Demonstration of Plasma Startup by Coaxial Helicity Injection

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The first successful results on the transfer of a coaxial helicity injection (CHI) produced discharge to inductive operation are reported. CHI-assisted plasma startup is more robust than inductive only operation. After hand off for inductive operation, the initial 90 kA of CHI-produced current drops to 40 kA, then ramps up to 170 kA, using only 30 mVs, more than 30% higher than that produced by induction alone. These significant performance enhancing results were obtained on the HIT-II spherical torus experiment (major/minor radius of 0.3/0.2 m).

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The spherical torus (ST) is a magnetic confinement concept that has the advantages of high beta and a projected high fraction of bootstrap current drive [1–3]. The favorable properties of the ST arise from its very small aspect ratio, which leaves very restricted space for the central solenoid to induce the toroidal current. Entirely removing the central solenoid would simplify the ST design and allow access to the lowest possible aspect ratio. This requires the demonstration of plasma startup and sustainment without the use of the central solenoid. Previous work on large aspect ratio tokamaks has demonstrated noninductive plasma startup using radio frequency (rf) current drive [4–6]. rf based plasma startup is yet to be demonstrated on an ST.

Coaxial helicity injection (CHI) does not rely on the central solenoid; therefore, it is a promising candidate for initial plasma generation in an ST and is being implemented on the NSTX device for plasma startup and for providing some edge current drive during the noninductive sustained operation phase [7]. CHI is a method in which voltage is applied to coaxial electrodes connected by magnetic flux and which are electrically insulated from each other [8]. Clear introductory descriptions of CHI are given in Raman [7], Jarboe [8], and Redd [9]. Reference [7] also contains a simplified CHI figure that explains how the CHI process is implemented.

Although an ST reactor is not expected to have a central solenoid, demonstration of the capability to hand off a CHI-produced plasma for inductive operation is the near-term objective of the NSTX program. Such a demonstration implies that in the future, after sustained noninductive current drive methods have been developed on an ST, CHI-produced plasmas could be directly handed off to these systems [1,2,10]. This Letter focuses on the plasma startup objective.

CHI is implemented on HIT-II by driving current along field lines that connect the inner and outer vessel components on the lower part of the machine. Titanium gettering is used as a wall conditioning method to obtain the highest current discharges. In these experiments a 4 mF, 3 kV capacitor power supply connected across the inner and outer vessel components (insulated from each other by ceramic rings at the bottom and top) is used to produce the injector current. A 62 mΩ resistor is in series with the capacitor to overdamp the circuit. The combination of toroidal field and poloidal field in the injector region causes the injector current to flow along helical field lines in the injector region. As the injector current exceeds a threshold value, the resulting $\Delta B_{\rm tor}^2$, $J_{\rm pol} \times B_{\rm tor}$, stress across the current layer exceeds the field line tension of the injector flux, causing the helical current structure to move into the main plasma chamber. This is the initial process that produces the toroidal current, measured by the plasma current Rogowski coil. The CHI-produced toroidal current initially flows on open field lines. Relaxation or other forced reconnection processes are then necessary to produce current that can flow along closed field lines. The first successful transfer of a CHI-produced plasma current for inductive operation and the robustness of an ST plasma generated using CHI startup are reported.

Since an inductive plasma configuration with CHI flux footprints resembles a lower-single-null-divertor configuration, it may seem to be a natural configuration to which an inductive drive could be applied. Indeed, this was done in previous experiments on both HIT-II and in NSTX and always resulted in an increase or a temporal extension of the CHI injector current. The plasma discharge would be sustained for as long as the injector current could be maintained. After the injector current reduced to zero, the plasma current would diminish to zero, even though substantial loop voltage still remained. Rapidly reducing the injector flux to zero while applying induction from the central solenoid allows the transformer to continue the current to ramp up to levels not achievable with the transformer alone.

Figure 1 shows data from a CHI-produced discharge without the use of transformer action. In this discharge, soon after the CHI plasma is established at 0.5 ms, the divertor flux is ramped to zero at the fastest possible rate. The measured divertor flux is shown in the bottom trace. The primary motivation for reducing the divertor flux is

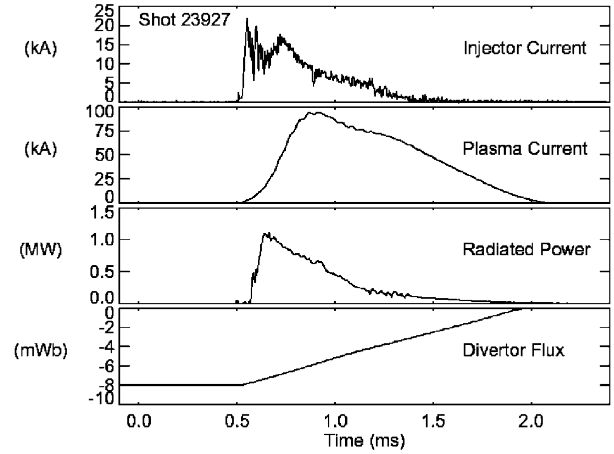

FIG. 1. CHI only discharge: Injector current, CHI-produced plasma current, radiated power signal from a wide-angle bolometer, and the measured divertor flux used to produce the CHI discharge. The calculation of the total radiated power assumes a uniform power per unit volume; the error due to detector sensitivity over the 50–100 eV energy range of interest is $\pm 10\%$. The detector is insensitive to energy below 10 eV. The detector sensitivity below 50 eV is about half that at 50 eV, the relative error (in the radiated power signal) between shots is less than 10%.

to produce a plasma containing some closed flux through forced reconnection. Figure 2 shows traces from a discharge in which induction from the central solenoid is added to a discharge such as the one described in Fig. 1. At $t = 1.2$ ms, a constant inductive voltage of 4 V is applied for 2 ms; thereafter, 3.2 V is applied for the next 6.8 ms. A total of 0.03 Vs are used and correspond to half-swing of the central solenoid. Prior to application of transformer action, the flux in the central solenoid is maintained at zero.

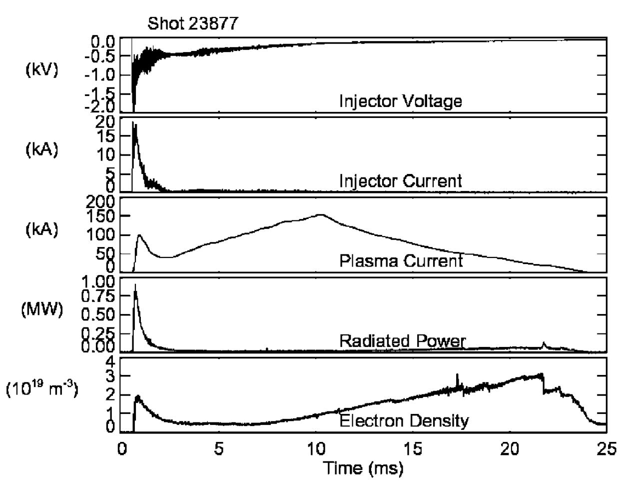

FIG. 2. CHI startup using half-swing of the central transformer. After the CHI discharge is produced, induction is applied at 1.2 ms. The top trace shows the applied injector voltage. The bottom trace shows interferometer measured electron density at the device midplane. The uncertainties on the injector voltage, injector current, and divertor flux are less than a few percent.

Figure 3 shows several traces produced in sequence starting from discharge No. 23915 and ending in discharge No. 23925. The first nine shots were conducted in sets of three. The first shot of the set is a case in which all the magnetic flux conditions necessary for producing the discharge in Fig. 2 are used but without application of the CHI injector voltage. The second discharge in the set is for the case in which the divertor flux is optimized for the maximum transformer produced current and again no CHI voltage is applied. In the third discharge, No. 23917, a CHI capacitor voltage of 1.7 kV is used with the flux conditions of discharge No. 23915. This sequence is repeated two more times. For the CHI started cases, the voltage is increased to 2.1 and 2.4 kV, respectively. The final two traces also correspond to the case of discharges with CHI startup.

Density traces for the shots corresponding to the second set are shown in Fig. 4. A far-infrared interferometer through the midplane along a major chord with major impact parameter of 0.35 m is used to obtain these data.

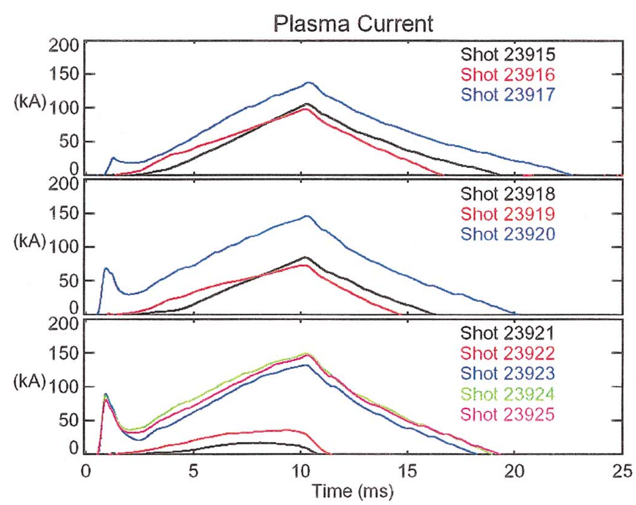

FIG. 3 (color). Sequence of eleven traces showing plasma current. Shot Nos. 23915, 23918, and 23921 correspond to discharges that have the same magnetic flux condition as that shown in Fig. 2, but with zero CHI voltage. Shot Nos. 23916, 23919, and 23922 contain only the magnetic flux conditions needed for inductive operation and do not contain the CHI injector flux component; the applied CHI voltage is zero. All other cases correspond to the case of discharges with CHI startup and have the same magnetic flux configuration as shot No. 23915. For all discharges a constant inductive voltage of 4 V is applied for 2 ms, followed by 3.2 V for the next 6.8 ms. After that the inductive voltage is zero. The absolute error in the plasma current measurement is 1.5% or 200 A, whichever is larger.

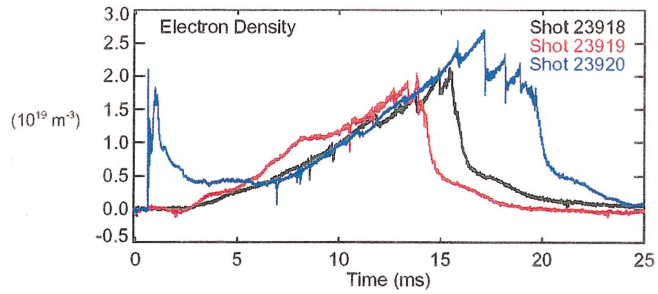

FIG. 4 (color). Interferometer measurement of electron density for three discharges shown in Fig. 3. These measurements have an error of $\pm 1 \times 10^{18}$ electrons/m^3.

Figure 5 also shows a sequence of traces, but with increased vertical field to avoid plasma wall interaction that can become pronounced as the plasma current increases. Discharge Nos. 23981, 23983, and 23987 are without CHI startup; all other discharges are with CHI startup. The reason for conducting these multiple sequences of shots is to ensure that varying wall conditions are not affecting the results and to clearly establish the significant enhancement in performance obtained with CHI startup.

Reducing the divertor flux forces reconnection in the injector region. Field line reconnection in the injector region should produce a closed-field-line plasma configuration in the vessel. Figure 1 shows the plasma current lasting longer than the injector current. Demonstration of the existence of plasma current when the injector current is zero has been a primary physics objective for the HIT and NSTX programs. This is a significant new result never before seen in CHI-produced discharges in the HIT program or in NSTX CHI plasmas. Since the external CHI circuit is not driving the plasma inside the main chamber, the main chamber plasma can result only from the presence of closed flux plasma.

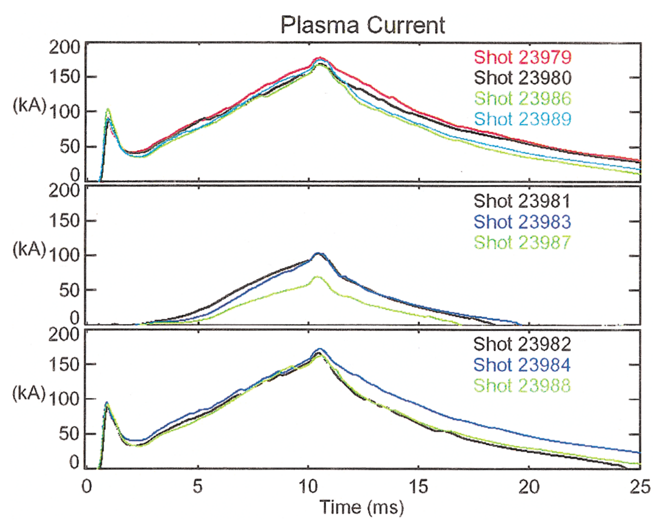

FIG. 5 (color). Comparison of discharges with the same magnetic flux configuration and with vertical field along the outer wall, and operated with and without the application of CHI voltage startup. In shot Nos. 23981, 23983, and 23987, no CHI voltage was applied. For shot No. 23988 the applied CHI voltage of 2.5 kV was above the threshold voltage of 2.4 kV used for the rest of the shots with CHI startup. The inductive voltage history is the same as that for the shot sequence in Fig. 3.

In summary, after application of voltage, the CHI process causes an open-field-line magnetic bubble to extend into the main chamber. The magnetic flux footprints are then forced to detach from the injector electrodes by using the external circuits to simply decrease the flux that penetrates the electrodes. This forces the open magnetic field lines in the lower portion of the expanded plasma to reconnect, producing closed field lines. The action of reducing the current in the divertor coils drives additional closed field line current in the plasma. This process requires only axis-symmetric reconnection.

This closed flux plasma is used as the initial target for the inductive drive provided by the central solenoid. In the discharge shown in Fig. 2, CHI produced 100 kA of plasma current. Induction is applied when this current drops to 80 kA. The current then continues to drop to 38 kA, after which it increases to 147 kA. The drop in the plasma current after induction is applied is related to the amount of plasma current remaining after the injector current has been reduced to zero, as described in the previous paragraph. This may be a consequence of current profile relaxation or some of the CHI-produced current may dissipate before the field lines are closed. The important result is that after application of induction the current does not drop to zero, rather nearly half of the CHI-produced current usefully couples to the inductive drive. Applying induction earlier during a CHI discharge resulted in less overall current being produced, probably because the radiated power of up to 800 kW was considerably more than about the 50–100 kW of inductive input power. Thus, the initial inductive energy goes to offset radiation losses and is not available for current drive. This result which shows the successful addition of current from a CHI-produced plasma to an inductive discharge is a new result never before demonstrated, and it shows that under proper operating conditions, plasma currents produced using electrode discharge processes can be sufficiently clean for usefully coupling to, and improving, inductive discharges.

The sequence of shots in Fig. 3 clearly shows the differences between discharges produced with and without CHI startup. For the first set of shots, the plasma current in discharges without CHI startup reach about 100 kA. During the second set, the currents reduce to about 80 kA, and by the time of the third set, the titanium conditioning of the walls has reduced to a level where it is no longer possible to produce a high current discharge using induction alone. In general, the current for the case with no divertor flux, during very good wall conditions obtained soon after titanium wall conditioning, is less than for the case in which the divertor flux is present. During diminished wall conditions, the case with no divertor flux always performs better than the case with some divertor flux. The cases with CHI startup remain remarkably robust even under diminished wall conditions. As the applied CHI voltage is increased, so does the initial CHI-produced plasma current and the magnitude of current that couples to the inductive drive. However, if the voltage is increased beyond a threshold value, 2.4 kV for this sequence of discharges (shot No. 23923), less of the CHI-produced current couples to the inductive drive. The increase in radiated power indicates the generation of a more resistive CHI-produced plasma in this case. Reducing the applied voltage to 2.3 kV (for the last two discharges) immediately produces the highest plasma current and highest CHI hand off current, even though the effect of titanium wall conditioning has diminished to a level where induction-only plasmas cannot be satisfactorily produced. The density traces in Fig. 4 show the density for the CHI-started case to increase for a longer period than for the inductive-only case. For these shots the density is observed to continue rising until the current drops to a very low value. The density rises longer because the current lasts longer in the CHI-started shots. It is interesting to note that after about 6 ms the CHI startup no longer affects the density.

The highest plasma current ever produced on HIT-II using a half-swing of the transformer is shown in Fig. 5. In the first shot, a 90 kA CHI-produced current is generated which reduces to 40 kA after application of induction, then it ramps up to 170 kA, using a total of just 0.03 Vs of central solenoid flux. In these two sequences shown in Figs. 3 and 5, the magnitude of the plasma current produced using CHI startup is consistently more than 130 kA, which is about 30% to 50% higher than currents produced by induction alone under similar conditions. These and the sequence of shots from Fig. 3 clearly demonstrate how CHI plasma startup is robust, even under diminished wall conditions.

In summary, successful transfer of a CHI-produced discharge for inductive operation can be achieved by the following three steps. First is the generation of a high current plasma discharge in which the radiated power during the current decay phase is of comparable magnitude to the input Ohmic power during hand off for inductive operation. The second step is to rapidly reduce the injector flux. The third step is to apply inductive drive during the lower-radiated-power phase, while there is still substantial CHI-produced plasma current.

Three significant new results are presented in this Letter. First, CHI has produced closed-field-line plasma current that persists after the injector current has been reduced to zero. Second, electrode-based CHI plasmas can be made sufficiently clean for fusion research purposes. This result is demonstrated by inductively ramping up the current in a CHI-started discharge using only 3.2 V. Finally, CHI is shown to be a viable plasma startup method for an ST. This result is demonstrated from the fact that there is significant performance enhancement in discharges with CHI startup.

Eventually, a solenoid-free current startup method will be used to show coupling to other noninductive current sustainment methods, but as a first step it is necessary to show that the current initiation method is of sufficiently high quality to usefully couple to an inductive discharge. This is, in fact, the near-term goal of the NSTX noninductive plasma startup program. Without central-solenoid-free startup, an ST is not expected to be a viable reactor device because in a reactor, the central solenoid cannot be adequately shielded from neutron radiation. The methods developed here are fully applicable to the NSTX device and can be implemented on NSTX to demonstrate noninductive plasma startup on a large ST. These results open up the possibility that further improvements to CHI-based systems should enable higher current CHI startup operation.

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