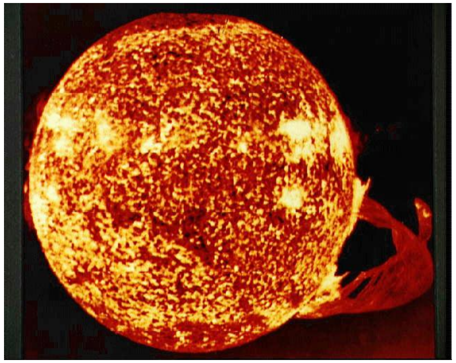
Experimental Investigations of Magnetic Reconnection

J Egedal

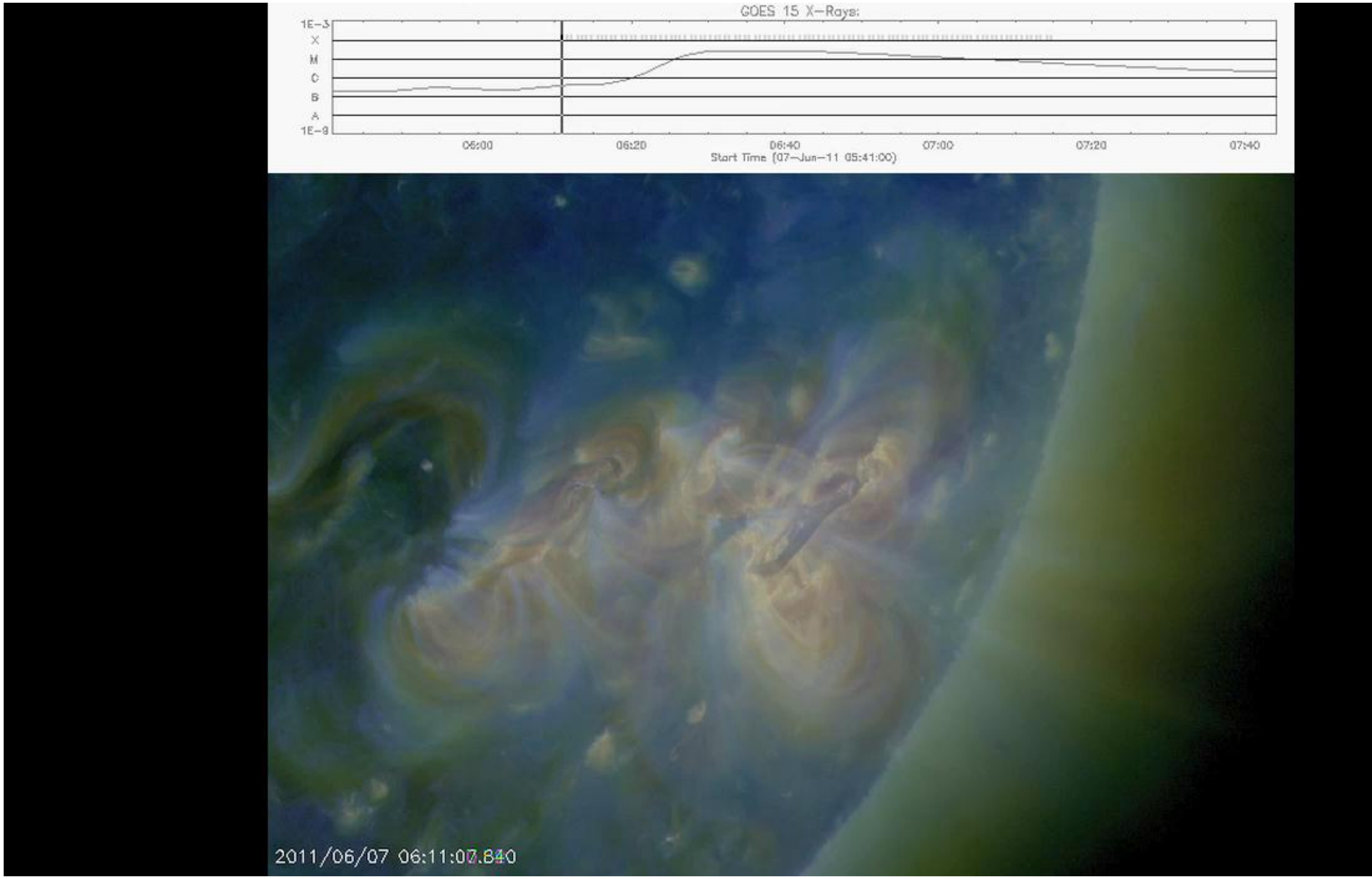
MIT, PSFC, Cambridge, MA



MIT PSFC

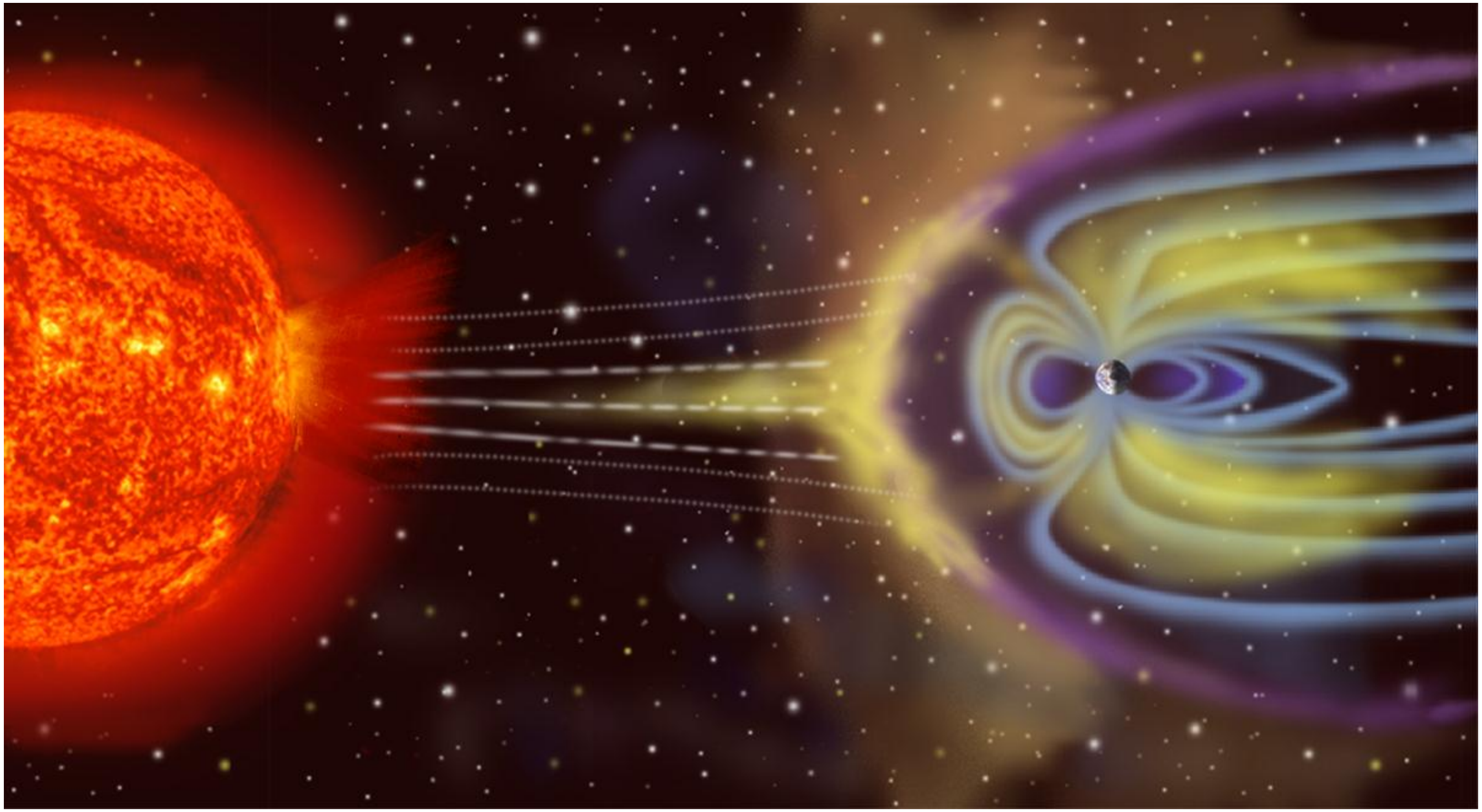
Coronal Mass Ejections

Movie from NASA's Solar Dynamics Observatory (SDO)

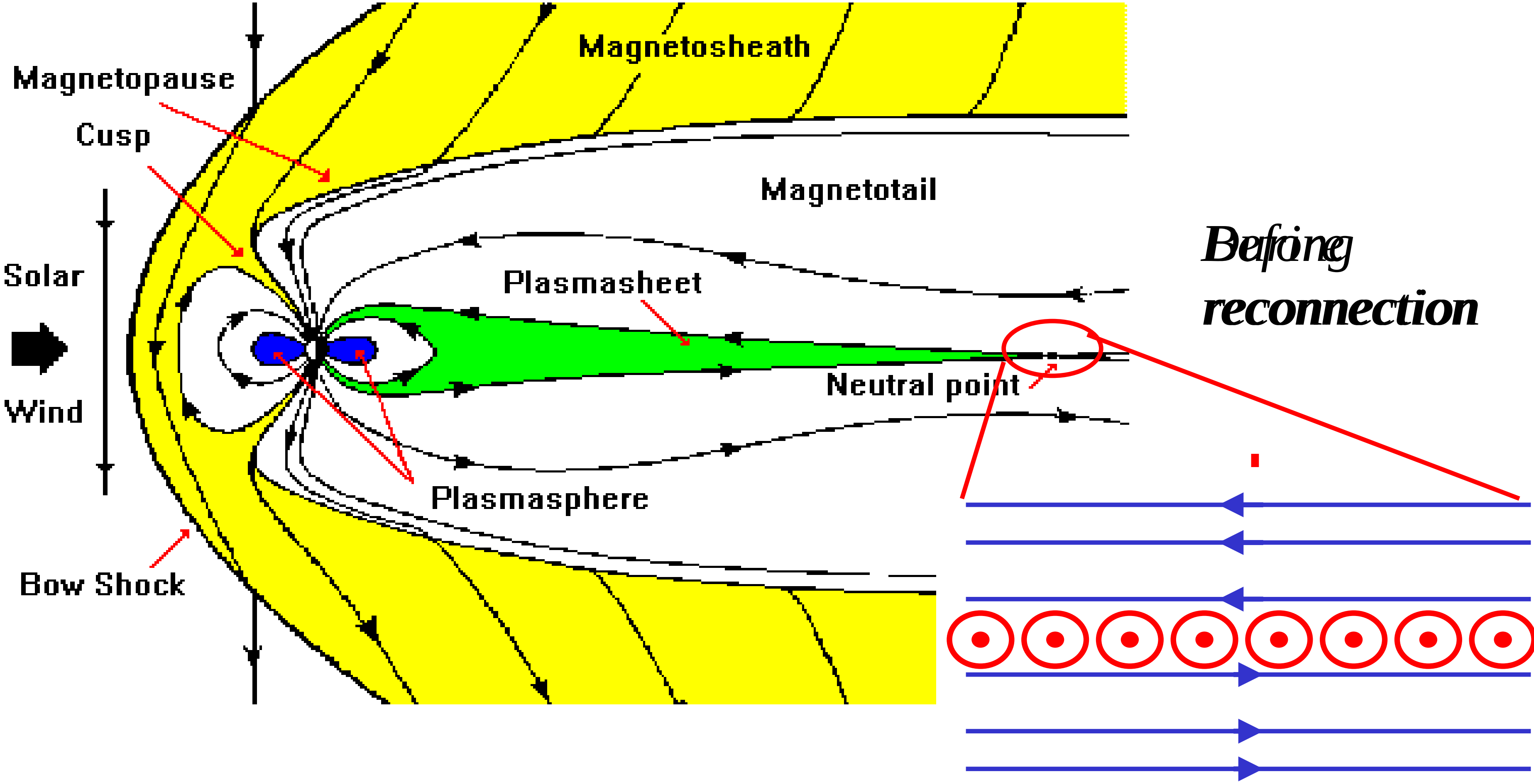


Space Weather

The Solar Wind affects the Earth's environment



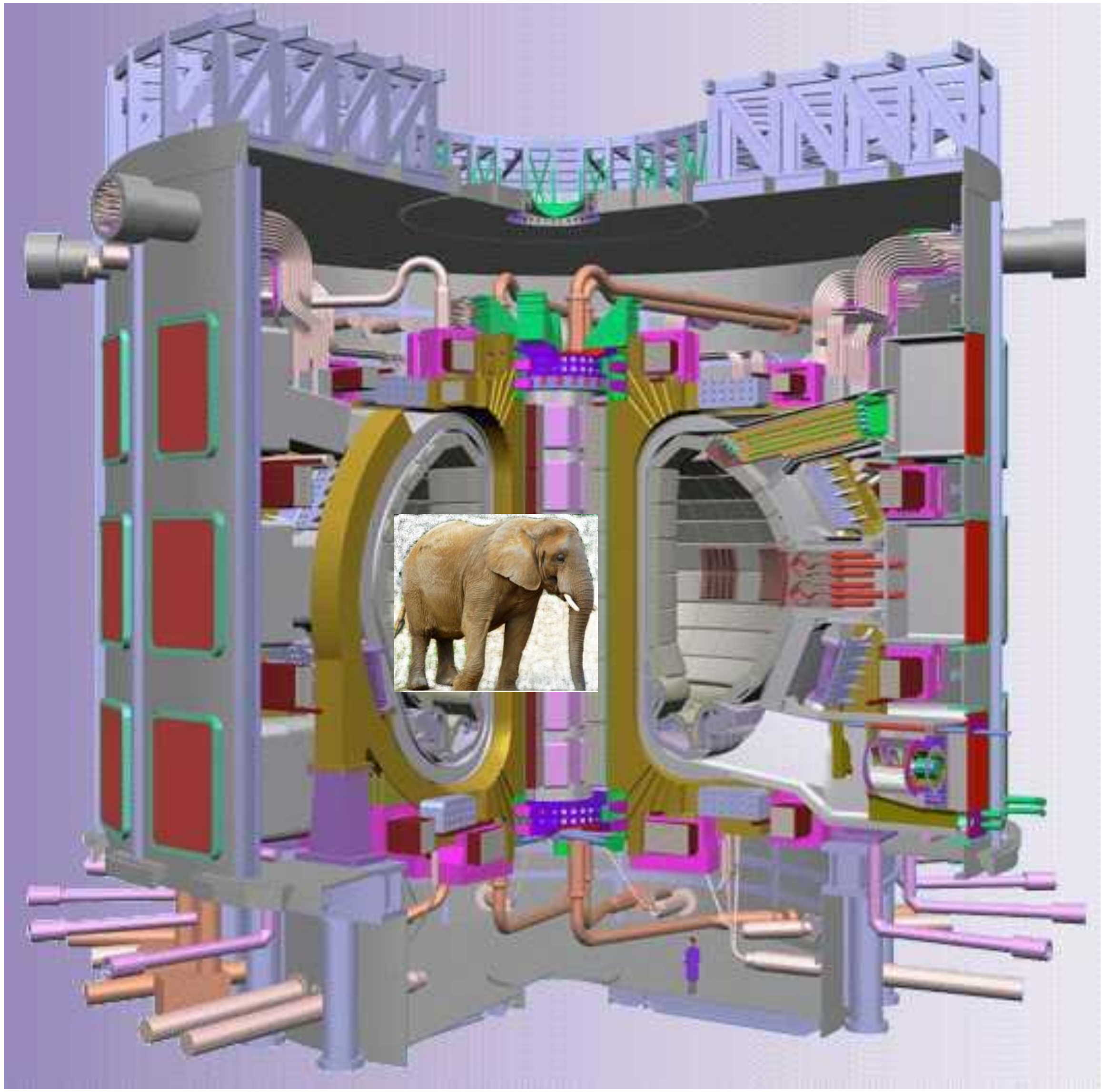
The Earth’s Magnetic Shield



The Daily-Show

Magnetic Fusion Devices

International Thermonuclear Experimental Reactor



Magnetic Fusion Devices

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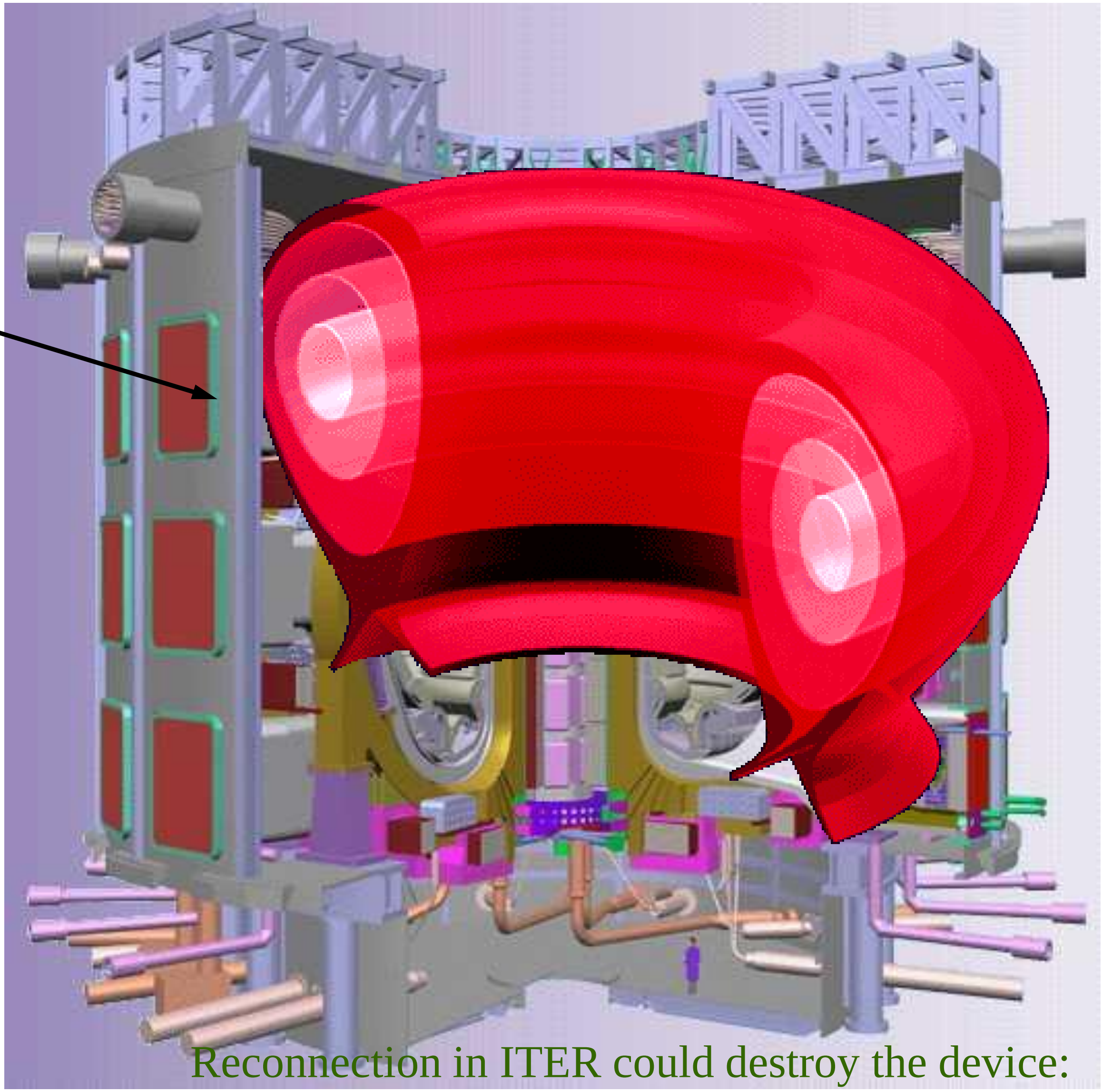
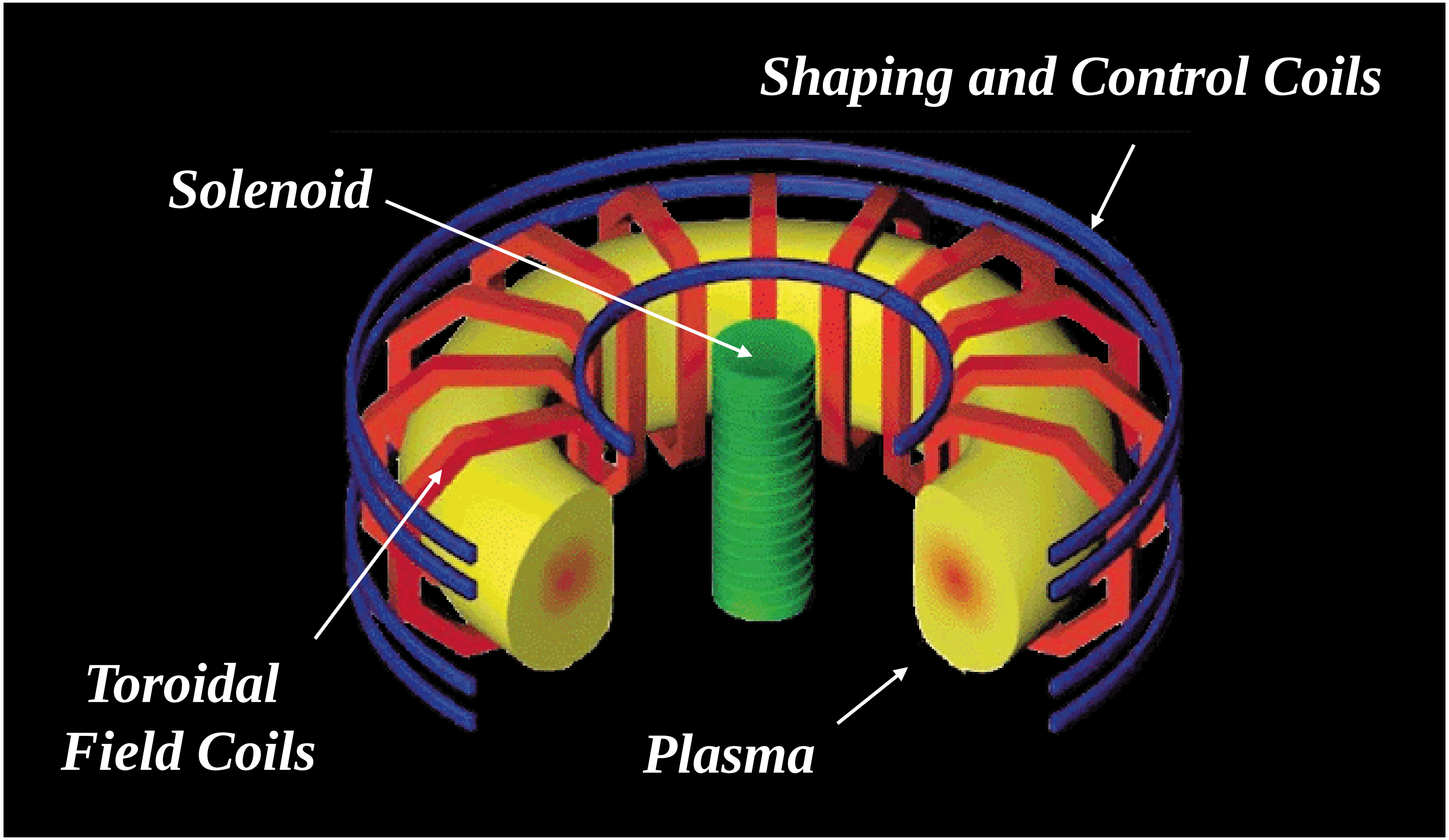


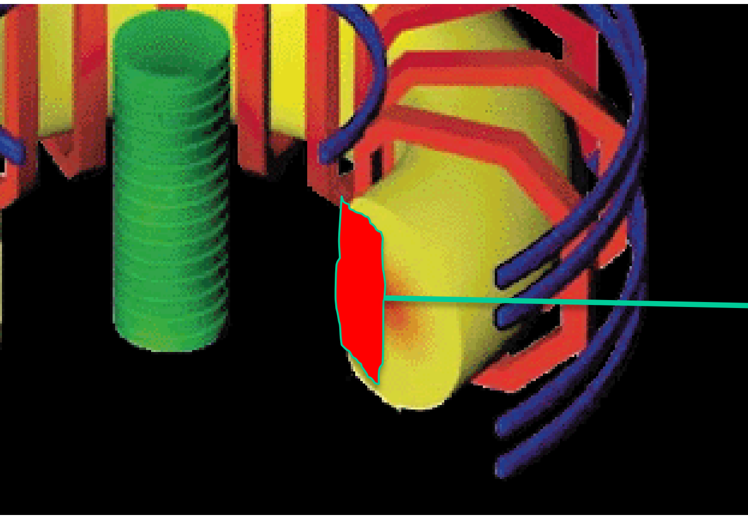
Reconnection in ITER could destroy the device:

The Tokamak Device

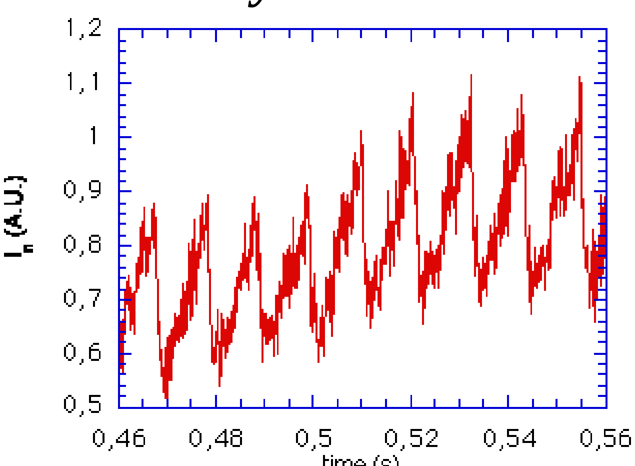
Best known confinement device on Earth

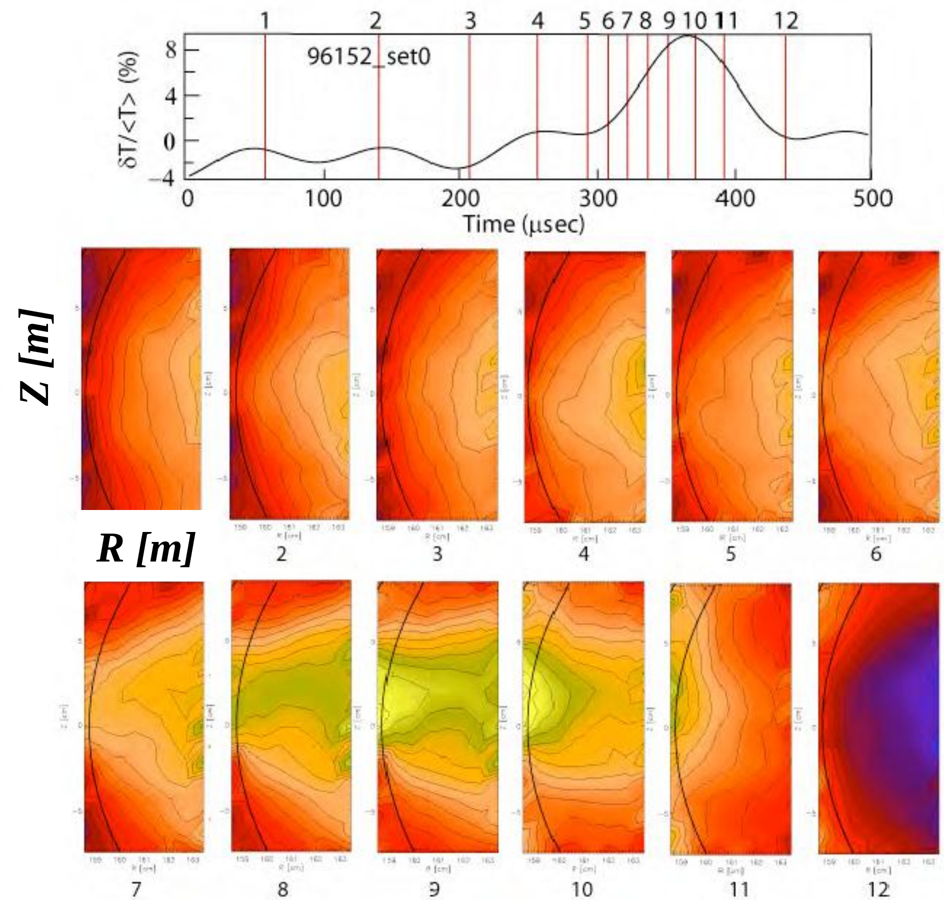


Sawtooth reconnection in Tokamaks



Neutron yield in a tokamak





H Park, PRL 2005: localized reconnection

Electromagnetism 101

- Faraday's law:

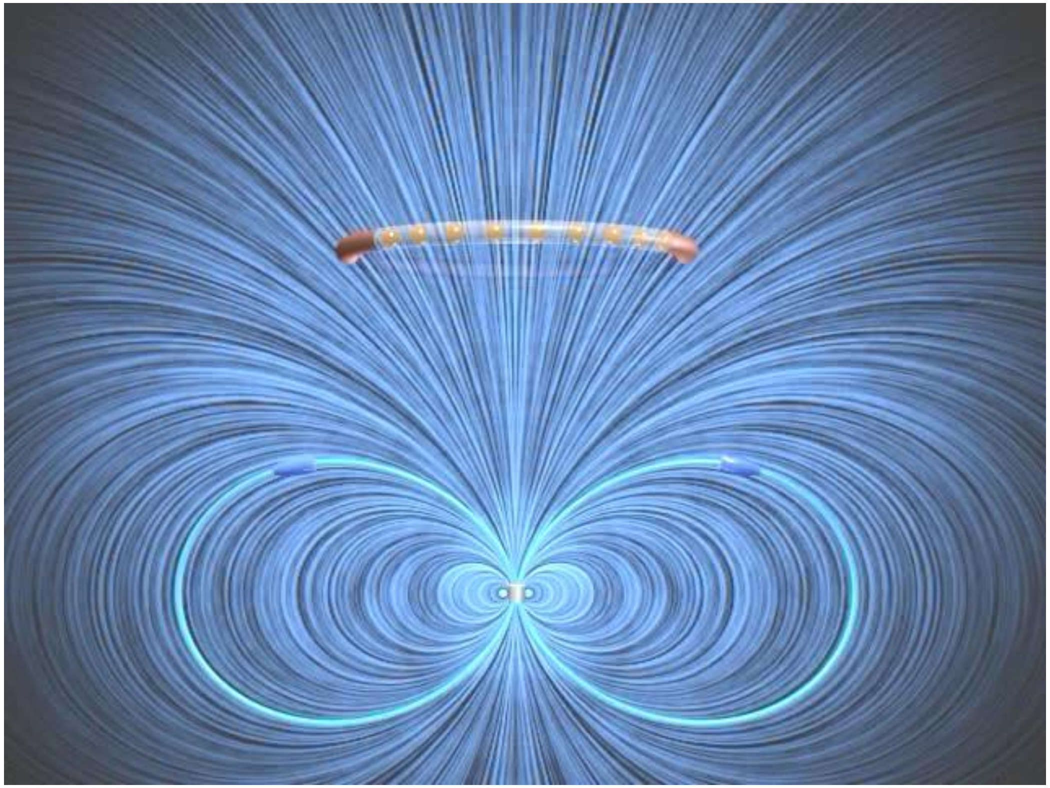
$$EMF = -Area \cdot \frac{dB}{dt}$$

- Faraday's law for a conducting ring: EMF=0.

- The magnetic flux through the ring is trapped

- This also holds if the ring is made of plasma

➔ plasma frozen in condition

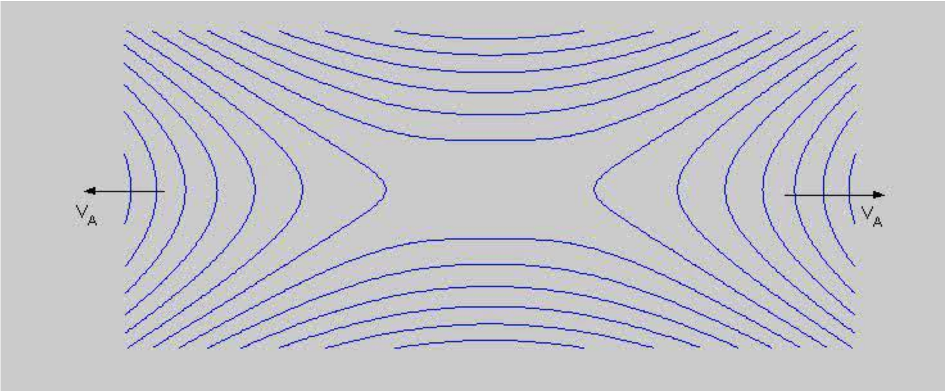


Reconnection: A Long Standing Problem

Simplest model for reconnection:

$\mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{j}$ [*Sweet-Parker* (1957)]

$$-\left.\frac{\partial\Psi}{\partial t}\right|_X = E_X = \eta j_x$$



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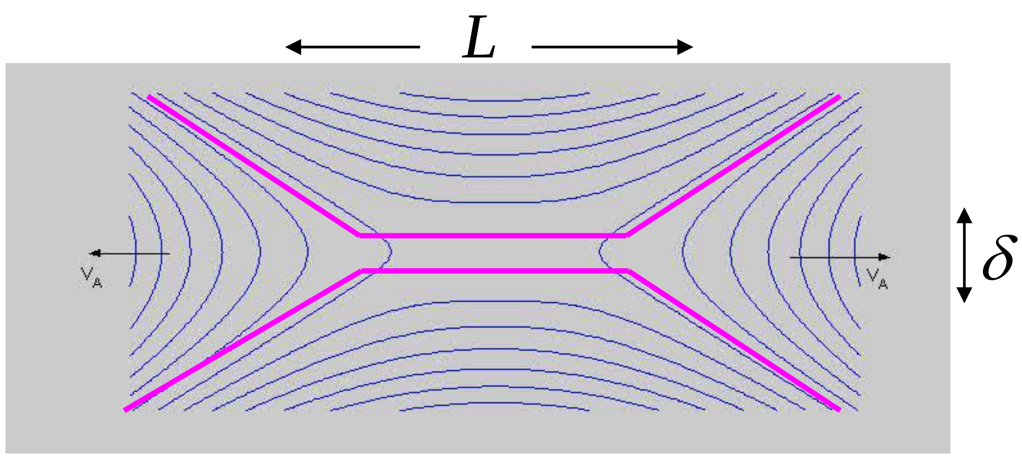


Outflow speed:

$$v_A = \frac{B}{\sqrt{\mu_0 n m_i}}$$

(Alfven speed)

Sweet-Parker: L >> δ:

$$t_{sp} = \sqrt{t_R t_A} = \sqrt{\frac{\mu_0 L^2}{\eta}}\sqrt{\frac{L}{v_A}}$$

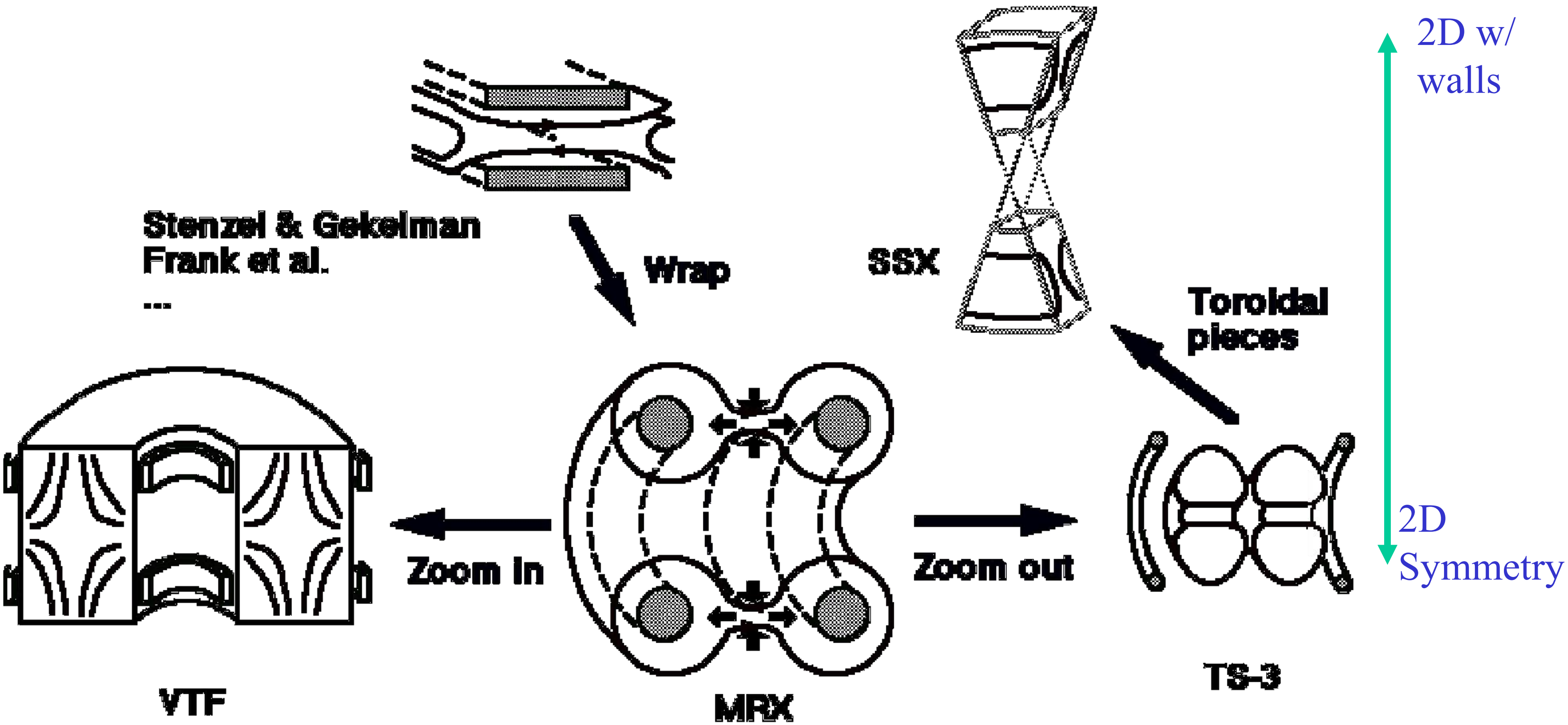
Unfavorable for fast reconnection

Two months for a coronal mass ejections

Outline

- The MRX experiment at PPPL
- 2D reconnection in VTF open configuration
  - Oscillatory reconnection response
- 3D reconnection in VTF closed configuration
  - Explosive reconnection response
- Conclusions

Family of Reconnection Experiments (H.Ji, PPPL)



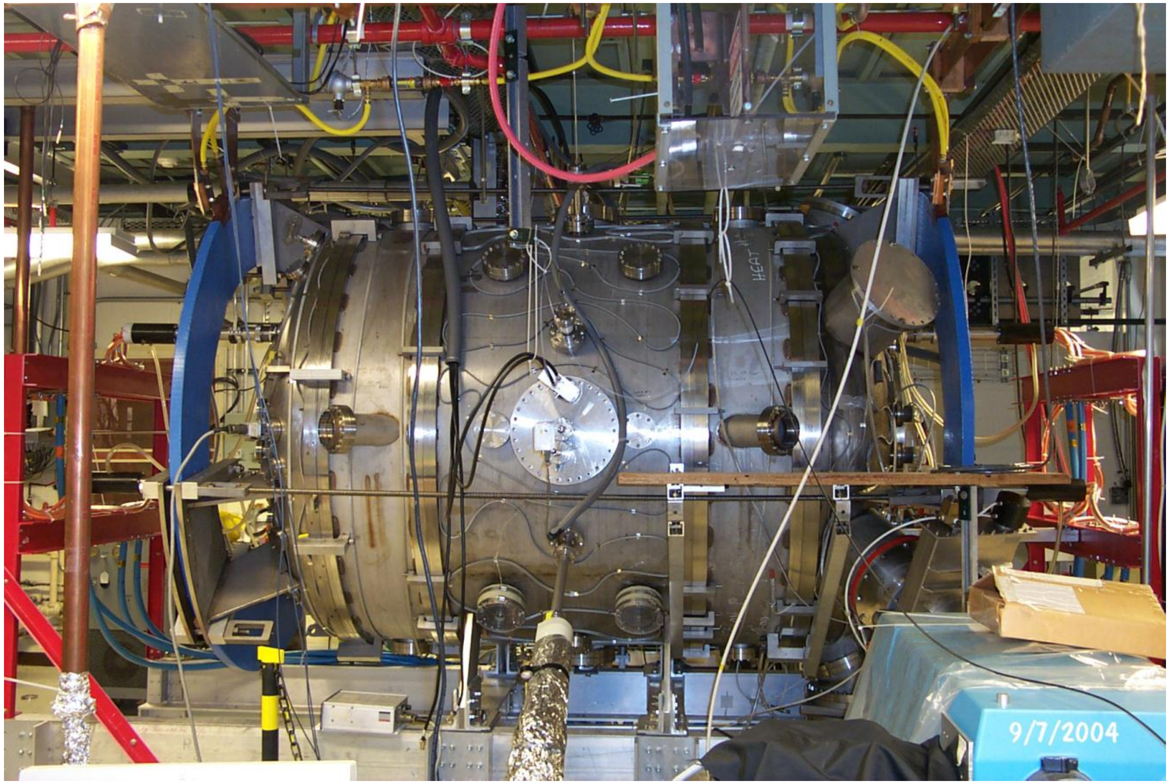
local ← boundary → global

steady state ← process → transient

collisionless ← collisionality → collisional

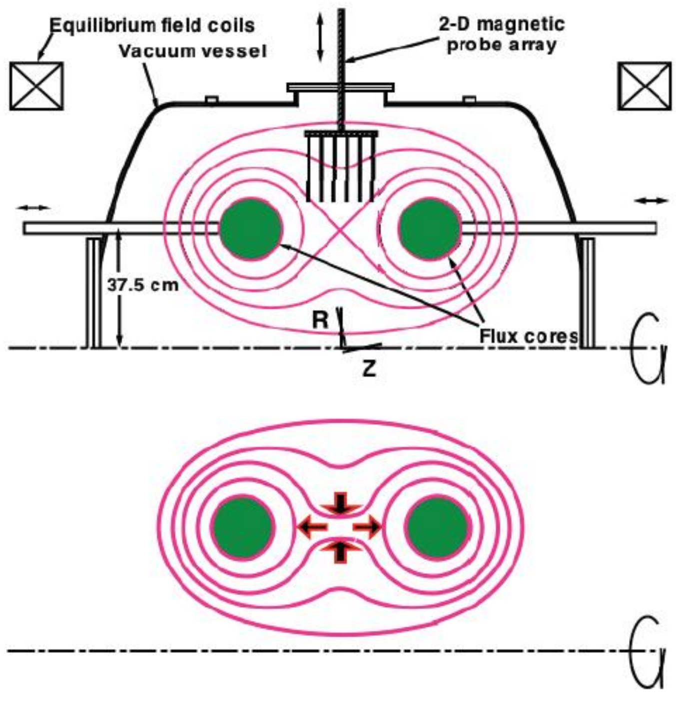
The MRX experiment at PPPL

M. Yamada, H Ji, et al.

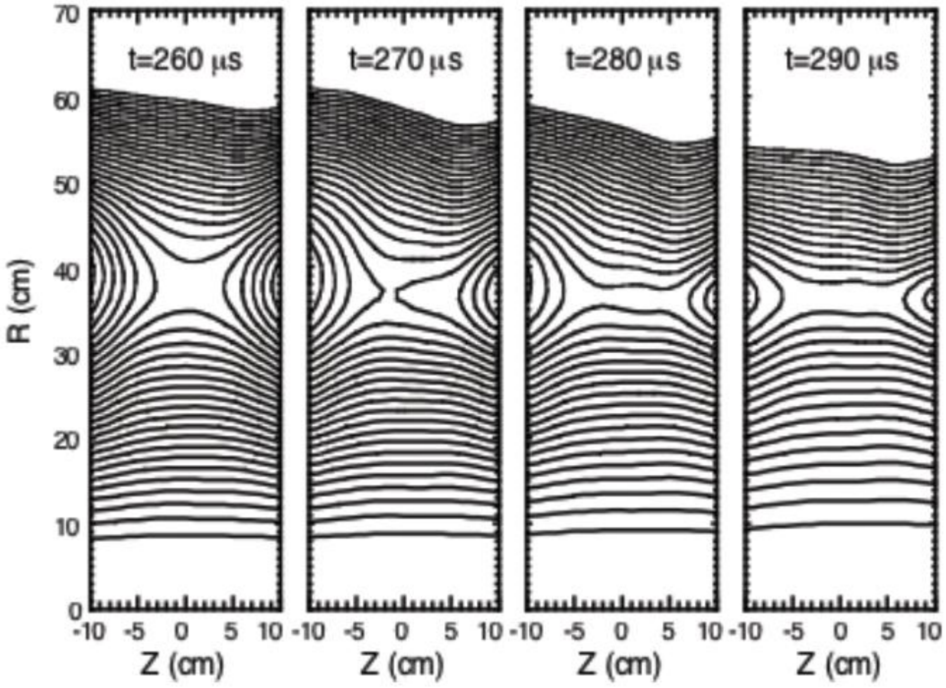


The MRX experiment at PPPL

Experimental Setup and Formation of Current Sheet



Experimentally measured flux evolution



n_e= 1-10 x10^{13} cm^{-3},

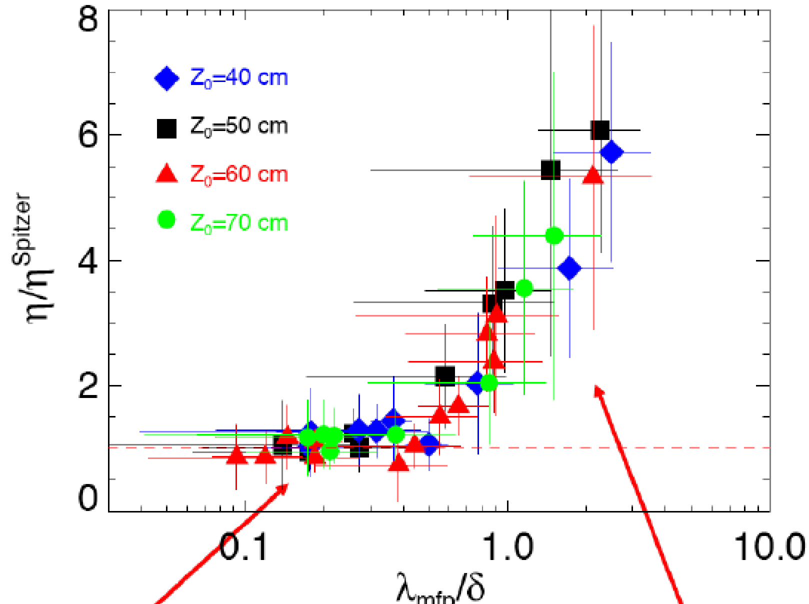
T_e~5-15 eV,

B~100-500 G,

Resistivity increases as collisionality is reduced in MRX

Effective resistivity

$$\eta^* \equiv \frac{E_\theta}{j_\theta}$$



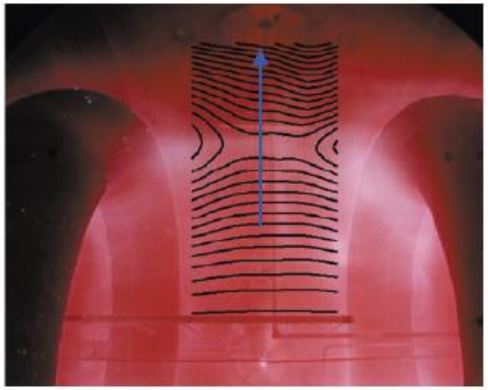
Close to classical Spitzer

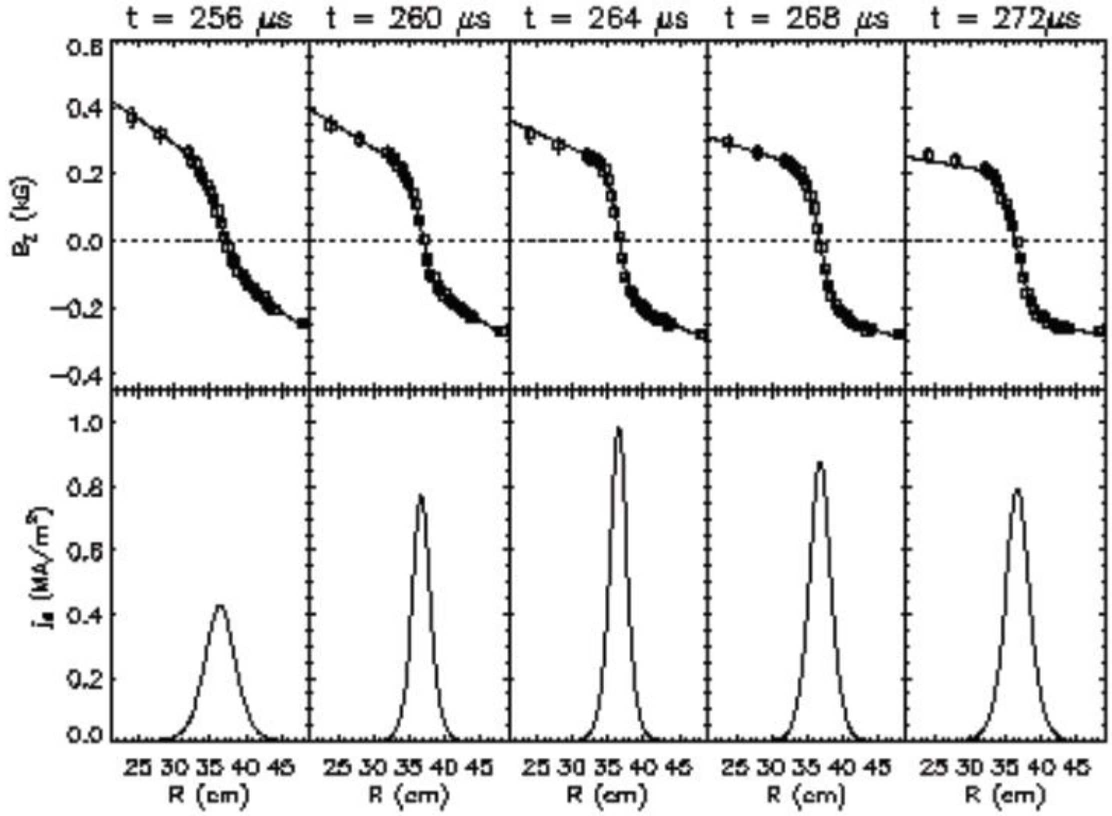
$$\eta_\perp^{Spitzer} = 1.03 \times 10^{-4} T_e^{-3/2} Z \ln \Lambda$$

Enhanced in low collisional plasma

Ji et al. '98
Trintchouk et al, '03
Kuritsyn et al, '06

The measured current sheet profiles agree well with Harris theory





$$B_z = -B_0 \tanh\left(\frac{x}{\delta}\right)$$

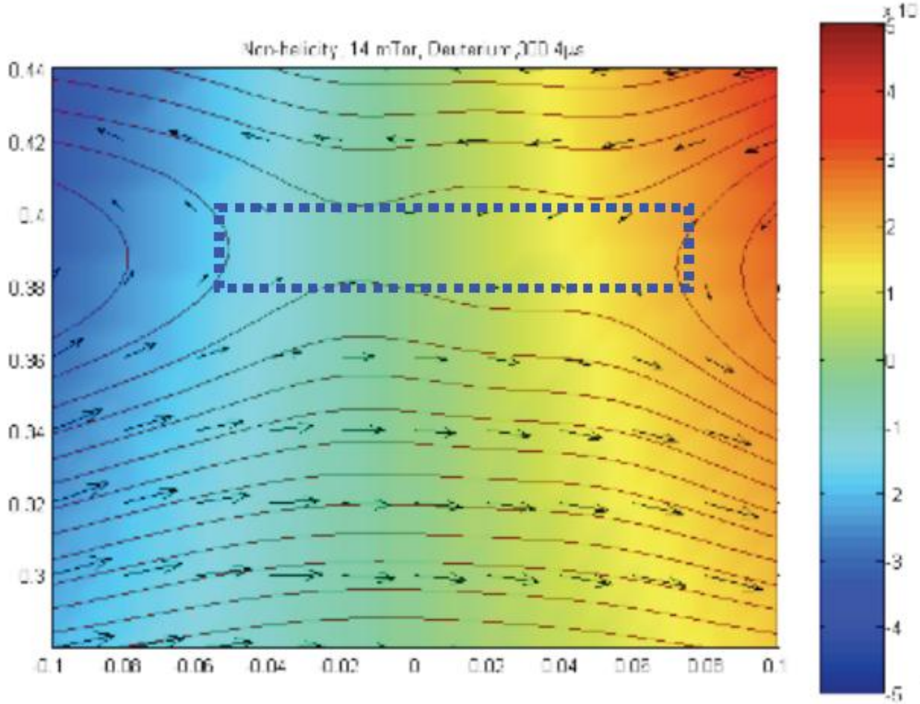
$$j_y = \frac{B_0}{\mu_0 \delta} \operatorname{sech}^2\left(\frac{x}{\delta}\right)$$

$$p = n_0(T_e + T_i)\operatorname{sech}^2\left(\frac{x}{\delta}\right)$$

$$\delta = \frac{c}{\omega_{\rm pi}} \frac{\sqrt{2(T_e + T_i)/m_i}}{V_i - V_e}$$

$$= \frac{c}{\omega_{\rm pi}} \frac{\sqrt{2}V_s}{V_{\rm drift}}$$

(Yamada, Ji, Kulsrud, et al., Phys. Plasmas, 7, 1781, 2000)



Neutral sheet Shape in MRX

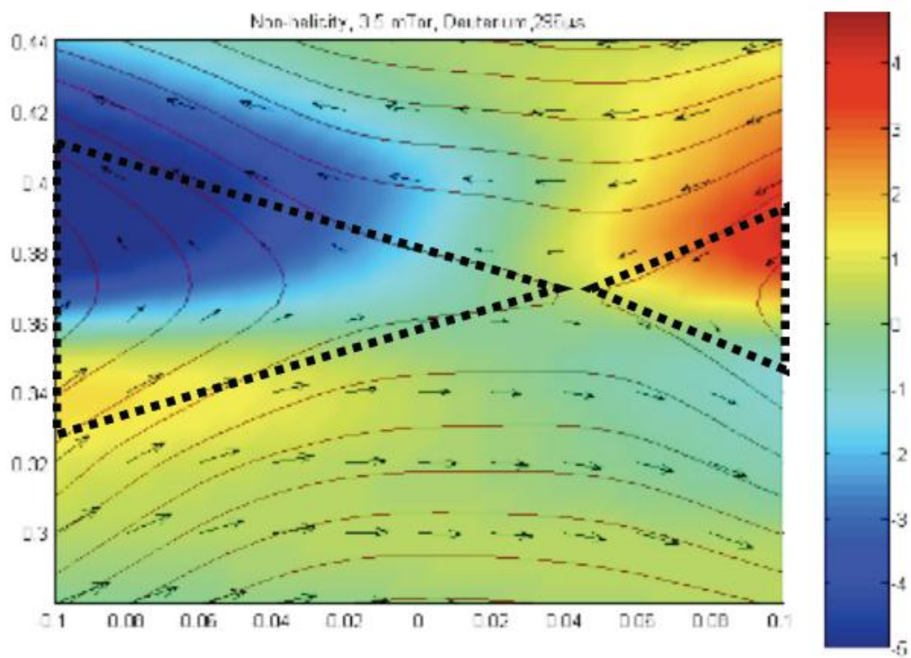
Changes from "Rectangular S-P" type to "Double edge X" shape as collisionality is reduced

Rectangular shape

Collisional regime: $\lambda_{mfp} < \delta$

Slow reconnection

No Q-P field



X-type shape

Collisionless regime: $\lambda_{mfp} > \delta$

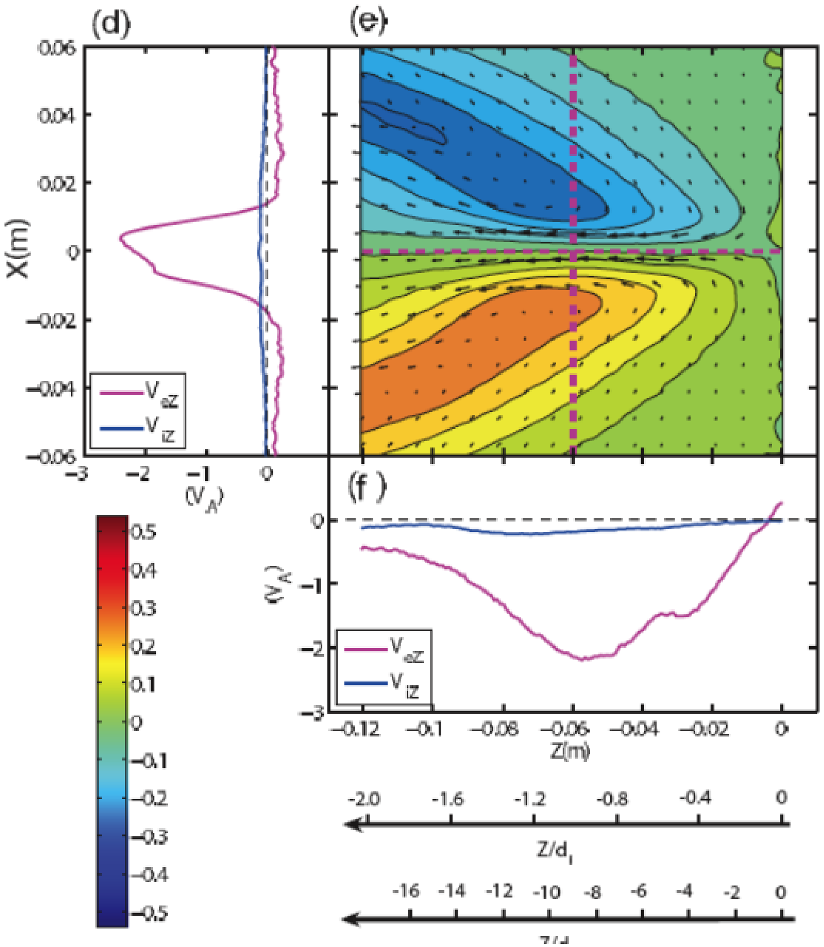
Fast reconnection

Q-P field present

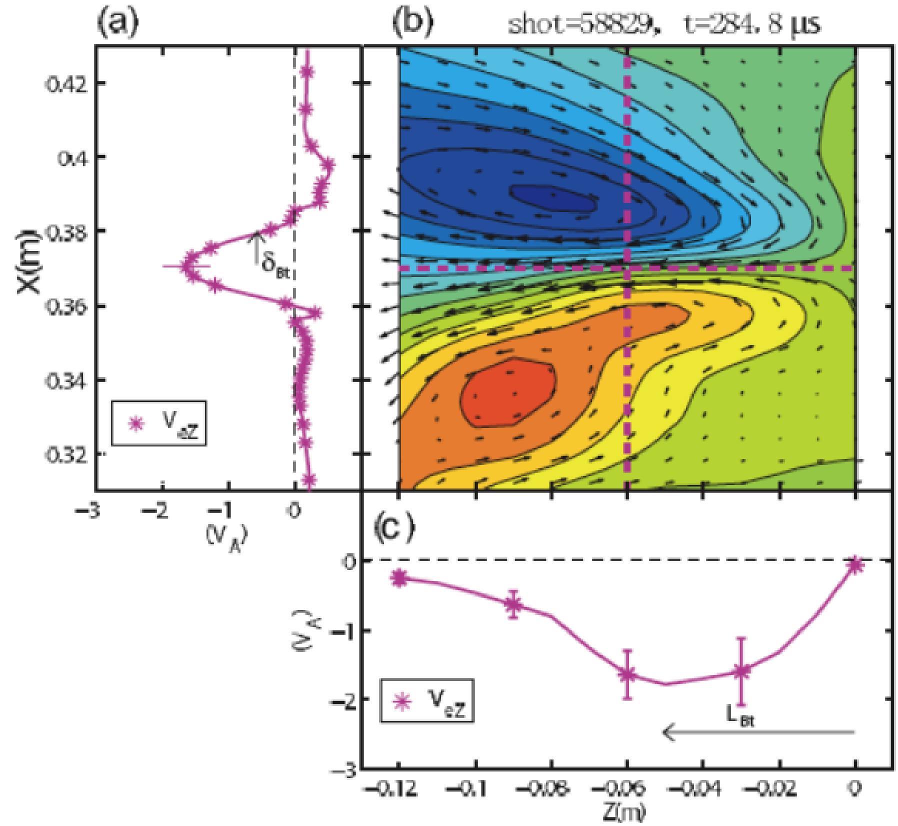
Yamada et al, PoP 2006

Experimental identification of e-diffusion region

PIC Simulation



Experiment



The electron diffusion region identified inside of the ion diffusion region in a laboratory plasma <=> The first observation of two-scale diffusion region [Ren et al, PRL 08, Ji et al GRL, 08, Dorfman et al '10]

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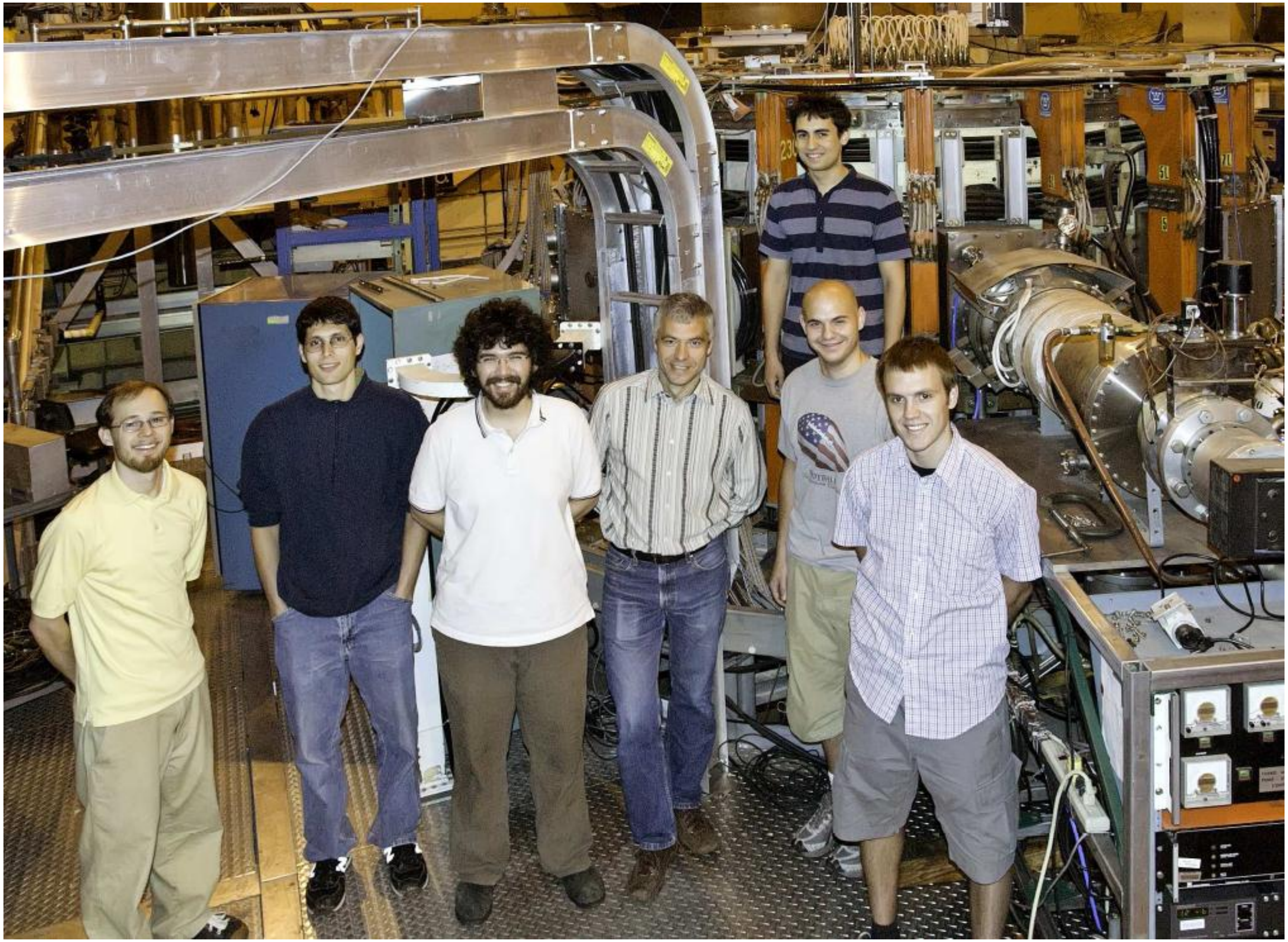
The Versatile Toroidal Facility (VTF)



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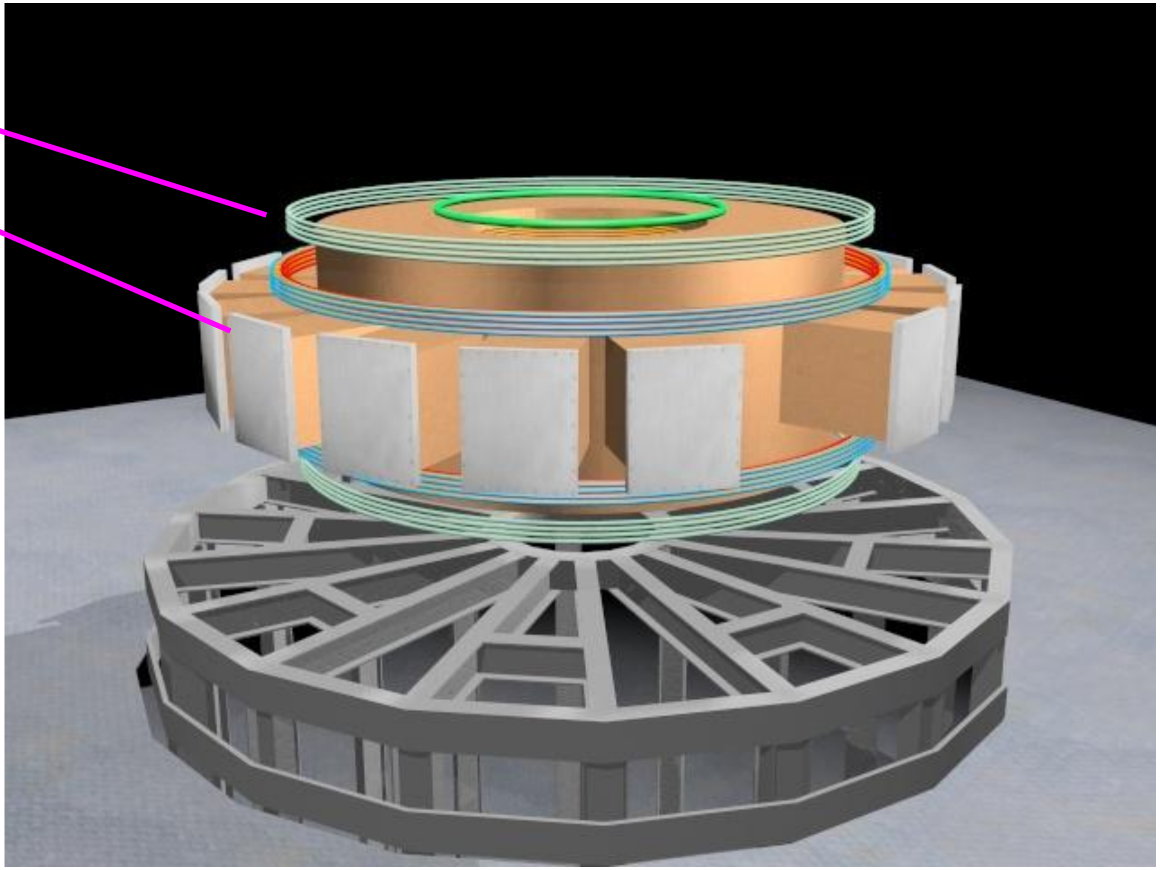

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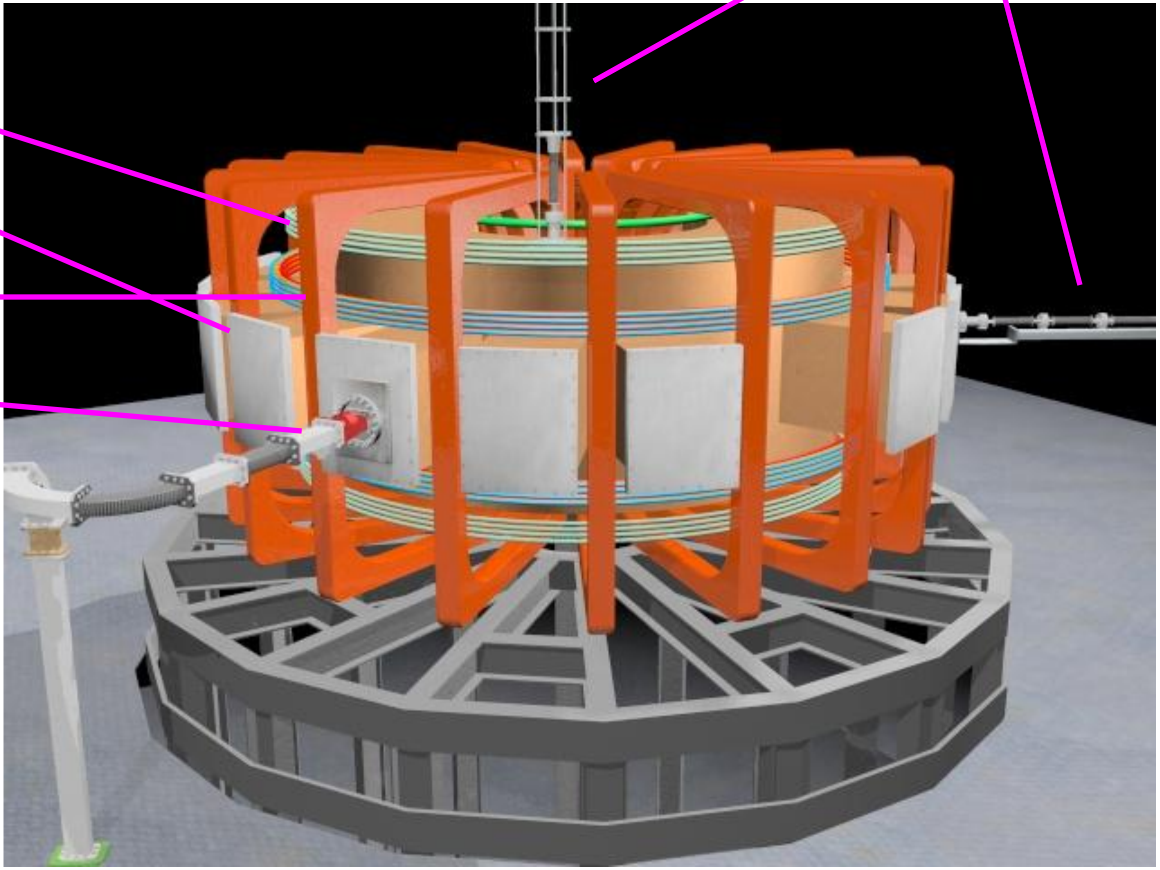

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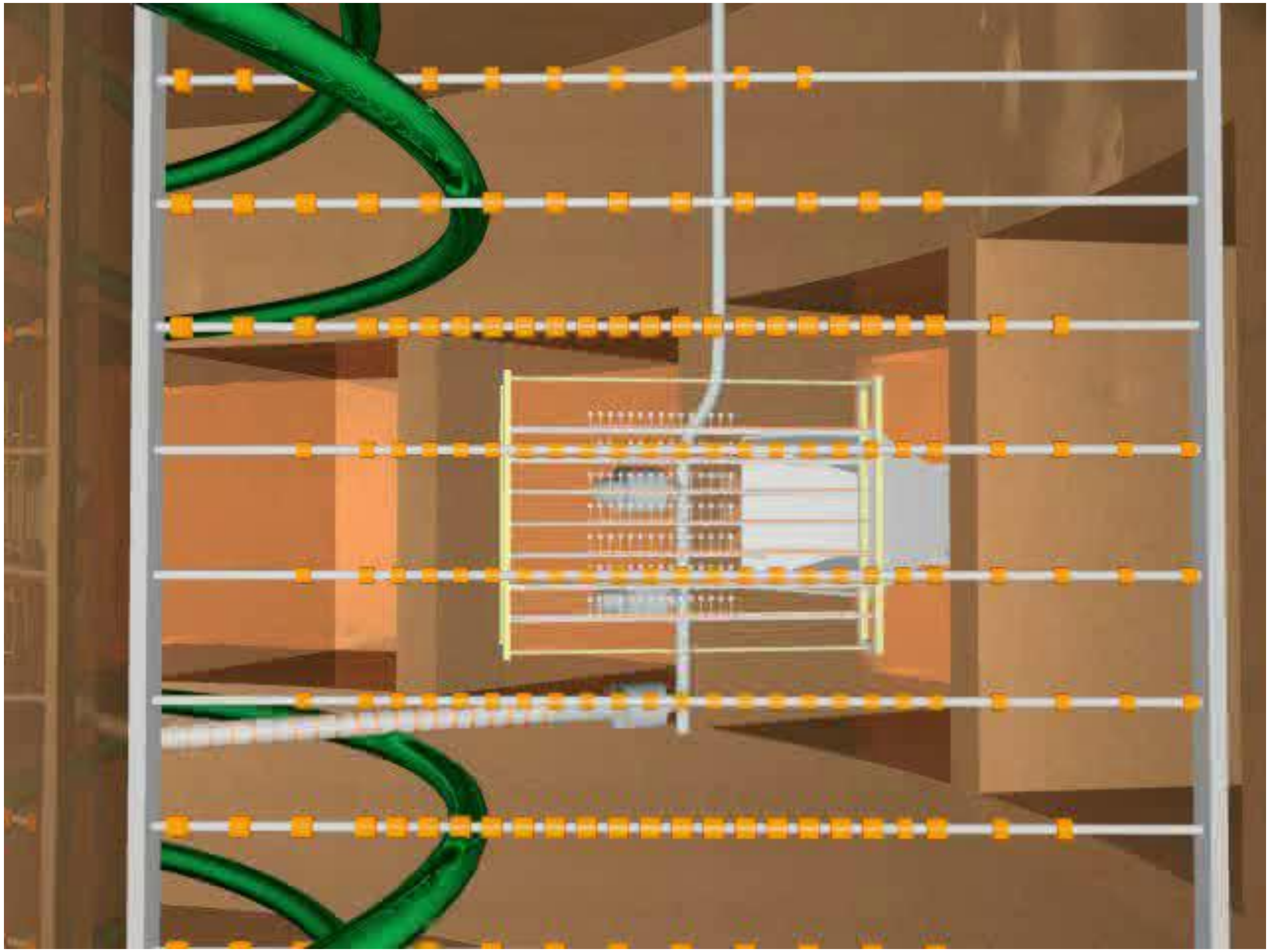


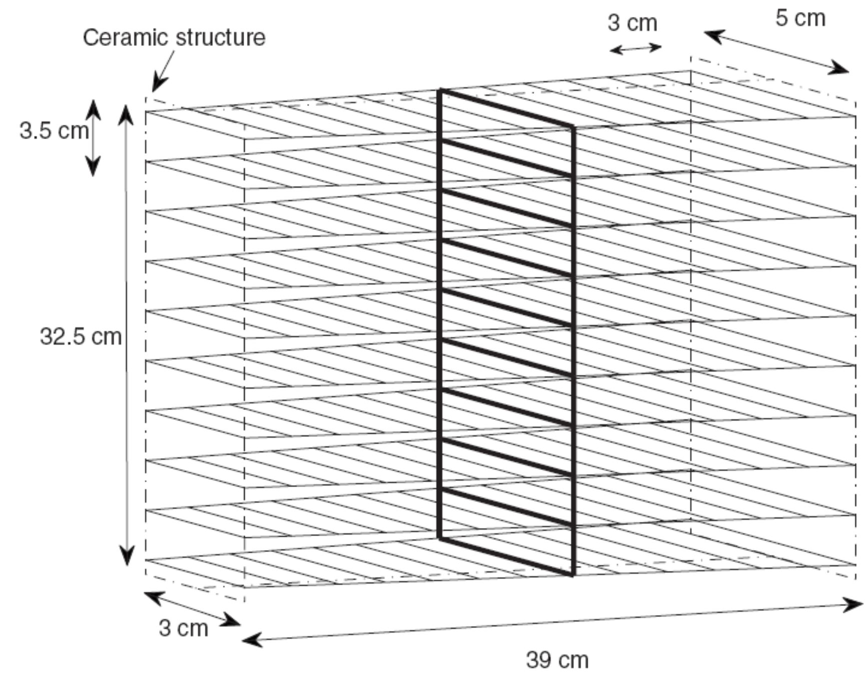
Magnetic Diagnostics

- Voltage in loops ~ (dB/dt) A
- Assuming toroidal symmetry we can use $\mathbf{B}_{\text{pol}}=\nabla\times(A_\phi \mathbf{e}_\phi)$ and build an array to integrate up A_ϕ

$$\Psi = RA_\phi$$

$$\Delta_R\dot{\Psi} = \dot{\Psi}(R_1,Z_0) - \dot{\Psi}(R_0,Z_0) = \int_{R_0}^{R_1} R\dot{B}_Z dR$$

$$\Delta_Z\dot{\Psi} = \dot{\Psi}(R_0,Z_1) - \dot{\Psi}(R_0,Z_0) = -R\int_{Z_0}^{Z_1} \dot{B}_R dZ$$

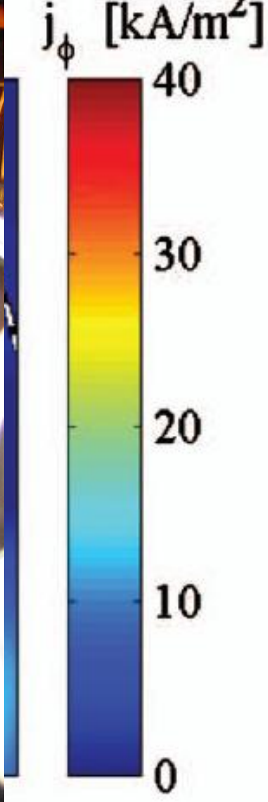


Magnetic flux array

Kesich et al., RSI 79, 063505 (2008)

Magnetic Array

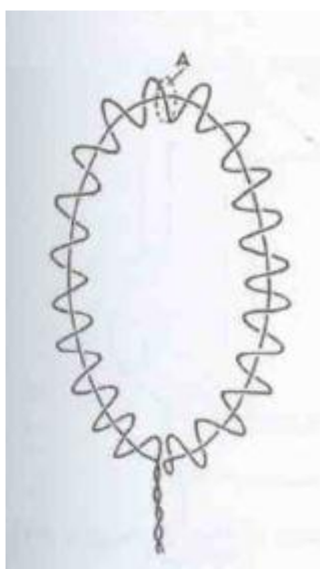
Measured current & magnetic field

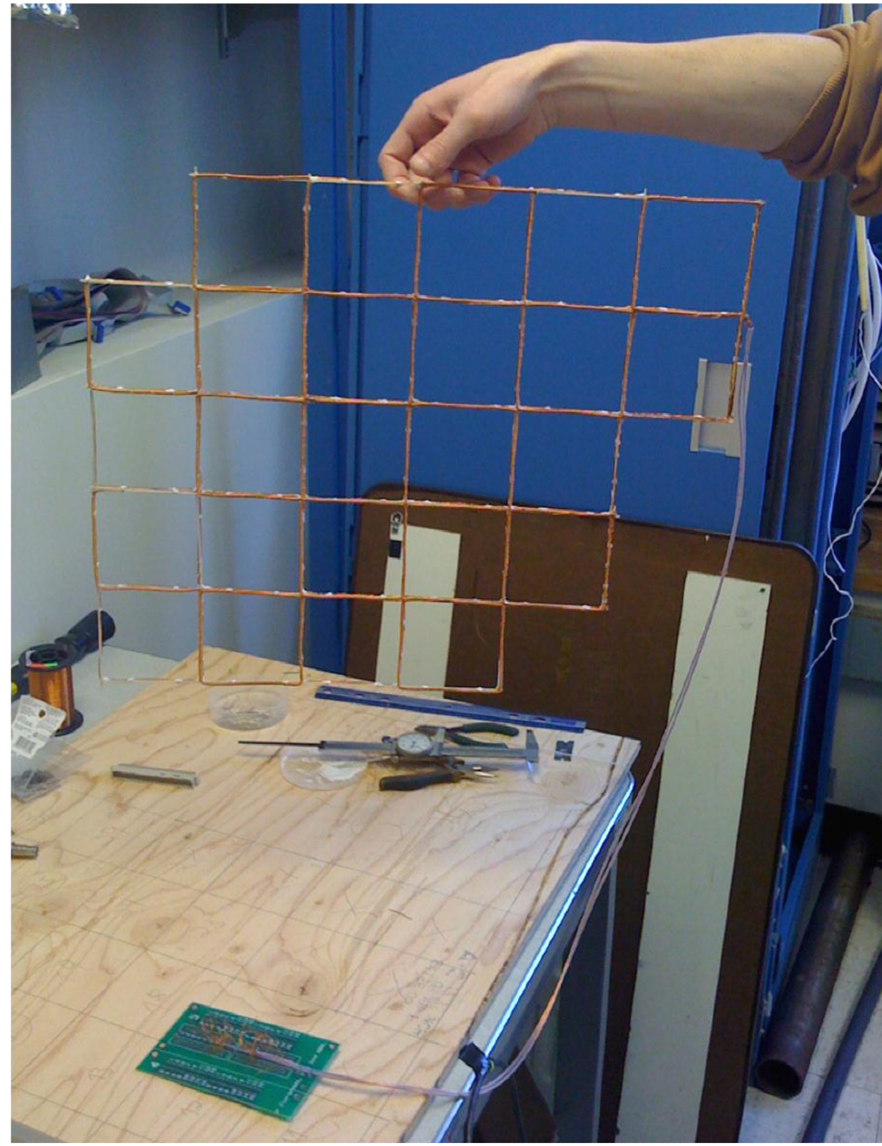


Rogowski Array

- Construction: copper wire wound on teflon tube
- Measures current through each opening

$$\Phi = n \oint_l \int_A dA\, \mathbf{B} \cdot d\mathbf{l},$$

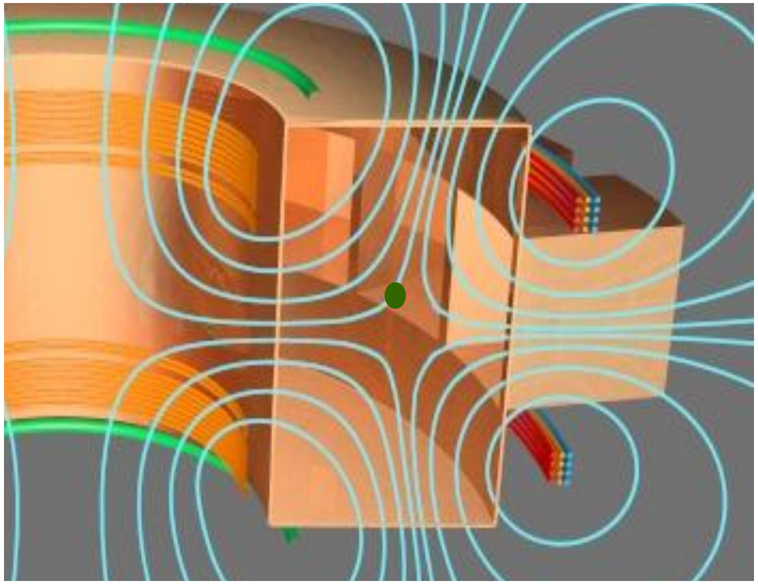


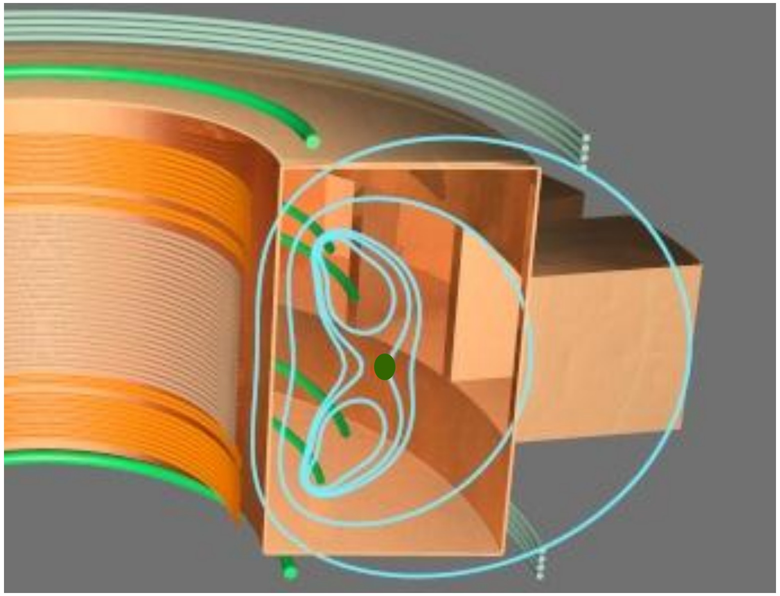


Two different magnetic configurations

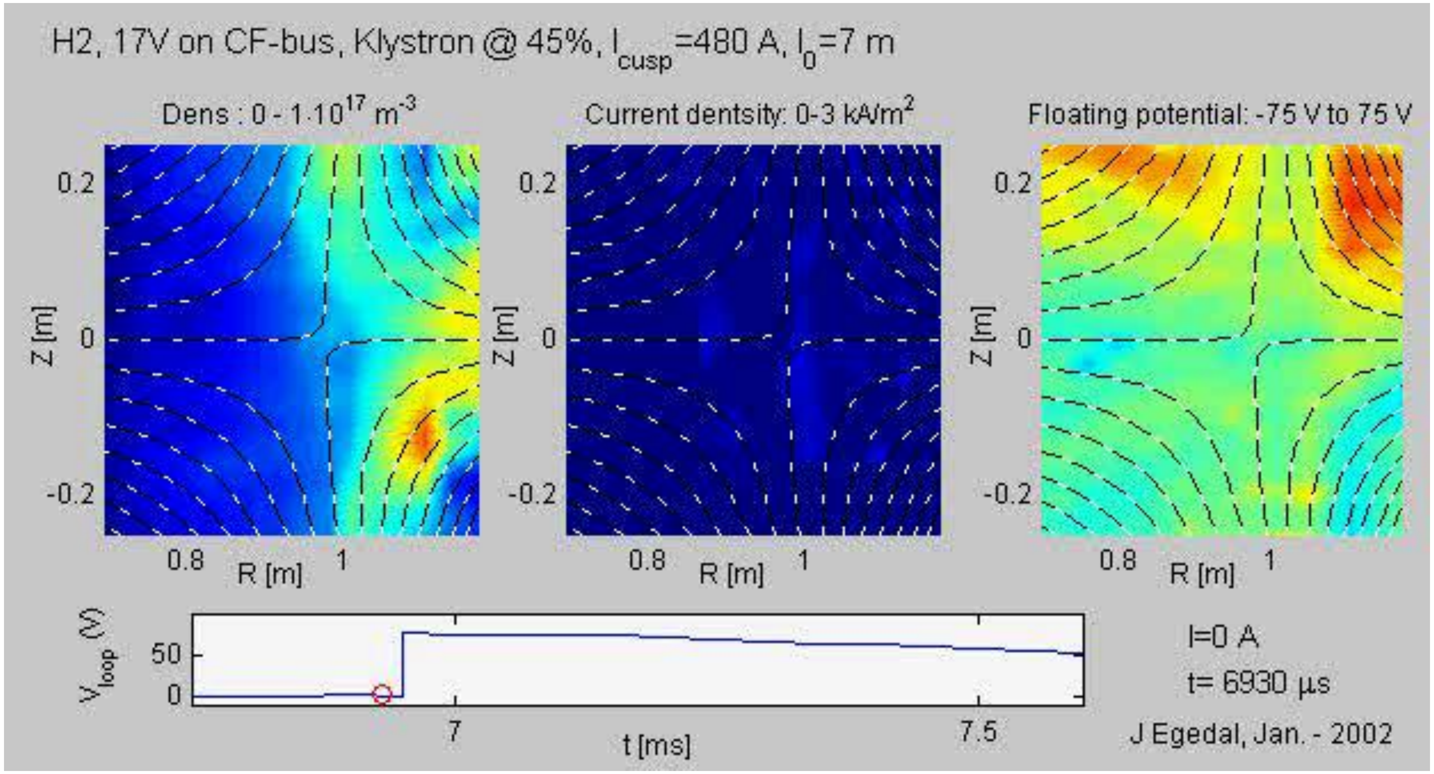
An open cusp magnetic field.
Fast reconnection by
trapped electrons.

A closed cusp by internal coil.
Passing electrons & spontaneous
reconnection events.



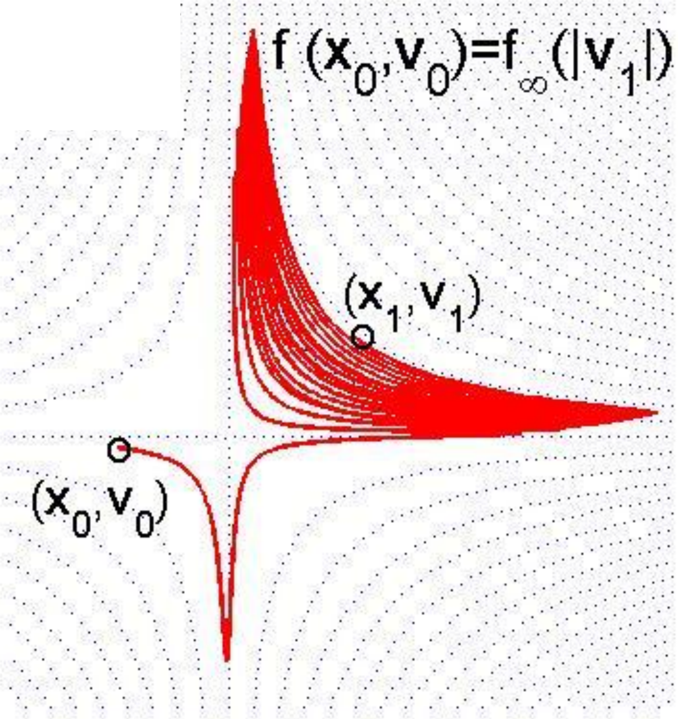


Plasma response to driven reconnection



Kinetic modeling

- Why is the experimental current density so small?
- Liouville/Vlasov's equation: df/dt=0
- For a given ($\mathbf{x}_0$,$\mathbf{v}_0$), follow the orbit back in time to $\mathbf{x}_1$
- Particle orbits calculated using electrostatic and magnetic fields consistent with the experiment.
- Massively parallel code evaluates $f(\mathbf{x}_0,\mathbf{v}_0) = f_\infty(|\mathbf{v}_1|)$.



J. Egedal et al., Computer Physics Communications , (2004)

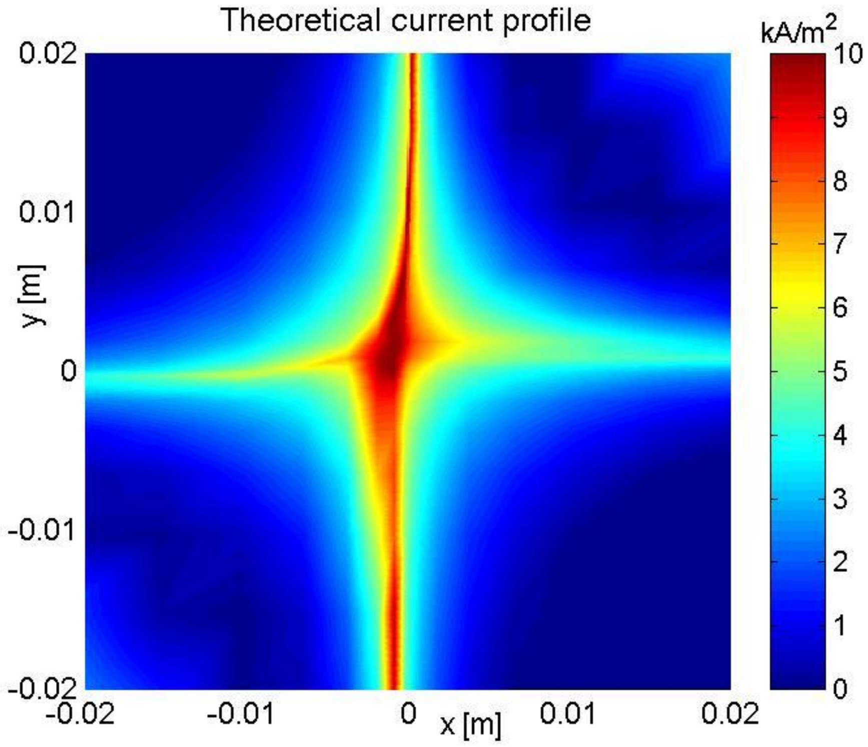
Kinetic modeling

- The current is calculated as $j_{\parallel} = \int \mathrm{v}_{\parallel} f \, d\mathrm{v}^3$
- Theory consistent with measurements

  (B-probe resolution: 1.5cm)

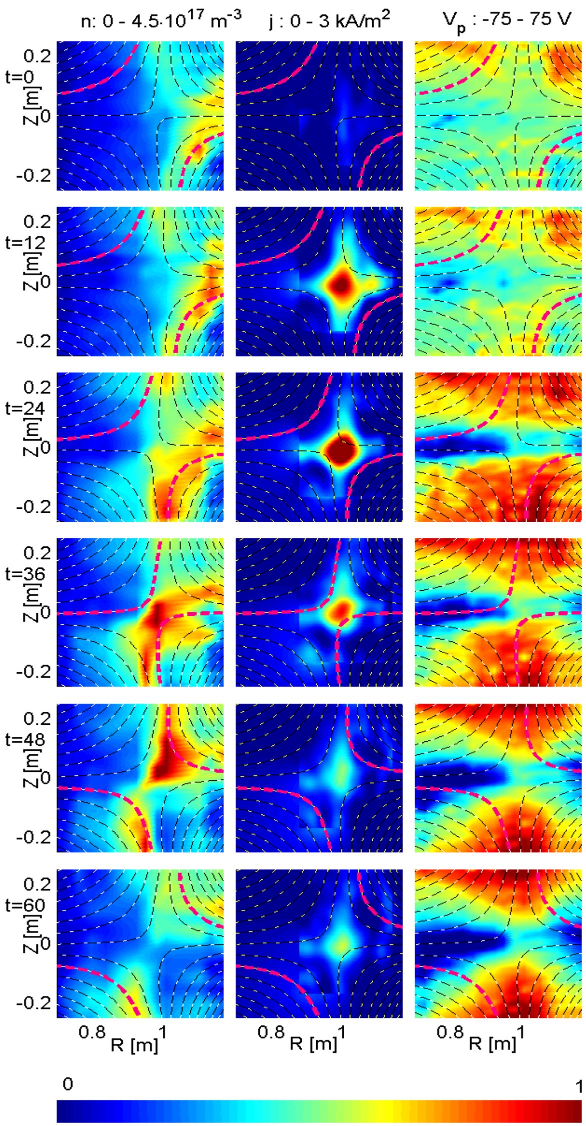
- Experimental scaling $j \sim n l_0 E_z$ is reproduced

Theory

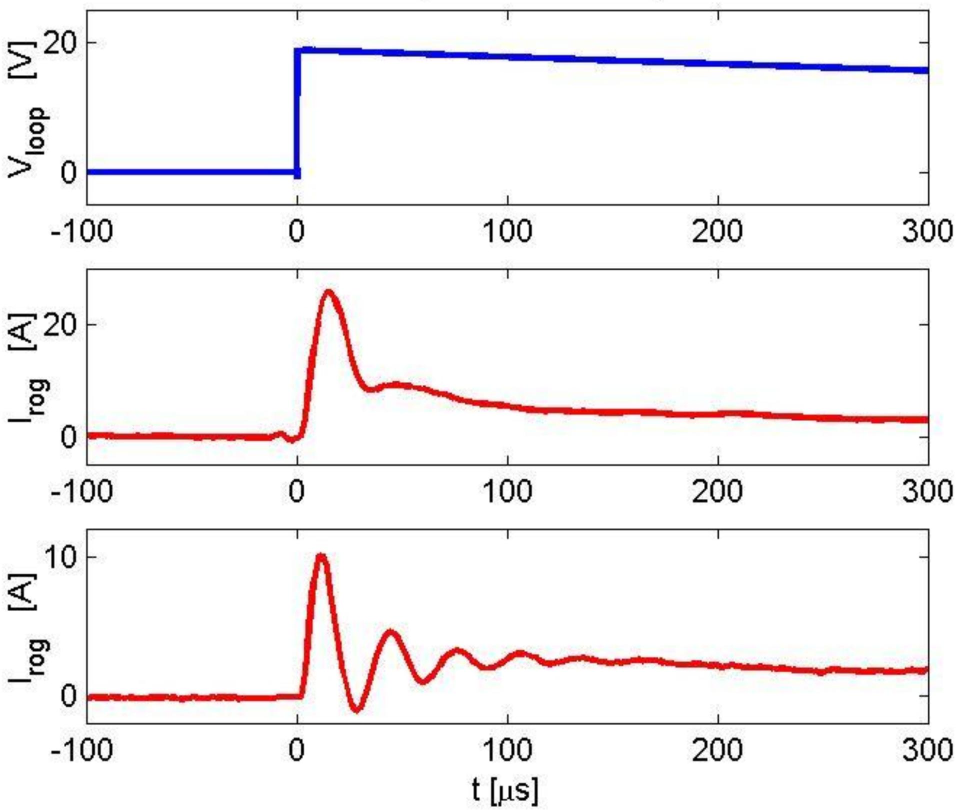


Experiment

Temporal evolution of the current channel

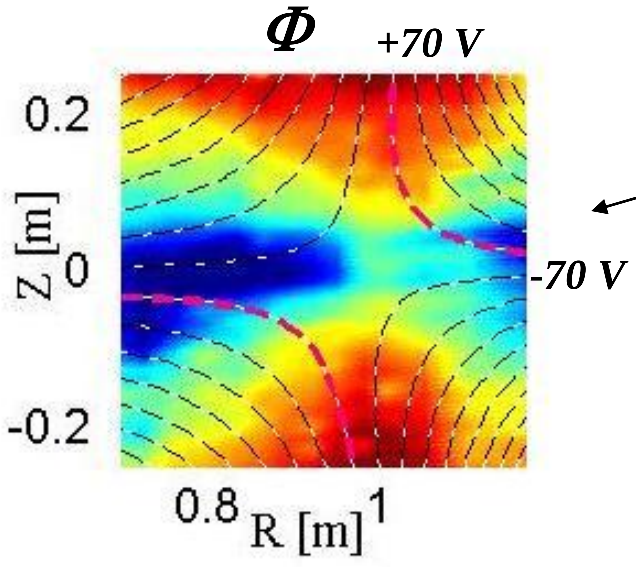


Time response of the toroidal current



Eigen response, f= 10-30 kHz

The electrostatic potential



Experimental potential, *Φ*

Electron flow:

$$v_{E\times B} = \frac{-\nabla\Phi \times \mathbf{B}_g}{B^2}$$

Ideal Plasma:

$$\mathbf{E}\cdot\mathbf{B} = 0 \quad {}_{ol}\cdot\mathbf{B}_{cusp} = 0$$

External fields

2mT

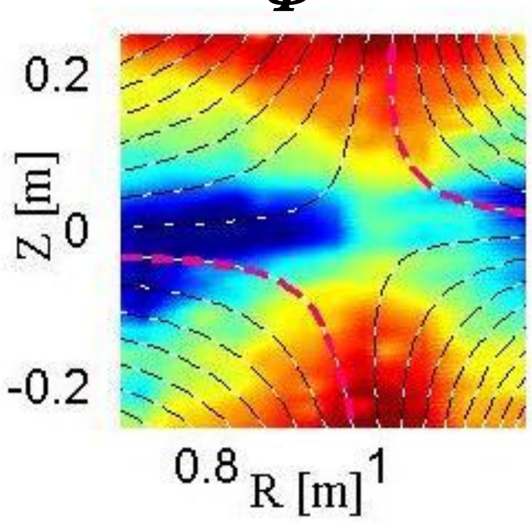
10V/m

87mT

∇Φ ~500V/m

The electrostatic potential

$\boldsymbol{\Phi}$

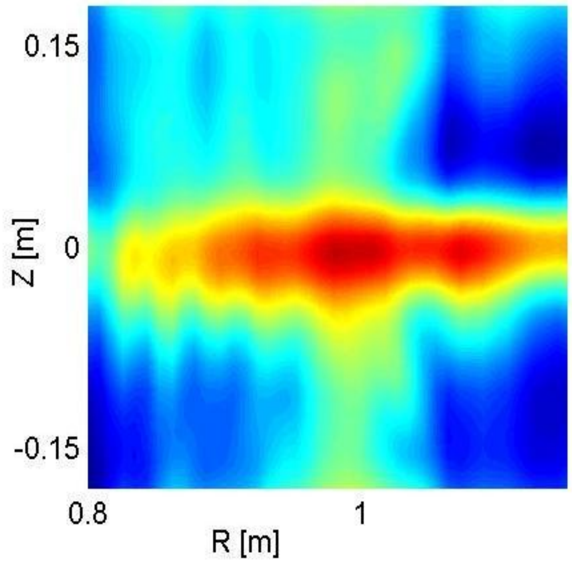


Ideal Plasma:

$$E_\phi B_\phi + \mathbf{E}_{pol} \cdot \mathbf{B}_{cusp} = 0$$

Frozen in law is broken where E•B≠0

$\mathbf{E} \cdot \mathbf{B}$



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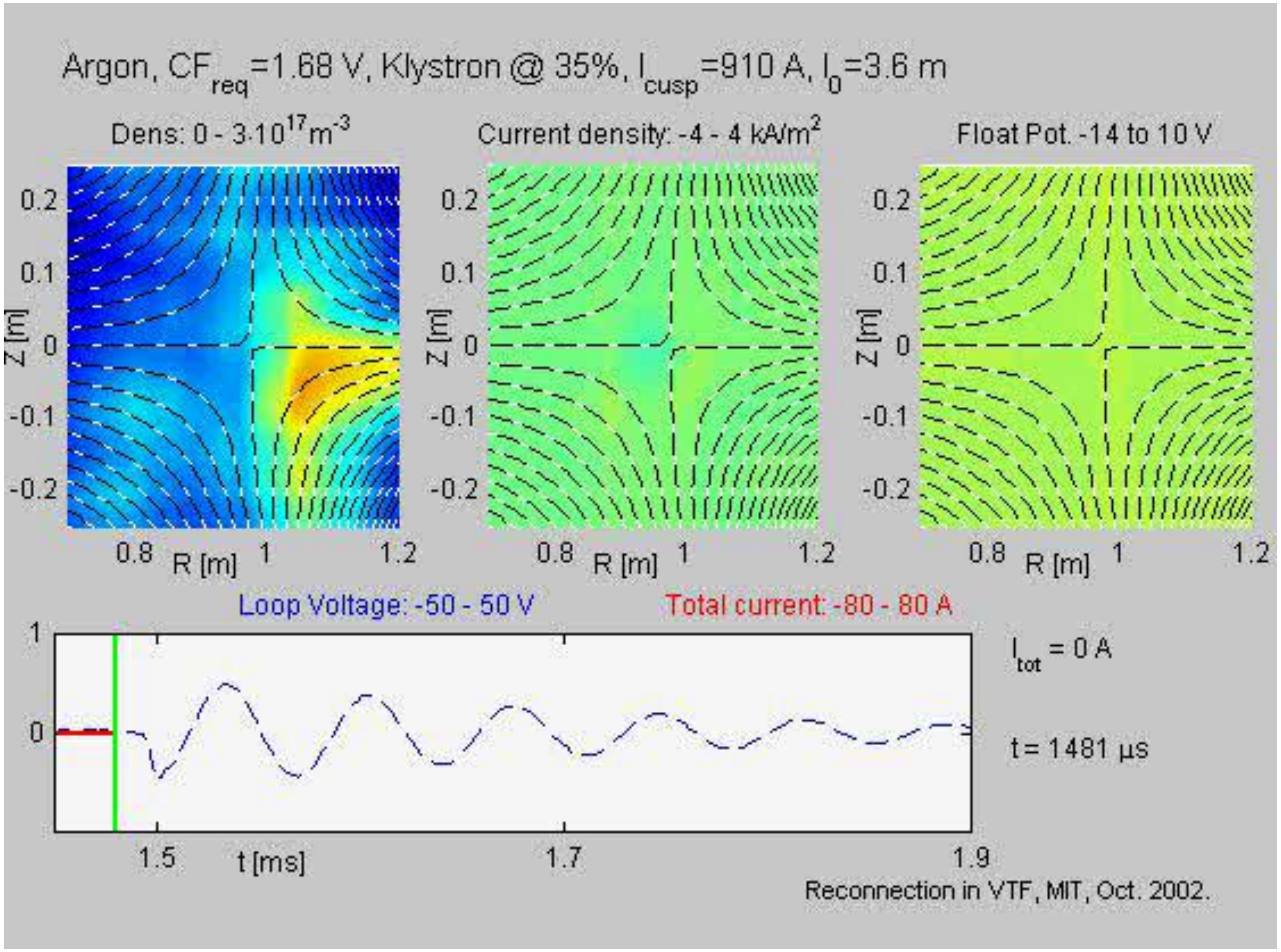


Ion polarization currents due to dΦ/dt

Ion polarization current:

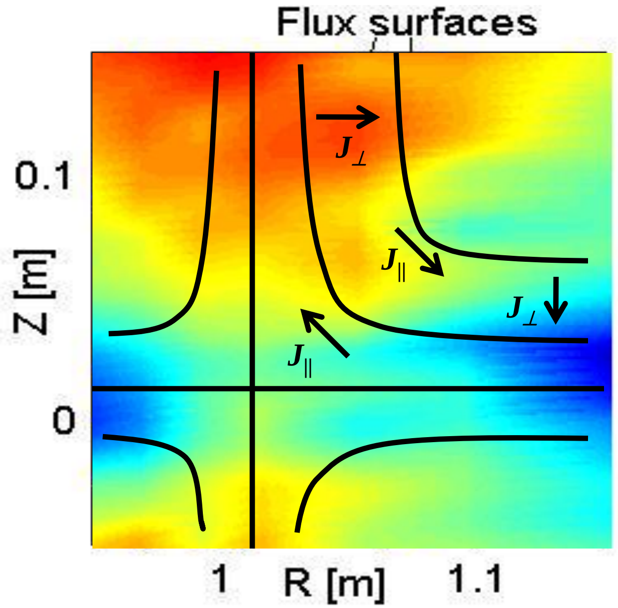
$$\mathbf{j}_{\perp} = -\frac{nm}{B^2}\nabla_{\perp}\left(\frac{d\Phi}{dt}\right)$$

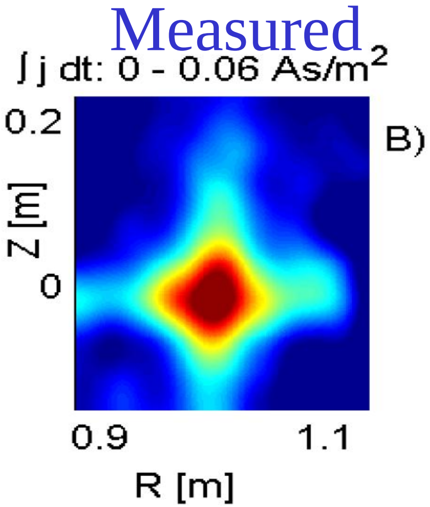
Quasi neutrality:

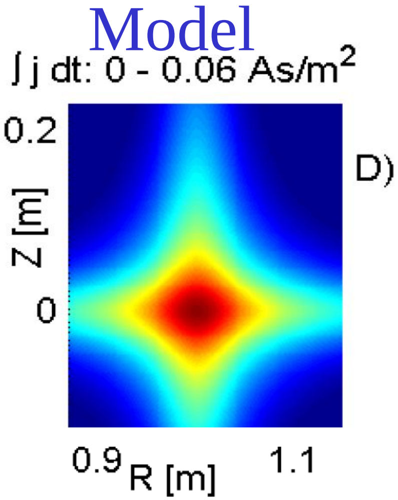
$$\nabla\cdot(\mathbf{j}_{\perp}+\mathbf{j}_{||}) = 0$$

$$\Downarrow$$

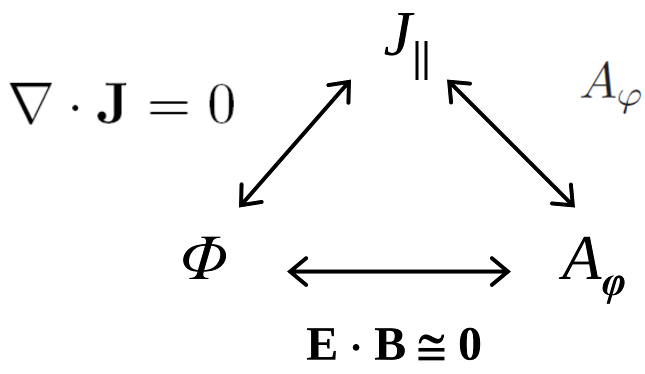
$$\frac{d}{dl_{||}}j_{||} = \frac{nm}{B^2}\nabla_{\perp}^{2}\left(\frac{d\Phi}{dt}\right)$$







Model for dynamical response

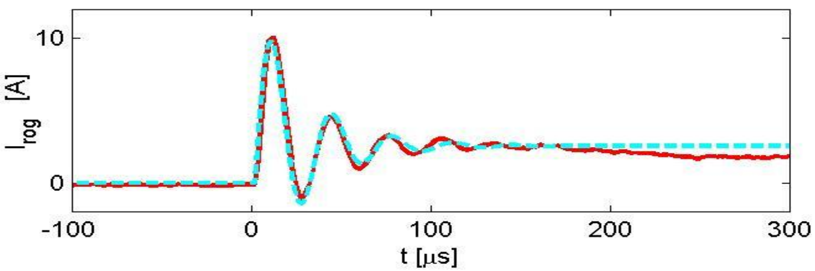


$$A_\varphi = \frac{\mu_0}{4\pi} \int \frac{J_{||}}{|\mathbf{r}' - \mathbf{r}|} d^3\mathbf{r}' \quad + A_{ext}$$

$$A_\varphi = \alpha_1 J_{||} + A_{ext} \; , \qquad J_{||} = \alpha_2 \, d\Phi/dt \; , \quad \Phi = - \alpha_3 \, dA_\varphi/dt \; ,$$

$$A_\varphi = - \alpha \, d^2 A_\varphi / dt^2 + A_{ext} \; , \qquad \alpha = \alpha_1 \alpha_2 \alpha_3 > 0$$

Oscillating solutions



Egedal et al., PRL (2003)

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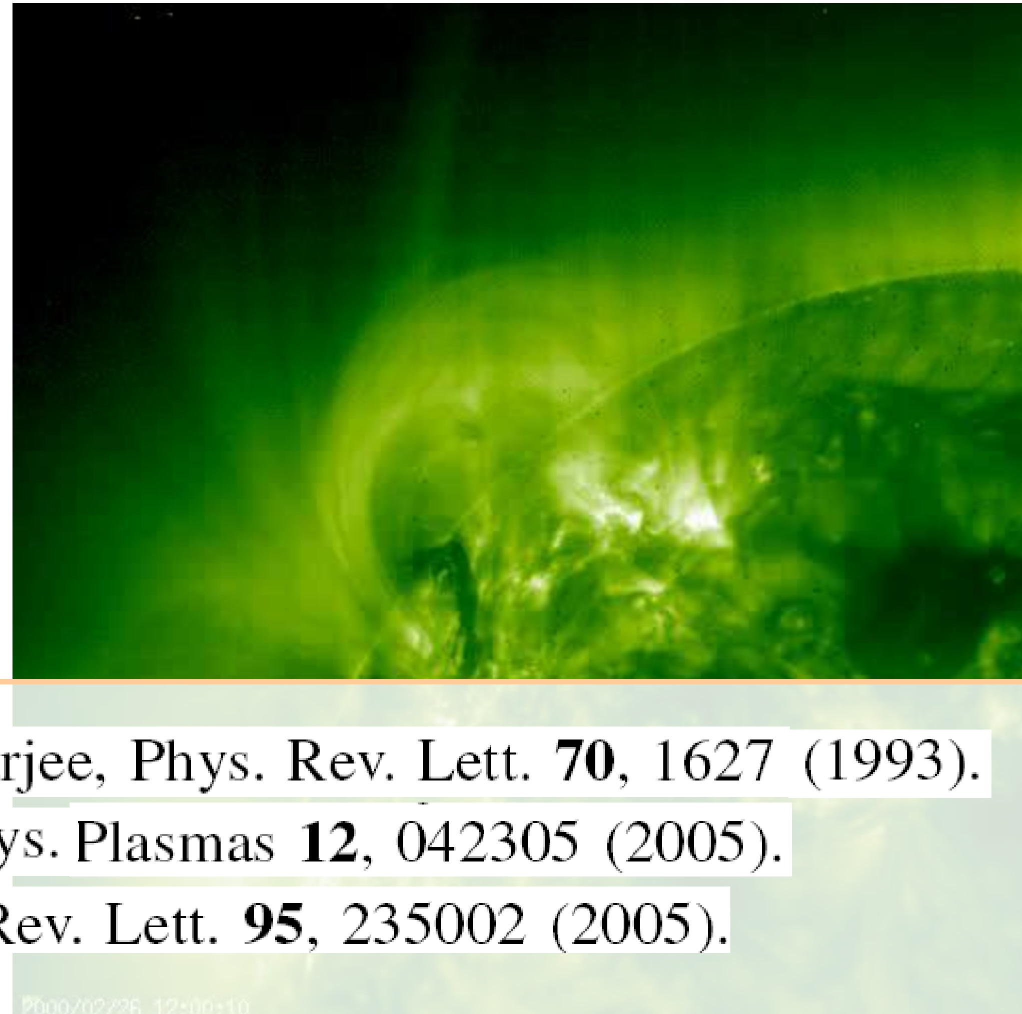
Spontaneous Reconnection

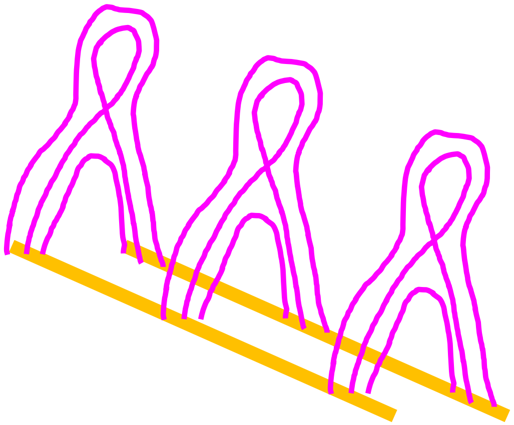
- *Coronal mass ejections:*
  - *The most powerful explosions in our solar system*



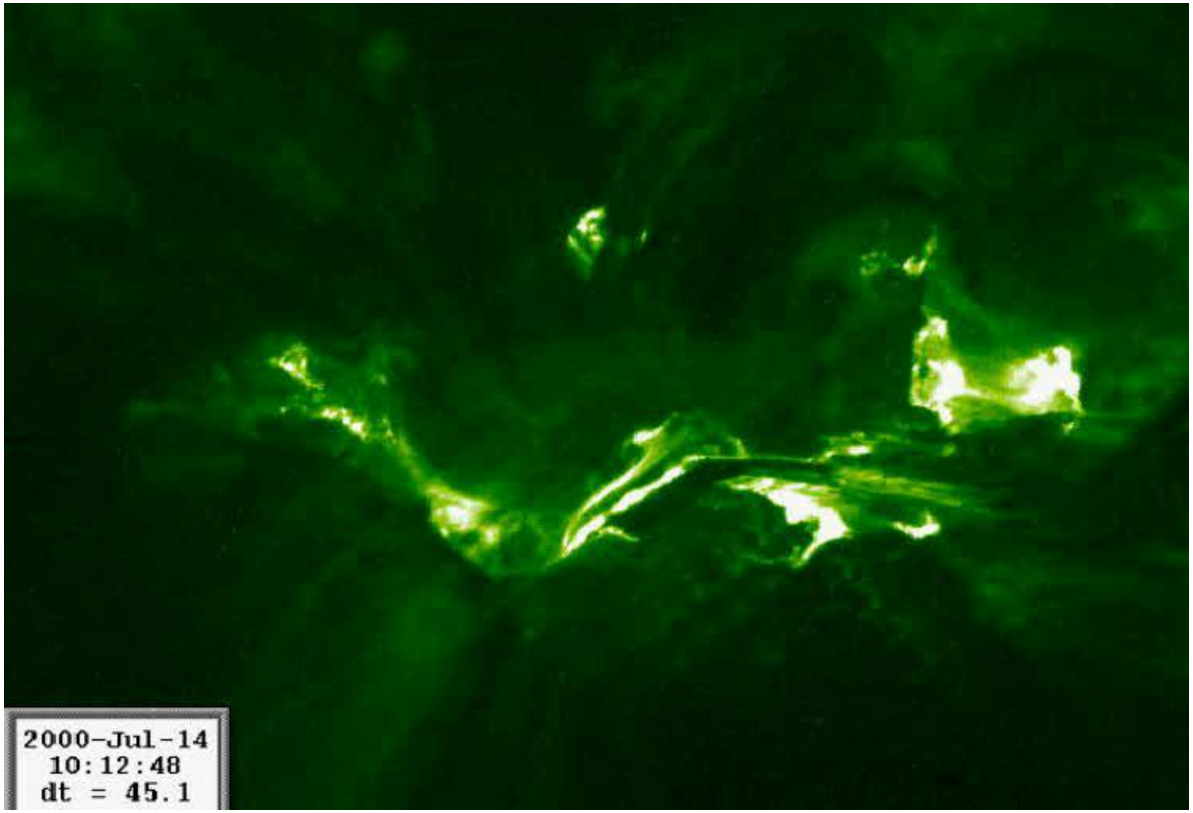
X. Wang and A. Bhattacharjee, Phys. Rev. Lett. **70**, 1627 (1993).
A. Bhattacharjee, *et al.*, Phys. Plasmas **12**, 042305 (2005).
P. A. Cassak *et al.*, Phys. Rev. Lett. **95**, 235002 (2005).

Other Outstanding Problems

Arcade

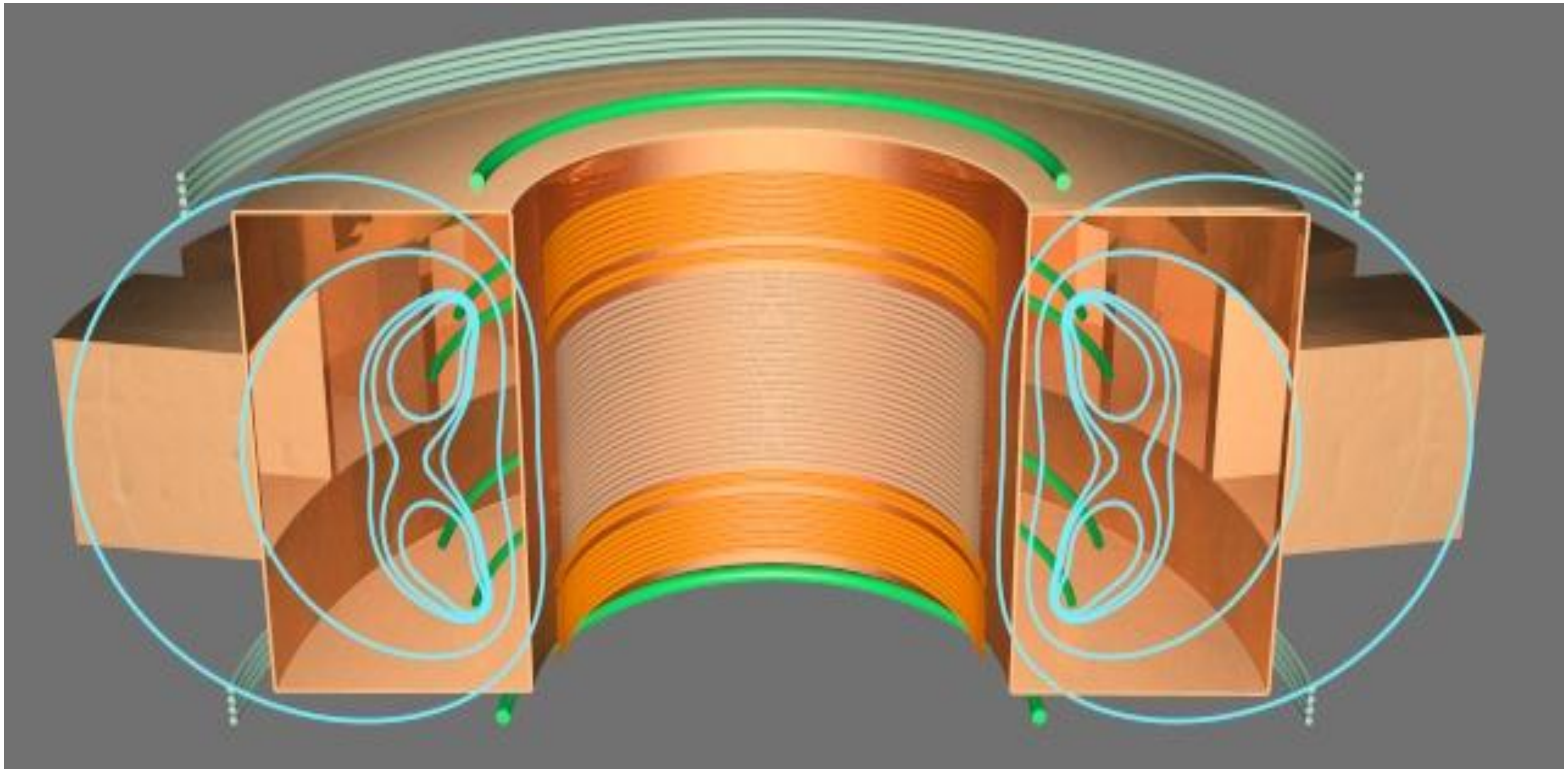


Arcade as seen from above



- **Heating**
- **3D effects**
- **Trigger**

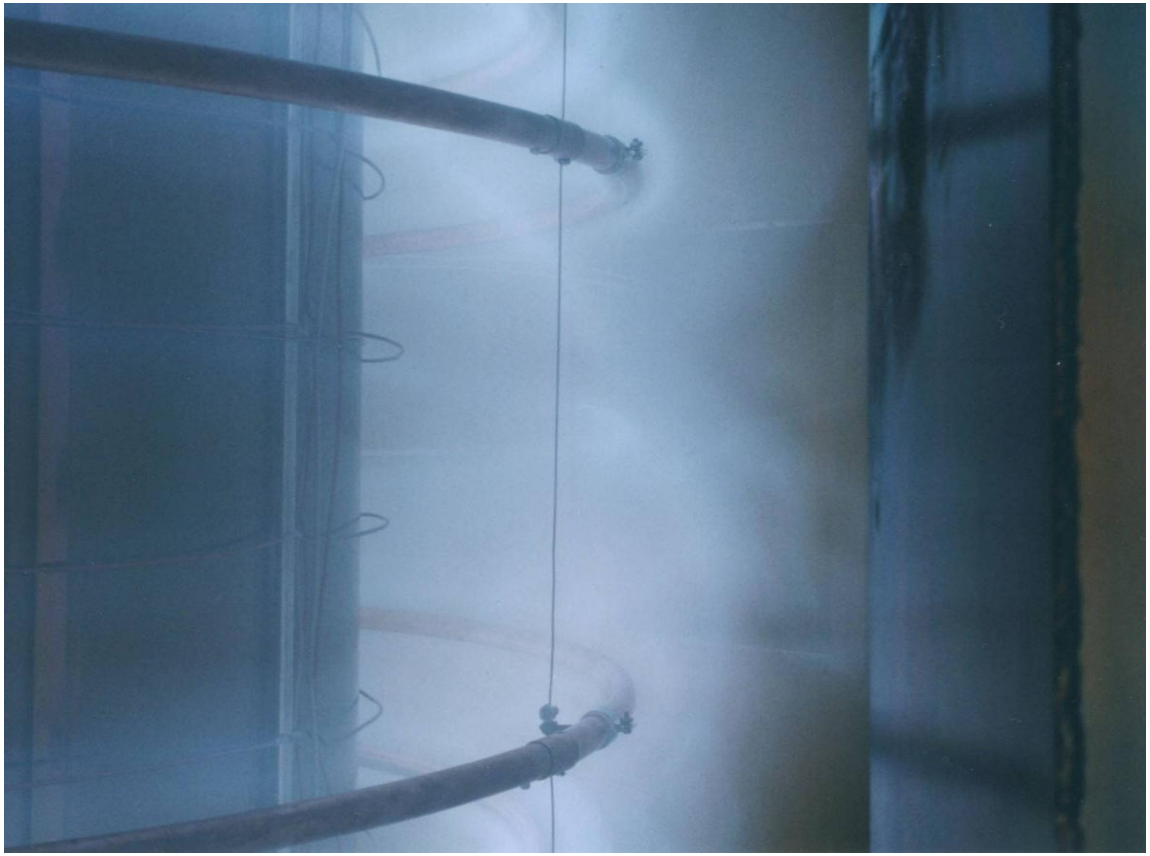
Closed Magnetic Configuration



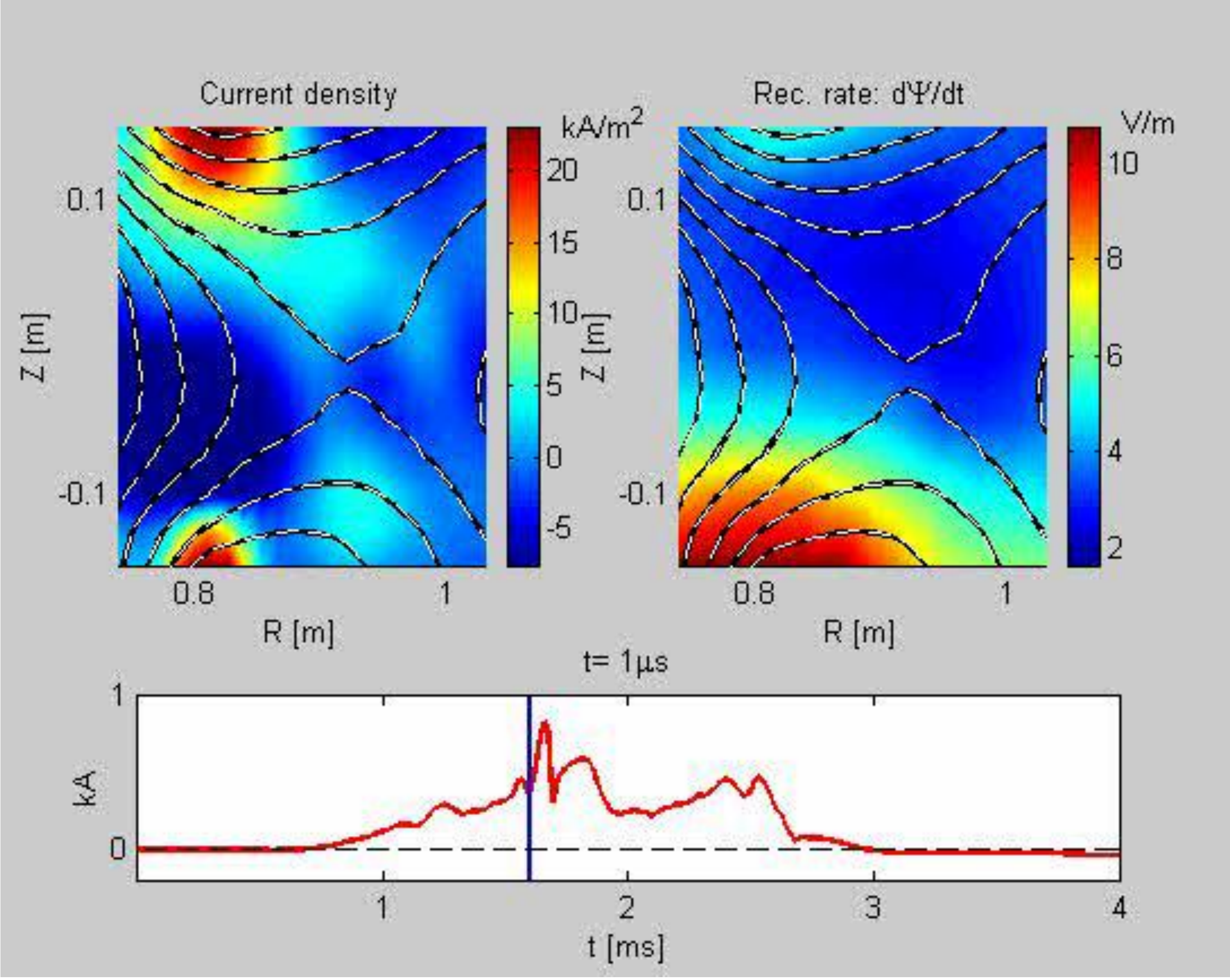
Plasma in the VTF Closed Configuration

– Visible light of
an Argon discharge

– $n_e \sim 10^{18}$ m^{-3},
$T_e \sim 15 – 25$ eV,
$\lambda_e \sim 10$ m.
$B_g \sim 50$ mT.
$B_p \sim 5$ mT

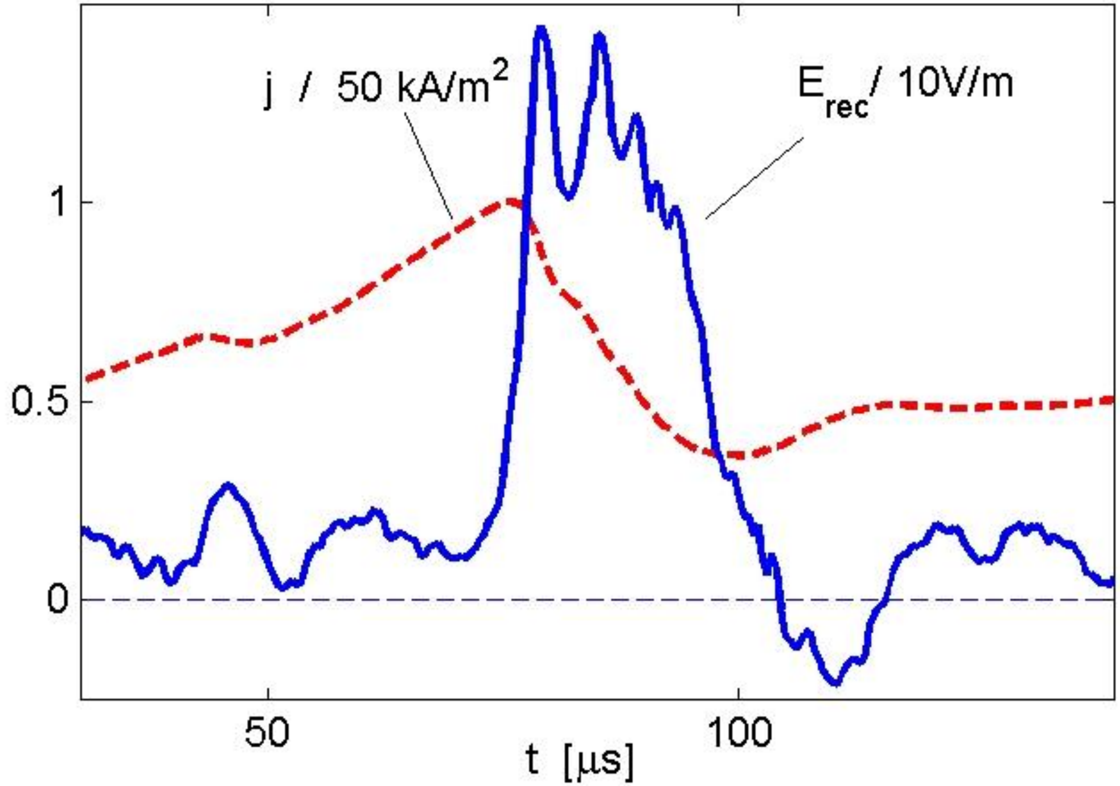


Spontaneous reconnection observed

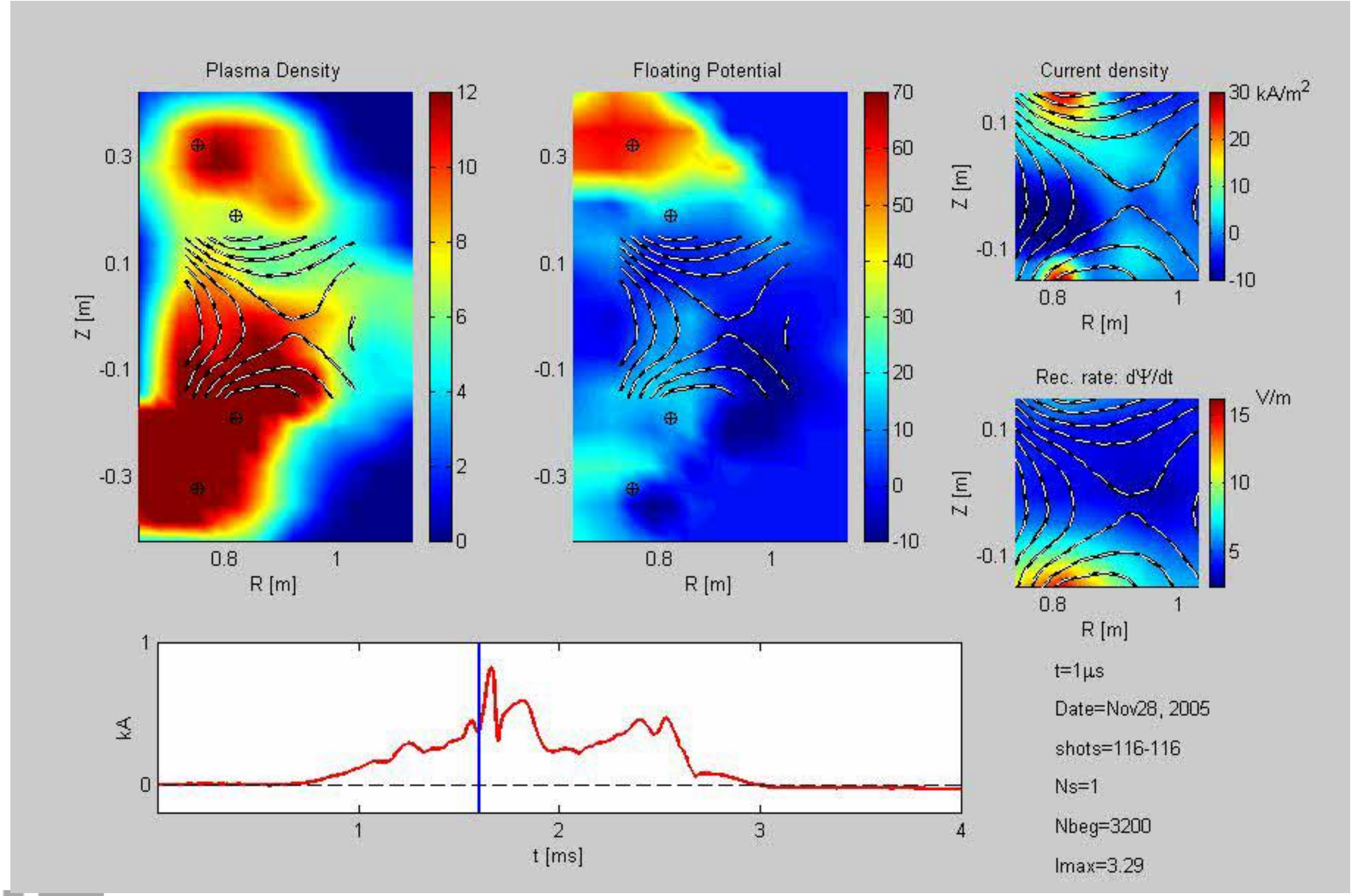


J. Egedal et al., (2007) Phys. Rev. Lett. **98**, 015003

No simple resistivity, $E \neq \eta * j$!

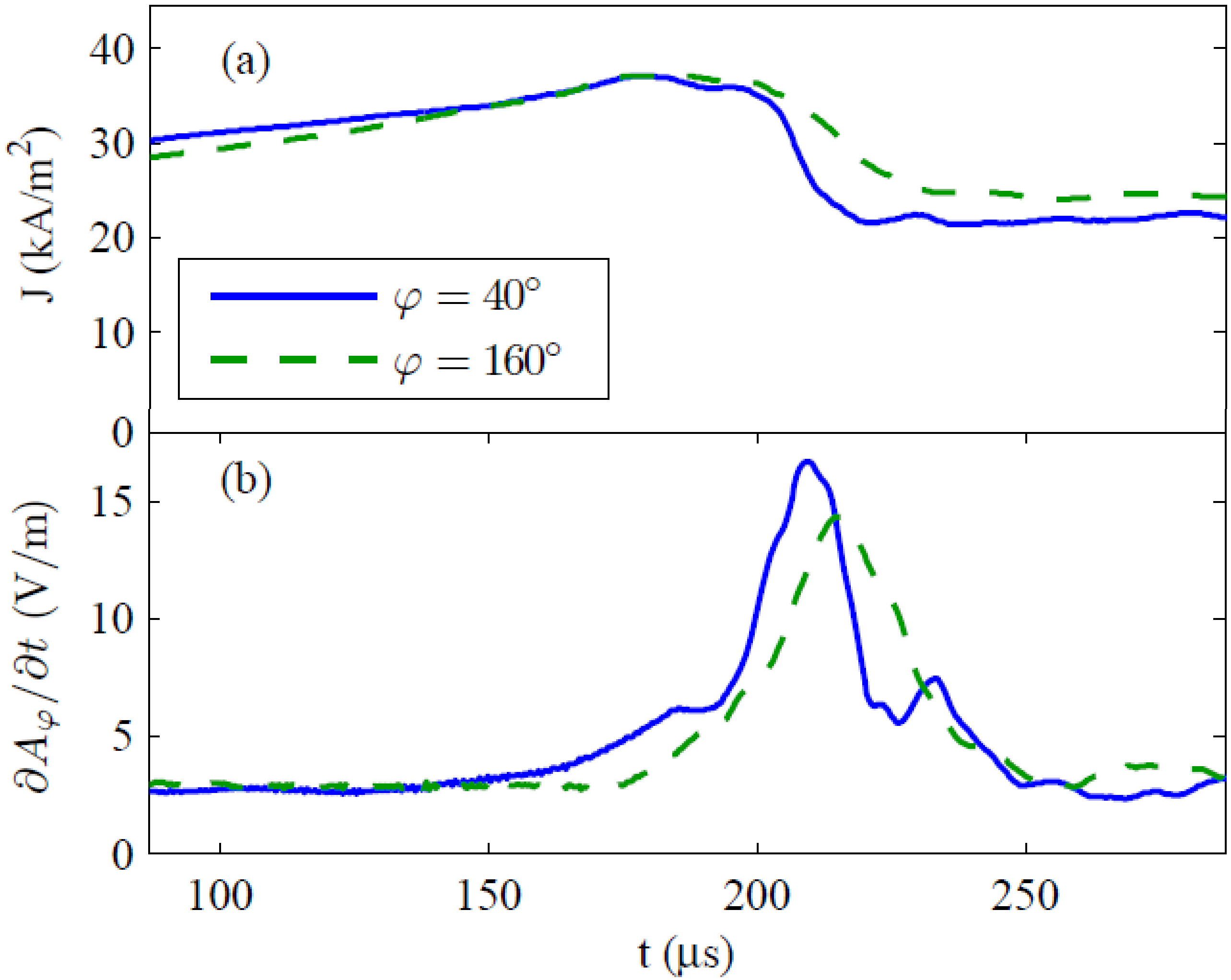


Plasma outflows



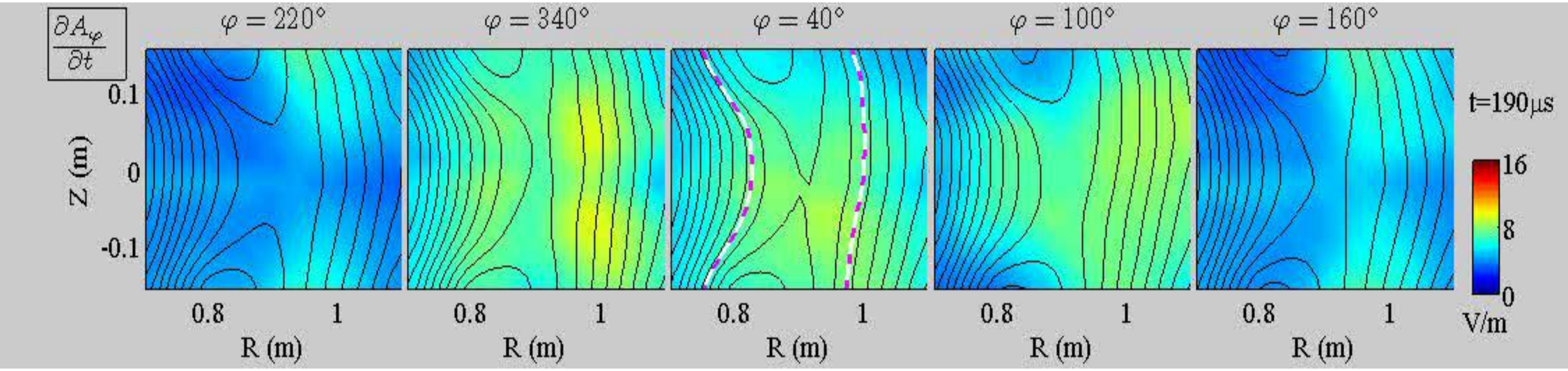
Toroidal Asymmetry: Delayed Onset

- Toroidal localized onset
- 5 μs delay

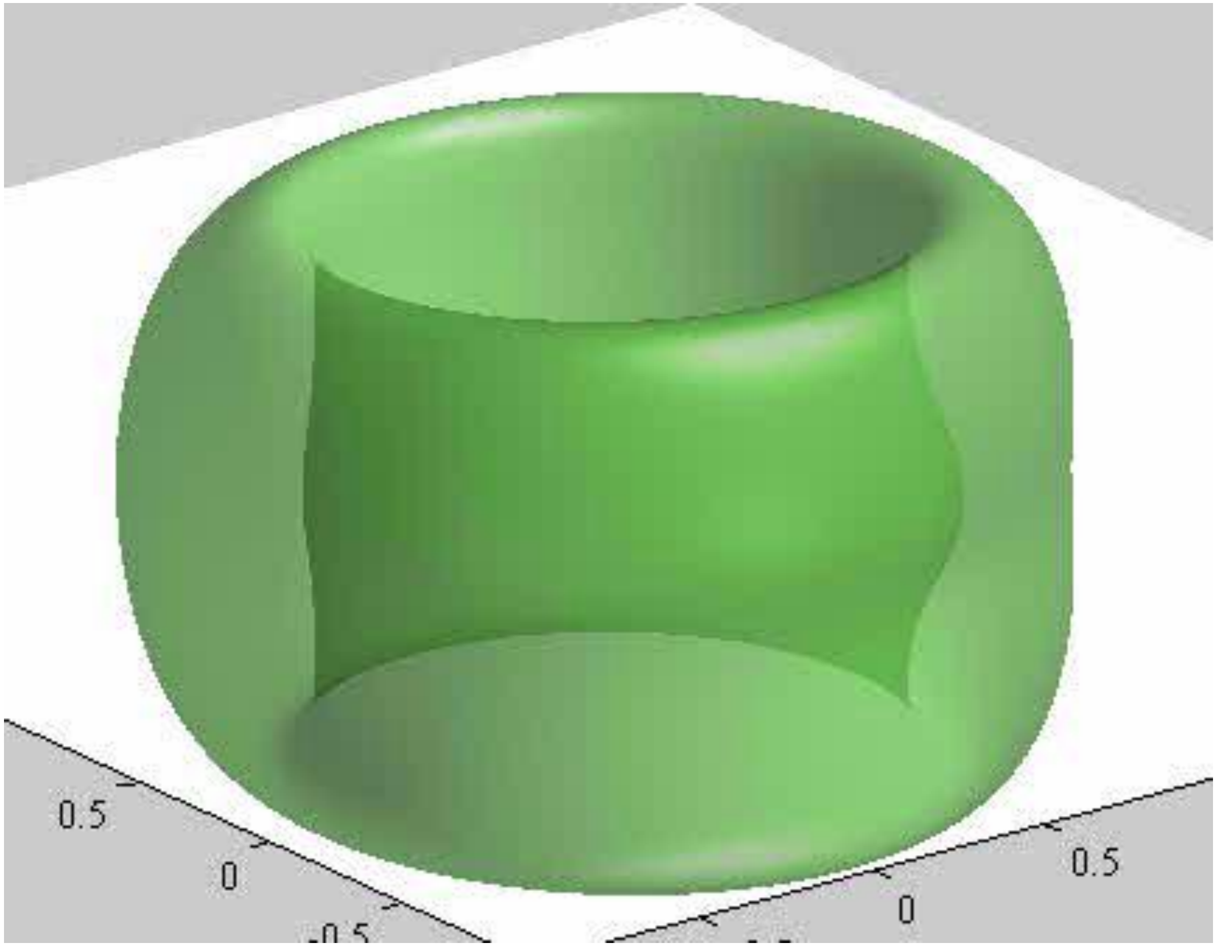


3D $\partial A_\varphi/\partial t$ Data Confirms Asymmetry

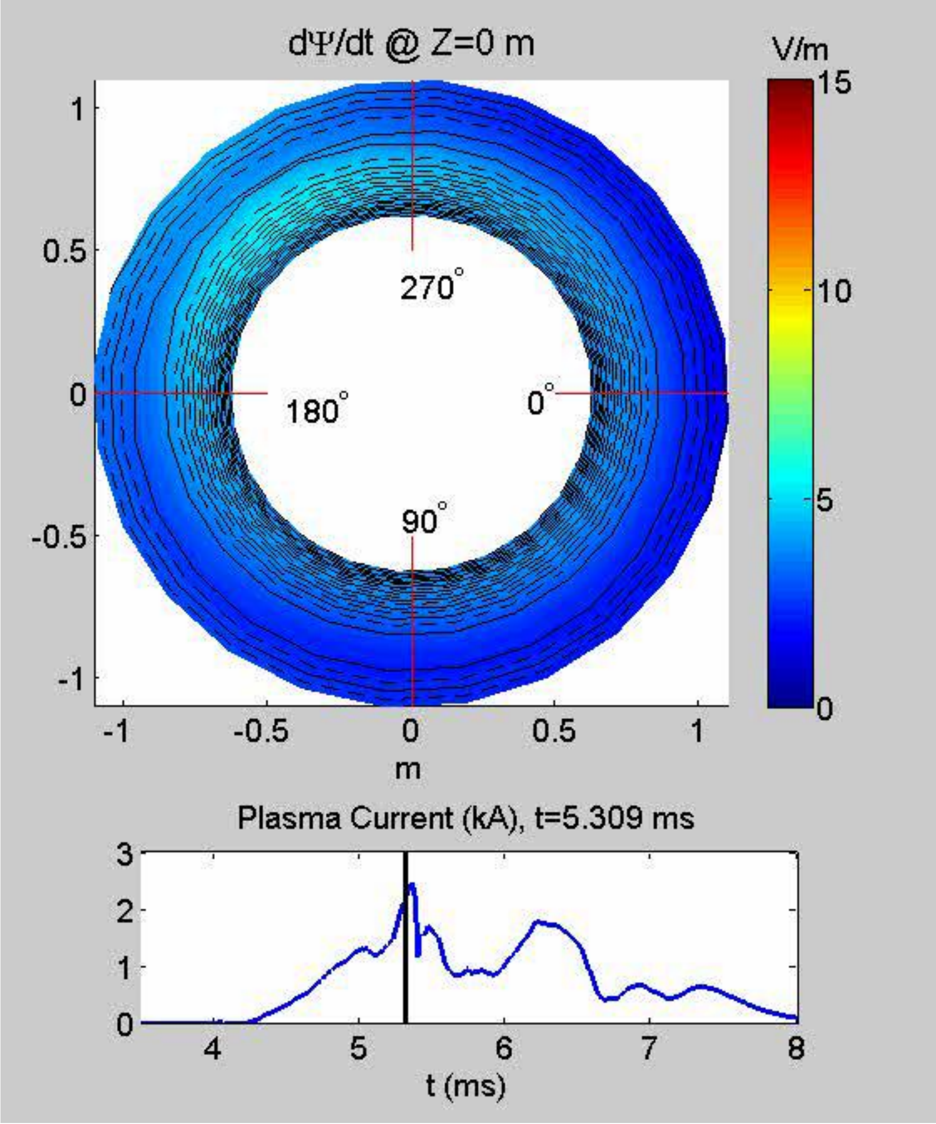
- Use 2 fixed arrays & variable onset location to construct full dataset
- Shift onset angle to $\varphi=0$, record relative angle of arrays



3D reconnection (Cartoon)

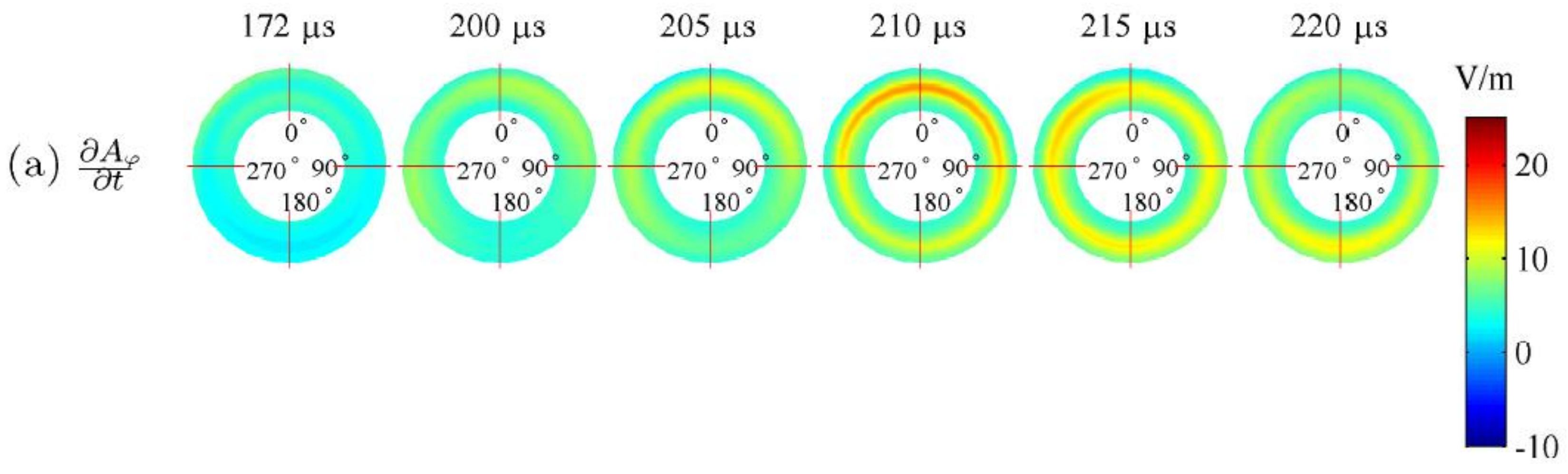


3D reconnection (Measurements)



Total E-Field is Localized

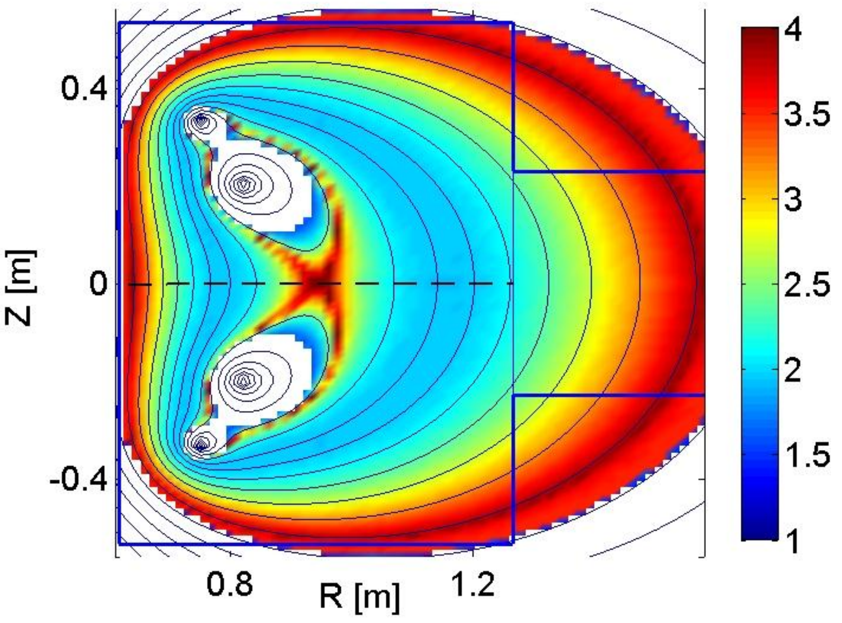
- Strong toroidal electrostatic E
- Φ_x measured at x-line, keeps total E localized;



Spontaneous reconnection only for rational q

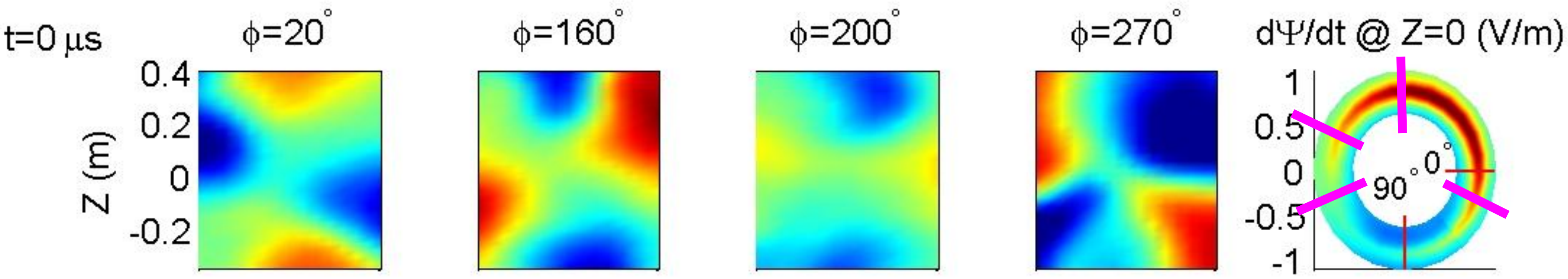
$$q = \frac{\textit{toroidal winding \#}}{\textit{poloidal winding \#}}$$

q-profile of VTF

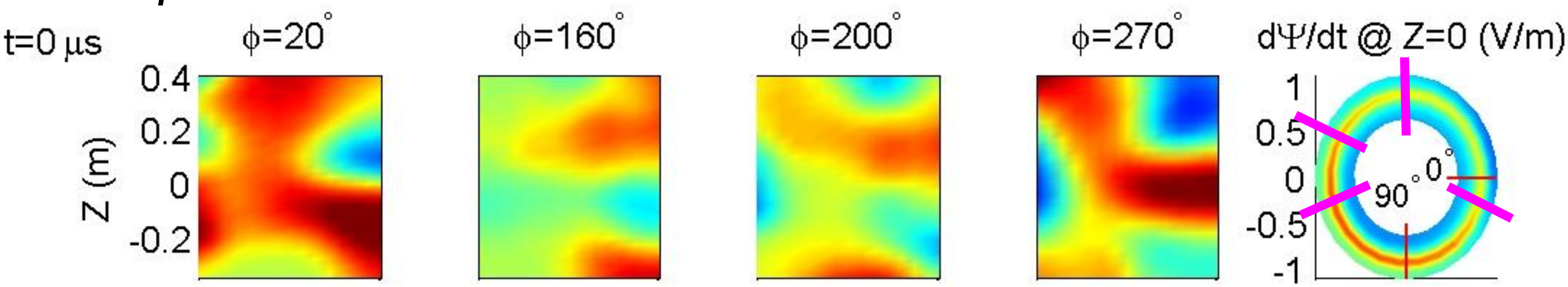


Large q=2 and q=3 modes observed during reconnection

V_{float} for q=2

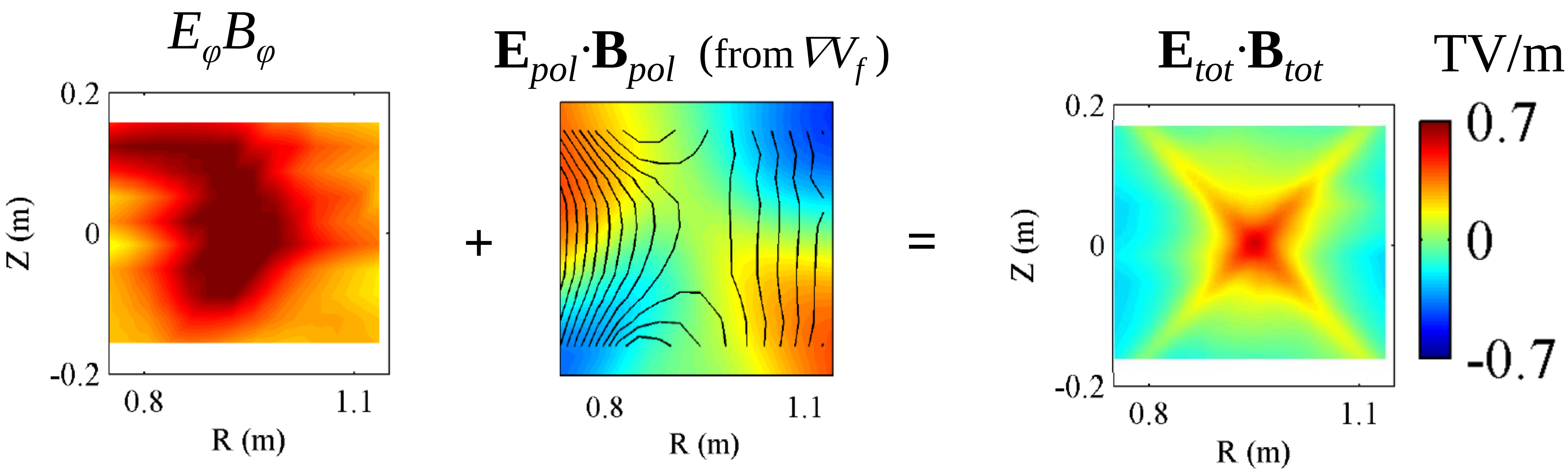


V_{float} for q=3



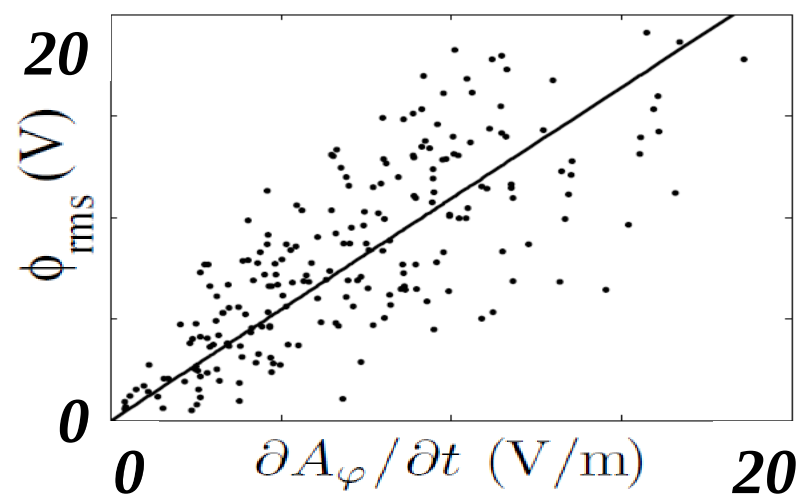
Potential maintains E·B~0 away from X-line

(ohm's law)



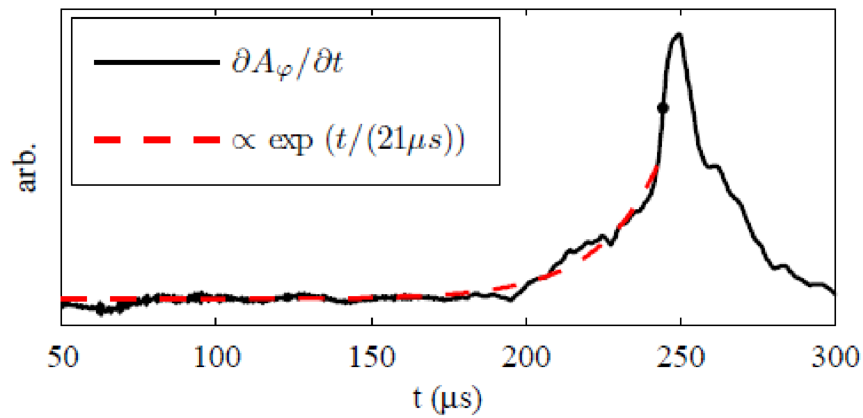
Experiments show

$$-\partial A_\varphi/\partial t \;\propto \phi_{rms}$$



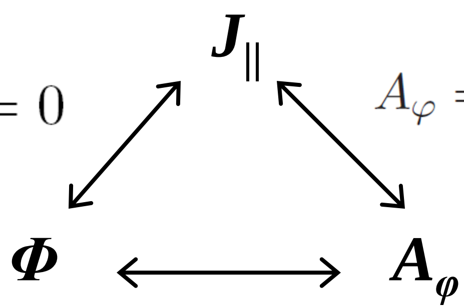
Exponential Growth in the Reconnection Rate

- Growth rate $\gamma \sim 1/(20\mu s \pm 6\mu s)$ at onset location



- Model for Onset

$$\nabla \cdot \mathbf{J} = 0$$

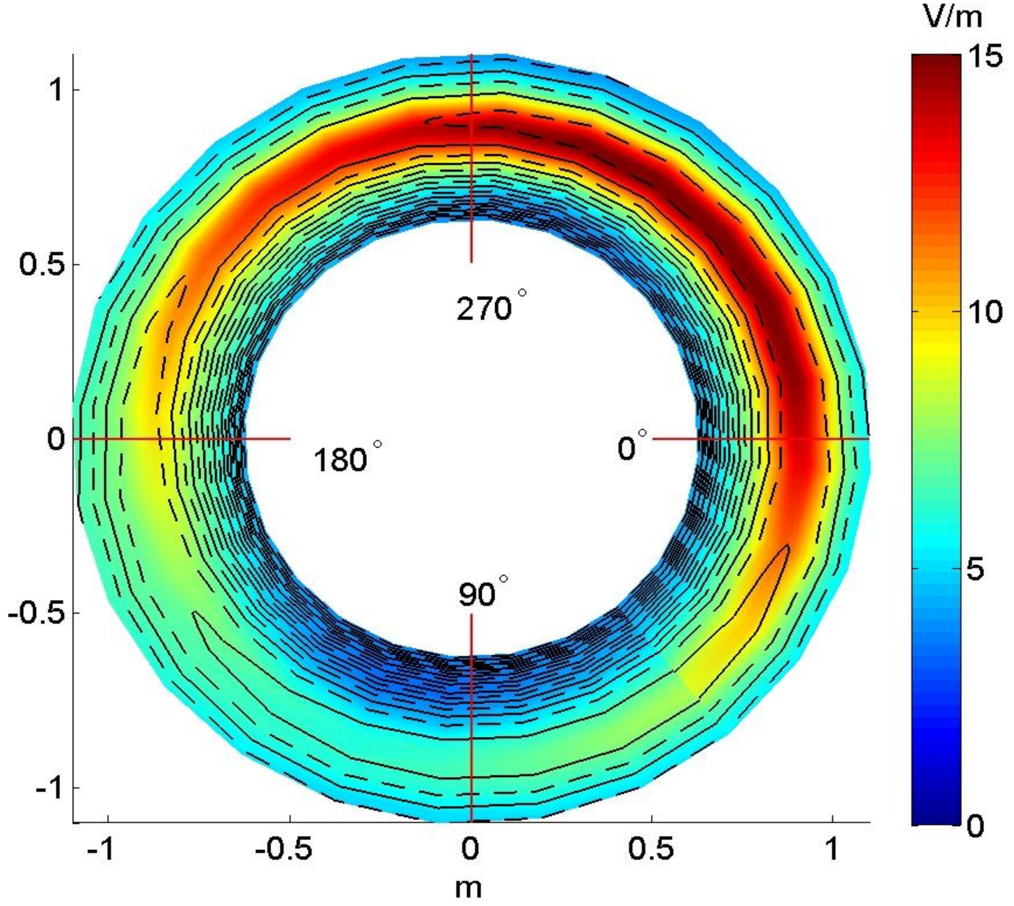


$$A_\varphi = \frac{\mu_0}{4\pi} \int \frac{J_{||}}{|\mathbf{r}' - \mathbf{r}|} d^3\mathbf{r}'$$

Ohm's Law

Current Continuity: Cartoon

$$E_{rec} = -\frac{\partial A_\phi}{\partial t},$$

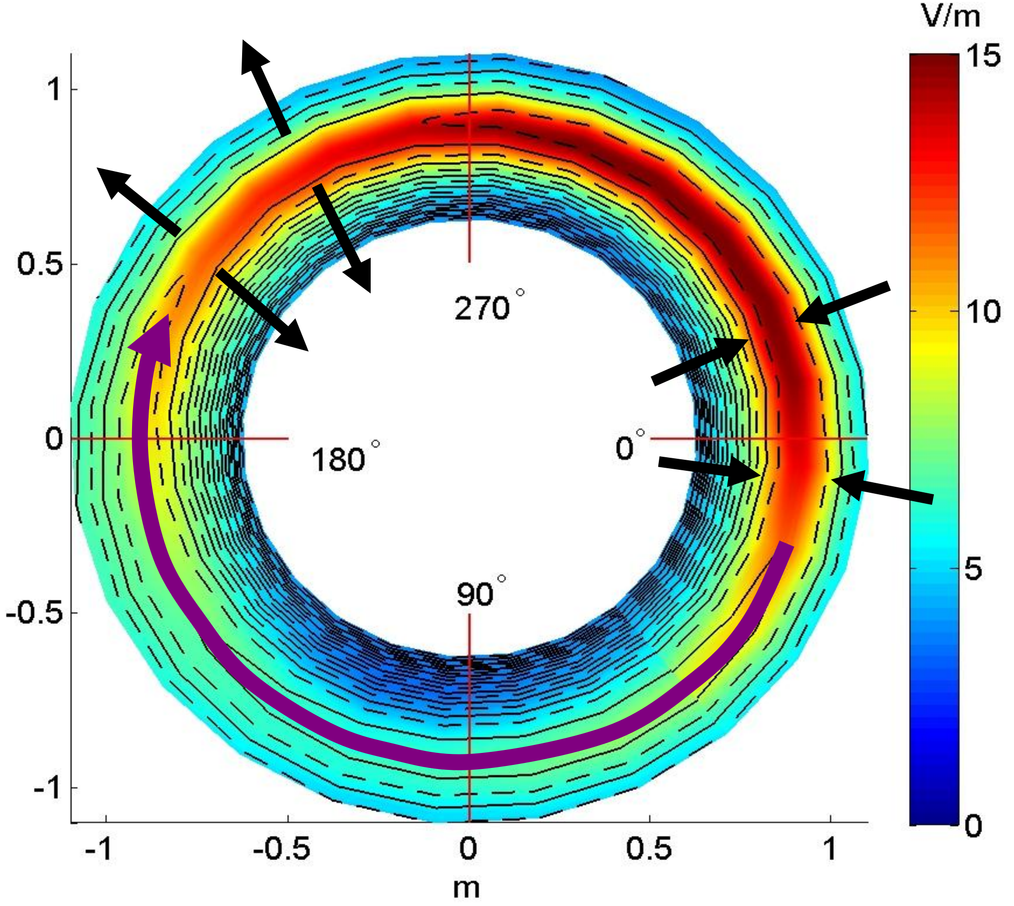


Current Continuity: Cartoon

$$\nabla \bullet \mathbf{J} = \nabla \bullet \mathbf{J}_{\parallel} + \nabla \bullet \mathbf{J}_{\perp} = 0$$

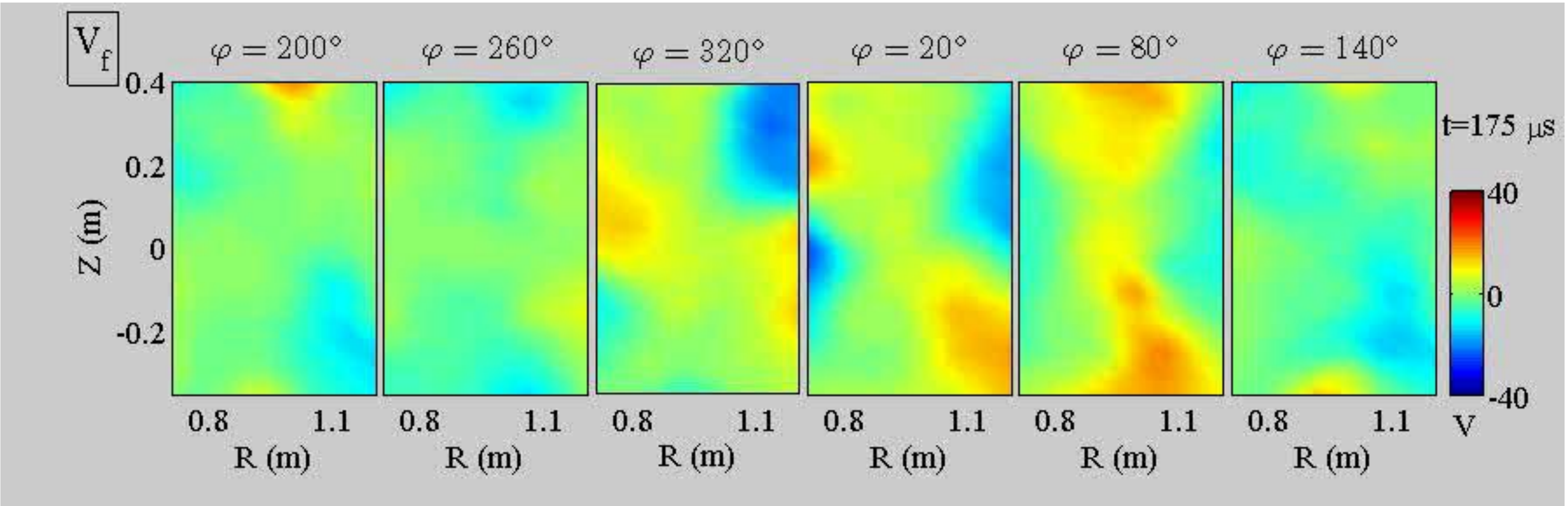
$$\mathbf{J}_{\perp} = \frac{nm}{B^2} \frac{d\mathbf{E}_{\perp}}{dt}$$

Ion polarization current



q=2 electrostatic mode

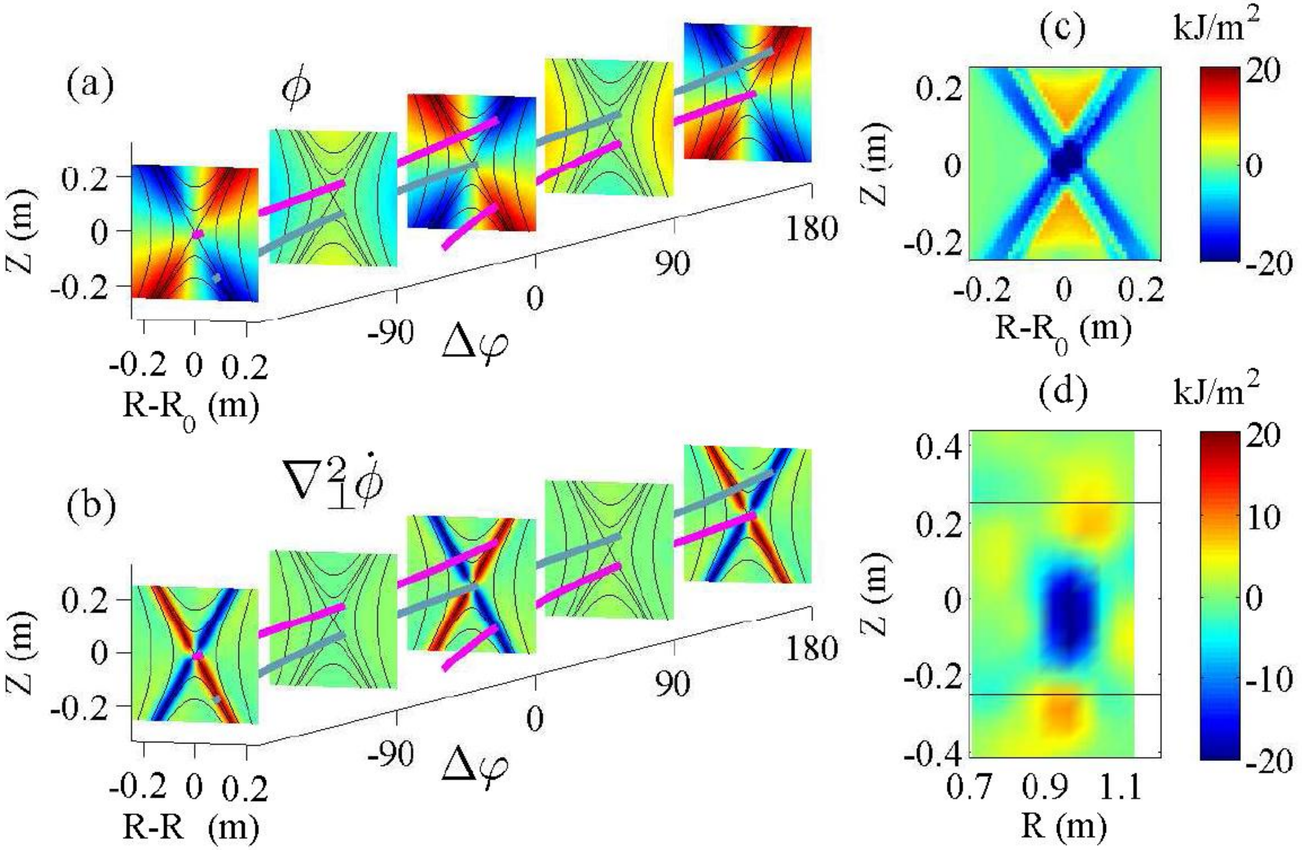
- Mode amplitude increases during reconnection onset

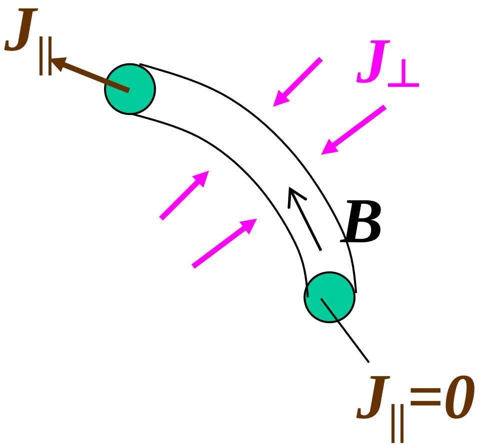


Growing q=2 Potential

- Ion polarization currents maintain $\nabla \cdot \mathbf{J} = 0$

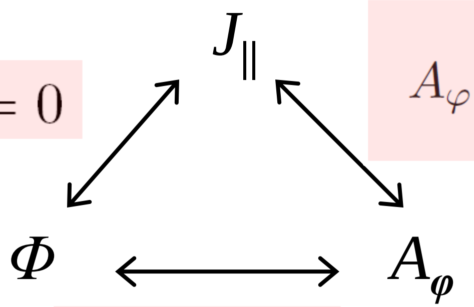
$$J_{||}(\mathbf{r}) = \int_{\text{edge}}^{\mathbf{r}} \frac{m_i n}{B^2} \nabla_\perp^2 \frac{\partial \phi}{\partial t} dl$$





Model for dynamical response

$$\nabla \cdot \mathbf{J} = 0$$



$$A_\varphi = \frac{\mu_0}{4\pi} \int \frac{J_{||}}{|\mathbf{r}' - \mathbf{r}|} d^3\mathbf{r}' \quad + A_{ext}$$

$$\boldsymbol{E \cdot B \cong 0}$$

$$A_\varphi = \alpha_1 J_{||} + A_{ext} \;, \qquad J_{||} = -\alpha_2\, d\Phi/dt \;, \qquad \Phi = -\alpha_3\, dA_\varphi/dt \;,$$

$$A_\varphi = \quad \alpha\, d^2 A_\varphi / dt^2 + A_{ext} \;, \qquad \alpha = \alpha_1 \alpha_2 \alpha_3 > 0$$

<u>Exponentially growing solution!</u>

N. Katz et al., (2010) Phys. Rev. Lett.

Conclusions

– Collisional reconnection model and the Hall effect have been verified in MRX

– In the collisionless regime of VTF important collisionless effects become evident

– Experiment offers the opportunity to address the trigger problem

– 3D effects are important!