Transient CHI Research on PEGASUS-III

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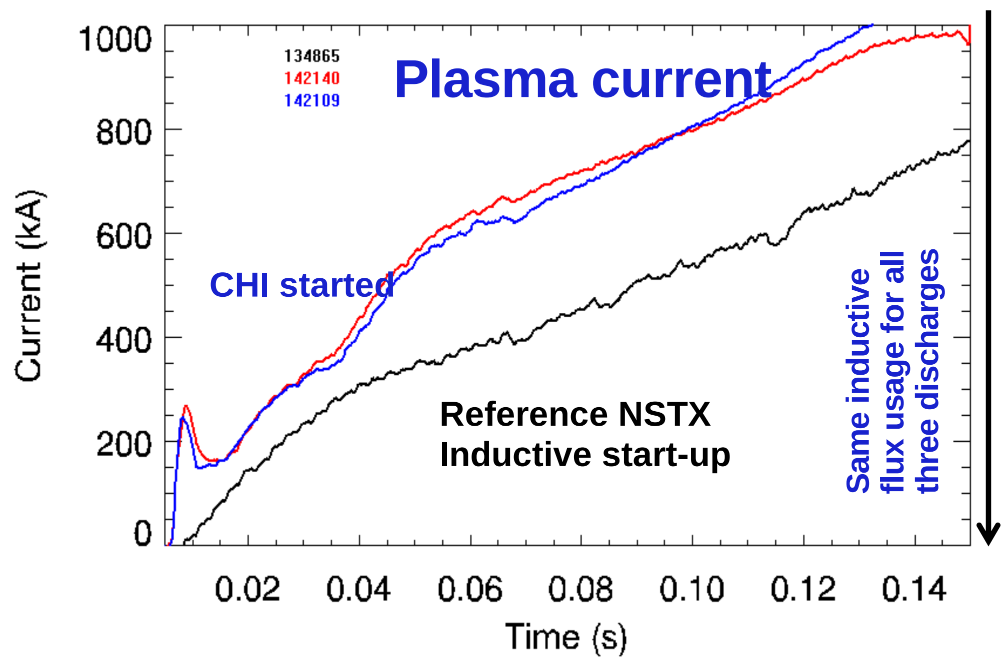
PEGASUS-III Experiment

Abstract

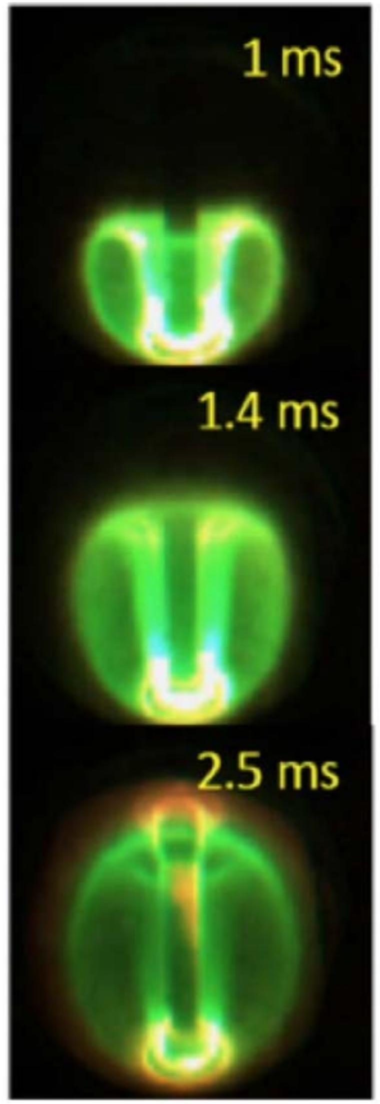
The spherical tokamak (ST) has the potential for high bootstrap current driven operation, which is necessary to reduce the reactor recirculating power, if the aspect ratio could be sufficiently reduced. This requires the capability for a method, other than the solenoid, to generate a substantial portion of the initial startup current. Pegasus-III is a ST non-solenoidal startup development station dedicated to solving this problem. One method being explored transient co-axial helicity injection (T-CHI). 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 (floating) biased electrode configuration, which will be a first of its kind for the reactor-relevant development of the CHI concept. The system is projected to generate plasma start-up currents at the levels that can be supported by the external poloidal field coils, ~0.3 MA, with an initial 0.15 MA capability using a 30 kA, 2 kV electrolytic capacitor bank power supply.

Work supported by US DOE grants DE-SC0019008 and DE-SC0020402, and DE-SC0019415

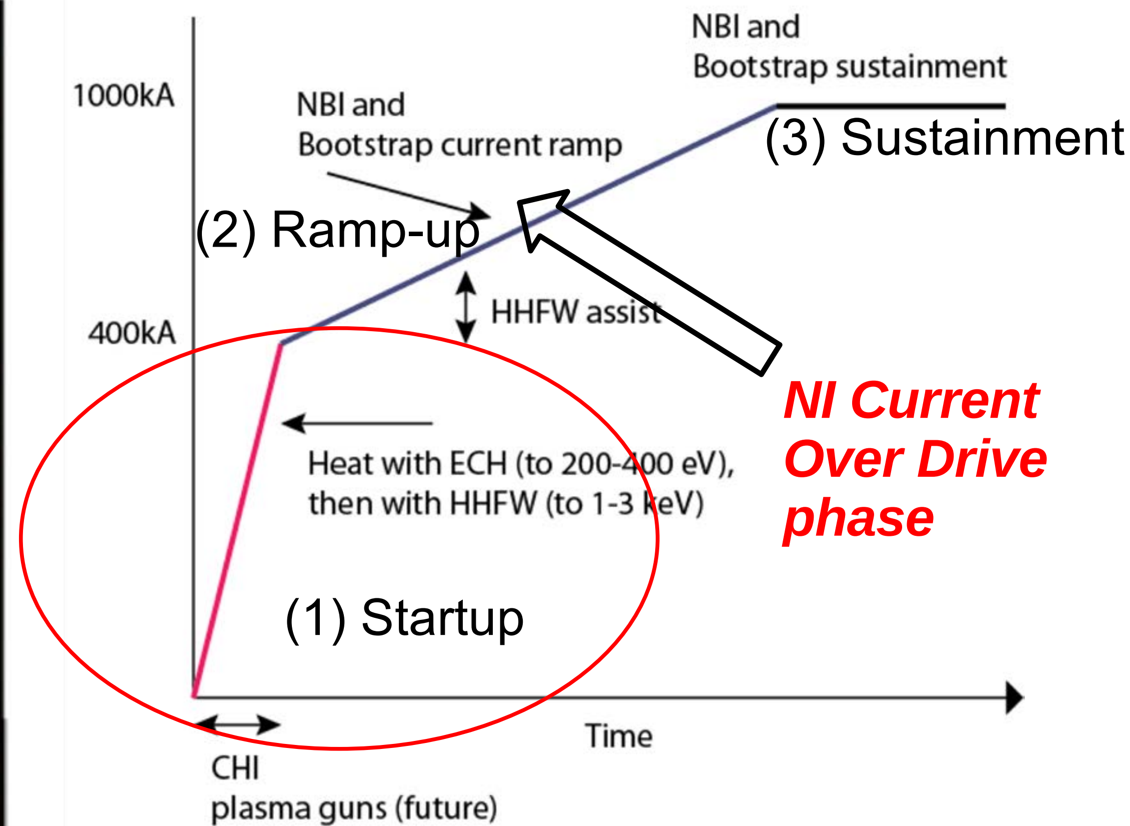
Plasma start-up in a ST involves three phases 1) solenoid free start-up, 2) non inductive current ramp, 3) non inductive current sustainment



- Transient Coaxial Helicity Injection on NSTX
  - 0.2 MA start-up currents ramped to 1 MA with inductive flux savings



Fast camera images of T-CHI discharge evolution in NSTX



The three phases of plasma startup and sustainment

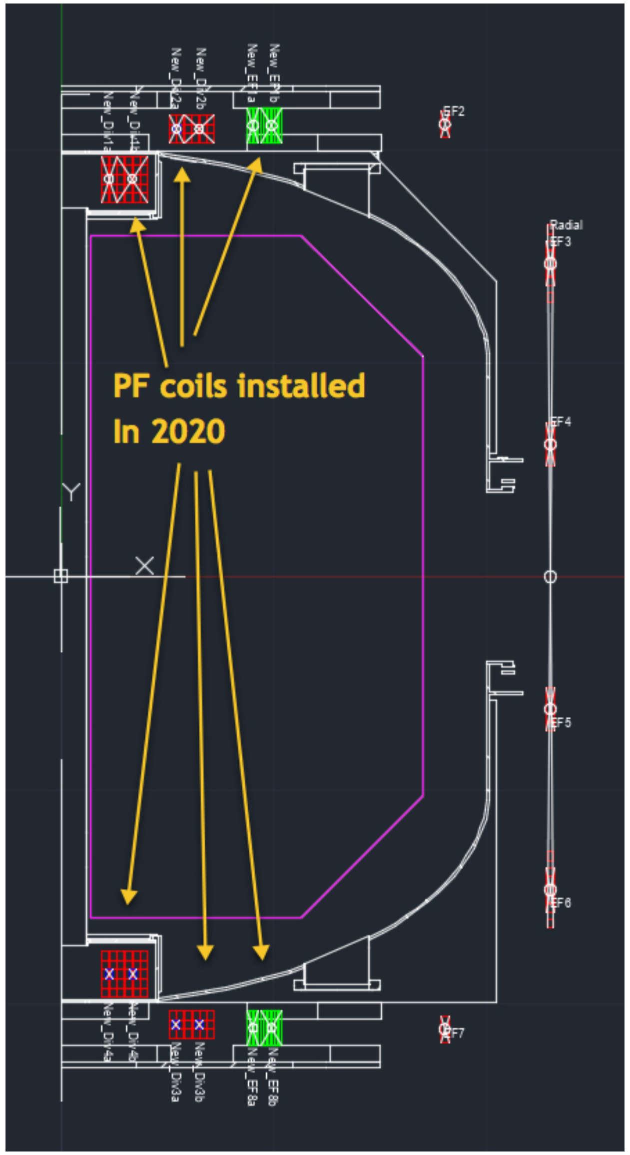
NSTX-U strategy
Poli et al, NF 55 (2015) 123011

Transient CHI Research Plan on PEGASUS-III

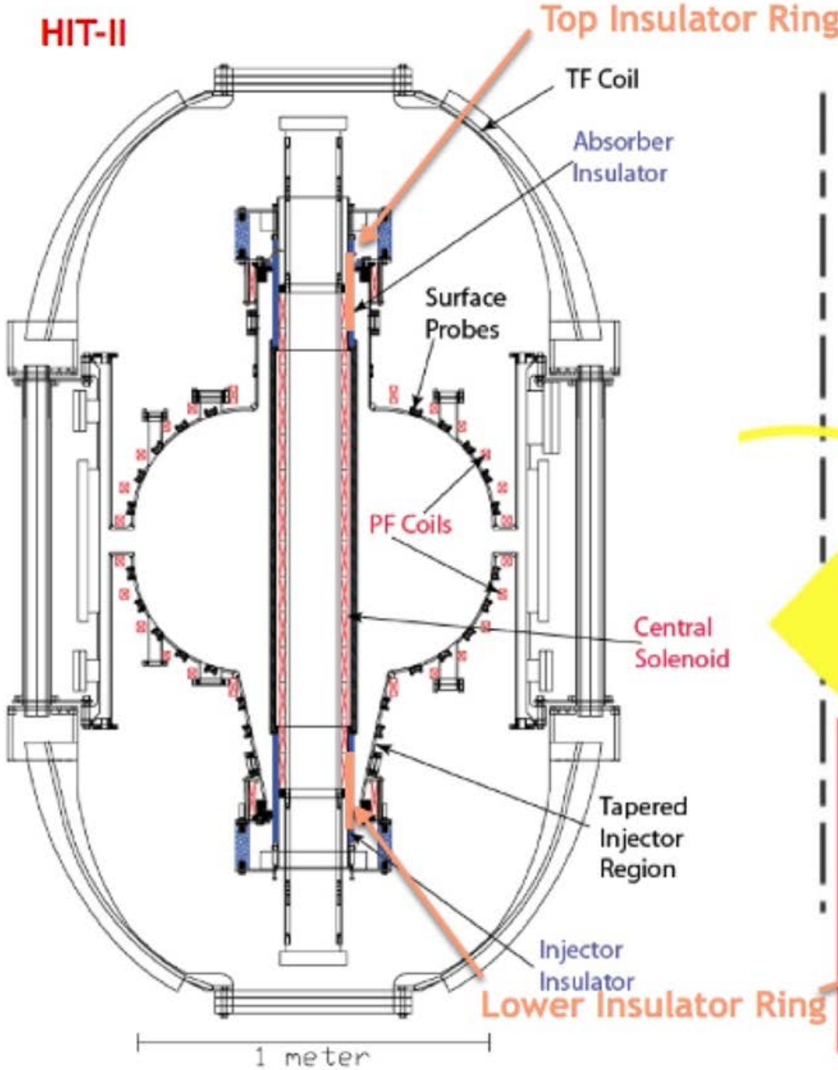
- Develop and test a double biased electrode configuration
  - Clearly defines current path
  - First ever test of concept to better control absorber arcs

- 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
  - Extent of injector current overdrive that is possible in a double biased configuration
  - External PF inductive drive to a CHI target
  - Study the requirements for CHI insulator gap location
  - Compare CHI discharge to MHD simulations
  - Heat CHI plasma using RF waves
  - Generate currents up to the external PF coil limits (~300kA)
  - Extend of the work of A.J. Redd et al. on HIT-II to assess level of steady state current that can be driven on a T-CHI discharge without degrading confinement

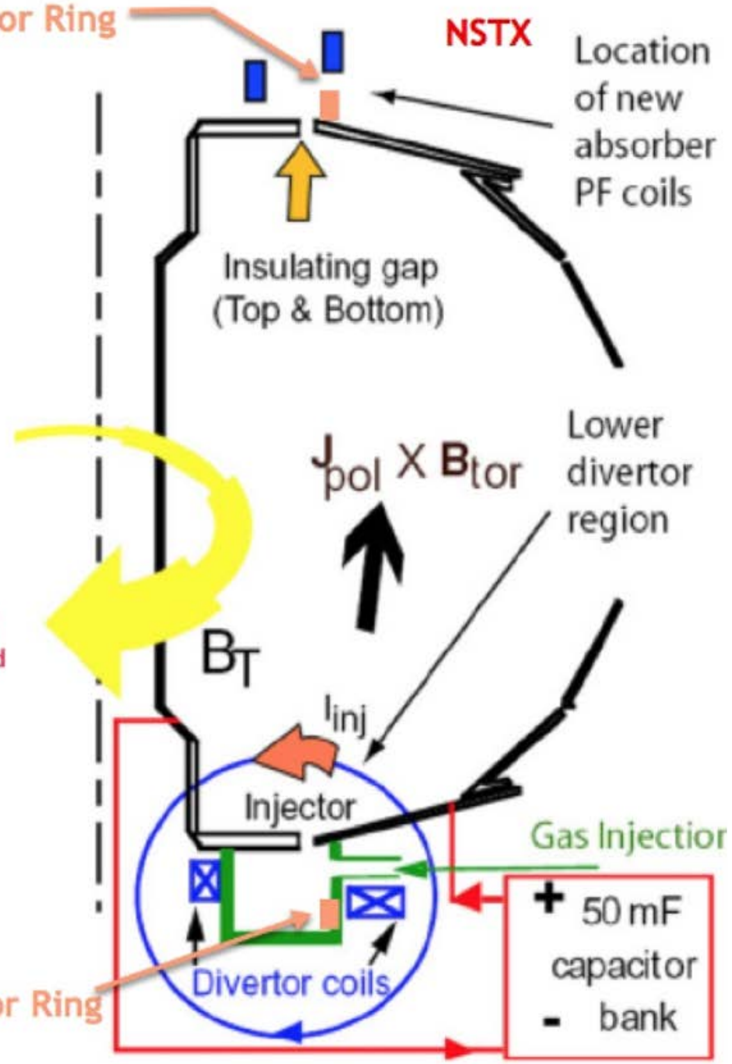
- Drive a T-CHI discharge using LHI to study synergisms with LHI and EBW (eventually with ECH)



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

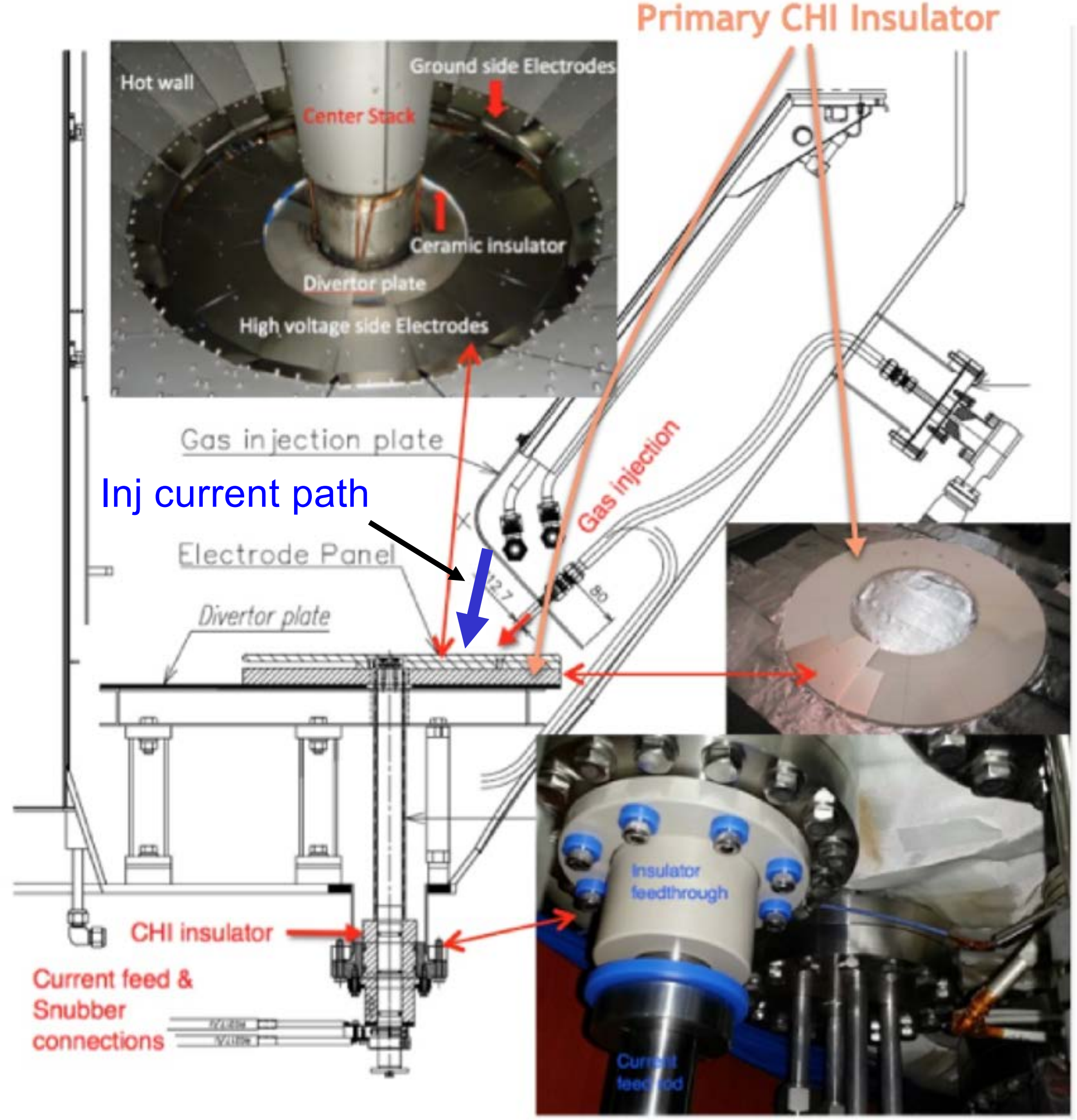


R/a = 0.3/0.2m, B_T = 0.5T



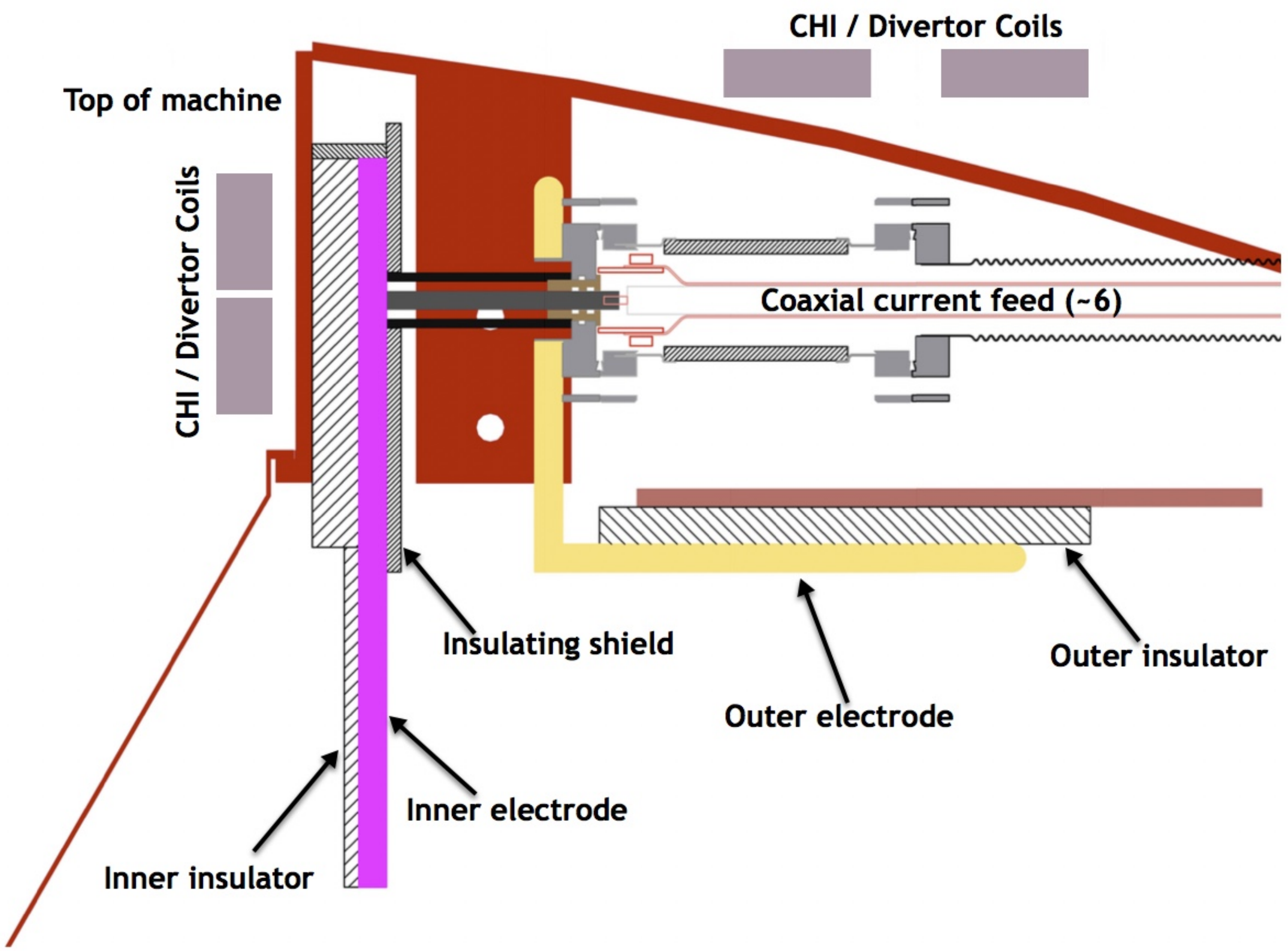
R/a = 0.86/0.66m, B_T = 0.55T

QUEST (Kyushu University, Japan)



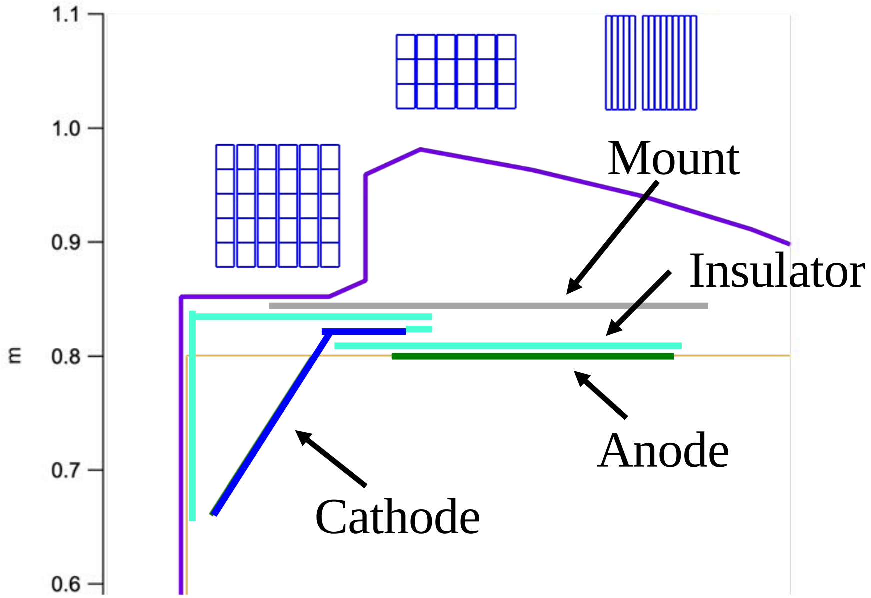
Early Concept of Double Biased Electrode for CHI

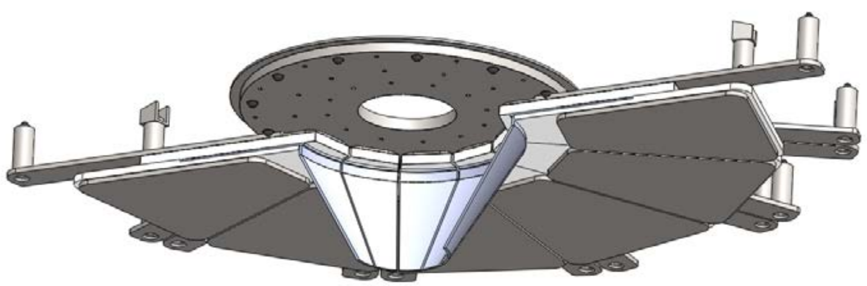
- Vacuum CHI insulators difficult to implement in reactor configurations
- QUEST is testing a single biased electrode configuration
- Double biased configuration is much more immune to spurious absorber arcs
  - Better suited for long-pulse S-CHI studies
- PEGASUS-III would be the first experiment to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



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

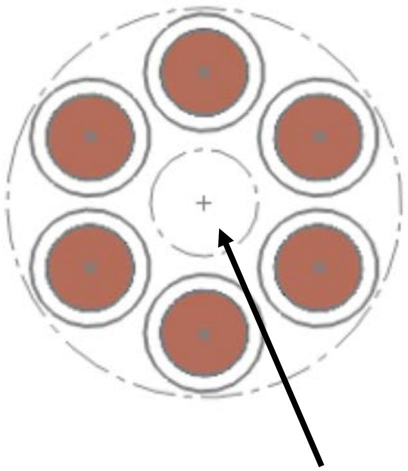
2D Sketch of Electrode Plate Concept

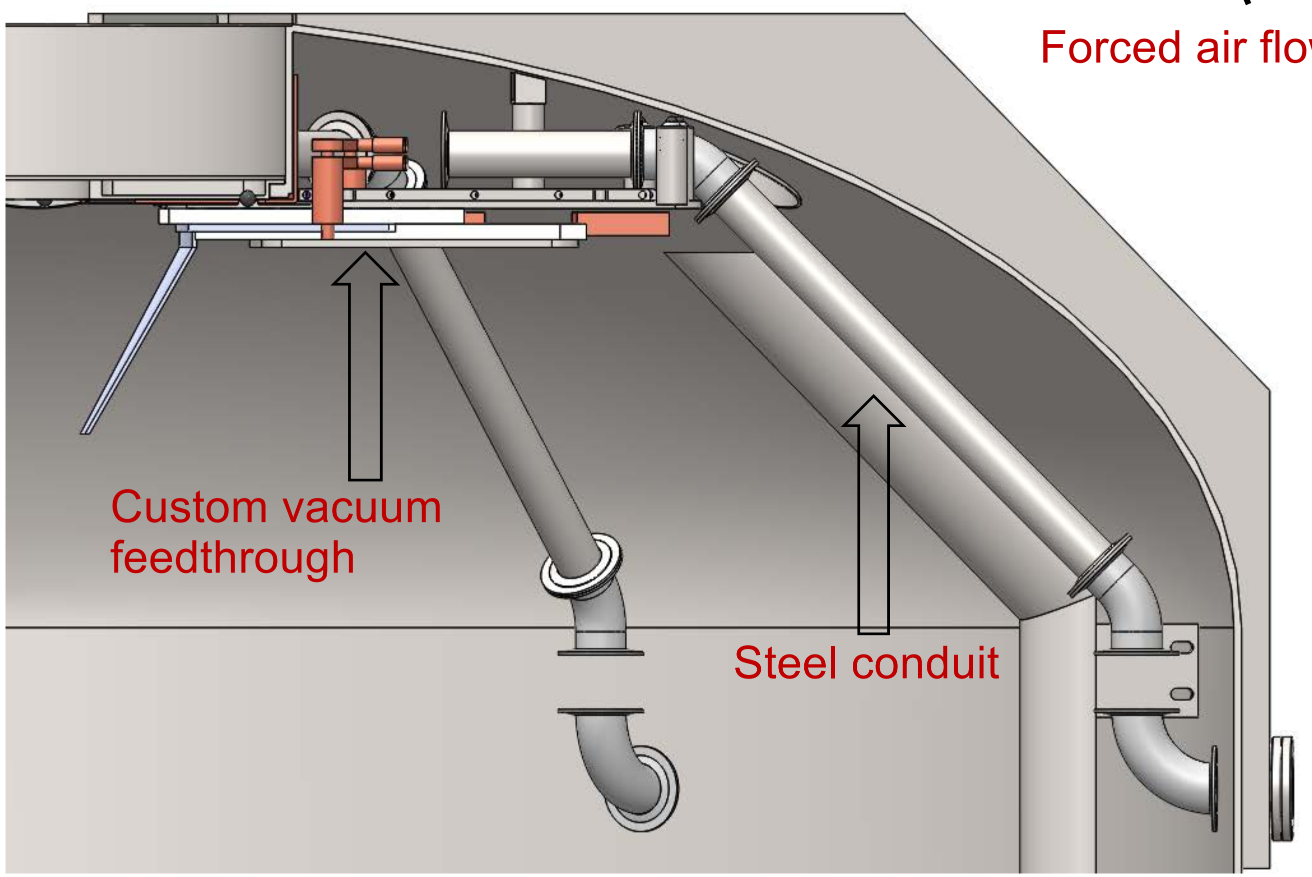




3D Sketch of Electrode Plate Concept

- 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





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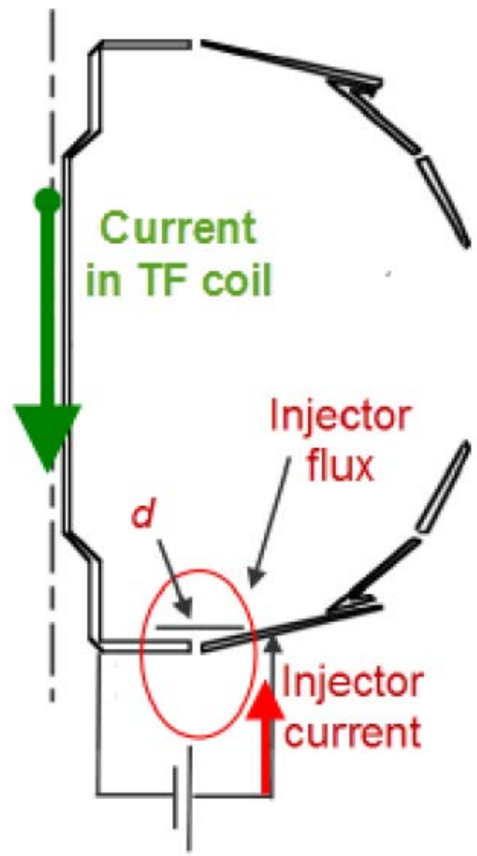
Scaling Relations for Transient CHI Based on Experimental Results From HIT-II, NSTX, and TSC Simulations

- 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}



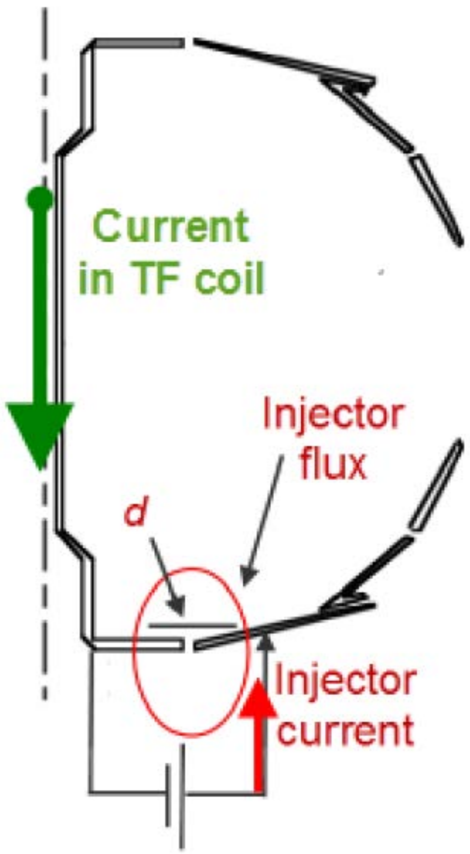
$$I_{\text{inj}} \geq \frac{2\psi_{\text{inj}}^2}{\mu_0^2 d^2 I_{\text{TF}}}$$

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

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

* 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



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

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

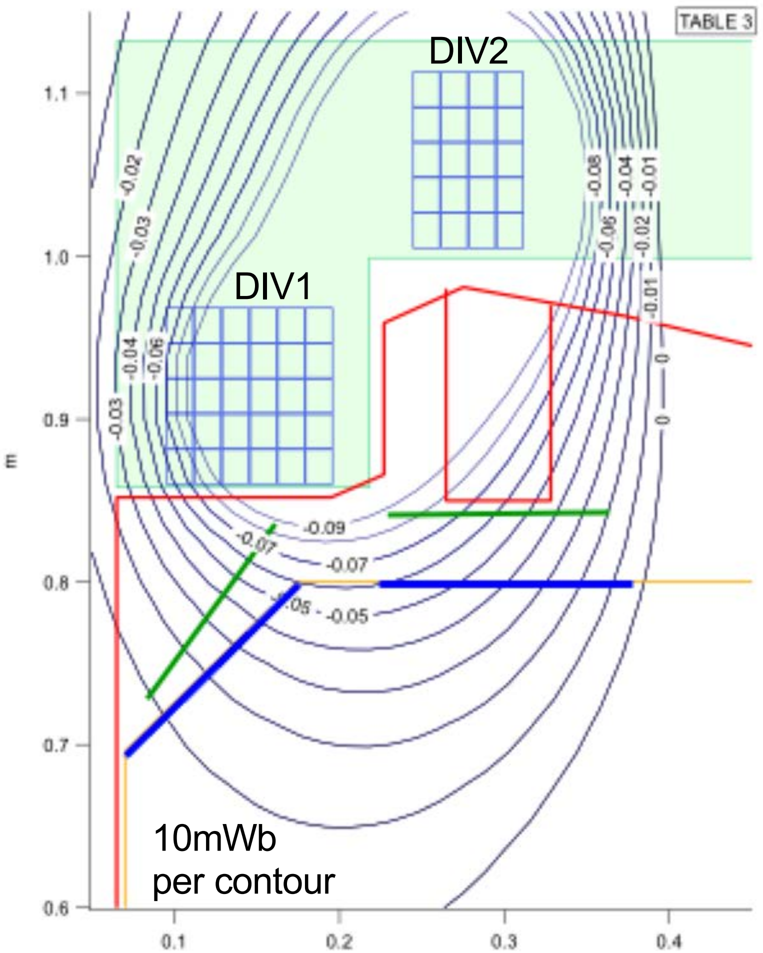
Parameter ‘d’, the injector flux footprint width, strongly determines required injector current and needs improved characterization

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

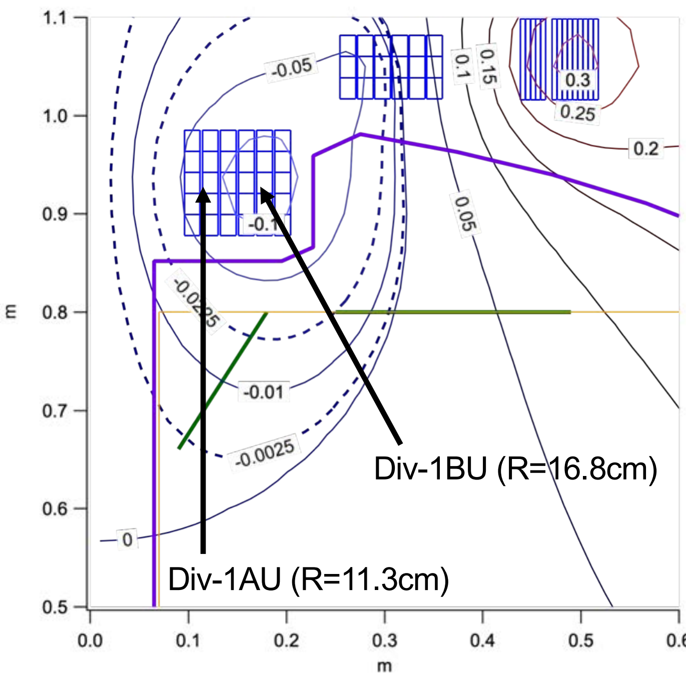
Ip (kA):	150.00
Rm (m):	0.45
B_T (T):	0.51
B_T @ CHI location (T):	0.82
Bt multiplier factor:	1.61
l_i - Plas normalized Inductance:	0.30
Enclosed Polo flux (mWb):	12.72
Flux conversion efficieny:	0.70
Injector flux (mWb):	18.18
Itf (kA):	1152.00
footprint width ‘d’ - (cm):	10.00
Inj Curr (kA)	22.60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

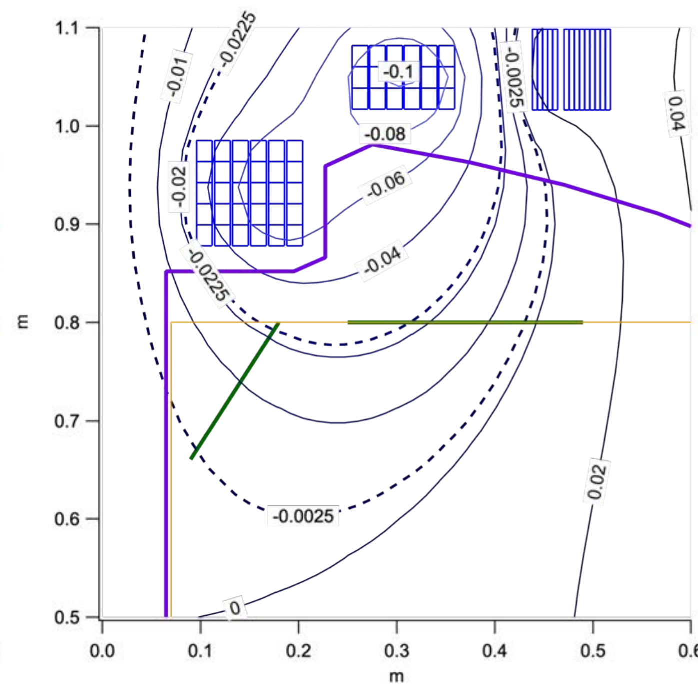
- At 20 mWb injector flux (I_p > 150kA) flux footprint can be varied significantly
  - Average separation from 17–27 cm
- At max injector flux, not a lot of room to manipulate d with consistent equilibrium

Narrow 20 mWb Footprint



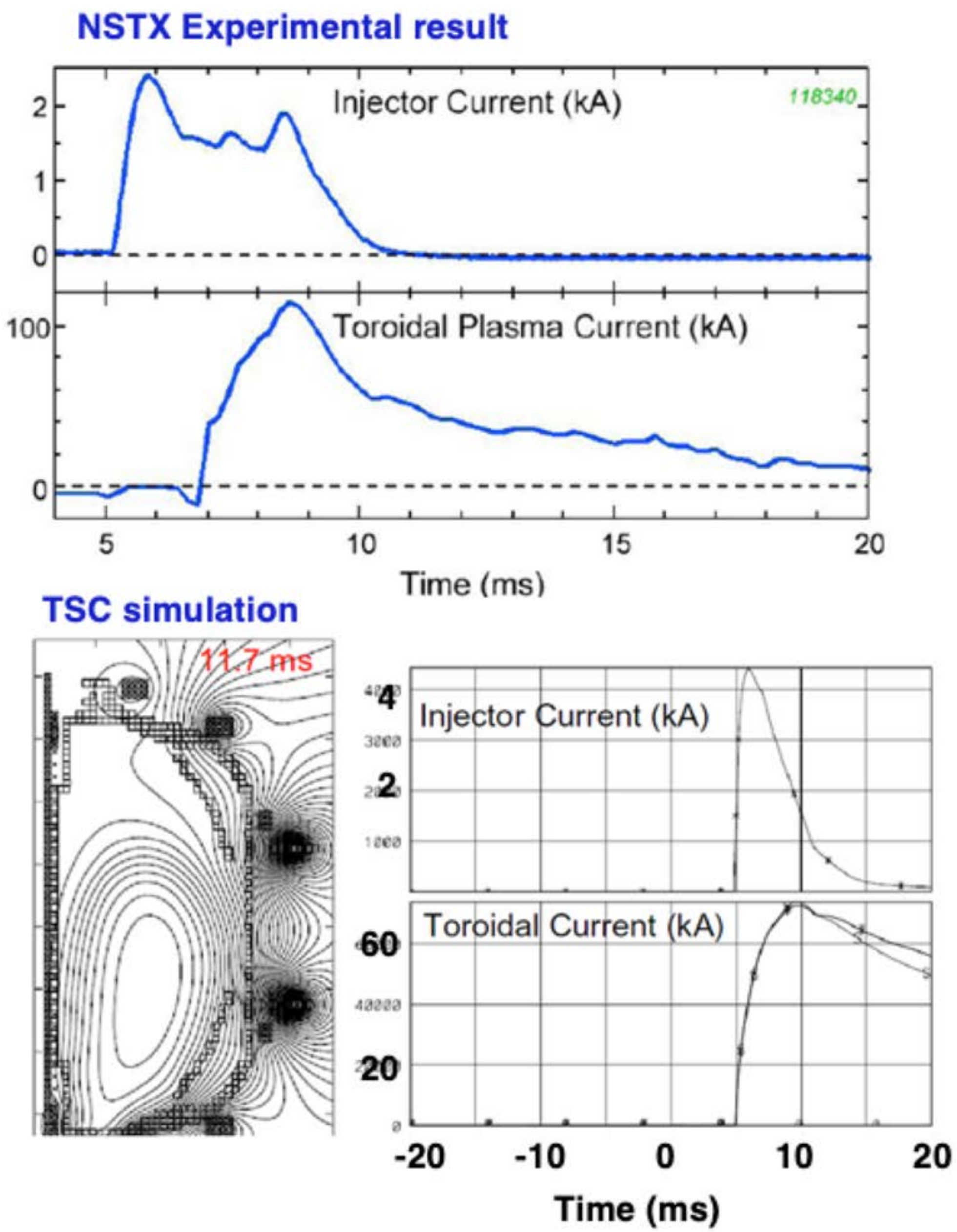
Div1, Div2 = -13kA
EF1 = 15kA

Wide 20 mWb Footprint



Div1, Div2 = -7kA
EF1a = 9.7kA
EF1b = 0

TSC (Tokamak Simulation Code)



TSC: Developed by S.C. Jardin

- Time-dependent, free-boundary, predictive equilibrium and transport, initially developed for TFTR inducive plasma studies.
- Solves MHD/Maxwell's equations coupled to transport and Ohm's law
- Requires as input:
  - Device hardware geometry
  - Coil electrical characteristics
  - Assumptions concerning discharge characteristics
- Models evolutions of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales.
- ST vacuum vessel modeled as a metallic structure with poloidal breaks (5 cm rectangular elements for NSTX)
  - An electric potential is applied across the break to generate the desired injector current

TSC Model of CHI on PEGASUS-III

NSTX-Ref	Pegasus Name	R	Z	Δr	Δz	# Turns
DIV 1AU	DIV 1A	11.3	93.15	3.22	10.73	10
DIV 1BU	DIV 1B	16.8	93.15	6.44	10.73	20
DIV 2AU	DIV 2A	27.1	104.93	4.83	6.44	6
DIV 2BU	DIV 2B	32.5	104.93	6.44	6.44	12
DIV 1AL	DIV 4A	11.3	-93.15	3.22	10.73	10
DIV 1BL	DIV 4B	16.8	-93.15	6.44	10.73	20
DIV 2AL	DIV 3A	27.1	-104.93	4.83	6.44	6
DIV 2BL	DIV 3B	32.5	-104.93	6.44	6.44	12
EF2U	EF2	90.007	106.0065	1.905	6.032	3
EF3U	EF3	114.823	73.382	1.905	10.307	5
EF4U	EF4	114.823	30.9965	1.905	10.16	5
EF5L	EF5	114.823	-30.9955	1.905	10.16	5
EF6L	EF6	114.823	-73.382	1.905	10.307	5
EF7L	EF7	90.007	-106.0065	1.905	6.032	3
	Radial	114.823	0.0000	1.6101	164.6688	4
EF1AU	New_EF1a	45.10915	105.718	2.5882	8.255	5
EF1BU	New_EF1b	49.40685	105.718	4.6812	8.255	9
EF8AL	New_EF8a	45.10915	-105.718	2.5882	8.255	5
EF8BL	New_EF8b	49.40685	-105.718	4.6812	8.255	9

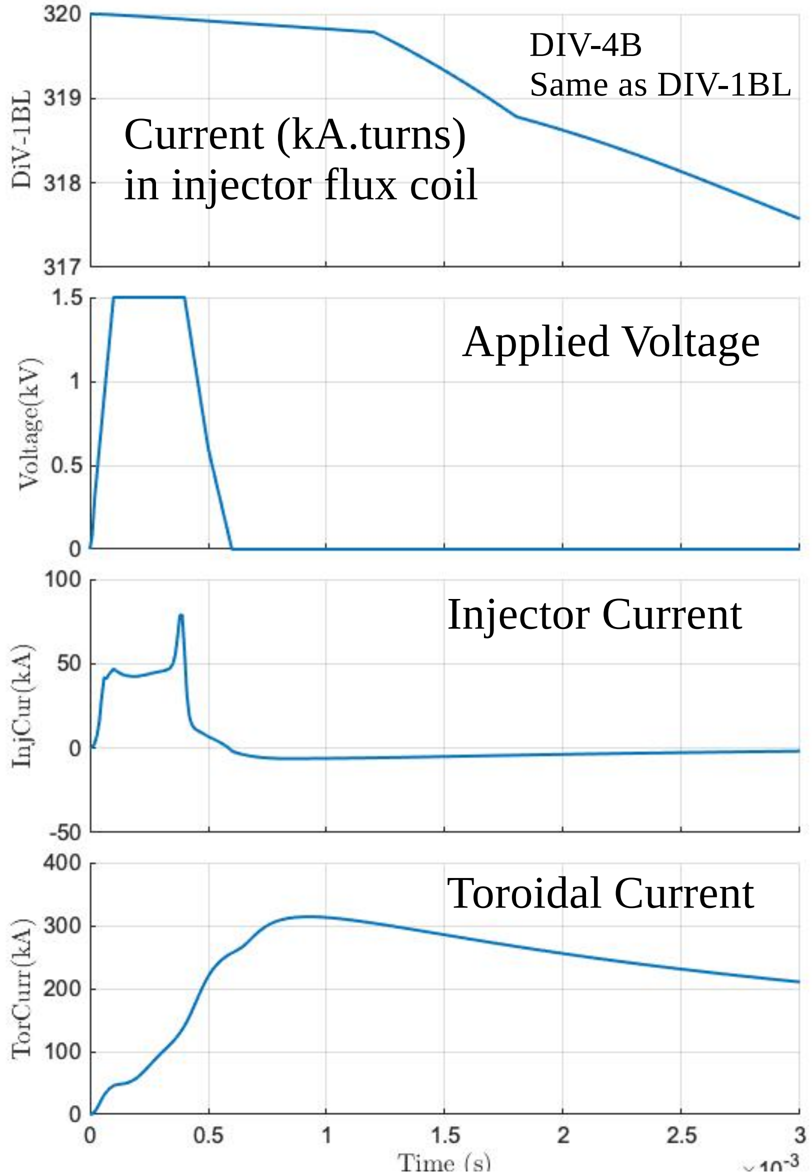
PEGASUS-III Coil Configuration

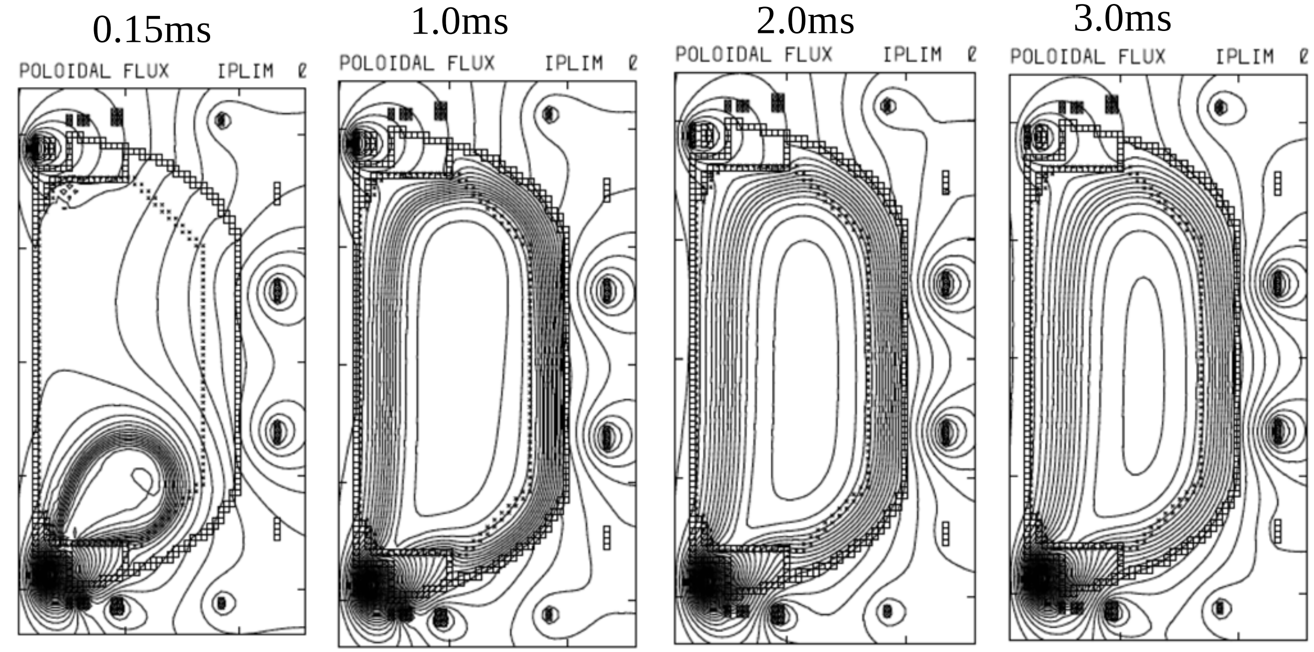
PF Coils used in TSC

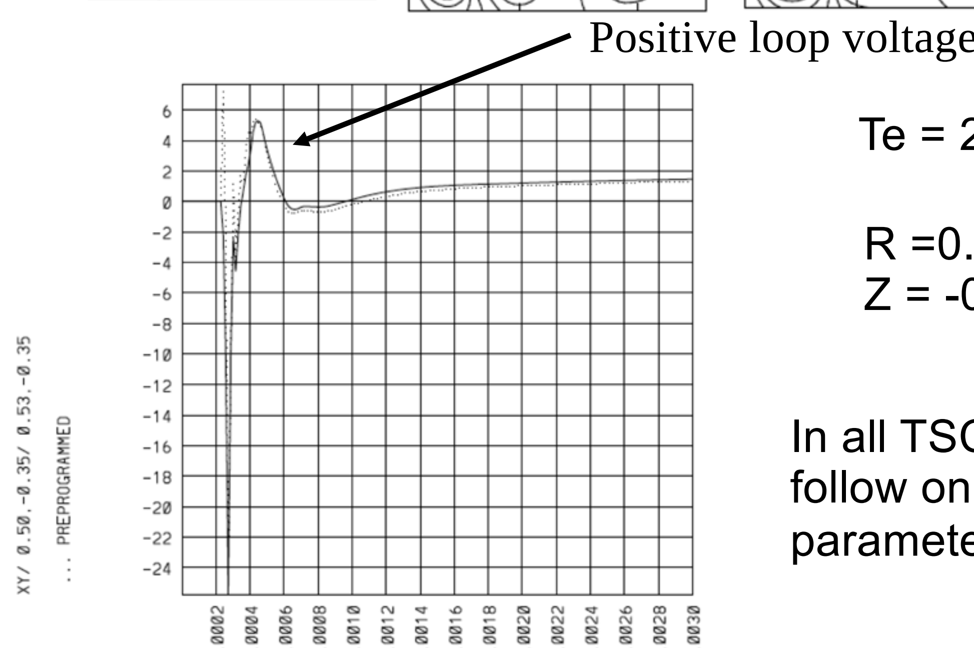
DIV 1AL (7) – 4kA
DIV 1BL (1) + 16kA
DIV 2AL (4) 0kA
DIV 2BL (12) -3kA
EF 1AL, EF 1BL (6) -1kA
EF7 (10) -1kA
EF 4, EF5 (5) -1kA
EF 2 (3) -1kA
EF 1AU, EF 1BU (2) 0kA
DIV 2BU (9) 0kA
DIV 2AU (8) 0kA
DIV 1AU (13) 16kA
EF3, EF6, DIV 1BU (14) 0kA

Vessel and coils modelled using 2.5 cm square elements

TSC simulations show persisting CHI produced toroidal current in the range of 250kA for 16kA in DIV-1B (4B) Coil







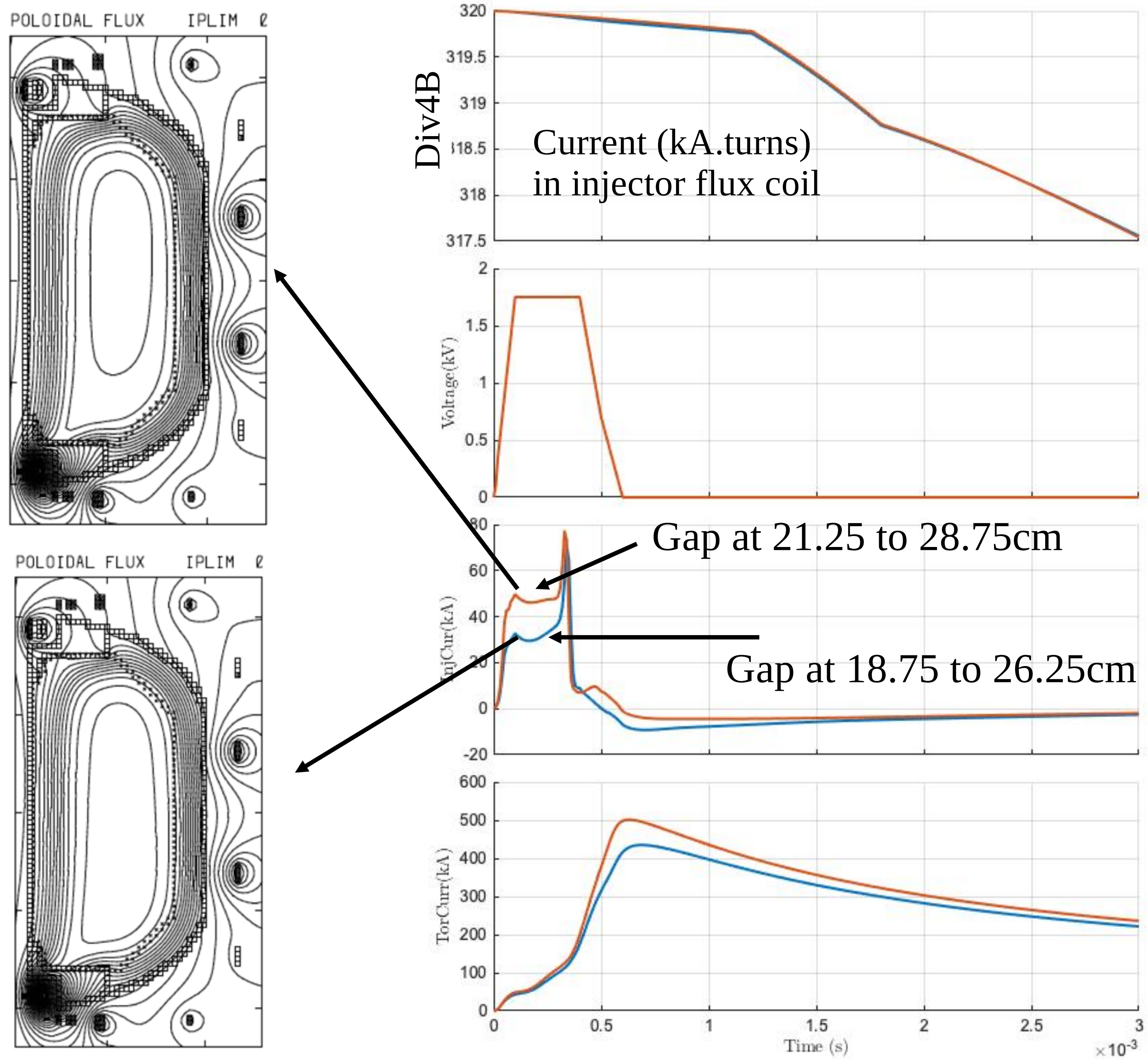
Te = 200eV

R =0.5-0.53m
Z = -0.3mm

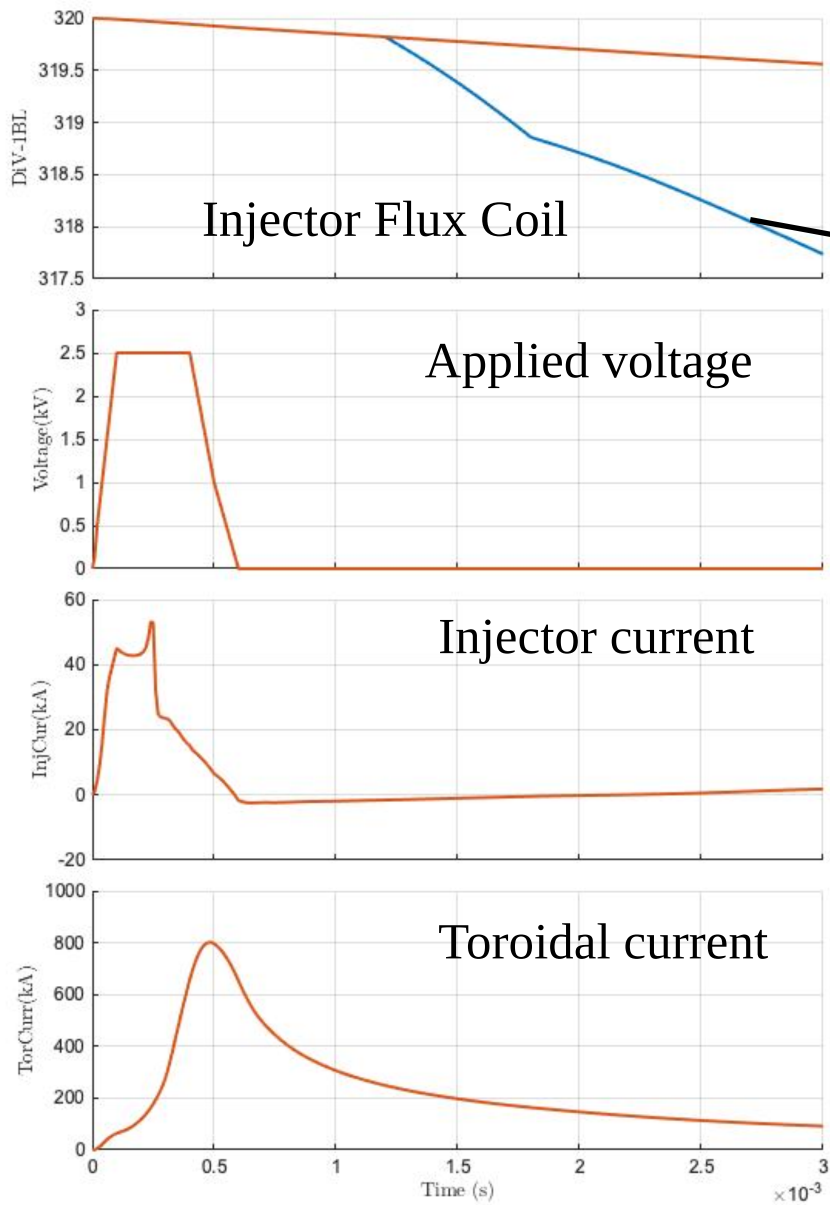
In all TSC simulations that follow only the mentioned parameter is changed.

Comparison of CHI insulator gap location

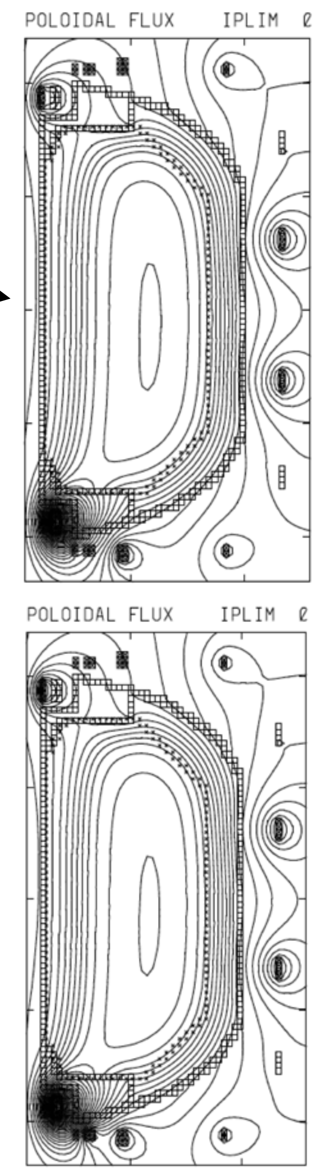
- Actual planned gap location has R = 18 to 25 cm
- CHI grid resolution of 2.5cm limits exact gap specification
- Moving the gap to a larger radius (by ~ 2.5cm) seems to help with flux closure
- But, the discharge at reduced gap radius also requires less injector current (effective B_T is higher)
- Both gap locations allow the injected flux to evolve into the vessel, and the sensitivity to the gap location and gap width are planned to be studied as part of the experimental plan on PEGASUS-III

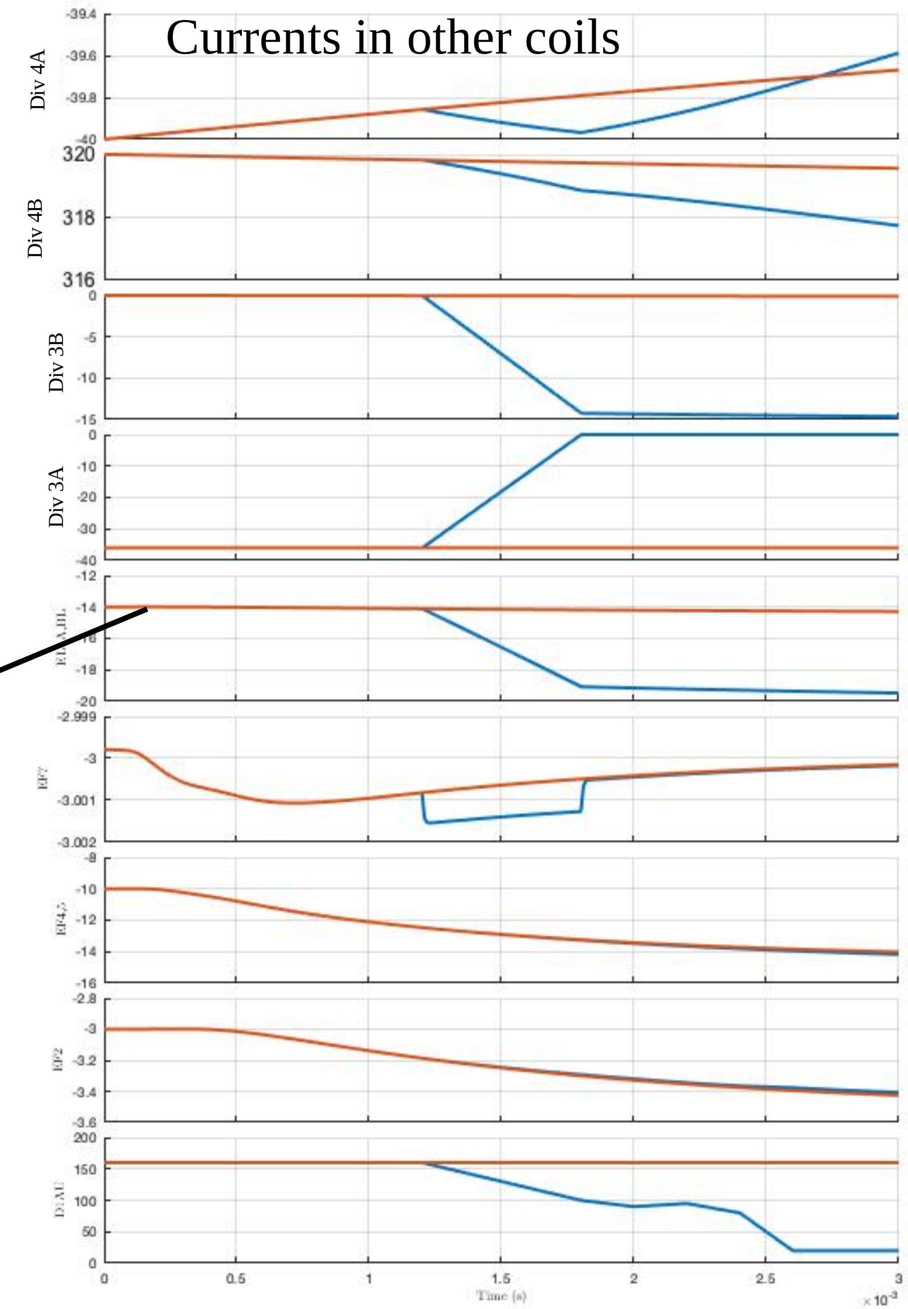


CHI produced toroidal current evolution is not altered by coil current ramps as wall time of ~10ms >> CHI discharge time



Poloidal flux at 1.73ms





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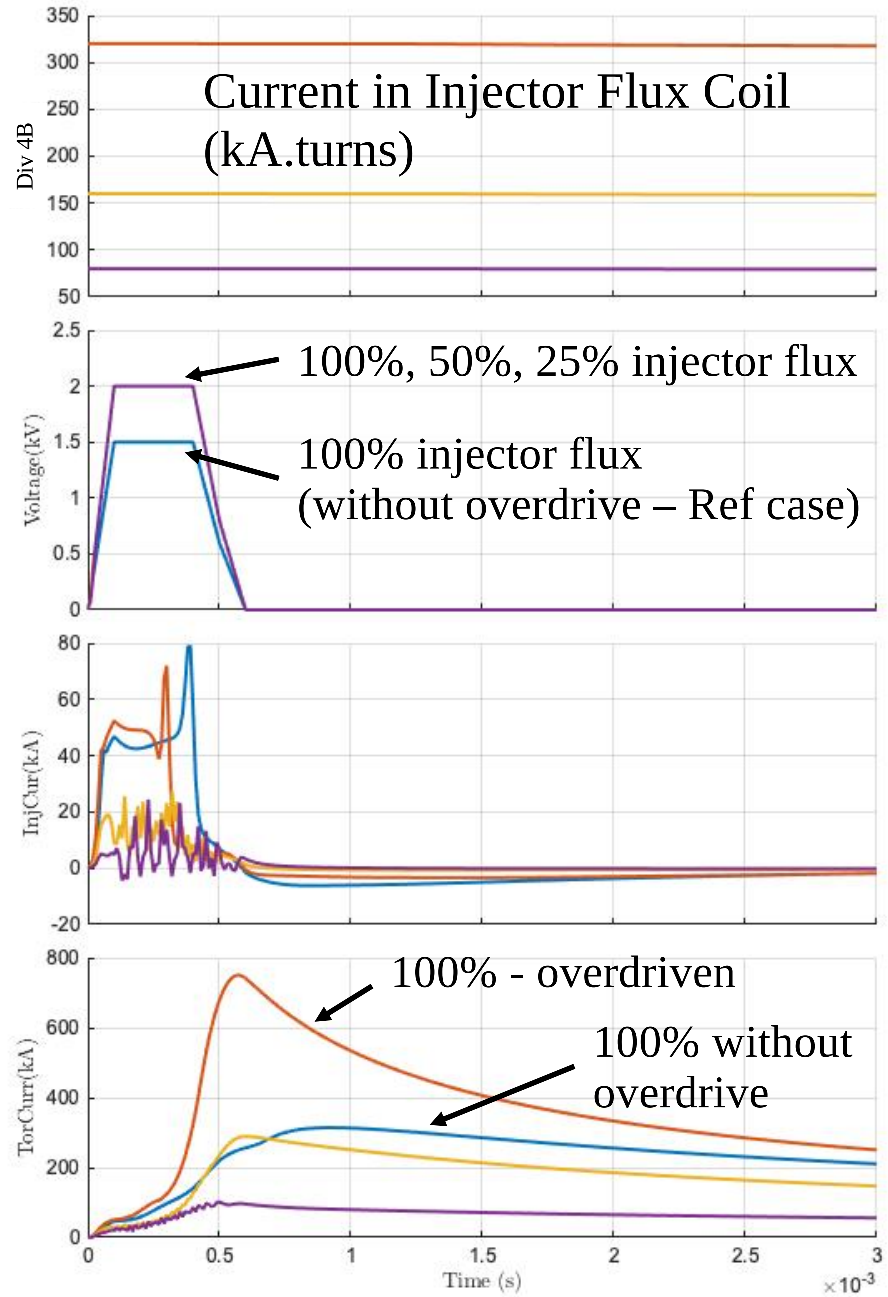
Red traces have steady currents in PF coils

Persisting toroidal current increases in proportion to injector flux

- At low injector flux numerical issues cause injector current oscillations
- Overdriving the system generates higher toroidal current as more flux is injected
  - Overdriving refers to applying a higher voltage, which increases the injector current and causes more of the injected flux to fill the vessel.
- Overdriving is difficult in the NSTX/HIT-II configuration because of the presence of the absorber at the opposite end
  - In this case the flux that makes contact with the upper divertor can short out the inner and outer vessel components and result in ending the discharge through a condition known as an absorber arc
- PEGASUS-III will study if overdriving is easier in a double biased configuration as the injected flux cannot short out the electrodes at the opposite end of the vessel



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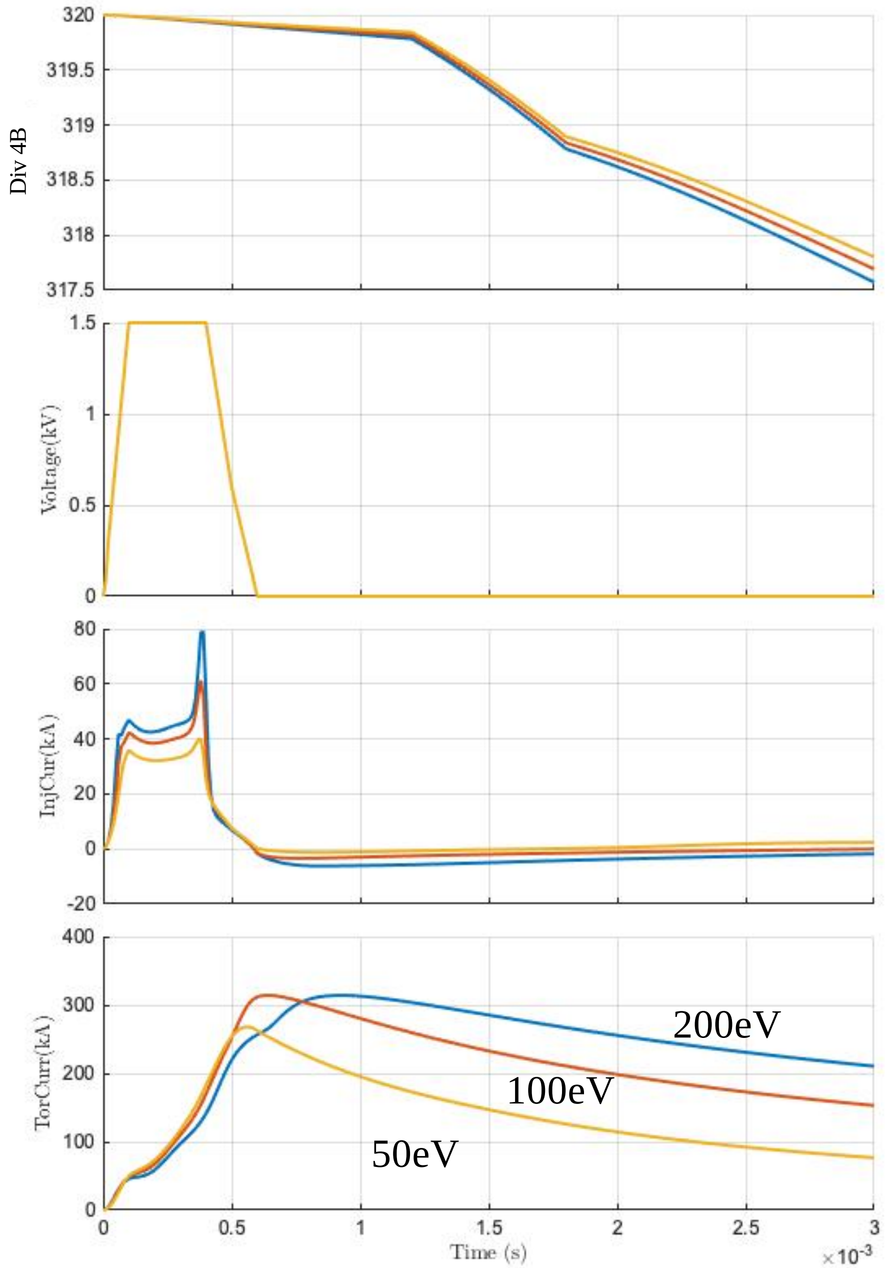
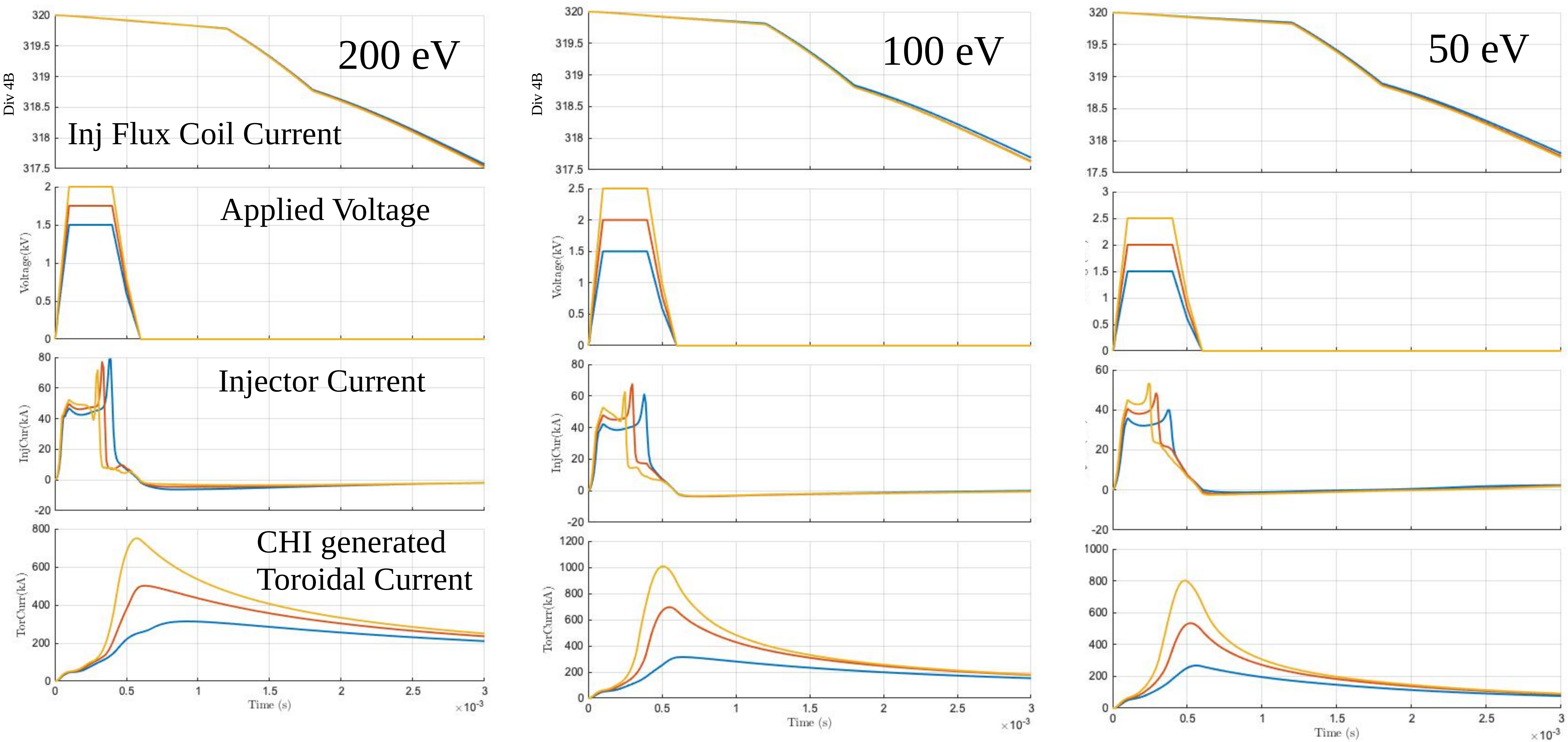
Injector flux evolves into the vessel for Te = 50 to 200eV, but current decays at a faster rate for the lower Te plasmas

- HIT-II transient CHI plasmas have attained over 30eV with less than 16mWb flux injection
- Higher levels of flux injection in PEGASUS-III and because of the absence of low-Z walls, PEGASUS-III transient CHI plasmas are expected to reach higher electron temperatures than that achieved on HIT-II
- The plan with transient CHI is to heat the decaying CHI plasma with ECH to increase its electron temperature
- External current drive would also be implemented in reactor scenarios to ramp the current to sustainment levels instead of letting it decay



At higher voltages, peak open flux current increases, but persisting toroidal current remains nearly the same



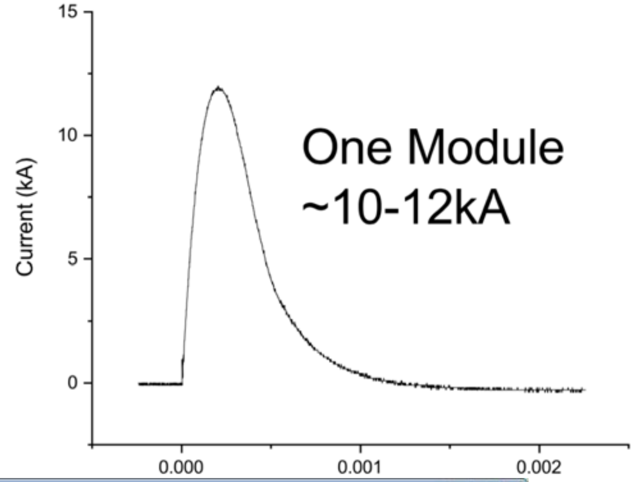
So there are limits to how much you can overdrive the system

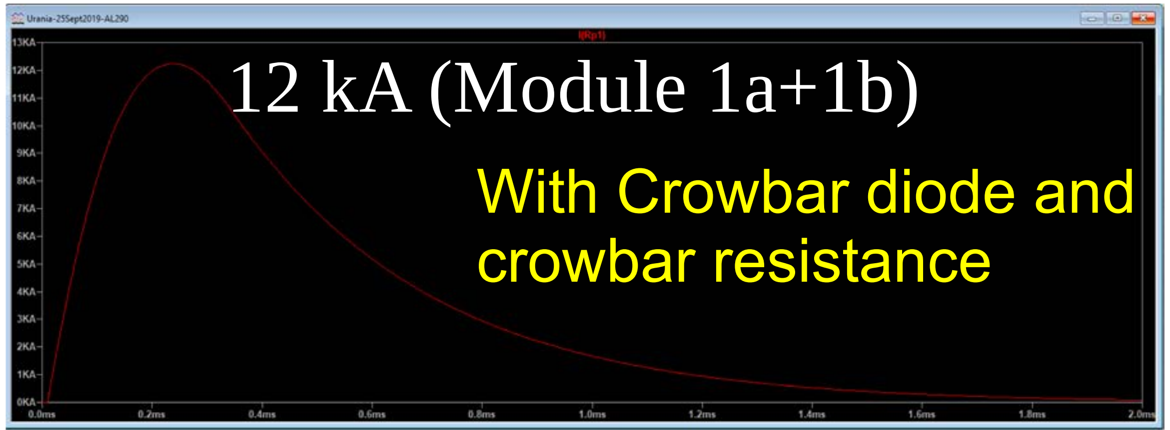
TSC Simulation Conclusions

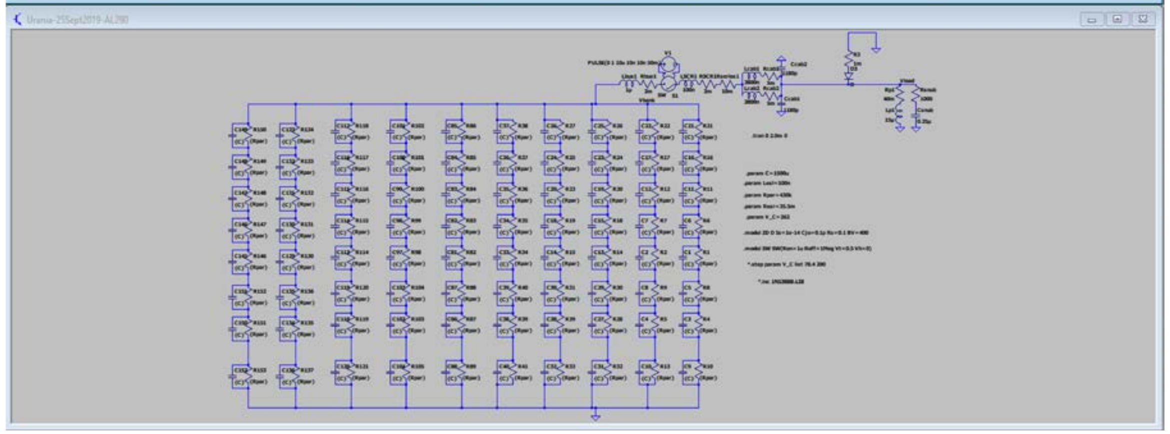
- Persisting toroidal currents at the 250kA level are seen for 16kA in just the DIV-4B coil, consistent with simple calculations
- The persisting toroidal current increases in proportion to the injector flux
- Some current overdrive can inject more flux
  - The limits of this will be studied on PEGASUS-III to see if the double biased geometry provides greater flexibility in this area
- Arbitrarily increasing the current overdrive increases the open field line current and does not contribute the current that persists after the injector current in reduced to zero
- As expected, the current decay rate of the persisting toroidal current decreases with increased electron temperature
- The exact location of the CHI insulator gap influences the flux evolution and persisting toroidal current, but in the vicinity of the planned gap location the effect may be small
  - Needs to experimentally studied as part of the development plan on PEGASUS-III
- Transient CHI discharge evolution into the vessel and the magnitude of the persisting current are attainable without any inductive ramps using the external PF coil currents

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

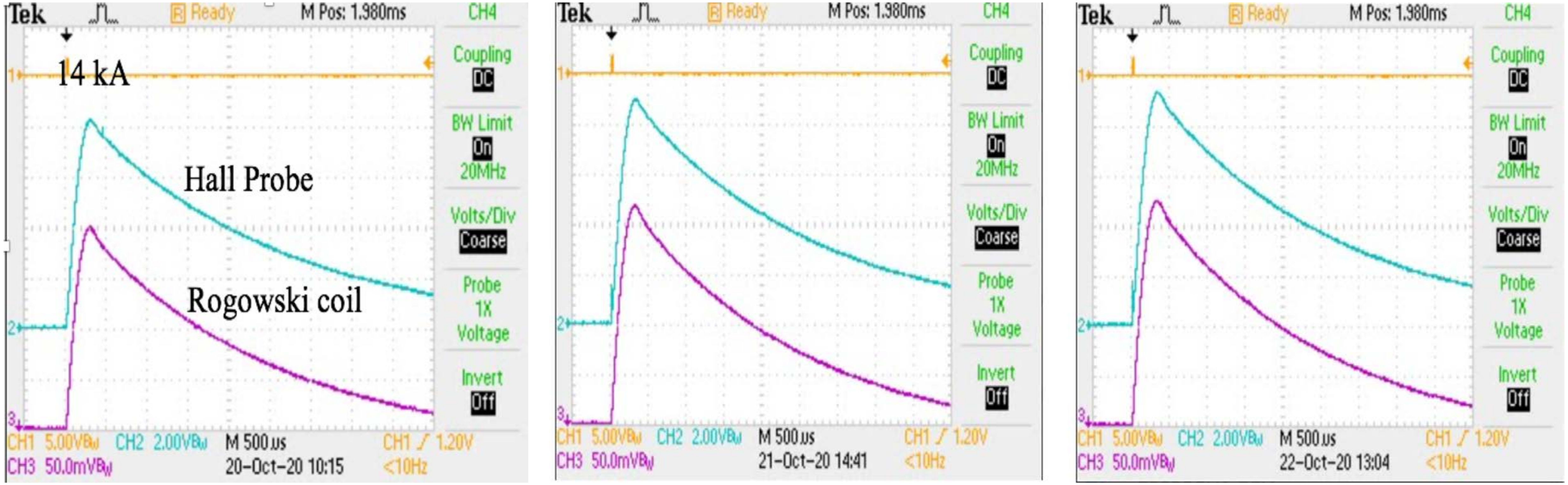
Module 1a+1b
80 Capacitors x 1500uF
8 (450V) in Series
10 in parallel
2100 V total
262 V/cap
R = 55.5 mOhm
L = 18 µH





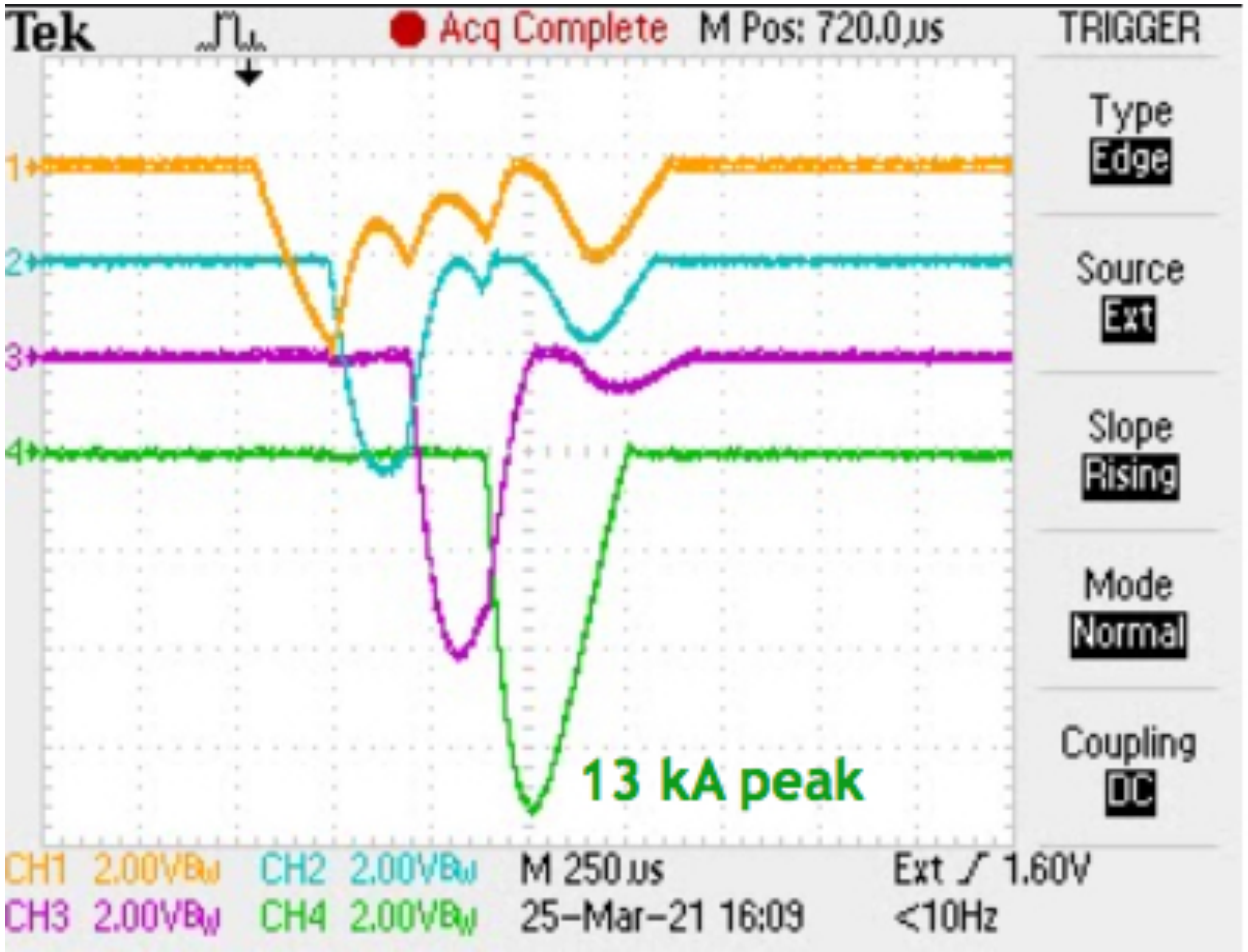


Current Measurements During the Testing of Modules 2, 3, and 4 during PS commissioning

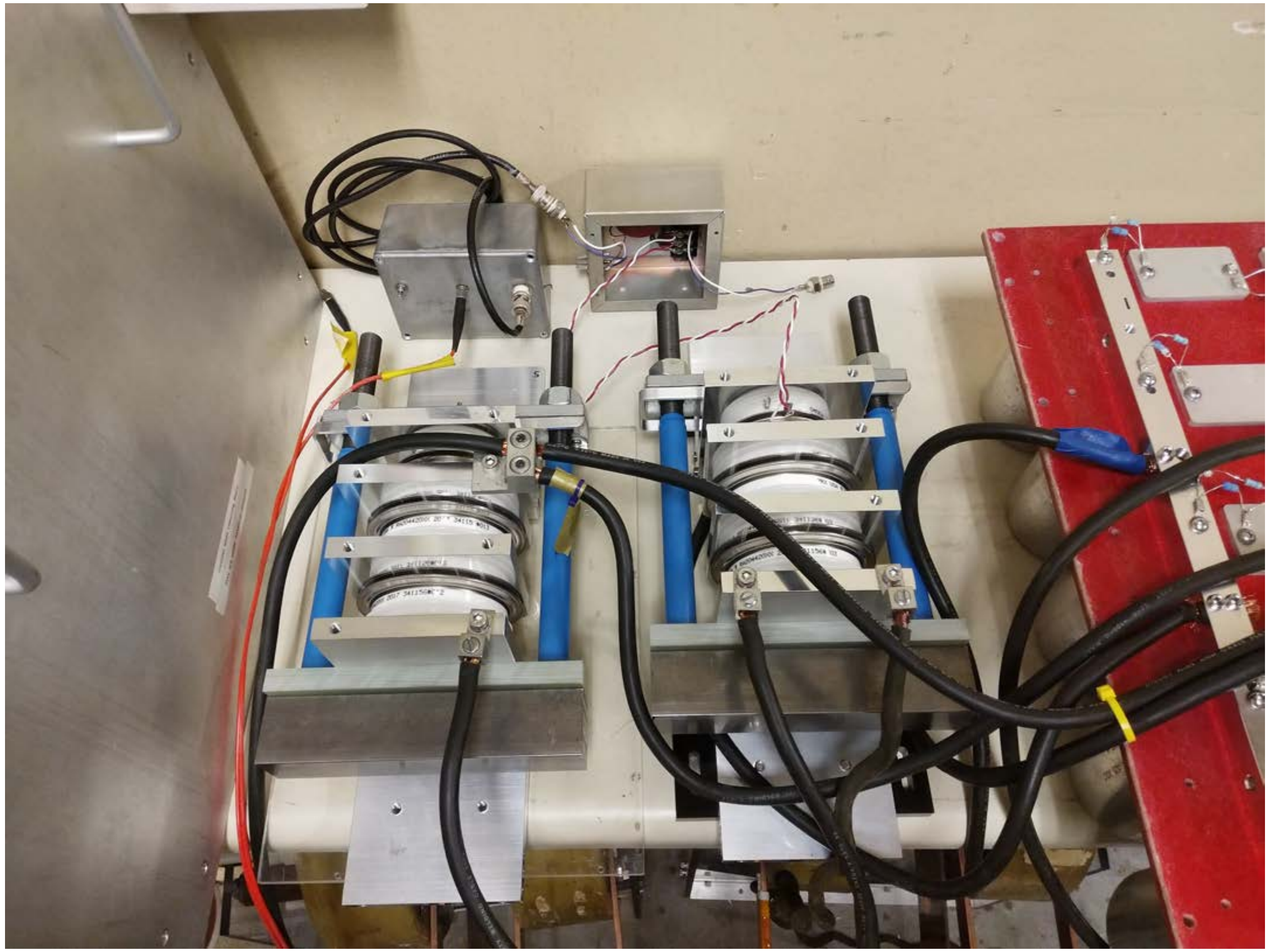


2kV testing of modules 2, 3 and 4. They all generate similar levels of current. The difference in current between the modules is because all of the 80 capacitors in a module have matched capacitors to keep them balanced as much as possible. Thus, the total capacitance of each module is different from that of that of the other modules.

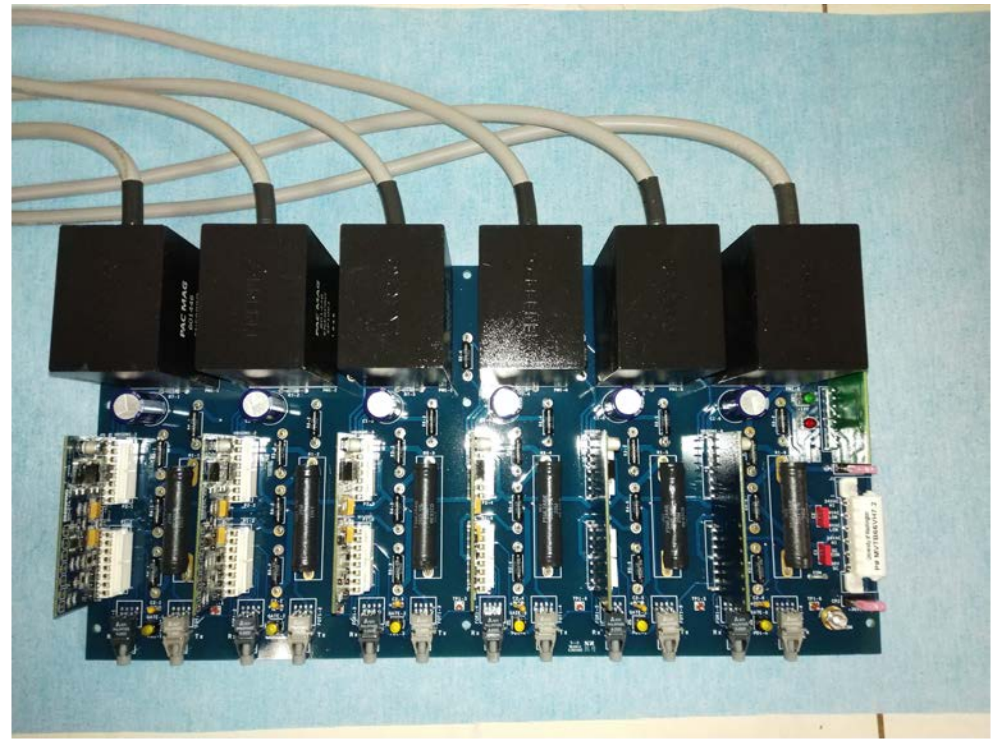
All Four Modules Discharged Full Power Testing



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



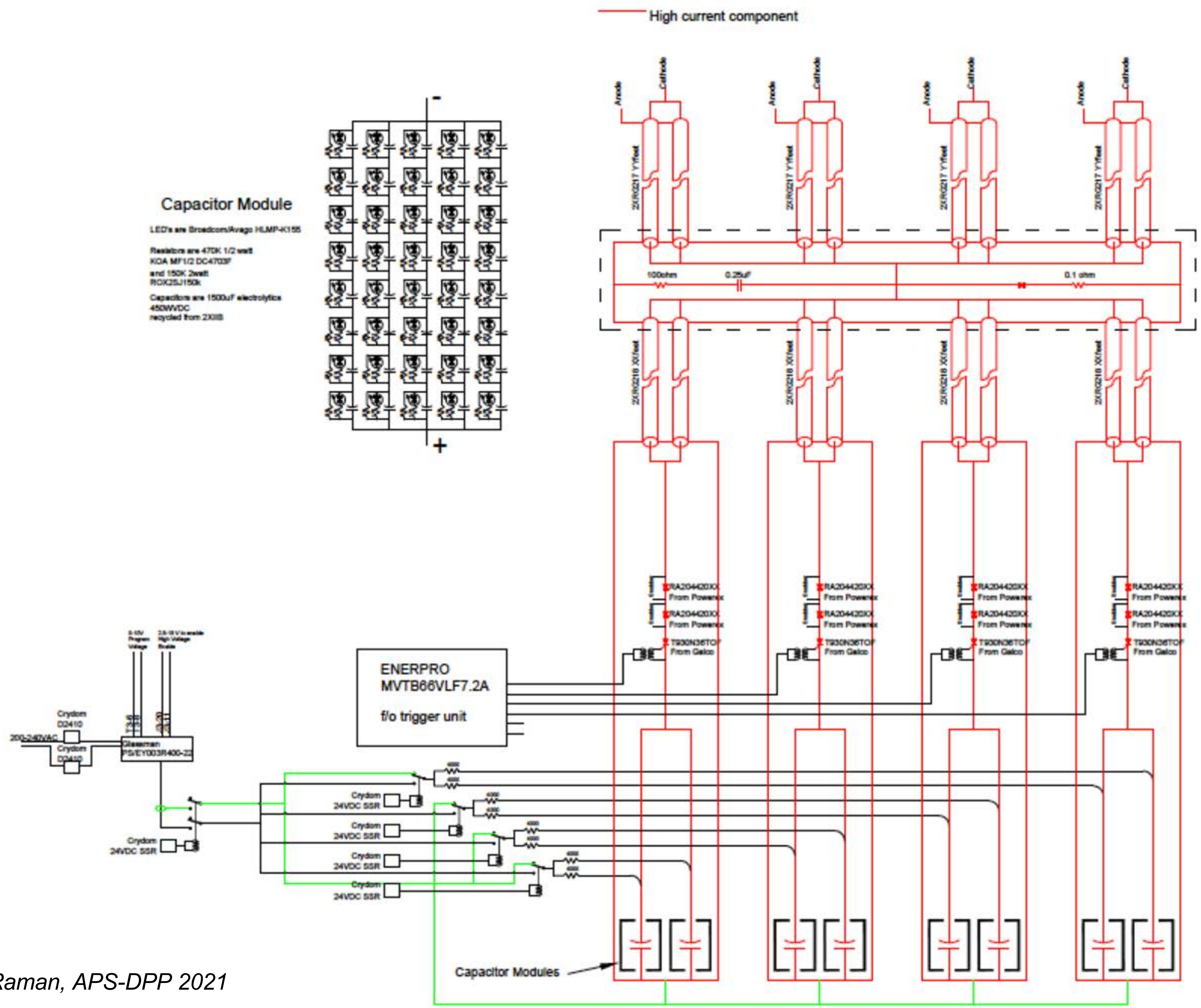
3.6 kV, 19.5kA Infineon SCR in series with two Powerex 4.4kV, 24kA diode (total 8.8kV standoff)

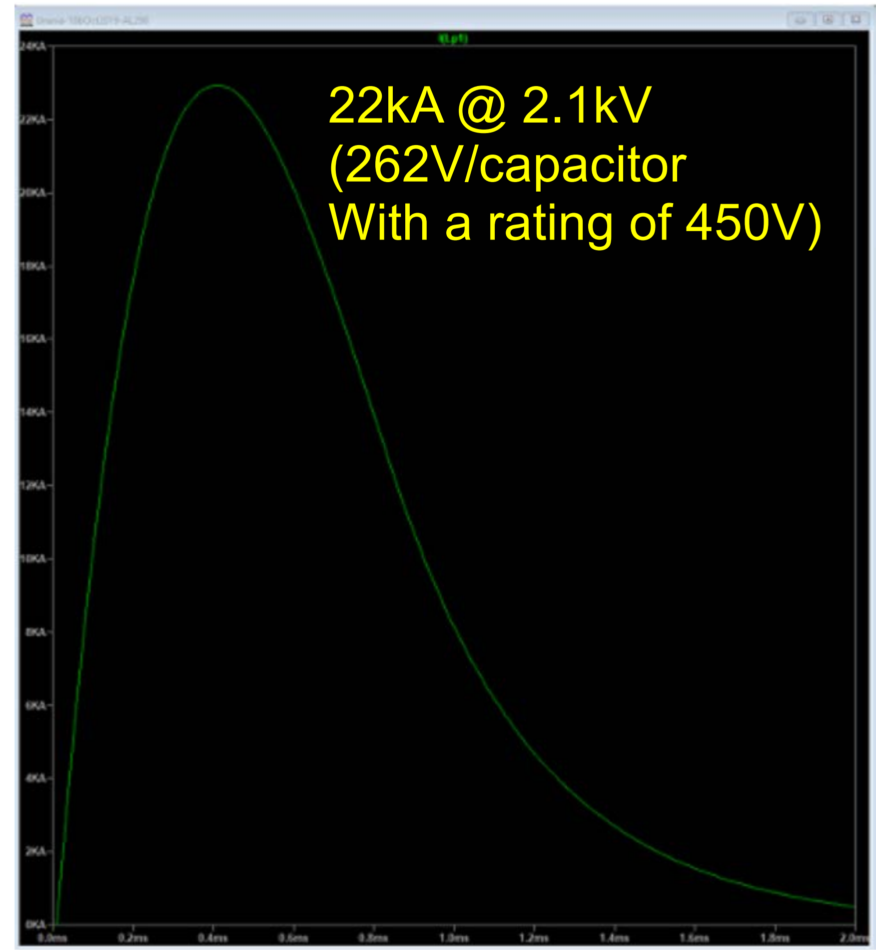


6-channel SCR trigger system (ENERPRO unit)

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

Full CHI PS Electrical Circuit





33kA at 3kV (375V/capacitor)

Finished and Assembled PEGASUS-III CHI PS

Transient CHI Studies on PEGASUS-III Will Improve Our Understanding of the CHI Scaling Relations 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
  - Increasing high I_p up to external PF coil limits as B_T is raised (goal: 0.15 → 0.3 MA)
  - Quantify the parameter 'd', flux shaping effects, the sensitivity to the CHI insulator location and insulator gap width, on the plasma internal inductance and on the closed flux conversion efficiency
  - Compare CHI discharge to MHD simulations
- Future: exploration of synergistic effects
  - T-CHI-to-LHI sustainment scenarios
  - RF auxiliary heating of T-CHI discharges