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Reduction of low-Z impurities during plasma start-up

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ABSTRACT

Reduction of low-Z impurities is essential during the plasma start-up in tokamaks. For plasma start-up using the method of Coaxial Helicity Injection (CHI) it has been found that conventional wall conditioning methods have been inadequate to generate a plasma with acceptably low levels of low-Z impurities. NSTX has now used a new combination of techniques to improve CHI start-up performance. These are the use of high-current discharge cleaning of the lower divertor surfaces, which function as the CHI electrodes, to remove loosely bound impurities, controlling the poloidal magnetic field to avoid plasma wall contact and the use of evaporated lithium coatings of the electrodes and other plasma-facing surfaces. Together, these techniques have enabled significant improvement in NSTX CHI performance leading to a saving of central solenoid flux and the first observation of electron temperatures during CHI exceeding the oxygen radiation barrier temperature.

1. Introduction

The National Spherical Torus Experiment (NSTX) [1,2] has been investigating the use of transient Coaxial Helicity Injection (CHI) to initiate a Spherical Torus (ST) discharge without reliance on the inductive central solenoid. Due to the restricted space for a central solenoid, this is essential for the viability of the ST concept. The method is also relevant to steady-state tokamak operation, as the central transformer coils of a conventional aspect-ratio tokamak reactor would be located in a high radiation environment but would be needed only during the initial discharge initiation and current ramp-up phases. Eliminating the need for a central solenoid provides greater flexibility in the selection of the aspect-ratio and simplifies the reactor design.

The importance of the reduction of low-Z impurities during the early phase of tokamak start-up was recognized early in tokamak research and spurred the development of vessel conditioning methods such as gettering, glow-discharge cleaning and boronization. Conventional vacuum conditioning methods alone have been inadequate to generate a sufficiently clean plasma discharge for the CHI-initiated plasma to transition successfully to subsequent inductive ramp-up of the plasma current. In addition to the well-established methods, NSTX has now used high-current discharge cleaning of the lower divertor plates, a "buffer field" to avoid plasma wall contact and lithium conditioning [3] to improve CHI start-up performance.

As shown in Fig. 1a, and as described in Ref. [4], CHI involves injecting current through the plasma from an external circuit along poloidal field lines that connect the lower divertor plates in the presence of a toroidal magnetic field. NSTX uses the lower divertor plates as the injector. The opposite end consisting of the upper divertor plates is referred to as the absorber. The $\mathbf{E} \times \mathbf{B}$ plasma drift is away from the injector region and into the absorber region. The initial poloidal field connecting the inner and outer divertor plates in the injector region is produced using the lower divertor coils, as shown in Fig. 1a.

To test the compatibility of CHI start-up with conventional operation in NSTX, induction has been applied to the CHI produced closed-flux plasma equilibrium by ramping the current in the central solenoid. If the CHI produced discharge has sufficiently low levels of impurities, the CHI produced discharge will ramp-up in current as it does during conventional inductive start-up. Fig. 2 shows waveforms from three discharges, before the recent improved conditioning, in which the size of the capacitor bank used for the initial CHI start-up was progressively increased. Induction is then applied using the same pre-programmed loop voltage in each case. The discharge with one capacitor reaches the highest current after it is coupled to induction whereas the discharge with three capacitors from the 2008 experiments does

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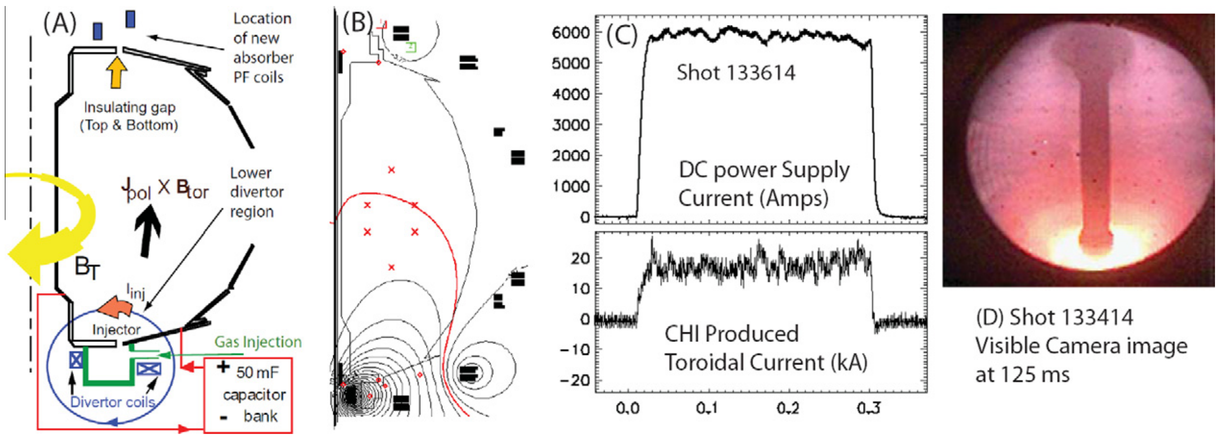

Fig. 1. (A) Pictorial of CHI formation in NSTX, (B) vacuum flux plot of discharge 133614 at 125 ms, (C) injector and toroidal currents and (D) image showing discharge in the divertor at 125 ms.

not couple to induction due to increased low-Z impurities in the CHI discharge.

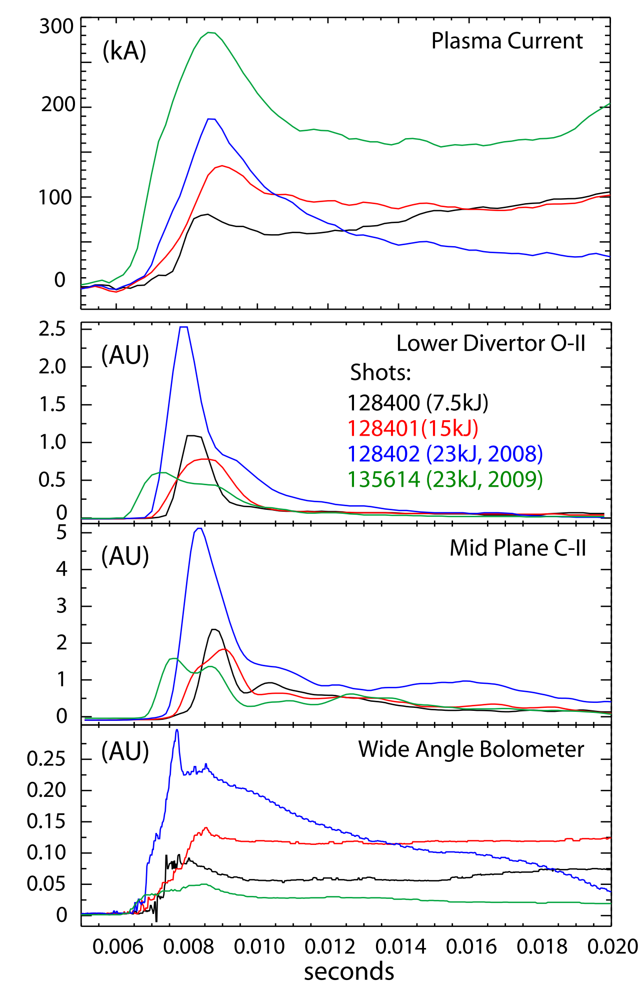

Fig. 2. Shown are the CHI produced toroidal current, the lower divertor oxygen signal the mid-plane carbon signal and radiated power from a wide angle bolometer. For divertor plates that are not well conditioned, as the size of the capacitor bank is increased, the carbon and oxygen line intensities increase as does the radiated power. The discharge with three capacitors (23 kJ, 2008) does not couple to induction. However, discharge 135614 form 2009 (shown in Fig. 4) has much lower levels of radiated power and couples well to induction.

2. NSTX vessel conditioning methods to improve CHI start-up

Results from both the concept exploration HIT-II experiment at the University of Washington and more recently from NSTX, have shown that multiple repetitions of the same CHI start-up improve the discharge performance. This is believed to be due to repeated interaction of plasma with the same divertor surfaces that progressively removes loosely bound low-Z impurities, notably oxygen. To increase the duty cycle of this plasma cleaning, extended discharges were produced between the CHI electrodes in NSTX using a rectifier power supply. Deuterium gas was injected while the lower divertor coils were programmed to generate poloidal flux that connected the electrodes and a toroidal field was applied. The current pulse could be maintained for as long as the fields could be applied and gas continued to be injected in the region of the electrode discharge. An example of such a discharge in NSTX is shown in Fig. 1B–D.

In running these electrode conditioning discharges it is necessary to ensure that the programmed poloidal flux stays attached to the vessel components. This requires that the injected current does not exceed the 'bubble burst' threshold at which the $\mathbf{J} \times \mathbf{B}$ force on the discharge exceeds the field line tension causing the plasma to expand into the vessel. The minimum I_{inj} to meet the bubble burst condition is $I_{inj} = 2\psi_{inj}^2/(\mu_o^2 d^2 I_{TF})$, where I_{TF} is the current in the toroidal field coil and d is the injector flux footprint width [5]. It is possible to remain below this threshold current by reducing the toroidal field or increasing the injector poloidal flux. The path of the current is then determined by controlling the shaping of the poloidal flux.

If a toroidally symmetric plasma-facing surface, such as a divertor plate, in a tokamak were electrically isolated from the other plasma-facing surfaces, it should, in principle, be possible to power the poloidal field coils to run a high-current (several kA) discharges to the other parts of the vessel surface to remove loosely bound surface contaminants and gases trapped near the surface. This technique has the potential for tritium removal from the vessel walls of a reactor. Examples of the capability to generate such widely varying flux patterns in NSTX are shown in Fig. 3. In this figure, the double ended arrows indicate the region of the outer vessel that would be cleaned. By continuously varying the flux pattern, a single extended discharge could be used to clean the entire vessel region. In NSTX, injector currents of up to 25 kA have been driven in shapes corresponding to the second, third and fourth frames in Fig. 3.

During these experiments the configuration similar to that which appears in Fig. 3e, was used for discharge cleaning. The

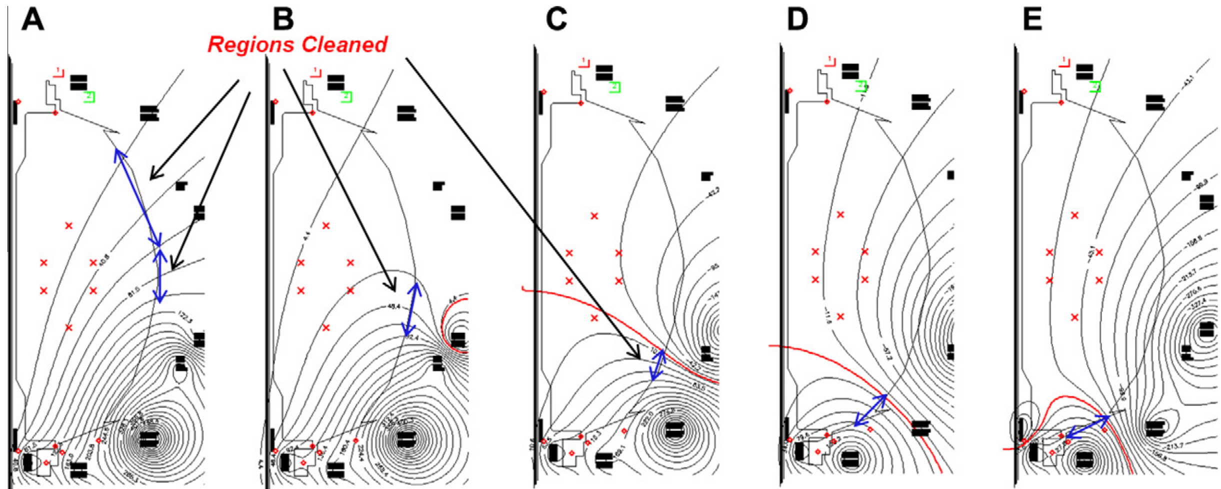

Fig. 3. Possible vacuum field patterns that can be obtained in NSTX for electrode discharge cleaning large portions of the outer vessel region.

actual configuration is shown in Fig. 1b. This was a static configuration and it was not swept as shown in the sequence of frames in Fig. 3. Because the primary objective was to clean the lower divertor plates, which are used as the CHI electrodes, only the configuration that is similar to that which is required for transient CHI start-up was required. The other configurations shown in Fig. 3 were experimentally run on NSTX for the purpose of CHI discharges aimed at steady-state current drive and not for discharge cleaning purposes. However, as a result of recent interest for ITER to liberate trapped tritium on vessel walls, these configurations are described as they have the potential to liberate trapped tritium from large surfaces areas of the vessel. These configurations are shown in this capacity as a method that could be tested if support for such experiments is expressed by ITER.

On NSTX, the transient CHI discharges use a small capacitor bank (with a typical stored energy of 25 kJ) for CHI discharge initiation. The long-pulse discharge cleaning method uses a DC rectifier power supply. A hardware configuration change is needed to switch from discharge cleaning to transient CHI operation. This configuration change is carried out after the day's end of experimental operations. As a result, in these experiments, about a day was used for the discharge cleaning followed by the transient CHI experiments run the following day. Fig. 3 in Ref. [6] shows the comparison before and after the long-pulse discharge cleaning. Because of the long-time needed for this switch-over, we have also conducted short pulse cleaning using a larger capacitor bank power supply. During this cleaning, 10 short pulse discharges (3 ms in duration with an injector current of 20 kA, instead of the 6 kA used for the long-pulse cleaning) was also tried and also showed the benefits of electrode cleaning. This result is shown in Fig. 4 of Ref. [7]. During the cleaning process, the filter scopes recording the oxygen and carbon impurities typically saturated. If the product of the injector current times the pulse duration is used as a measure of cleaning duration, these results would indicate that a single 300 ms long-pulse should provide beneficial effects. However, this is also a function of the level and depth of surface contaminants. In these experiments, a quantitative study characterizing the magnitude of surface contaminants and the required duty cycle has not been conducted. For such a characterization, it would be necessary to preload a known amount of impurity onto a sample probe, to run the cleaning discharges and to analyze the sample probe to determine the extent of contaminant removal for a given pulse. Such a study is possible but has not been conducted on NSTX.

It should be noted that the important parameter is the injector current and not the plasma current. The magnitude of the injector current and the surface area it interacts with determine the surface ion density for cleaning. The plasma current is a result of the presence of a toroidal field. The ratio of the plasma current to the injector current determines, how many times the current goes around toroidally for each poloidal transit. Thus doubling the toroidal field for the same injector current, while it would double the plasma current is not expected to increase the surface cleaning effectiveness, because the same number of ions are still bombarding the electrode surface. In this method, the toroidal field is an important knob that could be used to control the magnitude of the injector current. For a given applied injector voltage, a doubling of the toroidal field would increase the field line length by a factor of two and for the same plasma resistivity, would reduce the injector current by about half. At the same time it is necessary to minimize the toroidal field because too high a value of the toroidal field can cause the discharge to exceed the bubble burst condition, and make it difficult for the discharge to be controlled as the discharge will now have a tendency to detach from the electrode surface, such as during transient CHI start-up.

Although the plasma temperature has not been measured, because of the high neutral density and the graphite electrodes, the plasma electron temperature is not expected to exceed the carbon radiation barrier temperature of 6 eV at the electrode surface. The actual electron temperature is expected to be less than this value, possibly in the 2 eV range. The flux footprints impact an area of 6000 cm^2 on the inner divertor plate (cathode) and about 21,000 cm^2 on the outer divertor plate (the anode). Thus the ion current density to the inner plate is on the order of 1 A/cm^2 for the long-pulse discharges and increases to about 3.3 A/cm^2 for the short pulse discharges. The corresponding electron currents on the outer plate are 0.3 and 1 A/cm^2. It is useful to note that by further reducing the magnitude of the toroidal field the surface current density could be increased for the same applied voltage which was 800 V for the long-pulse discharges and 1.7 kV for the short pulse discharges. For the long-pulse discharge a series current limiting resistor ensured that the injector current was limited to 6 kA.

During CHI start-up, the expanding plasma can contact the upper divertor region, initiating an arc discharge across the insulating gap there. This condition, known as an absorber arc, can introduce impurities into the plasma. Since NSTX generally does not operate with plasmas connected only to the upper divertor, the upper divertor plates are not as well conditioned as the lower divertor plates. To avoid plasma contact with the upper divertor during CHI, NSTX recently implemented the use of two poloidal field coils in the upper divertor region (Fig. 1a). These coils provide

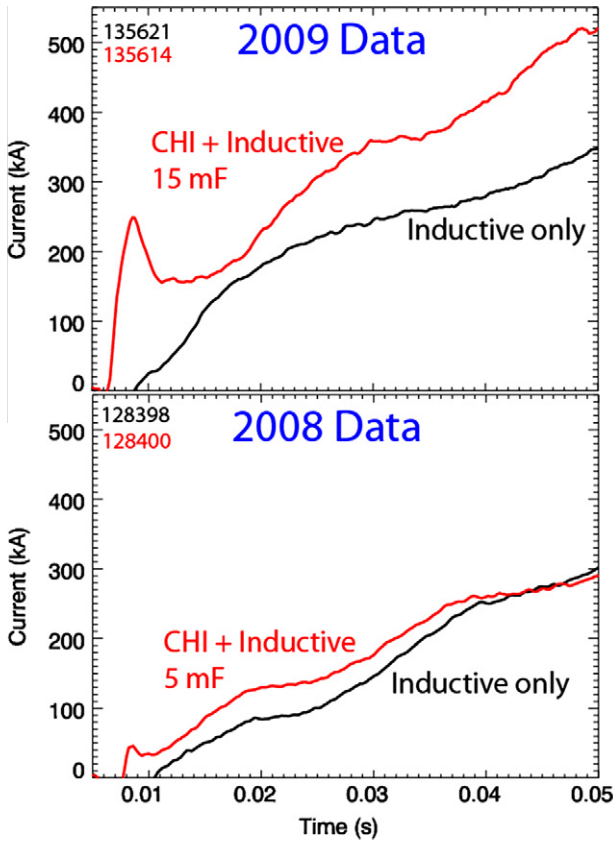

Fig. 4. As a result of implementing the new vessel conditioning methods, the discharge with three capacitors, now not only couples to induction, but produces more current than the inductive-only case. The best cases from the FY2008 and FY2009 NSTX run campaigns are shown.

a localized, short duration, ''buffer flux'' to avoid contact between the plasma and the upper divertor region. They are used only during the CHI phase which last for several milliseconds and affect the equilibrium locally near the top edge but have a small influence on the overall plasma equilibrium. They have been effective in suppressing absorber arcs across the upper divertor [4,7]. With the coils in use, the influx of oxygen impurity from the upper diverter region was considerably reduced.

Finally, the application of solid lithium coatings on the lower divertor with the lithium evaporators on NSTX has improved the reproducibility of CHI discharges. Lithium was expected to help CHI start-up by lowering the plasma density, so that the radiated power would decrease. Although this effect has been seen during the inductive ramp-up following the CHI initiation, it has not yet been evident during the CHI phase itself, possibly because the amount of lithium used in these discharge has not been large enough.

The result of the combined use of all these methods is shown in Fig. 4 which compares the best results from 2008 and 2009. As a result of implementing these methods during 2009, CHI discharges initiated with three capacitors could be successfully coupled to induction and had less radiated power as shown in Fig. 2. With four capacitors, even higher levels of current were generated and the resulting discharge performed better than induction, although in this case an inadequate amount of current in the absorber coils did lead to a weak absorber arc that ultimately caused the current to fall below the three capacitor case.

The method of driving current on open field lines to clean the CHI electrodes developed in NSTX has potential application for tritium removal in ITER if an internal toroidally symmetric plasma-facing component could be insulated from the rest of the vessel and serve as an electrode connected to a suitable power source. One possibility would be to insulate the lower dome of the divertor from the rest of the vessel. The vacuum poloidal flux would then be set up to connect between the dome and a desired location on the vessel. It is important to note that the insulator requirements are quite modest. The primary requirement is that its resistance be about two to three orders higher than the resistance of the plasma, which is typically in the few mΩ range. Second, it would not have to provide insulation during the strong neutron flux that will occur during high power plasma operation. Third, the insulator would be under compression, so the material requirements are relaxed. With this capability, conditioning CHI discharges could be run after several hours of normal plasma operation, similar to the helium glow-discharge applied between plasma pulses during routine operation of current tokamaks.

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