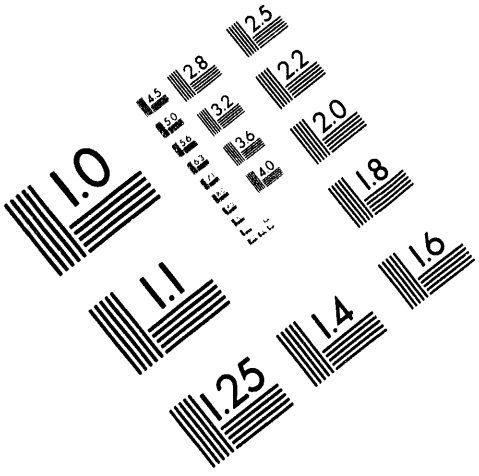

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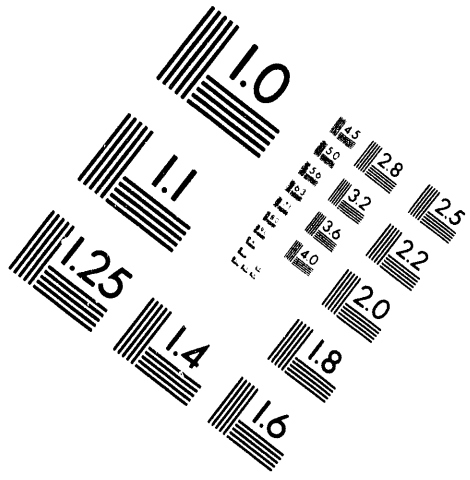

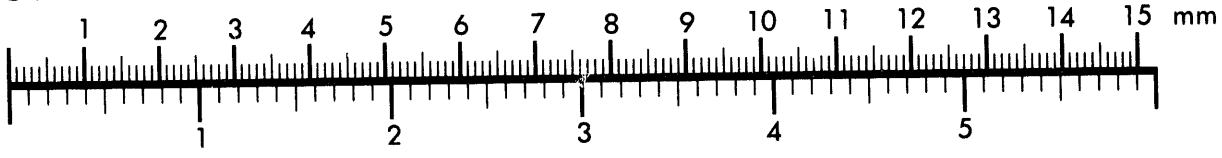

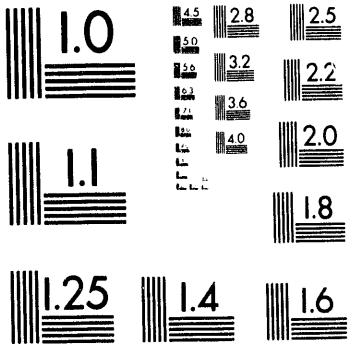

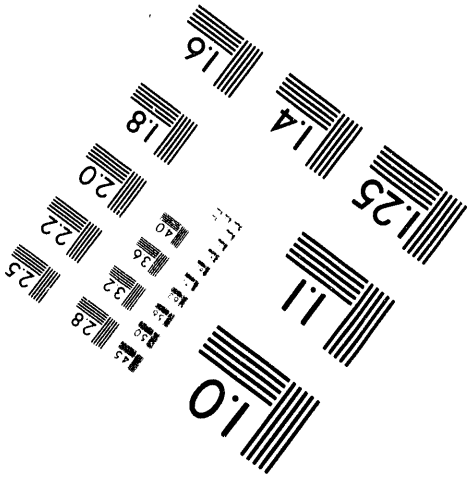

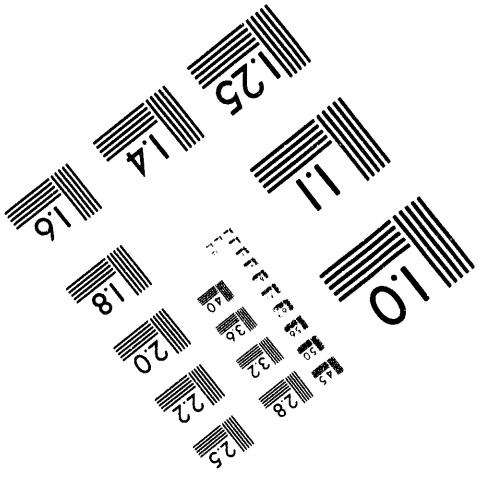

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BETA NORMAL CONTROL OF TFTR USING FUZZY LOGIC

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In TFTR plasmas heated by neutral beam injection, the fusion power yield increases rapidly with the plasma pressure. However, the pressure is limited by the onset of instabilities which may result in plasma disruptions that would have had an adverse effect on the performance of subsequent discharges and increase the risk of damage to internal components. The likelihood of disruption has been found to correlate with the normalized beta, defined as $\beta_N = 2\times10^8\mu_\circ < p_\perp > a / B_T I_p$ where $< p_\perp >$ is the volume-average plasma perpendicular pressure, a the mid-plane minor radius of the plasma, B_T the toroidal magnetic field and I_p the plasma current. Other variables, such as the peaking of the plasma pressure and current profiles, have been found to influence the threshold of β_N at which the probability of disruption begins to increase significantly. For TFTR plasmas with high fusion performance (TFTR "supershots") the probability of disruption has been found to increase rapidly for $\beta_N > 1.8$. Since confinement in this regime is affected by plasma-wall interaction, which can vary from shot to shot, operation at high β_N with preprogrammed heating power pulses can produce an unacceptably high risk of disruption. To reduce the risk of producing beta-limit disruptions during neutral beam heating experiments, a control system, the Neutral Beam Power Feedback System (NBPFS), has been developed to modulate the total heating power by switching individual neutral beam sources on and off in response to the evolution of the normalized beta so that the limit will not be exceeded.
The value of β_N is calculated in real time and transmitted to the NBPFS. The value of β_N and its calculated time derivative are input to a fuzzy logic controller which implements a proportional-derivative control based on the difference between β_N and a programmed reference level β_{NREF} which can be programmed as a function of time. The output of the controller is a set of twelve signals, one for each neutral beam source, which can block injection. These signals are updated every 10 ms in response to the plasma behavior. The tokamak operators specify the order in which sources will be turned off and on as the β_N limit is approached. The system has been in operation since May 1994 and has shown that the β_N can be controlled.

The Normalized Beta Signal

The normalized beta signal β_N is calculated in real time from the diamagnetic flux, ϕ_d using:

$$\beta_N = 200 E_\perp(MJ) / \pi b I_t(MA) I_p(MA)$$

where $E_\perp$ is the transverse plasma energy given by

$$E_\perp = \mu_\circ k_p R_p I_p^2 / 4 + I_t \cdot \phi_d$$

and b is the plasma half-height, R_p is the plasma major radius, I_t is the TF threading current ($= N_{TF} I_{TF}$) and k_p is the paramagnetic parameter (≈ 1 for TFTR). The plasma column dimensions used in these equations are calculated from the poloidal flux in six saddle loops and the poloidal field at four pickup coils mounted on the vacuum vessel. To derive the diamagnetic flux, the raw flux ϕ_m measured by a compensated poloidal loop encircling the plasma must be corrected for

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its residual couplings to the vacuum field and eddy currents in the vessel and the structure using the algorithm:

$$\phi_{a'} = \phi_m + A_1 I_t + A_2 I_t^3 + A_3\left(\int_0^t I_t(t')^2\,dt'\right) I_t + A_4 I_t'$$

where $A_1 \ldots A_4$ are constants and I_t' is the result when I_t is passed through a $s/(1+s\tau)$ differentiator with τ empirically determined to be about 0.2 second.

The calculations are carried out in real time using a stand-alone digital signal processor originally built to derive the plasma position. The original Plasma Position Calculator (PPC) described in reference 1 was modified with additional input and output channels and software modules to perform the calculation of β_N. The calculation is updated every 2 ms with the majority of this time being required to sample the inputs. Sixteen bit integer arithmetic is used in the PPC, although only the twelve bits are significant. This data is transmitted to the NBPFS as two serial bit streams at 307.2 kbaud. One of the lines carries the eight most significant bits and the other carries the four least significant bits and four status bits. There are also two spare bit streams for a future signal called X. The serial data streams are transmitted through fiber optic cables since the PPC is located in the upper data acquisition room (DARM) which is at machine potential, while the NBPFS is in the neutral beam control room.

Since the feedback unit is operating on a 10 msec cycle, five β_N values are received for each NBPFS cycle. These five values are averaged to remove high frequency noise which would effect the $d\beta_N/dt$ calculation.

Neutral Beam Interface

The NBPFS receives one signal from each of the twelve ion source controllers which indicates the ON/OFF condition of the source. This signal allows the feedback controller to only attempt to control those ion sources that are actually enabled. The ion sources are controlled by a permissive signal sent to each of the twelve acceleration voltage modulator-regulator units. These modulator-regulator units are used as the control elements since they are the only control point on the ion sources with a sufficiently fast response time.

Operator Interface

There are two operator interfaces to the feedback controller. First is a computer interface page used by the tokamak operators to modify commonly changed settings. These include the priority list for the order in which sources will be turned off and on, a button to allow bypassing the feedback controller, a button for activating a test mode, and a graphical editor for generating the beta normal reference β_{NREF} as a function of time.

The second interface is by a terminal which can be attached to a RS-232 interface on the front panel of the feedback controller. When the front panel key is turned to the PROGRAM position, the input grading functions, the input gain terms, and the fuzzy rules can be modified. Program patches for testing of code changes may also be implemented via the terminal.

In addition 26 channels of data are recorded and archived by transient digitizers. These include β_N, β_{NREF}, $\beta_N - \beta_{NREF}$, $\dot{\beta}_N$, the number of ion sources turned off, and the permissive signal to each ion source.

The Hardware

The feedback controller is built in a standard 6U Eurocard chassis. This chassis is split into two 3U bays. The lower bay contains custom designed electronics cards which provide the interfaces between logic level signals and the external signal levels. This bay also contains the serial data receivers, the analog input filtering, and the analog output buffers. The upper bay contains the computer that controls the whole system.

The system uses a G64 bus backplane. The processor is a Motorola 68000 running at 8 MHz, with 64 kbytes of EPROM and 16 kbytes of RAM. There is also 64 kbytes of battery backed RAM used to store the input grading function, the fuzzy rules, and other variables that need to be retained over a loss of power, but also need to be easily changed. Also used are four 32 bit parallel input/output boards, one 16 channel analog to digital converter board and one 8 channel digital to analog converter board.

The Software

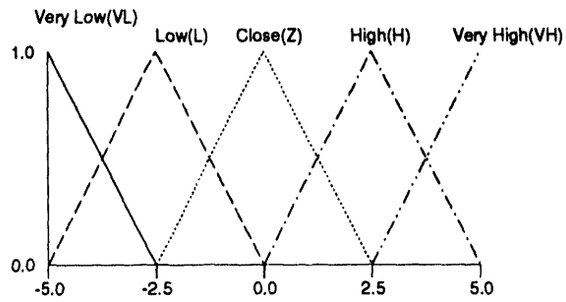
The NBPFS software has two major components which run independently of each other. The first is the receiver routines for the β_N and X data. Since the PPC runs off of its own 2 msec cycle clock, the data has to be received by the feedback controller on an interrupt driven basis. When an interrupt is generated by the serial receiver card, the data is read from the UART, checked for errors and loaded into a five element circular buffer. In test mode the buffer is filled with a value of 5.0, and if communications are lost the buffer is frozen with the last valid set of inputs.

The main program loop runs on a 10 msec cycle. This loop does the following functions:

- Set input sample/hold to hold
- Read analog inputs
- Set sample/hold to sample
- Read digital inputs
- If mode switch in PROGRAM run terminal server
- Do fuzzy logic
- Decode source permissives based on priority
- Write digital outputs
- Write analog outputs
- Wait for end of 10 msec cycle and start over

The Fuzzy Logic

The fuzzy logic calculations are done in three sections: the input analog values are mapped into fuzzy sets, the fuzzy rules are applied to the input sets, and the result is defuzzified to the final output, which in this case is the number of neutral beam ion sources that need to be turned off. The controller is implementing a proportional-derivative type control, so the inputs to the fuzzy controller are $\beta_N - \beta_{NREF}$ and $\dot{\beta}_N$, the time derivative of β_N. The analog inputs are multiplied by a gain term and then applied to a set of input grading functions which determine the membership of the input values to the various fuzzy sets.



Difference (Beta - Beta ref)*Beta gain
Figure 1

The graph in Figure 1 defines the five fuzzy sets to which the $\beta_N - \beta_{NREF}$ value could belong. For a given input value, five membership values, each of which will be between 0.0 (0% membership) and 1.0 (100% membership), will be obtained. For example, if the difference was -1.25 the result would be VL=0.0, L=0.5, Z=0.5, H=0.0, and VH=0.0.

In a similar fashion the five membership functions for the $\dot{\beta}_N$ input are derived from a graph with the same form as figure 1 but with an input range of -16 to +16. The $\dot{\beta}_N$ fuzzy variables are: Very Negative (VN), Negative (N), Zero (Z), Positive (P), and Very Positive (VP).

Once the inputs have been fuzzified, the fuzzy logic rules that determine what outputs will derive from which input conditions can be evaluated. The rules have the form shown in Figure 2.

beta dot \ beta	VL	L	C	H	VH
VP	FO	SO	MO	MO	MO
P	FO	FO	SO	MO	MO
Z	FO	FO	FO	SO	MO
N	FO	FO	FO	SO	SO
VN	FO	FO	FO	FO	SO

Figure 2: Fuzzy Rule Matrix

where:
FO = few ion sources off
SO = some ion sources off
MO = most ion sources off
The entries in this table are the 'AND' of the input terms where the 'AND' operator is defined as the numeric minimum function. For example, the first element of the table corresponds to the condition where the beta difference is very low and the beta dot is very positive. In this case the result is few sources off. To calculate the final three outputs all of the individual FO, SO, and MO terms are 'ORed' together where the 'OR' operator is defined as the numeric maximum function.

The final output, the number of ion sources to be turned off, is found by defuzzifying the three fuzzy output variables. This is done by average of maxima method, where FO is defined as 0 sources off, SO is 6 sources off and MO is 12 sources off:

$$N_{off} = FO \cdot 0 + SO \cdot 6 + MO \cdot 12 \,/\, FO + SO + MO$$

Results

The NBPFS was installed and tested in the spring of 1994. In April of 1994 a series of test shots was performed on TFTR with this system controlling the beams. These shots allowed us to optimize the beta difference gain and the beta dot gain. Since that time the system has been both used and bypassed depending on the needs of the experimental program, but in those cases where it was controlling the beams, it has been successful in limiting the β_N to the reference value. An example of the operation of this system when set to limit at β_N of 0.9 is shown in Figure 3 .

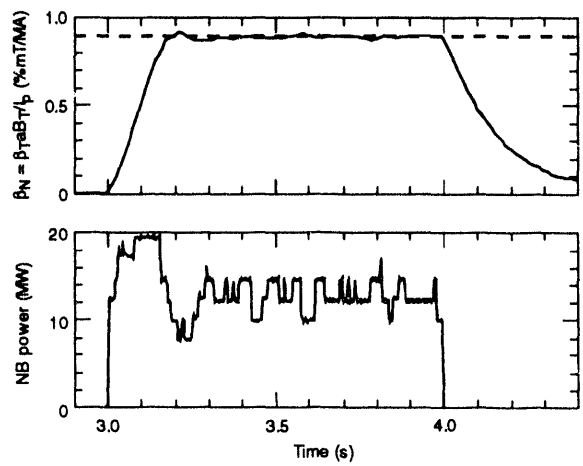


Figure 3
Evolution of β_N in a TFTR shot where the NBPFS was set up with β_{NREF}=0.9

Acknowledgments

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1) T. Senko, M. Bell, Design of a Plasma Position Calculator Using the ADSP2105 Digital Signal Processor, 15th IEEE/NPSS Symposium on Fusion Engineering, 1993, pg. 250.

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