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Implementation of β_N Control in the National Spherical Torus Experiment

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Abstract

We have designed and constructed a system for control of the normalized β in the National Spherical Torus Experiment [M. Ono, et al., Nuclear Fusion **40**, 557 (2000)]. A PID operator is applied to the difference between the present value of β_N (from realtime equilibrium reconstruction) and a time-dependent request, in order to calculate the required injected power. This injected power request is then turned into modulations of the neutral beams. The details of this algorithm are described, including the techniques used to develop the appropriate control gains. Example uses of the system are shown.

1: Introduction

In order to be viable as a candidate for fusion energy generation, tokamaks must operate without disruptions [1]. These events, which involve the rapid loss of the plasma stored energy followed by a fast quench of the plasma current, can cause severe damage to the tokamak in-vessel components, potentially necessitating costly repairs in future devices. There are many causes of disruptions, including plasma instabilities that occur when the plasma pressure becomes too large.

The plasma pressure is typically quoted as normalized to the toroidal magnetic field strength at the average midplane radius of the plasma; this is the toroidal β defined as $\beta_T = \frac{2\mu_0 \langle P \rangle}{B_T^2}$, where $\langle P \rangle$ is the volume-averaged total pressure. It has been found, however, that the toroidal β itself is not a good indicator of proximity to instability; rather, the maximum stable toroidal β scales with I_p/aB_T , where I_p is the plasma current in MA and a is the minor radius in meters (see [2] and references therein). Hence, we can define a quantity known as the normalized β , given by $\beta_N = 100aB_T\beta_T/I_p$. It is this quantity that we wish to regulate, in order to both operate safely near stability boundaries, and to enable controlled experiments where other parameters are varied as β_N is held fixed. This paper describes the implementation of a β_N controller for the National Spherical Torus Experiment (NSTX) [3].

The utility of β_N (or stored energy) control has been demonstrated by the implementation of similar systems on other tokamaks. Initial work in this regard was done at DIII-D [4], TFTR [5], and JET [6]. The DIII-D and TFTR cases used the plasma diamagnetism, either directly [4], or after further processing [5], as the measurement for

feedback. More recent work in this area has been done at JT-60, where a “functional parameterization” method was to calculate the stored energy in realtime [7] from diamagnetic flux and poloidal field measurements; a related study in that device [8] used feedback on the neutron emission rate to adjust the neutral beam injection power, in order to simulate the effect of fusion power heating the plasma. Recent DIII-D studies [9] have extended these studies to simultaneous control of β_N and plasma rotation, using the capability provided by having both counter and co- injecting neutral beams. Control of the plasma current profile with neutral beam injection (and other actuators) has also been demonstrated [10,11].

The remainder of this paper is organized as follows. Section 2 describes the hardware and software implementation of the controller, while section 3 describes the system identification method we have used for determining the appropriate proportional and integral gains. Section 4 presents some example uses of the system, with a short discussion following in section 5.

2: Controller Implementation

2.1 The NSTX device and control system.

The β_N control system in NSTX has been implemented as part of the NSTX installation [12,13] of the General Atomics plasma control system (PCS) [14,15], which has overall responsibility for plasma control. This includes control of the plasma current, poloidal and toroidal field coil currents, plasma boundary shape [16] and vertical position, gas fuelling, and 3-D fields & resistive wall modes [17-20].

The geometry of the NSTX neutral beam injection system [21] is shown in Fig.1. The neutral beam injection system on NSTX was inherited from the Tokamak Fusion Test Reactor (TFTR), which used four beamlines injecting up to 33MW of power [22]. NSTX has a single neutral beam line, equipped with three sources, injecting parallel to the plasma current. The sources are arranged in a horizontal fan with ~ 4 degrees spread between the individual beams. The tangency radii of the beams are approximately 70, 60, and 50 cm for sources A, B, and C respectively (the typical radius of the magnetic axis is 95-105 cm). The sources are typically operated with source voltages between 60 and 95 kV, with 40 kV operation available on request; 110 kV capability has been retained from the TFTR systems, but is not used. Note also that source A must be on, with a voltage of 90 kV, in order to collect data from the motional Stark effect (MSE) diagnostic [23].

2.2 The PID Controller

The formulation of the PID controller is as follows. The error is calculated as

$$e = \beta_{N,request} - LPF(\beta_{N,rEFIT}; \tau_{LPF}), \quad (1)$$

where $\beta_{N,request}$ is the requested value of β_N , and $\beta_{N,rEFIT}$ is the value of β_N computed by the rEFIT code [24]. See Ref. [16] for a description of the NSTX rEFIT implementation. $LPF(X;\tau)$ represents a single pole causal lowpass filter, which is used to eliminate noise in the rEFIT β_N calculation. This filter mimics a simple RC filter and is the solution of

$$\tau_{LPF} \frac{dY_{out}}{dt} + Y_{out} = Y_{in}.$$

This filter form is particularly convenient for implementation in real-time, as it can be implemented such that only values from the previous time-step need be saved. This can be seen by substituting $\frac{dY_{out}}{dt} = (Y_{out,i} - Y_{out,i-1})/\delta t$, $Y_{out} = Y_{out,i}$ and $Y_{in} = (Y_{in,i} + Y_{in,i-1})/2$ and solving for $Y_{out,i}$ (i is a time index):

$$Y_{out,i} = \frac{Y_{out,i-1} + \frac{\delta t}{2\tau_{LPF}}(Y_{in,i} + Y_{in,i-1})}{1 + \frac{\delta t}{\tau_{LPF}}} \quad (2)$$

This filter helps to smooth out transients in the rtEFIT β_N , though at the expense of adding a delay to the system. The value of τ_{LPF} is determined by a time-dependent PCS input waveform, and is typically set to 10-20 msec.

A PID operator is then used to calculate an injected power request as:

$$P_{inj} = P_{\beta_N} \bar{C}_{\beta_N} e + I_{\beta_N} \bar{C}_{\beta_N} \int edt + D_{\beta_N} \bar{C}_{\beta_N} \frac{de}{dt} + P_{pre-prog} \quad (3)$$

$$\bar{C}_{\beta_N} = \frac{I_P V B_T}{200 \mu_0 a \tau_E} \quad (4)$$

Here, we used $W = P_{inj} \tau_E$ and $\beta_T = \frac{2\mu_0 W}{V B_T^2}$ to related the injected power and normalized

β as $\beta_N = \frac{200 \mu_0 a P_{inj} \tau_E}{I_P V B_T} = \frac{P_{inj}}{\bar{C}_{\beta_N}}$ (here, W is the total stored energy in the plasma). The

parameter \bar{C}_{β_N} is used so that the gain P_{β_N} is dimensionless. Note that these formulas do not take into account any degradation of confinement with input power [25]. $P_{pre-prog}$ is a pre-programmed power request. During feedback, this is typically set to a constant equal to the final value pre-programmed power just before feedback is turn on. This helps avoid any instantaneous transients when switching to β_N control, with the integral term ensuring

that the error in Eqn. 1 goes to zero after sufficient time. The actual values of I_P and B_T are used in the real-time calculation of \overline{C}_{β_N} , based on data from the plasma current Rogowski and the toroidal field current. Typical values of the volume V (12 m^3), minor radius a (60 cm), and confinement time τ_E (40 msec) are fixed in the present version of the code, but could also be determined in realtime based on information from rtEFIT.

Finally, there is provision to bypass the PID operator entirely, and simply specify an injected power waveform as a function of time. This capability, demonstrated in Sect. 4, provides the ability to program fine power ramps without manually specifying the individual times for the beam modulations.

2.3 Algorithm constraints provided by the NSTX neutral beam hardware.

The neutral beam hardware itself [21,22] provides some important technical constraints on the algorithm. The process of forming the neutral beam places significant power on the source grid rails until the beam comes into full focus. The TFTR neutral beams have non-circular molybdenum grid rails as part of the accelerator. These components are not easily re-manufactured, and so an effort is made to preserve their lifetime by limiting the power flux onto them. Hence, we are presently limiting the system to 20 modulations per source per discharge.

There are also minimum values for the off (δt_{off}) and on (δt_{on}) times of the individual sources; the minimum values of these parameters are 10 msec. With regard to the minimum source on duration, it takes a finite time, typically 1-2 msec., to form the neutral beam. Beam on-times of less than 10 msec. result in both ambiguity in the actual average injected power, and a disproportionate fraction of the total power going into

source components and not the plasma. The minimum beam off-time of 10 msec is set by the need to clear the source of the previous plasma before initiating the new arc. Note that all use of the controller to date has used 15 msec. or longer durations for both the minimum on- and off-times.

Another set of constraints comes from the fact that the arc and filament power supplies for the sources are unregulated, so that one source coming on can pull down the voltages for the other sources. Hence, the sources are tuned for a given order of turn-on, typically source A first, followed by sources B and C. Deliberate or inadvertent deviations from this order can reduce the reliability of the source operations for a given shot. Furthermore, these variations can cause the high-voltage switch tube to oscillate, broadcasting RF noise into nearby control electronics.

Finally, as presently configured, the β_N controller can only “block” a source, i.e. turn it off. The block can then be removed, allowing the source to turn back on. The initial turn-on of any given source is programmed by the neutral beams operators. There is also an interlock on the system that turns the entire beam system off (with a 50 msec. delay) if the plasma current falls beneath 200 kA.

2.4 The Modulation Scheme

Although the injected power request generated by the PID operator is continuously variable, the neutral beams are not: they can only be on or off. The task of the modulation calculator is to make this translation, while taking into account the constraints from the beam injection hardware. This code is described below.

The controller has a 3x3 array specifying the modulation order of the sources; this array can be modified by the physics operator using a standard PCS interface. For

example, the typical first row with values [0,1,2] implies that first source A, then B, then finally C will turn on. If the controller requests 5 MW of input power and all sources are at 2 MW, then sources A and B will be fully on, while C will modulate with a 50% duty cycle. The modulations are counted, and if their number exceeds the maximum allowed, then the second row of the modulation order array comes into play. This row is typically filled with [0,2,1], such that the source doing the primary modulations (typically B or C), is switched with the less used source. The source that has exceeded its allowed number of modulations goes to a default on or off state determined by the physics operator before the discharge is initiated.

Once the duty cycles for the individual sources have been determined from the above steps, the controller decides whether or not to modulate each source. If the duty cycle for a given source is 100% ($f_{DC}=1$) and the source is already on, it is left on; if that source is off and the time since it was last turned off is greater than δt_{off} , then it is turned on, otherwise it is left off. If the duty cycle is 0% ($f_{DC}=0$) and the source is already off, it is left off; if that source is on and the time since it was last turned on is greater than δt_{on} , then it is turned off, otherwise it is left on.

The situation is slightly more complicated for cases with intermediate values of the duty cycle ($0 < f_{DC} < 1$). A quantity Δ is computed as:

$$\Delta = \max\left(\frac{\delta t_{off}}{1 - f_{DC}}, \frac{\delta t_{on}}{f_{DC}}\right) \quad (5)$$

If the source is on and time since it was last turned on is greater than $f_{DC}\Delta$, then the source is turned off. If the source is off and the time since it was turned off is greater than $(1 - f_{DC})\Delta$, then the source is turned on.

3: Determination of PID Gains

A necessary step in the implementation of the controller was to determine the PID gain parameters. We do this by *approximating* the system with a first-order plus dead time (FOPDT) model [26], noting that the degradation of confinement with power is an effect that falls outside the model. The system identification and controller tuning is then done with the Ziegler-Nichols (or process-reaction) method [26], a commonly used open-loop tuning method for FOPDT systems that was previously used for tuning strike-point position controllers in NSTX [27].

In this method, a step is placed in the neutral beam power $P_{inj}(t)$, and the details of the $\beta_N(t)$ response are studied. Three important parameters in the response are then used for tuning the controller. These are the delay between the change in the beam power and the change in β_N (τ_{dead}), the time-scale for the evolution of β_N (τ_{β_N}), and the change of beam power (δP_{inj}) normalized to the β_N change ($\delta P_{inj}/\delta\beta_N$). Once these values are determined, the PID parameters can be determined from Table 1. Here, we use

$K_0 = \frac{\delta P_{inj}}{\delta\beta_N} \frac{\tau_{\beta_N}}{\tau_{dead}}$, and the PID operator is defined in eqn. 3.

The step response of the FOPDT system is given by an exponential function, written for the purposes of this study as:

$$\beta_N(t) = \begin{cases} \beta_{N,0} & t < t_{step} \\ \beta_{N,0} + \delta\beta_N \left(1 - \exp\left(-\frac{t - t_{step} - \tau_{dead}}{\tau_{\beta_N}}\right) \right) & t > t_{step} \end{cases} \quad (6)$$

This equation is fit to the measured evolution of β_N , where $\beta_{N,0}$, $\delta\beta_N$, τ_{β_N} , and τ_{dead} are fit parameters and t_{step} is the time of the beam step-up. The fits of eqn (6) were done with

the Levenberg-Marquardt algorithm [28], as written in the MPFIT curve fitting libraries [29]. Initial guesses were provided for the parameters $\beta_{N,0}$, $\delta\beta_N$, τ_{β_N} , and τ_{dead} , and the algorithm adjusted them to best match the measured β_N evolution. The times included in the fitting process were from 20 msec before the beam turn-on to 150 msec afterwards. We note that although τ_{dead} includes the effect of various system delays and τ_{β_N} is related to the total energy confinement time, these identifications are not strictly correct. Rather, the purpose of the fitting step in eqn. 6 is to identify the characteristics of the first order system nearest to the actual dynamics, in order to design the controller.

Four examples of the application of the method are given in Fig. 2. Each case shows the neutral beam power and the β_N evolution, as well as fits to eqn. 6. The plasma currents are indicated in each figure. The fit parameters are shown in the frames, and are used with the formulas in table 1 to determine the appropriate gain parameters for feedback use.

We have generally chosen to use a proportional-integral controller for experiments in NSTX. Use of a purely proportional controller, with no additional pre-programmed power, causes the achieved steady state β_N to be less than the request. This can be seen by taking the steady state achieved normalized- β ($\beta_{N,achieved}$) and relating it to the input power as $P_{inj} = \bar{C}_A \beta_{N,achieved}$. The constant \bar{C}_A is different than \bar{C}_{β_N} above, as the former depends on the actual values of the plasma parameters (I_p , B_T , τ_E , etc.), while the latter is a constant in PCS; the power degradation of confinement is neglected in this simple calculation. Setting this specification for the injected power to be equal to that in Eqn. 3, and using proportional gain only allows the ratio of achieved to requested β_N to

be calculated as $\frac{\beta_{N,A}}{\beta_{N,Req}} = P_{\beta_N} / \left(\frac{\bar{C}_A}{\bar{C}_{\beta_N}} + P_{\beta_N} \right)$. This ratio approaches 1 for arbitrarily large

gain, though this might introduce instability into the system. The use of integral gain allows the error to approach zero for reasonable values of proportional gain. Derivative gain was not used, as the β_N signal from rtEFIT is sufficiently noisy that a reliable calculation of $d\beta_N/dt$ is not possible.

4: Example Use of the Algorithm.

A detailed example of the algorithm performance for a single discharge is shown in Fig. 3. The discharge in this case is a high-elongation ($\kappa=2.5$) high-triangularity discharge of the type described in Ref. [30], with $I_p=800$ kA. All neutral beams are operated with a voltage of 90 kV, corresponding to 2 MW of injected power per source.

The initial turn on of the sources is manually programmed, with β_N control starting at $t=0.2$ sec. The requested β_N is shown in frame b), as is the low-pass filtered β_N from rtEFIT. The requested β_N exceeds the measured value when feedback is first turned on, and the controller leaves all three beam sources on (black trace in frame c). The achieved β_N quickly exceeds the requested value, and the controller immediately begins to reduce the injected power. The controller reaches near steady-state by 500 msec, settling at approximately 4 MW of input power required to achieve the requested β_N .

Frame b) also shows the value of β_N calculated by the more accurate offline EFIT [31,32]. The offline calculation is systematically higher than the realtime calculation. The constraint set for the offline calculation is more comprehensive: the two reconstructions are constrained by similar poloidal field and flux measurement, but the offline calculation

is further constrained by a measurement of the diamagnetic flux and a rough estimate of the pressure profile. Also, unlike the realtime solution, the offline EFIT is a fully converged solution of the Grad-Shafranov equation. For these reasons, the offline calculation is a better measure of the true value of β_N . However, when considering a requested β_N evolution, it is necessary to request values consistent with the realtime calculation. We note also that the 15 msec time constant for the filter in eqn. 1 produces a small time delay in the rtEFIT calculation compared to that from offline EFIT.

An example application of the algorithm is shown in Fig. 4. This experiment was an attempt to study the onset of $n=1$ locked modes as a function of toroidal field and plasma current at constant β_N [33]; a large $n=1$ field was applied after $t=0.4$ seconds, resulting in the eventual development of a locked mode and disruption of the plasma.

The plasma current waveform is shown in frame a), with a range from 700 kA to 1100 kA in the study; the toroidal field was also changed from 0.34 T to 0.54 T, in order to maintain a constant safety factor. The value of β_N was requested to be 3.2 in all cases. The β_N controller was turned on at $t=180$ msec. The beams were pre-programmed to be the same before that time, and, as described above, that level of pre-programmed power was left in the P_{inj} request in eqn. 3 for the remainder of the discharge.

The evolution of β_N is quite different before the controller was turned on, as expected from the change in toroidal field. Once the controller is turned on, beam modulations are used to control the β_N value to the same level. Note that the low current discharge continues to have a value of β_N somewhat higher than the others. This is because the algorithm was not allowing source A to modulate, so as not to lose the MSE diagnostic data. We also note that the beam powers for sources B and C were reduced to

1 MW in the 700 & 900 kA cases, to provide a finer power control. The source B power was raised to 2 MW in the 1100 kA case so that sufficient power was available to achieve the requested β_N . Without the controller, multiple discharges would have been needed to determine the necessary beam power waveforms. Use of the controller enabled the experiment to be completed with much greater efficiency. Use of the controller for experiments with β_N nearer to ideal stability limits is described in Refs. [30] and [34].

As noted above, the present software also allows the injected power to be directly specified as an input waveform, with the algorithm then modulating the neutral beams to match the power request. An example of this is shown in Fig. 5. The plasma current is shown in frame a), while the requested and injected power are shown in frame b). There is a slow ramp in the request, which the modulation algorithm translates into properly spaced beam modulations. This programming of such modulations would be quite tedious by hand, but is made trivial by the present control software.

5: Discussion

The β_N control system has proven quite useful in NSTX. There are, however, some possible improvements that would further improve performance. These include:

- Addition of a causal median filter on the β_N values from rtEFIT. This would help prevent spurious realtime reconstructions, and the associated large error in eqn. 1, from setting off transients in the requested power.
- A realtime estimation of the confinement time τ_E in eqn. 4, based on the input power, stored energy, and stored energy rate of change. This would allow the

proportional and integral gain parameters to be more effectively constant over a range of plasma parameters.

- Improving the realtime calculation of β_N , either through improvements to the actual Grad-Shafranov calculation (more appropriate basis functions for ψ' and p' , for instance), or adding additional data constraints. Improvement here would likely also help with other controllers that use the rtEFIT output, such as the ISOFLUX shape controller [16].

A more fundamental limit on the algorithm comes from the observation that the disruptive β_N limit is not constant. For instance, the achievable stable β_N is known to be a strong function of parameters such as the pressure peaking factor and internal inductance [2,35-39] and plasma shape [2,38,40,41]. Furthermore, in the presence of an imperfectly conducting wall, the plasma will be unstable to a resistive wall mode [42,43], a pressure or current driven kink instability growing on the L/R time of the conducting wall. Hence, the operator of the algorithm must know exactly what β_N to request for a given plasma configuration. This problem could be eliminated by doing feedback on some variable even more sensitive to the plasma proximity to instability than β_N . Such a method was proposed in Ref. [44], where the plasma amplification of an applied $n=1$ field was suggested as a sensitive measure of the stability of the plasma. The present β_N control system is a first step toward implementing an advanced MHD controller of this sort. It also provides the groundwork for current profile control in NSTX-Upgrade [45].

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References:

- [1] M. SUGIHARA, Nuclear Fusion **47**, 337 (2007).
- [2] E.J. STRAIT, Phys. Plasmas **1**, 1415 (1994).
- [3] M. ONO, et al., Nuclear Fusion **40**, 557 (2000).
- [4] G.L. CAMPBELL, et al., *New DIII-D tokamak plasma control system*, in: Proceedings of the 17th Symposium on Fusion Technology, vol. 2, Rome, Italy, 14–18 September 1992, pp. 1017–1021.
- [5] J.E. LAWSON, et al., *Beta normal control of TFTR using fuzzy logic*, in: Proceedings of the 18th Symposium on Fusion Technology, vol. 1, Karlsruhe, Germany, 22–26 August 1994, pp. 739–742
- [6] N.H. ZORNIG, et al., Experimental results using the JET real time power control system, in: Proceedings of the 19th Symposium on Fusion Technology, vol. 1, Lisbon, Portugal, 16–20 September 1996, pp. 705–708.
- [7] T. OIKAWA, et al., Fusion Engineering and Design **70**, 175 (2004).
- [8] Y. NEYATANI, et al., Fusion Engineering and Design **36**, 429 (1997).
- [9] T. SCOVILLE, et al., Fusion Engineering and Design **82**, 1045 (2007).
- [10] J.R. FERRON, et al., Nuclear Fusion **46**, L13 (2006).
- [11] D. MOREAU, et al., Nuclear Fusion **43**, 870 (2003).
- [12] D. GATES, et al., Fusion Engineering and Design **81**, 1911 (2006).
- [13] D. MASTROVITO, et al., Fusion Engineering and Design **85**, 447 (2010).
- [14] B.G. PENAFLORE, et al., *A structured architecture for advanced plasma control experiments*, Proc. 19th Symp. On Fusion Technology (Lisbon, Portugal) (16-20 September) p. 965.

- [15] B.G. PENAFLOR, et al., *Fusion Engineering and Design* **71**, 47 (2004).
- [16] D.A. GATES, et al., *Nuclear Fusion* **46**, 17 (2006).
- [17] J.E. MENARD, et al., *Nuclear Fusion* **50**, 045008 (2010).
- [18] S.P. GERHARDT, et al., *Plasma Phys. Control Fusion* **52**, 104003 (2010).
- [19] S.A. SABBAGH, et al., *Phys. Rev. Lett.* **97**, 045004 (2006).
- [20] S.A. SABBAGH, et al., *Nuclear Fusion* **50**, 025020 (2010).
- [21] T. STEVENSON, et al., *A Neutral Beam Injector Upgrade for NSTX*, PPPL Report PPPL-3651, January, 2002.
- [22] L.R. GRISHAM for the TFTR group, *Plasma Devices and Operations* **3**, 187 (1994).
- [23] F. LEVINTON and H. YUH, *Rev. Sci. Instrum* **79**, 10F522 (2008).
- [24] J. R. FERRON, et al., *Nuclear Fusion* **38**, 1055 (1998).
- [25] E.J. DOYLE, et al., *Nuclear Fusion* **47**, S18 (2007).
- [26] D. XUE, Y.Q. CHEN, and D.P. ATHERTON, *Linear Feedback Control: Analysis and Design with MATLAB (Advances in Design and Control)*, Philadelphia, PA, Society for Industrial and Applied Mathematics (2008).
- [27] E. KOLEMEN, et al., *Nuclear Fusion* **50**, 105010 (2010).
- [28] P.R. BEVINGTON and D. K. ROBINSON, *Data Reduction and Error Analysis for the Physics Sciences*, McGraw-Hill, Boston, 1992.
- [29] C.B. MARKWARDT, 2008, "Non-Linear Least Squares Fitting in IDL with MPFIT," in proc. *Astronomical Data Analysis Software and Systems XVIII*, Quebec, Canada, ASP Conference Series, Vol. 411, eds. D. Bohlender, P. Dowler & D. Durand (Astronomical Society of the Pacific: San Francisco), p. 251-254 (ISBN: 978-1-58381-702-5; [Link to ASP title listing](#)). See also <http://purl.com/net/mpfit>.

- [30] S.P. GERAHRDT, et al., *Progress in the Development of Advanced Spherical Torus Operating Scenarios in NSTX*, Paper EXS/P2-08, Daejeon, South Korea (2010).
- [31] S.A. SABBAGH, et al, Nuclear Fusion **41**, 1601 (2001).
- [32] S.A. SABBAGH, et al., Nuclear Fusion **46**, 635 (2006).
- [33] R. J. BUTTERY, et al., *The Impact of 3D Fields on Tearing Mode Stability of H-Modes*, Paper EXS/P5-03, Daejeon, South Korea (2010).
- [34] S.A. SABBAGH, et al., *Resistive Wall Mode Stabilization and Plasma Rotation Damping Considerations for Maintaining High Beta Plasma Discharges in NSTX*, Paper EXS/5-5, Daejeon, South Korea (2010).
- [35] W. HOWL, et al, Phys. Fluids B **4**, 1724 (1992)
- [36] J.E. MENARD, et al. Nuclear Fusion **37**, 595 (1997)
- [37] J.E. MENARD, et al., Nuclear Fusion **43**, 330 (2003).
- [38] J.E. MENARD, et al, Phys. Plasmas **11**, 639 (2004).
- [39] S.A. SABBAGH, et al., Nuclear Fusion **44** 560 (2004).
- [40] E. LAZARUS, et al, Phys. Plasmas B **3** 2220, (1991).
- [41] D. A. GATES, et al, Phys. Plasmas **13**, 056122 (2006).
- [42] A. BONDESON and D.J. WARD, Phys. Rev. Lett. **72**, 2709 (1994).
- [43] A.C. SONTAG, et al., Nuclear Fusion **47**, 1005 (2007).
- [44] H. REIMERDES, et al., Nuclear Fusion **45**, 368 (2005).
- [45] J.E. MENARD, et al., *Physics Design of NSTX Upgrade*, 37th European Physical Society Conference on Plasma Physics, Dublin, Ireland, online:
<http://ocs.ciemat.es/EPS2010PAP/pdf/P2.106.pdf>

Figure Captions:

Figure 1: Schematic of the NSTX neutral beam injection geometry.

Figure 2: Example discharges used for open loop tuning of the β_N controller. Shown are the beam power, β_N evolution, and fits to the β_N evolution. Times displayed in text in the frames are in milliseconds, and rounded to the nearest millisecond. The increment of beam power is 4 MW in all cases.

Figure 3: Demonstration of β_N control in NSTX. Shown are a) the plasma current, b) the requested β_N , as well as that calculated by realtime and offline EFIT, and, c) the requested and actual injected power. Feedback is on from $t=0.2$ sec. onwards.

Figure 4: Demonstration of β_N control in NSTX. Shown are a) the plasma current, b) β_N , c) the requested power, and d) the actual injected power. Ramping $n=1$ fields are applied starting at $t=0.4$, where the plot becomes gray.

Figure 5: Demonstration of pre-programmed power ramps. Shown are a) the plasma current, b) the requested and injected powers.

Controller Type	P_β	I_β	D_β
P	K_0/\bar{C}_{β_N}	0	0
PI	$0.9K_0/\bar{C}_{\beta_N}$	$0.9K_0/(3.3\tau_{dead}\bar{C}_{\beta_N})$	0
PID	$1.2K_0/\bar{C}_{\beta_N}$	$1.2K_0/(2\tau_{dead}\bar{C}_{\beta_N})$	$1.2\tau_{dead}K_0/(2\bar{C}_{\beta_N})$

Table 1: Determination of the optimal PID parameters from the Ziegler-Nichols method.

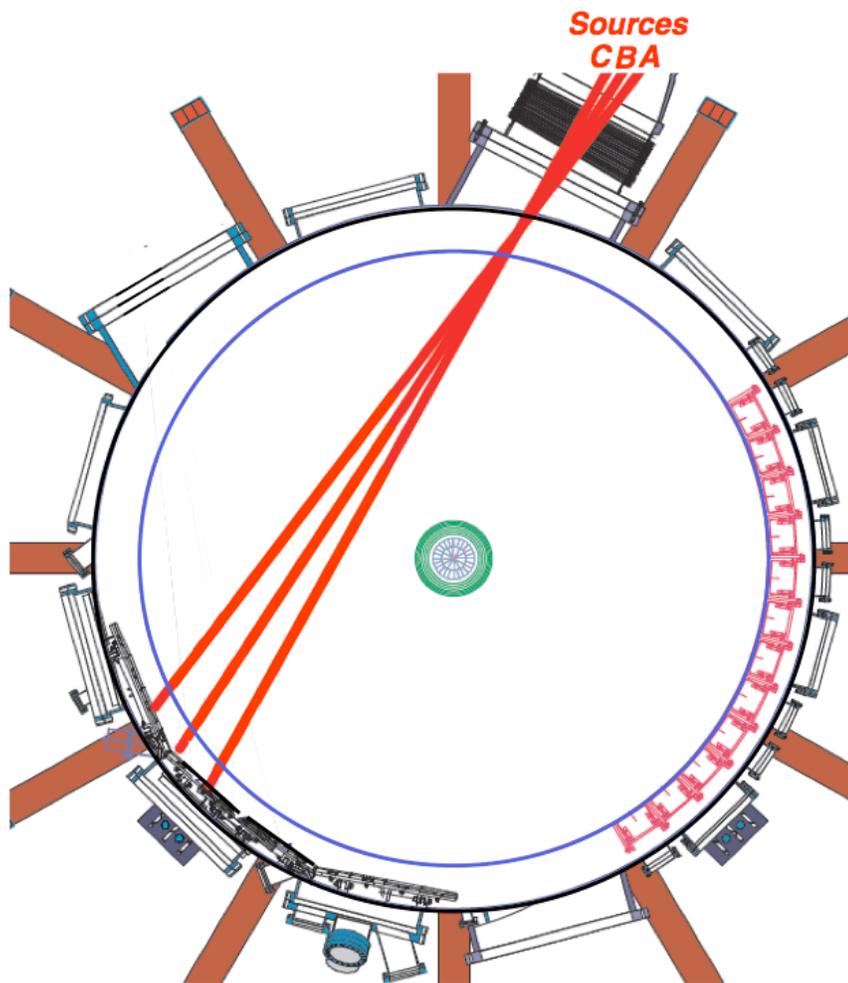


Figure #1

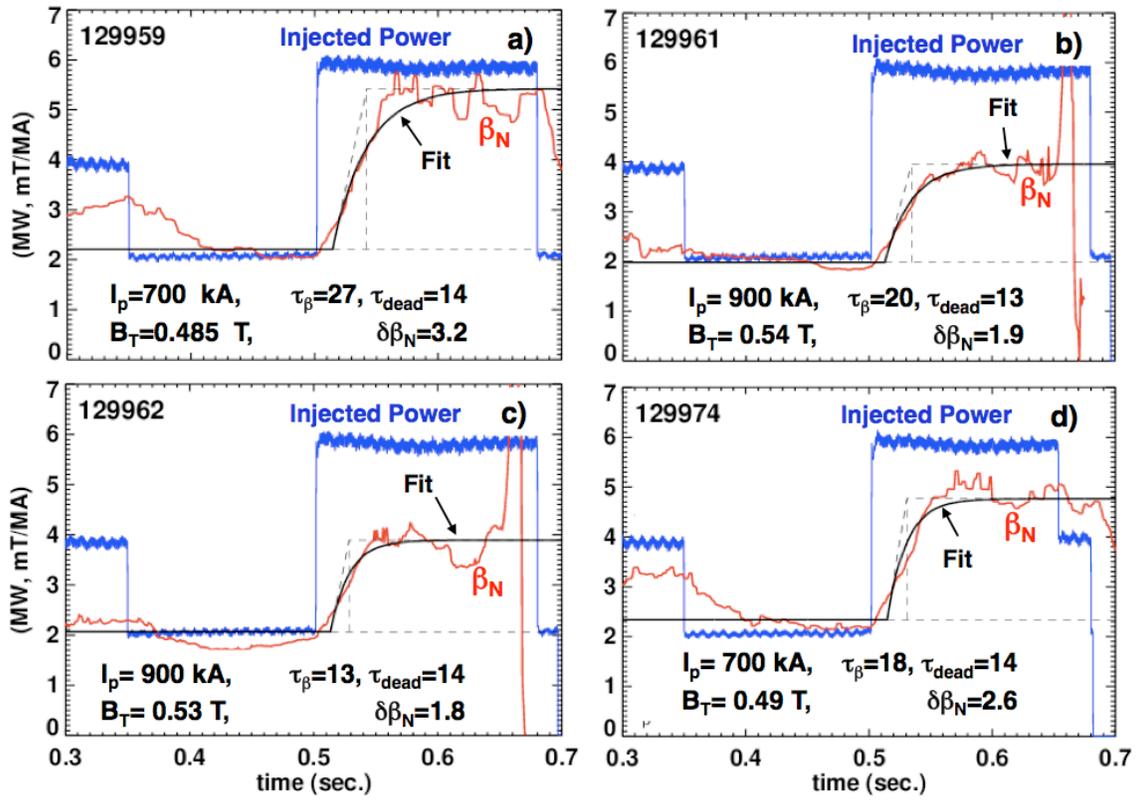


Figure #2

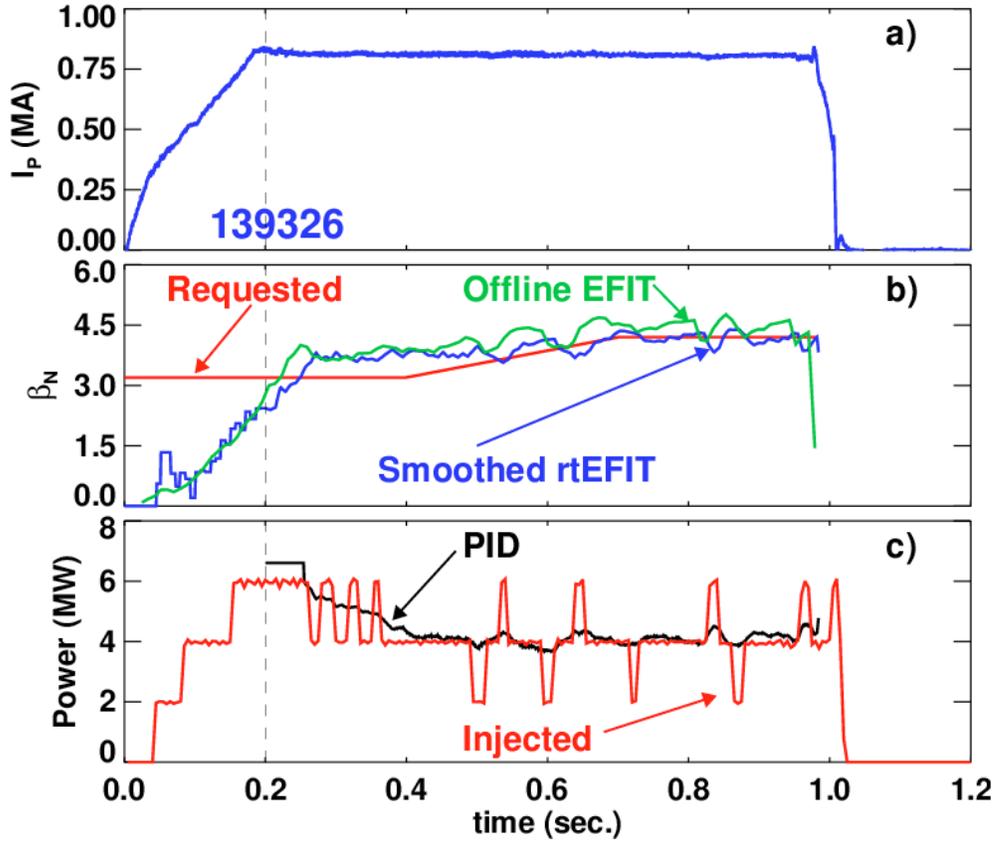


Figure #3

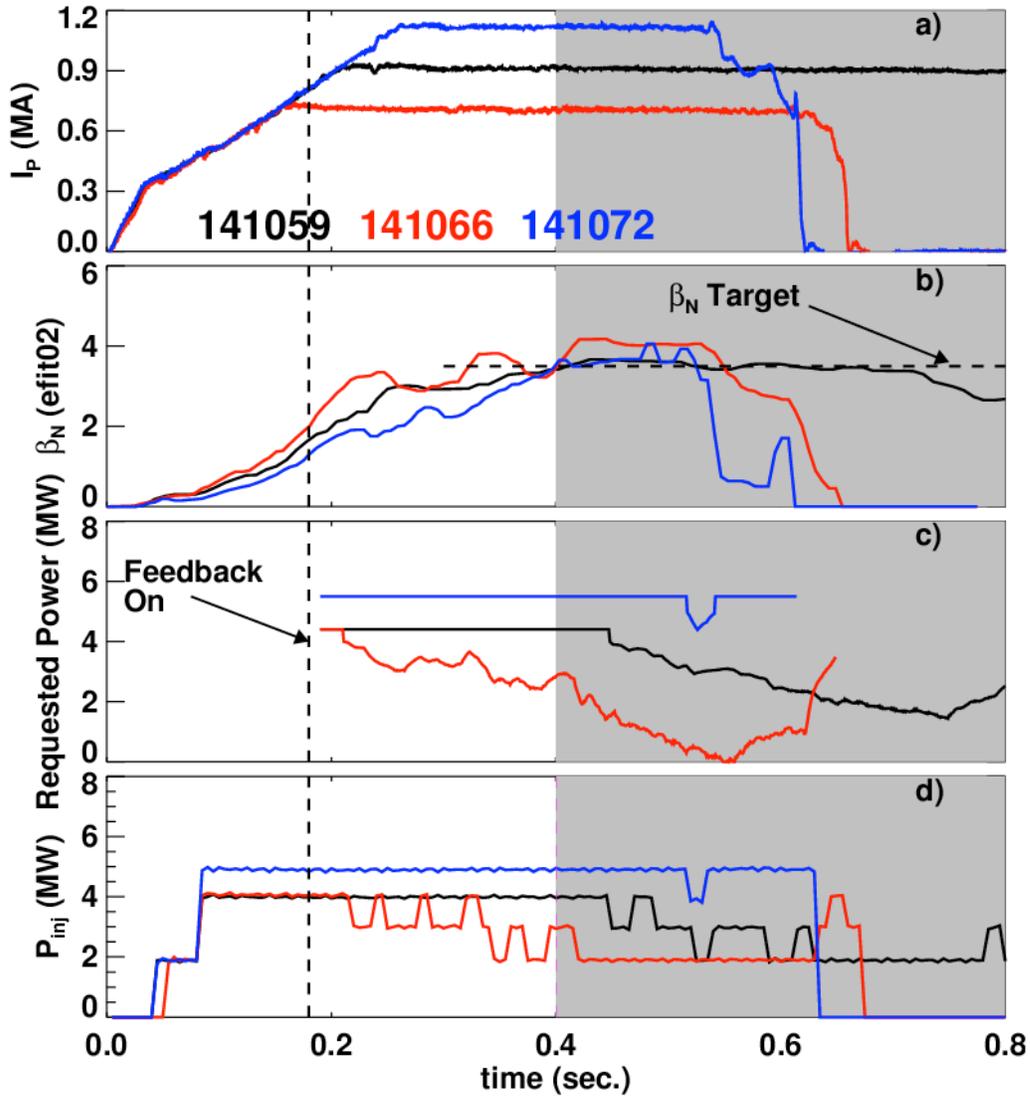


Figure #4

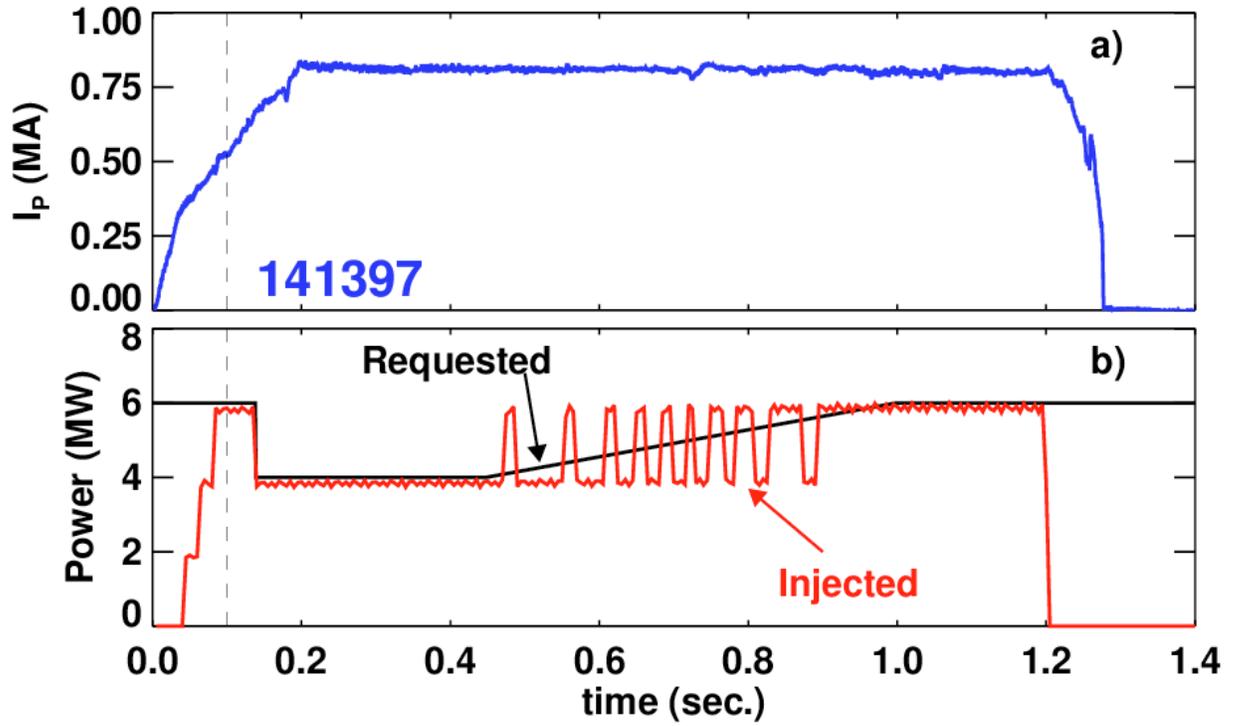


Figure #5

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