MST and the Reversed Field Pinch

John Sarff
• Tutorial-level review of tearing stability, magnetic relaxation, and transport in the RFP

• Ion-related physics topics

• A few details on RFP fusion perspectives (as time allows)
The Reversed Field Pinch magnetic configuration

- Magnetic field is generated primarily by the plasma current
- Small externally applied field:
  - Advantages for fusion
  - Large magnetic shear and weaker toroidal (neoclassical) effects, explores complementary/overlapping parameter space w/t the tokamak and stellarator
  - Basic science: magnetic self-organization and nonlinear plasma physics
Three synergistic research mission goals capture MST and the RFP’s opportunities in fusion and plasma science

• **Advance the physics and control of the RFP plasma configuration**
  – MST is one of two large RFP experiments
  – Centerpiece of U.S.’s proof-of-principle program

• **Advance the predictive capability of fusion science**
  – Physics closely related to tokamak and stellarator, leveraged by RFP geometry
  – Validation of key physics models and codes
  – Development and application of advanced diagnostics

• **Discover basic plasma physics and its links to astrophysics**
  – Magnetic self-organization
  – Processes: magnetic reconnection, particle energization, momentum transport, magnetic turbulence
RFP’s fusion advantages derive from the concentration of magnetic field within the plasma and small applied toroidal field:

- Small field at the magnets ▶ copper possible
  - $1/10^{th}$ the magnetic pressure at the magnets compared to high safety factor (e.g., tokamak)
    - $\frac{B_{\text{coil}}}{\langle B \rangle} \sim \frac{2}{3}$ (and $B_{T,\text{coil}} \rightarrow 0$)
    - Large fusion beta demonstrated:
      $$\text{fusion} \sim \frac{\langle p \rangle}{B_{\text{coil}}^2} = 28\% ; \quad \langle \ldots \rangle = 10\%$$

- Large plasma current density
  - Ohmic ignition is possible
    - No plasma-facing auxiliary heating components
  - High particle density limit, $n_{GW} \sim I_p / a^2$
Why might these features be important?

Example: Auxiliary heating is required for tokamak and stellarator plasmas, and it will likely be difficult to make RF antennas that maintain steady operation adjacent to 2.5 GW fusion plasma (a development “gap” for the tokamak & stellarator)

The RFP uses Ohmic heating, which is efficient and nearly invisibly crosses smooth material boundaries. It’s available in large quantity only at low safety factor, $q \sim B_t / I_p$ (which the RFP explores)

Reliability and maintainability of a fusion power system are essential, but difficult to assess until high-performance plasmas of very long duration become routine
The Madison Symmetric Torus (MST)

- Major and minor radii: \( R = 1.5, a = 0.5 \text{ m} \)
- Plasma current and magnetic field: \( I_p < 0.6 \text{ MA}, B(a) < 0.23 \text{ T} \)
- Plasma density and temperature: \( n \sim 10^{19} \text{ m}^{-3}, T_e \sim T_i \sim 2-3 \text{ keV} \)
MST is equipped with advanced diagnostics, many state-of-the-art that impact designs elsewhere.
Other RFP experiments in the world program

- **RFX-Mod**
  - High current, 2 MA
  - Self-organized helical configuration
  - Feedback control of RWMs
- **Extrap-T2R**
  - Feedback control of RWMs
  - High power density, all-metal wall
- **RELAX**
  - Low aspect ratio, A=2
A new RFP program at the University of Science and Technology of China, Hefei

- First plasma in 2015; parts now being assembled in new experimental hall
- Shell system suitable for plasma-boundary studies, e.g., high-Z, lithium
- Advanced active mode control (Phase 2)
- Advanced inductive current drive and 3D effects in helical state
- Collaboration with EAST team on the design and construction

Keda Toroidal Experiment (KTX)

\[ R = 1.4 \text{ m} \]
\[ a = 0.4 \text{ m} \]
\[ I_p = 0.5 \sim 1.0 \text{ MA} \]
\[ \Phi_{\text{mag}} = 5 \text{ V-s} \]
Tearing Modes and Relaxation Physics
Reversed BT forms with sufficiently large plasma current, and persists as long as induction is maintained.
However, a reversed-BT should not be in equilibrium

reversal implies:  \[
(\nabla \times B)_\theta = \frac{1}{R} \frac{\partial B_r}{\partial \phi} - \frac{\partial B_\phi}{\partial r} \neq 0
\]

\[\Rightarrow J_\theta \neq 0\] , which for finite \( \eta \)

\[\Rightarrow E_\theta = -\frac{\partial}{\partial t} \int B_\phi dS \neq 0\]

(non steady-state)
An apparent imbalance in Ohm’s law is related to the surprising BT reversal

- Basic MHD Ohm’s law: \[ \mathbf{E} + \mathbf{V} \cdot \mathbf{B} = \mathbf{J} \quad \text{and} \quad \mathbf{V} = \mathbf{E} \cdot \mathbf{B} / B^2 \]

- There is less current in the core than could be driven by \( E_\parallel \), and more current in the edge than should be driven by \( E_\parallel \)

\[ \Rightarrow \text{current profile is relatively flatter than the inductive drive} \]

\[ E_\parallel = \eta J_\parallel \]

Measured via MSTFIT equilibrium reconstructions
Tearing instability underlies the RFP’s nonlinear dynamics

\[ q(r) = \frac{rB}{RB} = \frac{m}{n} \]

- **Tearing resonance:**
  \[ 0 = k \times B = \frac{m}{r} B + \frac{n}{R} B \]

- **Magnetic Island:**
  \[ q = \frac{m}{n} \]

- **RFP parameters:**
  - \( m \) = poloidal mode number
  - \( n \) = toroidal mode number

- Plot showing points at \( m = 1, 1.6, 1.7, 1.8, \ldots \) with \( n \geq 6 \) resonances.
Tearing process is quasi-periodic, appearing as a sawtooth relaxation cycle.

Only a couple of unstable modes.

Linearly stable modes energized by nonlinear 3-wave coupling:

\[ k_3 = k_1 \pm k_2 \]
m = 0 mode facilitates nonlinear cascade and global core-to-edge communication

- Nonlinear coupling: $Q(k_3) \sim Q(k_1) \times Q(k_2)$

\[ \Rightarrow (m_3, n_3) = (m_1, n_1) \pm (m_2, n_2) \]

3-wave cascade:

- $Q(k_3) \sim Q(k_1) \times Q(k_2)$

(m=2 branch important for cascade to smallest scales)
A dynamo-like process arrests the peaking tendency of the current profile—i.e., how tearing instability saturates

- Ohm’s law: \[ \mathbf{E} = \frac{1}{en} \mathbf{J} \quad \mathbf{V} \quad \mathbf{B} \]

- Suppose there are non-axisymmetric quantities, i.e., from tearing instability: \[ \mathbf{B} = \langle \mathbf{B} \rangle + \tilde{\mathbf{B}} \]

  - Toroidal surface average
  - Spatial fluctuation

\[ \tilde{\mathbf{B}} \sim \tilde{b}(r)e^{imn} \]

- Then mean-field parallel Ohm’s law becomes:

\[ \langle E \rangle_{||} - \eta \langle J \rangle_{||} = \frac{1}{en} \langle \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle_{||} - \langle \tilde{\nabla} \times \tilde{\mathbf{B}} \rangle_{||} = \langle \tilde{\nabla}_e \times \tilde{\mathbf{B}} \rangle_{||} \]

  - Dynamo-like effects from magnetic instability

\[ \frac{\tilde{B}}{\langle B \rangle} \ll 1 \]
Computational model for tearing-relaxation recently extended to include two-fluid effects

- Nonlinear multi-mode evolution solved using NIMROD

\[
E = \mathbf{V} \times \mathbf{B} + \frac{1}{n_e} \mathbf{J} \times \mathbf{B} - \frac{1}{n_e} \nabla p_e + \mathbf{J} + \frac{m_e}{n_e^2} \frac{\partial \mathbf{J}}{\partial t}
\]

\[
m I \frac{dN}{dt} = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \times \mathbf{P}_{gyro} - \nabla \times n I \mathbf{W}
\]

New understanding: relaxation couples electron and ion momentum balance
Both MHD and Hall dynamo terms are measured large in MST

Turbulent emf during sawtooth relaxation event

\[ \langle \mathbf{j} \times \mathbf{b} \rangle_{\parallel} \]

\[ \langle \mathbf{v} \times \mathbf{b} \rangle_{\parallel} \]

Probe measurements in outer region

\[ q = 0 \]

\[ r/a \]

\[ V/m \]
The Reynolds and Maxwell stresses burst to huge amplitudes during relaxation events, tending to cancel
Stochastic Transport and Paths to Improved Confinement
Multiple tearing modes cause the magnetic field to become stochastic.
Stochastic transport in the collisionless limit

Consider a test particle streaming along a stochastic magnetic field

Magnetic field diffusion…

\[ \langle (r)^2 \rangle = D_m \ s \]

average radial displacement associated with field line diffusion

\[
D_m = \frac{\langle (\Delta r)^2 \rangle}{\Delta s} = \frac{\int_0^\infty \tilde{B}_r(0) \tilde{B}_r(s) \, ds}{B_0^2}
\]

… compounds collisional diffusion

\[
\chi_{st} = \frac{\langle (\Delta r)^2 \rangle}{\Delta t} = \frac{D_m \lambda_{mfp}}{\tau_c} = D_m v_T
\]

(case for \( mfp >> L_{ac} \))

Rechester & Rosenbluth, ’78 and others
Electron heat conduction in standard MST plasmas is close to expectations for stochastic transport

- Test particle picture works well when $D_m$ is evaluated directly from field line trajectories
Keen interest in the scaling of the magnetic fluctuation amplitude with Lundquist number and magnetic Prandtl number

- Lundquist number, $S = \tau_R / \tau_A \sim I_p T_e^{3/2} / n^{1/2}$, and Prandtl number, $P = \nu / \eta$, are the key dimensionless parameters in visco-resistive MHD.
- Renewed $S$-scaling studies are underway on MST, motivated by goals for validation studies and improved measurement capability, e.g., $Z_{\text{eff}}$.

...but $Z_{\text{eff}}$ in these measurements is known to be inaccurate

\[
S_{anom} = \frac{v_{\text{eff}} L}{\alpha R}
\]

Stoneking et al, PoP '98
Two paths to improved confinement in the RFP

Standard RFP
(many tearing modes)

Current Profile Control

Single-Helicity Self-organization
Spontaneous helical equilibrium creates stellarator-like plasmas in RFP experiments, studied extensively in RFX-Mod

- Tendency for quasi-single-helicity (QSH) appears at high current and high temperature

\[ \frac{\tilde{B}_{\text{helical}}}{B} = 2\% \]

\[ \frac{\tilde{B}_{\text{helical}}}{B} = 5\% \]

Magnetic Island

Helical Equilibrium

n=7 mode in RFX-Mod
MST produces large helical modes and has capable diagnostic set to measure 3D effects

- Growing collaborations with the stellarator community, e.g., opportunity to develop 3D equilibrium reconstruction methods and tools such as V3FIT
- MST diagnostics for equilibrium reconstruction:
  - Interferometry/Faraday rotation, MSE, 2-color SXR, Thomson scattering

\[ \frac{\tilde{B}_{helical}}{B} = 7\% \]
Understanding the dependence on plasma current in accessing the quasi-single-helicity (QSH) regime

- Lundquist number appears to be a unifying parameter for QSH transition

\[ S = \frac{R}{A} \sim I_p T_e^{3/2} n^{1/2} \]

\[ \tilde{B}_n / B \]

**Lundquist Number, \( S \)**

- \( S = 6 \times 10^5 \)
- \( S = 7 \times 10^6 \)

**Lundquist Number**

**Dominant Mode**

**Secondary Modes**

**\( I_p = 0.5 \text{ MA} \)**

- **RFX**
- **1.3 MA**

- **MST**
- **0.6 MA**

**\( I_p = 0.2 \text{ MA} \)**
Inductive pulsed poloidal current drive (PPCD) provides simple current profile control of tearing

- 30-fold decrease in $\chi_e$ at mid-radius
- 10-fold increase in global energy confinement
A simple Ohm’s law is attained with inductive control

**Standard Self-Organized**

- **Current Profile Control**

- **Strong dynamo**
  - $E_{||}$, $J_{||}$

- **Weak dynamo**
  - $E_{||}$, $J_{||}$
Confinement is (transiently) comparable to that for a tokamak with the same size and field strength

- Use same $\langle B \rangle$, $n$, $P_{\text{heat}}$, size, shape to define a tokamak reference via scaling
Ion Physics
Powerful ion heating occurs during the sawtooth crash

A large fraction of the magnetic energy released by reconnection is transferred to the ions

\[ T_i > T_e \]

\[ \Delta t \sim 100 \, \mu s < < e-i \text{ equil. time} \]

Clearly the ion heating mechanism is not collisional
Impurity ions are hotter, and the heating is anisotropic

- Key diagnostics:
  - Rutherford scattering for majority ions
  - Charge-exchange recombination spectroscopy (CHERS) for minority ions
  - Neutral particle energy analyzers for ion distribution
Heating depends on mass and charge.

Majority Ions

\[ \frac{E_{\text{ion}}}{E_{\text{mag}}} \]

- \( H^+ \)
- \( D^+ \)
- \( \text{He}^{++} \)

Minority Ions

- \( \Delta T \) (eV)
- \( Z/\mu \)

(varied fueling gas)
Spontaneous energetic ion tail is generated during the sawtooth crash

- Ion distribution is well-fit by a Maxwellian plus power-law tail
- D-D neutron measurements imply tail extends to $\gg 5$ keV

$$f_{D^+}(E) = A \ e^{-E/kT} + B \ E^{-\gamma}$$
PPCD timed to immediately follow especially large sawteeth confines the ion heat and helps maximize beta.
Impurity evolution reveals improved particle confinement and outward particle convection

- PPCD plasmas hot enough to burn through carbon in most of the plasma volume

![Graph showing fully-stripped carbon with improved confinement](image1)

![Graph showing Fast Thomson measurements capturing rapid increase in $T_e$](image2)

(10x514)
The minimal perpendicular collisional diffusion is classical in the RFP, despite its toroidal geometry.

Note: neoclassical modifications to parallel transport not negligible.

In the RFP:

The magnetic line of force is described in sec. 2.5 (The mirror ratio is \( \frac{1}{\nu} \).

The following relations hold, we find

\[
B = B_0 \left(1 + \frac{\nu}{\nu_p} \cos(kl) \right)
\]

The parallel motion of the guiding center is given by (see sec. 2.4).

### 3 Magnetic Configuration and Particle Orbit

#### 3.0

The trapped particle, the particle is trapped outside in the weak region of the magnetic field due to the mirror effect.

As the number of trapped electrons is \( \nu \), the condition;

\[
\nu = \frac{v}{R}
\]

This diffusion coefficient, introduced by Galeev-Sagdeev, can be used to describe the diffusion of plasma.

### 7 Diffusion of Plasma, Confinement Time

Fig. 7.3 Dependence of the diffusion coefficient on collision frequency in a tokamak.
Classical confinement of impurity ions when tearing is suppressed in PPCD plasmas

- Modeling of collisional coupling of multiple ions used for detailed comparison with measurements

\[
\frac{n_Z(r)}{n_Z(0)} = \frac{n_i(r)}{n_i(0)} \frac{Z T_i(r)}{T_i(0)}
\]

Classical profile

\[
\frac{n_Z(r)}{n_Z(0)} = \frac{n_i(r)}{n_i(0)} \frac{Z T_i(r)}{T_i(0)}
\]

Neo-classical profile (if MST was a tokamak)
Energetic Ion Physics and Ion Runaway During Sawteeth
<table>
<thead>
<tr>
<th>NBI Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>25 keV</td>
</tr>
<tr>
<td>Beam power</td>
<td>1 MW</td>
</tr>
<tr>
<td>Pulse length</td>
<td>20 ms</td>
</tr>
<tr>
<td>Composition</td>
<td>97% H, 3% D</td>
</tr>
<tr>
<td>Energy fraction</td>
<td>86%:10%:2%:2%</td>
</tr>
</tbody>
</table>
Energetic ion confinement is near-classical, even in standard RFP plasmas despite stochastic field.

- Ion motion deviates from electron motion due to $\nabla B$ and curvature drifts, and possibly orbit-averaging of fluctuations ($\rho_{fi, 25\text{keV}}/a \sim 0.2$)
First observations of energetic ion modes by NBI in an RFP, and transport from multiple-mode interactions

- Several bursting modes observed, that are nonlinearly coupled.
The fast ions are energized during the sawtooth reconnection event.
Abrupt change in the equilibrium magnetic field induces a large-scale inductive electric field.
The inductive electric field (~ 50 V/m) is sufficiently large to consider runaway process

- Test particle analysis (Furth and Rutherford, PRL '72):

\[ m \frac{dv}{dt} = qE^* - F \]

\[ E^* = E \cdot \left(1 - \frac{Z}{Z_{eff}}\right) \cdot f\left(\frac{n_{e}^{tr}}{n_e}\right) \]

\[ \frac{E^*}{E} \approx 80\% \text{ in MST} \]
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- Test particle analysis (Furth and Rutherford, PRL ’72):

\[ m \frac{dv}{dt} = qE^* - F \]

\[ E^* = E \cdot \left(1 - \frac{Z}{Z_{eff}}\right) \cdot f \left(\frac{n_e^{tr}}{n_e}\right) \]

\[ \frac{E^*}{E} \simeq 80\% \text{ in MST} \]

![Diagram showing friction on test ion with electric field levels before and after an event.](25 keV neutral beam injection)
Energy gained increases as the fast ion’s initial energy is increased (adjusted by the NBI voltage)
Energy gain is consistent with runaway acceleration

Density $\sim 0.5 \times 10^{13}$ cm$^{-3}$ (peak $E_\parallel \sim 60$ V/m)

Prediction for runaway using expt. parameters
RFP Fusion Perspectives
In the magnetic fusion context, the RFP is best known as a high beta, compact fusion reactor option

- Since 1990, the TITAN system study has provided an RFP development target
- TITAN concept has attractive/novel features:
  - Steady-state, via oscillating field current drive
  - High core radiation for power handling, uniform on first wall surface
  - Single-piece maintenance
  - Low cost-of-electricity (COE) projection

**TITAN Parameters**

- $a = 0.6$ m
- $R = 3.9$ m
- $I = 18$ MA
- $\beta_0 = 23\%$
- $\tau_E = 0.15$ s
- 2300 MW fusion
- 970 MW net elec.
TITAN is very compact … on purpose, to assess the potential benefits of a compact fusion power core

TITAN wall loading:
• 18 MW/m² neutrons
• 4.6 MW/m² radiation
System analysis indicates cost-of-electricity (COE) varies weakly above a threshold wall loading $P_n/A \sim 5\ \text{MW/m}^2$.

- COE levels out when the plasma minor radius is about the same as the blanket thickness (~1 m), a generic result for MFE.

Scaling TITAN to an ARIES-like size with $P_n / A \sim 5 \text{ MW/m}^2$

- Power scalings, taking $T$ fixed ($\sim 10\text{-}15$ keV)

$$P_{\text{fusion}} \sim n^2 V \sim n^2 a^2 R \sim 2B^4 a^2 R \sim 2I^4 R / a^2 \sim \frac{2I^4}{a^3} \frac{R}{a} a^2$$

$$P \sim I^2 R / a^2 \text{ (ohmic heating)}$$

- Scale with fixed $P_{\text{fusion}}$ and fixed temperature to ARIES-like wall load (5 MW/m$^2$)

<table>
<thead>
<tr>
<th></th>
<th>$R / a$</th>
<th>$P_n / 4\pi^2 a R$</th>
<th>$I_p$</th>
<th>$B(a)$</th>
<th>$n / n_G$</th>
<th>$\beta_0$</th>
<th>$P_\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITAN</td>
<td>3.9 / 0.6 = 6.5</td>
<td>20 MW/m$^2$</td>
<td>18 MA</td>
<td>6.0 T</td>
<td>0.63</td>
<td>22%</td>
<td>30 MW</td>
</tr>
<tr>
<td>ARIES-like</td>
<td>6.1 / 1.53 = 4.0</td>
<td>5 MW/m$^2$</td>
<td>30 MA</td>
<td>3.9 T</td>
<td>0.5 T=13 keV</td>
<td>15%</td>
<td>20 MW</td>
</tr>
<tr>
<td>$R/a = 4$</td>
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</table>

Consistent with analysis using TITAN system code
A comment on “fusion power goes like $B^4$”

- A common phrase in MFE, just the simple point:

$$P_{fusion} \sim n^2 V \sim \frac{n^2}{B^4} \frac{\langle B \rangle}{B^4} \sim 2B^4 V$$

- $B^4$ really defines a threshold magnetic field $\langle B \rangle \sim 5$ T for a reactor plasma
  - a little smaller $\Rightarrow$ not enough reactivity
  - a little bigger $\Rightarrow$ rapid increase in fusion power density & wall loading
  - Importantly, higher $B$ permits lower $\beta$ (an option for robust stability)

$$B^4 \sim \frac{P_{fusion}}{2V} \sim \frac{P_{fusion}}{A} \div \frac{1}{2a} \quad \Rightarrow \quad B \sim \frac{P_{fusion}}{A} \div \frac{1}{2a}^{1/4}$$

Hence $\langle B \rangle \sim 5$ T for any magnetic configuration, c.f., ARIES

The RFP’s advantage is $B_{coil} / \langle B \rangle < 1$
Ohmic heating (Lawson-like) power balance for ARIES-like RFP

- 1D profiles similar to present-day RFP assumed
- $a = 1.5$ m, $R/a = 4$, $I_p = 30$ MA, $\langle B \rangle = 5.6$ T, $B_{coil} \sim 3$ T, $P_n/A \sim 5$ MW/m$^2$, $P_{fusion} = 2.3$ GW

$$J/B \sim 1 \quad r^4$$
$$T \sim 1 \quad r^2, \quad n \sim 1 \quad r^8$$
$$Z_{eff} = 2, \quad Z_{neo} = 2$$
Ohmic ignition is possible in the RFP if energy confinement is similar to that of a tokamak.

Global Energy Confinement, $\tau_E$ (s)

- "ITER-like" means scaled as $\tau_E \sim \kappa a^2$
Summary

• MST program – a synergy of efforts that
  – Advance the RFP
  – Advance the science of toroidal confinement
  – Advance basic plasma physics

• Excellent progress in understanding key physics
  – Tearing and magnetic relaxation
  – Stochastic transport physics
  – Multiple paths to improved confinement
  – Emerging story on drift-waves, not covered here

• Understanding of ion physics is maturing
  – Heating characteristics more detailed than ever, but underlying mechanism(s) still elusive
  – Classical impurity ion confinement when tearing is reduced
  – Classical energetic ion confinement allows building fast ion pressure
  – NBI-driven EP modes observed for the first time in an RFP, which appear to limit the local fast ion pressure
MST and the world RFP program have achieved the Proof-of-Principle metrics that were established in 1998

- Proof-of-principle initiated in 2000, with a ramp of funding over several years

**RFP Proof-of-Principle Research Program**

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<tr>
<th>ISSUE</th>
<th>ACTIVITY</th>
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<tbody>
<tr>
<td>Confinement</td>
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<td>( \tau_E &gt; 10 \text{ ms} )</td>
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<td></td>
<td>• ( J(r) )-Control <em>(MST, others?)</em></td>
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<td>• Control <em>(exploratory concept expts.)</em></td>
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<tr>
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<td>• Test Oscillating Field Current Drive <em>(MST, others?)</em></td>
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**DECISION 2004**

High Current / Long Pulse Experiment
and/or
Advanced Control Experiments
or
Reduced RFP Research

Supporting Plasma Physics Theory & Expt.

**Figure 6.** World-integrated RFP proof-of-principle research program.
MST and the world RFP program have achieved the Proof-of-Principle metrics that were established in 1998

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<td>Configurations</td>
<td>• Optimize Geometry: shape, $R/a$, etc.</td>
<td></td>
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<tr>
<td></td>
<td>(exploratory concept expts.)</td>
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<tr>
<td>System Studies</td>
<td>• Renew with Advanced RFP Concepts</td>
<td></td>
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</tbody>
</table>

**Achieved:**
- 12 ms
- $T_e \sim 2$ keV, $T_i \sim 1$-2 keV
- 26%, with pellet injection
- Stable by active control
- 0.1 A/W, 10% drive
- Standard confinement
- New experiments estab.
- (near zero effort)

*Figure 6. World-integrated RFP proof-of-principle research program.*
Excellent progress warrants planning for a next-step RFP

- Build on progress in last decade in improved confinement, control of resistive wall modes, and demonstrated high beta.
- MST is not saturated in its capabilities, while RFX shows transformational new trends at high current.
- Resolution of high priority issues in confinement and sustainment requires higher current, longer pulse length.

<table>
<thead>
<tr>
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<th>ITER Era</th>
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<tbody>
<tr>
<td><strong>MST</strong></td>
<td>≥ 0.6 MA, maximize capability (U-profile control, energetic ions, limited OFCD, limited boundary)</td>
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<tr>
<td><strong>RFX</strong></td>
<td>2 MA, single helicity, active feedback control</td>
</tr>
</tbody>
</table>

Conceptual development path for the RFP, output from TAP/ReNeW.

**Advanced PoP**

- **Performance Extension**
  - **Design**
  - **Upgradable Facility Approach**
    - 2-4 MA Advanced PoP (S-scaling, long pulse profile control, OFCD)
    - ≥ 4 MA, integration with boundary control, shaping

- **CE 1**
  - Geometric Optimization (shape, R/a, …)

- **CE 2**
  - Advanced Boundary Control (low recycling wall, divertors, …)

**Extrap-T2R, now KTX**