Research Thrust on Plasma Startup & Ramp-up

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1. Mission and Scope Summary

ST Reactors are predicted to operate at high values of the bootstrap current fraction. The required non-inductive current drive for optimized reactors that benefit from high-beta operation is a few percent of the total current. Such operating scenarios significantly reduce the auxiliary power input and lead to high-Q operation. Many of these features are also shared by the tokamak AT configuration.

Full non-inductive operation means that adding inductive components that are not needed during steady-state operation simply add to the cost and complexities of designing and maintaining these systems during steady-state operation.

For the ST in particular, developing methods for full solenoid-free operation allow reactor systems to be designed without the inductive central solenoid.

In support of this need, several experiments have explored methods for solenoid-free current generation is STs and tokamaks. While significant levels of current have been generated using these techniques, the magnitude of the initial startup-up current needs to be increased by at-least a factor of three so as to allow direct coupling to other non-inductive current ramp-up methods (neutral beam injection and RF current drive). Additionally, the physics and engineering requirements for these current drive schemes differ, and the synergistic benefits of operating some of these current generation techniques in combination with each other has not been studied.

If the initial current generated by one or a combination of these methods could be boosted to well above 500kA, then the requirements on the subsequent current ramp-up system becomes easier.

A recent review by the Toroidal Alternates Panel, identified Solenoid-free plasma start-up and current ramp-up to full current with minimal or no central solenoid as a Tier I Spherical Torus issue. Under the detailed description, it states: *"...Approaches might include some combination of coaxial helicity injection (CHI), plasma gun start-up, use of the outer poloidal field coil set to generate a toroidal electric field or current overdrive using bootstrap and some form of RF current drive. Alternate approaches which attempt to provide required volt-seconds by means of an iron core transformer or mineral-insulated solenoid also need to be explored. Once established, the plasma current must be ramped up, again with minimal or no volt-seconds, to the multi-mega-Amp level. .."*

The mission of this research thrust is to develop capabilities for solenoid free startup methods that would lead to the generation of toroidal plasma currents in excess of 500kA. Furthermore these currents would be coupled to neutral beams and RF current drive to ramp to current levels that exceed 1MA. With the proposed upgrades to the NSTX device, this is a realizable goal for the ITER-era.

This document describes the research gaps to be filled so as to develop Transient CHI capability to its full potential.

2. Closing Research Gaps for Startup & Ramp-up

The methods for solenoid-free plasma start-up under consideration are: Transient Coaxial Helicity Injection (CHI), Plasma Gun Startup, Outer PF Start-up, and electron Bernstein wave (EBW) Startup. Some of the advantages, reactor requirements and research gaps for these methods are shown in Table 1. In the event that a combination of these methods are unable to generate the required levels of startup current, the use of a mineral insulated solenoid or an iron core solenoid have been proposed as methods to generate a few hundred kA of start-up current in a ST CTF.

Of these, MAST will study high-power EBW start-up. The Pegasus device has a dedicated program for studying Plasma Gun Startup, and a separate White Paper by A. Sontag et al., discusses development of this approach. Outer PF Startup has been studied in JT-60U, to a limited extent in NSTX and new dedicated experiments are planned on DIII-D. This paper describes progress to-date using the CHI approach and the research gaps to fill so as to enable current generation in excess of 500kA using CHI and the subsequent coupling to neutral beams and High Harmonic Fast Waves on NSTX for a demonstration of solenoid-free current generation and ramp-up that exceeds 1MA.

Transient CHI Startup: The *Transient CHI* method has now successfully demonstrated coupling 100kA of closed flux current to induction on both HIT-II and the NSTX devices. It has produced a record 160kA of non-inductively generated closed flux current in NSTX demonstrating its capability for high-current generation. Furthermore the scaling of this method to future devices is attractive. Startup currents in the 2.5MA level range appear possible in a ST CTF.

The operational sequence for Transient CHI in NSTX involves first energizing the toroidal field coils and the poloidal field coils to produce the desired flux conditions in the injector region. A pre-programmed amount of deuterium is then injected into the cavity below the gap between the inner and outer lower divertor plates. On NSTX A 15 – 40 mF capacitor bank at up to 1.75 kV charging voltage is connected by an ignitron switch to the inner vessel and inner divertor plates, acting as the cathode, and the outer divertor plates and passive stabilizer plates, acting as the anode to form a discharge. After a programmed delay of 3 – 10 ms, when the plasma has expanded into the chamber and the toroidal plasma current is near its peak, the injector is short-circuited by a "crowbar" ignitron causing the injector current to decay rapidly. The plasma column detaches from the injector region to form closed flux, analogous to the detachment of a solar flare on the surface of the sun. Most of the divertor flux then reconnects the divertor electrodes again by the shorter path. A feature of CHI plasma generation using this method is that flux closure can be demonstrated unambiguously by the persistence of plasma current after the injector current has been reduced to zero.

Reactor Insulation Requirements: Implementation of this method in a reactor requires the inner, the outer divertor plates or the dome region in a divertor to be electrically insulated from the rest of the vessel. The requirements on the insulator are not demanding as an insulator with a resistance of an Ohm or more would be adequate for this purpose. The primary requirement is that the current through the plasma load (which typically has an impedance of much less than 100 mOhms) significantly exceeds the current through the insulator. Furthermore this insulation capability is needed only during the initial several ms during plasma startup when no other sources of plasma or neutron radiation are present. After plasma startup this insulator could be shorted, if necessary. In a reactor environment, one possible way to implement this insulator would be to position it deep inside a dome divertor (positioned between the inner and outer divertor plates) in a “W” shaped divertor configuration, such as the type used on JET. This would shield the insulator from neutron radiation, while providing the needed insulation for the domed divertor region. Other insulation configurations are also a possibility.

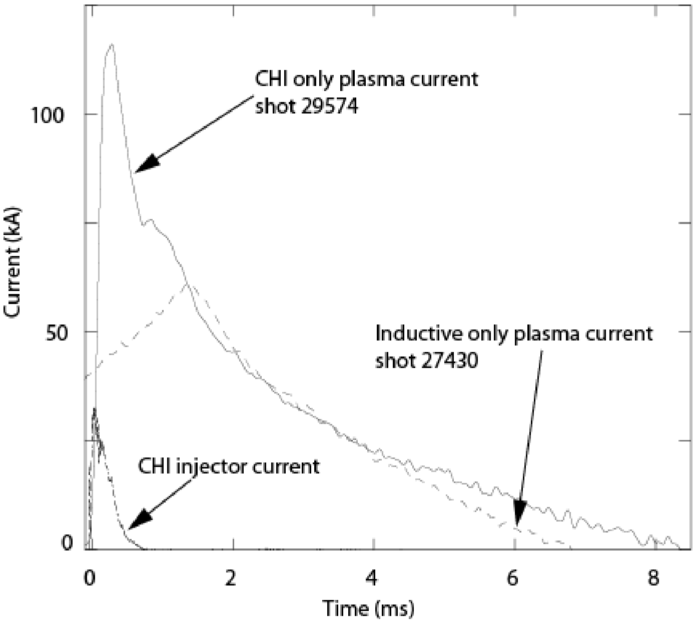

Figure 1. Comparison of the current decay time of similar magnitude plasma current plasmas produced using CHI and using the conventional inductive method. The current decay rate of a closed field line equilibrium is a good measure of the quality of the discharge. In this comparison current produced using CHI has the same decay rate as current produced using the standard, well-established, inductive method. 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. [R. Raman, T.R. Jarboe, et al., NF **45** (2005) L15-L19]

Because the insulation requirements are so modest, another possibility is that in future an appropriately designed conductor may be adequate for this purpose. More demanding insulator technology would be required for other components in a reactor and in comparison the requirements for the CHI insulator are much less demanding than for example the insulation capabilities for a mineral insulated solenoid. Although present insulator technology is deemed adequate, future developments in insulator technology between now and the time of a ST reactor design could be expected to provide even better solutions. *Thus, the requirements on insulator technology are not an issue for a solenoid-free startup method based on the CHI concept.*

Scaling: Research on HIT-II and on NSTX show that the attained toroidal current in a CHI discharge approximately follows the relation: $I_p = I_{injector}(\psi_{toroidal}/\psi_{injector})$. Here $I_{injector}$ is the external current provided by the power supply, $\psi_{toroidal}$is the toroidal flux inside the vacuum vessel and $\psi_{injector}$is the poloidal flux that connects the divertor plates [T.R. Jarboe, Fusion Tech. **15**, (1989) 7]. The ratio of the fluxes is referred to as the current multiplication factor. HIT-II achieved a current multiplication factor of 7 and NSTX has attained a current multiplication factor of 70. This is because of the much larger toroidal flux in NSTX discharges. As the toroidal field in future devices increases, so would the amount of toroidal flux available for current multiplication. Thus as one moves to larger devices, the current multiplication factor could be expected to further increase. For the purpose of this scaling exercise, we assume that ST-CTF would have a current multiplication factor of 50, a value that has been achieved on NSTX. On HIT-II, CHI discharges routinely operated at 30 kA of injector current. At this level of current density on the electrode surface, a device with the size of ST-CTF should handle 250 kA of injector current. Again, for the purpose of this scaling exercise, we assume an injector current of 50 kA in ST-CTF, a surface current density value easily demonstrated on HIT-II. This very conservative estimate results in a plasma current of 2.5 MA in ST CTF. *Thus with proper design of a CHI system, future STs have the potential to realize startup currents that are significant fractions of the total current, thus considerably easing the requirements on the subsequent current ramp-up system.*

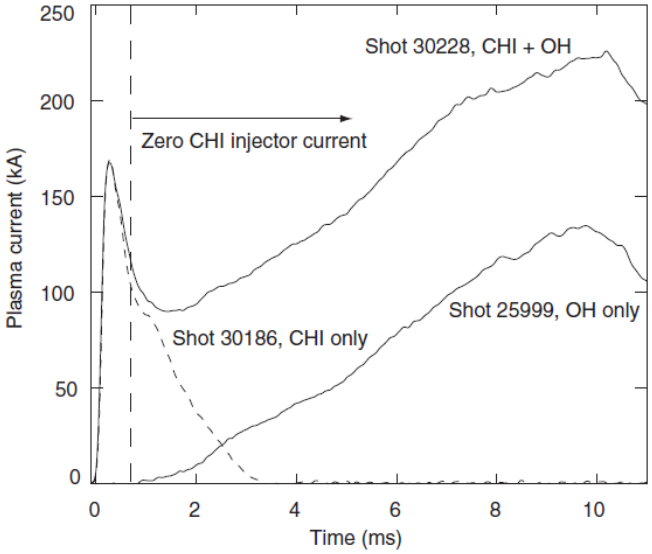

Figure 2. The dashed trace is a CHI-only discharge. The vertical dashed line shows the time at which the CHI injector current is reduced to zero. CHI current persistence beyond this time is due to the existence of a closed flux equilibrium. It is this closed flux plasma that is inductively driven in shot 30228. For comparison, an inductive-only discharge, using the central solenoid, under identical pre-programmed loop voltage time history (total 30mVs consumed) is also shown (shot 25999). [R. Raman, T.R. Jarboe, et al., NF **45** (2005) L15-L19]

Issues: *Low-Z impurities* - In order to realize high values of injector current, it is necessary that during startup the influx of low-Z impurities be reduced. This is the reason for the high values of injector current that could be realized on HIT-II. As shown in Figure 1 (from HIT-II), a discharge that operated with 30kA of injector current showed successful coupling to subsequent inductive drive and it out-performed what was possible with induction alone (Figure 2). Impurities were not an issue in these discharges that operated at high values of the injector current, showing that with clean electrodes, the influx of low-Z impurities could be reduced to a level where the power radiated by these impurities could be reduced to less than the power available from Ohmic heating. If auxiliary heating is available then the requirements on low-Z impurity influx is further relaxed. HIT-II operated with clean graphite cathode and a tungsten coated stainless-steel outer vessel anode. On NSTX, if the injector current exceeds 2-3kA, the influx of low-Z impurities (oxygen) increase to a level where the radiated power approaches the power available for Ohmic heating. Because of the presence of water and oxidized compounds on the surface of NSTX divertor plates, there are limits to how much the injector current can be increased on NSTX while maintaining low levels of low-Z impurity influx. A campaign on NSTX that uses metallic divertor plates would allow NSTX to increase the CHI stared current to much higher levels at low levels of impurity influx. Spheromaks operating with metal electrodes routinely produce discharges with 500eV electron temperatures.

500 kA current generation – A planned upgrade in NSTX would increase the available toroidal field to 1T. This essentially doubles the available toroidal flux in NSTX CHI discharges. This should further increase the current multiplication. With current multiplication values of 100 and with 5kA of injector current, 500kA of plasma current should be realizable in NSTX-U discharges.

Further improvements: During the design phase of NSTX-U, one or both of the lower divertor plates could be insulated from the rest of the vessel. Insulating both divertor plates would allow the effective applied CHI voltage to be doubled. Recent simulations using the TSC code (C. Kessel) have shown that at a toroidal field of 1T (possible using NSTX-U), with 6MW of HHFW coupled power (that should be possible with the new double feed HHFW antenna) and 6MW of NBI (that includes the proposed second tangential NBI for NSTX-U), it should be possible to ramp a 100kA discharge to 1MA. *On NSTX-U, a 300-500kA CHI target should thus allow NSTX to demonstrate full non-inductive startup and ramp-up, identified by the TAP as Tier-I ST goal.*

Table 1: Advantages, Reactor Requirements and Research Gaps for the different solenoid-free plasma startup methods

Method	**Advantages**	**Reactor Requirements**	**Research Gaps**
Transient CHI (NSTX is the only device at this time with CHI capability)	Compatible with superconducting (SC) PF coils Very favorable scaling to larger devices (2.5MA projected for ST CTF)	Either the inner, outer or dome region of the divertor needs to be insulated from the rest of the vessel, but present insulators could meet this need	Experiments needed in a metal electrode configuration to reduce low-Z impurities Demonstration of Ip > 500kA and coupling to NBI and RF
Plasma Gun Startup	Gun sources could be removed from reactor after plasma startup	Number of gun sources and size of guns	Scaling needs to be understood

	Possibly compatible with SC PF coils		
Outer PF startup	No new components needed	Requires sufficient loop-voltage capability from outer PF coils	Effect of blankets and other conductive components between coils and plasma on the available loop volts
EBW	Easy to install Compatible with SC PF coils	Requirements on RF capability for desired current levels	Scaling with microwave power and coupling to other non-inductive current drive methods High current generation to be demonstrated
Mineral Insulated Solenoid	Solenoid is a 40yr old system	Insulation requirements, especially under repeated pulsing after neutron bombardment cycles	Insulation and solenoid capability under repeated neutron fluence cycles is not known
Iron core solenoid	Passive component with some electrical insulation Requires non-SC PF coils	Insulation and installation requirements	Maximum attainable currents?

3. Elements of the Research Thrust

The following research elements should be performed as part of this thrust using the indicated resources:

1) NSTX – Transient CHI
    i) Test the capability of long injector current pulses to remove oxygen contaminants from the lower divertor surface

   - ii) Test the capability of the field nulling coils in the upper divertor region to reduce the influx of impurities during a condition known as an absorber arc
   - iii) Test the capability of Lithium as a plasma facing component to reduce the influx of oxygen impurities
   - iv) Test coupling of a high current CHI discharge to current ramp-up using HHFW

2) NSTX-U – Transient CHI
   - i) Use the 1T capability to further validate scaling relations
   - ii) Using improved electrical insulation, and electrode surfaces increase the CHI produced current to ~500kA

3) At 500kA, and at the higher toroidal field TSC simulations show that non-inductive current ramp-up and sustainment should be possible using NBI and HHFW – a demonstration is needed.

4) Predictive modeling – NIMROD & TSC
   - i) develop models for integrated startup and ramp-up
   - ii) validate models against experimental data