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NSTX Results Summary: RWM XPs+

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for the

NSTX Research Team

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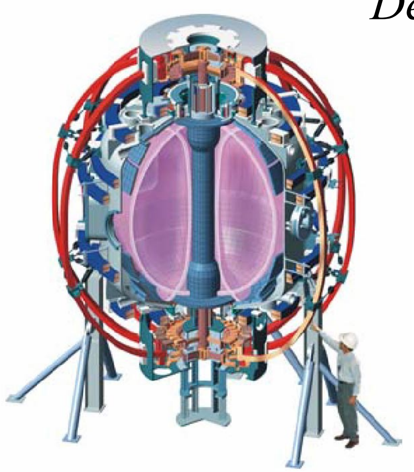

NSTX Results Review

September 20 - 21, 2004

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Significant progress in high β_N wall stabilization research

- Physics
  - Resistive wall mode (RWM)
    - Experiments examine unstable, resonant, and stable high β_N regimes
    - New/upgraded diagnostic capabilities to examine mode physics
    - Rotating RWM observed - useful in rotation damping physics study
  - Resonant field amplification
    - from stable RWM using initial RWM active coil pair
  - Transient q profile modification
    - I_p ramp-down to increase l_i, β_N; B_t ramp-down yielded high β_T, ω_ϕ/ω_A
- Performance
  - World record β_N = 7; device record β_p = 2.0
  - Device record core toroidal rotation ω_ϕ/ω_A = 0.48
    - Significant equilibrium modification due to rotation

…This presentation is an initial summary – more to come!

CY 2004 XP package supported RWM study

(P) In progress
(C): Completed

- RWM XPs
  - XP452: RWM physics using initial GMS coil (Sabbagh)
  - XP407: Passive stabilization physics of the RWM (Sabbagh)
  - XP453: DIII-D/NSTX RWM physics similarity XP (Sontag)
  - XP428: Dissipation and inertial effects on RWM stability (Sontag)
- Supporting XPs
  - XP408: Rotation damping physics in high β_N ST plasmas (Zhu)
  - XP414: Aspect ratio effects near the high β_p equilibrium limit (Sabbagh)
  - Important data from several other XPs (e.g. high β_t runs)

…Substantial XP/theory comparsion driven by significant new diagnostic coverage and upgrades

Theory provides framework for wall stabilization study

Fitzpatrick – Aydemir (F-A) RWM dispersion relation

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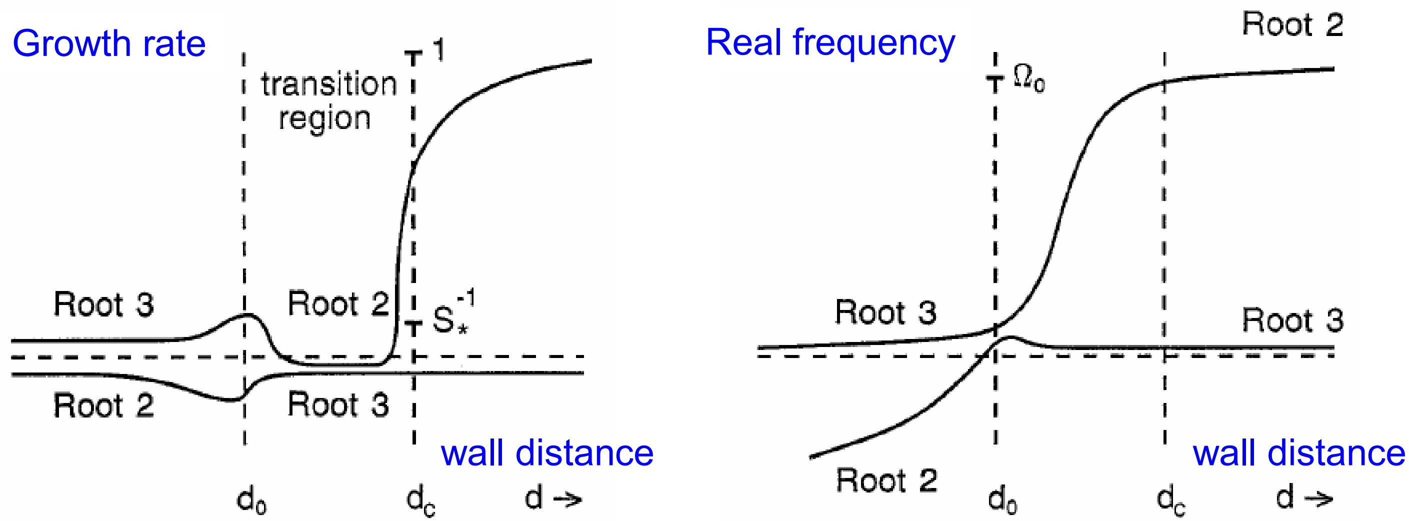

plasma rotation; $s \sim \beta_N$; $S_* \sim 1/\tau_{wall}$; poloidal mode number

$$\left[(\hat{\gamma} - i\hat{\Omega}_\phi)^2 + \nu_*(\hat{\gamma} - i\hat{\Omega}_\phi) + (1-s)(1-md)\right]\left(S_*\hat{\gamma} + (1+md)\right) = \left(1-(md)^2\right)$$

plasma inertia — dissipation — mode strength — wall response — wall/edge coupling

- RWM / external kink "branches" are eigenmodes of the system
- Examine stable/unstable operating regimes and resonances

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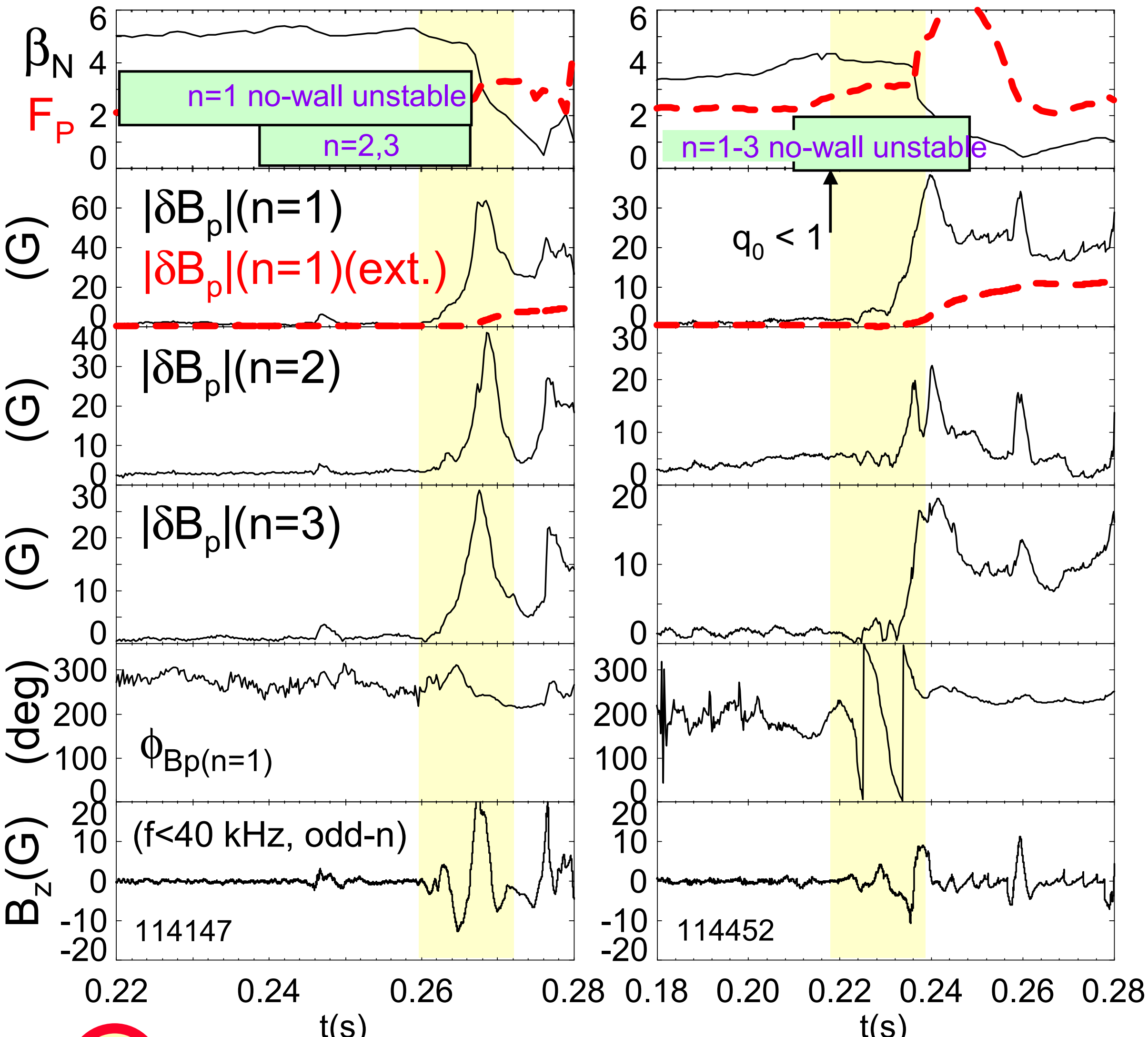
Unstable RWM dynamics follow theory

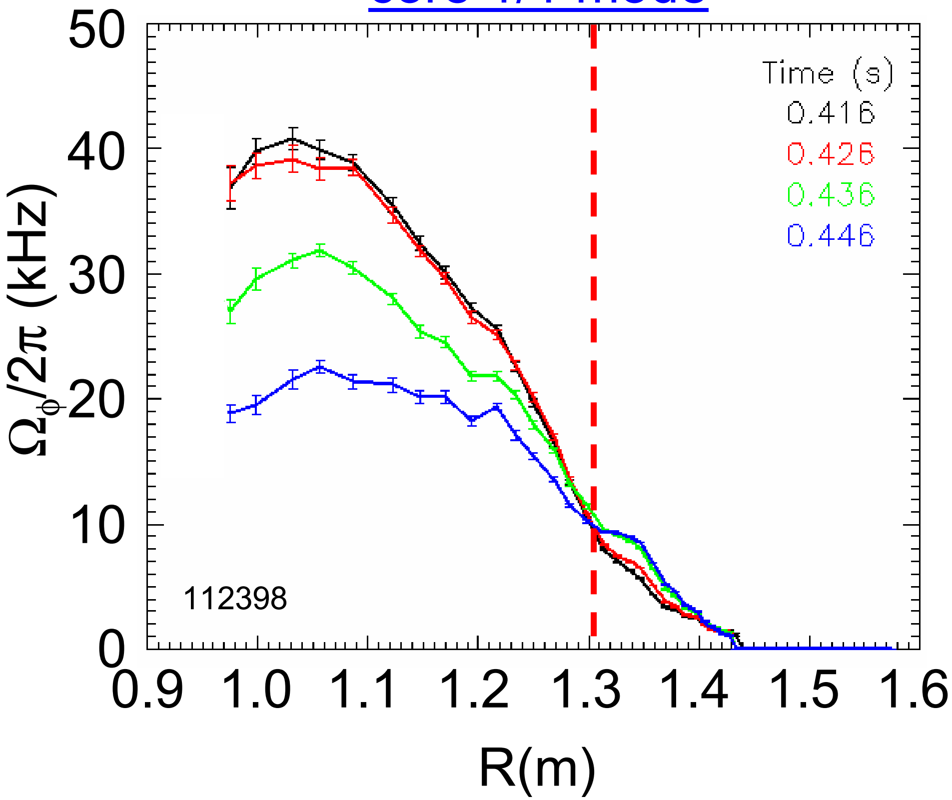
pure growth | rotation during growth



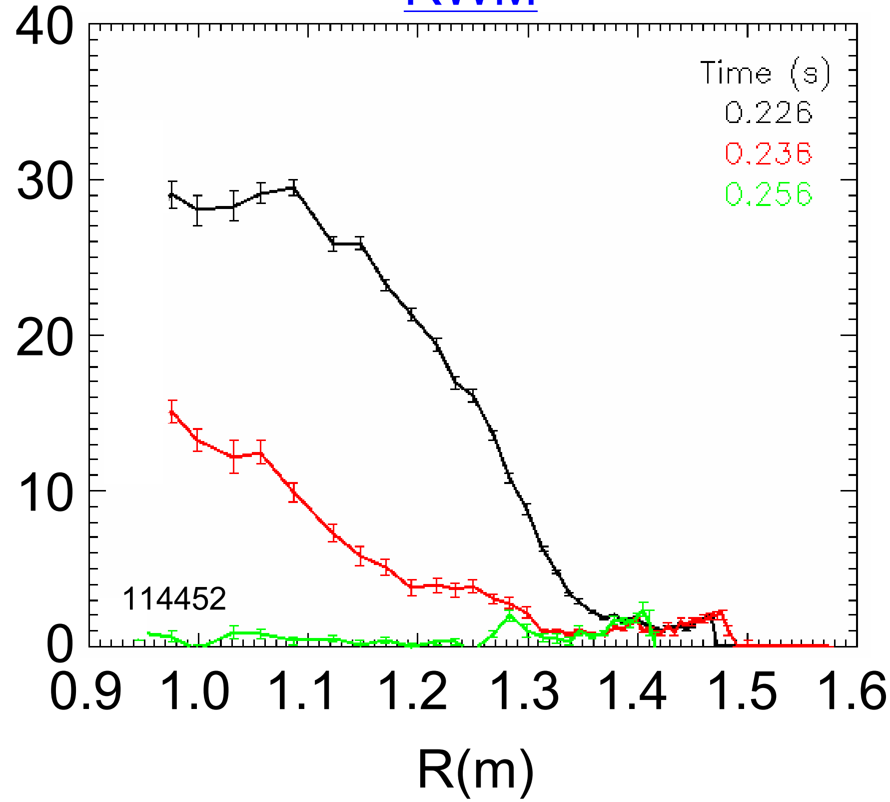
- F-A theory / XP show
  - mode unlock/ rotation can occur during mode growth
  - "RWM branch" phase velocity in direction of plasma flow
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
- n=1-3 unstable modes observed on new sensors
  - modes are ideal no-wall unstable (DCON) at high β_N
- Low frequency tearing modes absent

RWM rotation damping differs from other modes

core 1/1 mode

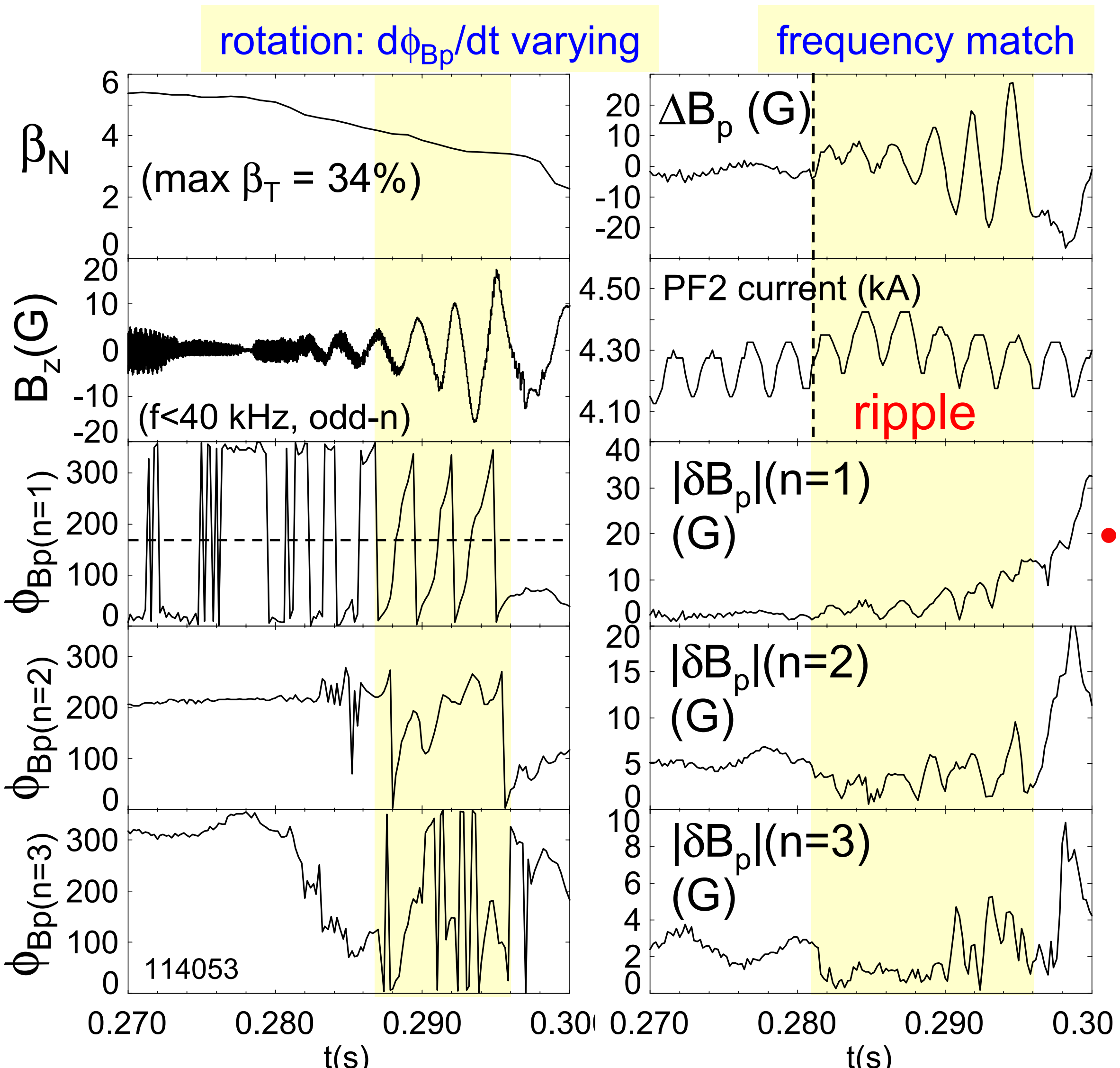


RWM



- Core rotation damping when 1/1 mode onsets
  - leads to “rigid rotor” plasma core
- Clear momentum transfer across rational surface near R = 1.3m
- Global rotation damping by RWM
  - 1/1 tearing mode is absent
- Edge rotation does not halt
  - consistent with neoclassical toroidal viscosity ~ $\delta B^2 * Ti^{0.5}$
  - analysis shown by W. Zhu

Resonance with AC error field possibly identified



Modified resonance

$$\left(S_* \nu_* / (1 + md) + 1\right)\hat{\omega}_f^2 + \left(s(1 - md) + \Omega_\phi^2\right) = 0$$

"static error field" response

New resonance

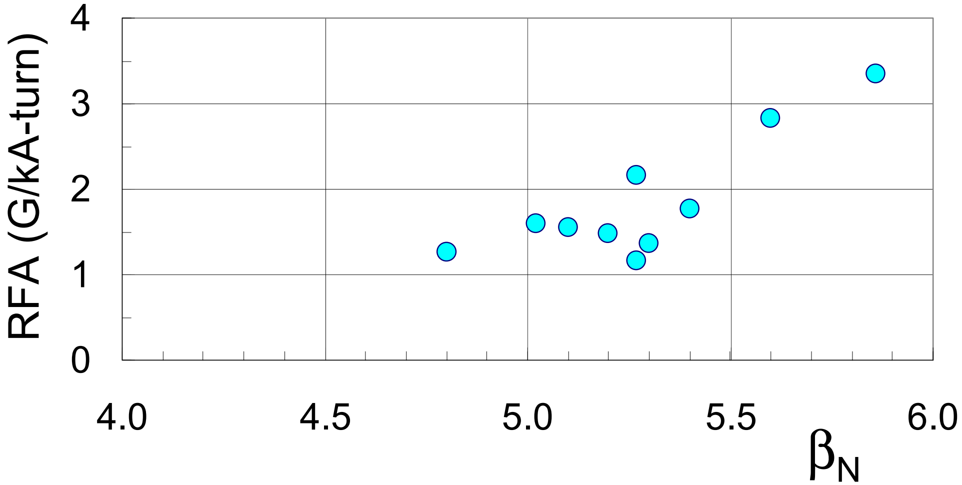
$$\hat{\omega}_f^2 = \nu_* (1 + md) / 2S_*$$

- Theory / XP show
  - Time-dependent error field yields new resonance
    - may be responsible for mode trigger
  - Mode rotates *counter* to plasma rotation – F-A theory shows as "kink branch"
    - n=1 phase velocity not constant due to error field
  - Rough calculation of $\omega_f/2\pi$ ~ 350 Hz; agrees with PF coil ripple
  - Initial results – quantitative comparison continues

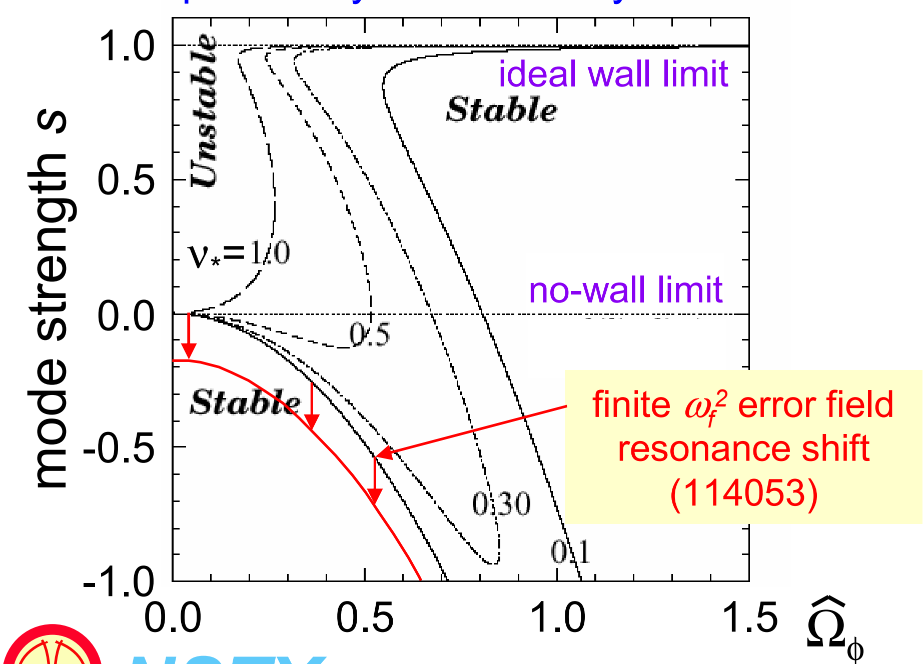
XP452: RWM coil pair yields first active RFA XP

- Resonant field amplification (RFA)
  - Pulsed, n=1 standing wave perturbation
  - RFA increases with increasing β_N
- Initial MHD spectroscopy
  - 20 – 60Hz modulation performed
    - Ripple from RWM coil circuit ~ 150 Hz range – extra analysis required
- DIII-D/NSTX RWM experiment attempted (XP453)
  - XP delayed due to B_t = 3 kG limitation
    - Couldn't eliminate large n=1 tearing mode in DIII-D shape at B_t = 3 kG

Resonant field amplification increases at high β_N

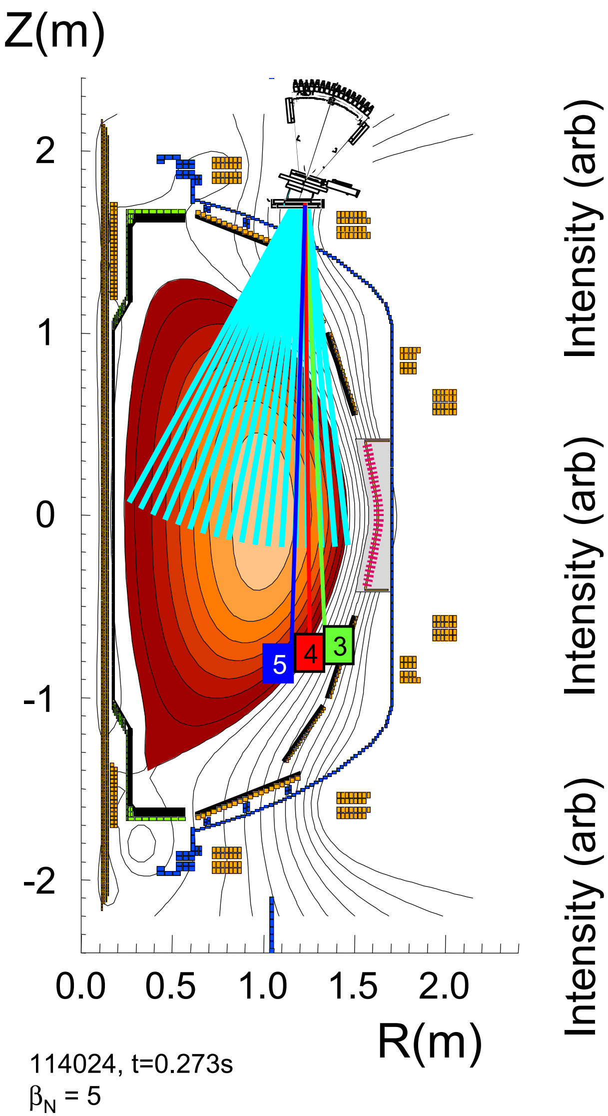


Fitzpatrick-Aydemir stability curves

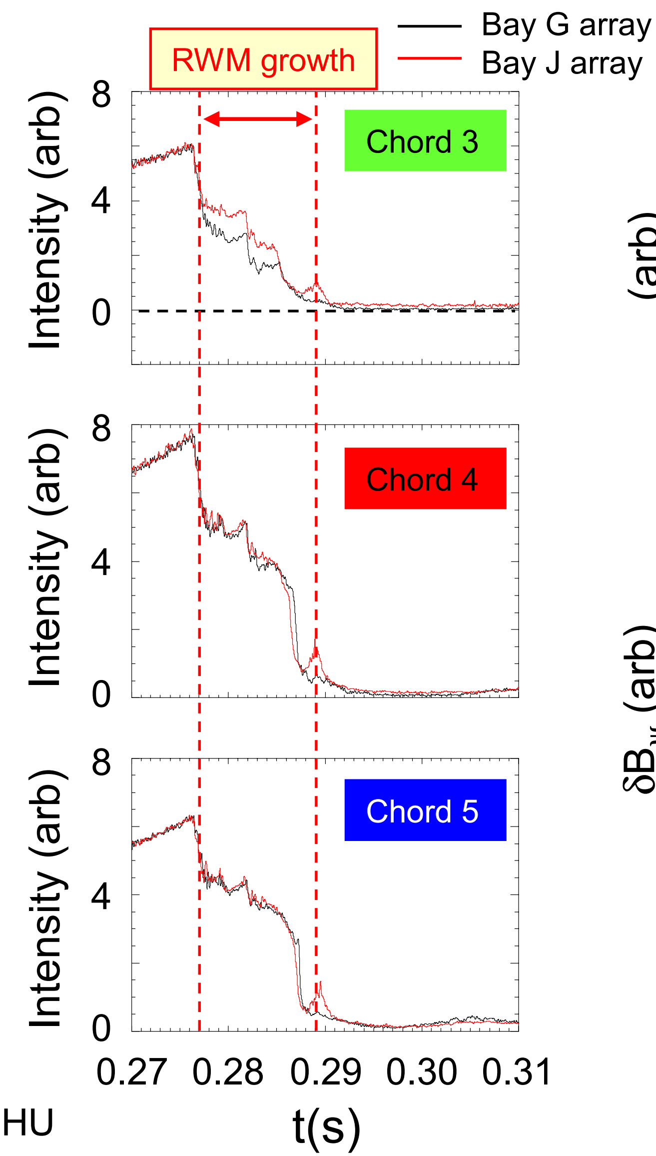


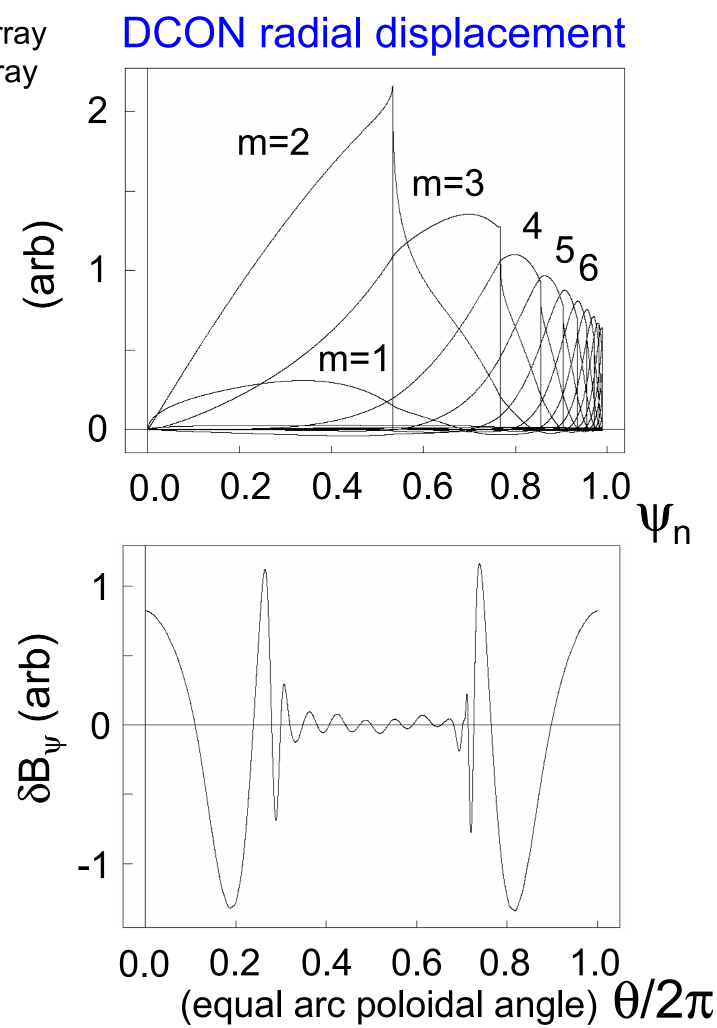
- Increase in RFA with increasing β_N consistent with DIII-D
  - DIII-D RFA: 0-3.4 G/kA-turn
  - thought to be *inconsistent* with F-A RWM theory (A. Garofalo, PoP 2003)
- AC error field ~ $\cos(\omega_f t)$
  - significantly shifts the error field resonance *away* from stability boundary
  - finite ω_f^2 resonances might fill amplification "gap" between modified error field resonance and stability limit
  - consequently, must be careful to include the effect of active error field resonances in RFA calculations

Two-toroidal position USXR: RWM not edge localized



K. Tritz, JHU



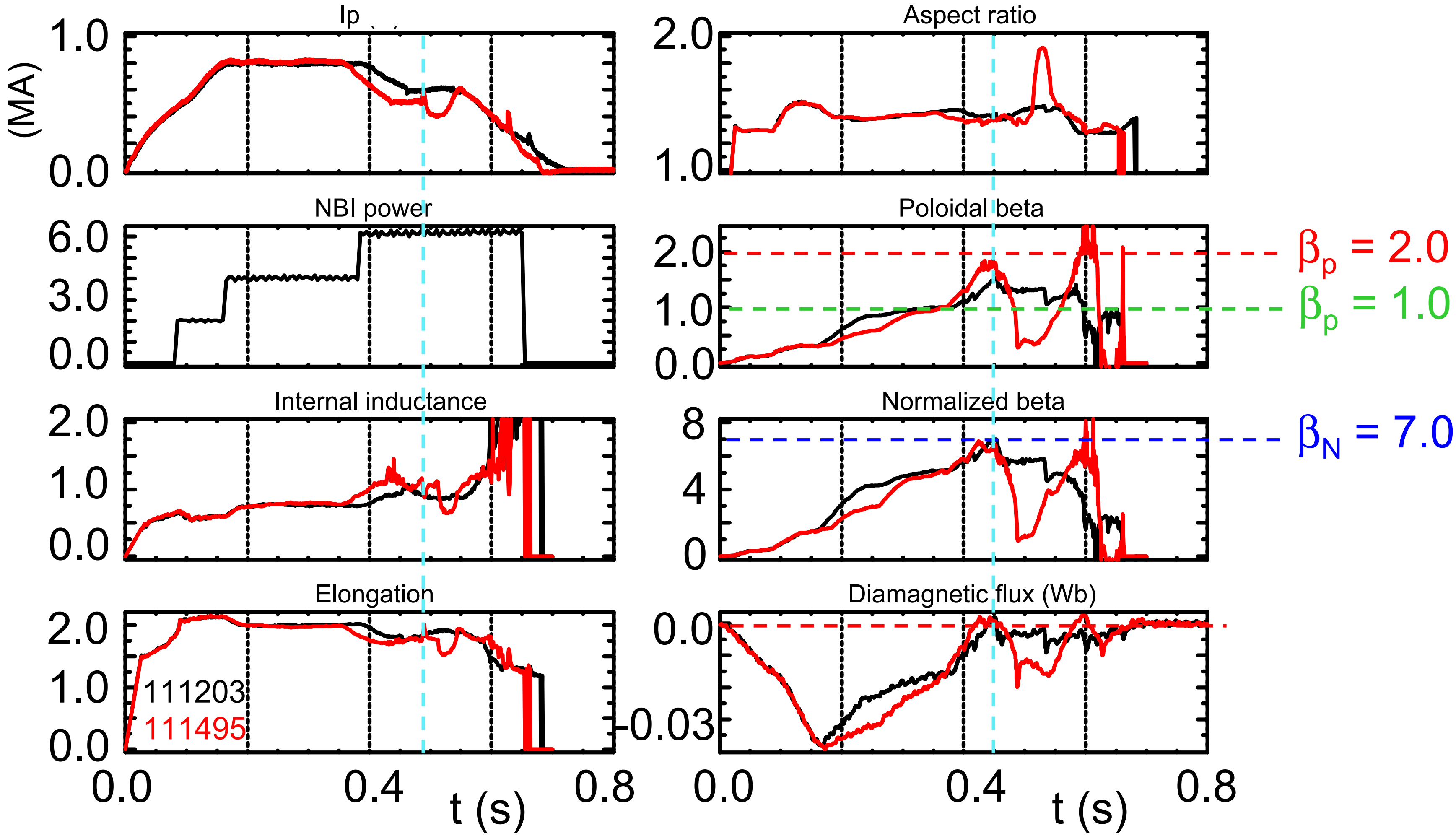


- Theory (DCON) shows global mode

XP414: Progress toward the ST equilibrium limit

- XP to examine rotation effects at low aspect ratio, high β_p
  - Early run (before vent for CHERS): calibrated CHERS not available
  - Late run: restricted to B_t = 3kG, limiting peak plasma performance
- High β_p target conditions established
  - CHERS data taken indicates high rotation targets, $f_\phi \sim 30$ kHz
  - Plasma β_p up to 2, world record $\beta_N = 7$, W_{tot} = 200 kJ
- Target development significantly improved mode behavior
  - Neutron collapse at $\beta_N = 7$ plasma indicates internal/global mode
  - Subsequently, beta collapses not correlated with neutron collapses
  - Last run (B_t = 3kG) showed that modes could be *eliminated* by maintaining $\kappa > 2$ during I_p ramp-down
- XP completion desired when $B_t > 4$ kG becomes available

High β_N plasma reaches β_p= 1.8; β_p = 2 late



- Highest β_p plasma is slightly diamagnetic (2 mWb)
- Plasmas approaching equilibrium limit ~ 2.5

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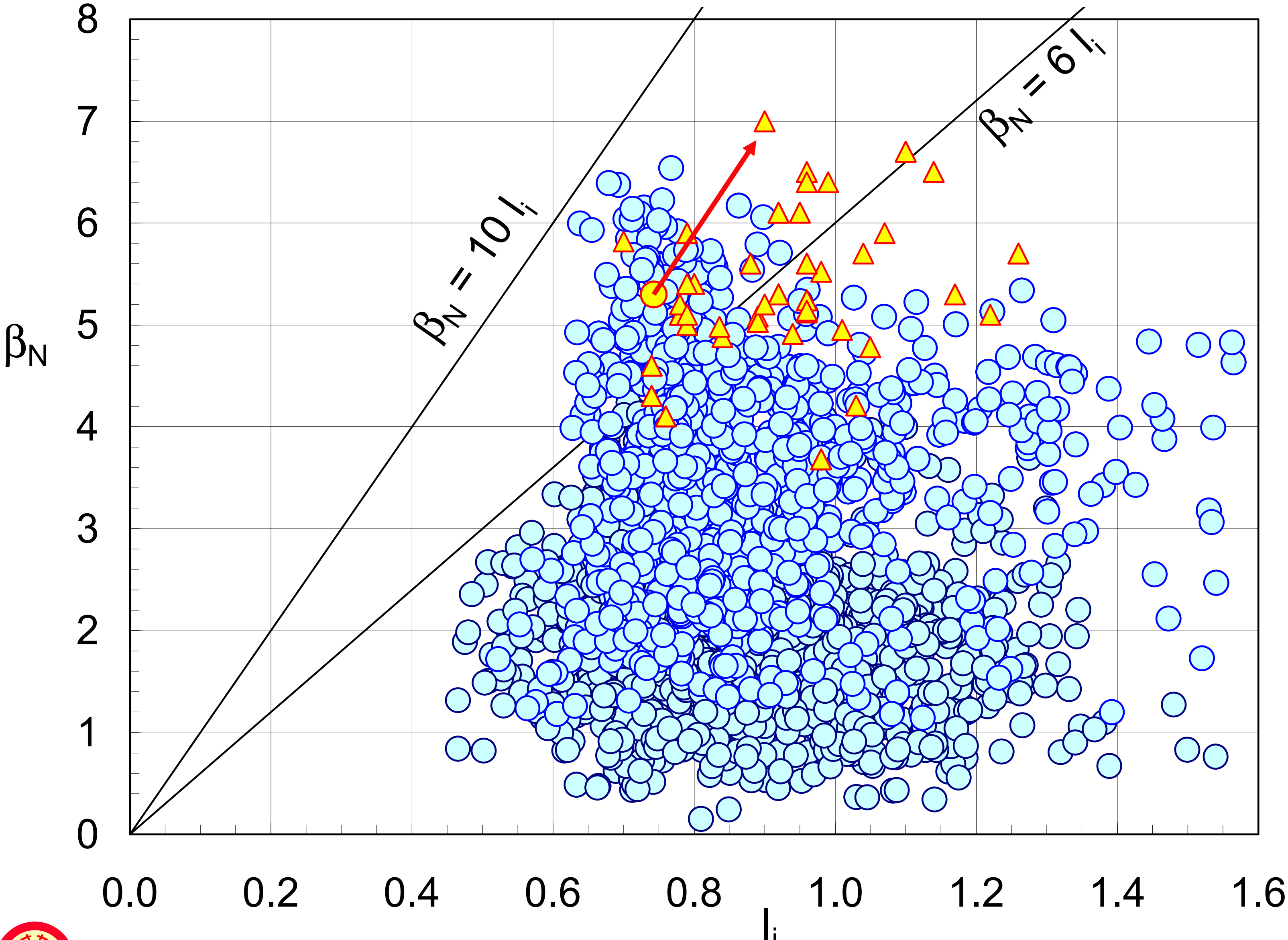
XP414 expanded high β_N operating space



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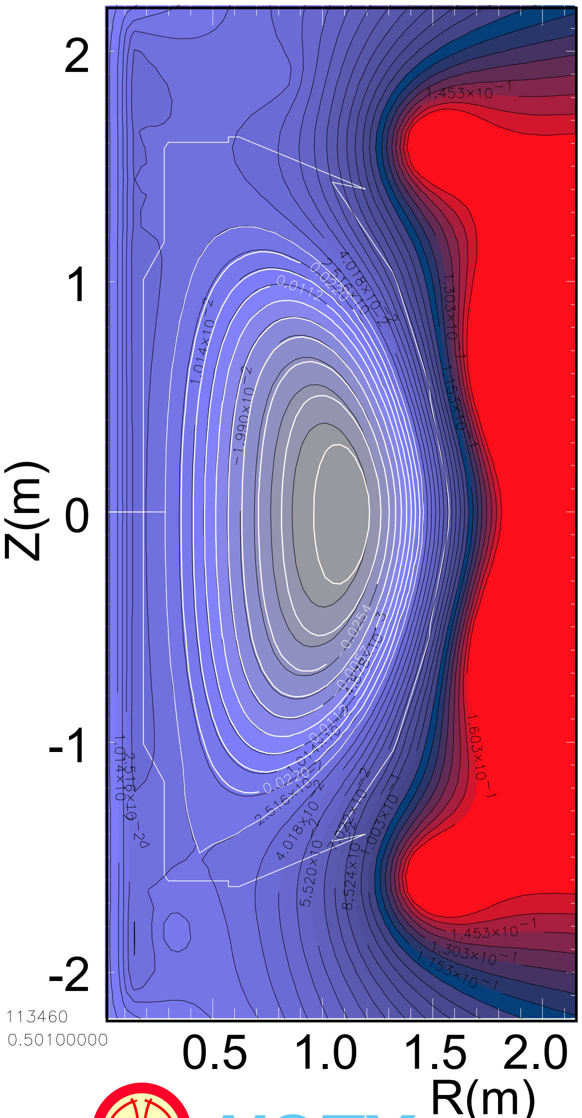
Between-shots equilibrium reconstruction with rotation introduced in 2004 (EFIT)*

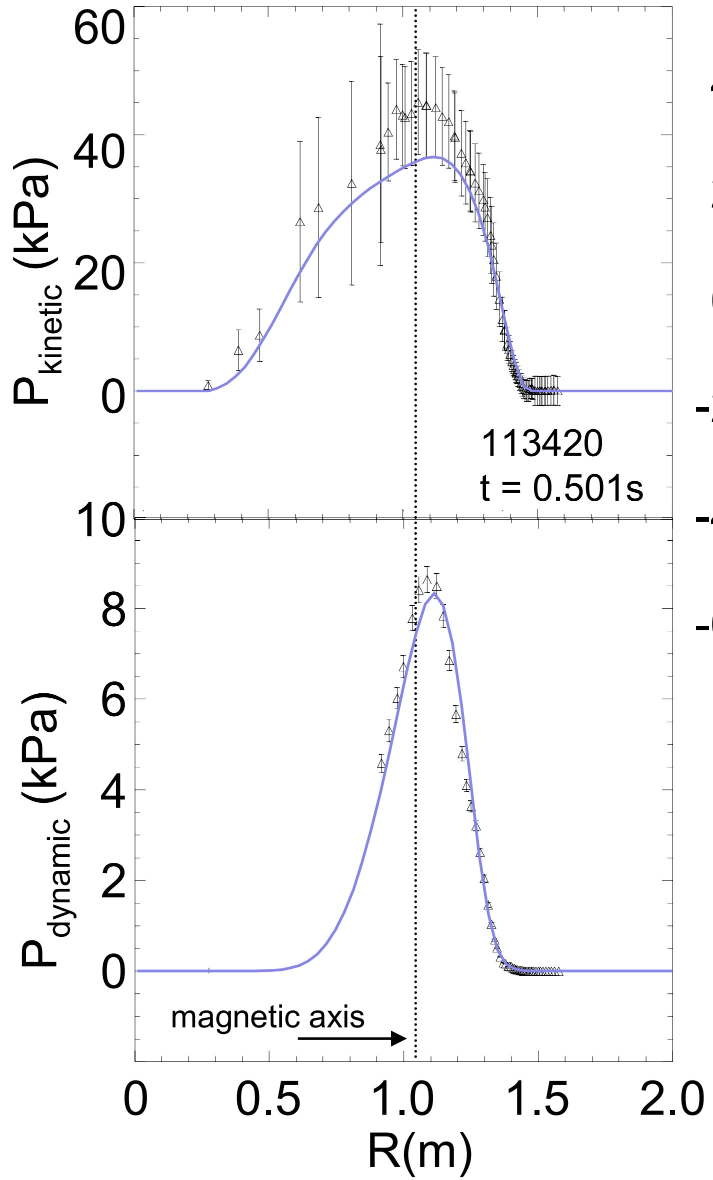
- Data
  - 51 radial channel, Δt =10ms CHERS data generated between-shots
    - Dynamic (rotational) pressure $P_d(\psi,R)|_{z=0}$
    - P_i available – reduces error bars on "partial kinetic" $P(\psi,R)|_{z=0}$
  - Significant upgrade of divertor magnetics set / vessel voltage monitors
    - Reduces uncertainty in X-point position and plate currents
  - Over 350 total measurements are used per time point
    - Allows fit with 21 free basis function parameters and *no* artificial constraints
    - Over 11,000 shot*times run – further testing still needed for 100% reliability
  - First shot with MSE data now being tested
- Physics constraints
  - Flux iso-surface constraint
    - Use $T_e = T_e(\psi(R)|_{z=0})$ *directly* from Thomson scattering data - rapid analysis
      - required to insure self-consistent solution with toroidal rotation
    - Better flux surface / q profile determination
    - Other data (e.g. soft X-ray emission) can be used as constraint

*in collaboration with Lang Lao (GA), Z. Cheng (IPPCAS)

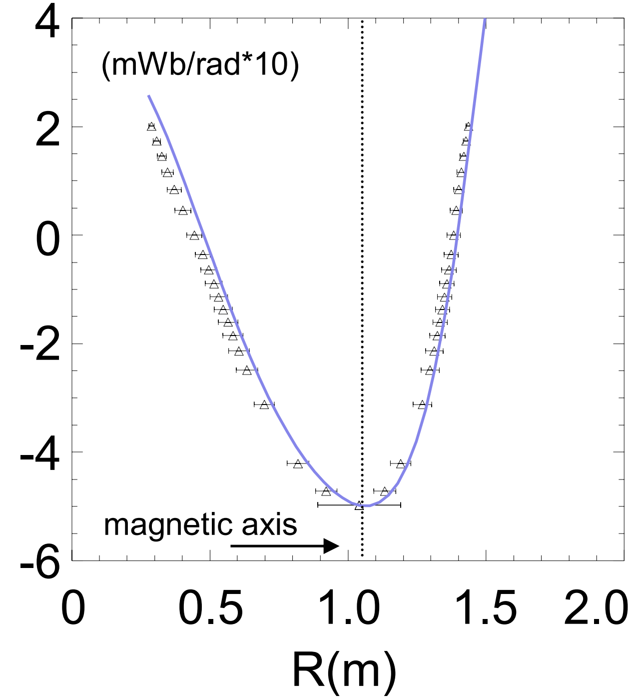
Significant separation of magnetic axis and peak pressure

Poloidal flux and pressure





ψ isosurface constraint



- V_ϕ broadens P profile
  - simple estimate for P_{fast}
  - completing testing of diagnostic consistency
- $(R_{pmax} - R_{axis})/a = 11\%$

Wall stabilization physics understanding improved by use of upgraded capabilities

- Unstable, resonant, and rotationally stabilized plasmas have been created and global modes diagnosed
- Greater insight on RWM physics critically aided by diagnostic upgrades
  - new internal RWM sensor array – n=1-3 modes measured
  - higher time and spatial resolution CHERS for T_i, Ω_ϕ (rotation damping)
    - key diagnostic, but issue with lack of carbon signal in many plasmas
  - two-toroidal position USXR data shows RWM not limited to plasma edge
- Initial RWM coil pair already used for first RFA experiments
  - RFA increases as β_N increases
- Equilibrium reconstruction with rotation now available

…analysis of CY2004 data has just begun!