Recent Results from the HIT-II and HIT-SI Helicity Injection Current Drive Experiments

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Abstract. Three important results are reported. 1) CHI startup has produced 100 kA of closed current without using poloidal field (PF) coils or any transformer action. The initial equilibrium is then driven to 240 kA with a 3 V transformer loop voltage, indicating high quality plasma. 2) For the first time CHI alone has produced toroidal currents (350 kA) that far exceed $q_a I_{inj}$, and with I_p/I_{tf} as high as 1.2. The key to these new results appears to be having the toroidal field small enough that relaxation will occur. 3) The steady inductive helicity injection spheromak experiment has operated at 5 kHz for 6 ms with current amplitudes up to 11 kA in each injector. The helicity injection rate is nearly constant with the **E**×**B** flow always into the plasma and not into the walls. NIMROD simulations of HIT-SI show a buildup of spheromak fields.

1. Introduction

A new method referred to as transient CHI startup has been used to produce substantial amounts of high quality closed flux plasma current [1,2]. By self-consistently increasing the injector flux, the externally produced toroidal flux and the power supply voltage the useful CHI produced closed flux current has been increased to about 100 kA, which is retained during the inductive ramp. CHI started plasmas outperform inductive-only discharges and consume less volt-seconds. A new operating regime has been discovered where, for the first time on HIT-II, the poloidal flux in the ST plasma greatly exceeds the initial injector flux. This flux amplification, that is common on spheromaks [3], was not previously observed on the HIT or HIT-II STs. These results were obtained on the Helicity Injected Torus-II (HIT-II) spherical torus experiment (major/minor radius of 0.3/0.2 m) [4]. Finally, inductive helicity injection is demonstrated in the new HIT-SI spheromak experiment and modeled with the 3D resistive MHD code NIMROD.

2. Transient CHI

Previous results from the HIT-II experiment have demonstrated the capability of a new CHI plasma startup method referred to as transient CHI to produce up to 50 kA of useful high quality closed flux current [1,2]. In this method, a small suitably sized capacitor bank is discharged across the lower divertor plate electrodes, which are connected by poloidal flux generated by divertor poloidal field coils. At sufficiently high injector currents, the resulting ΔB^2_{tor}, $J_{pol} \times B_{tor}$, stress across the current layer exceeds the field line tension of the injector flux, causing the helical current structure in the lower divertor region to move into the main plasma chamber. The capacitor bank is sized such that on time scales corresponding to the growth of the CHI produced discharge, the energy from the capacitor bank is mostly depleted. For sufficiently narrow flux footprint widths on the divertor plates, axisymmetric reconnection of the poloidal field lines near the injector electrodes causes a closed-flux equilibrium to form in the main chamber. Previous work on HIT-II has shown that in a sequence of repeated discharges, without performing wall conditioning between shots, the CHI-started discharges are considerably more reproducible than the inductive-only cases. CHI discharges can be initiated when the central transformer is pre-charged, or while the central transformer is in the process of being pre-charged during which time it induces a negative loop voltage on the CHI startup plasma[1].

The method used to double the CHI produced current, reported here, is of particular importance to large machines and reactors because it points to the potential for several hundreds of kA of CHI-produced, solenoid-free plasma startup current in larger machines. In this method, by self-consistently increasing the injector flux, the externally produced toroidal flux and the power supply voltage, the useful CHI produced closed flux current has been increased to about 100 kA [5]. Figure 1 (left) shows plasma current traces from such a CHI started discharge with and without handoff to Ohmic and the injector current for both conditions. The plasma current without handoff shows that almost 100 kA of plasma current continues to flow after the injector current is zero and, therefore, flows in a closed flux region. This is a considerable improvement from previous results because twice as much startup, closed current is produced. The current is produced without ramping down the divertor flux and the startup only equilibrium is longer lived. There is very little room for doubt that the startup plasma is a closed flux equilibrium, and with the Ohmic ramp of only 30 mWb the plasma current reaches a record value of 240 kA for HIT-II. This startup is so robust that the flux boundary conditions do not need to be manipulated during the shot to produce a high quality, diverted Ohmic discharge. The method is to be used on NSTX and could be applied to any toroidal device.

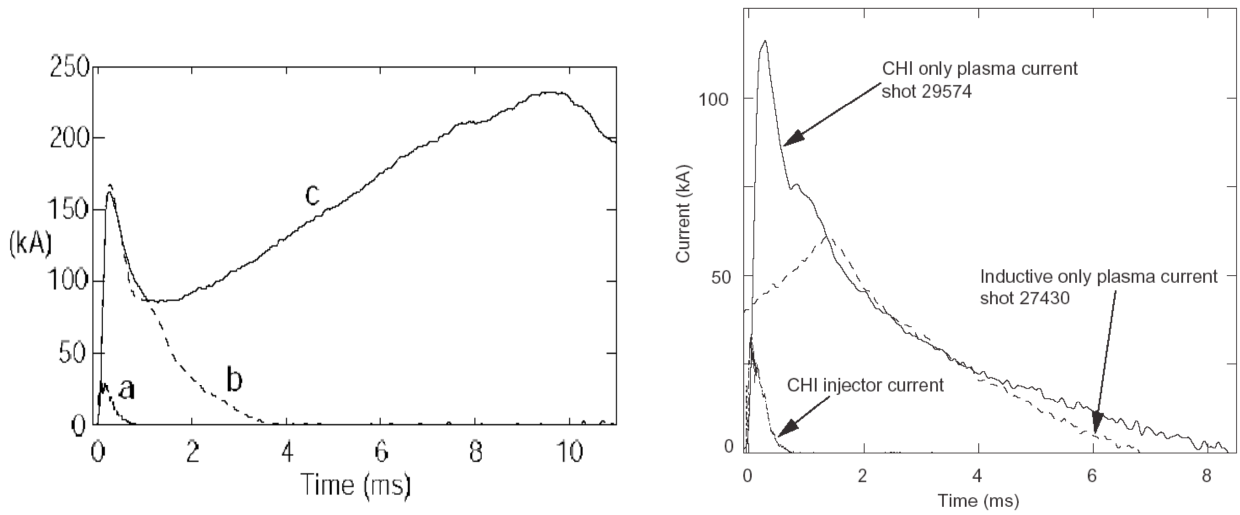


Figure 1 Left frame: a) Injector current, b) plasma current with CHI only (#28662), and c) plasma current with CHI startup plus 4V loop voltage for 0.3 ms < t < 2.3 ms and 2.9V for 2.3ms < t < 10ms (#28679). Right frame: Comparison of plasma currents of similar magnitude produced using CHI and using the conventional inductive method. The inductive discharge current has been displaced along the time axis to overlay the decay portion of the CHI discharge.

Figure 1 (right) shows the CHI injector current and the CHI produced plasma current from a CHI only discharge and compares it to an inductive discharge that has a similar magnitude of plasma current during the current decay phase. The inductive discharge trace has been displaced in time so that the time period of interest, which is the decay phase of the discharge, can be easily compared to the CHI produced discharge. For the inductive discharge, at the time of peak plasma current the loop voltage is reduced to zero so that starting from about 1 ms, both discharges are resistively decaying and are not being actively driven. Note that since the injector current is reduced to zero before t = 1 ms, the CHI discharge is not being actively driven by the external circuit during the time period of interest. This confirms that CHI is capable of producing closed flux equilibria of quality similar to that produced by the conventional inductive means.

3. Advances in Steady-State CHI Operation

Recent studies of CHI-driven plasmas in the HIT-II spherical torus have found and explored a new CHI operating mode, in which the discharges exhibit flux amplification, which is a buildup of poloidal flux to many times the total injector flux, a corresponding rise in the toroidal plasma current, and an inward relaxation of the current density profile. The discharges sustained in this operating regime can robustly reach peak currents in excess of 300 kA, with a few discharges transiently reaching plasma currents of over 350 kA, a record for small-scale ST devices [6].

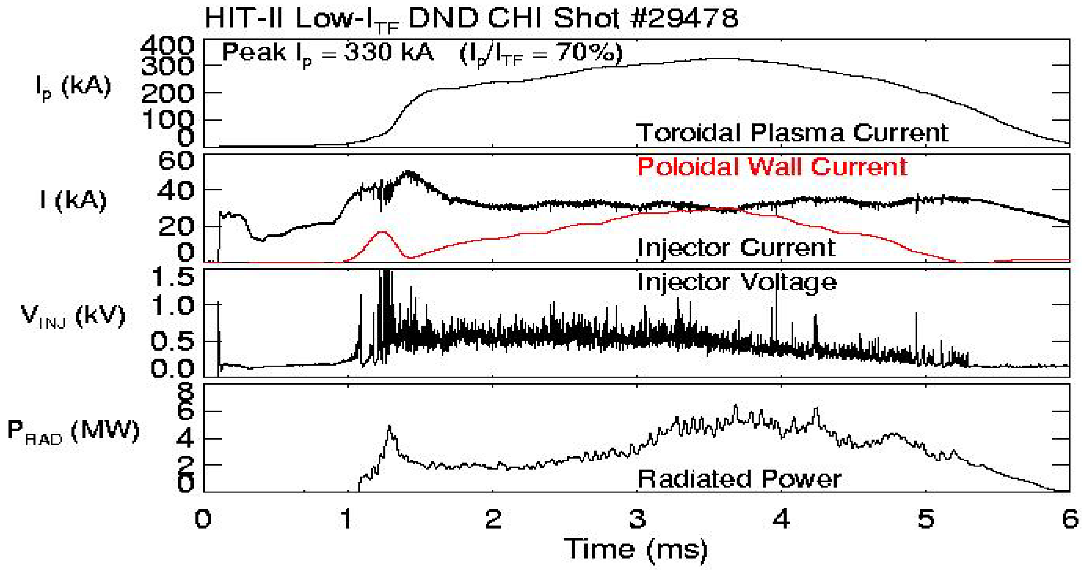


Figure 2 : Toroidal plasma current, Injector current (in black) and Poloidal wall current (in red), Injector voltage and Radiated power in the confinement region versus time for HIT-II CHI discharge #29478. This plasma had an unbalanced Double-Null Divertor (DND) poloidal flux boundary, and a relatively low toroidal field. The peak ratio of plasma current to toroidal-field coil current was 0.70.

Time traces for a typical CHI discharge in this new operating regime, HIT-II shot #29478, are shown in Figure 2. Notice that, after the rapid "bubble-burst" discharge formation at t = 1 ms, the plasma current continues to rise until reaching a peak of 330 kA. In general, the plasma current in these discharges increased until the inverse magnetic scale length for the main discharge (λ_{tok}, defined as $\lambda_{tok}=\mu_0 I_p/\phi_{tf}$, where I_p is the toroidal plasma current and ϕ_{tf} is the toroidal flux in the confinement region) is equal to the inverse magnetic scale length for the CHI injector (λ_{inj}, defined as $\lambda_{inj}=\mu_0 I_{inj}/\psi_{inj}$, where I_{inj} is the injector current and ψ_{inj} is the poloidal injector flux). This limit on the plasma current is consistent with the paradigm of the main ST discharge being sustained by the CHI injector through some (unspecified) relaxation process(es), as originally envisioned by Jarboe in 1989 [4]. Note, the post-formation injector current is approximately constant throughout this discharge, and equal to the "bubble-burst" value, as expected for a CHI-driven discharge [4]. The total current delivered to the CHI electrodes is the sum of the Injector Current and the Poloidal Wall Current; although this total bank current is as high as 55 kA in #29478, there are many cases of HIT-II CHI discharges exhibiting a current build-up (up to $\lambda_{tok}=\lambda_{inj}$) with total bank currents of less than 35 kA.

Poloidal flux generation in these CHI discharges is measured using internal magnetic probing. The probe used in these studies is a single stem of eight triple magnetic field probes, spaced

12 mm apart, inserted into the confinement region before the discharge begins. Assuming symmetry, the poloidal flux in the confinement region can be calculated from the probe-measured poloidal fields. Typical probing results are shown in Figure 3, from a discharge (#29388) in which the outermost magnetic field probe was located approximately at the wall, and the innermost probe at a major radius of 0.42 m. Note that the flux measured at the innermost probe reaches a maximum of approximately 16 mWb, which is much larger than the injector flux for this discharge (6 mWb) and still significantly larger than the total open flux (including vertical field) in the HIT-II device (11 mWb) . Note also that the rapid "bubble-burst" current rise corresponds to a measured poloidal flux that is close to the injector flux, but that the slower post-bubble-burst current build-up corresponds to the build-up of poloidal flux. Deeper probing of these discharges produces slightly degraded plasmas (peak currents reduced by 10-20% compared to corresponding unprobed or shallowly probed cases), but still measures an additional 1 to 2 mWb of poloidal flux between R=0.42m and the magnetic axis.

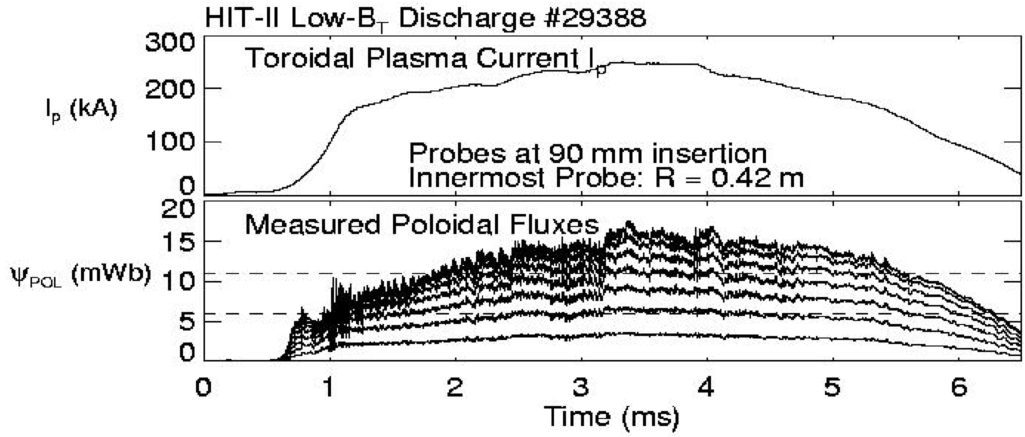


Figure 3: Toroidal plasma current and measured poloidal fluxes versus time for internally probed HIT-II CHI discharge #29388. The fluxes are calculated relative to the outermost field probe, located at the plasma-facing wall. The horizontal dashed lines correspond to the injector flux of 6 mWb and the total open flux of 11 mWb in the HIT-II device.

Empirically, there is a threshold for the buildup of toroidal plasma current and poloidal flux, which can be expressed in terms of the dimensionless product $\lambda_{inj}d$, where d is the effective inter-electrode distance. As can be seen in Figure 4, the current and flux build-up will not occur unless $\lambda_{inj}d$ is greater than a threshold of approximately one-third. This threshold can be understood in terms of a result from Ono *et al.* [7] in which it was found experimentally that the rate of magnetic relaxation in a system is related (non-linearly) to the angle between the reconnecting fields, with anti-parallel fields reconnecting the fastest and parallel fields by far the slowest. From $\nabla\times\mathbf{B} = \lambda\mathbf{B}$, λ is the rate of rotation of the magnetic field. Thus, the dimensionless product $\lambda_{inj}d$ is the change in field-line pitch across the injector in radians. Increasing the field-line pitch increases the rate of magnetic relaxation, and the finite threshold pitch for current build-up is interpreted physically as the rate of magnetic relaxation becoming larger than the rate of resistive decay. If the rate of closed-flux formation through relaxation exceeds the resistive decay rate, then the poloidal flux (and toroidal current) can build up until $\lambda_{tok} = \lambda_{inj}$, assuming that current and voltage can be supplied to the injector for a sufficiently long duration for the relaxation to complete.

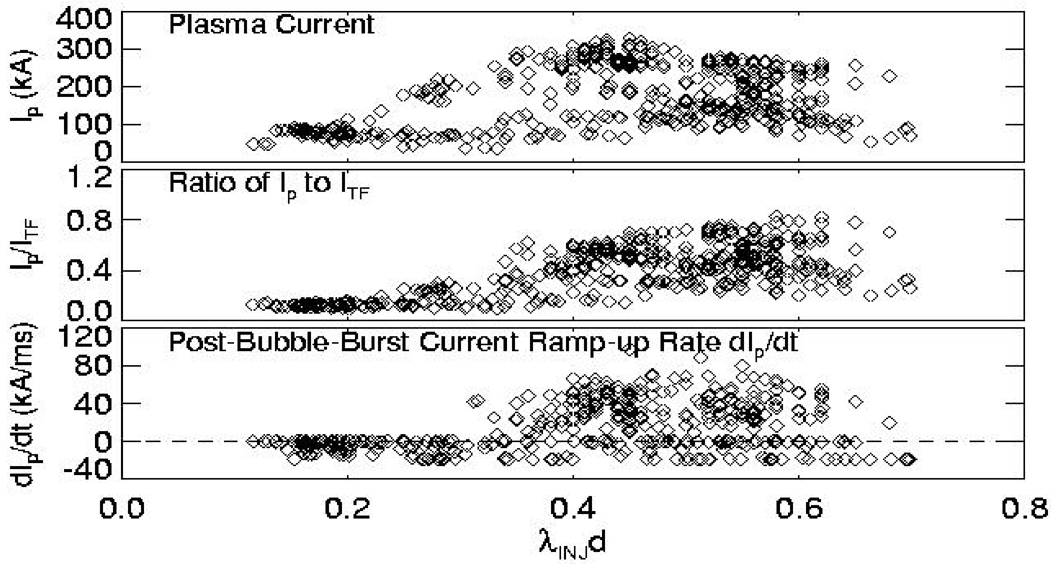


Figure 4 : Plasma current, I_p/I_{tf} ratio, and Post-Bubble-Burst I_p ramp-up rate versus $\lambda_{inj}d$ for 307 HIT-II CHI discharges. Note that the current (and flux) ramp-up rate is zero for values of $\lambda_{inj}d$ below a threshold.

Previous theoretical and empirical CHI scaling studies have established that the "bubble-burst" injector current is approximately equal to $(1/3)I_{tf}(\lambda_{inj}d)$ [4,6] , where I_{tf} is the total toroidal-field coil current in Amperes-turns. From this relation, from $\lambda_{inj}d = 1/3$, and from $\lambda_{tok} = \lambda_{inj}$, experimentalists can incorporate machine constraints (*e.g.*, an upper limit on I_{inj}) and produce a set of relations determining the experimental parameters required to replicate these results. Generally, this regime has a toroidal field (approximately limited by $I_{tf} < 27I_{inj}$) significantly less than that normally used in CHI operation on HIT, HIT-II and NSTX.

4. Demonstration of Steady Inductive Helicity Injection (SIHI)

HIT-SI is a spheromak designed to study Steady Inductive Helicity Injection [8,9]. Figure 5 is a drawing of HIT-SI. SIHI is implemented via two "helicity injectors", where each injector

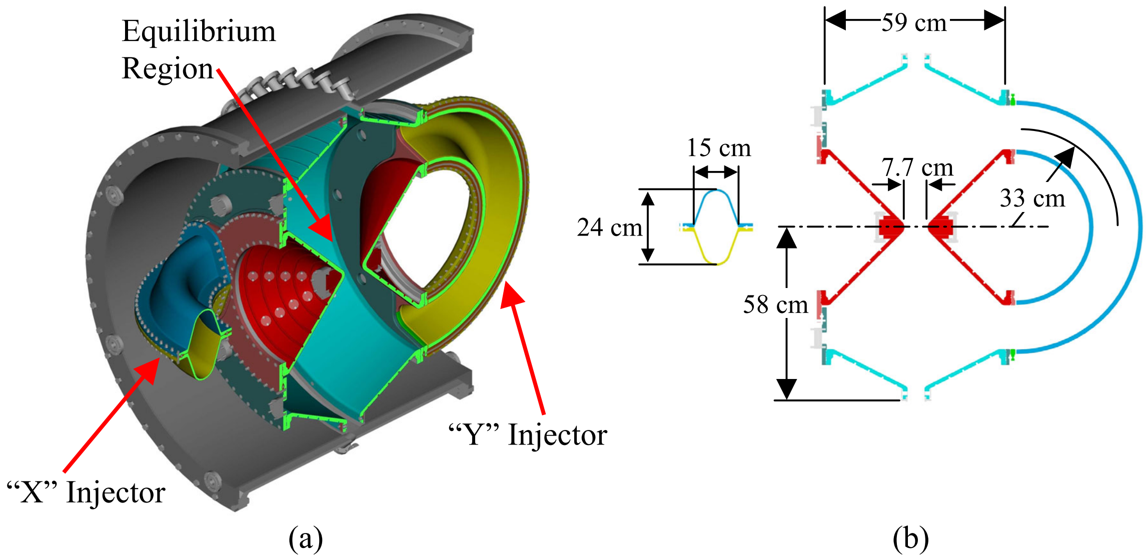
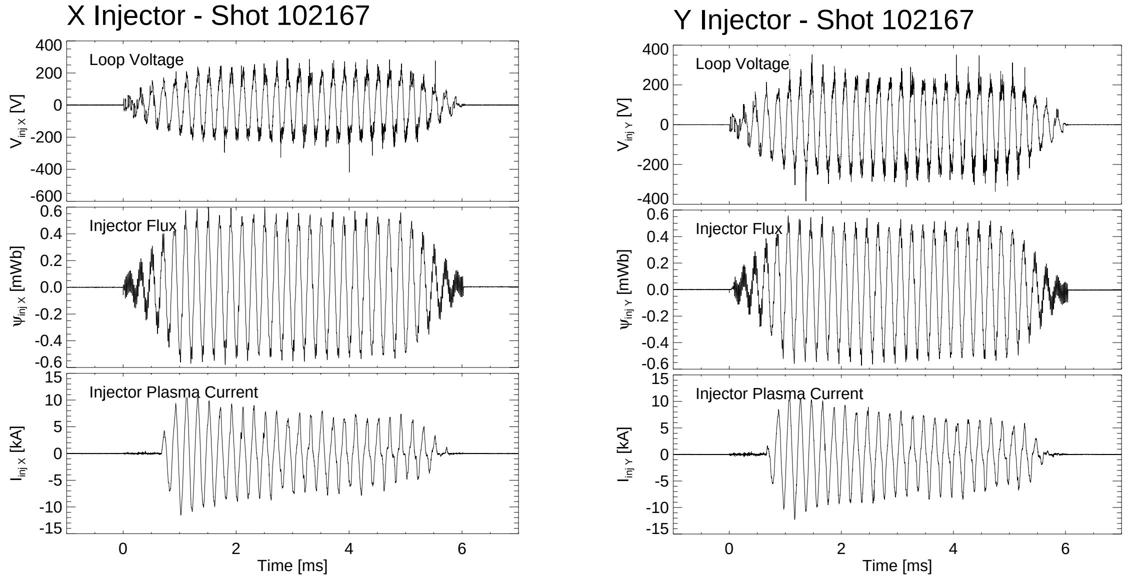


Figure 5. (a) A "cutaway" view of the HIT-SI device with the cross-section highlighted in green. (b) Selected dimensions of the HIT-SI flux conserver.

operates as a 180° segment of a reversed-field pinch. The toroidal loop voltage and toroidal flux in an injector oscillate sinusoidally and nearly in phase at 5 kHz.

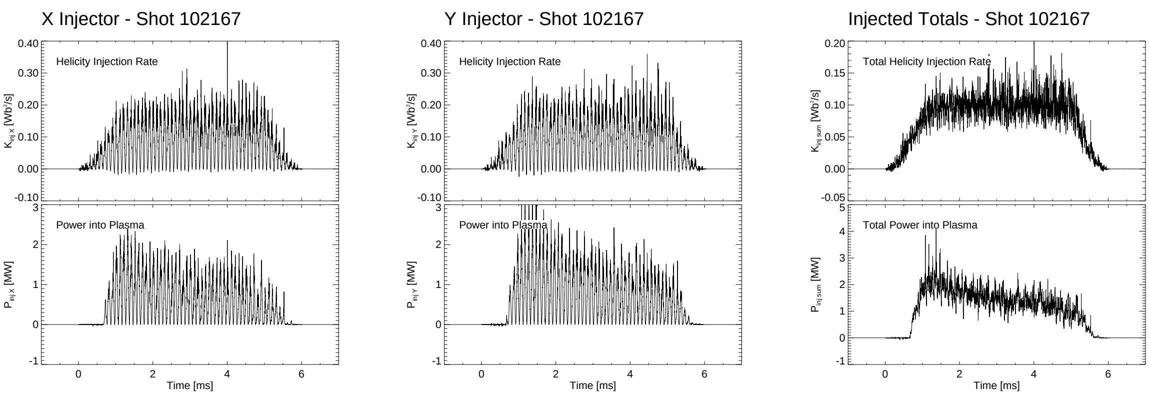
The two injectors operate simultaneously, as demonstrated in Figure 6. The amplitudes of the injector loop voltages are feedback-controlled at 200 V. The injector fluxes are also feedback-controlled to 0.5 mWb amplitude and in phase with the respective voltages. Breakdown is assisted by a plasma source that discharges at 0.5 ms. From that time, the injector plasma currents are a response to the loop voltage on each injector. The injector currents come to 12 kA, then the amplitudes slowly decrease to the end of the discharge.



(a) (b)

Figure 6. Operation of the helicity injectors on HIT-SI: (a) the "X"and (b) the "Y" injector.

The helicity injection rate and power input are almost always positive for each injector. A small phase difference exists between the injector voltage and flux, allowing the injector plasma current to align its zero-crossing with the loop voltage. The helicity injection rates and power inputs for the two injectors add in quadrature (Figure 7), such that the sums are positive definite for the discharge duration. Nearly constant helicity injection rate and power input are achieved. This is more true for the helicity injection rate because it is dependent only on feedback-controlled parameters, whereas the slight decrease in input power is due to decreasing injector plasma current.



(a) (b) (c)

Figure 7. Helicity injection rate and power input: (a) for the X injector, (b) for the Y injector, and (c) the sum of the injectors, showing nearly-constant helicity injection rate and power input.

An array of 3-axis magnetic field probes distributed toroidally along one injector provides observations of the magnetic structure of the injector plasma [9]. Toroidally asymmetric structures arise in the injector fields and propagate along the length on the injector at a speed that is Alfvénic in magnitude. No preferred propagation direction is observed. The speed tends to increase through successive injector cycles, suggesting an increasing Alfvén speed and thus a decreasing plasma density in the injector as the discharge progresses. Supporting evidence of this hypothesis is found in discharges with high injector flux amplitude and low pressure of the pre-discharge static fill. In these discharges, breakdown is observed and the injectors operate for a few cycles, but then the current amplitude quickly decays to zero. Discharges with higher gas fill pressure do not decay to zero injector current, but do exhibit decreasing amplitude in time; this may also be due to loss of injector plasma. Gas fuelling ports have been added recently to the midpoint of each injector to allow operation of the injectors at low density, high flux, and steady amplitude of the injector current.

5. Simulations of SIHI Spheromak Formation

The NIMROD code has been used to perform 3D simulations of HIT-SI and computationally demonstrate spheromak formation by Steady Inductive Helicity Injection. Previous simulations of a decaying spheromak in the HIT-SI geometry demonstrated a Lundquist number threshold for poloidal flux generation at around S=600 [10]. The injectors were added to the simulation via non-axisymmetric boundary conditions.

Normal magnetic fields are imposed at the locations of the injector openings into the bow-tie confinement region. These fields have the form of the toroidal fields of an RFP operated in spheromak mode (no toroidal field at the wall). The boundary conditions are calculated numerically as a Grad-Shafranov solution in an RFP with the appropriate major radius and an approximation of the injector cross-section. The experimental loop voltage is reproduced in the simulations using tangential electric field boundary conditions that produce a voltage difference between the two injector openings on one side. An electromagnetic electric field boundary condition is imposed to be consistent with the oscillating magnetic fields.

The resistivity is everywhere uniform on the grid except for in a thin region near the wall. Here, the resistivity increases linearly from the plasma value to a value that is several orders of magnitude larger at the wall. This is primarily done to model the insulating ceramic coating that keeps currents from flowing to the wall of the HIT-SI flux conserver. Having the additional resistivity at the injector strike points in the simulation serves two other advantages. First, it creates a high impedance source that causes the normal current density to closely match the imposed voltage profile. Second, it prevents line tying, which can inhibit dynamics.

A simulation at S=22, near to the initial operating regime of the device, resulted in no relaxation toward an axisymmetric configuration during the sustainment. When the injectors are shut off and the field lines are forced to close, the magnetic energy spectrum exhibits a growth in the n=0 component, which finally decays away more slowly than the higher n components as a spheromak with good flux surfaces forms in the volume. The decay time for the n=0 component is seen to depend critically the thickness of the edge resistive layer. A fast decay time is attributed to significant helicity dissipation that occurs in the limited region, despite little or no power dissipation. The results are consistent with a model described by Jarboe and Alper [11] for the loop voltage needed to sustain an RFP.
At lower resistivity (higher temperature) a significant n=0 component appears in the energy spectrum during the sustained phase. The n=0 component builds up for several cycles with

S=516. At 1.0 ms, the injector field magnitude was ramped to 1.5 times the previous value, at which point, both the n=1 (driving field energy) and n=0 (spheromak field energy) increased in magnitude. More significantly, the ratio of these two energies increased as S increased to 897, a necessary positive scaling for a favorable reactor configuration. The magnetic and kinetic energy spectra are seen in Figure 8.

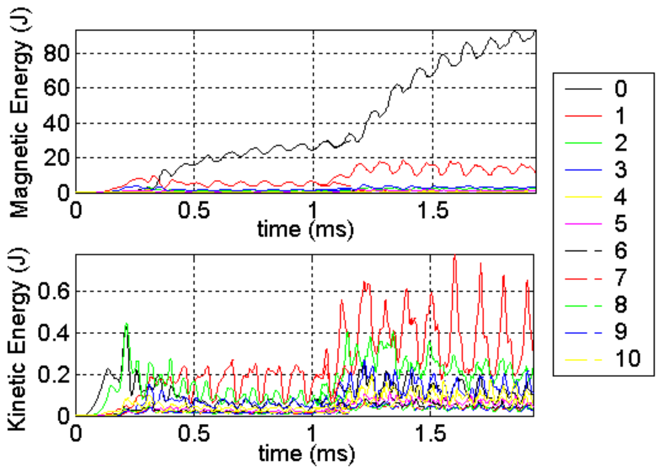


Figure 8. The magnetic and kinetic energy for each Fourier component. At 1.0 ms, the injector amplitude is ramped to 1.5 times the previous value, and S increases from 516 to 897.

6. Conclusion

Solenoid-free plasma startup current have been produced by transient CHI. The method does not need time changing poloidal field coil currents making it very attractive for reactors. The method is simple, insensitive to field errors and changing wall conditions, highly reproducible, and saves volt-seconds. A new steady state CHI regime has been discovered where poloidal flux amplification is observed for the first time on the HIT-II ST experiment and record plasma currents have been achieved. Exceeding a pitch angle across the injector about 1/3 radian allows access to the new regime. The new steady inductive helicity injection method of HIT-SI has just begun operation. NIMROD simulations of HIT-SI show a buildup of spheromak fields.

[1] RAMAN, R. et al., Phys. of Plasmas **11**, 2565 (2004).
[2] JARBOE, T. R. et al., “Progress with Helicity Injection Current Drive”, Fusion Energy 2002, 19th Conference Proceedings, Lyon, France, 14-19 October 2002.
[3] JARBOE, T. R., Plasma Phys. Control. Fusion **36**, 945 (1994).
[4] JARBOE, T. R., Fusion Technol. **15**, 7 (1989)
[5] RAMAN, R. et al., Non-inductive solenoid free plasma startup using coaxial helicity injection, submitted for publication.
[6] REDD, A.J.,et al. “Observation of magnetic relaxation and poloidal flux generation in coaxial helicity injection discharges in a spherical torus,” submitted for publication.
[7] ONO, Y. et al., Phys. Fluids B **5**, 3691 (1993).
[8] JARBOE, T.R., “Steady Inductive Helicity Injection and its Application to a High-Beta Spheromak”, Fusion Technology **36** (1999) 85.
[9] SIECK, P.E. et al., “Recent Results from the HIT-SI Spheromak”, IEEE Trans. Plasma Sci. (2004)
[10] IZZO, V.A. and Jarboe, T.R., Physics of Plasmas **10** (2003) 2903.
[11] JARBOE, T.R. and Alper, B., Physics of Fluids **30** (1987) 1177.