DESIGN DESCRIPTION FOR A COAXIAL HELICITY INJECTION PLASMA START-UP SYSTEM FOR A ST-FNSF

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Economics, design simplifications, and design optimizations, may require a Fusion Nuclear Science Facility (FNSF) based on an ST or AT concept to generate the plasma currents required for initial plasma start-up to be produced without reliance on the conventional central solenoid. The method of Transient Coaxial Helicity Injection (CHI) has been successfully used on the HIT-II device and on the thirty times larger in volume Proof-of-Principle NSTX device, to generate over 200 kA of plasma current, and to demonstrate the physics capability of this concept for the generation of substantial amounts of plasma currents in larger devices. The conceptual design of a transient CHI system for a ST-FNSF (B_T = 3 T, R = 1.7 m, A = 1.7, I_p = 10 MA) is described, in which the projected start-up current generation potential is about 2 MA.

I. INTRODUCTION

Both conventional aspect ratio tokamaks and spherical tokamaks (STs) have generally relied on a central solenoid to generate the initial plasma current and then to sustain that current against resistive dissipation. However, in a steady-state reactor, a central solenoid cannot be used for plasma current sustainment. Furthermore, the inclusion of a central solenoid in a tokamak to provide plasma startup capability limits the minimum aspect ratio. For reactors based on the ST concept, elimination of the central solenoid is essential, making alternate methods for plasma start-up necessary for such a reactor.

Substantial progress in tokamak research during the past two decades has made it possible to sustain the current non-inductively for significant periods of time,[1] and further development of this capability is a primary objective of the soon to be operational NSTX-U device.[2] The generation of toroidal plasma current by Coaxial Helicity Injection (CHI) was originally developed for spheromak plasma formation[3] and has been used on several spheromak experiments including on the SSPX, CTX and RACE devices.[4, 5] It has also been used in reconnection merging experiments[6, 7] and for spherical torus plasma formation.[8]

The first experiments utilizing CHI on NSTX (Ref. 9) and HIT-II (Ref. 10) used the method of *driven* or *steady-state* CHI for plasma current initiation. Such a system was also tested on the DIII-D tokamak.[11] However, the toroidal currents generated using this method could not be successfully sustained by applying inductive drive. Later, experiments on the HIT-II experiment at the University of Washington demonstrated that the method of *transient* CHI could generate high-quality plasma equilibrium in a ST that could be coupled to induction.[12] The transient-CHI method has now been successfully used on NSTX for solenoid-free plasma start-up followed by inductive ramp-up.[13] These coupled discharges have now achieved toroidal currents of 1 MA using significantly less inductive flux than standard inductive discharges in NSTX (Ref. 14).

This paper describes the conceptual design of a transient CHI system for a ST-FNSF device (B_T = 3 T, R = 1.7 m, A = 1.7, I_p = 10 MA).

II. REQUIREMENTS FOR TRANSIENT CHI PLASMA START-UP

Helicity is the linkage of magnetic flux with magnetic flux, and is well described in the book by Bellan.[15] In general, for helicity injection, the following hardware requirements must be met.[16] First, two electrodes are required. These electrodes must be insulated from each other. Second, magnetic flux should connect these electrodes. This is known as the injector flux, and in a transient CHI system, the current generation potential is directly proportional to the magnitude of the injector flux. Third, a power supply is needed to apply voltage to these electrodes. The voltage across the electrodes is referred to as the injector voltage, and the resulting current that flows along the magnetic field lines from one electrode to the other is referred to as the injector current.

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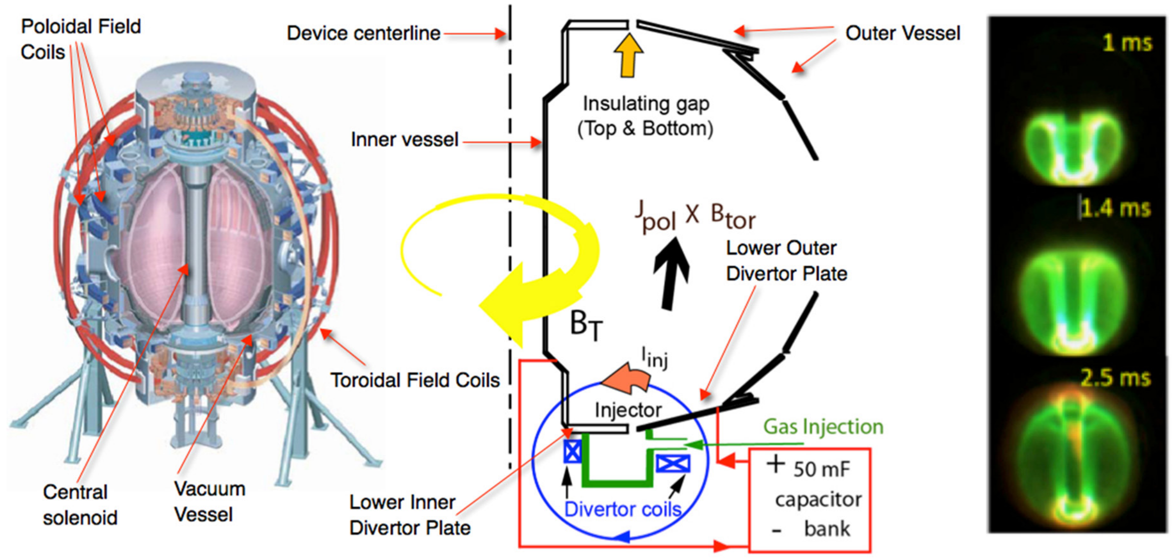

Fig. 1. Schematic drawing of the NSTX machine components, and cartoon showing components required for CHI start-up. The lower divertor coils are used for generating the CHI injector flux. Shown on the right are fast camera fish eye images of an evolving CHI discharge at 1, 1.4 and 2.5 ms after discharge initiation time.

The rate of helicity injection can be shown to be equal to $2V_{inj}\psi_{inj}$, where V_{inj} is the voltage between electrodes and ψ_{inj} is the magnetic flux that penetrates both electrodes. For successful helicity injection, four additional requirements should be met.[16] 1) The injected helicity must relax towards a configuration that has the desired magnetic equilibrium; 2) The region into which the helicity is being injected must provide a helicity barrier so that the injected helicity is confined; 3) sufficient helicity must be injected so that it overcomes any losses and a stable configuration can be formed, and in the case of steady-state current drive, the system must be sustained against losses by steady-state helicity injection; 4) the energy per unit helicity of the injected helicity must be higher than that dissipated by the equilibrium. This last condition is described by the relation, $\lambda_{inj} > \lambda_{tokamak}$, where $\lambda_{inj} = \mu_0 I_{inj}/\psi_{inj}$ and $\lambda_{tokamak} = \mu_0 I_p/\phi_{tokamak}$. Here $\phi_{tokamak}$ is the toroidal flux, and I_{inj} is the injector current, which is the current supplied by the external power supply.

The standard operating condition for CHI in NSTX uses the inner vessel and lower inner divertor plates as the cathode while the outer divertor plates and vessel are the anode. Figure 1 shows the layout of the NSTX machine and a cartoon of the systems used to enable transient CHI operations. A CHI discharge is initiated by first energizing the toroidal field coils and the lower divertor coils to produce magnetic flux linking the lower inner and outer divertor plates, which are electrically insulated by two toroidal insulators. One insulator is located at the top of the machine and the second at the bottom of the machine from where helicity is injected. After a programmed amount of gas is injected into the vacuum chamber, a voltage is applied between these plates, which ionizes the gas and produces current flowing along magnetic field lines connecting the plates. On NSTX, a 5 to 30 mF capacitor bank charged to 1.7 kV provides this current, called the injector current. As a result of the applied toroidal field, the field lines joining the electrodes wrap around the centerline of the device many times so the injector current flowing in the plasma develops a much larger toroidal component.

If the injector current exceeds a threshold value, the resulting $J_{pol} \times B_{tor}$ 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 be injected into the NSTX vessel. This is referred to as the "bubble-burst" current. Below this bubble-burst current, the field lines do not move and the injector is effectively a fixed impedance circuit. If, after the plasma fully fills the vessel, the injector current is rapidly reduced below the bubble-burst threshold, the plasma disconnects from the injector to form a closed field line configuration, which can retain a significant toroidal current.

While NSTX and NSTX-U use a design in which the entire inner and outer vessel components are electrically insulated by two vacuum toroidal insulators, the DIII-D design used a much simpler ring electrode configuration that was located near the outer divertor plate region [See Figure 1 in (Ref. 17). In this configuration, the divertor coils could be used to connect magnetic flux that links part of the DIII-D outer vessel to this ring electrode. On DIII-D up to 1 kV was applied between this electrode and the vacuum vessel to enable driven CHI operation.

It is useful to note that any system capable of driven CHI operation can easily support transient CHI operations. This is because in driven CHI, a continuous voltage is applied in order to maintain a given amount of injector current, whereas, in transient CHI, the voltage is applied for a very brief moment to produce a transient injector current pulse of the required magnitude and duration needed for the plasma bubble to fill the vessel. As shown in the fast camera fisheye images of a transient CHI discharge in NSTX, transient CHI discharges in NSTX take just 3 ms to form, after which the voltage across the electrodes is reduced to zero. After that, the CHI start-up system is essentially turned off. In a transient CHI system, it is much easier to obtain voltage insulation for two reasons. First, the voltage pulse is applied for a much shorter duration, and second, during this short period there is no pre-existing plasma in the vessel. This greatly facilitates establishing the initial path for the injector current, and maintaining it for the short duration needed to form the closed flux plasma configuration. Thus, the DIII-D ring electrode design is also capable of supporting transient CHI discharges, and in this paper, features from both the NSTX and the DIII-D CHI designs will be incorporated in the new designs discussed in section IV.

III. SCALING RELATIONS

The current required for satisfying this "bubble burst" condition is given by the relation:

$$I_{inj} = 2\psi_{inj}^2/(\mu_0^2 d^2 I_{TF}) \qquad 1$$

Here ψ_{inj} is the poloidal flux at the injector insulating gap, I_{TF} is the total current in the toroidal field coil and d is the gap between the injector flux "footprints" on the electrodes.[16]

The maximum toroidal current that can be generated is obtained by ensuring that $\lambda_{inj} > \lambda_{tokamak}$, which results in:

$$I_p < I_{inj}\,(\phi_{tokamak}/\psi_{inj}) \qquad 2$$

In NSTX the magnitude of the toroidal plasma current during CHI is typically 50 to 70 times that of the injected current. This is because, for a given value of the injector flux, the much larger vessel volume results in about a factor of ten higher toroidal flux. This current multiplication factor can also be increased by operating the device at higher toroidal field. This is a favorable scaling for future machines that are expected to operate at higher values of the toroidal field and may have a larger vessel volume.

By substituting Eqn. 1 for the injector current into Eqn. 2 for the toroidal current, and recognizing that the enclosed toroidal flux is directly proportional to the current in the toroidal field coil; for any given machine at a fixed (optimized) value of the parameter d, it can be seen that the generated toroidal plasma current is directly proportional to the magnitude of the injector flux.

NSTX transient CHI experiments have shown that a large fraction of the injector flux is efficiently converted to closed poloidal flux, typically about 80% [$\psi_p \sim 0.8\psi_{inj}$]. Here ψ_p is the closed plasma poloidal flux.

The resulting closed flux plasma current is given by the relation,

$$I_p = 2\psi_p/l_i R_p \mu_0 \qquad 3$$

$$l_i = (L_i/2\pi R_p)/(\mu_0/4\pi) \qquad 4$$

Where l_i is the normalized plasma internal inductance,[18] L_i is the internal plasma inductance,[18] μ_0 is the magnetic permeability, and R_p is the major radius of the plasma.

IV. TRANSIENT CHI DESIGN FOR ST-FNSF

The CHI electrode design for a ST-FNSF draws upon some of the design features used in NSTX and in the DIII-D ring electrode configurations, but with two added constraints necessary for a reactor installation. The first requirement is that the insulator used to achieve electrode

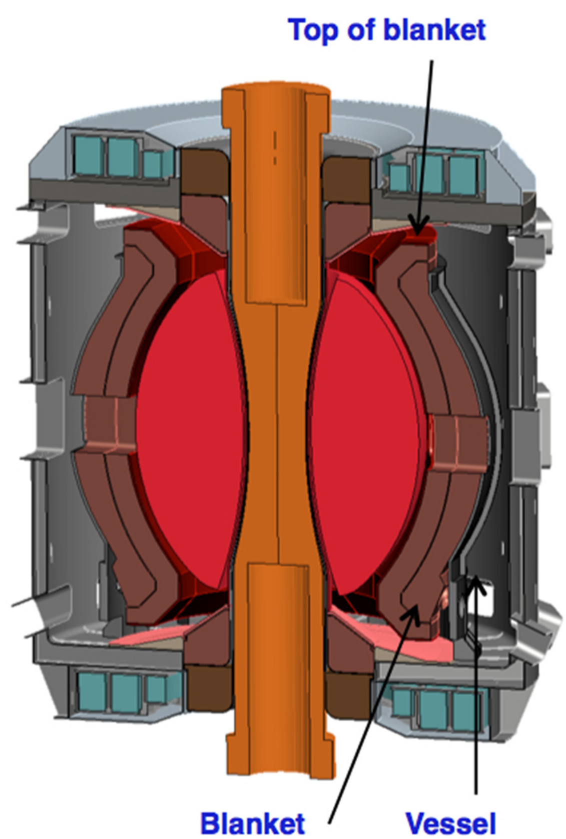

Fig. 2. The 1.7 m PPPL, ST-FNSF design.

insulation must be adequately shielded from neutrons. The second requirement is less stringent. It is preferable if the insulator is not used to achieve an O-ring seal with the vessel components, such as on NSTX. However, we note that if the insulator is sufficiently hidden away behind large structural components, such as for example in a machine equipped with advanced divertors such as the Snowflake, X or Super-X divertors,[19,20] then a NSTX-like design with vacuum seals that isolate the inner and outer vessel components is still possible. Two different designs are described.

NSTX-like CHI Configuration: In the first configuration, referred to as NSTX-like, the entire blanket assembly is insulated from the vessel wall. Figure 2 shows the overall layout of the ST-FNSF components. Figure 3 shows the implementation of the insulators. On the ST FNSF, the primary blanket structure is mounted off the outer vessel components using structural supports that are toroidally and poloidally distributed around the vessel. At each of these support points, flat insulator plates are used in-between the flat metal brackets that are welded to the blanket and vessel components. Insulated bolts are then used to connect the blanket supports to the vessel supports. This arrangement electrically separates the blanket from the vessel components. In this configuration, because the insulators are behind the

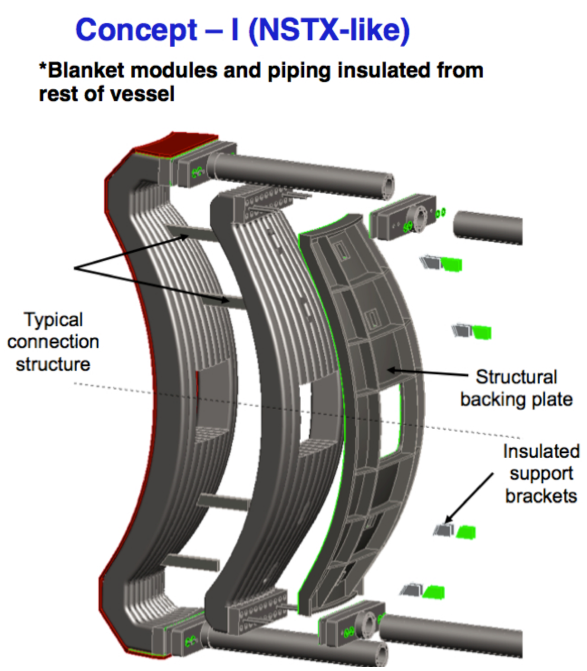

Fig. 3. In "NSTX-like" Concept – I, the ST-FNSF blanket would be supported off the outer vessel using the green insulating plates and sandwiched between metal supports and the assembly bolted together using insulating bolts. Note that this figure shows a view of the blanket structure only. Figure 2 shows the blanket in relation to the vacuum vessel.

blanket structure, and adequately shielded from neutrons, neutron dose to the MgO insulator is not an issue. However, it is also necessary to insulate the blanket piping from the vessel as these can provide an electrically-conducting path from the blanket to the vessel. Each of the piping connections also needs to be electrically separated using insulating breaks. Such breaks are routinely used on NSTX to isolate gas piping from the NSTX center stack potential, which during vessel high voltage testing can be elevated to voltages of up to 7 kV DC for periods of over a minute. In addition, components attached to the blanket piping system, such as pumps and heat exchangers, would be floated above ground potential for the duration of the CHI initiation phase. This phase on a ST-FNSF would last for less than 50 ms. Piping configurations similar to that used in the ARIES ST design[21] seems feasible for this application, but further simplification may be possible. The location of the insulators to achieve this isolation in shown in Figure 4.

The advantage of this design is that the CHI configuration is quite similar to the configuration on NSTX, which is a proven design for transient CHI start-up. On NSTX (and on NSTX-U) the entire inner vessel is subjected to high voltage during CHI operations, and current is driven along magnetic field lines that connect the outer vessel components (the anode) to the inner vessel components (the cathode). On this ST-FNSF configuration, the blanket would be raised to the higher potential, while the rest of the vessel, will be grounded (as on NSTX). The blanket will be biased positive with respect to the vessel. The blanket in this case, acts in a capacity similar to the inner vessel components on NSTX and NSTX-U.

In this NSTX-like configuration, the divertor coils permit injector flux values of >0.7 Wb, at a divertor coil current of just 0.8 MA turns. This is much less than the 10 MA turns limit for the divertor coils. This injector flux connects the lower part of the vessel to the lower part of the blanket module, as shown in Figure 5.

At a normalized internal plasma inductance of 0.35, which is the case for NSTX transient CHI discharges, from Eqn. 3, it can be seen that I_p >2 MA is possible. The resulting injector current, from Eqn. 1, for the electrode gap separation of 40 cm for this case results in an injector current of about 100 kA, which is only about a factor three higher that what was demonstrated on HIT-II (Ref 22).

DIII-D-like CHI Configuration: In the second configuration, a toroidal electrode plate is mounted on top of the blanket assembly and insulated from the blanket using a toroidal insulator. The injector flux connects the top of the vessel to this electrode plate, as shown in Figure 5. This is similar in configuration to the ring electrode used on DIII-D. At similar coil currents, the injector flux doubles. However, the much-reduced gap between the electrodes triples the required injector current

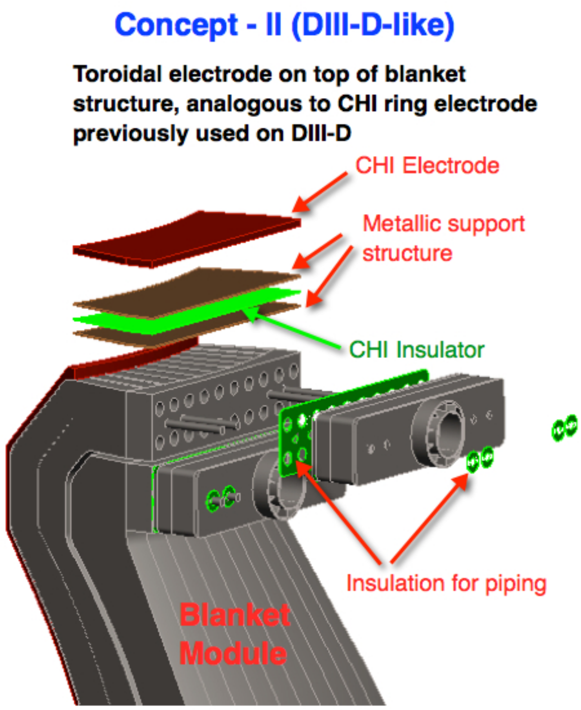

Fig. 4. In "DIII-D like" Concept – II, a toroidal electrode would be installed on top of the blanket and separated from the rest of the blanket using the green toroidal insulator plate. Note that for this configuration the green insulating sections for insulating the piping system are not required.

for 0.7 Wb flux injection to about 300 kA (Table I); however, the electrode current density of 50 kA/m^2 is still much less than the 300 kA/m^2 demonstrated on HIT-II. It is useful to note that this configuration is well suited for tokamak concepts that plan to use advanced divertors. The Snowflake, X-divertor and the Super X divertors all benefit from poloidal field coils that are located in close proximity to the lower divertor region. In the Super X divertor configuration the coils are also positioned at much larger major radius. The divertor field lines are then channeled through a narrow gap and then spread out on to the divertor plates. The same coils that are needed for maintaining these divertors could be used to generate the injector flux, and the electrodes would be placed on either side of the divertor flux channel. Because these coils are far away from the blanket structure and at much larger major radius, insulators at these locations would be well shielded from neutrons.

An advantage of this design is that the blankets and piping need not be insulated, but the configuration requires additional experimental validation, because the DIII-D ring electrode was removed before the demonstration of transient CHI discharges on NSTX, so the ring electrode was not used to demonstrate transient CHI plasma formation on DIII-D. In the DIII-D-like configuration, the blanket module and the piping are electrically connected to the rest of the vessel and will remain at ground potential. Only the electrode plate is at elevated potential during CHI plasma generation. So it is not necessary to float the components attached to the blanket piping system. Whereas, in the NSTX-like configuration, the blanket and the piping will be at elevated potential during CHI operations, so these need to be biased positive with respect to the rest of the vessel, including the inner vessel components, and the center stack. The MCNP calculated dose on the insulator is ~10^{10} Gy at the end-of-life [6 full power year (FPY)], which is much less than the dose limit of 10^{11} Gy for the MgO insulator. This is because the insulator is largely shielded by the blanket structure that is below the location of the insulator.

The inductive stored magnetic energy in the resulting 2 MA plasma is 0.7 MJ. The initial stored energy in the capacitor bank power supply must be about a factor of two higher than the inductive plasma stored energy, while being able to drive about 100-300 kA of injector current for a few ms needed for the plasma to grow and fill the vessel. Circuit simulations show that this can be achieved with a capacitor bank with a C = 200-300 mF, with an initial charging voltage of 4 to 7 kV. The HIT-II CHI system routinely operated with an initial charging voltage of 4 kV. The 4 kV limit was a power supply limit, and not the insulation limits of the HIT-II system, which was

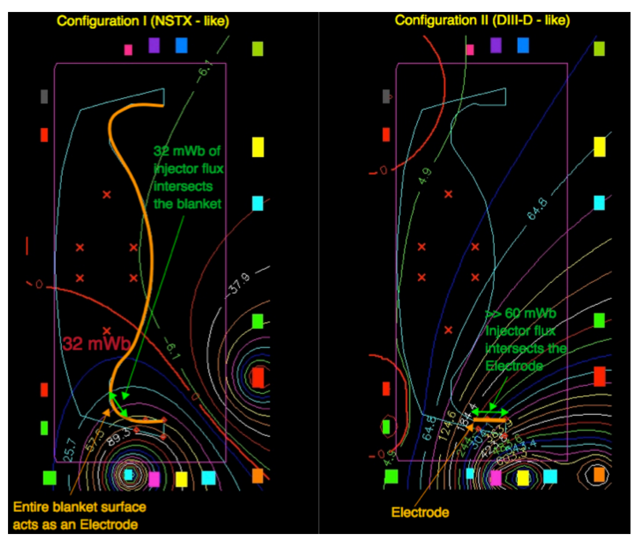

Fig. 5. Vacuum field calculations for Configuration I (left) and for Configuration II (right) showing the location of injector flux. For Configuration II, the injector flux will connect the divertor at the top of the machine, instead of at the bottom, as shown here. The thick orange line shows the electrode surface. Standard divertor coils are used to generate the injector flux. The maximum coil current limits are about 10 MA.Turns.

much higher. The NSTX capacitor bank is rated for 2 kV. On NSTX-U there is a planned upgrade of this capacitor bank to 3 kV. The NSTX-U vessel itself is designed for 4 kV operations. These voltage limits are required only for the short duration of the transient CHI phase, which is expected to last less than 50 ms, after which shorting relays could be engaged to short all components to ground potential during the current ramp-up and sustained operation phases.

TABLE I. Comparison of Relevant Quantities for Configuration I (NSTX-like) and II (DIII-D-like) for IP=2 MA and 0.7 Wb Injector Flux

Parameter	Config. I	Config. II
Plasma Current (MA)	2	2
Inductive Stored Energy (MJ)	0.7	0.7
Inj. Coil Current (kA.Turns)	0.8	0.42
Injector Current (kA)	150	335
Inj. Current density (kA/m^2)	30	50
Power Supply Capacitance (F)	200	300
Power Supply Voltage (kV)	4	7
Neutron dose at insulator (Gy) at 6 FPY	Very Small	$\sim 10^{10}$

V. SUMMARY AND CONCLUSIONS

Considerable progress has been made with transient CHI for plasma start-up without reliance on the conventional solenoid, on both HIT-II and the thirty times larger in volume NSTX device. HIT-II has operated with the highest electrode current densities to-date, utilizing 30 kA of injector current, with resulting electrode current densities of over 300 kA/m^2 to generate a high-quality closed flux plasma current of up to 100 kA. NSTX has generated about 200 kA of closed flux plasma current using about 50 mWb of injector flux. Because of the much higher injector flux capability on NSTX-U (over 250 mWb), the projected plasma current is much higher, with a planned start-up current magnitude of 400 kA. Application of transient CHI to future devices is investigated through a conceptual design study for solenoid-free plasma start-up in a ST-FNSF, which has resulted in two designs. The first configuration has many features similar to the proven NSTX design. In this configuration, the entire blanket structure is electrically insulated from the rest of the vessel. In the second configuration, a toroidal ring electrode is mounted on top of the blanket structure and this is used for the CHI discharge initiation. In both configurations, the use of less than 10% of the divertor coil current capability results in projected start-up current magnitude of 2 MA, which is believed to be adequate for further current ramp-up to the full 10 MA level using the available non-inductive current ramp-up methods on a ST-FNSF. The MCNP calculated dose on the insulator is $\sim 10^{10}$ Gy at 6 FPY, which is much less than the dose limit of 10^{11} Gy for the MgO insulator that would be used for this application.

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