Overview of Results from the MST Reversed Field Pinch Experiment

B.E. Chapman

representing the MST team and collaborators

Coauthors for this work

J.S. Sarff[1], A.F. Almagri[1], J.K. Anderson[1], F. Auriemma[5], M. Borchardt[1], B.N. Breizman[10], D.L. Brower[2], S. Cappello[5], W. Cappechi[1], D. Carmody[1], K. Caspary[1], M. Cianciosa[12], D. Craig[8], V.I. Davydenko[6], P. Deichuli[6], D.R. Demers[3], D.J. Den Hartog[1], J. Duff[1], W.X. Ding[2], S. Eilerman[1], A. Falkowski[1], P. Fimognari[3], C.B. Forest[1], P. Franz[5], M. Galante[1], J.A. Goetz[1], J. Hanson[12], R.W. Harvey[9], D.J. Holly[1], P. Innocente[5], A.A. Ivanov[6], J. Koliner[1], S. Kumar[1], J.D. Lee[1], M. Li[10], L. Lin[2], D. Liu[1], R. Lorenzini[5], E. Martines[5], K.J. McCollam[1], M. McGarry[1], V.V. Mirnov[1], B. Momo[5], L. Morton[1], S. Munaretto[1], M.D. Nornberg[1], P.D. Nonn[1], S.P. Oliva[1], E. Parke[1], P. Piovesan[5], J. Polosatkin[6], M.J. Pueshel[1], M. Puiatti[5], J.A. Reusch[1], J. Sauppe[1], A. Seltzman[1], C.R. Sovinec[1], D. Spong[7], M. Spolaore[5], H. Stephens[11], D. Stone[1], N.V. Stupishin[6], D. Terranova[5], M. Thomas[1], J. Titus[4], J. Triana[1], P.W. Terry[1], J. Waksman[1], G.C. Whelan[1], W. Young[1], P. Zanca[5], L.J. Zheng[10]

1) University of Wisconsin, Madison, Wisconsin, and the
Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas

2) The University of California at Los Angeles, Los Angeles, California

3) Xantho Technologies, LLC, Madison, Wisconsin

4) Florida A&M University, Tallahassee, Florida

5) Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, Padova, Italy

6) Budker Institute of Nuclear Physics, Novosibirsk, Russia

7) The Oak Ridge National Laboratory, Oak Ridge, Tennessee

8) Wheaton College, Wheaton, Illinois

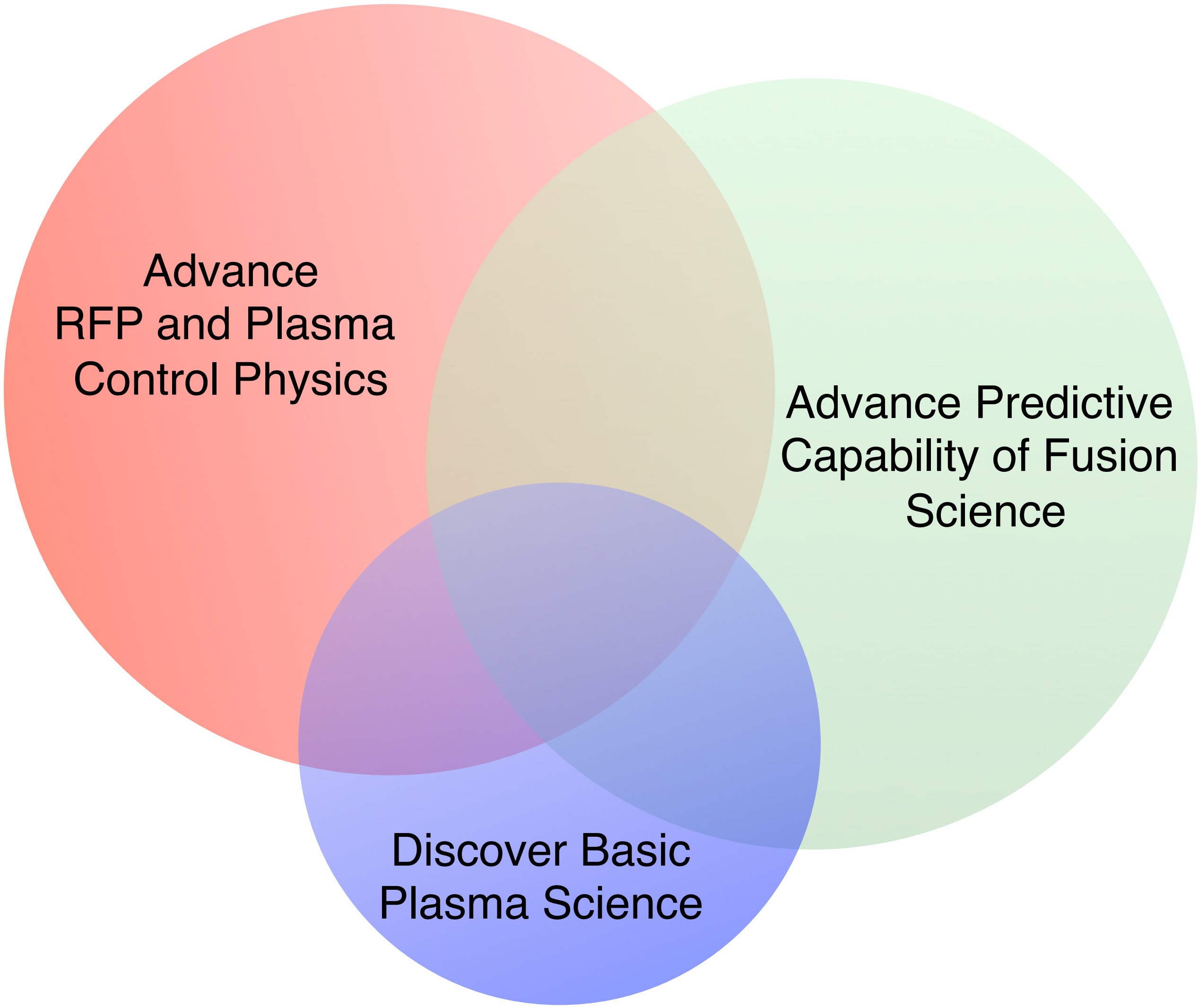
9) CompX, Del Mar, California

10) University of Texas at Austin, Austin, Texas

11) Pierce College, Lakewood, Washington

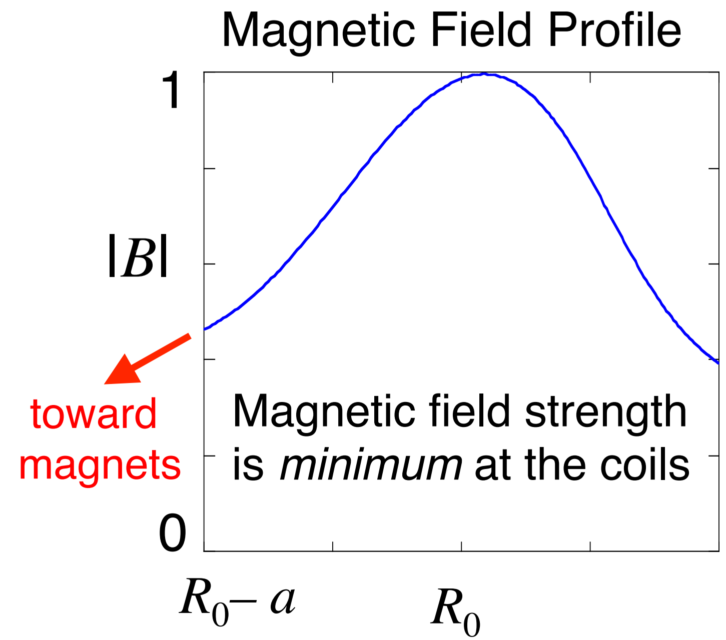
12) Auburn University, Auburn, Alabama

Synergistic motivations for MST research



Fusion potential of RFP stems from concentration of |B| within the plasma and small externally applied Bt

- |B| largely from plasma current
- Large plasma current density
  - Ohmic ignition may be possible
  - Large Greenwald limit
- Large demonstrated β



RFP a strong contributor to toroidal fusion science

- Physics closely related to tokamak and stellarator
- But RFP accesses unique parameter space

- Contribute to validation of key physics models and codes
- Contribute to development of advanced diagnostics

Outline

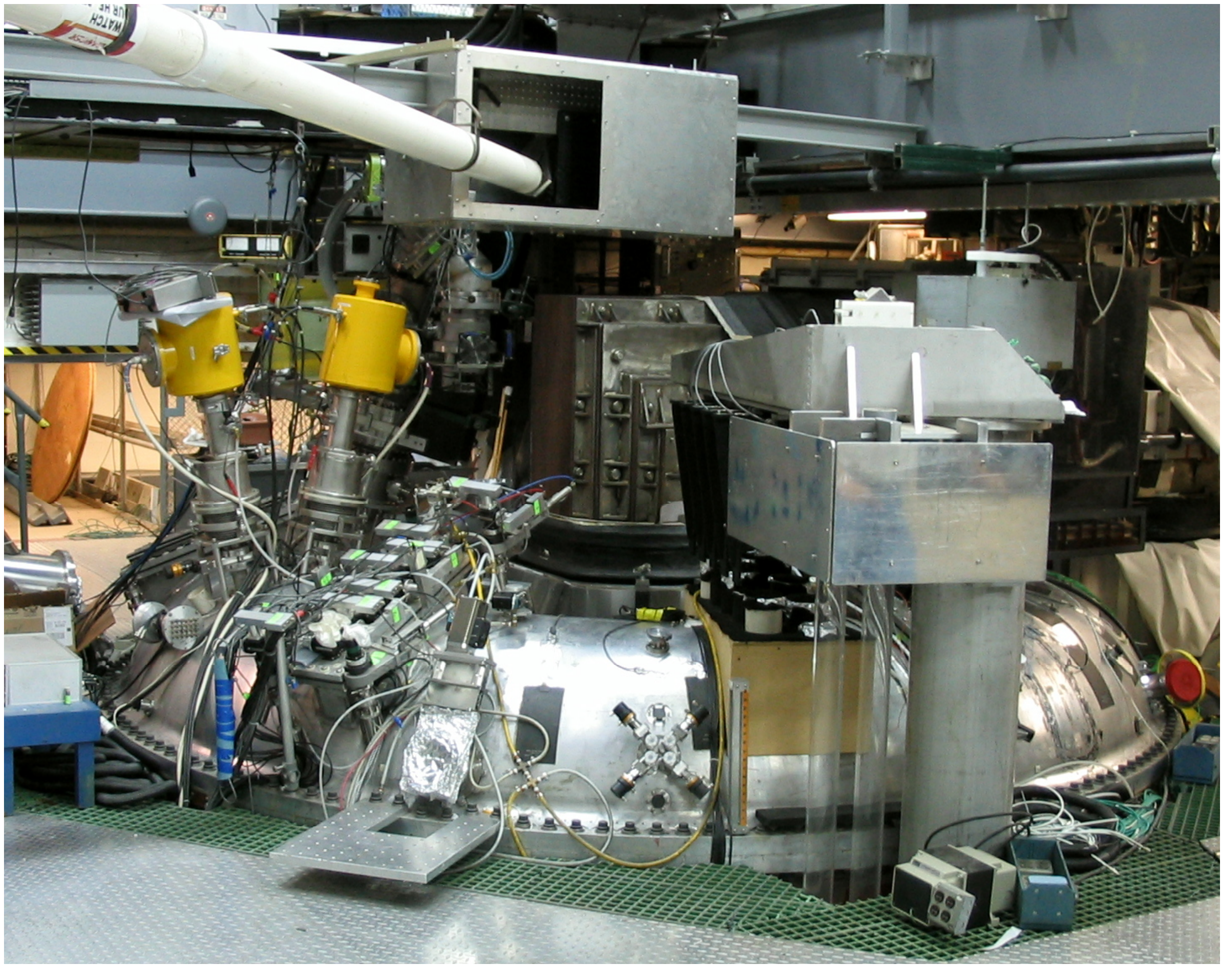
- Results connected to:

  J(r) control → micro-instability, high n_e, high β

  3D helical equilibria → theory, control, reconstruction

  Fast ion physics → internal fluctuation data, mode coupling, fast-ion runaway

A bit about the MST (Madison Symmetric Torus)

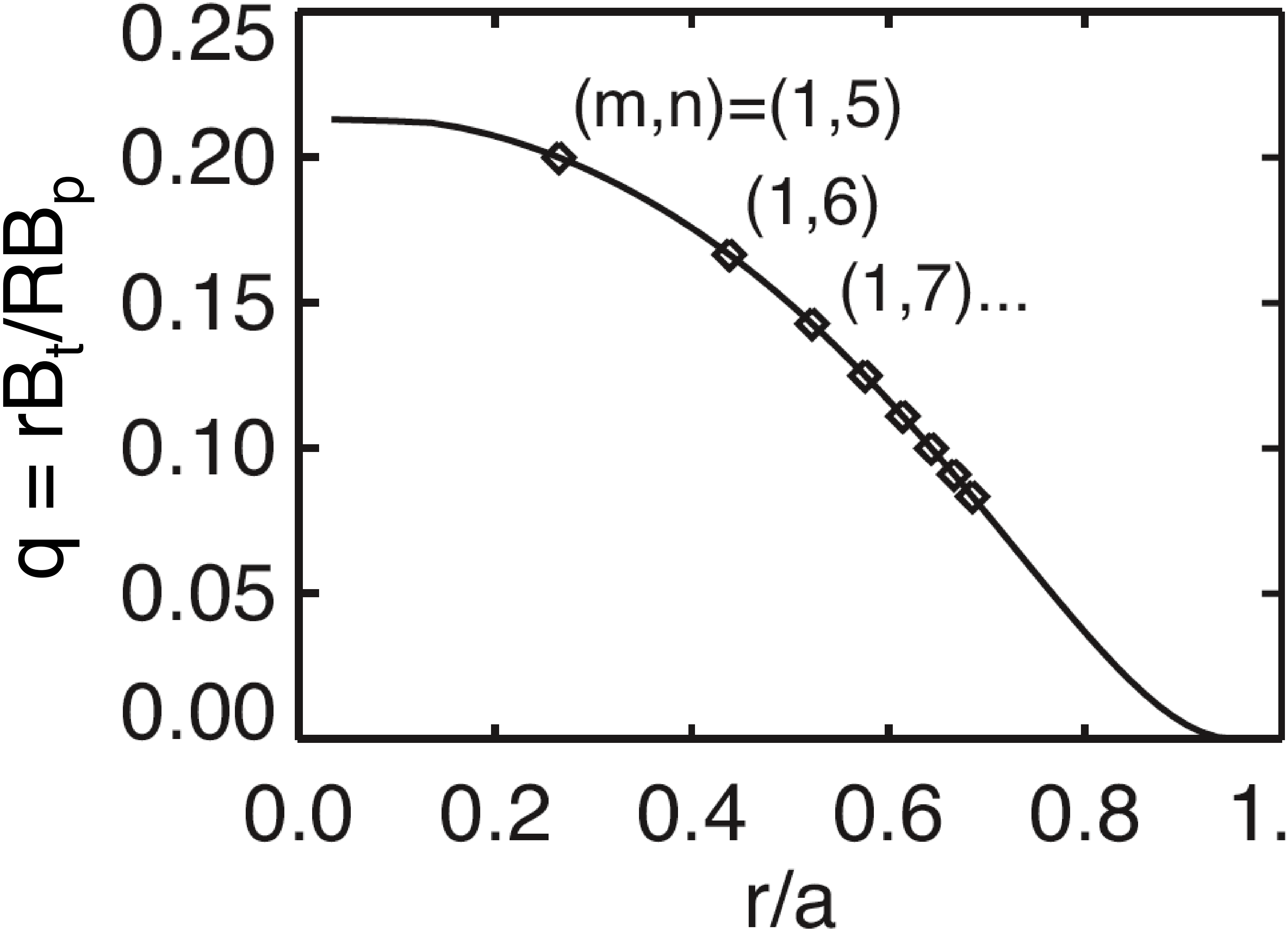


- $R = 1.5$ m
- $a = 0.52$ m

- Toroidally axisymmetric

- Advanced diagnostics

q < 1, many resonant surfaces for tearing modes

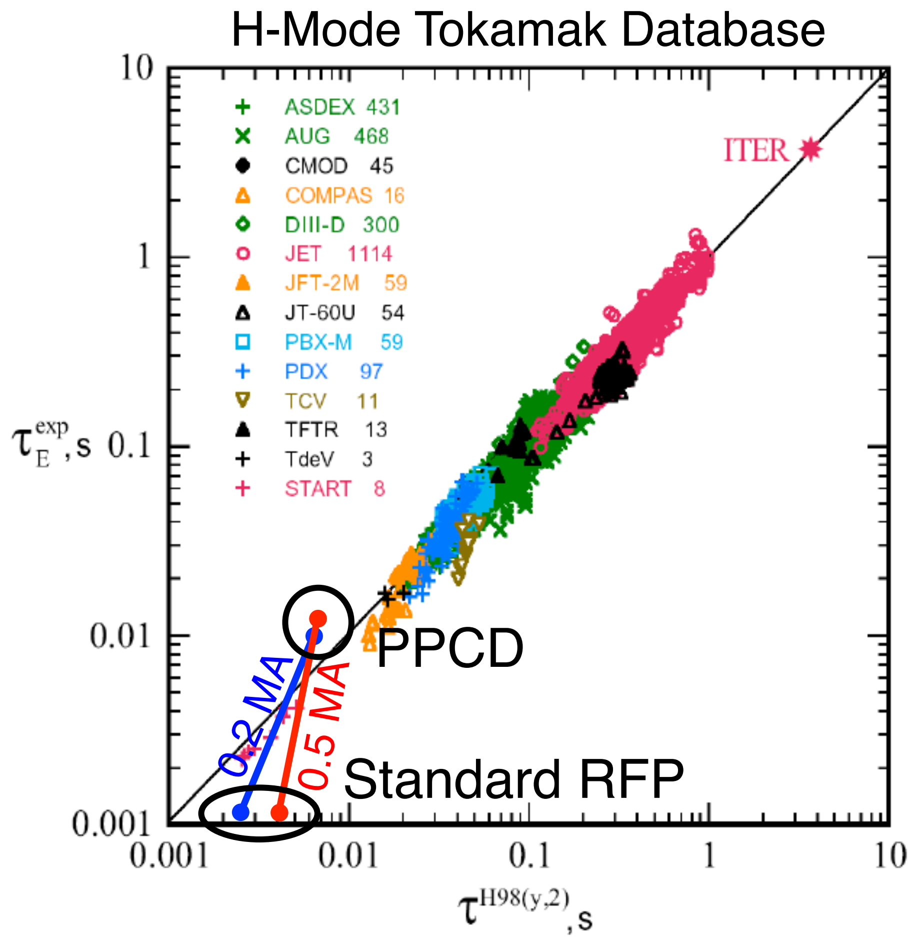


Results connected to J(r) control

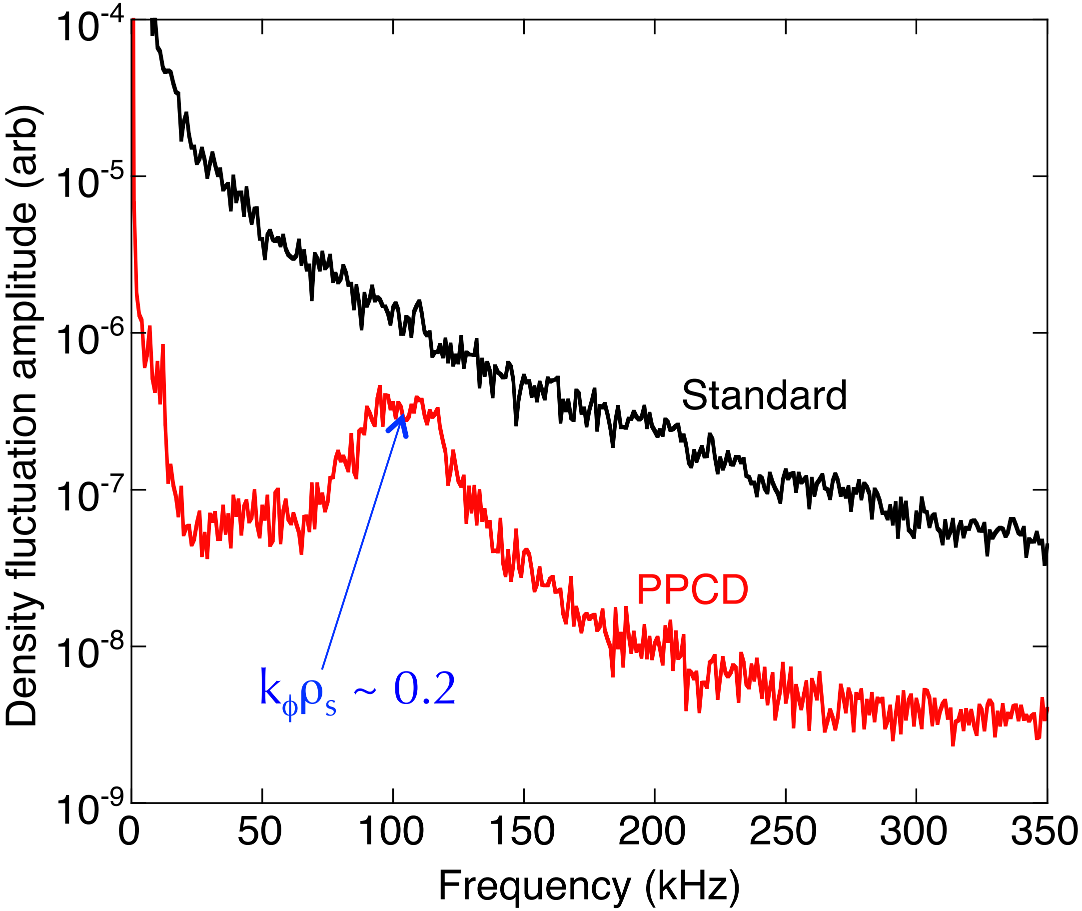
Reminder: J(r) control --> tokamak-like confinement

- Pulsed parallel current drive (PPCD) – inductive, transient
- $n_e \sim (0.1\text{-}0.2) n_{GW}$
- Tearing modes (macro-instabilities) suppressed

- Micro-instability becomes important?



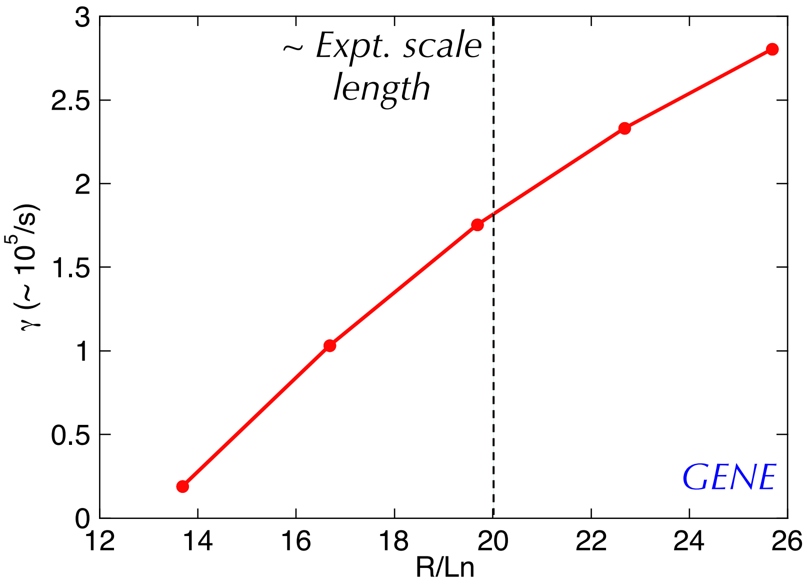
Micro-scale ñ measured via far forward scattering



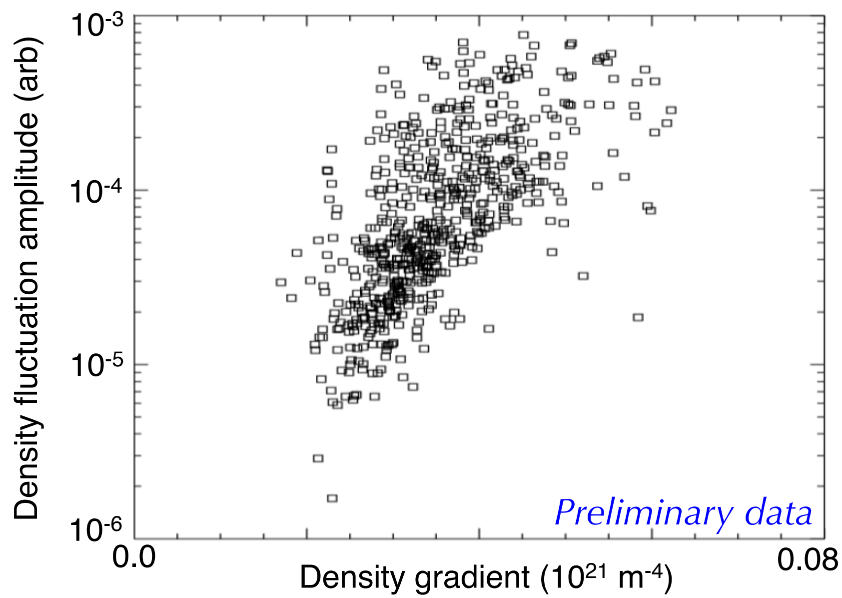
- Broadband fluctuation reduction with PPCD
- Except around 100 kHz

∇n-driven TEM likely source of micro-instability

- GENE predicts positive linear growth rate for TEM
- $k_\phi \rho_s$ ~ 0.2 comparable to measurement

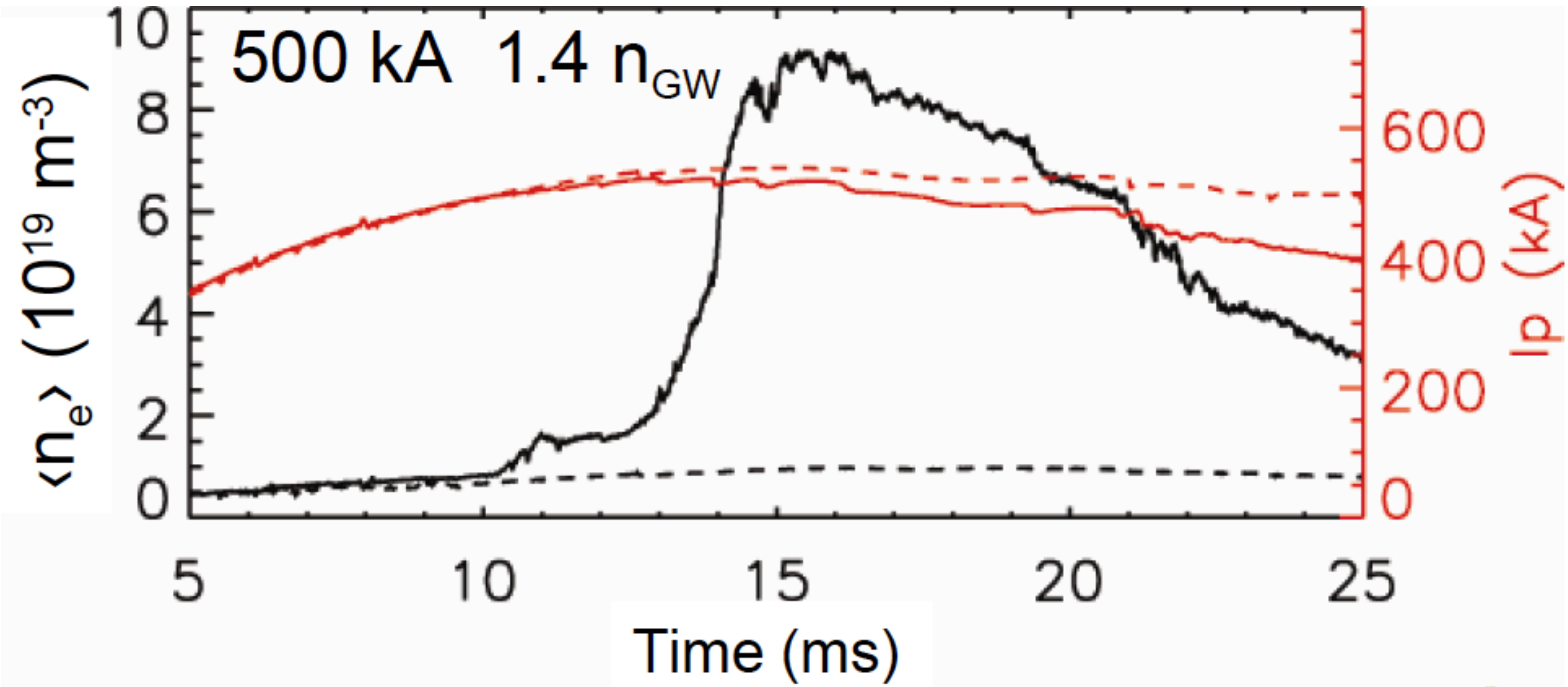


- ñ increases with local ∇n



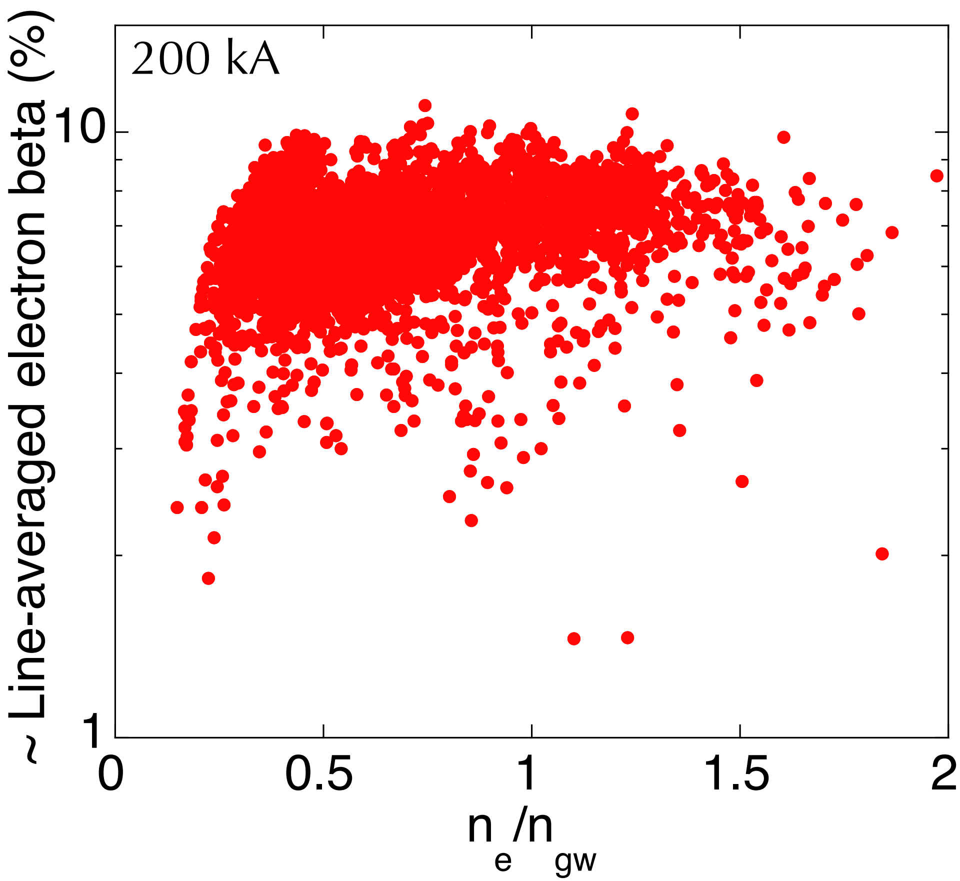
OV/5-1: P. Terry, "Overview of Gyrokinetic Studies on Electromagnetic Turbulence"

With pellet fueling of PPCD plasmas, Greenwald limit surpassed



- Non-disruptive

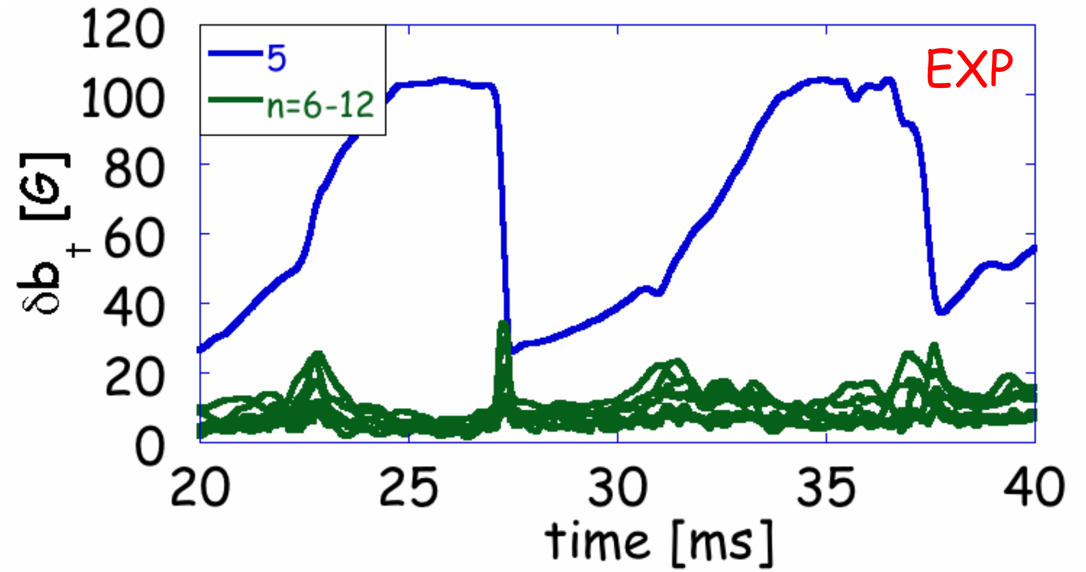
Large β with pellet injection, but β saturates

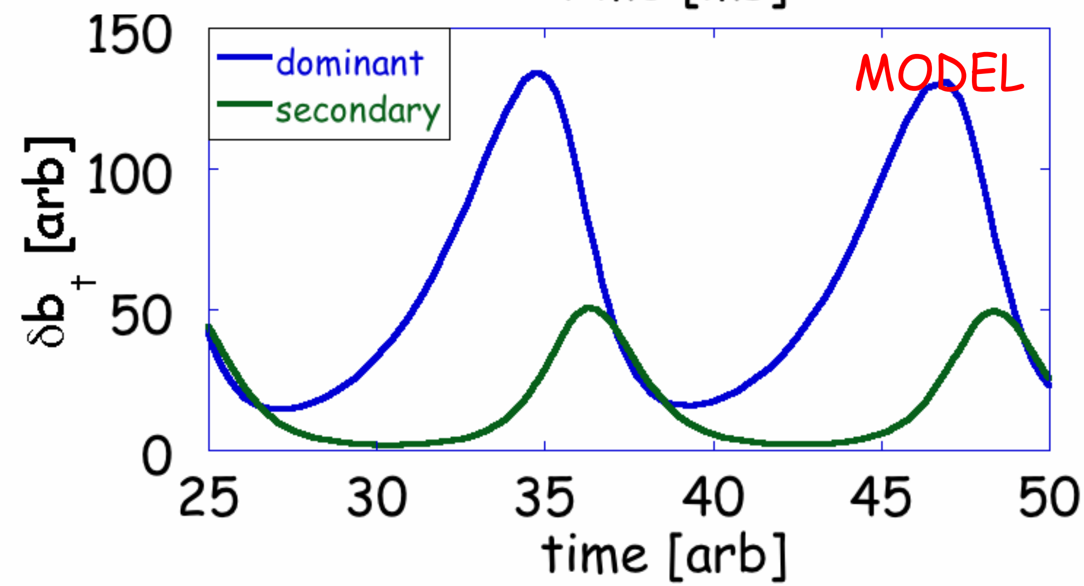


- β limit in RFP not previously established
- P_{oh} increases with density (3x increase here)
- Magnetic fluctuations also increase with density
- But without disruptions
- β limit "soft"
- Thus far, largest total β ~ 28% (thermal+non-thermal)

Results connected to 3D helical equilibria

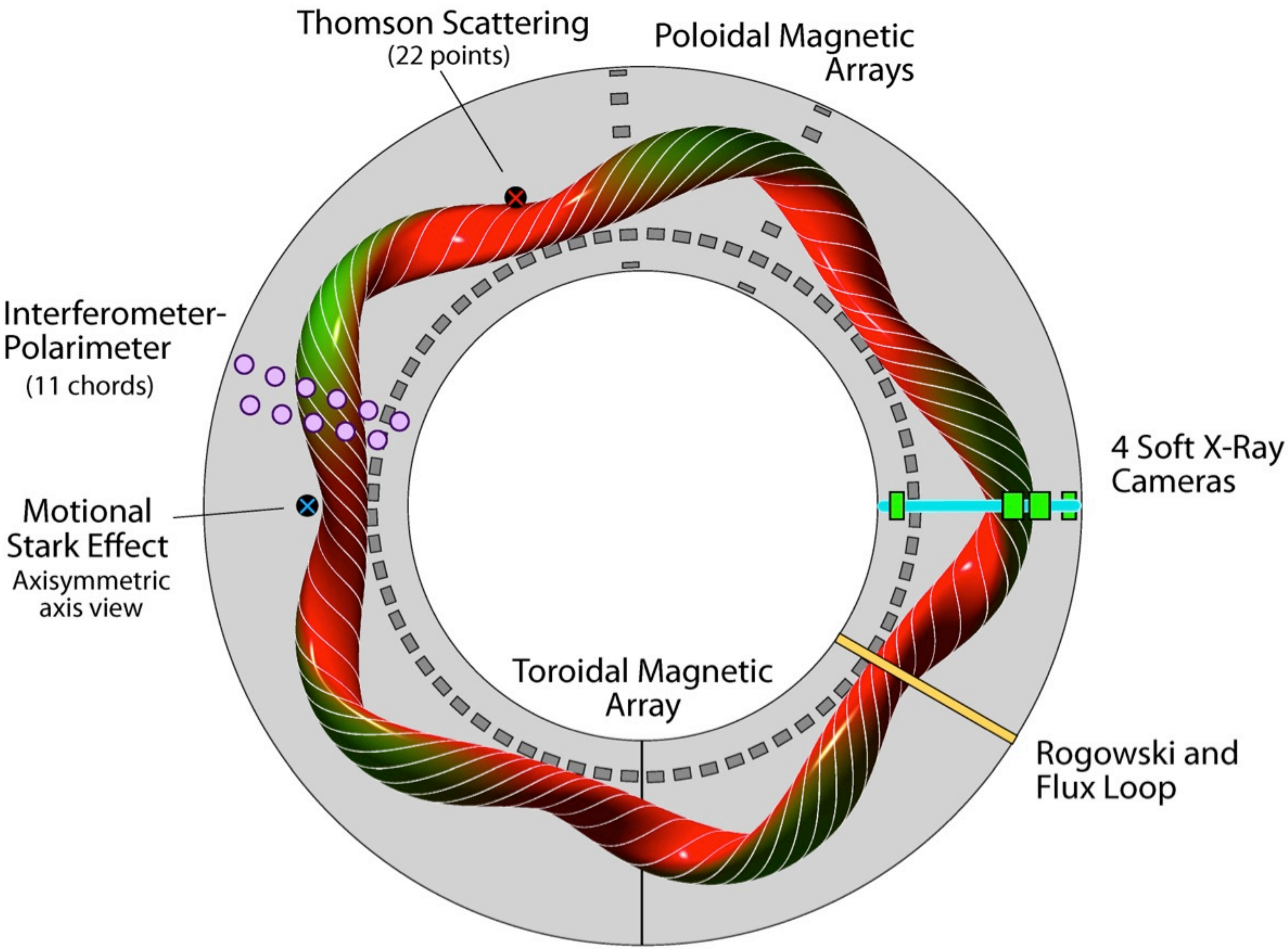
New theory for emergence and lifetime of 3D state





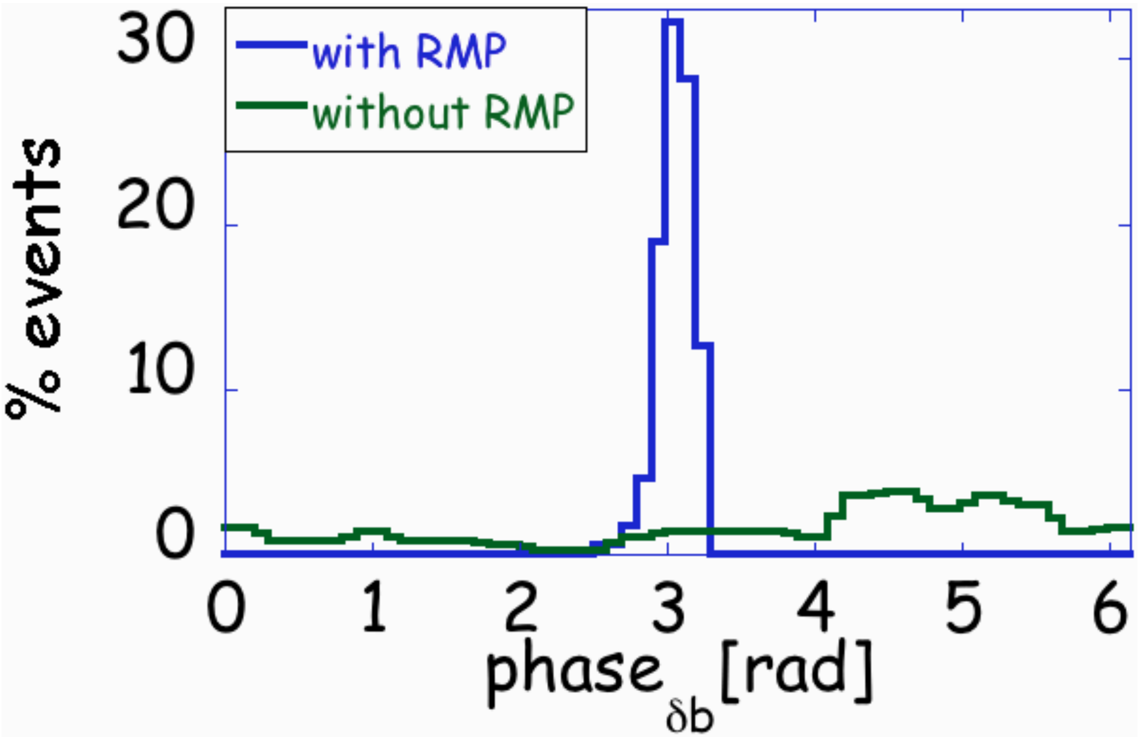
- 3D state emergence (at high Ip) & sustainment not entirely understood
- New model treats dominant mode as coherent vortex
- Sustained by magnetic, velocity shear
- Model captures expt. dynamics

MST well suited for diagnosis of 3D structure



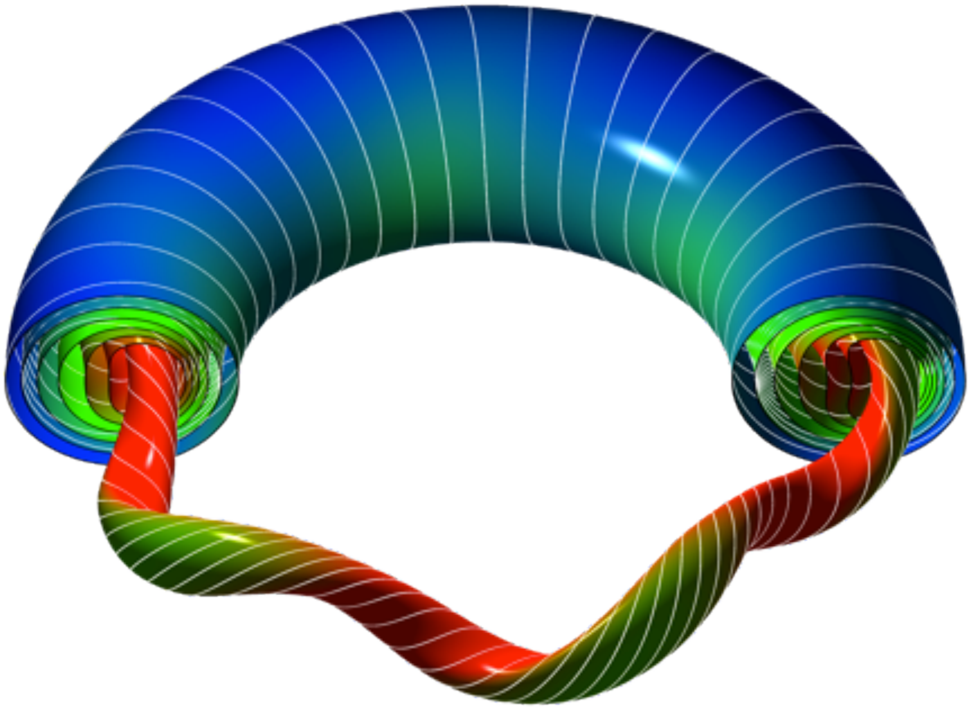
- But structure orientation not always ideal…

m = 1 RMP controls structure orientation



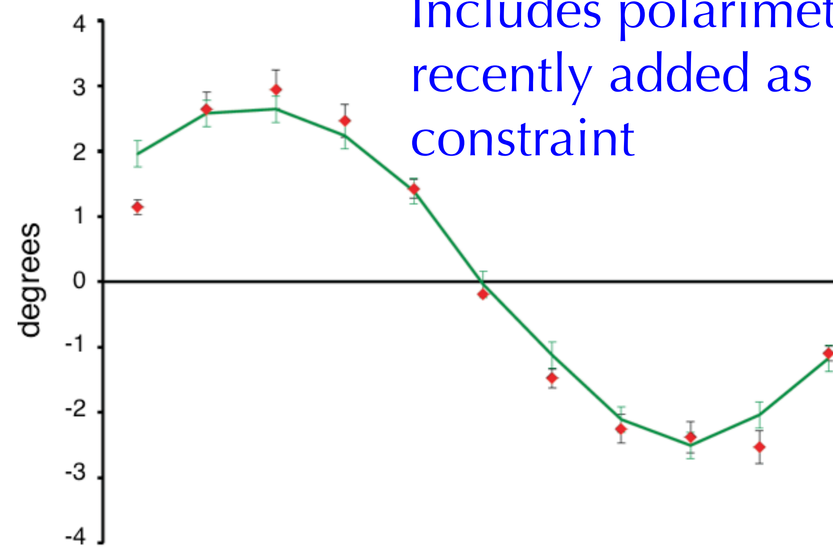
- Large single mode leads to locking due to eddy current in shell
- Tailored RMP waveform controls locking phase

V3FIT successfully applied for MST



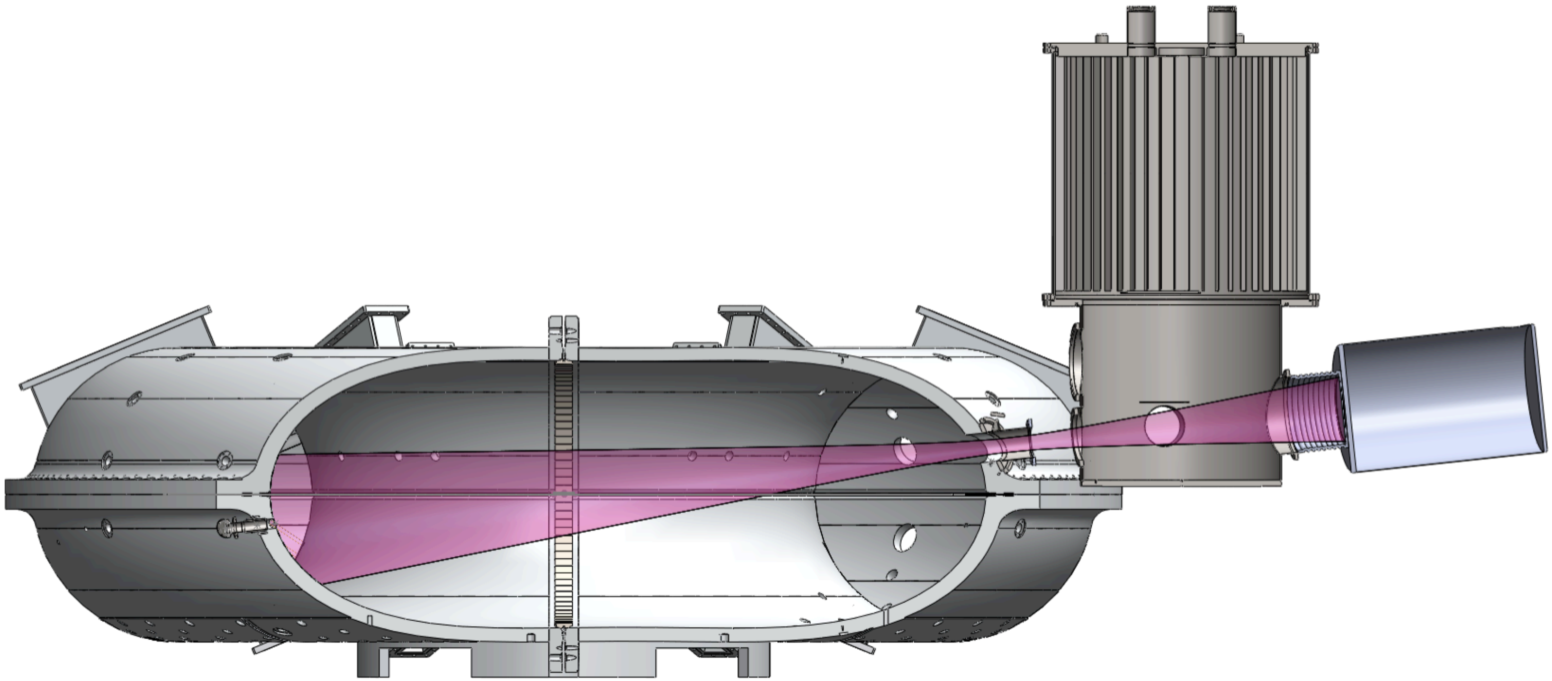
- Needed tool for 3D reconstruction in RFP
- Opportunity to test and advance stellarator tool

Includes polarimetry, recently added as constraint



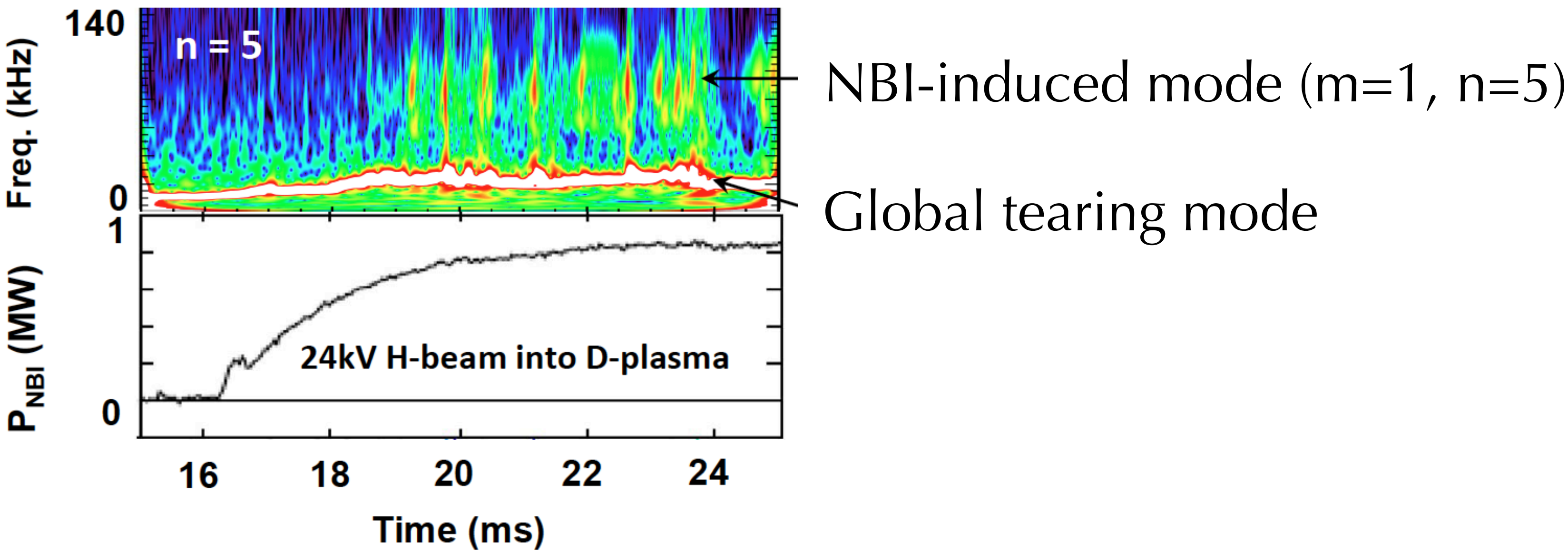
Results connected to fast ion physics

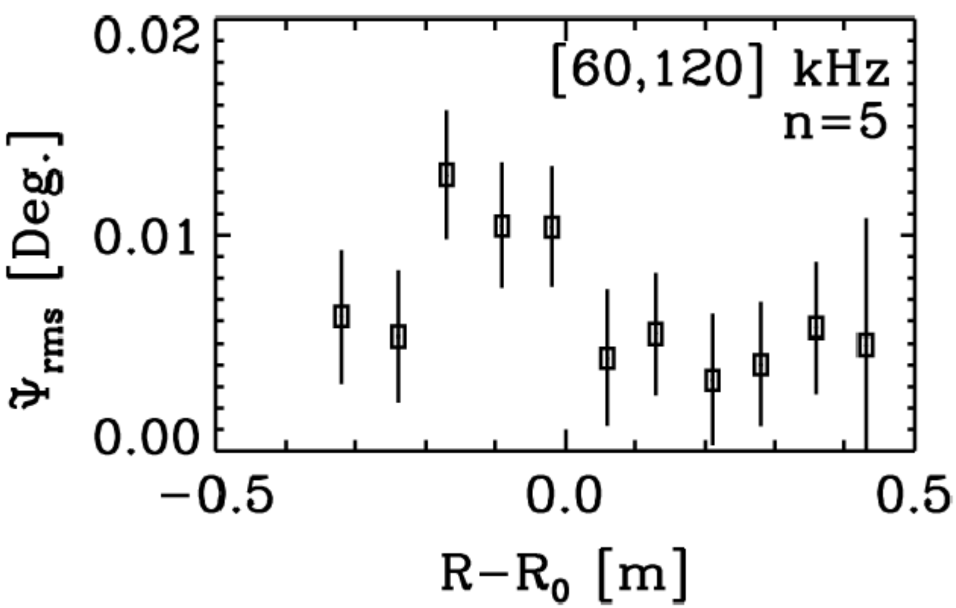
Tangential NBI a new control tool for RFP



NBI Parameter	Specification
Beam energy	10-25 keV
Beam power	1 MW max
Pulse length	20 ms
Composition	95% H, 5% D

Internal $\tilde{b}$ from EP mode measured for first time



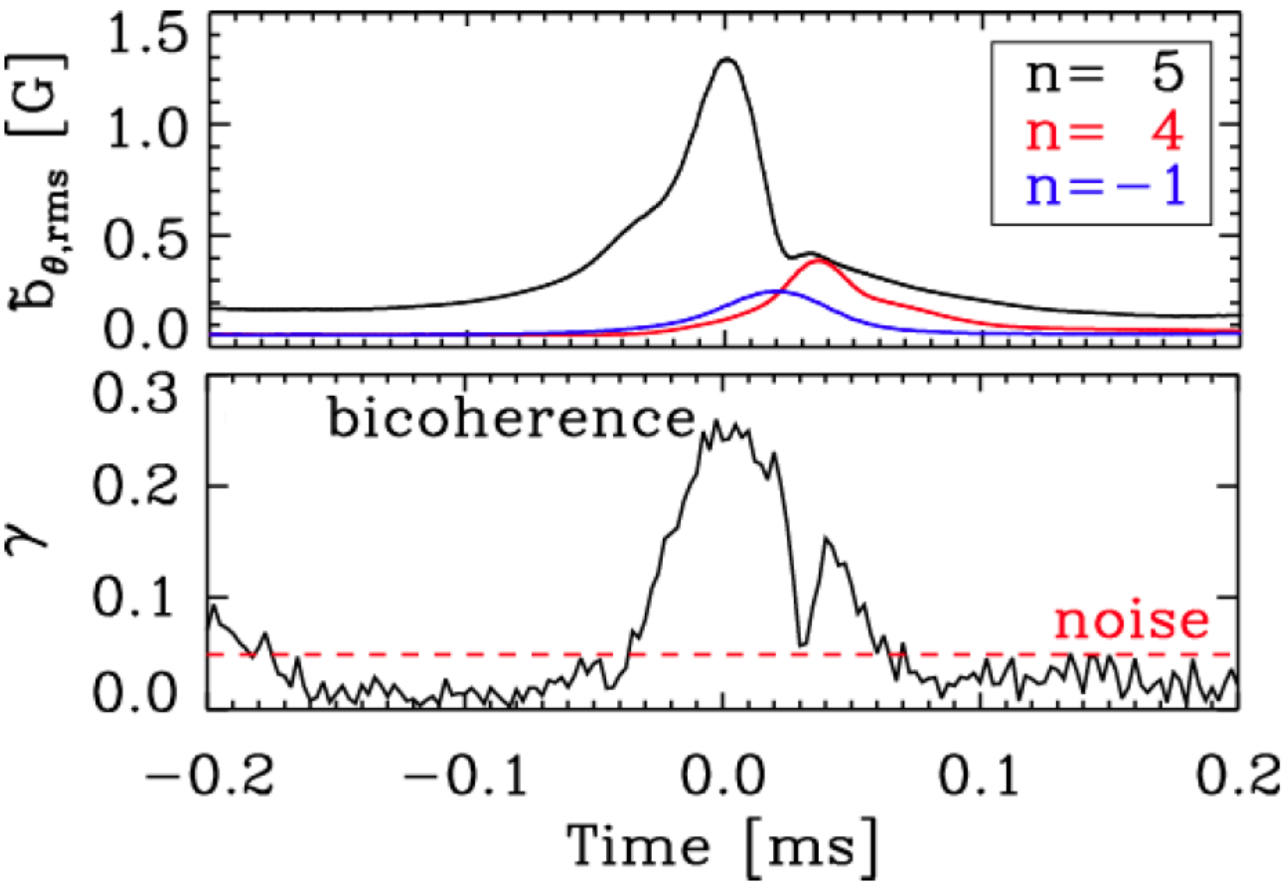


Faraday-effect:

$$\tilde{\Psi}_p = \underbrace{c_F \int \tilde{n}_e B_{z0} dz}_{\tilde{\Psi}_{\tilde{n}}} + \underbrace{c_F \int n_{e0} \tilde{b}_z dz}_{\tilde{\Psi}_{\tilde{b}_z}}$$

$$\boxed{\bar{\tilde{b}}_z = \tilde{\Psi}_{\tilde{b}_z} / (c_F \int n_{e0} dz)}$$

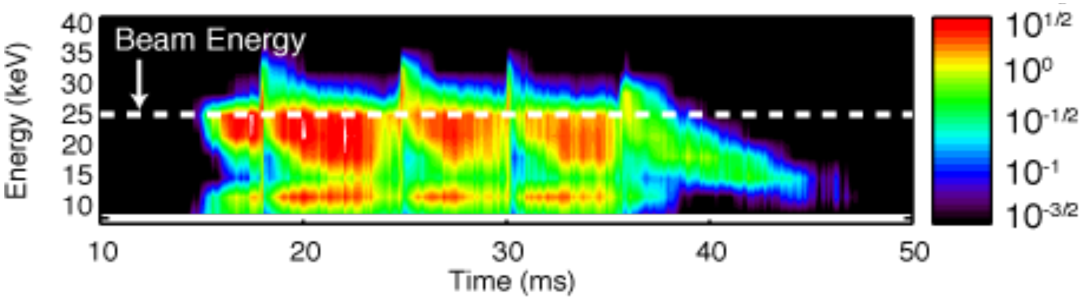
Three-wave coupling occurs between NBI-driven modes



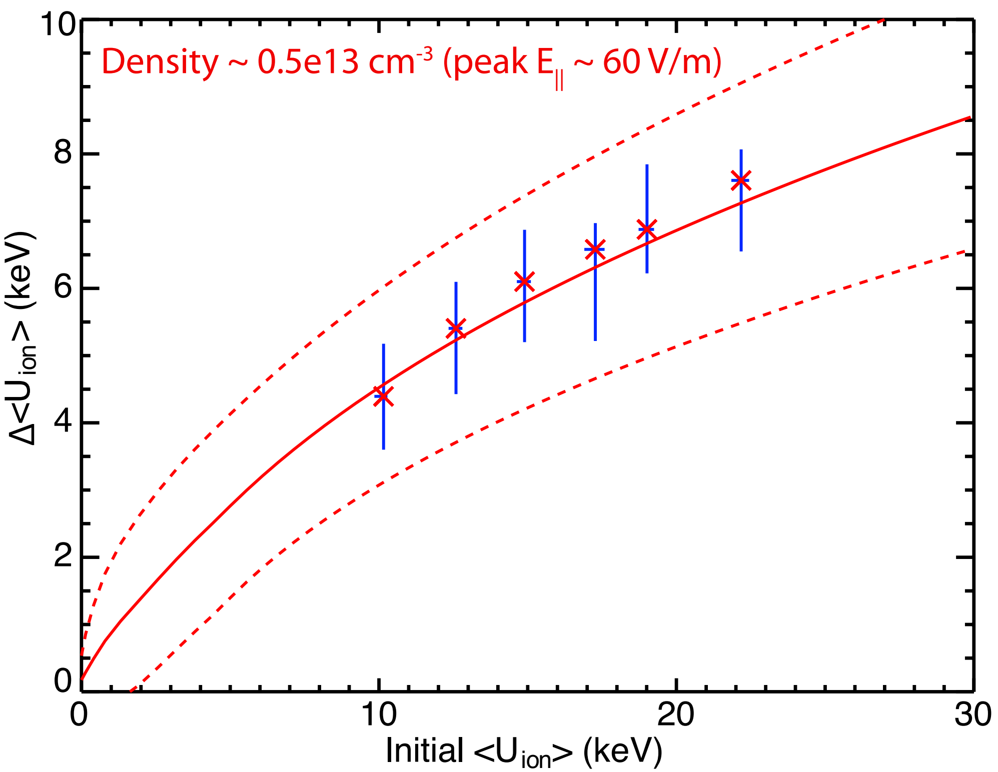
$$\gamma_{-1,4,5} = \sqrt{\frac{\left|\left\langle \tilde{b}_{n=-1}\tilde{b}_{n=4}\tilde{b}_{n=5}\right\rangle\right|^2}{\left\langle\left|\tilde{b}_{n=-1}\tilde{b}_{n=4}\right|^2\right\rangle\left\langle\left|\tilde{b}_{n=5}\right|^2\right\rangle}}$$

- Enhanced fast ion loss rate observed during such coupling

Fast ion runaway at global reconnection events



- From neutral particle analyzer



- $E_{//}$ due to global inductive change
- Increase in fast ion energy depends on initial energy
- Behavior as expected for runaway ions (accelerating field stronger than frictional drag)

Summary

- Micro-instability (TEM) in low-density PPCD plasmas
- $n_e > n_{GW}$ with pellet injection, without disruption
- High β, with transport-based, soft limit

- New theory to explain 3D equilibria
- Control of structure orientation with RMP
- Reconstruction with V3FIT

- Measured internal magnetic fluctuation structure of EP mode
- Three-wave coupling
- Runaway of fast ions at reconnection events