NSTX / NSTX-U EFIT and RWM Control (NSTX-U Phys. Ops. Course Talk #17)

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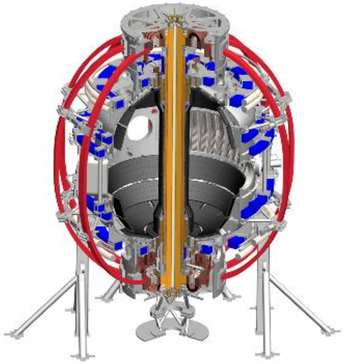
2015 Physics Operator Training
PPPL
10/13/15

V1.5



Recall other NSTX-U Physics Operator Training talks for related information in this talk

- NSTX-U Equilibrium Magnetics
  - Phys. Ops. Training Talk #11 – Equilibrium magnetics (C. Myers, et al.)
- NSTX/NSTX-U EFIT Visualization
  - Viewing tools: EFITVIEWER: Talk #3 (B. Davis, et al.)
- NSTX/NSTX-U RWM PID control and Mode ID algorithm
  - Phys. Ops. Training Talk #12 – 3D Fields (S.P. Gerhardt, et al.)

NSTX/NSTX-U EFIT – it's not your usual EFIT

- EFIT Implemented for NSTX
  - Since the start of NSTX operations, "magnetics-only" runs have been run between-shots
    - Includes detailed reconstruction of vessel currents; shaping coil currents
  - BUT ALSO – diagnostic geometry allows between-shots kinetic analysis
    - "Kinetic EFITs" are run between-shots in NSTX ("partial kinetic")
  - Also Beware! Certain aspects of NSTX EFIT and EFIT as run for DIII-D are different
    - e.g. NSTX EFIT MDSplus tree "EFIT02" is kinetic run (DIII-D: magnetic run)
    - "standard" EFIT code requires some alteration for NSTX / NSTX-U analysis
- Code execution
  - Implementation and daily oversight by Columbia U. group on NSTX/NSTX-U
    - Special analysis requests processed for Team members
  - Est: 125 equil/shot * 2000 shots/yr * 2 varieties of runs * 10 years = 5 million NSTX EFITs available for analysis (not including run requests for people, tests)

Talk Outline

- NSTX / NSTX-U EFIT
  - Between-shots, etc. NSTX EFIT analysis (and some references)
    - Magnetics-only → (S.A. Sabbagh et al., Nucl. Fusion **41** (2001) 1601)
    - Partial kinetic → (S.A. Sabbagh et al., Nucl. Fusion **44** (2004) 560) (stabilty analysis with partial kinetic reconstructions)
    - Kinetic with rotation → (S.A. Sabbagh et al., Nucl. Fusion **46** (2006) 635)
  - Access to documentation, analysis, some utilities
  - NSTX-U EFIT modeling (to date) and present development plans

- NSTX active RWM Control
  - PID control
  - Model-based RWM State-space Controller (RWMSC)

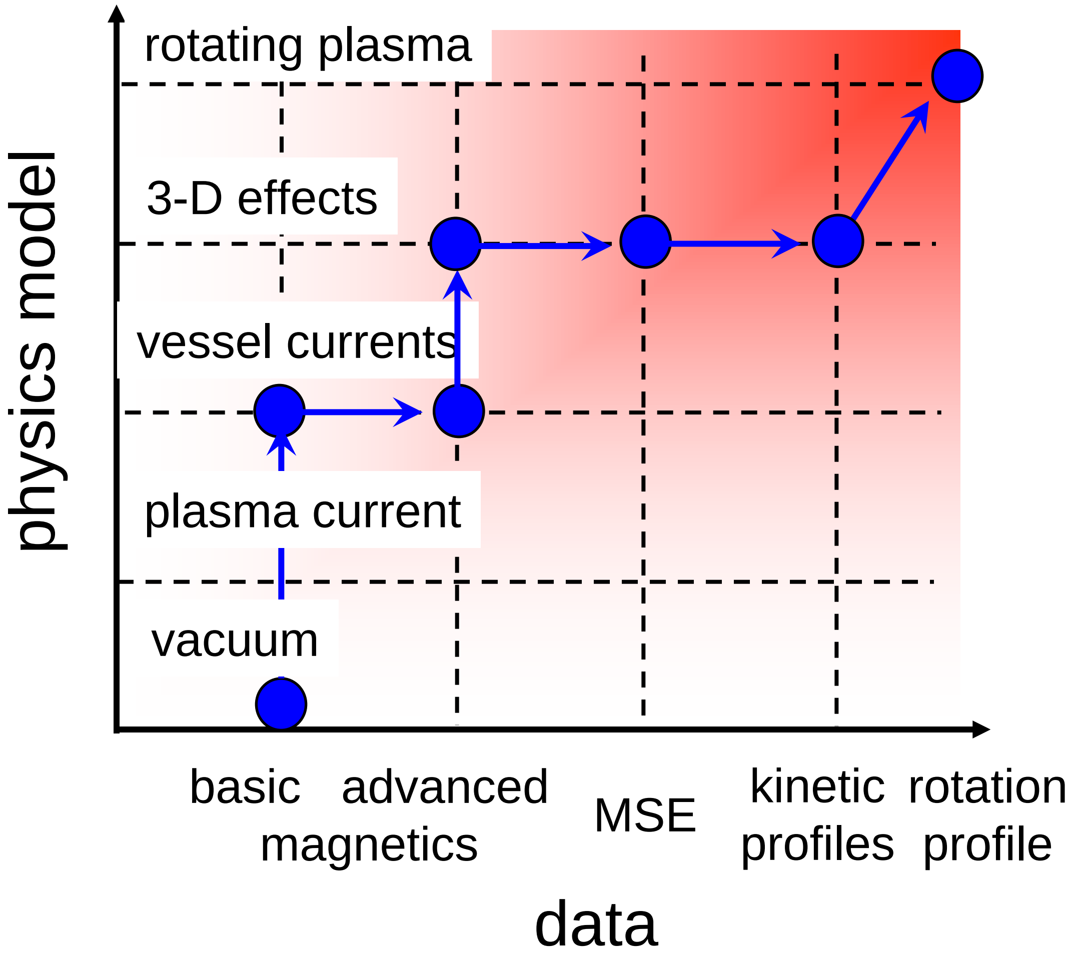
Rotating, high β ST plasmas provide opportunity for advancing equilibrium reconstruction

- ❑ Motivation
  - ❑ Equilibria are basic and essential components of plasma analysis
    - plasma parameters, profiles, boundary evolution, etc.
    - used for transport / stability analysis, RF studies, power handling, etc.
  - ❑ Reconstructions can be used to determine consistency between diagnostics

- ❑ Topics
  - ❑ Philosophy
  - ❑ Summary of reconstruction technique
  - ❑ Magnetic, kinetic, and kinetic + rotation reconstructions
  - ❑ Application to NSTX
  - ❑ Near-term and future directions

Goal: "rapidly" reconstruct "best" equilibrium

- Philosophy
  - "Best" model
    - for a given physics model / data set, reliably fit all data within error
    - improved physics/data set reduces artificial constraint
  - "Rapid" reconstruction
    - between-shots
    - Find constraint set for a given (data,model) pair
  - Upgrade toward "perfect" equilibrium
    - more complete physics
    - more complete data
    - less artificial constraint



EFIT[*] provides a flexible equilibrium solution

- Solve for (1) poloidal flux, ψ, and (2) toroidal current, J_t
  - that satisfy the GS equation: $\Delta^*\psi = -\mu_0 R J_t(\psi)$, where

    $\Delta^*\psi = R^2\nabla\bullet(\nabla\psi/R^2)$; $J_t = Rp'(\psi) + \mu_0 ff'(\psi)/(4\pi^2 R)$; $f(\psi) = RB_t$; $' \equiv \partial/\partial\psi$
  - that provide a least-squares fit to a set of constraints
- Typical constraints for fit
  - Diagnostic data - response from plasma and external coils
    - magnetic (flux loops, I_p, coils, diamagnetic loop, stabilizing plates)
    - P_e from Thomson scattering
    - P_i , V_ϕ, Z_{eff} from charge exchange recomb. spectroscopy (CHERS)
    - field pitch angle from motional Stark effect data
  - Specified global / local parameters (ℓ_i, β, q_0, edge J)
  - Specified profile shapes, or boundary
    - Yields shaping coil currents, diagnostic measurements

[*] L. Lao, et al., Nucl. Fusion **25** (1985) 1611

EFIT Parameterization of Equilibrium Solution

- $\psi_t = \psi_{plasma} + \psi_{coils}$, J_t solved on rectangular grid
- For fitting, J_t modeled using various basis functions
  - polynomial
    - $P'(\psi) = \Sigma (\alpha_j \psi_n)^j$
    - $FF'(\psi) = \Sigma(\gamma_j \psi_n)^j$
    - solution vector $\boldsymbol{\alpha} = [\alpha_j , \gamma_j]$
  - splines
    - greater profile flexibility, requires greater profile data resolution
- External coil currents I_c, reference flux ψ_{ref}
- Solution vector for fit
  - $U = [I_c , \boldsymbol{\alpha}, \psi_{ref}]$

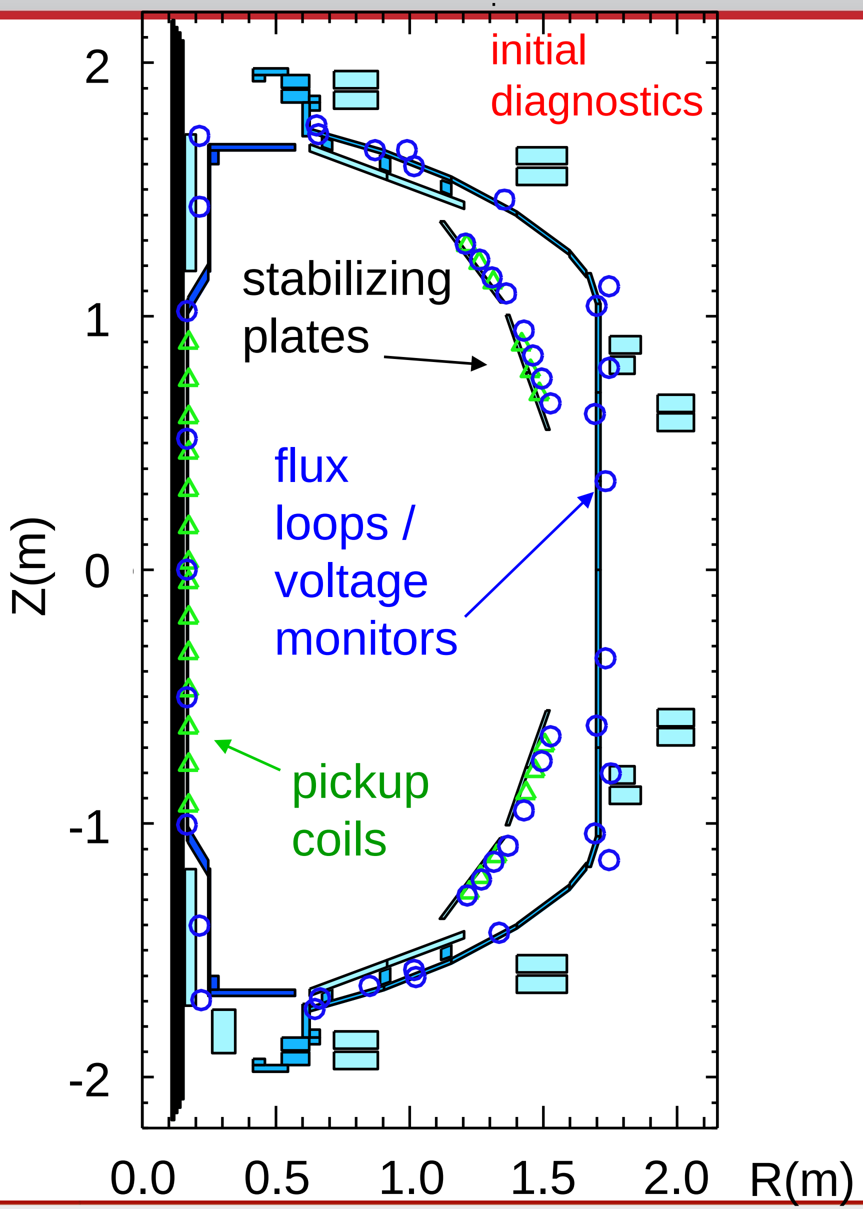
EFIT iterates finding J_t and solving for poloidal flux

- Constraint equations
  - D(t) = R x U(t)
    (Response matrix R; D(t) = diagnostics data / constraints)
  - Submatrices of R
    - Diagnostic response to I_{coils}: Coils Green function matrix G_c
    - Diagnostic response to J_t: Plasma Green function matrix G_p
    - Any extra data or artificial constraints relating the elements of U
- Find U that minimizes $\chi^2 = \Sigma(M_i - C_i)^2/\sigma_i^2$
  - Include fitting weights F: **|**F • R x U - F • D**|** is minimized
  - Invert by singular value decomposition to find U(t) : (F,R,D: are f(ψ))
- Solve for ψ
  - ψ_{coils} solved by Green function response given I_c
  - ψ_{plasma} solved by inverting Grad-Shafranov equation
    - finite difference method, converge to specified tolerance
  - Boundary / ψ surfaces determined by contour routine

NSTX EFIT* alterations required for low A geometry

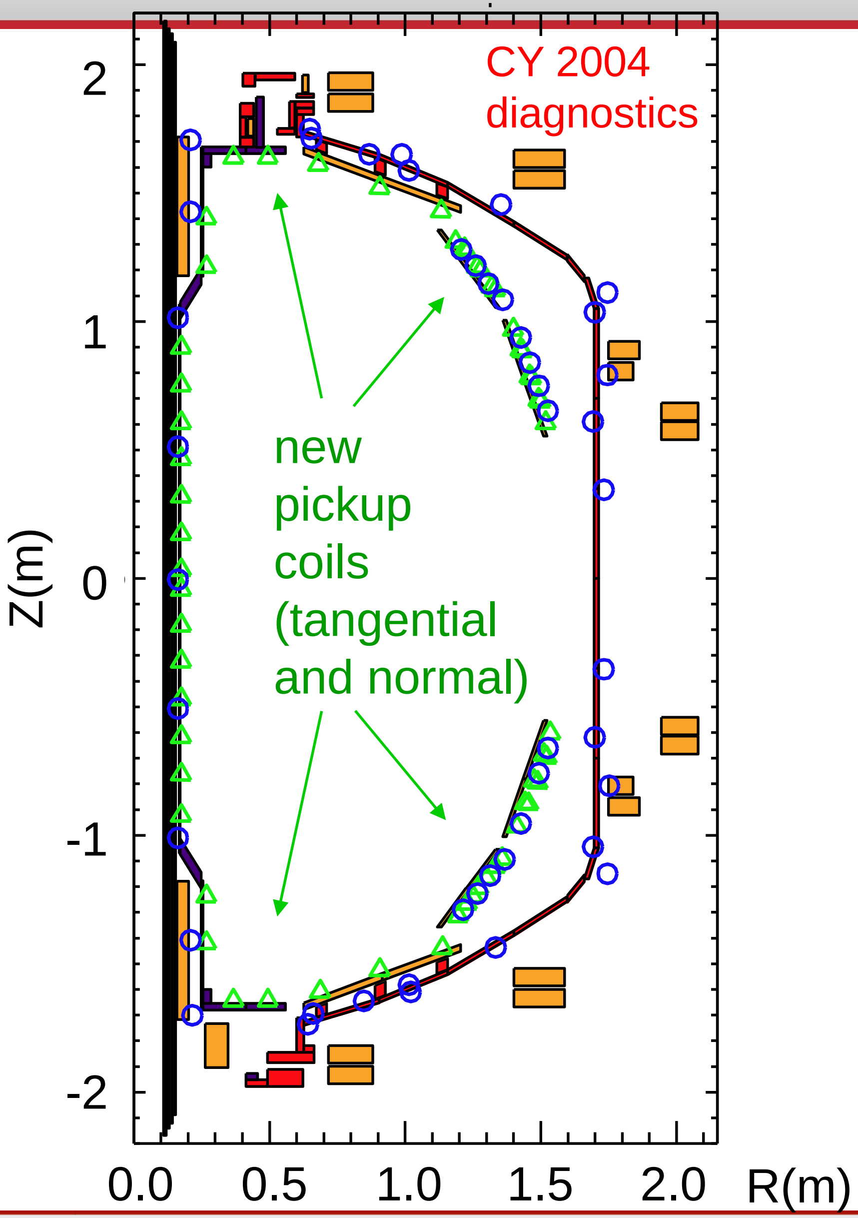
- Uniform discretization of elements at low aspect ratio
- Vessel currents required
  - Lower A components have lower resistance
  - Total vessel currents ~ 0.3 MA; plasma current ~ 1.0 MA
  - Vessel / plates broken into 30 groups (poloidally)
  - Wall currents determined by local loop voltage data (9 loops)
  - Vessel element resistances matched against independent model of vacuum field shots
- Stabilizing plates / divertor plates currents are included

*S.A. Sabbagh, et al., Nucl. Fus. **41** (2001) 1601.

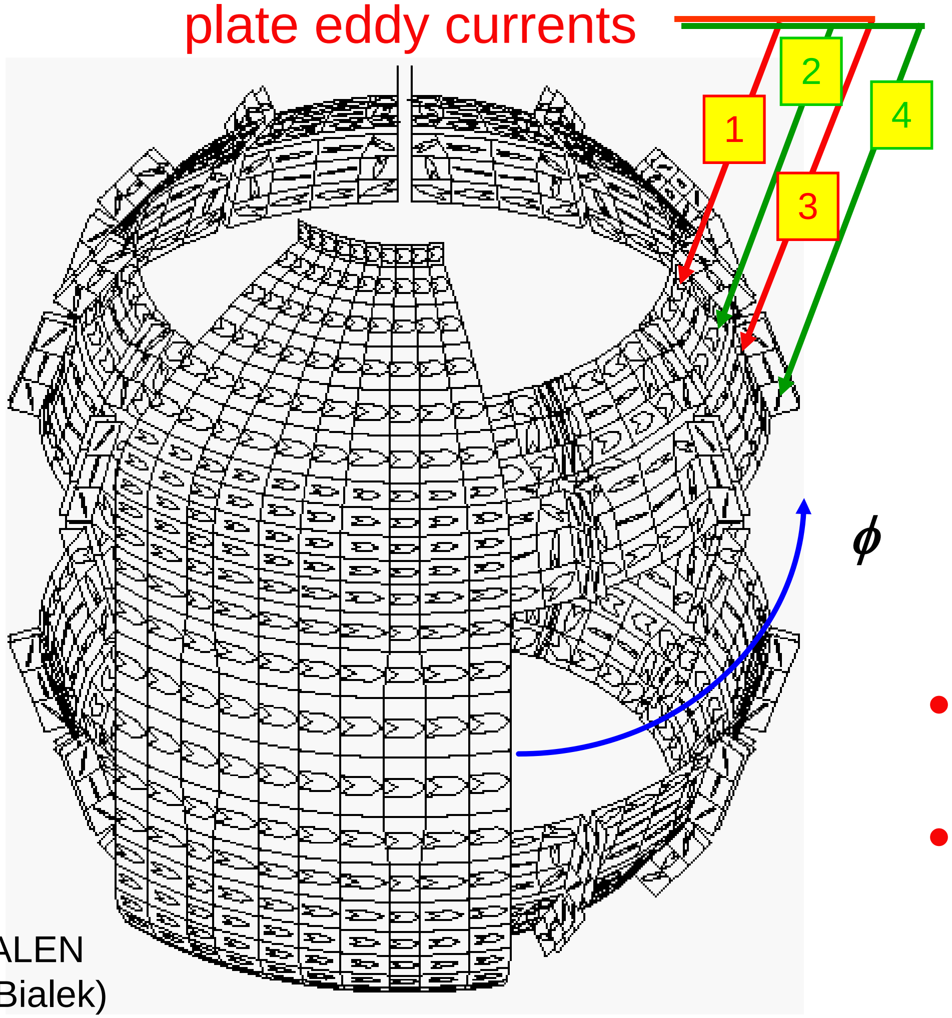


Expanded magnetics in 2004 yielded more accurate X-point and plate currents

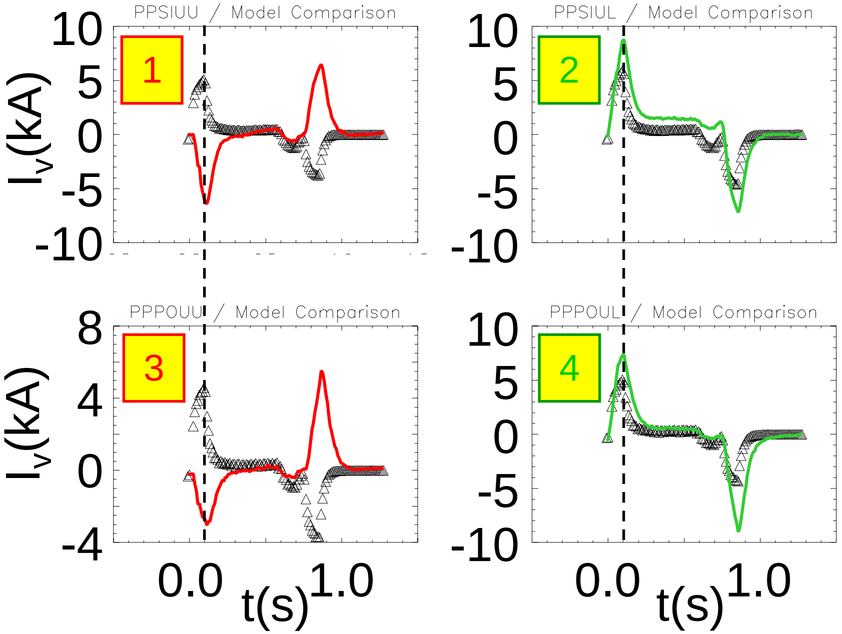
- Significant upgrade to magnetics set in 2004
  - 57 pickup coils vs. 23
  - 25 local loop voltage data vs. 9 for wall current distribution
  - Compensation for stray field from TF leads
- Stabilizing plates / divertor plates currents now better resolved



Expanded magnetics set reproduces 3-D eddy currents as axisymmetric currents in NSTX EFIT



VALEN
(J. Bialek)

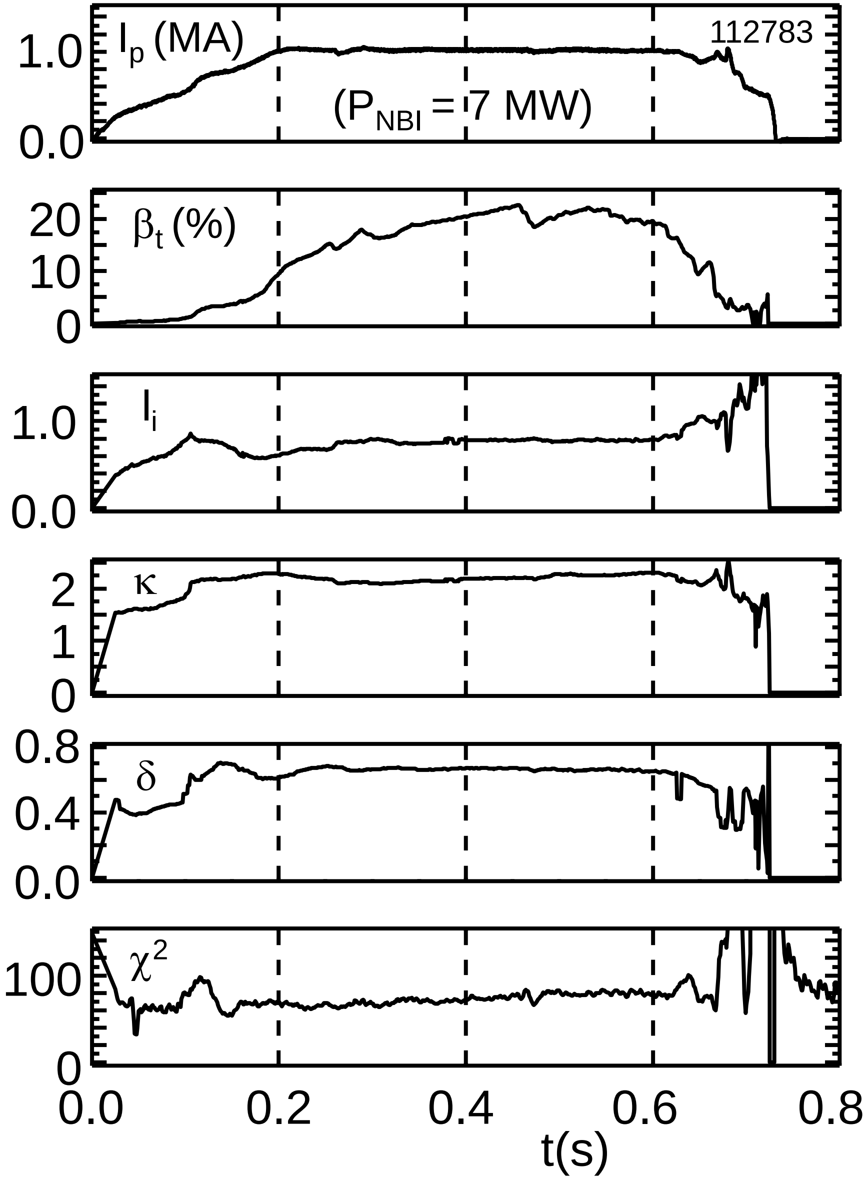


- Black points: plate current approximated from V_{loop} sensors
- Solid lines: EFIT reconstructed plate currents using all magnetics data
  - Fitted currents match 3-D eddy currents as a 2-D analog

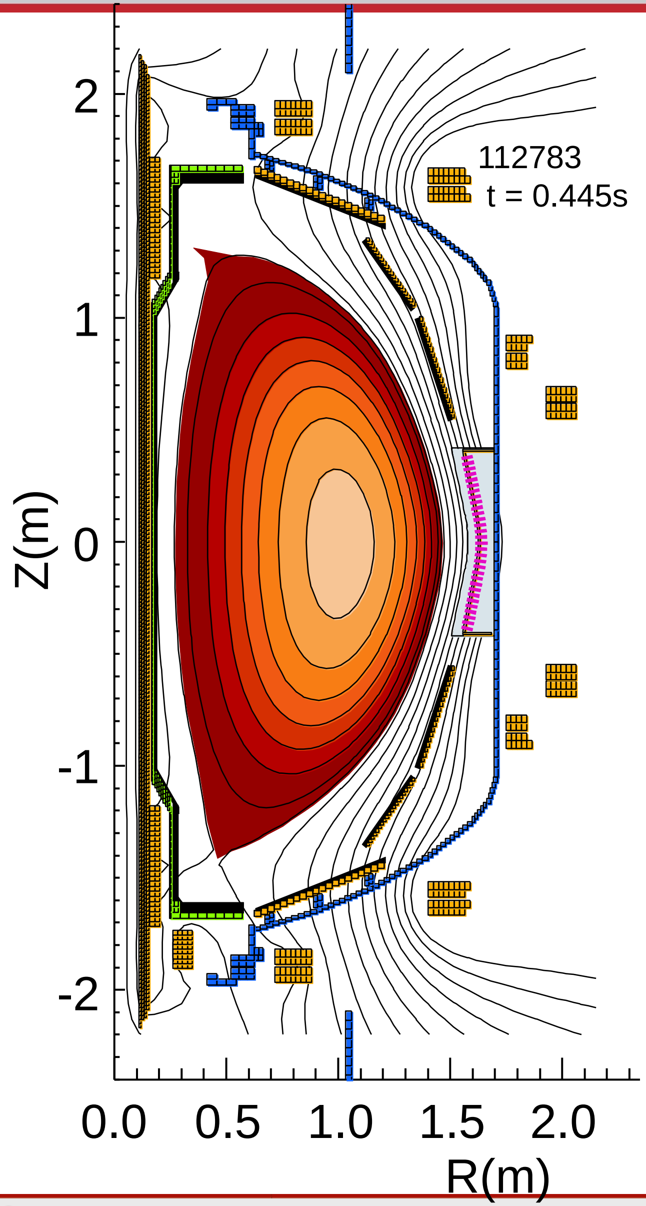
External magnetics data allow basic reconstruction

- Over 60 attempted variations to find final magnetics model ("EFIT01")
- Profile constraints: p'(0) = 0, (ff')'(1) = 0
  - ❑ constraints reproduce $q_0 = 1$ appearance, rational surface position from USXR
  - ❑ allows finite edge current (to model current transients)
- 4 profile variables (1 p', 3 ff'; 2nd order polynomial in p', 3rd order in ff')
- Goodness of fit χ^2 ~ 70 over majority of pulse for 108 measurements

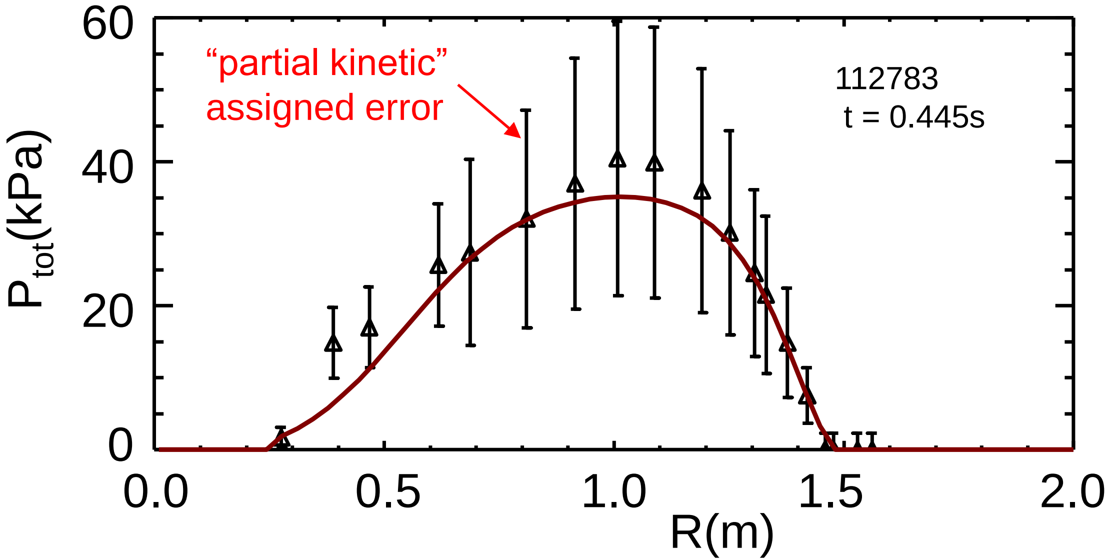
$\beta_t = 2\mu_0\langle p\rangle / B_0^2$



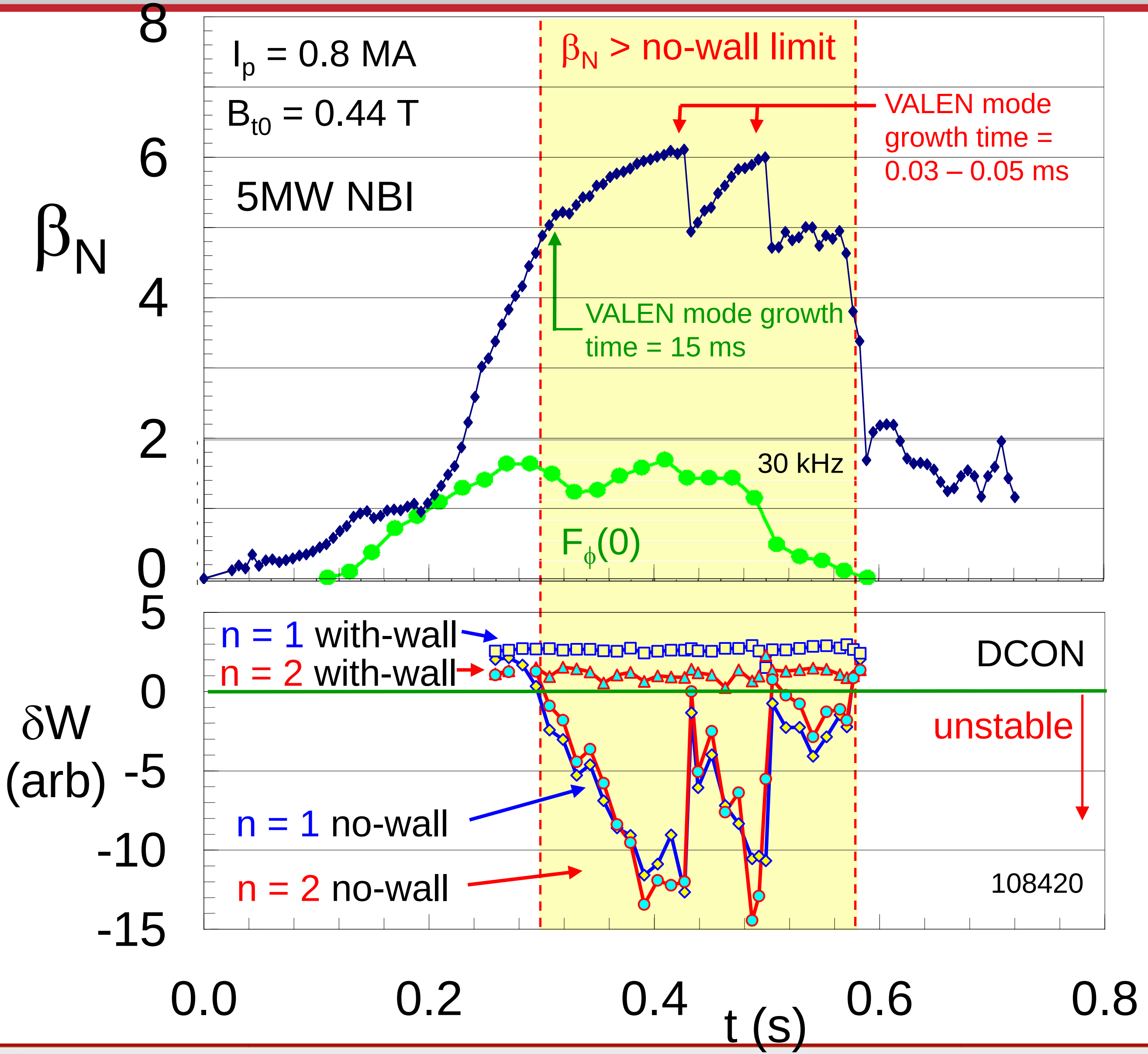
"Partial kinetic" prescription pioneered with NSTX EFIT reduces artificial constraint



- Over 110 attempted model variations used to find model
- 10 profile variables (5 p', 5 ff'); allows finite edge current
- External magnetics plus 20 Thomson scattering P_e points to constrain P profile shape
  - $P_{tot} = P_e + $ "P_i" $+$ "P_{fast}"; errors summed in quadrature (large total error)
- Diamagnetic flux to constrain stored energy
  - Greater freedom in ff' basis function for good fit over full discharge evolution and for various shots
- Weak constraints on p'(0), ff'(0) yield "reasonable" q(0)



NSTX EFIT equilibria used extensively in stability analyses

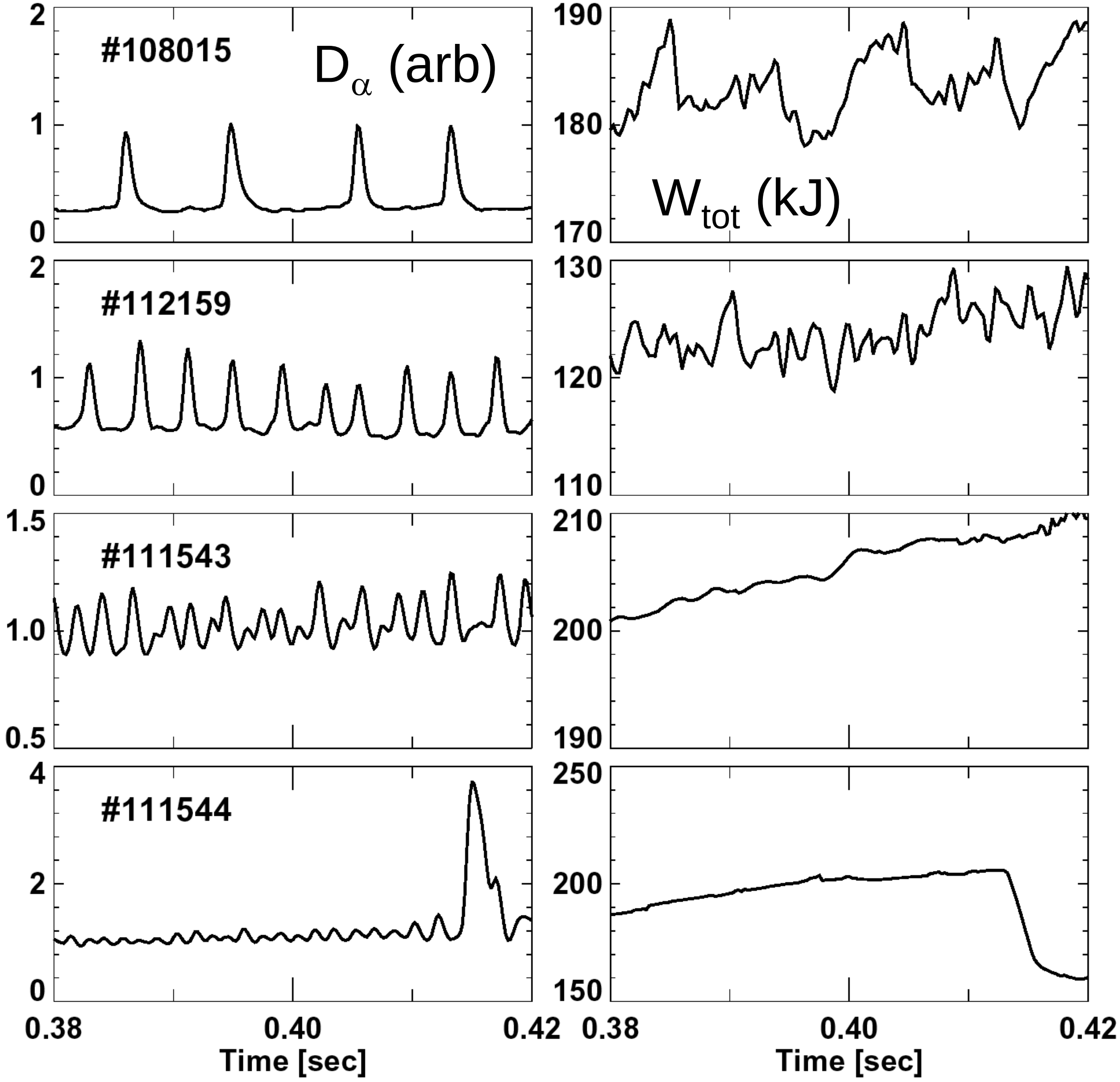


- Control room ideal stability analysis with DCON
  - time-evolved calculations
- Global mode growth rates in presence of passive stabilizers with VALEN
  - computed mode eigenfunction from DCON

$\beta_N = 10^8(\beta_t a B_0/I_p)$

DCON (A.H. Glasser)

High time resolution equilibrium analysis used in many studies (ELM study example)



Type I ELMs

Type II ELMs

Type V ELMs

Type V and giant ELM

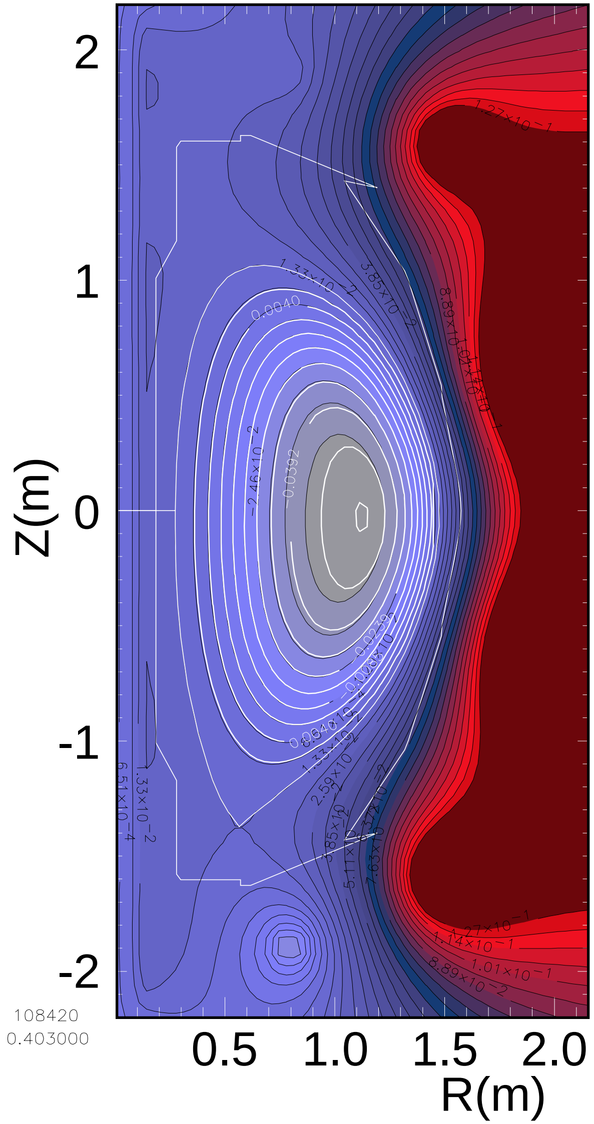
- 4000 equilibria per 1 second interval
- few kJ resolution W_{tot}

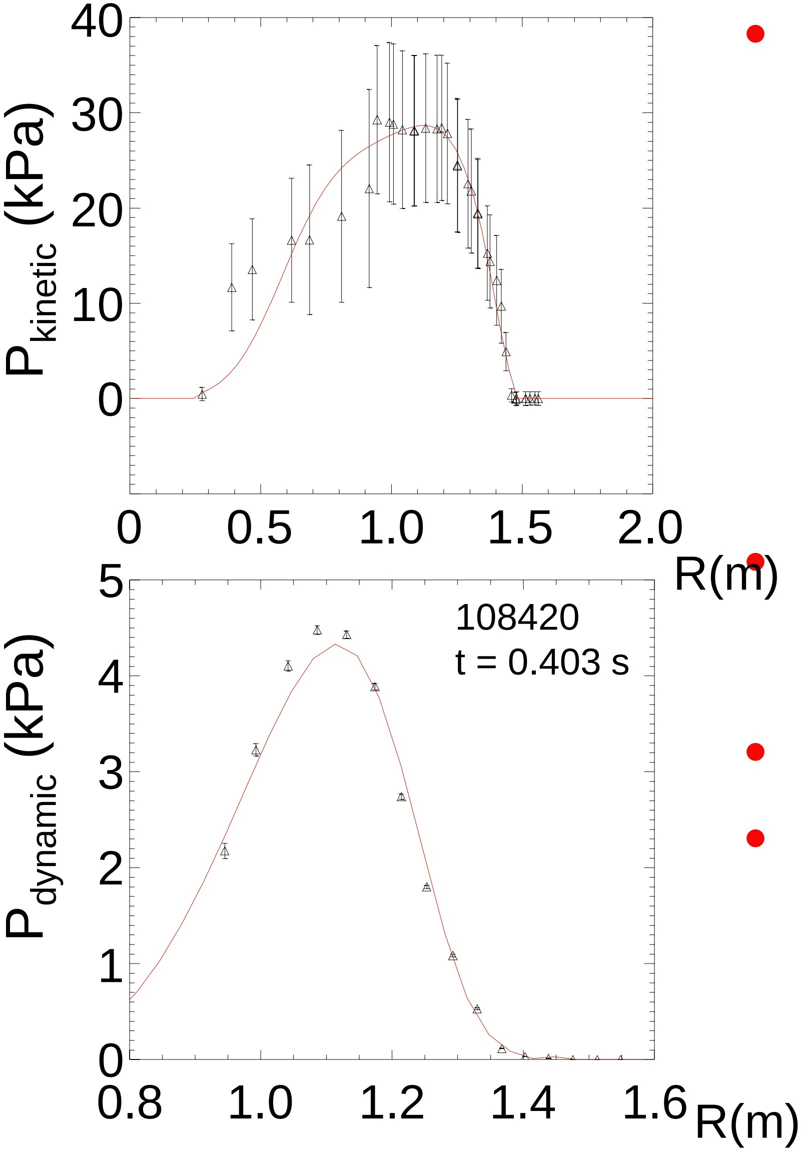
Pure toroidal flow allows a tractable equilibrium solution

- Solve $\nabla\phi$, $\nabla\psi$, ∇R components of equilibrium equation
  - MHD: $\rho\mathbf{v} \bullet \nabla\mathbf{v} = JxB - \nabla p$; ρ = mass density
    - $\nabla\phi$: $f(\psi) = RB_t$
    - ∇R: $2P_d(\psi,R)/R = p'(\psi,R)|_\psi$; $P_d \equiv \rho(\psi,R)\omega^2(\psi)R^2/2$ (Bernoulli eq.)
    - $\nabla\psi$: $\Delta^*\psi = -\mu_0 R^2 p'(\psi,R)|_R - \mu_0^2 ff'(\psi)/(4\pi^2)$ (G.S. analog)
  - Pure toroidal rotation and $T = T(\psi)$ yields simple solution for p
    - $p(\psi,R) = p_0(\psi) \exp(m_{fluid}\,\omega^2(\psi)(R^2 - R_t^2)/2T(\psi))$
- Constraints for fit
  - EFIT reconstructs two new flux functions: $P_w(\psi)$, $P_0(\psi)$
    - $P_w(\psi) \equiv \rho(\psi)\, R_t^2\omega^2(\psi)/2$; $P_0(\psi)$ defined so that:
    - $p(\psi,R) = P_0(\psi) \exp(P_w(\psi)/P_0(\psi)\,(R^2 - R_t^2)/R_t^2)$
  - Standard input: $P_w(\psi)$, $P_0(\psi)$ from approximation or transport code
  - New approach allowed by NSTX diagnostics
    - Solve for $P_w(\psi)$, $P_0(\psi)$ in terms of measured $P(\psi,R)|_{z=0}$, $P_d(\psi,R)|_{z=0}$

NSTX EFIT reconstructions included T_i, V_ϕ, Z_{eff} profiles by year 2004 (possible between-shots)

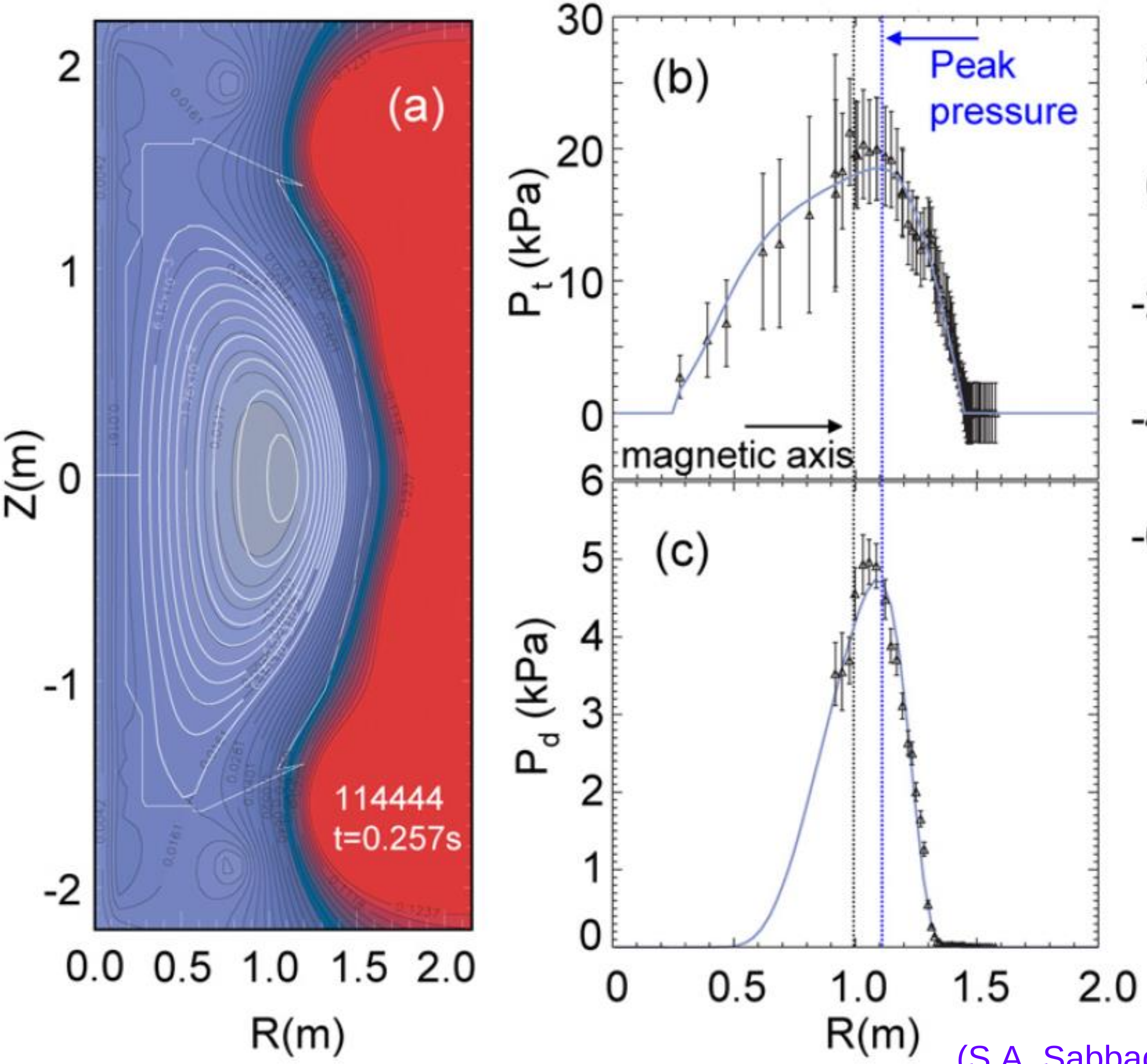
Poloidal flux and pressure

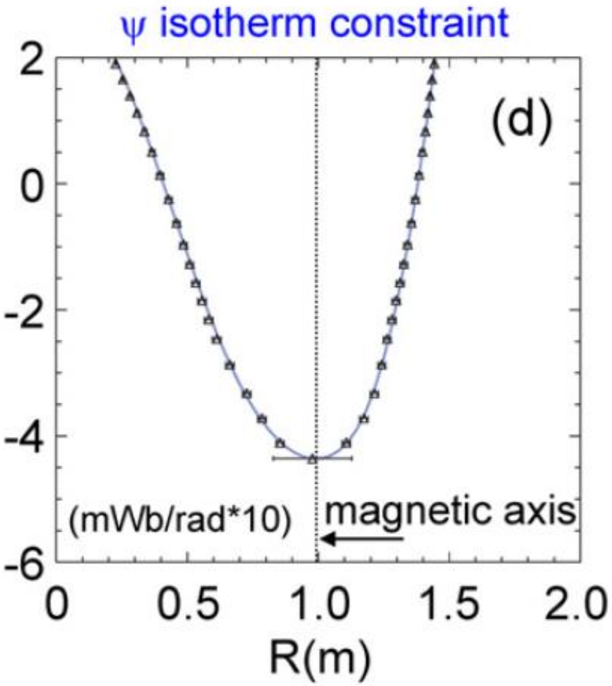




- Exact rotation solution fitting total and dynamic plasma pressure at (R, Z=0)
  - A few thousand shot*times test run
  - Simple estimate for P_{fast} (large error bars)
- Stored energy with/without V_ϕ = +/- 3%
- $(R_{pmax} – R_{axis})/a = 8\%$
- Significant drop in χ_{mag}^2 and χ_p^2 even though 50% more P channels and smaller error bars

Flux-Te isotherm constraint added to NSTX EFIT reconstructions with rotation in 2005





- $(R_{pmax} - R_{axis})/a \sim 18\%$
- Flux-Te isotherm constraint required to ensure assumptions made for G-S and Bernoulli equations are obeyed

(S.A. Sabbagh et al., Nucl. Fusion **46** (2006) 635)

NSTX EFIT: Diagnostics / model used for different between-shots analyses

- Magnetics-only:

  (~ 160 measurements/equil)

  - Model: pressure is a function of poloidal flux; vessel currents included
  - OH and shaping coil currents, I_p, flux-loops, pickup coils
  - Loop voltage monitors (to provide distributed vessel current input)
- Partial kinetic (between-shots): as “magnetics-only”, plus:
  - Thompson electron pressure profile
  - Diamagnetic loop
  - MSE (on request)

  (~ 200 measurements/equil)

- Kinetic + rotation (possible between-shots): adds:
  - Model: Allows separation of magnetic flux and pressure surfaces
  - CHERS ion pressure profile
  - CHERS dynamic pressure profile (1/2 ρV^2)
  - Flux-T_e isotherm constraint (req. for Bernoulli/G-S equation consistency)

  (~ 350 measurements/equil)

Where to find definitions of EFIT variables and other EFIT aspects?

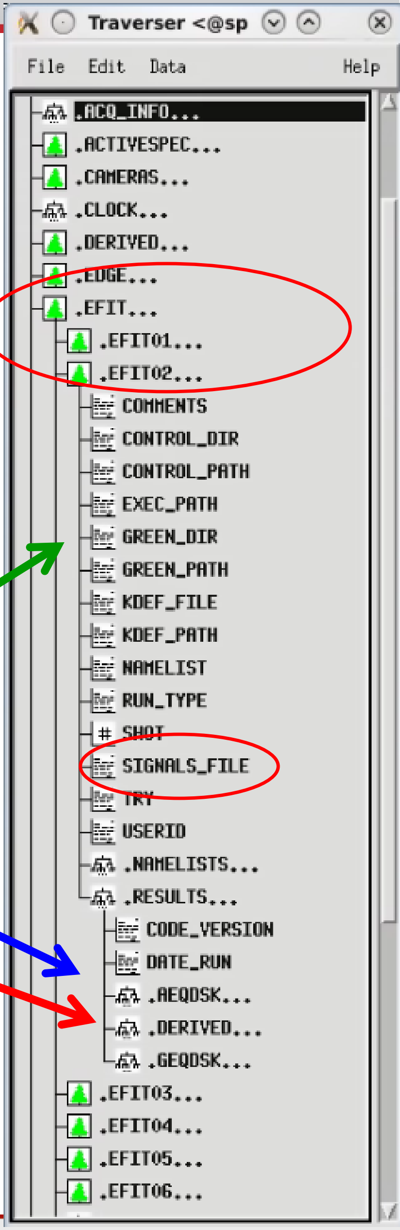
- EFIT Web page
  - https://fusion.gat.com/theory/Efit
  - DIII-D EFIT Tutorial
    - https://fusion.gat.com/theory-wiki/images/8/80/Lao_2013_EFIT_V4B.pdf
  - DIII-D EFIT tools: https://fusion.gat.com/theory/Efittools
- NSTX/NSTX-U list of variables, EFITVIEWER
  - http://nstx.pppl.gov/nstx/Software/Applications/a-g-file-variables.txt (eqdsk vars)
  - http://nstx.pppl.gov/nstx/Software/Applications/efitviewer.html
- PHOENIX Web page
  - Phoenix: set of utilities used to run between-shots NSTX/NSTX-U EFIT
  - http://www.pppl.gov/~sabbagh/PHOENIX/PHOENIXdoc.html
    - NOTE: WEB PAGE BEING UPDATED! (as of 10/13/15)
  - Contains
    - links to popular utilities: (i) 3D B field(R,Z), (ii) mapping, (iii) EQDSK retrieval
    - pointers to Green table areas, NSTX/NSTX-U executables, input files

Where do I find NSTX/NSTX-U EFIT Green tables, executables, model data files?

- Why?
  - EFIT input files range from being not well-commented to impenetrable
- For Who?
  - People wanting to run NSTX/NSTX-U EFIT stand-alone, interface between-shots EFIT with real-time EFIT, et al.
- NSTX/NSTX-U EFIT Green table areas
  - /p/spitfire/s1/common/Greens/NSTX/(Month)(Year)
  - Subdirectory name format: (Month)(Day)(Year)(Version)
    - Contains EFIT input files to build Green tables, and the tables themselves
      - These are typically impenetrable ASCII, (or binary)
    - Contains PHOENIX EFIT model data files
      - FILENAME: device(Month)(Day)(Year).dat: A well-commented ASCII file describing the NSTX/NSTX-U EFIT model (using standard EFIT conventions)
      - FILENAME: diagSpec(Month)(Day)(Year).dat: A well-commented ASCII file describing NSTX/NSTX-U magnetic diagnostics (standard EFIT conventions)
      - FILENAME: limiter(Month)(Day)(Year).dat: Specification of the limiter position
  - Signals used in NSTX EFIT runs (the “signals file”)
    - /p/spitfire/s1/common/plasma/phoenix/cdata (names: “signals_”(date)(version))

NSTX/NSTX-U EFIT: Locating results

- Local EQDSK repository
  - Past: All EQDSK files are saved for between-shots runs on local disk space for ~ past 2 years of run
    - Directory: /p/bigblue/equil_runs/NSTX(-U)/(Mon)(Year)/(shot)(try)
      - (try) = ‘x01m1a’ ➔ ‘EFIT01’ (‘magnetics-only analysis’)
      - (try) = ‘x01h1a’ ➔ ‘EFIT02’; (‘partial kinetic analysis’)
  - Future: All EQDSK files are planned to be available on local disks without the need to restore shots
- MDSPlus tree
  - Tags defining executable and Green tables used, etc.
  - “Standard” GEQDSK, AEQDSK trees (truly with MKS units)
  - “Non-standard” elements on “DERIVED” tree
    - Includes user-requested analysis (see next slide)
- Public utility to rebuild KEQDSK, GEQDSK, AEQDSK files
  - /u/sabbagh/public/plasma/phoenix/utilities/writekagfromdb
  - TAR file (IDL code): builds EQDSK files from any NSTX shot



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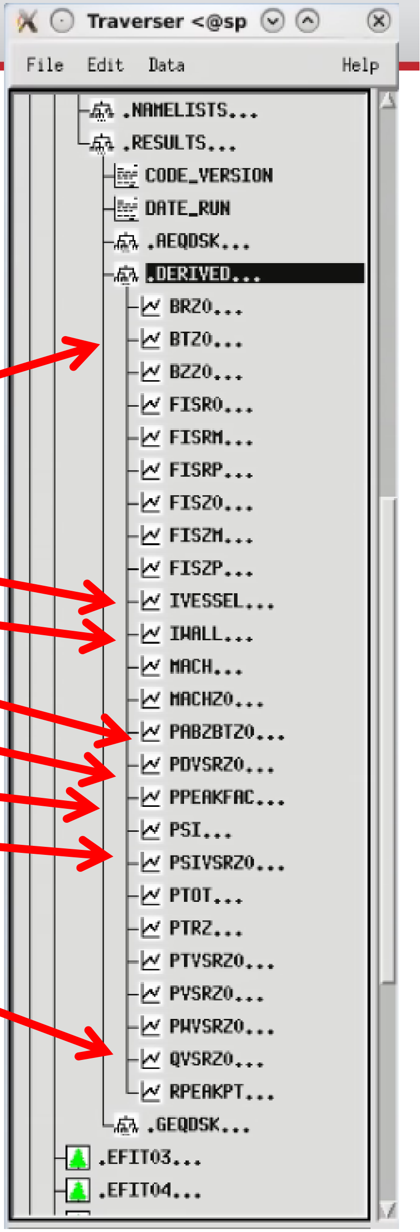
.ACQ_INFO...
.ACTIVESPEC...
.CAMERAS...
.CLOCK...
.DERIVED...
.EDGE...
.EFIT...
  .EFIT01...
  .EFIT02...
    COMMENTS
    CONTROL_DIR
    CONTROL_PATH
    EXEC_PATH
    GREEN_DIR
    GREEN_PATH
    KDEF_FILE
    KDEF_PATH
    NAMELIST
    RUN_TYPE
    SHOT
    SIGNALS_FILE
    TRY
    USERID
    .NAMELISTS...
    .RESULTS...
      CODE_VERSION
      DATE_RUN
      .AEQDSK...
      .DERIVED...
      .GEQDSK...
  .EFIT03...
  .EFIT04...
  .EFIT05...
  .EFIT06...
```

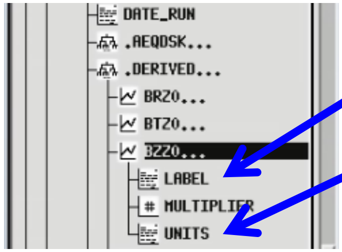
NSTX/NSTX-U EFIT: DERIVED tree

- NSTX EFIT DERIVED tree
  - Supplements the “standard EFIT” tree with analysis requested by the NSTX Team
  - Some examples:
    - BRZ0, BTZ0, BZZ0: Three B field component profiles at Z = 0
    - IVESSEL: Total vessel current
    - IWALL: Total wall current
    - PABZBTZ0: Field pitch angle vs. R at Z = 0
    - PDVSRZ0: Dynamic pressure vs. R at Z = 0
    - PPEAKFAC: Pressure peaking factor
    - PSIVSRZ0: Poloidal flux vs. R at Z = 0
    - QVSRZ0: Safety factor profile vs. R at Z = 0



.NAMELISTS...
.RESULTS...
CODE_VERSION
DATE_RUN
.AEQDSK...
.DERIVED...
BRZ0...
BTZ0...
BZZ0...
FISR0...
FISRM...
FISRP...
FISZ0...
FISZM...
FISZP...
IVESSEL...
IWALL...
MACH...
MACHZ0...
PABZBTZ0...
PDVSRZ0...
PPEAKFAC...
PSI...
PSIVSRZ0...
PTOT...
PTRZ...
PTVSRZ0...
PVSRZ0...
PWVSRZ0...
QVSRZ0...
RPEAKPT...
.GEQDSK...
.EFIT03...
.EFIT04...

- All variables on all EFIT trees have labels, units



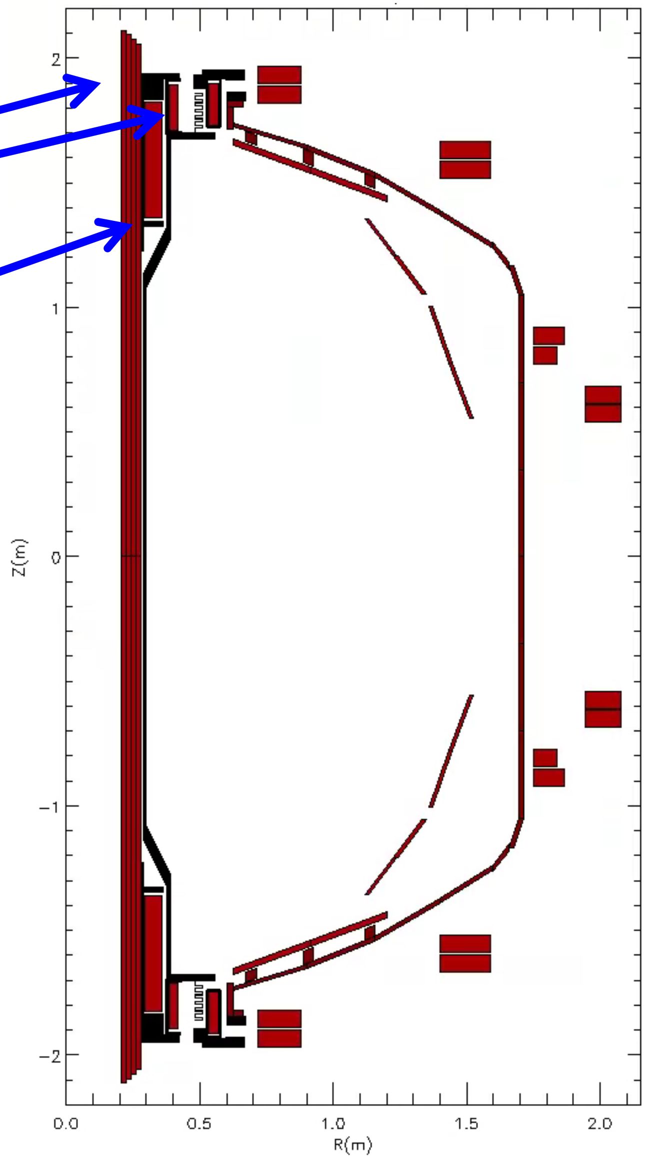
DATE_RUN
.AEQDSK...
.DERIVED...
BRZ0...
BTZ0...
BZZ0...
LABEL
MULTIPLIER
UNITS

How do I run NSTX/NSTX-U EFIT?

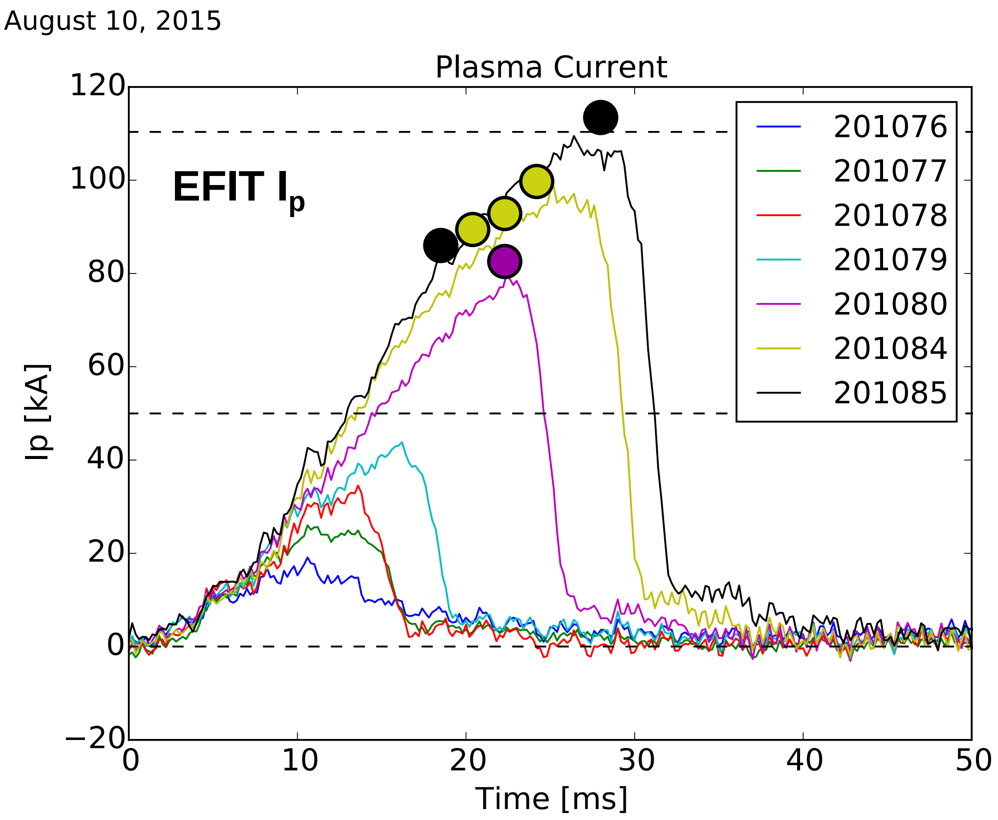
- Can cases be run stand-alone if desired?
  - NSTX/NSTX-U EFIT executables / input files can be found here:
    - /u/sabbagh/public/plasma/equilibrium/efit/exec ← executables here
    - /p/spitfire/s1/common/plasma/exec ← executables here
    - /p/bigblue/equil_runs/NSTX(-U)/(Mon)(Year)/(shot)(try) ← input files here
    - Create SYMBOLIC LINK "link_efitx" → Green table directories stated before
    - Note: no public utilities to build NSTX/-U KEQDSK (data input/control) files (although Sabbagh / Columbia U. group can build files for you)
- Why isn't it easier to build data files? Considering new tools
  - One Modeling Framework for Integrated Tasks (OMFIT)
    - http://gafusion.github.io/OMFIT-source/
  - Sabbagh has been following (extensive) OMFIT thread for a few months
  - Present plan (by Sabbagh / Columbia U. group) is to interface NSTX-U EFIT to OMFIT, enabling code execution, analysis display capabilities
    - This should make running stand-alone NSTX-U EFIT easier

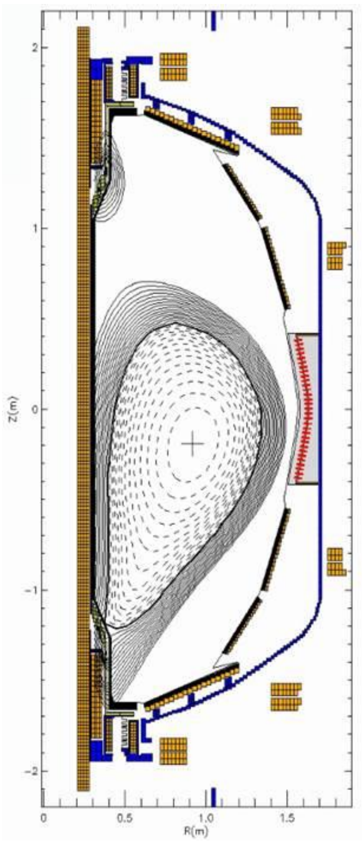
NSTX-U EFIT Model created and used for vacuum field test shots and CD-4 plasmas

- New NSTX-U model
  - New center stack / elements
  - New PF1 (a,b,c) coils
  - PF1 coils mandrels (new conducting regions)
  - New limiter specification
- Model for "3D" passive plate currents retained
  - We are close to completing computation of 2D equivalent of 3D effective resistances
    - Using the 3D vessel, plate, port modeling in the VALEN code



NSTX-U EFIT Model created and used for vacuum field test shots and CD-4 plasmas





<u>Shot 201085</u>

Time: 28ms

I_p = 117 kA

B_{T0} = - 0.482 T

R_0 = 0.8 m

Z_0 = - 0.2 m

I_{wall} ~ 0.4 MA

- Vessel current model essential for these runs
  - Up to 0.42MA vessel current modeled
  - Reconstructions challenging at I_p/I_{wall} ~ ¼, but successful (good magnetics)

NSTX-U EFIT: Present actions and near-term upgrade plans for CY2015-2016 run

- We have the latest EFIT code on the cluster. Tasks:
  - Complete the installation / testing of code (make needed alterations)
  - Speed tests for 128x128 spatial resolution (intended for 2015-2016+)
    - Two new dedicated computers (64 CPUs total) to support this
  - Speed tests for 2 – 4 times more time points
    - Will be needed for long-pulse NSTX-U operation
- PHOENIX code / EFIT alterations
  - Update / optimize scripts; update parallel processing
  - Changes to best support higher spatial, time resolution
    - I/O has been key bottleneck – need to improve / optimize I/O to highest performance = minimum between-shots processing time at high resolution
- New data / routine processing
  - Additional Thomson channels to be added
  - Routine between-shots reconstructions with MSE (when data available)

RWM Control on NSTX(-U): Model-based RWM state space controller in NSTX advances present PID controller

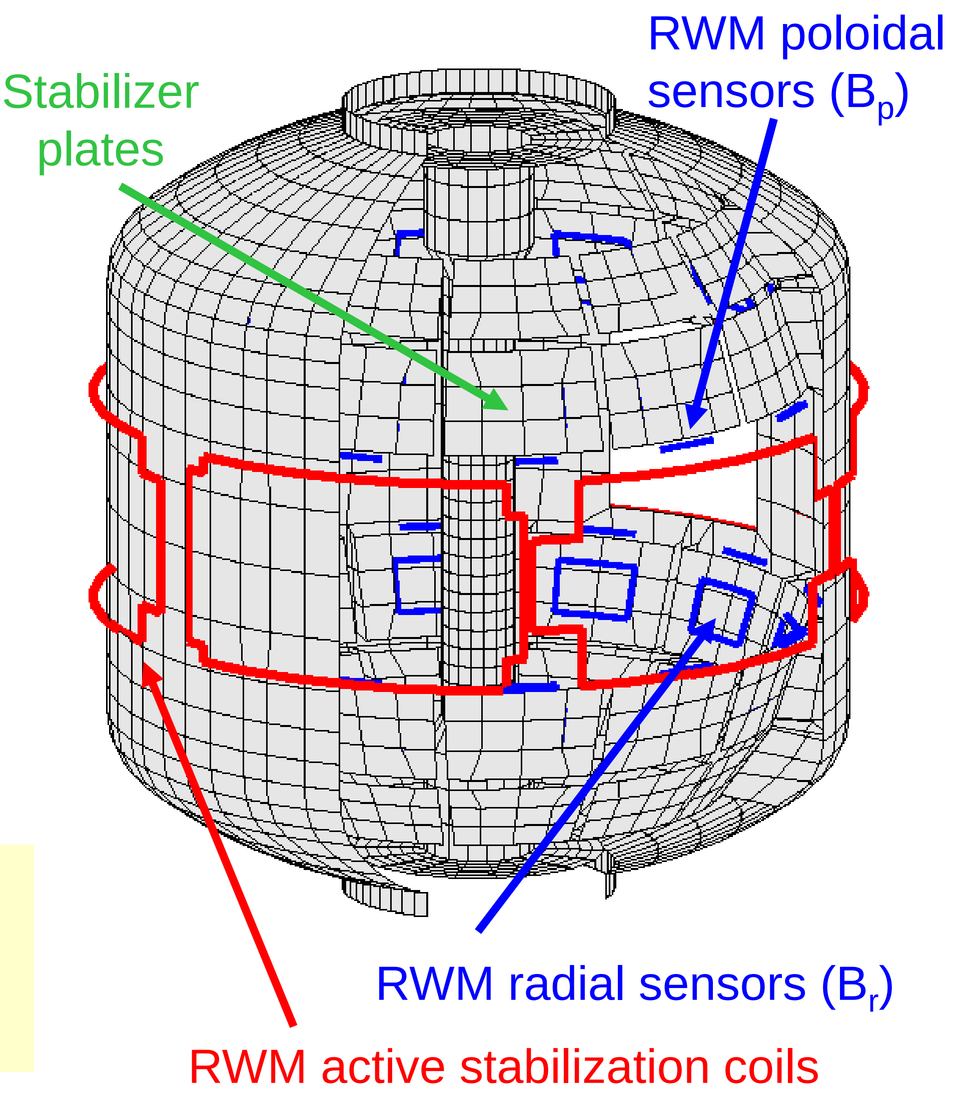
- PID (a successful workhorse)
  - Feedback logic operates to reduce n = 1 amplitude (n = 1 phase/ampl. input)
  - No a priori knowledge of mode physics, controller stability
  - Only knowledge of mode structure: spatial phase offset of upper/lower sensors

- State space control
  - States reproduce characteristics of full 3-D model: conducting structure, plasma response, mode shape, feedback control currents via matrix operations
    - Boozer permeability model used for plasma response
    - A key quantity to compare to measurements is mode pitch at large R
  - Observer (computes sensor estimates)
    - RWM sensor estimates provided by established methods (Kalman filter)
    - useful as an analysis tool to compare plant output to measurements
  - Controller (computes control currents)
    - Controller gain computed by established methods: gains for each coil and state
- Many shots taken in NSTX with RWM state space control
  - Two dedicated run days, near-record β_N/l_i in sustained plasmas, gain/phase scans, hundreds of shots run with low gain (e.g. observer scoping studies)

NSTX is a spherical torus equipped to study passive and active global MHD control

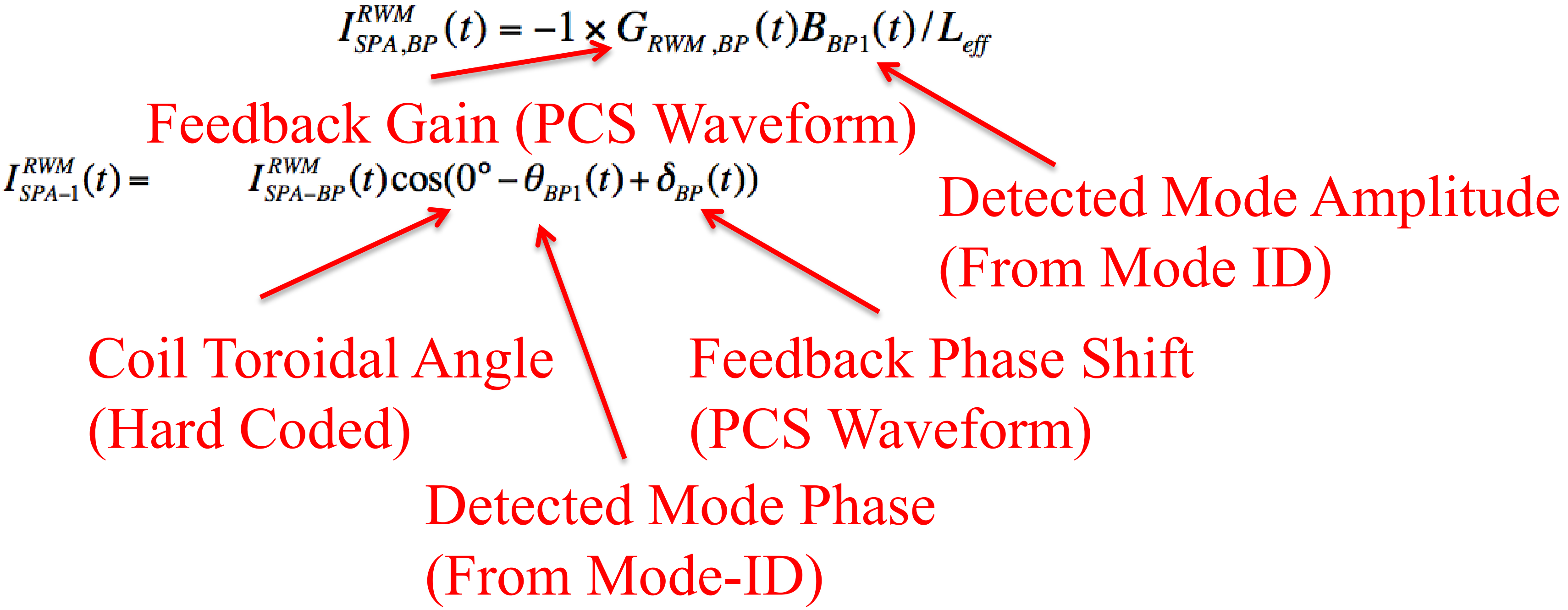
- High beta, low aspect ratio
  - R = 0.86 m, A > 1.27
  - $I_p < 1.5$ MA, $B_t = 5.5$ kG
  - $\beta_t < 40\%$, $\beta_N > 7$
- Copper stabilizer plates for kink mode stabilization
- Midplane control coils
  - n = 1 – 3 field correction, magnetic braking of ω_ϕ by NTV
  - n = 1 RWM control
- Combined sensor sets now used for RWM feedback
  - 48 upper/lower B_p, B_r

3D Structure Model



RWM PID Control: RWM/DEFC Feedback Methodology in the "tmf" Algorithm (see "3D Fields" Phys. Ops talk #12)

- We know the amplitude $B_1(t)$ and phase $\theta_1(t)$ of the detected 3D field, from both B_R and B_P sensors.
- Apply an n=1 field with:
  - Amplitude proportional to the detected 3-D field
  - Fixed phase shift from the detected 3-D field.



$$I^{RWM}_{SPA,BP}(t) = -1 \times G_{RWM,BP}(t)B_{BP1}(t)/L_{eff}$$

Feedback Gain (PCS Waveform)

$$I^{RWM}_{SPA-1}(t) = I^{RWM}_{SPA-BP}(t)\cos(0^\circ - \theta_{BP1}(t) + \delta_{BP}(t))$$

Detected Mode Amplitude
(From Mode ID)

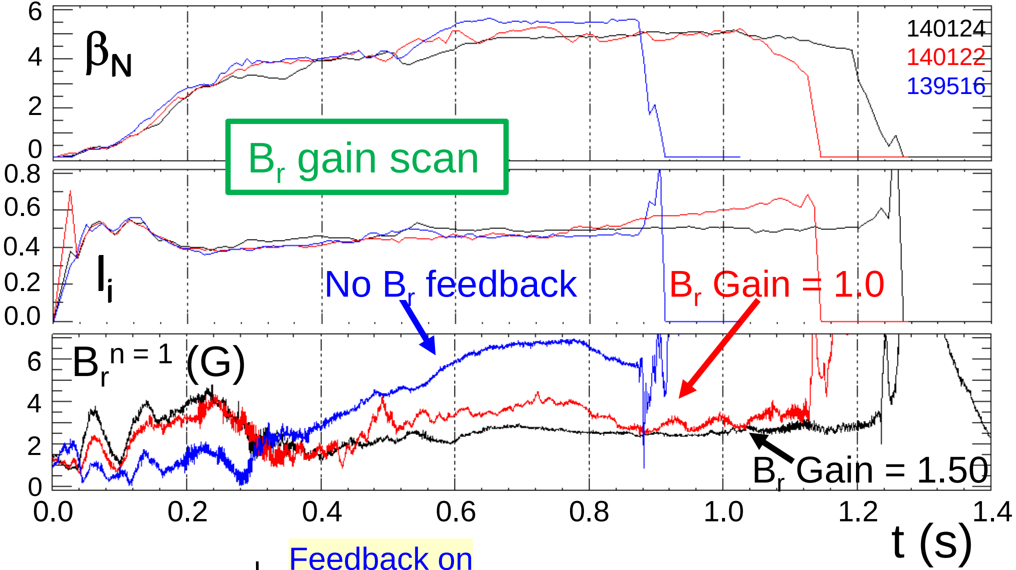
Coil Toroidal Angle
(Hard Coded)

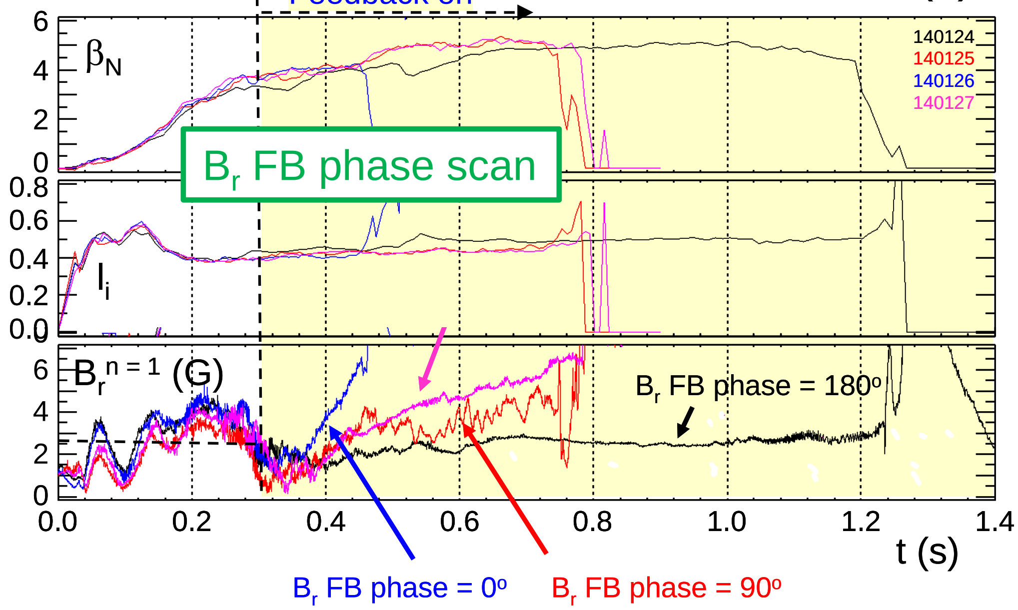
Feedback Phase Shift
(PCS Waveform)

Detected Mode Phase
(From Mode-ID)

Find full detail on RWM PID control / Mode ID algorithm in the PCS shown in Phys. Ops. Training Talk #12 – 3D Fields (S.P. Gerhardt, et al.)

Active RWM control: dual B_r + B_p sensor feedback gain and phase scans produce significantly reduced n = 1 field

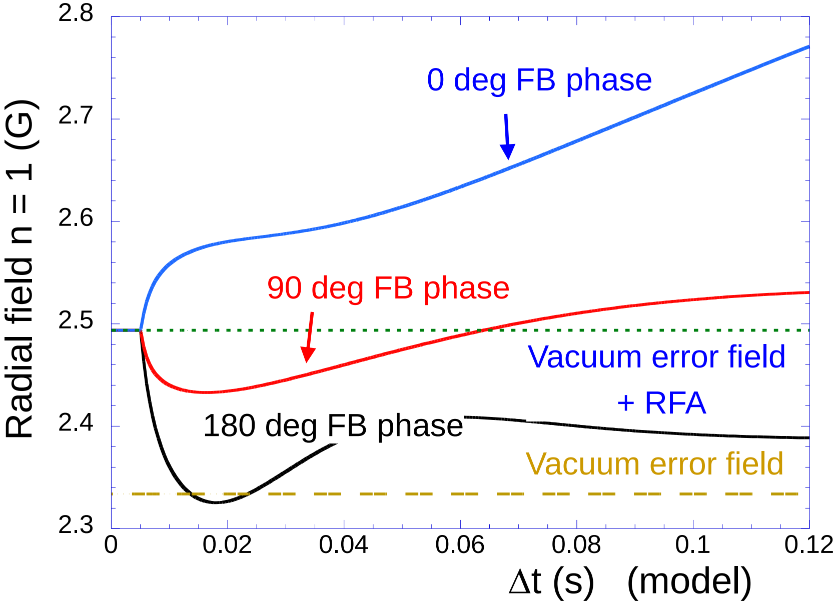




- Favorable B_p + B_r feedback (FB) settings found (low l_i plasmas)
- Time-evolved theory simulation of B_r+B_p feedback follows experiment

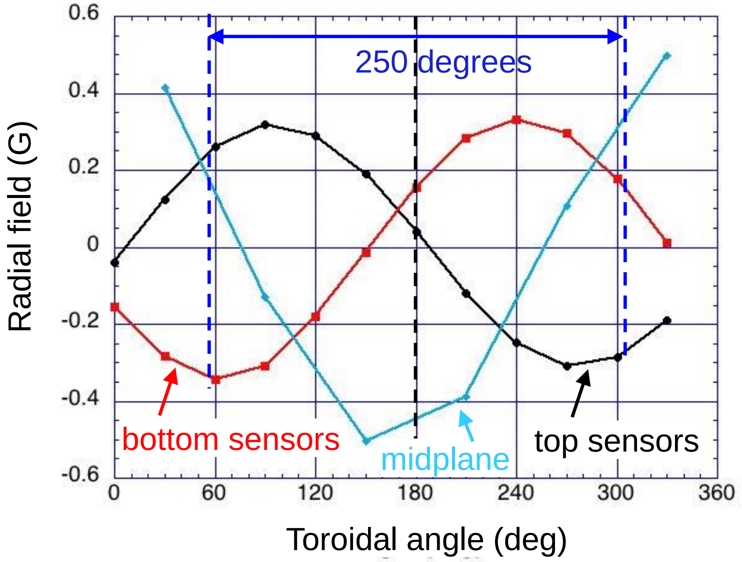
(S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007)

Simulation of B_r + B_p control (VALEN)

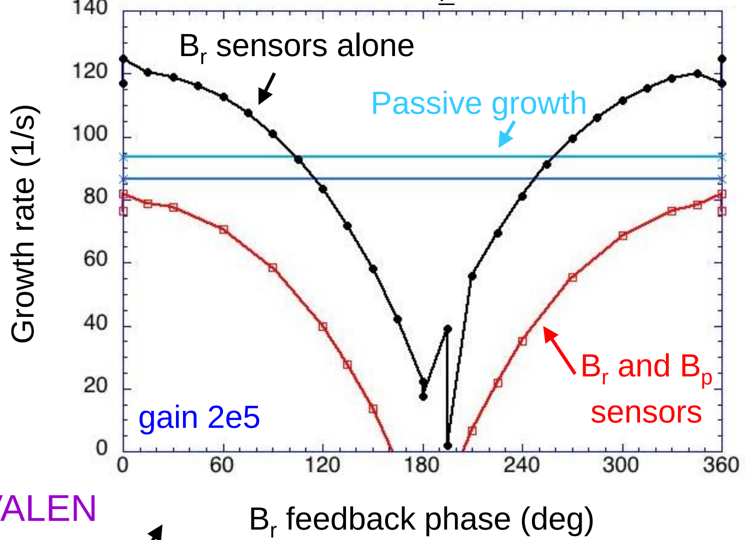


RWM feedback using upper/lower B_p and B_r sensors modeled and compared to experiment

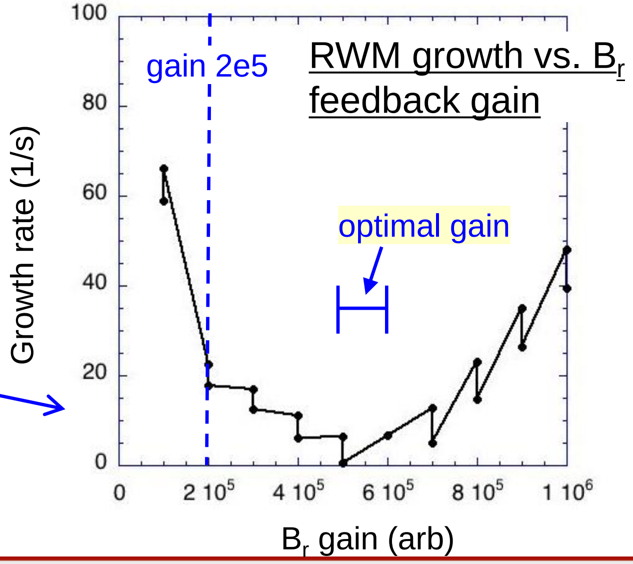
Modeled B_r field at sensors and midplane



RWM growth vs. B_r feedback phase



DCON, VALEN codes



RWM growth vs. B_r feedback gain

- Both B_r, B_p feedback contribute to active control
  - B_r mode structure and optimal feedback phase agrees with parameters used in experiment
  - B_r feedback alone provides stabilization for growth times down to ~ 10 ms ~ $\tau_{w\text{-radial}}$ with optimal gain
- Theory shows optimal feedback phase used in experiments; gain used is near optimal, but can be improved

New State Derivative Feedback Algorithm needed for Current Control in the NSTX RWM State-space controller (RWMSC)

Control vector, *u*; controller gain, K_c

Observer est., *y*; observer gain, K_o

K_c , K_o computed by standard methods (e.g. Kalman filter used for observer)

- State equations to advance

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -K_c\vec{x} = \dot{I}_{\mathrm{cc}}$$

$$\vec{y} = C\vec{x} + D\vec{u}$$

- Previously published approach found to be formally "uncontrollable" when applied to current control
- State derivative feedback control approach

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -\hat{K}_c\dot{\vec{x}} \longrightarrow \vec{I}_{\mathrm{cc}} = -\hat{K}_c\vec{x}$$

$$\dot{\vec{x}} = ((\mathrm{I} + B\hat{K}_c)^{-1}A)\vec{x}$$

e.g. T.H.S. Abdelaziz, M. Valasek., Proc. of 16th IFAC World Congress, 2005

  - new Ricatti equations to solve to derive control matrices – still "standard" solutions for this in control theory literature

Advance discrete state vector

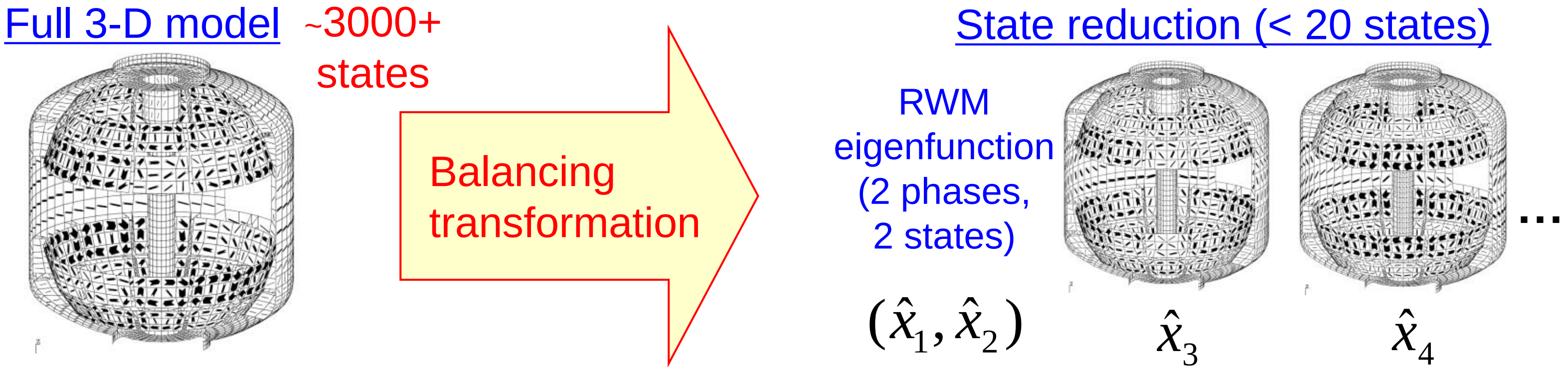
$$\hat{\vec{x}}_t = A\vec{x}_{t-1} + B\vec{u}_{t-1}; \hat{\vec{y}}_t = C\hat{\vec{x}}_t$$ (time update)

$$\vec{x}_{t+1} = \hat{\vec{x}}_t + A^{-1}K_o(\vec{y}_{sensors(t)} - \hat{\vec{y}}_t)$$ (measurement update)

Written into NSTX PCS

- General (portable) matrix output file for Phys. Operator
- Sabbagh has generalized offline IDL code for 6 SPAs
- Must now finalize PCS alteration with Keith Erickson

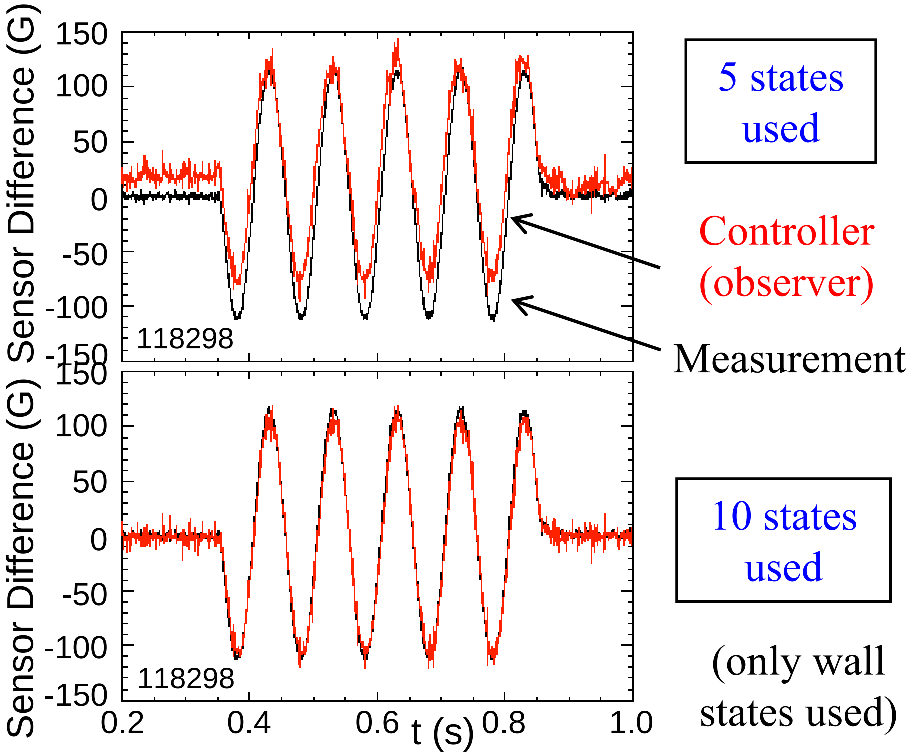
Model-based RWM state space controller including 3D model of plasma and wall currents used at high β_N



- Controller model can compensate for wall currents
  - Includes plasma mode-induced current
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, and be shielded (e.g. for ITER)

    Katsuro-Hopkins, et al., NF **47** (2007) 1157
- Straightforward inclusion of multiple modes (with n = 1, or n > 1) in feedback

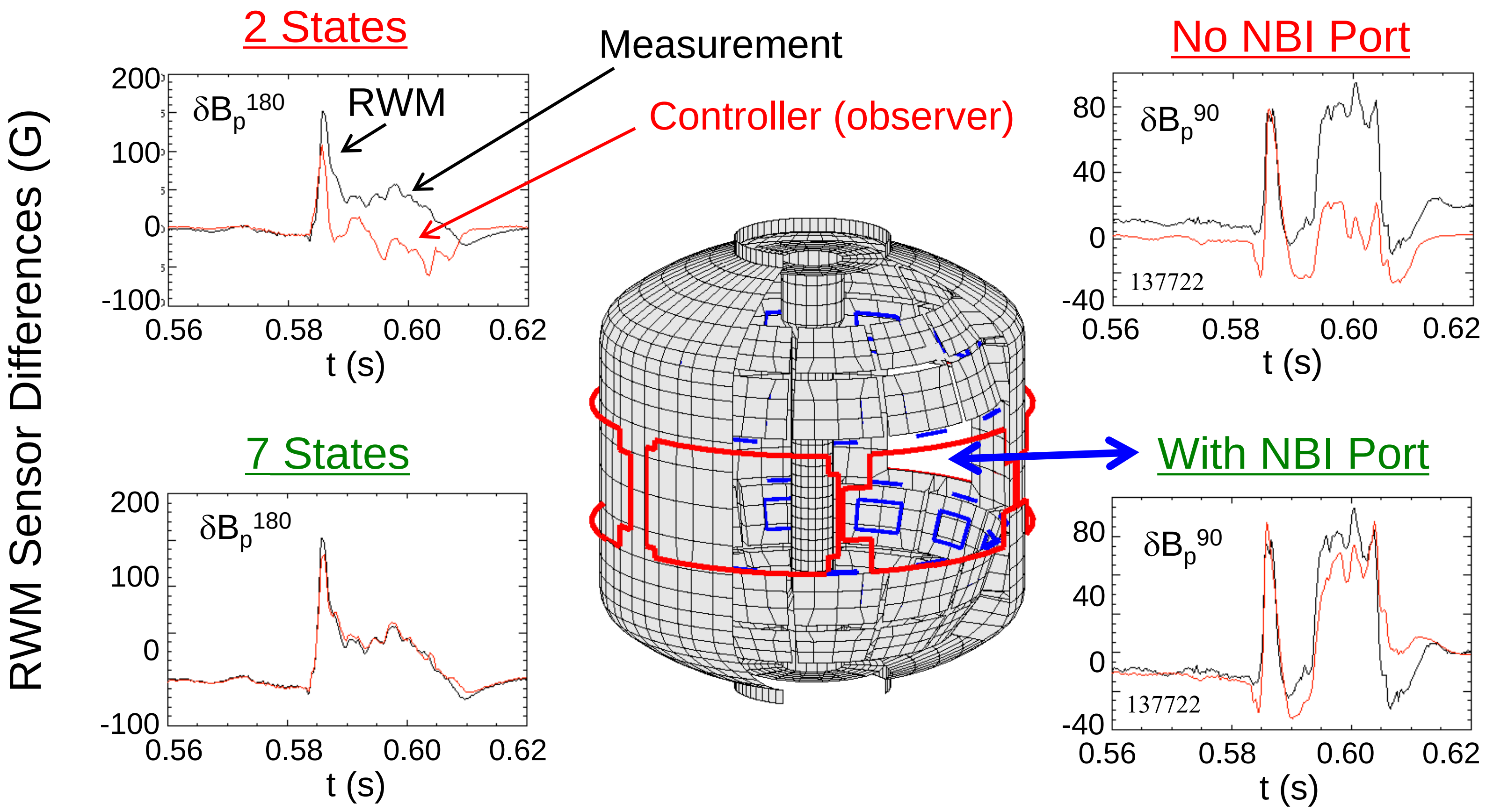
Controller reproduction of n = 1 field in NSTX



Open-loop comparisons between measurements and RWM state space controller show importance of states and model

A) Effect of Number of States Used

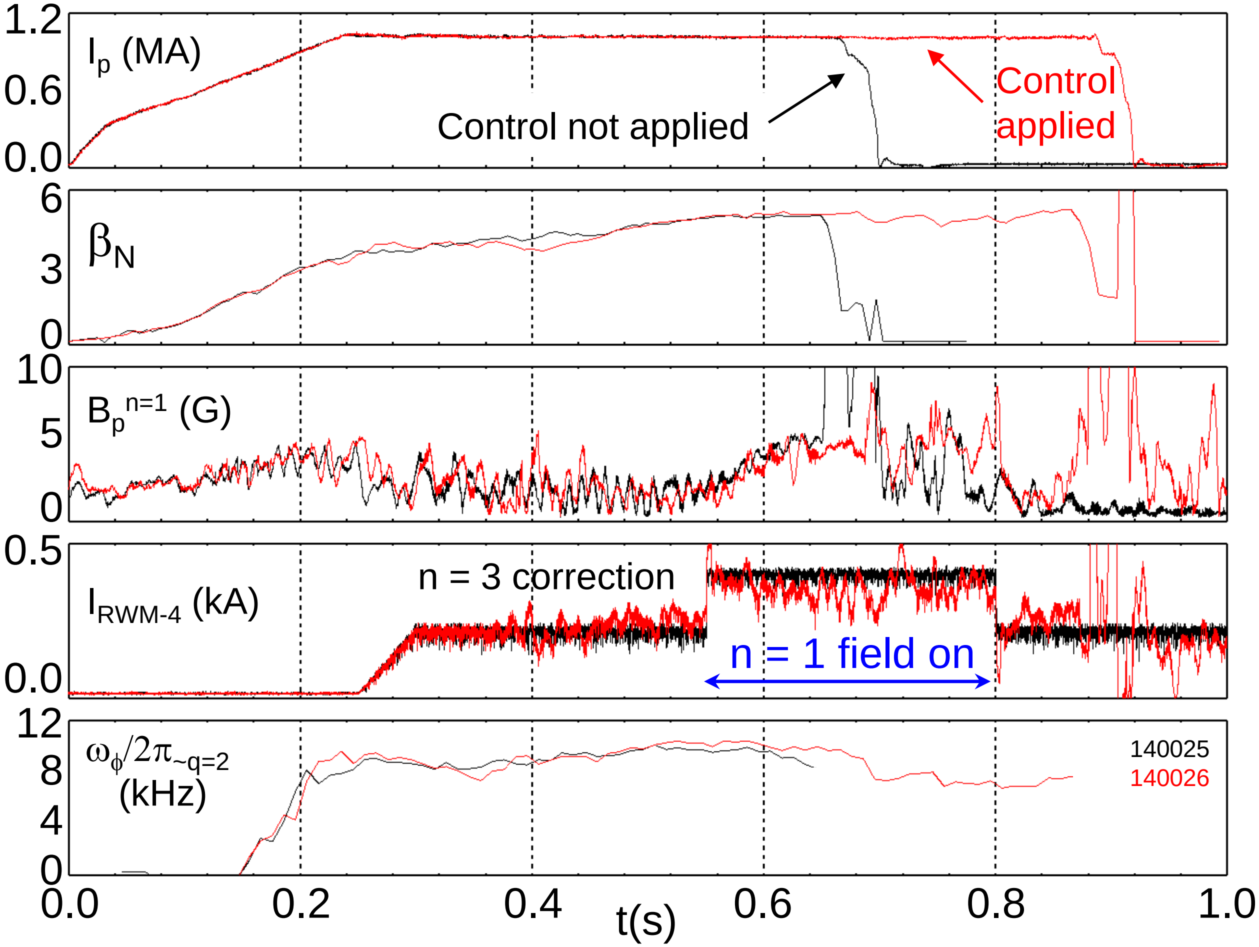
B) Effect of 3D Model Used



- Improved agreement with sufficient number of states (wall detail)
- 3D detail of model important to improve agreement

RWM state space controller sustains otherwise disrupted plasma caused by DC n = 1 applied field

RWM state space feedback (12 states)

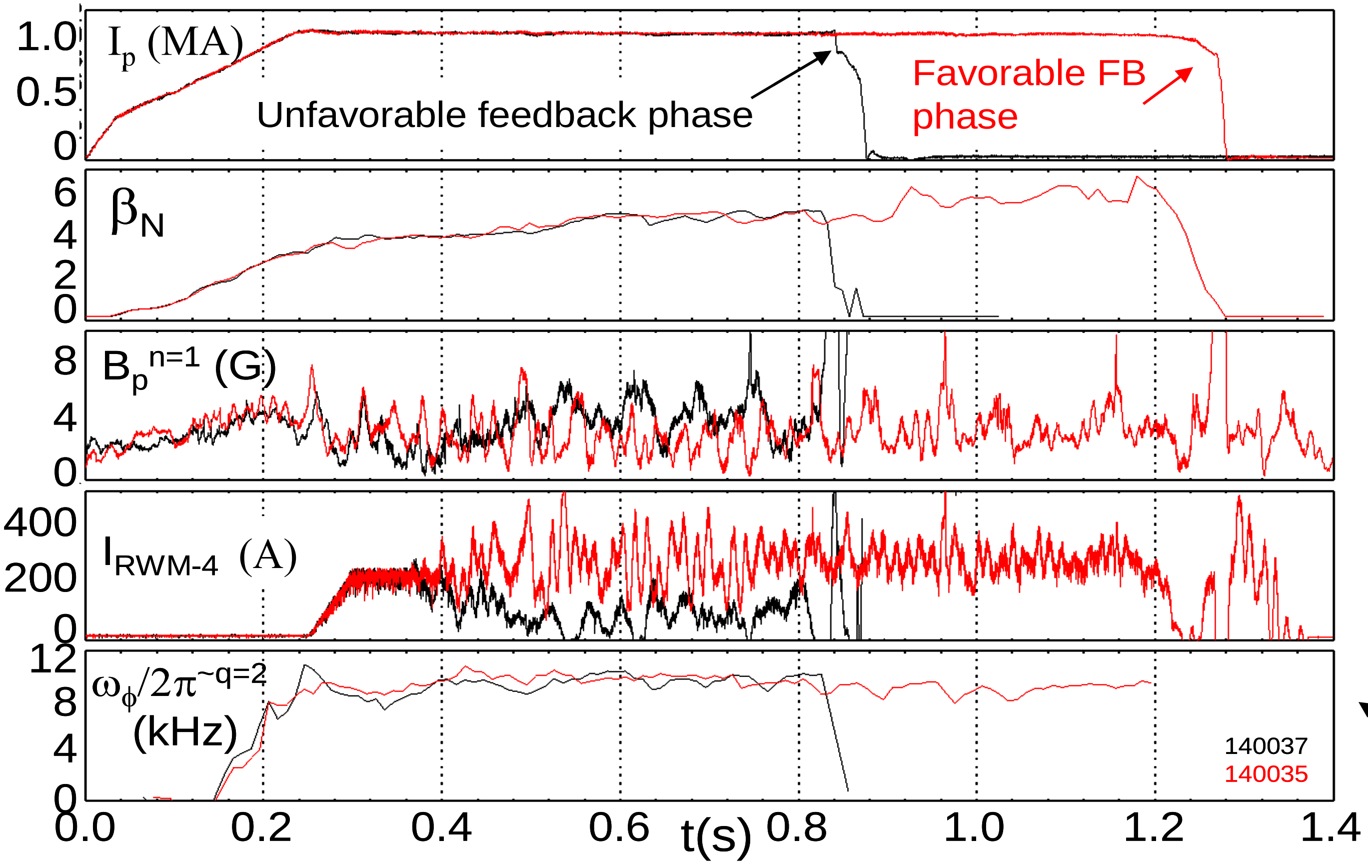


- n = 1 DC applied field test
  - Generate resonant field amplication, disruption
  - Use of RWM state space controller sustains discharge
- RWM state space controller sustains discharge at high β_N
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007

NSTX RWM state space controller sustains high β_N, low l_i plasma

RWM state space feedback (12 states)



NSTX Experiments

- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field
- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

- Run time allocated for continued experiments on NSTX-U

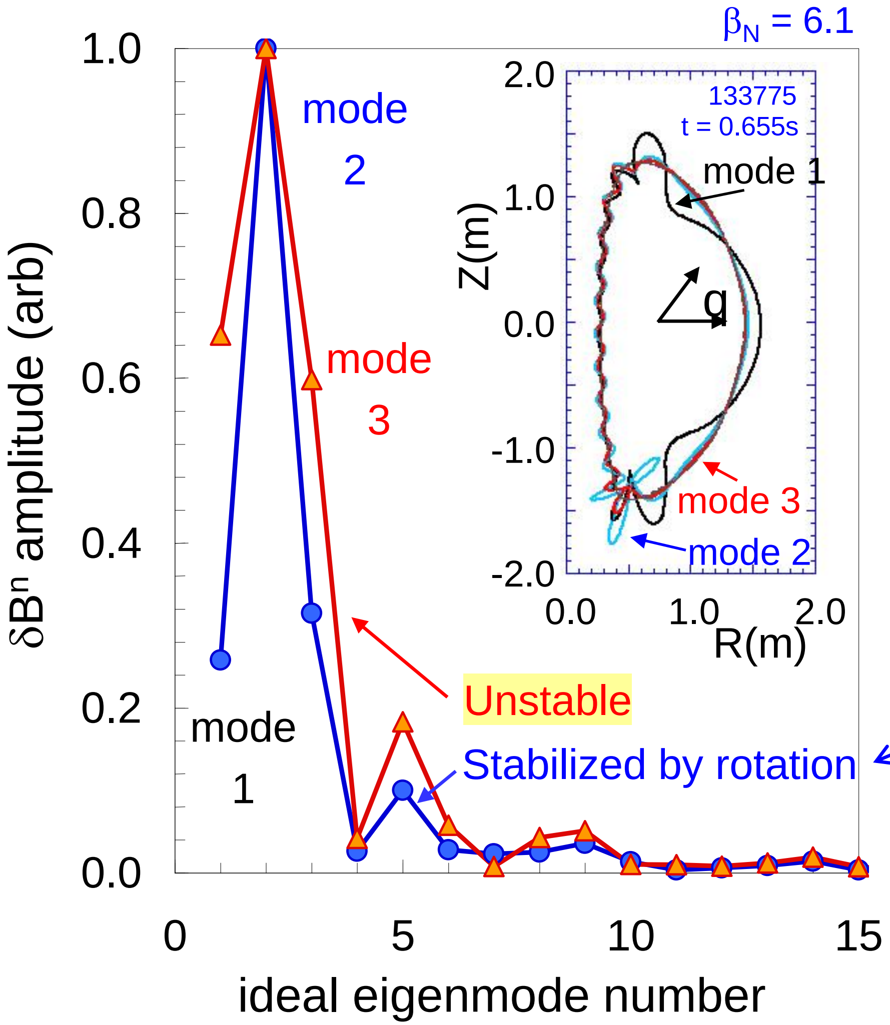
S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007

Updated RWM State-space controller: How parameters are specified through the PCS – STATUS and PLANS

- Sensors
  - PCS widget allows selection of what sensors are being used (easy to choose)
  - Initial plan for NSTX-U is to use B_p sensor differences (as for NSTX) (2015)
  - Will also upgrade to incorporate B_r sensors in the NSTX-U RWMSC (~ 2016)
- Actuators
  - Upgrade to utilize 6 independent SPA channels in the PCS (2015)
- Model
  - The control matrices (A,B,C,D) and vectors are loaded into the PCS by the Physics Operator by a file pre-created by MATLAB code in:
    - Filespace: /p/pcs/ops/lqg (filenames: "RWMSC-"(date)(version))
  - (2015/16) Addition of n=2 eigenfunction; secondary n=1 eigenfunctions
    - Accomplished by adding two rows in the plant matrix per mode
    - This is straightforward, and TRANSPARENT to the Physics Operator

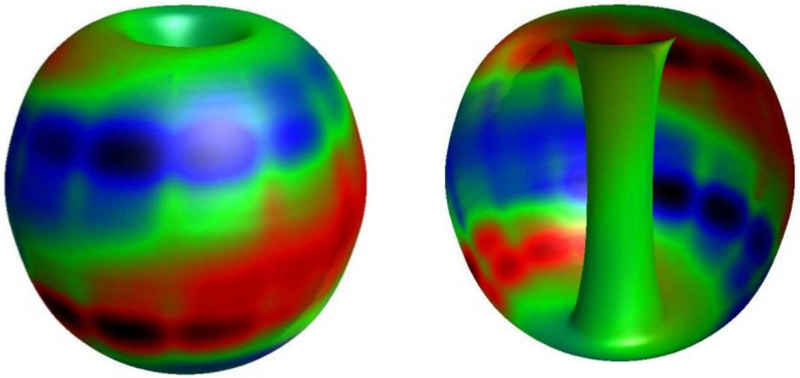
Multi-mode computation for RWM & DEFC: 2nd eigenmode component has dominant amplitude at high β_N in NSTX 3D stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

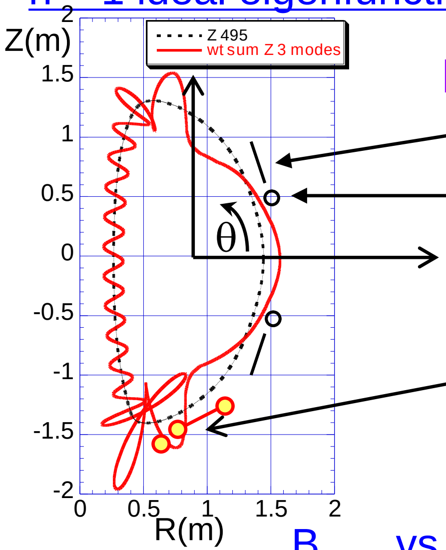
δB^n from wall, multi-mode response



- NSTX RWM not stabilized by ω_ϕ
  - Computed growth time consistent with experiment
  - 2nd eigenmode ("divertor") has larger amplitude than ballooning eigenmode
- NSTX RWM stabilized by ω_ϕ (or "α")
  - Ballooning eigenmode amplitude decreases relative to "divertor" mode
  - Computed RWM rotation ~ 41 Hz, close to experimental value ~ 30 Hz
- ITER scenario IV multi-mode spectrum
  - Significant spectrum for n = 1 and 2

3D analysis of extended MHD sensors (in NSTX-U 5Yr plan) show significant mode ampl. off-midplane, + divertor region

n = 1 ideal eigenfunction for high beta plasma

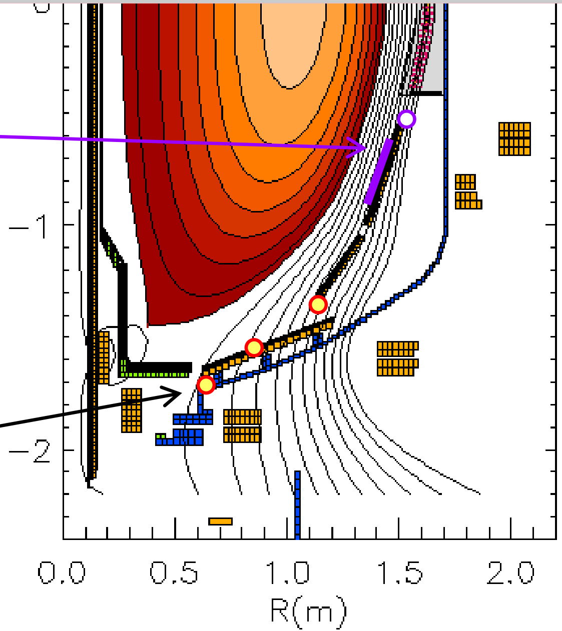


Present sensor locations

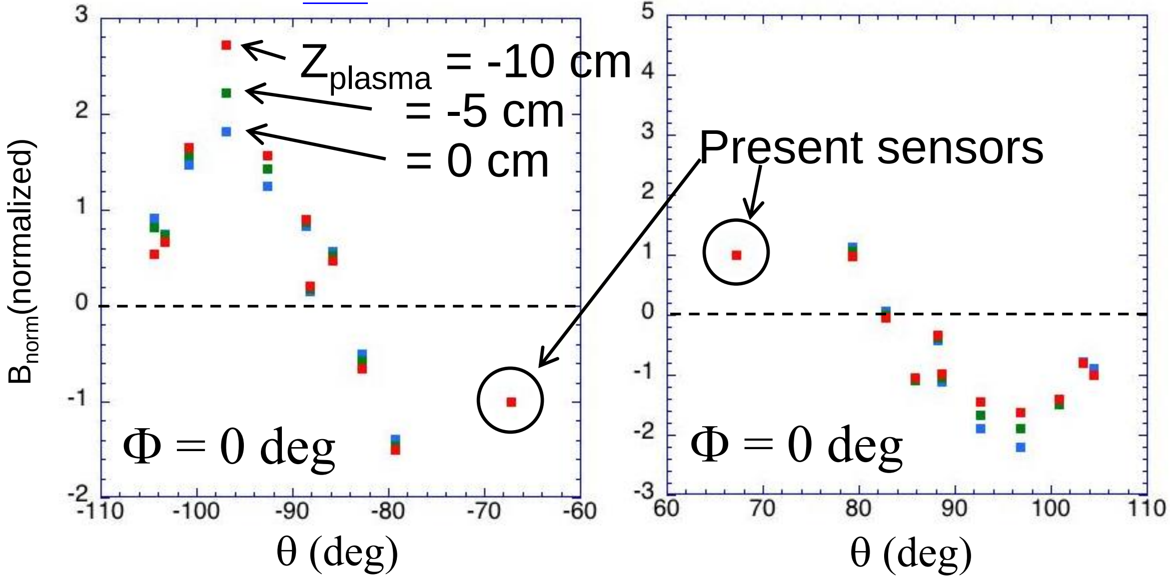
B_R sensors (nominally normal, B_{norm})

B_p sensors (nominally tangential, B_{tan})

New sensor locations (includes one new location above midplane)



B_{norm} vs. theta (normalized to present Br sensors)



- ❑ Model characteristics
  - ❑ New 3D model of divertor plate
  - ❑ 3D sensors with finite toroidal extent; n*A of existing sensors
- ❑ Results summary
  - ❑ Field amplitude up to factor of 6 larger with new sensors
  - ❑ Perturbed field reversals observed with new sensors
  - ❑ Signals sufficient with plasma shifted off-midplane

Supporting slides follow

Rotation feedback controller designed for NSTX-U using non-resonant NTV and NBI used as actuators

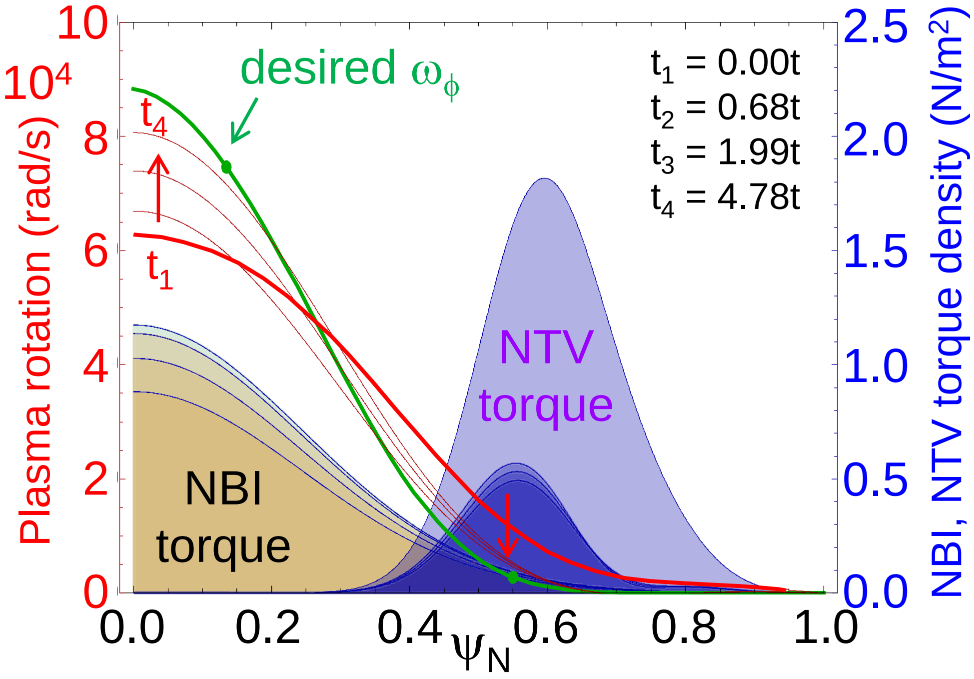
- Momentum force balance – ω_ϕ decomposed into Bessel function states

$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle \left(R \nabla \rho\right)^2 \right\rangle \frac{\partial \omega}{\partial \rho}\right] + T_{NBI} + T_{NTV}$$

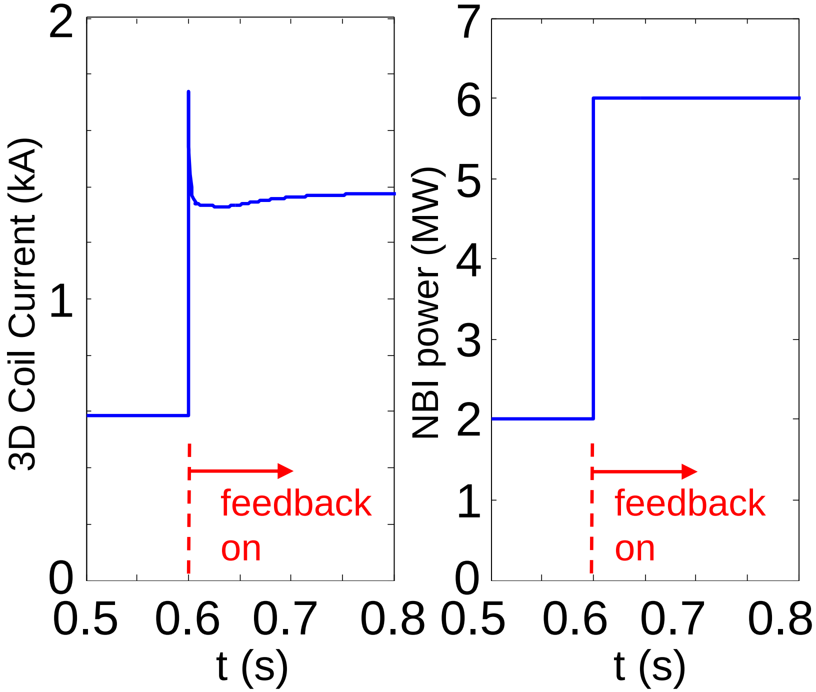
- NTV torque:

$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^{2} \omega\right] \quad \text{(non-linear)}$$

Rotation evolution and NBI and NTV torque profiles



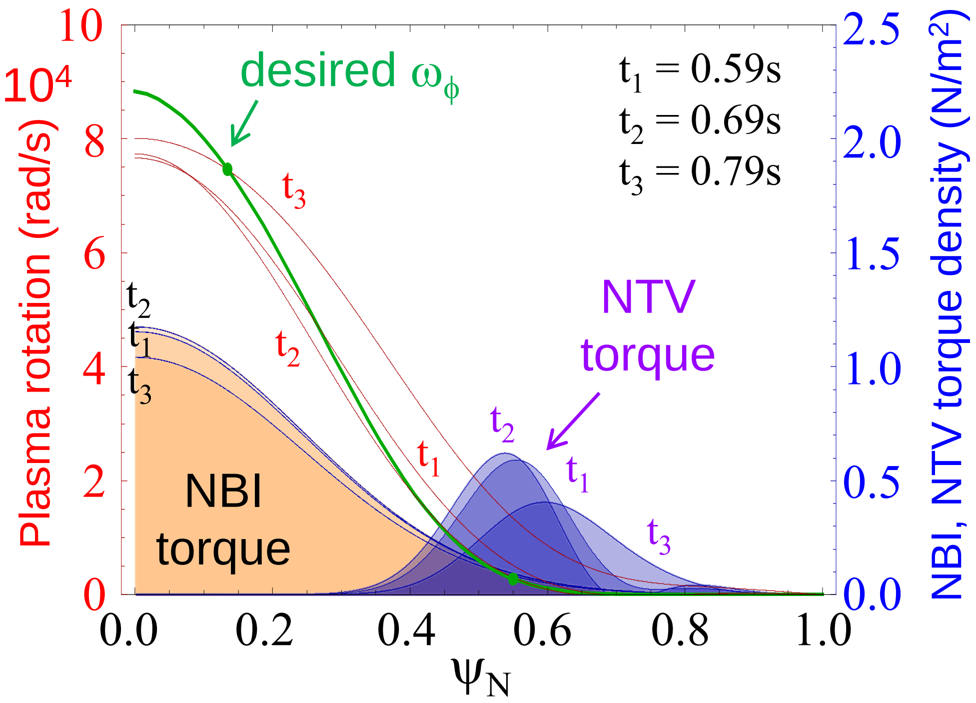
3D coil current and NBI power (actuators)



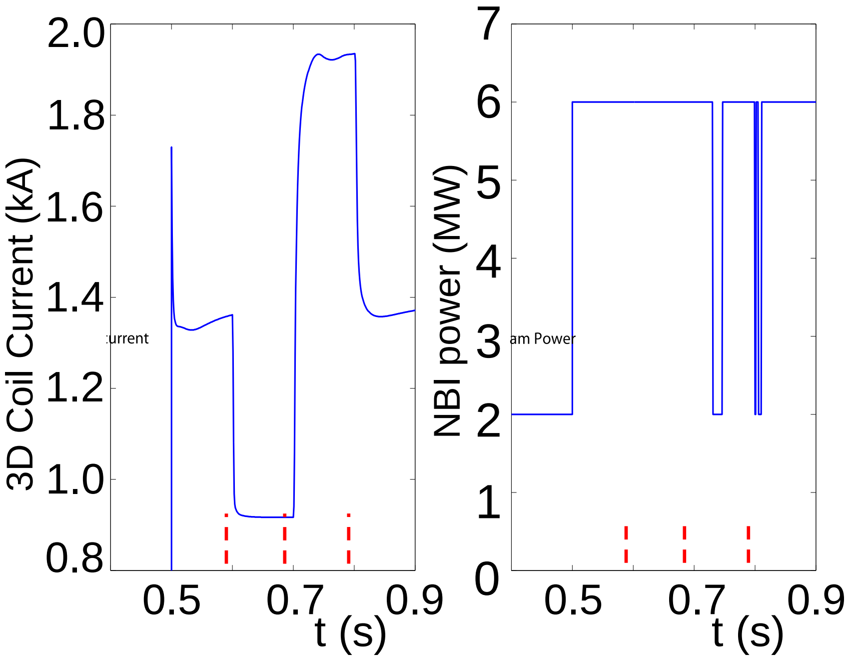
I. Goumiri (P.U. student), S.A. Sabbagh (Columbia U.), C. Rowley (P.U.), D.A. Gates, S.P. Gerhardt (PPPL)

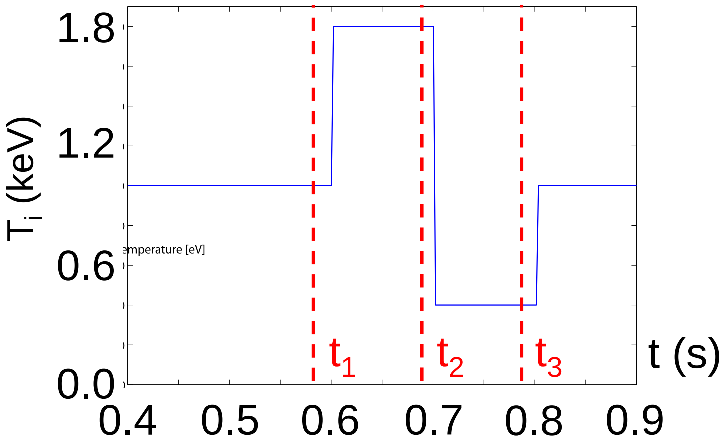
When T_i is included in NTV rotation controller model, 3D field current and NBI power can compensate for T_i variations

Rotation evolution and NBI and NTV torque profiles



3D coil current and NBI power (actuators)





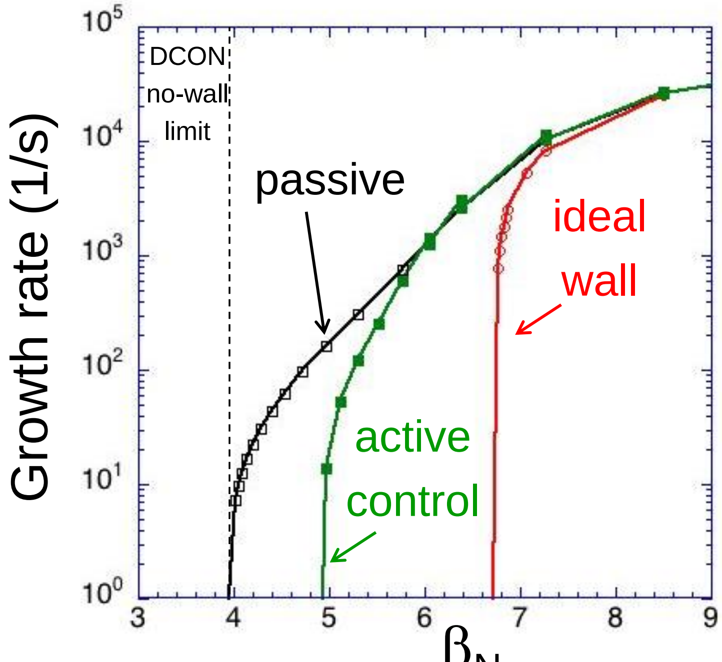
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_i^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^2 \omega\right]$$

K1 = 0, K2 = 2.5

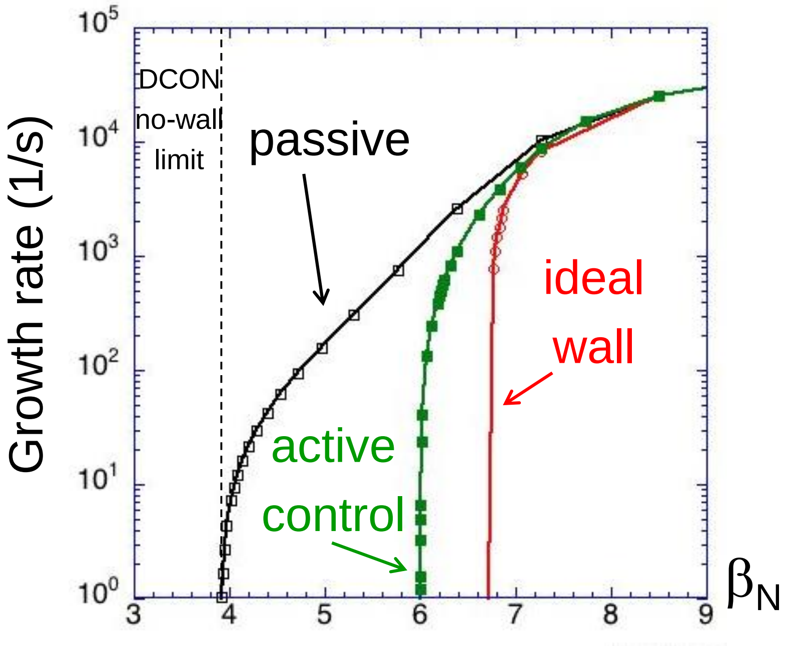
- NTV torque profile model for feedback dependent on ion temperature

NSTX-U: RWM active control capability increases as proposed 3D coils upgrade (NCC coils) are added

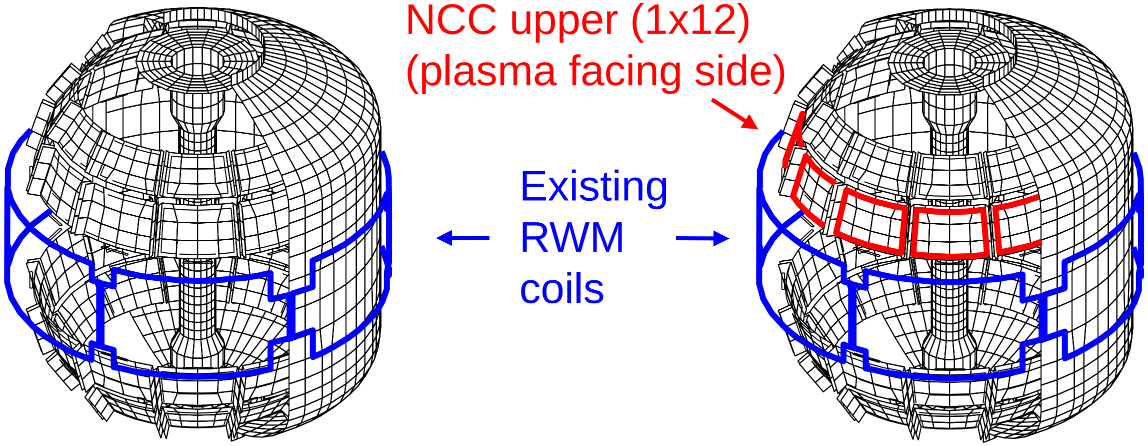
Using present midplane RWM coils



Partial NCC 1x12 (upper), favorable sensors



- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.52$

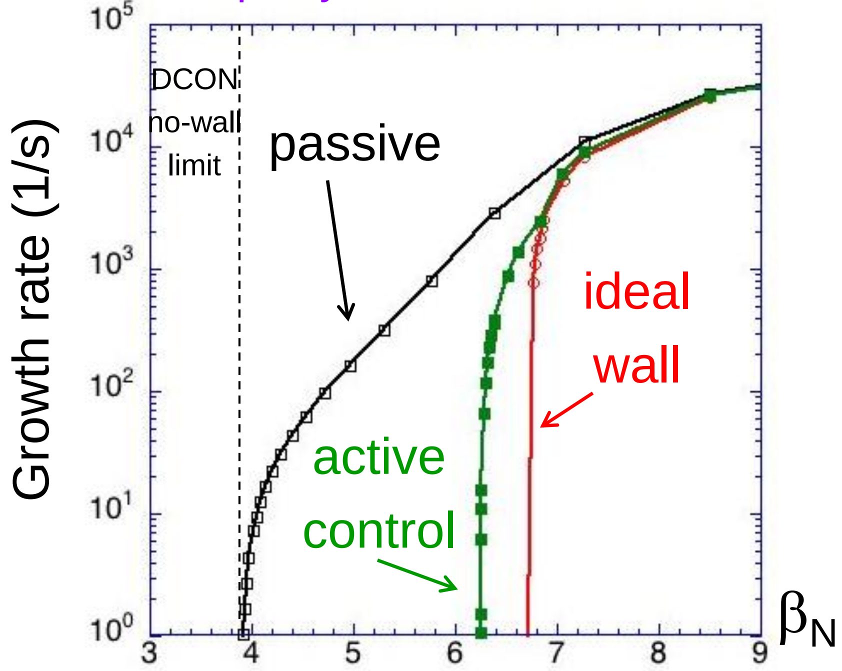


NCC upper (1x12)
(plasma facing side)

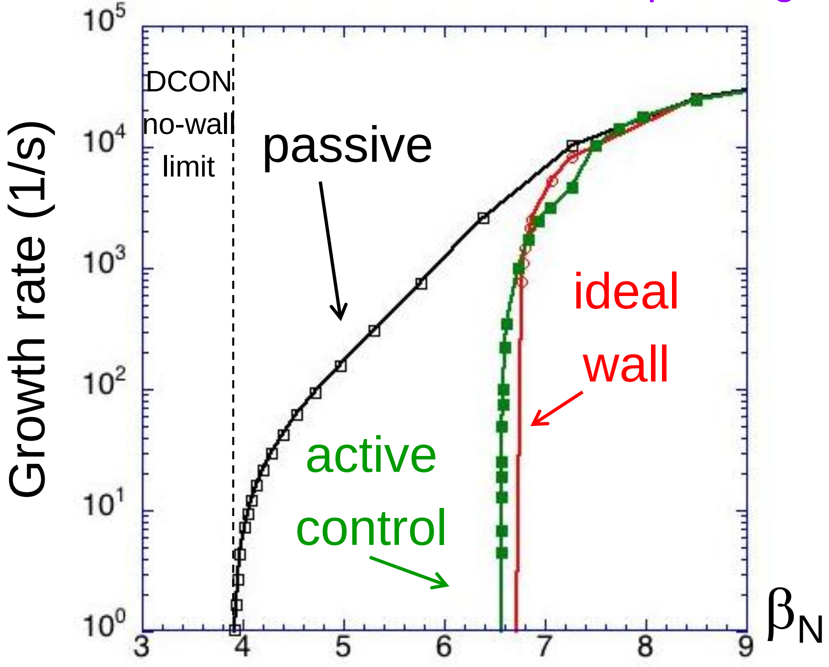
Existing
RWM
coils

Active RWM control design study for proposed NSTX-U 3D coil upgrade (NCC coils) shows superior capability

NCC 2x6 odd parity, with favorable sensors



NCC 2x12 with favorable sensors, optimal gain



- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.58$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.67$