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 improvent 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.

JNM Keywords: Divertor biasing; Conditioning procedures; SOL current; Impurities; NSTX.

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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, as well as the recognition that gas pre-fill in a narrow range is required for successful inductive plasma start-up at low values of the applied loop voltage. Recently during the development of plasma startup using the method of Transient CHI the importance of controlling the influx of low-Z impurities during the early phase of plasma start-up has become even more apparent. 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 now uses 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.

2. Plasma Start-up Using Transient CHI

NSTX has a major/minor radius of 0.86/0.68 m and a toroidal magnetic field at the nominal major radius up to 0.55 T. It is equipped with a central solenoid providing up to 0.7 Wb of inductive flux (double swung) which can generate plasma currents up to 1.5 MA. Most of the plasma facing boundary of NSTX is composed of graphite tiles.

As shown in Figure 1a, 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 **ExB** 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 Figure 1a.

For transient CHI discharge initiation, the toroidal field coils and the poloidal field coils needed to produce the desired flux conditions in the injector region are first energized. A pre-programmed amount of deuterium gas is then injected into the cavity below the gap between the inner and outer lower divertor plates and the 5 – 45 mF capacitor bank (1 – 9 capacitors) charged at up to 1.7 kV is connected by an ignitron switch to the inner vessel and inner divertor plates acting as the cathode, and the outer divertor plates and passive stabilizer plates acting as the anode. This initiates the CHI discharge. After a programmed delay of 3 – 10 ms, when the plasma has expanded into the chamber and the toroidal plasma current is near its peak, the injector is short-circuited by an ignitron causing the injector current to rapidly decay. This produces reconnection of the magnetic field near the lower divertor plate region and causes the plasma column to detach from the injector region to form closed flux.

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

3. 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 startup 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 Figures 1b-d. The discharges shown in Figure 2 in Reference 4 benefited from this type of electrode conditioning.

In running these electrode conditioning discharges it is necessary to ensure that the injected current stays on the open field line flux. This requires that the injected current does not exceed the ‘bubble burst’ threshold at which the **JxB** 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 Figure 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 Figure 3.

During CHI startup, 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 (Figure 1a). These coils provide 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 [6]. 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 Figure 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. 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.

4. Summary

In summary, using the method of transient CHI, for the first time in NSTX, CHI discharges have been successfully coupled to induction to show compatibility between CHI and the conventional inductive approach. While results similar to this have been previously demonstrated on the smaller HIT-II experiment, this is the first such demonstration on a large ST with a poloidal field configuration more prototypical of a compact ST reactor such as the Component Test Facility (CTF). This was possible as a result of implementing new wall and divertor conditioning techniques and through the use of a buffer magnetic field to minimize plasma wall contact.

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, as shown in Figure 5. 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 mOhm 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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References

[1] S.M. Kaye, M. Ono, M. Peng, et al., Fusion Technol., **36**, 16 (1999)
[2] M.G. Bell, R.E. Bell, D.A. Gates, et al., Nuclear Fusion, **46**, S565-S572 (2006)
[3] H.W. Kugel, et al., **S3-08**, 19th PSI Conference, San Diego (2010)
[4] D. Mueller, et al., Fus. Sci. and Tech. **57**, pages 371-274 (2010)
[5] T.R. Jarboe, Fusion Technol., **15**, 7 (1989)
[6] R. Raman, et al., Phys. Rev. Lett., **104**, 095003 (2010)

Figure Captions

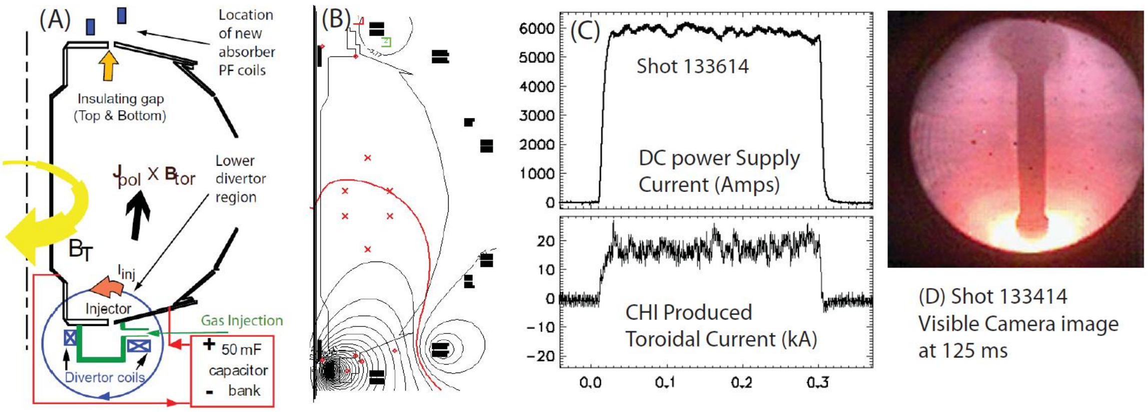
Fig. 1: (A) Pictorial of CHI formation in NSTX, (B) Vacuum flux plot of discharge 133614 at 125ms, (C) Injector and Toroidal currents and (D) Image showing discharge in the divertor at 125ms.

Fig. 2: Shown are the CHI produced toroidal current, the lower divertor oxygen and carbon signals 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) does not couple to induction.

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

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.

Fig. 5: One possible method to obtain divertor biasing capability in ITER. Shown is the divertor unit of ITER and the possible location for an insulator to insulate this dome region from the rest of the vessel.



(D) Shot 133414
Visible Camera image
at 125 ms

Figure 1

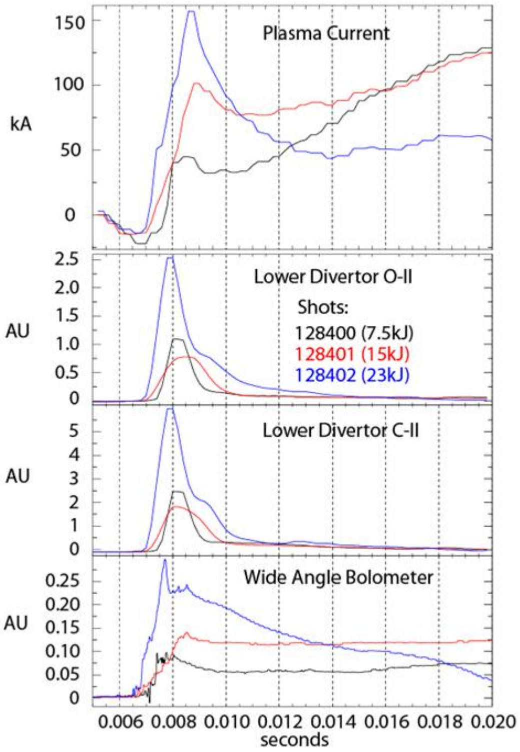


Figure 2

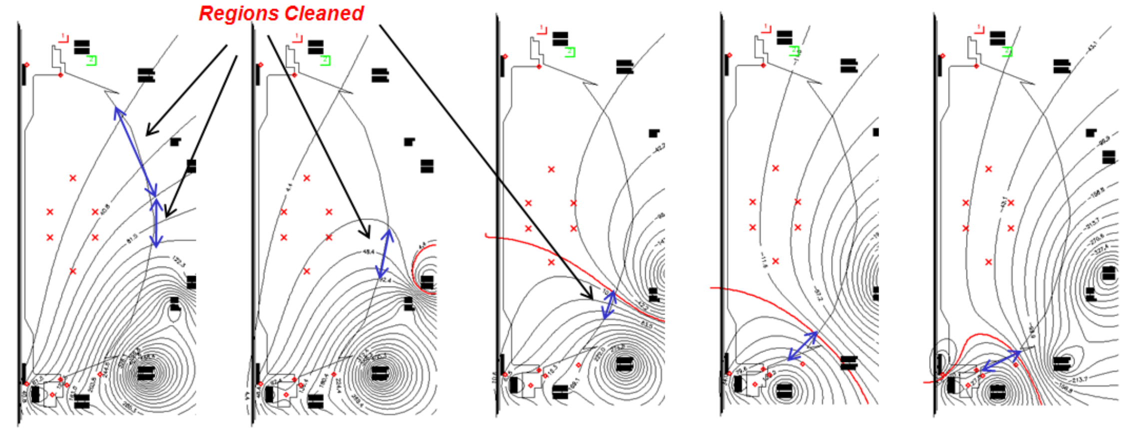


Figure 3

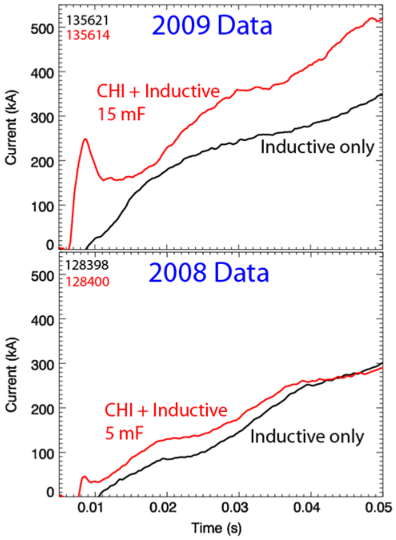


Figure 4

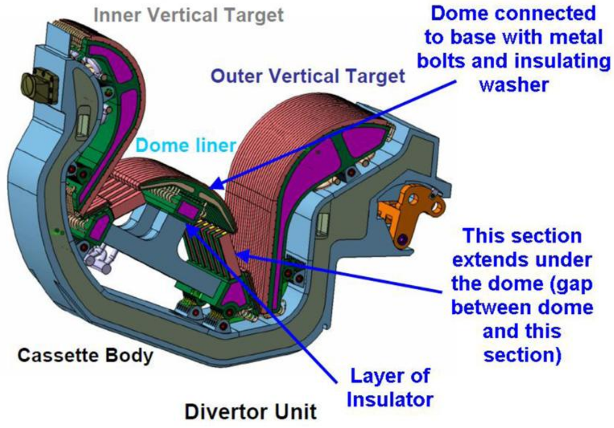

Inner Vertical Target
Dome connected to base with metal bolts and insulating washer
Outer Vertical Target
Dome liner
This section extends under the dome (gap between dome and this section)
Cassette Body
Layer of Insulator
Divertor Unit

Figure 5