CHI Research on PEGASUS-III

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PEGASUS-III Experiment

Abstract

The spherical tokamak (ST) may require, and the advanced tokamak would considerably benefit from the elimination of the central solenoid. PEGASUS-III is a ST non-solenoidal startup development station under design and fabrication dedicated to solving the startup problem. On PEGASUS-III, Transient and Sustained coaxial helicity injection (T- and S-CHI) will be explored, as well as possible synergies of CHI with local helicity injection and EBW heating and current drive. T-CHI has shown promising capability on the HIT-II and NSTX STs. However, in both these machines the vacuum vessel was electrically cut. For reactor applications a simpler biased electrode configuration is required in which the insulator is not part of the external vacuum vessel. To develop this capability PEGASUS-III will use a double biased electrode configuration, which would a first of its kind for the reactor-relevant development of the CHI concept. The system is capable of generating plasma start-up currents at the levels that can be supported by the external poloidal field coils, which is estimated to be ~300kA. The CHI design for PEGASUS-III will be described.

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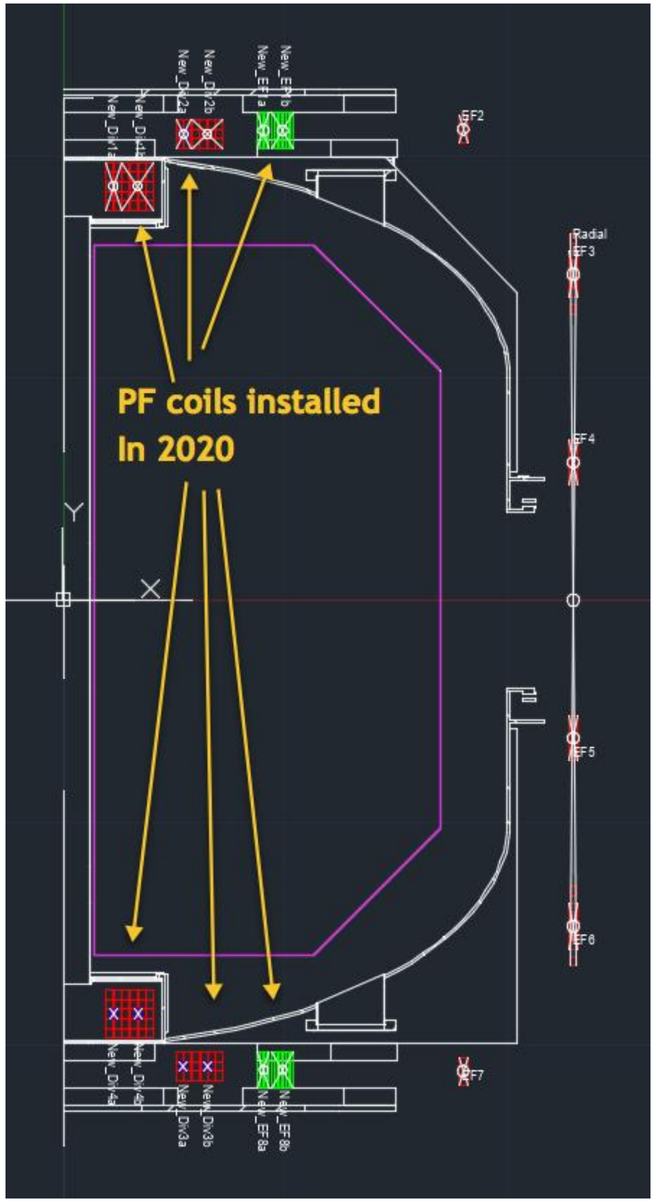
CHI Research Plan on PEGASUS-III

- Develop and test a double biased electrode configuration
  - Clearly defines current path
  - First ever test of concept to better control absorber arcs

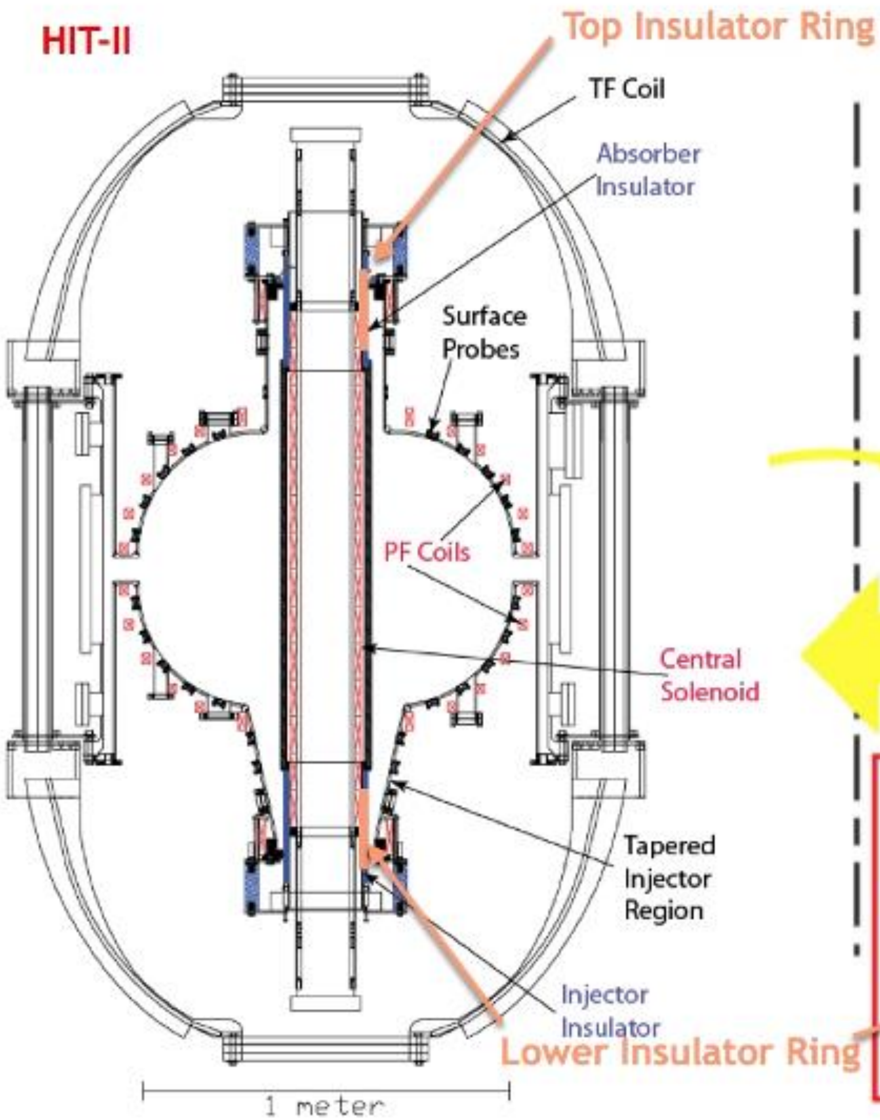
- Initiate Transient CHI discharge and optimize it to understand requirements for implementing it on NSTX-U
  - Quantify the range of the flux footprint width parameter 'd' that maximizes conversion of open flux to closed flux
  - Heat CHI plasma using EBW
  - Generate currents up to the external PF coil limits (~300kA)

- Drive a T-CHI discharge using LHI to study synergisms with LHI and EBW (eventually with ECH)

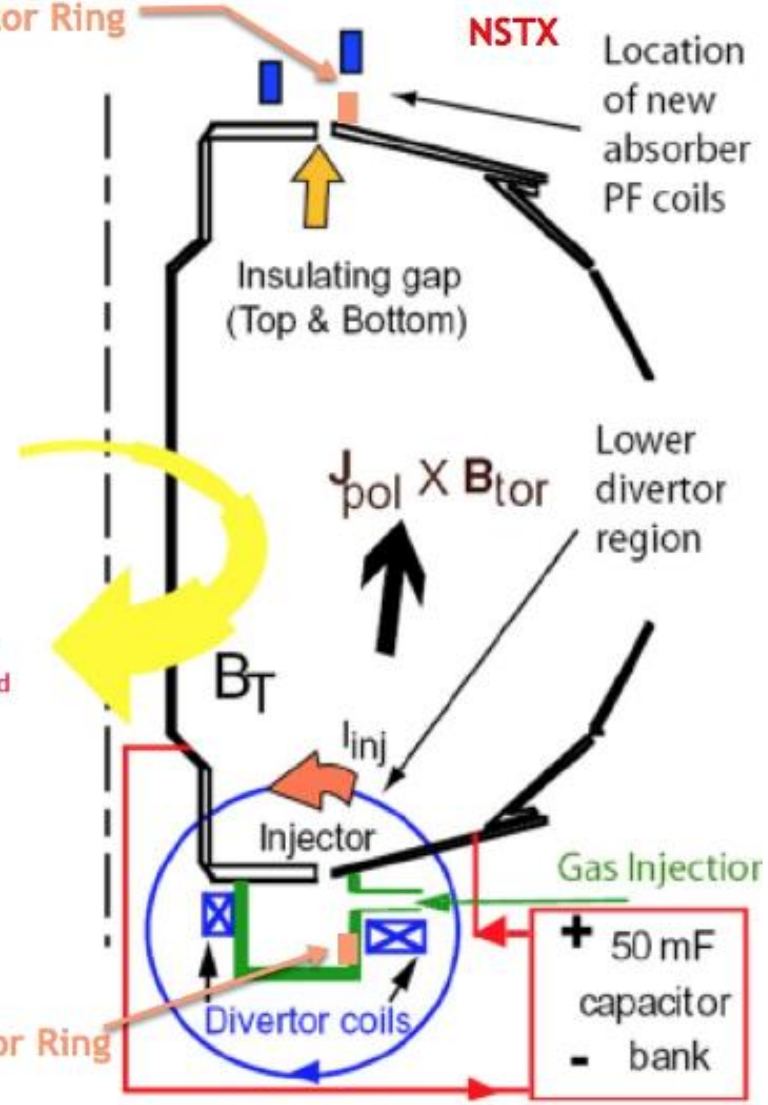
- Examine potential of Steady-State (driven) CHI
  - Extend of the work of A.J. Redd et al. on HIT-II to assess level of steady state current that can be driven without degrading confinement



HIT-II and NSTX Used Insulators as Part of the Vacuum Break, QUEST Uses a Single Biased Electrode

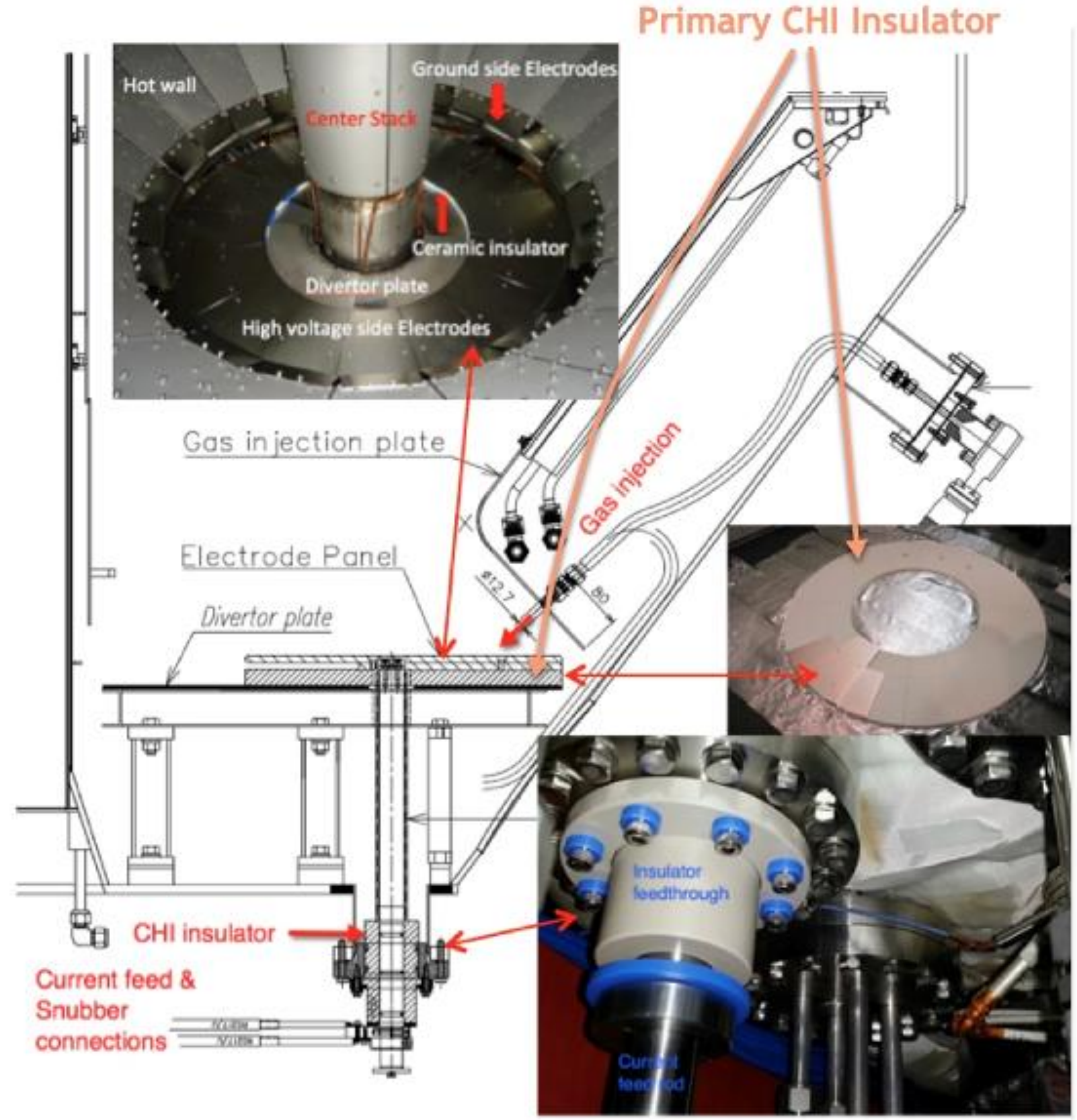


R/a = 0.3/0.2m, B_T = 0.5T



R/a = 0.86/0.66m, B_T = 0.55T

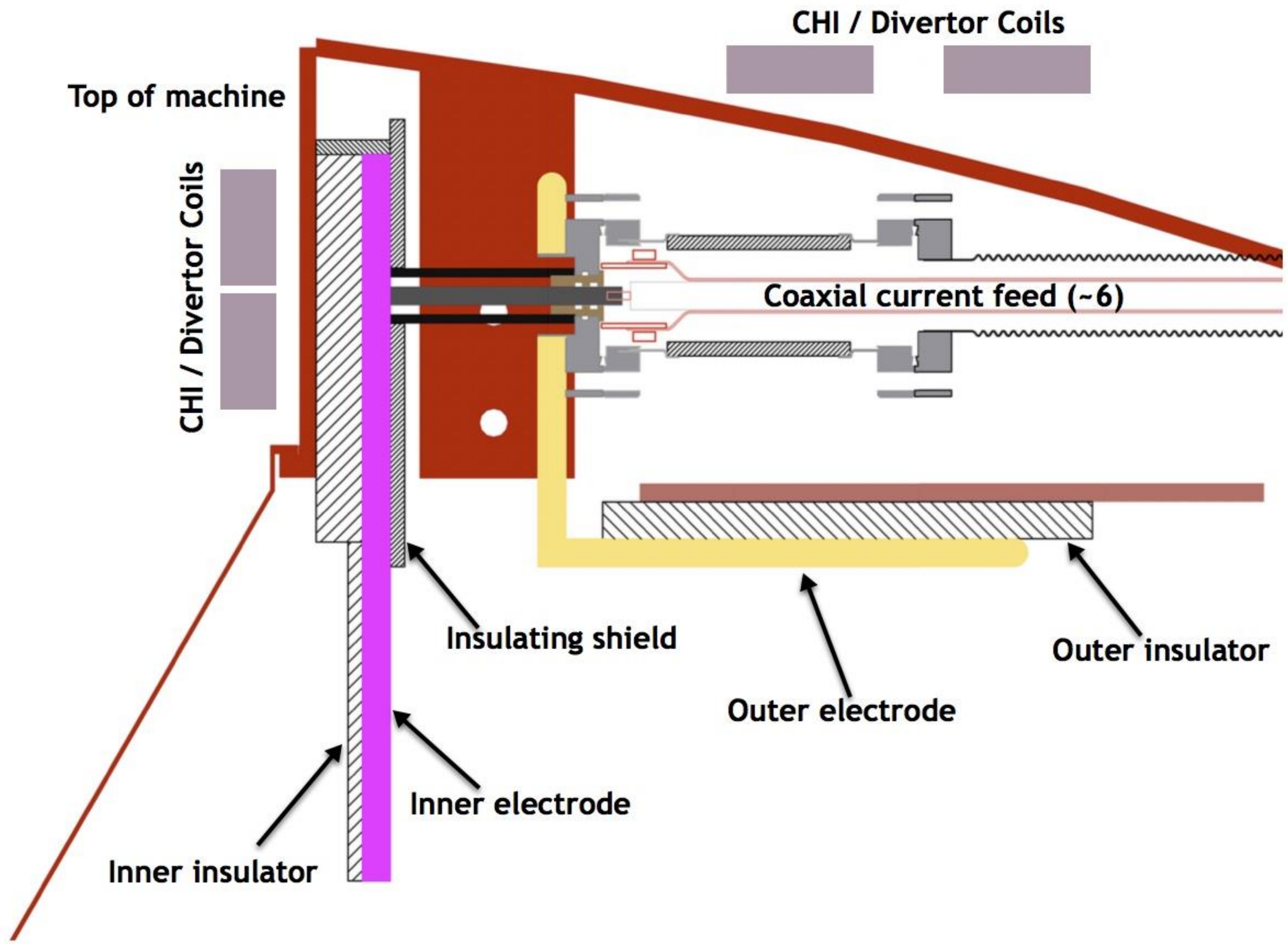
QUEST (Kyushu University, Japan)



Raman, APS-DPP 2020

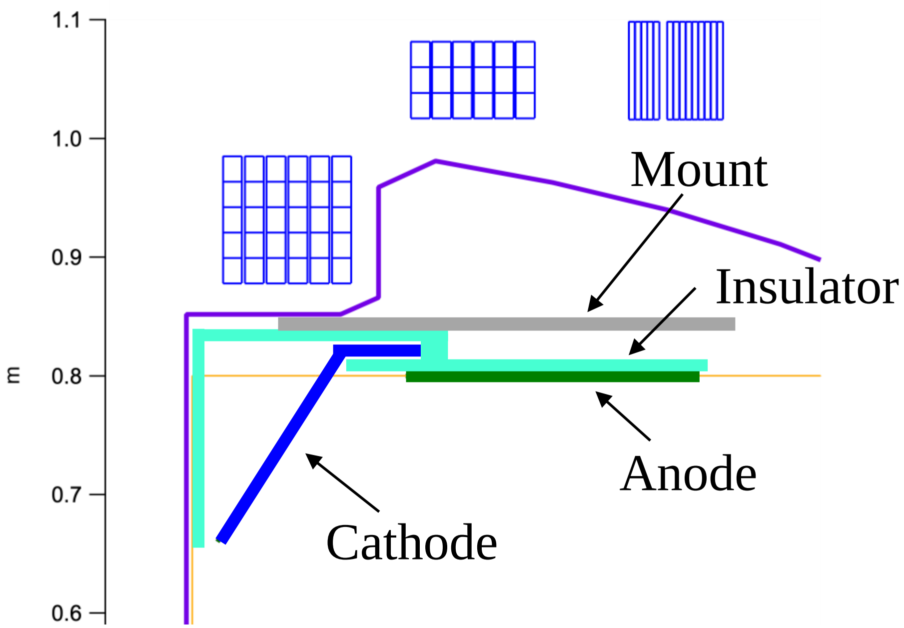
Early Concept of Double Biased Electrode for CHI

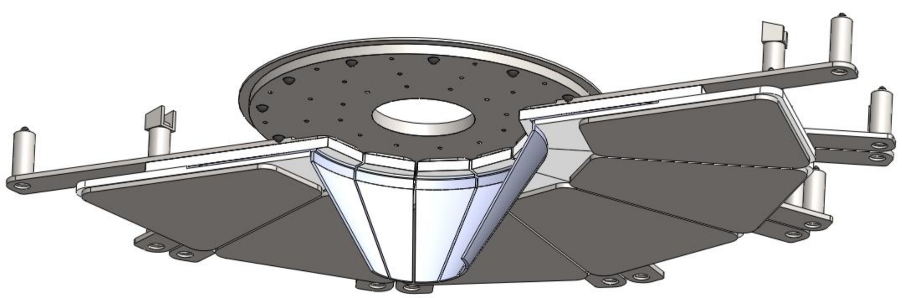
- Vacuum CHI insulators difficult to implement in reactor configurations
- QUEST is testing a single biased electrode configuration
- Double biased configuration is much more immune to spurious absorber arcs
  - Better suited for long-pulse S-CHI studies
- PEGASUS-III would be the first experiment to test and develop this configuration



Robust Feeds Under Design to Provide Symmetric Low Inductance Path for CHI and LHI Injector Currents

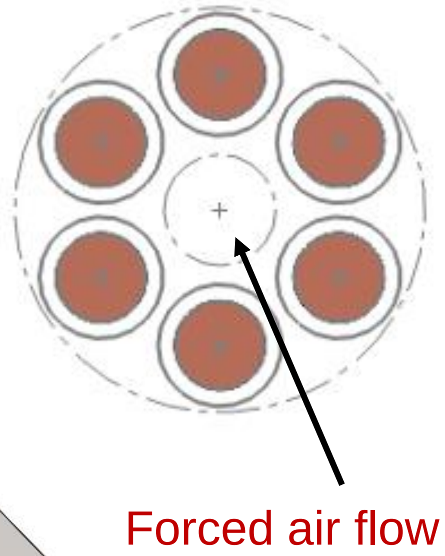
2D Sketch of Electrode Plate Concept

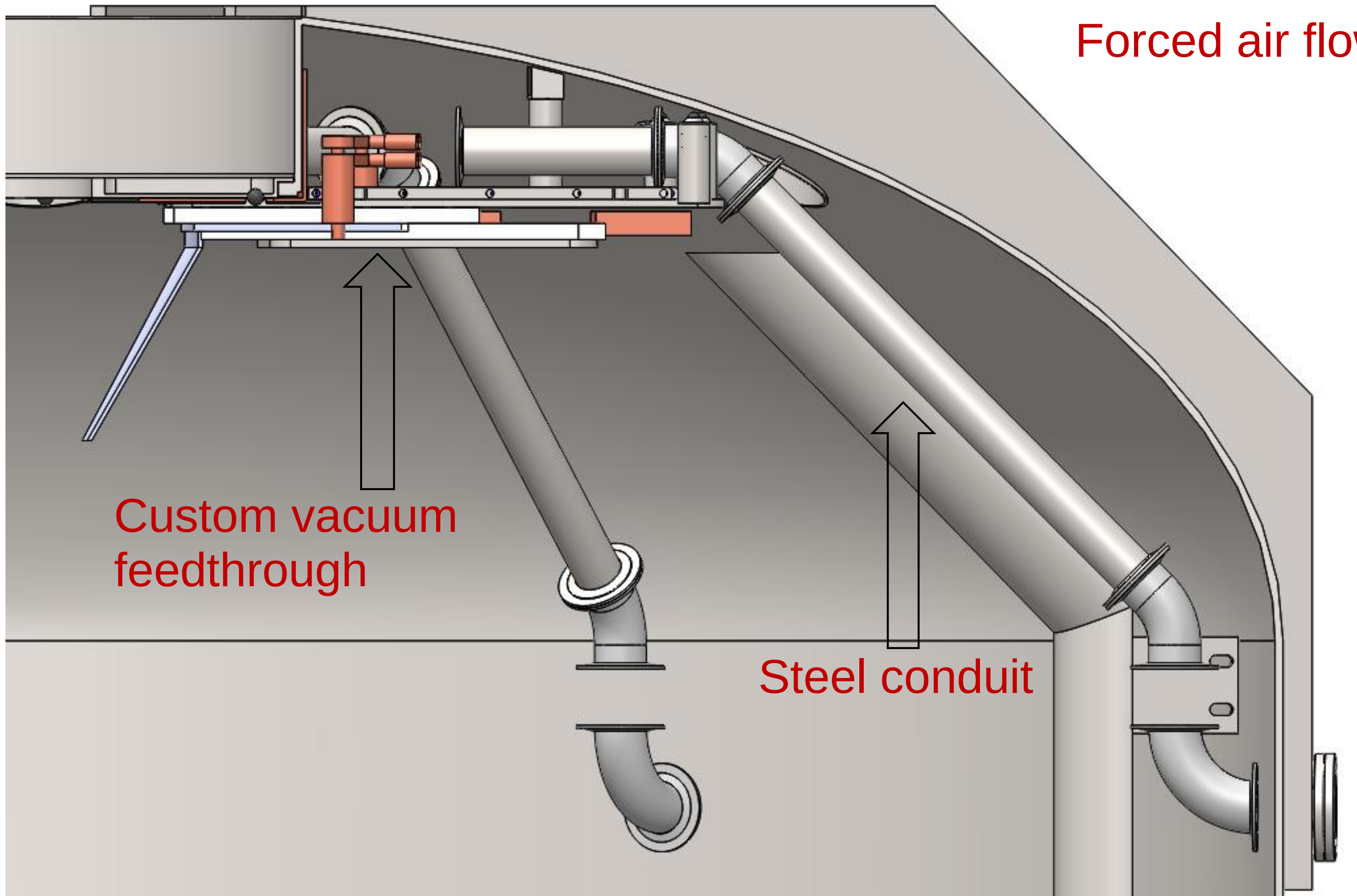




3D Sketch of Electrode Plate Concept

- 6 x 2 AWG cables inside steel conduit
- Steel conduit to be robustly supported to handle electromagnetic forces
- Six feeds toroidally distributed around the machine
- Individual feed currents monitored outside vessel





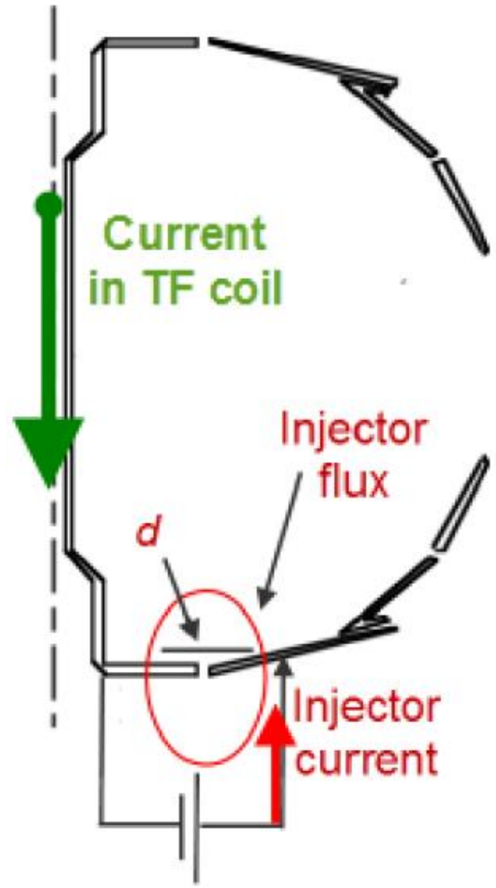
Raman, APS-DPP 2020

Scaling Relations for Transient CHI Based on Experimental Results From HIT-II, NSTX, and TSC Simulations

- Injector current* I_{inj} must meet *bubble-burst condition* for plasma to expand from injector to main vessel

- Toroidal current* generation is proportional to the ratio of toroidal flux ψ_{tor} to injector flux ψ_{inj}

- Capacity to generate plasma current I_p is proportional to ψ_{inj}



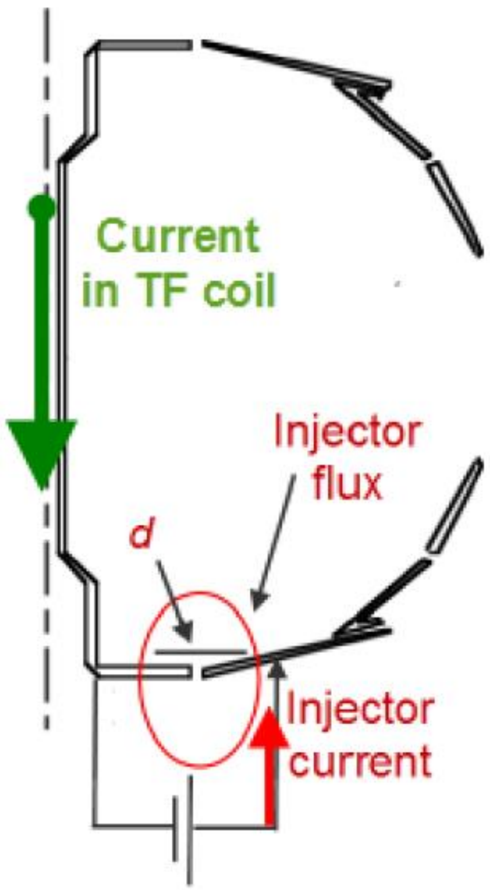
$$I_{\rm inj} \geq \frac{2\psi_{\rm inj}^2}{\mu_0^2 d^2 I_{\rm TF}}$$

$$I_{\rm p} \leq I_{\rm inj}\frac{\psi_{\rm tor}}{\psi_{\rm inj}}$$

$$I_{\rm p} = \frac{2\psi_{\rm pol}}{\mu_0 R_{\rm maj} l_i} \qquad \psi_{\rm pol} \leq \psi_{\rm inj}$$

* T.R. Jarboe, Fusion Tech. 15, 7 (1989)

Studies on PEGASUS-III Will Optimize CHI by Improved Quantification of Scaling Parameters in Support of Future Studies on NSTX-U



$$I_{\mathrm{inj}} \geq \frac{2\psi_{\mathrm{inj}}^2}{\mu_0^2 d^2 I_{\mathrm{TF}}}$$

Parameter 'd', the injector flux footprint width, strongly determines required injector current and needs improved characterization

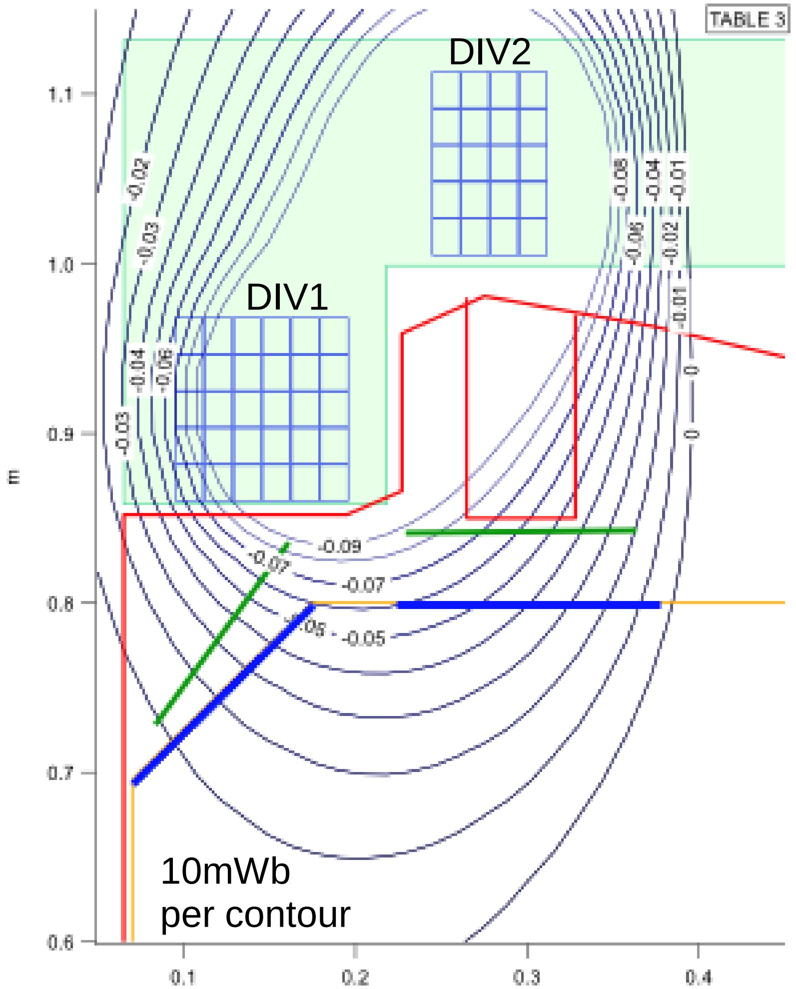
$$I_{\mathrm{p}} = \frac{2\psi_{\mathrm{pol}}}{\mu_0 R_{\mathrm{maj}} l_i} \qquad \psi_{\mathrm{pol}} \leq \psi_{\mathrm{inj}}$$

The attained plasma current is dependent on the plasma internal inductance, which is controlled by the edge current carrying open flux during CHI discharge initiation

External flux shaping coils will control the parameter 'd' and the width of the edge current channel

Close positioning of the divertor coils to the CHI electrodes would permit these important parameters to be studied on PEGASUS-III

Initial Studies to be Conducted with 10 to 25 mWb Flux Injection (~150 kA Current Generation)



DIV1/DIV2 = 16 kA
EF1-3 = 14.5 kA

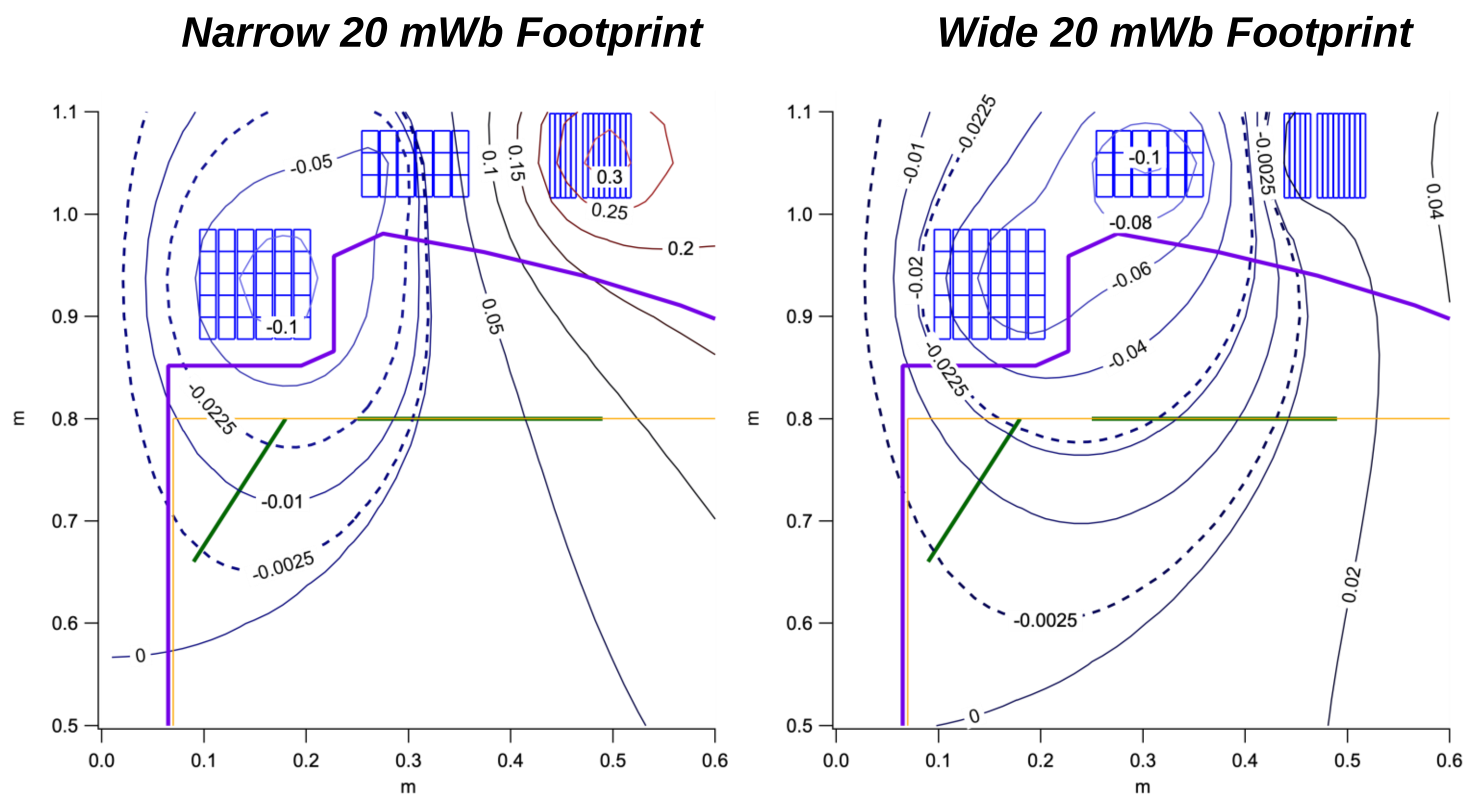
ψ_{inj} ~50mWb

Ip (kA):	150.00
Rm (m):	0.45
B_T (T):	0.51
B_T @ CHI location (T):	0.82
Bt multiplier factor:	1.61
l_i - Plas normalized Inductance:	0.30
Enclosed Polo flux (mWb):	12.72
Flux conversion efficieny:	0.70
Injector flux (mWb):	18.18
Itf (kA):	1152.00
footprint width ‘d’ - (cm):	10.00
Inj Curr (kA)	22.60
Plasma Inductance (uH):	0.08
Plas inductive energy (kJ):	0.95

Increasing ‘d’ would allow more flux to be injected at same level of injector current

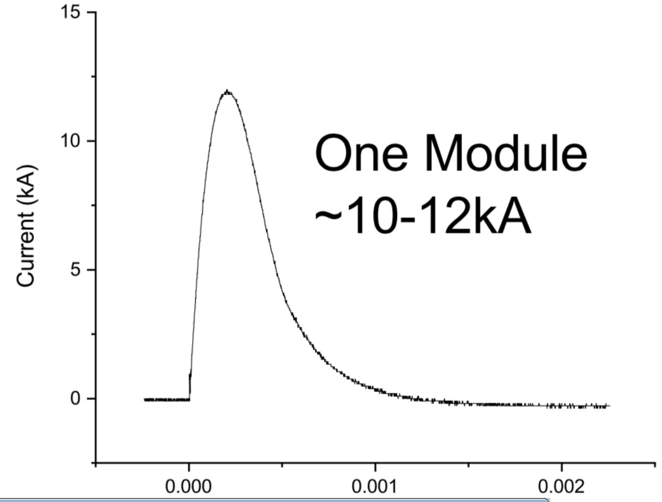
"d" Can be Changed on This Electrode Configuration by Adjusting the Divertor, EF Coil Currents

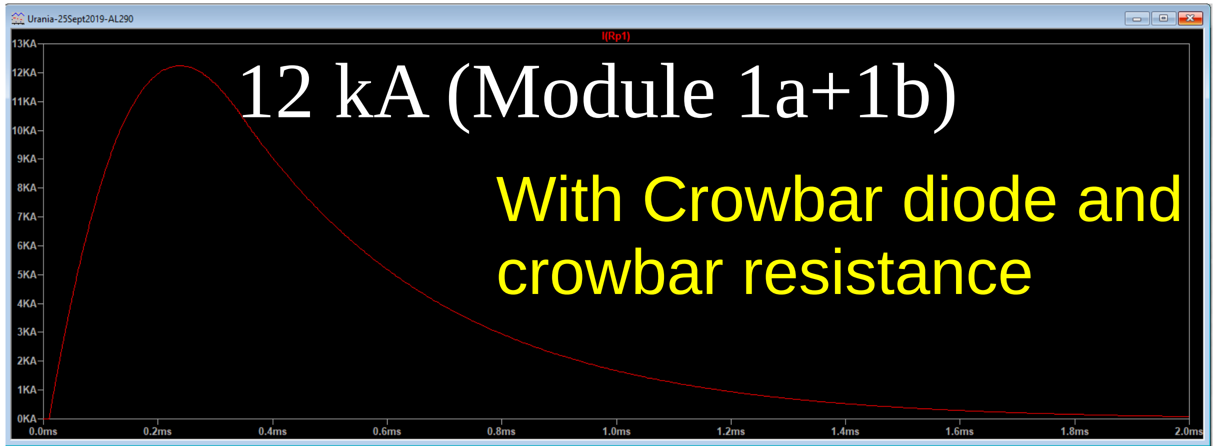
- At max injector flux, not a lot of room to manipulate d with consistent equilibrium
- At 20 mWb injector flux (I_p > 150kA) flux footprint can be varied significantly
  - Average separation from 17–27 cm

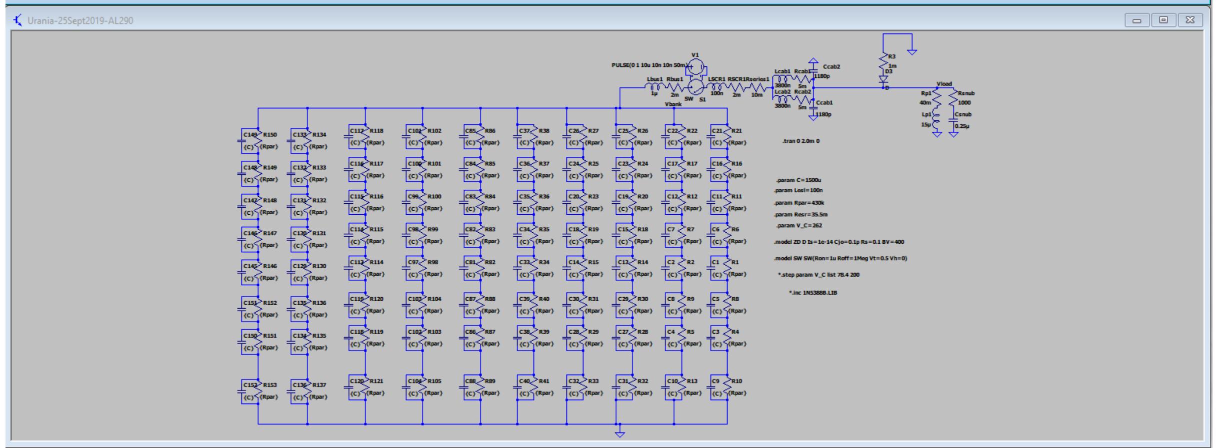


CHI Power Supply Uses Electrolytic Capacitor Bank for Driving the Injector Current (22–30 kA for Initial Studies Using Four Modules)

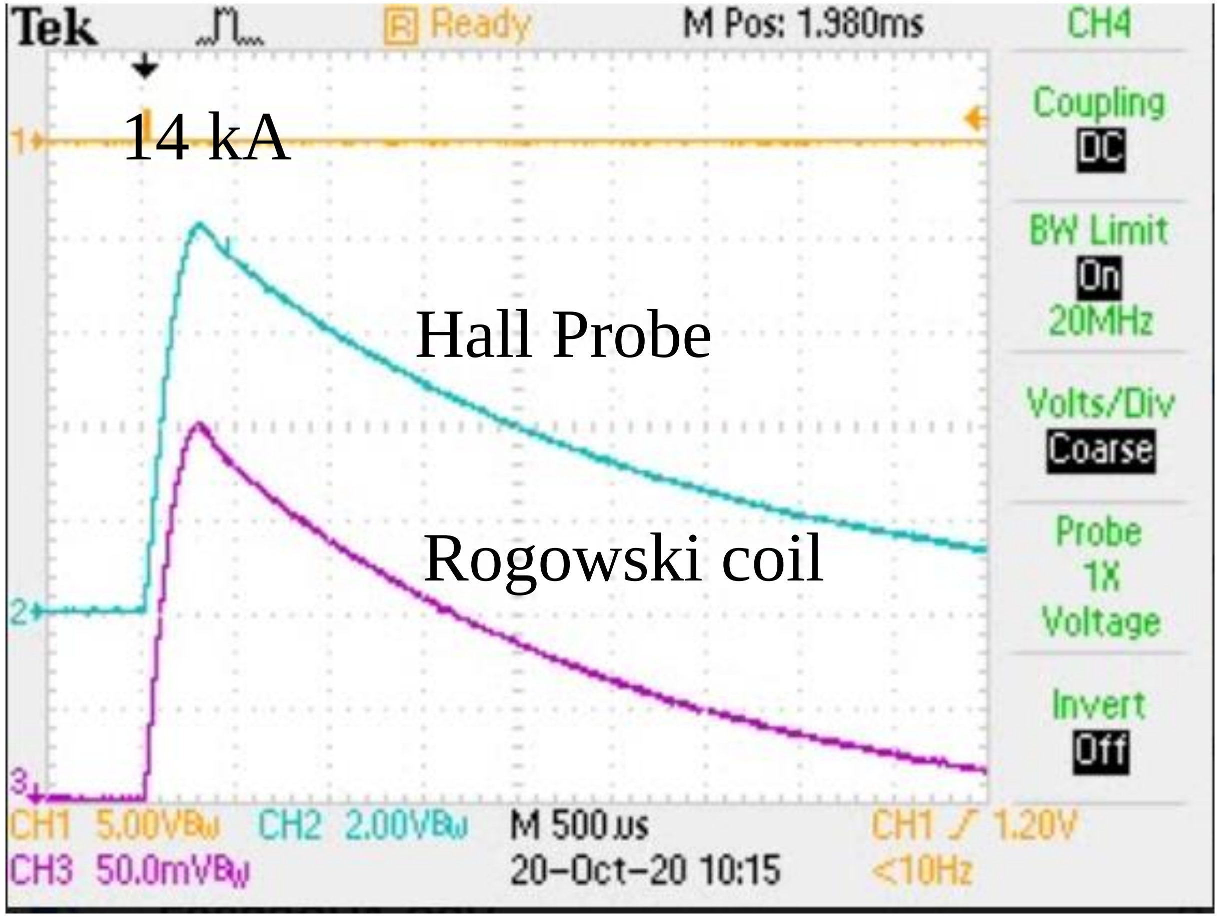
Module 1a+1b
80 Capacitors x 1500uF
8 (450V) in Series
10 in parallel
2100 V total
262 V/cap
R = 55.5 mOhm
L = 18 µH





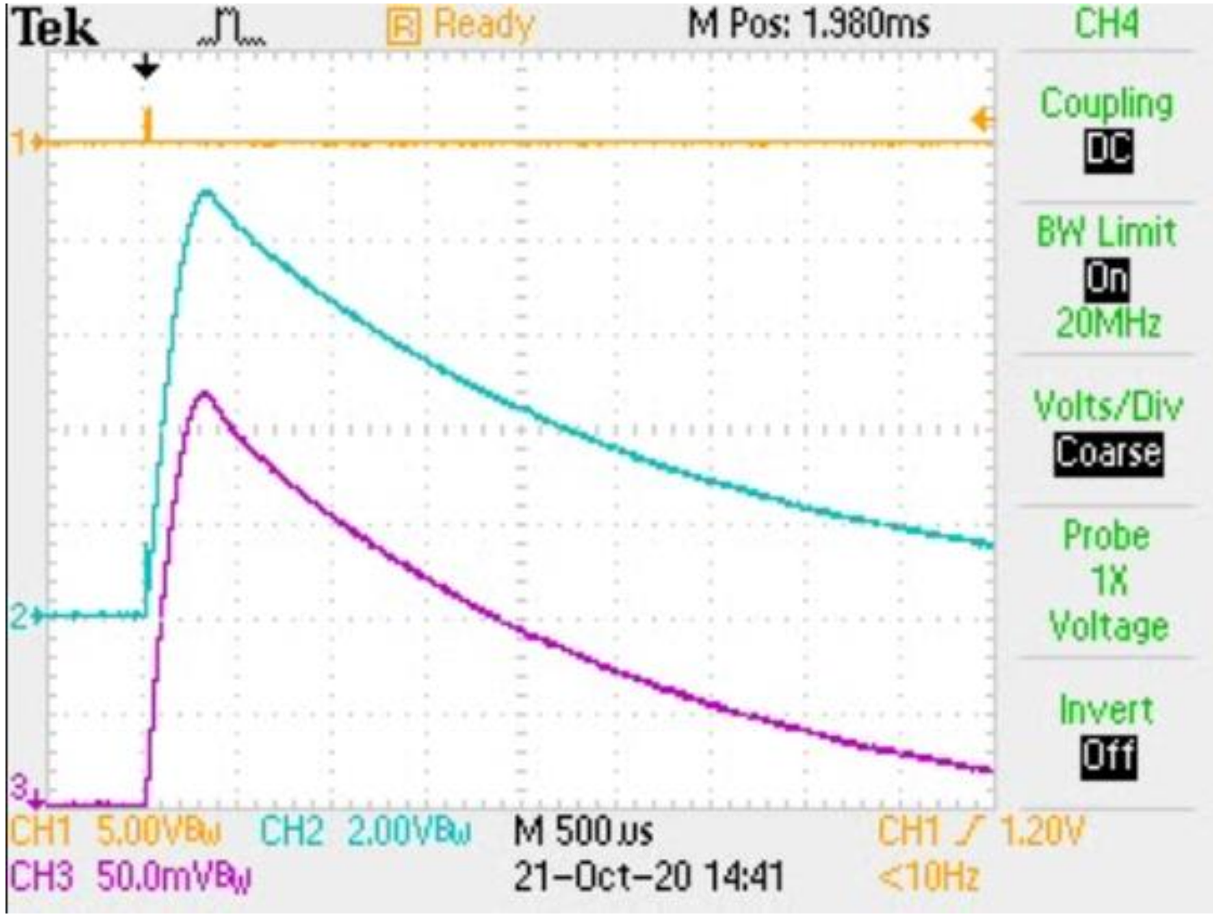


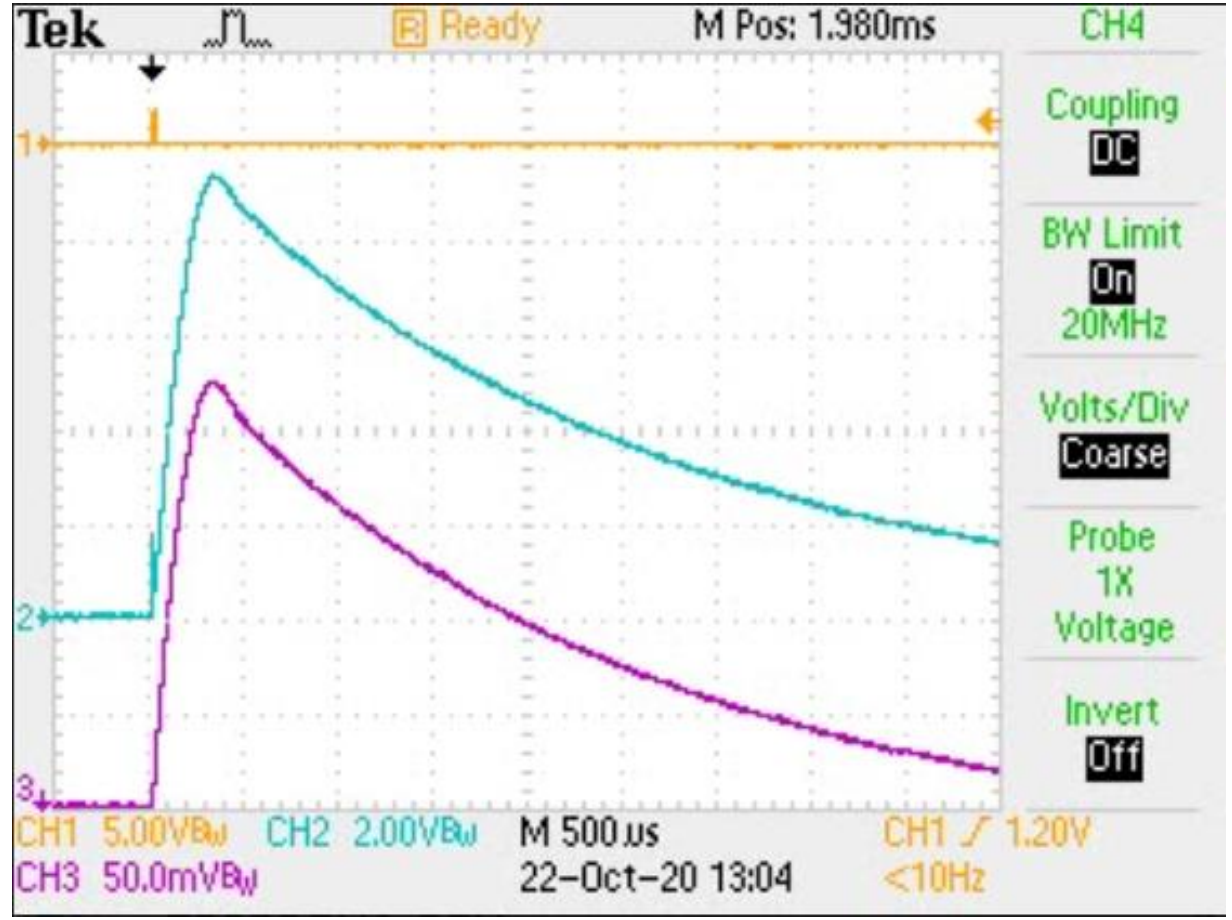
Current Measurements During the Testing of Modules 2A and 2B at 2 kV Charge Voltage



With Crowbar diode, reduced resistance, but no crowbar resistor (at 2 kV)

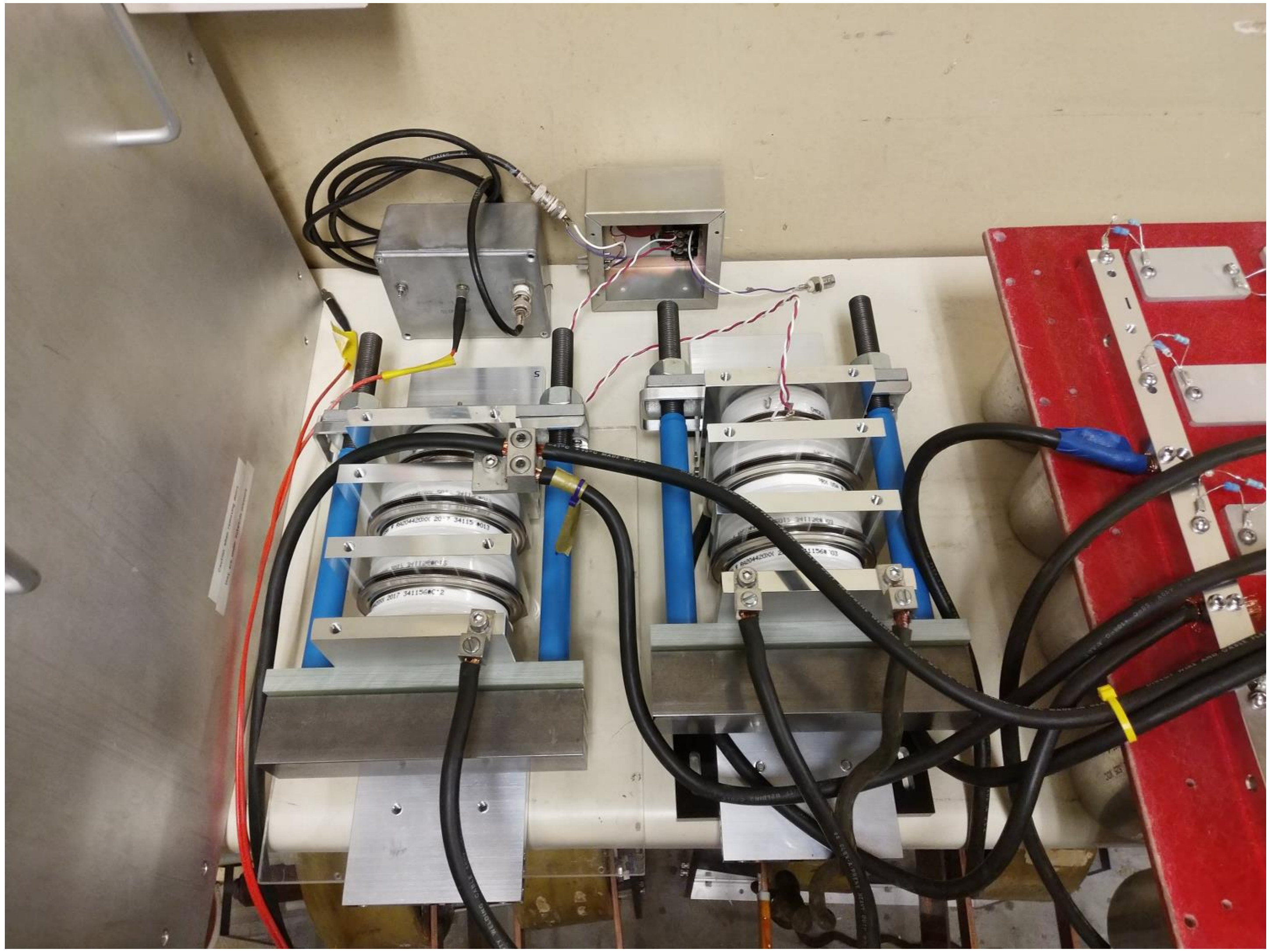
Current Measurements During the Testing of Modules 3A, 3B, 4A, and 4B (at 2 kV)



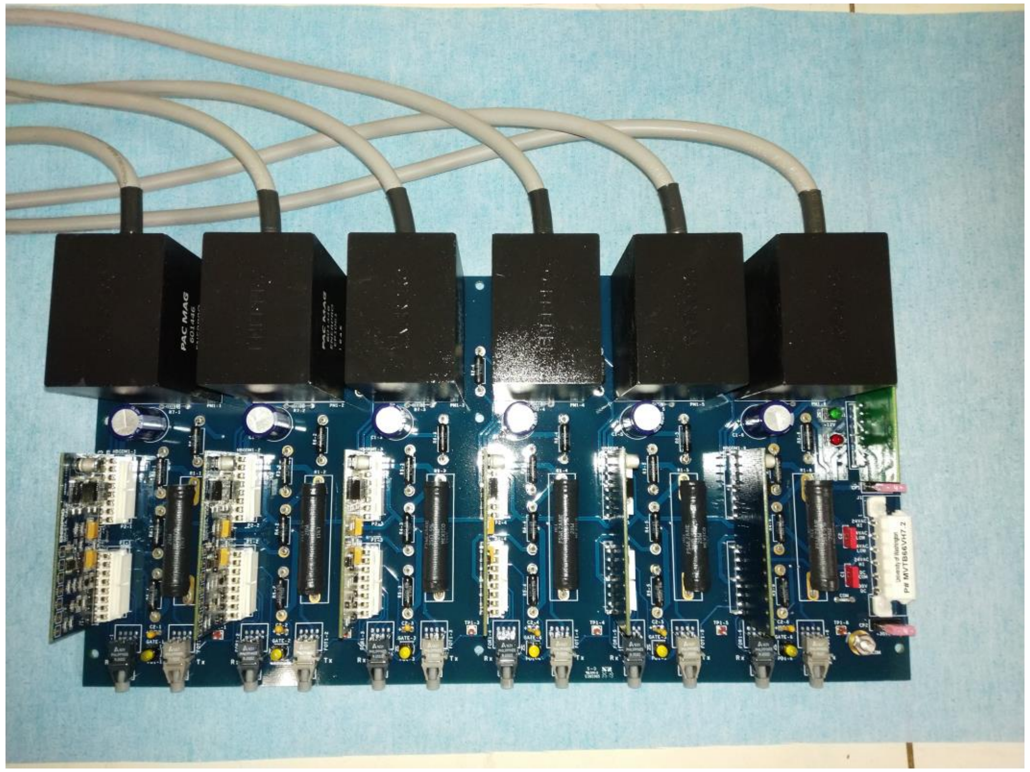


Small differences in total current from each module as the individual 80 capacitors in each module were matched to minimize variation within each module

CHI PS Uses High Voltage SCR and Diodes in Series for Triggering and Crowbar, and Enerpro SCR Triggers



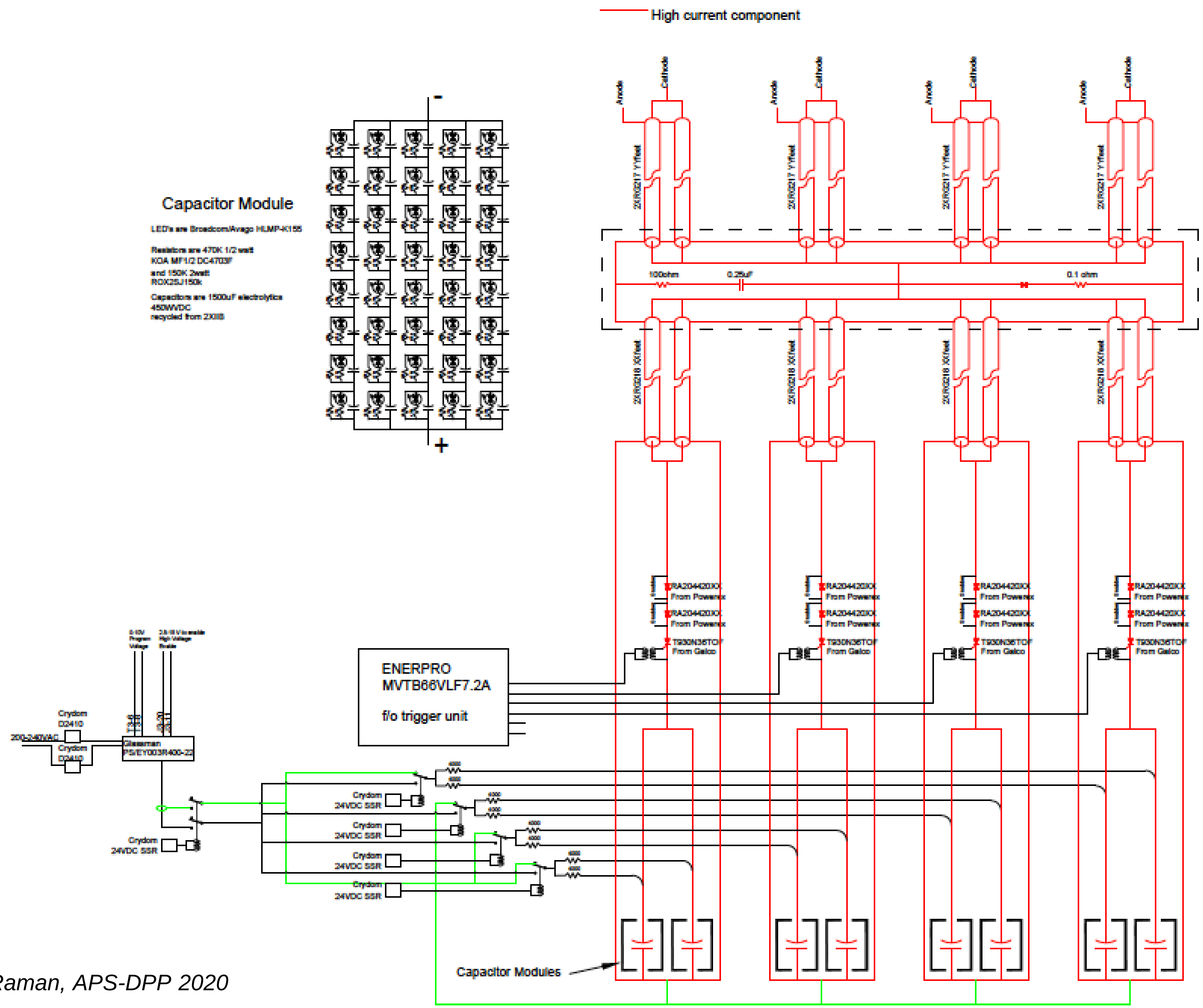
3.6 kV, 19.5kA Infineon SCR in series with two Powerex 4.4kV, 24kA diode (total 8.8kV standoff)

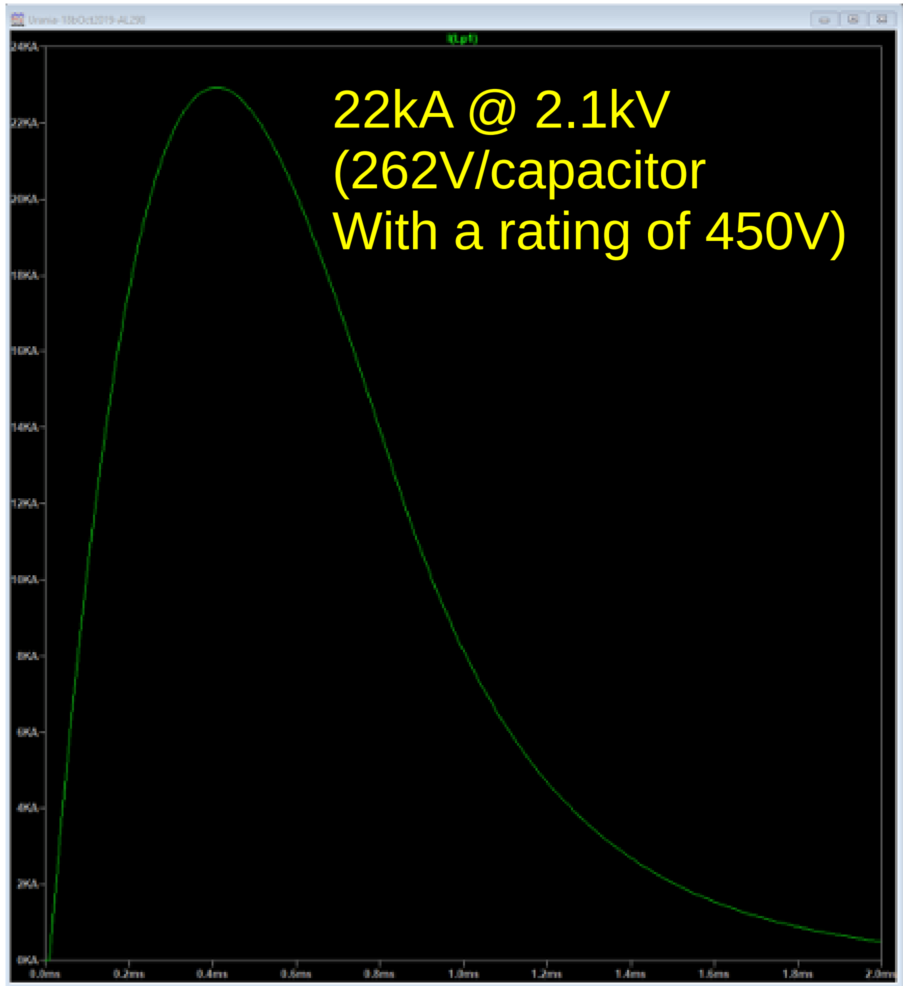


6-channel SCR trigger system (ENERPRO unit)

Crowbar diodes rated at 55kA to handle full power supply current

Full CHI PS Electrical Circuit





33kA at 3kV (375V/capacitor)

All Power System Components Tested Successfully at 2 kV

Switching Ross relays and solid-state relays to control the main relays

Diodes, SCRs, SCR trigger units

Glassman Power Supply (3kV, 400mA)

8 capacitors sub-modules (320 total capacitors)

Final wiring of the top three of the right-side rack to be completed prior to shipment to PEGASUS-III facility (but all systems tested at full power outside rack assembly)

Quantify the Parameter ‘d’ (Balance Between Injecting More Poloidal Flux vs. Increasing Flux Closure)

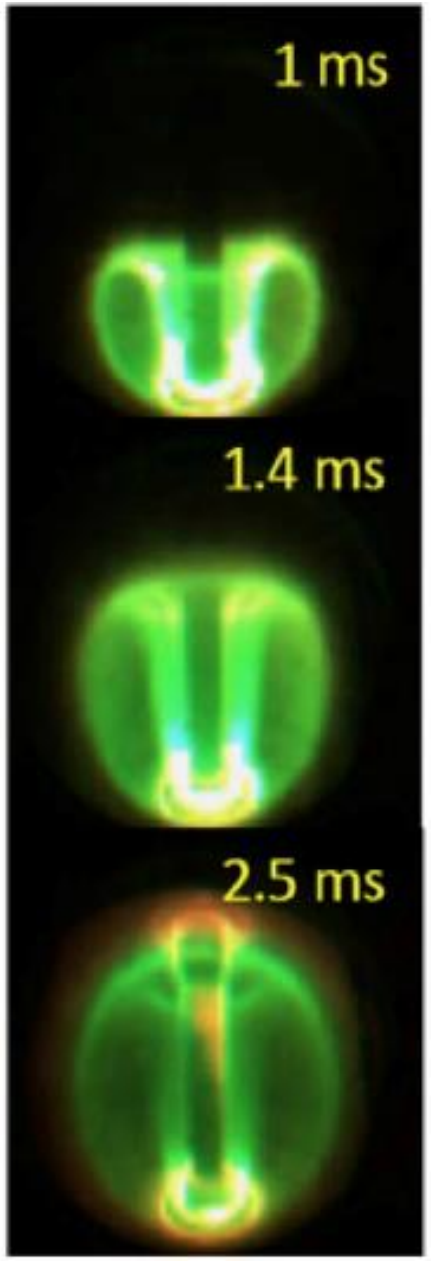
$$I_{\rm inj} \geq \frac{2\psi_{\rm inj}^2}{\mu_0^2 d^2 I_{\rm TF}}$$

The parameter ‘d’, which is the separation between the injector flux footprint width, plays an important role.

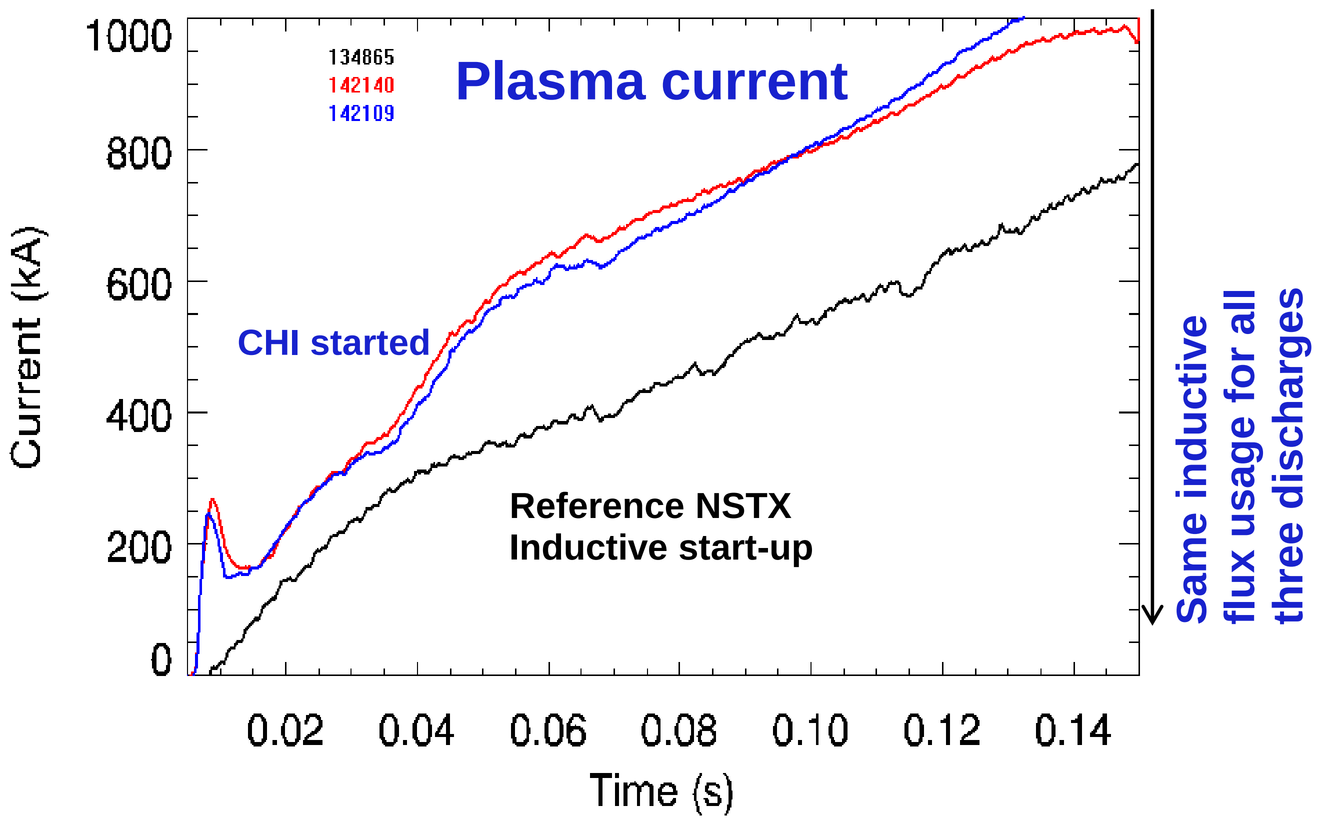
Due to limited run-time on NSTX, it has not been quantified.

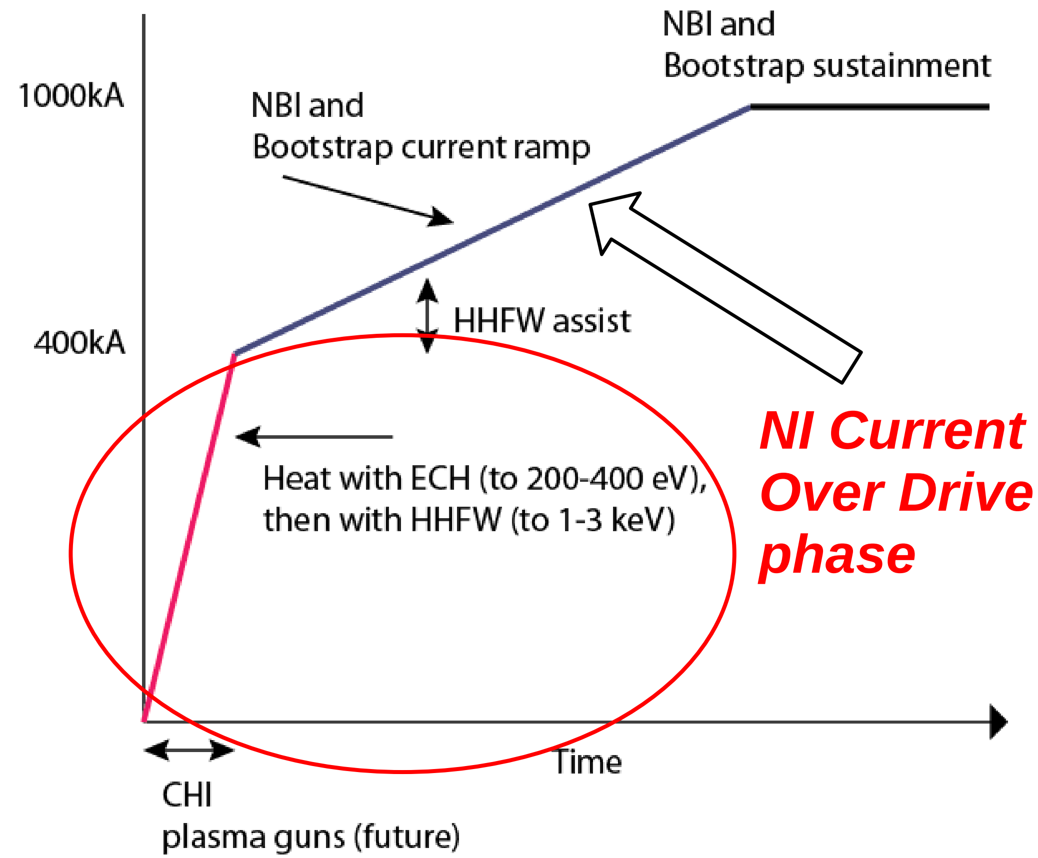
Reducing ‘d’ should ease conversion of open flux to closed flux (~70% conversion efficiency achieved on NSTX and in NIMROD simulations), but it also increases the required injector current (not good as a higher injector current could also inject more impurities into the plasma and degrade confinement – a primary issue with steady-state CHI), and the motivation behind the development of transient CHI for ST and tokamak applications.

Increasing ‘d’ allows more flux to be injected at the same level of injector current but at the expense of reducing closed flux conversion efficiency.



NSTX-U T-CHI Start-up Scenarios Would Likely Require Auxiliary Heating to Increase the CHI Electron Temperature for Full Non-Inductive Current Ramp-up Scenarios





- Transient Coaxial Helicity Injection on NSTX
  - 0.2 MA start-up currents ramped to 1 MA with inductive flux savings
  - Other modeling work (TSC) suggests that in high flux injection scenarios (~ 1 Wb), the inductive decay power may be sufficient to self-heat the plasma to keV electron temperatures, but RF heating is needed for present studies and for development towards reactor scenarios

Initial Assessment of the Useful Edge Current That Can be Driven Using S-CHI Without Degrading Confinement

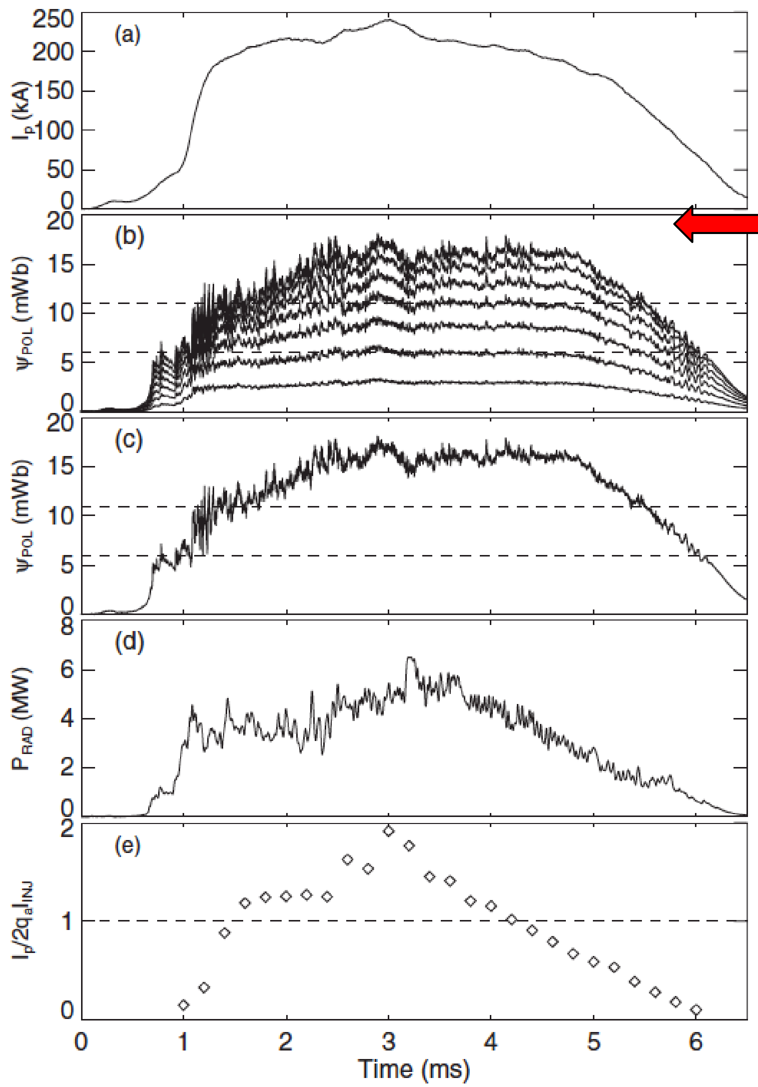


FIG. 4. (a) Toroidal plasma current, (b) measured poloidal flux (relative to the midplane gap) at each probe in the internal probing array, (c) measured poloidal flux (relative to the midplane gap) at only the innermost probe location of R=0.416 m, (d) radiated power, and (e) the ratio $I_p/2q_aI_{INJ}$ vs time for the typical flux-amplification discharge No. 29382. The horizontal dashed lines in (b) and (c) correspond to the injector flux of 6 mWb and maximum vacuum poloidal flux of 11 mWb. Discharge No. 29382 has HIT-like injector flux and double-null boundaries, with I_{TF}=320 kA.

Poloidal flux amplification has been measured in HIT-II using internal magnetic probes, but at extensive radiated power [Redd, et al. PoP 15, 022506 (2008)]

Very limited study has also shown capability for increasing edge current without degrading confinement, but these studies lack profile information [Raman, et al., PoP 11, 2565 (2004)]

These will be studied on PEGASUS-III with non-perturbative measurements to assess the capability of S-CHI, eventually with capabilities such as gas infused electrodes to reduce impurity injection.

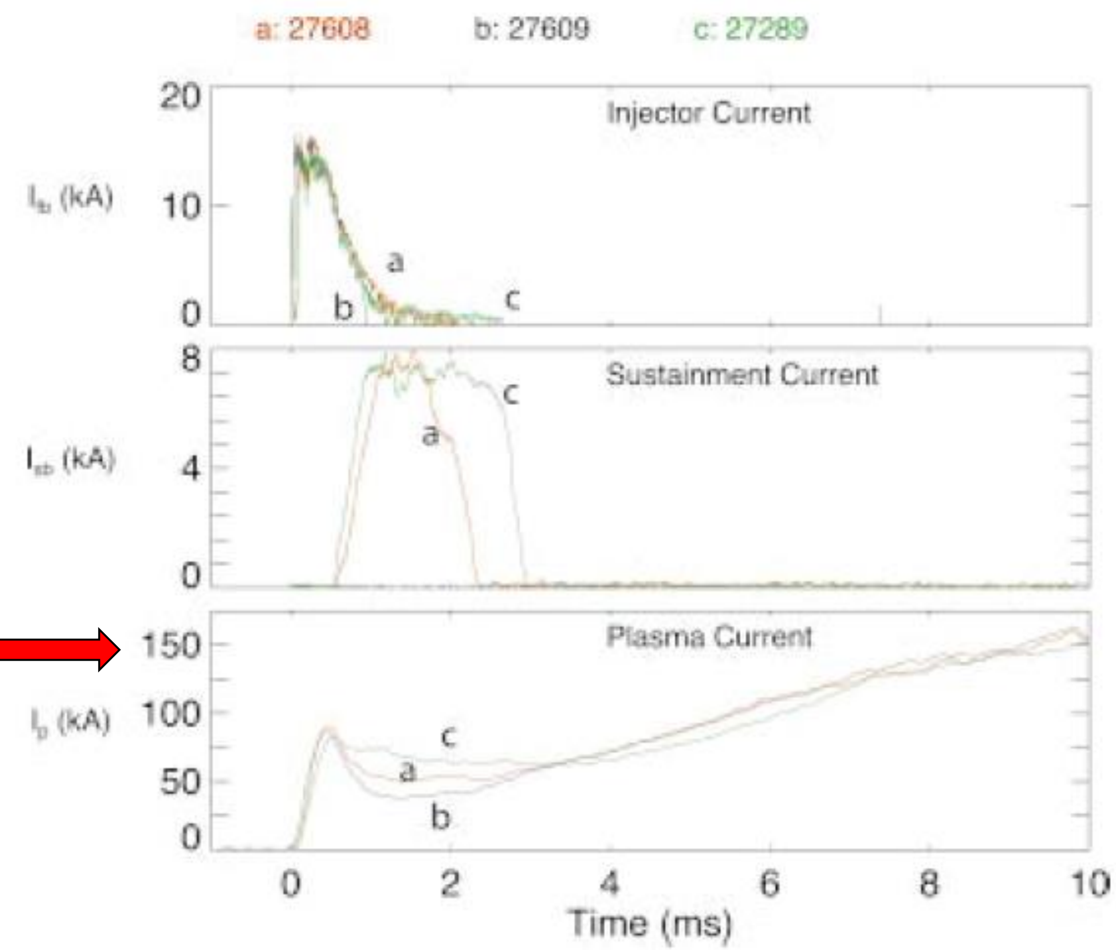


FIG. 10. (Color) Comparison of discharges with and without some edge current drive. In discharges 27608 and 27289, after initiation of a CHI started discharge, a second capacitor bank is discharged across the divertor flux during the portion of the discharge when the CHI produced current is handed-off to inductive drive. The motivation for this is to increase the level of the noninductively produced handoff current. Shown are the injector current, current provided by the second capacitor bank (the sustainment current) and the plasma current.

CHI Studies on PEGASUS-III Will Optimize and Improve Our Understanding of the CHI Scaling Parameters for MA-class Startup

- Develop and test a double biased electrode configuration
  - First test of novel electrode geometry
  - Supports transient, sustained CHI experiments
- First CHI studies on PEGASUS-III seek to establish and optimize T-CHI scenarios
  - Increasingly high I_p up to external PF coil limits as B_T is raised (goal: 0.15 → 0.3 MA)
  - Quantify the parameter ‘d’ and flux shaping effects on the plasma internal inductance and on the closed flux conversion efficiency
- Future: Sustained CHI and exploration of synergistic effects
  - S-CHI: impact of impurities and potential confinement degradation
  - T-CHI-to-LHI sustainment scenarios
  - RF auxiliary heating during HI