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Demonstration of solenoid free plasma start-up by CHI

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Abstract

Experimental results on the transfer of a Coaxial-Helicity-Injection- (CHI) produced discharge to inductive operation are reported. By self-consistenetly increasing both the injector flux and the externally produced toroidal flux, the useful CHI produced closed flux current has been increased to 100 kA, which is retained during the inductive ramp. CHI assisted plasma startup is more robust than inductive only operation and reduces volt-seconds consumption. These significant results were obtained on the Helicity Injected Torus-II (HIT-II) [T.R. Jarboe, Fusion Technol. **15**, 7 (1989)] spherical torus experiment (major/minor radius of 0.3/0.2 m).

1. Introduction

The need for central solenoid-free current startup is essential for the viability of the Spherical Torus concept, and advanced tokamak designs eliminate the central solenoid in order to improve reactor performance [2]. This points to the fundamental importance of developing methods for solenoid-free current startup. While there has been some work on central solenoid-free current initiation by Radio Frequency (RF) current drive in large aspect ratio tokamaks [3], these methods are yet to be adequately demonstrated on an ST. Furthermore these methods can greatly benefit from the presence of an initial closed flux seed current, which CHI startup could provide.

CHI relies on electrostatic helicity injection for current generation and it does not require time varying currents in any coils for discharge initiation. CHI is a promising candidate for initial plasma startup and it has the potential for providing edge current drive during the non-inductive sustained operation phase. The method relies on application of voltage to electrically separated coaxial electrodes connected by magnetic flux. On HIT-II, CHI is implemented by driving current along field lines that connect the inner and outer vessel components on the lower part of the machine. The source current, referred to as the injector current, is provided by a 1- 3.5 mF, 4 kV capacitor bank that is connected across the outer and inner vessel components at one axial end of the machine referred to as the injector region. Electrical separation of the inner and outer vessel components is achieved by toroidal ceramic insulators at both ends of the machine. The capacitor power supply is switched by an ignitron and the circuit is overdamped by a series 62 mΩ resistor.

A CHI discharge is initiated by first producing poloidal field connecting the injector electrodes. This is analogous to producing magnetic field lines that connect the lower inner and outer divertor plates in a tokamak. These static magnetic fields are produced by external poloidal field coils outside the outer vessel structure. This poloidal field in combination with the toroidal field produces a helical field line structure in the injector region. Application of sufficient voltage to these electrodes (or divertor plates) causes the breakdown. The resulting current flows on field lines connecting the electrodes. Increasing the applied voltage increases the injector current. 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 to move into the main plasma chamber. Rogowski coil sensors around the device measure the toroidal plasma current. This toroidal current is approximately the injected current times the ratio of the enclosed toroidal flux to the amount of injector flux that has extended into the vessel. This process, referred to as *driven* CHI or *steady-state* CHI, can be sustained indefinitely. The experiments described here use short pulse CHI discharges referred to as *transient* CHI, solely for the purpose of plasma current startup.

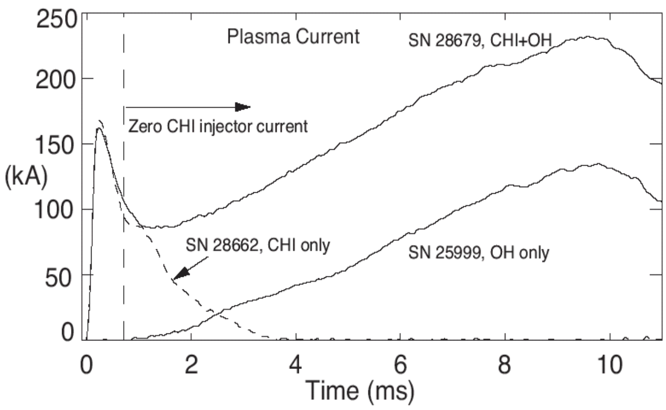

Figure 1: The dashed trace is a CHI only discharge. The vertical dashed line shows the time at which the CHI injector current is reduced to zero. CHI current persistence beyond this time is due to the existence of a closed flux equilibrium. It is this closed flux plasma that is inductively driven in shot 28679. For comparison, an Ohmic only discharge under identical pre-programmed loop voltage time history (total 30 mV.s consumed) is also shown (shot 25999).

2. HIT-II experimental results

As a first step in the demonstration of the use of CHI as a plasma start-up method, it is necessary to show that the quality of a CHI produced discharge is compatible with plasmas conventionally produced using the inductive method. Figure 1 shows plasma current traces from a recent CHI started and a reference inductive only discharges. In the CHI started case, 100 kA of useful closed flux current is produced, which is retained during the inductive ramp. The CHI only discharge (shot 28662) persists beyond the time of zero CHI injector (open field line) current. The continuing plasma current confirms the presence of a decaying closed field line equilibrium. In discharge 28679, induction from the central solenoid is applied to the CHI produced current after the CHI produced plasma current is fully established. The inductive voltage is pre-programmed. Four volts are applied from 0.45 to 2.45 ms, then 3 V are applied until 9.8 ms. This causes induction to couple to the decaying CHI produced plasma current and to increase it to about 230 kA. This coupling of the CHI produced plasma to induction clearly shows that the CHI produced plasma is fully compatible with plasmas produced using the inductive method.

For comparison, the current obtained by induction alone (with no CHI startup), using the same identical pre-programmed loop voltage history is also shown. The current produced by induction alone is about 100 kA less than for the CHI started case, demonstrating that CHI has produced 100 kA of high quality closed flux current, similar to that which can be produced by induction. Thus CHI plasmas can be made sufficiently clean for fusion research purposes.

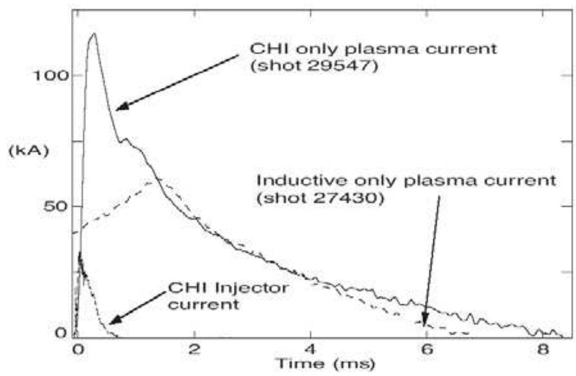

Figure 2: Comparison of the current decay time of similar magnitude plasma current plasmas produced using CHI and using the conventional inductive method. The figure clearly demonstrates that CHI is capable of producing closed flux plasma of quality similar to that which induction produces. The inductive discharge has been displaced along the time axis to overlay the current decay portion of the discharge, which is of interest for this comparison.

Figure 2 shows a CHI only discharge and compares it to an inductive discharge that has a similar magnitude of plasma current during the current decay phase. For the inductive discharge, at the time of peak plasma current, the loop voltage is reduced to zero. We note that the current decay rate for the CHI produced discharge is the same as that for the inductively produced discharge. This again shows that CHI has produced closed field line plasma of quality similar to that produced by the conventional inductive means.

Figure 3 shows the effect of self-consistently increasing the injector flux, the toroidal flux and the capacitor bank voltage. The Figure shows that the maximum attained useful closed flux plasma current increases with the optimised combination of injector flux and toroidal flux, which in this case is the external toroidal field, is increased. This can be understood as follows. The maximum poloidal flux in the closed flux plasma is proportional to the injected injector flux therefore the plasma current increases with injector flux. Increasing the toroidal flux allows one to inject more poloidal flux without substantially increasing the injector current [1]. For these discharges, there is a limit on the maximum injector current that can be driven for a given amount of injector flux. Increasing the injector current beyond this level results in a plasma with increased radiated power that does not couple to induction [4]. At higher injector flux the radiated power remains low even at the higher injector current probably because the larger amount of injector flux is able to provide additional heating. Because larger machines such as NSTX have the potential to inject about ten times more poloidal flux, but at similar levels of injector current as on HIT-II [5], larger machines have the potential for producing several hundreds of kA of useful current.

In a sequence of discharges that are repeated without between shot wall-conditioning, shown in Reference 6, the CHI started discharges are found to be considerably more reproducible than the inductive only cases [6]. CHI discharges can also 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 [6]. These results point to the very robust nature of the CHI startup process, which could also be used as an initial target by other solenoid-free current drive methods that generally require the presence of a high quality field null under very dynamic conditions, which is difficult to achieve in machines containing blanket structures.

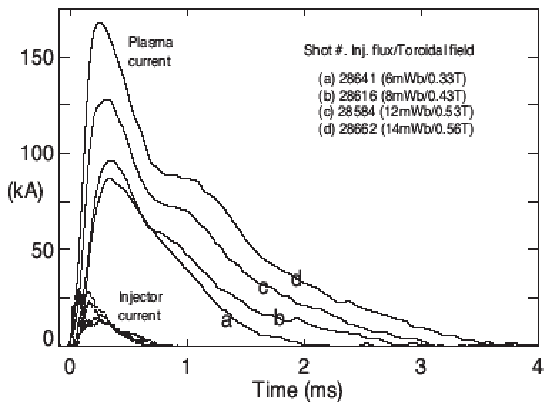

Figure 3: The amount of useful closed flux plasma current increases with the injector flux, which is a measure of the maximum poloidal flux the discharge can contain. The capacitor bank charge voltages for discharges (a) to (d) are 2.7, 2.7, 3.4 and 3.9 kV respectively.

In conclusion, it has been shown that the CHI process can be used to produce useful seed closed-flux plasma current. Closed flux is achieved by proper programming of the injector voltage, which can be easily achieved using a small capacitor based power system. The method does not rely on time changing poloidal field coil currents making it very attractive for reactors in which poloidal field coils would be located outside conductive vessel components and blanket structures. CHI startup works very well on HIT-II. The method is simple and highly reproducible. It saves volt-seconds and has allowed HIT-II to consistently produce higher current discharges than what is possible by induction alone. It is largely insensitive to field errors and changing wall conditions.

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