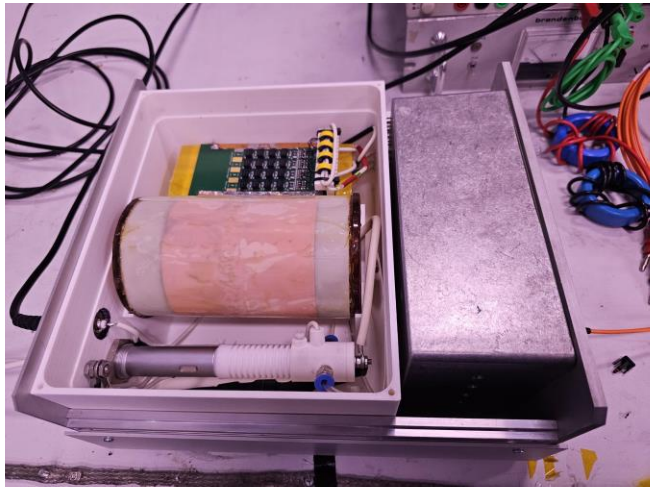

Lots of funs physics still to do

How can we join in Znet US?