SOLENOID-LESS PLASMA START-UP IN NSTX USING TRANSIENT CHI

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Experiments in NSTX have now unambiguously demonstrated the coupling of toroidal plasmas produced by the method of transient Coaxial Helicity Injection (CHI) to inductive sustainment and ramp-up of the toroidal current. The coupled discharges have ramped up to 700 kA and transitioned into H-mode with low inductance typical of the type of discharges needed for long-pulse operation, demonstrating the compatibility of the CHI startup method to conventional inductive operation used since the start of tokamak research. The method was first demonstrated on the smaller concept exploration device HIT-II at the University of Washington. These new results that were obtained on a machine built with mainly conventional components and on a size scale closer to a Component Test Facility, demonstrate that CHI is a viable solenoid-free plasma startup method for future STs and Tokamaks.

I. INTRODUCTION

A method to start a tokamak plasma without reliance on the central solenoid would provide greater access to lower aspect ratio configurations and reduce reactor cost as a result of a simpler design. The benefits on plasma performance improvement as a result of operating at lower aspect ratio are now well known [1,2]. At extreme low values of the aspect ratio, such as in a spherical tokamak (ST) based reactor, due to the very restricted space for the central solenoid, elimination of the central solenoid is necessary [3]. Coaxial Helicity Injection (CHI), a method originally developed for spheromak formation [4] is a promising candidate for solenoid-free plasma startup and for edge current drive during the sustained operating phase. The possibility of using CHI in an ST was first proposed in the late 1980's [5]. At that time, it was generally believed that the development of non-axisymmetric perturbations of the plasma equilibrium was needed for plasma startup using the CHI process in STs. This approach was initially investigated in NSTX and in several other STs. However, in a significant development during the past few years, it was shown that for the purpose of plasma startup, axisymmetric reconnection can produce a high quality startup equilibrium. This method referred to as *transient* CHI was first demonstrated on the HIT-II experiment at the University of Washington [6]. Using this method, solenoid-free plasma startup and subsequent coupling to conventional inductive drive has now been successfully demonstrated on the NSTX device as well.

II. IMPLEMENTATION OF CHI IN HIT-II AND NSTX

On the concept exploration HIT-II device and on the Proof-of-Principle NSTX device, CHI is implemented by driving current along externally produced field lines that connect the inner and outer vacuum vessel components in the presence of externally generated toroidal and poloidal magnetic fields. Figures 1 and 2 show the similarities and differences between the CHI systems on HIT-II and NSTX.

HIT-II (Figure 1) has a major/minor radius of 30/20 cm with a toroidal field at the machine mid-plane of up to 0.5 T, at an elongation of 1.7. The plasma volume is about 0.5 m^3. The outer vessel is fabricated out of 6 mm thick stainless; with the plasma facing side coated with 0.03 mm plasma sprayed tungsten. The inner vessel components including the center stack are fabricated out of 3.5 mm thick stainless steel and the plasma facing side is covered by a 12.5 mm thick graphite shield.

NSTX has a major/minor radius of 0.86/0.68 m, a typical plasma volume of 14 m^3 (about 30 times that of HIT-II) and a maximum plasma elongation of 3. As shown in Figure 2, NSTX is designed much like any other tokamak. Compared to HIT-II, there are fewer poloidal field coils. These coils are located about 0.5 m away from the plasma boundary and have a slower time response. Furthermore, there is no specific injector, rather the lower divertor plates are used as the injector. A single power supply powers the entire central solenoid. The typical time for flux to penetrate the NSTX outer vessel is about 10 ms, for HIT-II it is less than 0.5 ms for the outer shell and less than 0.2 ms for the inner shell. All plasma facing components in NSTX are composed of graphite tiles.

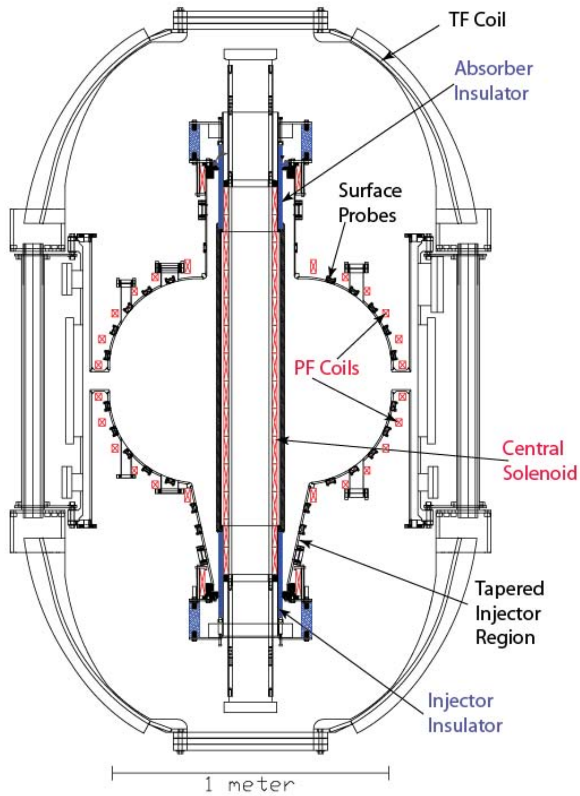

Figure 1: Layout of the HIT-II ST. 14 close fitting poloidal field coils are mounted close to the outer shell. The tapered region is used as the injector for discharge initiation. 4 close fitting poloidal field coils in this region are used to generate the injector flux that connects the tapered region (the anode) with the vertical region (the cathode). Two long toroidal ceramic insulators are used to electrically separate the inner and outer vessel regions. For plasma initiation, HIT-II uses two plasma injectors installed in the conical region [7].

II.A. Differences and Similarities between CHI Startup in NSTX and HIT-II

Some of the important differences between the two machines are: (a) The poloidal field in the HIT-II absorber region is actively controlled to minimize the poloidal flux that intersects the upper electrodes. This significantly minimizes the extent of absorber arc current during a CHI discharge, (b) HIT-II uses titanium gettering as a wall conditioning technique, whereas NSTX uses conventional He and D_2 glow discharge cleaning and more recently Lithium is being developed as a wall conditioning technique (c) the outer electrode on HIT-II is metallic, and the graphite inner electrode is aggressively conditioned using high current CHI discharges to remove surface contaminants, (d) in NSTX there is no specially

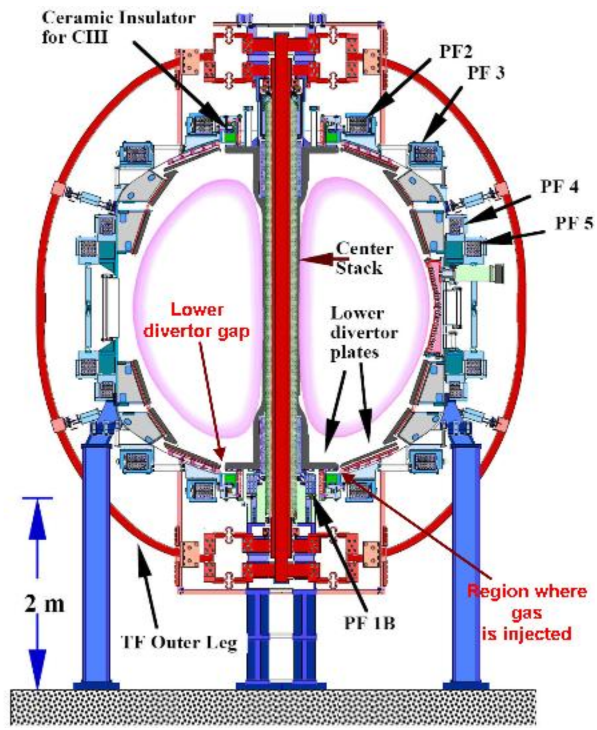

Figure 2: Layout of the NSTX machine. The outer PF coils are labeled PF2 to 5. The PF1B, present only in the lower divertor region, is used in combination with the PF2-lower coil to generate the injector flux. This produces poloidal flux that connects the lower inner and outer divertor plates. Two toroidal insulators (at the top and bottom of the machine) are used to electrically insulate the inner and outer vessel components. As shown in the figure, gas in injected in the region below the lower divertor plates. Below the gap in the lower divertor plates is an enclosed region so that all of the gas injected into this region must exit through the lower divertor gap.

designed injector, rather the divertor plates are used as electrodes, and (e) CHI discharges on HIT-II use capacitor banks charged up to 4 kV, whereas the voltage on NSTX is limited to 1.7 kV. Finally the PF coils on HIT-II are close fitting and fast acting.

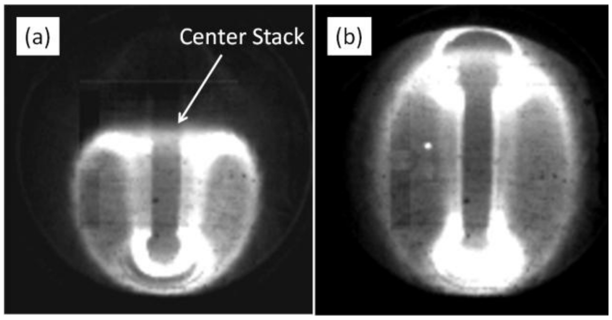

Figure 3: Fast camera fish eye images of a transient CHI discharge in NSTX (a) the image 0.9 ms after the capacitor bank is discharged shows a discharge evolving from the lower injector region. The dark cylindrical object in the middle is the NSTX center stack, (b) an additional 0.6 ms later, the CHI produced plasma has more fully filled the vessel. The dark region is the region carrying closed flux plasma current.

On both machines a CHI discharge is initiated by first energizing the toroidal field coil and then the poloidal field coils located near the injector region to generate poloidal flux that connects the injector electrodes. On HIT-II four close-fitting coils, as shown in Figure 1, are used to precisely shape the injector flux. On NSTX, two main coils near the injector region provide the required injector flux. Gas (plasma in HIT-II) is then injected into the injector region. This is followed by discharging a small capacitor bank across the injector electrodes. HIT-II uses a 0.5 – 4 mF capacitor charged up to 4 kV, whereas NSTX uses a 5 to 45 mF (typically 10 – 15 mF) capacitor charged to 1.7 kV. This results in an injector current, which is the current provided by the discharging capacitor that flows through the plasma load, of about 10 to 30 kA in HIT-II (for < 1 ms), and a current of about 1.5 – 5 kA (for < 3 ms) in NSTX. These currents are in the range required to meet a condition known as the 'bubble burst' condition. This condition requires that the injector current exceed a threshold value needed to overcome the poloidal field line tension of the injector flux. As this condition is satisfied the injector flux expands into the vessel and fills the vessel as shown by the fish-eye camera images in Figure 3. The size of the capacitor bank is chosen so as to provide adequate energy for the injected current to be maintained for the duration needed for the growing CHI discharge to fill the vessel. At about the time the CHI plasma fully fills the vessel, most of the capacitor bank energy is depleted, which causes both the voltage appearing across the injector and the injector current to rapidly diminish. On NSTX this reduction in the injector current is further improved by using an actively switched ignitron that short-circuits the capacitor through a small resistive load. If the injector flux footprints are sufficiently close together in the injector region, then because the injector current is no longer able to drive the CHI plasma load, the expanded CHI plasma detaches from the injector region through a process of axisymmetric reconnection near the injector region producing a closed flux equilibrium that now decays on a resistive L/R time scale.

An important difficulty when the transient CHI method was first tried on NSTX is that breakdown could not be attained unless the amount of injected gas exceeded about 10 Torr-liters. At this level of gas injection there was insufficient energy in the small capacitor bank to fully ionize and heat the resulting CHI plasma. Thus these plasmas quickly decayed away and the plasma current did not persist beyond the time duration of the injector current. HIT-II avoided this issue by directly injecting pre-ionized plasma using the plasma guns, which allowed a discharge to be initiated with relatively small amounts of injected gas. To overcome this issue, the gas injection location on NSTX was modified so that gas could be injected into a cavity region below the lower divertor plates. This caused the injected gas to emerge from the gap region between the lower divertor plates. Initial experiments also benefitted from the injection of 10 kW of Electron Cyclotron Heating at 18 GHz, which was also injected into the cavity below the lower divertor plates in an attempt to pre-ionize the injected gas to simulate conditions of the plasma gun sources used on HIT-II. This technique worked well, and allowed NSTX to demonstrate plasma current persistence [8]. As the charging voltage on the capacitor bank was increased above 1.6 kV, it was found that reliable discharges could be obtained without reliance on the ECH-Pi. During 2008, none of the CHI initiated discharges relied on ECH-Pi. Current persistence is a condition when the CHI produced plasma current persists after the injector current has been reduced to zero. This persistence can only be possible as a result of the L/R decay of a closed flux equilibrium. During 2008, it is this closed flux plasma that was coupled to induction to demonstrate coupling to standard inductive drive to show compatibility between CHI and the well established conventional inductive current drive method.

III. EXPERIMENTAL RESULTS

In Figure 4, we show traces for the injector current, the plasma current, and the applied inductive loop voltage for two CHI started discharges that were coupled to induction. In these discharges approximately 3 kA of injector current produces about 100 kA of toroidal current initially. During the decay phase of this current, induction is applied from the central solenoid by ramping its current from zero with a rectifier power supply with an open-circuit voltage of 4 kV. The decrease in the applied loop voltage over time is due to resistance in the central solenoid circuit. The external poloidal field coil currents needed for equilibrium are pre-programmed during the first 40 ms of the discharge. After that the standard NSTX plasma control system [9] is used to control the plasma radial and vertical position, using real-time data from external flux loops and magnetic probes. This causes the decaying plasma current to ramp-up, reaching a peak value of 700 kA for shot 128401. In these discharges, starting at about 40 ms, neutral beams are also injected at

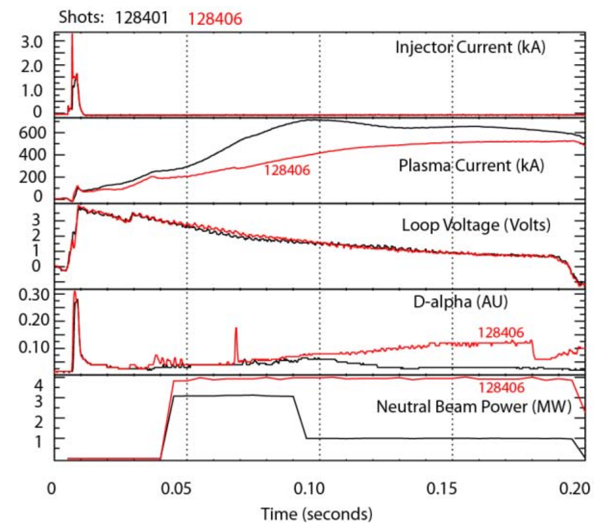

Figure 4: The CHI injector current, plasma current, applied loop voltage, D_α signal and the neutral beam power for an L-mode discharge (128401) and for a discharge that transitioned to an H-mode at 175 ms (128406). Both discharges have different gas programming.

a power of 3 - 4 MW to heat the plasma. During the neutral beam heating, discharge 128406 transitions into an H-mode at 175 ms. Evidence of the H-mode is the characteristic drop in divertor D_α emission (Figure 4) and the development of a broad electron density (N_e) profile measured by the Thomson scattering diagnostic (Figure 5). Figure 5 also shows the electron temperature (T_e) and electron density from Thomson scattering for discharge 128401 that did not transition to an H-mode. The fact that a CHI initiated discharge is able to transition to a discharge that has features suitable for a high-performance long-pulse operation bodes well for the application of this startup method to future machines.

Initial attempts to add inductive drive to CHI initiated discharges resulted in no increase in the plasma current. However, in these discharges there was a significant increase in the O-II emission when the loop voltage was applied. It was not until extensive conditioning was performed in the form of D_2 glow discharge cleaning (GDC) and electrode discharge conditioning that the plasma current could be increased by induction. Observation in NSTX is that as the size of the capacitor bank is increased above 10 mF, the radiated power signal approaches the input Ohmic power even though the CHI produced plasma current increases.

This increase in the radiated power signal is correlated with large increases in the oxygen and carbon line radiation signals. These signals increase because with a larger power supply the magnitude of the injector current increases. At a higher level of injector current more of the electrode surface contaminants are liberated into the plasma and contribute to increased energy losses during startup. With a larger capacitor bank part of the bank current not required to drive the primary plasma load flows along the surface of the upper insulator, in a condition referred to as an absorber arc, which provides an additional source of impurities. Future experiments in

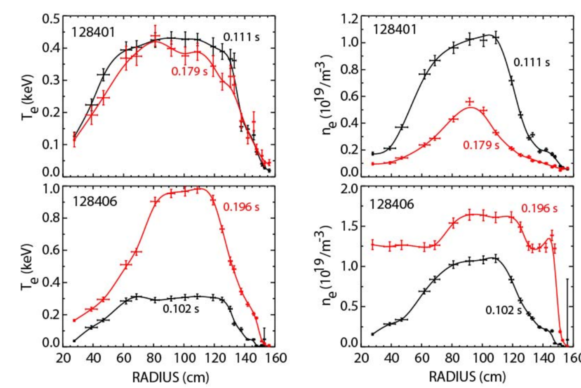

Figure 5: Electron temperature and density profiles from Thomson scattering diagnostic for the discharges shown in Fig. 4. The discharge that transitioned in to a H-mode reached central Te of 1 keV.

NSTX will use newly installed field control coils in the absorber region to minimize the poloidal field that connects the upper absorber electrodes to minimize this condition, as demonstrated on HIT-II.

As demonstrated in experiments on HIT-II [6], a CHI discharge cannot couple to induction if the radiated power approaches the input Ohmic power. For these plasmas with about 3 – 4 V of applied loop voltage and at a plasma current of 100 kA, the input Ohmic power is less than 300 – 400 kW during the inductive coupling phase. Thus it is essential that during the startup phase that either (a) the radiated power be kept low or (b) some form of auxiliary heating system such as Electron Cyclotron Resonance Heating be used to heat the target plasma.

During startup, because the plasma temperature is less than 20 eV the dominant radiation comes from low-Z impurities such as carbon and oxygen. For the graphite divertor plates used in NSTX, it is essential that surface contaminants be significantly reduced. On HIT-II which used graphite for the center stack and tungsten-coated stainless steel for the outer vessel, even with 30 kA of injected current the radiated power could be kept lower than the input Ohmic power [6], and because of this HIT-II discharges initiated by CHI showed significant savings of the inductive flux required to reach a given plasma current. A corresponding saving of inductive flux has not yet been reliably demonstrated in NSTX. For the near term, low-Z impurity radiation could be reduced on NSTX through an extensive high-current electrode discharge cleaning effort to remove impurities, notably water, from the graphite tiles in the injector. On NSTX, the highest electron temperature CHI discharges are associated with lower spectroscopic signals from oxygen lines. This in combination with the fact that HIT-II had a carbon cathode and was able to operate at much higher electrode current densities [10,6] than NSTX does also point to oxygen, rather than carbon, as the impurity of concern. Additionally newly installed coils in the upper divertor region will be used to eliminate the absorber arcs which also contribute impurities. Finally, a 350 kW ECH system capable of heating the startup plasma will be implemented on NSTX during 2010. With these techniques, NSTX discharges should be able to achieve reductions in the inductive flux consumption.

However, it is useful to note that for a reactor that has no central solenoid, the essential requirement for start-up is that solenoid-free started currents be capable of coupling to an alternate non-inductive current drive system, and this can be made easier using additional heating sources. Additionally future machines are likely to use metal rather than carbon over a large part of the divertor plates to reduce tritium retention and this may reduce radiation from low-Z impurities during plasma startup. Evidence for this comes from spheromak experiments using metal electrodes that have reached 500 eV electron temperatures [11].

For a method to be viable for solenoid-free plasma startup it is beneficial if the plasma parameters are similar to those produced using the conventional inductive technique; as this allows previously developed techniques for non-inductive ramp-up and sustainment of inductive plasmas to be easily adapted to the new startup method. A direct comparison of the current decay rate of CHI and inductively produced plasmas on HIT-II, as shown in Figure 2 of Reference 10, shows that with clean electrodes CHI can produce plasmas of quality similar to that produced using induction from the central solenoid. On HIT-II the electron temperature and density of CHI generated plasmas is in the range of 20 to 40 eV and 0.5-1.2×10^{19} m^{-3} respectively [6]. These are similar to the plasma parameters of 100 kA plasmas generated using inductive startup in HIT-II. On NSTX, the highest electron temperature of CHI produced plasmas is in the range of 10-30 eV, but usually it is 20 eV or less. With a more aggressive electrode conditioning effort or preferably with the use of metal divertor plates NSTX CHI discharges should be able to increase the electron temperature of CHI stared plasmas. The electron temperature of these plasmas could also be increased using an auxiliary heating system and there are plans on NSTX to add a 350 kW electron cyclotron heating system. The electron density of the CHI discharges in NSTX is about $1\text{-}5\times10^{18}$ m^{-3}. The Z-effective of these plasmas has not been measured; however, as long as the plasmas couple to a current ramp-up system, the Z-effective of the initial startup plasma should not be an important parameter. Indeed in NSTX and HIT-II if the radiated power approaches the inductive input power, which is about 200-400 kW, current ramp-up using induction is not possible. The CHI driven phase on NSTX is less than 3 ms. Thus on the time scales of non-inductive current ramp-up and sustainment (>100 ms), any impurities will likely diffuse out of the plasma in a few particle confinement times. Thus the ability to ramp-up the current in a CHI started discharge and its eventual transition to an H-mode means that the impurity levels are at an acceptable level. The use of high-Z electrode materials and auxiliary heating power further ease the requirements for current ramp-up of CHI started discharges.

Although in the present experiment the CHI started discharge has been coupled to induction, eventually it is necessary for this discharge to be directly coupled to neutral beams and radio frequency current drive. NSTX is pursuing this goal in two steps. The first step attempts to produce a CHI started discharge and couples it to induction, as demonstrated here, to show compatibility of CHI with the conventional startup and current ramp-up method. In parallel, there is an on-going effort on NSTX to produce a 200-300 kA inductive discharge and to couple it to High Harmonic Fast Wave (HHFW) current drive. Once this has been accomplished and the CHI started currents are increased to about the 200 kA level, the intermediate inductive step would be removed and the techniques developed for ramping a 200 kA inductive plasma using HHFW will be directly applied to the CHI target and further improved. There are also plans to increase the magnitude of the toroidal field in NSTX to 1 T. This is an important advantage for coupling CHI started discharges to NBI and HHFW, because, at the higher toroidal field the scaling for CHI discharges predicts a factor of two increase in the toroidal current as the toroidal field is doubled from the present ~0.5 T to 1

T. Additionally, recent work on NSTX shows improved coupling of HHFW to the plasma [12] at higher values of the toroidal field. In addition the HHFW system itself is being upgraded to a double feed antenna configuration. This should in principle increase the HHFW power coupled to plasma discharges. All these bode well for CHI start-up and non-inductive current ramp-up studies in NSTX.

IV. SUMMARY AND CONCLUSIONS

Using the method of transient CHI in NSTX, 160 kA of closed-flux toroidal current has been produced. Now, for the first time in NSTX, CHI started discharges have been successfully coupled to induction to show compatibility between CHI started discharges and the conventional inductive approach. While results similar to this have been previously demonstrated on the smaller HIT-II experiment, this is the first such demonstration on a large ST with a poloidal field configuration more prototypical of a compact ST reactor such as the Component Test Facility (CTF). Another significant new result is achieving a current multiplication factor up to 70, which is an order of magnitude larger than achieved in HIT-II and suggests a favorable scaling of the technique with machine size. The transitioning of the CHI-produced discharges in NSTX to a high confinement H-mode with low plasma inductance demonstrates the potential for the application of this method to future machines.

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REFERENCES

1. Y-K M. PENG, *Plas. Phys. Cont. Fus.,* **47** B263 (2005)
2. M.G. BELL, R.E. Bell, D.A. GATES, et al., *Nuclear Fusion*, **46**, S565-S572 (2006)
3. F. NAJMABADI, and the ARIES Team, *Fusion Eng. Design*, **41**, 365 (1998)
4. C.W. BARNES, et al., Physics Fluids **29**, 3415 (1986)
5. T.R. JARBOE, *Fusion Technol.,* **15**, 7 (1989)
6. R. RAMAN, T.R. JARBOE, W.T. Hamp, *Physics Plasmas* **14**, 022504 (2007)
7. D.J. DEN HARTOG, D.J. CRAIG, G. FIKSEL, and J.S. SARFF, *Plasma Sources Sci. Technol.* **6**, 492 (1997)
8. R. RAMAN, B.A. NELSON, M.G. BELL, et al., *Phys. Rev. Lett.,* **97**, 175002 (2006)
9. D. GATES, et al., Nuclear Fusion 46, 17 (2006)
10. R. RAMAN, T.R. JARBOE, R.G. O'NEILL, Nucl. Fusion **45**, L15-L19 (2005)
11. B. HUDSON, et al., Physics Plasmas **15**, 056112 (2008)
12. J. HOSEA, R.E. BELL, B.P. LeBLANC et al., Phys. Plasmas 15, 056104 (2008)