Solenoid-free plasma startup using transient CHI – Progress and Plans

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Transient Coaxial Helicity Injection (t-CHI), a solenoid-free plasma startup method, has now been shown to work across three STs with vastly different sizes and configurations. The plasma current scaling to reactor-scale devices is well understood. It is now also being deployed on the Pegasus-III ST. Studies for ST40 suggest a 0.5 MA current-generation potential, which would put it within a factor of 2-3 of the value required for emerging reactor systems such as ST-E1, STEP, STAR, and FAST.

Introduction

Reducing the size of the fusion core in a low-aspect-ratio tokamak would enable a fusion power plant to be built at a much lower cost, allowing private companies to proceed without a large initial investment. Fusion energy development may require several such facilities to test and develop the capabilities needed for long-pulse operation. A recent paper by Menard et al. convincingly shows that such a device would not be able to utilize a full-sized solenoid without compromising net electrical power generation while being tritium self-sufficient [1].

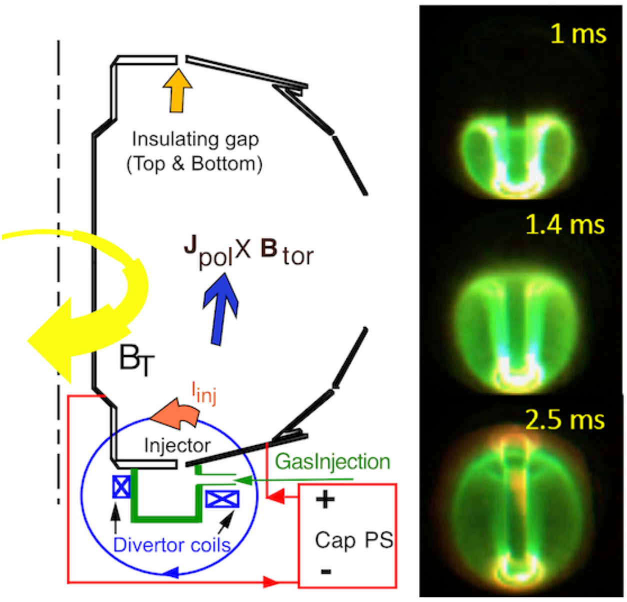

Fig. 1. Schematic of the NSTX machine components including the location of the insulating gaps between the divertor plates, the lower divertor coils used for generating the CHI injector flux. For CHI on NSTX, the vessel end opposite to the injector is referred to as the absorber region. Shown on the right are fast-camera fisheye images of an evolving CHI discharge at 1, 1.4, and 2.5 ms after discharge initiation [3].

In such devices, about 1-2 MA of plasma current generated via a solenoid-free plasma startup method would be ramped up primarily by non-inductive current drive methods. Transient Coaxial Helicity is a solenoid-free plasma startup method for which the scaling of plasma current generation to reactors is well understood. It has successfully generated closed-flux currents on three low-aspect-ratio tokamaks of vastly different sizes and configurations. These are HIT-II [2], NSTX [3], and QUEST [4]. Studies for ST40 suggest a 0.5 MA current-generation potential [5].

On NSTX, subsequent induction application to CHI-generated plasmas results in the discharge ramping to 1 MA with substantial solenoid flux savings, and, with subsequent neutral beam application, the discharge transitions to an H-mode. Compared to inductive startup, transient CHI plasmas naturally have much lower normalized plasma internal inductance, higher plasma elongation, and can form with a naturally diverted plasma configuration, features desirable for advanced scenario operations [3].

As shown in Fig. 1, a transient CHI discharge is generated by driving a short-duration pulse of current, using an external power supply (referred to as the injector current), along magnetic field lines (referred to as the injector flux) that connect divertor plates at one end of the ST. As the injected magnetic field lines expand into the vessel, the externally driven current is rapidly reduced to zero. This results in large-scale reconnection of the injected flux in the divertor region, thereby generating a closed-flux configuration.

The images in Fig. 1 show a discharge from NSTX in which about 0.2 MA of closed-flux current was generated 2.5 ms after the electrodes were first energized. Closed flux current during a transient CHI discharge is unambiguously assessed by measuring the toroidal plasma current that is retained after the open field line currents driven by the external power supply are reduced to zero. This is referred to as the persisting toroidal current after the CHI system is effectively switched off. The persisting current decays on an L/R time scale, much as an inductively generated plasma current would decay after the loop voltage generated by the central solenoid is reduced to zero. In MHD simulations, flux closure begins when the injector current is reduced from its peak value. So, while the actual generated closed-flux current may exceed the persistent current, estimating the current on open field lines can be ambiguous, but the toroidal current remaining after the injector current is reduced to zero is unambiguous.

The scaling of plasma current generation is a simple relation. It states that the generated plasma current is directly proportional to the injector flux or to the current driven in the main divertor coil that generates it. For fixed injector flux, the injector current is inversely proportional to the magnitude of the toroidal field [3]. A scaling that is very favorable for high toroidal field STs, such as the emerging ST reactor designs, as it means that for a fixed level of injector current, much more poloidal flux can be injected into the vessel, as it is this open poloidal flux that closes in on itself to generate the closed flux configuration.

Scaling to larger STs is well understood for the transient CHI method because it does not ramp the plasma current up gradually over a long period. For methods that slowly ramp up the plasma current, one needs to know how to adjust the external power input and other current-drive parameters to continuously compensate for the plasma's changing response and avoid MHD instabilities. In transient CHI, a major global reconnection event triggers the formation of a closed flux configuration [6], akin to the formation of a soap bubble, and this depends solely on the initial conditions. During the plasma formation phase, no feedback control, either from the PF coils or from other systems, is required. The PF coil parameters needed for the final equilibrium are pre-programmed.

Progress with transient CHI research

Transient CHI on the concept exploration device (HIT-II) and on the proof-of-principle device (NSTX) both employed toroidal ceramic breaks on the top and the bottom of the ST (Fig. 1). This allowed the entire inner vessel components to be electrically separated from the outer vessel. On both these devices, the outer vessel was at ground potential, and the inner vessel was at elevated potential. Subsequent studies of transient CHI implementation in a reactor [7] indicated that shielding the insulators from neutron irradiation may be easier if a simple biased-electrode configuration could be used. This motivated transient CHI activities on QUEST and on Pegasus-III [4,8].

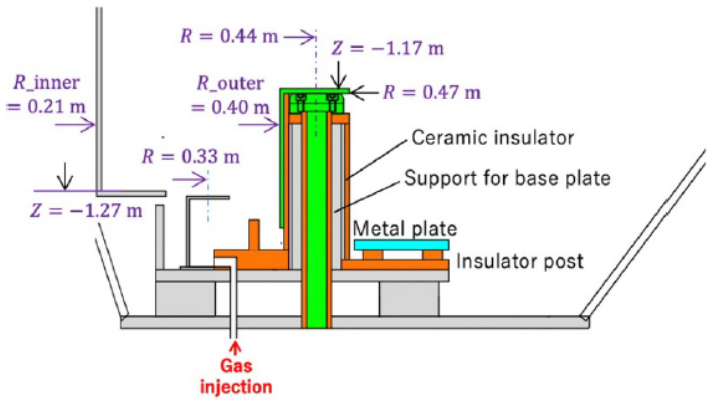

Fig. 2. Conceptual design for the modified CHI injector region for QUEST. The green regions show that a coaxial cylindrical electrode is mounted at the end of the outer divertor plate. These are insulated from the rest of the vessel and the support structure using ceramic components shown in brown. Reproduced from [9]. CC by 4.0.

The QUEST ST in Japan has now demonstrated that a CHI configuration based on a simple floating-biased electrode works just as well as the configurations used on HIT-II and NSTX [4]. An improved design of the single-biased-electrode configuration for QUEST is shown in Fig. 2 [8]. On QUEST, the lower outer divertor plate region is insulated from the rest of the vacuum vessel using ceramic insulators. In Fig. 2, regions at elevated voltage during the 1–2 ms duration when t-CHI is applied are shown in green. The brown regions are insulating ceramic components. The injector region is between the vertical cylindrical electrode at a radius of 0.4 m and the inner wall at a radius of 0.21 m.

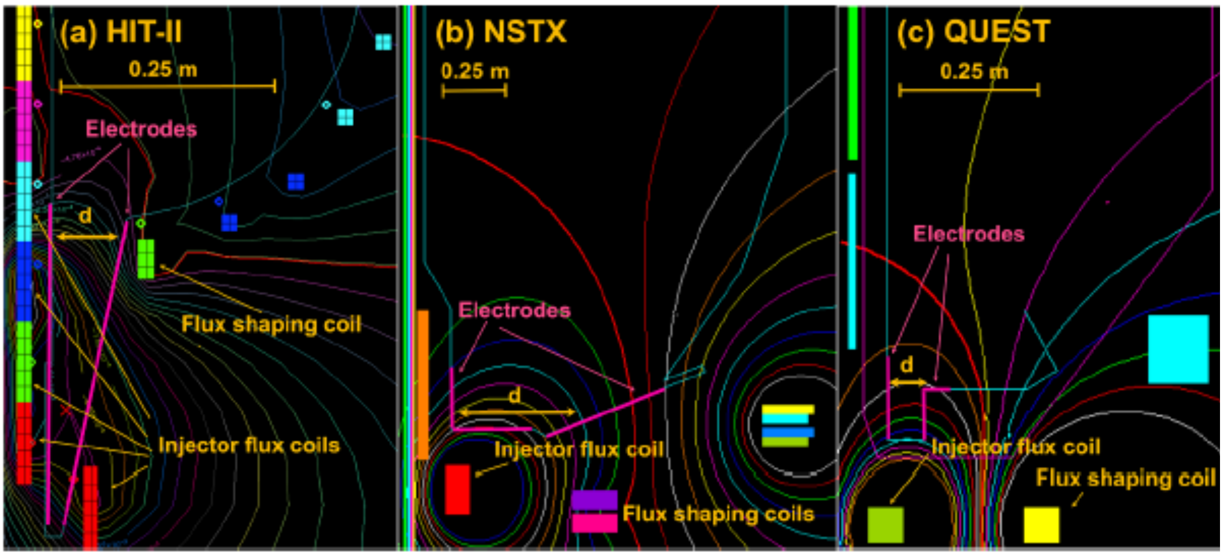

Fig. 3: Typical poloidal vacuum flux plots of the initial injector flux on (a) HIT-II, (b) NSTX, and (c) QUEST. In the (a) HIT-II and (c) QUEST closed injector configurations, most of the injector flux is confined to the region between the cylindrical electrodes. In (b) NSTX, which used an open injector design, the nearly horizontal electrode plates (the divertor plates) adjacent to the electrode gap necessitate the need for additional flux shaping coils to specify the injector flux footprint separation distance ‘d’. A smaller value for the parameter ‘d’ eases flux closure during the plasma formation phase. The thick pink lines mark the region of the CHI electrodes. Also marked are the injector flux coils and the flux shaping coils. Reproduced from [9]. CC by 4.0.

Here it is useful to note that the insulator need not be a perfect insulator. The electrical resistance of the insulator must be significantly higher than that of the plasma load so that nearly all the externally driven current flows through the plasma load. In experimental installations thus far, the insulator is typically shorted outside the machine with a high-power 50 Ohm resistor. This is done to provide an alternative path for the injected current in instances when plasma breakdown is not achieved. As seen in Fig. 2, QUEST uses a coaxial cylindrical electrode configuration as in HIT-II. Fig. 3 compares the CHI injector configurations and the dimensions used on HIT-II, NSTX, and QUEST [9].

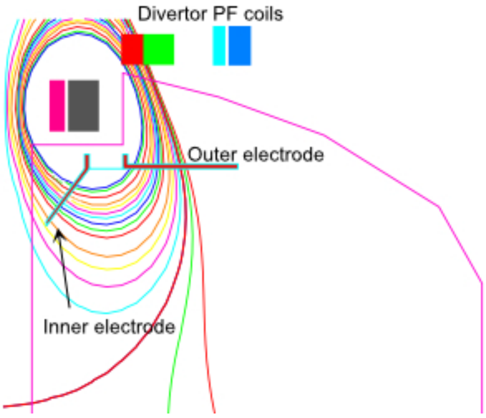

Fig. 4. On Pegasus-III, the CHI system is in the upper divertor region. The inner and outer electrodes are both insulated from the vacuum vessel. Several poloidal field coils are located near the injector region, which should permit finer control over the injector flux configuration.

Pegasus-III will use a double-biased electrode configuration and an injector configuration like that on NSTX. In a double-biased configuration, both the inner and outer divertor plates would be electrically insulated from the vessel and from each other. On Pegasus-III, the upper inner divertor plate would be at elevated potential, while the upper outer divertor plates would be at lower potential (Fig. 4). The capacitor bank leads would be connected to these two electrodes. The outer vessel would be at ground potential. The CHI electrodes would thus electrically float with respect to the vessel ground. This has the advantage that the externally driven current must flow from one divertor plate to the other. This would reduce the occurrence of spurious arcs, known as absorber arcs, in which current could flow from the high-voltage electrode to parts of the vessel connected by stray magnetic field lines.

Conceptual design studies for ST40 have examined both single- and double-biased electrode configurations [5]. The plasma startup scenario was modeled using the TSC code [5], and through an examination of the device hardware. It was found that the single-biased electrode configuration is relatively easy to implement. The CHI system could be installed on the upper part of the machine's vacuum vessel to avoid interfering with the ECH system in the lower part. The increased difficulty with the double-biased system is due to the need to design a new system on an already working facility. If CHI were to be part of the initial device conception phase, designing the double-biased configuration would be much easier.

Conclusions

Transient Coaxial Helicity Injection (t-CHI) has now been demonstrated on the concept exploratory device (HIT-II), on a proof-of-principle device (NSTX), and on QUEST using a reactor-relevant electrode configuration. All three devices differed substantially in size and configuration, attesting to the robustness of this plasma start-up method.

The transient CHI start-up method has been studied using the 2D TSC code [10] and the 3D resistive MHD code NIMROD [6].

Plasma current start-up at 0.2 MA has been demonstrated on NSTX. While the transient CHI current-generation scaling suggests the possibility of a >2 MA start-up, extrapolating to that level would benefit from an intermediate-level demonstration of current start-up.

The next step involves generating a 0.5 MA closed plasma with good vessel-wall coatings, such as Li, which was used on NSTX. NSTX has already demonstrated the coupling of inductive drive to a 0.2 MA transient CHI plasma with substantial flux savings and the compatibility of transient CHI-generated plasmas with H-mode operation. The next remaining step is to couple a 0.5 MA startup plasma to ECH, EBW, or NBI current drive. Such a demonstration, which ST40 is ideally positioned to carry out, would provide the necessary scientific and engineering basis and serve as a technical demonstration for solenoid-less plasma start-up and non-inductive current ramp-up for emerging systems such as ST-E1, STEP, STAR, and FAST to improve their designs aimed at minimizing the aspect ratio and increasing the net electrical power output.

Acknowledgments

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