Supported by Office of Science

NSTX error field results
(and needed modeling capabilities)

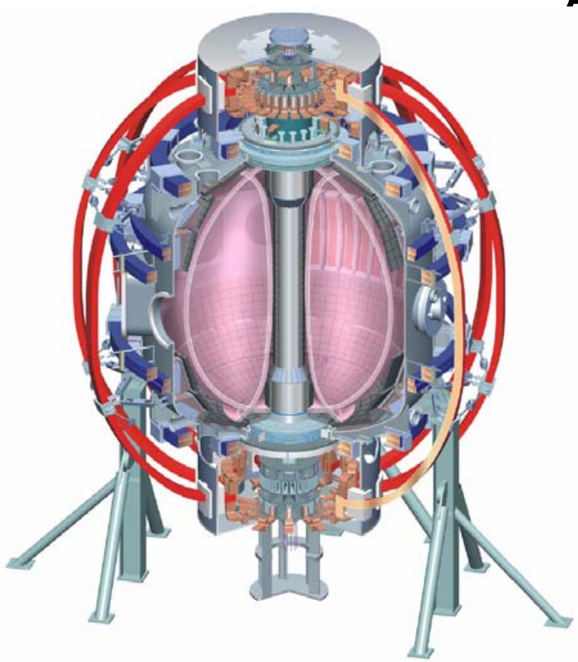
J. Menard

MHD SFG Meeting

April 19, 2006

PPPL

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

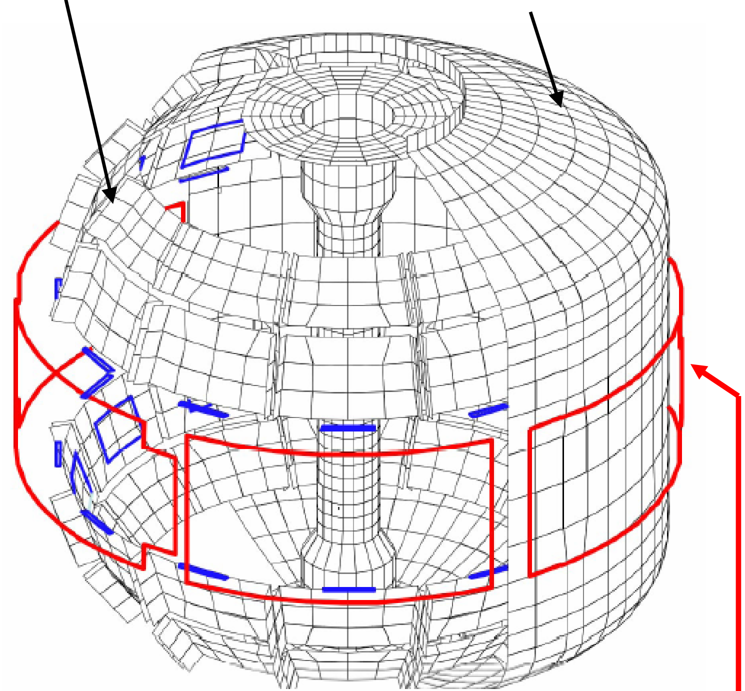


Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

6 non-axisymmetric RWM/EF coils and 3 switching power amplifiers (SPA) used in experiments

Copper passive conductor plates

SS Vacuum Vessel

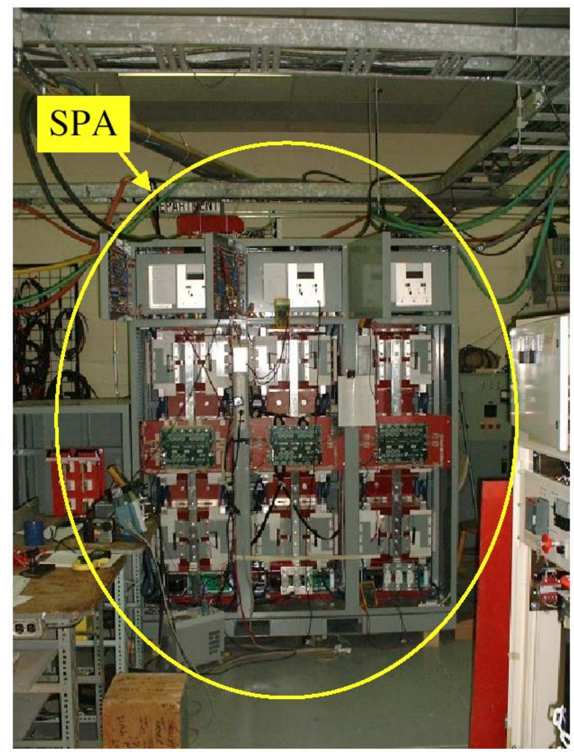


VALEN Model of NSTX (Columbia Univ.)

6 ex-vessel midplane control coils
+ 24 B_R and 24 B_P in-vessel sensors

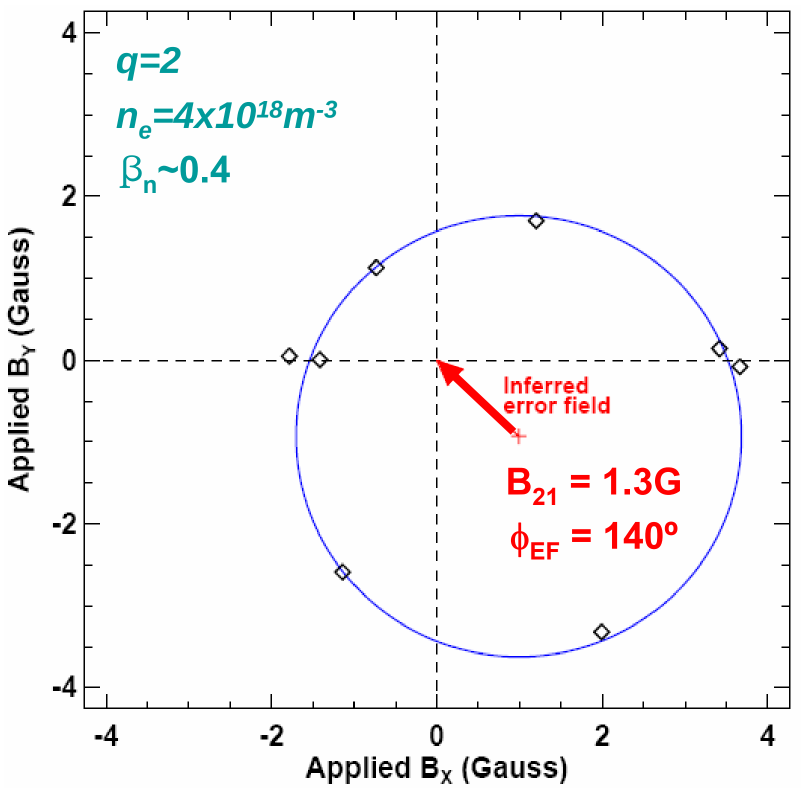
NSTX RWM/EF coil and SPA capabilities:

- 3 opposing coil pairs in anti-series (n=1, 3)
  - n=2 interconnection also possible
- 3 independent SPA circuits – 3.3kA, 7.5kHz
- Can produce 10-15G n=1 resonant $B_\perp$ at q=2
- EF correction, magnetic braking, feedback

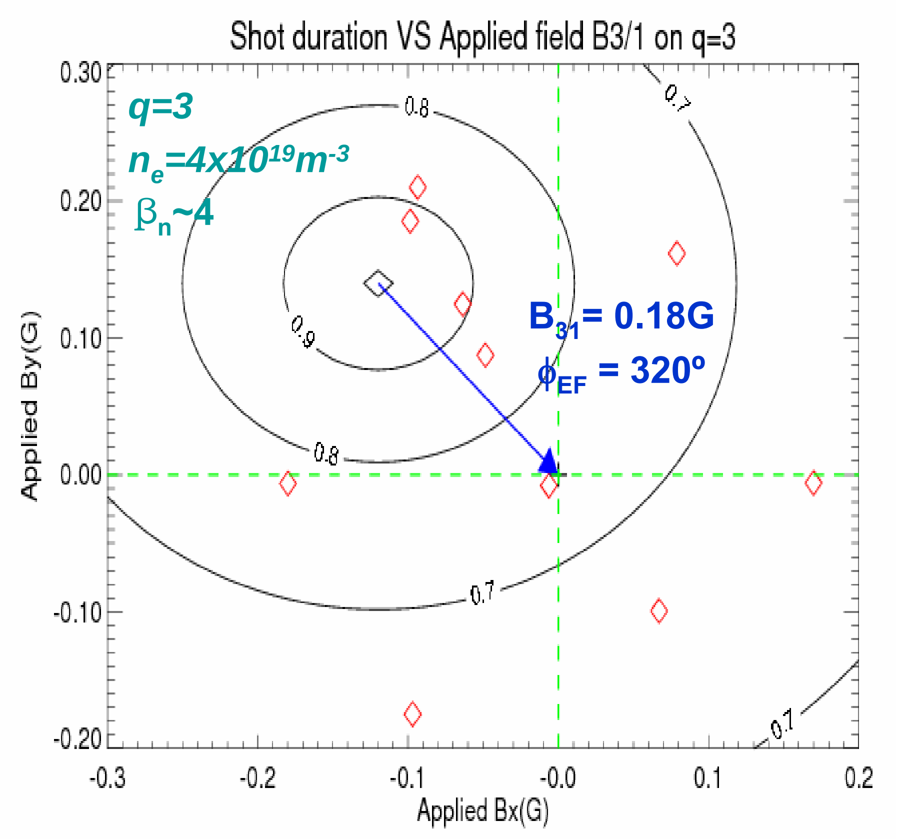


Error-field inferred from high-β experiments has direction <u>opposite</u> to that obtained at low n_e & β

Inferred 2/1 EF at Low-β

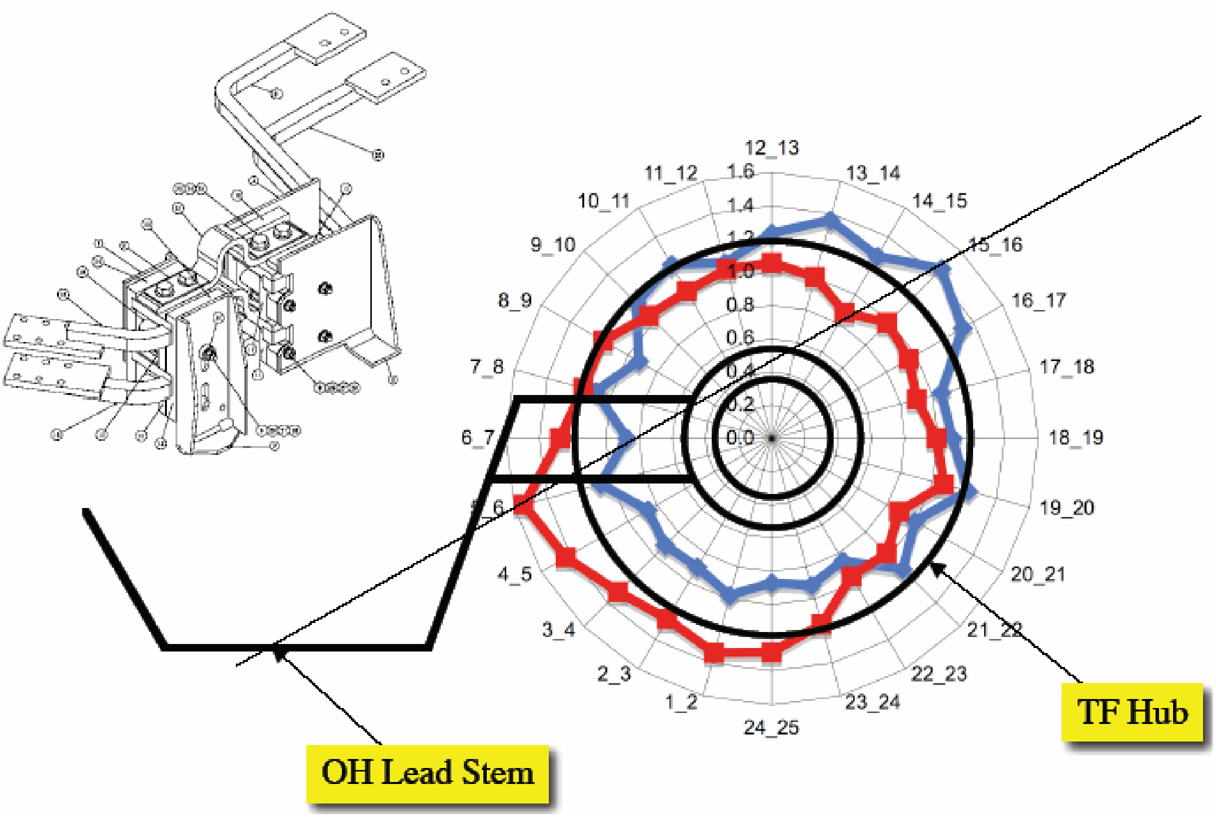


Inferred 3/1 EF at High-β

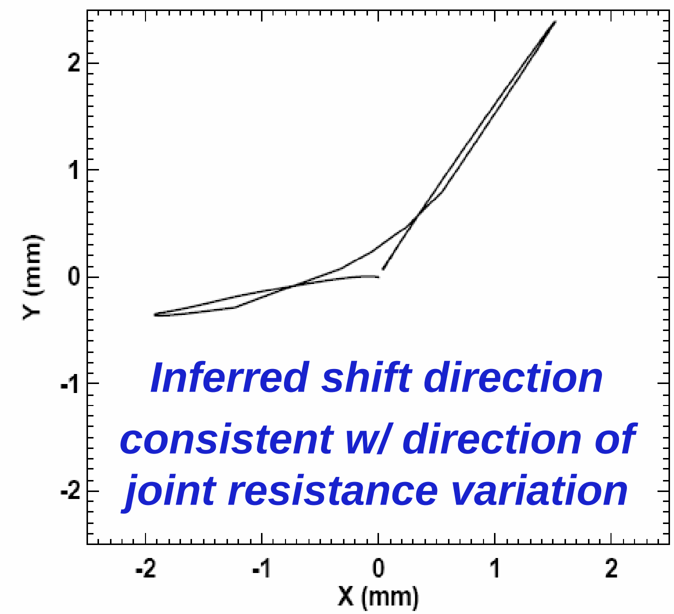


⇒ additional EF source is present, or EF is not static

TF flag-joint resistance measurements imply interaction between OH transformer and TF coil ⇒ TF motion



Magnetics measure n=1 radial field ∝ I_{OH} x I_{TF} ⇒
Can infer TF shift direction:



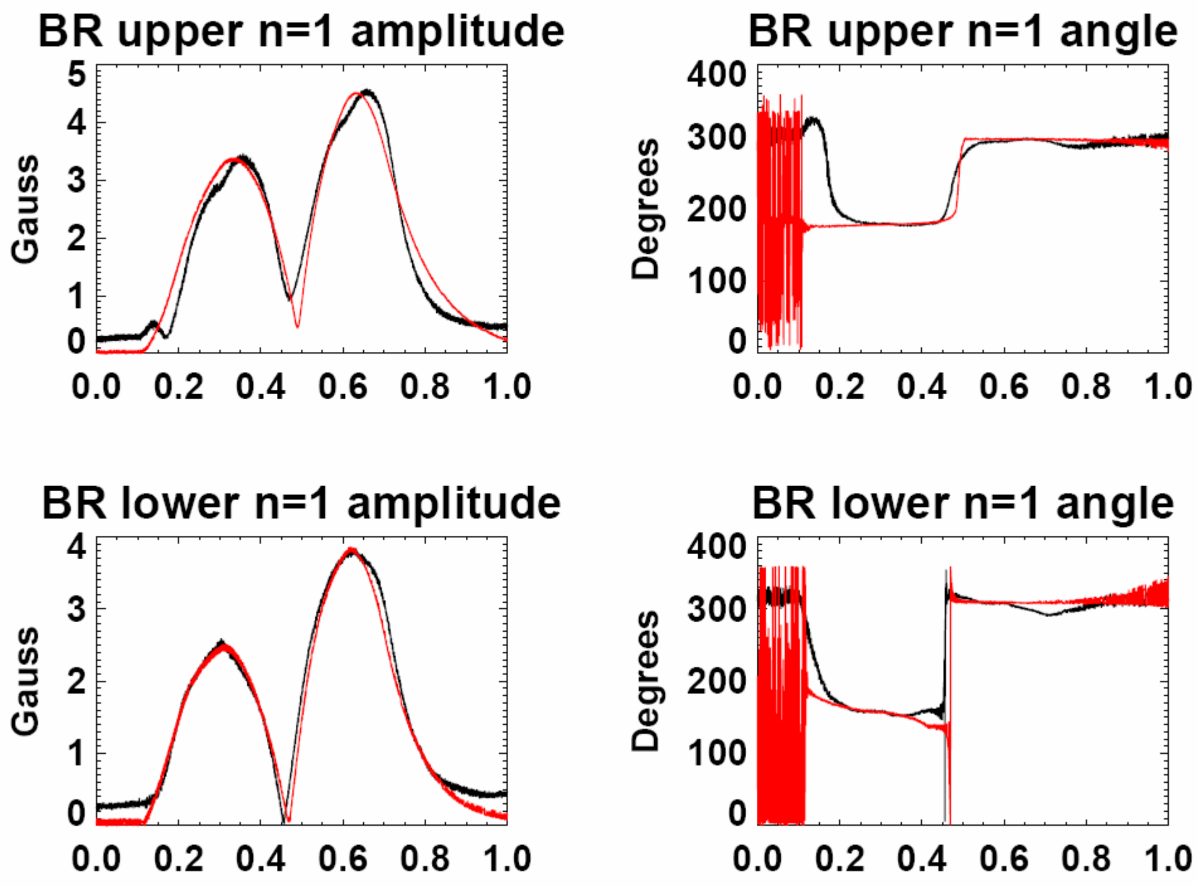
Accumulated data strongly suggests OH/TF interaction causes TF motion which creates a time-dependent error field that varies throughout shot <u>even when all other plasma parameters and coil currents are fixed</u>

Accurate modeling of n=1 B_R error field from OH×TF requires inclusion of time lag and polarity dependence

NSTX

- Have developed TF model allowing **both shift and tilt** – 4 degrees of freedom
- Filter time-constant of approx. 100ms needed to capture time lags (inertia?)
- **Prediction of EF at sensor → prediction of EF in plasma**

Measured
& Simulated
error field
at sensors

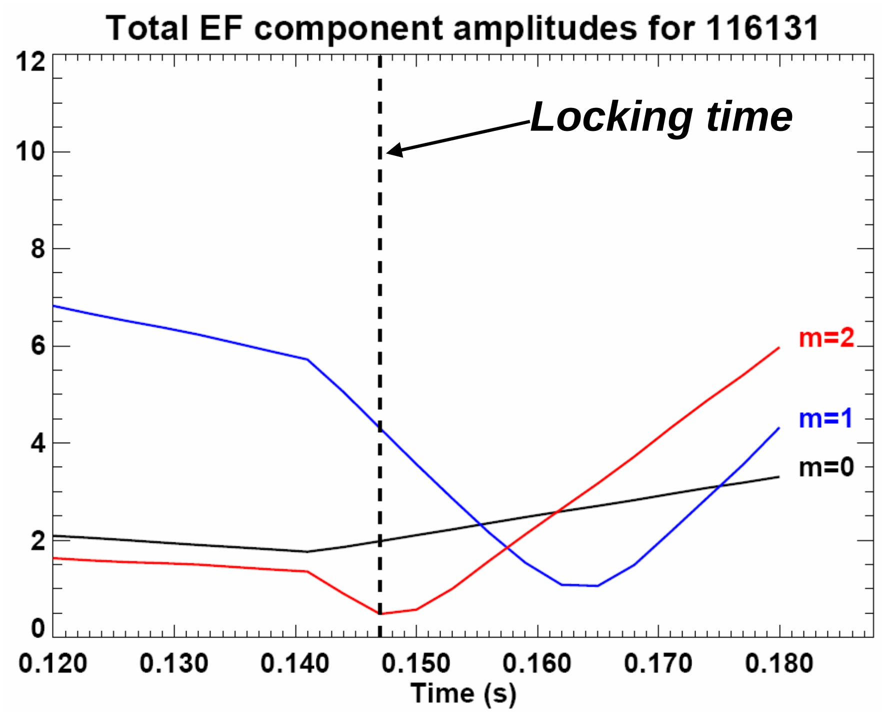


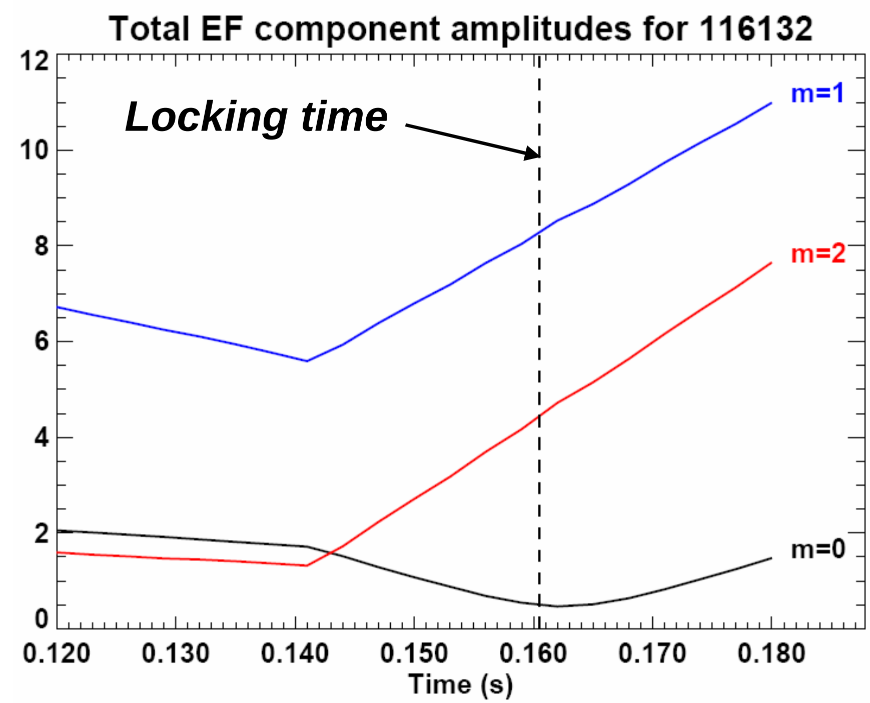
Locked-mode experiments indicate m=0 EF component may dominate rotation damping & locking

NSTX

Assuming I have all the signs correct…

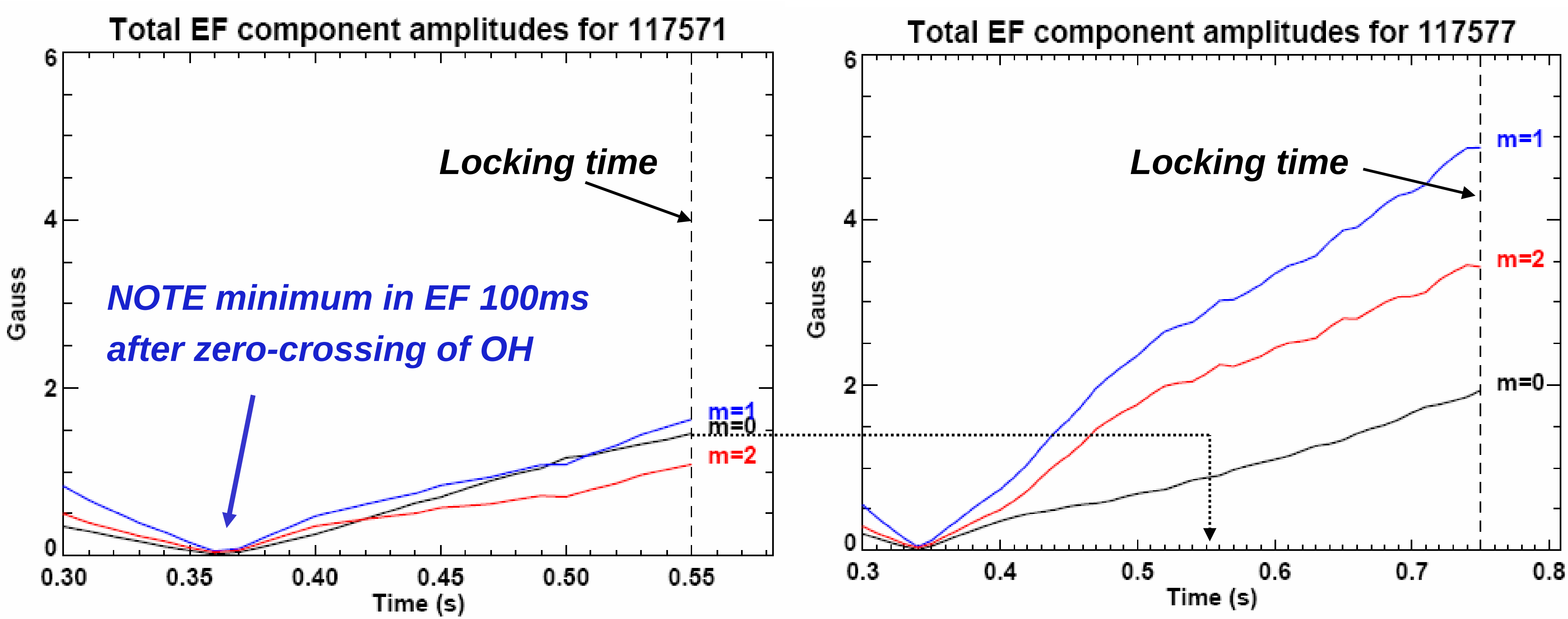
- m=1, 2 components ***larger*** in shot with later locking
- But, m=0 is reduced in shot with later locking
- NOTE: external EF is ramped linearly beginning at 140ms





High-beta experiments *also* indicate m=0 EF component may dominate rotation damping & locking

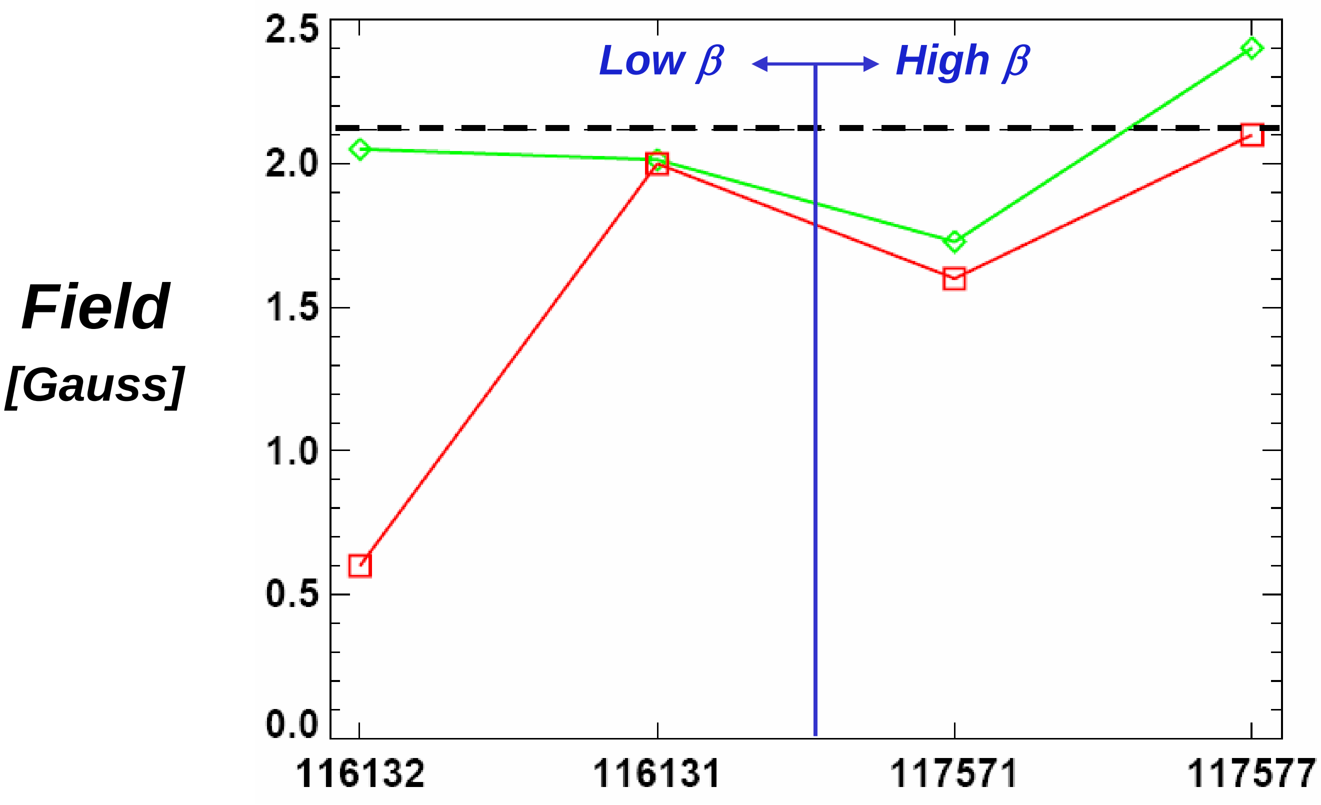
- NOTE: external EF reaches flat-top at 500ms
- m=1, 2 components are again ***larger*** in shot with later locking
- m=0 is again reduced in shot with later locking



Low and high-beta data can be used to compute empirical scaling for locking disruption threshold

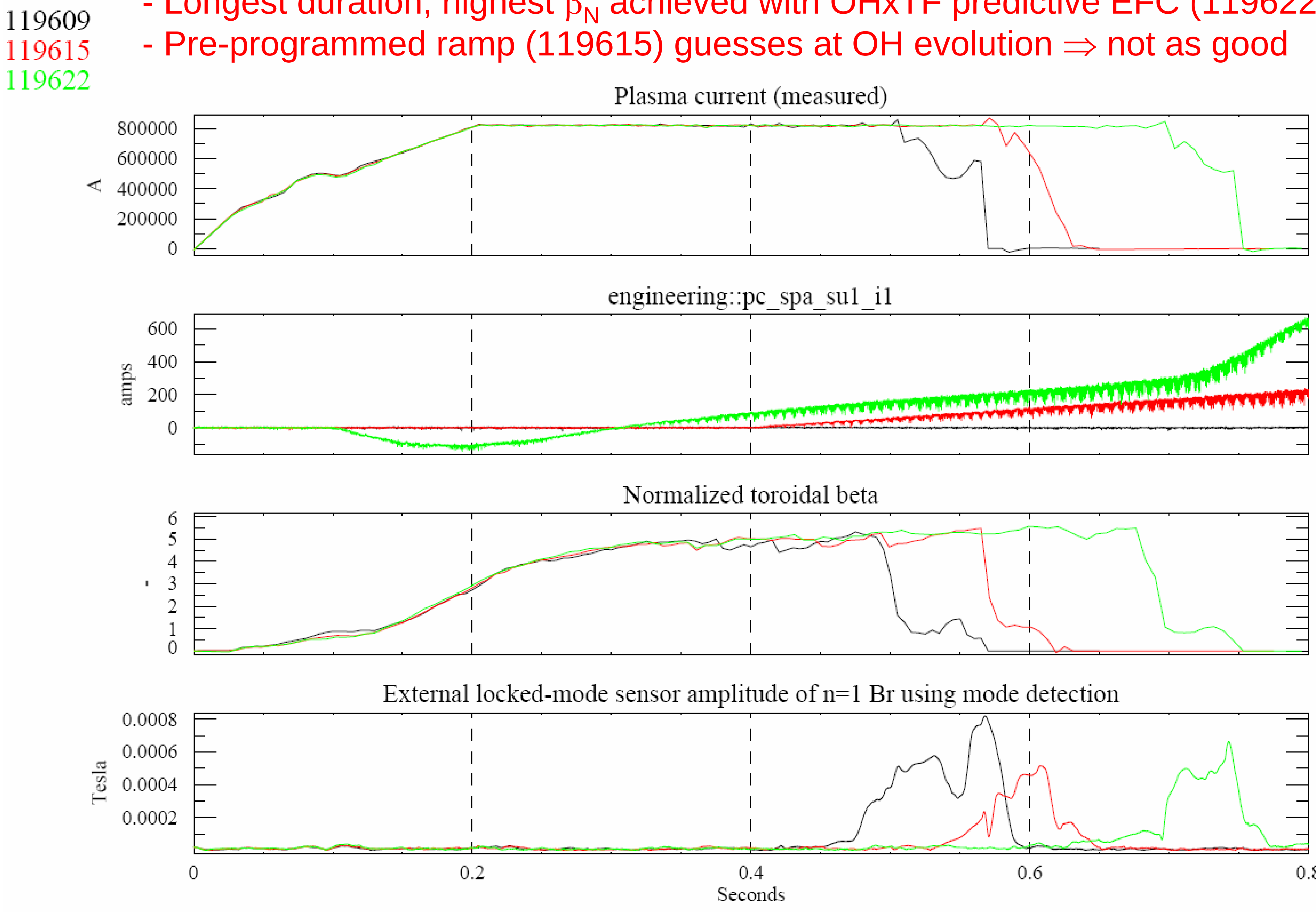
- **Empirical threshold: $\sqrt{B^2_{m=0} + 0.22\times B^2_{m=2}} < 2.1$ Gauss**
  - **Addition of m=1 component changes m=0+2 fit very little**

- Good fit with only m=0 and m=2 components: ± 12% variation
- Poor fit if only m=0 component is included: ± 38% variation



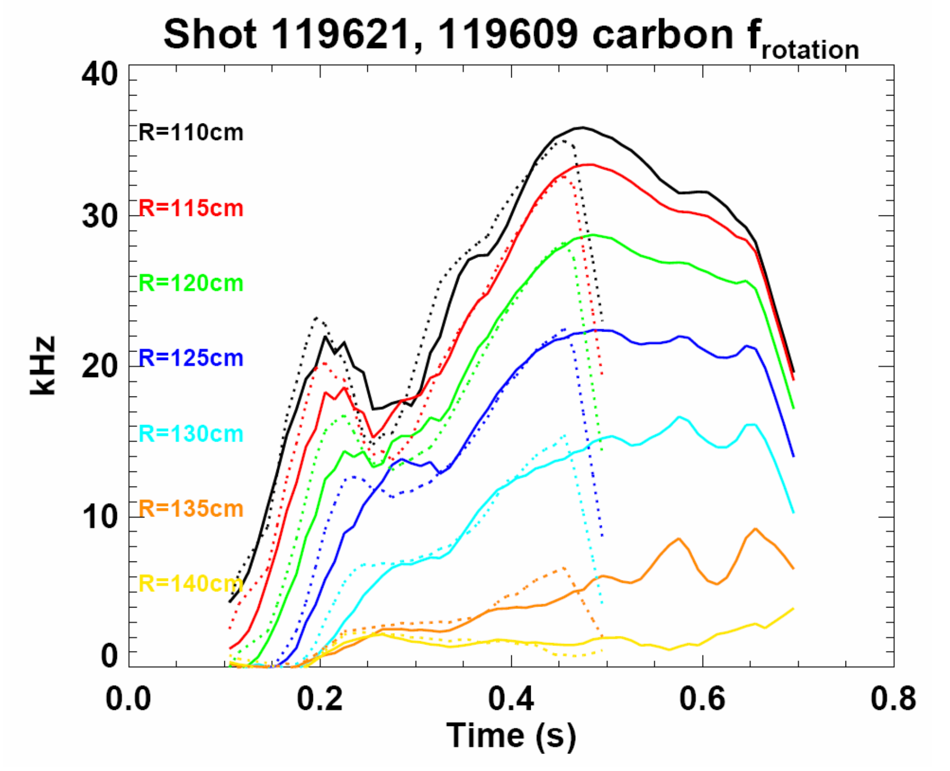
XP614: Comparison of EFC techniques at high β_N – Menard

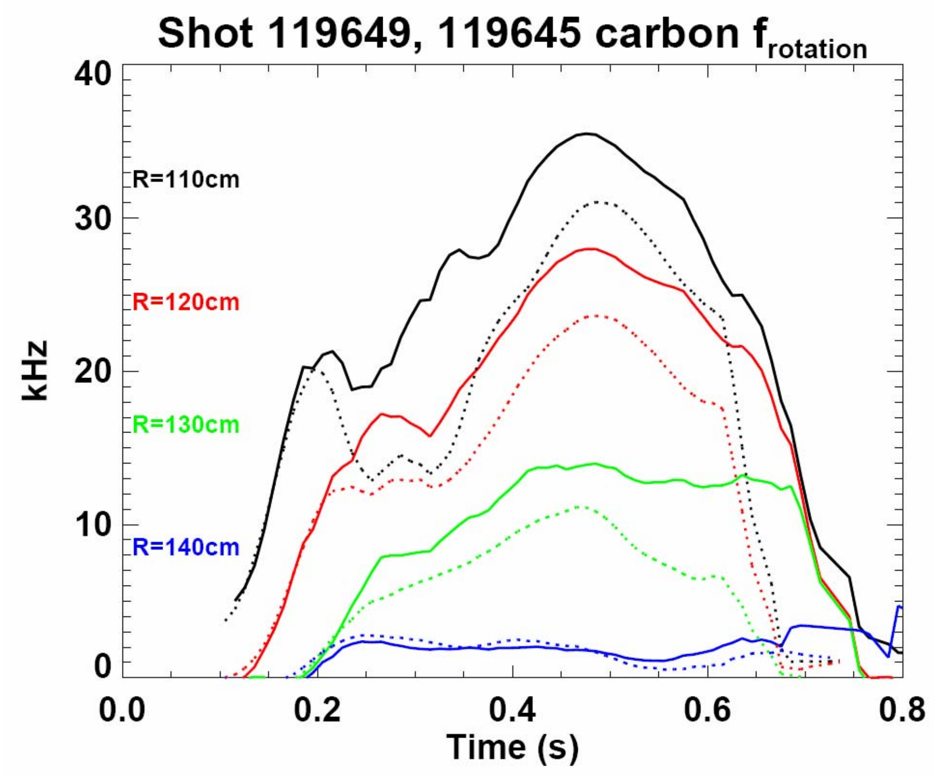
- Longest duration, highest β_N achieved with OHxTF predictive EFC (119622)
- Pre-programmed ramp (119615) guesses at OH evolution ⇒ not as good



Applying EFC sustains plasma rotation and can increase β
(119609 no EFC - dashed, 119621 w/ EFC - solid)

- Scan of EFC amplitude finds that optimal proportionality value (119649) results in higher rotation and beta than shot with non-optimal value (119645 - dashed)

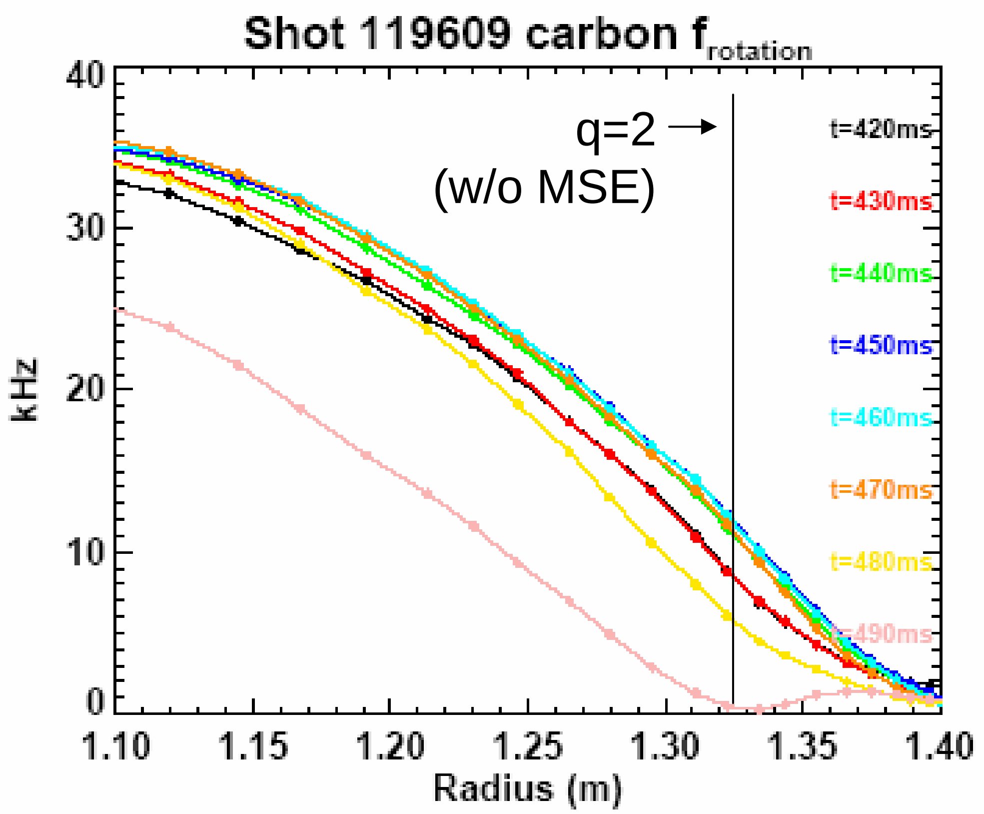




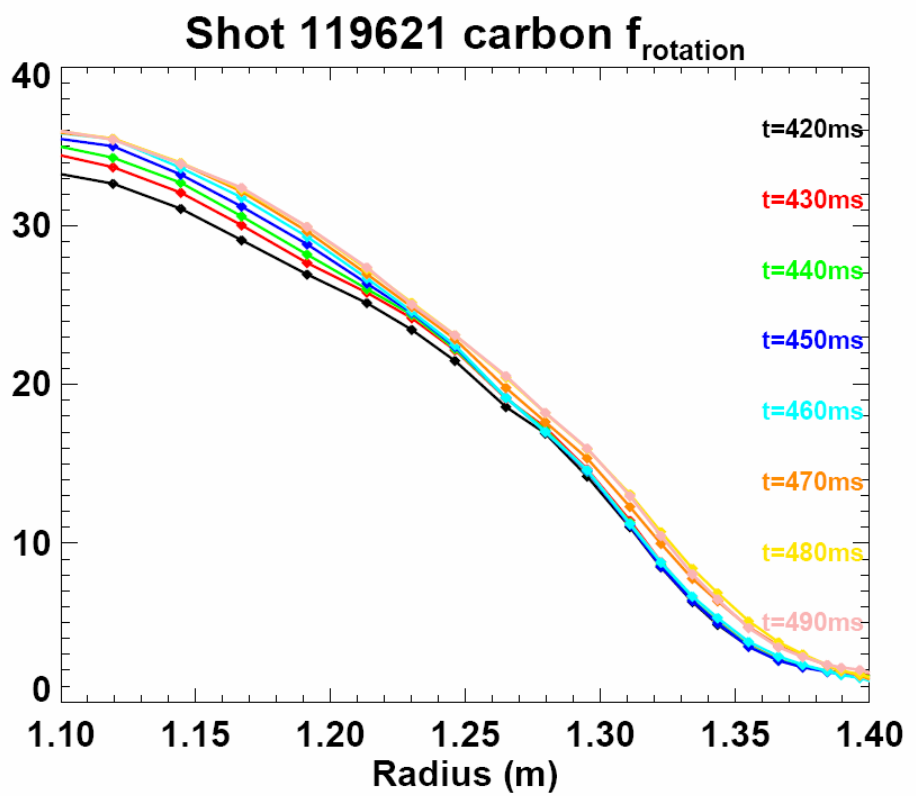
Rotation responds strongly to only 20% variation in EFC amplitude

Applying EFC keeps rotation high at location of q=2,3 surfaces

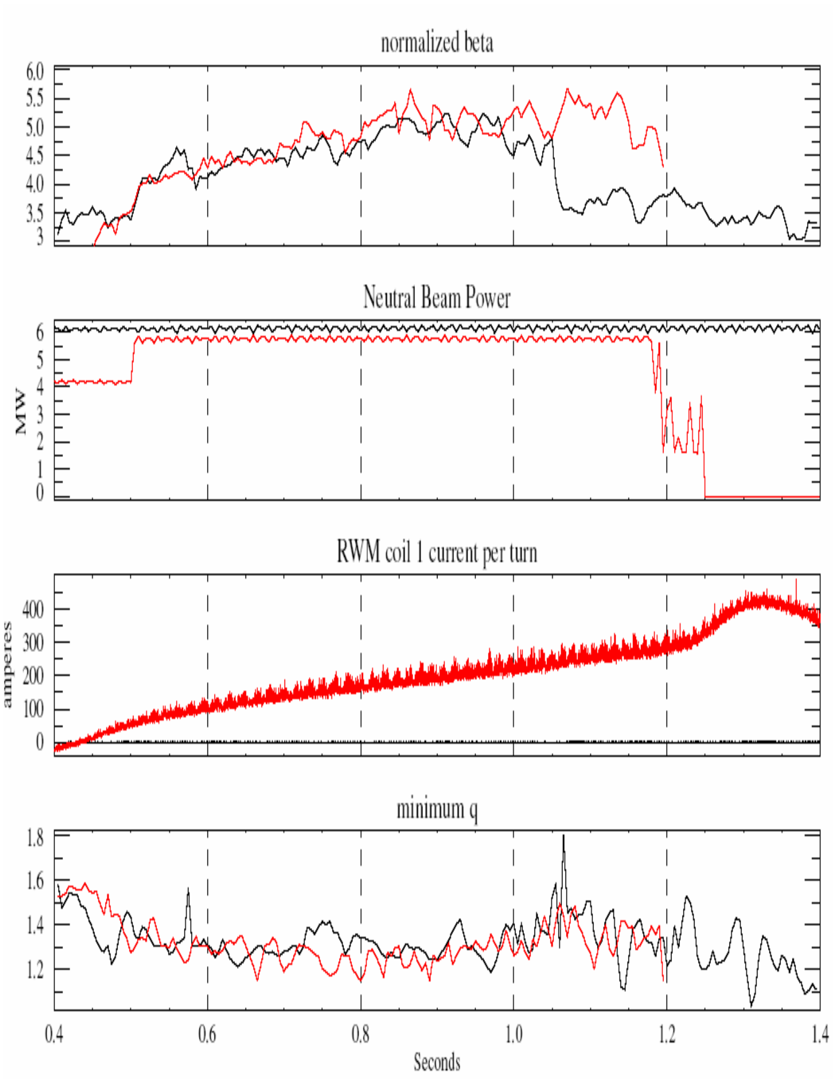
No EFC



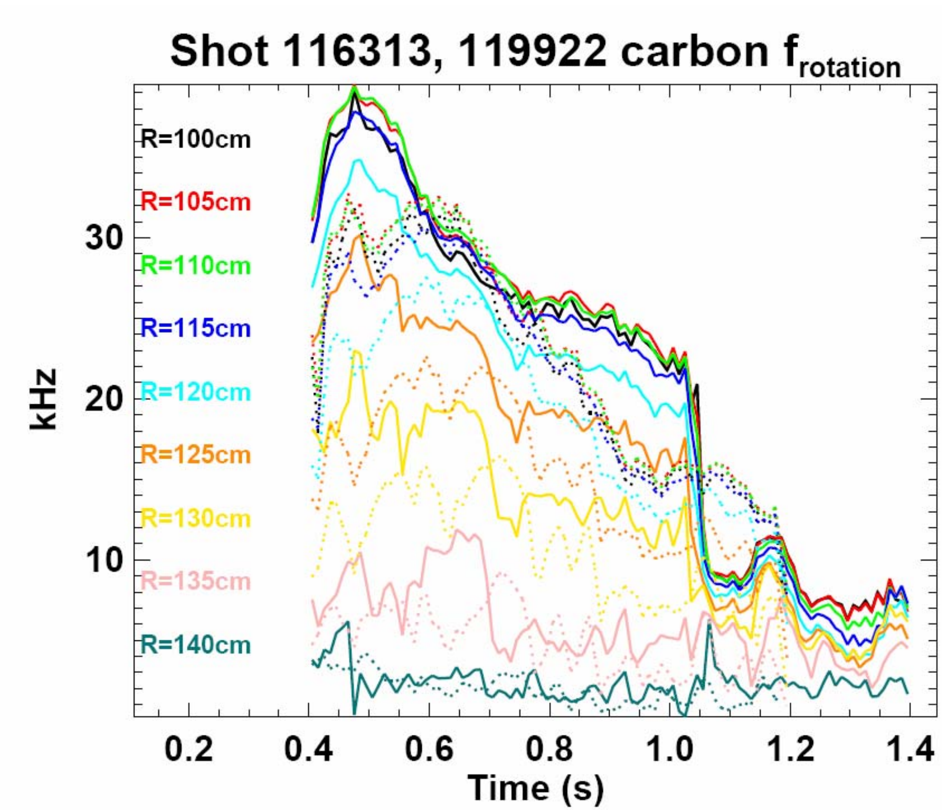
With EFC



High β_N phase is longer in recent 750kA long-pulse shots using EFC, but rotation is lower late in shot…

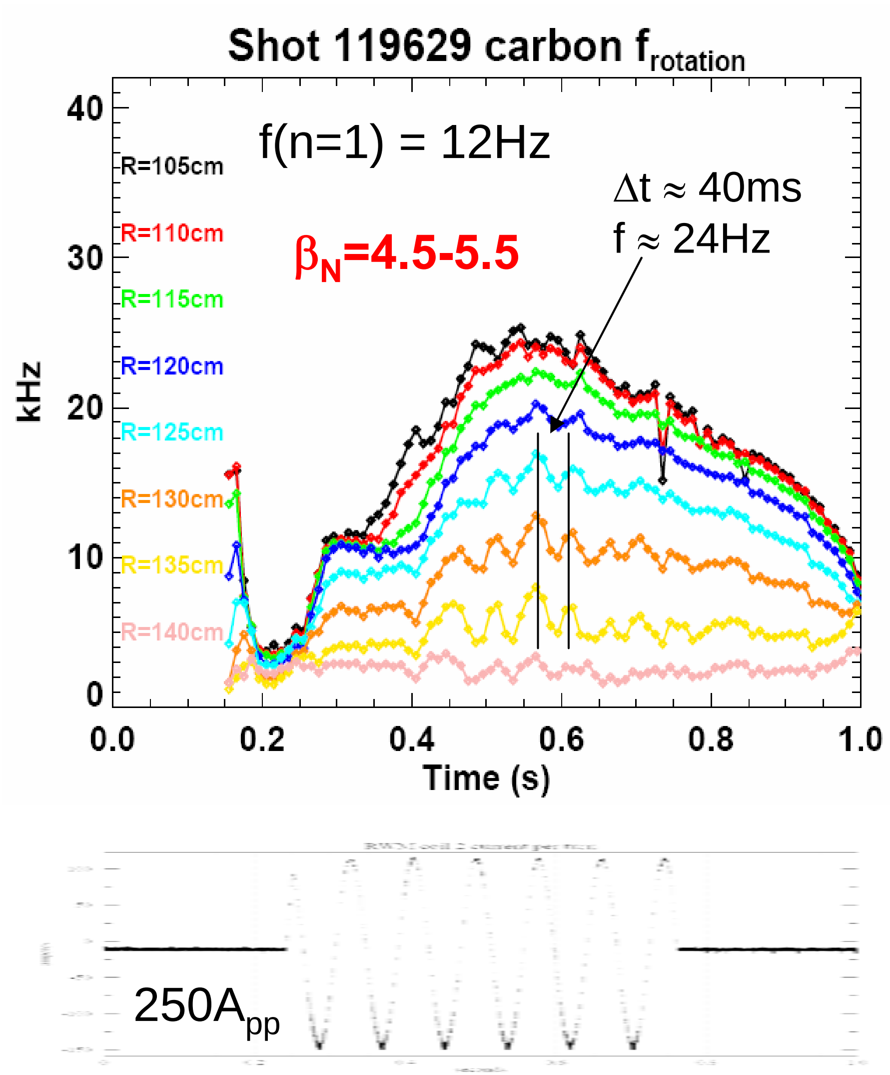


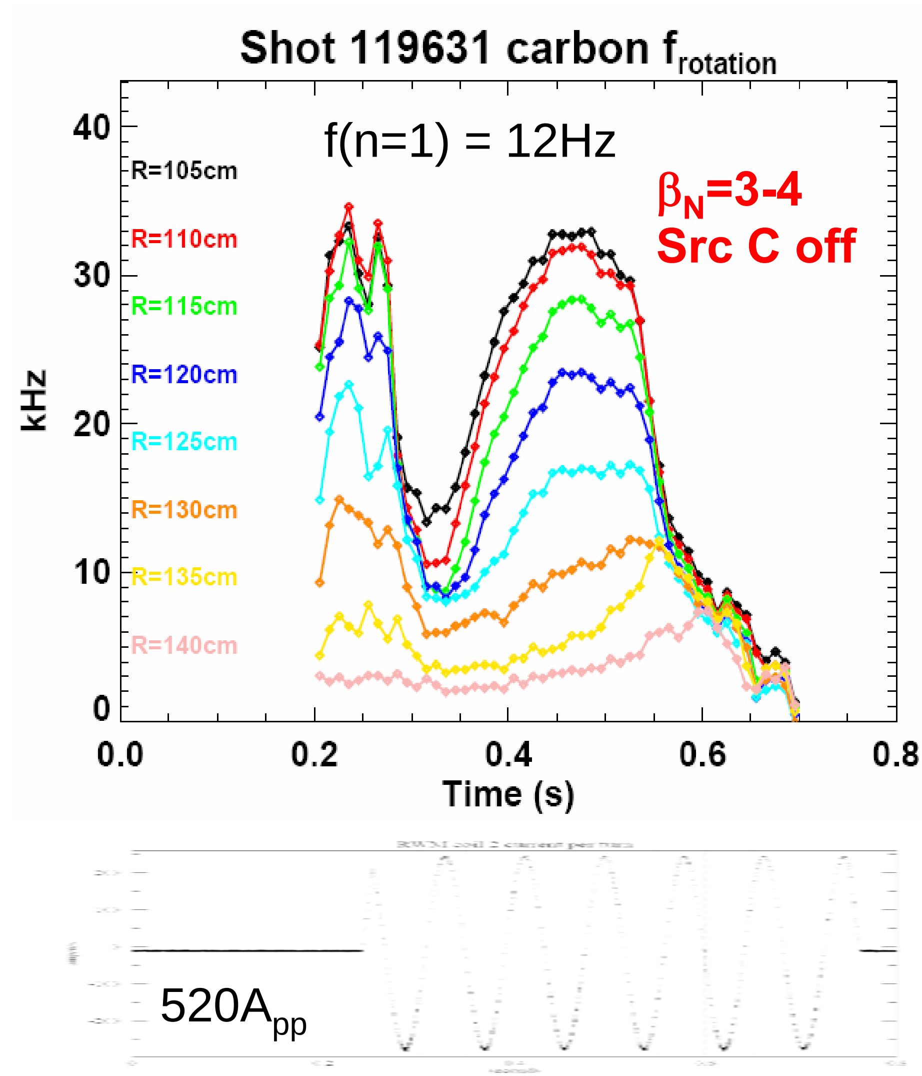
- After 800ms, rotation decreases with n=1 EFC current present
- Suspect EFC amplitude/phase is not optimal late in shot (higher I_{OH})
  - Similar trend seen in 1MA shots



XP618: Optimize error field correction vs. rotation – LaHaye, Strait

- Observe rotation modulation at 2nd harmonic of applied field
- Little to no rotation modulation observed below no-wall limit





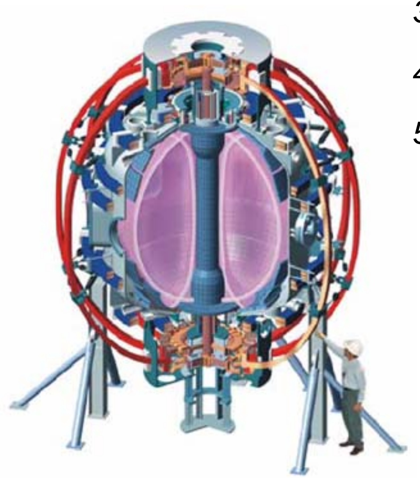
Supported by Office of Fusion Energy Sciences — Office of Science

Flow control and RWM physics in NSTX

Presented by J. Menard for:

S.A. Sabbagh[1], A.C. Sontag[1], W. Zhu[1], M.G. Bell[2], R. E. Bell[2], J. Bialek[1], D.A. Gates[2], A. H. Glasser[3], B.P. LeBlanc[2], F. Levinton[4], J.E. Menard[2], H. Yu[4], D. Battaglia[5], and the NSTX Research Team

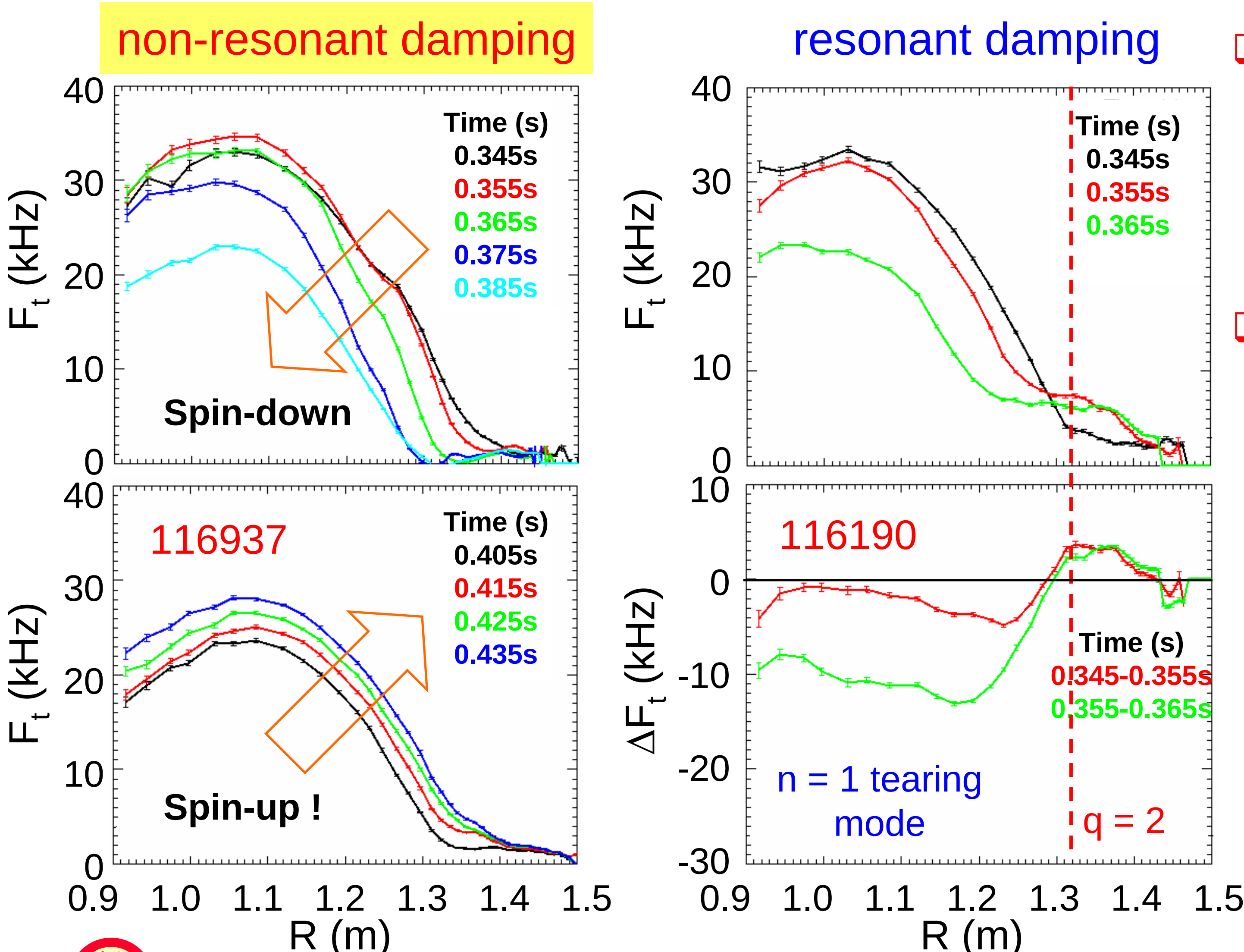
[1]*Department of Applied Physics, Columbia University, New York, NY*
[2]*Plasma Physics Laboratory, Princeton University, Princeton, NJ*
[3]*Los Alamos National Laboratory, Los Alamos, NM*
[4]*Nova Photonics, Inc., Princeton, NJ*
[5]*University of Wisconsin, Madison, WI*



US/Japan Workshop on MHD
February 8, 2006
Naka, Japan

Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
JAERI
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

Attention placed on studying non-resonant rotation damping physics



- Non-resonant
  - Global profile control by pulsing the applied field
- Resonant
  - Local JxB torque can explain damping by tearing modes
  - Outward momentum transfer across rational surface
  - Leads to rigid rotor core

Neoclassical toroidal viscosity (NTV) theory tested as non-resonant damping mechanism

Torque balance: $$-\rho R^2 \left(\frac{\partial \Omega_\phi}{\partial t} \right) = T_{\vec{J}\times\vec{B}} + T_{\mathrm{NTV}}$$

measured — computed

(Set = 0 here - tearing modes avoided.)

$$T_{NTV} = \mathrm{K} \cdot \left[R \frac{\pi^{1/2} p_i}{v_{t_i}} \Omega \varepsilon^2 \frac{1}{B_t^2} q \sum_{n,m\neq 0} \frac{\mu_{ps1} n^2 \left(b_r^{nm} \right)^2}{C_\nu + \mu_{ps1} \left| m - nq \right|} + T_{NTV}^{m=0} \right]$$

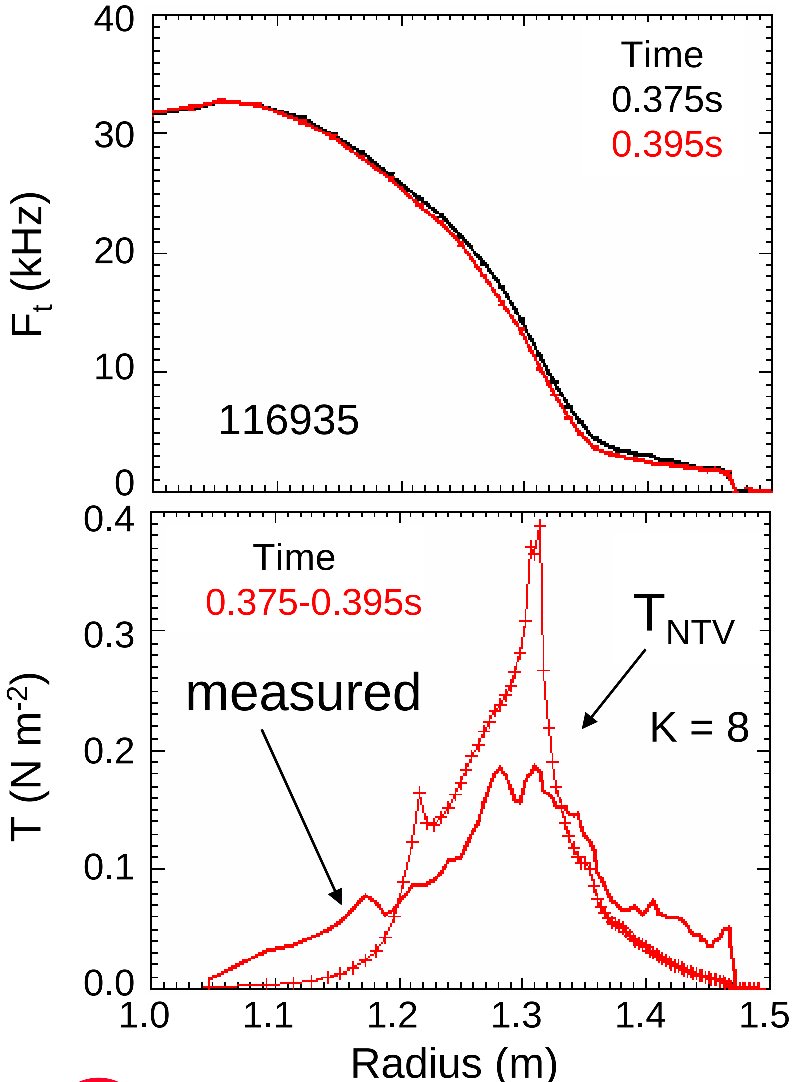
factor — $T_i^{1/2}$ — profiles — collisionality

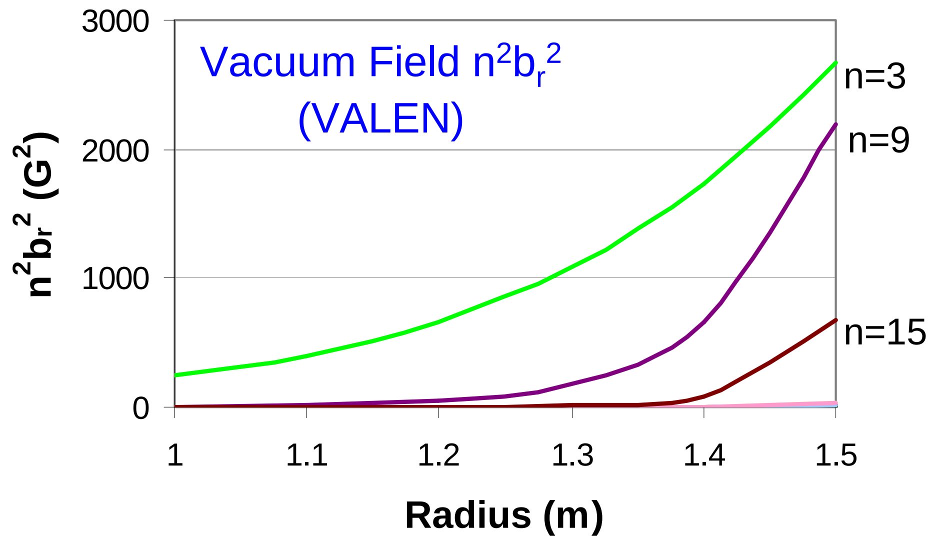
$$\mu_{ps1} = 1.365 \qquad C_\nu = \frac{2\sqrt{\pi}}{3} \frac{2\nu_{\mathrm{ii}}}{v_t / Rq}$$

Damping caused by kinked field

K.C. Shaing, Phys. Fluids 29 (1986) 521.; E. Lazzaro Phys. Plasmas 9 (2002) 3906.

Applied field alone yields moderate, global rotation damping

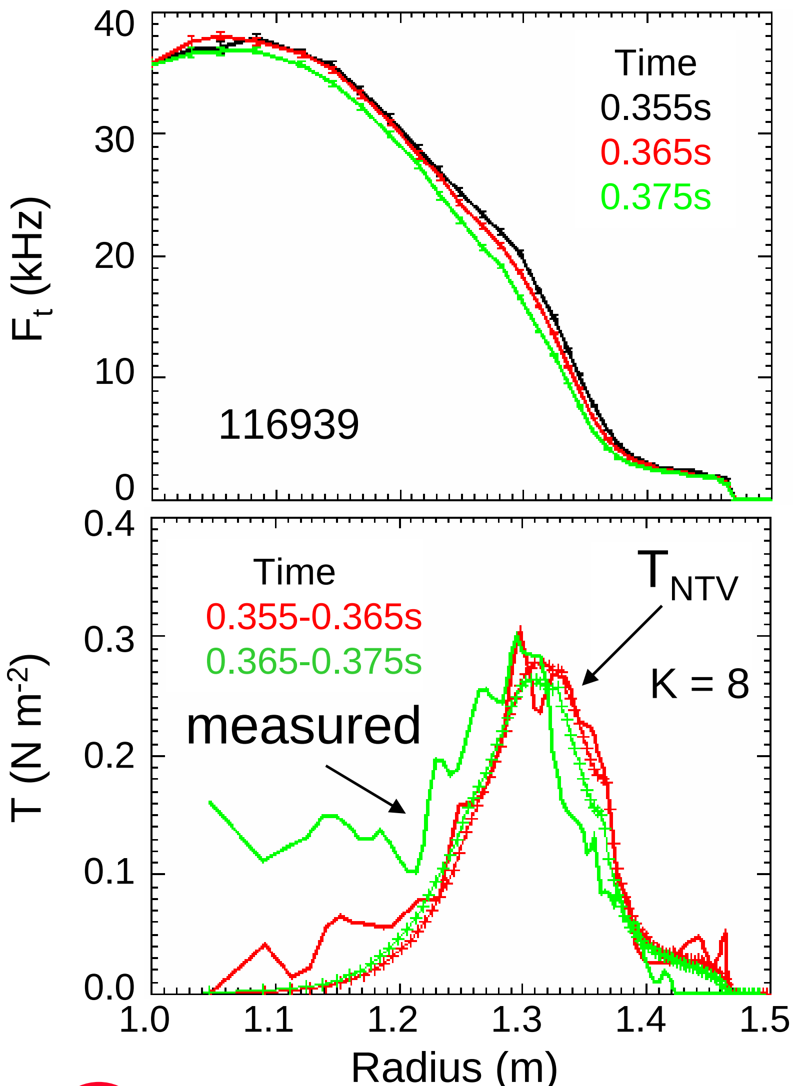


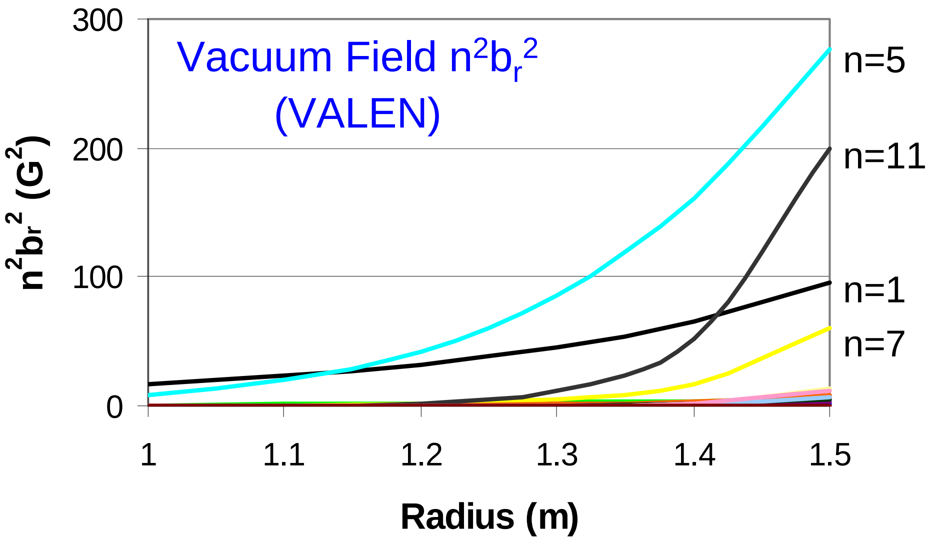


- n = 3 DC field (800A)
- Damping reduced at large R due to reduction in T_i
- n=1-15 field components included
- Resonant denominator in NTV theory might be overemphasized
  - Function of collisionality

NSTX

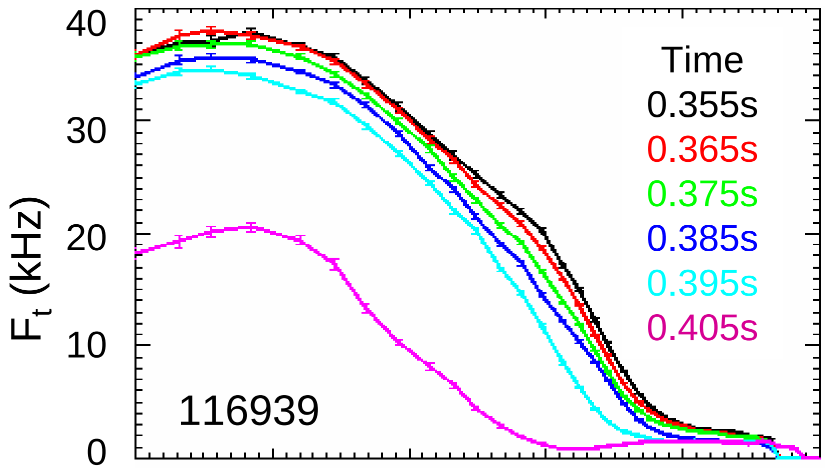
RFA enhances, broadens rotation damping

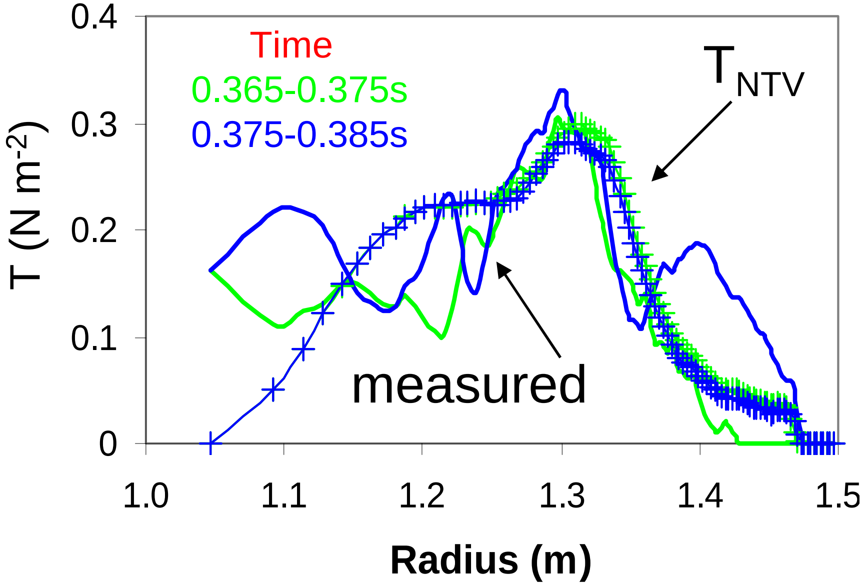


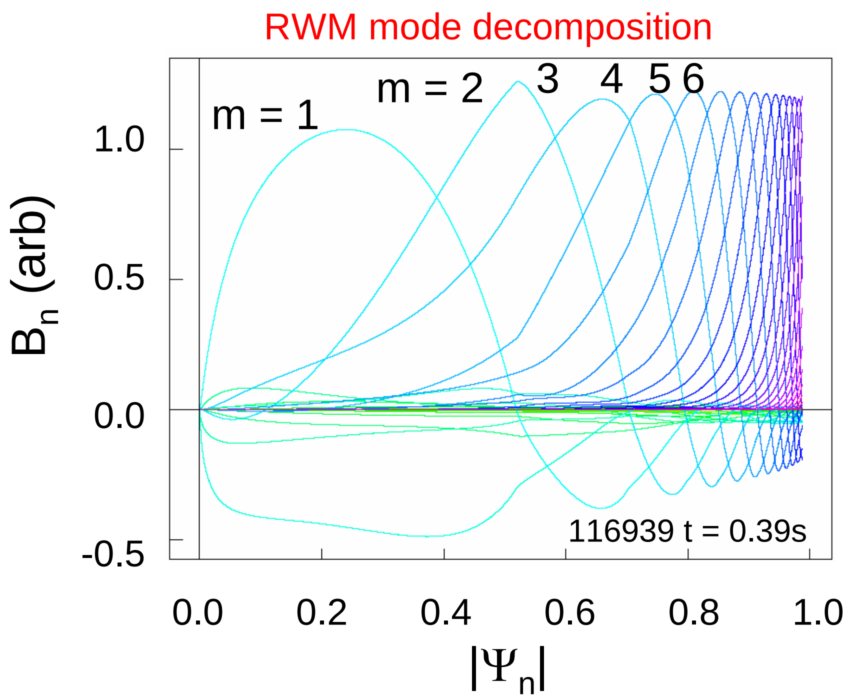


- n = 1 DC field (800A)
- n=5 torque larger than n=1 torque ($n^2 b^2$ scaling)
- n=1-15 components included
- Broadening damping profile

RWM eigenfuction can explain broader damping



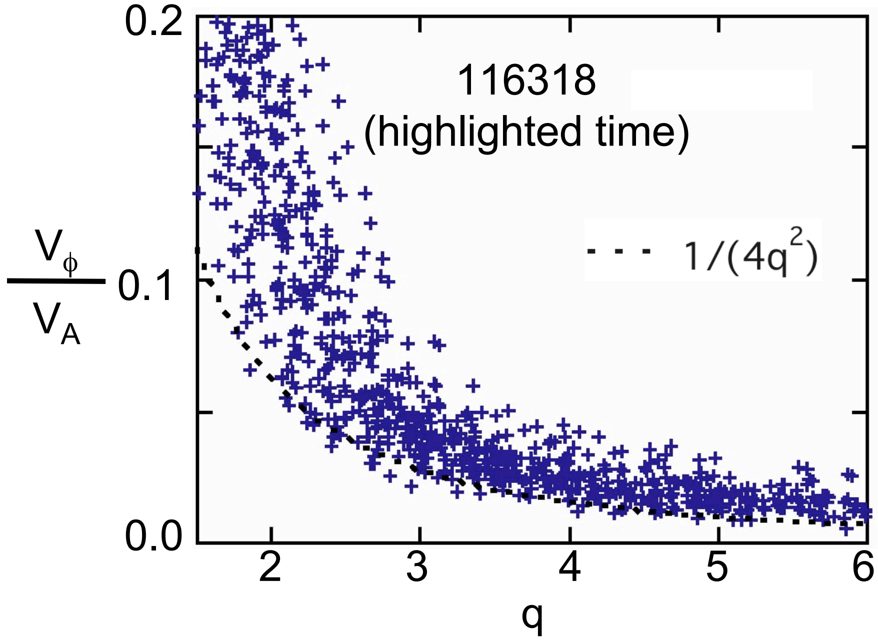


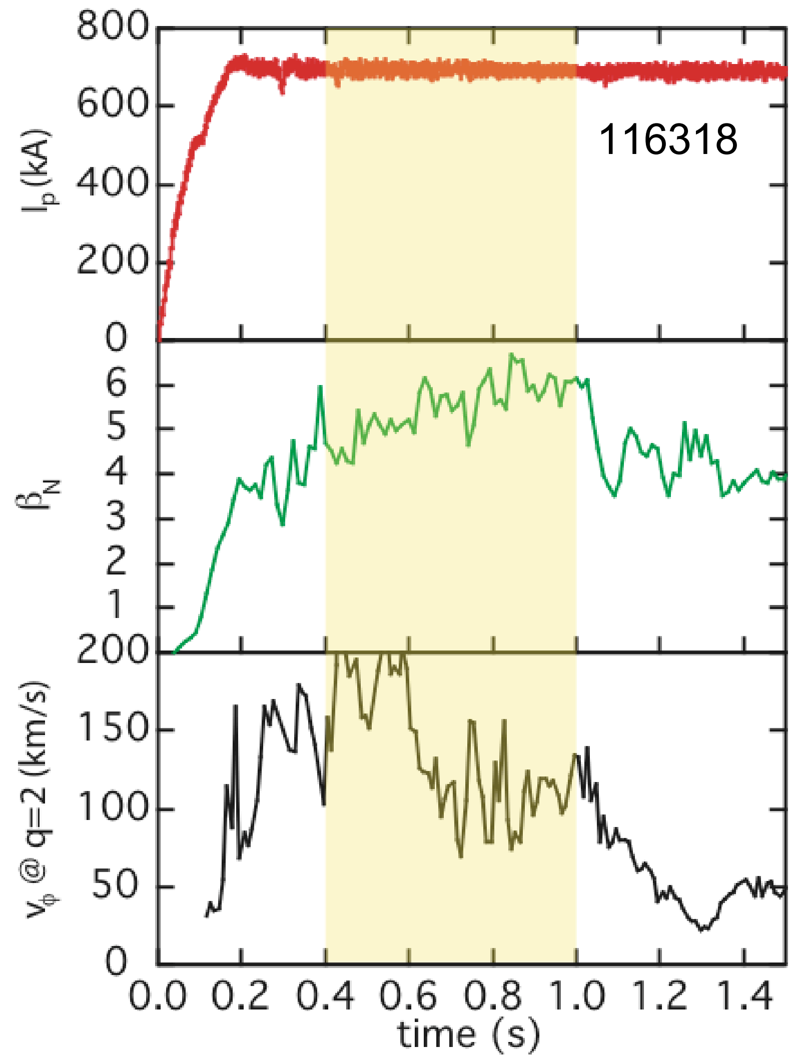


- DCON n = 1 (m = -12 to 26) RWM calculated eigenfunction
  - No-wall boundary condition
  - Need to evaluate with-wall boundary condition; inclusion of measured n = 2 component

High Toroidal Rotation Across Entire Profile Allows Sustained High β_N

- Entire rotation profile stays high during high-β period
  - Alfven speed normalization & q dependence from drift-kinetic theory
- Trend observed in numerous discharges

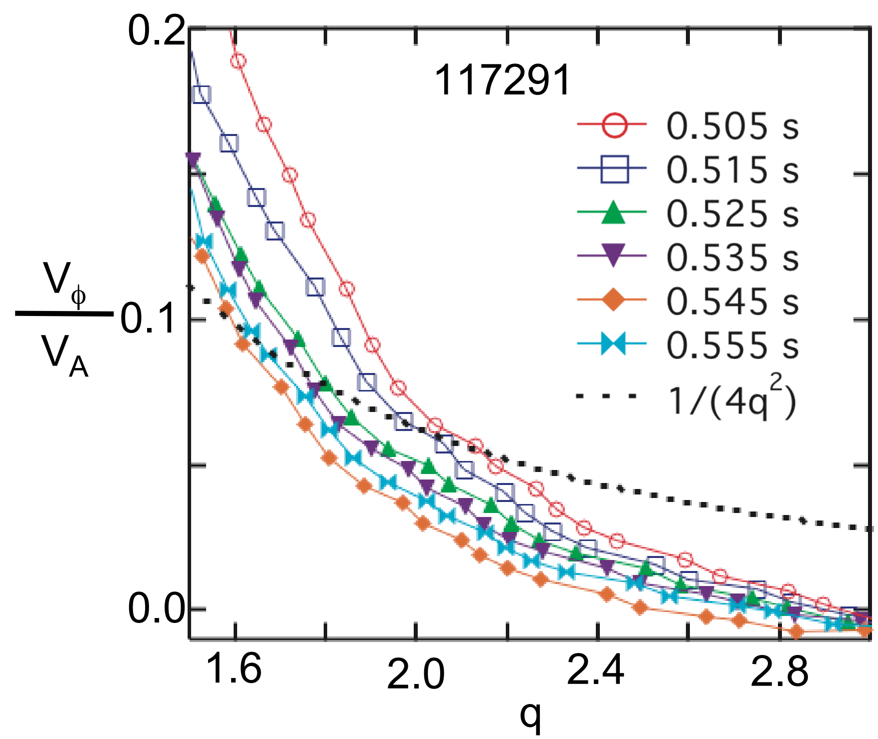


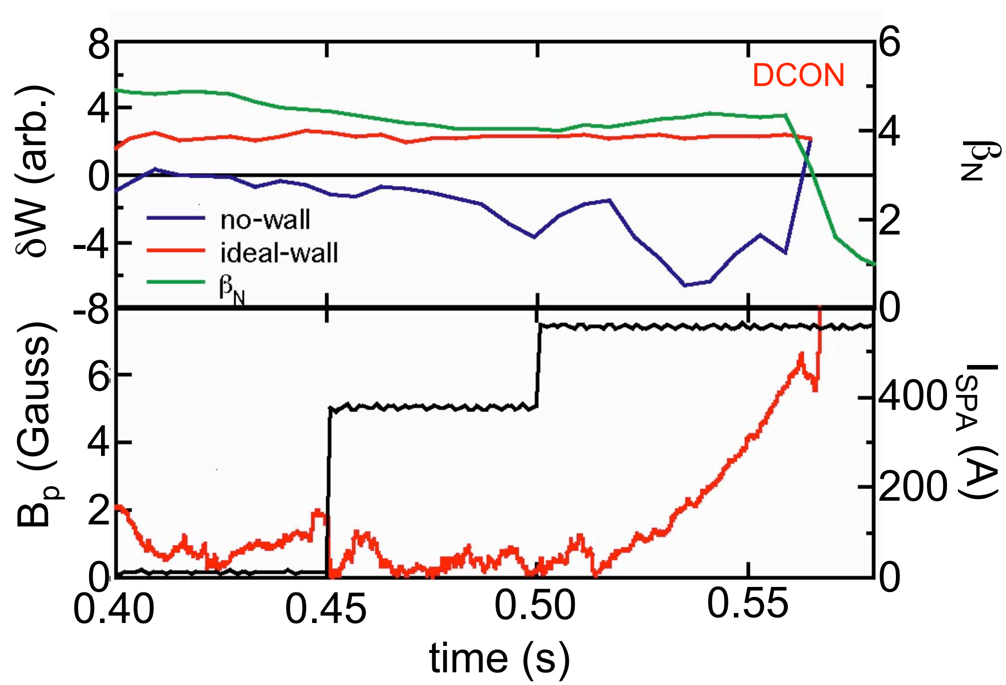


NSTX

Rotation on Higher Order Rational Surfaces Not Required for RWM Stabilization

- Plasma remains RWM stable with near zero rotation outside q = 3
  - Stable with near zero rotation outside ψ_N = 0.62
  - growth coincides with low rotation inside of q = 2

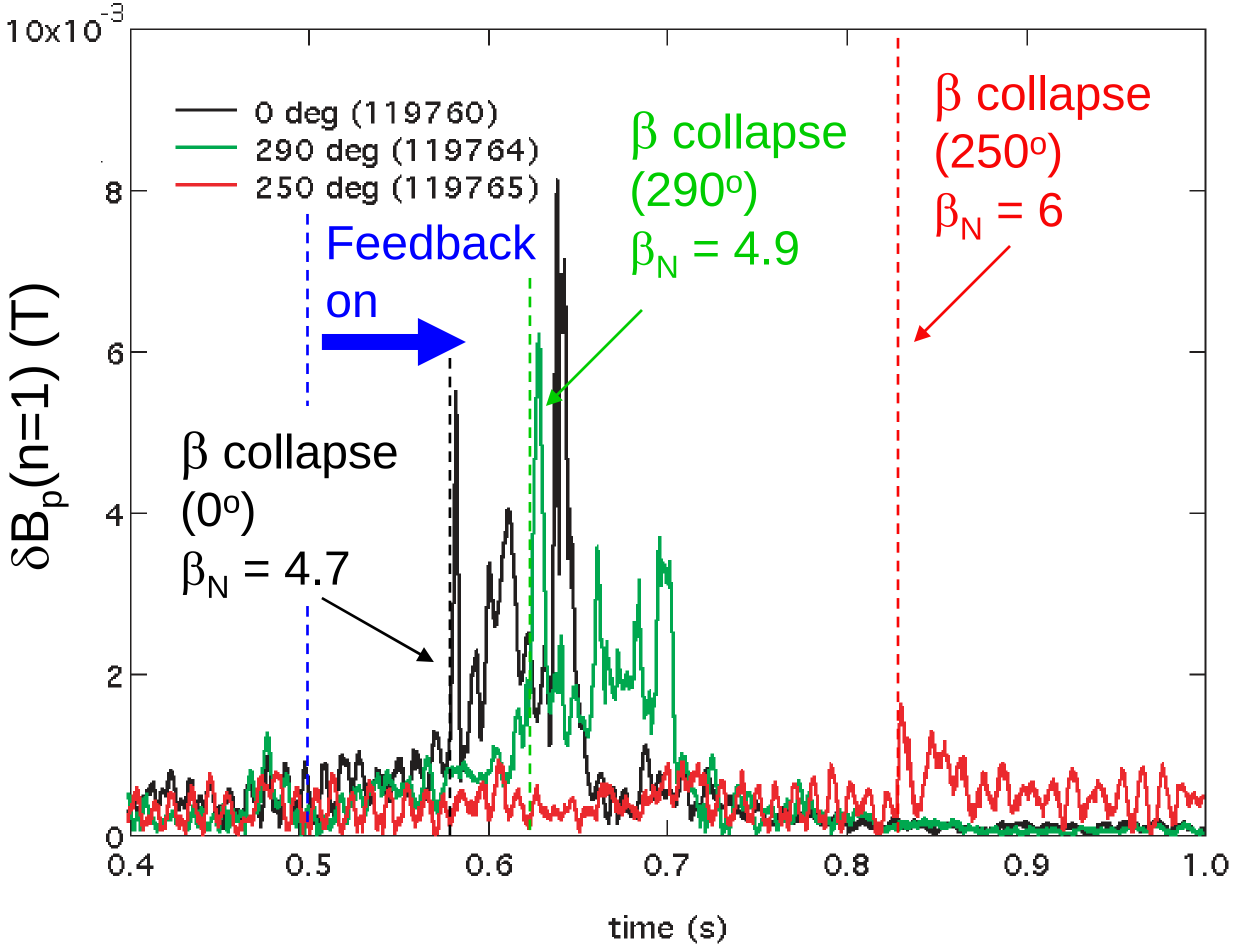




XP615: Active Stabilization of the Resistive Wall Mode at Low Aspect Ratio

- Goals (Part I):
  - Operate new RWM feedback system on 0.9–1.0 MA DND target
    - All aspects of RWM control system / RWM sensors worked well.
    - Good target plasmas with wide n=1 free window; high β_N up to 6.
    - Both locked/rotating RFA/RWM were observed/tracked by feedback.
  - Vary RWM feedback phase/gain to show control system influence
    - I_p = 1.0 MA target showed “best” phase <~ 270^o
    - I_p = 0.9 MA target more conclusive / finer scan; best phase = 225^o
    - “Best” phase depends on whether mode is rotating or not
  - Reduce plasma rotation with n = 3 braking to excite RWM if needed
    - RFA observed / RWM excited without braking in most cases
    - I_p = 0.9 MA target with phase = 250^o, 225^o required braking to excite mode

Setting RWM feedback relative phase in the range ~ 250º superior for longer pulse, higher β_N vs. ~ 0º



- Phase scan
  - Varied through 360º, finer scan in 270º range; 225º appears to be "best"
  - n = 3 braking required to generate RWM when phase set to most favorable settings

NSTX Experiment Summary

- Found non-static error field from OH$\times$TF interaction
  - Data suggests m=0 EF component dominates
  - Similar to Lazzaro's observations on JET w/ NTV model?
- Increased discharge duration using EFC at high-β_N
  - Attempting Dynamic EF Correction (DEFC, i.e. feedback)
  - Will compare "predictive" EFC to DEFC
- NTV theory consistent with observed flow damping from RFA and RWM
- First systematic attempts at RWM feedback using low-rotation target starting today

Desired code capabilities – a partial list

- Error field correction:
  - Rely on rotational stabilization of RWM to access β above NW limit
  - Requires minimization of flow damping
  - Need to know plasma response to EF and torque from 3D fields

- Need self-consistent “free-boundary” plasma response to non-axisymmetric fields – above and below no-wall limit
  - VMEC – useful below no-wall limit
    - How do plasma boundary and internal field respond to shifted/tilted TF?
  - Extend NMA code (DCON + VACUUM) to include coil + plasma eigenfunctions including ideal wall response (Chance/Chu)
    - Need plasma response above no-wall limit - wall stabilization from rotation
  - Need internal B-field structure for flow-damping from non-resonant NTV and resonant JxB torque from islands
    - Have DCON B-norm already for NTV (Zhu, Sabbagh)
    - Working on other B-components + singular currents from DCON (J.K. Park)
  - MARS-F – has 3D fields/coils, rotation, resistive wall, etc.
    - Working on benchmarking field calculations against DCON (me + JK Park)