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Control of plasma stored energy for burn control using DIII-D in-vessel coils

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Abstract. A new approach has been experimentally demonstrated to control the stored energy by applying a non-axisymmetric magnetic field using the DIII-D in-vessel coils to modify the energy confinement time. In future burning plasma experiments as well as magnetic fusion energy power plants, various concepts have been proposed to control the fusion power. The fusion power in a power plant operating at high gain can be related to the plasma stored energy and hence, is a strong function of the energy confinement time. Thus, an actuator that modifies the confinement time can be used to adjust the fusion power. In relatively low collisionality DIII-D discharges, the application of non-axisymmetric magnetic fields results in a decrease in confinement time and density pumpout. Gas puffing was used to compensate the density pumpout in the pedestal while control of the stored energy was demonstrated by the application of non-axisymmetric fields.

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1. Introduction

In a magnetic fusion power plant, the heating from alpha particles due to deuterium-tritium reactions dominates the energy balance in the plasma, which, depending on the temperature of the plasma and scaling of the energy confinement time, can result in a thermal runaway condition or in thermal stability. Previous studies for the burning plasma experiment, ITER, have shown that for the high temperature operating conditions of ITER and estimates of the global energy confinement time, the plasma should be thermally stable [1–9]. Many of these studies used zero dimensional analysis of the plasma performance and the resulting operational regime was characterized by POPCON plots [4]. Though the plasmas are predicted to be thermally stable, small variations in the energy confinement time will still result in large variations in the fusion power in a power plant, which will need to be controlled. A new approach has been experimentally demonstrated to control the stored energy by applying a non-axisymmetric magnetic field using the DIII-D in-vessel coils to modify the energy confinement time, which can be used in a power plant to control the fusion power.

Several techniques have been proposed to control the fusion power. The fusion power from deuterium-tritium reactions is proportional to $\int n_d \bullet n_t \langle \sigma v \rangle \, dV_p$. In the ion temperature, T_i, range between 10 and 20 keV, $\langle \sigma v \rangle$ is approximately proportional to T_i^2. Hence the fusion power scales as $\left(n_d \bullet n_t\right) \; T_i^2 \; V_p \; = \; V_p = p_i^2 V_p / 4$ for $n_d = n_t$ and $p_i = \left(n_d + n_t\right) T_i$. These simple considerations have motivated approaches to control the fusion power by controlling the ion temperature or the fuel density. Auxiliary heating can be used to control the ion temperature (e.g. references [3] and [10]). This is a standard technique in current tokamak discharges in which the stored energy is feedback controlled by varying the neutral beam or radiofrequency power. In a power plant, it is desirable to minimize the circulating power; however, this approach would tend to increase the requirements for circulating power and lower the fusion power gain, Q, of a burning plasma [9]. Control of the fuel density is also a standard technique in present tokamak discharges using gas puffing. In future power plants, as well as in ITER, pellet fueling may replace gas puffing. One potential issue with this technique is the dynamic range. The upper end of the density range is set by degradations in confinement and stability as the density approaches the Greenwald limit [11]. The lower end is set by the requirements for either divertor detachment or maintaining a highly radiative divertor. Another issue is that depending on the fraction of particles that enter into the divertor from the core and are removed by the pumping system, the timescale for reducing the density may be appreciably longer than the energy confinement time. Nonetheless, density control is an approach extensively discussed in the literature (e.g. in reference [4]) and would have to be considered even if on a slower timescale. A related approach is control of the deuterium to tritium ratio. This has the advantage of being decoupled from density control but has the related issue of the long timescale needed for modifying the isotope ratio. Another approach is the use of impurity injection to increase the power radiated and reduce the confinement as discussed [9]. In addition, the use of toroidal field ripple induced transport was proposed by Petrie and Rawls [12] to avoid thermal runaway due to the strong ion temperature dependence.

While the issues with the application of auxiliary heating and density control are not fundamental, they have motivated the examination of other complementary approaches that can be used in conjunction with them to control the fusion power. The energy confinement time has a strong impact on the fusion power. Therefore, one complementary approach is the use of a method that directly changes the energy confinement time. This can be illustrated by considering the following. In a burning plasma, the energy stored in the electron channel is comparable to that in the ion channel. Thus the fusion power scales approximately as W^2/V_p, where W is the total plasma stored energy. The plasma energy in steady-state can be approximately given by: $W/\tau_E = P_{aux} + P_{alpha}$, where P_{aux} is the auxiliary heating power and P_{alpha} is the alpha heating power, which for deuterium-tritium reactions is 0.2 P_{fusion}, not taking into account the fusion power generated in the blanket. The energy confinement time in high-confinement (H-mode) discharges is given by:

$$\tau_{E,TH}^{IPB98(Y,2)} = 0.0562\ H_{IPB98(y,2)} I_p^{0.93} B_T^{0.15} n_e^{0.43} P^{-0.69} R^{1.97} M^{0.19} \kappa_a^{0.78} \varepsilon^{0.58} \quad , \qquad (1)$$

where I_p is the plasma current, B_T is the toroidal field (TF), n_e is the volume-averaged density, M is the averaged mass number, R is the major radius and ε is the aspect ratio (a/R, a is the horizontal minor radius). The units are (s, MA, T, MW, $\times 10^{19}$ m^{-3}, AMU, m) and the elongation κ_x is defined as $\kappa_x = S_o/(\pi a^2)$ with S_o the plasma cross-sectional area [11]. The H-factor, $H_{IPB98(y,2)} = 1$, corresponds to a best fit to experimental data in the international database but can also be considered a variable that can correspond to different experimental conditions not reflected in the scaling variables. For a discharge in which alpha heating is negligible compared with auxiliary heating, the fusion power, which scales as W^2, scales as $P_{aux}^{0.62}$ $H_{IPB98(y,2)}^2$. In many current experiments to keep the stored energy constant the auxiliary heating power is feedback controlled to compensate for variations in the H-factor. In a power plant operating near ignition, the auxiliary power is very small compared with the alpha heating power. Thus for constant machine parameters including density, the fusion power would scale approximately as $H_{IPB98(y,2)}^{2/0.38}$ or $H_{IPB98(y,2)}^{5.3}$ if the auxiliary heating power were negligible. Since the empirical scaling does not capture all of the physics issues associated with both transport and macrostability, it suggests that techniques that can reliably affect the energy confinement time with respect to the nominal operating point defined by the empirical scaling have the potential to substantial change the fusion power.

The application of non-axisymmetric fields in TEXT [13] and Tore Supra [14] was accompanied by reductions in electron density. More recent experiments in low collisionality discharges on DIII-D have shown that the application of non-axisymmetric fields is accompanied by changes to the pedestal of the discharge, typically resulting in decreases in energy confinement and edge density as well as changes in the toroidal rotation velocity in the edge [15]. Hence, non-axisymmetric fields may serve as an actuator for controlling the fusion power. These fields can also modify edge localized mode (ELM) stability, which is a very important topic of substantial relevance to ITER. The focus here will be on regimes with modest changes in ELM stability in which the frequency of ELMs increases with the application of non-axisymmetric fields and is accompanied by changes in energy and particle confinement. An empirical approach is taken in noting the change in transport for these conditions even though a comprehensive understanding of these changes is not available at this time. It is worth noting that in higher collisionality and density discharges studied on DIII-D and ASDEX-Upgrade, the application of non-axisymmetric fields does not result in degradation in confinement or reduction in density [16,17]. The operating conditions under which the degradation in energy confinement takes place are still under study.

Feedback systems to control the stored energy by the application of auxiliary heating are widely used in current experiments to improve the discharge reproducibility by compensating for changes in confinement due to transport effects and MHD activity, which if uncompensated can either increase or decrease the stored energy relative to the nominal operating point. In a power plant, the choice of an operating point near but avoiding operating boundaries such as disruption limits would have to take into account the effect of the non-axisymmetric fields. Increasing the magnitude of the non-axisymmetric fields to decrease confinement could be used to stay within operating boundaries such as disruptions, compensate for the formation of internal transport barriers or other effects including high heat load to the divertor. If the operating point were to include a modest component of non-axisymmetric fields then decreasing the field could be used to increase the stored energy. In a power plant, operation away from limits that could lead to a disruption or overheat in-vessel components will have even greater importance than in current experiments. Thus, an actuator than can reduce (or increase) the stored energy and hence the fusion power is beneficial. This paper will illustrate that the application of non-axisymmetric fields to control the stored energy can be a potential actuator for a power plant.

2. Experimental Conditions

A lower single-null neutral-beam-heated DIII-D discharge with the strikepoint located such as to enable effective cryopumping was used throughout these experiments. The basic machine parameters were $B_T = 1.91$ T, $I_p = 1.36$ MA, a = 0.59 m, R = 1.77 m and $\kappa = 1.82$. The plasmas here heated by neutral beam injection using sources that injected in the direction of the plasma current (co-injection) unless otherwise noted when a source in the direction opposite to the plasma current was used (counter-injection).

Due to a hardware failure, only 11 of 12 DIII-D in-vessel coils ("I-coils") were available to create an even parity n=3 field. To compensate for the toroidal sidebands introduced by the missing I-coil, the ex-vessel coils ("C-coils") were used in n=1 configuration to correct the most detrimental poloidal harmonics of the undesired sideband [18]. Feedback commands to the I-coils were mapped to the C-coils, thus all non-axisymmetric coils were under simultaneous feedback control to deliver the purest possible n=3 field. Furthermore, baseline n=1 correction of the DIII-D intrinsic error field was also provided by the C-coil. In these experiments, the conditions were chosen to avoid fully suppressing ELMs by operating outside of known resonances in the edge safety factor. Nonetheless, the application of the non-axisymmetric fields increased the ELM frequency.

3. Feedback Approach

A baseline configuration was established and the current in the I-coil was controlled based on the difference between the stored energy in the plasma and a pre-set level. An even parity n=3 I-coil configuration was used in an ITER Similar Shape (ISS) discharge with $q_{95} \approx 4.1$. In these experiments the stored energy in the plasma based on magnetic measurements and EFIT reconstruction is used as a surrogate for the fusion power. In a power plant, direct measurement of the D-T neutron flux could be used. While neutron measurements are available in DIII-D, they are dominated by beam-target reactions. Hence, they would not simulate the fusion power from thermal reactions that would dominate ITER or a power plant. In these experiments, the maximum current in the I-coils was limited within the safe operating range for the coils as well as the ramp-rate to avoid mechanical resonances in the I-coil structure. A simple proportional gain feedback loop was used when the stored energy exceeded a pre-set level. When this feedback system was used the pre-set level is shown in the figures.

In addition to controlling the stored energy, gas puffing was used in some experiments to simultaneously control the pedestal density. Controlling the pedestal density was motivated by several considerations. In both ITER and a power plant, operation at relatively high density is desirable because it is possible to operate at lower temperature and higher reactivity for fixed beta and to increase the radiated power in the scrape-off and divertor. Furthermore, due to the density dependence in the energy confinement time scaling, it is desirable to operate at high density though as noted earlier the experimental data deviates from the scaling law projections in the vicinity of the Greenwald limit. In a tokamak power plant operating in steady state, current drive efficiency and fraction of bootstrap current need to also be considered in defining the density operating point. In ITER and most likely in a power plant, the density would be controlled by pellet injection. For the DIII-D experiments, Thomson scattering data is acquired and real-time analysis of this data is performed to obtain the density at the top of the pedestal. Then, deuterium gas injection is adjusted by changing the gas valve voltage using a proportional-integral-derivative (PID) controller to keep the pedestal density constant. This is in contrast with the normal core density feedback system used on DIII-D, in which interferometer data is used to measure and control the line-averaged density. When density feedback was used, the pre-set level is shown in the figures.

4. Experimental Results

4.1 Assessment of plasma response

A baseline was established as shown in figure 1 in which the non-axisymmetic field was generated by means of the in-vessel I-coils at the value of 4 kA and 2 kA. This illustrates a ~30% and ~24% decrease in the confinement at 4 kA and 2 kA respectively and ~33% and ~14% decrease in the pedestal density at 4 kA and 2 kA respectively. The H-factor was reduced by ~31% and ~21% in this case. The electron pressure at the top of the pedestal decreased by ~36% and ~17%. Figure 1 illustrates that even with modest applications of the non-axisymmetric fields there is sufficient reduction in the energy confinement time to affect the fusion power. This also points out that the change in the pedestal density must be considered in controlling the plasma response.

4.2 Assessment of feedback control using the application of non-axisymmetric fields

To examine the control of the plasma, three discharges were compared. The stored energy without the application of the non-axisymmetric field was 1.1 MJ in shot 155408. In the subsequent experiments, the pre-programmed value of the stored energy was set to 1.0 MJ to evaluate whether the application of the non-axisymmetric fields can control the stored energy (shot 155410) and compare it with conventional stored energy feedback using the neutral beam system (shot 155409). As shown in figure 2, the application of the non-axisymmetric fields enables control of the stored energy to the pre-programmed level. The regulation of the stored energy by means of I-coil feedback yields comparable to or more stationary conditions than by the conventional approach of varying the neutral beam power. The standard deviation as measured using the stored energy waveforms sensitive to fluctuations such as ELMs is nearly the same with both control approaches, whereas the standard deviation using the filtered waveforms on the timescale of the control loop indicate that it is reduced when the I-coils are used. This is likely due to the neutral beam control using a much coarser actuator, which involves turning on or off a full beam source (~2 MW) compared with the continuous variation achievable with the coil current. Furthermore, the temperature and density profiles are found to have less variability as a function of time.

While these results are encouraging, they are not a demanding test of whether the feedback system can compensate larger excursions in the plasma parameters. To simulate a larger transient for instance due to an intrinsic improvement in the alpha heating or in plasma transport rates resulting in improved confinement, the neutral beam power was increased from 5.67 MW to

6.85 MW and then further to 7.73 MW (figure 3). The control loop was set to keep the stored energy constant. For comparison, the H-mode scaling relationship would indicate that the stored energy should increase by 10% whereas to keep the stored energy constant the confinement decreased about 30% in response to the application of the non-axisymmetric fields and power degradation with H-mode scaling. The ability to change the confinement this much illustrates that this is a potentially powerful tool in controlling the fusion power. With the choice of gain in the feedback loop and the restrictions of coil current, the stored energy was kept constant to within 3% of the value prior to the increase in heating power.

4.3 Incorporating pedestal density feedback

In the previous experiments reported above, the pedestal density changed with the application of the non-axisymmetric fields. By combining stored energy control and pedestal density control, it was possible to decrease the variation in the pedestal density as shown in figure 4. Since the change in pedestal density was small with the modest applied coil currents, this was not a demanding test.

In figure 5, a "power surge in neutral beam power" as performed in figure 3 was used to create a more demanding situation to control both the stored energy and the pedestal density. The results shown in figures 4 and 5 indicate that fueling can compensate the loss in density associated with the application of a non-axisymmetric field.

4.4 Initial assessment of compatibility with higher values of β_N

The reduction in confinement with the application of non-axisymmetric fields raises the question whether, in addition, there is an adverse impact on the beta-limits. Figure 6 is a comparison of three discharges with different values of I-coil current using all co-injection. In these discharges, the neutral beam power was feedback controlled to increase the stored energy with time. The application of non-axisymmetric fields did not result in a stability limit over the range studied and values of $\beta_N \sim 2.7$ were obtained. This is similar to previous ELM suppression experiments on DIII-D in the advanced inductive regime with $\beta_N \sim 2.5$ [19] and very recently $\beta_N \sim 2.9$ [20].

4.5 Initial assessment of impact of reduced torque

Initial studies were performed replacing one co-source with a counter-source. The maximum stored energy in those discharges with and without the application of non-axisymmetric fields was observed to be lower. All of the discharges with the counter source had large MHD oscillations. As shown in figure 7 under these conditions, the energy confinement time is a strong function of the applied torque. In this experiment, a counter source (labeled 21L) was turned on at 3 s for 2 s. The stored energy was kept constant by feedback controlling the power in the co-sources. The energy confinement time decreases from ~205 ms to ~140 ms. Observation of reduced energy confinement with reduced torque is common for discharges that have initially high $E \times B$ shearing rates from co-injection (NBI) [21,22]. There is often an increase in MHD amplitude as well. The observation that both the stored energy and the rotation velocity decrease with the application of the non-axisymmetric fields raises the question whether this technique can be used in discharges which are rotating less and in the presence of increased MHD activity.

For comparison, two discharges in which a counter-source replaced a co-source at different times are shown in figures 8 and 9. The stored energy was controlled by the application of non-axisymmetric fields. In these discharges there is a complex interplay between transport and MHD activities and the application of non-axisymmetric fields and applied torque from the neutral beams. For example, in shot 155440, the stored energy and the energy confinement time is the same at ~3.7 s and ~4.7 s despite the torque being different. Though the applied torque in the two shots at ~4.7 s is different; the energy confinement time is the same.

The toroidal rotation velocity responds in part to the applied torque from neutral beam injection; however, it is also affected by changes in the n=1 and n=2 MHD activity and the application of the non-axisymmetric fields. During the co-injection phase (prior to 3 s) of shots 155428 and 155440 (figure 9), the rotation velocity decreased with the application of I-coil feedback starting at the edge but also due to changes in MHD activity. The estimated integrated torque from neoclassical toroidal viscosity due to the non-axisymmetric fields can be significant compared with the injected torque. A detailed comparison of experiment with theory was not done, in part, due to the complexity associated with MHD activity in these discharges and the sensitivity of the results to the plasma equilibrium. The addition of a counter source further reduced the rotation in the core and in the edge, as would be expected. Though the torque is larger in shot 155440 at 4.5 s than 2.8 s, the rotation velocity is less than in the earlier phase of the discharge (2.8 s); however, the non-axisymmetric field is larger at 4.5 s. It is also observed that the MHD activity is higher and the momentum transport is worse, both giving a larger effective momentum diffusivity, χ_ϕ that inhibits rotation re-spinning up despite the increased NBI torque. The reason for this seemingly hysteresis effect in the pedestal rotation velocity is not understood even though the global parameters of stored energy and pedestal density are controlled. Solomon *et al.* [22] reported a related observation in advanced inductive (AI) discharges, without the application of non-axisymmetric fields. When starting from a low torque AI discharge, if the torque is ramped up to levels typical for co-injection discharges, then the usual high confinement and rotation of rapidly rotating AI plasmas is not recovered.

What is perhaps striking is that though multiple effects are going on in these discharges including changes in plasma rotation, and MHD activity, it was possible to use this relatively simple feedback technique to control simultaneously the stored energy and the pedestal density, though for a brief period of time in shot 155428 the in-vessel coil current was limited to a preset maximum of 4 kA.

5. Analysis and Implications

The use of non-axisymmetric fields to control the stored energy by modification of the energy transport has been demonstrated in a tokamak at low collisionality. The application of this approach to control the plasma reactivity in a burning plasma experiment was studied by examining fast ion and thermal profile effects using TRANSP. Using the measured temperature and density profiles, the calculated stored energy is in good agreement with magnetic measurements as shown in figures 10 and 11. The effect of the in-vessel coils in a discharge with a "power surge", corresponding to increased neutral beam injection power, is to keep the total stored energy constant but decreases the fraction of thermal stored energy due to the increased energy in the beam ions.

TRANSP also predicts that the neutron flux is in good agreement with the measured flux [figure 12(b)] using the standard beam model in TRANSP, which does not take into account the effect of the non-axisymmetric fields. The uncertainty in the neutron flux is ±15%. Most of the neutron flux is due to beam-target reactions as shown in Fig. 11a. The time dependence of the ratio of the measured neutron flux to the calculated neutron flux does not change significantly (within ±5%.) with the application of the non-axisymmetric fields. This is a tighter constraint than the comparison with the stored energy in figure 10 since it is a direct assessment of the fast ion contribution, which is only ~20% of the total stored energy. Thus for these conditions, the achievement of control of the stored energy despite the increased heating power was not due to a decrease of the fast ion component but of the thermal component, which is what is desirable in a burning plasma experiment. If the effect of the non-axisymmetric fields were to predominately expel the fast ion component, burn control might be feasible but the use of the stored energy as a surrogate for the plasma reactivity would have been incorrect.

TRANSP has also been used to evaluate profile effects and address whether the application of the non-axisymmetric fields merely changes the stored energy in the plasma periphery or the value of Z_{eff}. A profile weighted "fusion reactivity" is calculated approximately from $\int n_d \bullet n_t \langle \phi v \rangle \, dV_p$ by assuming $n_t = n_d$ but using the measured Z_{eff} profile to obtain the depletion due to carbon impurities and by assuming that $\langle \sigma v \rangle$ scales at T_i^2 and comparing this quantity with W^2, which has been the surrogate for fusion power used in this paper. This analysis is for shot 155412, which included a 4 kA and 2 kA in-vessel current pulse as shown in figure 13. No significant variation is observed in the ratio of the computed "plasma reactivity" to the stored energy squared. Thus, as expected the use of the total stored energy is a reasonable surrogate for this study and the effect of the non-axisymmetric fields was not to merely modify the energy stored in the plasma periphery. In a burning plasma, direct measurements of the fusion power from thermal reactions will be possible and the use of the stored energy as a surrogate will not be needed.

These experiments were conducted over a limited parameter range. Further work is required to understand the relationship between the application of non-axisymmetric fields and confinement degradation and density pumpout. Nonetheless, in low collisionality regimes of operation in which this occurs this appears to be a powerful technique to alter the confinement. As noted earlier in a burning plasma operating near ignition, variations of ~10% in the confinement time may be sufficient to control the plasma in conjunction with other actuators to define the operating point. These experiments indicate that this is achievable. These experiments did not indicate significant changes to the β_n limits, which is encouraging. The compatibility of this technique with the use of the in-vessel coils for ELM suppression was not studied and remains an open research topic.

This work also suggests the question whether the stored energy in a stellarator power plant can be controlled by a set of trim coils. Theoretical work indicates that subtle changes in the shape of a stellarator may affect the confinement time thus, motivating this line of research [23].

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Fig. 1. Four and two kA pulses of the in-vessel coils (I-coils) were applied to observe the decrease in the global energy confinement time and edge pedestal density. (a) I-coil current. (b) neutral beam power, (c) plasma stored energy, (d) energy confinement time, and (e) pedestal density.

Fig. 2. The plasma-stored energy was controlled by applying a non-axisymmetric field (n=3) using the I-coils in a closed feedback loop (green 155410) and compared with a shot without feedback control (black 155408) and with a shot with neutral beam power feedback (red 155409). (a) Plasma stored energy, (b) neutral beam power, (c) energy confinement time, and (d) I-coil current.

Fig. 3. The plasma-stored energy was controlled by varying the current in the I-coils in response to variations in the neutral beam heating power. (a) Plasma stored energy, (b) neutral beam power, (c) energy confinement time, and (d) I-coil current.

Fig. 4. Comparison of two shots with (155419) and without pedestal density control (155410). (a) plasma stored energy, (b) neutral beam power, (c) energy confinement time, (d) I-coil current, (e) pedestal density, and (f) gas influx rate.

Fig. 5. Comparison of a discharge without pedestal density feedback (155414) with shots with pedestal density feedback (155420) in the presence of a “power surge”. (a) plasma stored energy, (b) neutral beam power, which is the same in both discharges, (c) energy confinement time, (d) I-coil current, (e) pedestal density, and (f) gas influx rate.

Fig. 6. Comparison of three discharges with different pre-programmed values of I-coil current and pedestal density feedback. Comparable values of stored energy were achieved, without triggering a disruption. Density feedback kept the pedestal density constant. (a) Plasma stored energy, (b) neutral beam power, (c) energy confinement time, (d) I-coil current, (e) pedestal density, and (f) gas influx rate.

Fig. 7. A counter source (21L) was turned on at 3 s in a discharge (red curve) in which the co-neutral beam heated power was feedback controlled to maintain the stored energy constant. In this discharge, the current in non-axisymmetric coils was off. a) Plasma stored energy, (b) total neutral beam power and power in counter source (shown in red), (c) energy confinement time, (d) pedestal density, and (e) gas influx rate.

Fig. 8. Comparison of discharges with a ctr-source replacing a co-source. In shot 155428, the ctr-source was applied at 3 s for 2 s and in shot 155440 at 3 s for 1 s. In shots 155428 and 155440 the stored energy was controlled by I-coil feedback and the density by gas puffing. (a) Plasma stored energy, (b) total neutral beam power and power in counter source, (c) energy confinement time, (d) I-coil current, (e) pedestal density, and (f) gas influx rate.

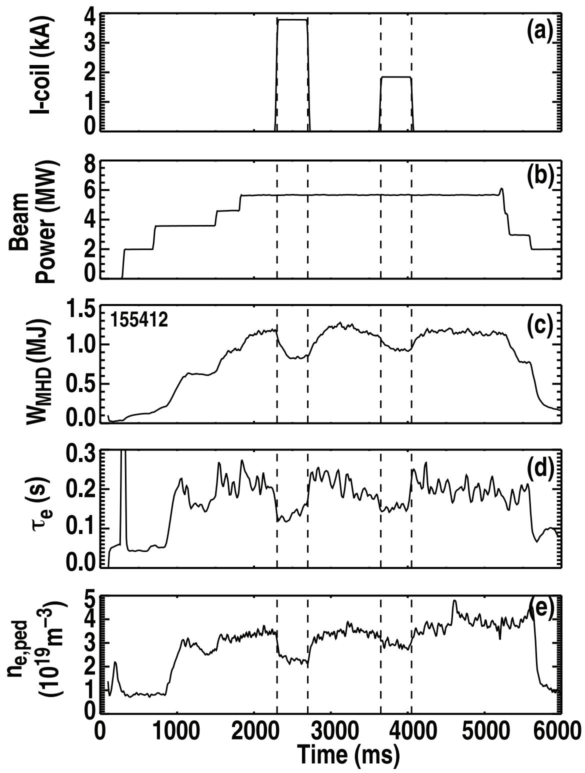
Fig. 9. For the discharges shown in figure 8, (a) injected torque, (b) MHD activity, (c) toroidal rotation velocity at $\rho = 0.3$ and (d) $\rho = 0.75\rho$ 75.

Fig. 10. TRANSP analysis of the total stored energy as well as the thermal and fast ion component as a function of time for a discharge (155414) with a "power surge" is compared with magnetics analysis using EFIT. The I-coil current evolution is shown as well.

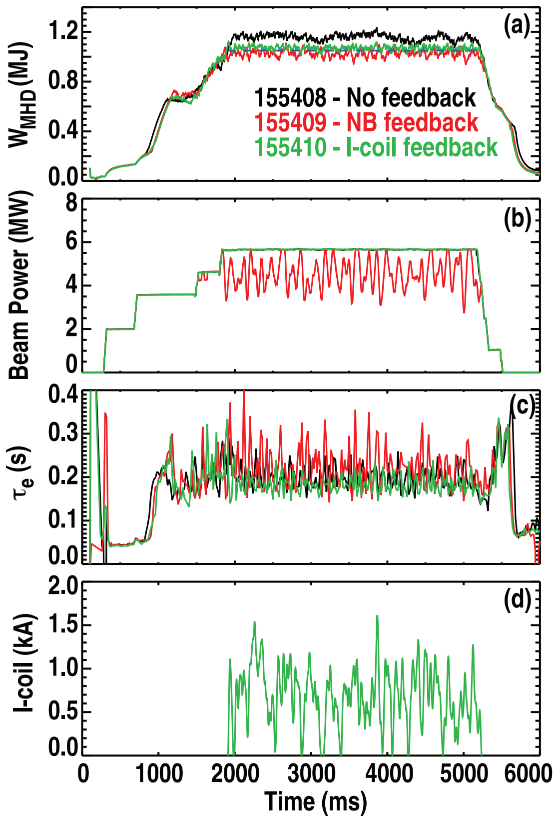
Fig. 11. Ratio of stored energy from TRANSP to the energy from magnetics measurements for the discharge shown in figure 10. The ratios of the calculated thermal and beam ion stored energy to the measured total is shown for comparison. The I-coil current evolution is shown as well.

Fig. 12. (a) TRANSP calculations of the total neutron flux and that due to beam target, beam-beam and thermonuclear reactions for shot 155412 in which the I-coils were turned on and off are compared with the measured neutron flux. (b) The ratio of the predicted flux to measured flux is shown for comparison and the evolution of the I-coil current.

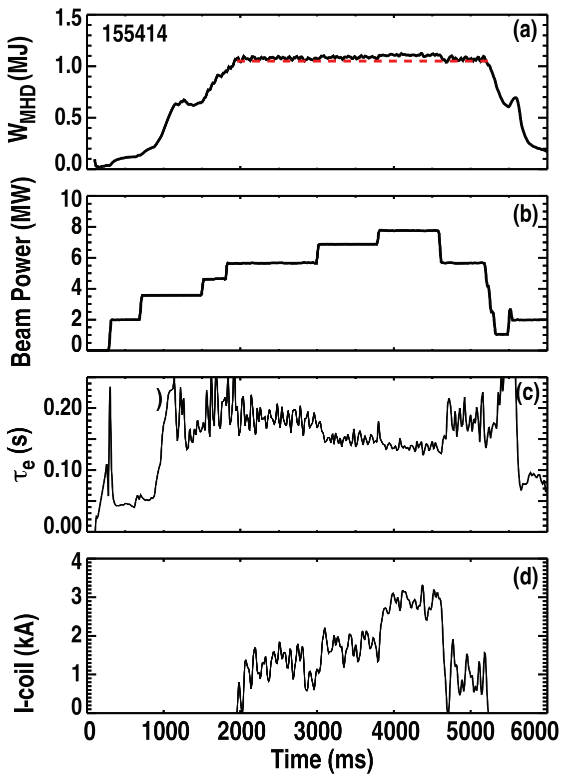
Fig. 13. (a) "Plasma reactivity" as described in the text based on TRANSP analysis (b) square of the plasma-stored energy, (c) ratio of "plasma reactivity" to stored energy squared and (d) the current in the non-axisymmetric coils for shot 155412.



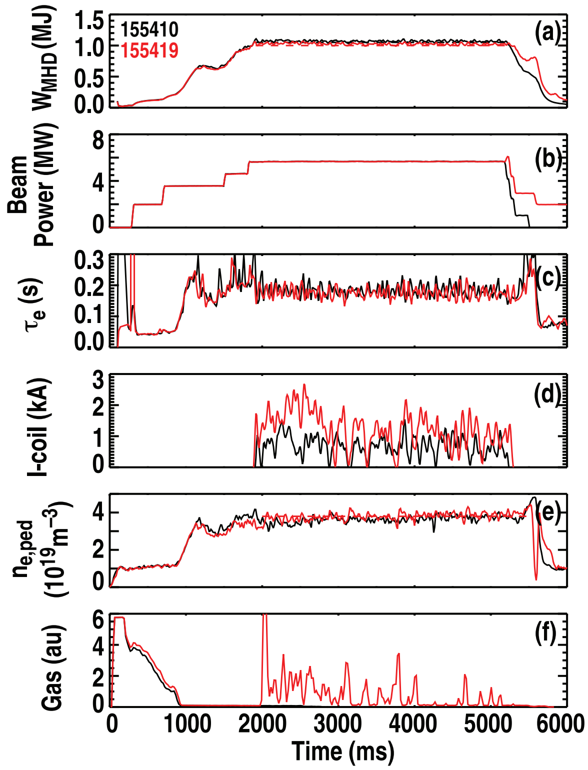
R.J. Hawryluk Figure 1



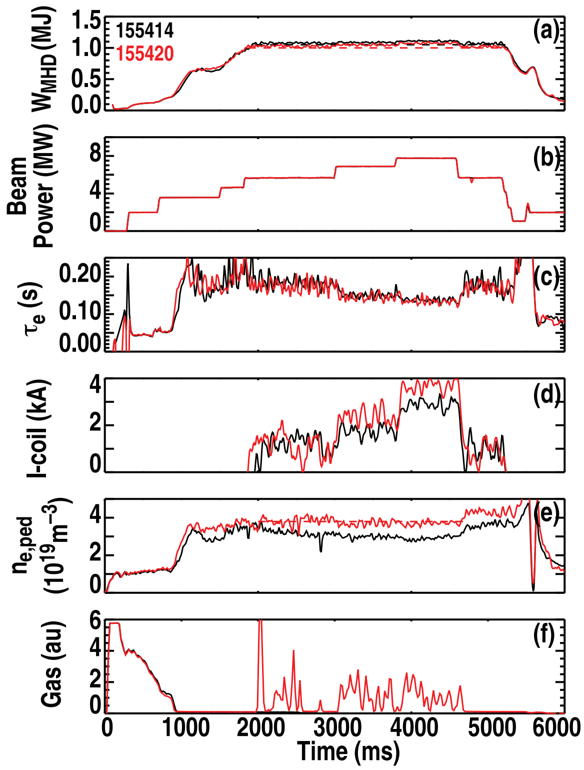
R.J. Hawryluk Figure 2



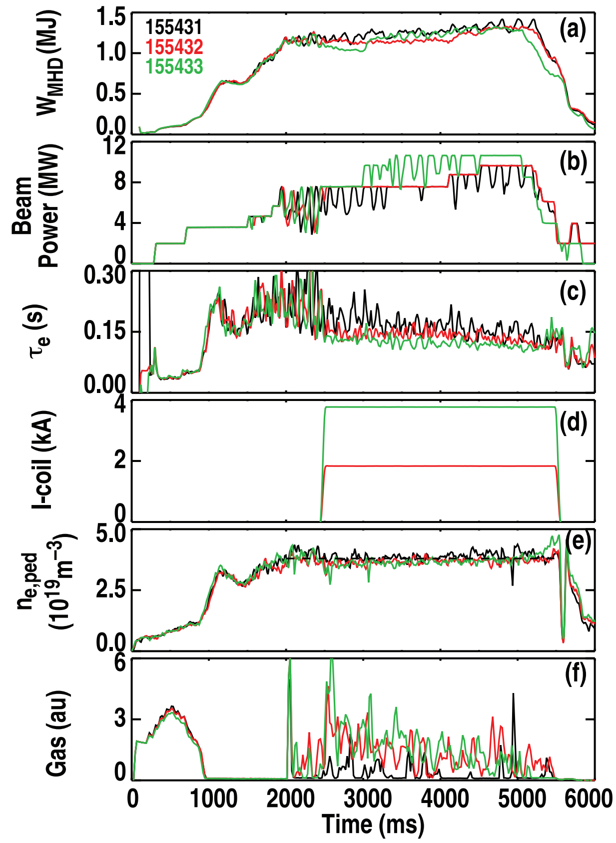
R.J. Hawryluk Figure 3



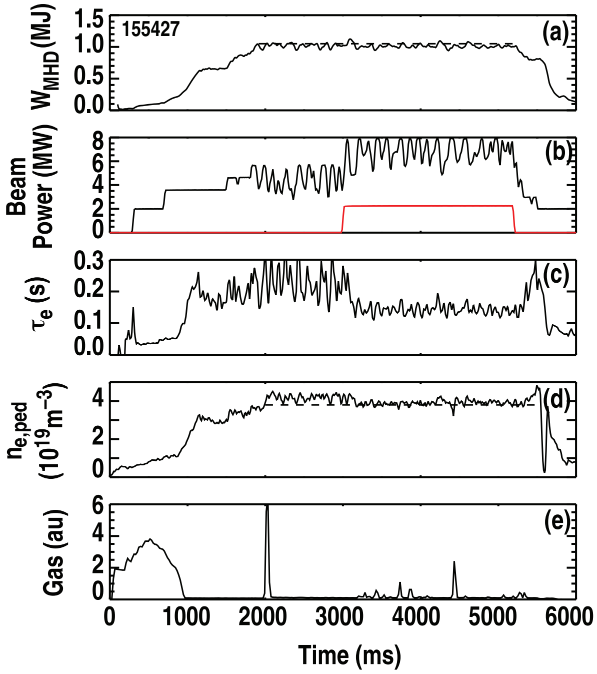
R.J. Hawryluk Figure 4



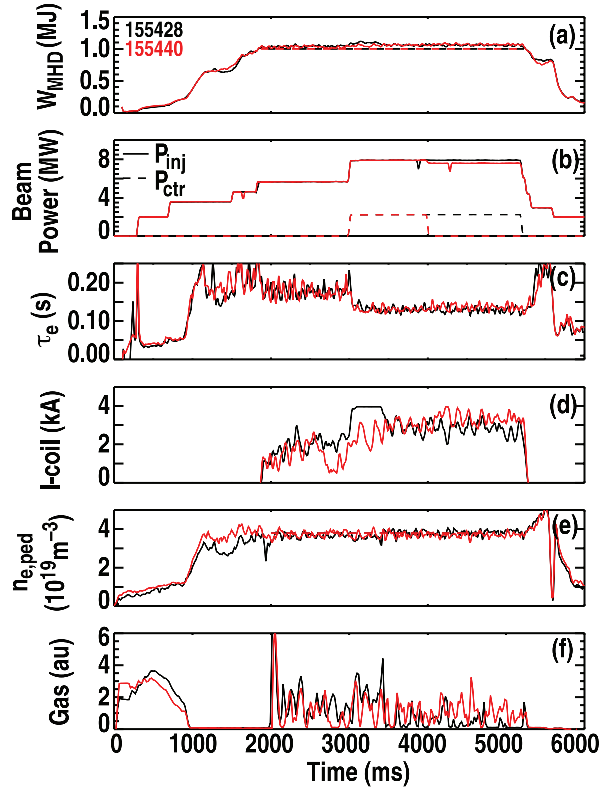
R.J. Hawryluk Figure 5



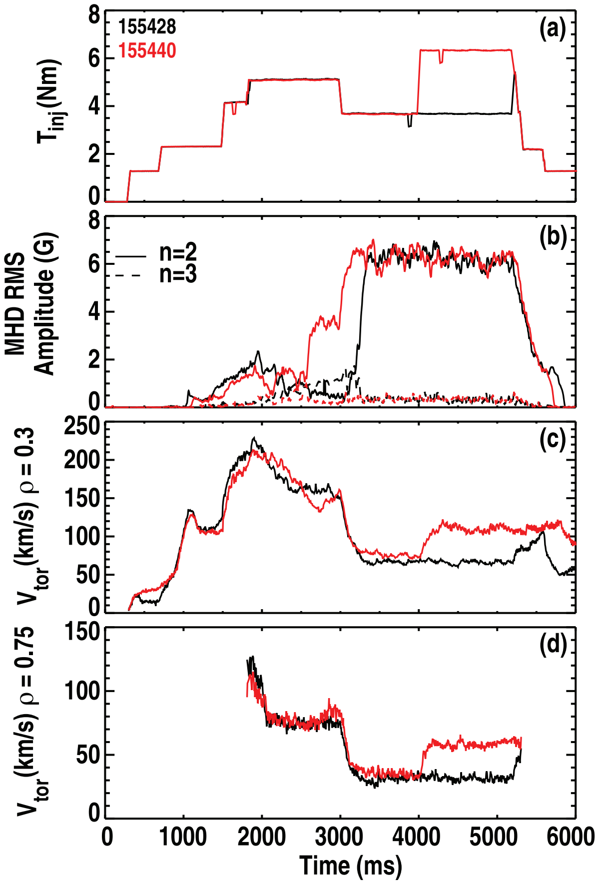
R.J. Hawryluk Figure 6



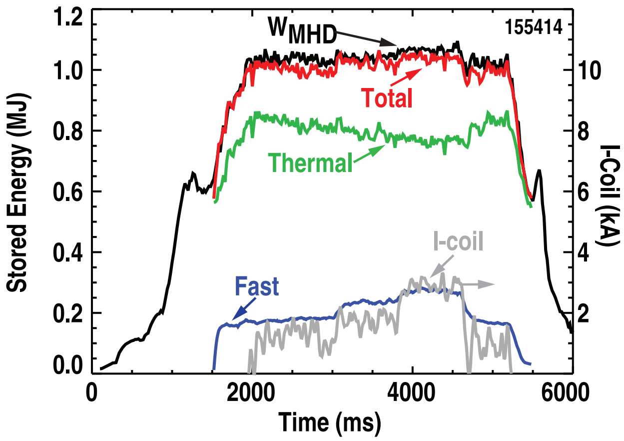
R.J. Hawryluk Figure 7



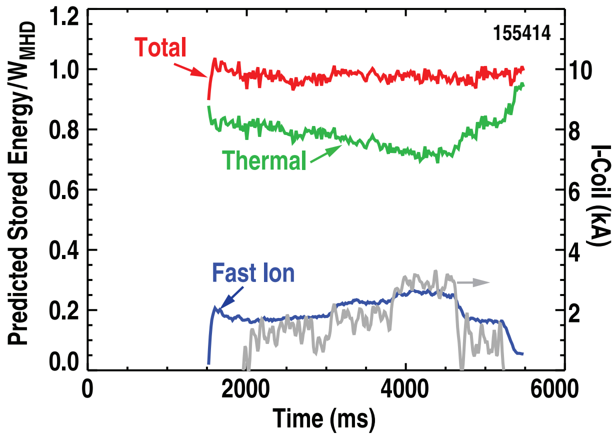
R.J. Hawryluk Figure 8



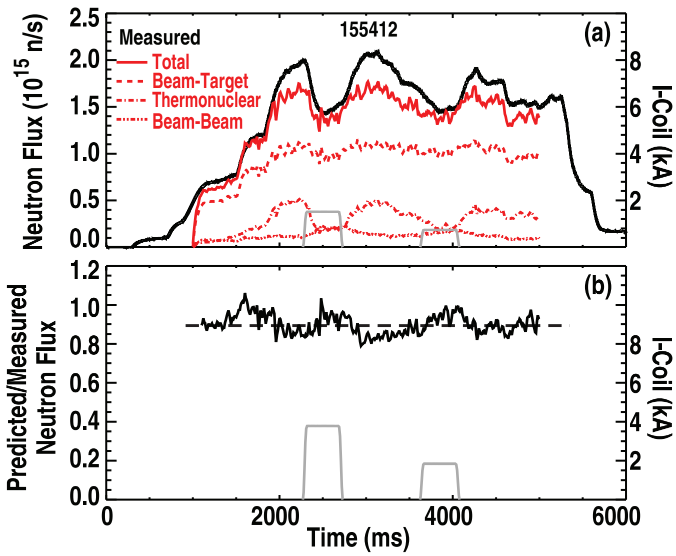
R.J. Hawryluk Figure 9



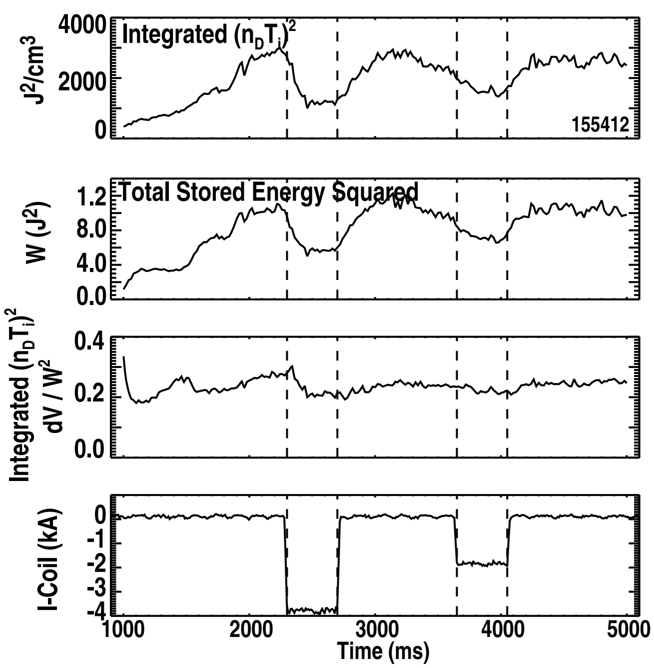
R.J. Hawryluk Figure 10



R.J. Hawryluk Figure 11



R.J. Hawryluk Figure 12



R.J. Hawryluk Figure 13

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