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Solenoid-free plasma startup in NSTX using coaxial helicity injection

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The favorable properties of the Spherical Torus (ST) arise from its very small aspect ratio. However, small aspect ratio devices have very restricted space for a substantial central solenoid. Thus methods for initiating the plasma current without relying on induction from a central solenoid are essential for the viability of the ST concept. Coaxial Helicity Injection (CHI) is a promising candidate for solenoid-free plasma startup in a ST. Recent experiments on the HIT-II ST at the University of Washington, have demonstrated the capability of a new method, referred to as transient CHI, to produce a high quality, closed-flux equilibrium that has then been coupled to induction, with a reduced requirement for transformer flux [R. Raman, T.R. Jarboe, B.A. Nelson, et al., Phys. Rev. Lett., 075005-1 (2003)]. An initial test of this method on NSTX has produced about 140 kA of toroidal current. Modifications are now underway to improve capability for transient CHI in NSTX.

Key words: solenoid-free, non-inductive, CHI, ST, NSTX, plasma startup, spherical torus, coaxial helicity injection

1. Introduction

The Spherical Torus is a magnetic confinement concept that has the advantages of high beta and a projected high fraction of bootstrap current drive. The favorable properties of the ST arise from its very small aspect ratio. However, such devices have very restricted space for a central solenoid, which restricts the inductive pulse duration, making sustained non-inductive operation necessary. Elimination of the central solenoid is essential for the viability of the ST concept and considered very important for the next generation of ST experiments. Thus, the development of methods to initiate and sustain a ST discharge without reliance on the central solenoid is a major element of the NSTX program plan(1 2).

Coaxial Helicity Injection (CHI) is a promising candidate both for plasma startup and for edge current drive during the sustained phase. The possibility of using CHI in a ST was first proposed in the late 1980's(3). The first experiments on helicity injection current drive in a ST were conducted on the Current Drive Experiment-Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory (PPPL)(4). The concept gained support as a result of experiments conducted on the Proto-Helicity Injected Torus, and the Helicity Injected Torus - I (HIT-I) at the University of Washington(5). These experiments used a thick conducting copper wall for equilibrium control of the CHI produced plasma configuration. These were followed by two other experiments, the Helicity Injected Spherical Torus (HIST) in Japan and the SPHEX device in the UK(6 7). These devices also employed passive wall stabilization for equilibrium control and confirmed that CHI could be used in the presence of an external toroidal field for the generation of a plasma configuration. Later HIT was rebuilt as the HIT-II experiment, which extended CHI to a true ST device by employing poloidal field coils for equilibrium control.

The CHI method drives current initially on open field lines creating a current density profile in the poloidal (R-Z) plane that is hollow. Taylor relaxation(8) 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 needed for usefully coupling CHI to other current drive methods and to provide CHI produced sustainment current during an extended non-inductive phase.

In CHI discharges, there exists a minimum voltage between the injection electrodes that can produce sufficient injector current to allow the injector flux to expand into the main vessel. This is generally refereed to as the “bubble-burst” current. Below this bubble-burst current, the field lines do not move and the injector is effectively a short circuit. Once the bubble-burst current is exceeded then the injector acts

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approximately as a current regulator and the plasma flows away from the injector at the E/B speed with the back e.m.f. of this motion equal to the applied voltage.

Helicity injection current drive is based on the fact that because magnetic field energy decays faster than the helicity, the configuration tends to relax towards a state of minimum energy while conserving helicity. Helicity measurements during magnetic reconnection events on START[9] showed that this conservation applies to hot spherical tokamaks. Helicity is the linkage of magnetic flux with magnetic flux and in toroidal geometry is given by $K = 2\int\phi d\psi$, where ϕ is the toroidal flux inside a flux surface and ψ is the poloidal flux, defined to be zero at the wall. In general the rate of change of helicity is given by $dK/dt = 2\int_{vacuum} \mathbf{E}\bullet\mathbf{B}\, dV - 2\int_{plasma} \mathbf{E}\bullet\mathbf{B}\, dV$, where the first integral is calculated over the plasma volume V in the absence of plasma current but with the same magnetic field and flux boundary conditions as apply to the second integral, performed in the presence of the actual plasma[10]. The first integral can be thought of as the injection term and is equal to $2V_{inj}\psi_{inj}$ for CHI where V_{inj} is the voltage between the coaxial electrodes and ψ_{inj} is the flux that penetrates both electrodes. The second integral can be thought of as the resistive dissipation of helicity and is often called K/τ_K. A very important implication of the Taylor minimum energy principle is that $\int_{pls} \eta\mathbf{j}\bullet\mathbf{B}\, dV = \int_{pls} \mathbf{E}\bullet\mathbf{B}\, dV$. This is not to imply that $\mathbf{E} = \eta\mathbf{j}$ locally. For transformer current drive the helicity injection rate is $2V_{loop}\phi_{wall}$.

A requirement for successful CHI current drive is that the energy per unit helicity of the injected helicity must be higher than that dissipated by the equilibrium ($\lambda_{inj} > \lambda_{tokamak}$, where $\lambda_{inj} = \mu_o I_{inj}/\psi_{inj}$ and $\lambda_{tokamak} = \mu_o I_p/\phi_{wall}$); and the injected linked flux must flow into the equilibrium volume.

It was generally believed that the development of non-axisymmetric plasma perturbations is needed for plasma startup using CHI. This mode of CHI operation can be referred to as *steady state* CHI, during which the CHI injector circuit is continuously driven for some time ($t_{pulse} > t_{L/R}$). A very significant development during the past two years has been the demonstration of a new mode of CHI operation, referred to as *transient* CHI[11]. This mode involves an axisymmetric reconnection and has been highly successful on the HIT-II experiment. While the steady state approach is still needed for sustained edge current drive, transient CHI has been extremely successful on HIT-II. The exploration of transient CHI in NSTX is described in a subsequent section.

1.1 Implementation of CHI in NSTX

The nominal NSTX machine parameters are: major/minor radii of 0.85/0.65 m, elongation ≤ 2.5, plasma volume 12.5 m^3 [1]. The stainless steel vacuum vessel of NSTX (volume 30 m^3) 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 plates as shown in Figure 1. Four pairs of poloidal field coils (PF2, 3, 4 and 5) placed symmetrically above and below the mid-plane outside the vacuum vessel are available for equilibrium control. The lower divertor region has an additional coil (PF1B) positioned below the inner divertor plate. The PF1B and lower PF2 coils allow the vacuum CHI injector flux to be set up so that it connects the lower inner and outer divertor plates as shown in Figure 2. We refer to the lower gap connected by the poloidal field as the injector and the complementary upper gap as the absorber because when voltage is applied toroidal flux flows out of the injector and into the absorber. These coils allow for the generation of up to 500 mWb of injector flux, defined as $\int B_{poloidal}\bullet dS$, where the surface of integration is over the entire center stack and inner divertor plates (the inner vessel components).

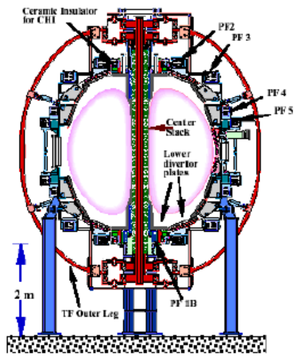

Fig. 1: The NSTX Machine layout showing the locations of the upper and lower insulator rings which allow the inner divertor plates and center stack to be biased with respect to the outer components to produce CHI.

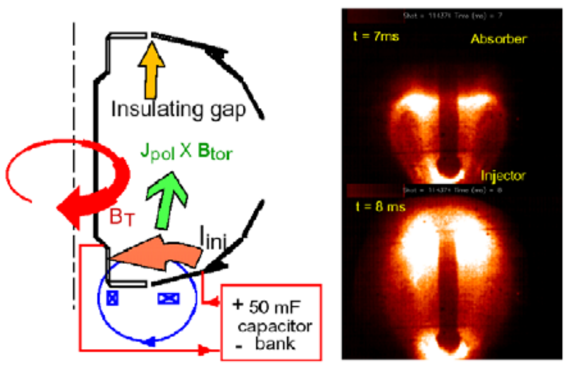

Fig. 2: Implementation of CHI on NSTX. The fish eye camera images show the growth of a transient CHI discharge in the NSTX vessel.

CHI is implemented on NSTX by driving current along field lines that connect the inner and outer lower divertor plates. The poloidal field connecting the lower inner and outer divertor plates is shown by the loop in Figure 2. A 50 kA, 1 kV programmable power supply is available to be connected across the inner and outer vessel components, to drive the injector current. During 2004, instead of the programmable power supply, a 50 mF capacitor bank was used at up to 1 kV for transient CHI operation. 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 are the anode. A dedicated gas injection system injects gas from four ports in the lower inner divertor plates, each toroidally separated by 90 degrees. For the CHI operation, four fixed volume plenums were filled to a specified pressure and quickly emptied into the divertor region by opening four fast valves.

The operational sequence for CHI involves first energizing the toroidal field coils and the CHI injector coils to produce the desired flux conditions in the injector region. The CHI voltage is then applied to the inner and outer divertor plates and a pre-programmed amount of gas is injected from the inner lower divertor plate ports. These conditions cause the gas in the lower divertor region to ionize and result in current flowing along helical magnetic field lines connecting the lower divertor plates. The ratio of the applied toroidal field to the poloidal field causes the current in the plasma to develop a strong toroidal component, the beginning of the desired toroidal plasma current. If the injector current exceeds a threshold value, the resulting ΔB_{tor}^2, ($\mathbf{J}_{pol} \times \mathbf{B}_{tor}$), stress across the current layer exceeds the field-line tension of the injector flux causing the helicity and plasma in the lower divertor region to move into the main torus chamber. Once extended into the vessel, currents need to be driven in the poloidal field coils for equilibrium position control.

1.2 Transient CHI

A feature of CHI plasma generation using this method is that unambiguous flux closure can be demonstrated by the persistence of plasma current after the injector current has been reduced to zero. Closed flux is achieved by appropriate programming of the injector current, which can be easily achieved using a small capacitor based power system. The capacitor bank is sized so that the energy in the capacitor bank mostly drains by the time the CHI produced plasma has fully elongated. This causes the expanding plasma column to detach from the injector region, through a process of 2D axi-symmetric reconnection and produce 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, the short way around; some of the remaining capacitor energy is dissipated along these field lines, in the private flux region.. The method is simple and highly reproducible and works very well on HIT-II. It has allowed HIT-II consistently to produce higher current discharges than was possible by induction alone. It is largely insensitive to field errors and changing wall conditions[11].

The first attempts to apply transient CHI in NSTX used a brief voltage pulse using the programmable rectifier power supply, while simultaneously ramping down the PF1b and PF2L coil currents. Two issues were quickly apparent. These were (a) a significant variability in the discharge initiation time and (b) the inability to reduce the injector current quickly once the discharge formed. The power supplies used for CHI are well suited for the long pulse steady-state discharges. However for transient CHI, the timing of the voltage pulse needs to be synchronized with the gas injection, so that the least amount of gas could be used for initiating the discharge. When the injected gas pressure was reduced, the thyristor switches used in the rectifier power supplies did not maintain a voltage across the load.

Further supporting experiments on HIT-II showed that proper injector current programming was required and that there was, in fact, no need to ramp-off the injector flux or change the divertor coil currents[12]. This new finding considerably simplifies the application of transient CHI on future larger machines as magnetic flux need not penetrate conductive structures on a fast time scale, and because the method is compatible with the use of super-conducting PF coils. This led to the design and construction of a capacitor based power system for transient CHI experiments in NSTX.

A 50 mF CHI-specific capacitor bank for transient CHI was designed and commissioned. Although the capacitor bank was designed for 2 kV operation, initial experiments were restricted to 1 kV. The system is comprised of up to ten 5 mF capacitors in parallel and an ignitron switch. A 50 mΩ resistor in series with each capacitor protects the system in case of a short circuit within a capacitor. The overall system resistance is about 5 mOhm with all capacitors in parallel. This in combination with about 1 μH of external inductance ensures that the capacitor bank system is critically damped. Most of the external inductance is due to 5 RG-218 coaxial cables connected in parallel, which are used for current transmission from the bank to the main CHI current feed terminals on NSTX. The peak current capability of this system is about 50 kA, with a current pulse quarter-cycle time of 2 ms.. To protect NSTX, for example in case the CHI discharge fails to initiate, the capacitor bank is automatically discharged into a resistive load about 80 ms after the switch ignitron is triggered. The primary results from the 2004 run are summarized below.

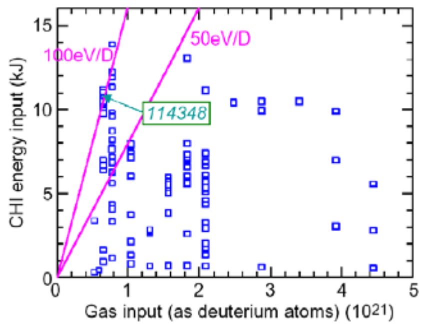

Fig. 3: Plot of total amount of injected gas versus energy input per particle. Only for the lowest total gas injection cases, is there is sufficient energy in the capacitor bank to ionize fully and heat the injected particles. Reducing the amount of injected gas with improved pre-ionization and increasing the capacitor bank voltage closer to the full 2 kV limit will increase the available energy by a factor of four and provide adequate energy per particle.

To test the new capacitor system under varying load conditions, scans of the injector flux and gas pressure were conducted. At high injector flux (85 mWb, corresponding to 9.4 kA in the PF1B coil), no bubble burst was observed even at an injector current level of 20 kA. This is consistent with our understanding of the bubble-burst current magnitude, which states that this current is proportional to the ratio of the injector flux squared divided by the current in the TF coil[3].

Operation at this condition also required higher gas injection pressure for breakdown, which implies less available energy per injected particle. This is shown in Figure 3, which shows that discharges with the least amount of injected gas have more energy per particle. These discharges with the lowest amount of injected gas also had the lower injector flux values, 45 mWb, corresponding to a PF1B coil current of 3.5 kA. As shown in Figure 4, discharges with lower injector current also had the higher current multiplication ratio, I_p/I_{inj}. A record 40 times current multiplication was seen in NSTX for the first time. This is an important result as it allows the possibility of operation under low divertor heat flux conditions. Further reductions to the gas injection pressure were restricted by the a failure to break down the gas. Further improvements to the pre-ionization system and increases to the capacitor bank voltage are needed to operate at lower gas pressures.

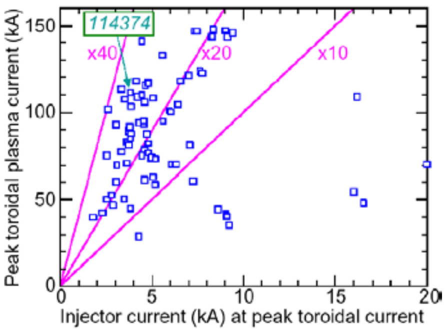

Fig. 4: Plot of the obtained toroidal current to injector current. Discharges with the lowest injector current have the highest current multiplication. Discharges with the lower injector current also have the lower injector flux and the lower values for the total gas injection.

An example of a discharge obtained at the lowest possible gas injection pressure is shown in Figure 5. The discharge shows the production of about 140 kA of toroidal current, but persistence of the toroidal plasma current beyond the end of the injector current pulse has not yet been observed. Current persistence signifies the presence of a closed flux equilibrium (for an example see Figure 2 in Reference 11). Thomson scattering measurements of the electron temperature show that the electron temperature increases as the total amount of injected gas decreases, consistent with the data from Figure 5, again pointing to the need for a further reduction in the total amount of injected gas. The highest electron temperature thus far measured in NSTX transient CHI discharges is 16 eV.

An important feature of these discharges at the lower total gas injection is that absorber arcs do not terminate the discharge. An absorber arc is a condition that occurs when current flows along the absorber insulator surface (or in the gap region between the divertor plates at the top of the machine). This is an undesirable condition as it reduces the productive injector current and also has the potential to damage the CHI absorber insulator. In the previous NSTX experiments, when absorber arcs occurred, their resistance was much less than that through the main plasma load, so the main CHI discharge would quench. For the shot shown in Figure 5, at 11 ms, an absorber arc initiates. This is seen both on the fast camera fish-eye images and from the rise in the injector current. However at 13 ms the absorber arc quenches and the discharge transfers back to the injector. This is because of the improved insulator configuration in the new absorber[14], which for the case of low gas pressure cases increases the impedance of the absorber to a level that is comparable to that of the main plasma load. So in these new discharges when the CHI was operated at low gas pressure,

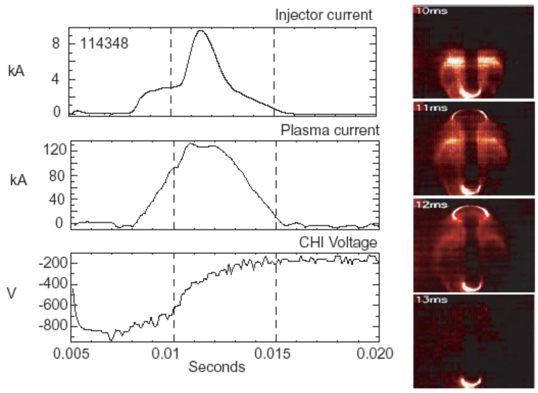

Fig. 5: A transient CHI discharge using the capacitor bank. The images on the right are fish-eye visible images from a fast camera.

the occurrence of an absorber arc did not quench the main CHI plasma discharge. Operating CHI with even less gas injection should further reduce the severity of the absorber arcs.

2. Discussion

For the transient CHI process the capacitor bank must satisfy certain requirements. First there must be sufficient energy in the capacitor bank to produce the bubble-burst current. The bubble burst current requirement states that the injector current is proportional to Ψ^2_{inj}/ I_{tf}[3]. The strong dependence of the required injector current on the injector flux and the weaker dependence on the current in the toroidal field coil has been seen in the HIT-II experiments and in previous NSTX experiments. For the injector flux values of interest, based on previous experiments in NSTX, an injector current of up to 35 kA may be needed for transient CHI experiments. The 50 mF capacitor bank charged to 2 kV easily satisfies this requirement.

The second requirement is related to how quickly the CHI discharge can fill the vessel. This is dependent on the applied injector voltage as this sets the rate at which toroidal flux moves across the injector and absorber gaps. For nominal conditions at 0.3 T on axis, there is about 1.4 Wb of toroidal flux inside the NSTX vessel. For 500 V across the injector electrodes, the time needed to displace all of the toroidal flux within the vacuum vessel is about 2.8 ms. Doubling the injector voltage will reduce this time to about 1.4 ms. Again, the quarter cycle pulse duration of the capacitor bank in NSTX satisfies this requirement.

The third requirement is that there should be sufficient energy in the capacitor bank to fully ionize and heat all of the injected gas. Typically about 50 eV is needed per ion for ionization and about 60 eV per ion to increase the plasma temperature to 20 eV. In present experiments, the lowest amount of injected gas was 1.1×10^{21} deuterium atoms, which should require 17 kJ for complete ionization and heating. The lowest gas injection was set by breakdown limits. This is consistent with the data shown in Figure 3, which shows that even for the lowest gas injection cases there was barely sufficient energy available for ionization and heating. The data also showed that the highest measured electron temperature of 16 eV was for a low gas injection case and for the high gas injection cases, electron temperatures were much lower and generally around 6 eV. Increasing the voltage level to 2 kV provides a factor of four increase in available energy. In addition at the higher voltage, breakdown should occur at lower gas pressures, which should allow even less amount of gas to be injected. Both these essential changes to the operating conditions for transient CHI should cause the temperature of the CHI discharge to increase, a condition that is necessary for a demonstration of current persistence after the injector current has been ramped to zero.

The fourth condition defines the maximum toroidal plasma current that can be produced in terms of the energy available from a given capacitor bank system: $^1/_2 L_p I_p^2 = {}^1/_2 CV^2$. The inductance of the toroidal plasma current on typical closed flux surfaces in NSTX is about 0.5 to 1 μH[13]. For 17 kJ used in the 2004 experiments, the maximum possible current in the plasma should be 180 – 260 kA. Experimentally the maximum CHI produced toroidal current was 150 kA. At 2 kV, the upper limit on the CHI produced current is 400 – 600 kA.

A final requirement is that the flux footprints on the CHI electrodes should be sufficiently narrow and that currents need to be provided in the external poloidal coil system to maintain the CHI produced discharge in equilibrium. As part of NSTX machine upgrades for producing more elongated plasma in NSTX, the PF1A coil is being redesigned to reduce its length to half its present value while displacing the axial center of the coil away from the center by half its former length. This modification benefits CHI plasmas as well as it allows a further reduction to the injector flux footprint width. For equilibrium, currents will be pre-programmed in the PF coil system corresponding to values needed for the final equilibrium that would exist after the CHI injector current has been reduced to zero. An added benefit for 2005 operations is the availability of the PF4 coil, in which a small (few kA) current can be driven (in the same direction as the plasma current) to pull the evolving CHI discharge onto the conductive passive plates. This has three advantages. First, image currents on the passive plates will maintain the initial transient CHI discharge in equilibrium. Second, the main CHI discharge is directed away from the gap in the absorber region thus reducing the incidence for absorber arcs. Finally, this is also the condition that is needed for next-step experiments during which the initial CHI produced current will be ramped to higher current levels using the outer PF coils. At present three different outer PF startup scenarios have been proposed for NSTX. Two of these cases rely on the presence of a high quality field null, while the third relies on high power auxiliary heating. For these methods the most challenging part is achieving the initial phase of breakdown and closed current establishment without using too much of the available inductive volt-seconds from the outer PF coil system. The pre-existence of a toroidal plasma equilibrium will allow the available inductive volt-seconds from the outer PF system to be used more efficiently to ramp the initial current to higher values. For all these cases, the loop voltage is highest near the outer part of the vessel, so it is preferred that the closed field line equilibrium rest on the outer passive plates rather than the inboard center stack.

3.0 CHI related hardware modifications to NSTX

Absorber modifications: The original NSTX absorber had the disadvantages of a short insulator on the outboard side of the vessel, the possibility for easy connection of the cathode and anode vessel regions by magnetic flux and a lack of nearby PF coils to reduce the poloidal field in the absorber.

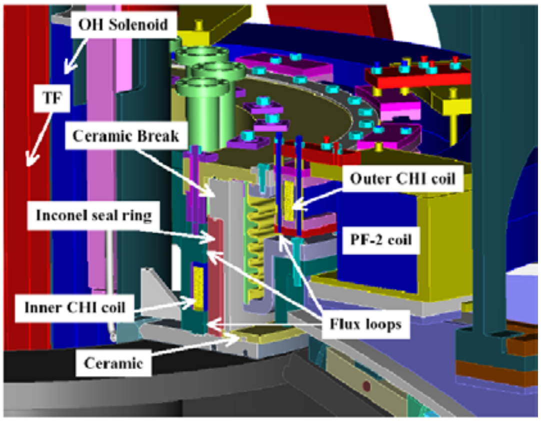

Fig. 6: The present NSTX CHI absorber insulator and surrounding structure.

A 3-D drawing of the absorber now in place is shown in Figure 8[14]. The design for this absorber drew extensively on the very successful design features used on the HIT-II experiment. Its primary features are a long insulator on the inboard high-field side, as on HIT-II, improvements to minimize the possibility of connection of the anode and cathode by magnetic field lines and two nearby PF coils to null stray fields in the absorber. Although these absorber coils have not yet been used, results show the new absorber to be more resistant to arcs.

Improved pre-ionization: The lowest neutral pressure at which a discharge could be initiated was limited by the lowest pressure at which breakdown could be obtained. On HIT-II, plasma injectors are used to initiate CHI discharges[15]. Because of the high levels of magnetic field near the NSTX center stack region and the 350^0 C bake-out temperatures in NSTX, these injectors cannot be installed in the required location in the injector region. However, calculations show that injecting gas from beneath the lower divertor plate region while injecting about 10 kW of ECH power into the region, will produce a combination of gas and ionized plasma conditions similar to that produced by the plasma guns on HIT-II. This combination of gas and plasma will be forced to pass through the gap between the lower divertor plate region, where it is needed for breakdown.

Calculations show that breakdown should be possible for a reduction in gas pressure by up to a factor of five to eight. At these reduced levels of gas injection, the energy per ion will increase to levels where the capacitor bank energy will no longer be marginal as it is in present experiments. Two ports in the region below the divertor plates are being installed. One port will be used for gas injection. The second port will be used to redirect an ECH wave guide (from the existing ECH system) to the region below the divertor plates.

4.0 Summary

Transient CHI experiments on NSTX thus far have succeeded in about 140 kA of toroidal current using less than 4 kA of injector current. Considerable progress has been made on the HIT-II experiment, which, during the past two years, has been used in a supporting role to develop new CHI startup scenarios for NSTX. The new methods recently developed on HIT-II are now being implemented on NSTX.

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