NSTX

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XMP-65 Optimization of β-Control
XP-1019: Test of β-Control for Disruptivity Reduction

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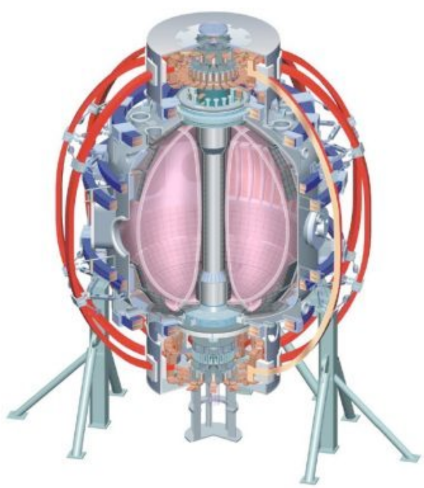
S.P. Gerhardt, E. Kolemen, D. A. Gates, S. A. Sabbagh

Macrostability TSG Group Review



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Overview

- Background
  - Rudimentary PCS control of NB injection was shown in 2008.
  - β_N control was demonstrated in 2009.
    - Not "tuned up".
  - Improved rtEFIT basis vectors were implemented at the very end of the 2009 run.
- Goals of Proposed XP:
  - Achieve reasonable values of the parameters in the β_N control algorithm.
  - Test the ability of β_N control to enable non-disruptive operation near the β_N limit.
- Contributes to:
  - MS Milestone R(10-1): Assess sustainable beta and disruptivity near and above the ideal no-wall limit.

Implementation of β_N Control in NSTX

- Compare filtered β_N value from rtEFIT to a request, and compute an error.

$$e = \beta_{N,reqeust} - LPF\left(\beta_{N,RTEFIT};\tau_{LPF}\right)$$

- Use PID on the error to compute a new requested power.

2009 PID Algorithm

$$\Delta P_{inj} = P_{\beta_N}\overline{C}_{\beta_N} e + I_{\beta_N}\overline{C}_{\beta_N}\int edt + D_{\beta_N}\overline{C}_{\beta_N}\frac{de}{dt}$$

$$P_{inj,i} = P_{inj,i-1} + \Delta P_{inj}$$

$$\overline{C}_{\beta_N} = \tau\frac{I_P V B_T}{200\mu_0 a}\cdot\frac{dt}{0.001}$$

2010 PID Algorithm

$$P_{inj} = P_{\beta_N}\overline{C}_{\beta_N} e + I_{\beta_N}\overline{C}_{\beta_N}\int edt + D_{\beta_N}\overline{C}_{\beta_N}\frac{de}{dt}$$

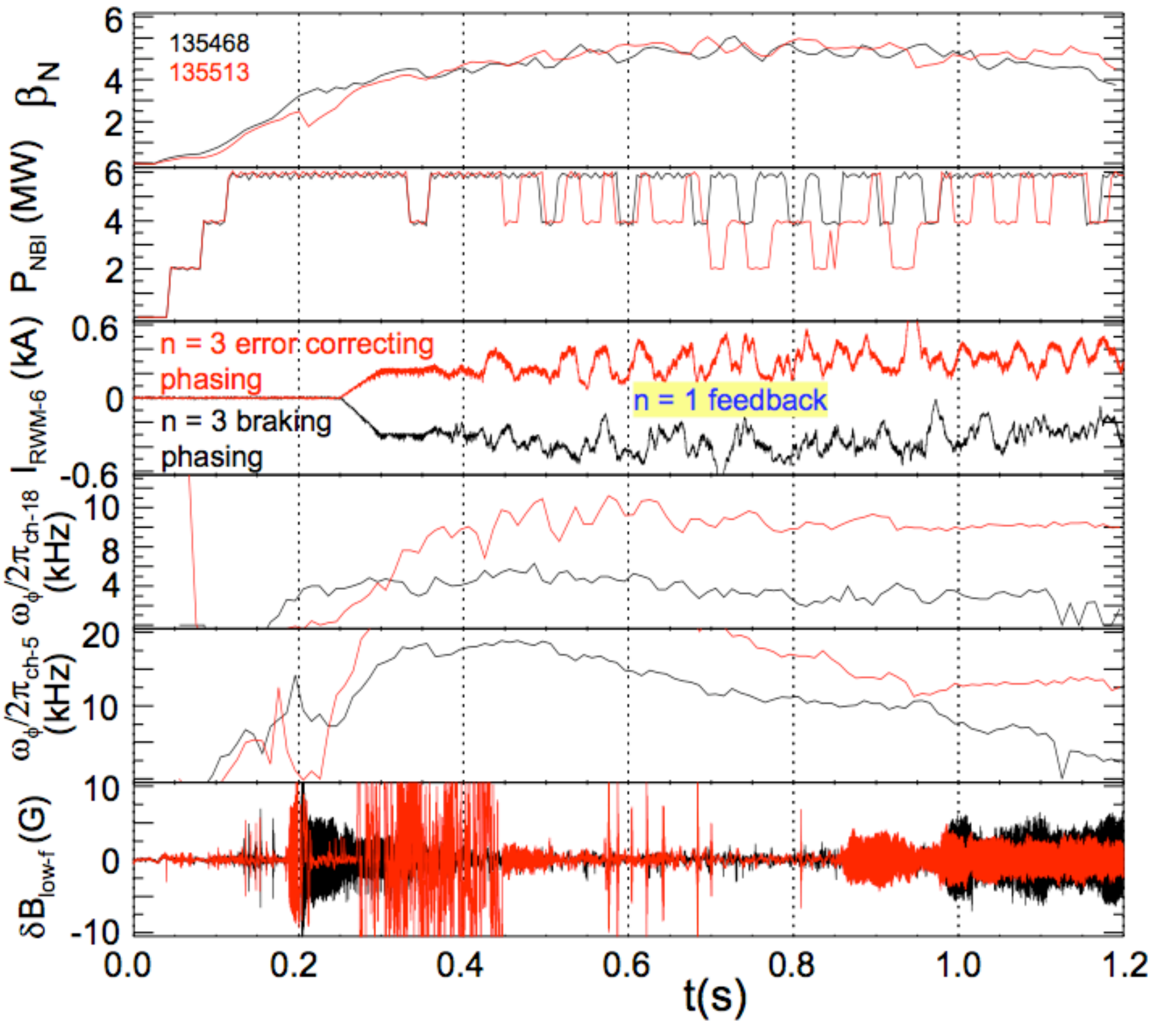
$$\overline{C}_{\beta_N} = 1000\cdot\tau\cdot\frac{I_P V B_T}{200\mu_0 a}$$

- Use power from the PID operation, source powers, and "batting order" to determine the duty cycles for each source.
- Use the duty cycles and min. on/off times to determine when to block.

Many Available Adjustments

- Filter time constant on the β_N value sent from rtEFIT.
  - Useful for smoothing transients and "noise" in the rtEFIT β_N.
- Proportional, integral, and derivative gains.
  - Determines the response of the system to transients.
- Batting order array.
  - Determines which sources modulate
  - Switch to a different source if a given source reaches the maximum number of blocks.
  - *Also able to prevent A modulations, to keep MSE and CHERS.*
- Source powers
  - Can be adjusted in order to prevent modulations.
- Minimum Source On/Off Times.
  - Smaller values will lead to better control, but possibly at the expense of source reliability.
  - 20 msec. has been used so far, with reasonable success (still rather coarse compared to the confinement time).
- With a few additional lines of code: explicit injected power request.
  - Request a power waveform, and PCS determines modulations to achieve it.

β_N Control Has Been Demonstrated in 2009



- ***β_N algorithm compensates for loss of confinement with n=3 braking.***
- ***Control works over a range of rotation levels.***
- ***Modulations in β_N are not severe, even with 20 msec on & 20 msec off.***
- ***Goal of XP is to optimize the system.***

S.A. Sabbagh, 2009 NSTX Results Review

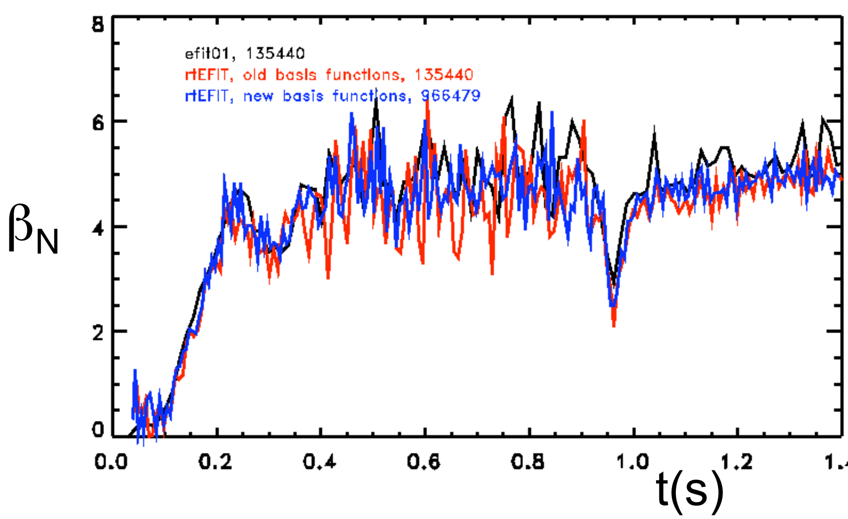
Modifications to the rtEFIT Basis Functions Resulted in Improved Real-time Reconstructions

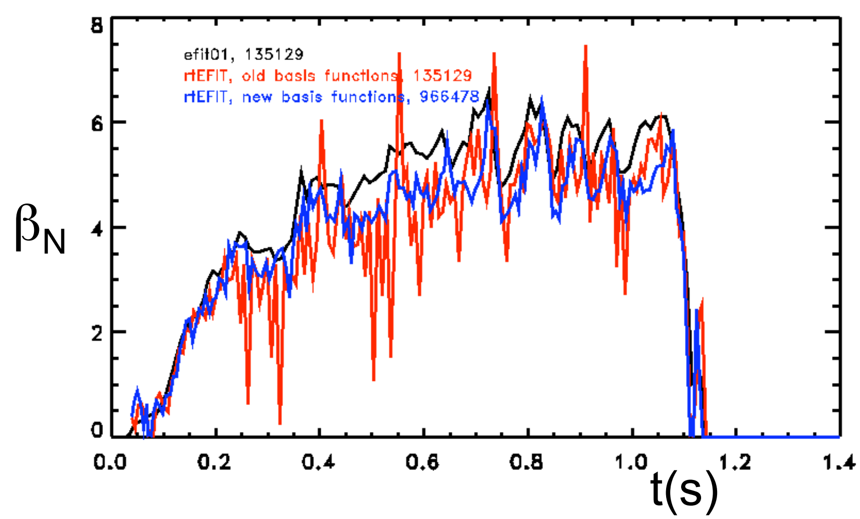
- Occasional poorly converged equilibria lead to incorrect outer gap, β_N
  - Kick off an deleterious transient in the vertical field coil current.
  - Edge current not allowed
- New basis function model based on those developed for off-line magnetics-only reconstruction (Columbia University)
  - Tested on literally > 2 million equilibria
  - Finite edge current through ff'(ψ_n)
- Considerable real-time reconstruction improvement
  - Reduction in β_N "noise" indicative of improved reconstructions

$$p'(\psi_n) = a_1\psi_n(1-\psi_n)$$

$$ff'(\psi_n) = b_0 + b_1\psi_n\left(1-\frac{1}{3}\psi_n^{\,2}\right) + b_2\psi_n^{\,2}\left(1-\frac{2}{3}\psi_n\right)$$

rtEFIT, Old Basis Functions *rtEFIT, New Basis Functions* ***Offline Calculation***





Improvement made on 2nd to last day of run…SPG & DG (& SAS?) agree that we should start the run with these.

Simple Model For NB β-Control

- Coupled equations for the stored energy in thermal particles and fast particles.

$$\frac{dW_{th}}{dt} = \frac{W_f}{\tau_f} - \frac{W_{th}}{\tau_{E,th}}$$

$$\frac{dW_f}{dt} = P_{inj} - \frac{W_f}{\tau_f}$$

$$\tau_{E,th} = \tau_{E,0}\left(\frac{4\times 10^6}{P_{inj}}\right)^{p_{\exp}} + \textbf{random fluctuations}$$

$$W = W_{th} + W_f$$

$$\beta_N = \frac{100\cdot 2\cdot \mu_0\cdot a\cdot W}{I_P\cdot V\cdot B_T} + \textbf{noise}$$

$$P_{inj} = P_{\beta_N}\overline{C}_{\beta_N} e + I_{\beta_N}\overline{C}_{\beta_N}\int e\,dt + D_{\beta_N}\overline{C}_{\beta_N}\frac{de}{dt}$$

- Three free parameters in model:
  - Coefficient on time-scale for thermal energy loss: $\tau_{E,0}$
  - Time-scale of energy transfer from fast to thermal particles: τ_f
  - Power degradation on the thermal confinement: p_{exp}
- Simple model designed for control.
  - No direct fast-ion loss (Shine through, charge exchange, bad orbit).
  - Collapse thermal electron and ion energy loss rates into a single parameter.
- Tune the model parameters (τ_f, $\tau_{E,th}$, p_{exp}) against TRANSP runs of shots with NB modulations.
- Use model in a feedback simulation to estimate gain.

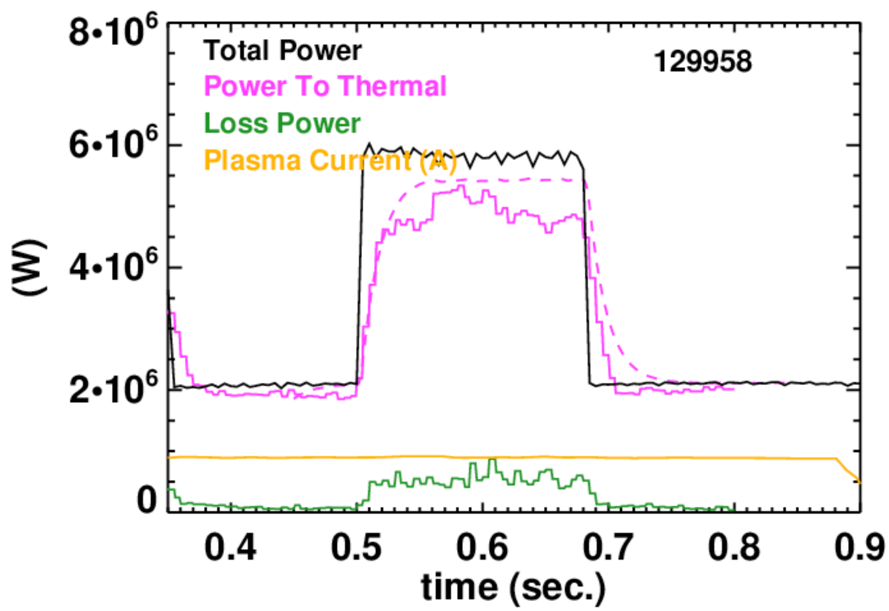
Example of Model

$$\frac{dW_{th}}{dt} = \frac{W_f}{\tau_f} - \frac{W_{th}}{\tau_{E,th}} \qquad \tau_{E,th} = \tau_{E,0}\left(\frac{4\times 10^6}{P_{inj}}\right)^{p_{\exp}}$$

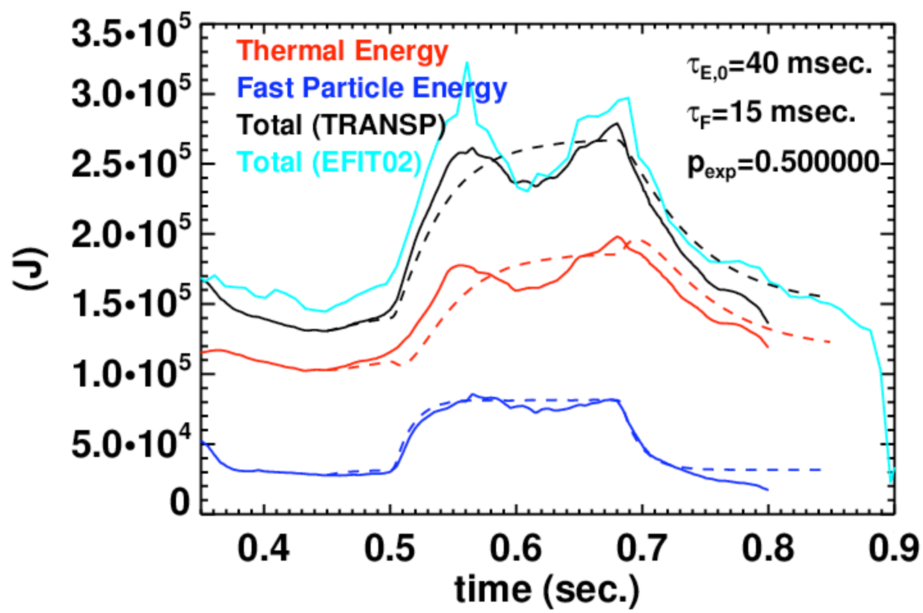
$$\frac{dW_f}{dt} = P_{inj} - \frac{W_f}{\tau_f} \qquad W = W_{th} + W_f$$

- Solid: TRANSP Quantities
- Dashed: Model
- 900 kA fiducial like discharge
  - Enforced that source C is only 80% absorbed in the model.

Power



Energy



Procedure For Picking Gains (2010 Gain Scheme)

Feedback Equation (proportional FB only):

$$P_{inj} = P_{\beta_N}\overline{C}e = P_{\beta_N}\overline{C}\left(\beta_{N,req} - \beta_N\right)$$

$$\overline{C}_{\beta_N} = 1000\cdot\tau\cdot\frac{I_P V B_T}{200\mu_0 a}$$

Relationship between β_N, W_{MHD}, and P_{inj}:

$$\beta_N = \frac{100\cdot 2\cdot\mu_0\cdot a\cdot W}{I_P\cdot V\cdot B_T} = C_{\beta\to W_{MHD}} W = C_{\beta\to W_{MHD}}\tau P_{inj}$$

Combine these to relate P_{inj} to $\beta_{N,req}$:

$$P_{inj} = \frac{P_{\beta_N}\overline{C}}{1 + P_{\beta_N}\tau\overline{C}C_{\beta\to W_{MHD}}}\beta_{N,req}$$

Combine these to relate β_N to $\beta_{N,req}$:

$$\beta_N = \frac{P_{\beta_N}\tau\overline{C}C_{\beta\to W_{MHD}}}{1 + P_{\beta_N}\tau\overline{C}C_{\beta\to W_{MHD}}}\beta_{N,req}$$

Choose $P_{\beta N}$ to achieve a given $f=\beta_N/\beta_{N,req}$:
This yields $P_{\beta N} \approx 1\text{-}3$ for $f=0.7$, $\tau=0.04$

$$P_{\beta_N} = \frac{f}{1-f}\frac{1}{\tau\overline{C}C_{\beta\to W_{MHD}}} = \frac{f}{1-f}\left(\frac{1}{1000\cdot\tau^2}\right)$$

Choose $I_{\beta N}$ as $P_{\beta N}$ normalized by a representative time:
This yields $I_{\beta N} \approx 40$

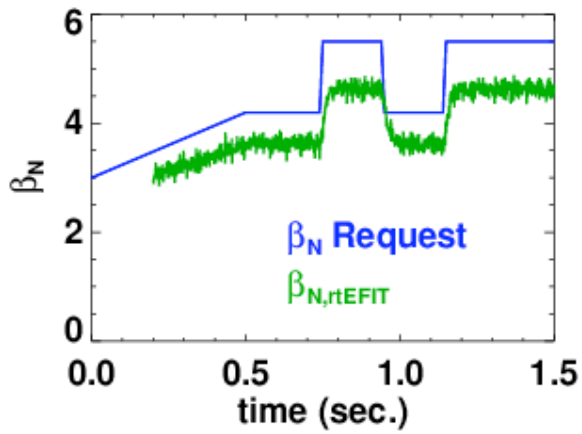
$$I_{\beta_N} = \frac{P_{\beta_N}}{\tau}$$

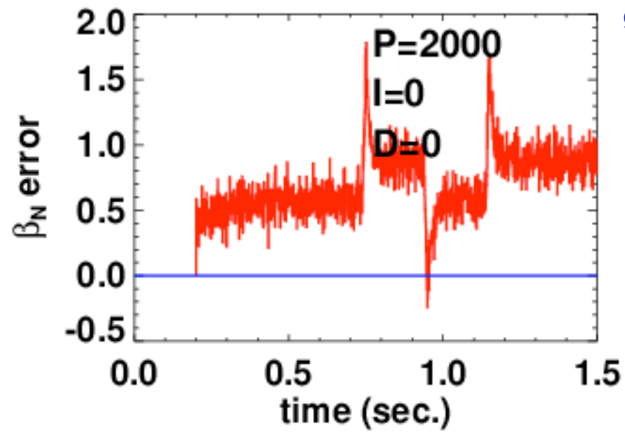
Confinement is an uncertainty in determining the optimal gains.

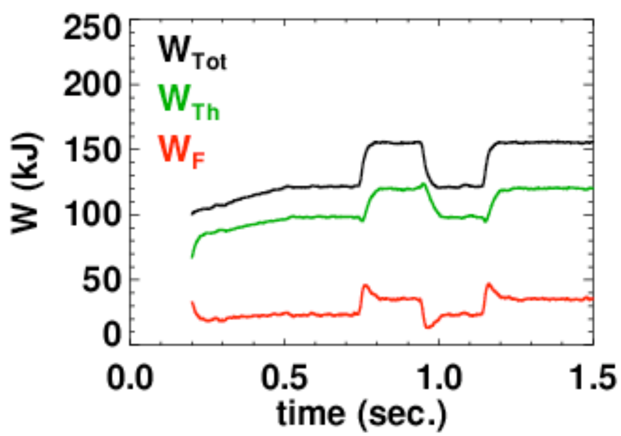
Simulation #1: Proportional FB Only, Continuous Power, With Noise in Confinement and β_N

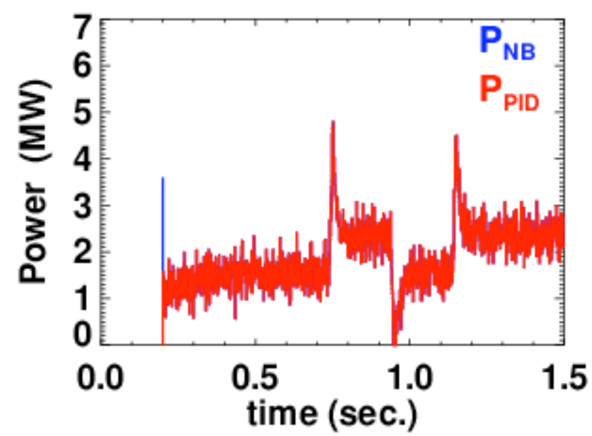
Offset error for with I=0

(need to divide gains by 1000)





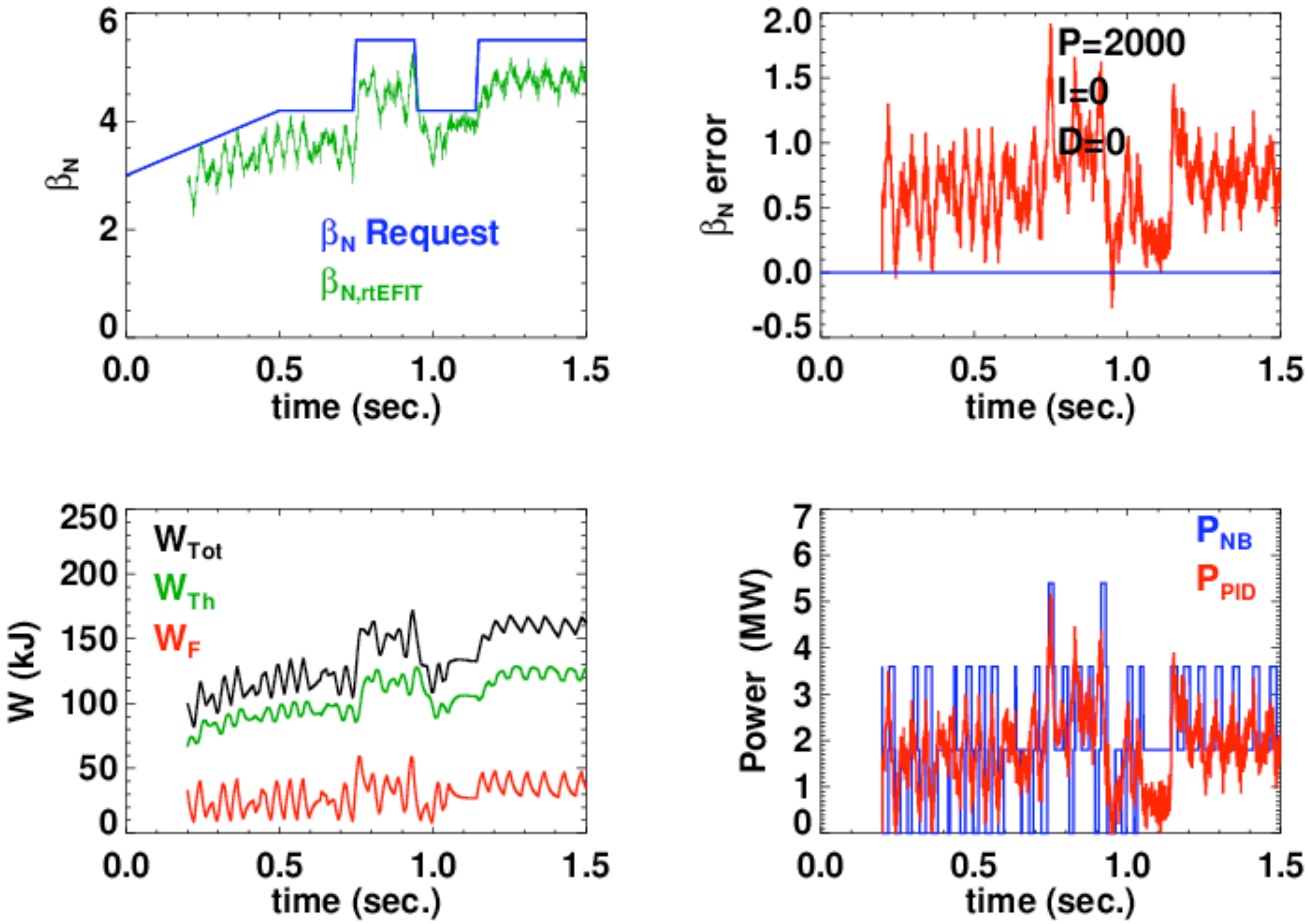




Simulation #2: Proportional FB Only, Modulating All Sources, With Noise in Confinement and β_N

Offset error for with I=0

(need to divide gains by 1000)

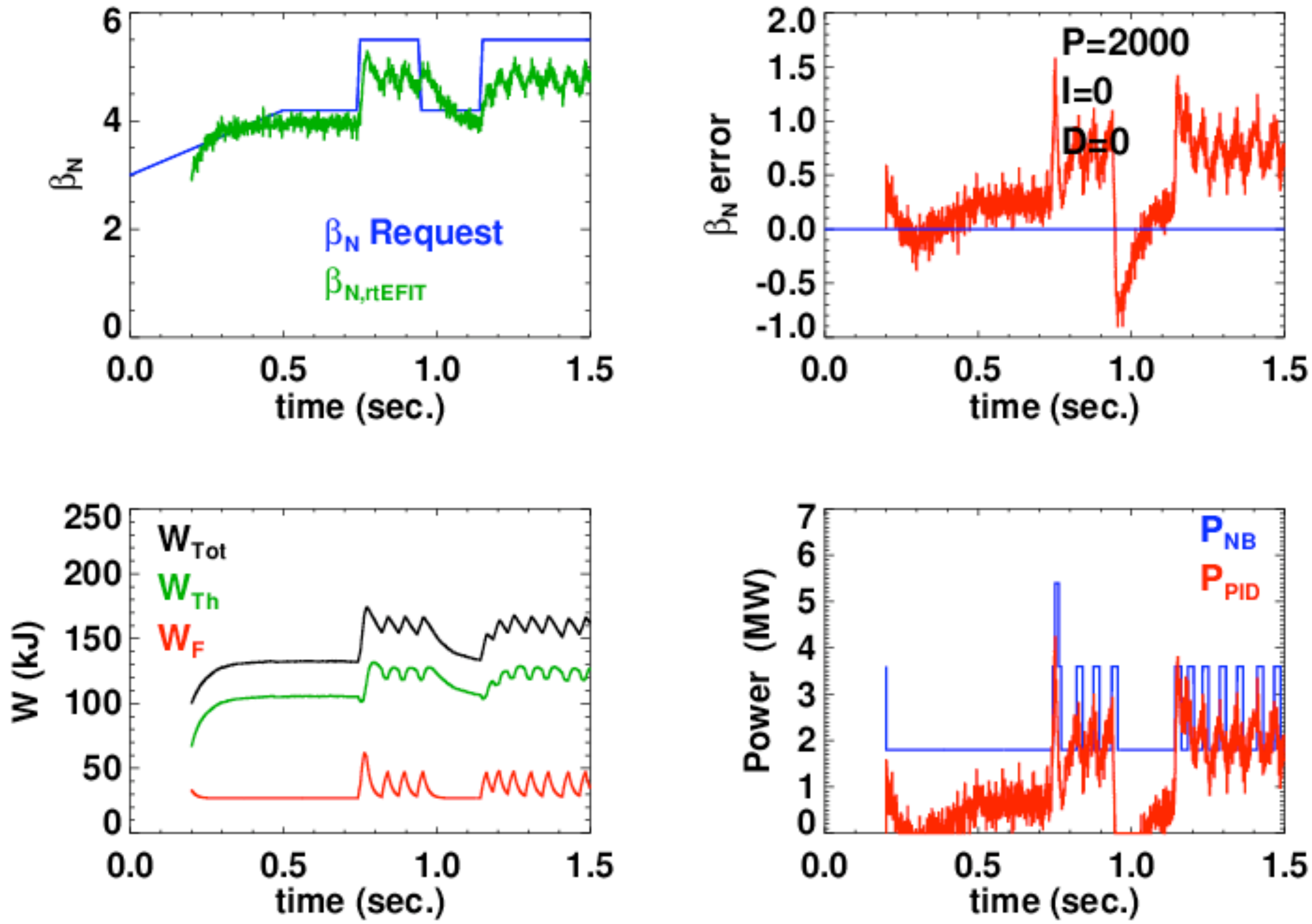


Algorithm Modulated both A & B

Simulation #3: Proportional FB Only, Modulating B & C Only, With Noise in Confinement and β_N

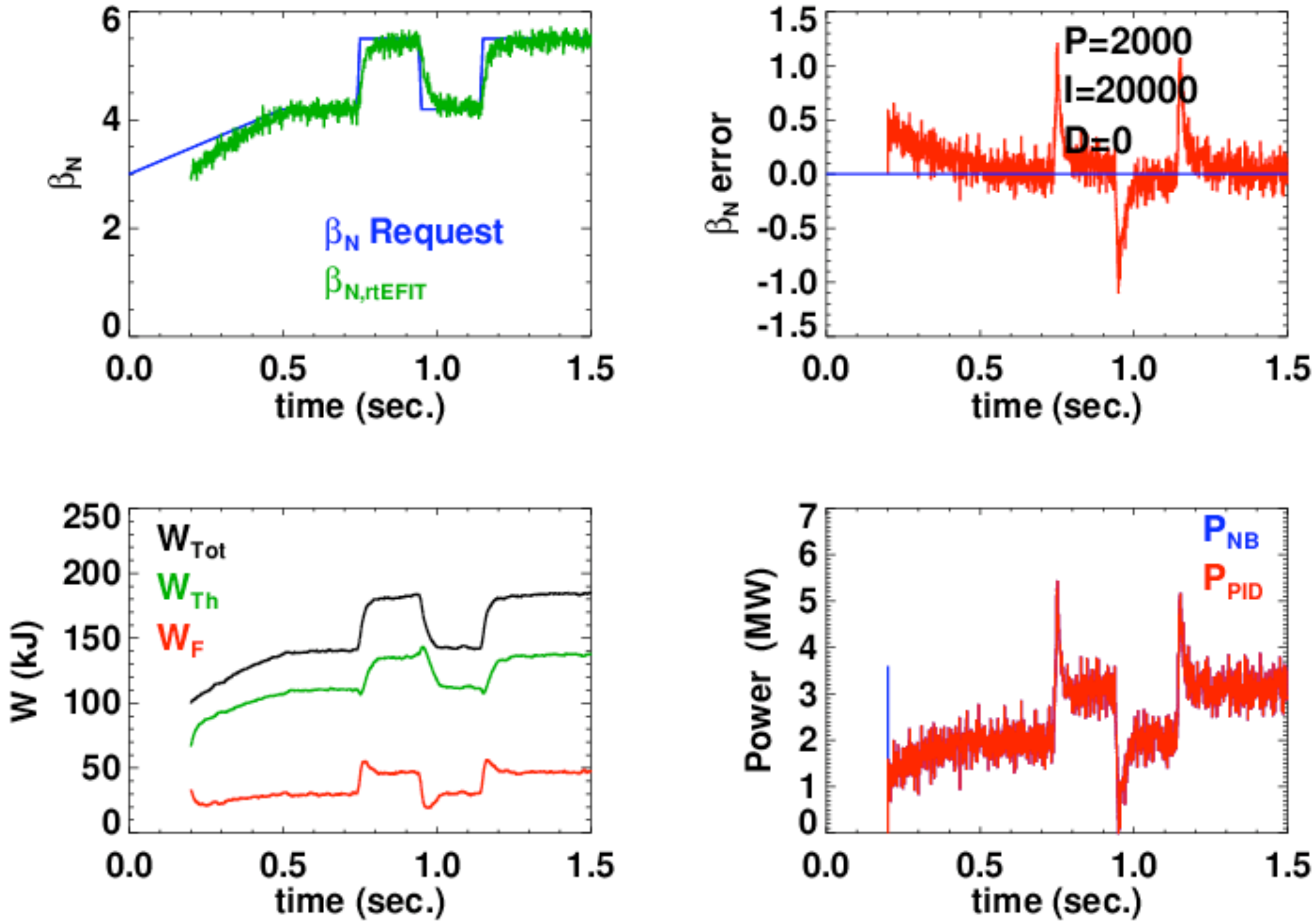
Offset error for
with I=0

(need to divide
gains by 1000)



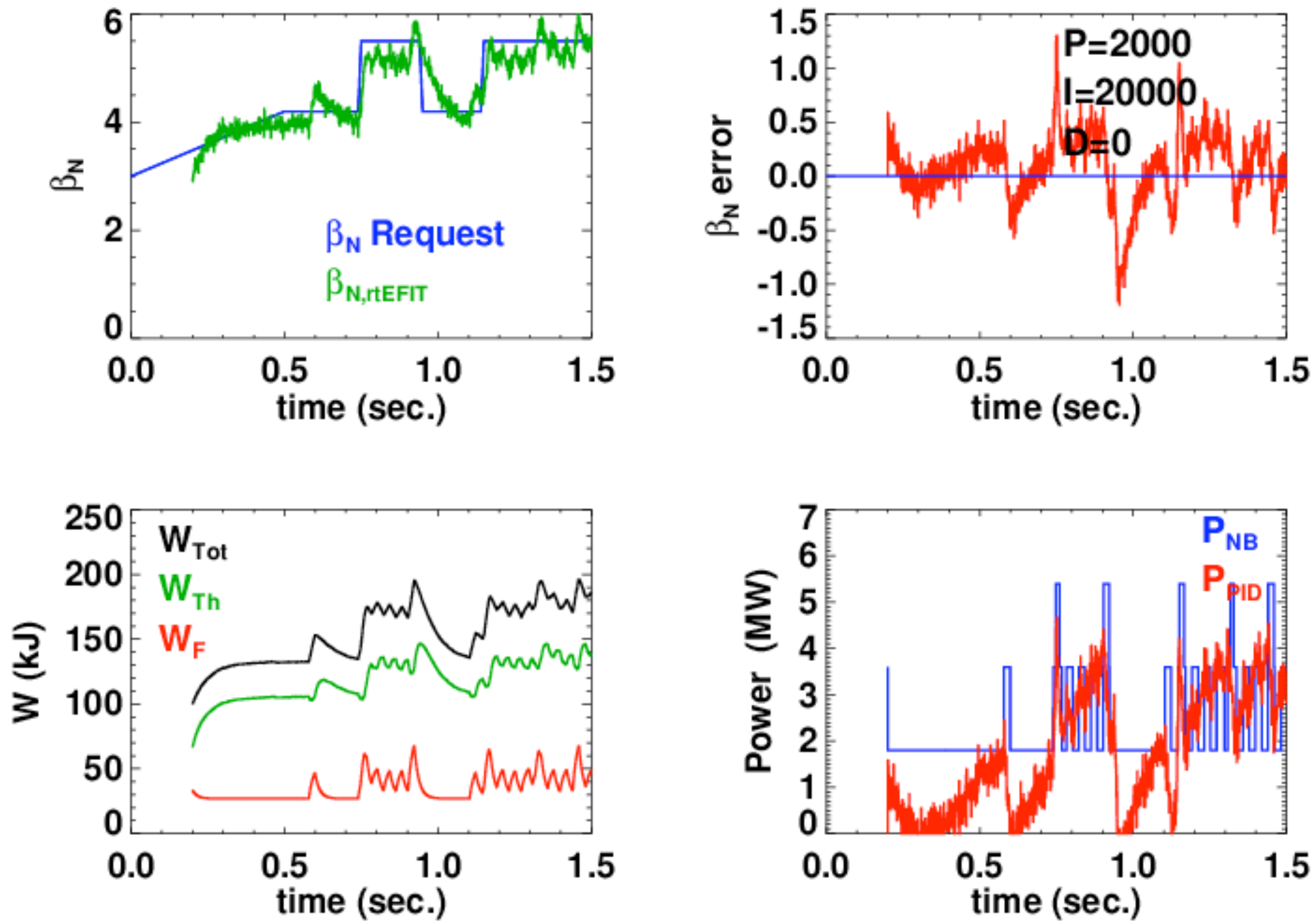
Simulation #4: Proportional + Integral FB, Continuous Power, With Noise in Confinement and β_N

(need to divide gains by 1000)



Simulation #5: Proportional + Integral FB, Modulating B & C Only, With Noise in Confinement and β_N

(need to divide gains by 1000)

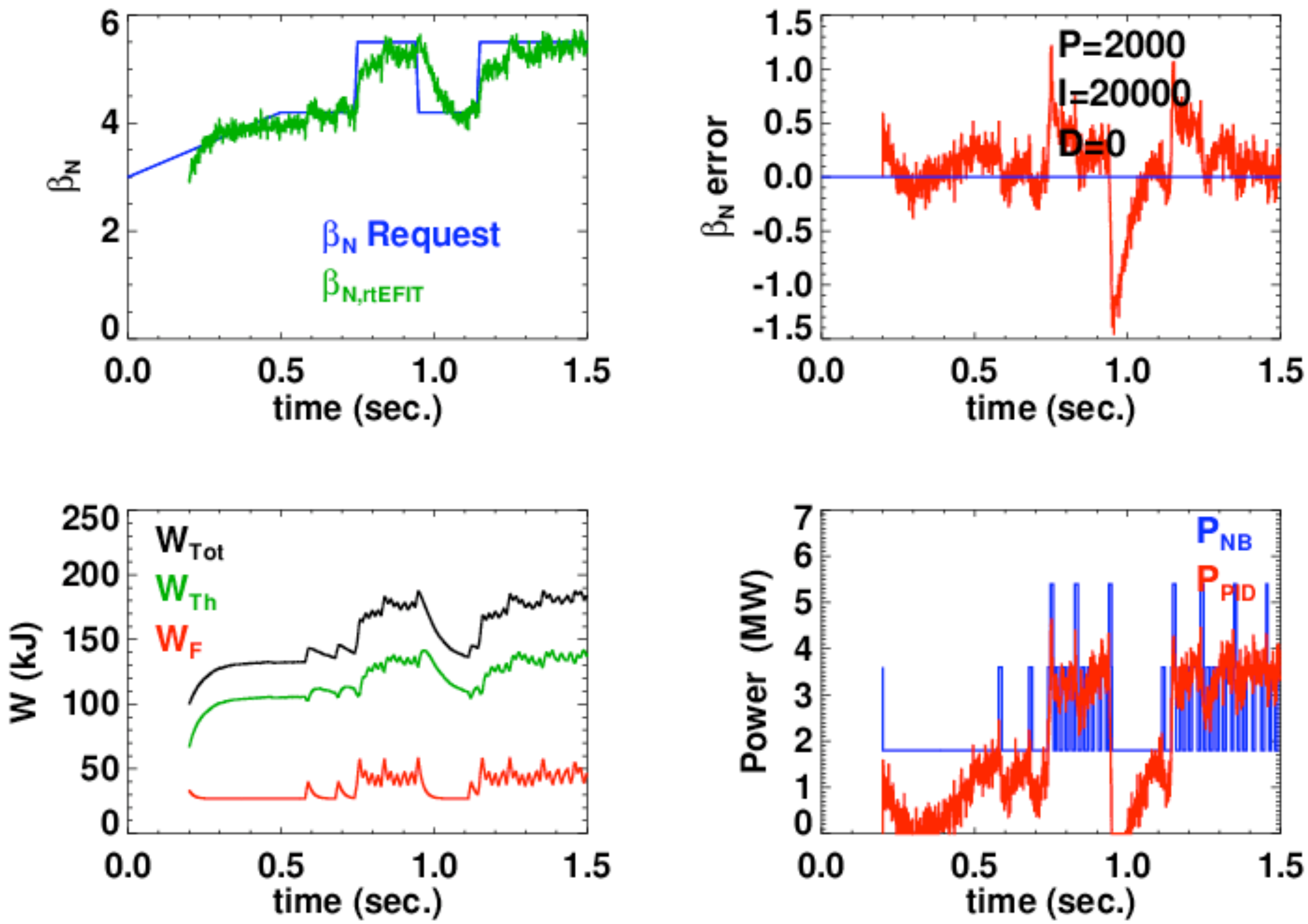


Simulation #5: Proportional + Integral FB, Modulating B & C, With Noise in Confinement and β_N, Rapid Modulation

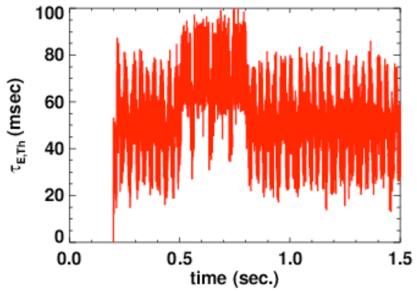
10 msec on/10 msec off, no limits on # of blocks

(previous simulations had 20 on/20 off, 19 blocks max)

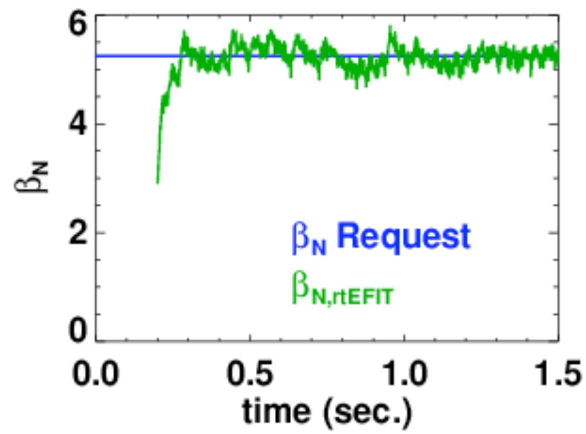
(need to divide gains by 1000)

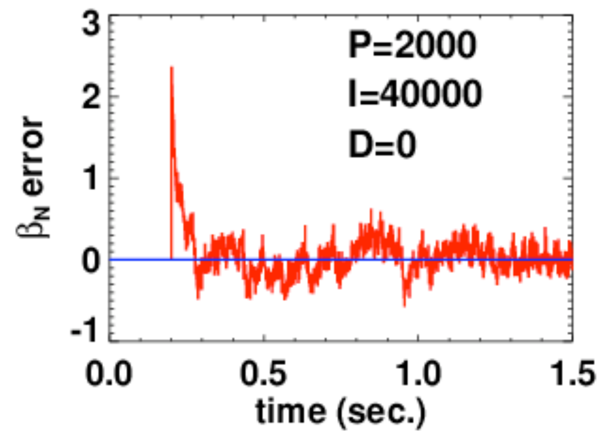


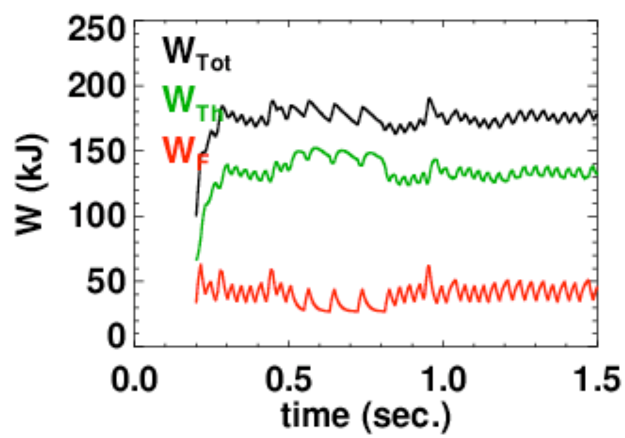
Simulation #6: Proportional + Integral FB, Modulating B & C, With Noise in Confinement and β_N, Confinement Change

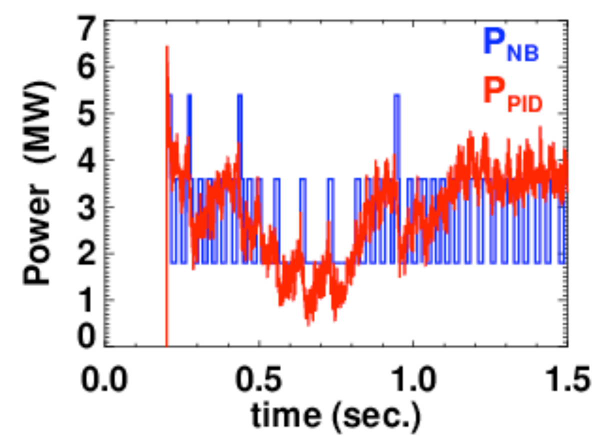


(need to divide gains by 1000)



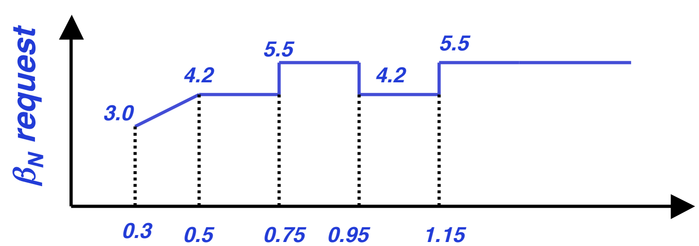




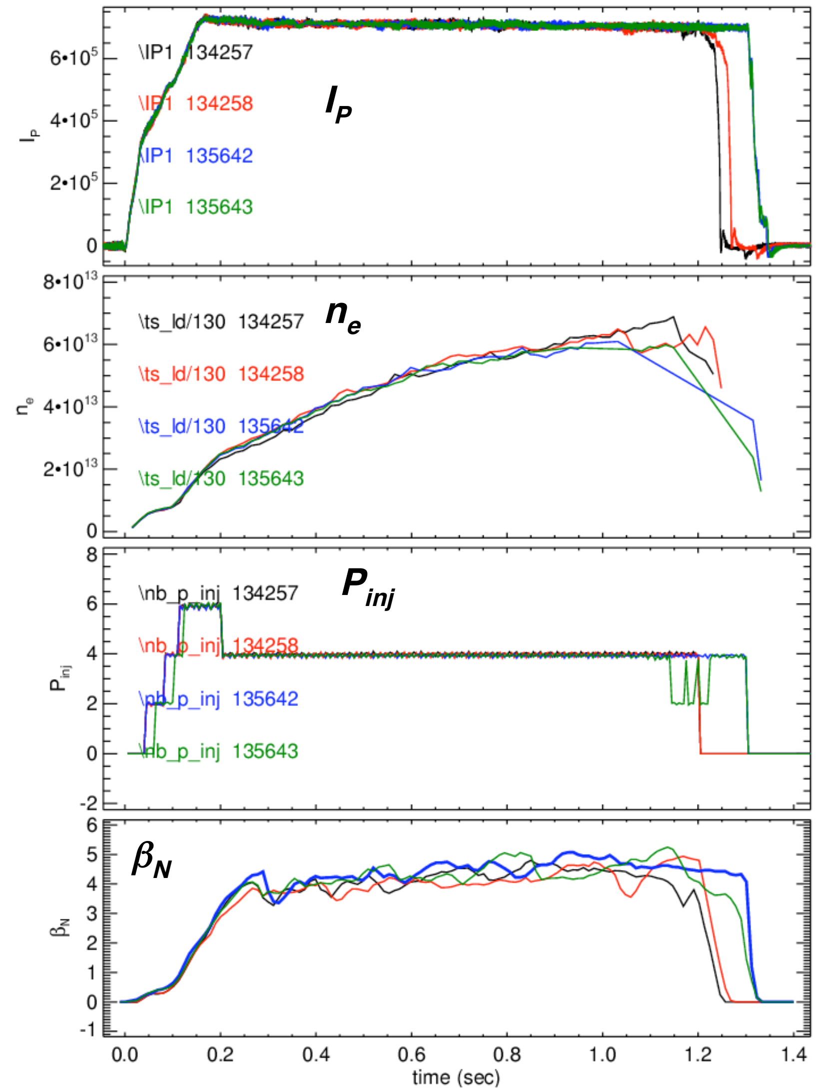


XMP Step: Algorithm Optimization Philosophy

- Establish a high-performance reference.
  - Should be long pulse at 4 MW, to allow room for modulations.
  - Consider 700-800 kA fiducial.
- Add in β_N control with reasonable parameters, steps and ramps in β_N request.
- Adjust gains to achieve best match to desired waveform.
- What min on/off times to use?
  - 20/20 was used last year.
- Use full RWM control.



Potential Target: Long Pulse 700 kA with Fiducial Shape.



XMP Step: Algorithm Optimization Shot List

- Testing Algorithm In Background (as many shots as necessary)
  - Check modified gain scheme.
  - Check batting order transitions.
  - Check quality of β_N calculation.
- Establish 4MW target with pre-programmed beams. (1 Shots)
- Introduce beta-feedback waveform, modest gains. (2 Shots)
  - Usewaveforms with Steps
  - 20 on / 20 off to begin with.
  - P=2, I=0
- Increase gains in small increments. (4 shots)
  - P=2, I=10
  - P=2, I=20
  - P=3, I=40
- Repeat optimal with 15 on / 15 off modulations. (2 shots)
  - May need to adjust the batting order.

XP Step: Test For Disruptivity Reduction Philosophy

- Establish a discharge regime that disrupts with a 6 MW of input power.
  - Maybe just use the previous 700 kA target?
  - Long pulse 700 kA, 0.4 T, high-κ target from XP-836 (135440)?
- Re-run with β_N request reasonably below the disruptive value.
  - Should not disrupt any more
- Increase the β_N request in small increments (a few shots) to where it disrupts.
  - Bracket the unstable heating power.
- Use pre-programmed beams with about the same power waveform.
  - These are pre-programmed
  - Re-run and see if the level of β_N fluctuations is increased, disruptions re-appear.
- Status of RWM Control?
  - Inclined to use slow control (DEFC), but not fast feedback.
  - Provides test of disruption control in the wall-stabilized regime.

XP Step: Test For Disruptivity Reduction Shot List

- Reload Target Shot (2 Shots)
  - Particular shot TBD.
  - Demonstrate disruption at 6 MW of power.
- Establish a series of discharges with various levels of β_N requests. (6 shots)
  - β_N=4.5, 5.0, 5.5, 6.0, 6.5,…or until disruptive RWM activity begins.
  - Maybe test intermediate values of β_N
- Repeat marginally stable case with approximately matched input power. (6 shots)
  - Reduce the requested beam power waveform to ~5 time points.
    - Enter these into PCS
  - Use pre-programmed power request and let PCS determine the modulations frequency.