Laboratory observations of magnetic reconnection resulting from multiscale instability cascade

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Overview

- How does ideal MHD plasma couple to microscale?
- How does it happen so fast (impulsively)?

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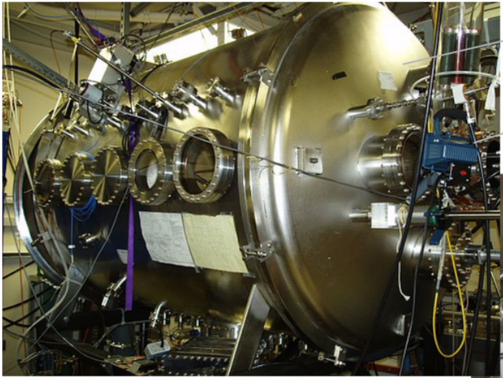
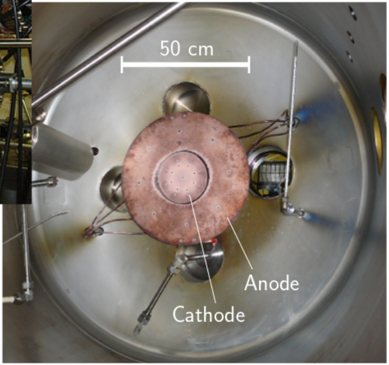
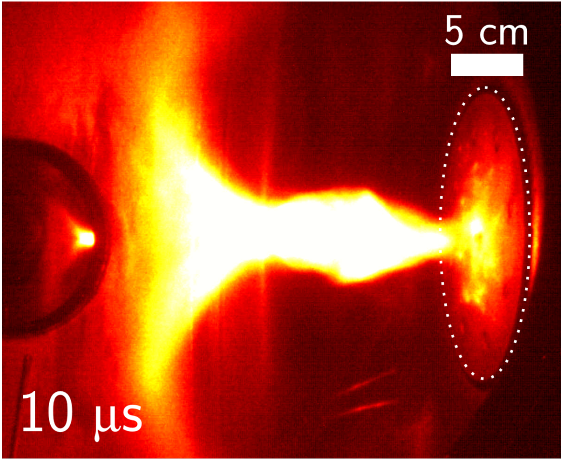
$\longrightarrow$ Instability of an instability

Caltech experiment setup

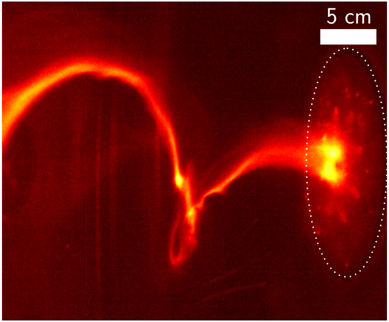






T$\sim$ 1 – 2 eV, n$\sim$ 10^{21-22} m^{-3}, B$\sim$ 0.1 T

Current-driven ideal MHD kink instability



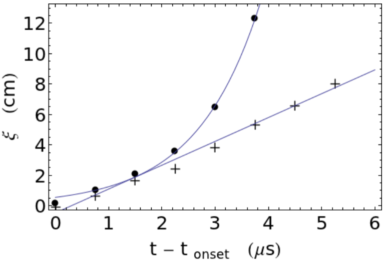
Kruskal-Shafranov instability criteria:

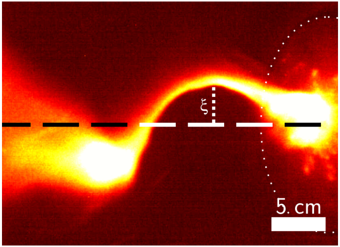
$$q(a) = \frac{2\pi a B_z(a)}{L B_\phi(a)} < 1$$

In experimental parameters:

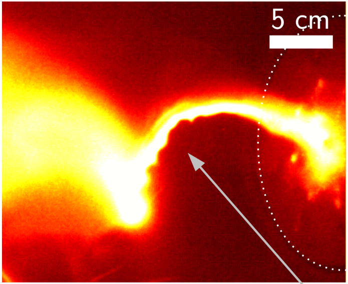
$$\lambda_{gun} = \frac{\mu_0 I_{gun}}{\Psi_{gun}} > \frac{4\pi}{L}$$

Kink instability growth rate: Linear or exponential

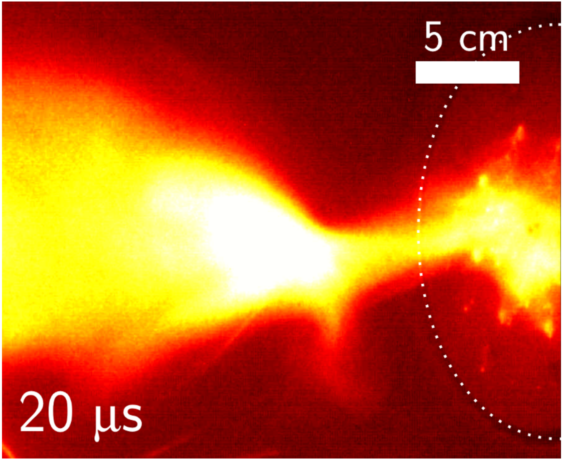




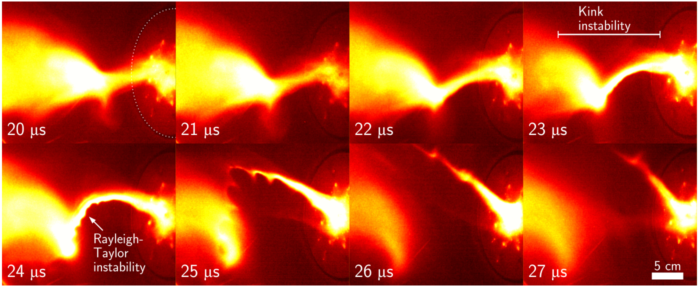
Rayleigh-Taylor instability



On trailing edge of outward accelerating filament
$\lambda \approx 2$ cm


5 cm
20 μs

Calculate effective gravity at time of Rayleigh-Taylor onset



In this case, offset is:

$$\xi(t) = 6 \times 10^{-3} \exp[8 \times 10^{5}(t - t_0)]$$

Rayleigh-Taylor first appears at $t = 24\ \mu$s; acceleration is:

$$g(t) = (8 \times 10^{5})^2 \xi(t) \approx 4 \times 10^{10}\ \text{m/s}^2$$

Calculate predicted Rayleigh-Taylor growth rate

R-T growth rate:

$$\gamma^2 = gk\left(\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} - \frac{2\left(\mathbf{k}\cdot\mathbf{B}\right)^2}{\mu_0\left(\rho_2 + \rho_1\right)gk}\right)$$

Assumptions:

$\mathbf{k}\cdot\mathbf{B} = 0$ (fastest growing mode)

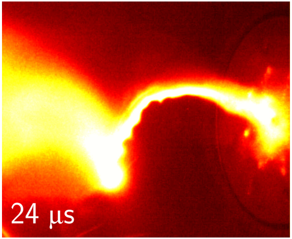
$\rho_2 \gg \rho_1$ (density in filament much greater than just outside filament)

R-T growth rate becomes:

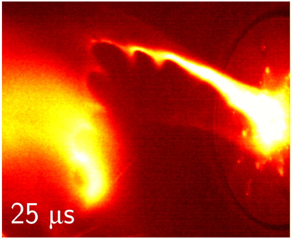
$$\gamma^2 = gk$$

$$\approx 4 \times 10^{10}\frac{2\pi}{0.02} \Longrightarrow \gamma \approx \boxed{3 \times 10^6\ s^{-1}}$$

Estimate observed Rayleigh-Taylor growth rate



$t_1 = 24\ \mu s$
$A_1 \approx 0.5$ cm

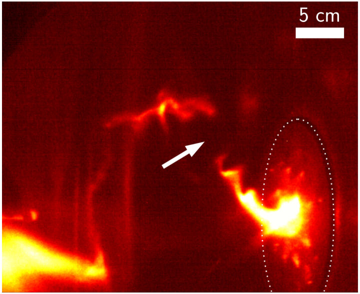


$t_2 = 25\ \mu s$
$A_2 \approx 1.5$ cm

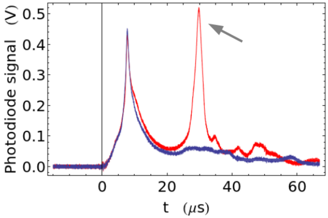
$$\frac{A_2}{A_1} = \exp\left[\gamma\left(t_2 - t_1\right)\right]$$

$$\frac{1.5}{0.5} = \exp\left[\gamma\left(1 \times 10^{-6}\right)\right] \Longrightarrow \gamma \approx \boxed{1 \times 10^{6}\ s^{-1}}$$

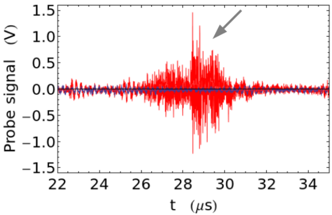
Plasma reconnects after Rayleigh-Taylor instability



Burst of EUV radiation



Excitation in whistler wave frequency range



Non-MHD scale at time of reconnection

$$\frac{v_d}{v_A} = \frac{J_z}{nq}\frac{\sqrt{\mu_0 n m_i}}{B} \approx \frac{\mu_0 J_z}{B_z}\left(\frac{c}{\omega_{pi}}\right)$$

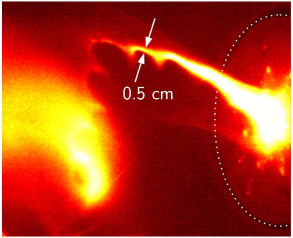
$$\approx \frac{4\pi}{\lambda_z}\left(\frac{c}{\omega_{pi}}\right)$$

$$\approx \mathcal{O}(1)$$

MHD assumes $\frac{v_d}{v_A} \ll 1$, so this is non-MHD scale

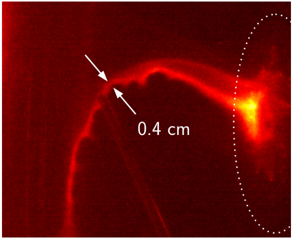
Rayleigh-Taylor is necessary but not sufficient for reconnection

Argon



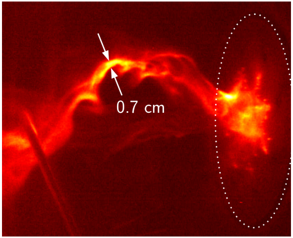
$c/\omega_{pi} = 1$ cm
$d = 0.5$ cm
Reconnection observed

Nitrogen



$c/\omega_{pi} = 0.5$ cm
$d = 0.4$ cm
Reconnection observed

Hydrogen



$c/\omega_{pi} = 0.2$ cm
$d = 0.7$ cm
No reconnection observed

Conclusion

- Plasma starts on ideal MHD scale
- Kink instability
- Non-inertial frame, effective gravity
- Rayleigh-Taylor instability
- Magnetic reconnection when plasma on “microscopic” scale

Question: What determines whether the kink amplitude grows linearly or exponentially?

Non-MHD scale at time of reconnection: details

The magnetic field and wavevector have form

$$\mathbf{B} = B_\phi \hat{\phi} + B_z \hat{z} \qquad \text{and} \qquad \mathbf{k} = k_\phi \hat{\phi} + k_z \hat{z} = \frac{m}{r}\hat{\phi} + \frac{2\pi}{\lambda_z}\hat{z}.$$

Using $\mathbf{k} \cdot \mathbf{B} = 0$, these equations combine to give us

$$\mathbf{k} \cdot \mathbf{B} = \frac{m}{r} B_\phi + \frac{2\pi}{\lambda_z} B_z = 0 \Rightarrow B_\phi = \frac{2\pi r}{\lambda_z} B_z.$$

Ampére's law gives us

$$\mu_0 J_z = \frac{1}{r}\frac{\partial}{\partial r}(r B_\phi),$$

combining these two gives

$$\frac{J_z}{B_z} = \frac{4\pi}{\mu_0 \lambda_z}.$$