Integrated Study of Solenoid Free Tokamak Startup on the PEGASUS and URANIA Experiments

J.A. Reusch, G.M. Bodner, M.W. Bongard, M.T. Borchardt, R.J. Fonck, J.A. Goetz, A.K. Keyhani, B.A. Kujak-Ford, B.T. Lewicki, M.D. Nornberg, A.C. Palmer, C. Pierren, A.T. Rhodes, N.J. Richner, C. Rodriguez Sanchez, C.E. Schaefer, J.D. Weberski, and G.R. Winz

University of Wisconsin – Madison, Madison, WI, USA

Introduction – Initiating current without using magnetic induction from a central solenoid is critical for the development of the spherical tokamak (ST) as a reactor-relevant configuration, and may benefit the advanced tokamak as well. The PEGASUS program has focused on developing the physics and technology basis for non-solenoidal tokamak startup using local helicity injection (LHI). LHI utilizes compact, edge-localized current sources (A_{inj} > 8 cm^2, $I_{inj} \leq 8$ kA, $V_{inj} \leq 1.5$ kV) for plasma startup and sustainment, and can initiate > 200 kA of plasma current (I_p) in a low-field ($B_T(0) \leq 0.15$ T), near-unity aspect ratio (A) ST [Fig. 1(a)]. LHI initiated plasmas have been successfully handed off to Ohmic (OH) H-mode sustainment, resulting in the highest stored energy in PEGASUS to date [Fig. 1(b)] [1].

Recent work has focused on assessing: I_p scaling; current drive mechanisms; characteristics of LHI plasmas; and the physics and engineering tradeoffs inherent in the choice of injector location. Two helicity injection systems with similar capabilities have been used for the experiments, one on the low-field-side (LFS) near the outboard mid-plane and a second on the high-field-side (HFS) in the lower divertor region [Fig. 1(a)]. These experiments inform a next generation LHI system design and machine upgrade to further advance LHI startup.

Physics Basis for LHI – If conditions for magnetic relaxation and radial force balance are met, a force-free current directed along the field can relax through helicity-conserving magnetic turbulence to form a tokamak-like plasma [2]. First-principles simulations of LHI with the NIMROD code have been performed [3]. These simulations reproduce this initial relaxation and current drive process, providing insight into the early phase LHI dynamics.

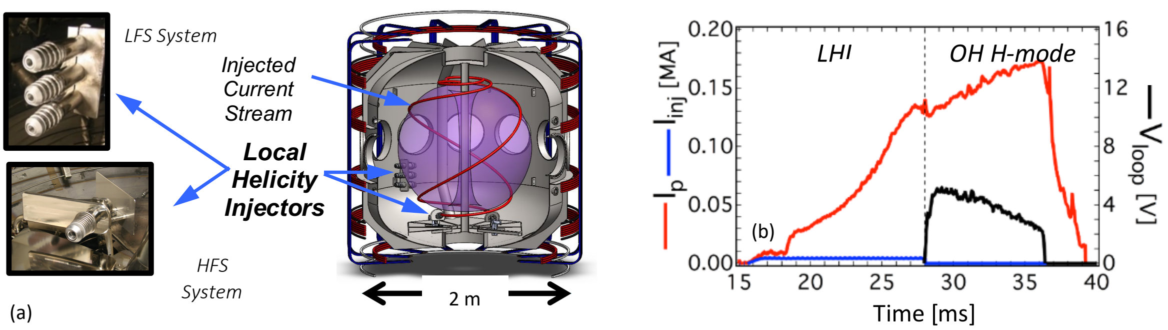

Fig. 1: (a) Helicity injectors (right) and 3D CAD of Pegasus (left) with calculated plasma and injected current streams for illustration; (b) I_p, V_{inj}, and V_{loop} from LHI - Ohmic handoff with H-Mode transition in OH phase.

While such detailed models give insight into the underlying processes occurring in LHI, reduced models inform system design and operational behavior. The absolute upper limits on the achievable I_p from LHI are set by helicity balance ($I_{HL} \propto A_{inj}V_{inj}/R_{inj}<\eta>$) and the Taylor limit [$I_{TL} \propto (I_{TF}I_{inj}/w)^{1/2}$]. Here A_{inj}, V_{inj}, and R_{inj} are the injector area, voltage, and radius respectively, $<\eta>$ is the volume averaged resistivity, I_{TF} is the toroidal field rod current, and w is the effective injector width. Combining these limits with Poynting's theorem gives a 0-D power balance model for the LHI plasma (see [4] for a detailed discussion of this model). Here the plasma is treated as a circuit element with inductance and resistance. The effective loop voltage from helicity injection, $V_{LHI} \propto A_{inj}V_{inj}/R_{inj}$, and the non-solenoidal inductive loop voltage from the changing poloidal field and plasma parameters, V_{IND}, balance the resistive dissipation. This yields an ordinary differential equation that is solved to obtain $I_p(t)$.

These models help to inform the performance and behavior of LHI plasmas, however, a confinement model and deeper understanding of the underlying current drive mechanism are needed to move beyond PEGASUS. To this end, experiments to determine the I_p scaling with V_{LHI} were performed at various B_T levels while maintaining little to no V_{IND}, constant shape, and constant electron density. Somewhat surprisingly, a linear scaling of I_p with V_{LHI} was observed in the most complete $B_T(0) \sim 0.045$ T set [Fig. 2(a)]. This scaling implies a constant total plasma resistance as the drive is increased. However, the T_e profile varies significantly as V_{LHI} is varied, seemingly contradicting this interpretation [Fig. 2(b)]. Initial analysis suggests that, with a modest increase in $<Z_{eff}>$ (from 1 to 2.5) as I_p increases, neoclassical resistivity is sufficient to explain the implied constant plasma resistance.

Besides the positive scaling of I_p with V_{LHI}, there is a modest increase in current drive efficiency with B_T. At the maximum B_T in PEGASUS [$B_T(0) \sim 0.15$ T], the T_e profiles are more strongly peaked and are comparable to OH L-mode T_e profiles at these B_T and I_p values [Fig. 2(c)]. In all LHI discharges, n_e is peaked with densities of 0.8 - 2.5x10^{19} m^{-3} in the core and with the T_e decreasing as n_e is increased. Note that these kinetic profiles are comparable for V_{IND}

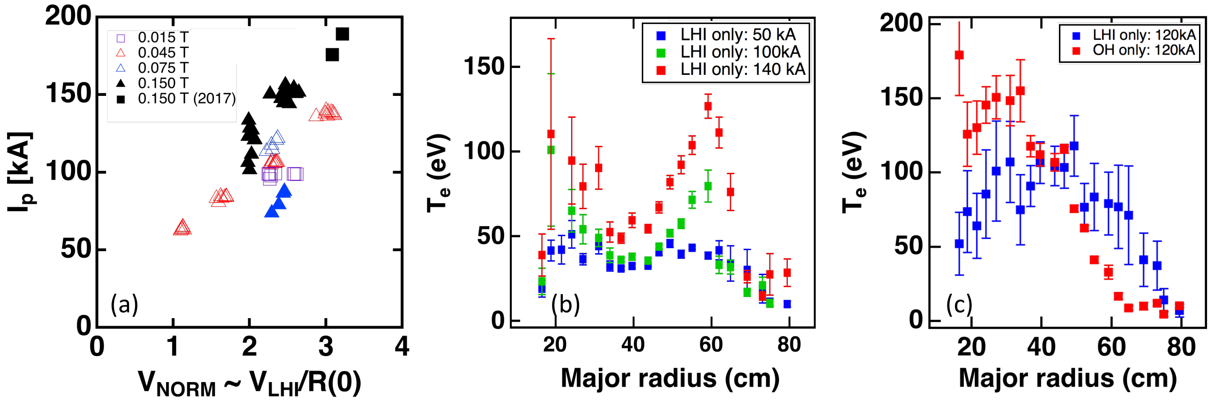

Fig. 2: (a) I_p vs. V_{LHI}; (b) T_e vs R for LHI at three I_p (V_{LHI}) levels at $B_T(0) \sim 0.045$ T; (c) T_e vs. R for pure LHI and pure Ohmic drive at $B_T(0) \sim 0.15$ T.

dominated and V_{LHI} dominated LHI scenarios run with either the LFS or HFS system, suggesting that the transport is not dependent on injector location or dominant current drive source.

Another important consideration for the scaling of LHI is the underlying current drive mechanism. A growing body of evidence suggests that the critical magnetic fluctuations required for helicity transport, and thus current drive, in LHI are high frequency (and presumably short wavelength). This is in contrast to past work suggesting low frequency $n = 1$ activity might be solely responsible for LHI current drive [5]. Recent work in LFS LHI discharges indicates the correlation of high-frequency activity with reconnection-driven ion heating [6]. Additionally, with low B_T HFS LHI discharges, a regime has been found in which the low frequency $n = 1$ magnetic activity spontaneously reduces by an order of magnitude. In such "reduced MHD" plasmas, the current drive efficiency actually increases, indicating that the low frequency activity is not strongly contributing to the net sustaining current drive (i.e. well after the initial tokamak formation stage) [7].

The magnetic fluctuation activity in HFS LHI plasmas has now been characterized using high-bandwidth insertable magnetic probes. This data indicates substantial high-frequency spectral content well beyond the ion cyclotron frequency (f_{ci} ~ 600 kHz). Figure 3(a) shows the auto-power spectra from a probe just inside the plasma edge for three discharges at different V_{LHI} (and I_p) levels. Below f_{ci} there is a power law decay consistent with MHD turbulence (-5/3). New data show that the spectral power > 1 MHz (>>f_{ci}) is observed to increase with I_p and/or V_{LHI}. Together, these observations suggest that this high frequency activity may be critical for LHI current drive.

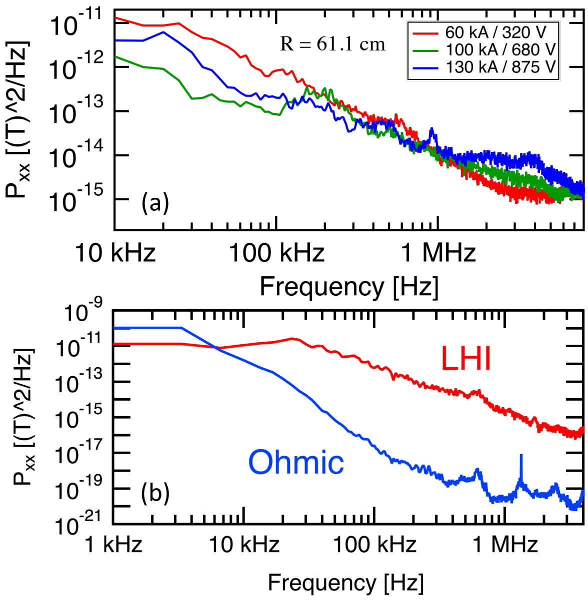

Fig. 3: Magnetic fluctuation auto-power showing (a) high-frequency (>1MHz) magnetic activity increases with I_p, V_{LHI}; (b) high frequency activity substantially higher in LHI than OH.

Recent experiments have similarly diagnosed Ohmic L-mode plasmas. Significantly lower fluctuation power is present in Ohmic plasmas [Fig. 3(b)], with signal levels consistent with the diagnostic noise sensitivity occurring at $f \geq 0.3$ MHz. LHI exhibits substantially higher fluctuation power, with measurable signal extending to > 4 MHz.

LHI at low B_T and A enables access to an extreme ST operating regime. LHI driven plasmas with near unity β_t, high β_N, high I_N, low l_i, and high κ have been achieved [8,9].

Next Generation LHI System and Facility Upgrade – A major component of the recent research at PEGASUS has been the assessment of the physics and engineering tradeoffs between

LFS and HFS injection. For given injector parameters, HFS injection has increased V_{LHI} and naturally produces very high κ plasmas, while LFS injection has a lower relaxation threshold and large V_{IND} from the dramatic shape evolution of the plasma [10]. The kinetic profiles and achievable I_p are similar for both systems. Thus, the choice of injector location for future systems is driven by practical rather than physics considerations. In this, LFS injection is generally preferred due to easier port access on the outboard side.

An important realization from the interpretive analysis of LFS LHI discharges that influences next-step injector design is that they are typically Taylor limited early in the discharge [4]. Increasing I_{TL} at the time of relaxation leads to greater than linear increases in the maximum achievable I_p, even though the discharge is limited by helicity balance later in time. Figure 4 shows an example of this effect in PEGASUS where I_{TL} was increased through increased I_{TF}.

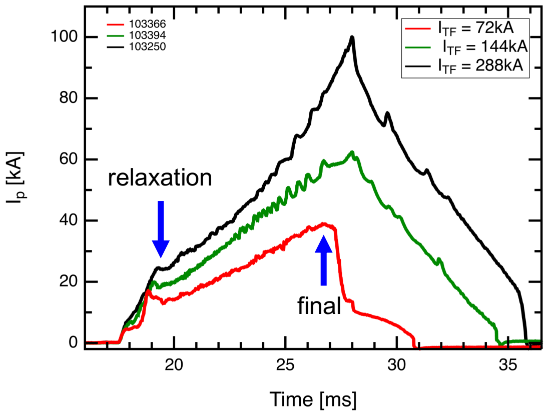

Fig. 4: I_p at three different TF levels showing the impact of raising the initial I_{TL} on the final I_p.

A major upgrade to the PEGASUS device is underway to provide a four-fold increase of I_{TF} (or $B_T \sim 0.6$ T). This will not only significantly increase I_{TL}, it will also enable scaling and confinement studies at B_T levels relevant to larger machines. Beyond LHI, the upgraded experiment (renamed URANIA) will have a new mission: to examine, compare, and possibly combine several leading non-solenoidal tokamak startup candidates in a single experiment. Initial techniques under consideration are: LHI; sustained and transient coaxial helicity injection; electron Bernstein wave heating and current drive; and poloidal field induction. The overarching goal of the upgrade machine is to establish the optimum non-inductive technique to provide routine MA-class startup on NSTX-U and beyond.

Acknowledgements

This work supported by the United States Department of Energy grant numbers DE-FG02-96ER54375 and DE-SC0019008.

References

[1] Thome, K.E., *et al.*, *Nucl. Fusion* **57**, 022018 (2017)
[2] Taylor, J.B., *Rev. Mod. Phys.* **58**, 741(1986)
[3] O'Bryan, J.B. and Sovinec, C.R., *Plasma Phys. Control. Fusion* **56,** 064005 (2014)
[4] Barr, J.L., *et al.*, *Nucl. Fusion* **58**, 076011 (2018)
[5] Eidietis, N.W., *et al.*, *J. Fusion Energy* **26**, 43 (2007)
[6] Burke, M.G., *et al.*, *Nucl. Fusion* **57**, 076010 (2017)
[7] Perry, J.M., *et al.*, *Nucl. Fusion* **58**, 096002 (2018)
[8] Schlossberg, D.J., *et al.*, *Phys. Rev. Lett.* **119**, 035001 (2017)
[9] Reusch, J.A., *et al.*, *Phys. Plasmas*, **25**, 056101 (2018)
[10] Bongard, M.W., *et al.*, *Nucl. Fusion* **59**, 076003 (2019)