Physics Progress of Reversed Field Pinch Magnetic Confinement

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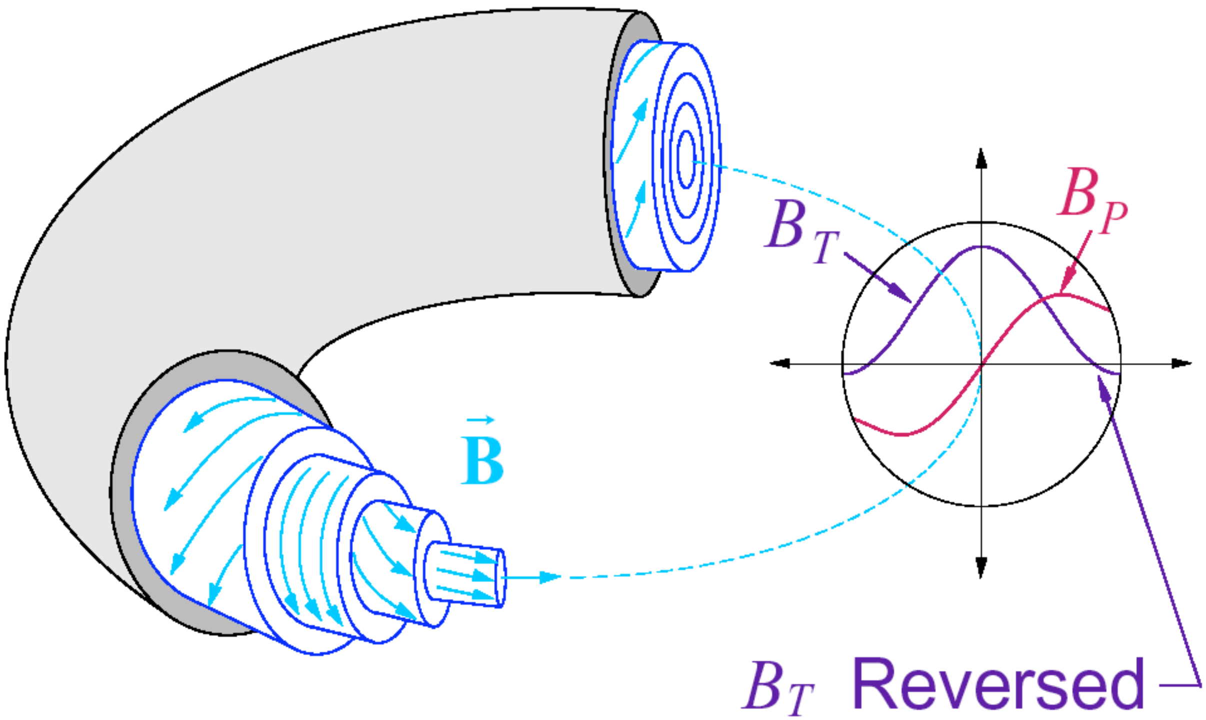
The Reversed Field Pinch magnetic configuration

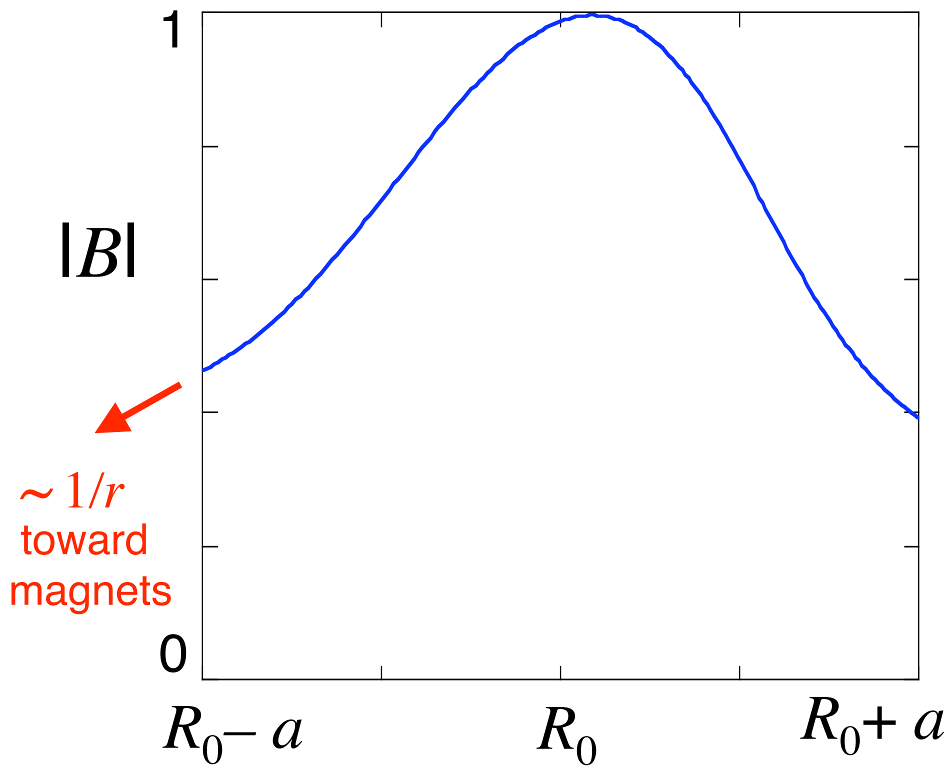
- Magnetic field is generated primarily by the plasma current
- Small externally applied field:
  - Advantages for fusion
  - Magnetic self-organization and nonlinear plasma physics
  - Large magnetic shear and weaker toroidal (neoclassical) effects

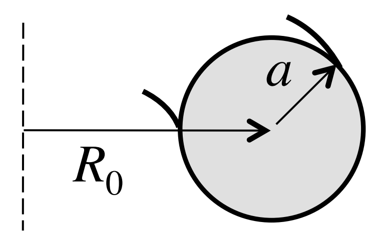


RFP's fusion advantages derive from the concentration of magnetic field within the plasma and small applied toroidal field

- Small field at the magnets, allows choice for normal conductors
  - 1/10th the magnetic pressure at the magnets than for a tokamak (very high $\beta_{eng} \sim \langle p \rangle / B^2_{\max}$)
  - Promotes reliability and maintainability

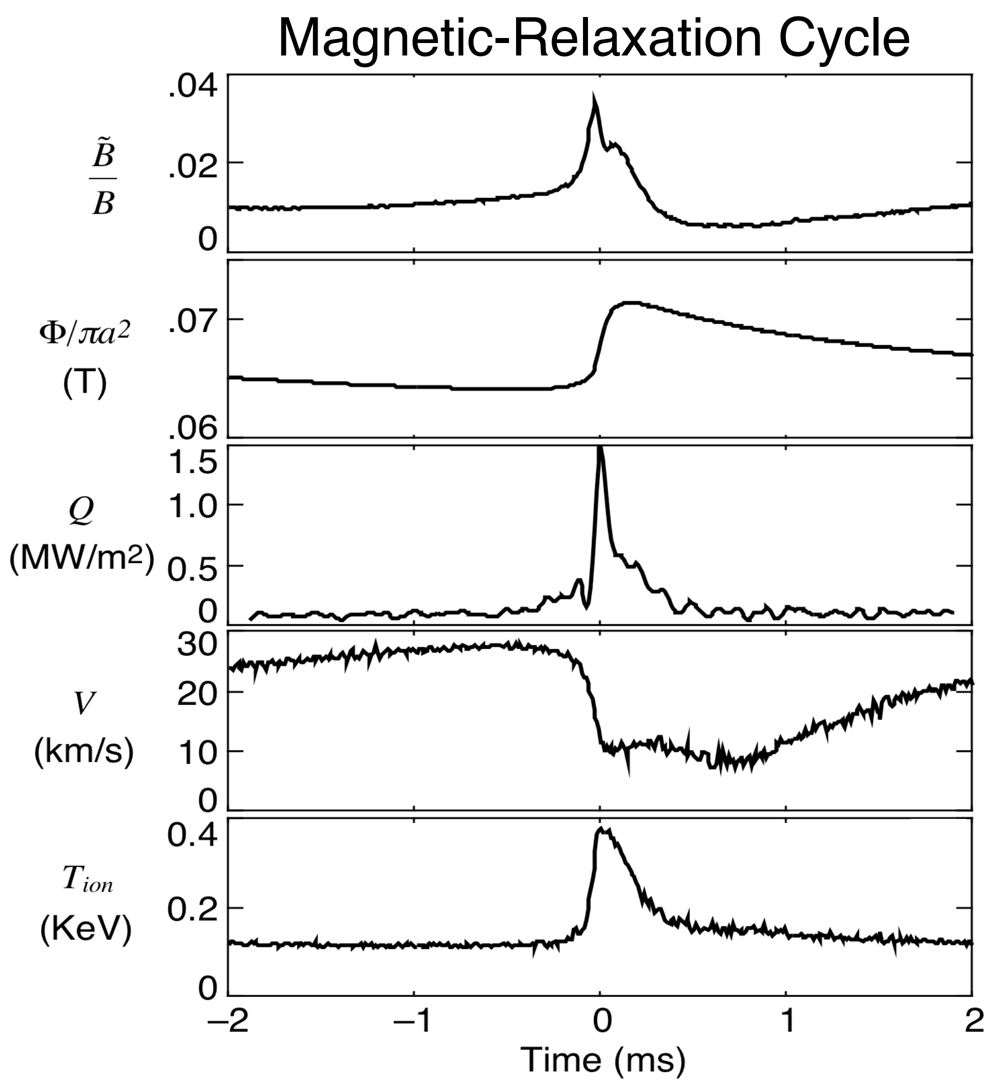
- Large plasma current density
  - Ohmic heating for a burning plasma is possible
  - Minimal or no plasma-facing auxiliary heating systems
  - High particle density limit ($n_G \sim I_p / a^2$)





The RFP exhibits fascinating magnetic self-organization and nonlinear plasma physics

- Processes are related to astrophysical plasmas.



Magnetic Reconnection

Dynamo

Stochastic Transport

Momentum Transport

Non-collisional Ion Heating

A number of physics advances have enabled an improvement in RFP performance and its fusion prospects

- Mature theory for nonlinear, 3D, resistive MHD physics, now being extended to include two-fluid and kinetic physics.
- Discovery of spontaneous helical equilibria at high current, leads to a 5-fold improvement in energy confinement.
- Control of magnetic chaos, yielding a 10-fold improvement in energy confinement.
- Transition from magnetic transport to a regime likely dominated by electrostatic turbulence.
- Stabilization of >10 simultaneously occurring MHD kink instabilities (resistive wall modes) using active feedback control methods.
- Strengthened physics basis for steady-state current sustainment using inductive electric fields.

Outline

- Essential physics of the standard RFP
  - MHD tearing magnetic reconnection
  - Dynamo behavior
  - Stochastic transport
- Beyond the standard RFP
  - Quasi-single-helicity dynamo
  - Current profile control for tearing suppression
  - Improved confinement
- Ideal MHD stability control
  - Resistive wall modes
  - Mode control
- Current sustainment, using magnetic self-organization

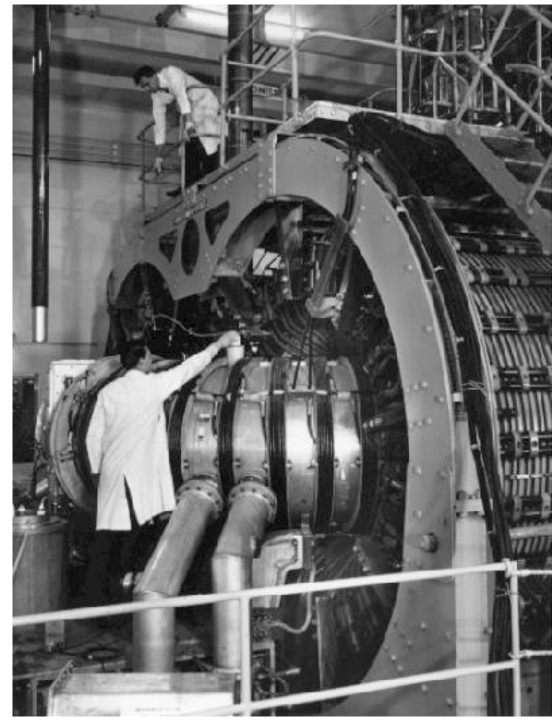
Current RFP research builds on seminal work from a number of programs, especially the 1980's experiments

- RFP begins with "quiet period" coincident with spontaneous toroidal field reversal in the ZETA experiment (late 1950's).

- More than 20 experiments since.

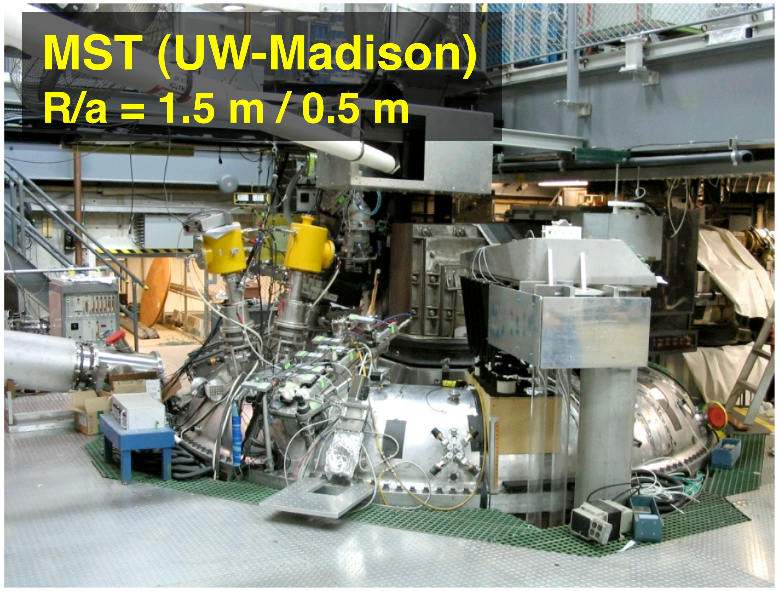
- Relaxation theory of J.B. Taylor (1974) provides key insight on reversed toroidal field, the genesis for "magnetic self-organization."

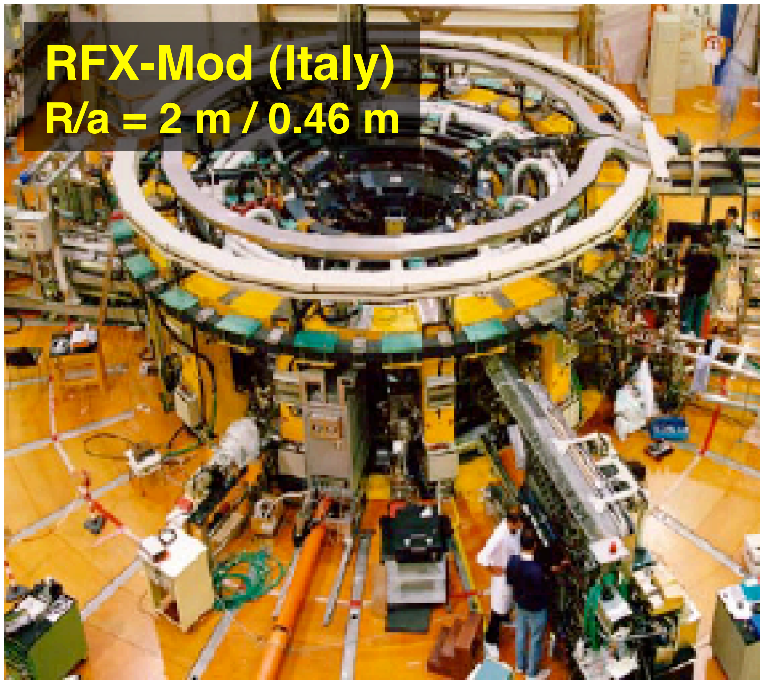
- 1980's medium-size experiments:
  - ZT-40M, LANL
  - OHTE, GA
  - HBTX series, Culham
  - TPE series, Japan
  - REPUTE, Japan

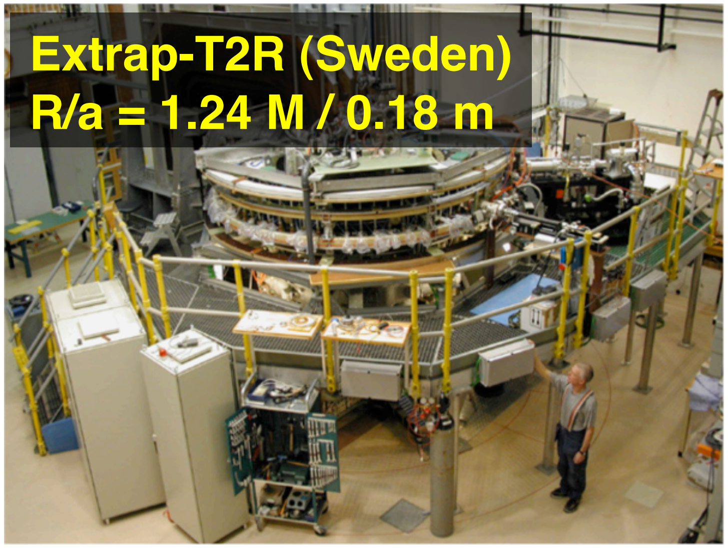


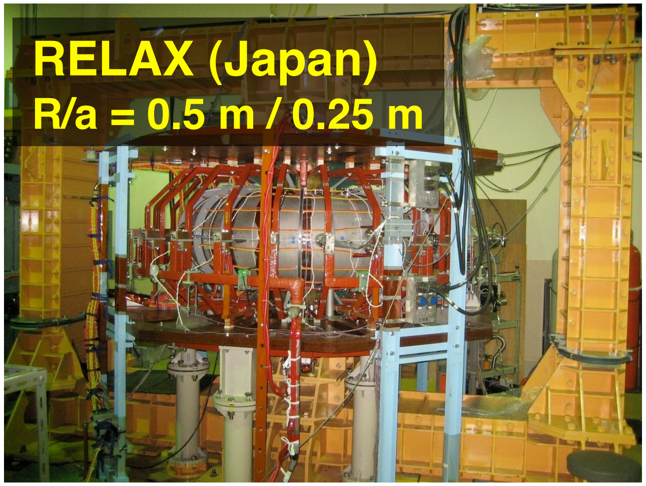
ZETA, Harwell Lab, England

Present RFP experiments









Tearing Reconnection and Dynamo (Standard RFP)

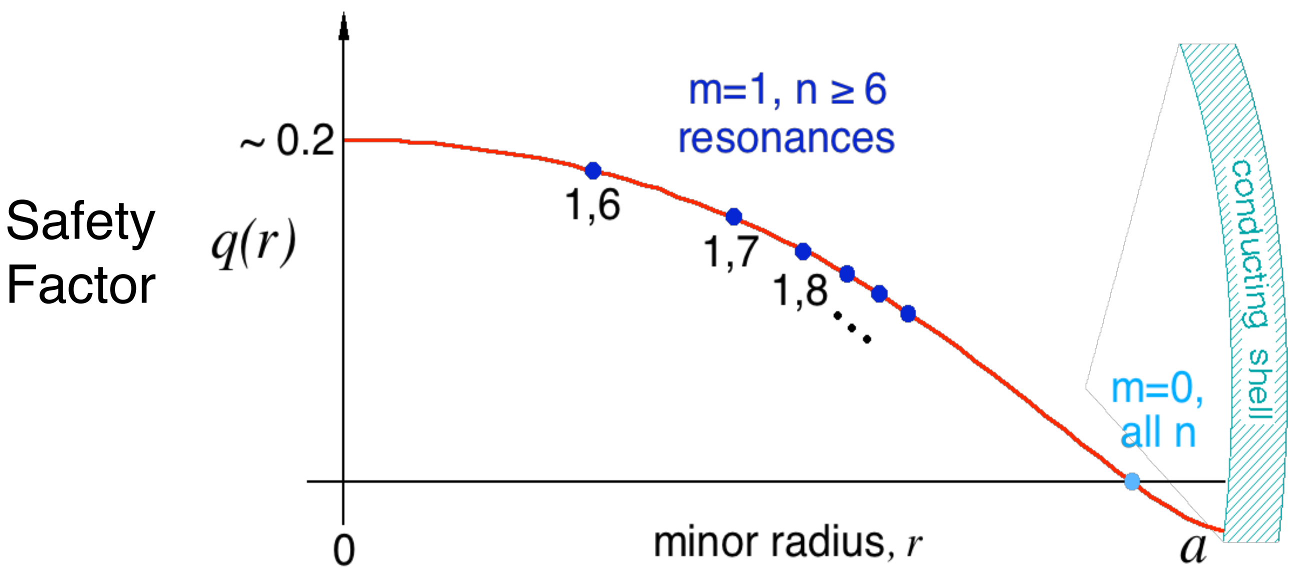
Tearing instability underlies much of the RFP's dynamics

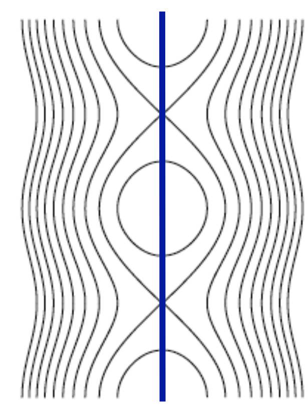
- Modes are resonant at locations where $\mathbf{k} \cdot \mathbf{B} = 0$
- Stability depends on $J_{||}(r)$ profile, and therefore the current drive method
- Nonlinear mode coupling can energize a broad mode spectrum

$$0 = \mathbf{k} \cdot \mathbf{B} = \frac{m}{r} B_\theta + \frac{n}{R} B_\phi \quad \Rightarrow \quad q(r) = \frac{r B_\phi}{R B_\theta} = \frac{m}{n}$$

m = poloidal mode number

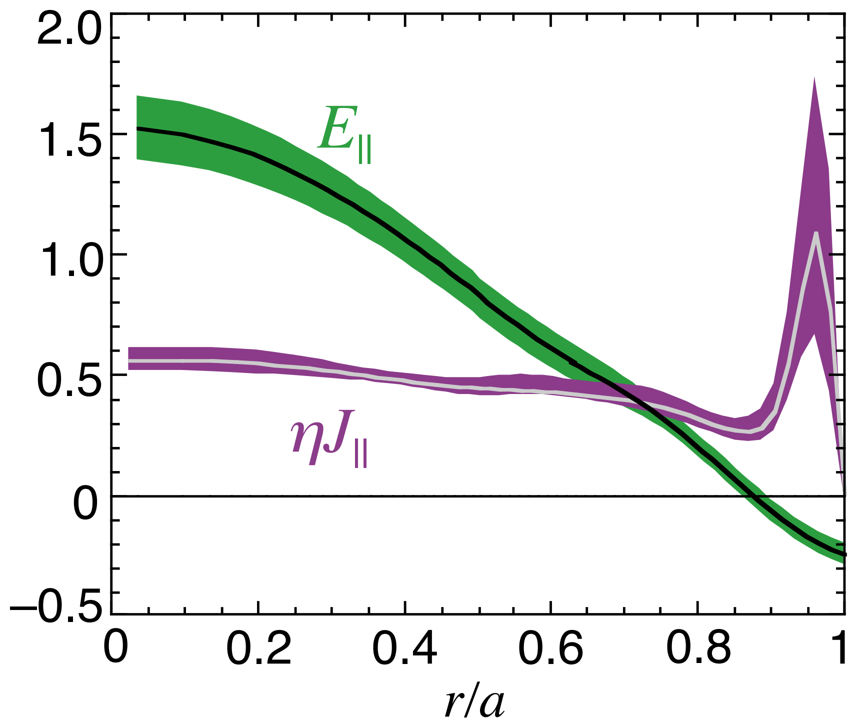
n = toroidal mode number





An apparent imbalance in Ohm's law reveals the RFP's dynamo behavior

- Steady toroidal induction tends to drive a peaked (unstable) current profile.
- Equivalent to the mystery of a sustained reversed toroidal field.



"$V \neq IR$"

Measured via equilibrium reconstructions.

MST, Anderson et al., 2004

Nonlinear, resistive MHD provides a base model for the origin of the RFP dynamo

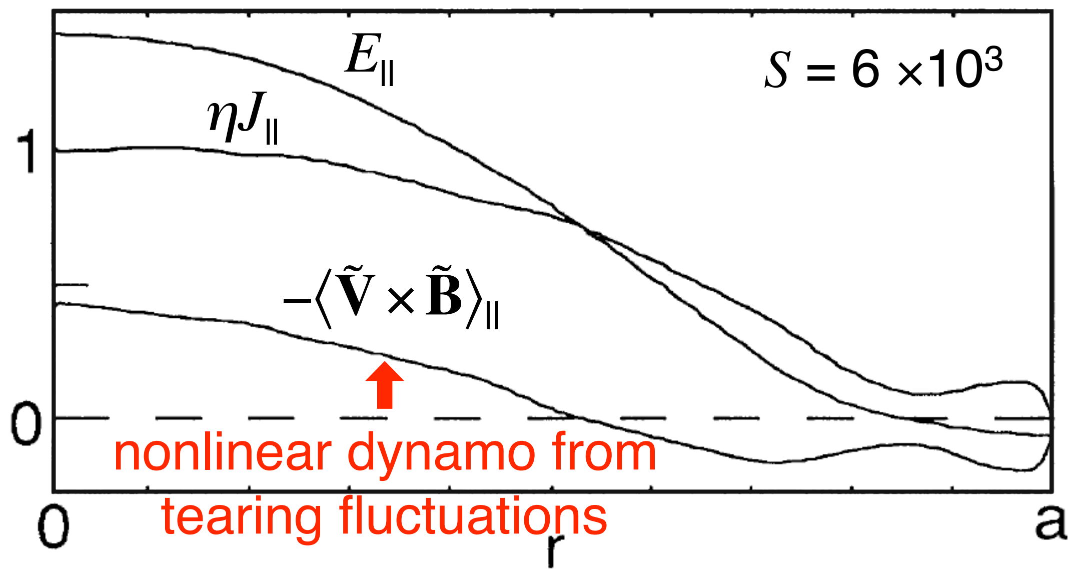
$$\mathbf{E} = \eta\mathbf{J} - S\,\mathbf{V}\times\mathbf{B}$$

$$S = \frac{\tau_R}{\tau_A} = \text{ Lundquist number}$$

$$\rho\frac{\partial\mathbf{V}}{\partial t} = -S\,\rho\mathbf{V}\cdot\nabla\mathbf{V} + S\mathbf{J}\times\mathbf{B} + P_m\nabla^2\mathbf{V}$$

$$P_m = \nu/\eta = \text{ Magnetic Prandtl number}$$

Ohm's Law



Dynamo emf maintains the current profile close to marginal stability.

$\tilde{\mathbf{V}}, \tilde{\mathbf{B}} =$ fluctuations associated with tearing modes

Schnack, Caramana, Nebel; Kusano, Sato; Cappello, Pacganella (1980's)

Generalized Ohm's law permits several possible mechanisms for dynamo action

$$\mathbf{E} - \eta\mathbf{J} =$$

$$-\mathbf{V}\times\mathbf{B} + \frac{1}{en}\mathbf{J}\times\mathbf{B} - \frac{1}{en}\nabla p_e$$

"MHD" "Hall" "Diamagnetic" ($\nabla_\perp \tilde{p}_e$)

(REPUTE, TPE, Ji et al.)

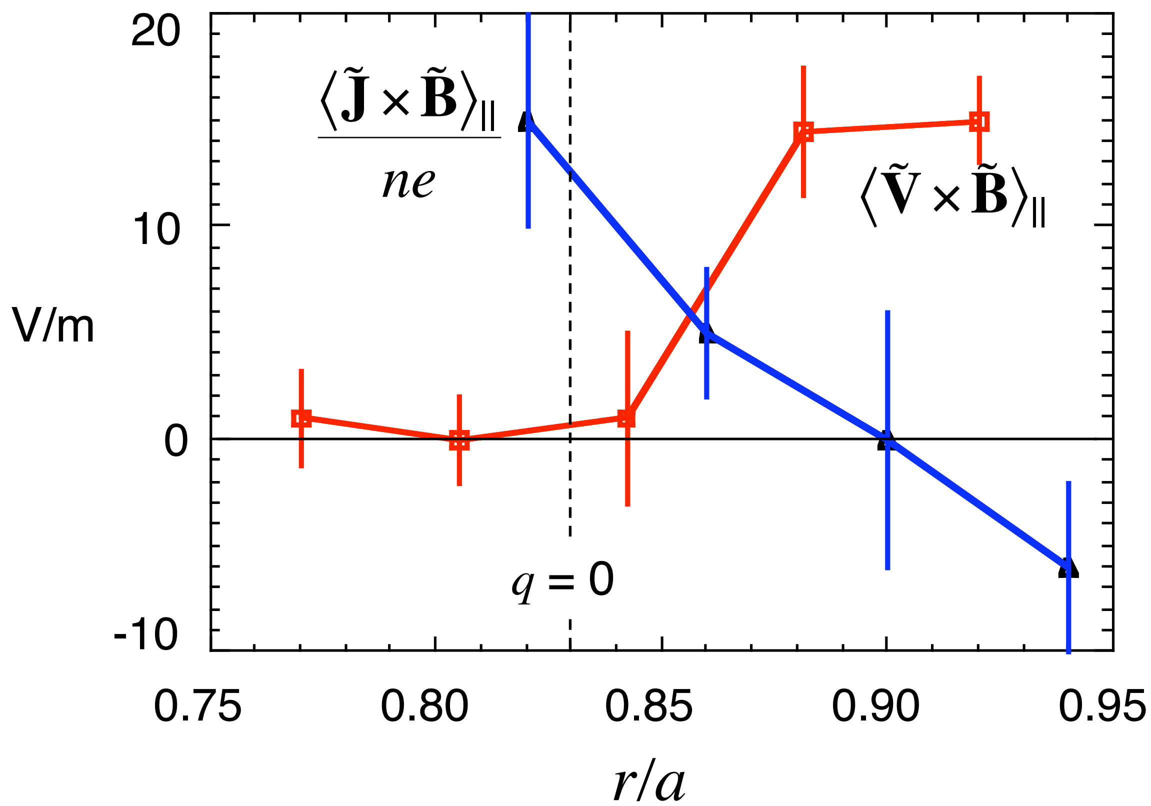
(Lee, Diamond, An)

Also "Kinetic" dynamo, i.e., stochastic transport of current

(ZT-40M, Jacobson, Moses)

Both MHD and Hall mechanisms are present in the RFP

- Similar behavior measured in the core plasma region, by Doppler spectroscopy and Faraday rotation.

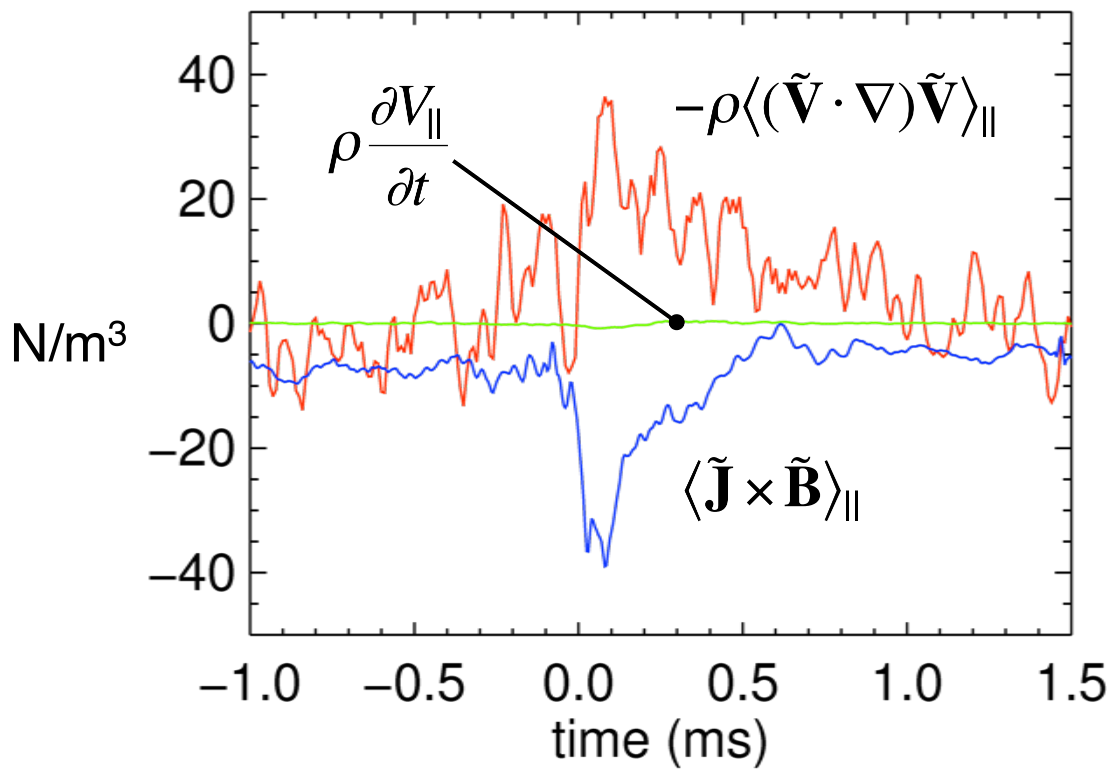


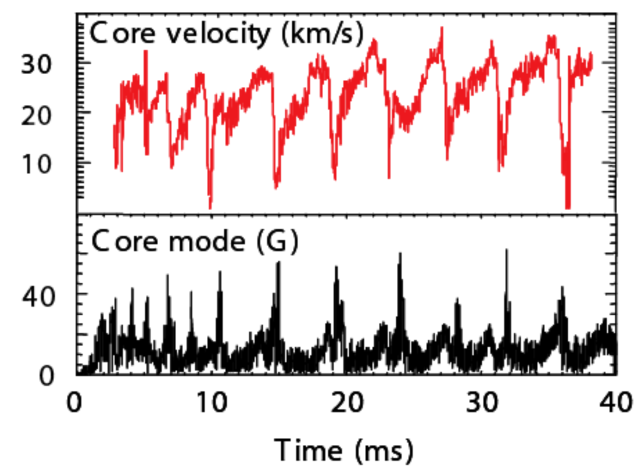
MST, Den Hartog, Ding, Fiksel, et al

Tearing-driven momentum transport is coupled to the dynamo

Parallel momentum balance: $$\rho \frac{\partial V_{\parallel}}{\partial t} = \langle \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle_{\parallel} - \rho \langle (\tilde{\mathbf{V}} \cdot \nabla) \tilde{\mathbf{V}} \rangle_{\parallel}$$

Hall dynamo ⇔ parallel Maxwell stress

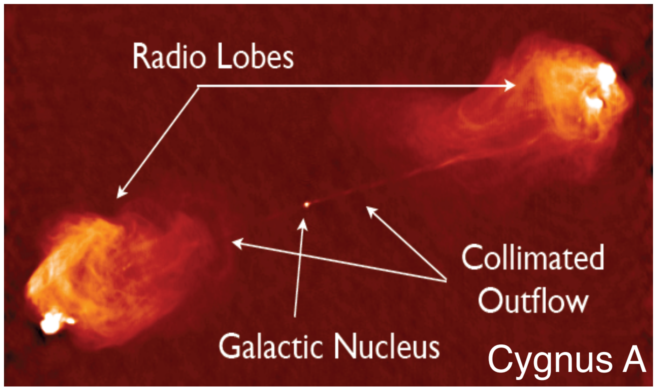




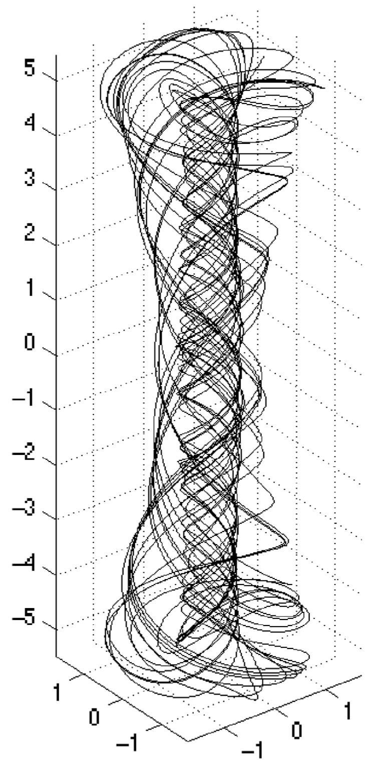
MST, Kuritsyn et al, 2008

RFP (and spheromak) self-organization inspires modeling of magnetically dominated astrophysical jets

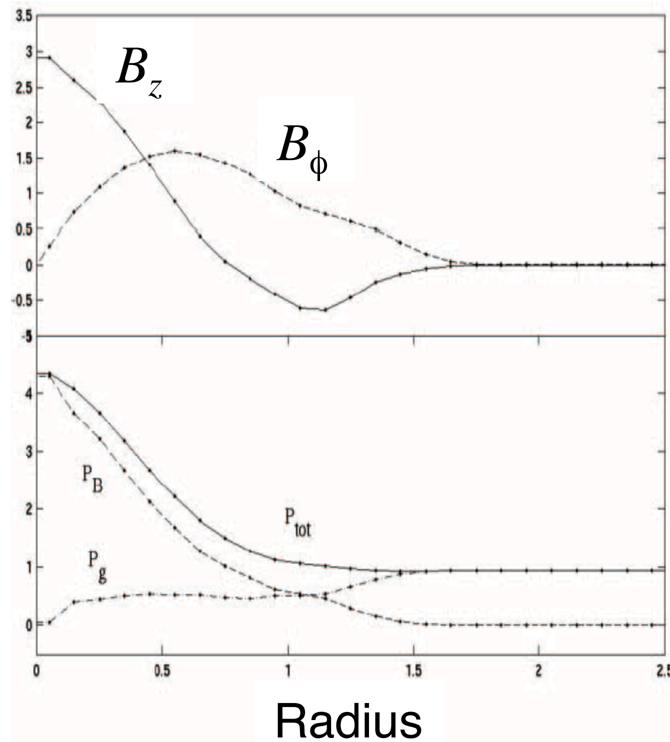
- RFP-like flux conversion can transport magnetic energy from its source in the accretion disk that produces the jet.



Carilli and Barthel, A&A Review (1996)



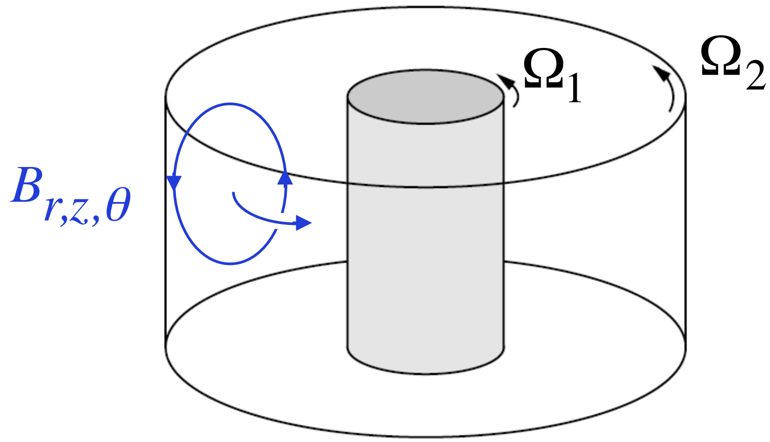
RFP-like mean fields

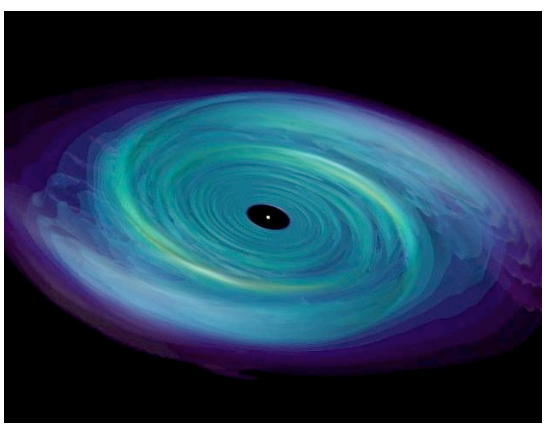


Li et al, 2006
Carey, Sovinec, 2009

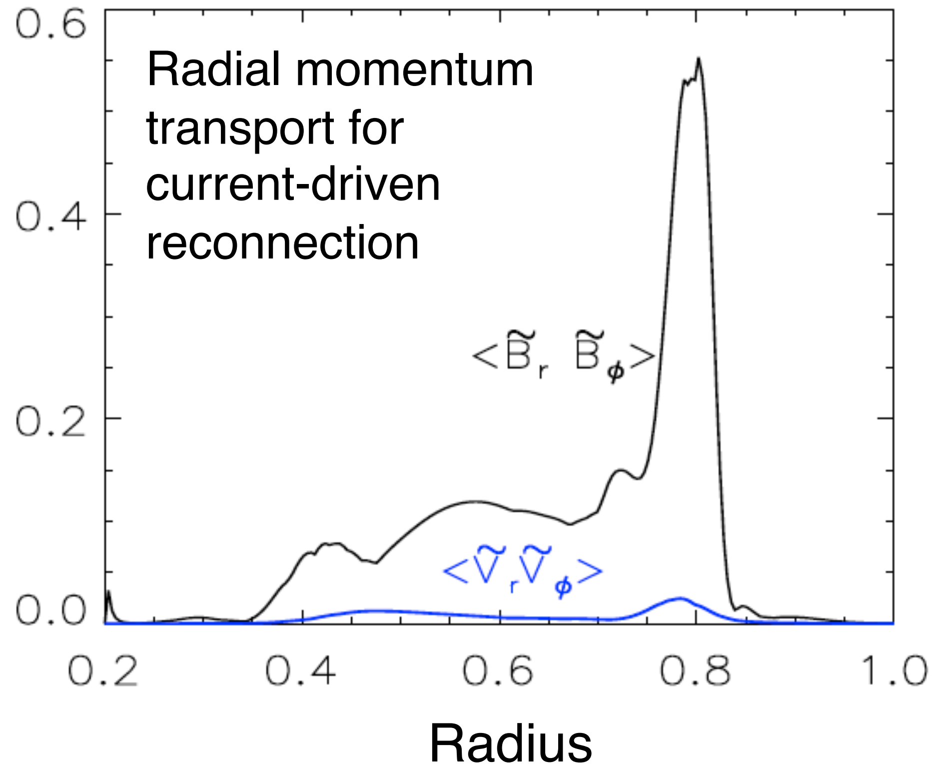
Possibility for momentum transport from current-driven reconnection in astrophysical accretion disks

- Nonlinear computation underway for MRI-stable thick-disk geometry.



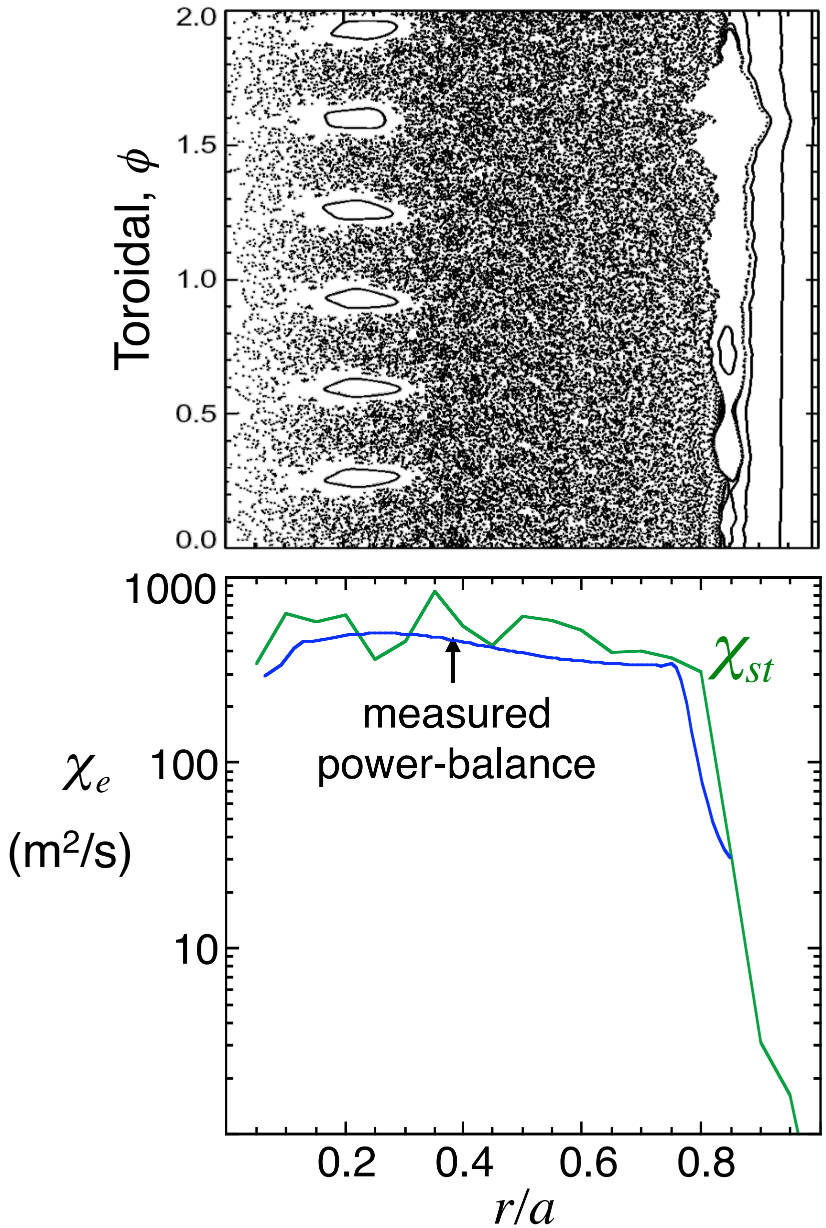


M. Owen and J. Blondin



Ebrahimi et al., 2009

Stochastic magnetic transport from multiple tearing modes has been the dominant challenge for RFP energy confinement



Test particle expectation:

$$\chi_{st} = v_{th} D_m$$

$$D_m = \frac{\langle (\Delta r)^2 \rangle}{\Delta s} = L_{ac} \langle \tilde{B}_r^2 \rangle / B_0^2$$

(aka Rechester-Rosenbluth)

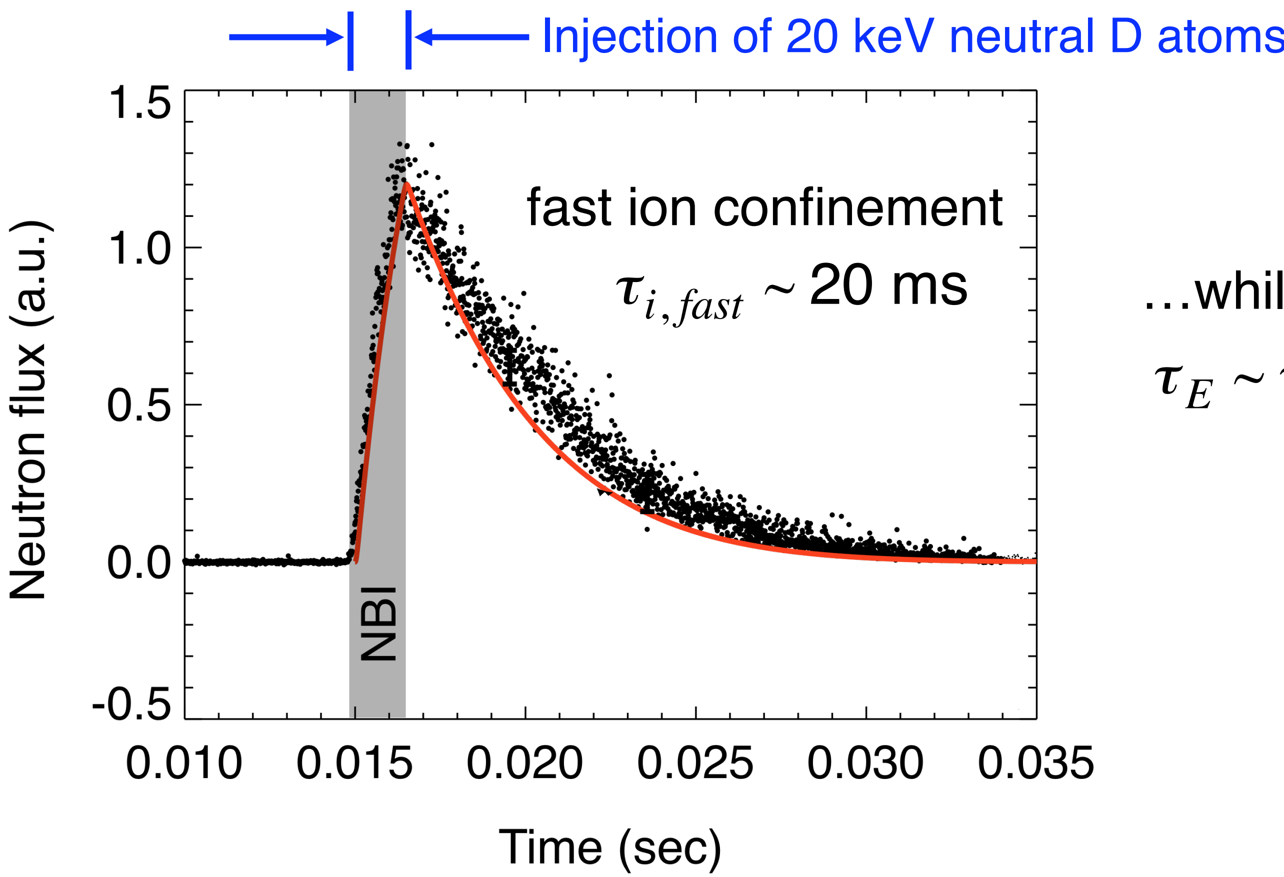
Agrees with experiment, if D_m is evaluated explicitly for an ensemble of field line trajectories.

Particle flux is surprising, exceeding ambipolar-constrained expectation
D. Brower, KI3.4, Tues

MST, Biewer et al, 2003

Energetic ions less affected by stochastic magnetic field

- Explained by decoupling of guiding center and magnetic field trajectories.
- Important for neutral beam injection (NBI) and alpha particle confinement.
- Perhaps important for propagation of high energy cosmic rays, etc.



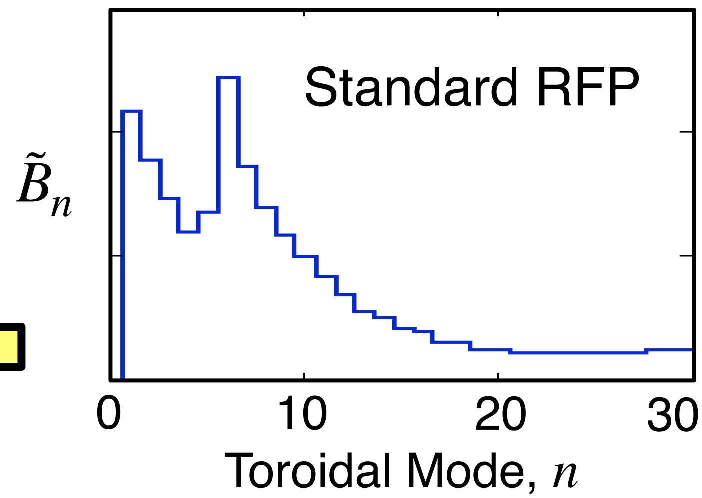
…while thermal

$\tau_E \sim \tau_p \sim$ 1 ms

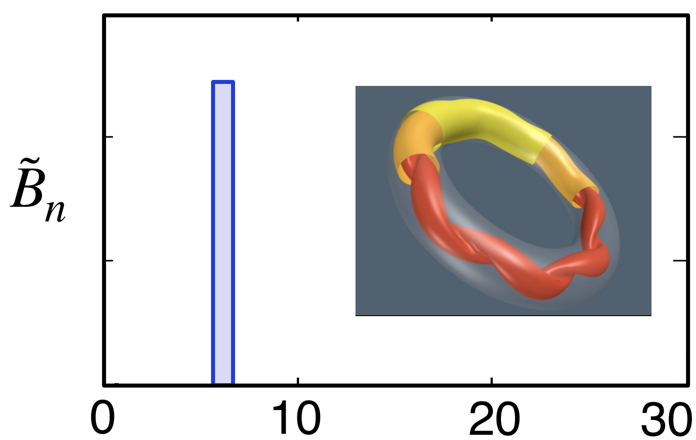
MST, Fiksel et al., 2005

Beyond the Standard RFP

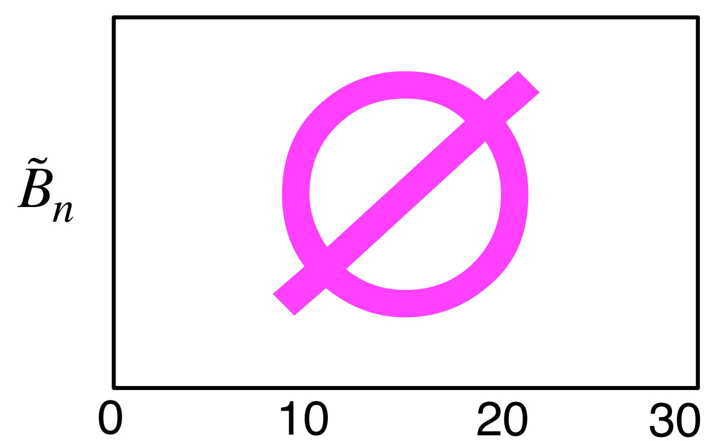
Two paths to eliminate magnetic chaos and transport in the RFP have emerged



Single-Helicity Dynamo

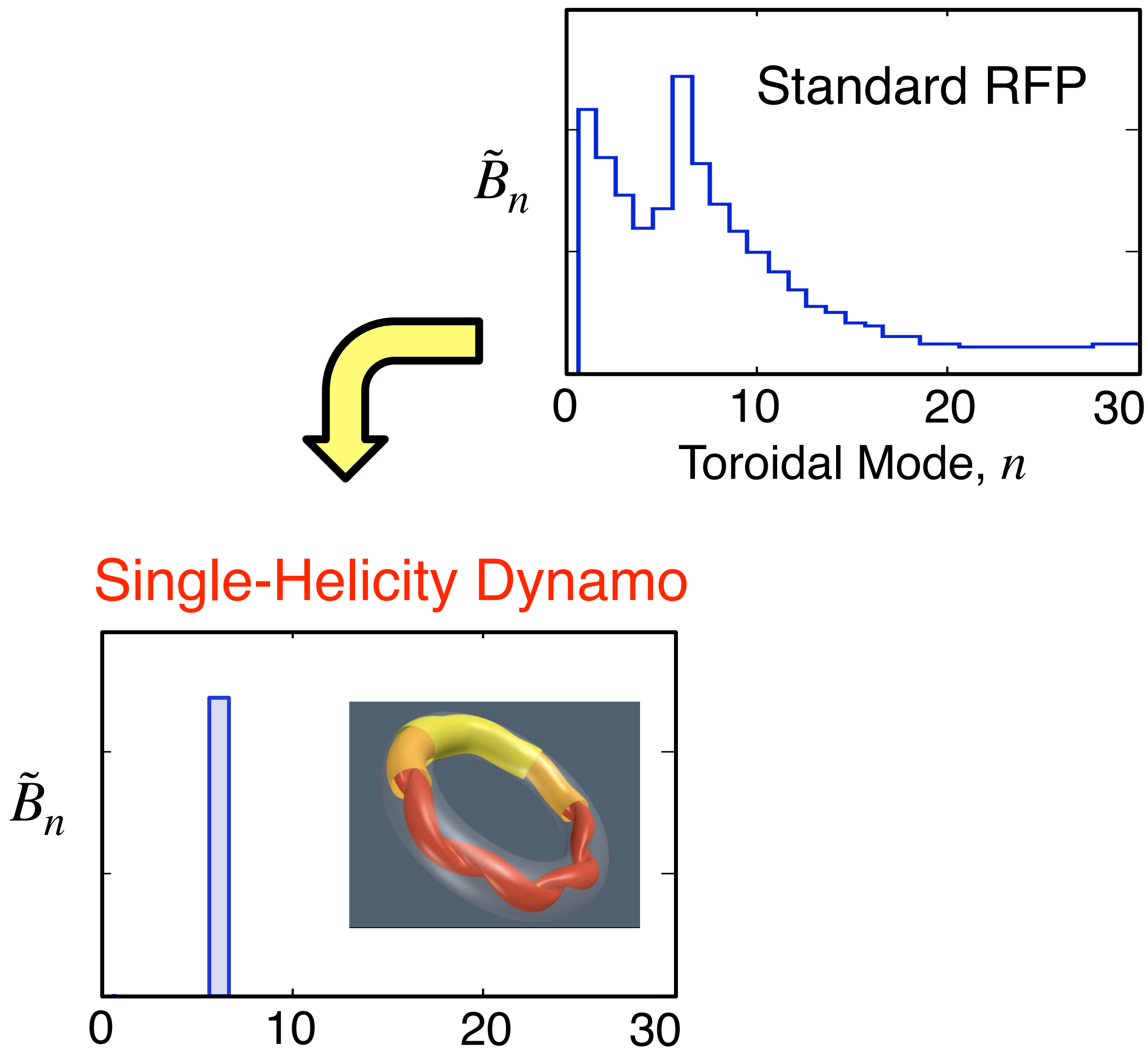


Current Profile Control



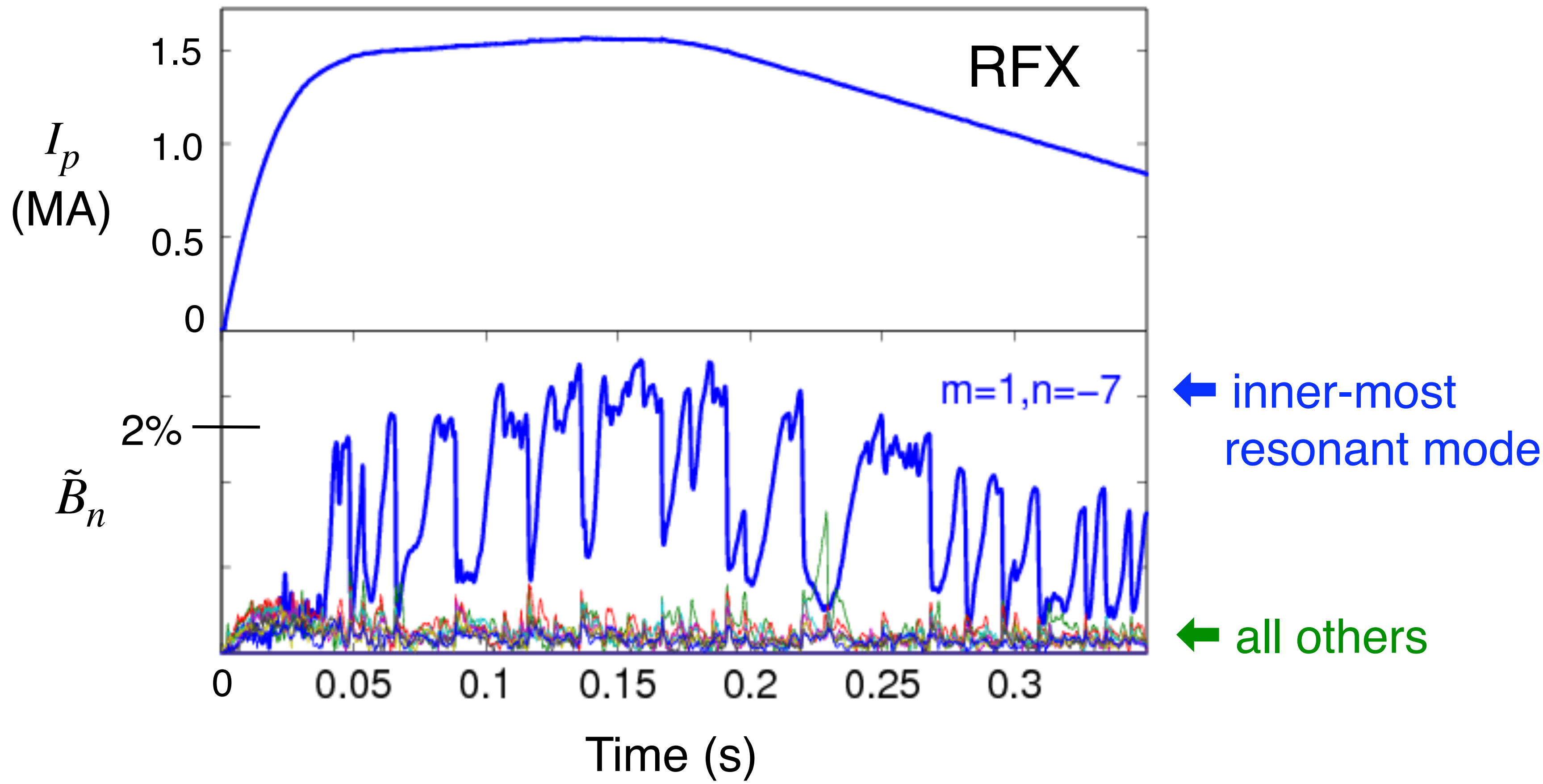
“one or none”

Two paths to eliminate magnetic chaos and transport in the RFP have emerged



A tendency for one large tearing mode is observed as the plasma current is increased

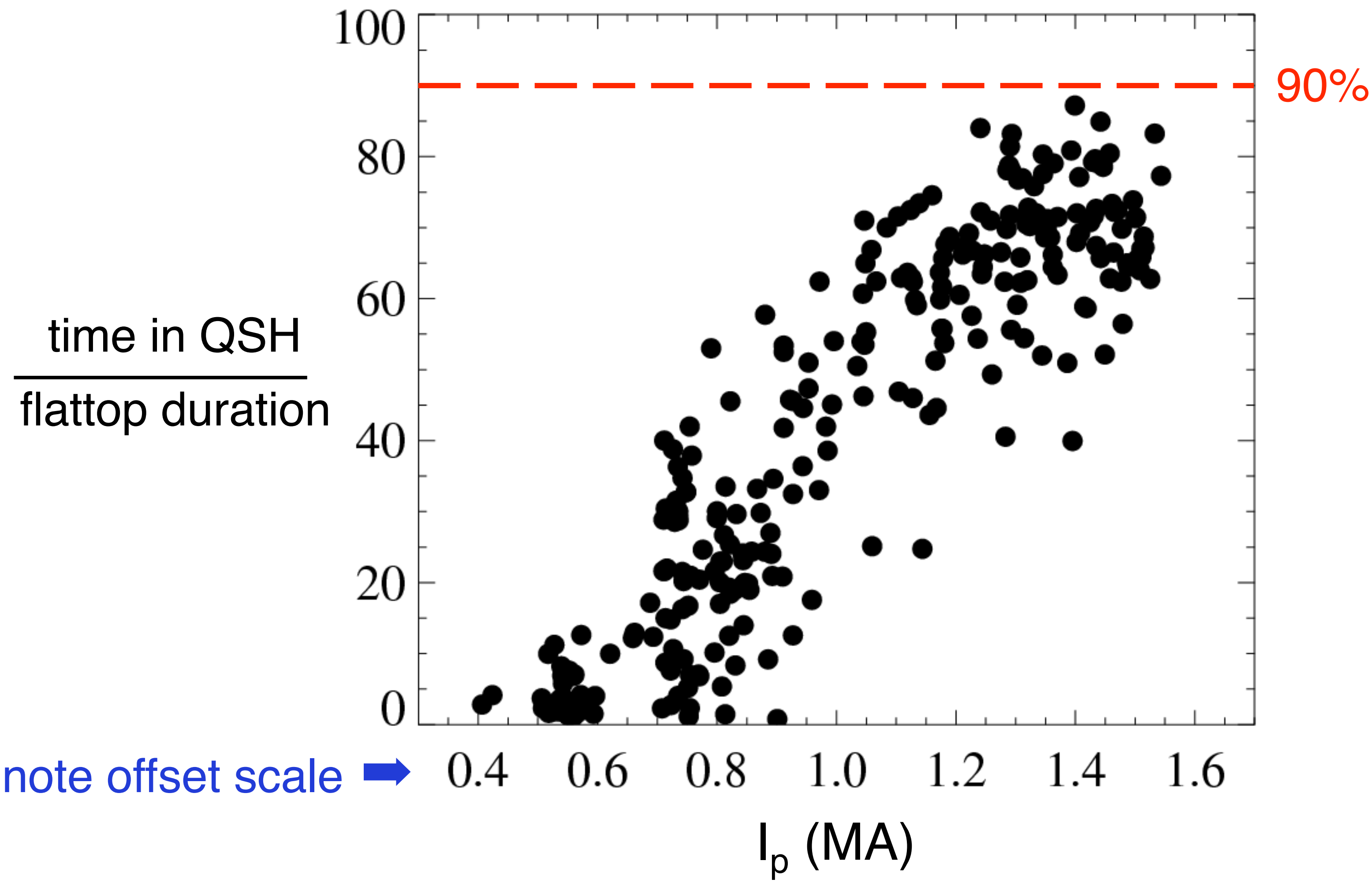
- “Quasi Single Helicity” (QSH) self-organized RFP



P. Martin, NI3.5, next session

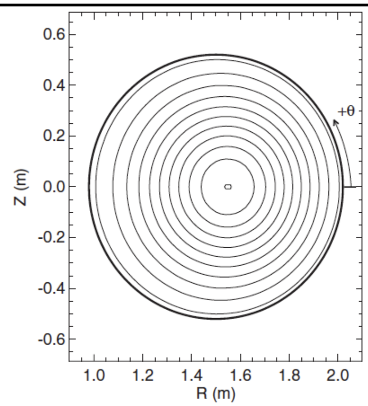
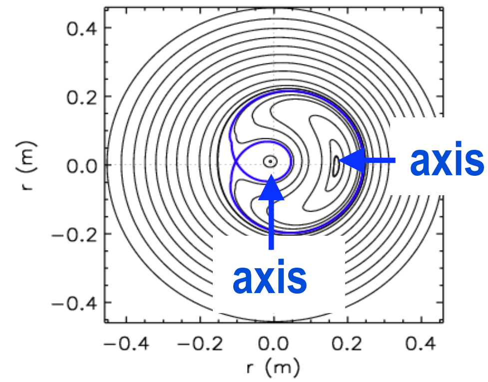
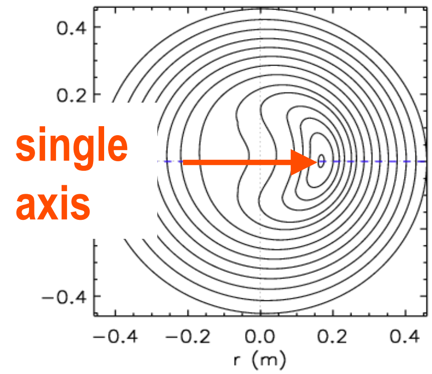
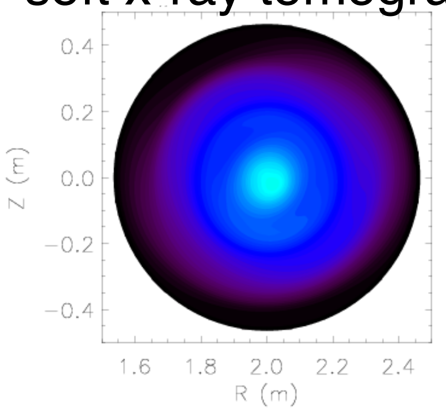
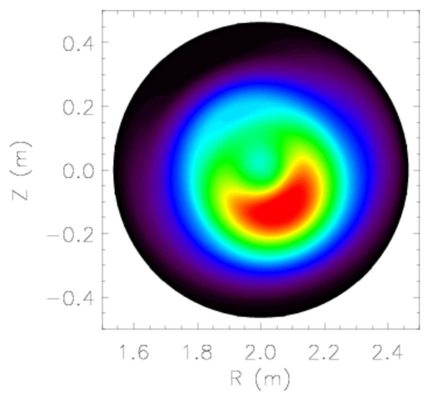
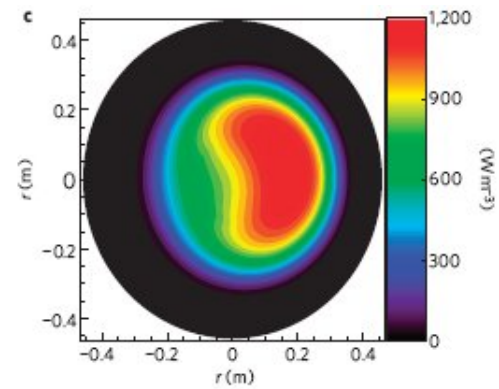
Persistence of quasi-single-helicity increases with current

- A new discovery at high current.



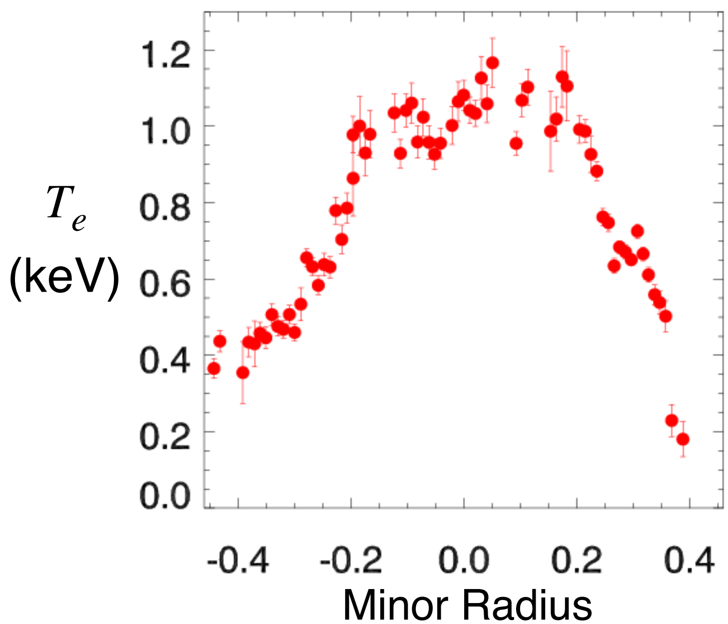
RFX, Valisa et al., 2008

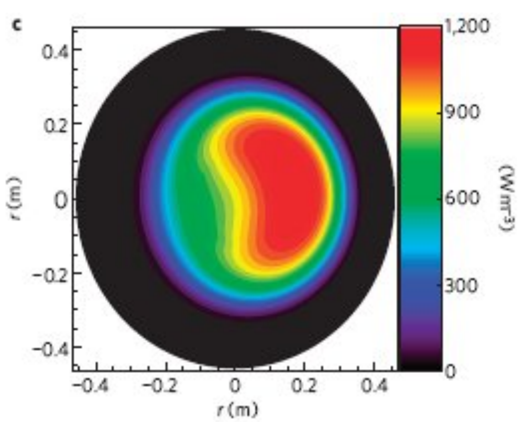
Transition to helical equilibrium occurs when the dominant mode amplitude exceeds ~ 4% of the axisymmetric field

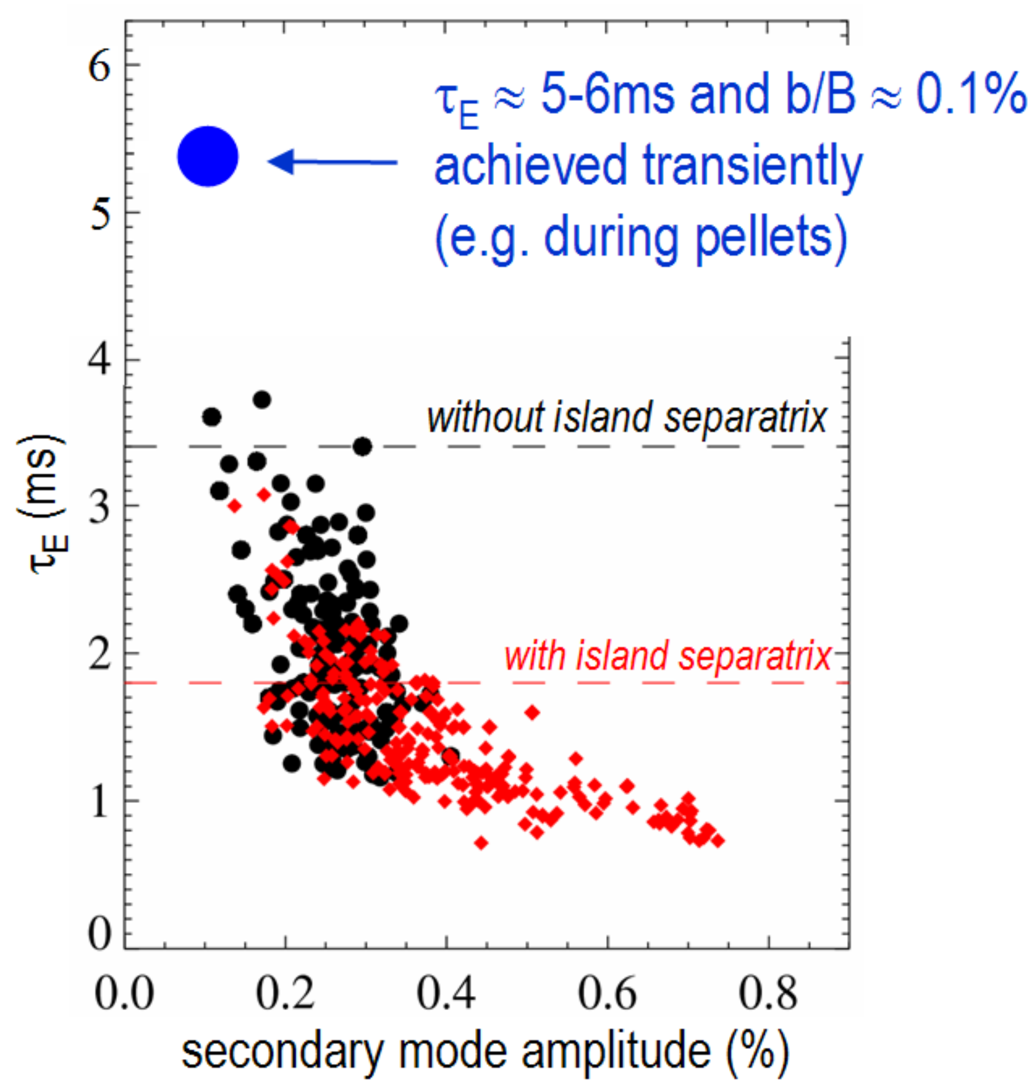
Multiple Helicity	Double Axis	Single Helical Axis
no island	helical island	helical equilibrium
		
soft x-ray tomography 		

RFX, Puiatti et al, 2009

Energy confinement improves up to 5-fold when the single-axis QSH state is created

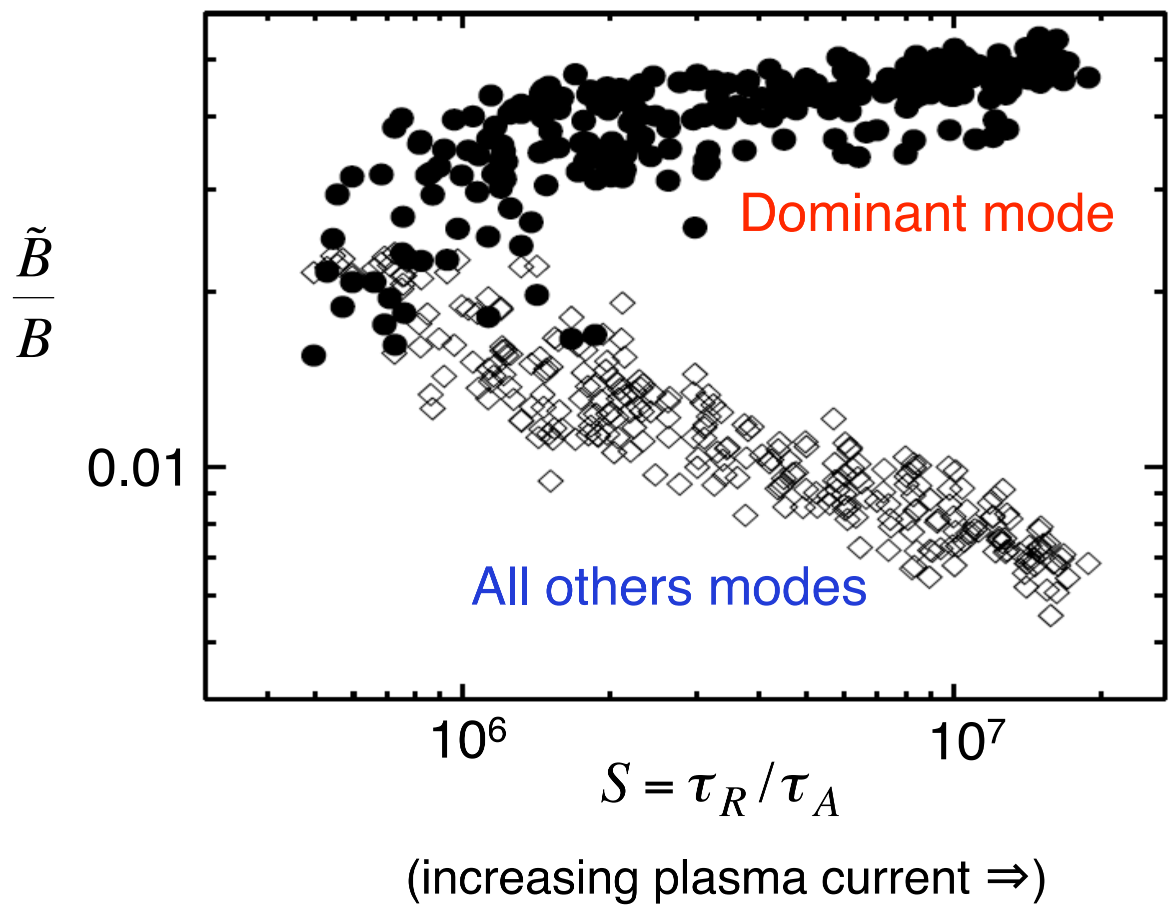






Quasi-single-helicity state appears to be the natural scaling for tearing and dynamo in a self-organized RFP

- Single-helicity bifurcation and chaos healing predicted by Cappello, Escande et al, and also Finn et al., in high dissipation limit

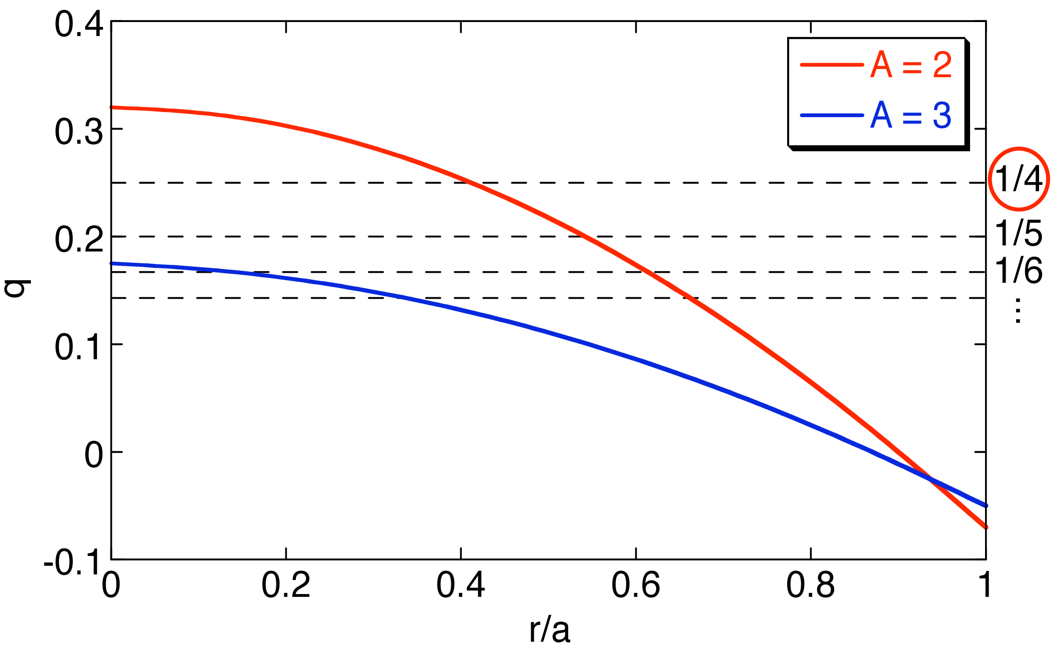


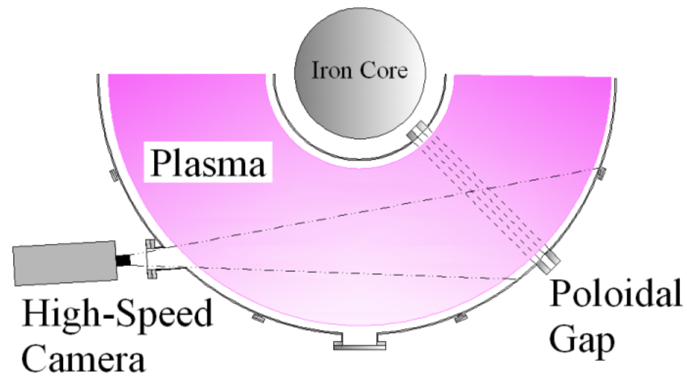
RFX, Piovesan et al, 2008

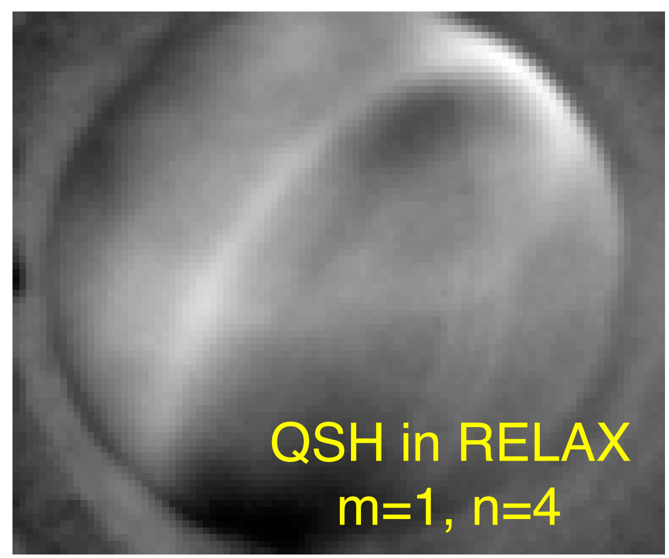
Shaping and aspect ratio remain to be optimized for the RFP

- New RELAX experiment is exploring low aspect ratio R/a=2
- 2D and 3D shaping likely important/beneficial (note: OHTE experiment)

Tearing resonances more separated at low R/a

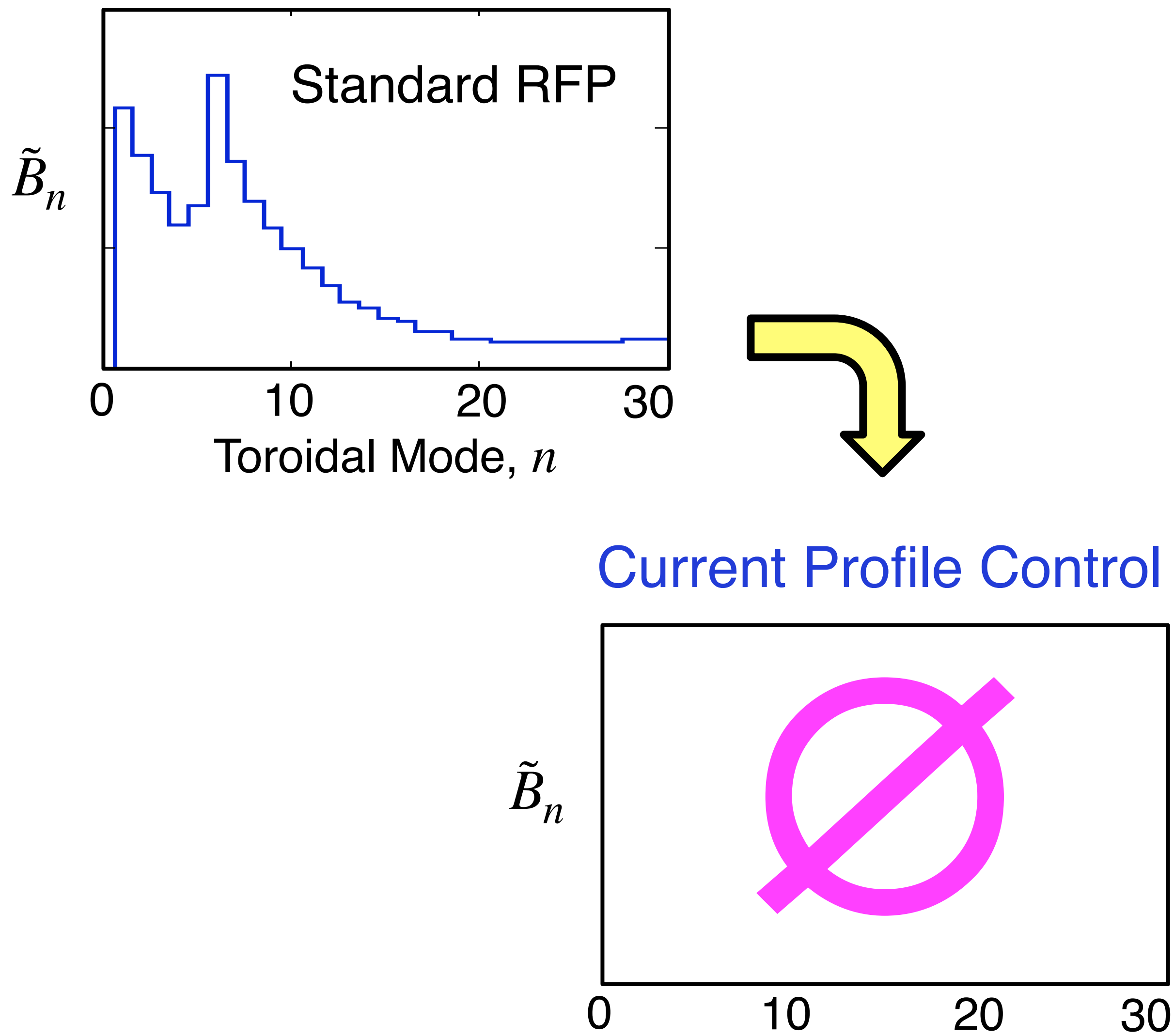




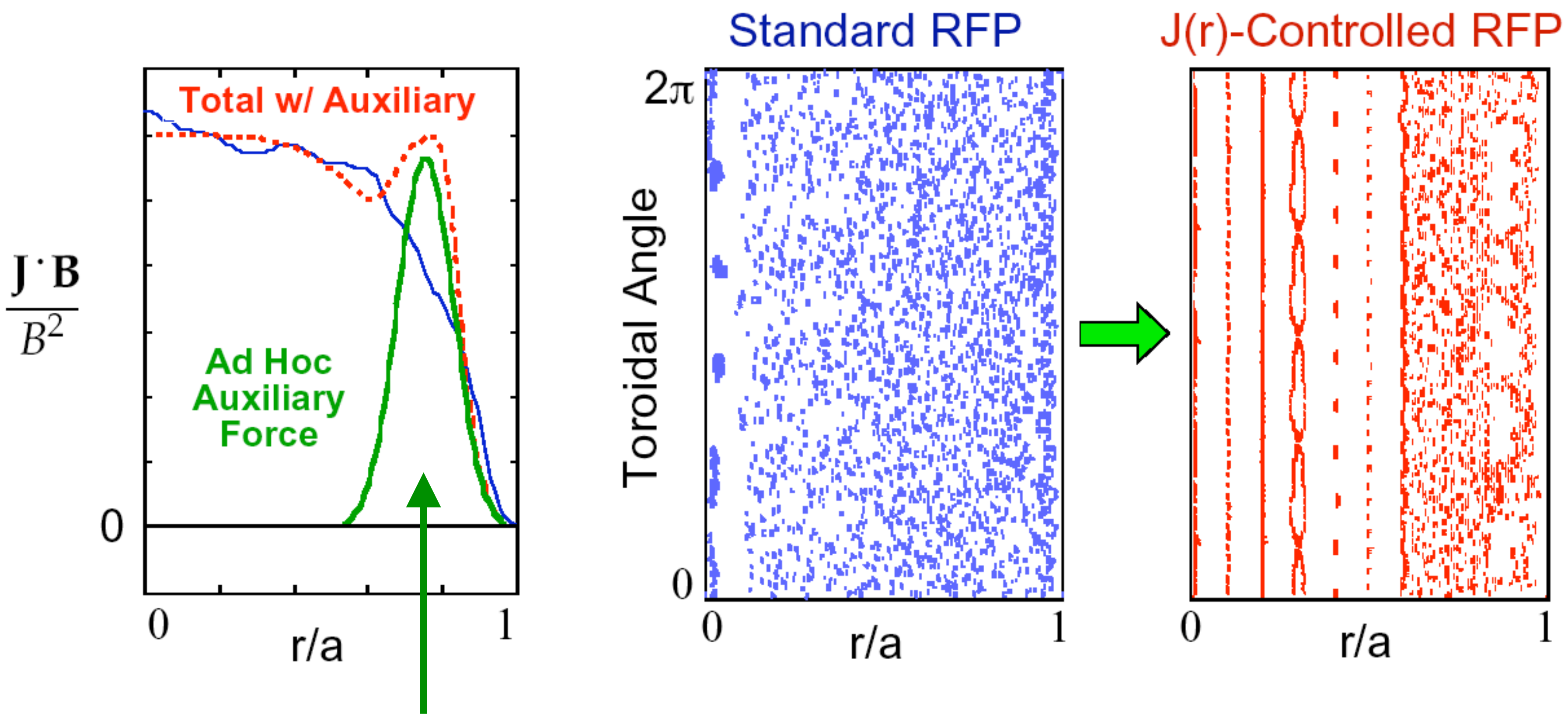


RELAX, Masamune, 2008

Two paths to eliminate magnetic chaos and transport in the RFP have emerged



Tearing stability depends on the current profile, suggesting modification of the current drive method



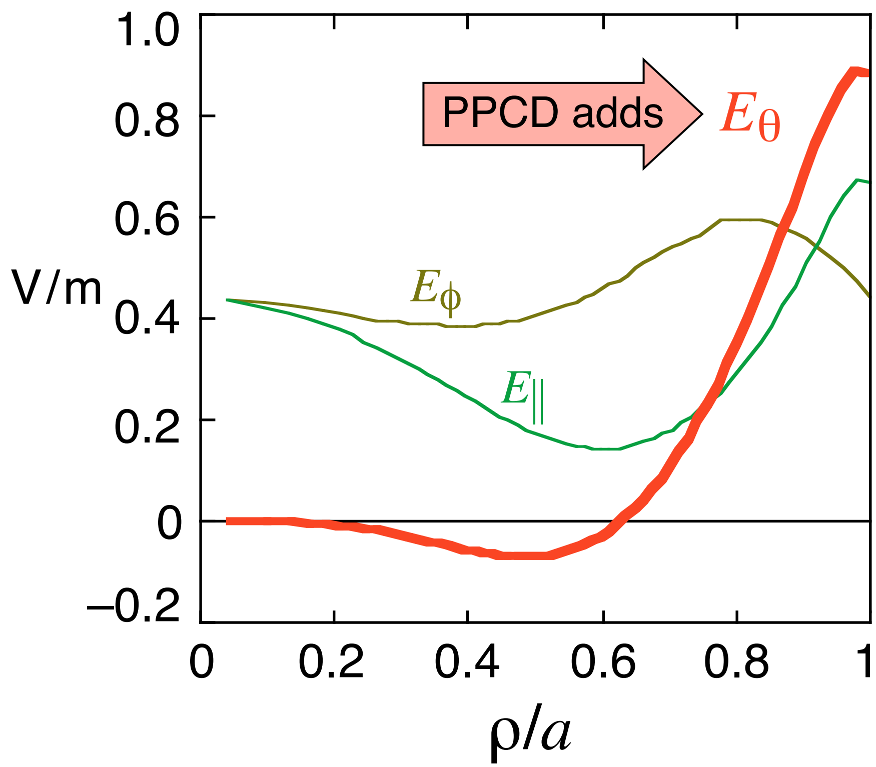
Current drive “replaces” dynamo

Mostly *poloidal* current drive

Sovinec, Prager, Ho 1999

Inductive pulsed poloidal current drive (PPCD) provides simple transient control

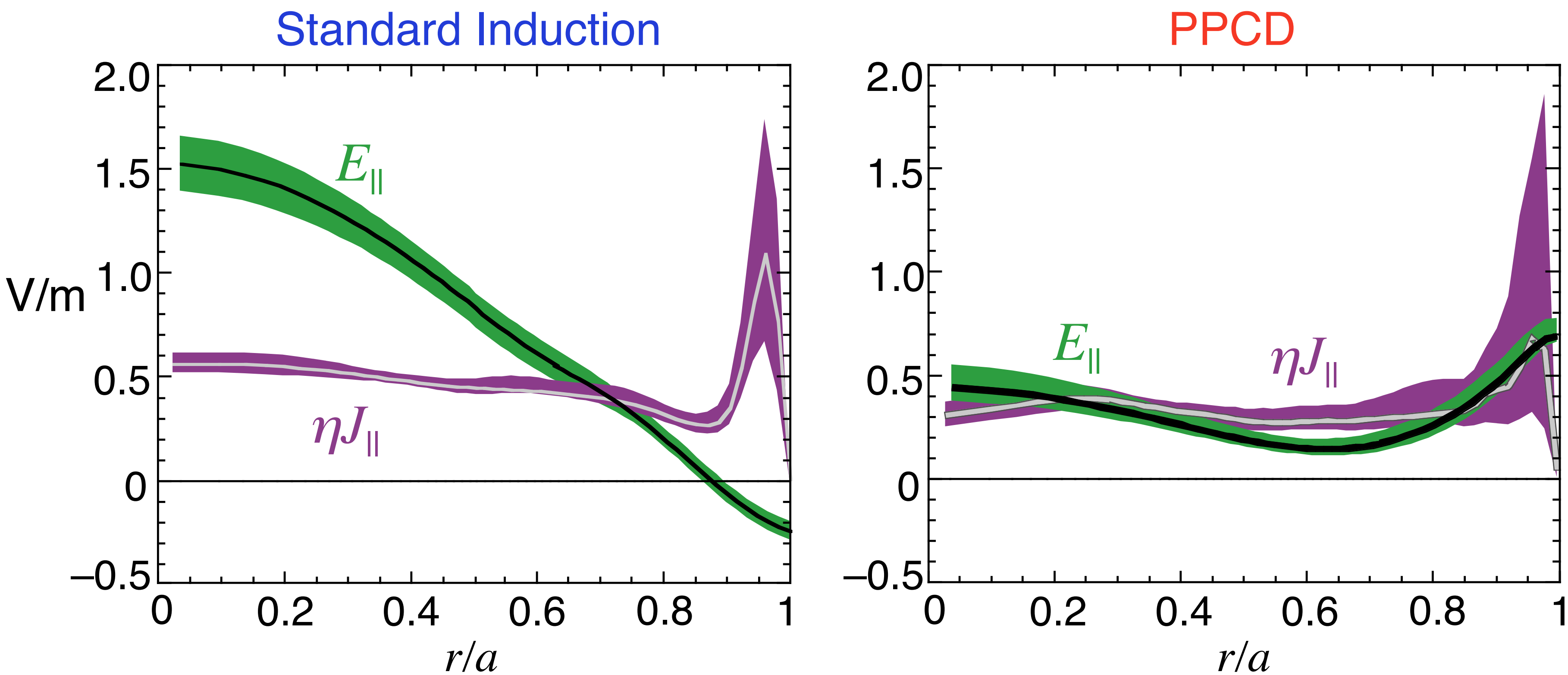
- Nebel et al. proposed a self-similar current ramp-down based on similar logic (differs in detail from PPCD programming)
- Gimblett proposed even earlier (unpublished)



Ramping the toroidal magnetic field creates poloidal induction.

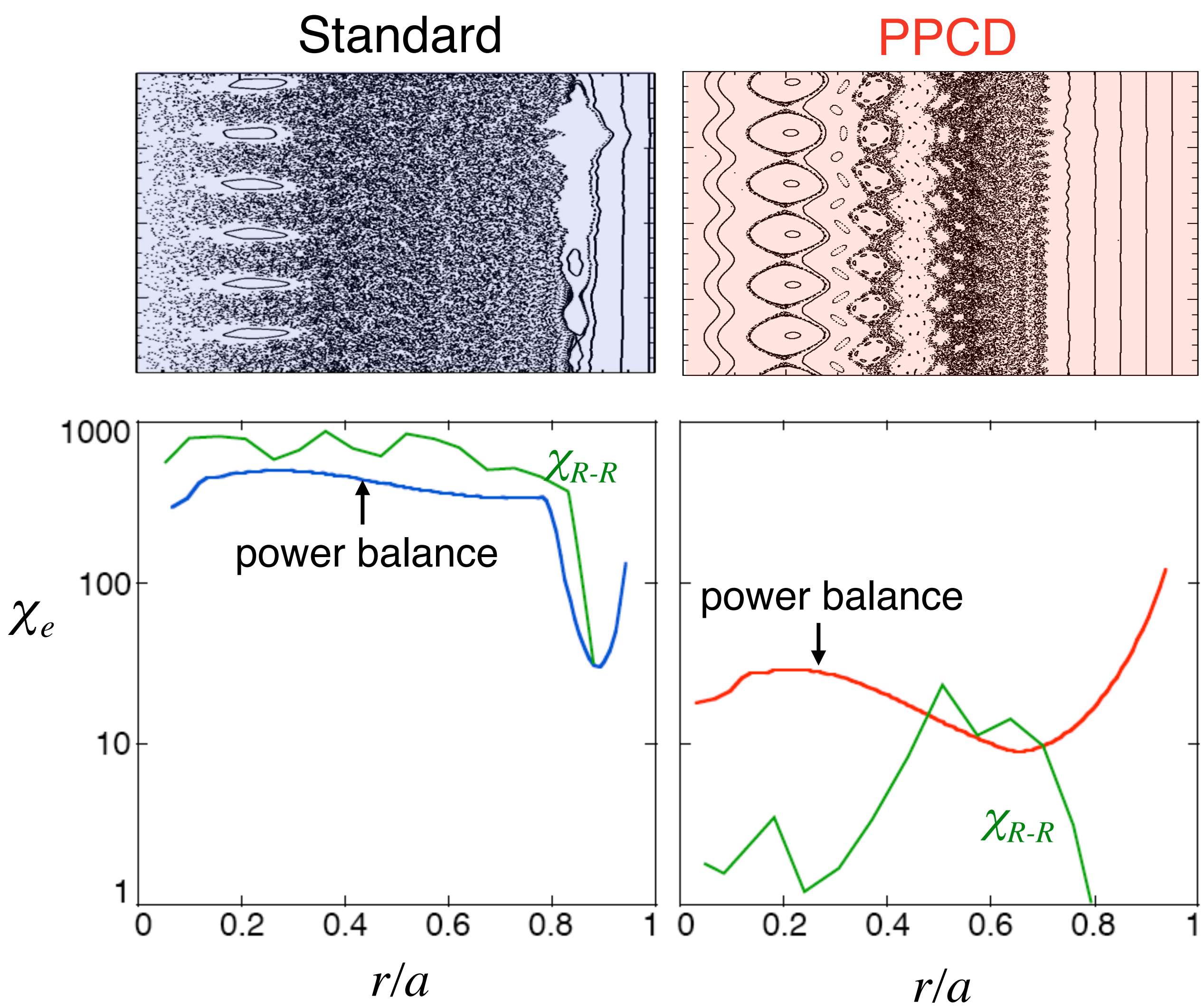
MST, Sarff, Chapman et al

A dynamo-free RFP



MST, Anderson et al., 2004

Controlling magnetic chaos leads to huge reduction in energy transport, and 10-fold increase in global confinement



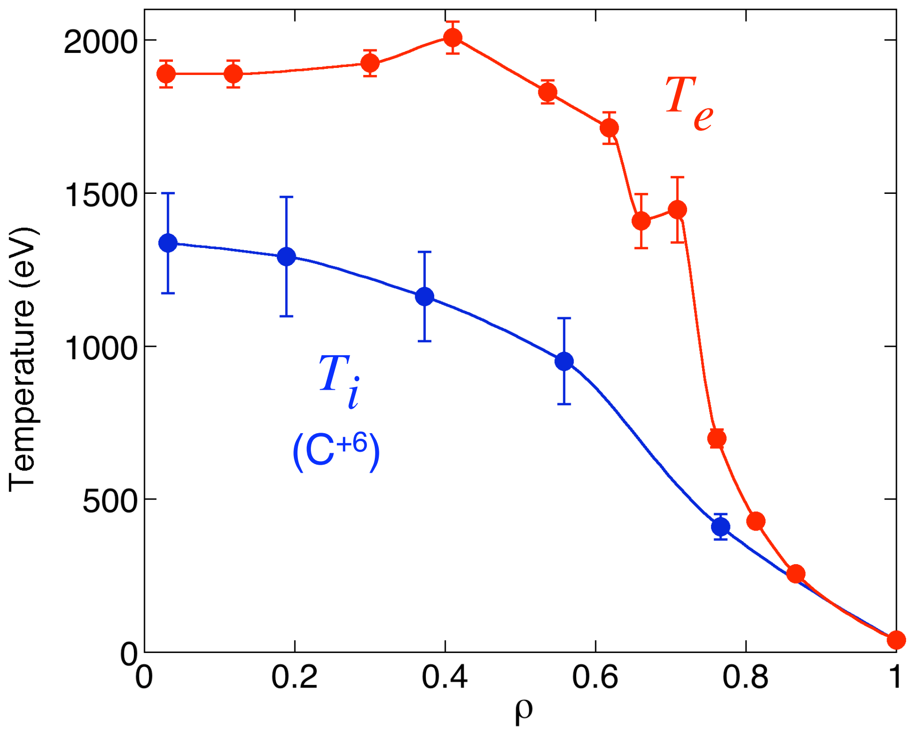
30-fold decrease of χ_e in the core!

Maximum confinement and beta to date

Maximum Confinement

$I_p = 0.5$ MA, $n/n_G = 0.13$

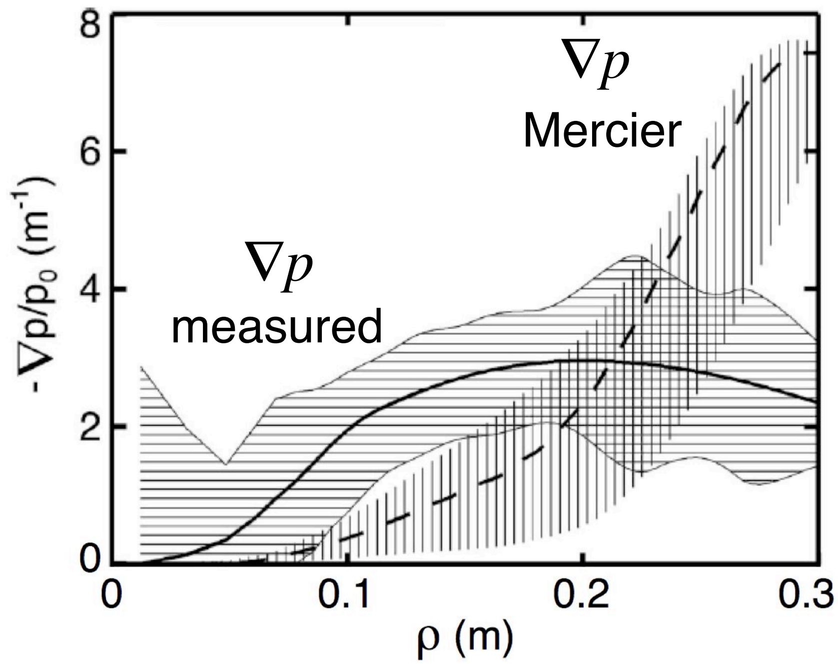
$\tau_E = 12$ ms, $\beta = 10\%$



Maximum Beta

$I_p = 0.2$ MA, $n/n_G = 1.2$

$\tau_E \sim 6$ ms, $\beta = 26\%$

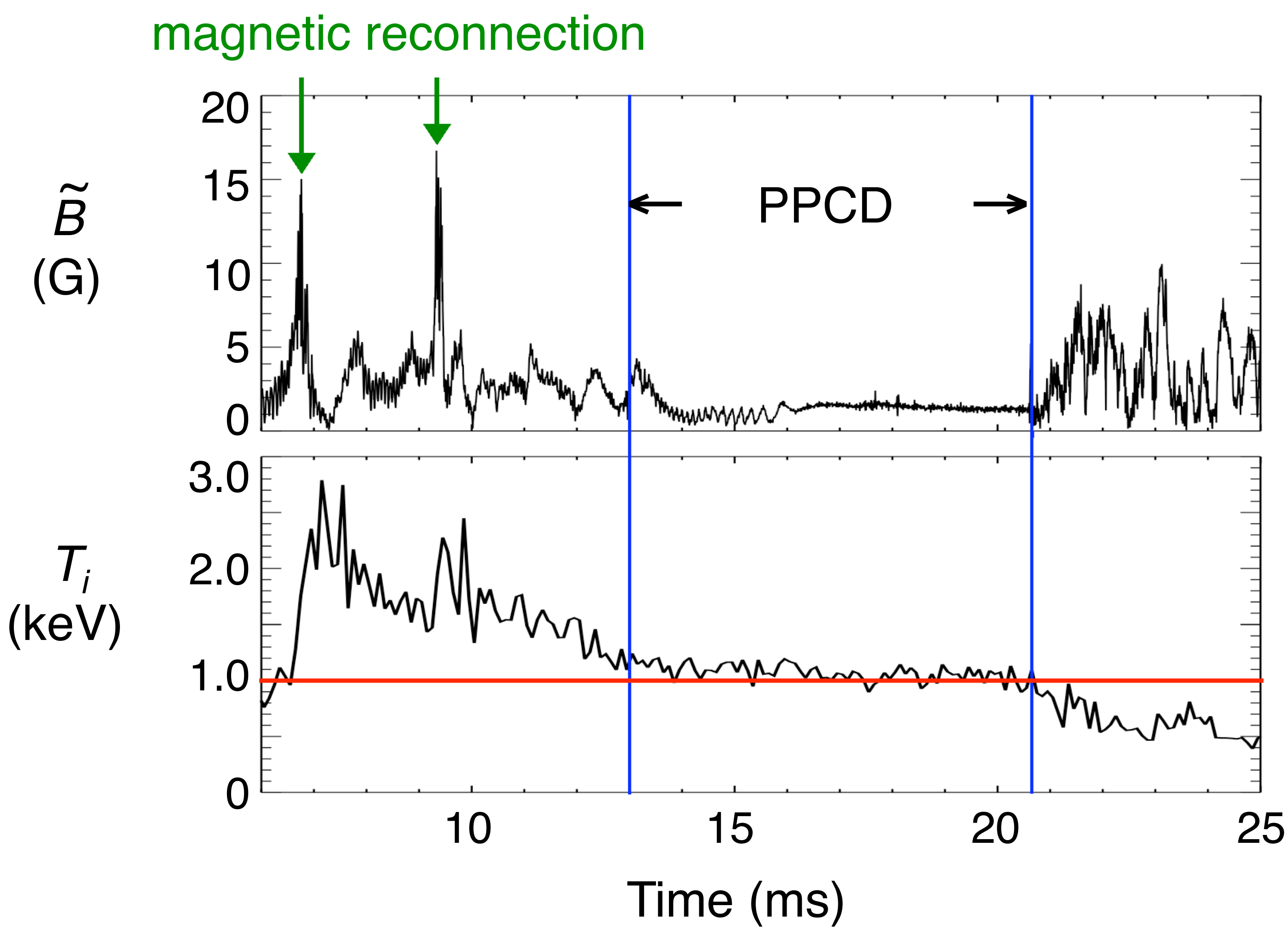


(PPCD with pellet injection)

MST, Chapman et al., 2008

Strong non-collisional ion heating occurs during magnetic reconnection events

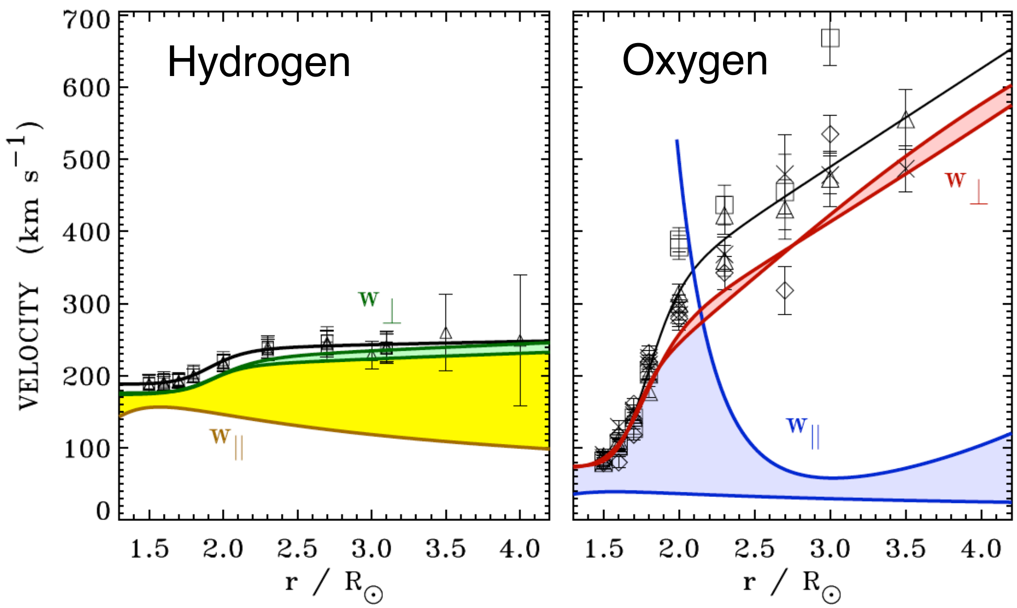
- Mechanism not yet understood.
- Effective to “pre-heat” ions prior to current profile control.



Ions in the solar atmosphere require non-collisional heating

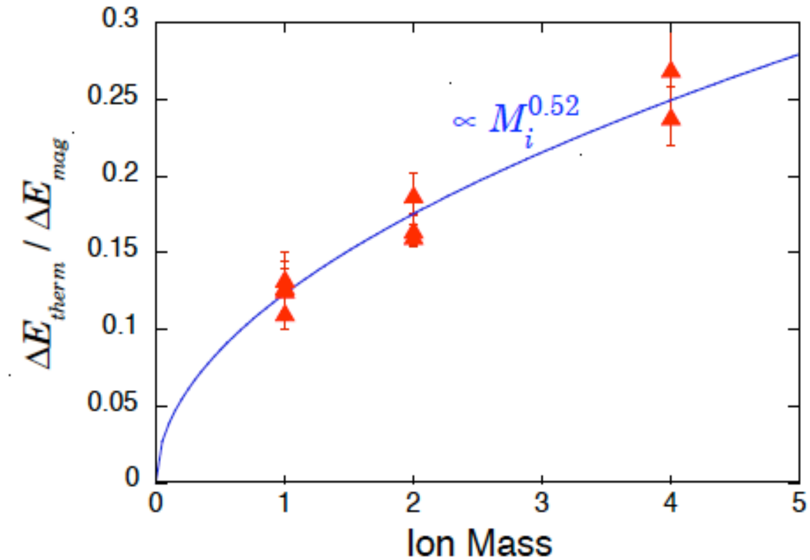
- Heavier ions are hotter, in the corona and RFP (and other lab plasmas).

Solar Corona



Cranmer et al., ApJ, **511**, 481 (1998)

RFP

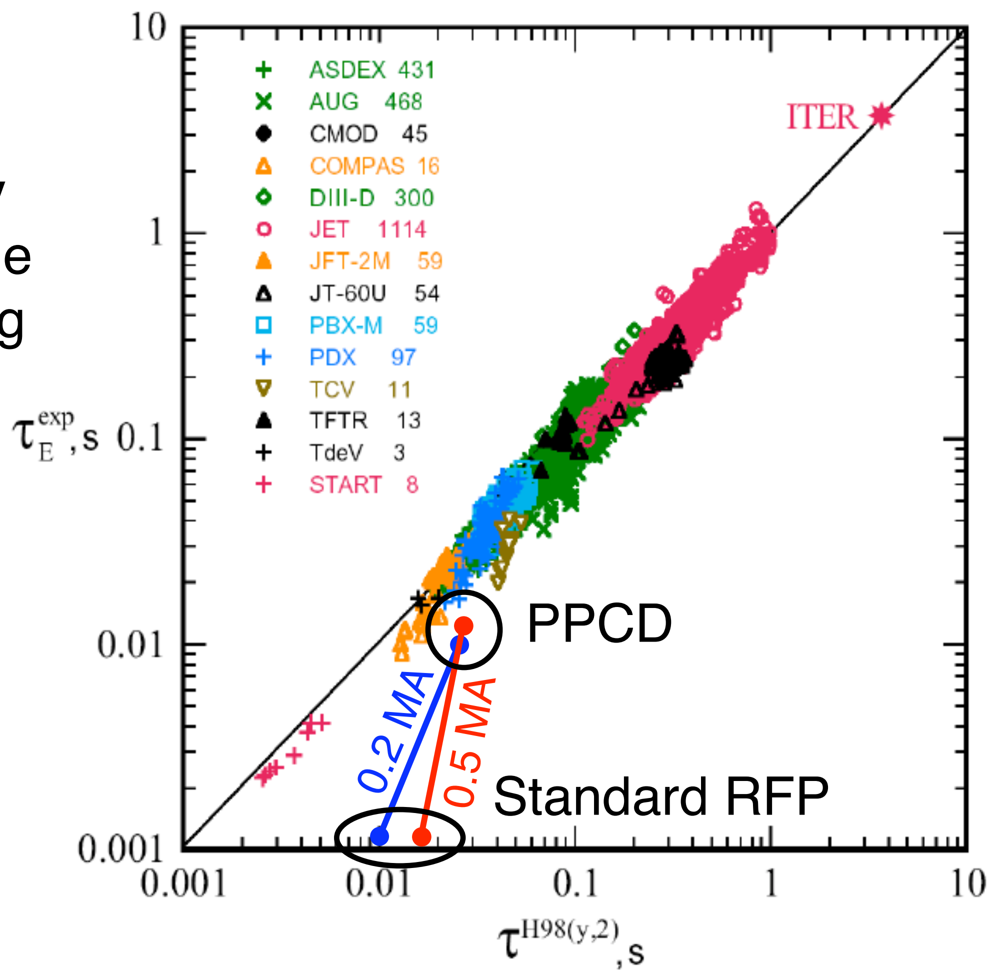


G. Fiksel, BI2.5, Mon

Improved confinement is comparable to that expected for a tokamak of the same size and current

- Use same I_p, n, P_{heat}, size, shape to define a tokamak reference.
- $\langle B \rangle$ is 5X smaller in the RFP compared this way.

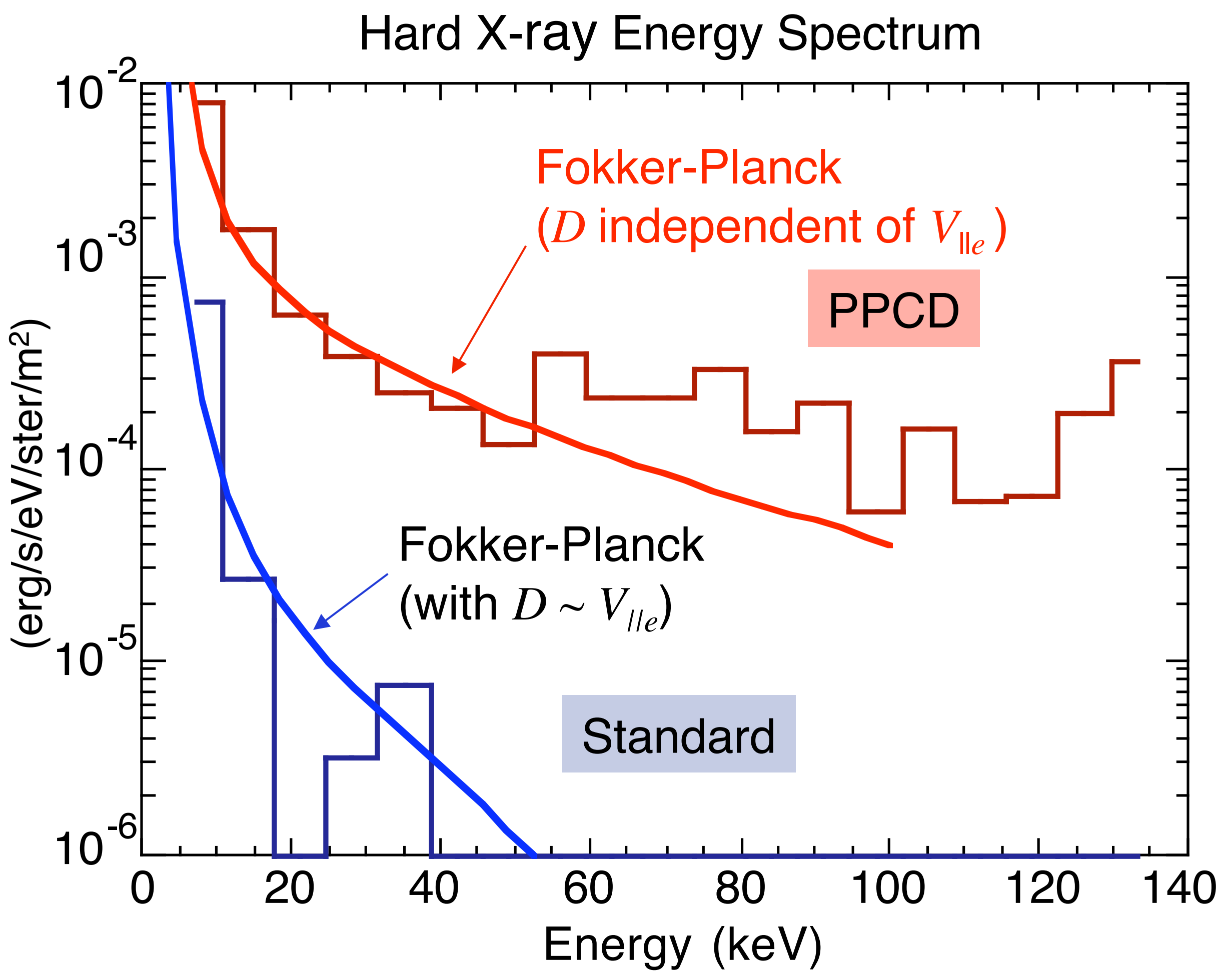
ELMy H-Mode Scaling



Does not imply tokamak scaling applies to the RFP.

Velocity-independent diffusion of energetic electrons suggests transition to electrostatic transport

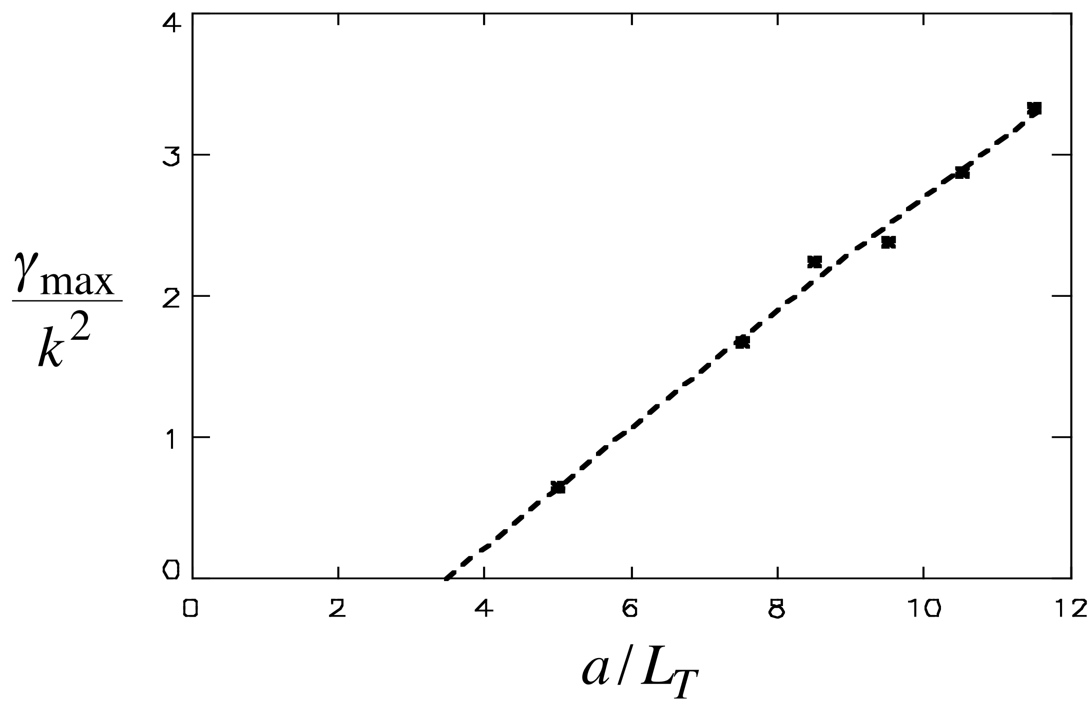
HXR Energy Flux



MST, O'Connell et al, 2003

Ion temperature gradient (ITG) instability is possible in the RFP

- Gyrokinetic code GYRO modified for RFP equilibrium.
- Unstable modes $k_\perp \rho_i \sim 0.1 - 0.5$ (similar to tokamak).
- Mode structure is *not* localized to outboard region (weak toroidicity).



Critical temperature gradient is larger in the RFP by $\sim R/a$

$\gamma_{\max}$ = linear growth rate

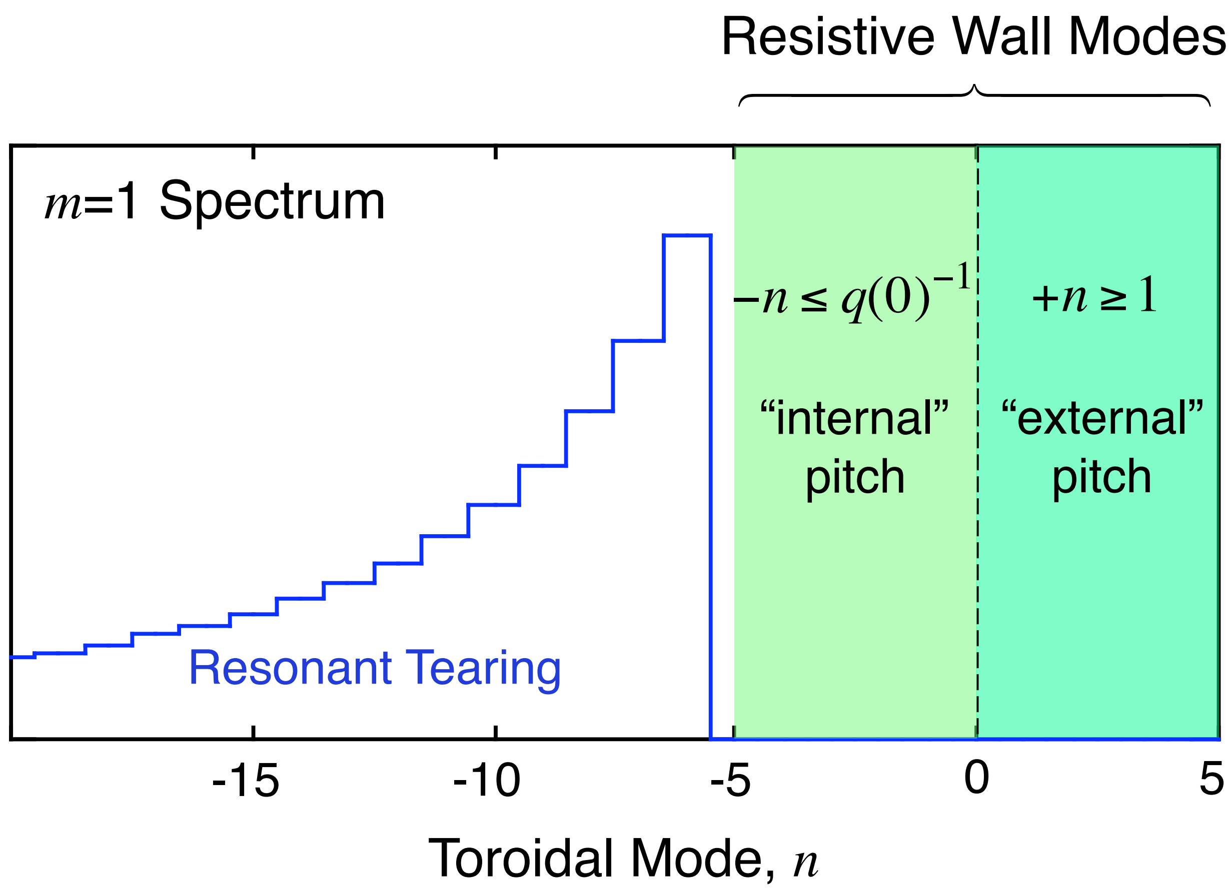
k = most unstable mode, varying L_T

Tangri, Terry, Waltz, 2009

Ideal MHD Stability Control

Non-resonant ideal MHD kink modes are unstable in the RFP, even at zero plasma pressure

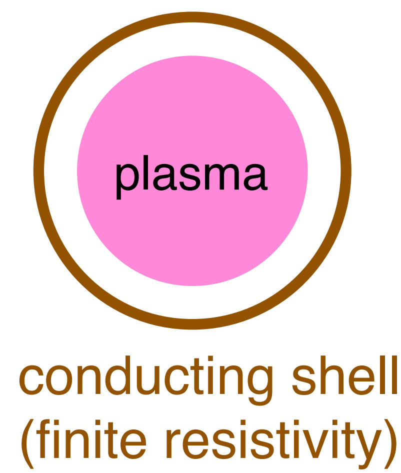
- A conducting shell surrounding the plasma prevents Alfvénic growth.
- Common issue for high beta configurations (pressure-driven in tokamaks)



growth rate

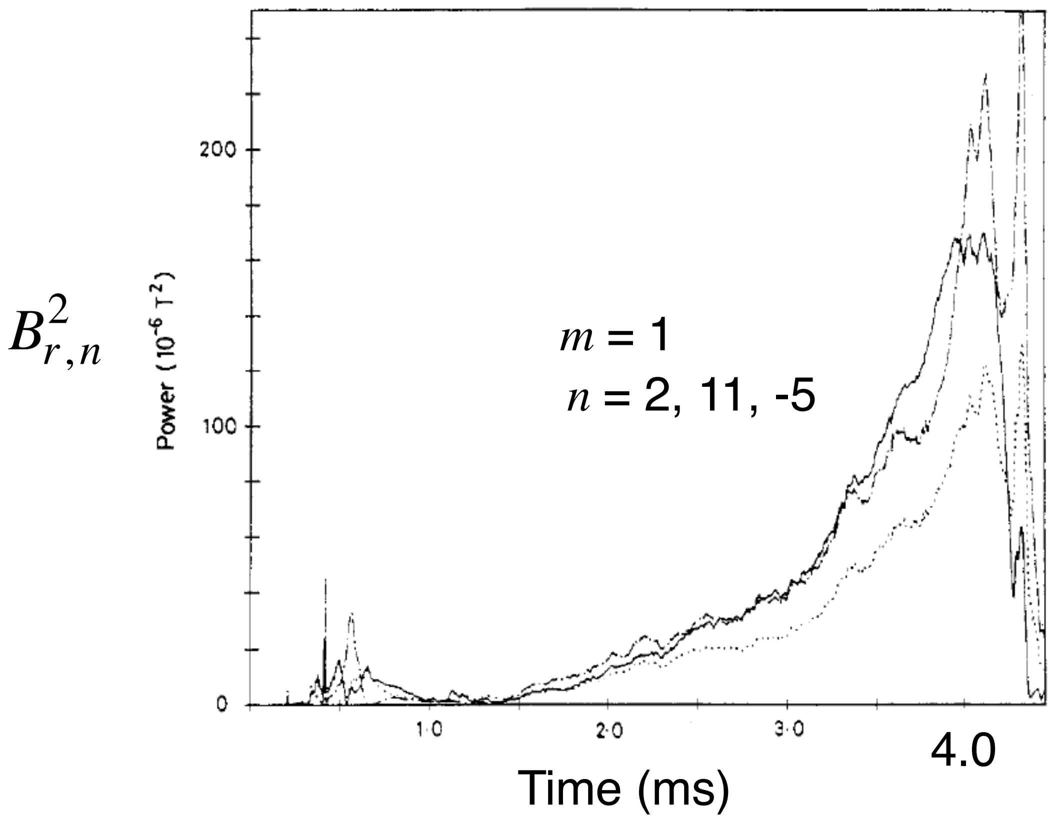
$$\gamma \sim \tau_{wall}^{-1}$$

τ_{wall} = flux diffusion time



First observation of a resistive wall mode, and first mode control, in the HBTX-1C experiment

- Helical sine-cosine feedback coils stabilized the single m =1, n =2 mode

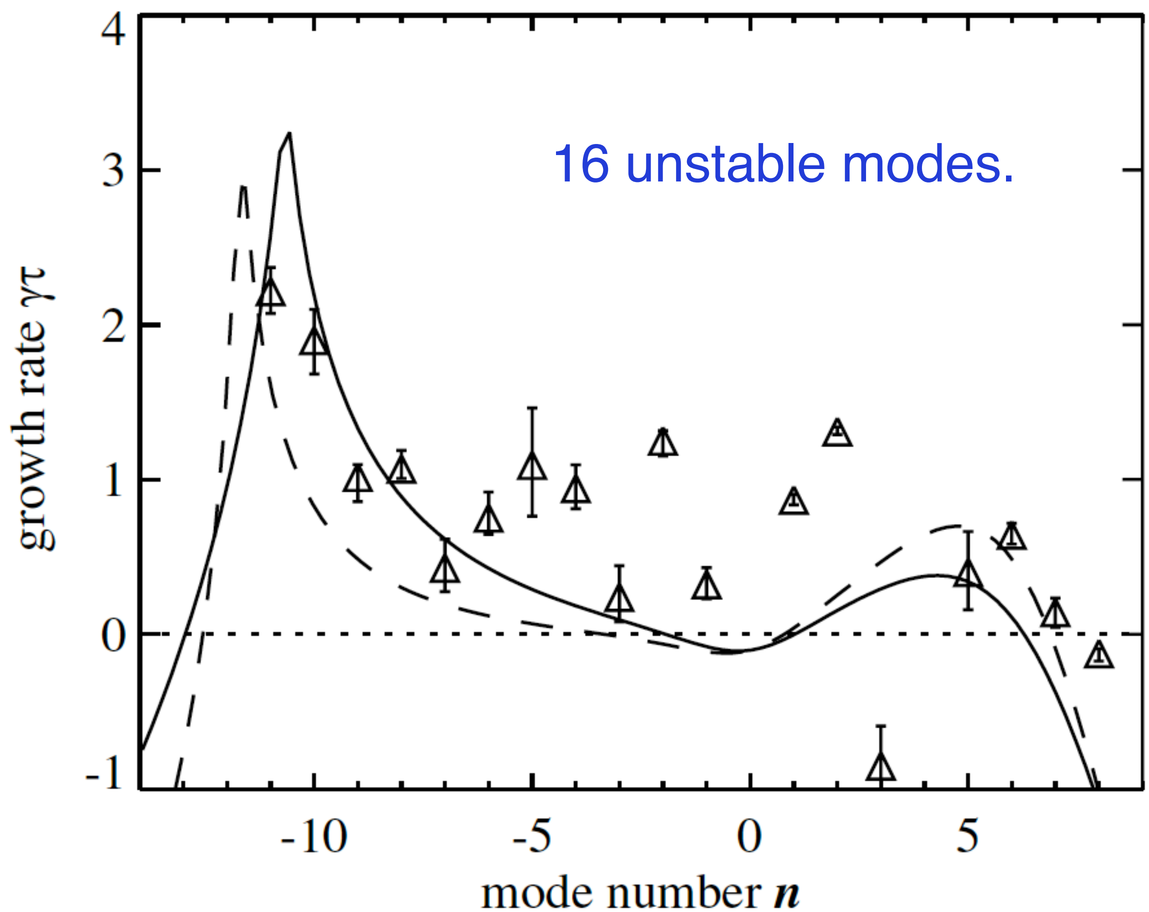


τ_w = 0.5 ms

HBTX-1C, Alper et al., 1990

RWM research renewed in earnest with Extrap-T2R and RFX-Mod

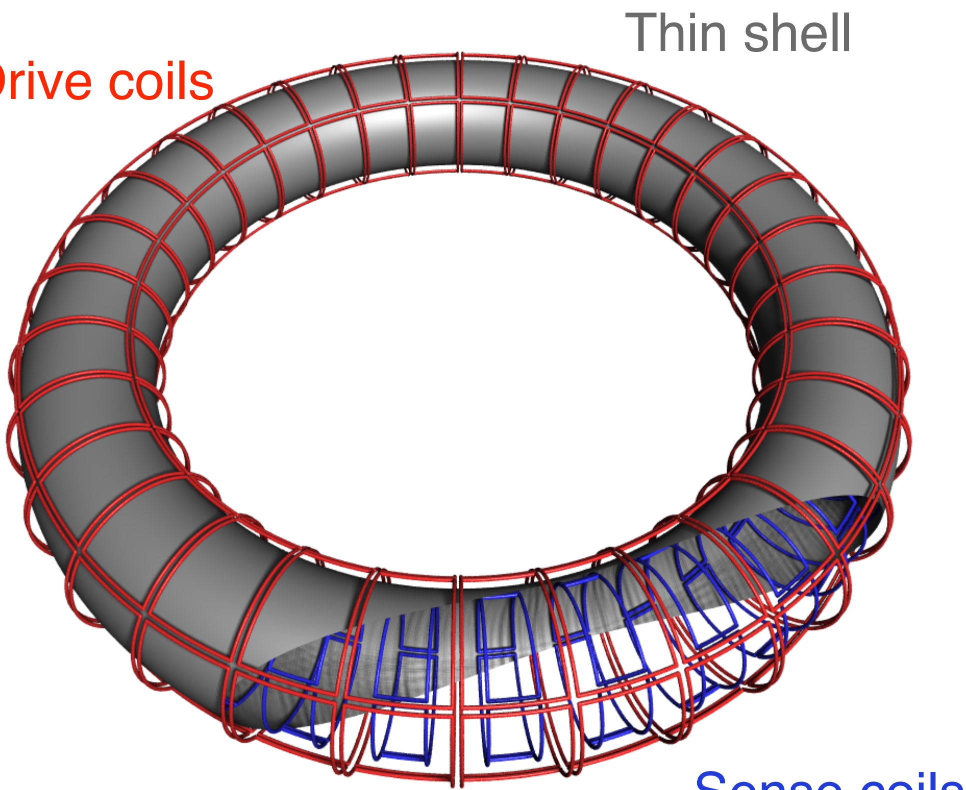
- Measured growth rates in good agreement with MHD theory.



Extrap T2R, Brunsell et al, 2003

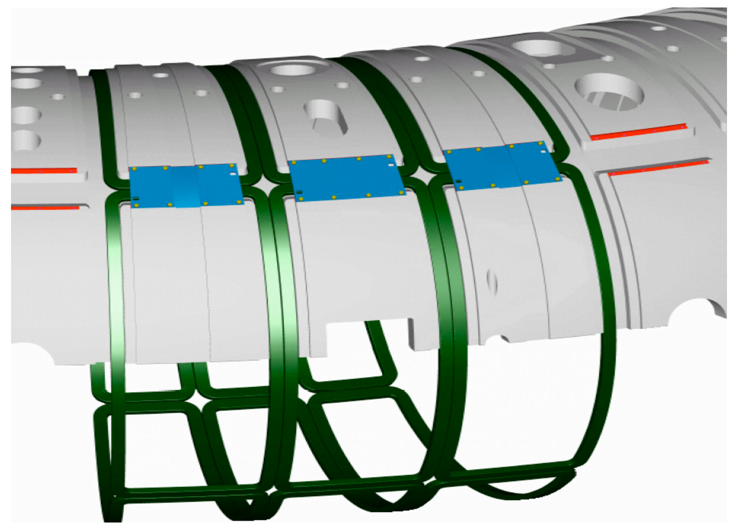
Saddle coils covering 2D surface are used for feedback control

- The thin conducting shell slows the mode growth to a manageable rate.



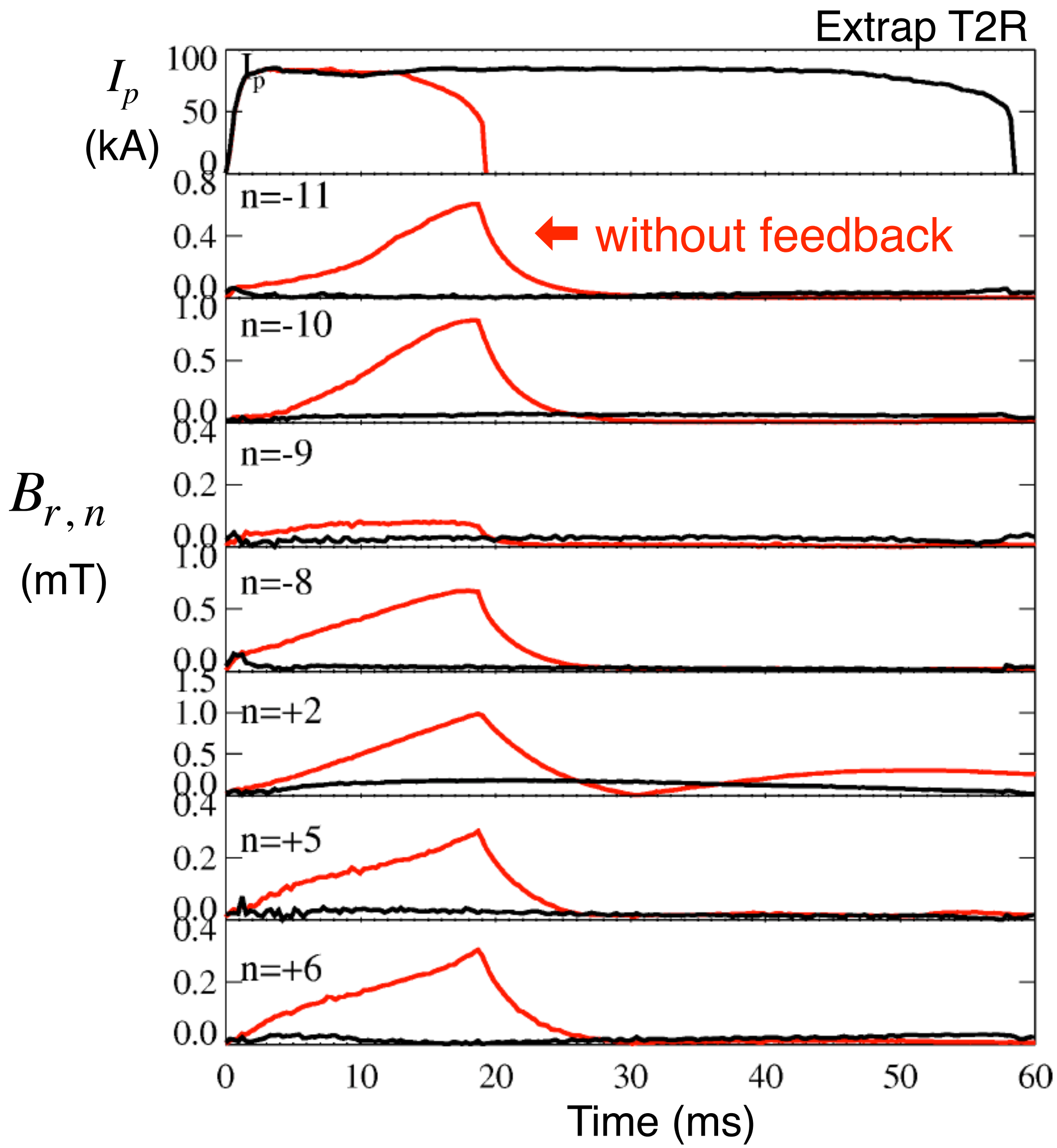
RFX: 4 × 48
Extrap: 4 × 32

RFX Saddle Coils



Separate power supply
for each coil.

Feedback-stabilization of all RWMs demonstrated



RFX:

τ_{pulse} = 0.45 s

$\tau_{pulse} / \tau_{wall} = 10$

Extrap T2R:

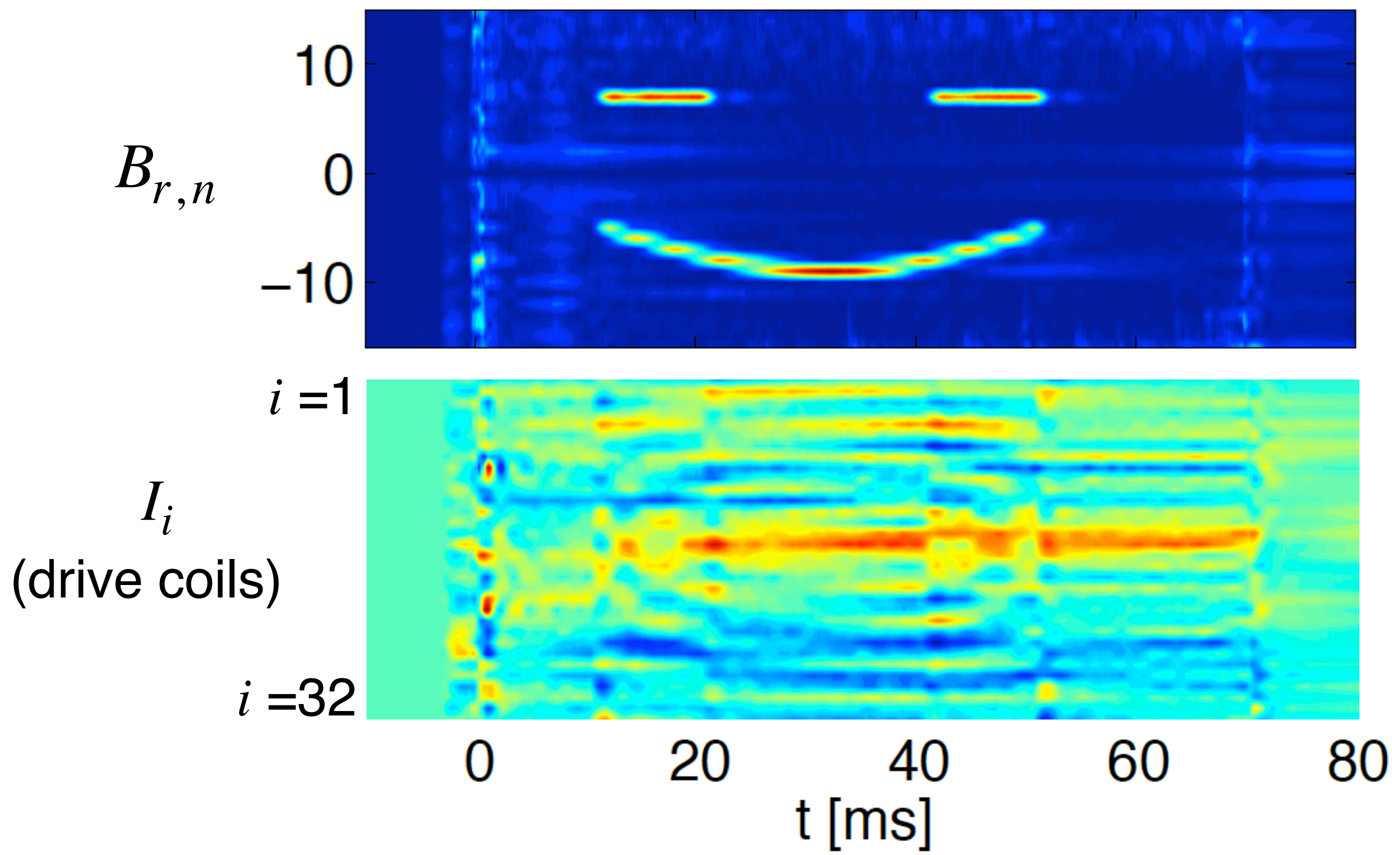
τ_{pulse} = 0.1 s

$\tau_{pulse} / \tau_{wall} = 14$

Extrap T2R, Brunsell et al, 2003
RFX, Paccagnella et al, 2006

Advanced RWM control evolving rapidly

- Fun example showing robust control of the unstable mode spectrum.
- Other advances, like "clean mode control" in RFX have been crucial to reduce plasma-wall interaction and facilitate high current operation.



Extrap, Olofsson et al., 2008

Current Sustainment

Steady-state RFP operation is demanding

- The neoclassical pressure-driven current is insufficient for the RFP, even at its high $\beta \sim 25\%$.

- Relatively large current requires efficient current drive, applied externally (and therefore offers some control).

- Inductive current drive would be great: simple, efficient, remote

  (Note that pulsed inductive scenarios could be attractive, given reduced magnet requirements.)

DC plasma sustainment using AC *inductive* current drive

- Invented via magnetic helicity balance (Taylor relaxation theory).
- Plasma behaves like a nonlinear rectifier!

$$\frac{\partial K}{\partial t} = 2V_T\Phi - 2\int \mathbf{E}\cdot\mathbf{B}\,dV \qquad K = \int \mathbf{A}\cdot\mathbf{B}\,dV$$

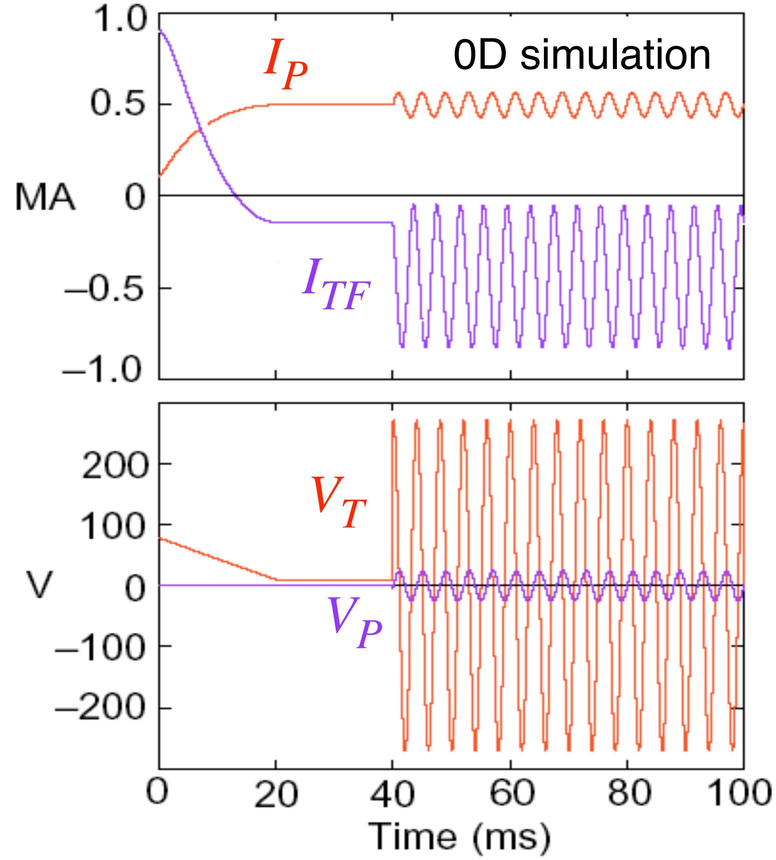
oscillate

$$V_T = \hat{V}_T \sin\omega t \qquad \Phi = \frac{\hat{V}_P}{\omega}\sin\omega t + \Phi_{dc}$$

$$\langle 2V_T\Phi\rangle = \frac{\hat{V}_T\hat{V}_P}{2\omega}\sin\delta \qquad \delta = \text{Relative phase of oscillators}$$

DC helicity injection
(implies DC current)

"Oscillating Field Current Drive"

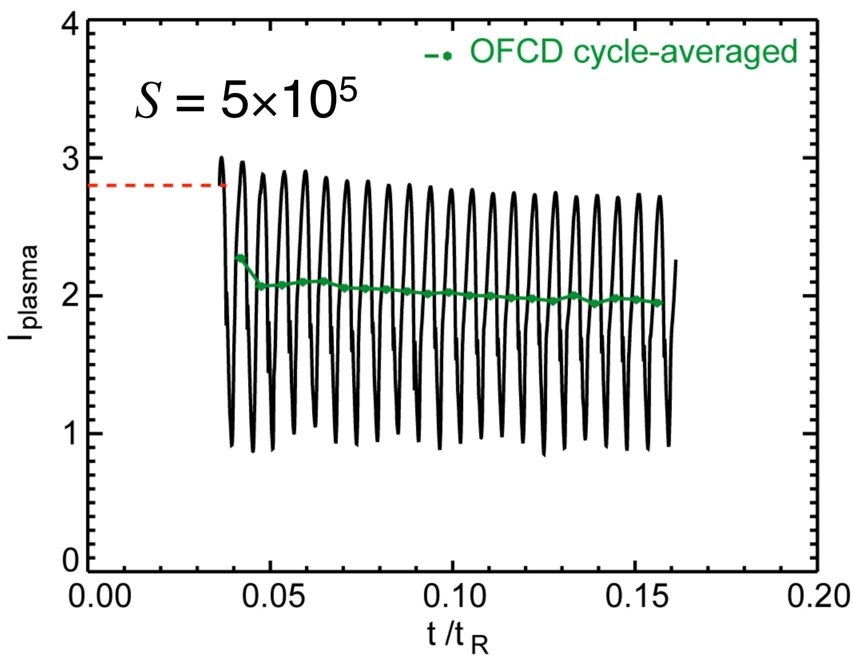


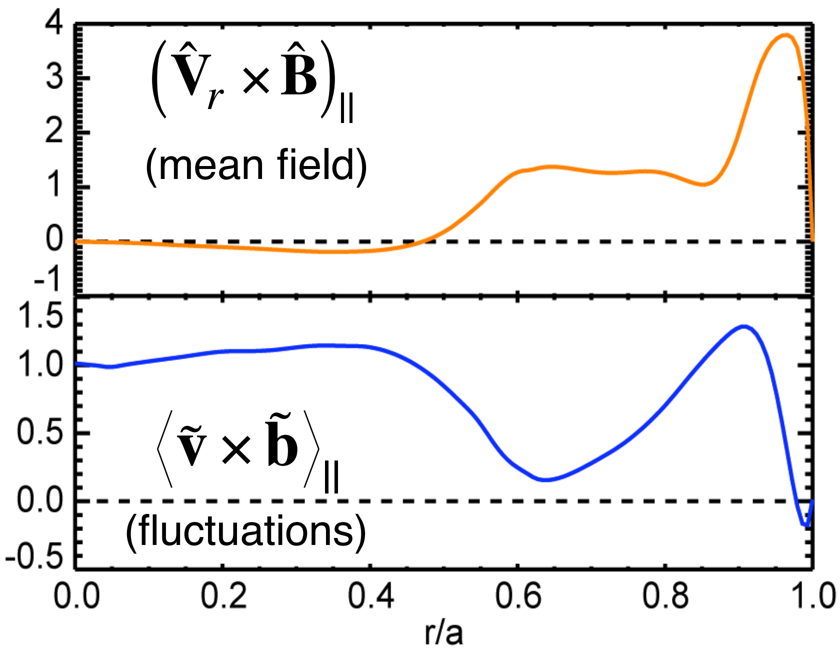
Bevir and Gray, 1981

Nonlinear, resistive MHD computation confirms and extends OFCD physics basis

- Same physics model as for dynamo-relaxation with conventional induction.
- AC modulation amplitude scales with Lundquist number as $S^{-1/4}$

Nonlinear MHD Computation

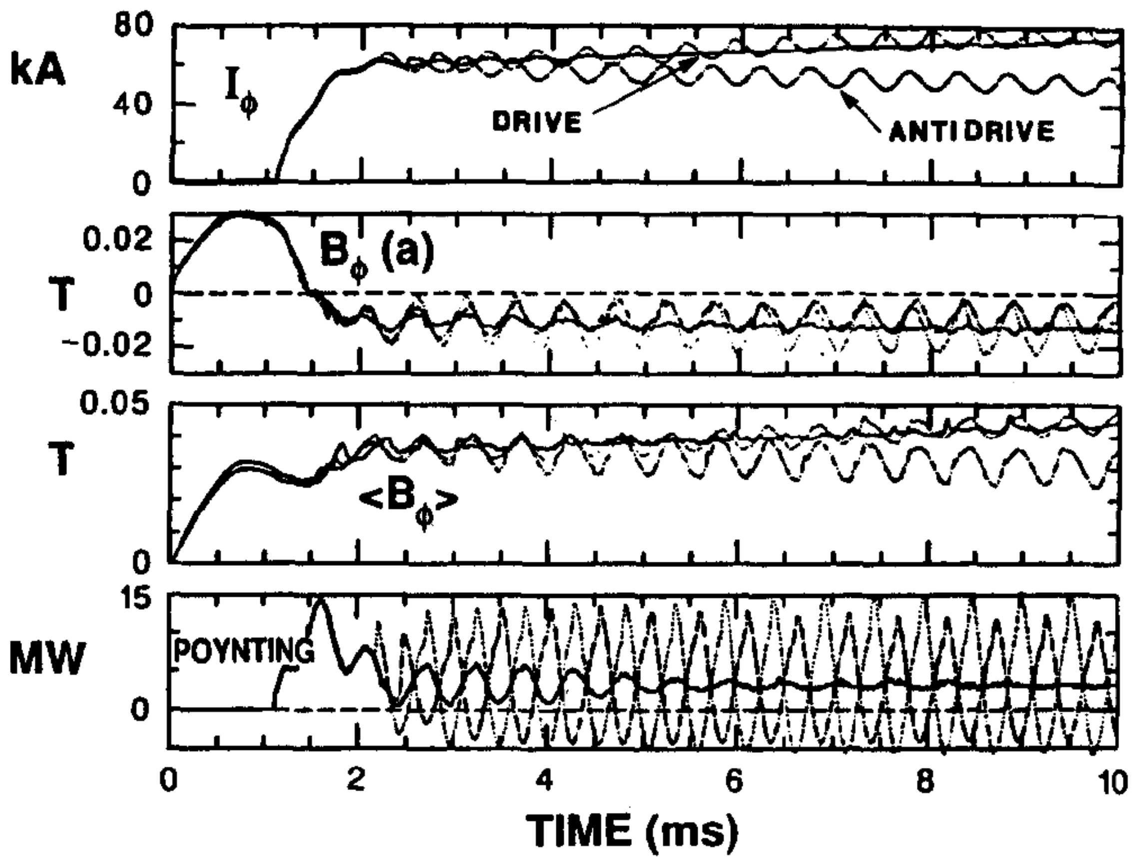




Ebrahimi et al, 2003

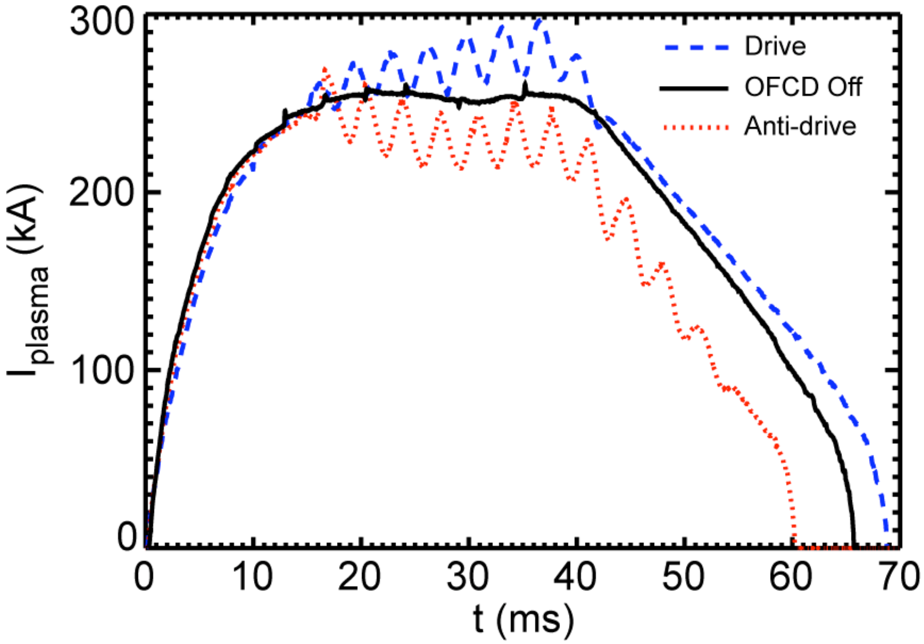
OFCD first tried on ZT-40M, demonstrating partial current drive

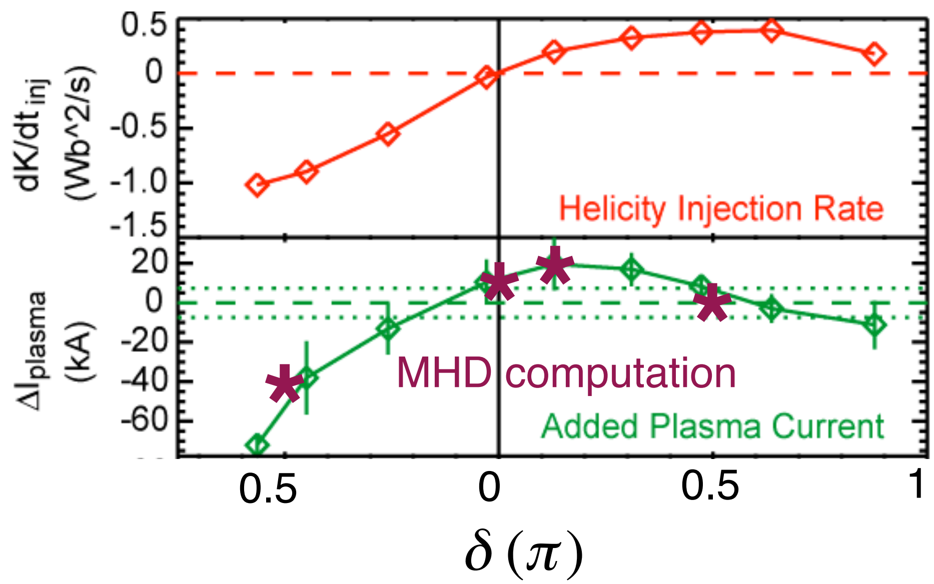
- 5% current drive (amount to be expected)
- Correct oscillator phase dependence



ZT-40M, Schoenberg et al., 1988

10% OFCD current drive demonstrated on MST





L/R settling > pulse length
(saturated current drive likely 15-20%)

So far, current drive agrees with MHD expectations

MST, McCollam et al, 2006

Summary

- The performance and understanding of RFP magnetic confinement steadily improves

- Rich opportunity for magnetic self-organization physics, both for fusion and basic science, with connections to astrophysics

- Discovery of spontaneous helical equilibria at high current is changing the stigma of poor confinement in a self-organized RFP

- Tokamak-level confinement demonstrated transiently using profile control, while maintaining high beta

- Robust MHD stability using advanced control methods

- Many other physics advances not covered here (apologies to my RFP colleagues)

Looking forward

- Limiting transport mechanism(s) and confinement scaling must be established, especially the dependence on plasma current.
- Integration of good confinement and current sustainment is crucial, and different than for high bootstrap current scenarios (in some respects a more controlled approach is likely!)
- Higher current operation will be essential to resolve key issues
- Much left to do for optimized active control, especially with fusion environment boundary conditions.
- Plasma-boundary interface could require unique solutions, with unique possibilities.
- Geometric optimization of the RFP is barely studied (an opportunity), e.g., 2D and 3D shaping, aspect ratio

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