The Reversed Field Pinch

Toroidal confinement in the limit of small applied B_T

Presented by D. Den Hartog and S. Prager

Outline

- Long-term objectives
    - as a fusion energy system
    - for fusion energy science
- The world RFP program
- Scientific issues for RFP development
    - status
    - unknowns
    - gaps
    - how to plug the gaps
- Implications for facilities

Long-term objectives

RFP as a fusion energy system

Mission:

Develop the scientific and technical basis for a fusion power source that uses a small externally applied magnetic field

Twenty year focus:

Form the basis for a burning plasma experiment by developing an attractive self-consistent integrated scenario: favorable confinement with resistive wall stabilization in a sustained high beta plasma

Long-term objectives

For fusion energy science

Understand

- *the influence of magnetic self-organization on fusion plasmas*

- *plasmas with weak field and magnetic self-organization suppressed*

Large part of presentation will expand on second objective
- a new fusion physics regime,

First discuss first objective

Objective: understand influence of magnetic self-organization on fusion plasmas

Applications

tokamak, STs, and stellarators during strong MHD activity;

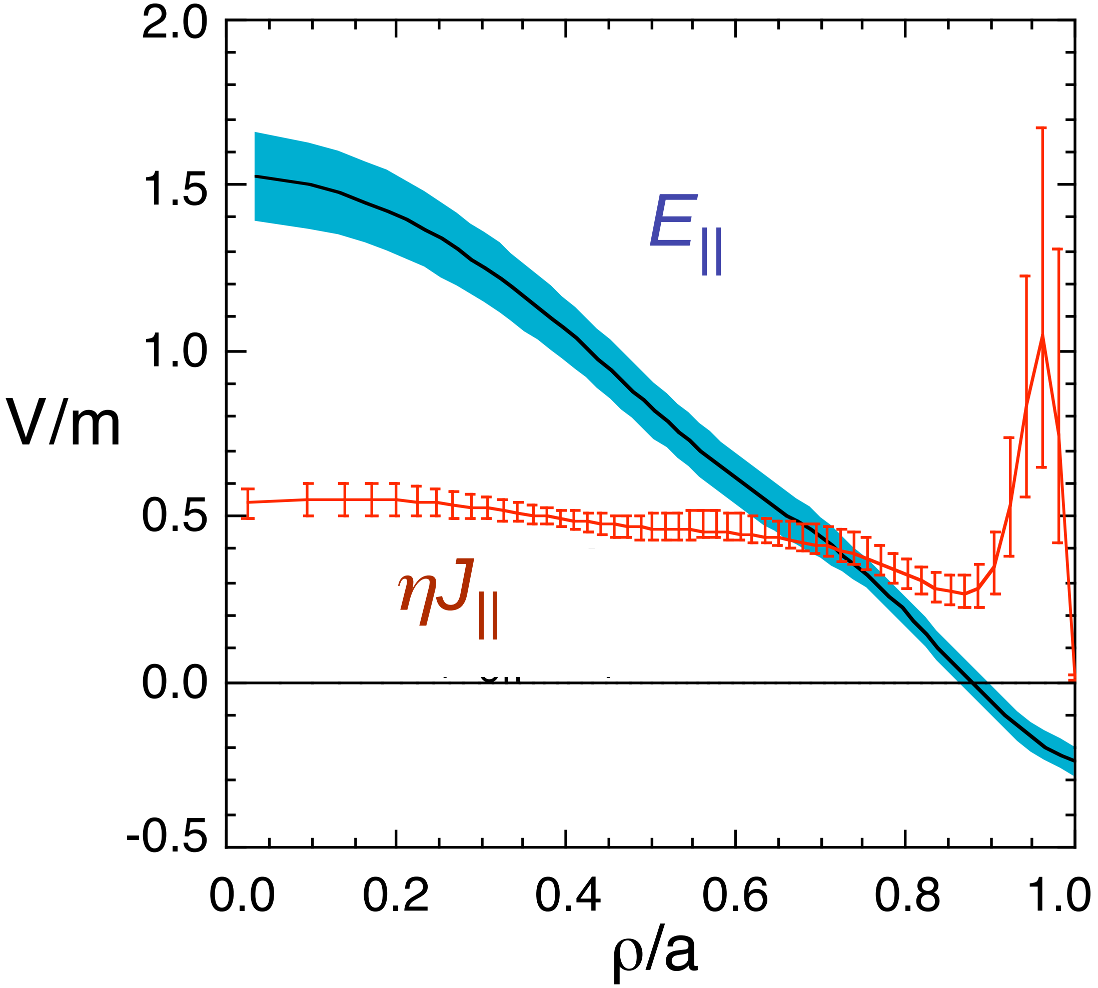
spheromaks, ergodic divertors, RFP

In the RFP self-organization can occur as an event (sawtooth crash)

Five coupled topics

- transport from stochastic magnetic field
- momentum transport from magnetic fluctuations
- ion heating from reconnection
- dynamo
- multiple, coupled reconnections

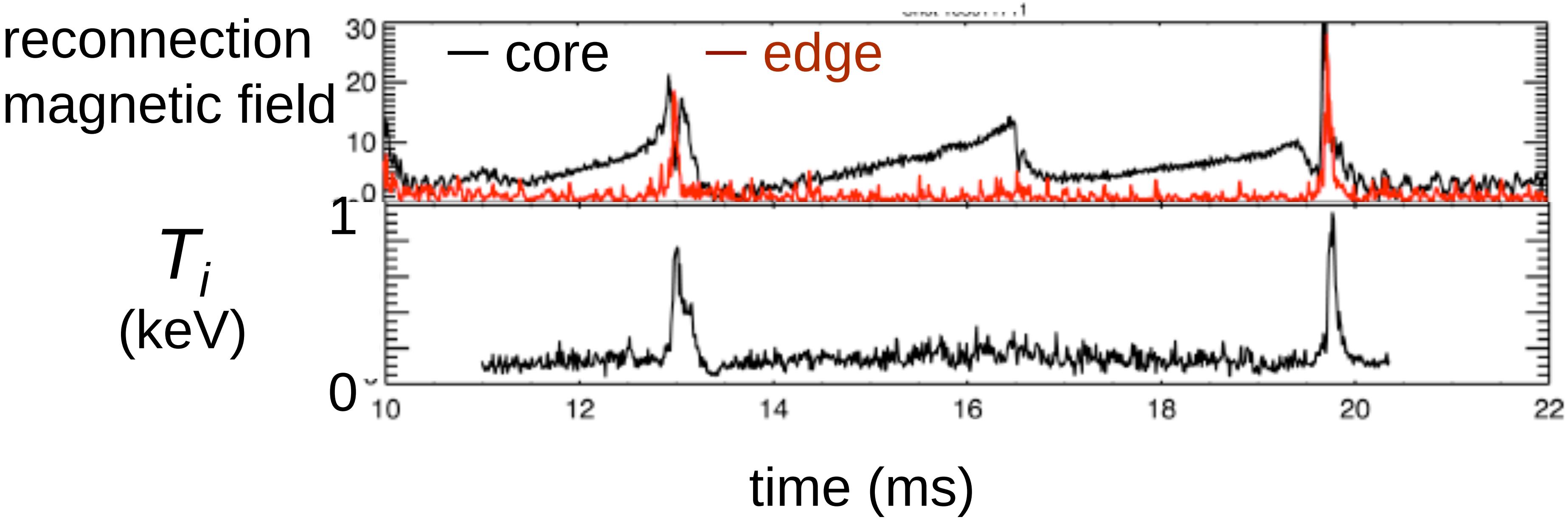
Dynamo



$$E_{\|} \neq \eta J_{\|}$$

The influence of multiple, coupled reconnections

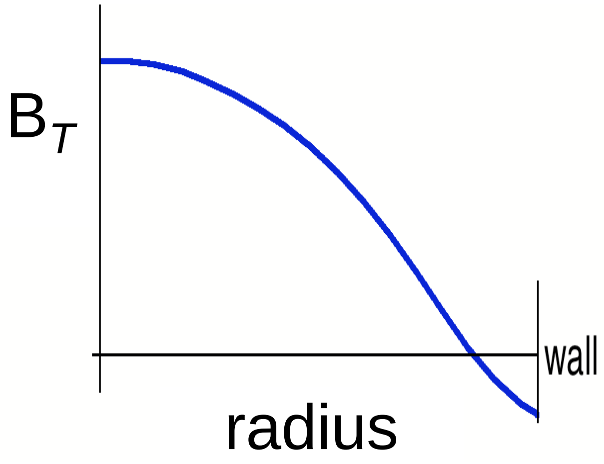
strongly enhanced magnetic self-organization



Question from panel on science goals:

What is the value of understanding low toroidal field plasmas - there must be high field inside the plasma to have confinement?

Inside plasma B_T is low in that $q < 1$
(inside: $B_T \sim B_P$, on surface $B_T \ll B_P$)



Science goals seem to be very ambitious and broad. How do we measure progress? Does this mean validation of models?

YES, but also “leading” models via new regimes and processes

Status of models to validate

- momentum transport, multiple reconnections, and dynamo

  MHD, two-fluid, kinetic computation in hand or underway

  Physical mechanisms developed and developing

- Ion heating

  mechanism a mystery at the moment,

  above models are relevant

- Transport from stochastic field

  MHD plus heuristic transport estimates,

  Self-consistent models to be developed

Spin-off: Astrophysics

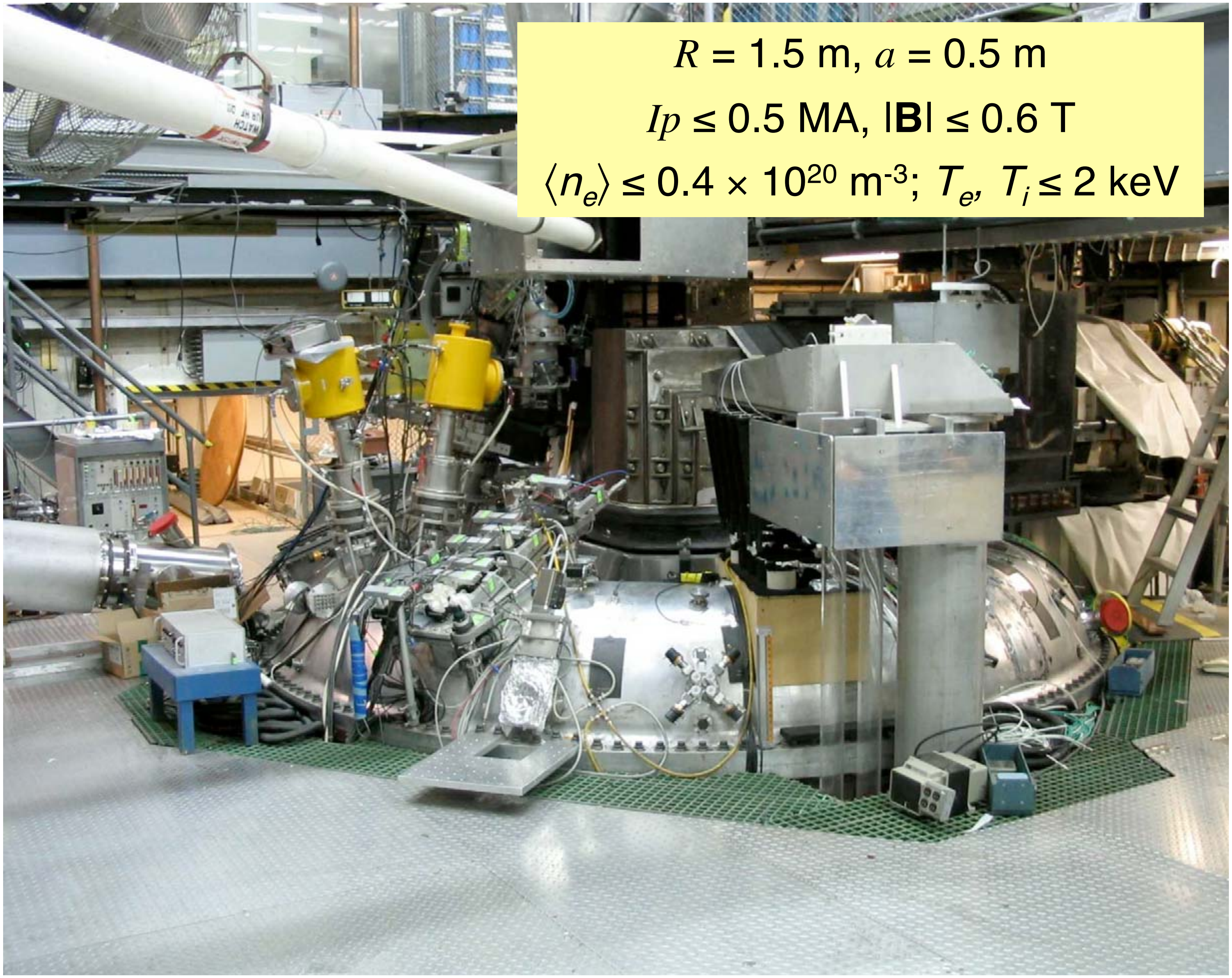
RFP program arguably unique among fusion concepts

International RFP Experimental Program

There are four complementary RFP experiments in the world.

- Two larger experiments
  - MST (UW–Madison)
  - RFX-mod (Italy)
- Two smaller experiments
  - Extrap-T2R (Sweden)
  - RELAX (Japan)

MST is an ohmic RFP operated at moderate current.



$R = 1.5$ m, $a = 0.5$ m

$Ip \leq 0.5$ MA, $|\mathbf{B}| \leq 0.6$ T

$\langle n_e \rangle \leq 0.4 \times 10^{20}$ m^{-3}; T_e, $T_i \leq 2$ keV

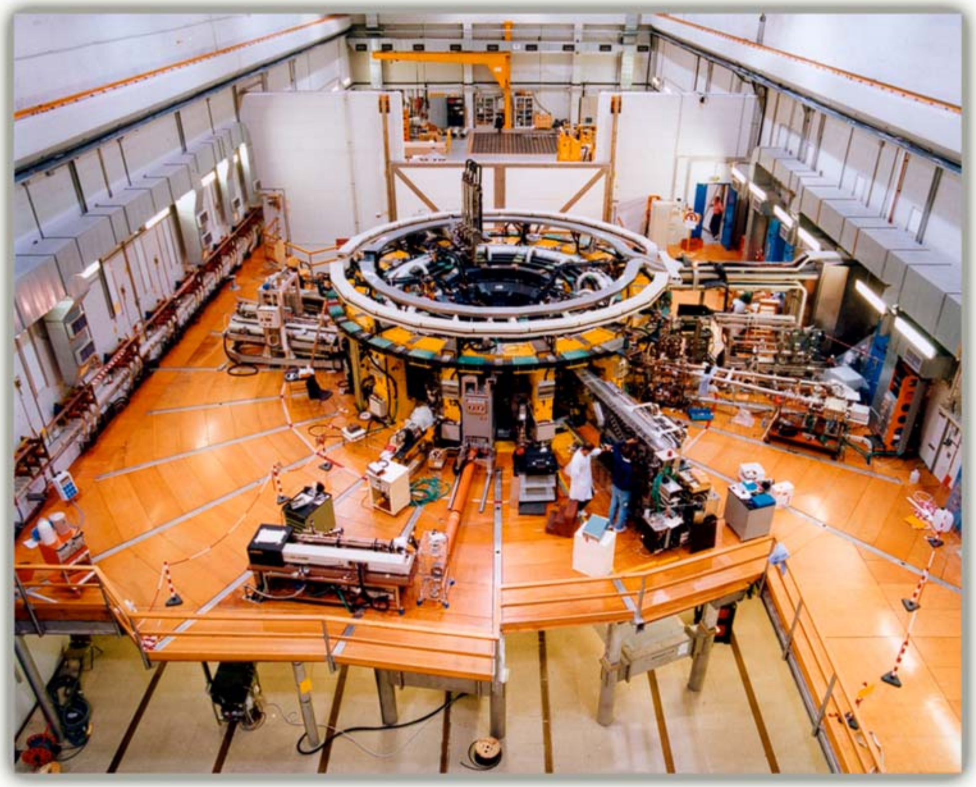
The MST program focuses on confinement and beta studies, through current profile control and auxiliary heating.

- Confinement improvement through current profile control
  - Further optimization of inductive current profile control
  - Two rf techniques in development for current profile control
    - Lower-hybrid
    - Electron Bernstein waves (EBW)
- Beta limit physics
  - neutral beam (1 MW, 20 ms)
  - pellet injector

- Good diagnostic set with some unique capabilities
  - Simultaneous FIR interferometer and polarimeter
  - Heavy ion beam probe
  - Rutherford scattering and CHERS
  - Motional Stark effect
  - Multi-point, multi-pulse Thomson scattering

RFX-mod is a high current, moderate pulse length RFP with a full-coverage feedback coil set.

- The RFX-mod program focuses on
  - Optimizing confinement at high plasma current
  - Magnetic boundary control of RWM and internal modes



$R = 2$ m, $a = 0.46$ m
$I_p \leq 2$ MA

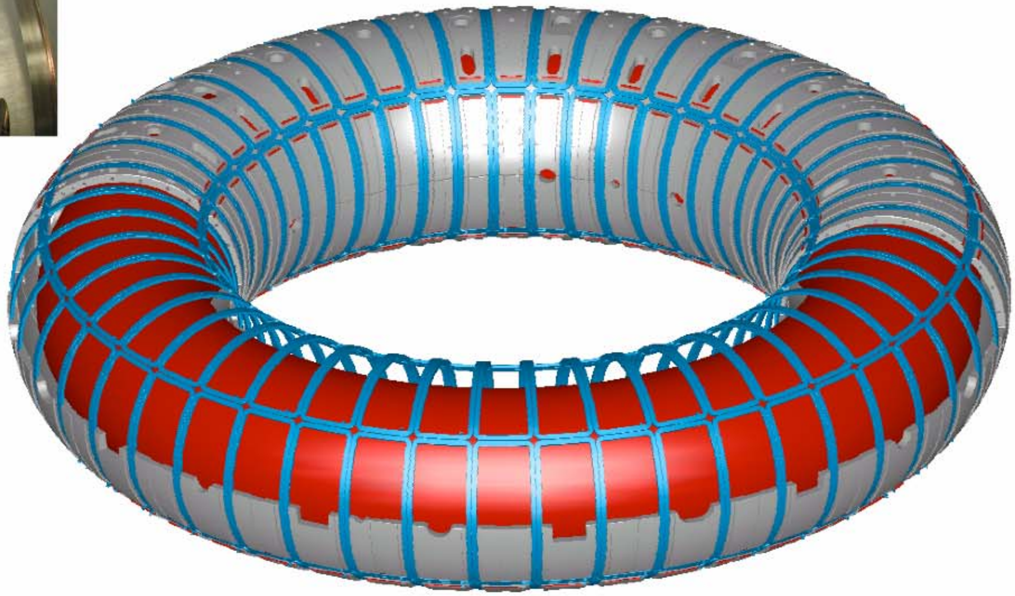
Good diagnostic set

RFX has full coverage with active coils.

Total of 192 active coils.

100% coverage of the mechanical structure external surface.

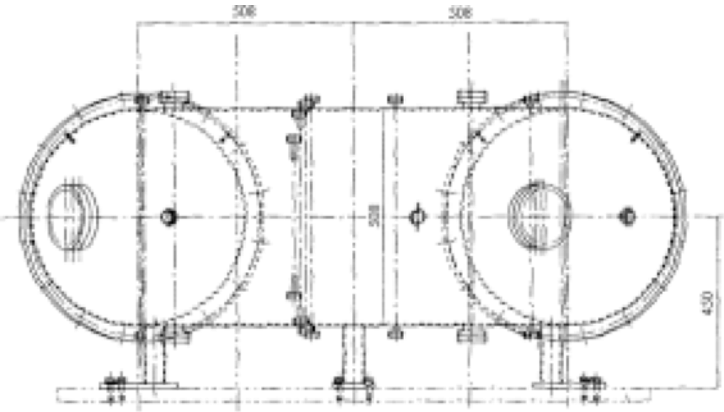
Each saddle coil is fed with its own power supply.



Extrap T2R (Sweden) and RELAX (Japan) are small concept exploration experiments.

- Extrap T2R is has full-coverage feed back coils, thin resistive shell, and all-metal wall.
  - *R* = 1.24 m, *a* = 0.18 m
  - Shell time constant: 6 ms
  - Plasma pulse length: ≤ 100 ms

- RELAX is a low-aspect ratio RFP under construction.
  - New parameter space for RFP configuration
  - Spatial separation of major resonant surfaces in core is increased



Side view

RFP facilities

Facility	***R/a***	***Ip* (MA)**	**Pulse length (s)**	**Plasma boundary**	**Mission**
MST (UW-Madison)	3	0.5	0.1	Conducting shell, small coverage graphite limiter	Confinement with profile control, beta, current sustainment
RFX-mod (Italy)	4.3	2	0.5	Full feedback coil coverage, full graphite limiter	Confinement at high current, magnetic boundary control
Extrap-T2R (Sweden)	6.9	0.3	0.1	Full feedback coil coverage, molybdenum limiters	Optimizing magnetic boundary control
RELAX (Japan)	2	0.1	0.01	Conducting shell	Small aspect ratio

Panel question on U.S. role in the world RFP program

- *The RFP program is an international program; what are the U.S. roles relative to other parts of the program?*
  - The U.S. program has emphasized confinement and beta, and current sustainment. In the rest of the world program, there is strong emphasis on mode control and resistive wall instabilities, high current operation, and low aspect ratio.

Scientific issues for RFP development

- confinement
- beta
- resistive wall instabilities
- current sustainment
- plasma-boundary interaction
- self-consistent RFP reactor scenarios

For each issue will discuss:

status, unknowns, gaps, how to plug gaps

Confinement

Status

Standard RFP:

- Causality between magnetic fluctuations and transport well-established

- Extensive understanding

- Transport about 10x higher than comparable tokamak

The “standard RFP” is obsolete

Two approaches to improved confinement

- Current profile control
- Single helicity state

Improved confinement by current profile control

- Reduce $dJ_{||}/dr$, free energy source for fluctuations
- Suggested by theory
- Realized transiently by inductive programming

Improved confinement by current profile control

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- Realized transiently by inductive programming

Results

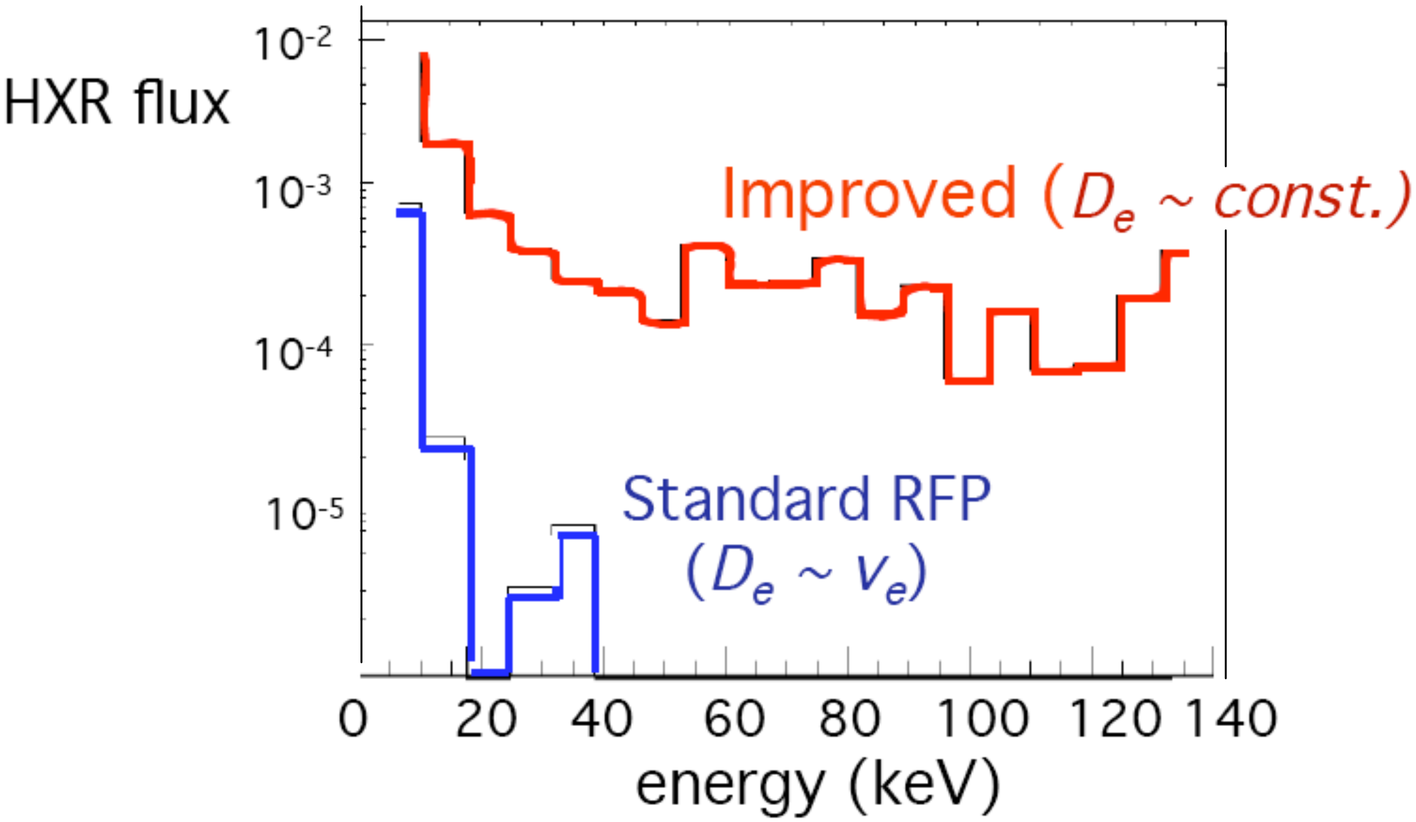
•Confinement improved 10-fold to “tokamak-like”

•Good confinement of thermal electrons and ions, energetic electrons and ions

•Temperature increases with current
(0.6 keV at 0.2 MA
2.0 keV at 0.5 MA)

- Transition from magnetic to electrostatic transport (Fokker-Planck modeling of HXR emission)

MST



Second approach: Single helicity states

- All modes suppressed except one, yielding a helical state without magnetic stochasticity
- MHD computation predicts onset of state for sufficient dissipation

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- MHD computation predicts onset of state for sufficient dissipation

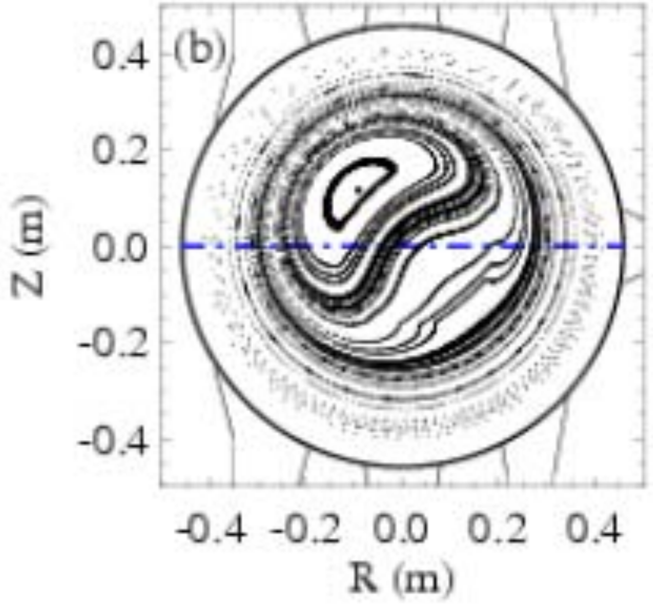
Experiments to date:

- At high current the plasma naturally evolves in the direction of an SH state
- Confinement improves 4-fold (at high current)

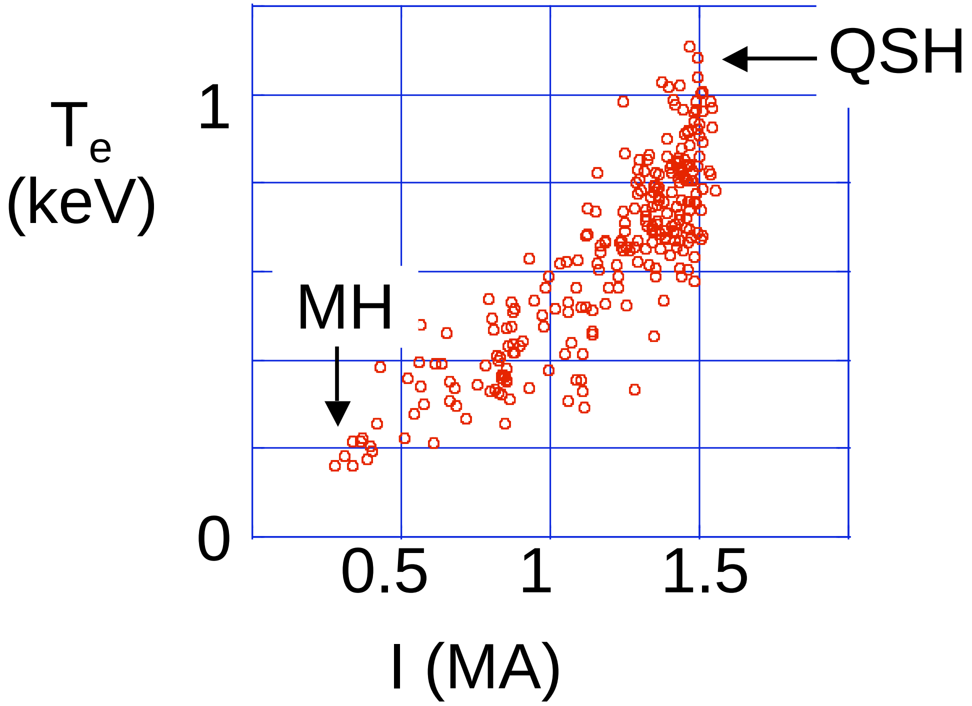
Experimental results:

RFX

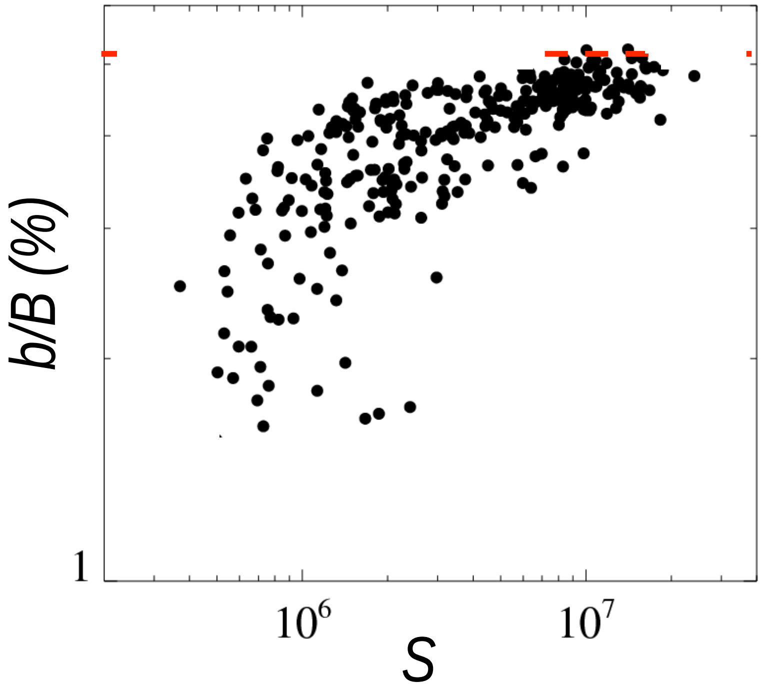
At high current the plasma evolves toward an SH state



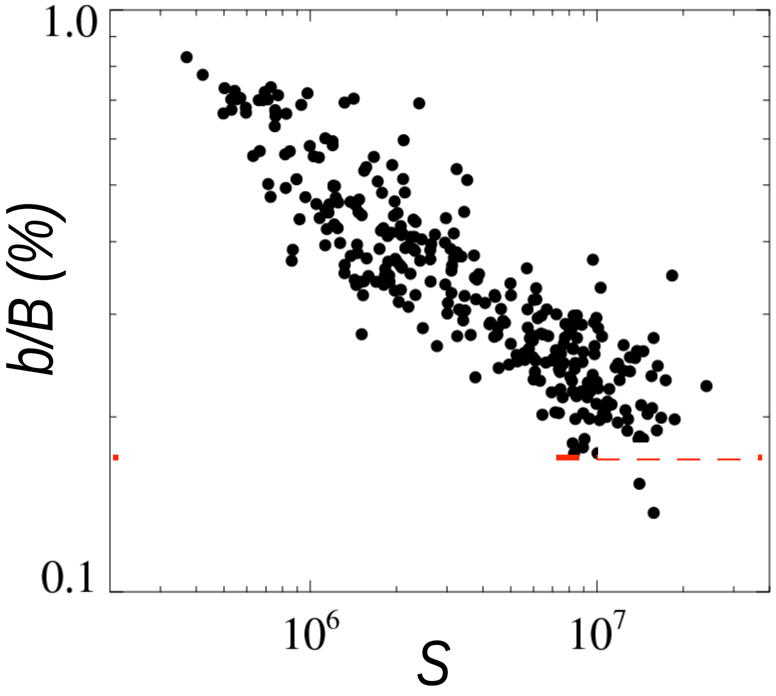
T_e increases with current



Approaches SH state as Lundquist number increases



Dominant mode (m = 1, n = -7)



Secondary modes (1,-8 to -15)

Question from panel on single helicity:

What is primary motivation for studying SH states?
A possible path toward a reactor or a curiosity?

Path toward a reactor

How much of the plasma volume is involved?

Intention: 100%

Experiment to date: ~ 25%

Experimental basis for expected benefits?

Above current and confinement dependence

Confinement unknowns

Improved confinement regime (via j control)

- transport physics - a new fusion physics regime,
  q < 1 plasma dominated by electrostatic transport

- Behavior in steady state

Single helicity state

- How to achieve a complete SH state?

  Naturally at high current?

  Via helical magnetic boundary control?

Question from panel on electrostatic transport

- What parameters characterize electrostatic transport at low field?

  Unknown: a new regime, just beginning to be studied theoretically. Expectations from beginning ITG calculations are normalized gyroradius, magnetic shear, curvature drift frequency, beta.

- How much can we learn from early tokamaks where field was weak?

  Not much. Weak field of RFP yields $q < 1$, strong negative magnetic shear, strong curvature drift frequency - not found in tokamaks

- Can we make contact with extensive tokamak theory and code?

  Strong potential; e.g., gyrokinetic simulation of RFP beginning now

- Is there something beyond dimensionless parameters, such as field direction (toroidal vs poloidal) that may require new or upgraded RFP facility?

  No; except that we need to assure it continues toward fusion conditions

Confinement gaps and plugs

Gaps:

electrostatic transport: how does it depend upon parameters, such as normalized gyroradius

magnetic transport: how does it scale with Lundquist number and current? How does SH state quality scale?

Will the favorable trends with current continue?

Plugging the confinement gap

Consider 3 scaling scenarios (for discussion only)

1. Electrostatic dominated tokamak-like
2. Magnetic transport dominated RFP constant beta scaling
3. Magnetic transport dominated weak scaling with S

Plugging the confinement gap

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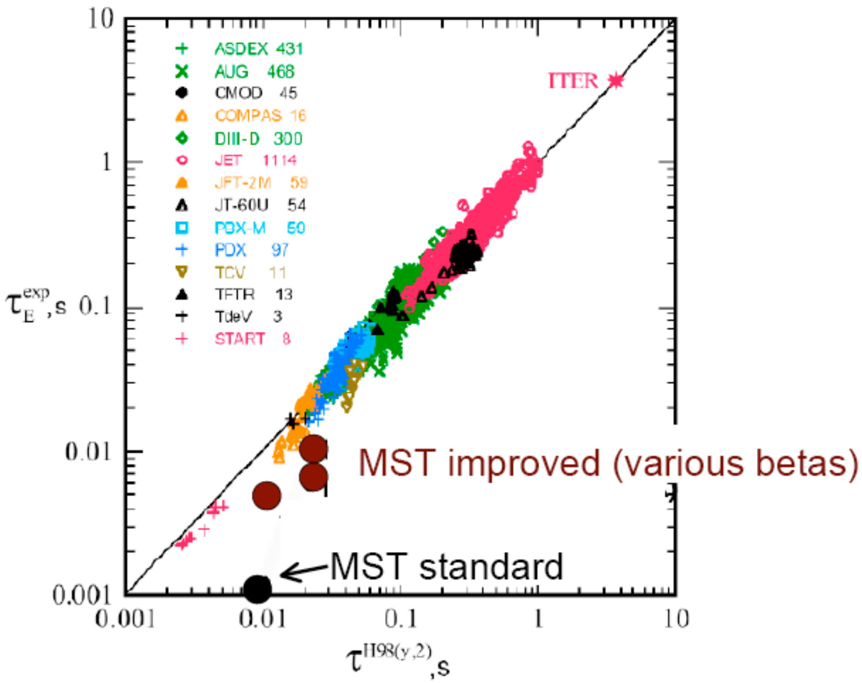

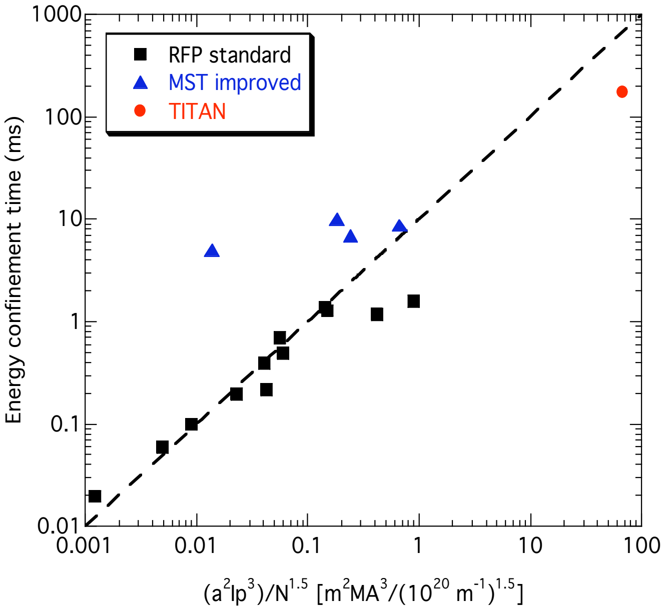

A next step facility should distinguish scalings and extend physics parameters

Example:

MST-size, 1.5 MA, 0.5 sec, with J(r) control

Scaling 1: τ_e ~ 30 ms

Scaling 2: τ_e ~ 5 ms

Scaling 3: τ_e ~ 1 ms

S increases ~ 10x to 10^7 for standard RFP

~ 100x to 10^8 for improved confinement

Normalized gyroradius decreases 3x

Beta limits

Status

Known theoretical limits:

localized interchange, global tearing (pressure-driven)

Experimental status:

all RFPs attain $\beta = \dfrac{\langle p \rangle_V}{\langle B^2 \rangle_S} \sim 10\%$

With pellet injection into improved confinement

β = 26%, no limit yet

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Known theoretical limits:

localized interchange, global tearing (pressure-driven)

Experimental status:

all RFPs attain $\beta = \frac{\langle p \rangle_V}{\langle B^2 \rangle_S} \sim 10\%$

With pellet injection into improved confinement

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Unknowns: experimental beta limit,

theoretical nonlinear evolution,

effect of shape and profiles (optimization)

Question from panel on beta

How meaningful is it to relate beta to the external toroidal field applied? Should beta be defined as $\frac{\langle p\rangle_V}{\langle B^2\rangle_V}$ *?*

- For engineering, choose

$$\beta_{eng} = \frac{\langle p\rangle_V}{B_{coil}^2}$$

or

$$\beta_{eng} = \underset{\substack{\nearrow \\ \text{High}}}{\beta}\,\underbrace{\frac{\langle B^2\rangle_S}{B_{coil}^2}}_{>1 \text{ for RFP}} \quad \text{where} \quad \boxed{\beta = \frac{\langle p\rangle_V}{\langle B^2\rangle_S}}$$

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- For physics, we evaluate stability for a given equilibrium, no need to choose a beta definition

Using the external toroidal field is of some engineering utility, not for physics.

If present experiments reach levels required for RFP reactors, seems like studying beta limits is a low priority

We agree that it is lower priority than confinement and sustainment,

But, it is an important area for physics (e.g., nonlinear MHD) and as a lever for further reactor optimization

Beta gaps

- NBI and pellets might discover beta limits in MST

Steps beyond MST

- Greater confinement and duration to facilitate NBI thermalization
- Higher S values, since evolution of pressure-driven MHD modes depend on S

Resistive wall instabilities

Status

Theory:

predicts multiple resistive wall instabilities at zero beta *and* enhancement of tearing modes beyond their ideal wall amplitude

Experiment:

All modes suppressed through feedback

Resistive wall instabilities

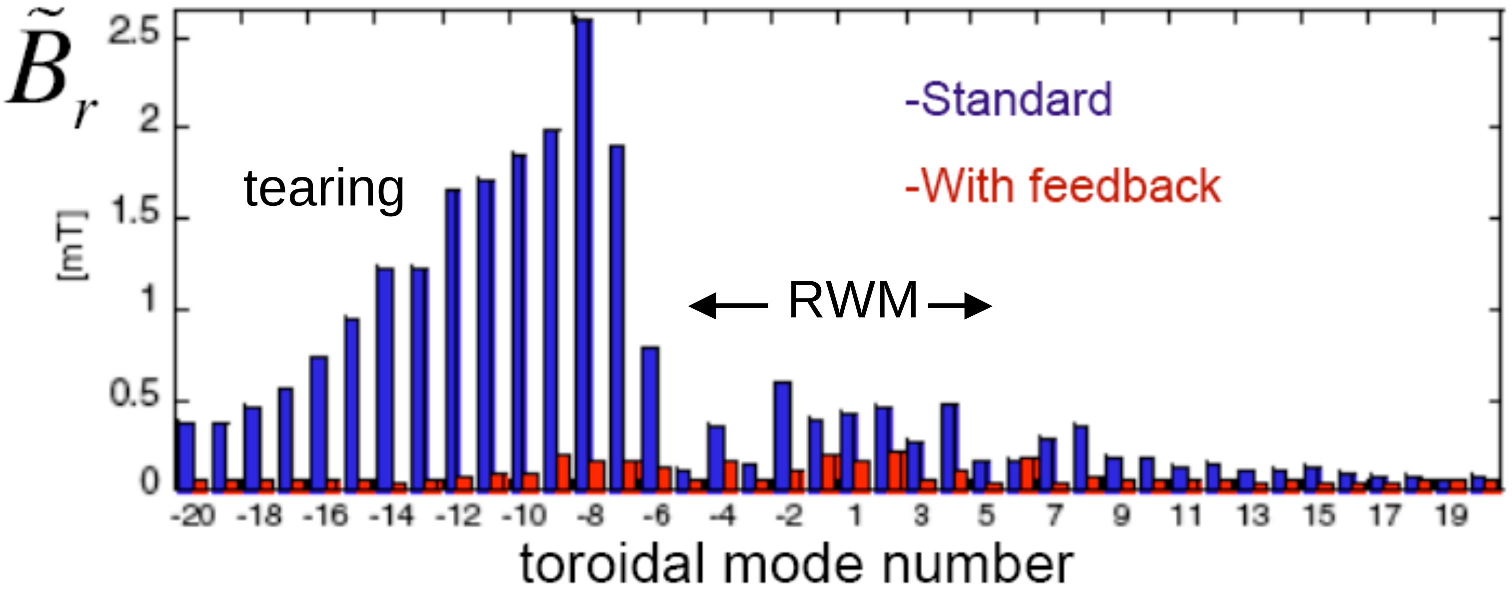
Status

Theory:

predicts multiple resistive wall instabilities *and*
enhancement of tearing modes beyond their ideal wall amplitude

Experiment:

Suppresses all modes through feedback



RFX

RWM unknowns

compatibility with reactor
(proximity, number, geometry of coils)

RFX has capability for next step studies

Panel question: thus, are RWM studies a low priority?

Yes, relative to confinement and sustainment,

But it remains an important reactor ingredient to optimize,

Physics studies are of broad relevance

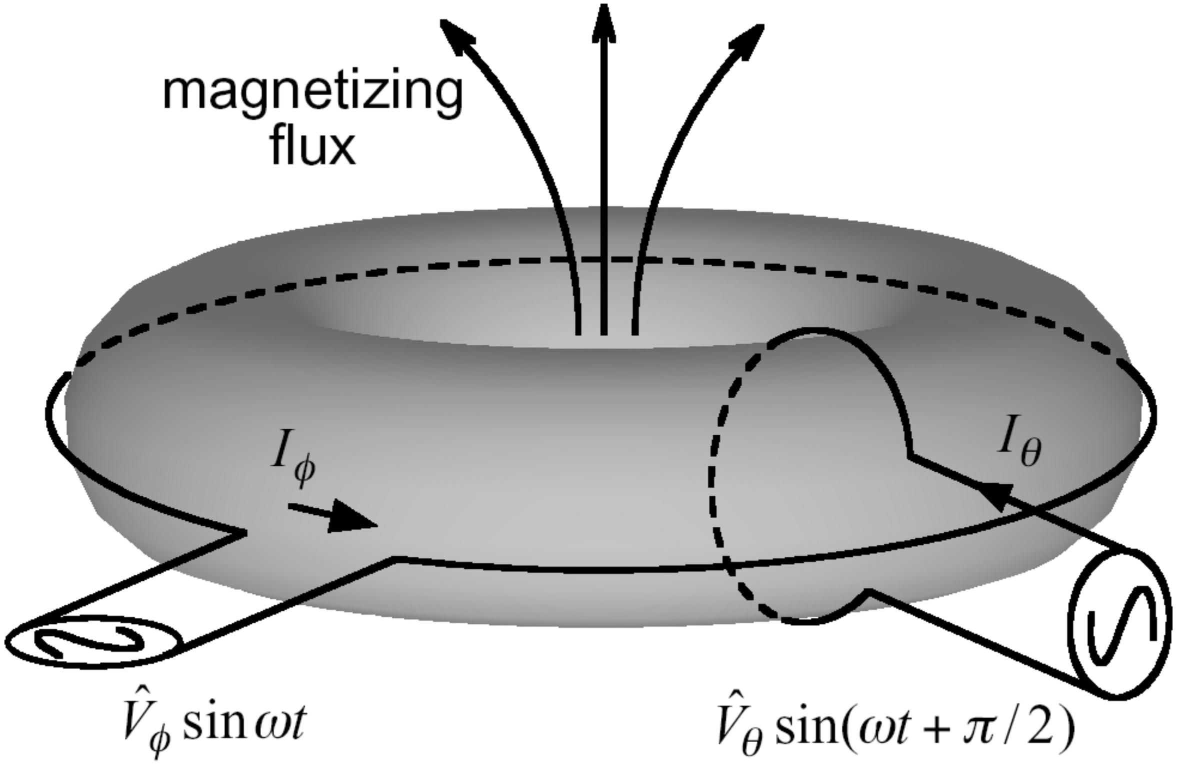
Current Sustainment

Current sustainment is a major challenge for the RFP.

- Current sustainment is difficult in the RFP
  - Must have a large plasma current (poloidal field dominant)
  - Pressure-driven current is relatively small unless $\beta \sim 1$
  - Usual inductive formation is pulsed, not steady-state (not RFP specific)

- Possible solution:
  - Inductive “Oscillating Field Current Drive” (*aka* AC helicity injection)
    - Efficient
    - Possible reactor scenarios (basis for TITAN operation)

For oscillating field current drive (OFCD), purely AC loop voltages are applied at low (audio) frequency.



Dynamical explanation: Oscillating pinch beats with oscillating field to produce parallel induction.

All oscillating components are mean-field (0,0).

Separate AC & DC parts:

$$\mathbf{E} = \hat{\mathbf{E}}$$

$$\mathbf{B} = \hat{\mathbf{B}} + \overline{\mathbf{B}}$$

↑ AC amp.

↑ cycle avg.

Cycle-average Ohm's law:

$$\cancelto{0}{\overline{\mathbf{E}}} + \overline{\mathbf{V}\times\mathbf{B}} = \eta\overline{\mathbf{J}}$$

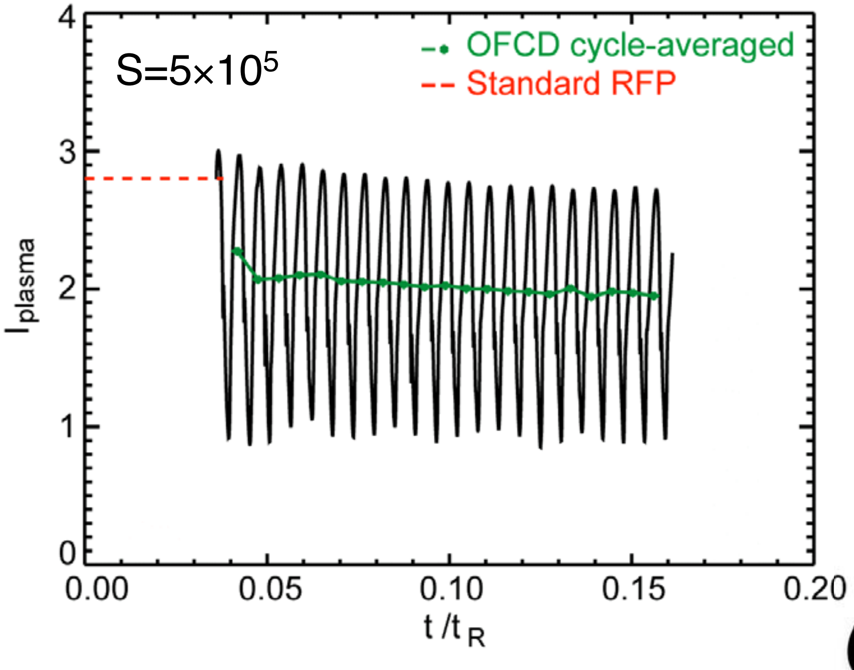
$$\hat{\mathbf{V}}_r \times \hat{\mathbf{B}} = \left(\frac{\hat{\mathbf{E}}\times\mathbf{B}}{B^2}\right)\times\hat{\mathbf{B}} = \left(\frac{\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}}{B^2}\right)\overline{\mathbf{B}}$$

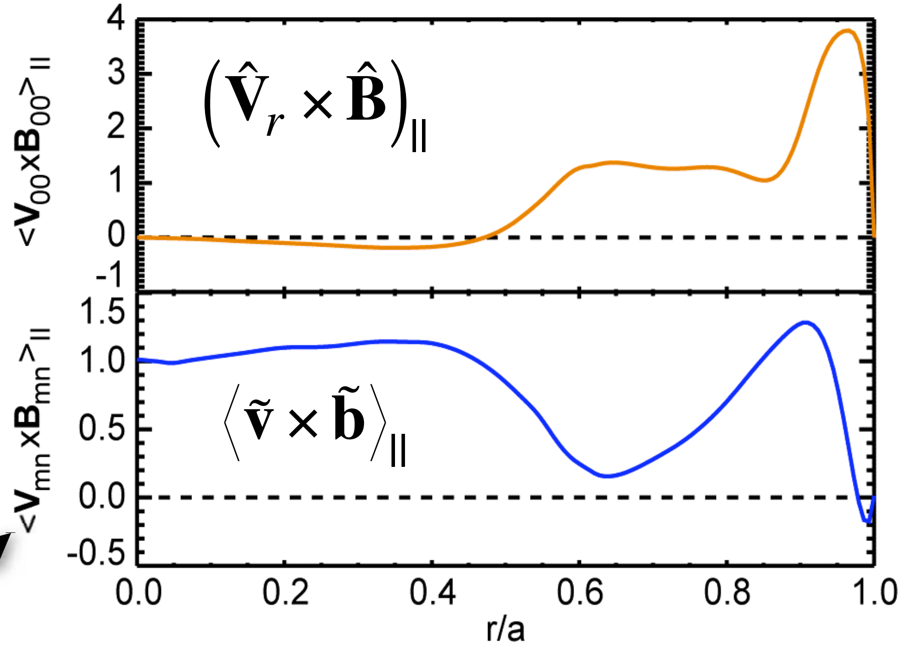
↑ mean-field pinch

↑ parallel induction

- Parallel induction drives edge-peaked plasma current
  - Small AC ripple associated with plasma inductance
  - Tearing fluctuations relax current inward

Nonlinear resistive MHD computation demonstrates OFCD current drive.





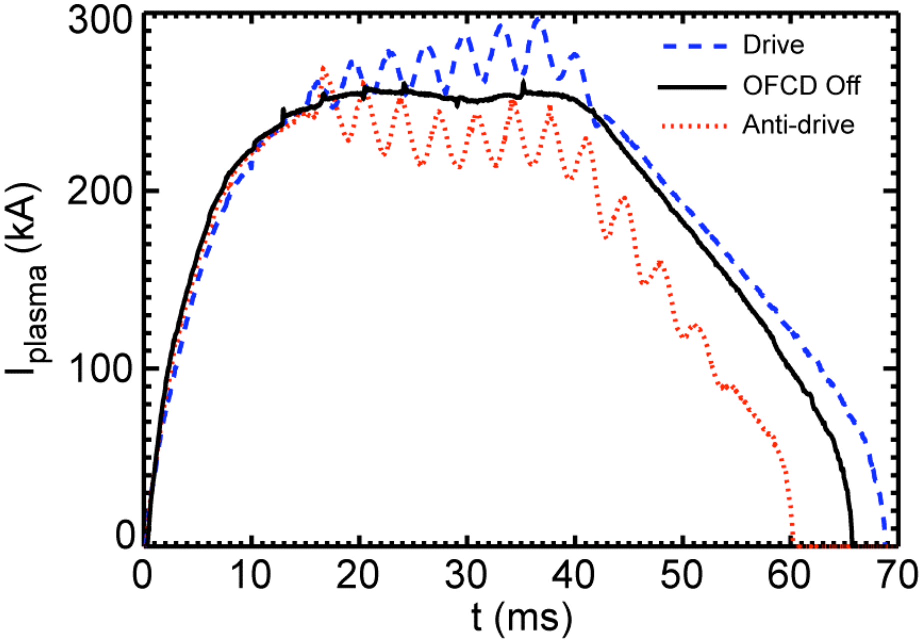
Fluctuation-induced emf (dynamo) from MHD tearing at amplitudes similar to steady induction.

↓

Is OFCD compatible with confinement requirements?

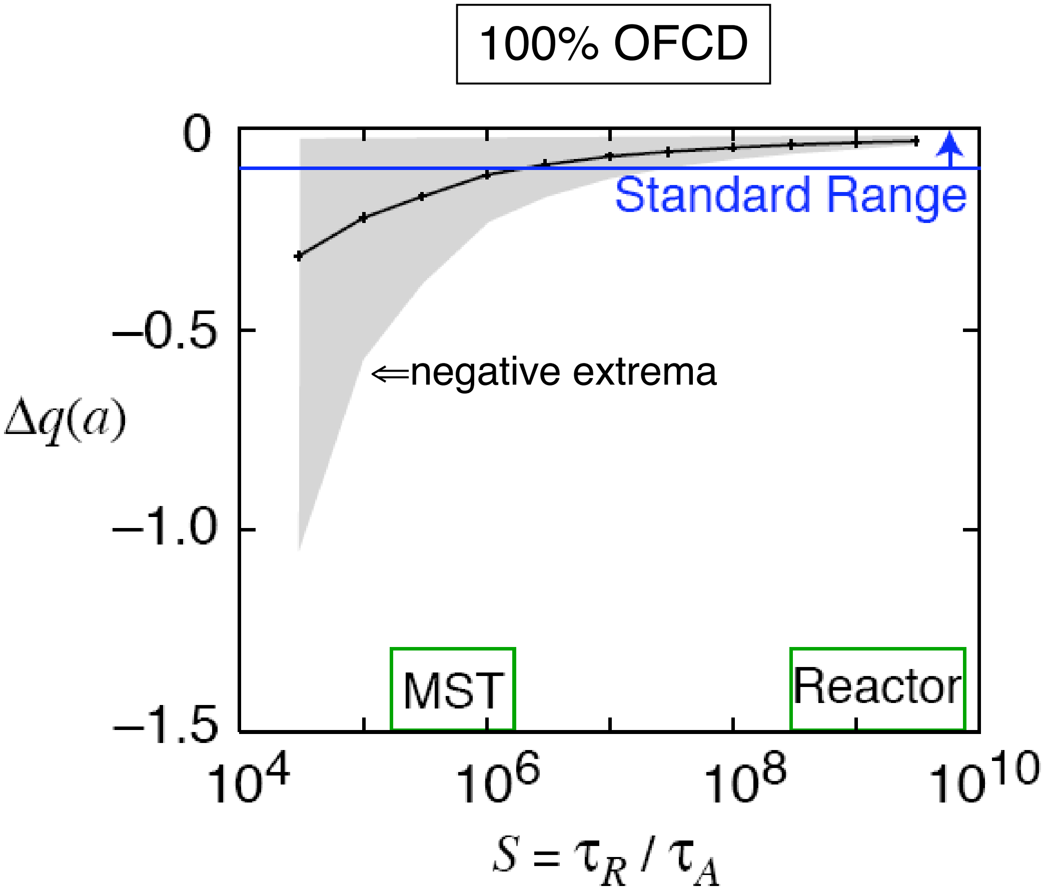
OFCD on MST produces 10% increase in plasma current.

- Installed oscillators: 280 Hz, 1 MVA (insufficient power for 100% drive).



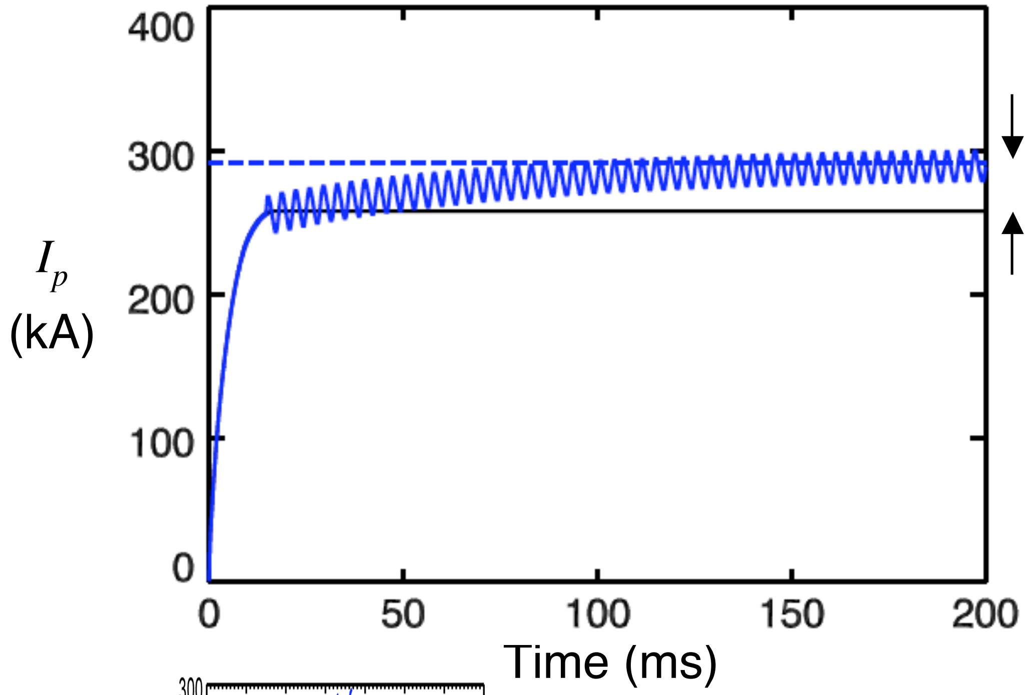
OFCD current drive efficiency measured the same as for steady induction (≈ 0.1 A/W)

Lundquist number scaling projects small equilibrium modulation for reactor-like parameters.

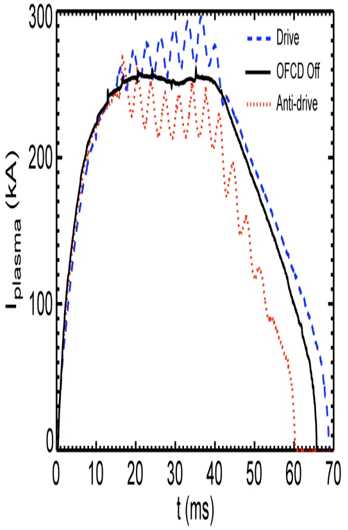


Large, cyclic equilibrium modulation for $S < 10^6$, but small modulation for $S > 10^7$.

The L_p/R_p time for saturated OFCD current addition is longer than the pulse length of MST.



≈ 15% addition predicted
for MST oscillators
$(\delta = \pi / 5)$



Current Sustainment Unknowns and Gaps

- OFCD will not be confirmed until a 100% current drive demonstration is done
  - Underlying physics can be assessed as fractional current drive is increased

- Compatibility of OFCD with required energy confinement is unknown
  - At high Lundquist number, expected that
    - OFCD equilibrium modulation small
    - Reduced turbulence required for current profile relaxation

- To close the gap and enable necessary OFCD study:
  - High Lundquist number ($S > 10^7$)
  - Pulse length longer than L/R time
  - OFCD power capability to 100%

Panel questions on OFCD and current sustainment

- *Do you mean that OFCD has driven 10% of the plasma current?*
  - Yes, this is the result from MST.

- *What kind of plasma conditions are needed to demonstrate 100% OFCD at reasonable parameters?*
  - $S > 10^7$, pulse length > L/R time.

- *What is the expected current drive efficiency of OFCD? Does this kind of power stress the first wall?*
  - Ohmic efficiency, 0.1 A/W in present experiment. As long the oscillations are small the first wall is not stressed.

- *Is OFCD really a viable option? Favorable influences on confinement by OFCD are required for a steady-state RFP reactor. What is the confidence of a multi-keV plasma coexisting with OFCD?*
  - The suitability of OFCD for reactor operation is not known with the present knowledge base. A high temperature, high S plasma may require substantially reduced OFCD oscillation, and the magnetic turbulence required for current profile relaxation may be smaller (and confinement better). The scaling of these parameters needs to be experimentally determined.

OFCD and current sustainment questions, cont'd

- *Where does the community think current drive could be in 20 years?*
  - Test physics promise of OFCD at high *S* and longer pulse length.

- *Do we have other backup schemes for current drive?*
  - Possible alternatives are hybrid mode (discussed later), or bootstrap current from extreme equilibria.

- *Is there a physics basis to expect that development of rf current drive in the RFP will be less or more challenging than in the tokamak?*
  - Physics suggests that the magnitude of the challenge is similar.

Plasma-boundary interaction

The majority of RFP experiments have been in circular cross-section, limited plasmas.

- No experimental tests of a toroidal field divertor or pumped limiter
  - TITAN employed a toroidal divertor and highly radiating plasma

- Present experiments have graphite or metal limiters, with varying coverage
  - Control of impurities is not advanced
  - Localized heating of the wall not an issue if plasma maintained axisymmetric

- Present status may be similar to tokamak era when attention to boundary plasma control began to have an enormous influence on plasma behavior.

- Unknowns and gaps:
  - The best means to control the boundary in the RFP is not known
  - Existing facilities are not equipped to study control techniques such as magnetic divertors or liquid metal first walls
  - Large physics database from poloidal divertor tokamaks should be helpful

Panel questions on plasma-boundary interaction

- *Is there a credible path forward for designing a high-power RFP with means for adequate boundary plasma control?*
  - As for all configurations, this is challenging; work is beginning on a path forward for the RFP.

- *Will the first wall be able to handle required increases in heating/current drive power in next step experiments and pulse lengths?*
  - With an axisymmetric plasma boundary, RFX-mod has demonstrated the required power handling capability with 100% graphite limiter coverage. However, this may not be the best solution for plasma-boundary control.

- *Are there geometric factors which make the RFP particularly hard or particularly easy?*
  - Aspect ratio flexibility may be an advantage for the RFP. A toroidal field divertor is probably preferable.

- *Instead of a PoP experiment, can a CE experiment address these issues?*
  - Aspects of divertor geometry, pumped limiter operation, or liquid metal boundary could be tested on a CE experiment.

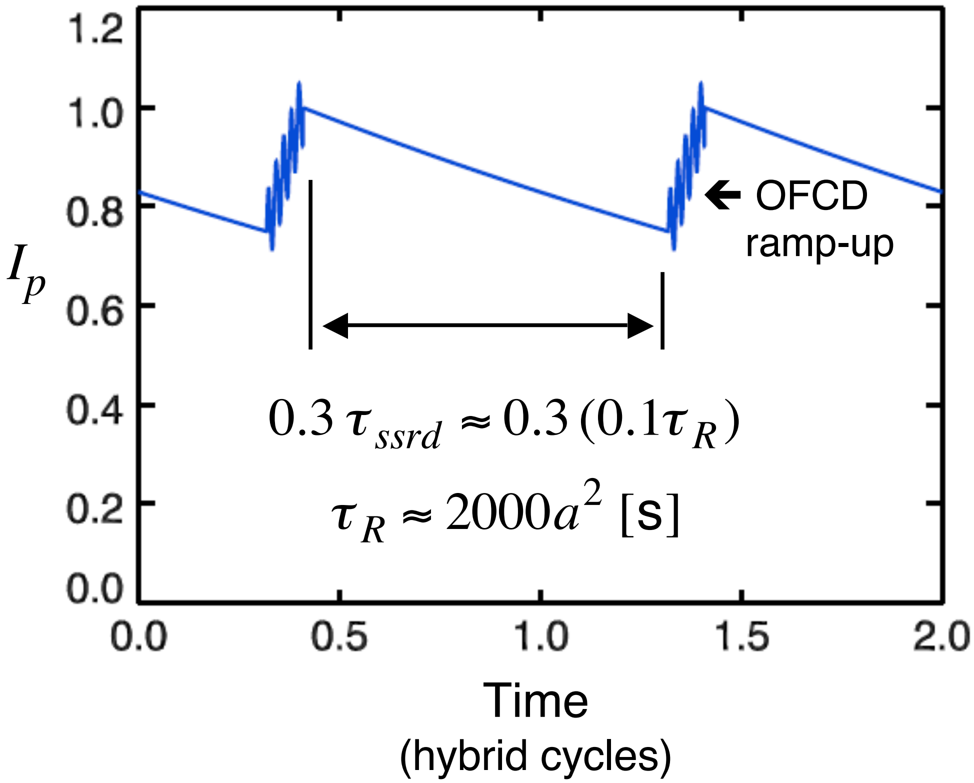
Self-consistent RFP reactor scenarios

The highest priority integration issue for the RFP is efficient current sustainment with good confinement.

- Possible scenarios for sustainment, in order from steady-state to pulsed:
  - OFCD steady-state (TITAN)
    - Compatibility with confinement not yet determined
  - Ultra-high beta steady-state
    - Physics basis is at extreme parameters
  - “Hybrid” inductive (nearly) steady-state
    - Fully inductive scenario, without magnetizing flux accumulation
  - Pulsed induction
    - Single helicity
    - Current profile control

- Gap
  - No current facility is able to produce self-consistent plasma scenarios
    - Need RWM control, current profile control, beta enhancement, OFCD

Possible hybrid inductive reactor scenario: self-similar ramp-down for pulsed burn, OFCD for ramp-up.



- Features:
  - Fully inductive current drive
  - More consistent with established RFP confinement physics
  - Possible reduced mechanical stress compared to conventional pulsed

- Requires modest confinement during the OFCD ramp-up to minimize recirculating power inefficiency ($T_{e0} > 2$ keV ?)

OFCD and current sustainment questions, cont'd

- *Is self-similar decay a major thrust of RFP research and is it envisioned to be a strong candidate for a reactor? If so, then what are the key issues that must be understood, or are spheromak results sufficient? Is MST capable in testing this concept or does it require a new facility or upgrades?*
  - Self-similar ramp down is not yet a major research thrust, and its reactor suitability is unknown. Key issues are profile constancy during ramp down, magnetic turbulence level, and remaining transport. Spheromak results contain physics similarities, but not predictive capability due to geometry differences. MST should explore this concept with a power supply upgrade; test would not be definitive due to pulse length limitations.

Synthesis of facility needs

- Advanced proof-of-principle experiment with focus on confinement and sustainment.
- Facility for plasma/boundary issues.
- Integrated performance extension facility

Confinement/sustainment PoP Experiment

- Establish confinement basis for continuation of RFP development
- Definitively test sustainment scenarios
- Also validate high beta physics
- Requires auxiliary control
- Include active control of resistive wall modes

Requirements

Confinement

I ~ 1.5 MA, $S \geq 10^7$ for dynamic range on scaling

Pulse length > energy confinement time, slowing down time

Sustainment

$S \geq 10^7$ for small OFCD oscillations

Pulse length ≥ L/R time for OFCD,

≥ 0.1 resistive diffusion time for self-similar rampdown

Example:

	MST/RFX	PoP
a (m)	0.5/0.46	0.5
R (m)	1.5/2.0	1.5
Current (MA)	0.5/2.0	1.5
Pulse length(s)	0.1/0.5	0.5
Temperature (keV)	2/1	1 - 5
Density (10^{14} cm $^{-3}$)	0.1-0.3/0.3	0.4 - 1
Energy confinement time (s)	0.01/0.003	0.03

Example:

	MST/RFX	PoP	PE
a (m)	0.5/0.46	0.5	0.8
R (m)	1.5/2.0	1.5	2.4
Current (MA)	0.5/1.5	1.5	4
Pulse length(s)	0.1/0.5	0.5	5
Temperature (keV)	2/1	1 - 5	5 - 10
Density (10^{14} cm $^{-3}$)	0.1-0.3/0.3	0.4 - 1	0.4 - 1
Energy confinement time (s)	0.01/0.003	0.03	0.3

step before BPX

Timing of experiments

- PoP experiment: ready to design now
- PE experiment: design halfway through physics phase of PoP experiment
- BPX: design halfway through physics phase of PE experiment

Summary

- Past decade: course-changing RFP results (confinement, RWM, beta)

- Roll-forward and roll-back planning (from BPX) are roughly consistent

- RFP is a promising configuration - relative to its next step

  (true for other configurations as well)