Progress on CHI Plasma Start-up and MGI Experiments on NSTX

R. Raman[1], T.R. Jarboe[1], B.A. Nelson[1], D. Mueller[2], S.C. Jardin[2], C.E. Kessel[2], D.P. Stotler[2],
T. Abrams[2], M.G. Bell[2], S.P. Gerhardt[2], S.M. Kaye[2], B.P. LeBlanc[2], J.E. Menard[2], M. Ono[2],
E.B. Hooper[3], V.A. Soukhanovskii[3], and the NSTX Research Team
[1]*University of Washington, Seattle, USA*
[2]*Princeton Plasma Physics Laboratory, Princeton, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, USA*

Transient Coaxial Helicity Injection (CHI) in NSTX has generated toroidal plasma currents up to 300 kA. When induction from the central solenoid is then added to these discharges they maintain up to 300 kA additional current compared to discharges initiated by induction only. CHI initiated discharges in NSTX achieved 1 MA of plasma current using 65% of the solenoid flux of standard induction-only discharges. The CHI-initiated discharges have low plasma density and normalized internal plasma inductance of 0.35 through the inductive ramp, typical of advanced scenarios planned for future STs. The Tokamak Simulation Code (TSC) has been used to understand the scaling of CHI generated toroidal current with variations in the external toroidal field and injector flux. These simulations show favorable scaling of the CHI start-up process with increasing machine size, consistent with theory. Scaling based on the analysis of experimental results and TSC simulations indicates the possibility for substantial current generation by CHI in the upgrade to NSTX, which is now under construction. These results demonstrate that CHI is a viable solenoid-free plasma startup method for future STs. In support of ITER disruption mitigations studies, we are using the DEGAS-2 Monte Carlo code to optimize Massive Gas Injection (MGI) systems for NSTX-U. These would allow for a comparison of the benefits of injecting gas from the lower divertor region into the private flux region and the high field side region versus injection from the conventional mid-plane region.

Plasma Start-up: Tokamaks and spherical tokamaks (STs) have relied on a central solenoid to generate the initial plasma current and to sustain that current against resistive dissipation. However, a central solenoid cannot be used for plasma current sustainment indefinitely. The inclusion of a central solenoid in a tokamak for plasma start-up alone limits the minimum aspect ratio and adds cost and complexity. For reactors based on the ST concept, elimination of the central solenoid is necessary so alternate methods for plasma start-up would be needed.

CHI research on NSTX initially used the method of *driven* or *steady-state* CHI for plasma current generation [1]. Although substantial toroidal currents were generated using the steady-state approach, it was found that these discharges could not be successfully ramped up in current when induction was applied. Supporting experiments on the HIT-II experiment at the University of Washington demonstrated that the method of *transient* CHI could generate high-quality plasma equilibrium in a ST that could be coupled to inductive drive [2]. Since then the transient-CHI method has been successfully applied to NSTX for solenoid-free plasma start-up followed by inductive ramp-up [3]. These coupled discharges have now achieved toroidal currents >1 MA using significantly less inductive flux than standard inductive discharges in NSTX.

Experimental Results: CHI is implemented in NSTX by driving current along field lines that connect the inner and outer lower divertor plates as described in detail in Reference [1-3]. In NSTX the inner vessel and lower inner divertor plates are the cathode while the outer divertor plates and vessel are the anode. Prior to initiating a CHI discharge the toroidal field coils and the lower divertor coils are energized. The lower divertor coils produce magnetic flux linking the lower inner and outer divertor plates, which are electrically isolated by a toroidal insulator in the vacuum vessel. A programmed amount of gas is then injected into the vacuum chamber and voltage is applied between these plates, which ionizes the gas and produces current flowing along magnetic field lines connecting the plates. In NSTX, a 5 to 30 mF capacitor bank charged to 1.7 kV provides this current, called the injector current. As a result of the applied toroidal field, the field lines joining the electrodes wrap around the major axis many times so the injector current flowing in the plasma develops a much larger toroidal component.

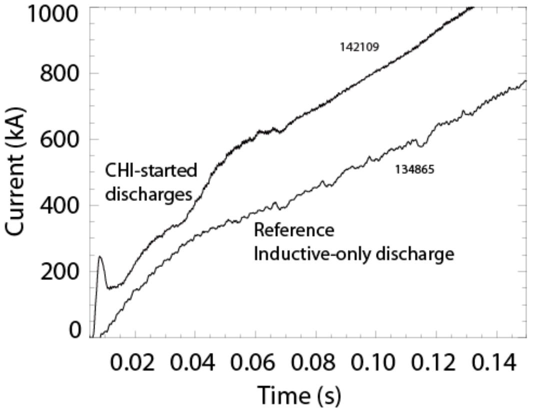

Fig. 1. Shown are a CHI started discharge and a reference inductive-only discharge

Significant improvement in the performance of CHI discharges in NSTX were achieved by reducing the low-Z impurities, mainly oxygen and carbon in the initial electrode-driven plasma as described in Reference [4]. The lower divertor plates, which are used as the CHI electrodes were initially, cleaned using an extended electrode discharge. The CHI system itself was used for this purpose by running many discharges at high injector current but with greatly increased injector flux connecting the lower divertor plates. This cleaning was followed by coating the lower divertor plates with lithium from a pair of evaporator ovens mounted at the top of the vacuum chamber, as described in Reference [5]. Detailed results on the coupling of CHI started discharges to induction are described in recent references [3,6]. The results on the reduction in central solenoid flux required to reach normal plasma current are briefly summarized here. In Fig. 1 we are comparing the plasma current trace for a recent CHI started discharge that was followed by inductive ramp-up to a standard discharge on NSTX initiated and ramped up by induction only. The inductive-only discharge is from the NSTX database, assembled over 10 years of operation that reached 1 MA in a shorter time than other L-mode discharges. At 132 ms the CHI-started discharge consumes a total of 258 mWb of central solenoid flux to ramp up to 1 MA. At this time the reference inductive-only discharge gets to about 0.7 MA and it does not reach 1 MA until 160 ms, by which time 396 mWb of central solenoid flux had been consumed. Typical L-mode discharges in NSTX require at least 50% more inductive flux than discharges assisted by CHI to reach 1 MA. It is important to note that, due to failure of one of the lithium evaporators, the recent CHI discharges did not benefit from full lithium coverage of the lower divertor plates, so that the achieved flux savings may have been hindered by exposed graphite that may have contributed some low-Z impurities.

These new results [3,6] also show that these plasmas have both a very high elongation of $k \approx 2.6$ and, as a result of the hollow electron temperature profile and rapid inductive ramp, very low internal inductance $l_i \approx 0.35$ from the start of the discharge. Finally, these plasmas are relatively free of MHD activity despite having low density, which has previously been associated with increased instability during normal inductive startup.

TSC Simulations: TSC is a time-dependent, free-boundary, predictive equilibrium and transport code [7]. It has previously been used for development of both discharge scenarios and plasma control systems. TSC has now been used to simulate CHI start-up plasmas in NSTX [8] and is now being used to model the full non-inductive start-up and non-inductive ramp-up scenarios in support of the NSTX-U device, which is under construction.

Generation of closed flux in TSC is as a result of an effective toroidal loop voltage induced by the CHI ejected poloidal flux that decreases as the injector current is reduced to zero. Reference [8] also provides additional details including showing consistency with earlier theoretical predictions [9]. It also shows that CHI scaling with toroidal field is favorable for larger machines and that with acceptable amounts of injector current, peak plasma currents on the order of 600 kA could be generated using the injector poloidal flux capability of the present NSTX if the toroidal field were increased to 1 T. The higher toroidal field allows the same level of poloidal flux to be produced in the plasma at lower level of injector current.

The application of CHI on NSTX and on HIT-II combined with recent simulations with the TSC code has revealed many important aspects of CHI physics and its application to future machines. The key results, not all of which are covered in this paper but described in the supporting references, are briefly summarized below.

- NSTX and HIT-II, two machines of quite different size (NSTX plasma volume is 30 times that of HIT-II), have both achieved significant levels of start-up current through CHI.
- On NSTX, the method is highly efficient, producing more than 10 Amps/Joule of initial stored capacitor bank energy.
- The scaling to larger machines with higher toroidal field is quite favorable: NSTX achieves 10 times the current multiplication factor (plasma current / injected current) of HIT-II.
- The CHI generated plasmas on NSTX have desirable properties including low inductance and electron density and high elongation needed for subsequent non-inductive sustainment utilizing the bootstrap current and NBI and RF waves.
- Simulations with the TSC code show agreement with the theoretical prediction for CHI as it is scaled to larger machines. These simulations indicate the importance of an auxiliary electron heating system to boost the temperature of CHI discharges.

Massive Gas Injection Studies in NSTX-U: Predicting and controlling disruptions is an important and urgent issue for ITER and impacts the designs for reactors based on the ST and Tokamak concepts. Disruptions have been such a ubiquitous feature of tokamak operations for decades that, while work is in progress to develop reliable methods to avoid disruptions, some may be unavoidable. For these cases, a fast discharge termination method is needed to minimize the deleterious effects of the disruption, particularly the generation of large populations of runaway electrons. Massive Gas Injection (MGI) is one approach to addressing this difficult issue for ITER. NSTX-U plans to compare MGI from different poloidal locations to assess the gas penetration efficiency. We are starting to model gas penetration using DEGAS-2 and it appears that the scrape-off-layer plasma may place limits on the achievable gas penetration fraction to the separatrix.

At present Massive Gas Injection (MGI) appears to be the most promising method for safely terminating discharges in ITER [10-12]. MGI involves the rapid injection of gas with an inventory several times the inventory of the plasma discharge. Usually some fraction of the injected gas has a high-Z component such as argon or neon. Requirements for the mitigation of disruption effects fall into three categories: (1) Reducing thermal loads on the first wall; (2) reducing electromagnetic forces associated with "halo" currents, i.e. currents flowing on open field lines in the plasma scrape-off layer; and (3) suppressing runaway electron (RE) conversion in the current quench phase of the disruption. To accomplish these in ITER, it is projected that about 500 kPa-m^3 of helium with some noble gas fraction will be required.

The present understanding of disruption mitigation using massive gas jets is based on work conducted on DIII-D, Alcator C-MOD, ASDEX-U, JET and other large tokamaks, and is summarized in References [10-12].

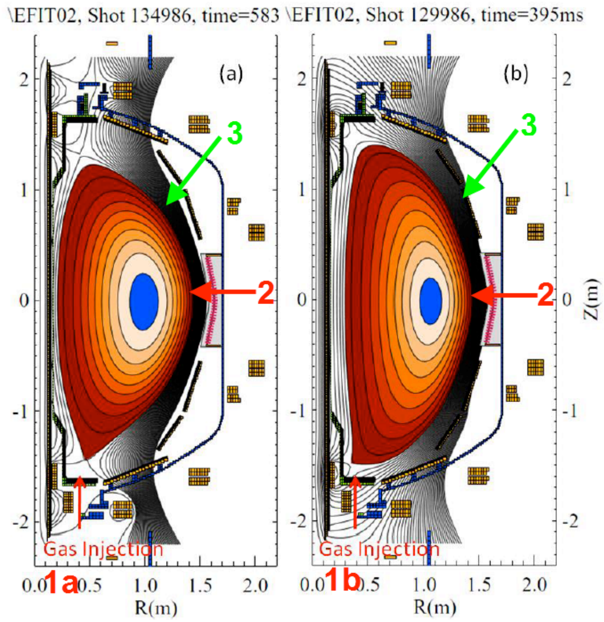

Fig. 2. Shown are the planned Massive Gas Injection locations on NSTX-U. (1a) Private flux region, (2) mid-plane injection, (1b) high field lower SOL region and (3) outer SOL above the mid-plane.

NSTX-U can offer new insight by injecting gas into the private flux and lower x-point regions of its divertor discharges to determine if this is a more desirable location for massive gas injection. Injection from this new location has two advantages. First, gas injected directly into the private flux region does not need to penetrate the scrape-off-layer. Second, because the injection location is nearer the high-field side in standard D-shaped cross-sections, the injected gas should be more rapidly transported to the interior as known from high-field side pellet injection and from high-field side gas injection work on NSTX. By comparing massive gas injection from this new location to injection of a similar amount of gas from the outer mid-plane, NSTX-U can provide additional knowledge to disruption mitigation physics and new data for improving computational simulations. To plan for these experiments, an effort has been initiated to model the gas penetration using the DEGAS-2 code [13]. Preliminary results from these simulations [14] suggest that gas penetration to the separatrix could be significantly affected by plasma parameters outside the separatrix.

This work is supported by U.S. DOE Contracts DE-AC02-09CH11466, DE-FG02-99ER54519 AM08 and DE-SC0006757

[1] R. Raman, T.R. Jarboe, D. Mueller, et al., Nucl. Fusion **41**, 1081 (2001)
[2] R. Raman, T. R. Jarboe, B. A. Nelson, Phys. Rev. Lett., vol. **90**, 075005-1 (2003)
[3] R. Raman, D. Mueller, T.R. Jarboe, et al Phys. Plasmas **18**, 092504 (2011)
[4] R. Raman, D. Mueller, B.A. Nelson, T.R. Jarboe, et al., Phys. Rev. Lett., **104**, 095003 (2010)
[5] H. W. Kugel, M.G. Bell, J.W. Ahn, et al., Physics of Plasmas **15,** 056118 (2008)
[6] B.A. Nelson, T.R. Jarboe, D. Mueller, et al., Nucl. Fusion **51**, 063008 (2011)
[7] S.C. Jardin, N. Pomphrey and J. Delucia, J. Comput. Phys. **66**, 481 (1986)
[8] R. Raman, S.C. Jardin, J. Menard, et al., Nucl. Fusion **51**, 113018 (2011)
[9] T.R. Jarboe, Fusion Technol., **15**, 7 (1989).
[10] D. G. Whyte, et al., Journal of Nuc. Materials, **363-365**, 1160-1167 (2007)
[11] G. Pautasso, et al., Plasma. Phys. Cntrl. Fusion **51**, 124056 (2009)
[12] E.M. Hollmann, et al., Physics of Plasmas **17**, 056117 (2010)
[14] D.P. Stotler and C.F.F. Karney, Contrib. Plasma Phys. **34**, 392 (1994)
[15] R. Raman, D.P. Stotler, T. Abrams, et al., IEEJ Trans. Fundam. Mater., **132**, No 7 (2012) - accepted