Overview of the RFX-mod Fusion Science Program

P. Martin, M.E. Puiatti and the RFX Team & Collaborators

Overview of Results from the MST Reversed Field Pinch Experiment

J. Sarff and the MST Team & Collaborators

CONSORZIO RFX

MST

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

24th IAEA FEC Conference • San Diego, CA USA • Oct 8-13, 2012

RFX-mod and MST Collaborators

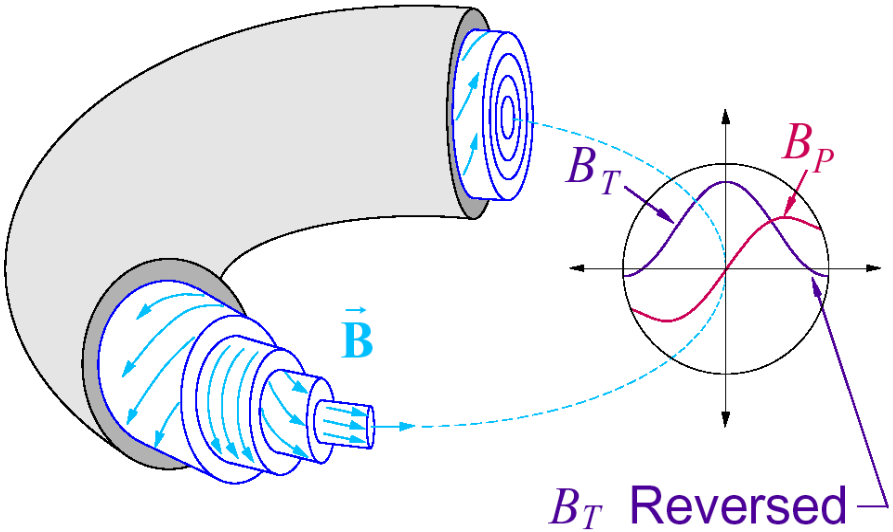
- Université de Provence, France
- Max-Planck-Institut für Plasmaphysik, Germany
- Centro Ricerche Energia ENEA Frascati, Italy
- CNR-IENI, Padova, Italy
- CNR-IFP, Milan, Italy
- CREATE, DAEIMI, Università di Cassino, Italy
- BINP, Novosibirsk, Russia
- Laboratorio Nacional de Fusión, Madrid, Spain
- Universidad Carlos III de Madrid, Spain
- KTH, Stockholm, Sweden
- EPFL, Lausanne, Switzerland
- EURATOM/CCFE Fusion Association, UK
- AIST, Tsukuba, Japan
- JAEA, Naka, Japan
- Department of Physics, Nankai University, PRC
- IFTS, Zhejiang Univ, SWIP, PRC
- USTC, Hefei, PRC
- Auburn University, AL, USA
- CompX, Del Mar, CA, USA
- FAR-TECH, Inc., San Diego, USA
- Florida A&M, FL, USA
- General Atomics, USA
- LLE, University of Rochester, NY, USA
- Los Alamos National Laboratory, USA
- Oak Ridge National Laboratory, USA
- Princeton Plasma Physics Laboratory, USA
- UCLA, Los Angeles, CA, USA
- Wheaton College, IL, USA
- Xantho Technologies, Madison, WI, USA

Progress in RFP research

- Assessing the RFP's fusion potential and understanding key physics
  - High current and accessibility to the quasi-single-helicity regime
  - Classical confinement of impurity and energetic ions
  - Intrinsic rotation and momentum transport
  - Validation of nonlinear MHD models
  - Improved active control
- Connections to tokamak and stellarator research
  - Similar physics in different parameter regimes, e.g., micro-turbulence
  - 3D equilibrium reconstructions using a variety of diagnostics
  - Advanced wall coatings for improved density and impurity control
  - Novel tokamak experiments in RFP devices, e.g., $q(a) < 2$
- New RFP program in China
  - University of Science and Technology, Hefei (another university setting)
  - Construction in collaboration with EAST team

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

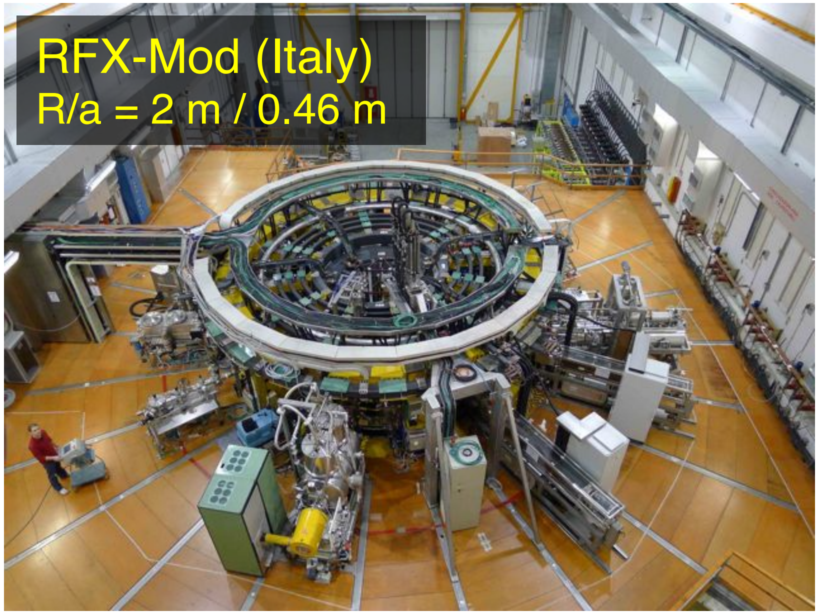
- Small field at the magnets, allows choice for normal conductors
  - 1/10th the magnetic pressure at the magnets than for a tokamak
  - Very high $\beta_{eng} \sim \langle p \rangle / B_{\max}^2$

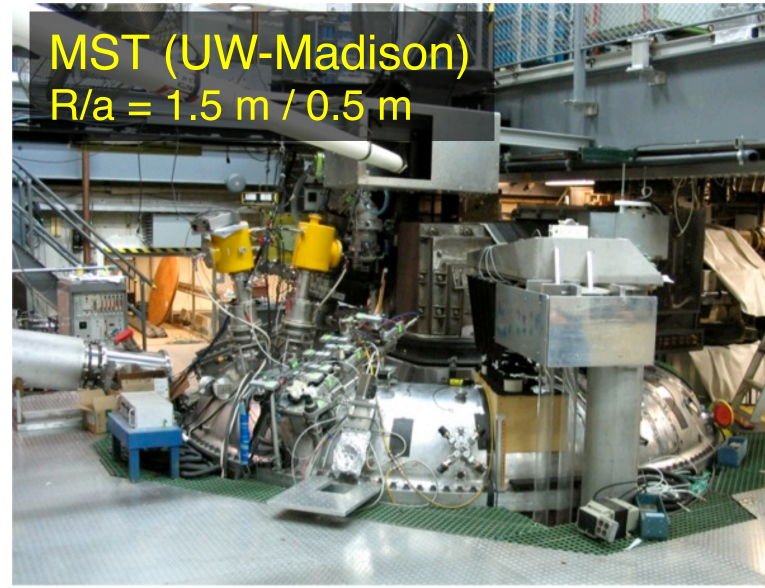


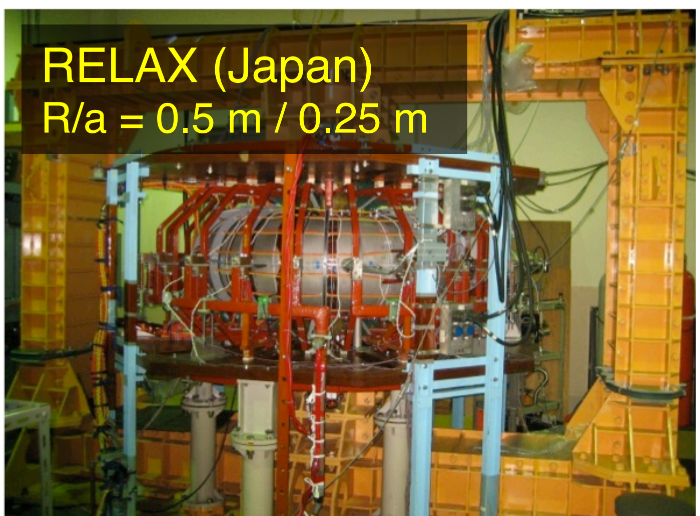
- Large plasma current density
  - Ohmic heating to burning plasma conditions is possible
  - Minimal or no plasma-facing auxiliary heating components
  - High particle density limit ($n_G \sim I_p / a^2$)

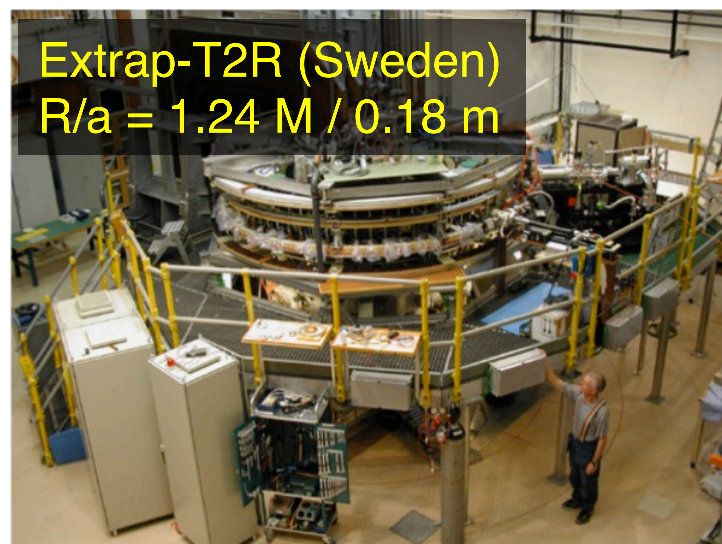
- These advantages promote the reliability and maintainability of a fusion system

World’s RFP experiments









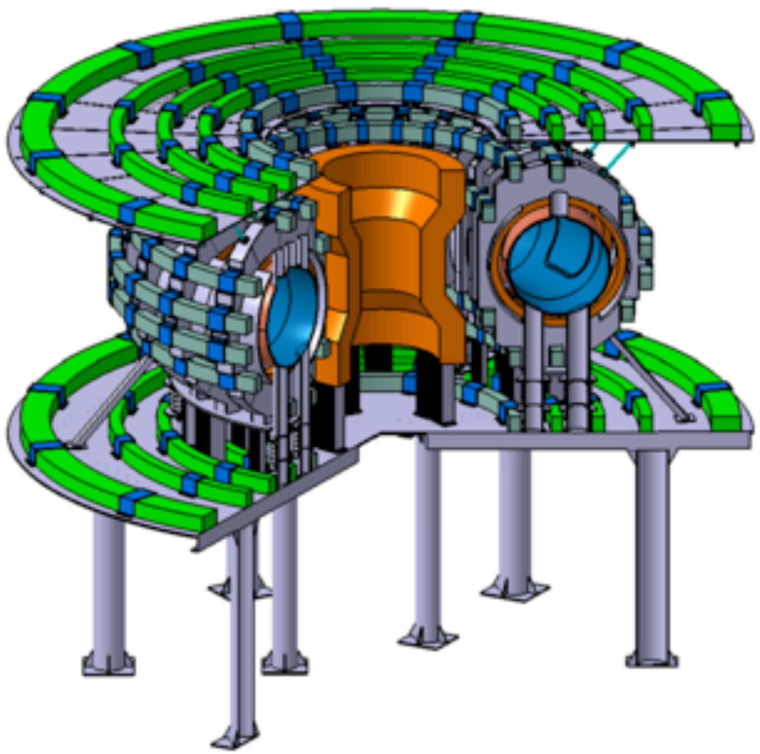
New RFP program at USTC in PRC is aimed at important issues for both the RFP and toroidal confinement generally

- Project authorized in August, 2011
- Shell system that facilitates plasma-boundary studies, e.g., rapid entry
- Advanced active mode control (Phase 2)
- Construction in collaboration with EAST team

Keda Toroidal Experiment (KTX)
USTC, Hefei, PRC

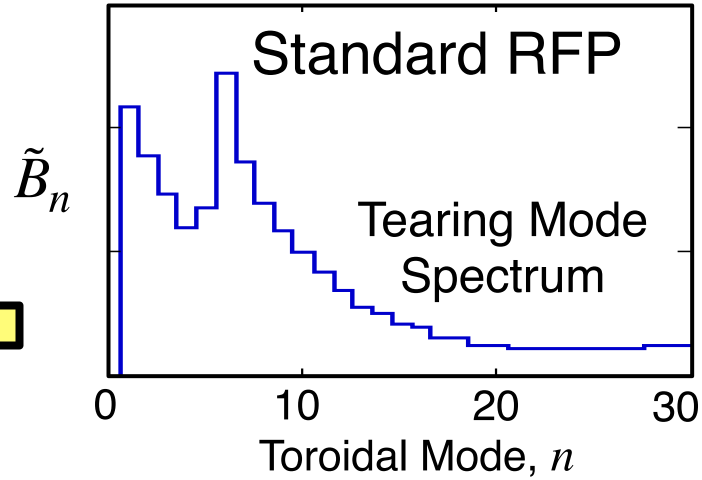
R = 1.4 m, a = 0.4 m

I_p = 0.5-1 MA

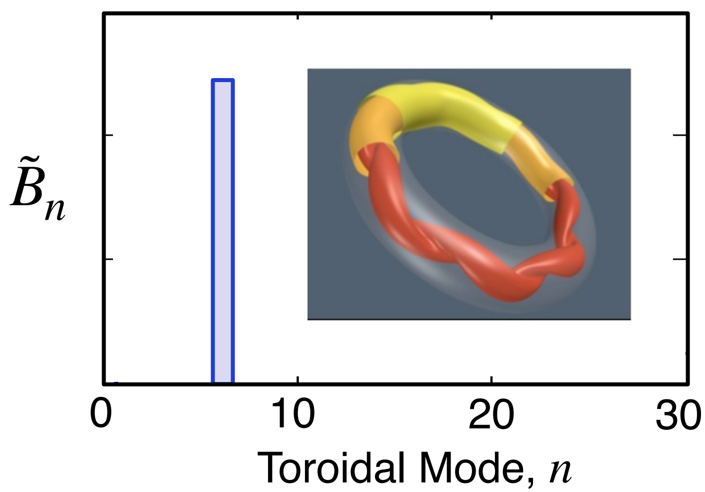


Optimizing and Understanding the Quasi-Single-Helicity Regime

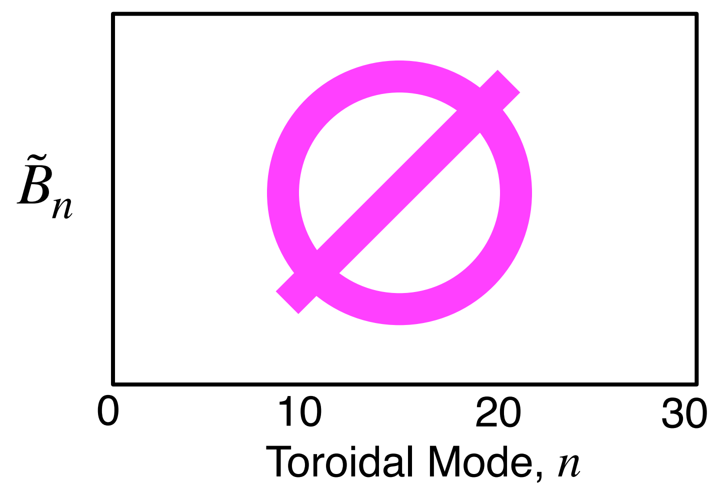
Two paths to improved confinement in the RFP



Single-Helicity Self-Organization

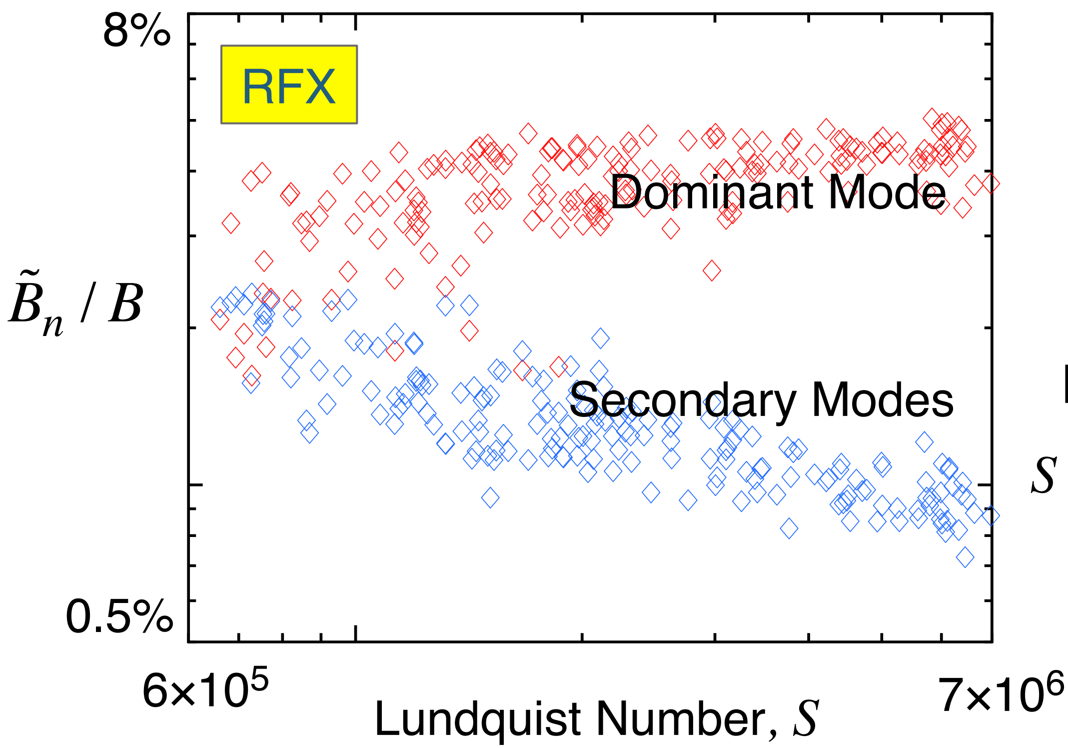


Current Profile Control



Understanding the dependence on plasma current in accessing the quasi-single-helicity (QSH) regime

- First observed in RFX-mod, now in MST at lower I_P
- Lundquist number appears to be a unifying parameter for QSH transition



Lundquist Number

$$S = \tau_R / \tau_A \sim I_p T_e^{3/2} n^{-1/2}$$

I_P = 0.5 MA ——— RFX ———→ 1.3 MA

Lorenzini et al, Nature Physics (2009)

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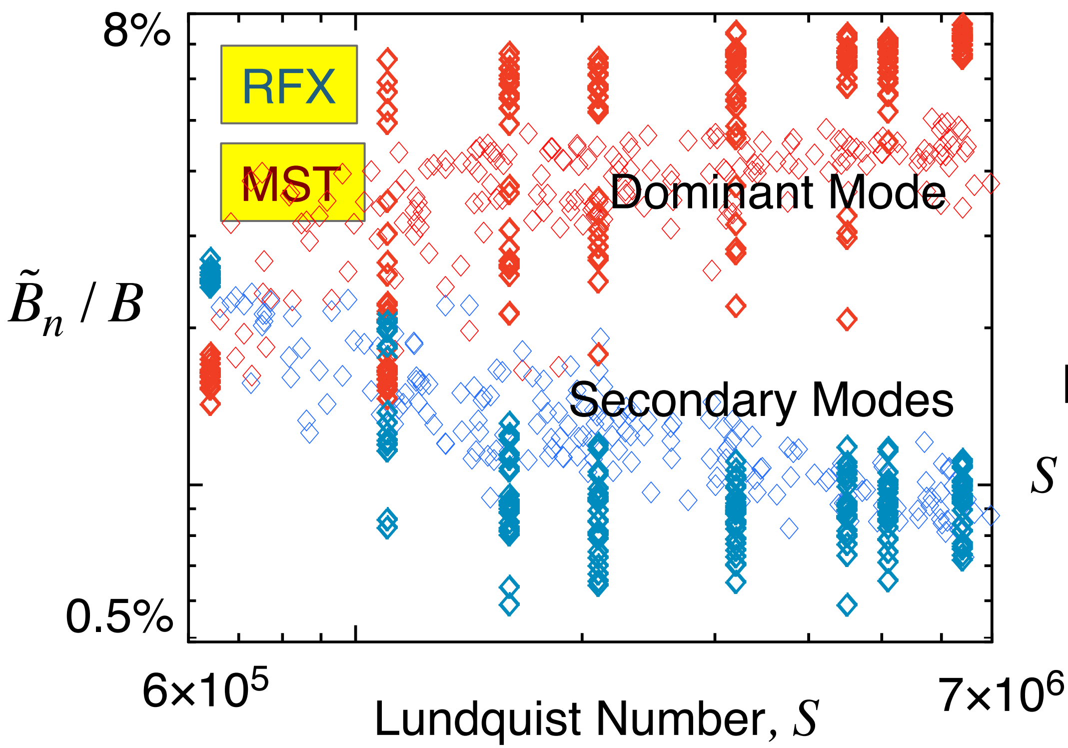


Lundquist Number

$$S = \tau_R / \tau_A \sim I_p T_e^{3/2} n^{-1/2}$$

I_P = 0.5 MA —— RFX ——→ 1.3 MA

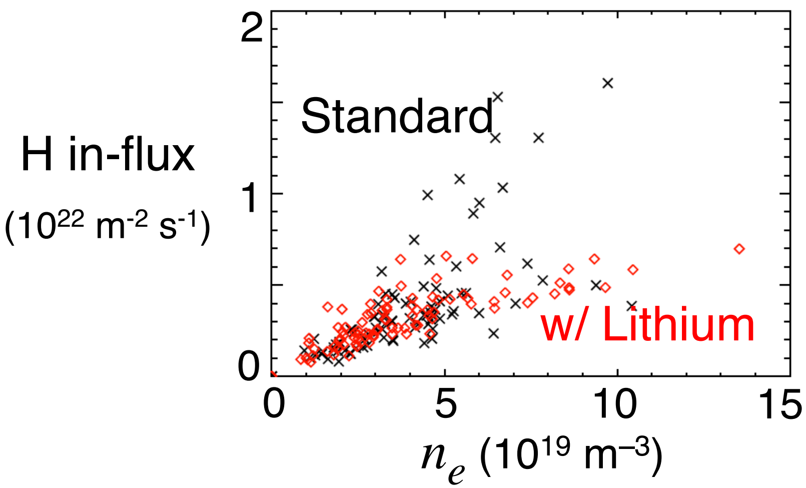
0.2 MA —— MST ——→ 0.6 MA

B. Chapman, EX/P6-01   Lorenzini et al, Nature Physics (2009)

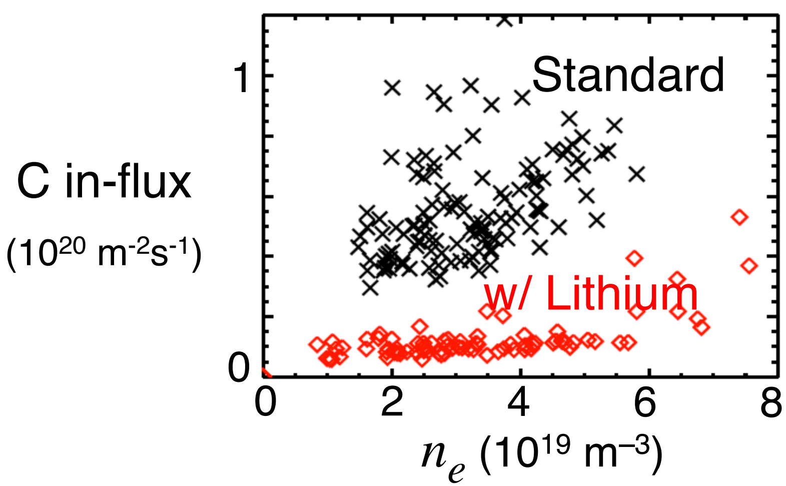
Lithium coating of RFX's carbon wall improves density control, allowing access to high density at high current ($n / n_G = 0.5$)

RFX

- Reduced hydrogen recycling



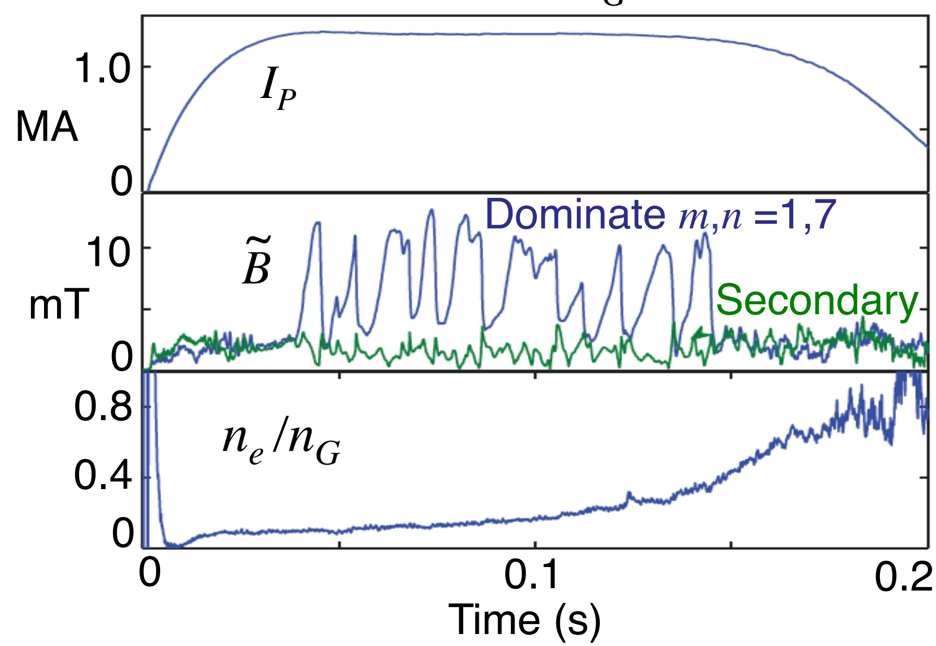
- Reduced impurity in-flux



Lithium deposited by:

- Multi-pellet injector
- Liquid lithium limiter

QSH with $n / n_G \leq 0.35$



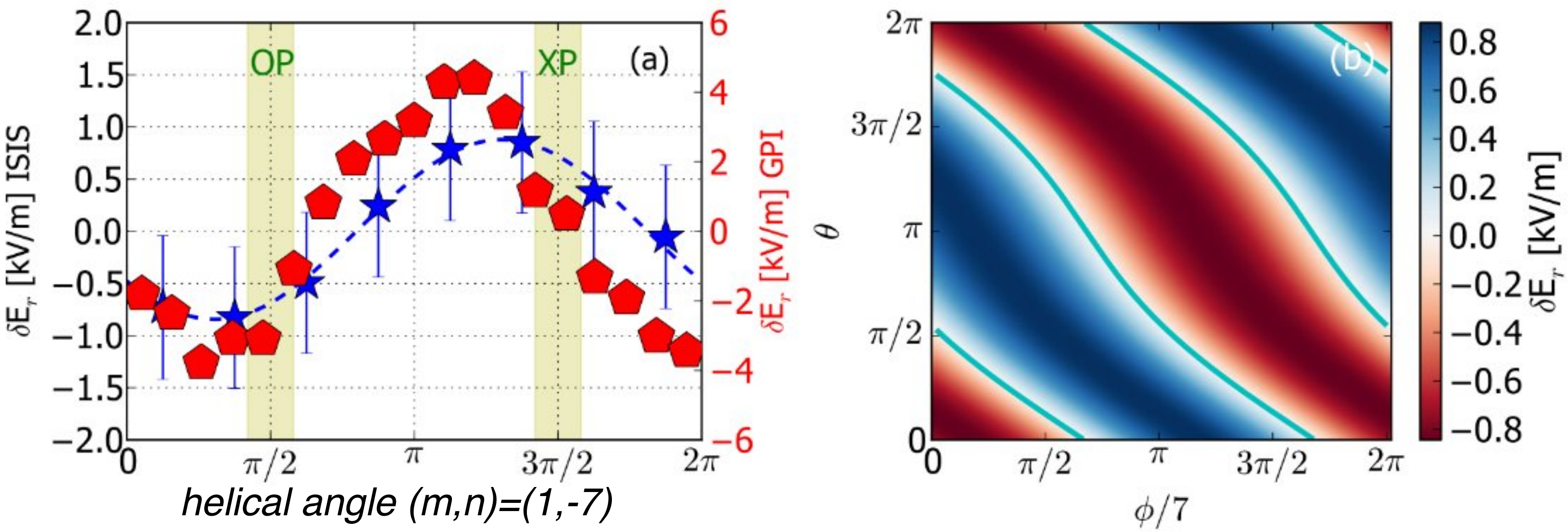
M.E. Puiatti, EX/P5-01

The helical core modulates the kinetic properties at the edge

- E_r is constant on helical flux surfaces, with ripple consistent with the helicity of the dominant QSH perturbation

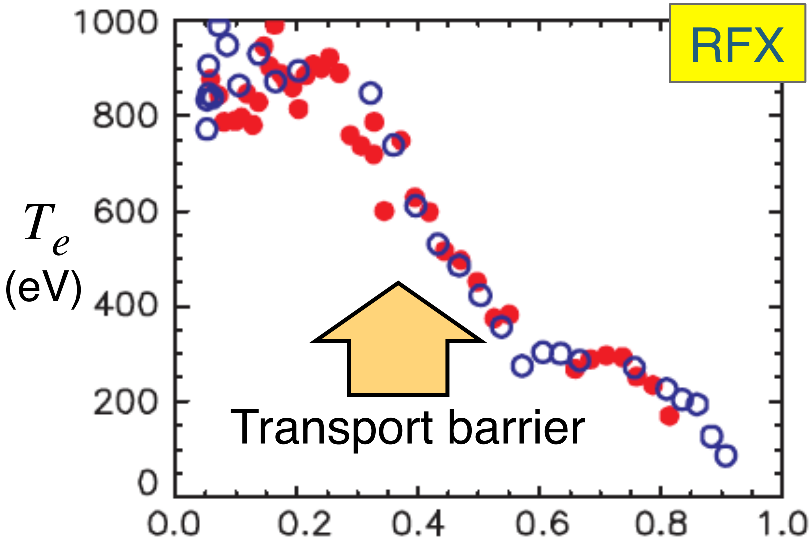
RFX

E_r measured by probes and gas-puff imaging (GPI)



3D equilibrium reconstructions for the single-helical-axis (SHAx) limit of QSH using V3FIT and VMEC

- Variety of profile diagnostics being incorporated into 3D reconstructions
- Dynamic 3D state, with varying strength and orientation of helical structure

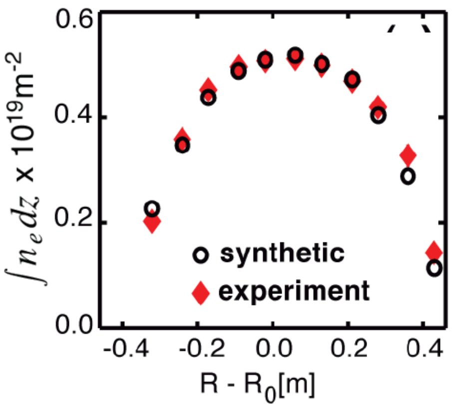


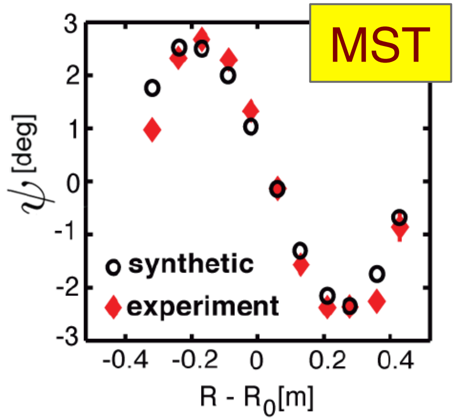
V3FIT for RFX includes:

- Magnetics
- Thomson scattering profile
- Soft x-ray tomography
- Density profile

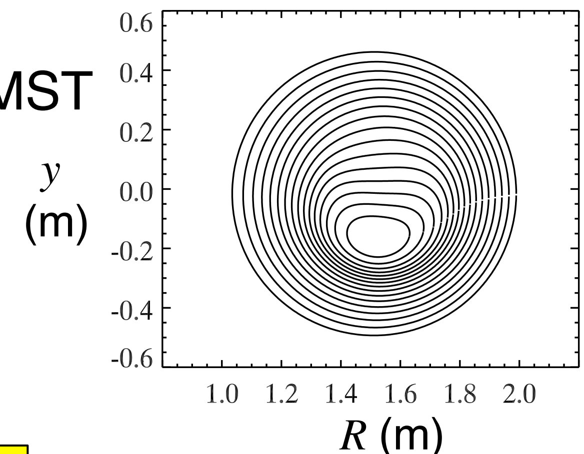
L. Carraro, EX/P3-04; M. Valisa, EX/P3-11

FIR interferometry and Faraday rotation (not yet in V3FIT)





Initial V3FIT for MST (magnetics only)



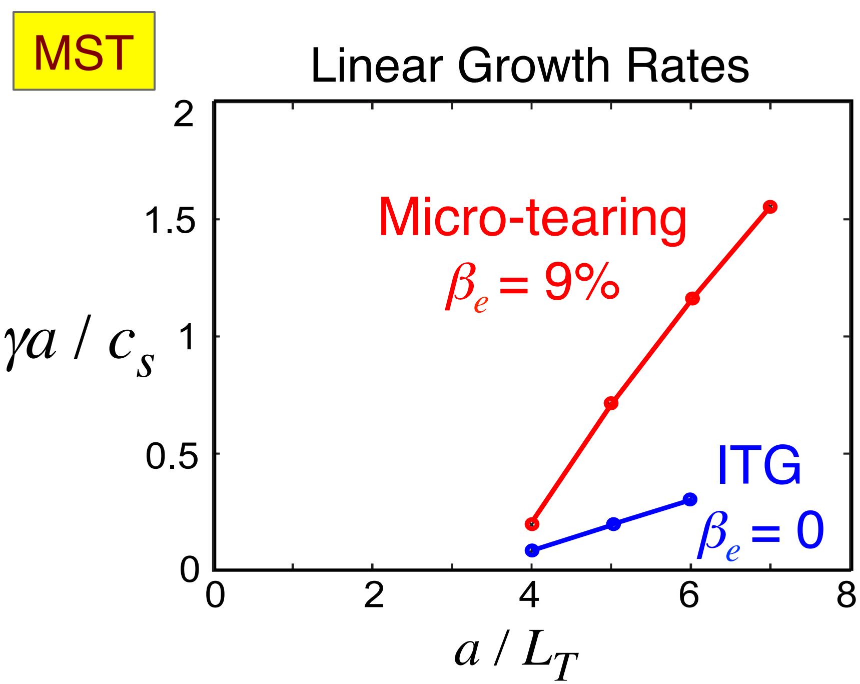
J. Hanson, TH/7-2

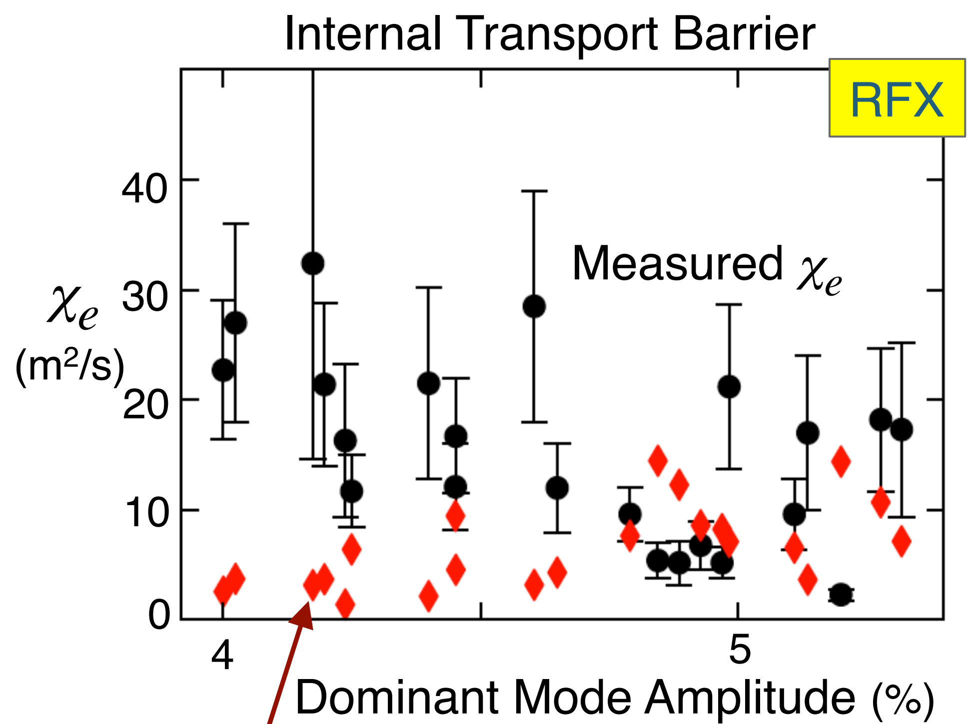
B. Chapman, EX/P6-01

Confinement Physics

Micro-turbulence could limit confinement in improved RFP confinement regimes and the QSH internal transport barrier

- Micro-tearing (MT) is emerging as dominant microinstability in the RFP
- Larger critical gradient than for tokamak (both MT and ITG)
- MT growth rate remains significant at low collisionality, attributed to differences in curvature drift





Quasi-linear estimate of MT-driven transport, increasing when helical states are purer

D. Carmody, TH/P02-10

L. Carraro, EX/P3-04

Classical confinement of impurity ions in MST plasmas with inductive profile control

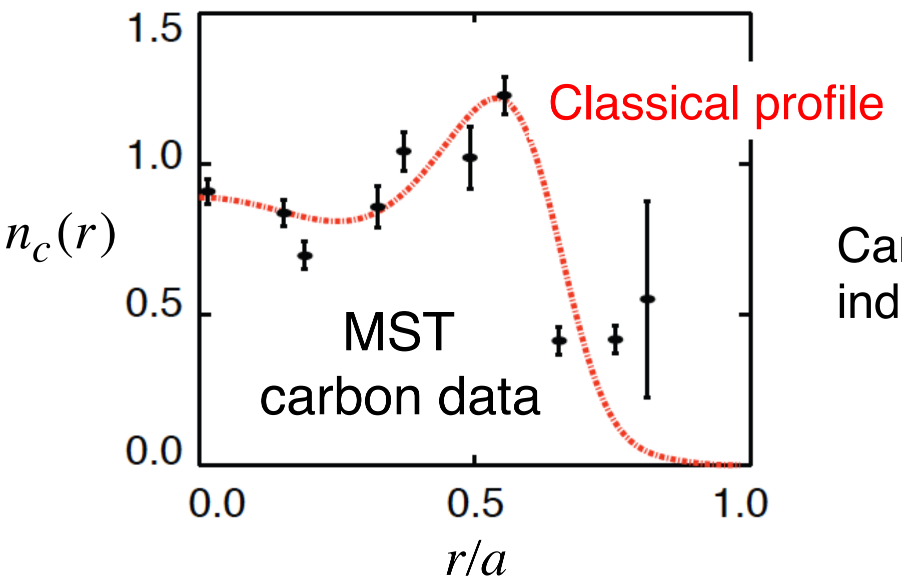
MST

- Reduced tearing yields 10-fold increase in global confinement
- The "neoclassical" enhancement of perpendicular transport is small in the RFP, e.g., banana orbit width < gyro-radius

Classical Transport

$$\frac{n_Z(r)}{n_Z(0)} = \left[\frac{n_i(r)}{n_i(0)}\right]^Z \left[\frac{T_i(r)}{T_i(0)}\right]^{-0.5Z-1}$$

"temperature screening"



Carbon is expelled from the core when inductive profile control is applied

Classical confinement of impurity ions in MST plasmas with inductive profile control

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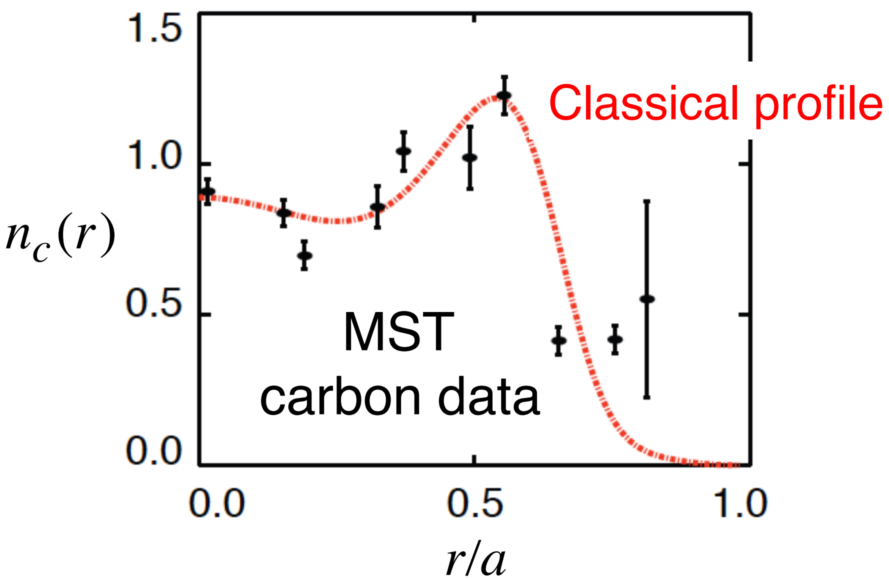
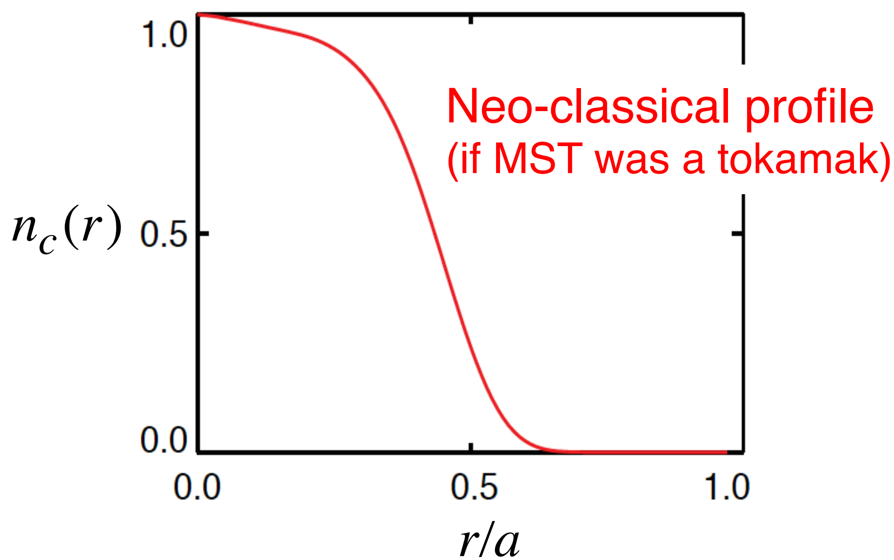


Neo-classical Transport (Tokamak)

$$\frac{n_Z(r)}{n_Z(0)} = \left[\frac{n_i(r)}{n_i(0)}\right]^Z \left[\frac{T_i(r)}{T_i(0)}\right]^{1.5Z}$$

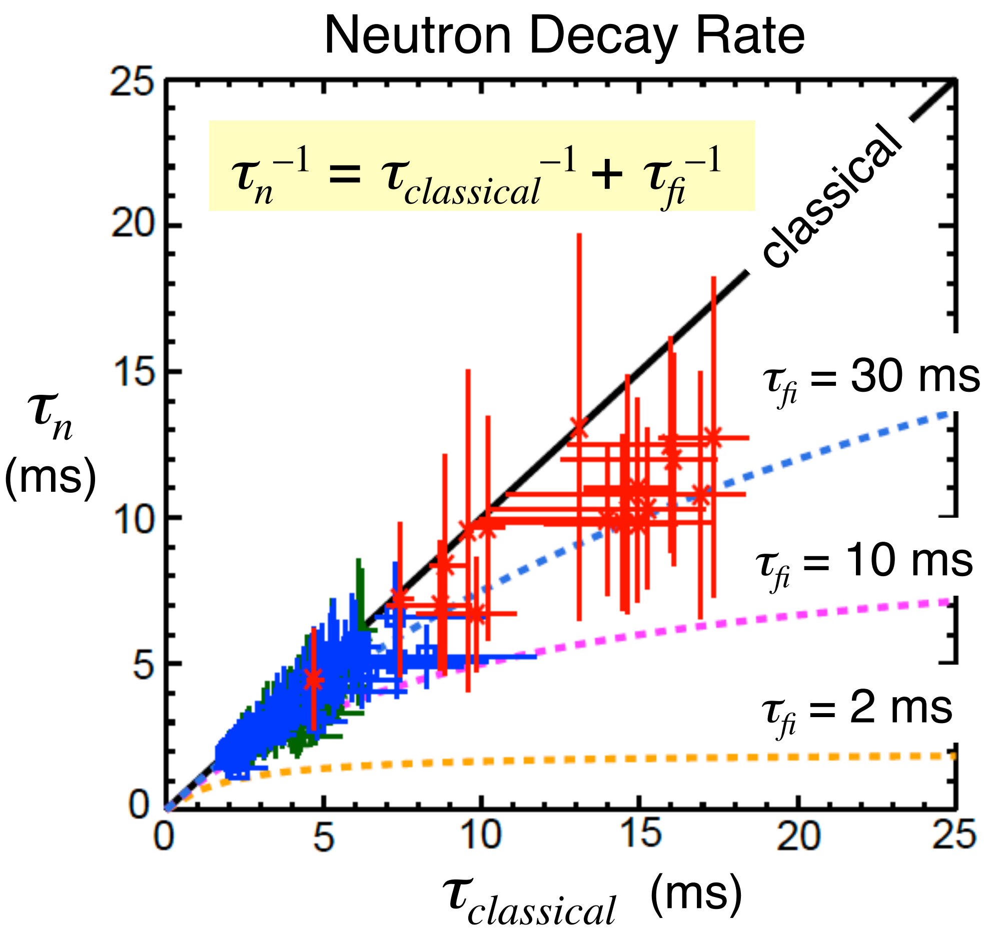


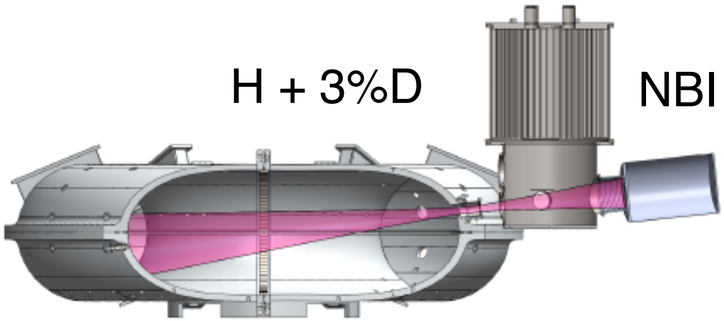
J. Anderson, EX/P3-16

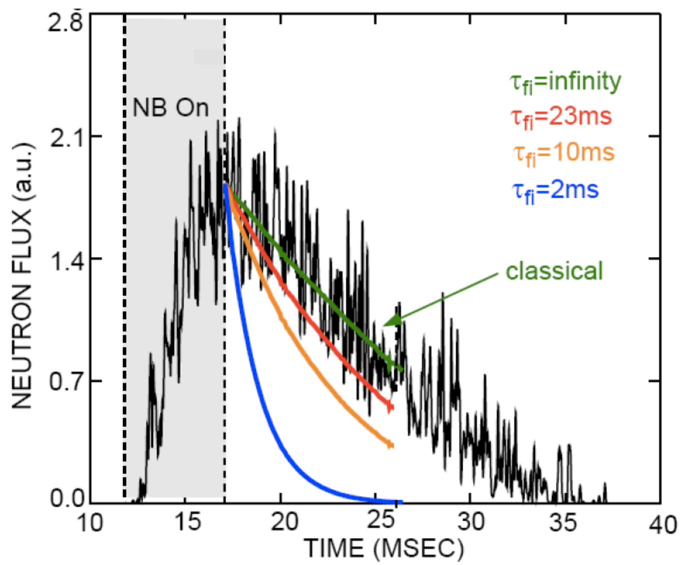
Fast ion confinement is also close to classical, even in the standard RFP with stochastic magnetic field

MST

- Tangential 1 MW, 25 keV neutral beam injector on MST
- Super-Alfvénic ion source, with projected $\beta_{fast} / \beta_{th} > 0.5$







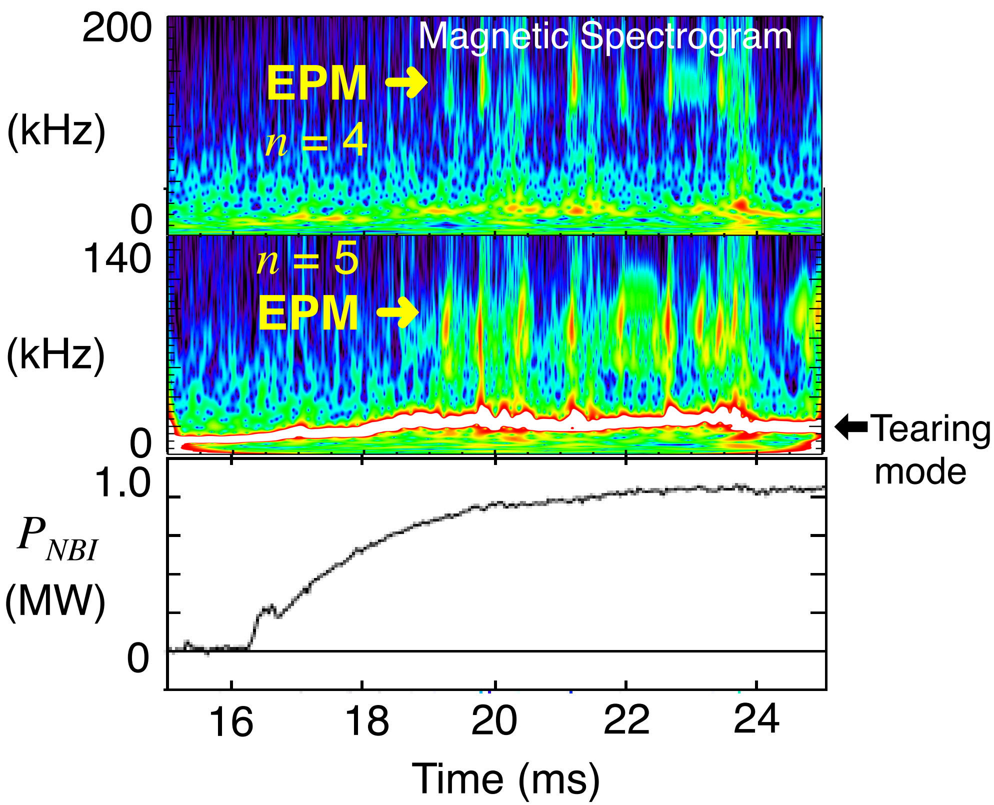
J. Anderson, EX/P3-16

First observation of energetic ion modes by NBI in an RFP

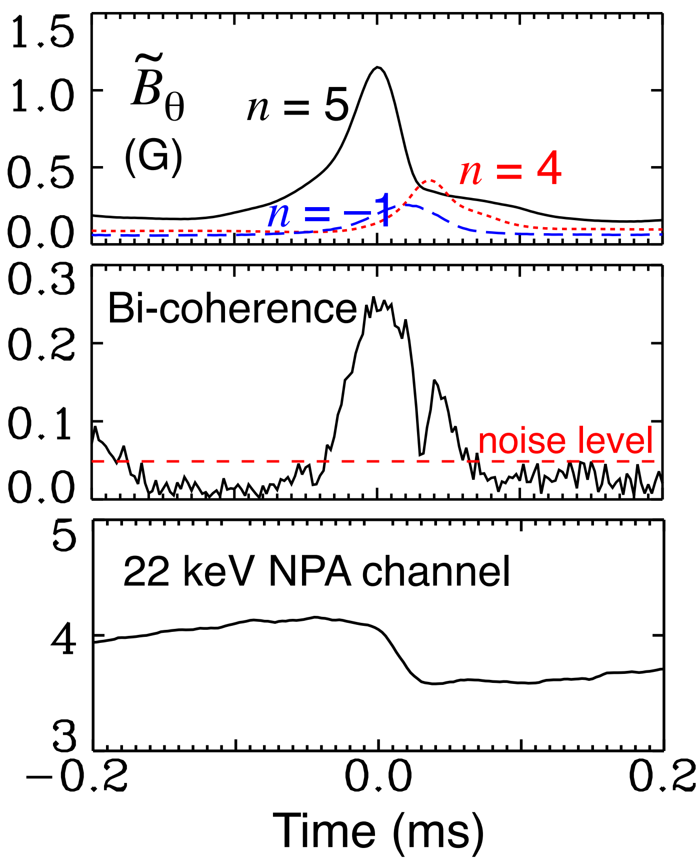
MST

- Several bursting modes observed, with frequency scalings that are EP-like and Alfvénic
- Frequencies too small for TAE modes (AE3D, STELLGAP)

Energetic Particle Modes



Hint of fast particle re-distribution

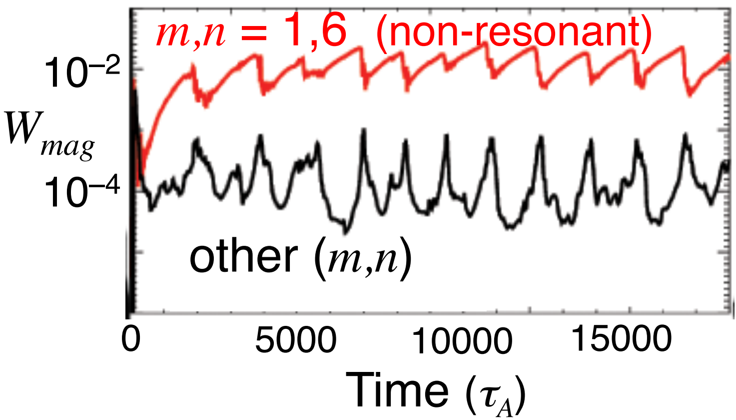


Nonlinear MHD Modeling
&
Flow and Momentum Transport

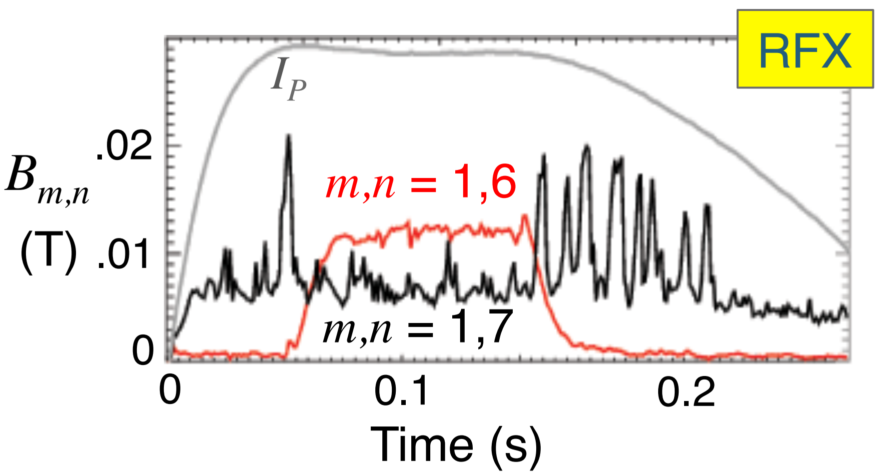
Nonlinear, 3D visco-resistive MHD modeling captures many of the dynamics seen in experiments

- RFP provides great opportunities for rigorous validation of nonlinear MHD

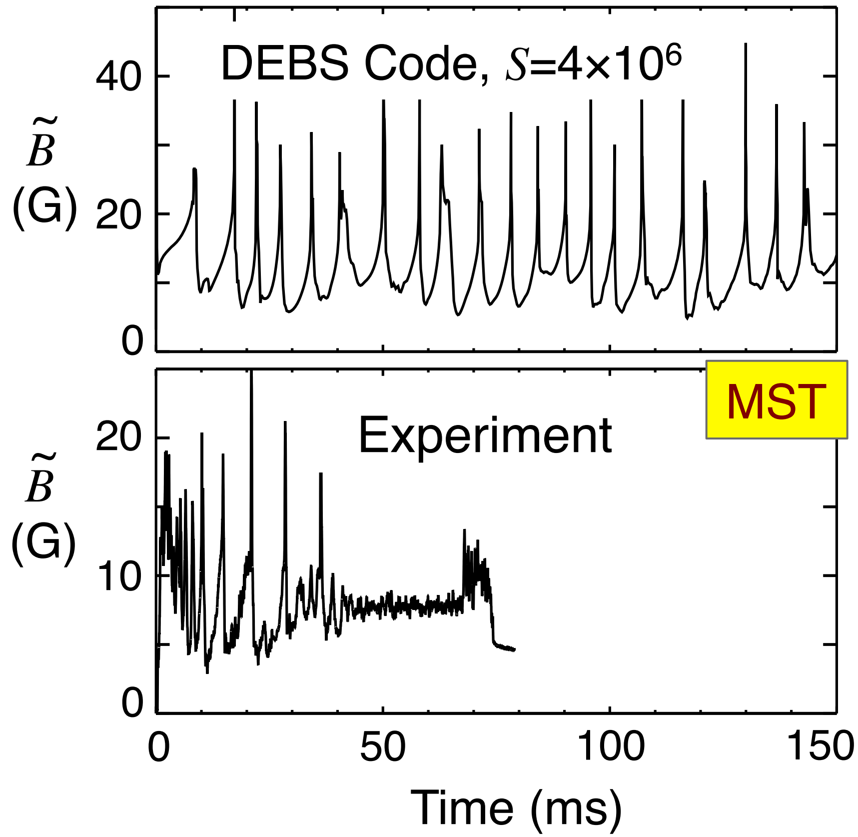
Applied ***non-resonant*** helical mode simulated in MHD code and tested in RFX



SPECYL Code



Computation uses MST's experimental resistivity (magnitude and profile)



S. Cappello,TH/P2-16

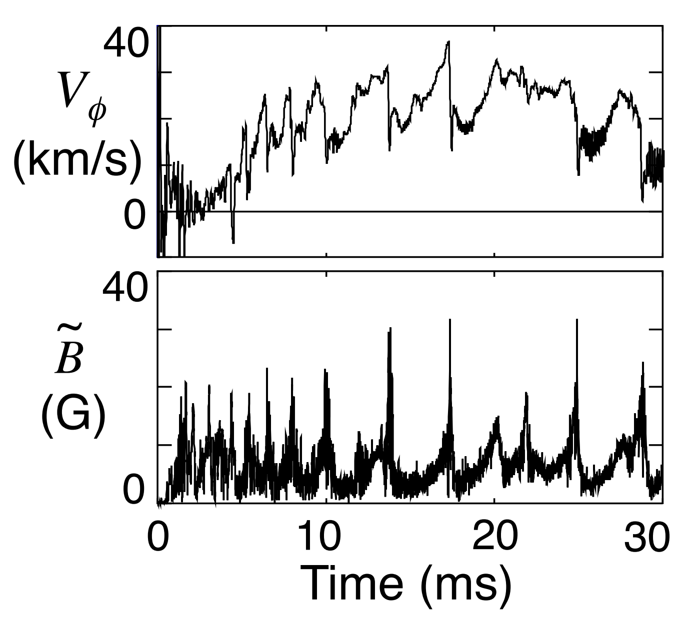
D. Den Hartog, EX/P3-17

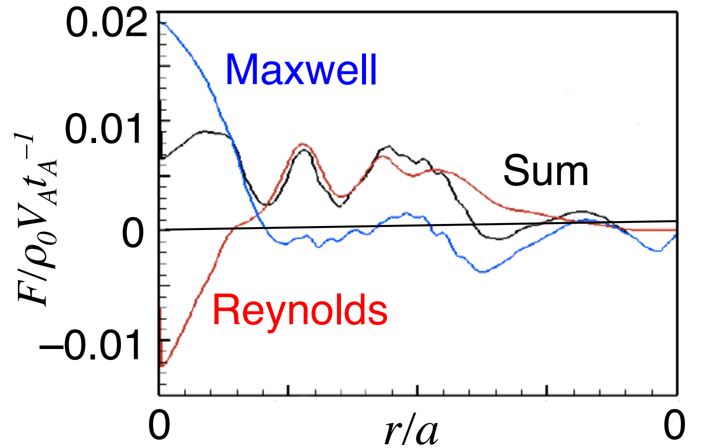
Momentum transport and intrinsic flow associated with magnetic fluctuations and tearing modes

MST

- NIMROD modeling with non-reduced MHD equations provides context to understand large but opposing Reynolds and Maxwell stresses
- New "kinetic stress" from correlated pressure-magnetic fluctuations

Intrinsic flow and impulsive momentum transport in MST (no applied torque)

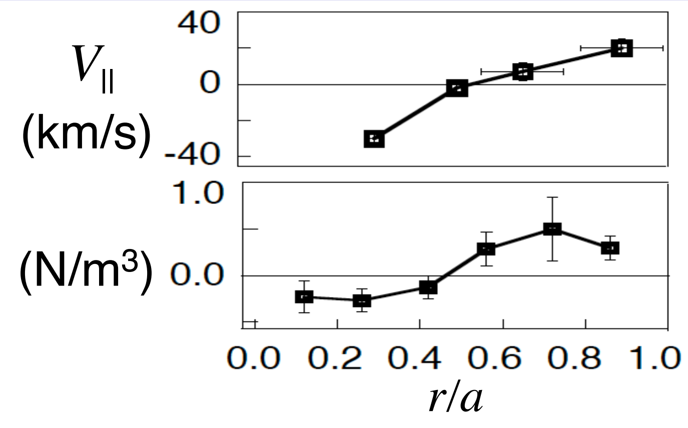




NIMROD modeling shows coupled current and momentum relaxation

$$\nabla \cdot \langle \tilde{p}_{\|,i} \tilde{B}_r \rangle / B$$

"kinetic stress" in the between-crash spin-up phase



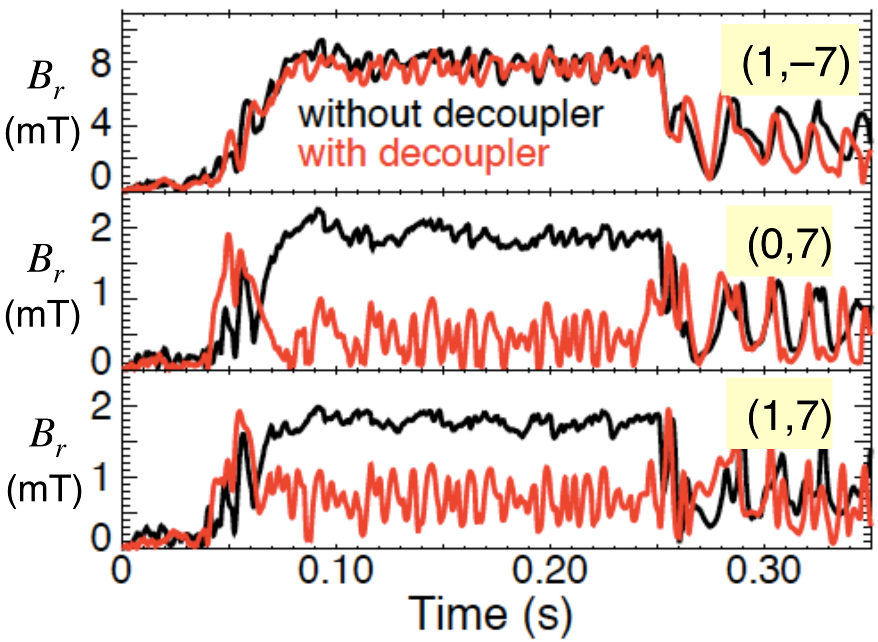
C. Sovinec, TH/P3-08
W. Ding, EX/P3-08

Active Mode Control

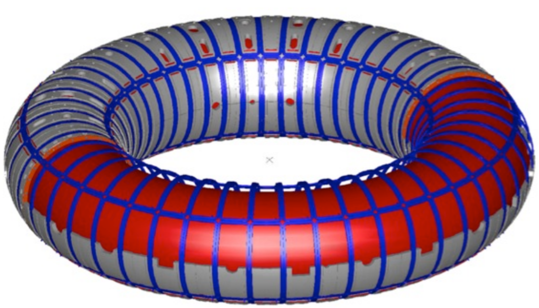
RFX has the most complete coil system for active control of MHD stability among fusion experiments

RFX

- 192 coils, each independently driven
- Refined for the RFP, now applied to novel tokamak experiments in RFX
  - Control of both resistive wall modes and tearing modes
  - Applied 3D magnetic shaping
- Recent improvements
  - Dynamic mode decoupler, separates applied fields and 3D system response (ports, gaps, etc)
  - Upgrade underway to reduce latency for control



Stimulated QSH through applied (1,–7) helical field

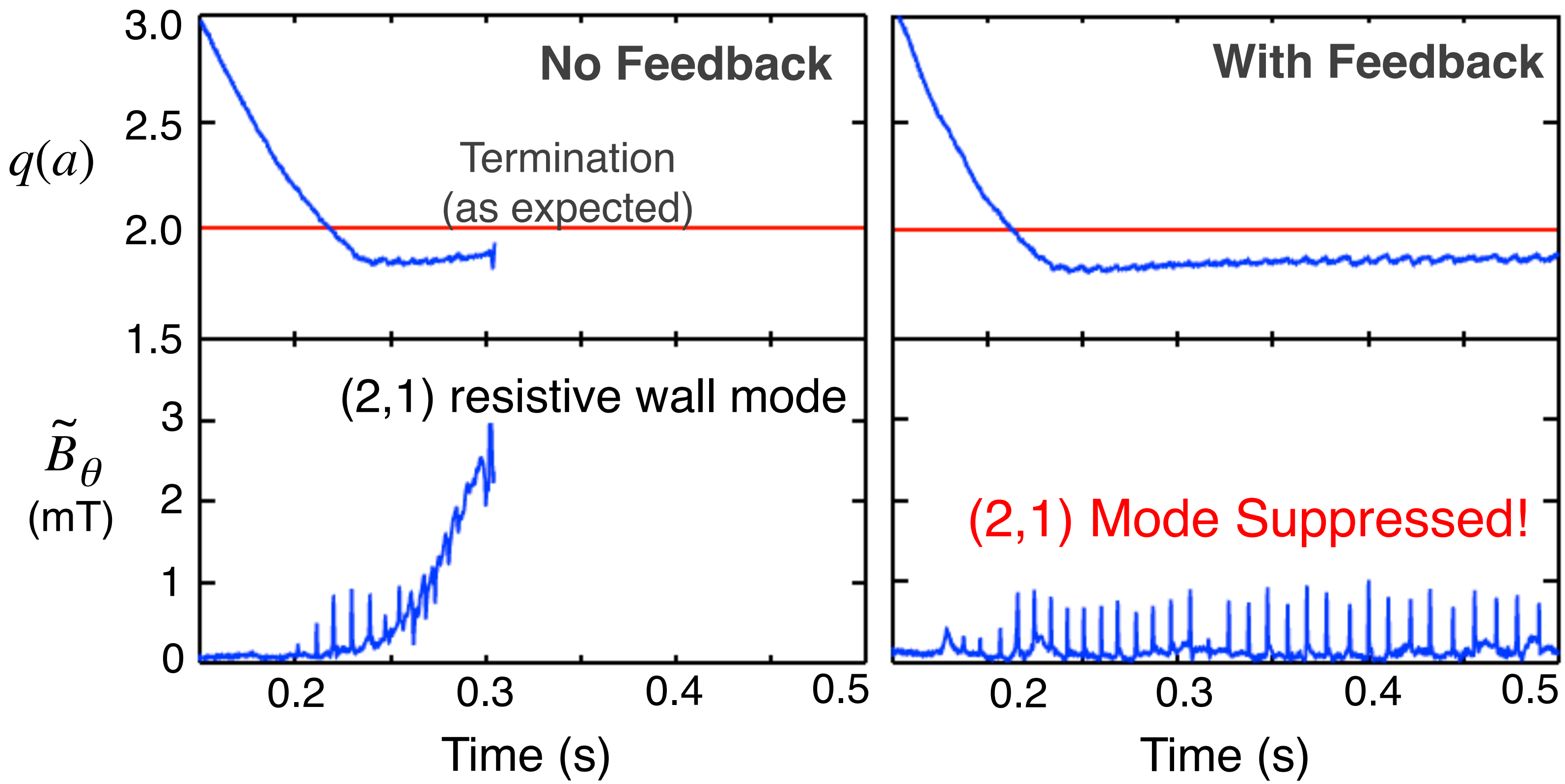


L. Marrelli, EX/P5-38

Active feedback control of (2,1) mode in RFX tokamak plasmas yields stable operation with $q(a) < 2$

RFX

- Only 6 coils required (covering 3% of the surface)
- Clean-mode-control with radial field sensors is essential, to remove feedback sidebands
- Joint experiments with DIII-D this year (2012 Torkil Jensen Award)



L. Marrelli, EX/P5-38
M. Valisa, EX/P3-11

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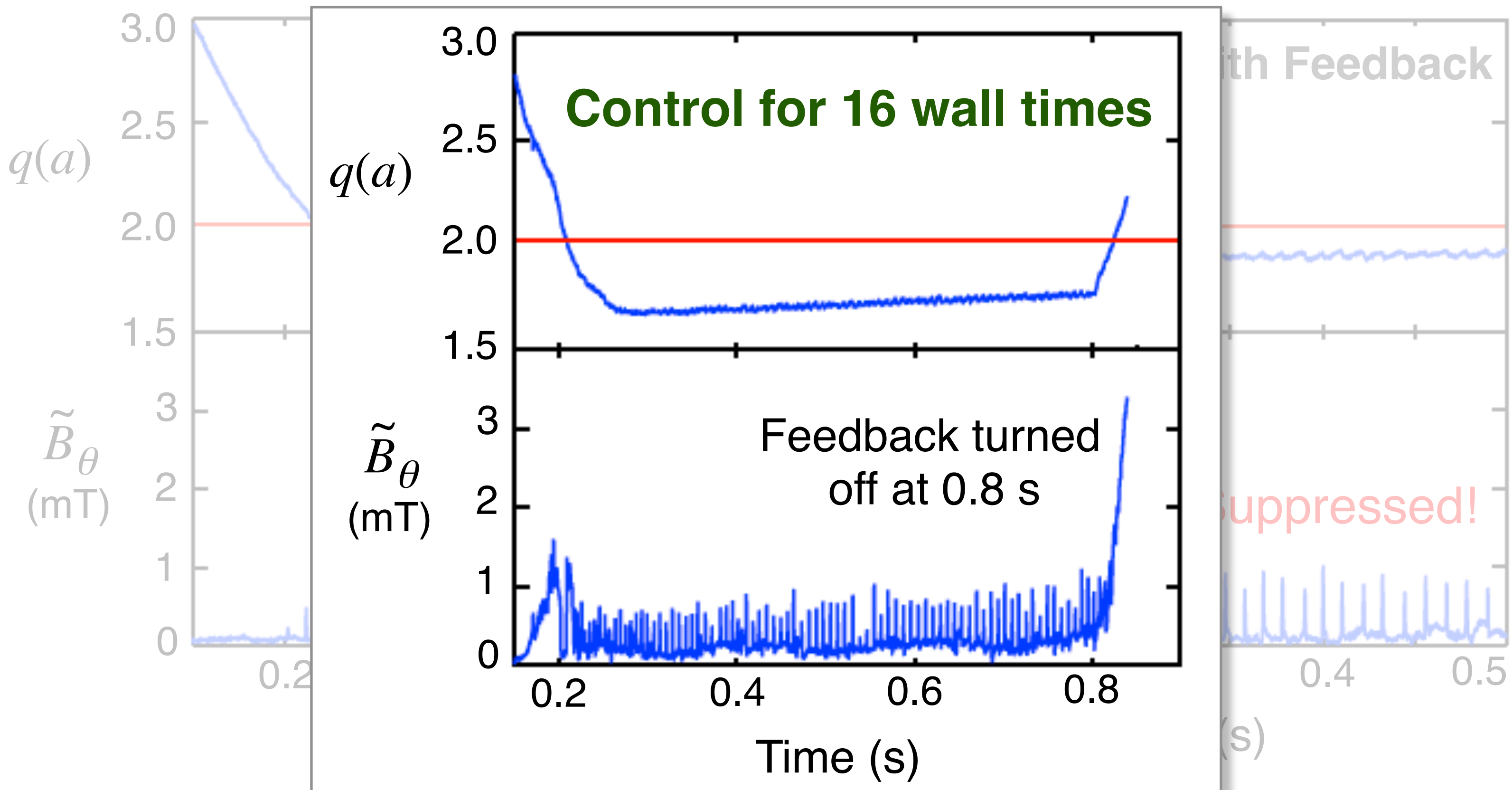
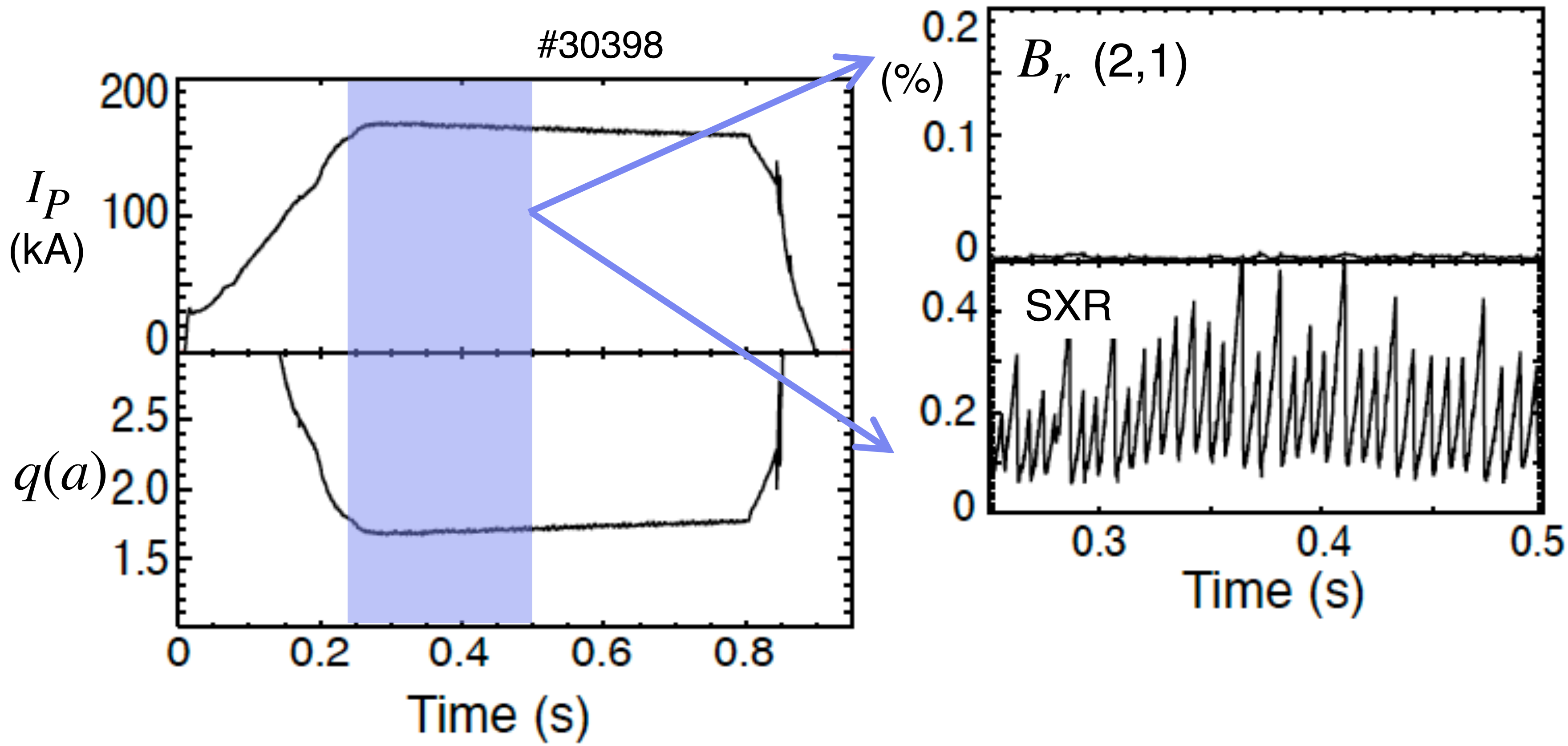


L. Marrelli, EX/P5-38
M. Valisa, EX/P3-11

Allowing the (2,1) mode a small, controlled residual amplitude reduces sawtooth activity

RFX

- Slow 10 Hz rotation programmed for the controlled 2/1 mode
- Reduced sawtooth activity sustained for several wall times $\tau_{wall} \approx$ 50 ms, without other growing MHD modes



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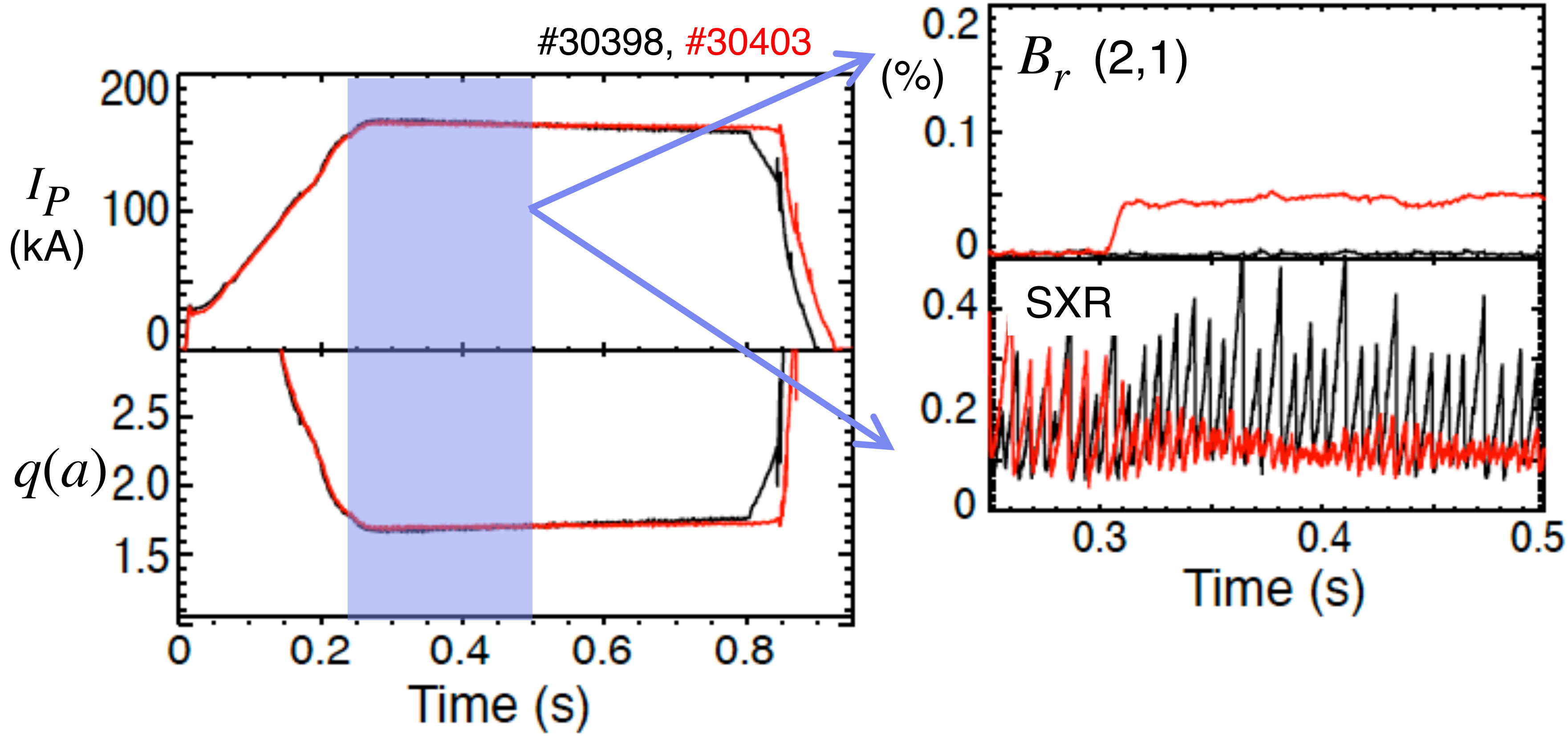
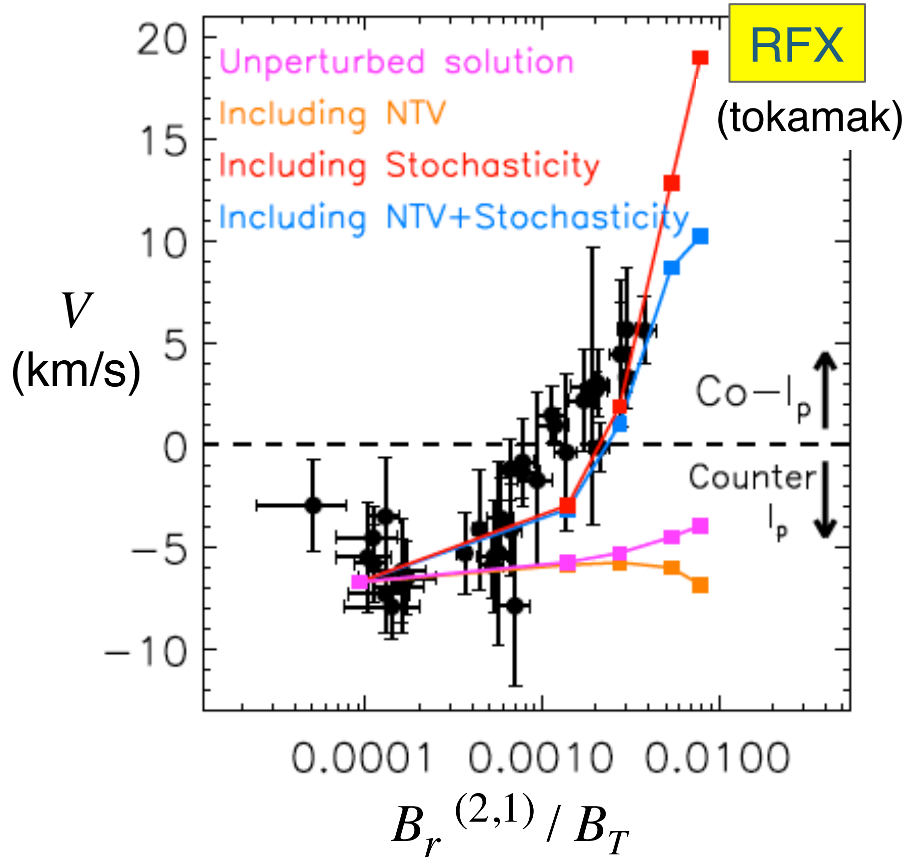


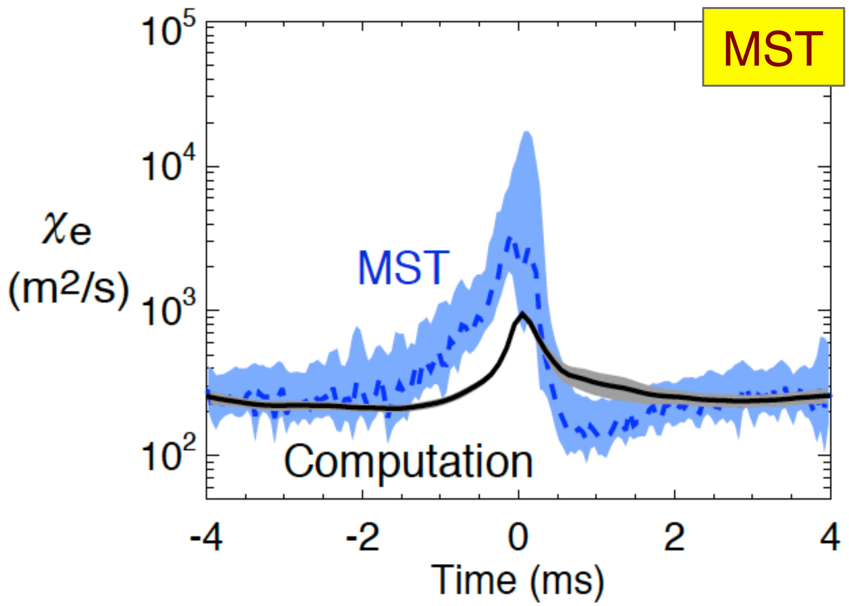
L. Marrelli, EX/P5-38

Transport in a stochastic magnetic field

As residual (2,1) and harmonics are increased, intrinsic flow is reversed, interpreted as ambipolar E_r from stochastic field + NTV



Heat transport agrees with test-particle expectation (aka Rechester-Rosenbluth), with ~ 2X trapped electron reduction



3D stochastic field derived from DEBS nonlinear computation, with magnetic spectrum amplitudes scaled to experiment (~ 1/2X)

M. Valisa, EX/P3-11

D. Den Hartog, EX/P3-17

Summary

- Improving RFP performance through increased plasma current, I_P
  - Access to quasi-single-helicity regime
  - Density control widens operating space
  - Ground work in both RFX-mod and MST to maximize and optimize high current operation
- Understanding key physics
  - Classical confinement of impurity and energetic ions
  - Micro-turbulence in improved confinement scenarios
  - Intrinsic rotation and momentum transport
- Advancing toroidal confinement
  - Optimized mode control
  - Novel tokamak experiments with $q(a) < 2$
  - Equilibrium reconstruction for 3D geometry
  - Validation of nonlinear plasma models
- New RFP program at USTC in Hefei, PRC

RFP papers at this conference

- TH/P2-10 – Carmody
- TH/P2-16 – Cappello
- EX/P3-04 – Carraro
- EX/P3-08 – Ding
- TH/P3-08 – Sovinec
- EX/P3-11 – Valisa
- EX/P3-16 – Anderson
- EX/P3-17 – Den Hartog
- EX/P4-21 – Frassinetti (EXTRAP-T2R)
- EX/P4-24 – Masamune (RELAX)
- EX/P5-01 – Puiatti
- EX/P5-38 – Marrelli
- EX/P6-01 – Chapman
- EX/P8-02 – Vianello

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