Opportunities and Context for Reversed Field Pinch Research

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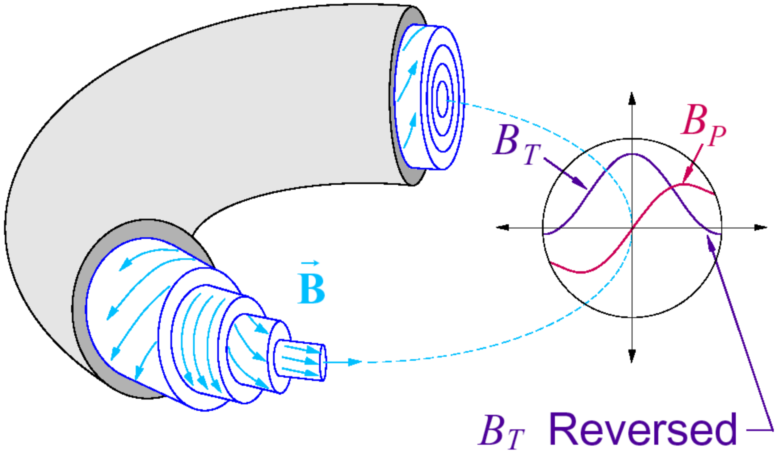
and

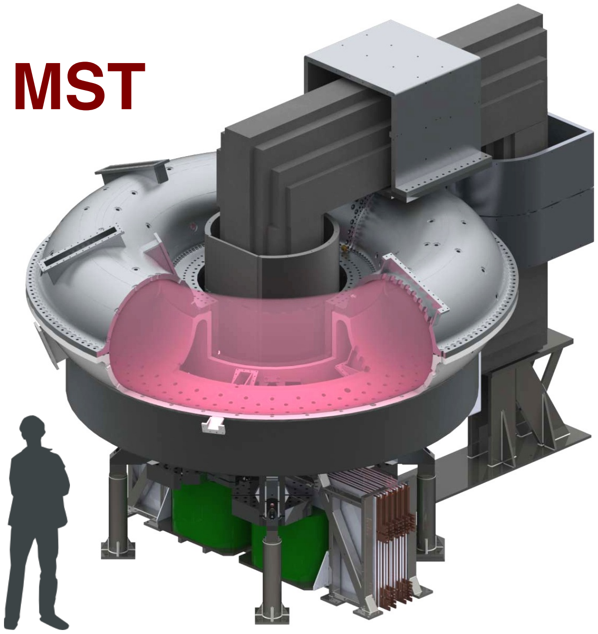
Collaborators

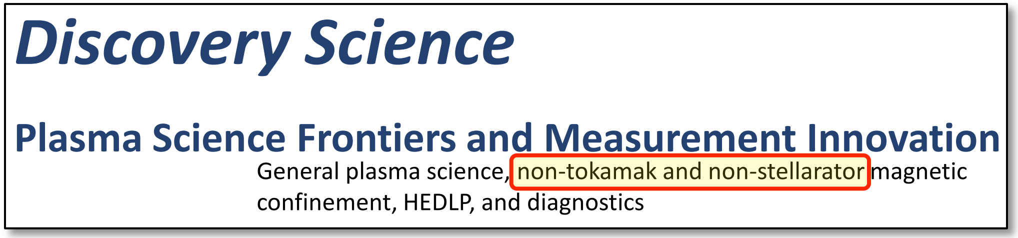
FESAC Strategic Planning Meeting • Gaithersburg, MD • June 5, 2014

The Reversed Field Pinch magnetic configuration

- Magnetic field is generated primarily by the plasma current
- Small externally applied field:
  - Advantages for fusion: ohmic ignition, minimized field at magnet surfaces
  - Explores complementary parameter space w.r.t. the tokamak and stellarator, e.g., large magnetic shear and weaker toroidicity
  - Basic science: magnetic self-organization and connections to astrophysics






Discovery Science

Plasma Science Frontiers and Measurement Innovation

General plasma science, non-tokamak and non-stellarator magnetic confinement, HEDLP, and diagnostics

E. Synakowski, FESAC, Apr 9, 2014

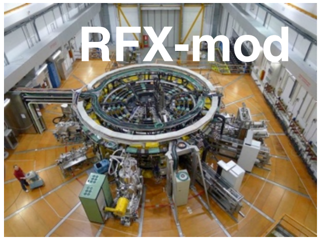
MST research (and RFP generally) is highly collaborative, with ~ 60 researchers involved

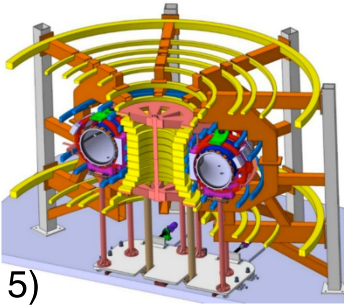
- UCLA – advanced interferometry, Faraday rotation, studies of confinement and magnetic self-organization
- Xantho Technologies – heavy ion beam probe, studies of electrostatic turbulence and transport
- Wheaton College, IL – advanced spectroscopic diagnostics, studies of magnetic self-organization
- LANL – RFP theory, CMSO
- ORNL – RFP theory (energetic ion physics, 3D equilibrium physics)

collaborators with FES funding under “MST Research” umbrella

- Conzorio RFX, Italy (RFX-mod) – joint RFP experiments
- Royal Institute of Technology, Sweden (Extrap-T2R) – joint RFP experiments
- Kyoto Institute of Technology, Japan (RELAX) – joint RFP experiments, validation studies
- University of Science and Technology, China (KTX) – development of new RFP program
- Budker Institute, Russia – neutral beam-based diagnostics and heating: MSE on GDT
- Florida A&M University – neutral particle analyzer, magnetic turbulence
- Auburn University – V3FIT 3D equilibrium reconstruction
- University of Strathclyde, Scotland – atomic modeling, ADAS
- CompX, Inc. – Fokker-Planck modeling
- General Atomics – Thomson scattering, plasma control system
- National Institute for Fusion Science, Japan – fast Thomson scattering
- University of Chicago – links to astrophysics, CMSO
- Princeton U and PPPL – links to astrophysics, CMSO
- Swarthmore College – links to astrophysics, CMSO
- Pegasus, HSX (UW-Madison)– diagnostics, EBW
- UW Astronomy – CMSO

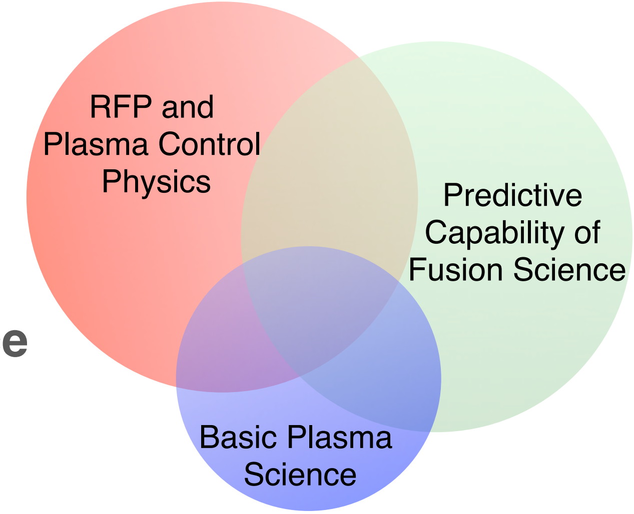
Other RFP Expts





KTX
USTC, Hefei
(1st plasma 2015)

Three synergistic research mission goals capture 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

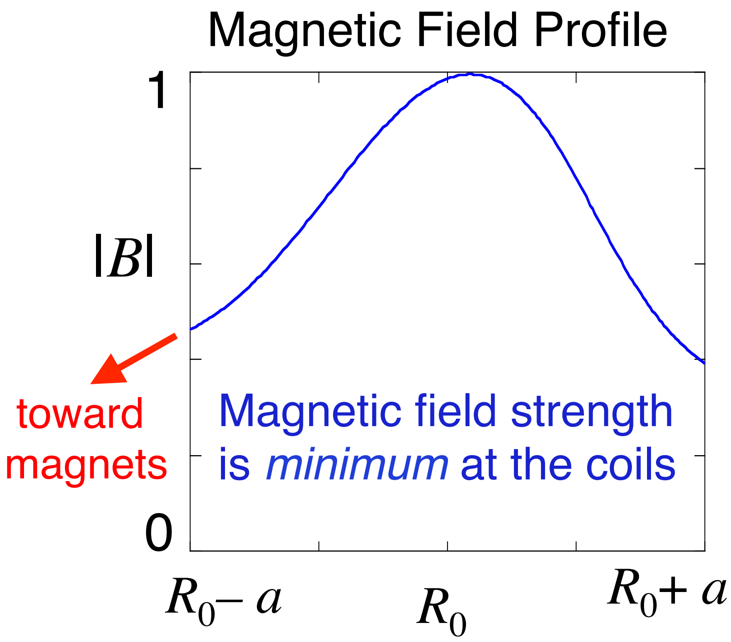
- **Advance the predictive capability of fusion science**
  - Physics closely related to tokamak and stellarator, leveraged by RFP geometry
  - Validation of key physics models and codes
  - Development and application of advanced diagnostics

- **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

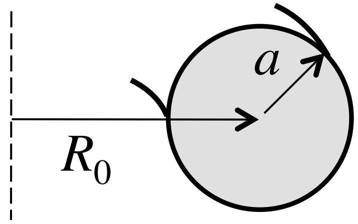
- Small field at the magnets ➡ copper possible
  - 1/10th the magnetic pressure at the magnets compared to high safety factor (e.g., tokamak)
  - $\dfrac{B_{\mathrm{coil}}}{\langle B \rangle} \sim \dfrac{2}{3}$ (*and* $B_{\mathrm{T,coil}} \longrightarrow 0$)
  - Large fusion beta demonstrated:
  - $\beta_{\mathrm{fusion}} \sim \langle p \rangle / B^2_{\mathrm{coil}} = 28\%$, $\langle \beta \rangle = 10\%$

- Large plasma current density
  - Ohmic ignition is possible
    - ➡ No plasma-facing auxiliary heating components
  - High particle density limit, $n_{\mathrm{GW}} \sim I_{\mathrm{p}} / \pi a^2$


Magnetic Field Profile

toward magnets

Magnetic field strength is *minimum* at the coils



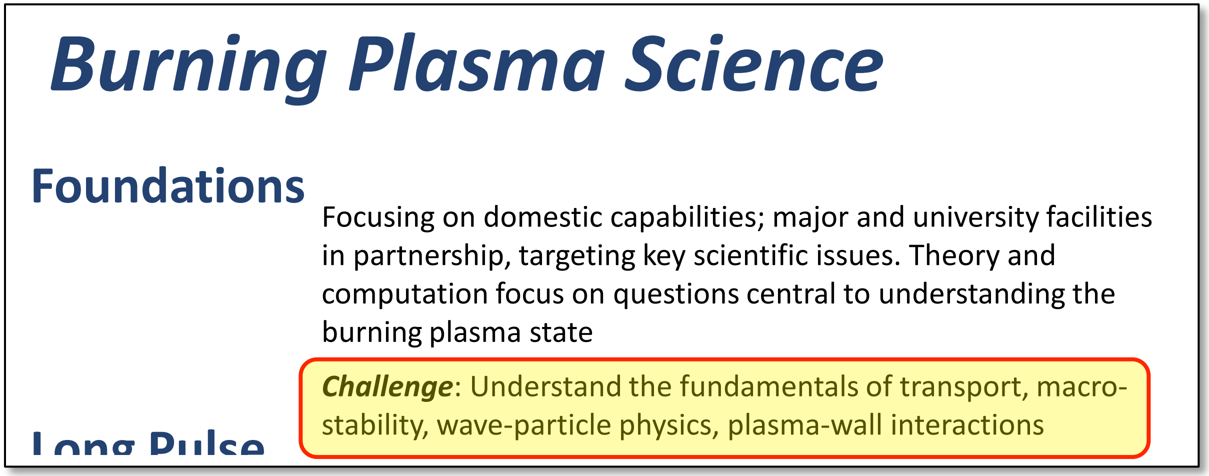
These features promote the reliability and maintainablity of a fusion power system

Resolution of the key scientific issues for the RFP advances fundamental understanding of fusion science more generally

- Prioritized issues for the RFP identified in FESAC TAP and ReNeW:

MST research is directed at these

  - Identify transport mechanisms and establish confinement scaling
  - Current sustainment
  - Integration of current sustainment and improved confinement
  - Plasma boundary interactions
  - Energetic particle effects
  - Determine beta-limiting mechanisms
  - Active control of MHD instabilities ⬅ European RFP's have made tremendous progress in RWM control
  - Self-consistent reactor scenarios



Burning Plasma Science

Foundations

Focusing on domestic capabilities; major and university facilities in partnership, targeting key scientific issues. Theory and computation focus on questions central to understanding the burning plasma state

Challenge: Understand the fundamentals of transport, macro-stability, wave-particle physics, plasma-wall interactions

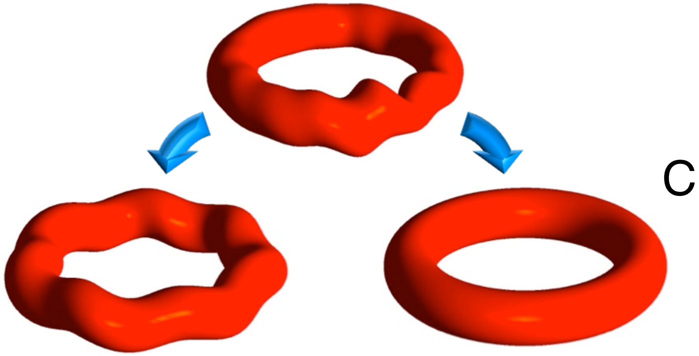
Long Pulse

RFP scientific issues are similar to those for the tokamak and stellarator

E. Synakowski
FESAC, Apr 9, 2014

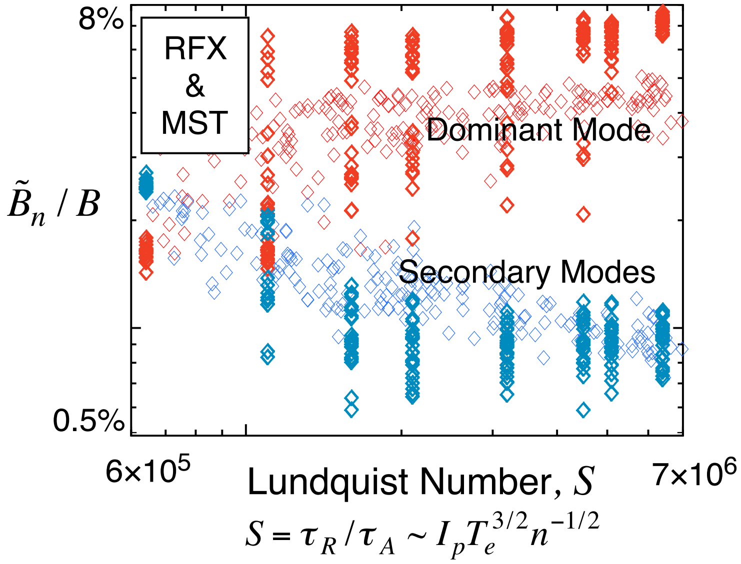
Understanding transport processes and plasma control are major themes in current RFP research

- Minimize tearing instability and magnetic transport using inductive profile control
- Optimize the stellarator-like spontaneous 3D helical equilibrium

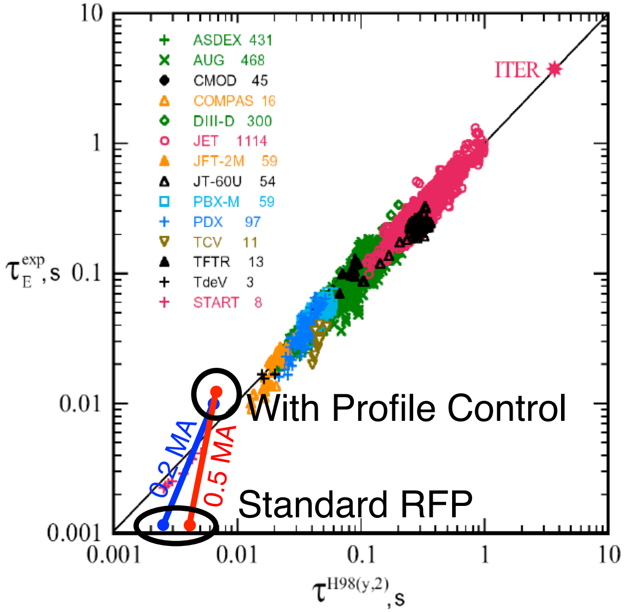


3D Helical Equilibrium

Current Profile Control



Transition to 3D Equilibrium



Tokamak-like Confinement in MST

RFP research advances predictive fusion science

- Important physics processes advanced through experiment, theory, and modeling
  - Transport in a stochastic magnetic field
  - Transport from electrostatic turbulence at low q with reversed magnetic shear
  - 3D effects, particularly the stellarator-like quasi-single-helicity regime
  - Density and beta limiting mechanisms
- Advanced diagnostic development has broad impact, e.g., FIR polarimetry, pulse-burst Thomson scattering, HIBP
- Validation of models and codes
  - Nonlinear MHD and extended MHD (e.g., NIMROD)
  - MHD with kinetic effects from energetic particles
  - Micro-instabilities and gyrokinetics (e.g., GENE)

Opportunities noted in recent planning documents:

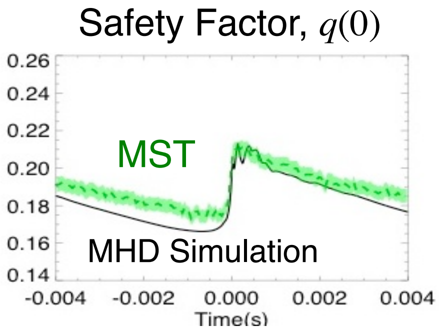
- ReNeW, especially Thrust 6, “*Develop predictive models for fusion plasmas…*”
- *“Report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Sciences Program”*, R. Rosner, et al, 2013

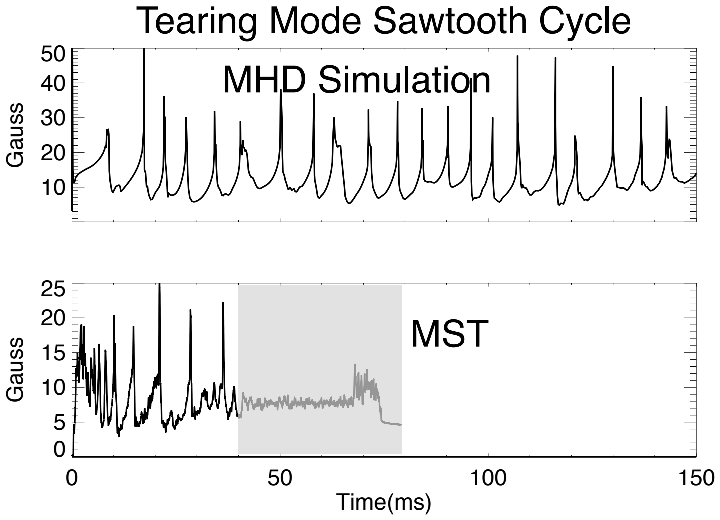
Excellent opportunities for validation of important physics models and codes

- Nonlinear, visco-resistive MHD is ripe for rigorous validation

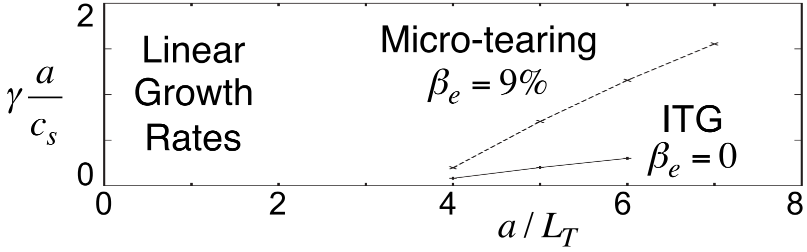
MST's advanced diagnostic set provides crucial data

Control tools yield several distinct operating regimes

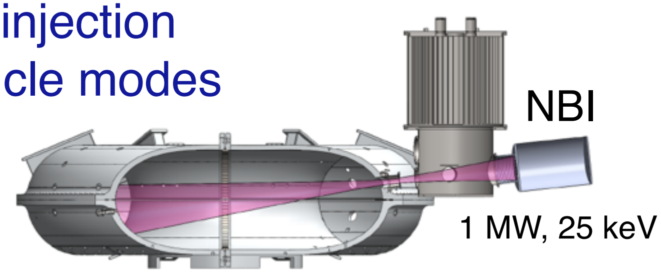


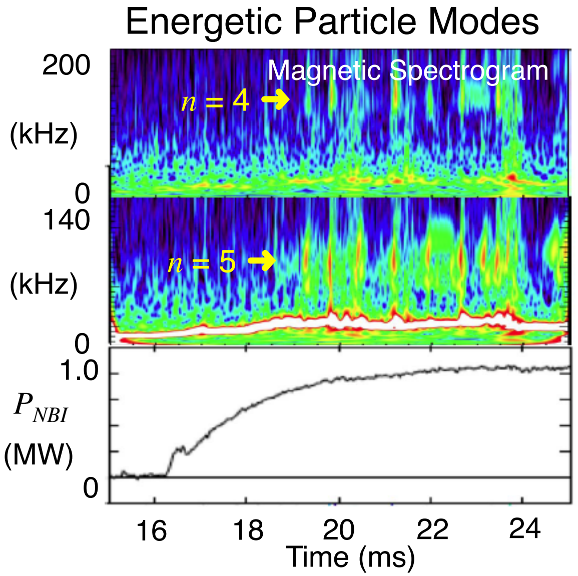


- Investigation of high-k instabilities is already challenging established theory and modeling



- MST's neutral beam injection drives energetic particle modes (unique for RFP)

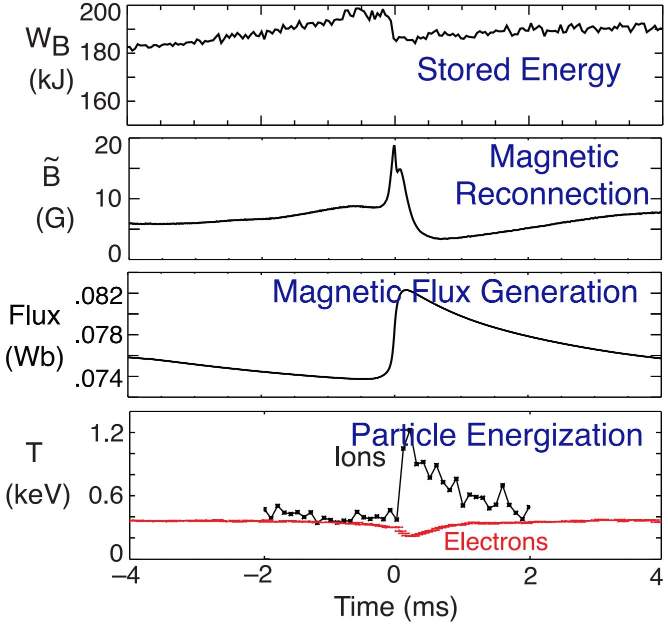




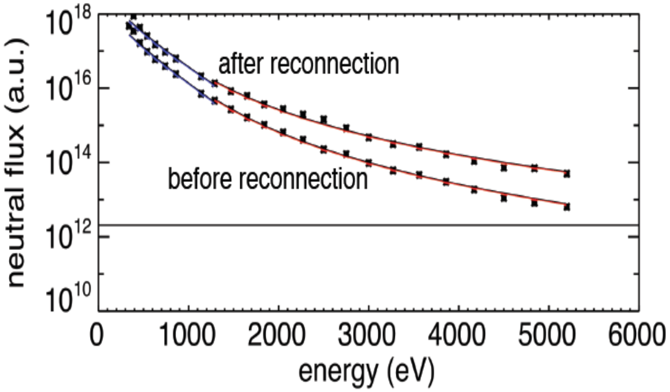
RFP behavior has been a major inspiration for the basic plasma physics concept of magnetic self-organization

- Processes are important in plasma astrophysics: magnetic reconnection, particle energization, magnetic turbulence, dynamo and momentum transport

Bursty reconnection is common (the “onset” problem)

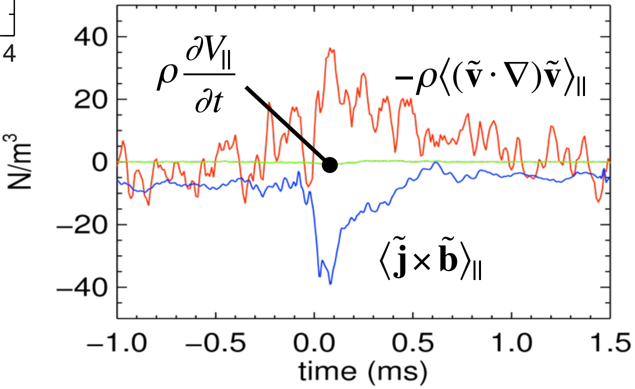


Energetic ion tail in MST is reminiscent of non-thermal features in astrophysical settings



Taylor-like relaxation of both electron and ion momentum

Measured Turbulent Stresses



Extended MHD Model

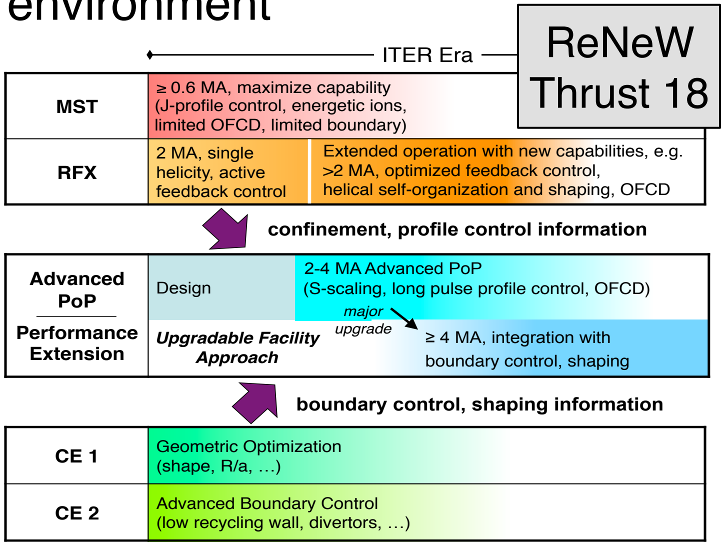
$$\mathbf{E} = -\mathbf{V}\times\mathbf{B} + \tfrac{1}{ne}\mathbf{J}\times\mathbf{B} - \tfrac{1}{ne}\nabla p_e + \eta\mathbf{J} + \frac{m_e}{ne^2}\frac{\partial \mathbf{J}}{\partial t}$$

$$nm_i\frac{d\mathbf{V}}{dt} = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\Pi_{gyro} - \nabla\cdot\nu nm_i\mathbf{W}$$

Exemplar opportunity for validation of single-fluid and extended MHD codes

Recommendation and outlook for RFP research

- A vigorous program (experiment, theory, computation) is needed to maintain U.S. leadership in RFP research and exploit MST's unique capabilities
  - A 5-year renewal proposal was submitted to FES in April
  - Rigorous validation, in particular, demands well-diagnosed, well-controlled plasmas and strong collaboration with theory and computation (current resources marginal)
  - Current MST Research funding of $5.7M is 20% smaller than the $7M level in FY 2011
- Modest investments can bring the MST facility to its intrinsic limits
  - Programmable power supplies to optimize inductive control (high leverage in the RFP)
  - Support for advanced diagnostics to enable rigorous validation (hardware, personnel)
- MST/RFP creates a fantastic environment for mentoring graduate students and postdocs, best done in a state-of-the-art research environment
- Planning for a next-step RFP should begin now:
  - Proof-of-principle metrics (1998) are achieved
  - Higher current is required to resolve key issues
  - Near-term emphasis on validation will continue to strengthen the scientific basis
  - Rudimentary development path is discussed in FESAC TAP and ReNeW Thrust 18



ReNeW Thrust 18

ITER Era

MST

≥ 0.6 MA, maximize capability (J-profile control, energetic ions, limited OFCD, limited boundary)

RFX

2 MA, single helicity, active feedback control

Extended operation with new capabilities, e.g. >2 MA, optimized feedback control, helical self-organization and shaping, OFCD

confinement, profile control information

Advanced PoP

Design

2-4 MA Advanced PoP (S-scaling, long pulse profile control, OFCD)

major upgrade

Performance Extension

Upgradable Facility Approach

≥ 4 MA, integration with boundary control, shaping

boundary control, shaping information

CE 1

Geometric Optimization (shape, R/a, …)

CE 2

Advanced Boundary Control (low recycling wall, divertors, …)