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Design and Operation of the Electrical Noise Suppression System for CHI on NSTX and NSTX-U

Z. Gao, R. Ramakrishnan, C. Neumeyer, D. Mueller

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Princeton Plasma Physics Laboratory
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Zhi Gao (Andy), Princeton Plasma Physics Lab, Princeton, NJ, agao@pppl.gov
Raki Ramakrishnan, Princeton Plasma Physics Lab, Princeton, NJ, agao@pppl.gov
Charles Neumeyer, Princeton Plasma Physics Lab, Princeton, NJ, neumeyer@pppl.gov
Dr. Roger Raman, University of Washington, Seattle, WA, rraman@pppl.gov
Dr. Dennis Mueller, Princeton Plasma Physics Lab, Princeton, NJ, mueller@pppl.gov

Author: Zhi Gao (Andy)
Email: agao@pppl.gov
Phone: 609-243-2211
Address: Engineering Office 104,
Mail box, MS-08, PO Box 451,
Princeton, NJ, 08543

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Abstract #: 18163

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Zhi Gao (Andy), Princeton Plasma Physics Lab, Princeton, NJ, agao@pppl.gov
Raki Ramakrishnan, Princeton Plasma Physics Lab, Princeton, NJ, agao@pppl.gov

Abstract – Coaxial Helicity Injection (CHI) is a novel system for solenoid-free plasma current initiation on Tokamaks and Spherical Tokamaks (ST). The method uses divertor coils to produce magnetic flux that connects the lower divertor plates on NSTX/NSTX-U, which are electrically insulated from each other. A voltage is applied across the divertor plates using a 50 mF, 2 kV capacitor bank and D_2 gas in injected in the lower gap, which drives a current along the helical field lines connecting the plates. Electromagnetic forces cause the discharge to expand into the vessel and a combination of magnetic reconnection and inductively driven current form a plasma with closed flux surfaces inside the vessel. On NSTX-U it is planned to increase the voltage limits to up to 3 kV.

As the injected flux closes on itself to generate a tokamak-like equilibrium, rapid changes to the plasma circuit inductance can generate high voltage spikes. To suppress these spikes, two voltage suppression systems are employed. The first is a capacitor based snubber system, load balanced between the inner and outer vessel components of NSTX/NSTX-U. The second is a Metal Oxide Varistor (MOV) system. The MOV system is deployed at three toroidal locations around the device. Design calculations are able to closely match the observed behavior on NSTX. Design details for both these systems, including improvements to the MOV system for NSTX-U, will be discussed in conjunction with experimental measurements from NSTX.

Keywords: Coaxial Helicity Injection (CHI); NSTX-U; Plasma start-up; Helicity injection; non-inductive

I. Introduction

The favorable properties of the Spherical Torus (ST) confinement concept arise from its small aspect ratio [1]. Because of the limited space in a spherical torus to accommodate an internal inductive coil, an essential feature of future spherical torus designs will be the inclusion of an effective means to initiate the plasma and to drive plasma current without relying upon inductive drive. Coaxial Helicity Injection (CHI) has been shown to be effective for initiation and for ramp-up on the Helicity Injected Torus (HIT) [2], the Helicity Injected Torus-II (HIT-II) [3] and the National Spherical Torus Experiment (NSTX) [4] to drive up to 390 kA of toroidal current [5].

NSTX-U has a major/minor radius of 0.93/0.55 m and a toroidal magnetic field at the nominal major radius up to 1 T (0.55 T on NSTX). It is equipped with a central solenoid providing up to 2.1 Wb of inductive flux (double swing) which can generate plasma currents up to 2 MA. The outer poloidal field coils are identical to the ones used on NSTX and will be located about 0.5 m away from the plasma boundary. The entire plasma facing boundary, as on NSTX, will initially be composed of graphite tiles. Starting from 2017, in a staged approach, NSTX-U will undergo an upgrade during which many of the graphite tiles will be replaced with metallic tiles. NSTX-U will rely largely on lithium coatings of the plasma facing surfaces to reduce the influx of low-Z impurities and to reduce wall recycling. The lithium coating systems on NSTX-U will expand on the capabilities available on NSTX, by allowing full coverage of both the lower and upper divertor tiles. NSTX-U will also be equipped with a second tangential neutral beam system that is well aligned to drive current. Much of the NSTX-U plan for full non-inductive start-up, in which CHI will be used as the front end, and subsequent non-inductive current ramp-up to the steady-state current sustainment levels will rely extensively on the new second neutral beam system capability. [6]

II. History of CHI

CHI was originally tested in the HIT-II experiment at University of Washington and then successfully scaled up in NSTX. In NSTX, it has generated closed flux plasma currents up to 200 kA. With induction from the central solenoid added to these discharges, it achieved 1 MA of plasma current using 65% of the solenoid flux of standard induction-only discharges. The CHI-initiated discharges have low plasma density and normalized internal plasma inductance of 0.35 through the inductive ramp, typical of advanced scenarios planned for future STs.

An important objective of the NSTX-U program is to ramp-up CHI-initiated discharges non-inductively to the steady-state current sustainment levels. In support of this goal, the Tokamak Simulation Code (TSC) has been used to conduct initial simulations of a full discharge modeling in which a CHI-started discharge is ramped-up in current to 1 MA using a combination neutral beam current drive and bootstrap current overdrive.

As shown in Figure 1, CHI is implemented on NSTX-U by injecting current through the plasma, on open field lines, using an external capacitor bank based power supply. These field lines, known as the injector flux, are generated using the lower divertor coils. On NSTX-U, the primary injector coil that is closer to the divertor gap

(Figure 2), will provide most of the injector flux, and initial start-up scenarios will rely only on this coil for generating the injector flux. The magnetic flux generated by this coil will connect the lower inner and outer divertor plates that are electrically separated by the injector gap. Electrical separation of the inner and outer vessel components is achieved using two toroidal ceramic insulators, one at the bottom and an identical one at the top of the machine. About 1 to 3 Torr-L of deuterium gas would be injected in the region below the divertor plates, at the location marked in Figure 2, and a 2 kV capacitor bank (20 to 50 mF) will be discharged across the lower divertor plates. The capacitor charging voltage is planned to be increased to 3 kV to achieve better results.

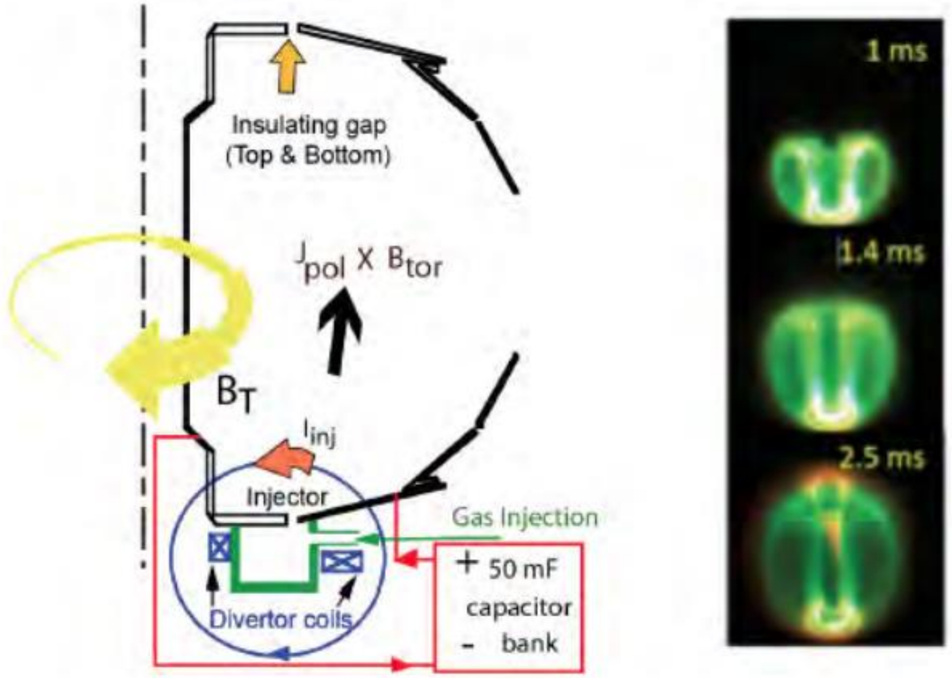


Figure 1 Cartoon showing components required for CHI discharge initiation in NSTX-U, and fish eye camera images of an evolving CHI discharge in NSTX

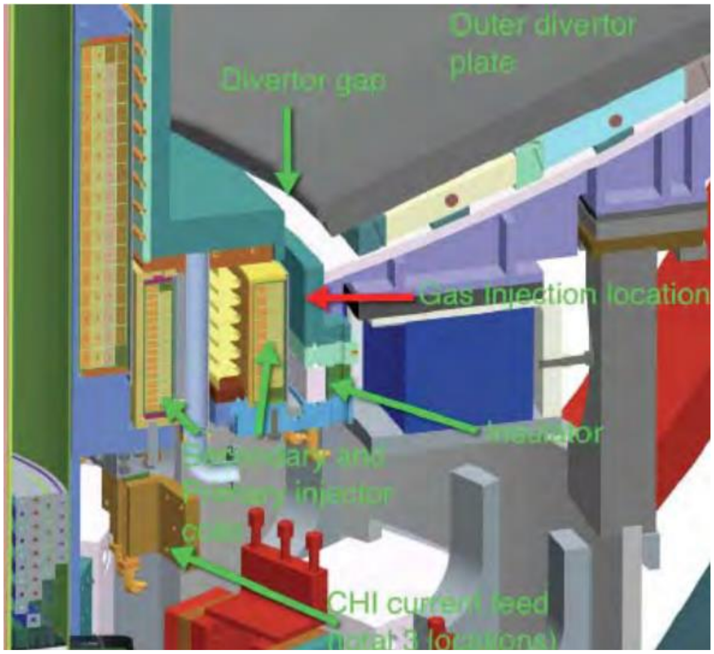


Figure 2 3-D drawing of the lower divertor region of NSTX-U showing the secondary and primary injector flux coils, gas injection location and the CHI insulator

The high-voltage electrical discharge will initiate a plasma discharge on the open-field lines. Because of the presence of a strong toroidal field, the driven current develops a strong toroidal component. This is the initial process of toroidal current generation. If the driven current magnitude is increased, so that the J X B toroidal force exceeds the magnetic field line tension of the injector poloidal flux [7], then the injected poloidal flux will extend into the NSTX-U vessel as shown by the fast camera images for a discharge evolution in NSTX. The plasma grows quickly, in about 2 to 5 ms, to fill the vessel. For transient CHI, on this time scale, the injector current is rapidly reduced. Through the choice of an appropriately sized capacitor bank much of this happens naturally as the stored energy in the capacitor bank is depleted. This process is sometimes assisted through the use of a fast crowbar system that is described later.

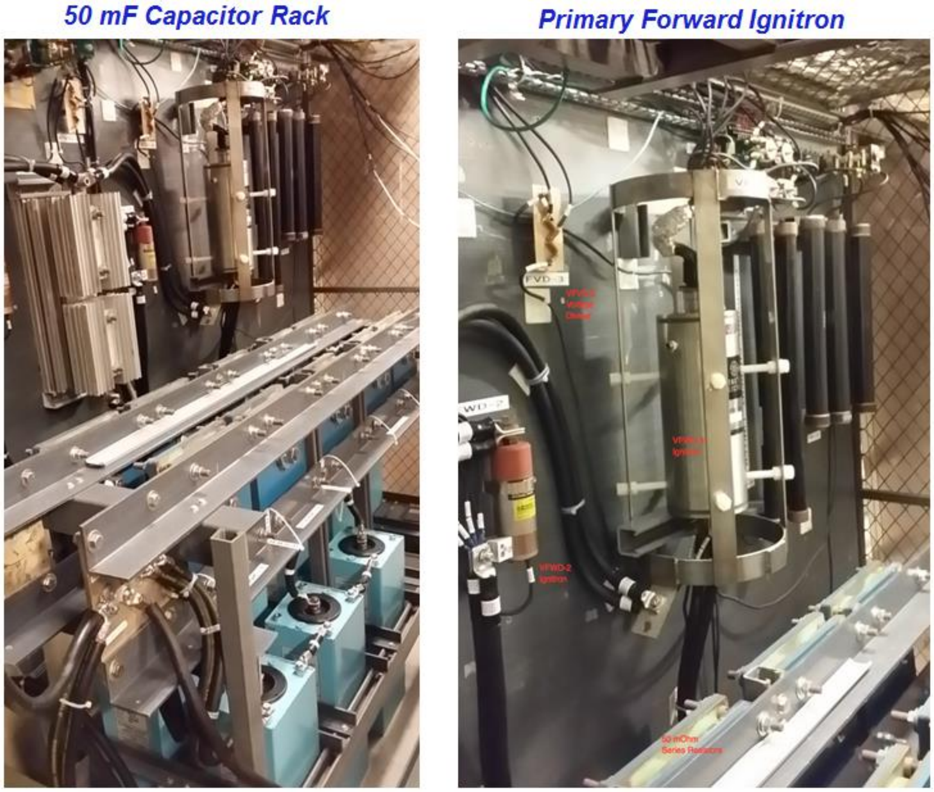
In addition to this, other poloidal field coils in the divertor region are driven in a polarity opposite to that used for the primary injector coil to reduce the flux foot print width on the lower divertor plates. This narrow flux footprint facilitates magnetic reconnection, which causes the injected poloidal flux to remain in the vessels as a closed flux plasma configuration after the field lines re-connect near the injector region.

The generated closed flux plasma on NSTX carried over 200 kA of current, and this value is projected to increase to over 400 kA in NSTX-U due to the much higher magnitude of the available injector flux and capacitor bank system capability. The subsequent non-inductive current ramp-up scenarios on NSTX-U would use this initial target for a demonstration of non-inductive current ramp-up and sustainment.

III. CHI on NSTX-U

The CHI system in NSTX-U is primarily composed of three sub-systems – the capacitor based power supply and firing system, the noise suppression system and the internal discharge mechanism. The capacitor based power supply system and firing circuit is located in the basement directly underneath the NSTX-U machine. It is connected through five RG-218 cables 25 feet in length and 16 feet of bus run to the main grounding switch, which can be used to ground both the inner and outer vessels when CHI is not used. The snubber circuit is located near the machine through another 10’ of cable and connected directly to the ring bus. The ring bus is located directly below the machine and is used to provide three electrical connection points to the ground and high-voltage connections to NSTX-U. The four line to ground surge suppressors are located on the ring bus with equal spacing.

Figure 3 shows the picture of the 50mF capacitor rack located in the basement directly underneath the NSTX-U machine. These capacitors are rated for 2kV, 5mF each. The firing circuit uses three ignitrons that can be discharged at different times. Typically, the large D-sized ignitron, which is connected to two or three capacitors discharges first. This is followed by discharge of an additional one or two capacitors connected to smaller A-sized ignitrons, which can also be seen in Figure 3. When the firing command is given, the ignitron conducts within 0.1ms and discharges the energy stored in the capacitors into the CHI electrode gap.


50 mF Capacitor Rack

Primary Forward Ignitron

Figure 3 Picture of the Capacitor based power source and the forward firing mechanism

The noise suppression system for CHI on NSTX-U consists primarily of an RC snubber and MOVs that are connected line-to-line as well as line-to-ground. The primary objective of the noise suppression system is to suppress the voltage spikes due to the rapidly changing plasma current as well as voltage imbalance between the inner and outer vessel. Figure 4 shows the outline of the CHI noise suppression system. The snubber circuit consists of two 50uF capacitor and six 100uF capacitors in parallel as well as two 200 mohm resistors in series. It is connected across the terminals of the inner and outer vessels.

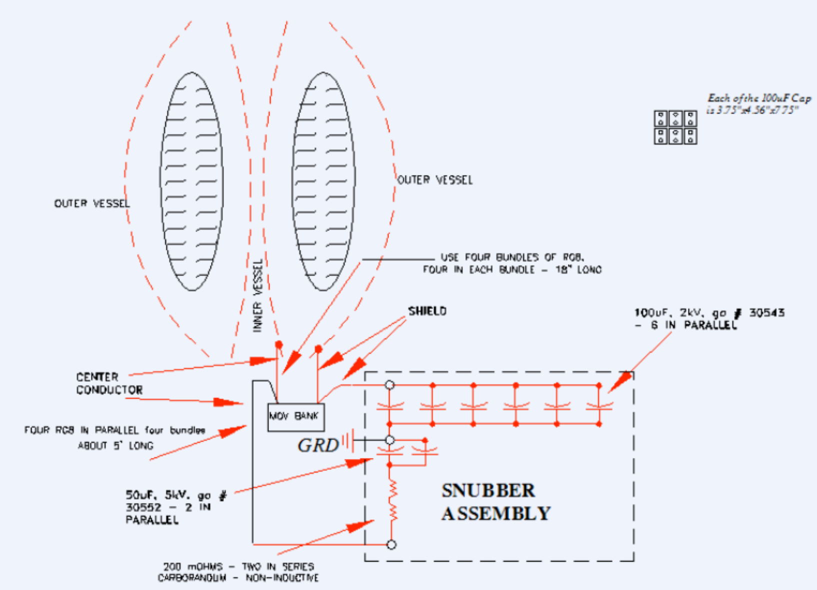


Figure 4 Outline of the CHI noise suppression system

Figure 5 is a snapshot of the snubber assembly near the bottom of the NSTX-U machine. One side of the box is connected to the class 3 ground (the inner vessel potential) and the other side connected to the vessels terminals.

Figure 5 Snapshot of the Snubber Assembly located near the NSTX-U machine

IV. Design of the Noise Suppression System

One of the biggest challenges that faced the design team was the transient voltage seen by the equipment during plasma initiation and disruption. As the injected flux closes on itself to generate a tokamak like equilibrium, rapid changes to the plasma circuit inductance can occur. These fast current interruptions, as the parts of the CHI plasma disconnect from the externally driven circuit can induce extremely high transient voltages at the terminal of the machine. Due to unbalances in the stray inductance and capacitance at each terminal, voltage unbalance between the terminals will also occur. It is prudent to have strong means of transient voltage suppression to reduce the voltage spikes within design envelopes.

To assist in design, an electrical simulation model was established in the electromagnetic simulation software PSCAD to evaluate the effect of the noise suppression system on the voltage spikes. Figure 6 shows the model used in PSCAD. As shown here, the MOVs, capacitors, resistors, stray resistance/capacitances/inductances and cables are all modeled in detail. The forward ignitron is modeled using a timely controlled switch with a series resistance. Since the formation and disruption of the plasma current is a very complex process. The CHI plasma current was modeled as a fixed inductance, accounting for a plasma inductance of order 20-80uH and the 10:1 ratio of I_p to I_{chi}. Various plasma disruption scenarios were evaluated during the design phase. An instantaneous 50% plasma current disruption was assumed to be the worst case scenario. In reality, with a correctly configured external capacitance, during re-connection events, the current disruption should be much less than 10%.

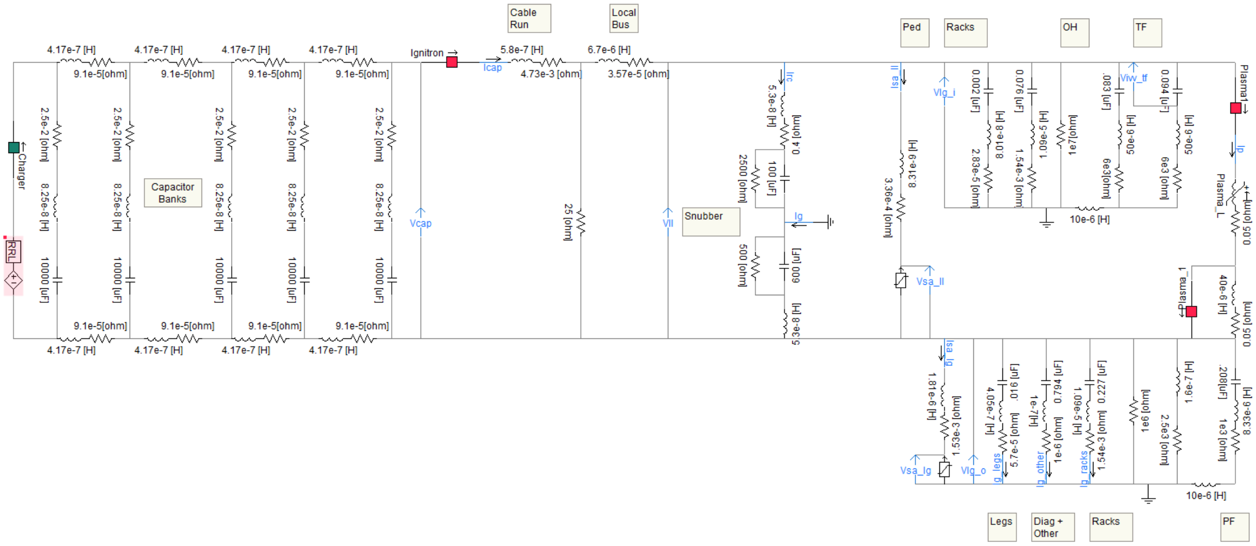


Figure 6 Outline of the CHI Model in Simulation Software PSCAD

Figure 7 shows the resulting voltage and currents from a 50% instantaneous plasma disruption. The forward ignitron was given a command to conduct at 3 ms after the simulation starts. The plasma current starts 0.5 ms after and a 50% plasma disruption occurs at 5 ms. As shown here, the peak transient voltage is around 3.35 kV, which is within the designed equipment withstand capability. The actual voltage increase is about 2.5kV in the simulations, with a 3.35kV L-C high frequency oscillation that is seen in the simulations, but not in the experiment. For comparison, experimental data from a discharge that experienced a large voltage transient is also shown, and is found to be about 2.5kV.

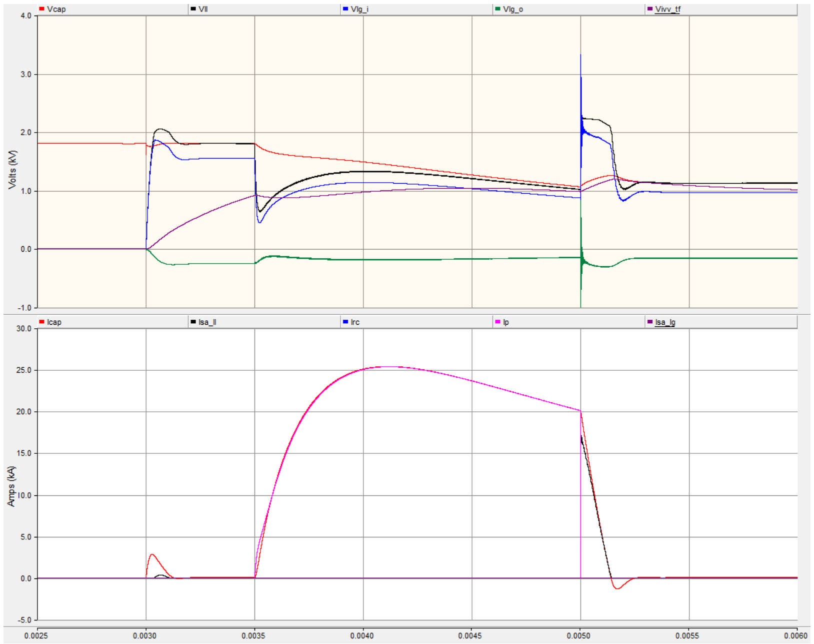


Figure 7 Resulting voltage and current for a 50% plasma current disruption

Various combinations of snubber and MOV ratings were evaluated during the design phase. In the scenario shown here, the capacitors were charged to 1.8 kV. It is also planned that the future CHI operation will have a 3 kV charging voltage, which should result in a higher plasma current.

V. Conclusion

The application of CHI on NSTX has revealed many important aspects of CHI physics and benefits to future large fusion experiments, especially Spherical Torus class of machines. With the aid of the computer simulation program PSCAD, the engineering team was able to simulate and design the noise suppression system in response to various plasma disruption scenarios. With the upgrade and new features added to the system, more analysis will be performed to ensure safe and liable operation of the CHI system.

ACKNOWLEDGMENT

We acknowledge the support of the NSTX-U Engineering and Physics Teams for support with the CHI system design for NSTX-U. In particular we thank J. Chrzanowski, R. Hatcher, H. Schneider, P. Sichta, L. Morris, K. Tresemer and A. Jariwala for support with CHI hardware design. This work is supported by US DOE Contract No. FG03-96ER5436, DE-FG02-99ER54519 and DE-AC02-09CH11466

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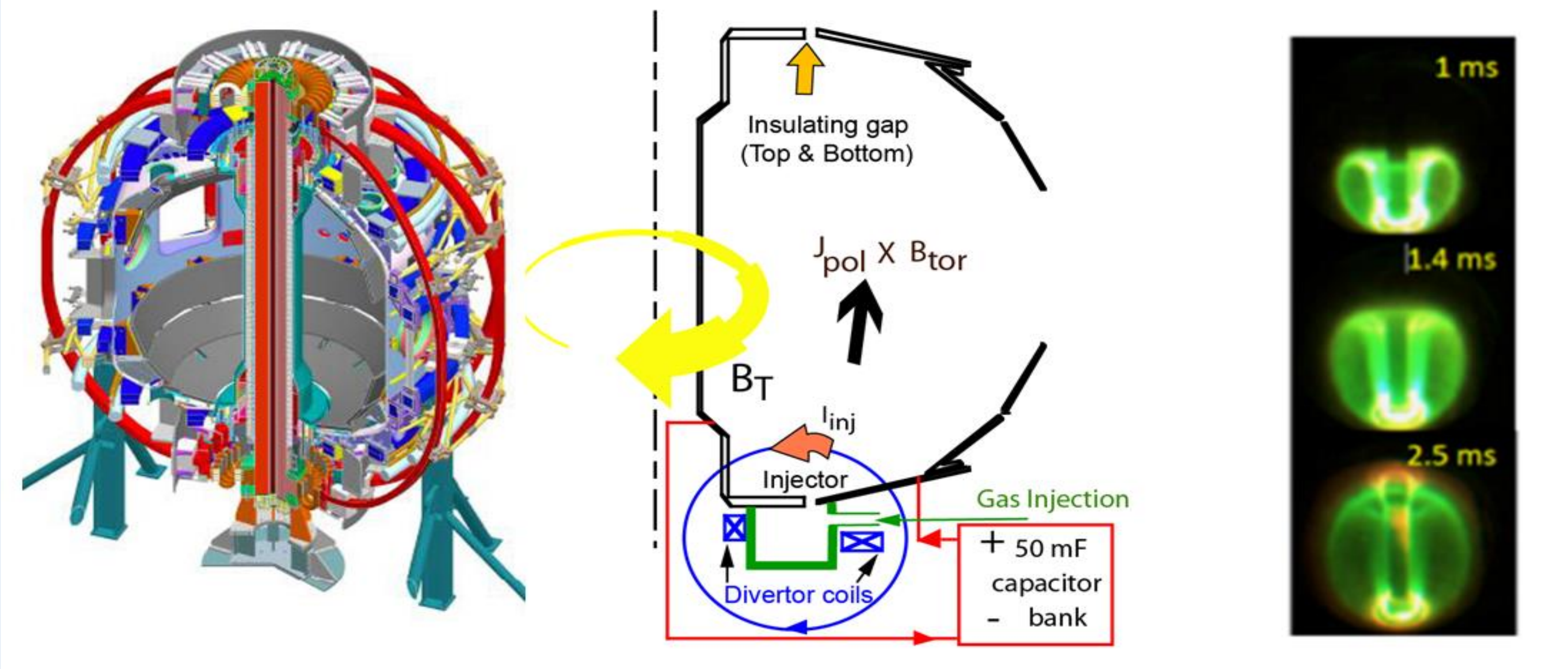

Components required for CHI discharge initiation in NSTX-U, and fish eye camera images of an evolving CHI discharge in NSTX

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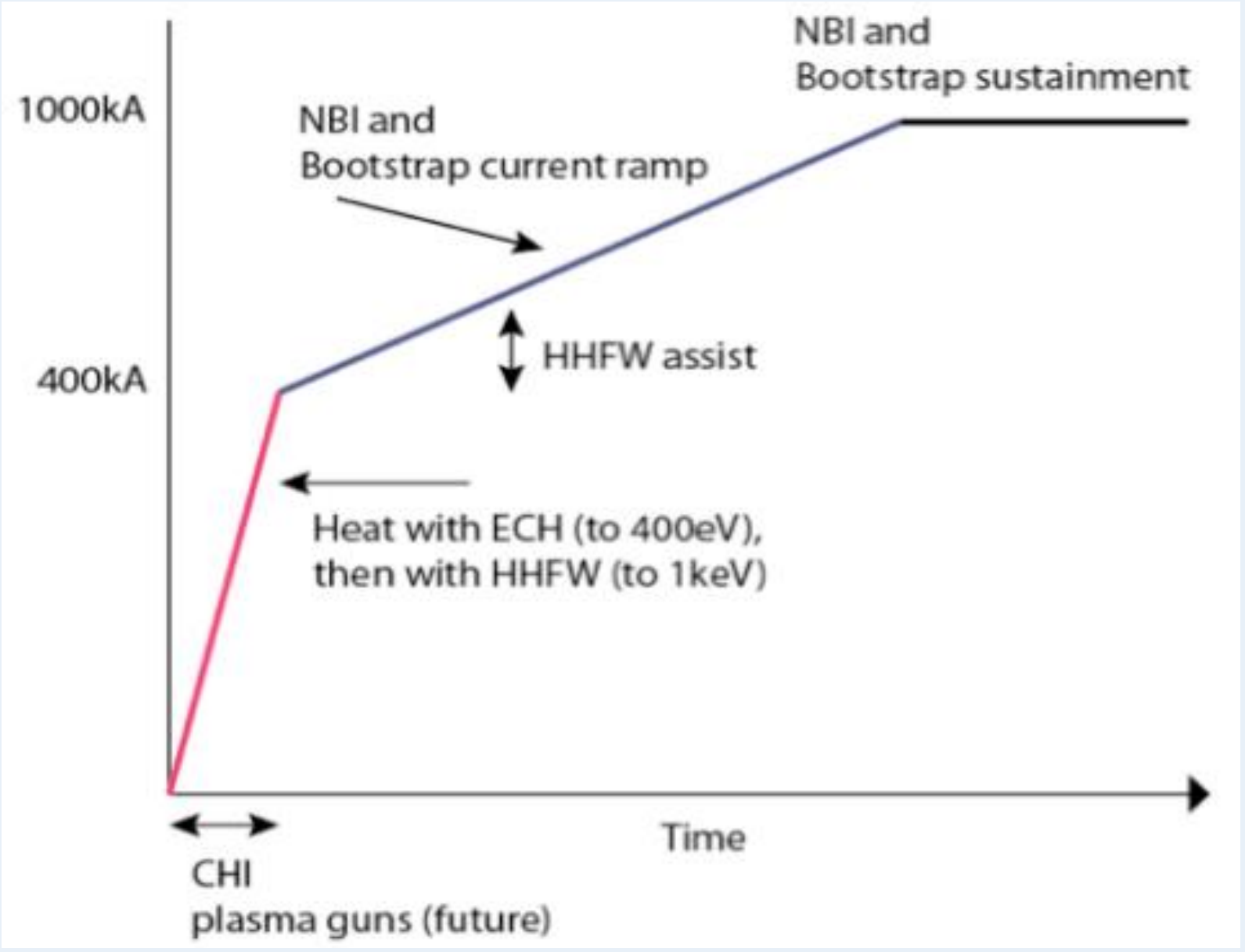
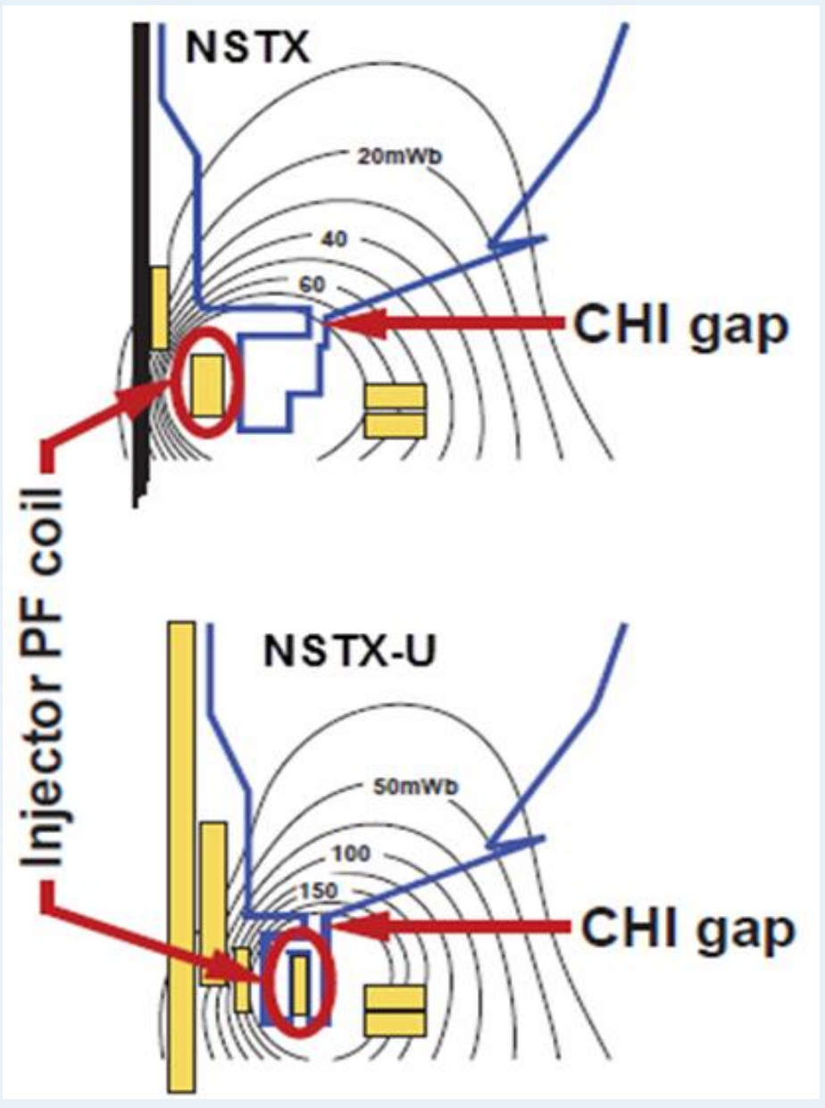


CHI Start-Up and Ramp up Strategy



Inject flux in NSTX-U is ~2.5 times higher than NSTX

Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Major radius [m]	0.86	0.93	1.2	2.2
Minor radius [m]	0.66	0.62	0.80	1.29
B_T [T]	0.55	1.0	2.2	2.4
Toroidal flux [Wb]	2.5	3.9	15.8	45.7
Sustained I_p [MA]	1	2	10	18
Injector flux (Wb)	0.047	0.1	0.66	2.18
Projected Start-up current (MA)	0.2	0.4	2.0	3.6

Transient CHI Scaling: Generated Toroidal Current is proportional to Injector Flux

Acknowledgement

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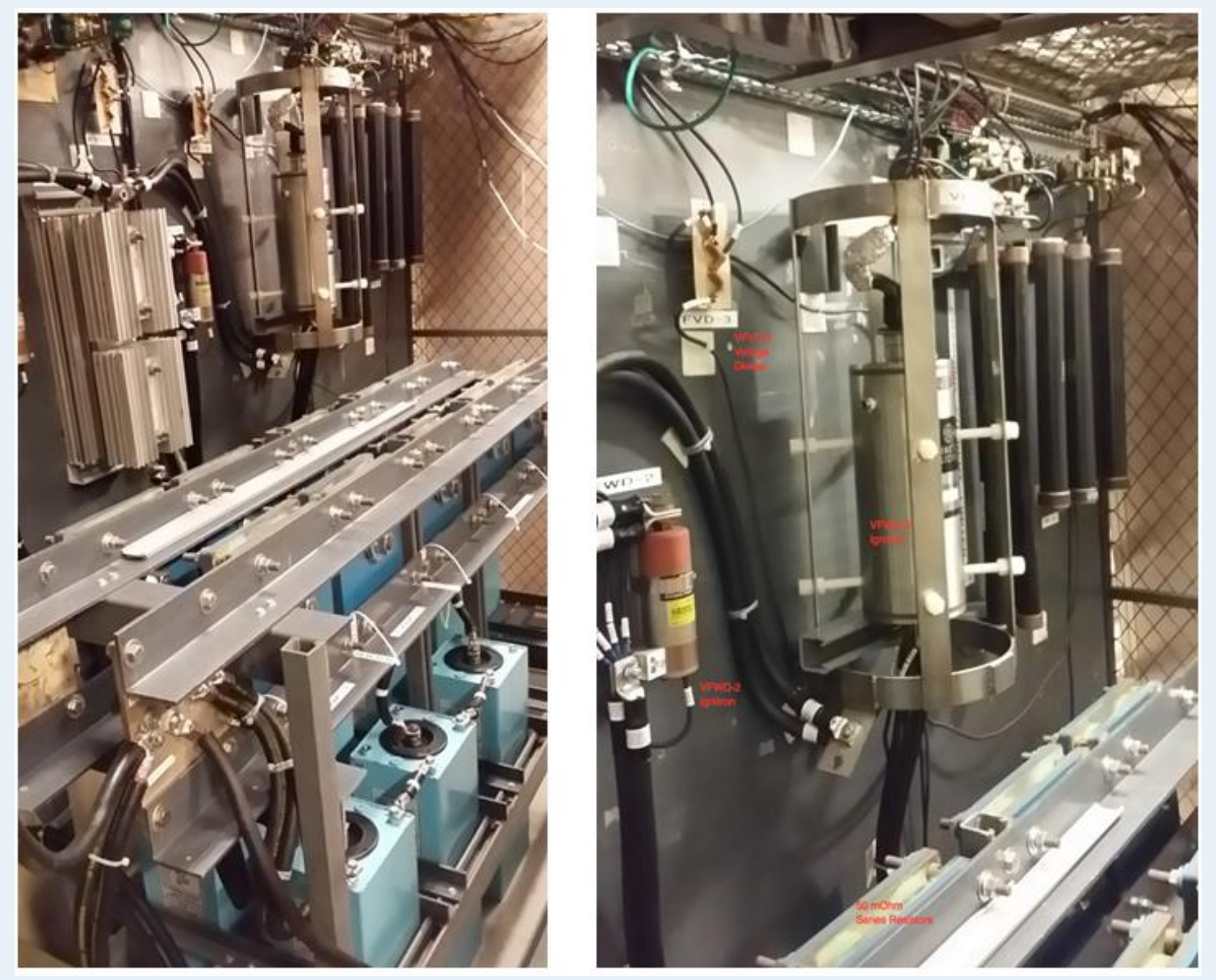
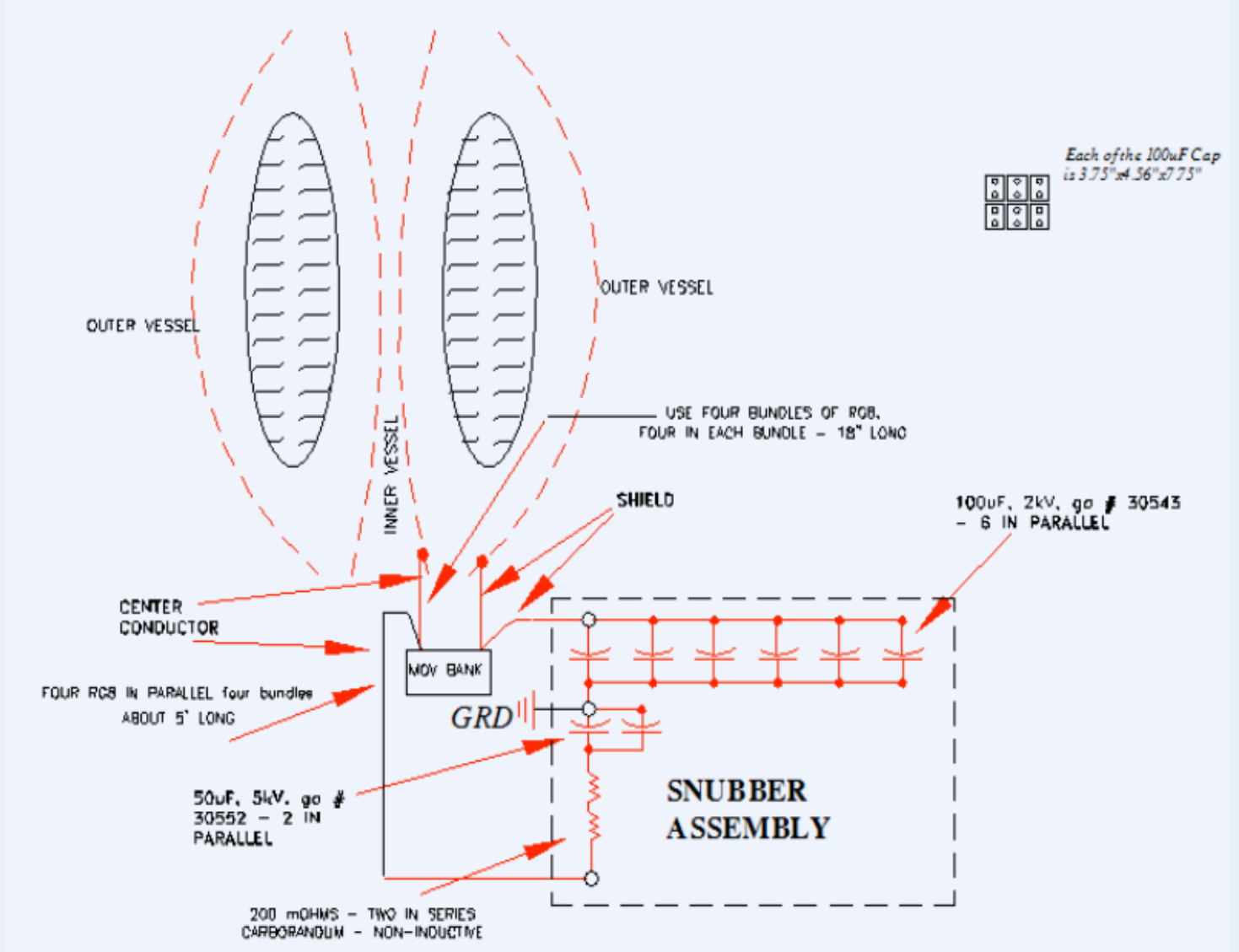
Capacitor Rack and the Firing Ignitron



Outline of Noise Suppression System



System Design

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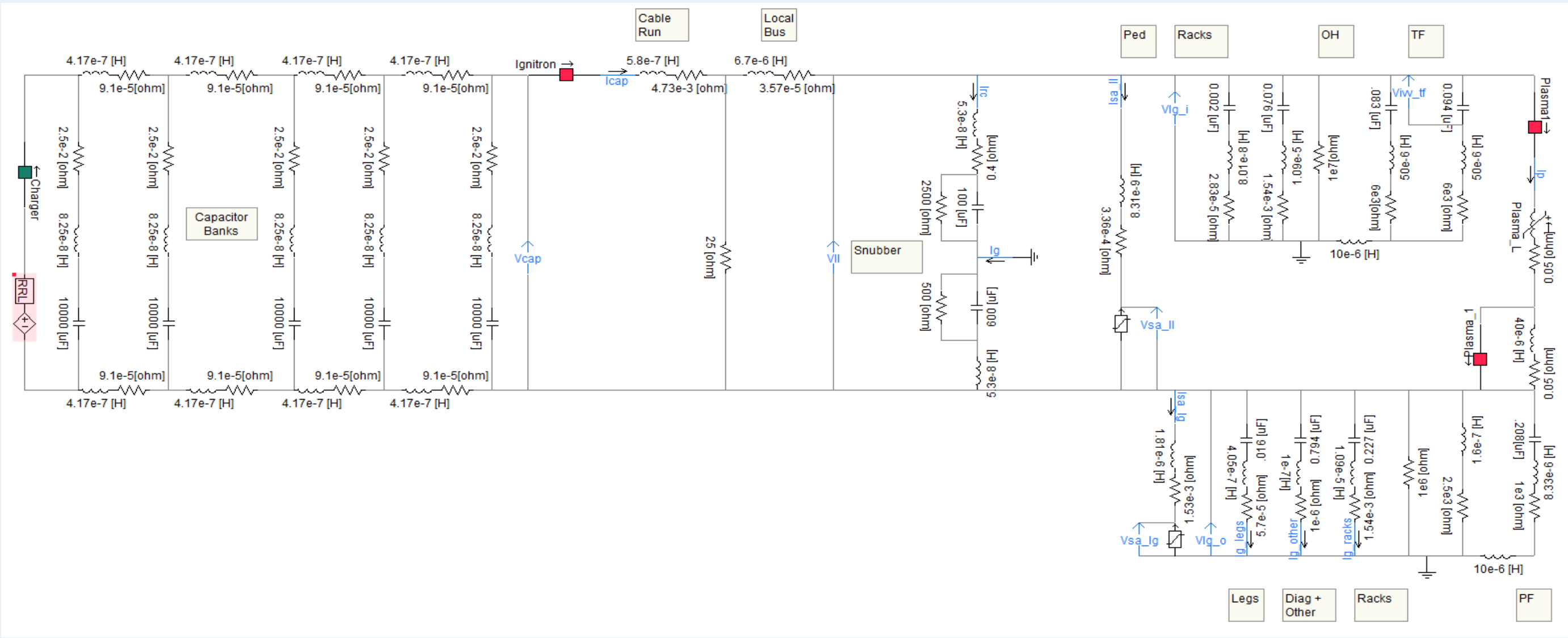
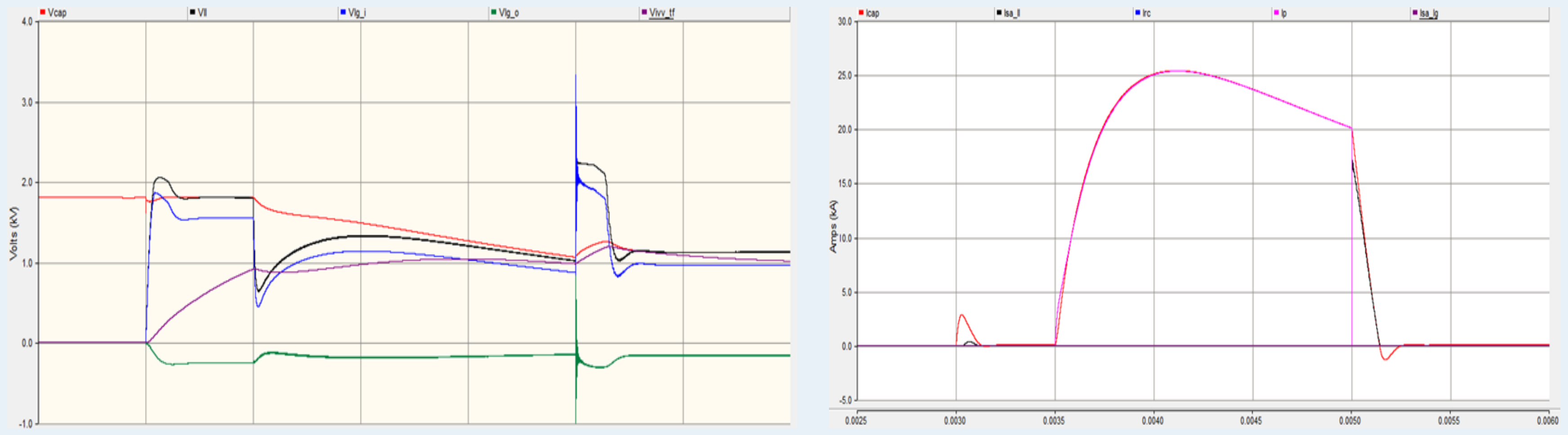


Simulation Model in PSCAD



Simulated Voltage Profile Resulting from 50% Plasma Disruption

P.O. Box 451, Princeton, NJ 08543
Phone: 609-243-2245
Fax: 609-243-2751

E-mail: publications@pppl.gov

Website: http://www.pppl.gov