3.4 OH-Solenoid-Free Start-Up Research

The elimination of in-board ohmic heating solenoid is required for the ST to function as an attractive fusion power plant. An in-board ohmic solenoid, along with the shielding needed for its insulation, increases the size and, hence, the cost of the plant. Thus ST-based fusion systems including the CTF (Component Test Facility) and power plant designs (e.g., ARIES-ST) assume complete elimination of the ohmic solenoid. Indeed designs for advanced tokamak reactors such as the ARIES series of devices also eliminate the central solenoid. The investigation of plasma start-up without the ohmic solenoid is a major component of the NSTX research program. The NSTX OH-solenoid-free plasma startup program addresses the IPPA goal 3.2.1.4 "Characterize the integration of non-inductive plasma startup via magnetic reconnection such as using Coaxial Helicity Injection (CHI) with other noninductive and inductive current drive techniques. Investigate a number of non-inductive techniques to start and to increase the plasma current in ST plasmas while at the same time minimizing magnetic flux and helicity injection."

Of the three US major magnetic fusion facilities (DIII-D, NSTX, C-Mod), at the present time NSTX is the only one actively conducting OH-solenoid-free start-up research. We will describe the Coaxial Helicity Injection and Outer-Poloidal-Field Coil Start-up concepts in detail in Sections 3.4.A and 3.4.B respectively. The rf-based start-up and ramp up concept is covered in the EBW section Sec. 3.3 and also in Chapter 4. At the end of this section (3.4) the overall plans for non-inductive start-up development in NSTX and the associated tool development are summarized.

Coaxial Helicity Injection - The only approach invested experimentally so far on NSTX for ohmic-solenoid-free start-up concept is coaxial helicity injection (CHI) as described in Sec. 3.4.A. This CHI concept is an outgrowth of the spheromak research [1]. A number of smaller helicity injection experiments were performed with some success prior to introducing it on NSTX [2,3,4,5,6]. The NSTX CHI has already produced about 400 kA of toroidal current with a record current amplification of 14 accompanied by distinct n=1 relaxation activities [7,8]. The CHI research on NSTX has been benefited greatly from a close collaboration with the HIT-II experiment at the University of Washington. The CHI near term research goal is to establish an understanding of the current penetration process and to confirm the existence of closed flux surfaces and to demonstrate coupling of the CHI produced current to other non inductive current drive methods.

Outer-Poloidal-Field-Coil Start-up - Because of the criticality of OH-solenoid-free start-up issue for ST research, the NSTX PAC has urged the NSTX team to pursue alternate methods of OH-solenoid-free start-up. We propose in Sec. 3.4.B, a concept utilizing only the outer poloidal-field coils to start-up the plasma current without the ohmic solenoid [9]. In our initial assessment, this outer poloidal field coil approach could generate up to 500 kA of plasma current utilizing the existing poloidal field coils and power supplies on NSTX. This method can be tested during the early phase of the 5 year plan, since much of the needed hardware is in place on NSTX.

RF-Based Start-up - Finally, there is a possible rf based concept using ECH/EBW [10]. The ECH/EBW experiment can be tested when the ECH/EBW high power system becomes available in FY 07-08 as described in Sec. 3.3. By using a trapped particle configuration, strong ECH/EBW electron heating can generate sufficient electron precessional toroidal current (~ tens of kA) to generate closed flux surfaces. Once the closed flux surfaces are formed, the bootstrap effect increases the plasma current. One can then inject multi-MW HHFW power to ramp the current up by further increasing the bootstrap and other pressure driven currents in addition to the active current drive (see Chapter 4.)

3.4.A. Coaxial Helicity Injection

3.4.A.1 Research Program Goals for Coaxial Helicity Injection

CHI is a promising candidate for non-inductive current initiation and has, in addition, the potential to drive edge current during the sustained phase of a discharge for the purpose of controlling the edge current profile. Other possible benefits include inducing edge plasma rotation for transport barrier sustainment and controlling edge SOL flows. The development of these methods will improve the prospects of the ST as a fusion reactor.

3.4.A.2 CHI implementation on NSTX

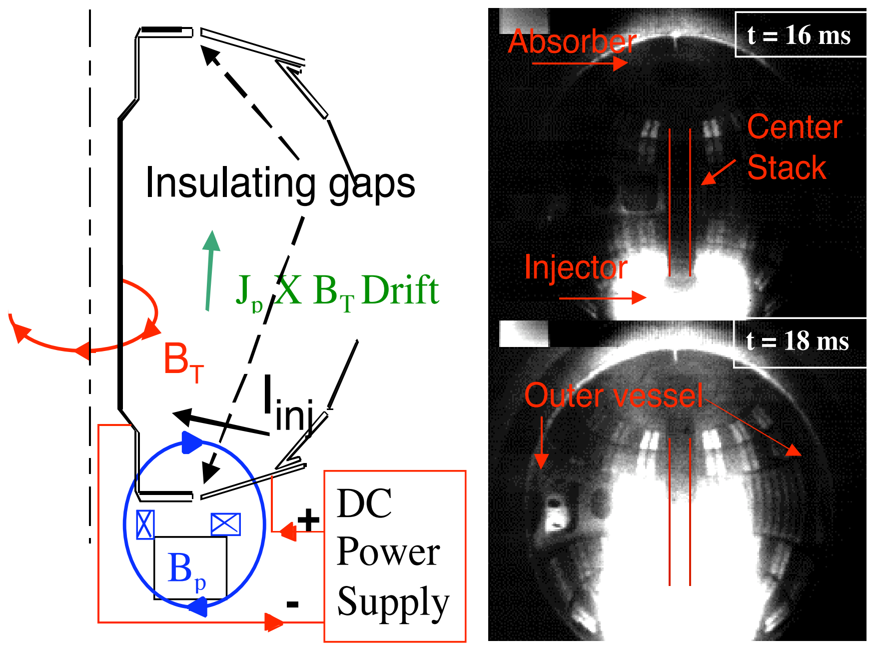


Figure 3.4.A.1 Schematic of aspects of an NSTX CHI experiment, showing the insulating gaps in the vacuum vessel, the biasing between the inner and outer vessels, and the JxB force that transports the plasma arc into the vessel. On the right are visible camera images of a CHI discharge on NSTX shortly after discharge initiation.

The CHI set up in NSTX is shown in Fig. 3.4.A.1. The NSTX stainless steel vacuum vessel is fitted with toroidal ceramic breaks at the top and bottom so that the central column and the inner divertor plates (the inner vessel components) are insulated from the outer wall and the outer divertor. CHI is implemented by driving current in the plasma along field lines that connect the inner and outer lower divertor plates which act as electrodes. A 50kA, 1kV DC power supply is connected across the inner and outer vessel components, to drive the injector current. The standard operating condition for CHI in NSTX uses the inner vessel and inner divertor plates as the cathode while the outer divertor plates and vessel is the anode. A dedicated gas injection system in the lower divertor region injects gas from four ports in the lower inner divertor plates, equally separated toroidally. The CHI method drives current initially on open field lines creating a current density profile that is hollow. Taylor relaxation predicts a flattening of this current profile through a process of magnetic reconnection leading to current being driven throughout the volume, including closed field lines. Current penetration to the interior is eventually needed for usefully coupling CHI to other current drive methods and to provide CHI produced sustainment current during the long pulse non-inductive phase.

Experiments to date in NSTX have shown that CHI can be applied to a large ST for the production of substantial toroidal current [7]. CHI in NSTX has successfully generated 390*kA* of toroidal current using about 28*kA* of injector current [8]. Discharges lasting for 330*ms* have been produced using pre-programmed coil currents in the preferred "narrow" footprint condition [7]. Results to-date show the CHI plasma to be very dynamic with indications, both on magnetic pickup coils and in the soft x-ray emission, of large scale reconnection activity. Development of an equilibrium feedback control system is needed before these high current plasmas can be made stable for the purpose of discharge characterization.

3.4.A.3 Theory Status

Assessment of flux closure in a driven system, which is a requirement for plasma initiation and sustainment requires several experimental and theoretical tools. Ultimately, a direct current profile measurement using MSE is needed for an unambiguous demonstration of producing closed flux during a CHI discharge. However, in transient CHI discharges, demonstrating the persistence of toroidal current after the injector current has been ramped to zero would be sufficient for a demonstration of closed flux generation. In addition, consistency between the measured electron pressure profile and the time-averaged 2-D closed flux reconstruction from an axisymmetric analysis code, such as EFIT, would provide confidence that CHI is producing closed flux.

The Thomson Scattering diagnostic needed for electron pressure characterization is fully functional. MSE is expected to be available for first experiments in 2005, and available with full profile capability in 2006. The ESC code [12] has the capability for including current on open field lines and in the private flux region and has the capability for including wall currents. This code has already been used to reconstruct CHI discharges. These features have also now been implemented on the EFIT code [13] through collaboration with General Atomics. In the past the MFIT code [14] which is a current filament fitting code, has been used for control room use to obtain approximate estimates of the location of the CHI plasmas.

The TSC code [15] has been used to model the evolution of CHI discharges. The installation of the new absorber, as described in chapter 2, is expected to allow the routine production of absorber arc free discharges. This would allow for the capability to modify and improve the CHI boundary shape. We expect to use TSC simulations to help us with designing these new discharge scenarios. The 3D MHD code, CHIP [16], developed at Los Alamos National Laboratory, is being used to understand CHI reconnection physics. The code has been used to model CHI processes in a simple geometry. Implementation of the actual NSTX geometry will allow for a closer comparison of the simulation results with the experimental results, and help guide and understand the experiments.

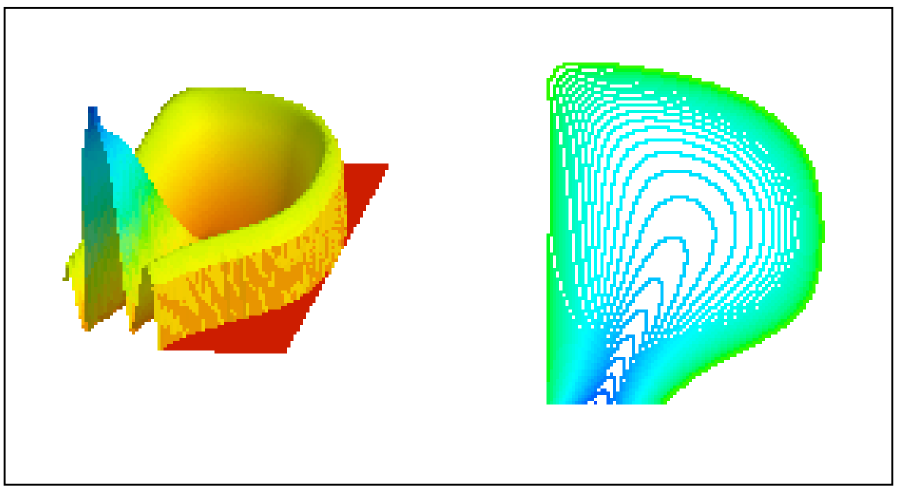


Figure 3.4.A.2: : The CHIP MHD code simulations showing surface plot of RJ_{ϕ} and contour plot of poloidal flux for a strongly driven CHI discharge.

3.4.A.4 Experimental Approaches to CHI: Transient and Long Pulse

Experiments on NSTX have until now focused on long pulse CHI discharges. These discharges have the potential to meet both the plasma startup requirement and the current sustainment requirement. However, recent experiments on HIT-II have successfully demonstrated a new method (referred to as transient plasma startup) for plasma startup and handoff to inductive operation [8,17]. The transient plasma startup method has resulted in volt-seconds savings. It has increased the reproducibility of inductive discharges and has considerably improved the performance of the HIT-II experiment by producing record plasma currents. These new results have motivated us to decouple on NSTX the plasma startup and current sustainment goals.

There are two objectives for CHI research on NSTX. The primary objective is to start-up the NSTX plasma using CHI and to hand it off initially for inductive operation and then later to a non-inductive current drive system. The second objective is to provide edge current drive during sustained non-inductive operation, for the purpose of controlling the edge current profile.

The plan is to meet the start-up objective by using transient CHI plasmas. However, the long pulse high current discharge development experiments will be continued, as these may have the potential to provide higher plasma startup currents and because these types of discharges could provide edge current drive for sustained non-inductive operation. The edge current demonstrations would require steady-state CHI discharges.

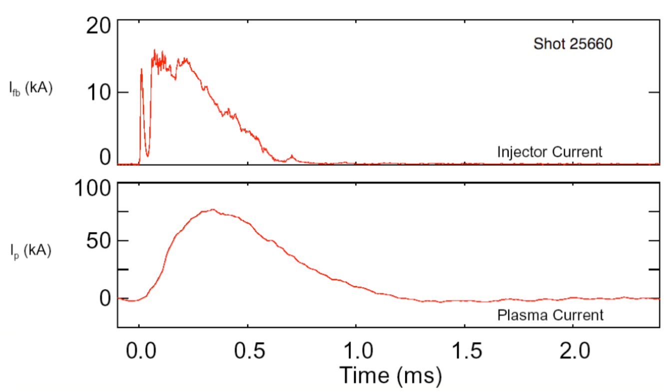


Figure 3.4.A.3: Shown are the CHI injector current and the CHI produced plasma current during transient CHI start-up.

Since this recent work on the HIT-II experiment on the transient CHI plasma start-up has fundamentally revised our thinking on CHI research, here we briefly review the HIT-II results. Plasma start-up using a transient CHI plasma handed off to induction has three steps. These involve (1) establishing a sufficiently high quality CHI discharge, (2) forcing detachment of the CHI flux footprints from the CHI electrodes and (3) applying induction from the central solenoid. During August 2002, these three steps were successfully tested on the HIT-II spherical torus at the University of Washington. CHI produced discharges that were handed-off to inductive operation resulted in significant volt-seconds savings. This is shown in Figure 3.4.A.3, which shows persistence of plasma current after the CHI injector current has been reduced to zero. This can only happen if there is closed flux current within the confinement chamber. This closed flux current has been successfully utilized in the HIT-II experiment to couple to and improve the quality of inductive discharges. As an example, we show in Figure 3.4.A.4, the coupling of this CHI produced current to inductive drive from the central solenoid. The top trace shows the voltage applied to the CHI electrodes to produce the short pulse CHI discharge. The second trace shows the injector current. The initial short blip in the third trace corresponds to the CHI produced plasma current. As the CHI produced current begins to decay, induction is applied from the central solenoid. This causes the plasma current to ramp up to about 150kA. Typical currents obtained using induction only, without the use of CHI startup are about 100kA. Under a systematic experimental study, as shown in Figure 3.4.A.5, it was found that CHI startup is a very robust technique, with discharge reproducibility much better than what can be obtained with induction alone, and it is much less sensitive to wall conditions than inductive only discharges.

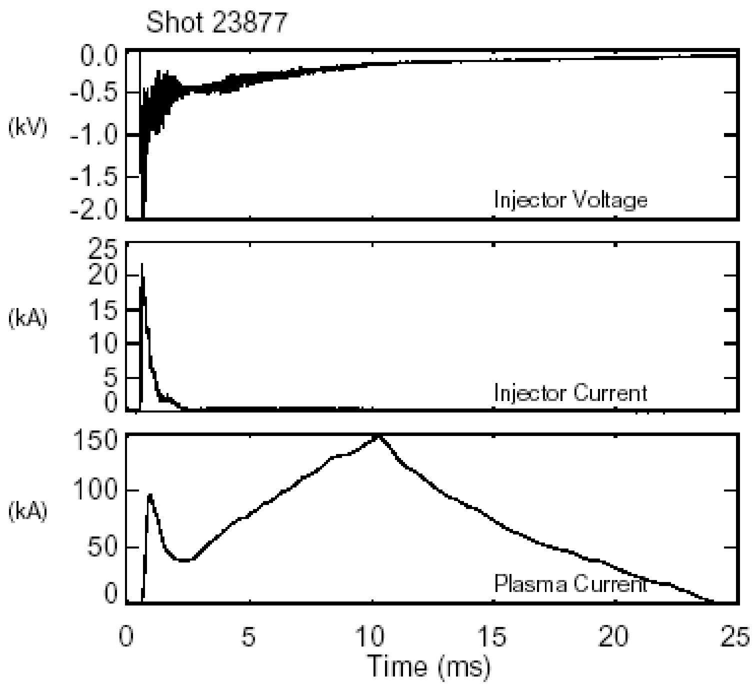


Figure 3.4.A.4: Coupling of a CHI produced discharge to inductive drive from the central solenoid. Shown are the applied CHI voltage, the injector current and the plasma current.

Three new results came out of this new method. First it was shown that CHI produces closed flux plasma, second it was shown that the plasma was of sufficiently high quality to couple to an inductive

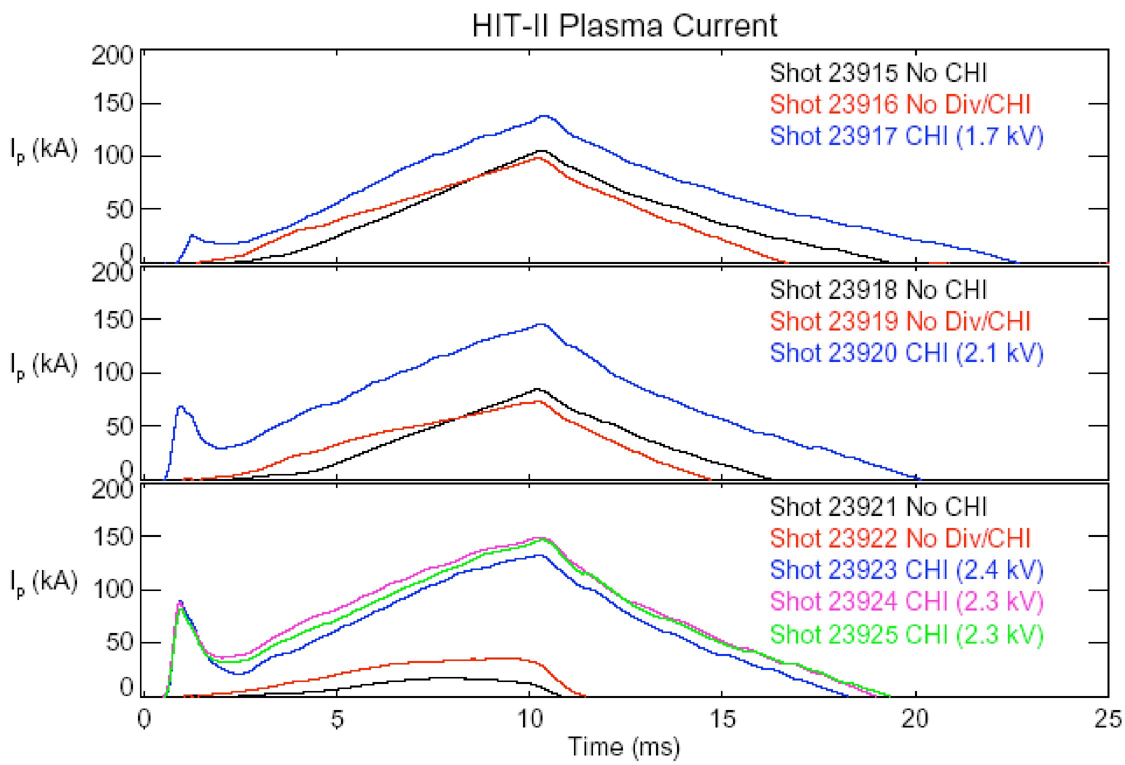


Figure 3.4.A.5: Continuous sequence of eleven traces showing plasma current. Shot 23917 has CHI start-up. Shots 23915, 23918 and 23921 correspond to discharges that have the same magnetic flux condition as in 23917, but with zero CHI voltage. Shots 23916, 23919 and 23922 contain only the magnetic flux conditions needed for inductive operation, and do not contain the CHI injector flux component; the applied CHI voltage is zero. Shots 23917, 23920, and 23923 correspond to the case of discharges with CHI startup, and have the same magnetic flux configuration as shot 23917. 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

discharge without degrading the inductive discharge. Third it was shown that CHI improved the performance of the inductive discharge by saving transformer volt-seconds. Additional work has shown that the method does not rely on any time changing poloidal field coil currents, and requires only the application of a short (few ms) voltage pulse to a pre-established vacuum magnetic flux condition. Because of this the method is very well suited to reactors where the poloidal field coils will be located outside blanket structures, which would not allow the possibility of rapidly changing magnetic fluxes inside the vessel. Additionally, a correlation has been found between the CHI produced plasma density and its ability to couple to induction, indicating a need for improved pre-ionization to enable CHI discharge initiation at lower pressures. The method is fully adaptable to NSTX and will be implemented on NSTX.

To implement the transient CHI start-up on NSTX, during FY 03 we will investigate the possibility of building a small capacitor based power supply, as on the HIT-II experiment, for transient CHI discharge initiation on NSTX. The present NSTX DC power supplies used for applying the CHI voltage were designed for long pulse operation, are not fast enough because of external inductances and the nature of the thyristor switches that does not allow the CHI current to be rapidly ramped up or the current to be rapidly reduced to zero, an operating feature necessary for transient CHI discharge initiation.

The current plan, therefore, is to implement the same procedure on NSTX for a demonstration of plasma start-up and hand-off to inductive operation during FY 04. Some NSTX hardware modifications (gas injection, speeding up CHI coils, absorber PF coil activation for absorber field control) will be implemented if needed. The 5 yr CHI program plan on NSTX is now described in greater detail.

3.4.A.5 New engineering tools and improvements for the CHI program

Some engineering improvements will be implemented for the CHI program as new information becomes available both from experiments and theoretical modeling.

1. *Investigate new methods for pre-ionization:* The ability to generate a CHI plasma discharge at low densities should produce a warmer CHI plasma with a longer current decay time. It may also produce higher initial CHI startup currents. Another benefit is the ability to operate at lower CHI injector voltages. Improvements to the pre-ionization system could range from modifications to the existing ECH system to improve its effectiveness to application of high power (multi-MW) HHFW for higher density pre-ionization and further heating.

2. *Consider higher CHI voltage capability:* The goal is to reduce the injector current while increasing the CHI produced toroidal current. It is important to conduct a study to see how the injector voltage affects this. This is an important control knob but the increased probability of absorber and external arcs at the higher voltage cannot be ignored. On the other hand, if voltage excursions during reconnection are large and the system is protected from these voltage excursions, the increased voltage requirement may not pose significant additional risks. FY 04 experimental operations are expected to provide experimental data that will allow for a re-examination of the need for increased injector voltage capability.

3.4.A.6 Plans for 2004 - 2008

The NSTX absorber region has been rebuilt to reduce the probability of absorber arcs. This in addition to absorber poloidal field control is expected to considerably reduce the incidence of absorber arcs. During the CHI operations in FY 03, no absorber arcs were evident. These results are preliminary as the absorber has not undergone full commissioning, but this is the first time ever that absorber arc-free operation has been possible for a whole day of operation in NSTX.

Our overall goal for this 5-yr research is to learn how to design CHI engineering systems for an ST reactor. Development of this knowledge requires the demonstration of two goals. These are: (1) transferring a CHI produced plasma to the inductive system and (2) transferring a CHI produced plasma to a non-inductive current drive system. In addition, developing the needed technology will maximize current generation using the CHI process. Other developments such as a demonstration of edge current drive and or inducing edge plasma rotation or controlling SOL flows by CHI will contribute toward the NSTX integrated scenario development.

<u>Solenoid-free startup and ramp-up of plasma current using transient CHI</u>

Additional items related to the use of CHI and other current drive techniques in these studies is discussed in Chapter 4.

2003: Initiate transient CHI experiments in NSTX

Following the success of the transient technique developed recently on HIT-II, a transient CHI scenario was developed. This involved a simultaneous ramp-down of poloidal field (PF) control coils with CHI current to detach the footprints of the CHI discharge, forcing reconnection and creating persistent toroidal current. A limited experimental operation was conducted. Planned discharges in the 100kA range were produced, but the persistence of closed flux was not seen in these limited discharges. Investigations into the cause of this resulted in the testing of new ideas on HIT-II, which showed that the injector current waveform shape was the key factor and not the action of ramping-down of the divertor coil currents. Issues related to discharge initiation timing and gas pressure were also identified as issues on NSTX that severely limited the number of useful discharges that could be produced. New procedures for discharge initiation are under development for implementation during the next CHI run.

2004: Transfer a CHI produced plasma to other current drive mechanisms

The simplified start-up procedure developed on HIT-II which does not rely on divertor PF coil ramp-down will be used to transfer a CHI produced discharge for inductive operation. The method uses the PF1B and PF2L coils to produce about 80mWb of injector flux that connects the lower divertor plates in a narrow flux foot print condition. Negative currents are driven in the PF3L and 3U coils so as to produce a magnetic well within the chamber. An appropriate magnitude of current will be provided in PF5 for vertical stability, while ensuring that the magnetic well configuration is maintained. The purpose of this magnetic well is to provide a stable region within the vessel where the CHI produced plasma could be trapped, near the mid-plane and on the center stack casing. A small amount of positive current will be driven in PF2U, to reduce the magnitude of the stray fields in the absorber, to avoid absorber arcs. Then, compared to previous experiments, a reduced amount of gas will be injected from a new gas injection plenum that was installed after the end of the previous CHI campaign. A short voltage pulse (few ms) will be applied to quickly ramp-up the CHI current and then to quickly quench the injector current after the plasma discharge begins to fill the vessel. This process, will cause the expanding CHI column to detach from the injector connecting flux, producing a closed field line plasma configuration that is now trapped in the pre-formed magnetic well. Induction from the central solenoid will be applied to demonstrate coupling of this plasma to induction. After initial demonstration of this concept, optimization of the injector current pulse in conjunction with strong auxiliary heating will be used to raise the level of the CHI produced current to as high a level as possible (during FY 05).

After techniques for handing a persistent CHI plasma to ohmic induction are developed, coupling to high harmonic fast wave heating will be investigated. Induction from the outer poloidal field coil system will be used to boost the current of a CHI discharge to levels where it can be driven using HHFW.

2005: Refine handoff and control of CHI to HHFW– Techniques for coupling CHI-initiated discharges to HHFW will be optimized. MSE measurements of the current distribution will be performed in this time period. In parallel, using optimized bias power pulse, by heating the CHI produced plasma with HHFW and/or NBI, we will increase the transient CHI startup current to ~ 300 kA levels.

2006: Extend CHI-to-HHFW coupled discharges to discharges with neutral beam injection, with the goal of solenoid-free ramp-up to a high poloidal beta target – CHI and HHFW and/or poloidal field induction, will be applied to raise the current to a value high enough to assure adequate fast ion confinement with the application of neutral beams. Neutral beam current drive and bootstrap current overdrive will be applied subsequent to or in parallel with HHFW to maximize the current developed. The preferred method for startup, transient or steady-state CHI (see below), will be determined.

With arrival of the 1MW EBW system in FY 06, synergistic effects of CHI and high power EBW will be also investigated.

2007 – 2008: Apply techniques for volt-second savings to high confinement, high bootstrap fraction, high beta plasma targets.

The techniques developed through 2006 may yield benefits regarding flux consumption that can be used in generating plasmas with the highest toroidal betas and high fractions of bootstrap current for periods of time longer than a current diffusion time.

Steady-state CHI operations

Even if transient CHI is successful in enabling solenoid-free startup, steady-state CHI techniques will be developed because of its potential for driving high level of currents (~ 500 kA) in NSTX, and because of the possible benefits of edge biasing and edge current drive in a pre-existing closed field line plasma.

2005: Assess benefits of improvements in PF flexibility to increase insulation in absorber region for high current CHI operations – CHI startup to 300 kA of toroidal current will be reestablished. Absorber magnetic insulation through absorber field nulling will be assessed in scans of applied bias voltage, gas pressure, and toroidal field.

Flux closure will be assessed in the most favorable conditions using detailed magnetics measurements and a measurement of the pressure profile using Thomson scattering. Magnetics measurements will be used to constrain 3-D MHD theoretical calculations. Measurements of magnetic helicity transport will be performed using an edge probe.

This development will take advantage of the rapidly evolving control system on NSTX. This control system will enable both programmed and feedback control of poloidal fluxes.

Develop edge biasing in ohmic plasmas – This will mark the beginning of investigations of the effects of edge biasing on edge rotation, the L-H transition, impurity influxes, and edge turbulence.

2006: Establish the preferred technique for plasma startup (transient or steady-state CHI) – This is described above in the section on transient CHI.

Establish edge current drive in an established CHI discharge – The effects on plasma performance will be assessed. Studies of edge effects will be expanded in this research period.

2007 – 2008 Extend operations to allow solenoid free ramp-up to high beta poloidal plasmas. Use CHI where possible to enable volt-second savings in highest performance, high beta plasmas – The goals regarding CHI ramp-up and volt-second optimization remain the same as for the transient CHI approach, discussed previously.

3.4.B. Plasma Start-up Using Outer Poloidal Field Coils

3.4.B.1. Introduction - As an alternative to CHI, we propose to investigate a concept for solenoid-free inductive plasma startup utilizing only the outer poloidal-field coils of NSTX. We describe an experimental setup for generating up to 500 hundred kiloamperes of plasma current in NSTX by this method. Such a plasma would provide a suitable starting point for the non-inductive current ramp-up experiments described in Chapter 4. If successful, this concept, is applicable as a possible start-up method for the NSST (Next Step ST) device [18], and will provide a crucial element for future ST-based nuclear facilities, such as the Component Test Facility (CTF) as described in Chapter 6.

The MAST experiment routinely uses poloidal field coils at a larger major radius than the plasma but still inside the vacuum chamber to initiate the plasma, However, to be able to extrapolate the technique to future experiments, and fusion energy systems, it would be advantageous to use only the poloidal field coils located outside the vacuum vessel wall for startup.

3.4.B.2. Basic Concept of the Plasma-Start-Up with Outer Poloidal Coil System - Using only the outer PF coils of NSTX, shown in Fig. 3.4.B.1, we are able to satisfy the conditions for plasma start-up which have been established by many previous experiments using a conventional central solenoid. There are three important conditions which need to be satisfied for inductive startup:

1. A region of low poloidal magnetic field must be created over a sufficiently large region of the vacuum vessel poloidal cross-section to allow the ionization avalanche to develop in the applied toroidal electric field. The condition for highly reliable breakdown can be expressed as $E_T \cdot B_T / B_P >$ ~1 kV/m, where E_T is the induced toroidal electric field, B_T is the toroidal magnetic field and B_P is the average poloidal (*i.e.* transverse) magnetic field. However, the application of suitable rf waves to break down the gas can relax this condition. For example, on DIII-D, operating at $B_T = 2$ T, with high-power ECH pre-ionization (~ 800 kW), start-up was achieved at $E_T = 0.3$ V/m with $B_P > 5$ mT over most of the vessel cross-section [19]. This represents with a value of $E_T \cdot B_T / B_P \approx 0.12$ kV/m.

The benefit of pre-ionization with even a very small ECH power (~ 20 kW) has been shown on NSTX (and also other ST devices including CDX-U, START, MAST, and PEGASUS) [20]. The proposed configuration for NSTX startup achieves $E_T \cdot B_T / B_P$ ~ 0.12 kV/m, comparable to the value achieved on DIII-D.

2. The field null, which is produced transiently by the combined effects of currents in the PF coils and the induced currents in the machine structure, must be maintained for a sufficient duration ~ 3 milliseconds to develop the avalanche. DIII-D experiment found that the time required increased as the loop voltage was reduced. However, with high power ECH pre-ionization (~ 800 kW) was able to shorten this process on DIII-D to ~ 2 msec even at low loop voltage. The field null is maintained in the proposed NSTX startup configuration for 3 msec.

3. After breakdown, the poloidal field coils must provide both fields to maintain plasma equilibrium and sufficient flux change for the current to ramp up to the desired level. The change in the vertical field required for equilibrium produces additional flux during the current ramp-up. These requirements are met in the proposed configuration.

3.4.B.3. Outer Poloidal Field Start-Up Configuration on NSTX – We propose to utilize the existing poloidal coil sets and available power supplies on NSTX for solenoid-free start-up. In Fig. 3.4.B.1 (a) the poloidal coils installed on NSTX are shown. The required current levels in Fig. 3.4.B.1 (a) are consistent with the current rating of the coils and power supplies for the short durations needed for this experiment. The mid-plane vertical field generated by the combination of PFs 2, 3, and 5 is compared with that generated by PF 4 in Fig. 3.4.B.1 (b). The combined field is shown in Fig. 3.4.B.1(c); the field null is created around R = 1.4 m. In Fig. 3.4.B.2 (a), the resulting two dimensional poloidal field contours are shown. As can be seen in Fig. 3.4.B.2 (a), a high quality field null is created. From Fig. 3.4.B.2 (b), one can see that about 0.16 Wb (at R = 1.0 m) is available for the current ramp up for this particular set of coil currents. In NSTX, under an optimized condition, about 0.3 Wb from the solenoid can produce a 1 MA discharge. Thus, the 0.16 Wb flux swing available from this scenario at R ≈ 1.0 m could, in principle, produce plasma currents of order 0.5 MA.

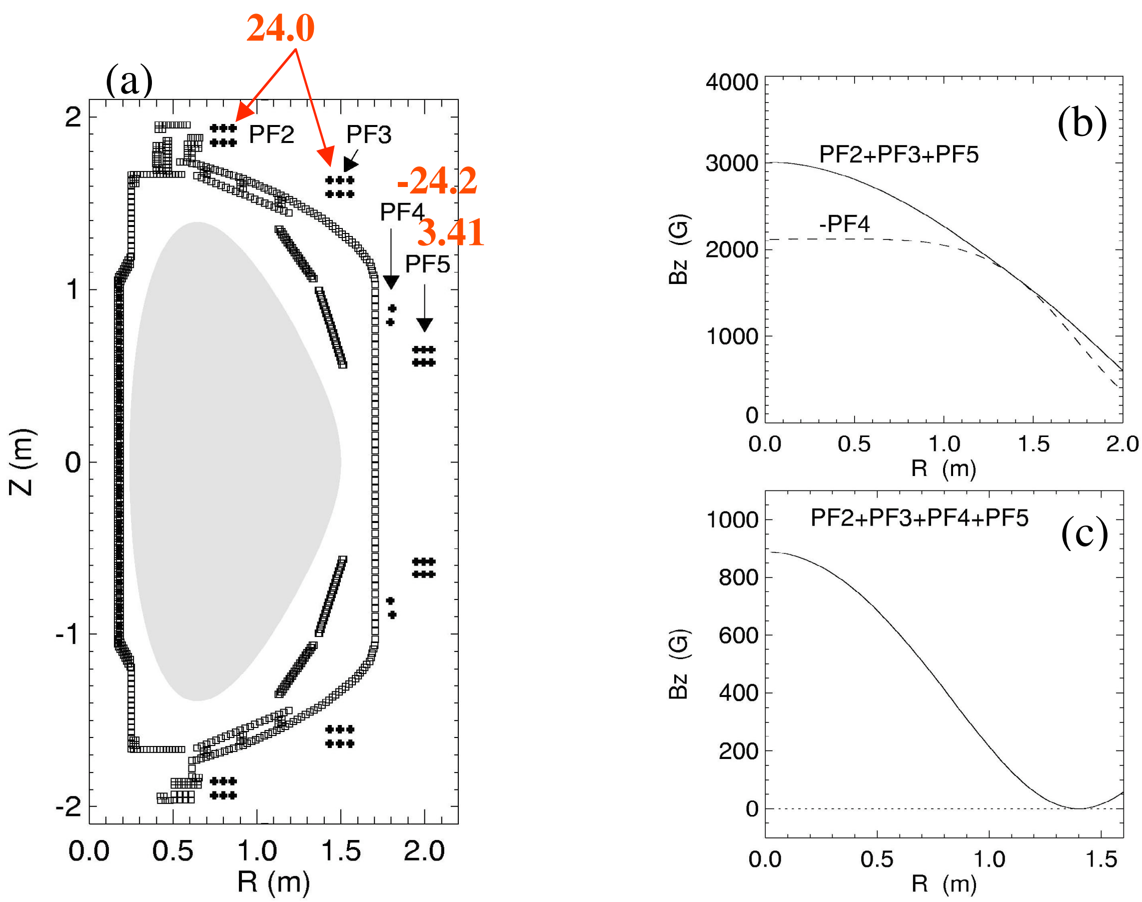


Fig. 3.4.B.1. NSTX Configuration. (a) A schematic of the NSTX polodial field coil set up. The required coil currents are indicated. (b) The mid-plane vertical field for the combination of PFs #2,d #3 and#5 and PF #4. (c) The mid-plane vertical field generated by PFs 2, 3, 4, and 5.

Pre-Ionization – On NSTX, start-up has been routinely achieved for a relatively low loop voltage of ~ 2 V with ECH pre-ionization. For the outer-PF-only start-up scenario, we expect to be able to generate a loop voltage up to 6 V transiently, corresponding to a toroidal electric field of 0.7 V/m at the radius of the field null, R = 1.4 m. The toroidal field there is up to 0.35 T. Within the broad region where the poloidal field is < 20 G, the value of $E_T \cdot B_T / B_P$ is above 0.12 kV/m. Since DIII-D was able to initiate the plasma for $E_T \cdot B_T / B_P$ as low as this value with strong ECH pre-ionization, start-up should be also feasible in NSTX if adequate pre-ionization is provided. Experiments planned on JT-60U will provide further information on the initiation condition with intense pre-ionization [21]. For NSTX, with a combination of ECH (~ 20 kW) and HHFW (~ 1 MW), a favorable pre-ionization condition may be created. On CDX-U, this combined ECH-HHFW technique was indeed shown to be effective in creating relatively robust preionized plasmas [22]. This preionization can be further developed and its effectiveness tested in the near term on NSTX using the existing ECH and multi-MA HHFWsystems. In a longer term, 1-MA ECH (FY 06) can be made available with the arrival of the high power to EBW system.

Maintenance of Field Null – During the initiation, it is important to maintain the field null for about

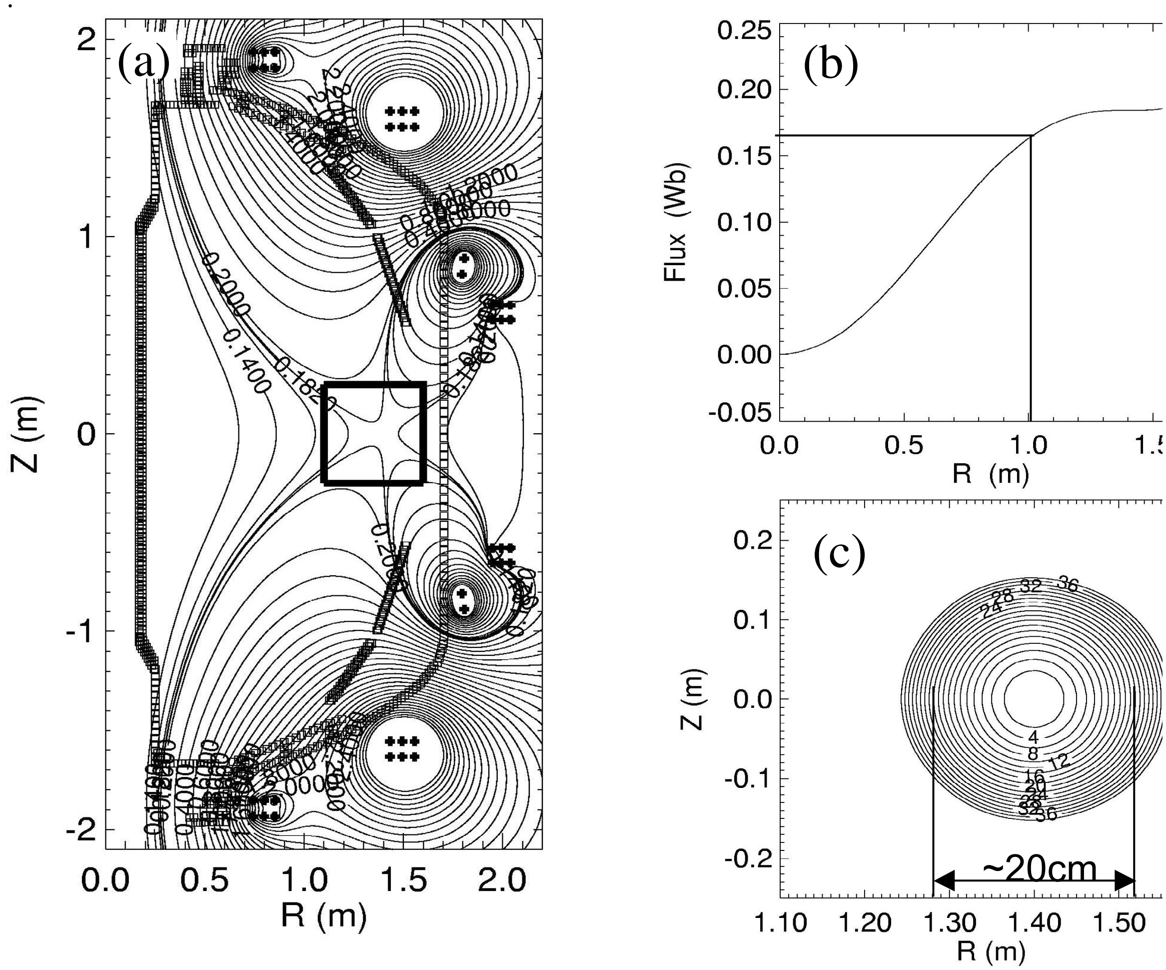


Fig. 3.4.B.2. The NSTX null-field configurations. (a) Flux contours. (b) Flux radial profile. (c) Mod-B surfaces of the field null region

3 ms to create the avalanche. Since the poloidal field is changing rapidly during this period and inducing significant vacuum vessel eddy currents, a dynamic modeling code to include the vacuum vessel eddy

currents has been implemented. This analysis shows that it is indeed possible to maintain the field null for about 3 ms, which should be long enough to initiate the avalanche process with the aid of sufficient pre-ionization as described above. The plasma stability with the presence of the eddy currents is an issue needs to be further investigated. The presence of the nearby passive plates in NSTX should aid the vertical stability. The PF 4 vertical position can be adjusted if needed.

Hardware and Modeling Requirements – This proposal for outer-PF-coil start-up uses the existing coils on NSTX and available power supplies to minimize the hardware modification required and disruption of the on-going experimental program. At present, the PF 4 coils are not energized but the existing PF1b power supply can be connected to the PF 4 coils relatively quickly. The PF 5 coil power supply must eventually be made bi-polar since its initial current is opposite to the direction needed for the plasma equilibrium. The subsequent current ramp up will require PF 5 to provide much of the equilibrium vertical field. However, for the initial test of the concept, the crucial initial breakdown and avalanche process can be tested by reversing the PF 5 connection to its existing power supply. The bi-polar capability can be implemented relatively quickly after confirmation of successful initiation. Once the plasma initiation is successful, feedback control must be introduced to maintain the plasma equilibrium and shape during the current ramp-up. The TSC code [23] will be utilized for the development of suitable current ramp-up scenarios to guide the development of control algorithms. The early application of HHFW electron heating should facilitate pre-ionization and subsequent HHFW current drive will produce current ramp-up.

3.4.B.4 Plans for 2003 - 2008

2003: Preparatory work scopes:

- Continue the basic start-up calculations including the wall eddy currents
- Assess basic power supply reconfigurations
- Analyze electro-magnetic forces and needs (if any) for further bracing of PF coils.

2004: Initial Plasma Initiation Experiments:

- Develop effective pre-ionization capability using ECH, HHFW and appropriate gas injection.
- Conduct initial breakdown and current initiation experiment up to ~ 100 kA with strong ECH/HHFW pre-ionization using the existing uni-polar supply for PF 5.
- After confirming successful breakdown, implement needed hardware changes including the bi-polar capability of PF 5.
- Develop optimized current ramp-up scenarios using TSC.
- Develop required magnetic sensors and control algorithms based on the TSC simulation.

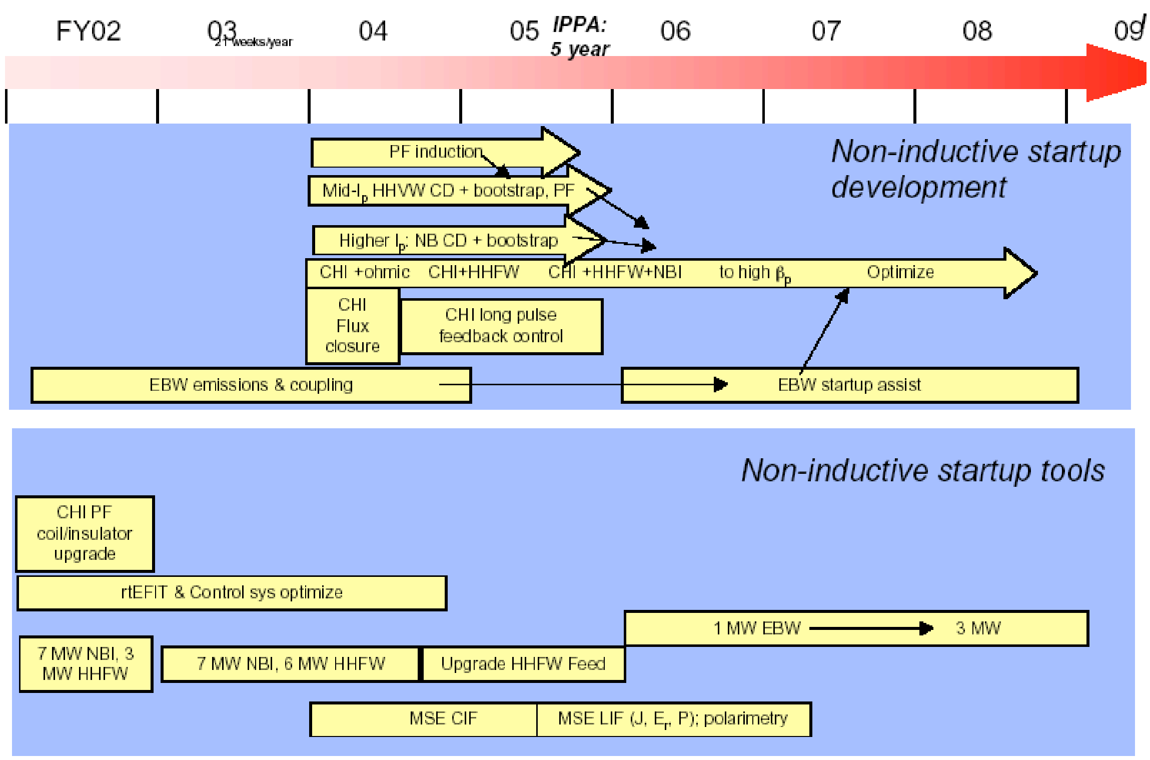
2005-06: Start-up Demonstration Experiments:

- Establish a few hundred (Ip ~ 300 - 500 kA) plasma discharges without use of the OH solenoid and higher power HHFW.
- Apply HHFW and/or NBI to achieve high beta poloidal discharges without the OH solenoid.
- Develop comprehensive understanding and predictive capabilities of the outer polidal field coil plasma start-up concept for future devices including NSST.

2007 -08: Assist the non-inductive research as a tool for ohmic-solenoid-free start-up.

3.4.B.5. Conclusions and Discussions – A plasma start-up concept using only the outer PF coils has been introduced. This method appears capable of generating in NSTX a solenoid-free start-up current of a few hundred kiloamperes, comparable to that produced by CHI. Once a significant level of plasma current is established, it should be possible to use other means of non-inductive current drive such as the bootstrap over-drive, and/or NBI / RF current drive to further ramp up and maintain the current (as described in Chap. 4.) The outer PF coil start-up concept can be implemented relatively quickly with minimal facility modifications and, if successful, can play an important role in the non-inductive research phase of NSTX as described in this Five-Year plan. The concept scales favorably toward larger and higher field devices, such as NSST, since the higher field tends to ease the breakdown requirements and the amount of available flux scales with the square of the major radius and linearly with the field. If successful, it will give us a method for the ohmic-solenoid-free start-up of future ST devices to a significant level of plasma current.

OH-Solenoid-Free Start-Up Plan



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