Transient CHI System Design Studies for PEGASUS-III

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Abstract — Transient coaxial helicity injection (transient CHI), first developed on the Helicity Injected Torus-II (HIT-II) and later on the National Spherical Torus Experiment (NSTX) for implementing solenoid-free plasma current startup capability in a spherical tokamak (ST), is now planned to be tested on the PEGASUS-III ST using a novel double-biased configuration. Such a configuration is likely needed for transient CHI deployment in a reactor. The transient CHI system optimization will be studied on PEGASUS-III to enable startup toroidal persisting currents at the limits permitted by the external poloidal field coils. A transient CHI discharge is generated by driving injector current along magnetic field lines that connect the inner and outer divertor plates on one end of the ST. Simulations using the Tokamak Simulation Code are used to assess the transient CHI toroidal current generation potential and electrode gap location on the PEGASUS-III. While past transient CHI systems have used high-voltage, oil-filled capacitors for driving the injector current, for improved safety, PEGASUS-III will use a high-current capacitor bank based on low-voltage electrolytic capacitors. The designed and fabricated system is capable of over 32 kA. The modular design features permit the system to be upgraded to higher currents, as needed, to meet the future needs of the PEGASUS-III facility.

Keywords — Transient CHI, plasma startup, noninductive, helicity injection, spherical torus.

Note — Some figures may be in color only in the electronic version.

I. INTRODUCTION

A requirement for a tokamak reactor is to have sufficiently low recirculating power to make it economical for electrical power generation. A recent design study explored the importance of aspect ratio optimization in a compact $R_o = 3$ m, high-field, high-temperature superconductor toroidal field (TF) spherical tokamak (ST) advanced tokamak, with the requirements for electrical self-sufficiency and a tritium breeding ratio of at least 1. The design study for a compact $R_o = 3$ m fusion nuclear science facility showed that for a given inboard neutron shield thickness, the net electrical power of the configuration substantially increased with decreasing aspect ratio $A$ and peaked at $A \sim 1.8$ (Ref. 1). However, at this aspect ratio, even for the case with the thinnest neutron shield thickness of 0.3 m, the current ramp-up fraction of a single-swing central solenoid was only about 30% of the full required current. For a shield thickness of 0.5 m or higher, the current generation capability of the solenoid was negligible. If the aspect ratio was increased to above 3, then it was not possible for the configuration to generate any net electrical power at all. Thus, reduced reliance on a central solenoid would be beneficial for the compactness of a fusion pilot plant.

Figure 1 shows the typical scenario for current startup and ramp-up to the sustained operating levels in a low aspect ratio tokamak. Phase 1 is the startup phase. This could be without or with a reduced use of flux from the central solenoid. During this phase, a nonsolenoidal current startup method would generate most of the startup
The method referred to as transient CHI is implemented by driving current along magnetic field lines that connect the inner and outer divertor plates on one end of the ST. This region is referred to as the injector region. For transient CHI, it is necessary that the inner and outer divertor plate regions be electrically separated from each other and that there is also a physical gap between these plates. After the TF coil is energized, divertor PF coils in the injector region are also energized in a configuration that produces poloidal magnetic flux that connects the inner and outer electrodes. For transient CHI startup, gas would be injected in the gap between the injector divertor plates and a small capacitor bank (typically 5 to 20 mF on NSTX and on current experiments) charged to about 1.5 to 3 kV would be discharged across the divertor plates. If the injector current exceeds a threshold value, the resulting \( J_{\text{pol}} \times B_{\text{tor}} \) force would exceed the magnetic field line tension of the injector flux, which would cause the magnetic helicity and plasma to be injected into the main torus chamber.

Coaxial helicity injection can be applied using two different methods. The first CHI studies used a method known as steady-state or driven CHI. With this method, after the plasma expands to fill the vessel, the external power supply continues to drive the current to maintain the elongated field line structure. In this scenario, one relies on some form of non-axisymmetric three-dimensional (3-D) modes to generate closed-flux surfaces, which are then sustained through dynamo current drive action. While \( I_p > 350 \text{ kA} \) could be generated on HIT-II (Ref. 15) and over 400 kA on NSTX (Ref. 16), the resulting plasmas could not be coupled to a subsequent inductive drive as a result of the plasma being too resistive. Later studies utilized the transient CHI scenario. In this scenario, immediately after initiation and on the timescales needed for the poloidal flux to be injected into the vessel, the driven injector current is rapidly reduced toward zero. Reduced injector current generally causes the injected flux to pull back into the injector region. However, if the injector flux footprints are sufficiently narrow, it is possible for the injected poloidal flux to reconnect in the injector region, generating closed-flux surfaces. This is because it now becomes more difficult for the injected flux to pull back through a narrow magnetic throat, and it may be easier for a large volume of plasma already in the vessel to reconnect at the magnetic throat and remain within the vessel. The physical mechanism leading to the reconnection of oppositely directed magnetic field lines in a transient CHI discharge has been studied by the 3-D resistive magnetohydrodynamic (MHD) code NIMROD. These simulations show...
that a local two-dimensional (2-D) Sweet-Parker-type reconnection is triggered in the injector region, which is responsible for oppositely directed magnetic field lines in the injector region to reconnect leading to the formation of closed-flux surfaces. The method of transient CHI was first developed on HIT-II and considerably improved on the NSTX device.\textsuperscript{18} On NSTX, over 200 kA of closed-flux plasma current was generated. The resulting target plasmas were ramped up to 1 MA using a central solenoid drive, with solenoid flux savings proving that the concept is compatible with the standard inductive method.

The rest of this paper is organized as follows. In Sec. II, simple relations are used to estimate the toroidal current generation potential of Pegasus-III. In Sec. III, the transient CHI current generation estimates are improved by modeling using the Tokamak Simulation Code\textsuperscript{19} (TSC). In Sec. IV, an electrolytic capacitor-based power supply to be used to drive the transient CHI injector current is described. Section V is a brief summary of the main results from this paper.

II. SIMPLE ESTIMATES FOR THE TRANSIENT CHI CURRENT STARTUP CAPABILITY ON PEGASUS-III

Pegasus-III (Ref. 20) has a nominal major radius $R_o$ of 0.4 to 0.45 m, and an aspect ratio $\geq 1.22$. It is intermediate in size between the HIT-II ($R_o = 0.3$ m) and the NSTX ($R_o = 0.86$ m). Compared to the two previous machines on which transient CHI was developed, PEGASUS-III has all metal, plasma-facing walls that should benefit transient CHI startup as the source of low-Z impurities would be reduced. On both the HIT-II and the NSTX, toroidal ceramic insulators were used to electrically separate the inner and outer vessel components to enable transient CHI operation. The use of large vacuum ceramic insulators in a reactor-sized device may not be possible,\textsuperscript{21} so an alternate method is needed for the transient CHI electrodes.\textsuperscript{22} The QUEST device is developing a single-biased configuration in which one of the divertor plates is insulated from the rest of the vessel using a toroidally continuous (but segmented) nonvacuum insulator that separates the electrode plate from the outer divertor plates, as described in Ref. 23. PEGASUS-III will employ a double-biased insulator configuration in which both the inner and outer divertor plates will be insulated from the vessel as described in Ref. 24. The electrodes will be insulated from the vessel by ceramic plates that separate the vessel components from the electrodes, analogous to that on QUEST. Voltage would be applied across these floating electrodes. This configuration is anticipated to be more robust toward spurious arcs (referred to as absorber arcs in transient CHI terminology). Because both electrodes are floating with respect to the main vacuum vessel, the current path is much better defined in that it must flow from one electrode to the other, so it is much more difficult for the driven injector current to find a shorting path to other parts of the vessel. This capability should provide greater control over the magnetic flux configurations and the applied voltages that may be possible on PEGASUS-III.

Figure 2 shows the planned location of the inner and outer divertor plates on PEGASUS-III. Also shown are the poloidal coil locations to be used for transient CHI discharge initiation. Figure 2 also shows the initial vacuum injector flux configuration that uses 16 kA in the DIV-1B coil. The currents in the other nearby injector flux coils are adjusted to provide a suitable injector flux configuration. The injector flux for this coil configuration is 23 mWb. The approximate separation between the injector flux footprints on the electrode surfaces, indicated by the letter “d” is in the range of 7 to 12 cm. The smaller separation distance is the lower limit set by the physical separation between the electrodes. The larger separation distance is more difficult to precisely specify, as it depends on the location of the majority of the field lines that carry the injector current. The footprints are the location on the electrode surface where the injector flux leaves and enters the electrodes. As the footprints are spread out over some radial extent and the injector current that flows on each field line depends on both the field line length and the conductivity of the field lines, the parameter d is an approximate value. It has been shown by Jarboe\textsuperscript{25} that the current driven along these field lines needs to satisfy a condition known as the bubble burst condition, i.e., when the $J \times B$ forces balance the magnetic field line tension of the injector flux $\psi_{inj}$, as given by the relation

$$I_{inj} = \frac{2\psi_{inj}^2}{(\mu_0 d^2 I_{TF})},$$  

(1)

which represents the minimum current required to satisfy the bubble burst condition. $I_{TF}$ is the current flowing in the center post of the TF coil. For $I_{TF} = 1.152$ MA, this relation provides an approximate estimate for the bubble current in the range of 80 kA (for $d = 7$ cm) to 27 kA (for $d = 12$ cm) for the case shown in Fig. 2. The higher current is clearly an overestimate as most of the field lines are separated by more than the physical gap separation distance, but the injector current may also be more concentrated along the field lines near the gap region as they have a shorter length and are more densely packed. Once expanded into the vessel, the maximum current...
Here it is helpful to briefly review the concept of magnetic helicity injection. Magnetic helicity \( K \) is the linkage of magnetic flux with magnetic flux and is defined as \( K = \int \mathbf{A} \cdot d^3 \mathbf{r} \), where \( A \) is the magnetic vector potential and \( B \) is the magnetic field. The integral is over a volume within a flux surface. In the case of CHI, it represents the linkage of the toroidal flux with the poloidal flux. The rate of magnetic helicity injection during CHI is given as \( 2V\psi \), where \( V \) is the electrode voltage and \( \psi \) is the amount of the flux connecting these electrodes. \(^{25}\) Finite resistivity causes helicity to decay on the resistive diffusion timescale, but the magnetic energy decays on a faster magnetic reconnection timescale. During these short reconnection timescales, fluctuations dissipate the magnetic energy while keeping the global helicity constant, causing the configuration to relax toward the Taylor\(^{26}\) minimum energy state, while satisfying the relevant boundary conditions for the isolated system. The resulting magnetic field strives to satisfy the force-free equation \( \nabla \times \mathbf{B} = \lambda \mathbf{B} \), where \( \lambda \) is a global constant. \( \lambda \) has units of energy per unit helicity, and for the injector and the tokamak, it is defined as \( \lambda_{\text{inj}} = \mu_0 I_{\text{inj}}/|\psi_{\text{inj}}| \) and \( \lambda_{\text{tok}} = \mu_0 I_{\text{tor}}/|\psi_{\text{tor}}| \). For helicity injection into the tokamak vessel to be possible, the parameter \( \lambda_{\text{inj}} \) in the CHI injector region must exceed the parameter \( \lambda_{\text{tok}} \) in the tokamak vessel. Once relaxation of the injected flux into the tokamak is completed, the injected current flows in the entire plasma region and not just in the edge region. Under these conditions, \( \lambda_{\text{inj}} = \lambda_{\text{tok}} \). This equality results in Eqs. (2) and (3).

At a TF of 0.6 T, the toroidal flux in PEGASUS-III in the region occupied by the plasma is estimated to be about 200 to 250 mWb. This results in a maximum current multiplication factor in the range of 9 to 11 for the case in Fig. 2. The resulting maximum open field line current could be expected to be in the range of 240 to 300 kA for this injector flux configuration and for an injector current of 27 kA. The current multiplication factor is an important number from a reactor materials technology aspect, as in a fusion reactor it is necessary to reduce the injector current as much as possible as it is directly related to electrode erosion and to the subsequent influx of impurities into the plasma that can degrade the plasma quality generated by the transient CHI discharge. In addition, a higher current multiplication factor also implies a smaller injector current power supply. Thus, the higher toroidal magnetic fields anticipated in future ST designs considerably benefit transient CHI systems, as a given amount of injector current (that would be dictated by electrode current density limits) can now inject a much larger amount of poloidal flux into the vessel.

Fig. 2. Vacuum flux calculations showing the initial magnetic configuration for a transient CHI startup on PEGASUS-III.
Estimating the closed-flux current in a transient CHI discharge on a relatively small experiment is more difficult as it depends on the details of plasma resistivity (which influences the closed-flux current decay time) and the actual current profile that is achievable in a specific device. Nevertheless, it is possible to estimate a range of values for the closed-flux current generation. In a transient CHI discharge, if the injector flux footprints are relatively close to each other, the fraction of injected open flux that closes can be relatively high (>70% on NSTX) (Refs. 27 and 28). The resulting value of the closed-flux plasma current will then be dictated by the actual current profile within the closed-flux volume as in a standard inductively started plasma discharge. Based on NSTX results, a value for the normalized plasma internal inductance is assumed to be 0.3, but it could be lower than this during the initial phase of flux closure as the toroidal current in a transient CHI discharge is initially concentrated near the plasma edge. The resulting closed-flux plasma current can be calculated from the relation:

$$\psi_p = I_p R_p l_0 \mu_0^2 / 2.$$  \hspace{1cm} (4)

To be about 190 kA for this initial configuration, but would increase to 284 kA as the normalized plasma internal inductance reduces to 0.2. The terms in relation (4) from left to right are the closed poloidal flux, the closed-flux plasma current, the plasma major radius, the normalized plasma internal inductance, and the magnetic permeability. Here, we assume that 70% of the open injector poloidal flux [in Eqs. (2) and (3)] forms the closed poloidal flux, which is a reasonable assumption based on NSTX experimental work and NIMROD (Ref. 28) simulations.

III. TSC SIMULATIONS

In this section, the simple estimates for transient CHI current generation capability are improved using simulations with the TSC. The TSC is a time-dependent, free-boundary, predictive equilibrium and transport code. It was originally developed to model the TFTR and PBX (Ref. 31). It has undergone minimal modifications to support transient CHI studies on NSTX (Ref. 32), and it proved helpful in developing the initial divertor coil current configuration for NSTX transient CHI studies. Indeed, the very first successful transient CHI discharges on NSTX were obtained after TSC simulations indicated the need to reverse the current polarity in a coil adjacent to the injector flux coil. These first TSC simulations for PEGASUS-III were primarily to estimate the divertor coil currents to be driven during the initial phase of transient CHI studies on PEGASUS-III. The experimental results from PEGASUS-III will then be used to further improve the TSC simulations and to obtain better agreement between the experimental and TSC simulations.

The TSC solves the MHD/Maxwell’s equations coupled to transport and the Ohm’s law equations. For simulating the plasma evolution in a transient CHI discharge, it requires as inputs the device hardware characteristics, such as the location of the transient CHI insulator gap, the applied transient CHI voltage, the coil and vessel electrical characteristics, and the electron temperature. The plasma equilibrium and field evolution equations are solved on a 2-D Cartesian grid. The grid is specified as square elements. Since its original development for the TFTR and PBX, it has not been optimized to take advantage of recent developments in the computational architecture, consequently, the computational run time very rapidly increases with a smaller grid size. The grid size used for the NSTX was 5 cm. For PEGASUS-III, reasonable computation times of about 15 h have been possible on the portal cluster, with a much smaller grid size of 1.5 cm.

Boundary conditions between plasma, vacuum, and conductors are based on the fact that the poloidal flux and tangential electric field are continuous across interfaces. The circuit equations are solved for all the PF coil systems with the effects of induced currents in passive conductors included. Open field lines are included, and the halo current is computed as part of the calculation. In this modeling, the PEGASUS-III vacuum vessel is modeled as a metallic structure with a poloidal vessel at the bottom of the machine to model the transient CHI gap. An electric potential V is applied across the break.

The TSC allows for the possibility of global reconnection, as it solves Ohm’s law, which allows for the formation of closed-flux surfaces in the presence of a loop voltage, much as closed-flux surfaces are produced during inductive current drive using a central solenoid. In TSC simulations, a positive inductive voltage is generated during the decay phase of the transient CHI–injected poloidal flux, which is responsible for flux closure during transient CHI discharges. The TSC does not have the capability to model the effects of full 3-D (Ref. 34) or local reconnection physics, such as that which would occur during the steady-state or the driven CHI approach that requires non-axisymmetric modes to drive current. As the transient CHI concept relies primarily on axisymmetric global 2-D-type reconnection, the global flux closure modeling of these discharges is possible using the TSC.
The code does not permit the initiation of a transient CHI discharge from the top of the vessel and with the $\mathbf{J} \times \mathbf{B}$ force directed down into the vessel. It is necessary for the TF to be in the negative direction and the applied electric field for transient CHI to also be in the negative radial direction. For the transient CHI injector located in the lower part of the vessel, this configuration results in the $\mathbf{J} \times \mathbf{B}$ force being directed up into the vessel. On the PEGASUS-III experiment, the TF is positive and the applied electrode voltage is in the radial negative direction. For the transient CHI system located on the top of the vessel, the $\mathbf{J} \times \mathbf{B}$ force is directed down into the vessel. Because of the symmetric nature of the PF coils on PEGASUS-III, this is not an issue for the simulations. The transient CHI discharge in these simulations is initiated from the lower divertor region using the corresponding coils that are identical to the ones on the upper part of the machine. Thus, for example, for the case shown in Fig. 2, instead of the DIV-1B coil, the corresponding coil DIV-4B that is located in the lower divertor region is used.

Three different sets of simulations have been conducted. For the first case, the injector flux magnitude is changed. In the second case, the location of the transient CHI injector region is changed. In the third case, the electron temperature is changed. For all cases, the current in the PF coils is maintained constant in time, with no current ramps on the PF coils. The electron temperature is assumed to be constant in time and spatially uniform within the plasma region because the injected current flows along magnetic field lines. The initial temperature is largely controlled by the presence of low-Z impurities, which one tries to minimize through wall-conditioning practices and on PEGASUS-III also using metal walls. The TF at the device major radius is 0.6 T for all cases. A 0.5-ms voltage pulse of a given magnitude is applied across the transient CHI gap. The dominant current is in the divertor coil chosen to be the transient CHI injector flux coil. Currents flowing along the injector flux that connect the inner and outer electrode plates cause these field lines to expand into the vessel. Then, as the field lines fully fill the vessel, the injector voltage is rapidly turned off. Results from these cases are described here.

Figure 3 shows the results from the injector flux variation. The injector flux coil (DIV-4B) current shown in Fig. 3a is changed to values corresponding to 25%, 50%, and 100% on the traces labeled 1, 2, and 3, respectively, of its initial planned current capability. Initial experiments would begin with the lower injector flux values and progressively move on to cases with more injector flux, as the safe operating procedures for transient CHI are adequately established at the lower energy levels. If the PF coil currents in the injector region are varied in a self-similar manner, the generated injector flux is directly proportional to the current in the main injector flux coil. For the full 16-kA current in the injector coil that has 20 turns, the generated injector flux for this configuration is about 23 mWb. In the first set of simulations, the applied voltage shown in Fig. 3b is the same for all three cases. Figure 3c shows the resulting injector current, and Fig. 3d shows the resulting transient CHI–produced toroidal current. The injector voltage is reduced to zero at about 0.5 ms. This causes the injector current to reduce to zero at about this time for all cases. After the injector voltage is reduced to zero, which causes the injector current to also decrease, the $\mathbf{J} \times \mathbf{B}$ forces responsible for poloidal flux injection are no longer adequate to keep the field lines stretched inside the vessel. As this injected flux tries to pull back into the injector region, as previously noted, the decreasing poloidal flux inside the vessel would induce a positive loop voltage triggering the generation of closed-flux surfaces in the TSC simulations.

Figure 4 shows the resulting poloidal flux for a typical case (for case 2 in Fig. 3) at different times during the discharge. In a physical experiment, the injector current is also the current driven by the external power supply. In the simulations, the injector current is calculated based on the circuit parameters. During the actively voltage-driven phase, the injected current flows along the main inductive plasma load. This actively driven current is about 50 kA at the full injector flux level. The effect of rapidly reducing the voltage is to cause much of the current flowing in the main inductive CHI plasma load to remain within the CHI plasma inside the vessel. The separation of the large inductive CHI plasma load from the electrodes should cause an inductive voltage spike across the electrodes that would cause currents to continue to flow through the injector circuit. This current would now flow through a shorter path across the electrodes. The much-reduced inductance and resistance of this shorter current path, somewhat like an absorber arc, are probably responsible for the current spike. This final current spike is not seen in the experiments on the NSTX. The TSC simulated diagnostic that measures injector current is prone to error when there are large inductive voltages, so it is not claimed that the large current spikes shown are physical. To quantify this, numerical convergence studies are planned for future years.

A comparison of traces 1, 2, and 3 in Fig. 3 shows that as the injector flux is increased, the transient CHI–produced toroidal current increases, but not in an exact
proportion as Eq. (4) would suggest. As the injector flux is increased, less voltage is needed to drive a given injector current because the connection length between the electrodes decreases. Since the TSC simulations also account for currents induced in nearby structures as the current on field lines rapidly increases, the use of a fixed voltage is not appropriate for all injector flux cases. This is somewhat seen in the trace marked 4, which is for the full injector flux case for which the applied voltage was increased from 1.5 to 1.75 kV. It shows the peak toroidal current rapidly increases, and it improves the agreement with Eq. (4). However, the persisting current increases by a much smaller amount. The initial increase in the toroidal current is due to the increased injector current that results from a higher applied voltage during the actively voltage-driven phase. The persisting current, which occurs after the voltage is turned off, should be independent of the injector current. A more detailed study is needed to fully understand the impact of such changes to the injector voltage. Equation (1) was derived for an idealized situation that does not consider the details of the tokamak vessel geometry. For the NSTX transient CHI configuration, a much more detailed study was conducted in which the changes to the injector flux were scanned as a function of the applied voltage. The results shown in Fig. 5 of Ref. 32 indicate that the simple scaling is
reasonably accurate. However, these first TSC simulations in the PEGASUS-III geometry clearly show that the relationship between the required voltage for variations in the injector flux and the resulting toroidal current generation needs further study.

This also raises the question of the permitted injector voltage limits for transient CHI. It is important to note that the injector current is the relevant parameter, but it is controlled by the applied voltage, and experimentally, voltage is the knob that is used in the control room. On both the HIT-II and NSTX, the peak applied voltage had a narrow range, as increasing the voltage beyond that level would cause the expanding poloidal flux to contact the electrode gap on the top of the machine (referred to as the absorber gap), which would then provide an alternate shorter current path for the driven injector current. This would generate a spurious arc, known as an absorber arc, that would deplete the injector current from the main transient CHI discharge and result in the discharge abruptly terminating. But on a machine with a double-insulated electrode, there is no such physical gap on the opposite end of the machine that can short out the transient CHI injector current. This may make it possible to increase the injector voltage beyond the limits that were possible on the HIT-II and NSTX in a condition referred to as current or voltage overdrive. This would cause more of the magnetic field lines that normally would not meet the bubble burst condition to now also grow into the vessel and contribute to toroidal current generation.

To examine this further, two different injector flux cases were tested. These are shown in Fig. 5. Case 1 (Fig. 5) is based on case 3 in Fig. 2. It uses 320 kA-turns in the main injector flux coil DIV-4B and −40 kA-turns in DIV-4A, but at an injector voltage of 1.75 kV. In case 2 (Fig. 5), the current in the DIV-4A coil is changed in polarity and increased to +100 kA-turns. In addition, the current in the EF1AB coil is doubled from −14 to −28 kA-turns, and current in the EF7 coil is increased from −3 to −20 kA-turns. The result is that a higher level of injector flux is now more tightly packed on the divertor plate, resulting in a narrower injector flux footprint width. Case 1 has 23 mWb of injector flux, whereas case 2 has 43 mWb of injector flux. Although the injector flux has nearly doubled, the increase in toroidal current, shown in Fig. 5f, for all other conditions remaining the same is small. Figure 5e shows that the resulting increase in the injector current is modest. Increasing the injector voltage to 1.87 kV causes the initial peak in the toroidal current to increase, but the persisting current shows almost no change. Voltage increases beyond this level are not beneficial. The poloidal flux plots corresponding to the initial injector configuration and much later in time are shown in Figs. 5a through 5d.

In the previous cases, as the injector flux was increased in a self-similar manner, the toroidal current largely increased with injector flux in a manner consistent with the current-to-flux scaling, with the understanding that some additional optimizations may be needed. In the present case, in which a substantial change to the injector flux shape was made, the resulting increase in toroidal current was small, suggesting that the impact of injector flux shaping is another parameter that needs to be studied.
there may be limits on these two parameters in an open injector geometry, which will be studied experimentally on PEGASUS-III.

Figure 6 compares two cases in which the electrode separation location is changed. Case 1 corresponds to the location planned to be used on PEGASUS-III, in which the electrode gap is slightly closer to the inner wall than in case 2. Otherwise, there are no major differences between the two cases. The main difference being that the case with the slightly smaller injector current (with the gap farther away from the inner wall) has a slightly higher toroidal current. The resulting changes to the injector current and the transient CHI–generated toroidal current are small, suggesting that the exact location of the gap is probably not a sensitive parameter for the transient CHI configuration to be used on PEGASUS-III.

For transient CHI, the location of the insulator gap in relation to the position of the injector flux coils is an important design consideration as it determines both the amount of divertor coil poloidal flux that can connect the transient CHI electrodes and the injector flux shaping that can be achieved. Although the TSC studies suggest that this difference is small for the PEGASUS-III configuration, this too needs to be studied on PEGASUS-III by shifting the electrode positions on PEGASUS-III as part of a future optimization process to understand its role in an open electrode configuration, but probably as a lower priority activity.

Figure 7 shows the effect of varying the electron temperature from 50 to 200 eV, with all other conditions remaining the same. At lower electron temperatures, the plasma resistivity is higher, so the current and flux expand more rapidly. This results in more initial toroidal current as an increased amount of toroidal flux links the expanded poloidal flux. At lower electron temperatures, due to the higher resistivity, the current also decays faster. Likewise, at higher electron temperatures, the magnetic diffusion is smaller, resulting in less flux expansion and initial current generation, but the generated current decay time is also slower resulting in a higher level of persisting current. These effects cause the current peak to appear later in time for the higher electron temperature cases. Case 4, which is at higher voltage but also at 200 eV, follows the same initial current increase rate as case 3, which is also at 200 eV. But the higher voltage allows a higher peak current than in case 3. This trend of the initial toroidal current peak appearing earlier in time and with a higher current peak for the lower electron temperature plasmas is also seen in NIMROD simulations, which can be seen in Fig. 1 in Ref. 37.

Transient CHI discharges on the HIT-II were able to attain electron temperatures of over 30 eV in a machine that
contained graphite wall components. As the energy injected into the plasma during a transient CHI discharge is small (0.5CV^2 = 20 kJ for typical NSTX discharges), limiting the injection of low-Z elements such as oxygen and carbon is essential. Reducing these were found to be crucial to enable successful transient CHI discharge initiation on the NSTX (Ref. 38). PEGASUS-III, being an all metal machine, should have less low-Z impurity issues than either the NSTX or the HIT-II, permitting the plasma to heat up more easily. Future reactors are anticipated to have either metal walls or liquid lithium walls, both of which are ideal for transient CHI startup. Indeed, on the NSTX, the best transient CHI discharges were obtained after the walls were coated with lithium. The impact of the full metal wall on the attained intrinsic electron temperature will be of particular importance. Impurity doping studies may be utilized to relate the PEGASUS-III results to the HIT-II and the NSTX and to compare to simulations.

**IV. PEGASUS-III INJECTOR POWER SUPPLY SYSTEM**

All previous transient CHI systems relied on oil-filled, high-voltage capacitors for generating the injector current. Thus, for example, most transient CHI discharges on the NSTX used four 5-mF capacitors in a parallel configuration charged to 1750 V. A single igniton switch was used. The system had few components, as all components were rated for high-current and high-voltage operation.

Increased pulsed power safety requirements at the PEGASUS-III facility require the use of low-voltage, low-current electrolytic capacitors and the use of silicon
controlled rectifier switches. The capacitor chosen for the PEGASUS-III transient CHI power supply is a 450-V, 1.5-mF capacitor (model Mallory LES21823-A 235-7445K). The current limit for these capacitors is not well established. Currents of 1.3 kA have been reliably achieved during laboratory tests for designing the transient CHI power system for PEGASUS-III, and higher currents may be possible. The present design is therefore based on the 1.3-kA limit per capacitor.

Figure 8 shows the overall schematic for the capacitor bank power supply. The present system is composed of four modules. Each module is composed of two submodules. The submodule consists of 5 capacitors in a parallel configuration and 8 capacitors in a series configuration, for a total of 40 capacitors. The series configuration is used to reduce the maximum voltage applied to each capacitor. If each capacitor is charged to the full 450 V, then the series maximum voltage of the system would be 3.6 kV. The parallel configuration is used to increase the total supplied current. A combination of a high-voltage SCR switch (3.6 kV, with 20-kA current capability) in series with two diodes for reverse voltage protection are used to switch each module consisting of 80 capacitors. The diodes each have a rating of 4.4 kV and 24 kA each, providing a total reverse voltage suppression capability of 8.8 kV. The individual module currents are measured using both a Hall probe and a Rogowski coil. The Hall probe (model GMW CPCO-12000-77-BP10) is nominally rated for 12 kA, but seems to provide a reliable measurement at currents approaching 16 kA. The Rogowski probe current limit is over 30 kA.

The current output for each module is through two RG-218 coaxial cables. These cables were chosen over the smaller-sized RG-217 cable to reduce the overall resistance of the transmission cable. The cable resistance and inductance for a single 10-m-long cable is 20 mOhms and 2.5 μH, respectively. A total of four modules are used to provide a current of about 32 kA at a charging voltage of 2 kV into a dummy load in which the current rise time is about 0.5 ms. The level at which the system has been tested is adequate for the initial

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Fig. 8. Schematic of the transient CHI power supply for PEGASUS-III.
transient CHI studies on PEGASUS-III. This is at present limiting the current on each capacitor to 825 A and a maximum voltage of 250 V, both of which are well below the maximum design limits of 1.3 kA and 450 V. The system is upgradeable to higher currents through the addition of additional modules or possibly through operation at increased voltage, as all the power components can support operation at 3 kV.

Figure 9 shows the fully assembled system. From the top to the bottom, rack 1 (left) consists of the control panel that can be switched for either manual or remote operation. The next two rows contain the SCR/diode assemblies, with each row containing assemblies for two modules. Below this is the fiber-optic trigger junction panel that receives a fiber-optic signal from a remote computer control system that is then fed back to an ENERP6 six-channel SCR trigger module. As only four modules are used at present, the system capacity can be increased to six modules. Below this is a 3-kV/400-mA Glassman direct current power supply. Below this are the electrolytic capacitors for submodules 1A and 1B. The second rack is composed of six submodules. The voltage of each submodule is measured using a resistive voltage divider network, which can be used for remote monitoring. A digital voltage readout on the front of the submodule quickly provides the charge status of each submodule. As shown in Fig. 8, connected across each capacitor is a 150 kOhm resistor used for voltage balancing across capacitors and a LED-resistor combination, also connected across each capacitor. The LED lights up when the capacitor is adequately charged. This is used as a means to quickly identify any failed capacitors, which can be replaced. During assembly of each submodule, the capacitance of each capacitor was individually measured and matched so that all capacitors in each submodule, especially those in the series configuration, all have closely matched capacitance. Each of the 320 capacitors in the four-module system is cataloged so that failed capacitors can be replaced using a nearly identical capacitor, which can be obtained from a spare storage that also has the individual capacitors cataloged.

Figure 10 shows current traces from the operation of all modules at a voltage of 2 kV. The current trace from each module is also plotted using calculations using LT Spice electrical circuit simulator software. The net total current from all four modules is 32 kA at 2 kV. As a consequence of carefully matching all

![Fig. 9. Photo of the PEGASUS-III transient CHI capacitor bank power supply. The bank as tested has an energy rating of 19 kJ at 2 kV. At 3 kV, the energy rating increases to 42 kJ. If two additional modules are added, the energy rating would further increase to 63 kJ.](image)

![Fig. 10. Experimentally measured and simulated current output from each of the four modules operated in parallel into a dummy inductive load with an inductance of 20.5 μH and 5 mOhm. The individual modules have a capacitance of 2.373, 2.174, 2.334, and 2.559 mF, respectively.](image)
capacitors within a submodule, the modules all have different values of capacitance. This is reflected in the difference in the current output from each module at the same charging voltage. The module current traces show a rapid drop starting about 0.7 ms due to the use of a freewheeling diode across the inductive load. The power system is upgradable to higher current capabilities. Operating the system at 3 kV would increase the total output current to about 48 kA. The individual capacitor current would increase to 1.2 kA. The applied voltage to each capacitor would increase to 375 V. Two more modules can also be added, permitting the total current to increase to 55 kA.

V. CONCLUSIONS

At sufficiently reduced aspect ratio, the ST has the potential for a compact demonstration fusion reactor with tritium and electrical power self-sufficiency. However, as the aspect ratio is reduced, the space available for a central solenoid drastically decreases, and at a sufficiently low aspect ratio, there is insufficient space for a solenoid that can generate the needed amounts of plasma current. Thus an alternate method, other than the solenoid, is needed to generate a substantial portion of the initial startup current. PEGASUS-III is a ST nonsolenoidal startup development device dedicated to solving this problem. The transient CHI method has shown promising capability on both the HIT-II and the NSTX. However, in both of these machines, the vacuum vessel is electrically separated using toroidal ceramic insulators. For reactor applications, a simpler biased electrode configuration is required in which the insulator is not part of the external vacuum vessel boundary. To develop this capability, PEGASUS-III will use a double (floating)–biased electrode configuration, which will be a first of its kind for the reactor-relevant development of the transient CHI concept.

In addition to developing the double-biased configuration, PEGASUS-III will also optimize transient CHI and study the maximum toroidal currents that can be generated in an open injector flux configuration. Initial TSC simulations suggest that the persisting transient CHI–generated current (after the transient CHI system is turned off) should exceed 200 kA. The TSC simulations have also indicated the need for certain optimization parameters. The first is the need to better understand the injector flux–to–current generation scaling in an open injector flux configuration, as the injector flux is first increased in a self-similar manner and later using different injector flux configurations in which the injector flux footprint width is changed. The extent of potential injector current/voltage overdrive that is possible in a double-biased configuration is of great interest, as this would allow more of the injector flux to be injected into the vessel. The intrinsic electron temperature of transient CHI discharges on PEGASUS-III is of considerable interest as it is an all metal machine. These discharges could be doped with low-Z impurities to relate back to previous studies on the NSTX and the HIT-II to understand the permitted limits on low-Z impurity contamination levels in transient CHI discharges. The importance of the location of the physical transient CHI gap also needs to be studied for the open electrode configuration, but as a lower priority activity.

To support the experimental studies, a power supply based on low-voltage, low-current electrolytic capacitors has been designed, tested, and built. The present system is composed of four modules containing a total of 320 individual capacitors. At 2 kV, the peak current capability is 32 kA. System components can support 3-kV operation without exceeding the voltage or current limits of the individual capacitors, and this capability will be implemented as needed as part of experimental operations on PEGASUS-III. The system is modular, and should the need arise, it has the capability to increase the total number of modules to six and the total injected current to 55 kA.

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Data Availability Statement

Data is available online at http://hdl.handle.net/1773/49170.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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