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Milestone Report

Status Report on High β_p Experiments at High Plasma Current

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MILESTONE REPORT

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Introduction

This report summarizes LLNL's involvement in recent high β_p experiments on the DIII-D tokamak at General Atomics. These experiments were done in collaboration with several members of the DIII-D physics staff from GA and from other collaborating institutions and could not have succeeded without this joint effort. In this report, we summary a specific, limited set of experiments to extend high β_p operation with enhanced core confinement to higher plasma currents. Our interest in these experiments stems from the non-inductive current drive requirement for steady-state advanced tokamak regimes which can most reasonably be met by operation with a high bootstrap current fraction.

Our previous high β_p experiments on DIII-D focused on low current, 0.4 MA, H-mode discharges with co-directed (along ohmic) beam injection and were characterized by on-axis safety factor $q_0 > 1$. These experiments demonstrated: 1) enhanced core confinement, with profile peaking dominated by increases in density ($\times 2$) and smaller increases (~ 20 - 30%) in electron and ion temperatures, 2) high bootstrap current fractions ($\sim 80\%$), driven by the core pressure gradient with bootstrap current peaking off-axis, and 3) access of the core to second stability for ideal ballooning [1]. For these experiments the improved confinement occurred spontaneously as the current profile broadened and q_0 increased on resistive time scales. Density peaking is indicative of a transport barrier but was limited to the core inside $r/a \approx 0.4$ and thus global confinement times did not show significant increases.

Two distinct classes of experiments have been used, one employing a ramp of the ohmic current to explore transient, high performance regimes and the other using a slow evolution of the plasma equilibrium to explore steady state concepts. Typically, the transient experiments achieved some of the highest values of β_p but were terminated with an MHD type β -limit, after which stored energy drops rapidly. Some of the more interesting high β_p discharges are achieved during a slow relaxation of the equilibrium. Since the evolution occurs on a resistive time scale, we operated mostly at lower values of plasma current, $I_p \approx 0.4$ MA, where the lower electron temperatures resulted in time constants comparable to the DIII-D discharge duration. In addition, the bootstrap and neutral-beam current drive fractions are also larger, and, because the bootstrap current profile is broader than ohmic, the total current relaxes toward a broader profile. During this period, the plasma evolves to conditions which exhibit virtually no MHD activity as the on-axis safety factor, q_0 , naturally rises from $q_0 \approx 1.2$ early in time to $q_0 \approx 3.0$ late in the discharge. Although a correlation of the q profile and MHD fluctuations with the increase in core confinement was observed, necessary and sufficient

conditions for the improved confinement were not established. This quiescent state with its slowly varying current distribution makes the high β_p operation a good candidate for future experiments involving active feedback control of the current profile.

Additional analysis relevant to the higher plasma current (I_p) experiments addressed some of the issues associated with transport [2] and fast ion confinement [3]. These investigations are summarized before we discuss results for experiments aimed at the higher current operation. The approach we followed in an attempt to extend high β_p operation to higher I_p was to use early neutral beam injection into an ohmic current ramp up to get to $I_p \approx 1$ MA, in order to get $q_0 > 1$ early in time. This was followed by a negative current ramp down to reach the desired operating current of 0.6 to 0.7 MA, without waiting for the slow evolution process.

1.0 Transport analysis at 0.4 MA

Detailed analysis of transport, including time dependence of the changing profiles, was carried out for shot 77676 [2]. Fig. 1 shows the single-fluid thermal diffusivity χ_{eff} in the core at the time of transition to improved confinement, $t = 3.36$ s, and also later in the shot after strong density peaking within $r/a \leq 0.4$ has occurred, $t = 4.01$ s. Electron χ_e and ion χ_i were similar.

Outside the core, only χ_i could be determined because of poor quality radiated power data due, in part, to the fast ion losses and the broad scrape-off layer present during this operation. These results show near ion neo-classical values in the core, increasing to $\chi_i \sim 10\chi_{i,neo}$ well outside the core.

Measurements of the current profile by means of the motional Stark effect (MSE) diagnostic indicate a monotonic q -profile. The Rebut-Lallia transport model, shown for comparison, predicts transport well above neo-classical and does not model our experiment within the core; outside the core, transport is similar to Rebut-Lallia predictions.

The results for particle diffusivity, D_e , are plotted in Fig. 2. Inside the core, D_e shows a factor two decrease at an incremental time " δ " just after the transition to high confinement. This decrease in diffusivity reflects the rapid rate of increase of central density, which is dominated by neutral beam fueling. After core density peaking, D_e is much smaller and approaches ion neo-classical values. This result may indicate a strong dependence of particle diffusivity with density.

2.0 Quiescent operation

One of the most striking characteristics of the steady-state high β_p operation is the connection between the q profile, the MHD stability and the consistency with the theoretical modeling of kink/ballooning modes [4]. Immediately after initiation of early neutral beam injection into an ohmic equilibrium with $q_0 > 1$, the plasma becomes unstable to $m/n = 2/1$ MHD modes, consistent with internal kink modes predicted by the GATO [5] code using experimentally measured pressure profiles. As the plasma relaxes on resistive time scales, the current profile broadens and q_0 gradually increases as the current density on axis decreases. The $m/n = 2/1$ mode drops in amplitude to nearly undetectable levels before converting abruptly to a $3/1$ mode when q_0 approaches 2.0. The $3/1$ mode drops in amplitude as q_0 continues to rise.

As q_0 approaches 3.0, the core electron density has been observed to double when the $3/1$ mode stabilizes, as indicated by a large decrease in the amplitude of this mode. The rapid rise in core density, and along with it the off-axis bootstrap current in the core, limits the rise in q_0 which relaxes in time to lower values. Eventually, this uncontrolled rise in bootstrap current gives way to an unstable current distribution with the on-set of MHD activity late in the shot. Typically, the modes detected are consistent with predictions from the GATO code. Two important intervals are present during these discharges in which the plasma remains in a quiescent state for several energy confinement times: $1.5 < q_0 < 2.0$ for $\delta t \approx 1.2$ seconds and $2.5 < q_0 < 3.0$ for $\delta t \approx 0.8$ seconds.

In addition to kink mode analysis of this configuration, ballooning stability analysis using the MBC [6] and Camino [7] codes was also completed. For a given current distribution, the MBC code determines the critical pressure gradient for ballooning mode instability. This analysis indicated that, during the quiescent phase, there is essentially no pressure gradient limit for the ballooning instability. The Camino code provided estimates of the regions of stability in terms of the shear vs. pressure gradient (S vs. α). Likewise, we found that the discharges that successfully evolve to a peaked density configuration exhibit profiles which have no stability limit during the quiescent phase, with the entire plasma cross-section having access to the second stable region.

From the standpoint of stability, the important consequence of these experiments is that a current density profile, i.e. $q(r)$, can be generated which is simultaneously stable to both kink and ballooning modes in a discharge dominated by bootstrap current. The evolution of plasma parameters during these times must therefore be determined solely by particle sources, heating, and transport. The rapid and uncontrolled rise in density that drives the

bootstrap current ultimately limits the duration of these discharges. This merely re-emphasizes the need for well aligned bootstrap current drive and for active control of fueling and the current density profile as we approach steady state conditions.

3.0 Fast Ion Confinement

As the major source of auxiliary heating and non-inductive current drive, adequate confinement of fast ions is essential for maximizing the performance of high β_p discharges. Understanding of this anomalous loss process is important for our efforts to extend this regime to the higher I_p conditions. To evaluate the level of fast ion confinement, measured and computed quantities such as the neutron yield, stored energy and kinetic profiles are compared. Computed quantities are determined using the ONETWO transport code and the measured kinetic profiles for the thermal electron and ion temperatures and densities.

During high power ($P_{inj} > 5$ MW), low current steady-state operation, measurements of the neutron yield and the stored energy are less than half of their predicted quantities when the full beam power is used to model the experimental results. In addition, the predicted Shafranov shift exceeds that which is indicated by both the radial electron cyclotron emission (ECE) and soft x-ray (SXR) diagnostics. These discrepancies, which do not exist during low power operation ($P_{inj} < 5$ MW), can be resolved if the injected neutral beam power for ONETWO modeling of high power discharges is reduced. The fraction of "prompt" fast ion losses is then equated with the required reduction of P_{inj} , which in some cases can exceed 50%. These losses are viewed as prompt because over 90% of the neutron yield during high β_p operation is from beam-target neutrons generated by the high energy component of the fast ion distribution function. These prompt losses are additive to the approximately 15% loss due to first-orbit and charge-exchange losses, which are modeled well by the transport code.

High β_p discharges, which contain a large fast-ion pressure component are vulnerable to collective fast particle instabilities such as Alfvén eigenmodes. These beam driven instabilities can significantly reduce the heating and current drive efficiencies by seriously depleting the fast ion distribution function. They are also of concern during long pulse operation because of the potential for excessive heating and damage to the internal hardware. Several results indicate that beta-induced Alfvén eigenmodes (BAE) [8] are the cause of poor fast ion confinement. First, a strong correlation between their presence and periods of poor fast ion confinement has been established. Second, when bursts of these modes are present, analysis from the active charge exchange diagnostic indicates that the fast ion content in the

core of the plasma is depleted. And third, the component of stored energy parallel to the toroidal magnetic field saturates and/or collapses during periods of strong BAE activity. The observed BAE activity is characterized by low toroidal mode numbers, and frequencies in the plasma frame of about 60% of the expected TAE mode frequencies.

Improved fast ion confinement has been observed under two different conditions. These include the use of lower energy neutral beams and negative I_p ramps. In the first case, several items are thought to be contributing. These include: a) a reduction of the fast ion pressure gradient resulting from a broader fast ion deposition profile, b) faster thermalization of the beam ions as a result of their slower velocity and c) a reduction in the instability drive resulting from a larger increase between the Alfvén velocity and the injected ion velocity. In addition to the improved fast ion confinement, a dramatic reduction of the Alfvén activity resulting from a decrease in the injection beam energy has been observed. Characteristic high frequency activity with toroidal mode numbers $n=3$ through $n=8$ is all but non-existent at the lower beam energy.

In the second case, peaked current density profiles ($l_i \leq 2.4$) are produced using negative inductive ramps. The level of fast ion loss ($\sim 10\%$) remains low as long as the edge current density is negative. This excellent fast ion confinement phase lasts for up to five thermal energy confinement times following the completion of the ramp. The overall performance of these discharges reaches record levels: $\beta_p = 5.0$, $\epsilon\beta_p = 1.5$, $\beta_N = 3.5$, and $\tau_E/\tau_{ITER-89P} = 2.5$. Following this high confinement phase, the level of fast ion loss increases to $\sim 50\%$ as the edge current density becomes positive and the central current density profile relaxes (l_i decreases) on a resistive time scale. The contrast in fast ion confinement and thermal plasma performance between high and low l_i conditions illustrates the importance of current profile control in obtaining high performance during high β_p operation.

4.0 Operation at higher I_p

The large bootstrap fraction demonstrated for the high β_p experiments at 0.4 MA are quite attractive for an advanced tokamak reactor because of greatly reduced requirements on non-inductive current drive. However, higher plasma current (lower edge q) is necessary to further increase confinement and to provide acceptable beta limits. Following the low I_p experiments, we tried to extend the results to more reactor relevant, higher current discharges. Consequently, experiments were done at higher current using early beam injection during current ramp-up, followed by ramp-down to a lower final value. Based on the favorable results seen with $q > 1$ at lower current, this technique was used in an attempt to achieve $q_0 > 1$ early in the

discharge to avoid the very slow resistive profile relaxation at higher current expected for the higher electron temperatures.

The achievement of $q_0 > 1$ by this technique is shown in Fig. 3 for a 0.6 MA discharge. For this discharge, moderate core peaking of density and electron temperature was observed during the indicated interval $t=1.8-2.9$ s and the increase in the core electron pressure profile during this interval is shown. At this current, profile peaking occurred within the same volume as observed at lower current, i.e., within the footprint of the injected neutral beams which peaked on-axis for the relatively low edge densities of these experiments ($n_{\text{edge}} \leq 3 \times 10^{19} \text{ m}^{-3}$). Although these experiments did show core peaking for several shots at currents of 0.6-0.7 MA, the results were not reproducible, perhaps due to wall conditioning at the time of these experiments, and a clear correlation with q variations was not established. Bootstrap current fractions were modest ($\sim 40\%$) and we were not successful with beam heating at high power into a core-enhanced discharge.

Other experiments with counter-directed (opposite ohmic) beam injection have been carried out on DIII-D for other purposes. These experiments did include the high β_p regime and we analyzed data from these discharges for comparison with the co-injection experiments. Counter-directed neutral beam injection experiments were done in DIII-D with the objective of controlling the radial electric field (E_r) shear. This would alter the transport within the plasma through $\mathbf{J} \times \mathbf{B}$ forces produced by radial currents driven by rapid losses of fast ions injected onto bad orbits [9]. Plasma discharge currents of 0.4 and 1.0 MA were investigated. The 0.4 MA shots were high β_p discharges and their investigation provided interesting comparisons with the co-directed beam injection experiments already discussed.

The counter-injection discharges showed enhanced core confinement equal to, or somewhat better than, the results for co-injection. In Fig. 4 we plot several time dependent parameters to compare both co-(77676) and counter-injection (82059) results. Injected beam power was greater for 82059, but, when fast ion first orbit losses are taken into account ($\sim 40\%$ losses for counter-injection compared to $\sim 10\%$ losses for co-injection), the net beam power was actually smaller during counter-injection. For the counter-injection discharge, electron density increased much more rapidly and to a higher value. Neutrons peaked early in the discharge and then decreased, at least in part due to increasing density and decreasing T_e which reduce slowing down times. A noteworthy characteristic of these discharges was the reproducibility of the improved confinement. Similar to shot 77676, the peaking of the core pressure profile produced a large internal bootstrap current ($\sim 80\%$). Both co- and counter-injection plasmas showed significant

spin up of the toroidal velocity in the core; on-axis toroidal velocity reached $3 \times 10^5 \text{ m-s}^{-1}$ for counter and $2.3 \times 10^5 \text{ m-s}^{-1}$ for co-injection condition.

Production of a current profile with small but reversed central shear (RCS) appears to be a natural result of counter-injection. This occurs because the centrally peaked beam driven current was of opposite sign to the initially established ohmic current and produced a hollowing out of the total current profile. A comparison of the q profiles for both co- and counter-injection discharges is shown in Fig. 5. The much flatter central q profile is evident for counter injection. Both shear in the radial electric field, controlled by toroidal rotational flow and plasma pressure gradients, and RCS are believed to be important for plasma stability and transport. Further analysis to evaluate the magnitudes of E_r shear for these shots, may provide insight into the relative role of E_r shear and RCS for transport in these discharges. These experiments are relevant to on-going experiments in DIII-D with RCS, a leading candidate for an advanced tokamak reactor.

5.0 Proposed high β_p counter injection experiment

The objective of this experiment is to investigate enhanced core confinement using counter-injection neutral beams at higher current, where better confinement and higher beta are expected. An advantage of counter-injection is the natural occurrence of an RCS profile. Previous experiments with counter-injection investigated discharges at 0.4 and 1.0 MA. At 0.4 MA edge density was low and, as described above, the characteristics of this configuration were high bootstrap current fractions, strong core peaking, a RCS current profile, and strong core spin-up. Enhanced core confinement in these discharges was much more reproducible than the co-injection experiment (77676). The experiments at 1.0 MA did not show enhanced confinement in the core, but edge density was high which prevented good beam penetration to the plasma core.

The proposed experiment would investigate confinement with plasma currents above 0.4 MA. Key requirements for the experiment are:

1. Edge density must be kept low, at higher current, to insure core beam penetration. If high edge density prevents good beam penetration for H-mode, an L-mode discharge can be used to keep edge density low.
2. Close attention must be paid to outer wall heating because of large first orbit losses, particularly as beam pulse lengths are extended. This may be less of a problem at higher current where banana orbits widths are smaller.

A follow-on experiment could be done with hydrogen neutral beams if excellent results are obtained with deuterium. Even though confinement would probably decrease for hydrogen compared to deuterium, the effective beam efficiency should be much greater since banana widths in hydrogen are

less (much smaller bad orbit losses, estimated at $\sim 10\%$) and beam penetration is greater at higher density (about $\times 2$ greater line density with H).

6.0 Summary

The low plasma current experiments resulted in very dramatic peaking of the core plasma density accompanied by smaller increases in the electron and ion temperatures inside $r/a = 0.4$. These experiments provided evidence for the possibility of advanced tokamak operation at very high bootstrap current fractions, 80%, with extended periods of time essentially free of MHD fluctuations. Limiting factors for this mode of operation at low current are its susceptibility to fast ion losses ($\sim 50\%$) and the limited increase in global confinement time due to localization of the density peaking to the core region.

In order to improve the global confinement time, β limits, and fast ion confinement, we performed experiments directed at demonstrating high β_p , enhanced confinement operation at higher plasma currents. This mode of operation is complicated by the fact that improved confinement associated with the higher I_p results in higher electron temperatures giving resistive evolution times exceeding the DIII-D shot duration. Thus, merely waiting for the (slower) evolution to peaking of the density profile is not possible as was the case at $I_p = 0.4$ MA. We thus used a combination of early neutral beam timing with current ramping to "freeze in" the desired current distribution and we obtained limited success in that some profile peaking was observed but not as spectacular as observed at the lower plasma current. In table 1, we summarize the status of our high β_p experiments to date.

We are continuing to analyze these results and model the temporal evolution using the Corsica code at LLNL. Recent analysis of the high β_p configuration indicates the importance of understanding and controlling the fueling and current profiles. It has also pointed to a possible relationship to the reversed central shear configuration that has apparent advantages for stability and is being pursued as one of the attractive options for an advanced tokamak reactor. Due to its operation with $q_0 > 1$ and well behaved temporal variations of $q(r)$, future high β_p experiments are currently scheduled for the development and demonstration of active q -profile control. We will continue to explore the role of high β_p for its high bootstrap fraction characteristics and its relationship to reverse shear operation.

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Table 1. Status of high β_p experiments

Motivation: Obtain AT operating scenario -large bootstrap fraction (reactor economics), good confinement and beta limits.

The following experiments transiently showed an enhanced core n or T - the increased core pressure gradient can drive large bootstrap currents.

Experiment	Main results	Important issues/problems
1993 - Constant current evolving discharge (e.g. 77676, 0.4 MA)	<ul style="list-style-type: none">• $2 < q_0$• slow core increase• core D_e and χ_{eff} near neoclassical, second stable access• high bootstrap - $\sim 80\%$	<ul style="list-style-type: none">• not easily reproducible• fast ion losses• is enhancement q_0 related?• need to raise current
1994 - Increase current - (I_p ramp up/down to 0.6-0.7 MA)	<ul style="list-style-type: none">• $1.5 < q_0 \leq 2$• slow core pressure increase for few shots	<ul style="list-style-type: none">• not easily reproducible or robust?• is enhancement q_0 related?
1994 - Counter NB injection (-0.4 MA)	<ul style="list-style-type: none">• $1 < q_0 < 2$• rapid core increase to parameters like 77676• seems to show weak reversed central shear	<ul style="list-style-type: none">• discharges reproducible• large bad orbit losses in D (leads to short duration?)• is enhancement q_0 related?

Figure 1. Thermal diffusivity during enhanced core confinement in high β_p discharge 77676.

Figure 2. Particle diffusivity during enhanced core confinement in high β_p discharge 77676

Figure 3. High β_p (≈ 2) core profile peaking at $I_p = 0.6$ MA.

Figure 4. Comparison of q profile for co- and counter-injection of neutral beams during enhanced core confinement at $I_p = 0.4$ MA.

Figure 5. Comparison of co-(77676) and counter-injection (82059) discharge parameters at $I_p=0.4$ MA.