Reconnection and dynamo in the laboratory

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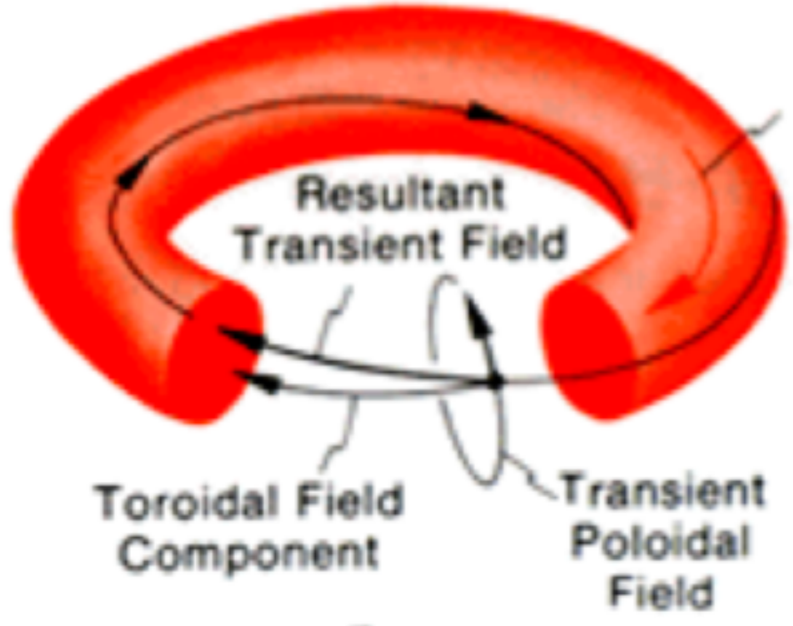
Outline

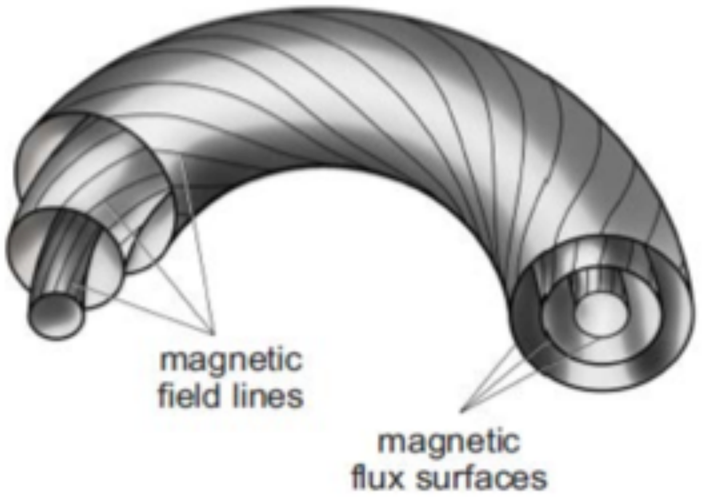
- Reconnection/dynamo effects in fusion plasmas
  - tokamak
  - reversed field pinch

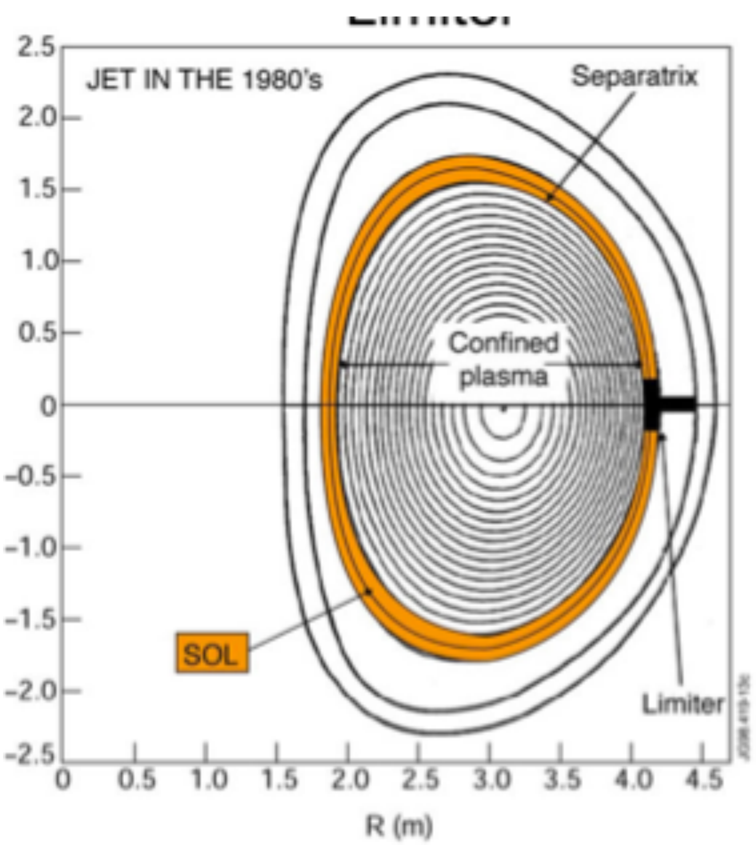
- Basic reconnection experiments

Reconnection in axisymmetric tori

Helical B-lines and magnetic surfaces





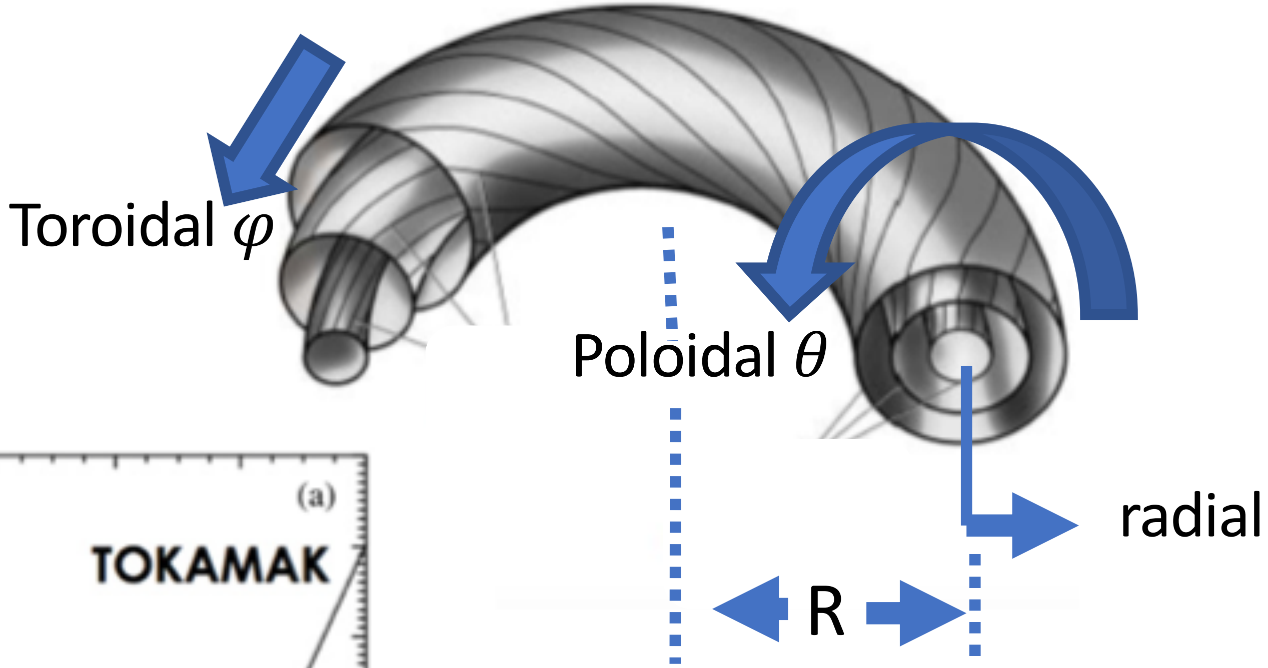


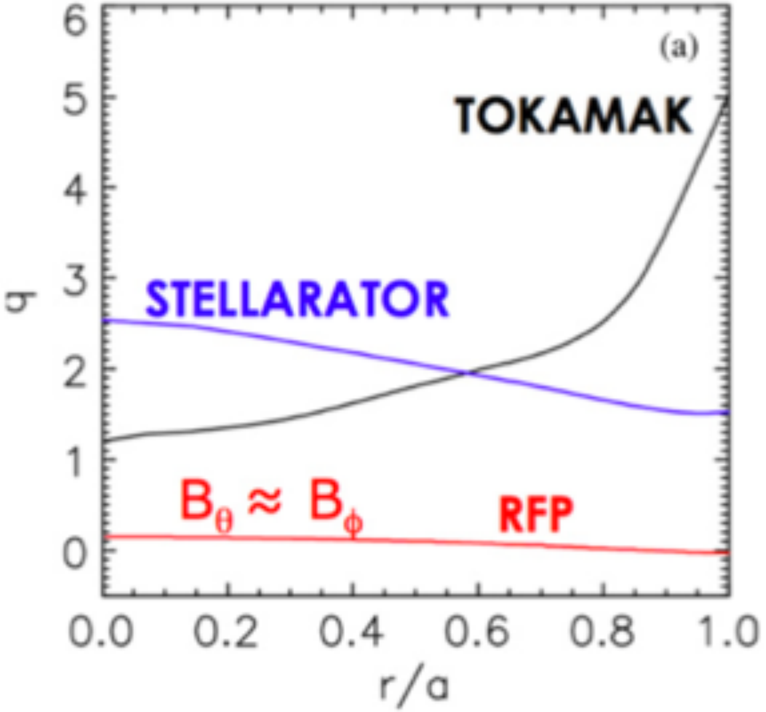
Measure of twist of field lines

$$q = \frac{number\ of\ toroidal\ windings}{poloidal\ winding}$$

$$q = \frac{rB_T}{RB_P}$$

Safety factor

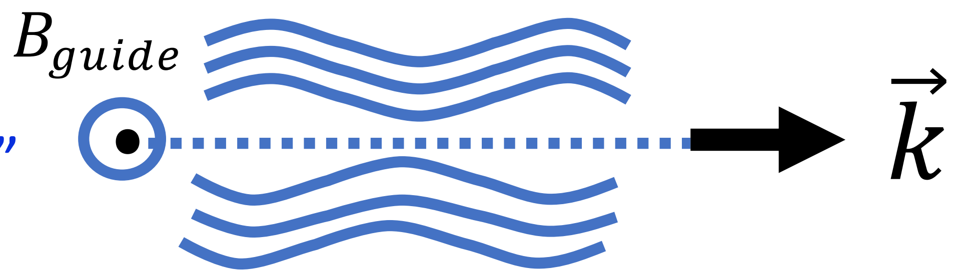




Where does reconnection occur in a torus?

recall, reconnection occurs where

$\vec{B} \cdot \vec{k} = 0$ the "reconnecting field"



$$\boldsymbol{B} = B_p\,\hat{\boldsymbol{\theta}} + B_T\hat{\boldsymbol{\varphi}}$$

$$\boldsymbol{k} = \left(\frac{m}{r}\right)\hat{\boldsymbol{\theta}} - \left(\frac{n}{R}\right)\hat{\boldsymbol{\varphi}}$$

m = poloidal mode number
n = toroidal mode number

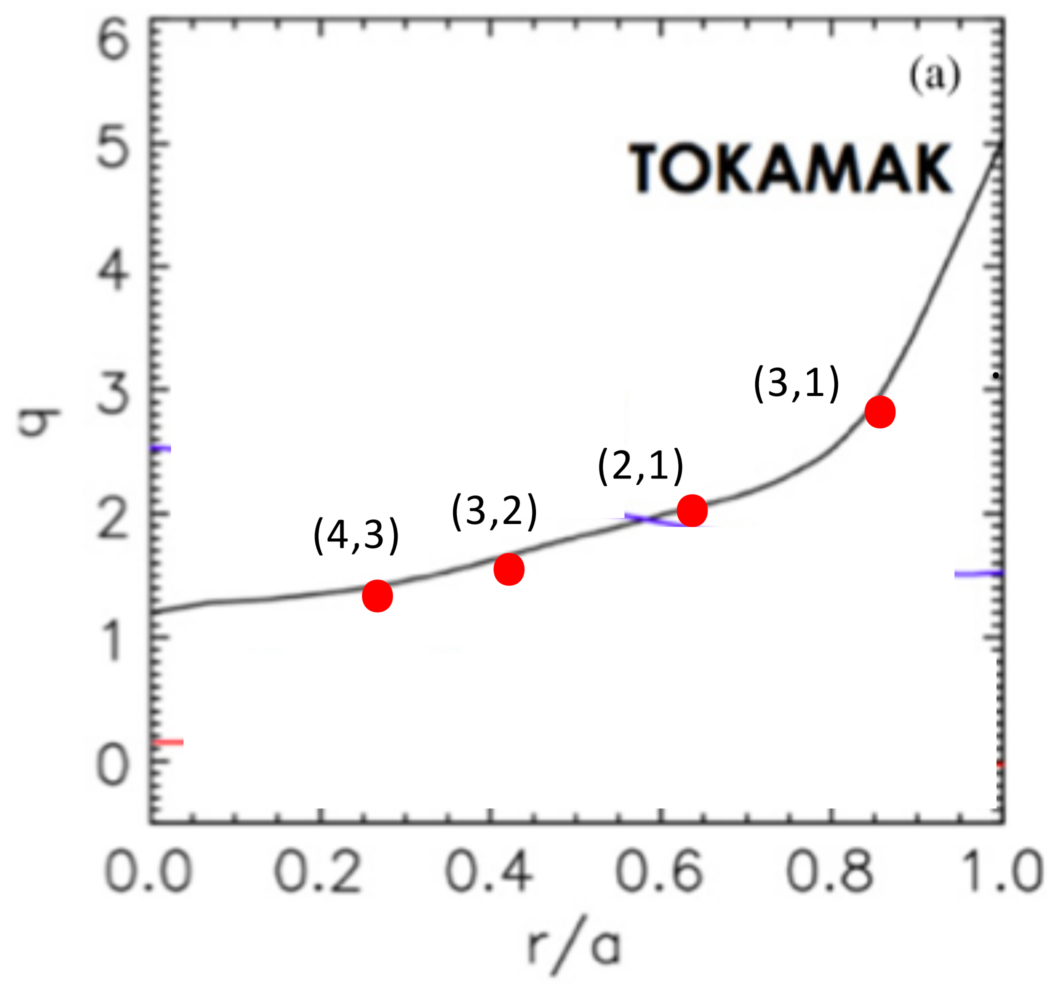
$$\vec{\boldsymbol{B}} \cdot \vec{\boldsymbol{k}} = \left(\frac{m}{r}\right)B_p - \left(\frac{n}{R}\right)B_T = 0$$

or

$$q = \frac{m}{n}$$

Reconnection occurs on mode-resonant surfaces, or rational surfaces

Where does reconnection occur in a torus?



$$q = \frac{m}{n}$$

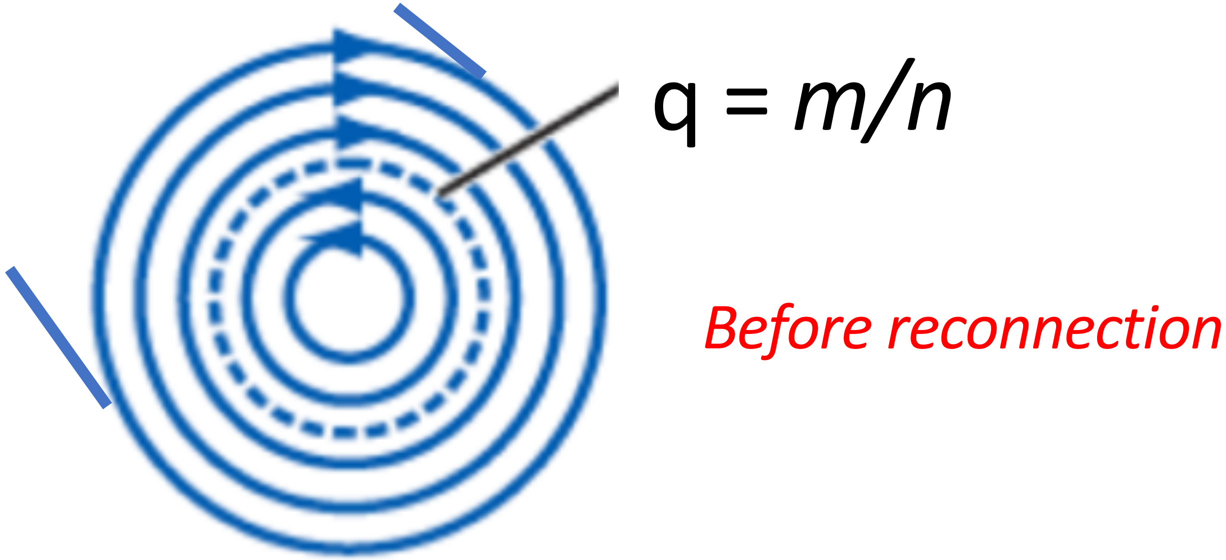
Show reconnection surfaces for

(m, n) = (2,1), (3,1), (4,3), (3,2)

As m,n increase, the modes become stable

Plot the reconnecting component of B

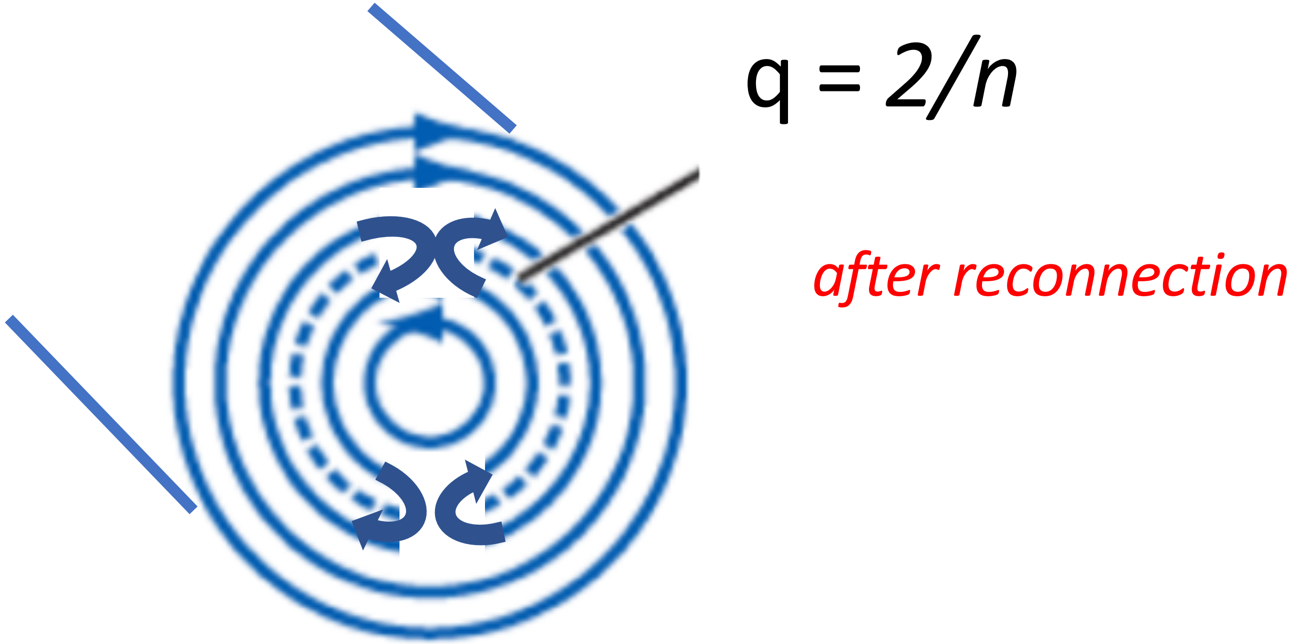
$$\vec{B}\cdot\vec{k} \sim q - m/n$$



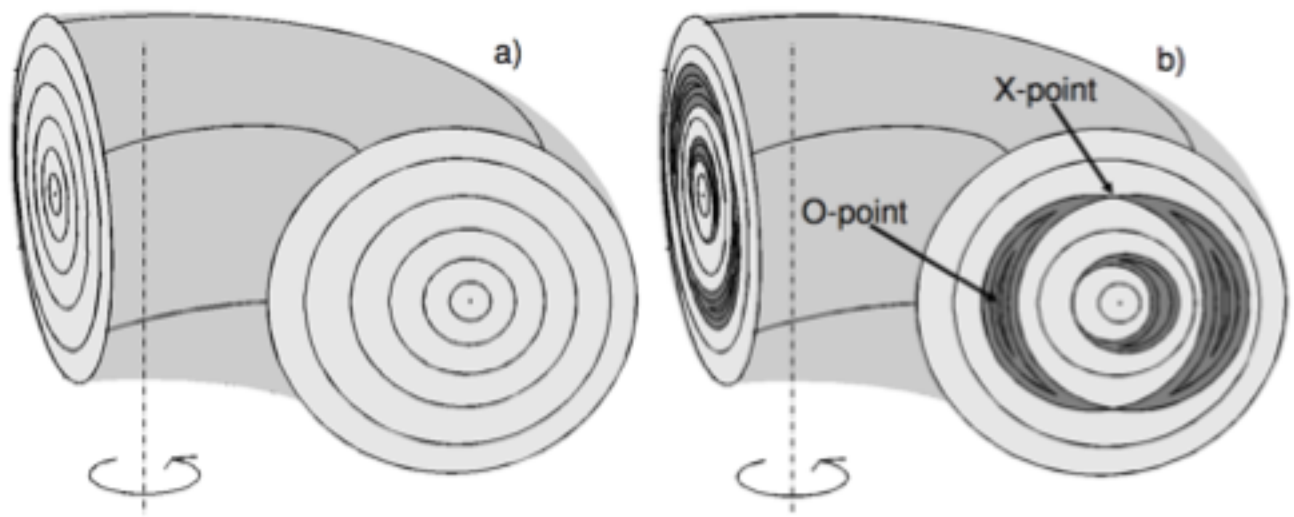
Consider reconnection due to m = 2 perturbation

Magnetic islands form

2 islands since m = 2



Magnetic surfaces break into islands



Outermost islands:

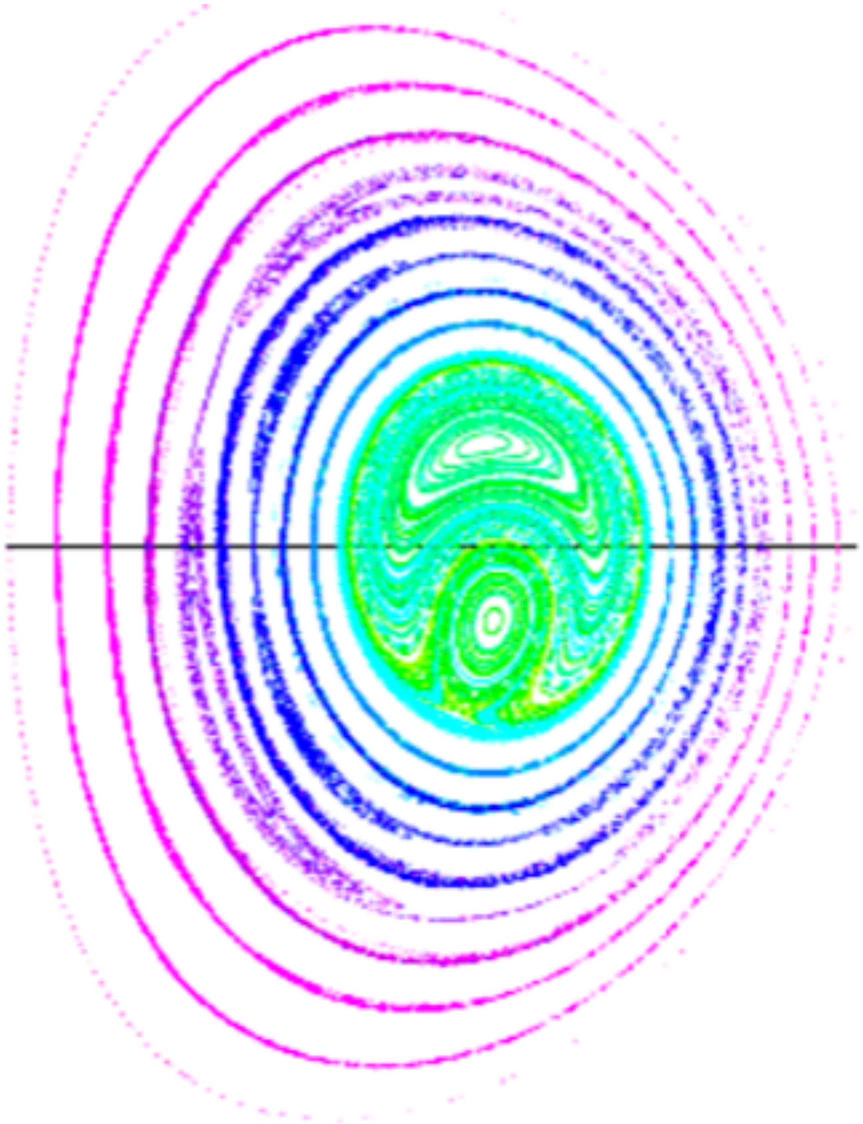
m = 2, n = 1
at q = 2 surface

innermost island:

m = 1, n = 1
at q = 1 surface

Islands also observed in MHD computation

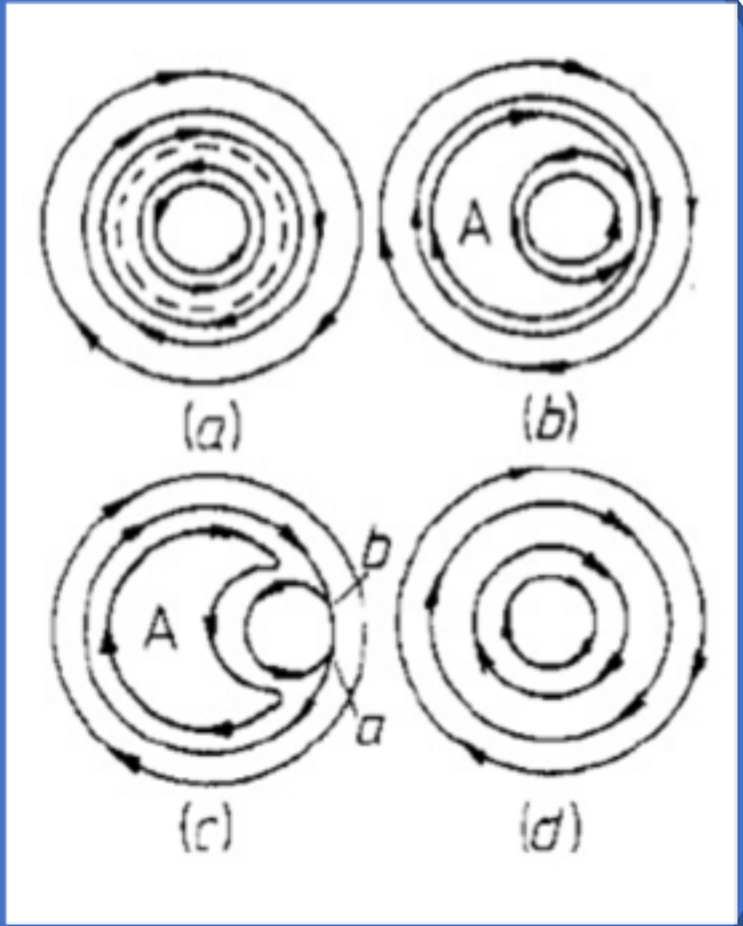
Puncture plot



Can see islands at
q = 1/1, 3/2 , 2/1 surfaces

Evolution of reconnection at q = 1 surface

The Kadomtsev model



m = n = 1 island grows, all the way to the center,

Eventually the island central axis (at the q = 1 surface) becomes that of the tokamak

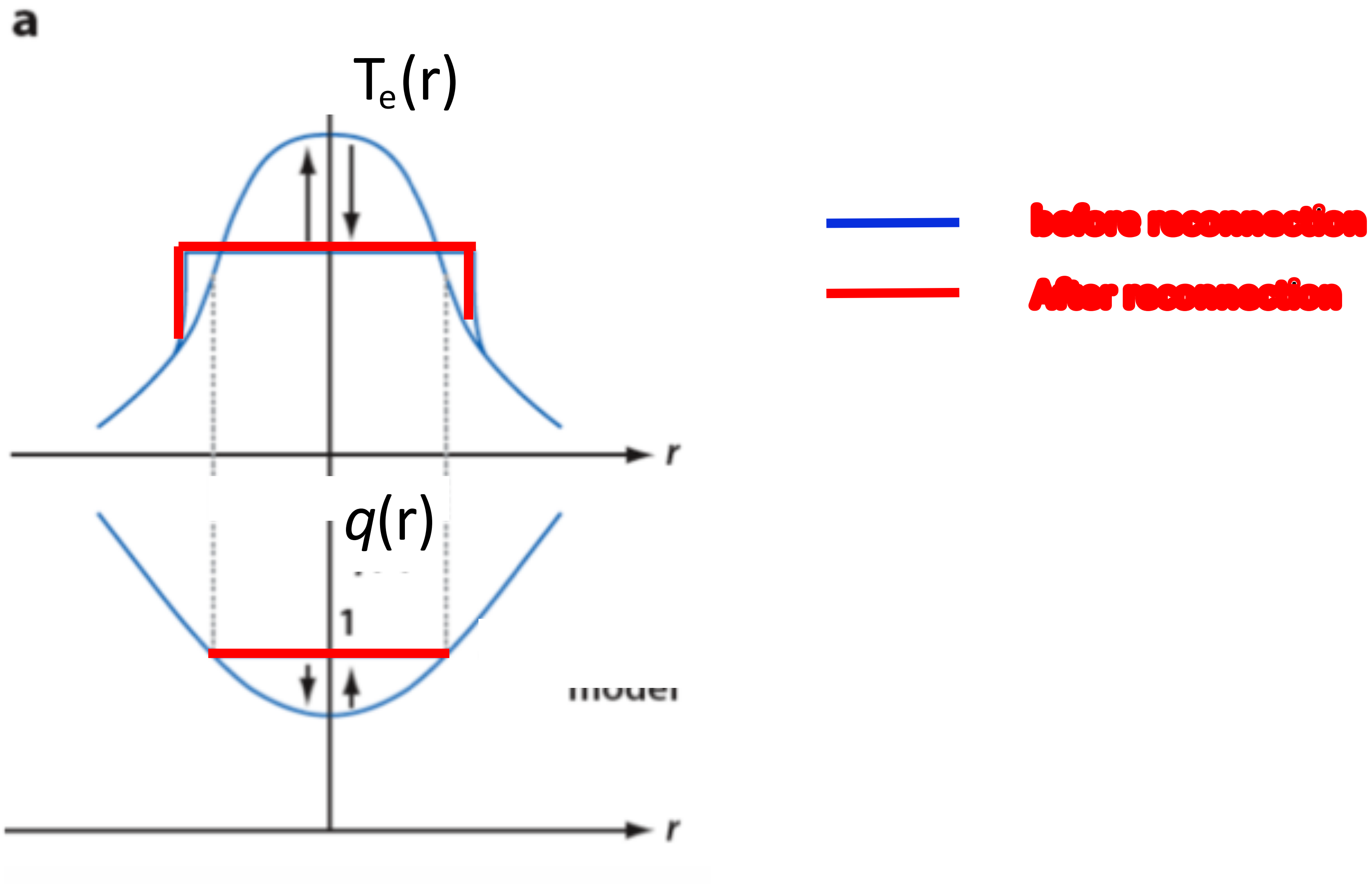
Expect at sawtooth crash:

central safety factor q → 1

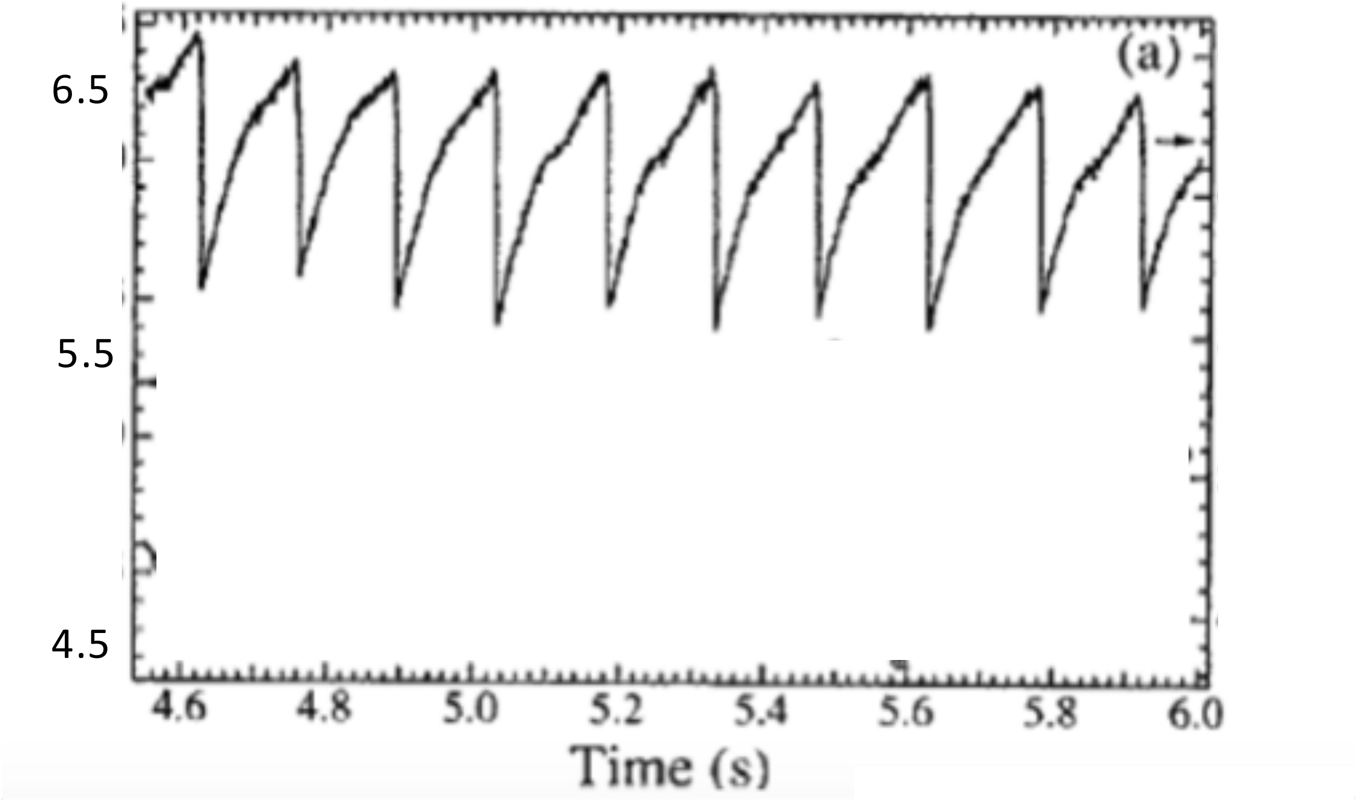
temperature flattens across island

The plasma reheats, the current re-peaks, and the process repeats

Kadomtsev model of reconnection at q = 1 surface

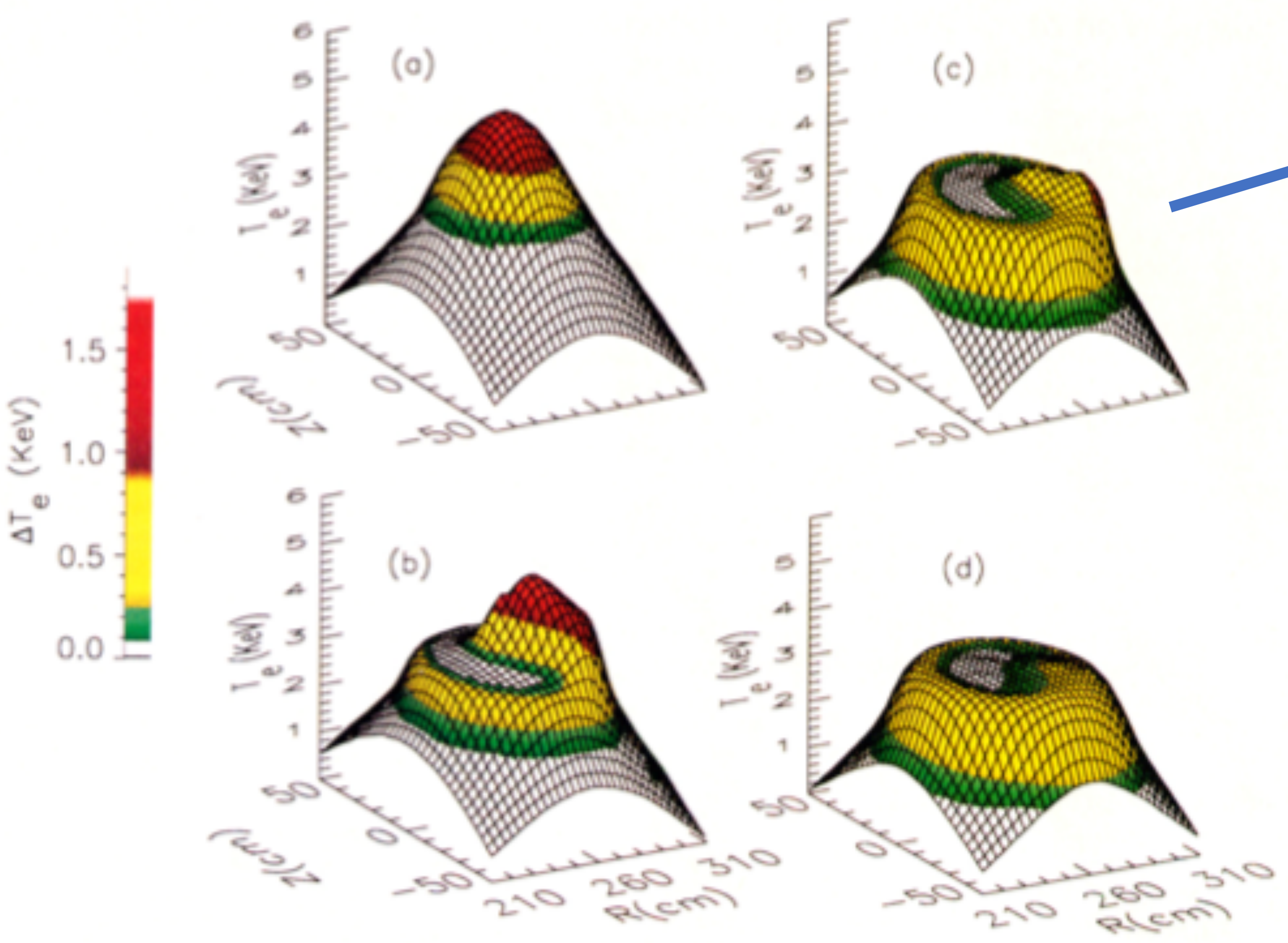


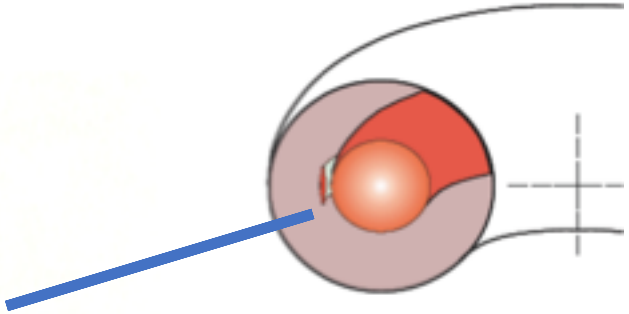
The temperature reduction (energy transport) is observed



Island structure *observed* in 2D temperature measurements

Electron temperature evolution

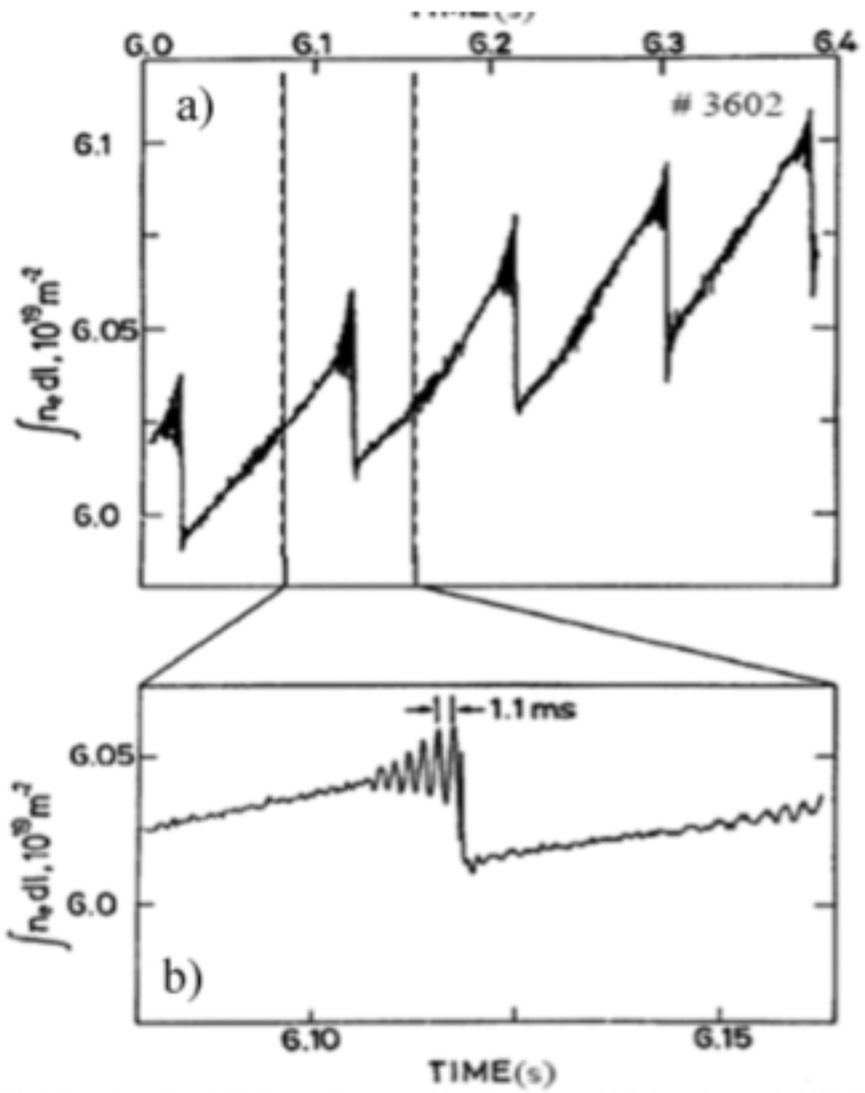




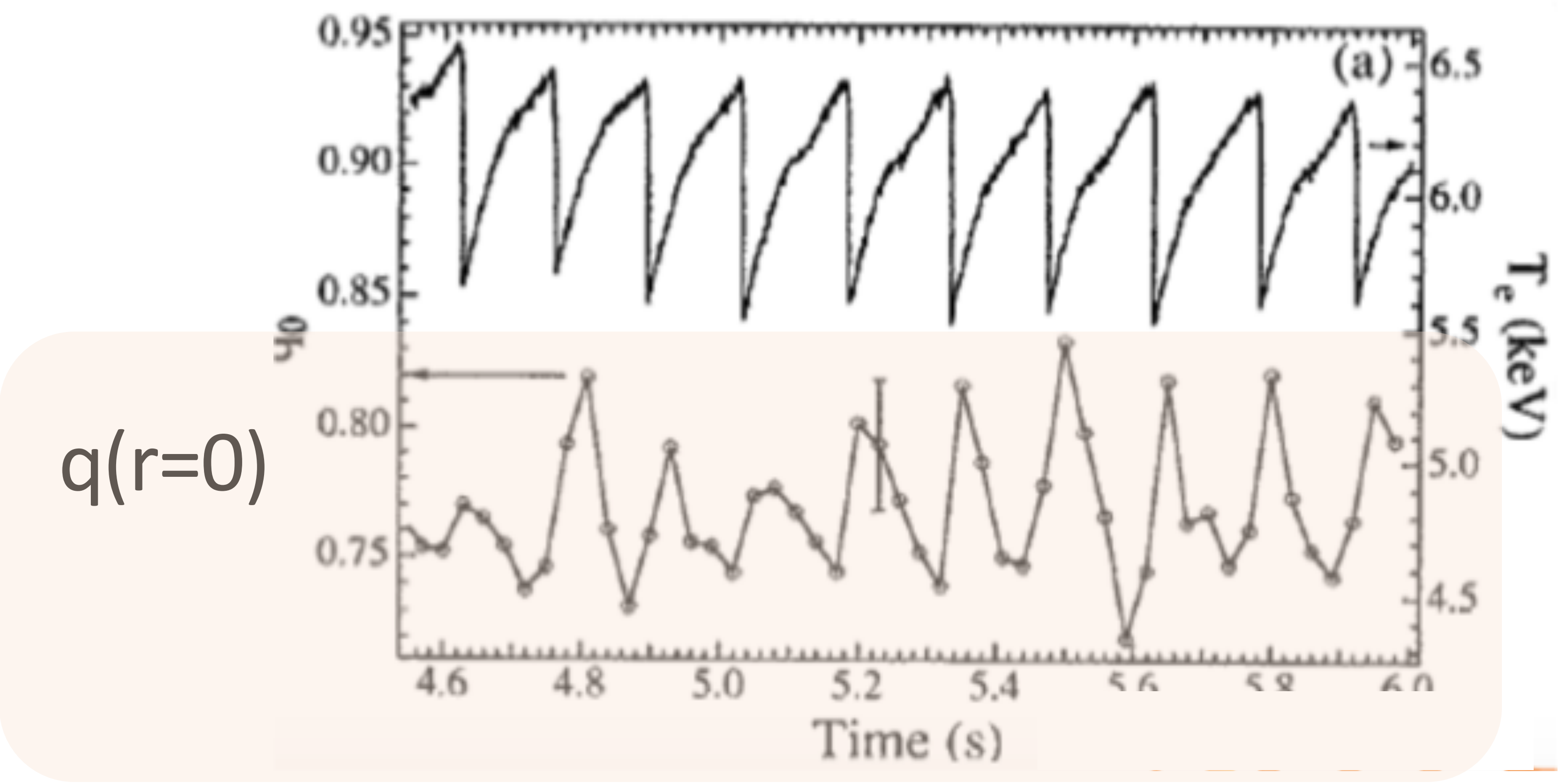
Instability observed to grow prior to reconnection event

Crash observed in density
(similar to temperature)

Precursor oscillations
(also observed in magnetic field)



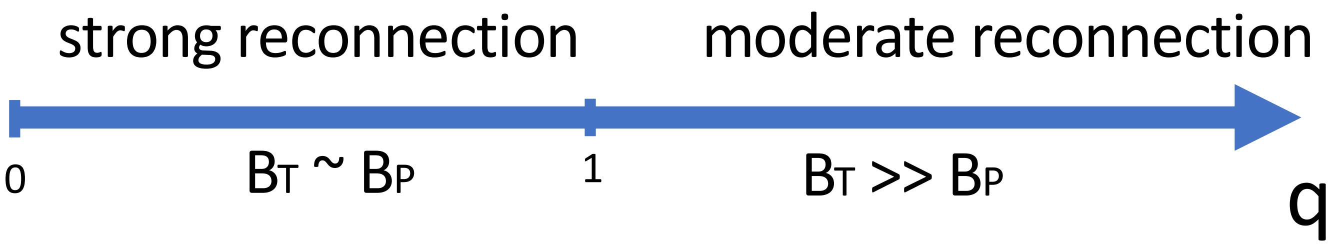
But, q(r=0) does NOT always rise to unity



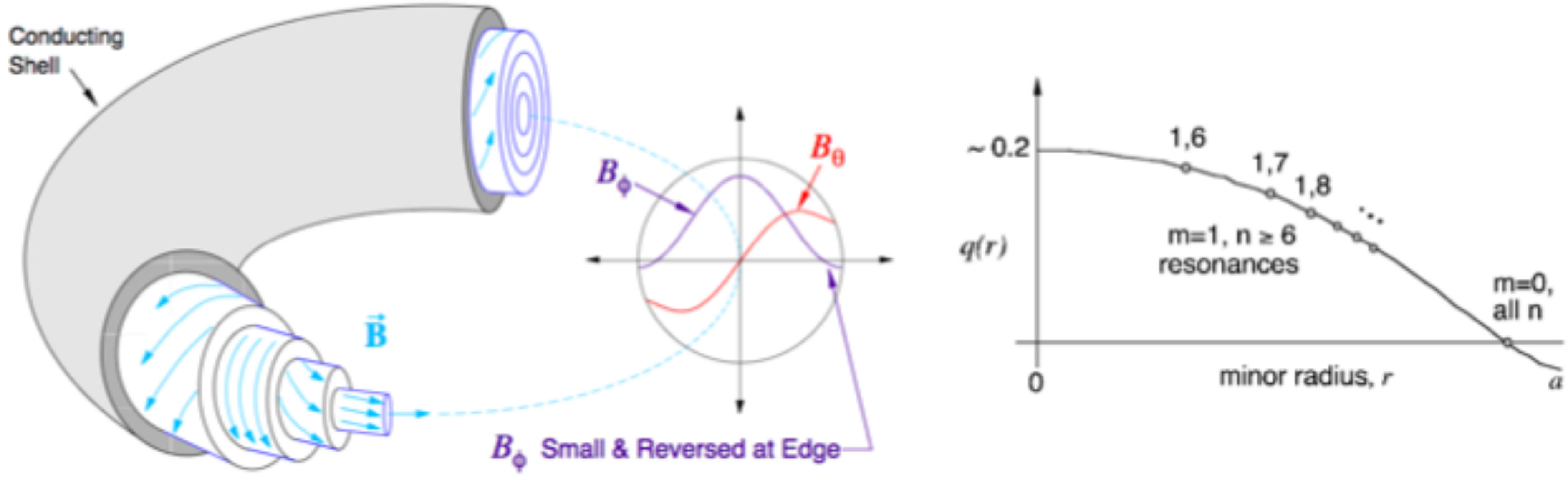
Continuing issues: why is reconnection incomplete?,
why crash so fast?

Axisymmetric tori vary in the strength of reconnection

$$q \sim \frac{B_T}{B_P} \sim \frac{externally\ produced\ field}{internally\ produced\ field} \sim \frac{stabilizing\ influence}{destabilizing\ influence}$$



Reconnection in a torus at low q

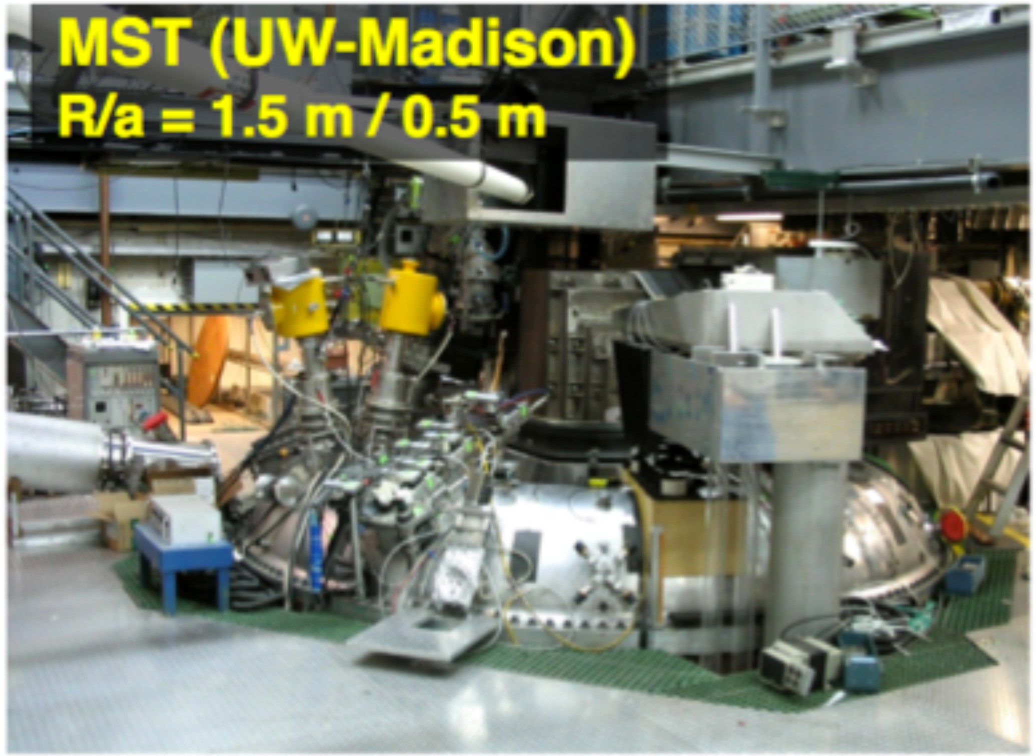


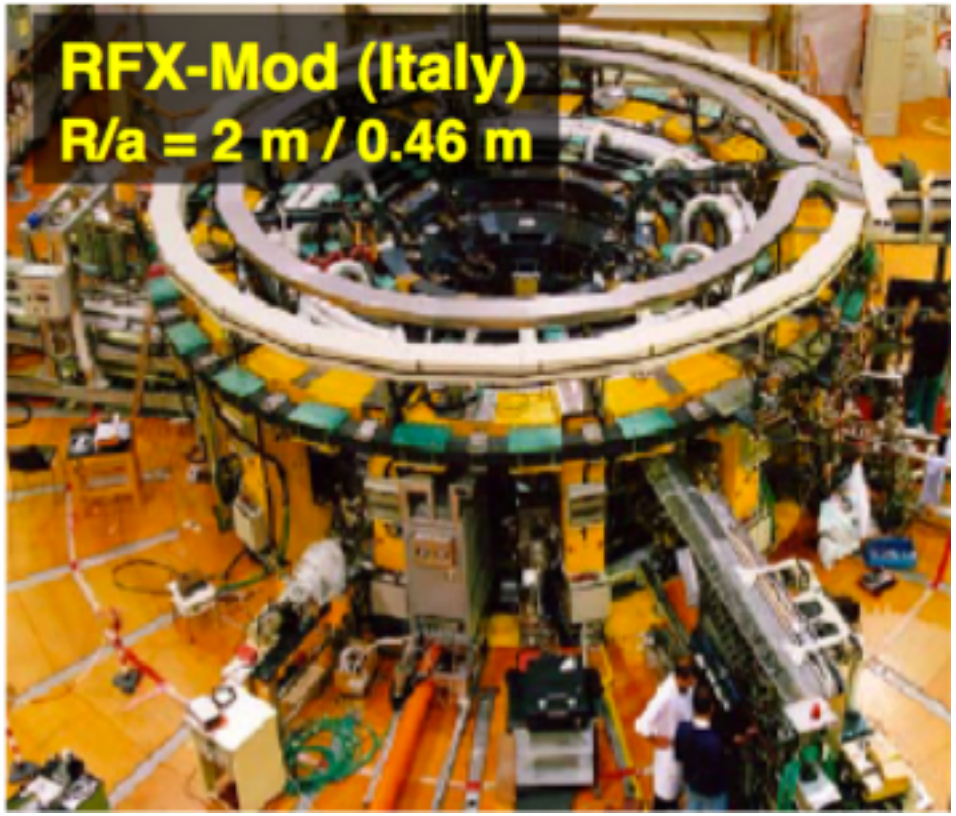
Called a "reversed field pinch"

Exhibits strong sawtooth oscillations

Sawtooth crash = reconnection event = "magnetic self-organization"
(current-driven tearing modes re-organize plasma)

RFP facilities





Reconnection (or MSO) event

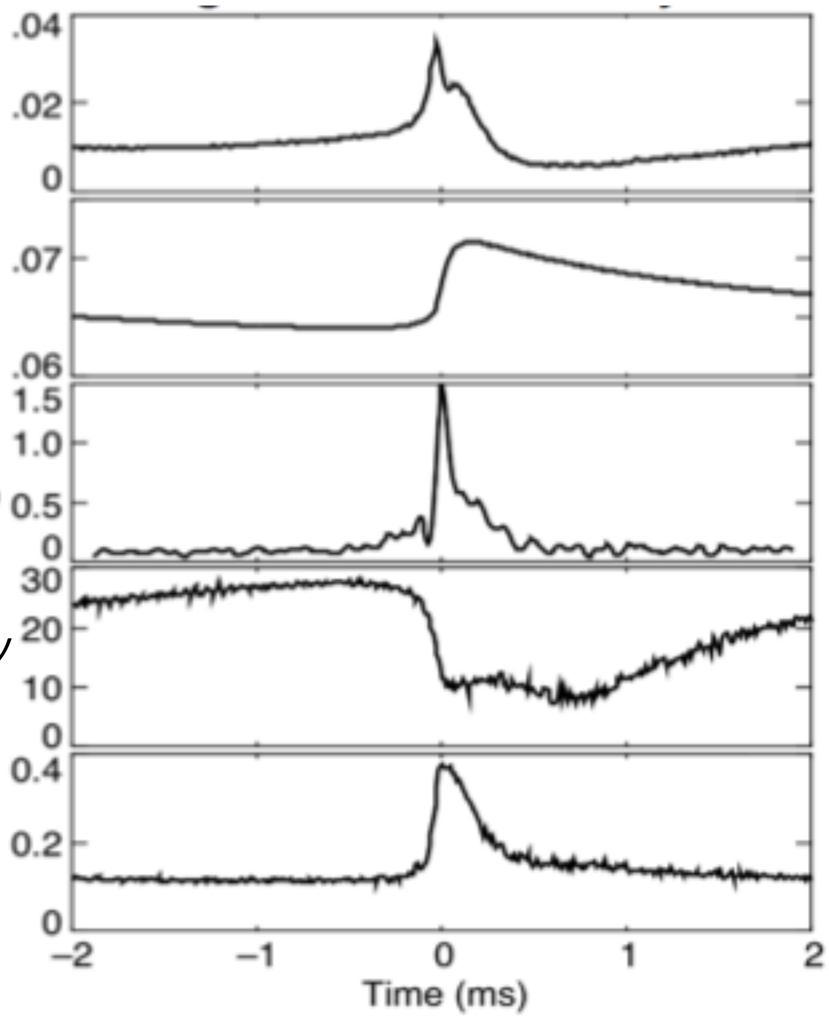
Magnetic fluctuation
$^{B}/_{B}$

Toroidal magnetic flux
(T)

Heat flux
(MW/m2)

Toroidal rotation velocity
(km/s)

Ion temperature
(keV)



Magnetic Reconnection

Dynamo

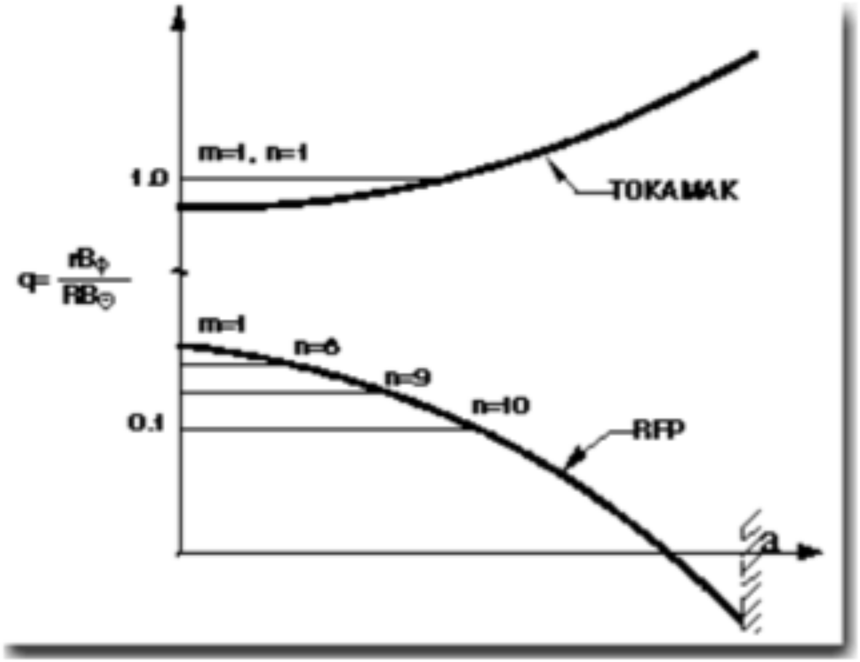
Stochastic Transport

Momentum Transport

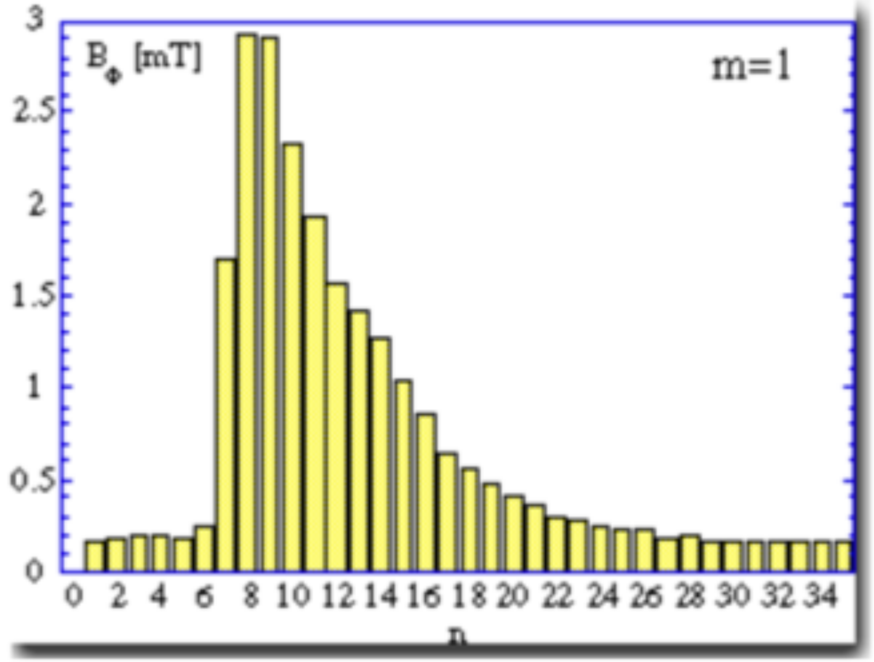
Non-collisional Ion Heating

Describe each effect

Reconnection: multiple tearing modes



Magnetic field, $\widetilde{B(n)}$



Toroidal mode number, n

The many tearing modes interact nonlinearly

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B} - \eta \vec{j})$$

Let $B_k = b_k e^{i(kx - \omega t)}$

Then $\frac{\partial b_{k1}}{\partial t} = \nabla \times (v_{k2} \times b_{k3})$, where $k_1 = k_2 + k_3$

Nonlinear mode coupling,

Eigenfunctions for modes with different k values overlap radially

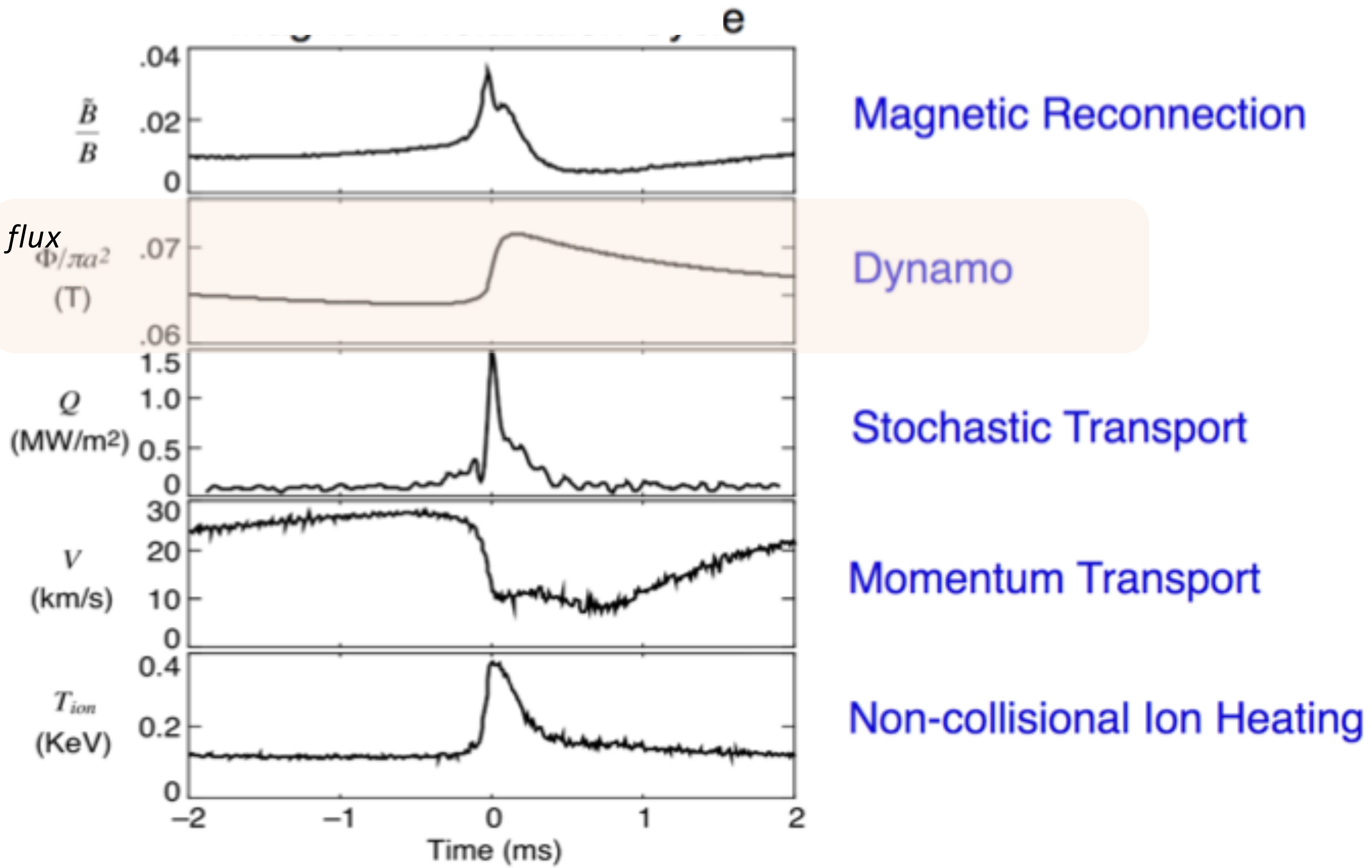
Energy flows between modes that satisfy the 3-wave sum rule,

Growing tearing mode saturate by transferring energy to stable modes

(and by flattening the current density profile)

Not fully turbulent, but part way there

Reconnection (or MSO) event



Toroidal magnetic flux (T)

The observed dynamo effect

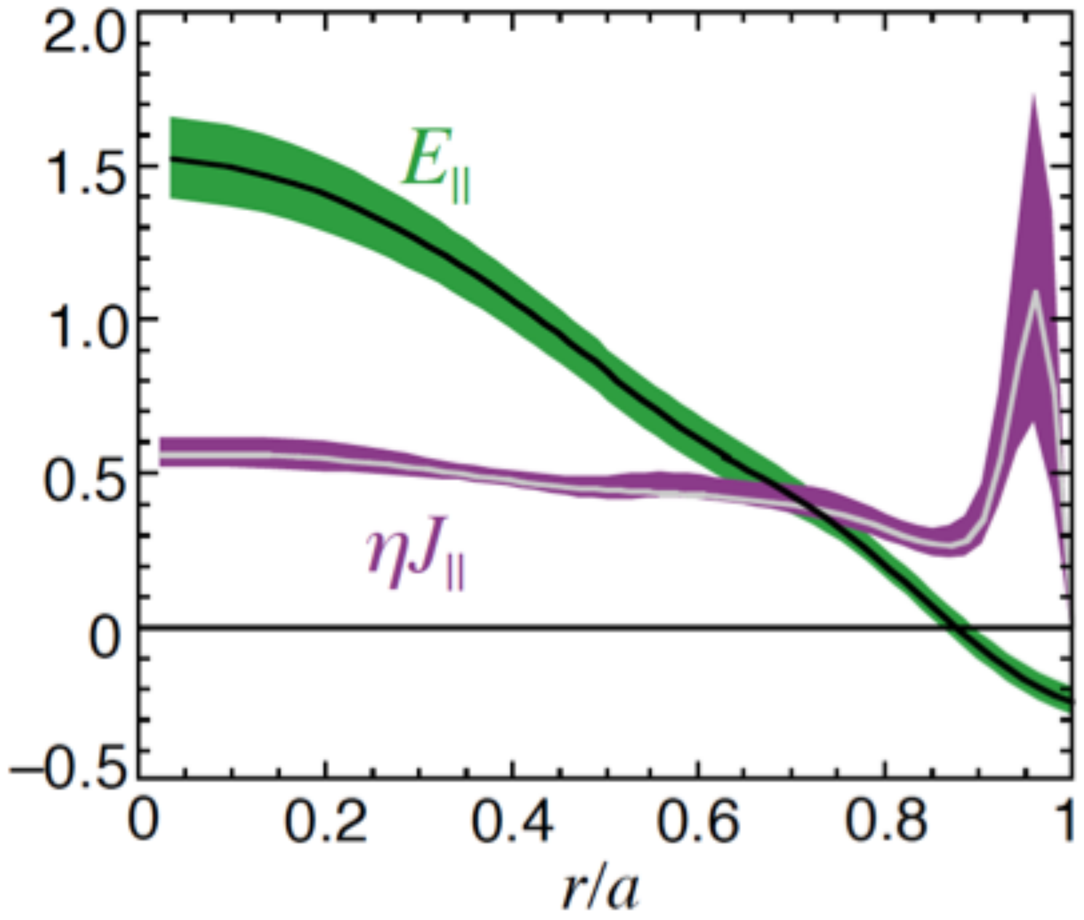
It is not a full dynamo

Overall magnetic field strength is not increasing

The current density profile is flattening by dynamo processes

A simple Ohm's law is *not* satisfied

$$E_{||} \neq j_{||}$$



Other mechanisms for current generation

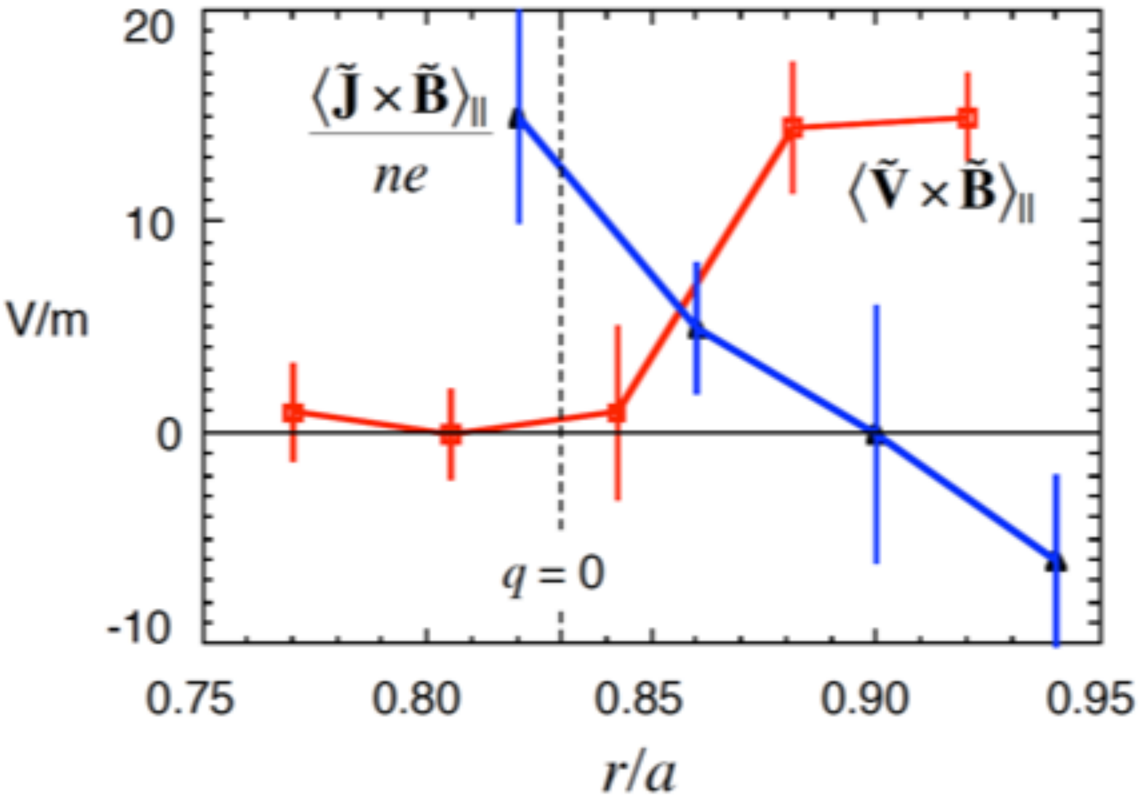
$$\eta\langle j\rangle = \langle \boldsymbol{E}\rangle + \langle \tilde{\boldsymbol{v}} \times \tilde{\boldsymbol{B}} \rangle + \frac{1}{ne}\langle \tilde{\boldsymbol{j}} \times \tilde{\boldsymbol{B}} \rangle$$

MHD dynamo

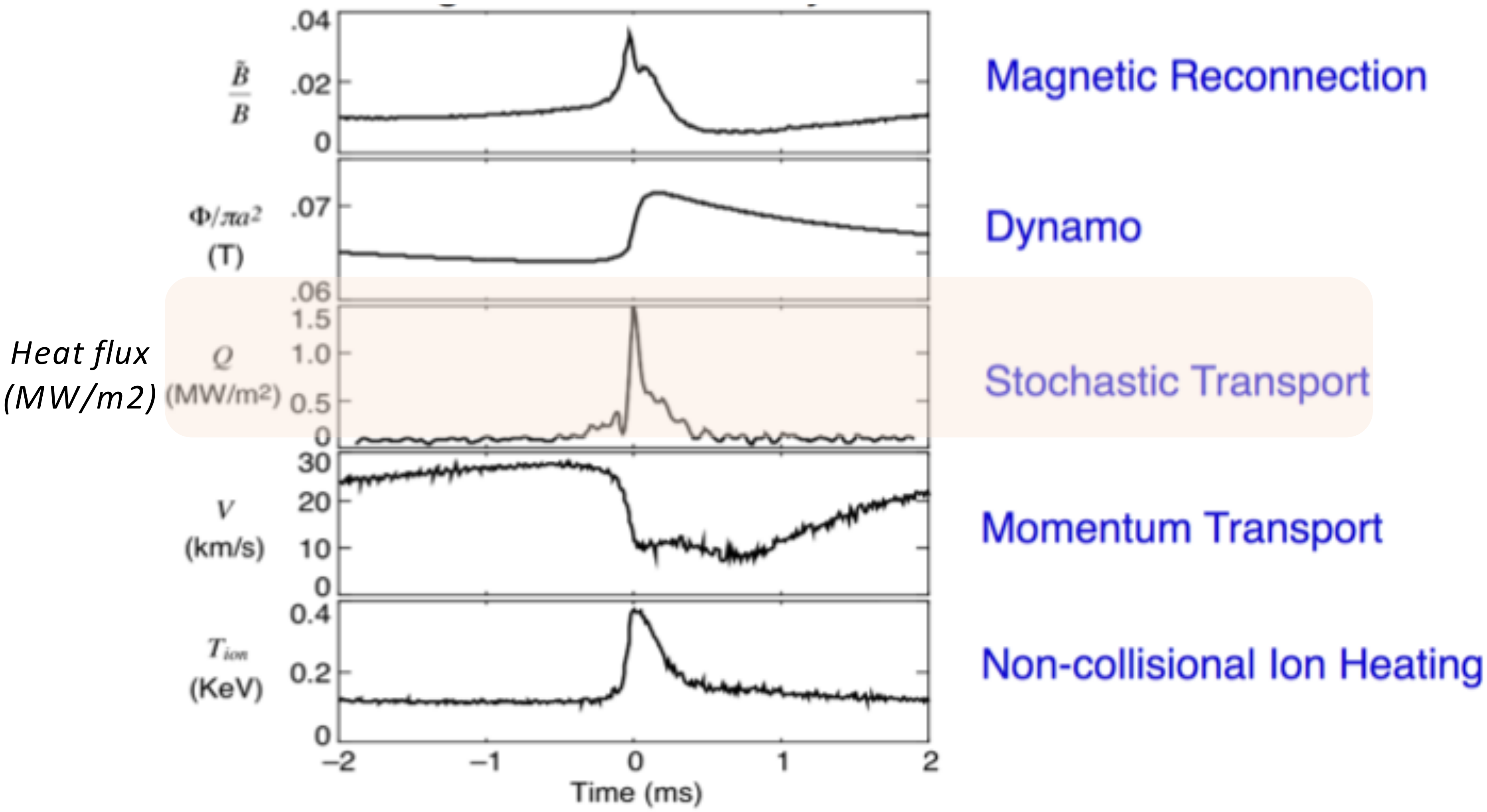
Hall dynamo

Terms measured in plasma edge region,

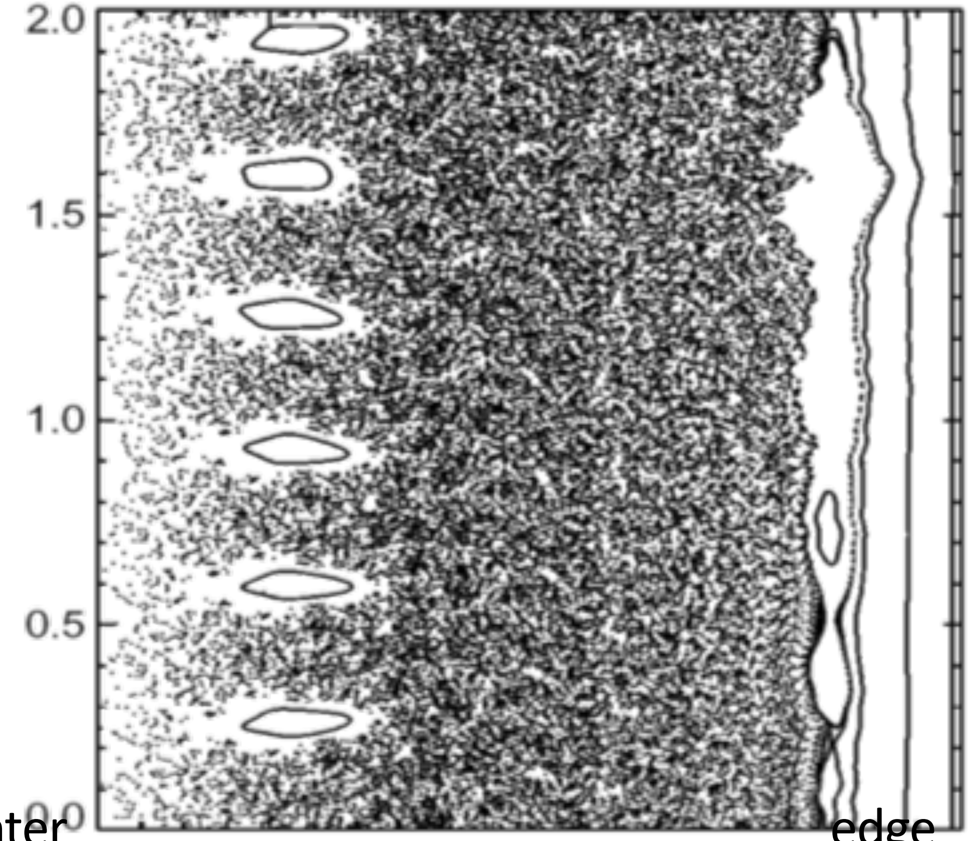
Also important in core (spectroscopy and Faraday rotation)



Reconnection (or MSO) event

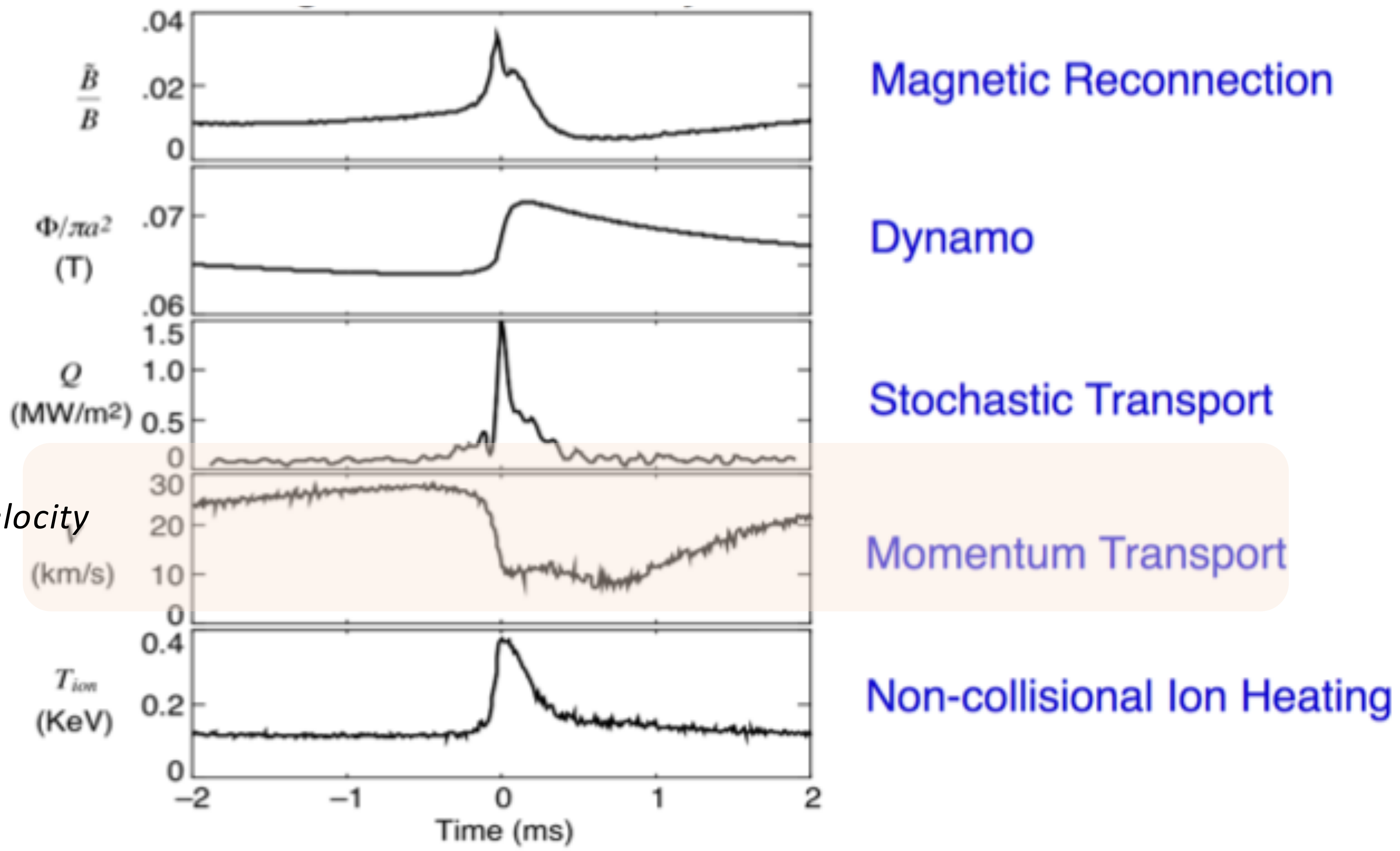


MHD computation of field lines in presence of multiple tearing instabilities

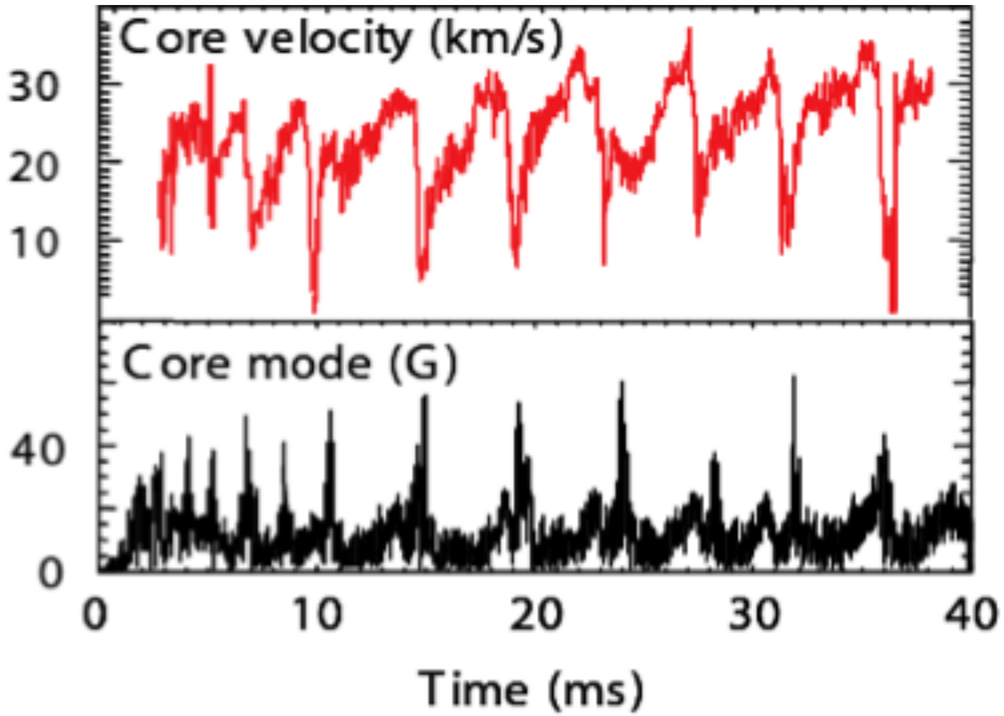


Measured energy transport consistent with computed chaotic field

Reconnection (or MSO) event



Momentum transport



Sudden change in rotation correlated with reconnection

Rotation increases in edge (transport)

Why is momentum transported?

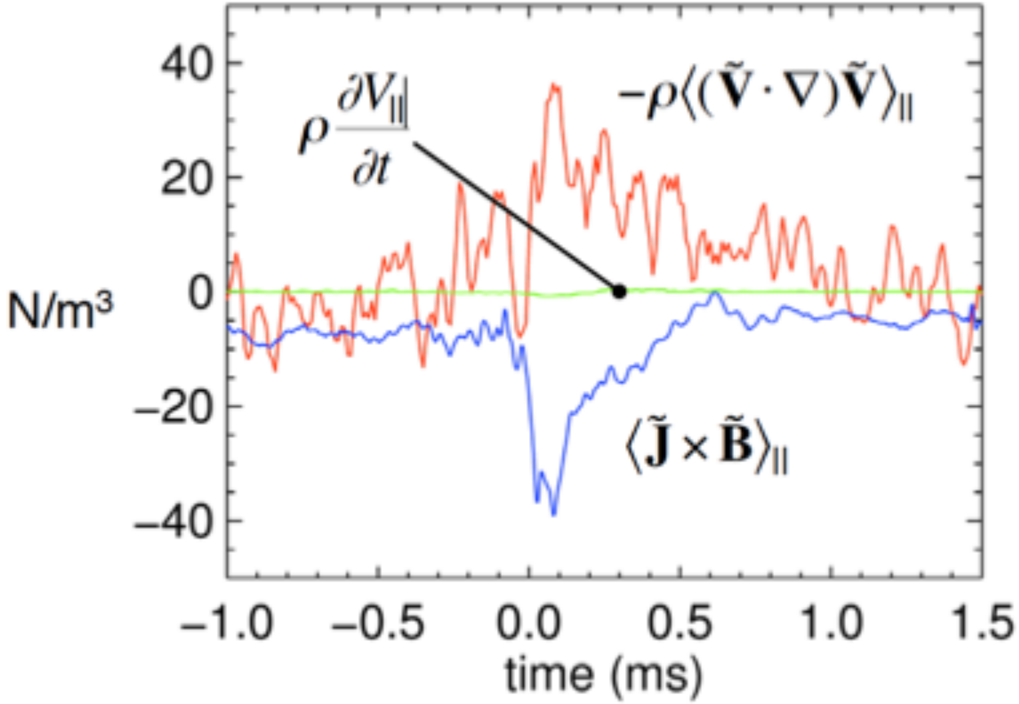
Momentum transport

$$\rho \frac{\partial \langle v \rangle}{\partial t} = \langle \tilde{j} \times \tilde{\boldsymbol{B}} \rangle - \rho \langle \tilde{\boldsymbol{v}} \cdot \nabla \tilde{\boldsymbol{v}} \rangle$$

Maxwell stress (related to Hall dynamo)

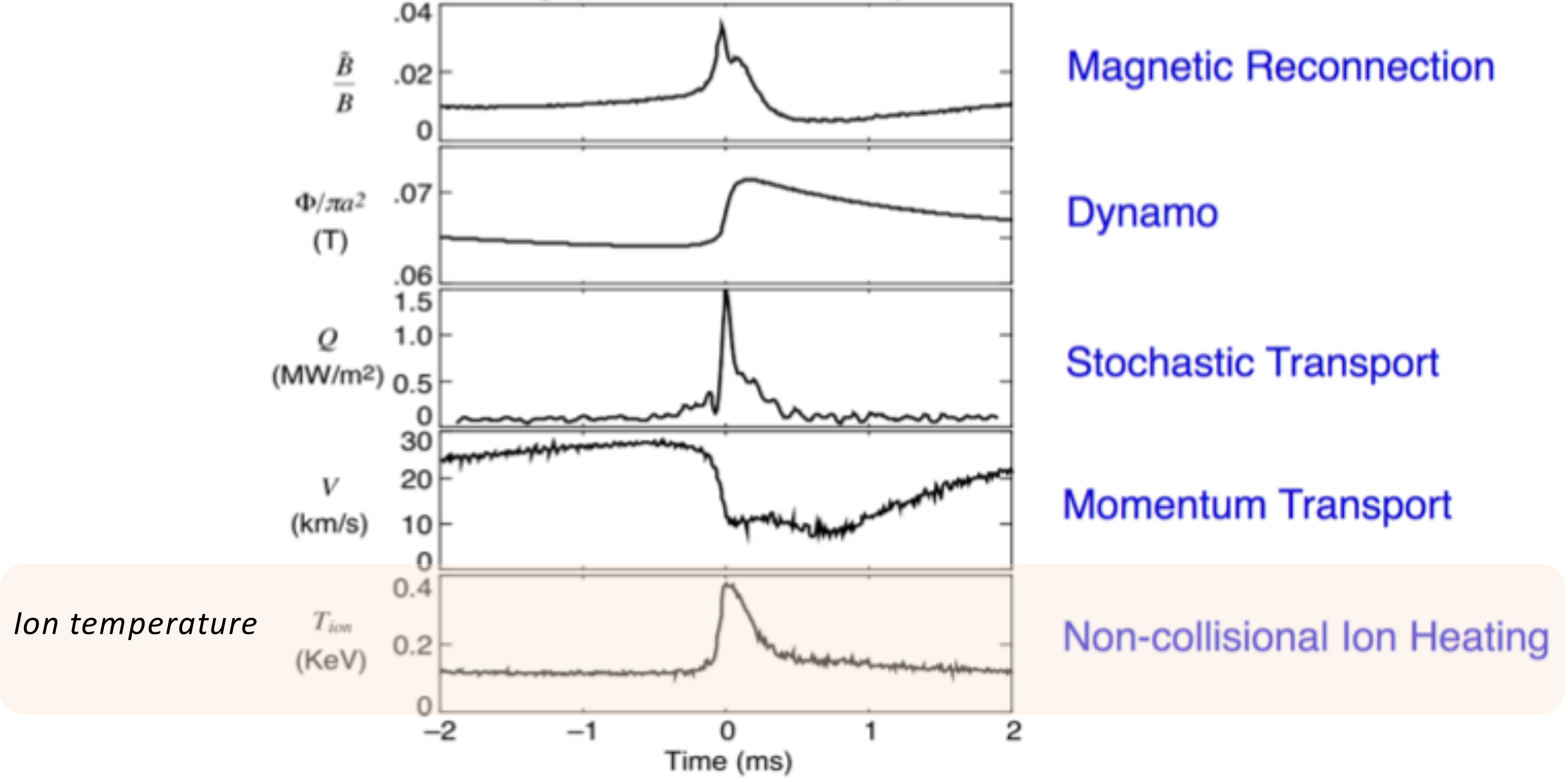
Reynolds stress

Terms measured



Both effects large and *almost* cancelling

Reconnection (or MSO) event



Explanation of ion heating

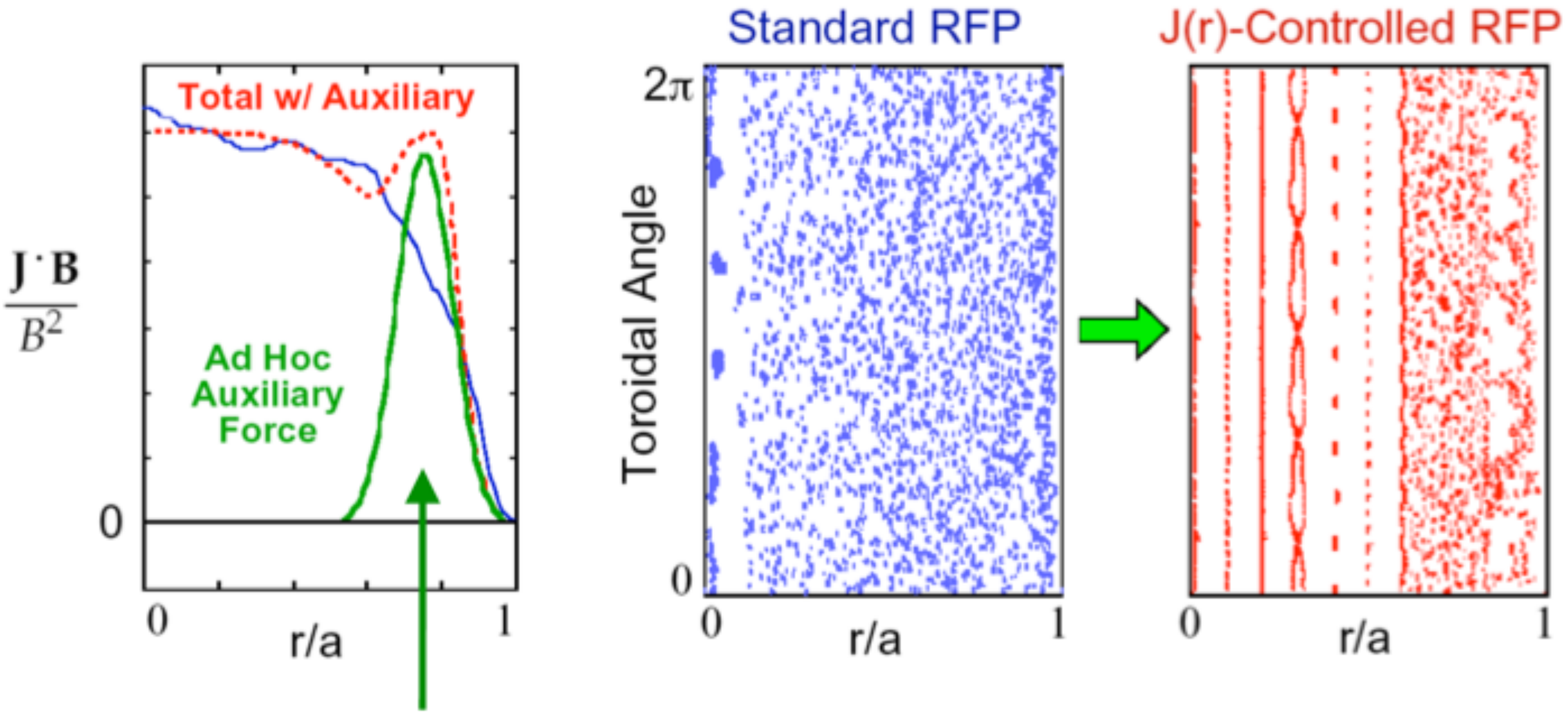
?????????

Energy source in magnetic energy,

But transfer mechanism not yet known

Control of reconnection and MSO

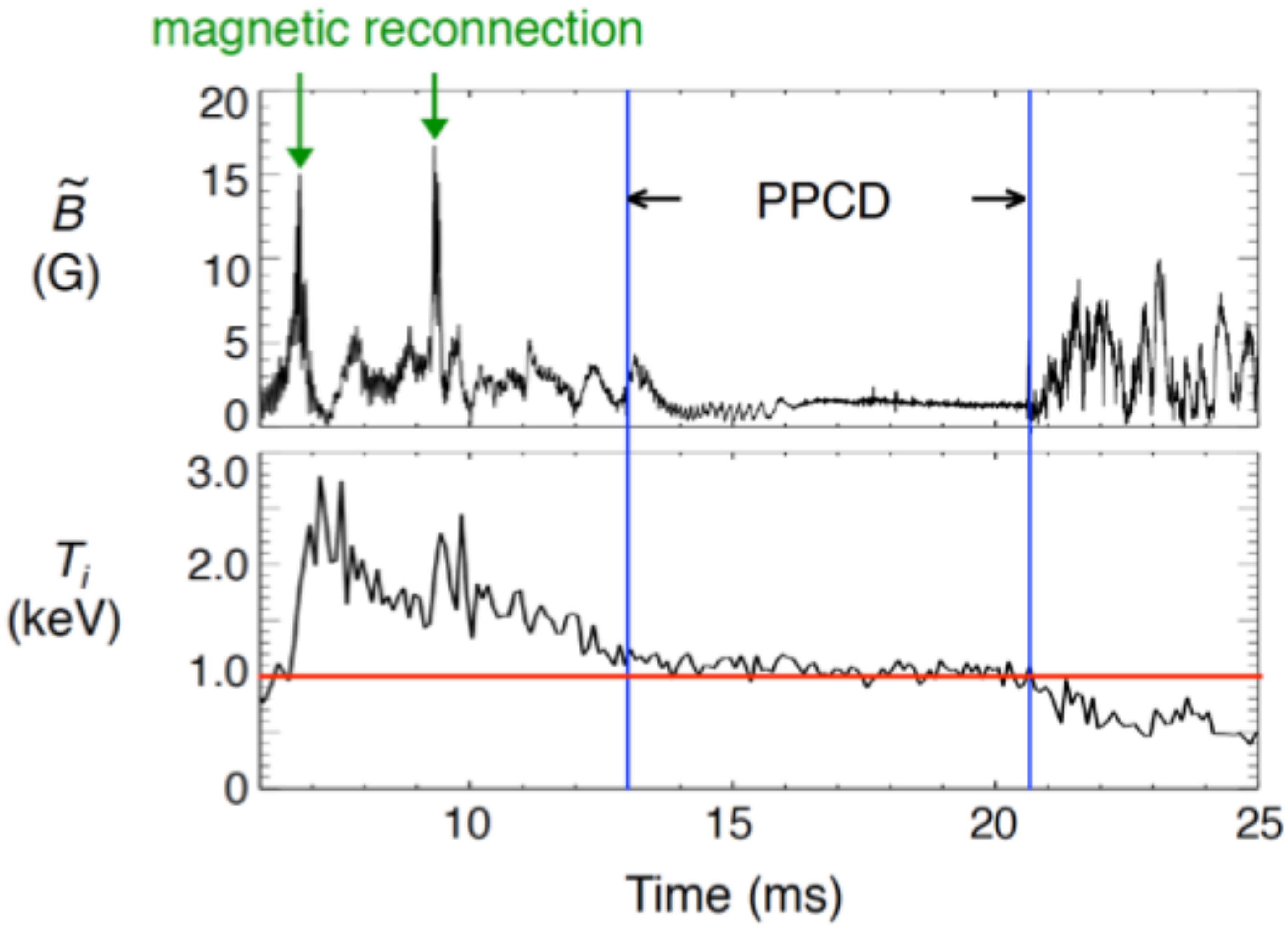
Suppress reconnection (tearing instability) - by driving edge current to reduce dj/dr



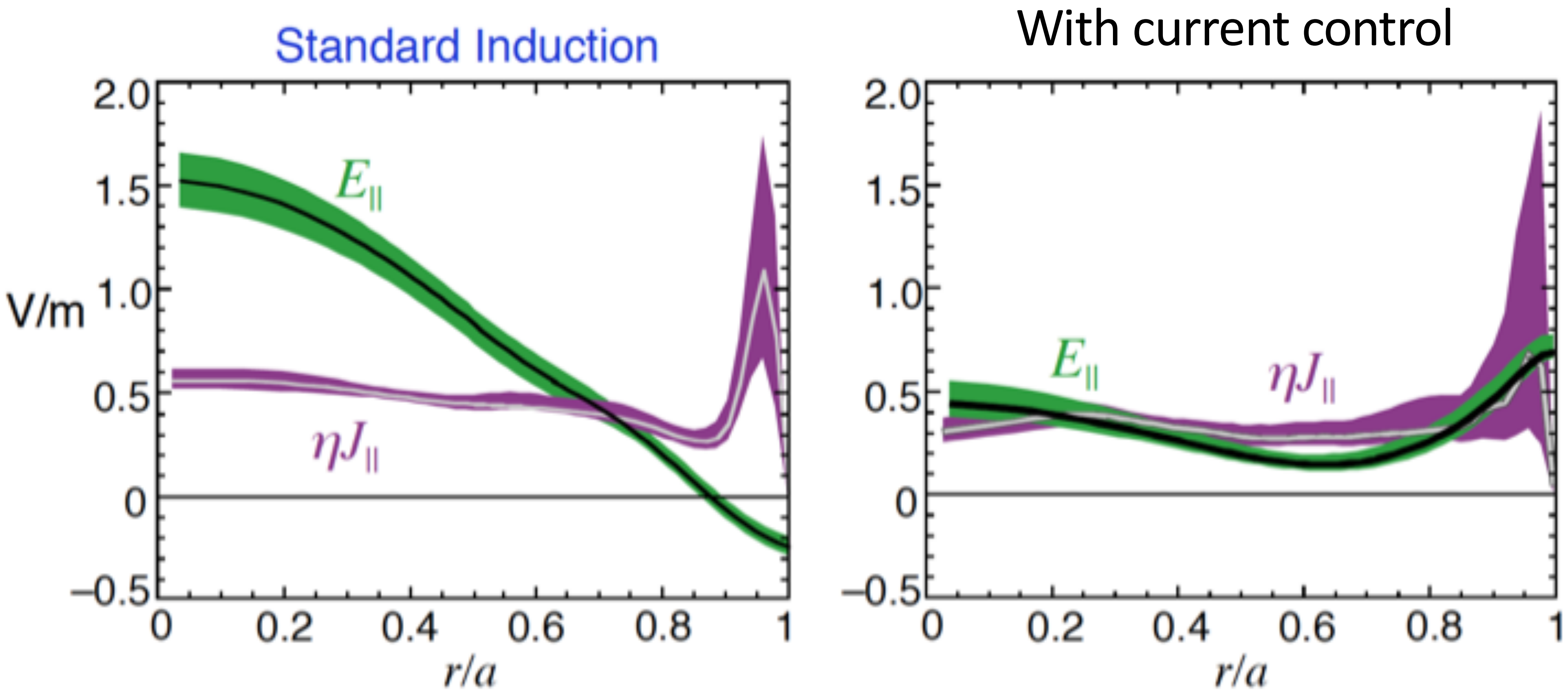
Current drive “replaces” dynamo

Mostly *poloidal* current drive

Reconnection and ion heating suppressed

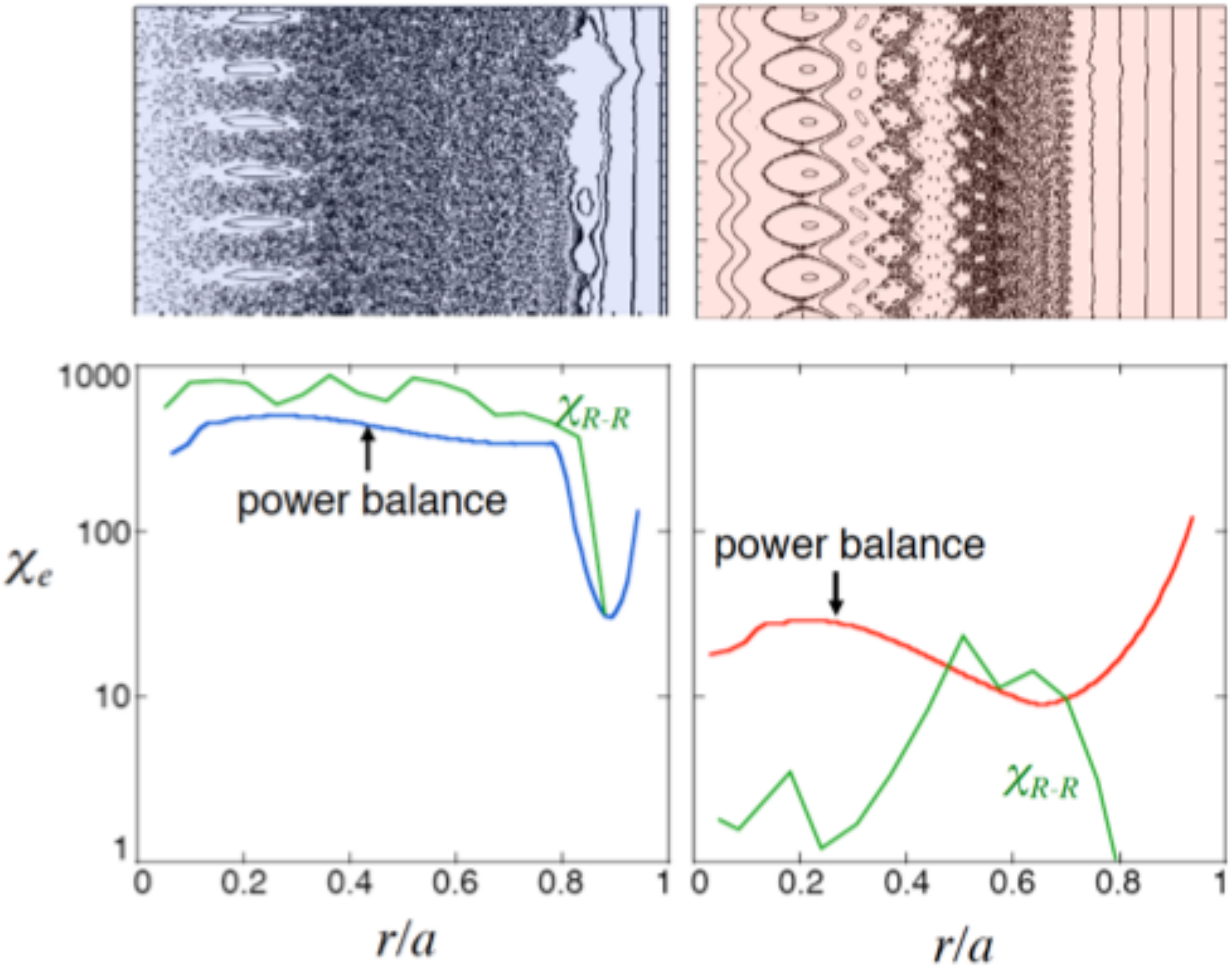


The dynamo disappears



Magnetic chaos and energy transport reduced

Electron thermal diffusivity



30-fold decrease of χ_e in the core!

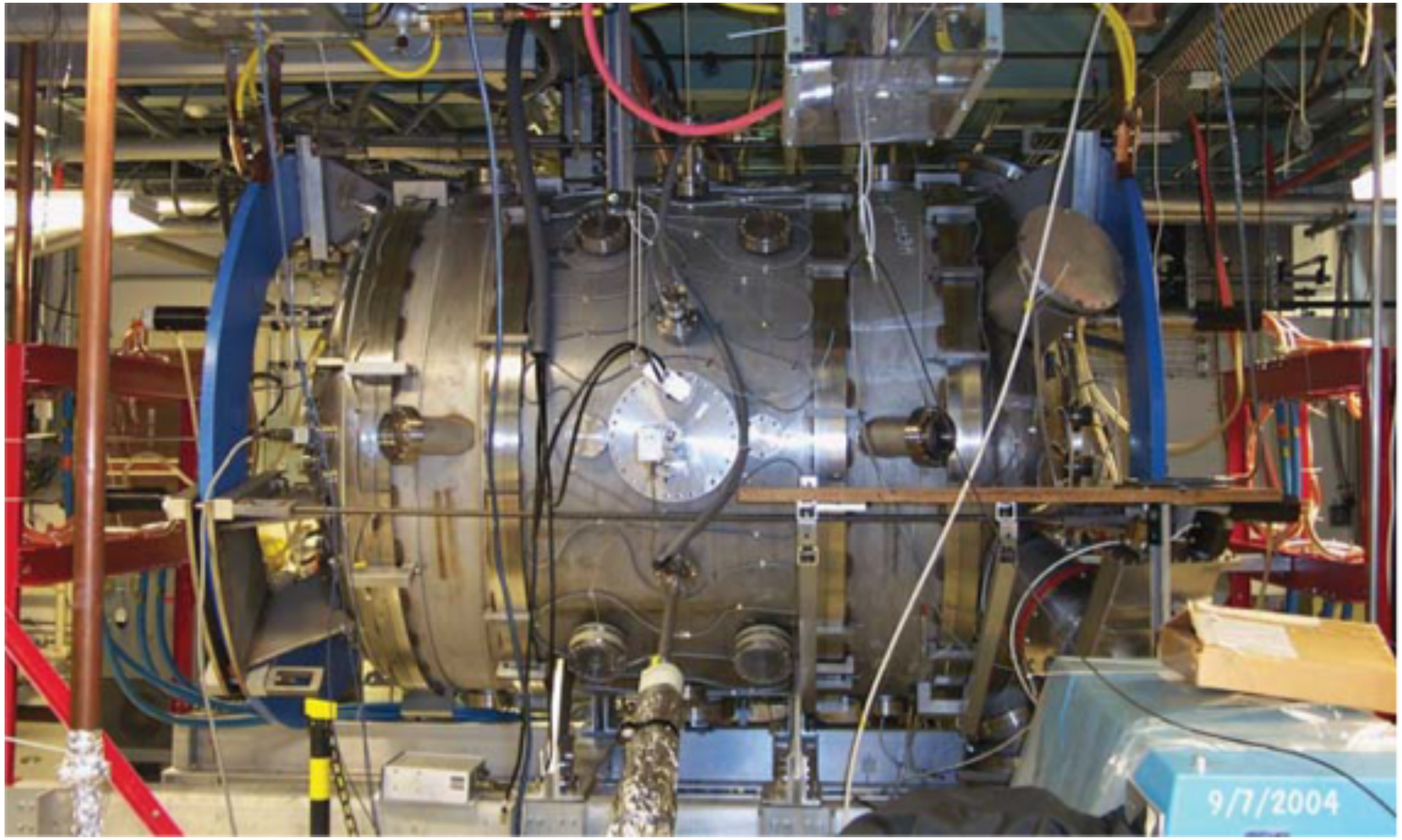
Basic reconnection experiments

Set up specifically to investigate reconnection in a controlled manner

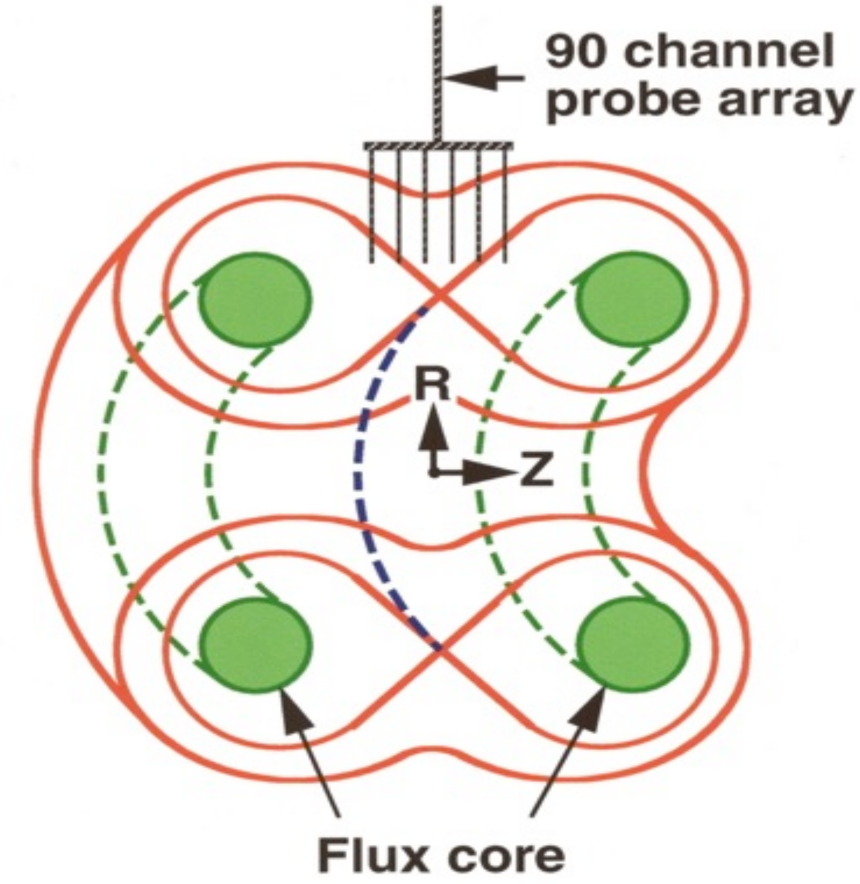
Dedicated Laboratory Experiments on Reconnection

Device	*Where*	*Since*	*Who*	*Geometry*
3D-CS	Russia	1970	Syrovatskii, Frank	Linear
LPD, LAPD	UCLA	1980	Stenzel, Gekelman, Carter	Linear
TS-3/4	**Tokyo**	**1990**	**Katsurai, Ono**	**Toroidal, Merging**
MRX	**Princeton**	**1995**	**Yamada, Ji**	**Toroidal, Merging**
SSX	**Swarthmore**	**1996**	**Brown**	**Toroidal**
VTF	**MIT**	**1998**	**Fasoli, Egedal**	**Toroidal**
Caltech exp	Caltech	1998	Bellan	Coaxial
RSX	Los Alamos	2002	Intrator	Linear
RWX	Wisconsin	2002	Forest	Linear
Laser driven merging	US, UK, China,	2006	Nilson, Li, Zhong, Dong, Fox, Fiksel	Planar
VINETA II	Max-Planck	2012	Grulke, Klinger	Linear
TREX	Wisconsin	2013	Egedal, Forest	Toroidal
FLARE	Princeton	2016	Ji et al	Toroidal
HRX	Harbin, China	2018	Ren et al	3D

Magnetic Reconnection Experiment (MRX)



Experimental Setup in MRX



Toroidal current - -> poloidal magnetic field
in coil

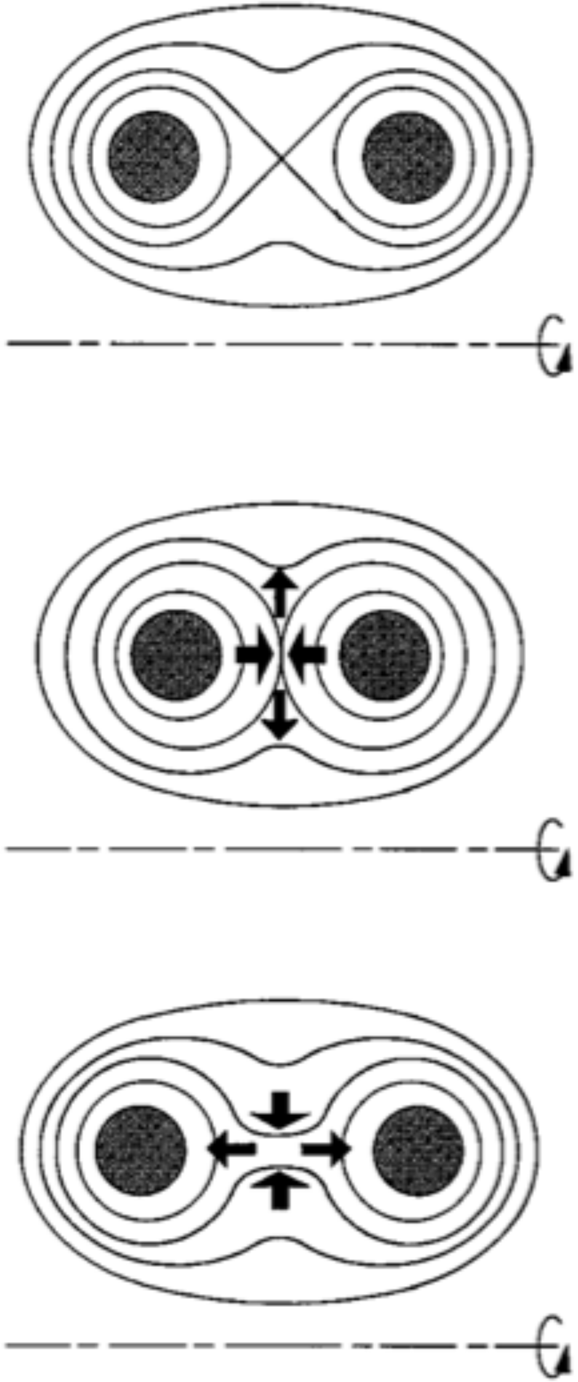
Time-varying - -> poloidal E field -> plasma
poloidal current

Driving reconnection

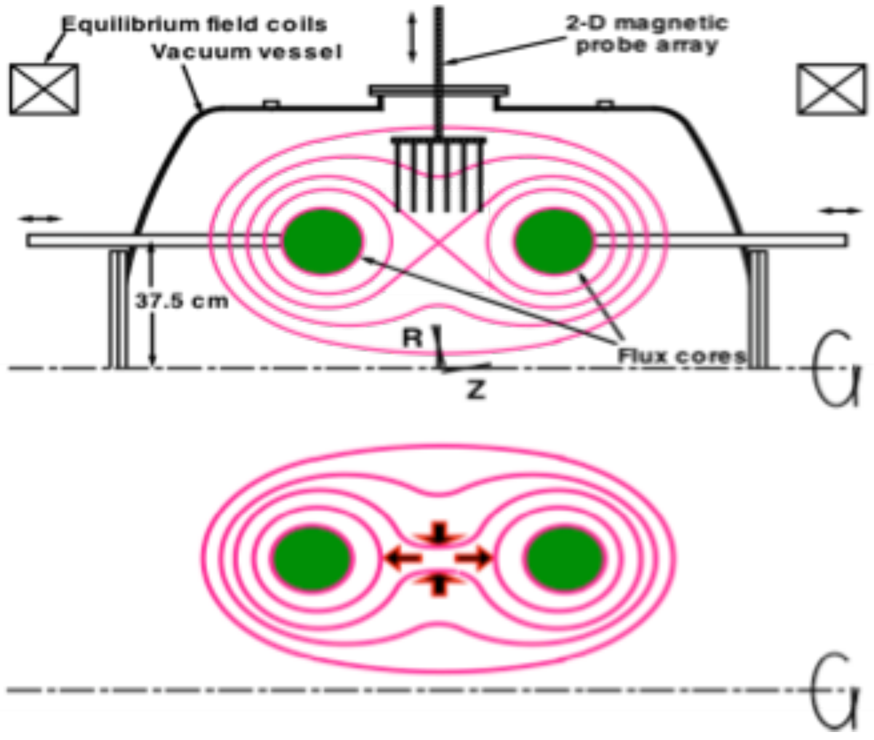
No reconnection when $dI_{PF}/dt = 0$

"Push" reconnection when $dI_{PF}/dt > 0$

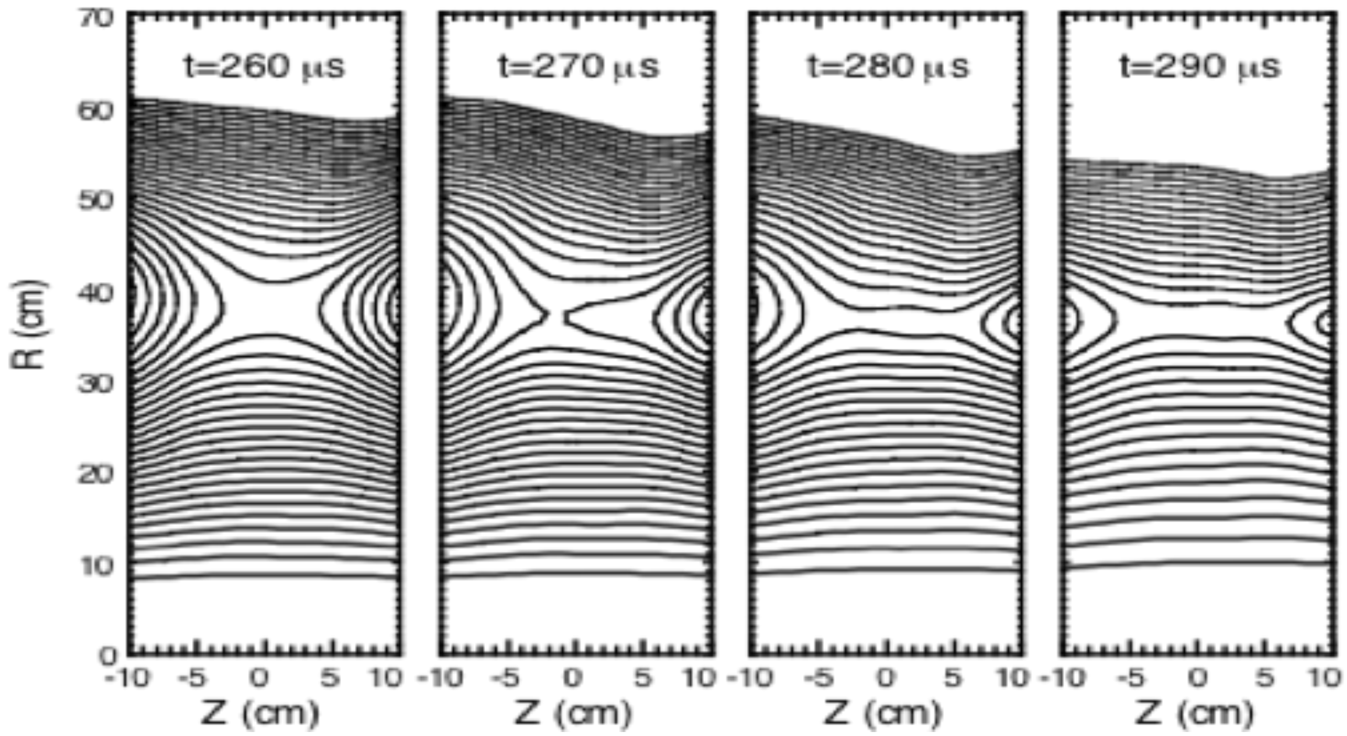
"Pull" reconnection when $dI_{PF}/dt < 0$



Details of reconnection measured



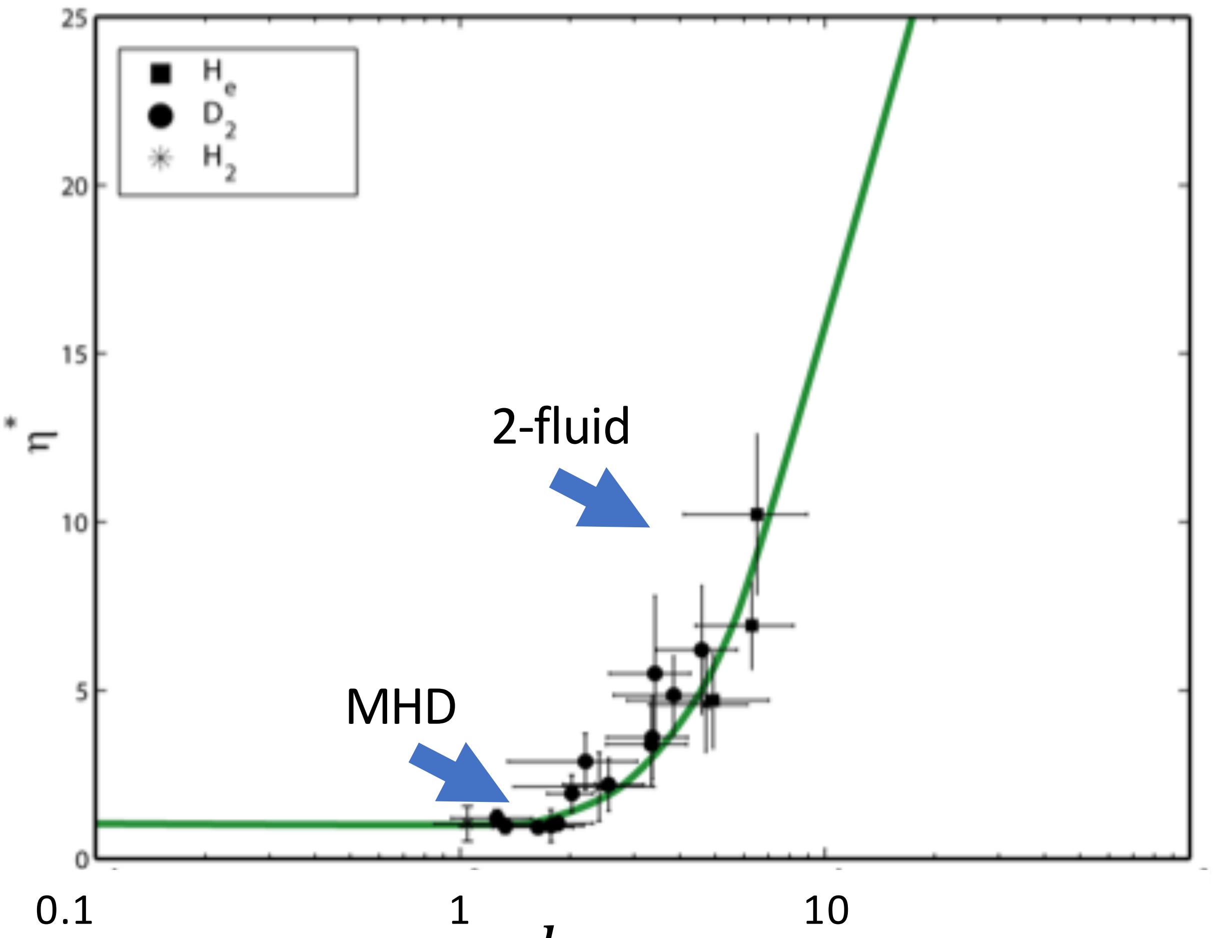
Experimentally measured flux evolution



n_e= 1-10 x10^{13} cm^{-3},
T_e~5-15 eV,
B~100-500 G,
S $\lesssim$ 1000

Formation of current sheet

Measured transition from MHD to two-fluid regime

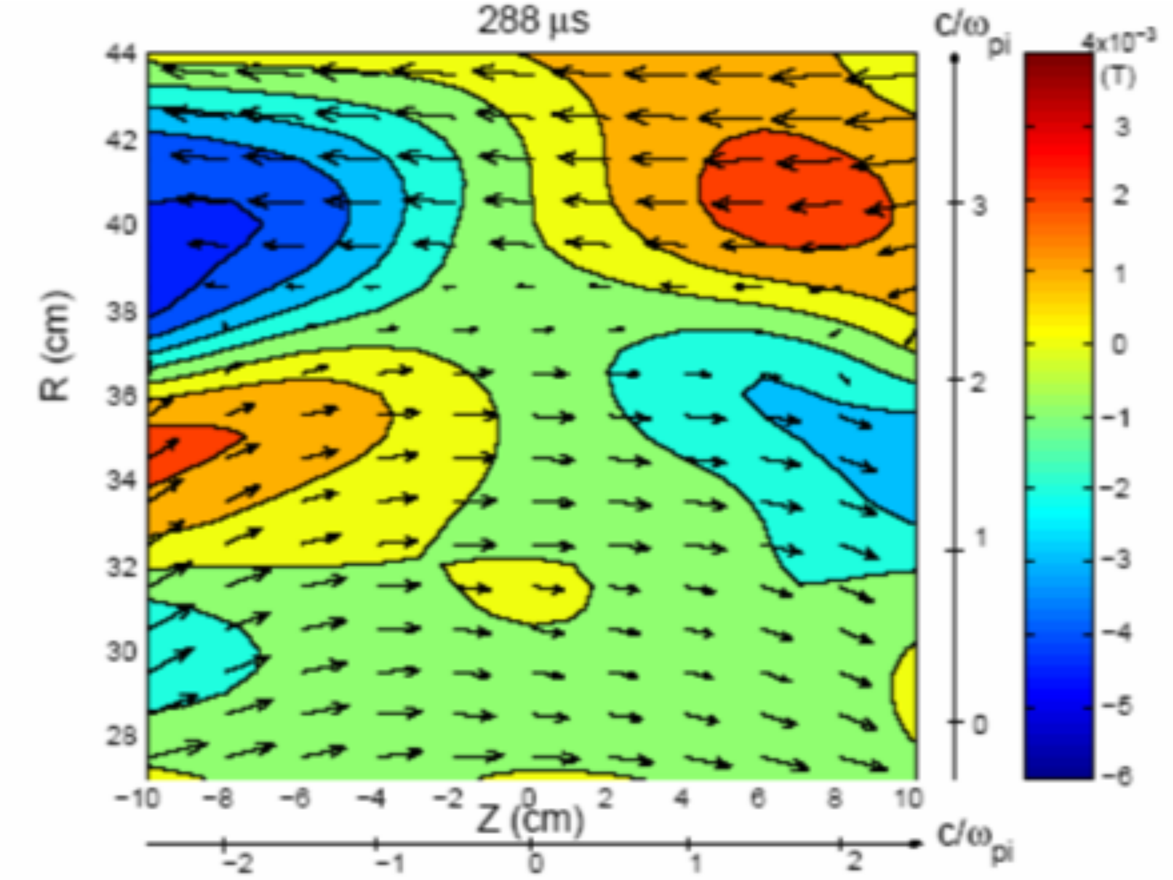


$\frac{E}{\eta j}$

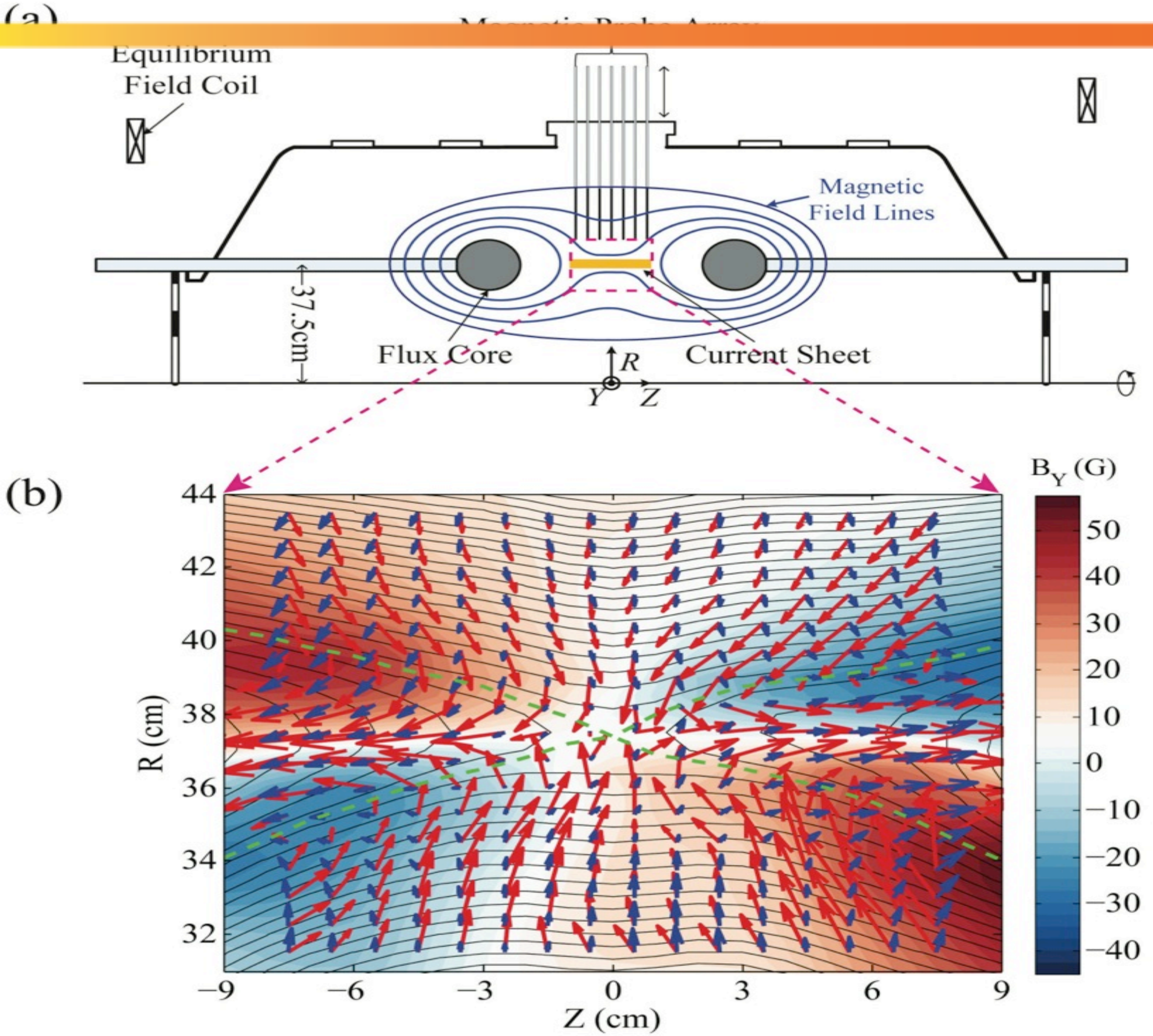
d_i / δ_{SP}

$d_i = c / \omega_{pi}$

Observe field structure predicted by Hall effect (quadrupolar)



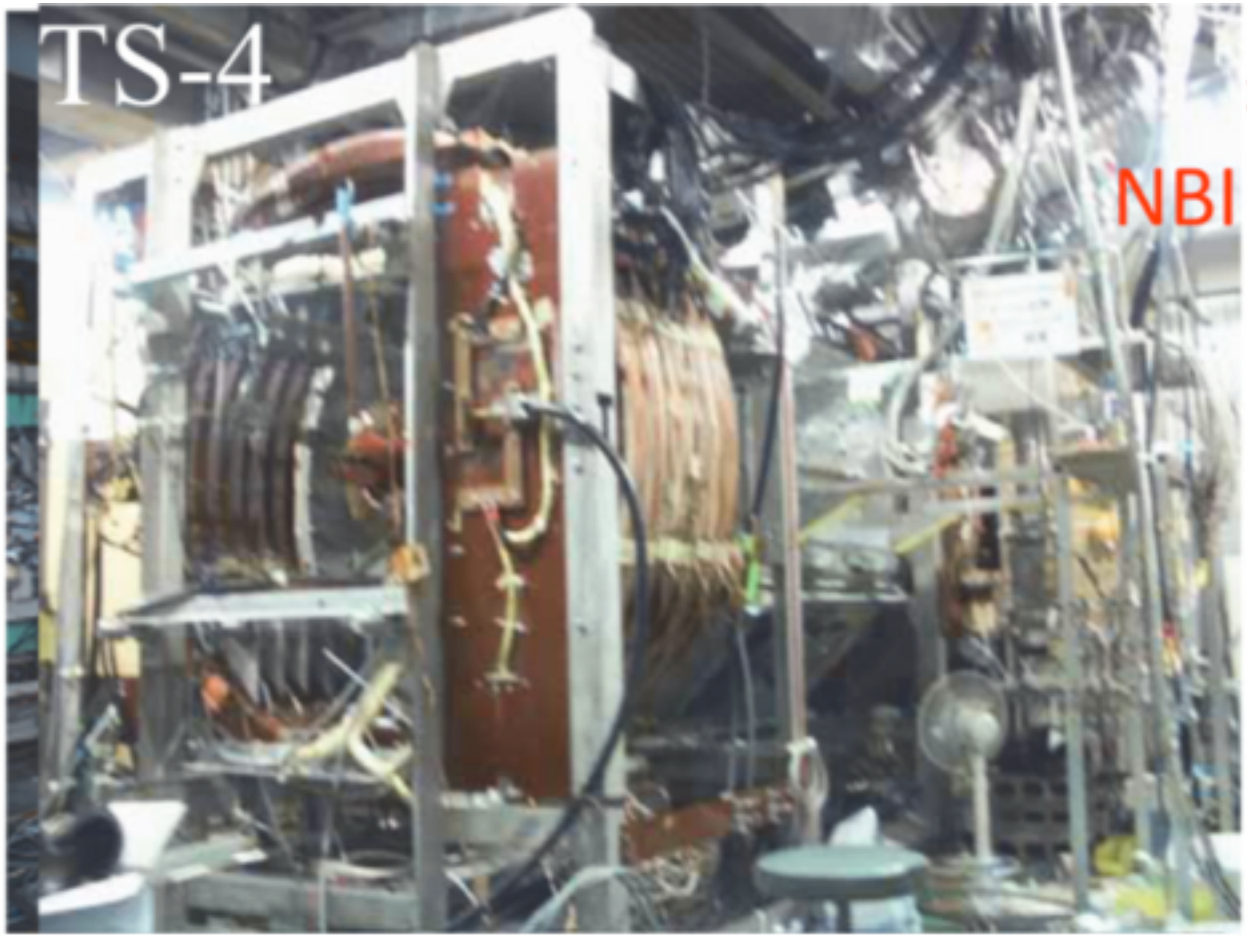
Electron and ion flow velocity measured

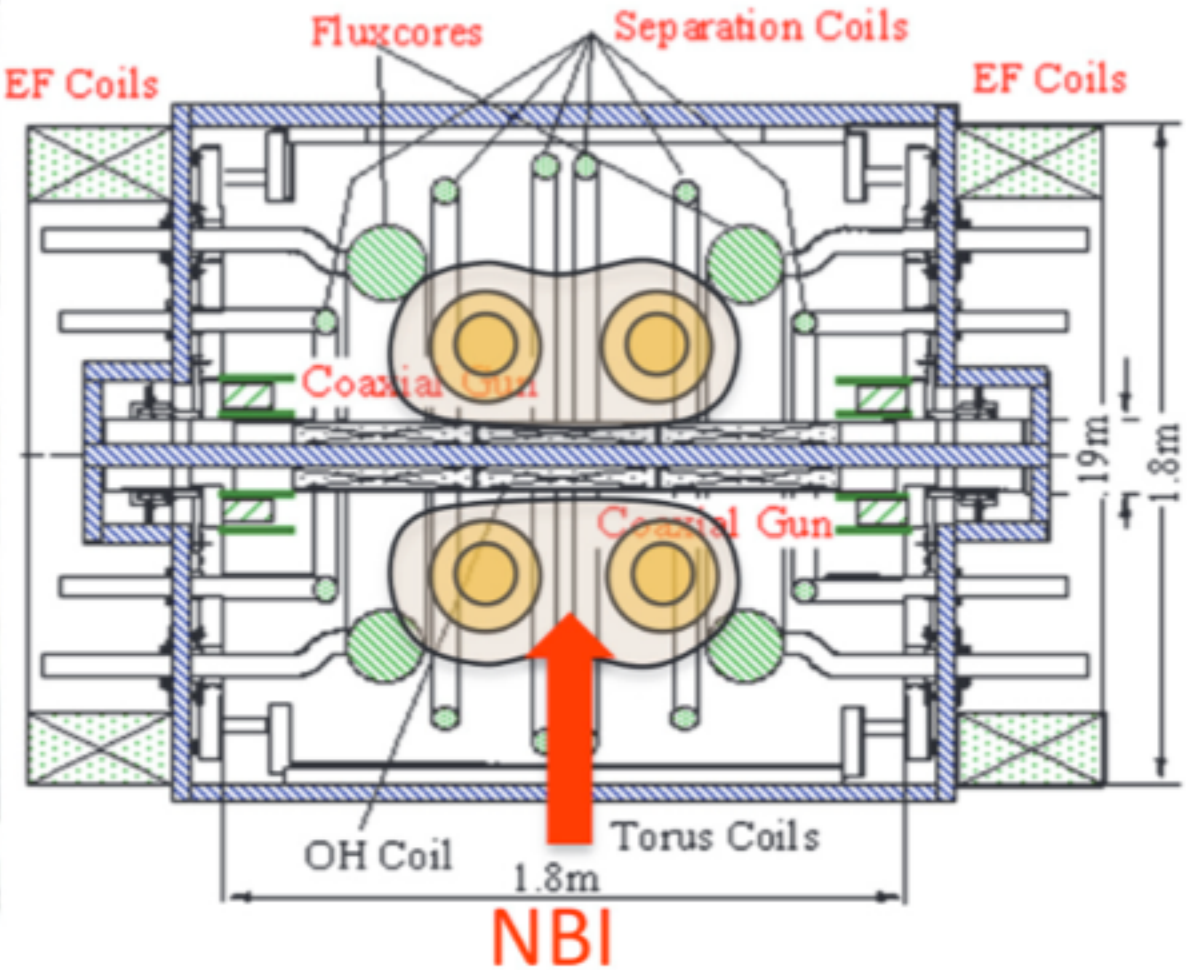


Electron and ion flow vectors

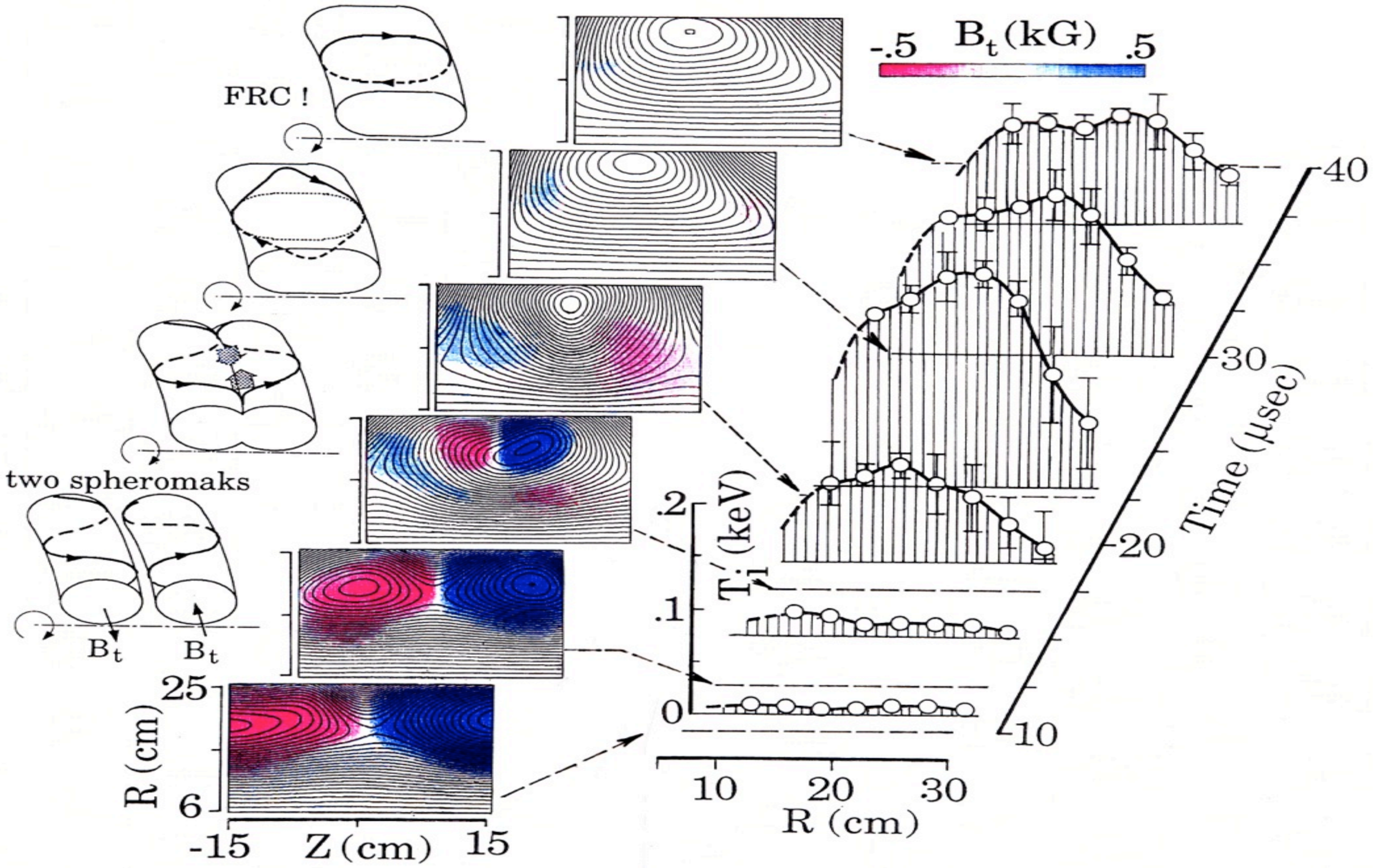
:

plasma merging device (Tokyo)





Strong ion heating during reconnection



More experiments possibly for Friday lecture

- High energy density physics (laser driven)
- Liquid metal experiments for dynamo
- Other new experiments: Wisconsin, Princeton…