

Solenoid-Free Plasma Startup using Transient CHI Progress & Plans

Supported by



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What is Transient Coaxial Helicity Injection (t-CHI)?

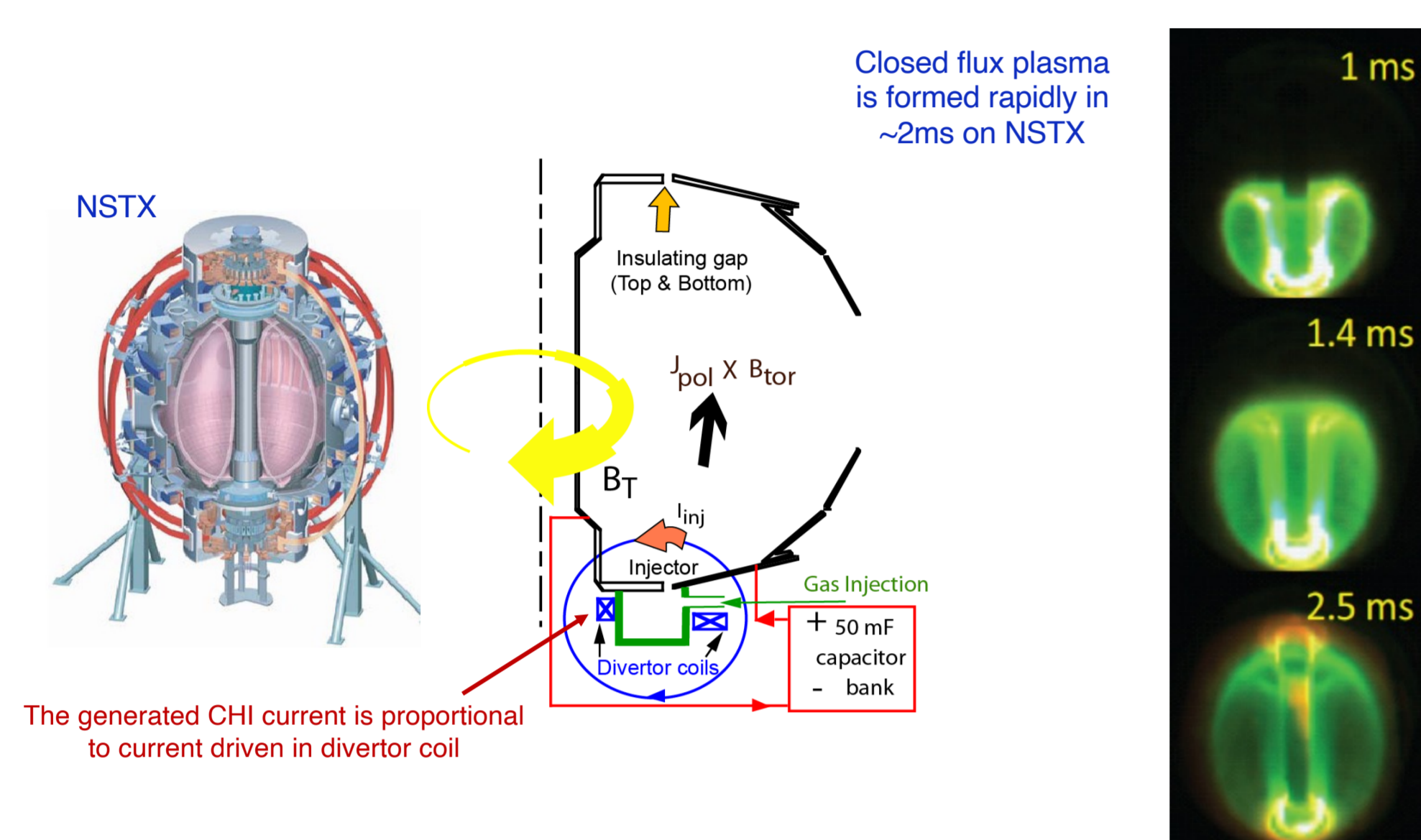
- It is a method to startup a tokamak plasma without using the solenoid

Why is it important?

- The scaling for high current plasma startup using t-CHI (for reactors) is well understood
- The method has now been shown to work well on three different STs of vastly different sizes and configurations (HIT-II, NSTX, QUEST). Now being implemented on Pegasus-III
- Reducing the size of the solenoid, or removing it, reduces aspect ratio making it smaller with less capital investment
- The solenoid is an inductive component, so it cannot be used to drive steady-state current in a tokamak plasma

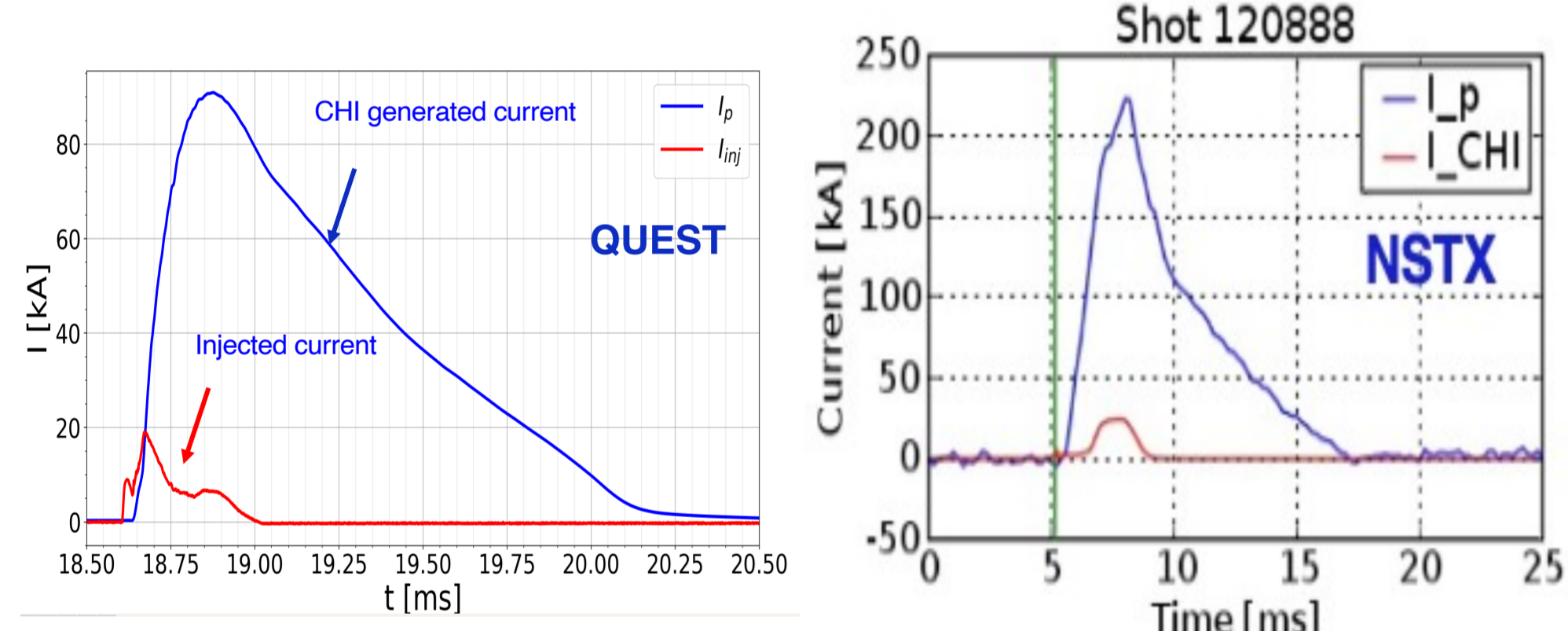
- Design studies show that a Low Aspect Ratio Tokamak needs some Solenoid Free Plasma Startup capability to increase electrical power generation while being tritium self-sufficient [J.E. Menard et al., NF 56 (2016) 106023]

How is a Transient CHI plasma generated?



- Voltage is applied to electrically insulated divertor plates connected by magnetic flux generated by the divertor coils
- The external driven power supply current (I_{inj}) on the field lines causes it to be injected into the vessel (like a soap bubble)
- The applied voltage is turned off after a few ms
- Axisymmetric global reconnection the injected magnetic flux leads to the formation of closed magnetic flux surfaces

Closed Flux Plasma Current Generation on QUEST & NSTX



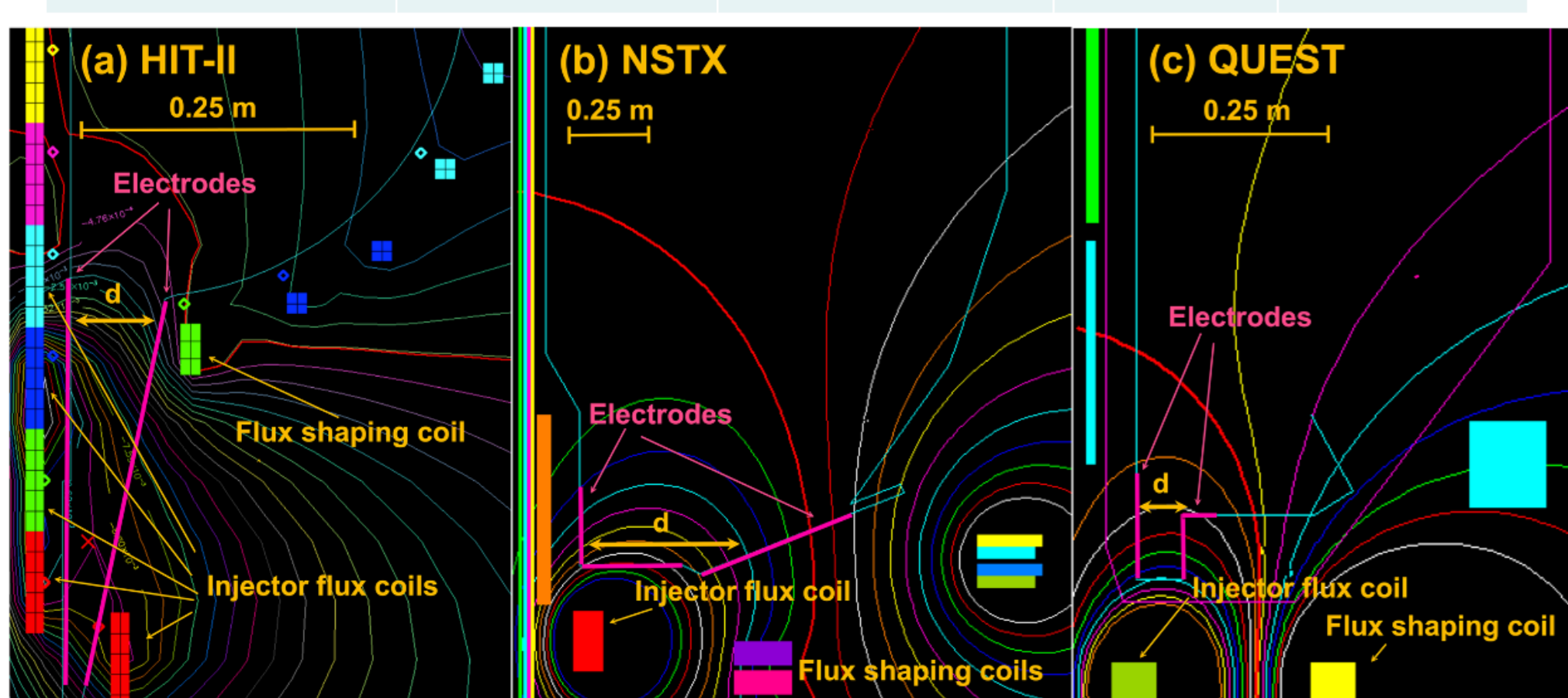
- The red trace shows the external power supply current
 - The blue trace shows the current produced by t-CHI
 - After the power supply current is zero, the CHI system is fully OFF. The current shown by the blue trace is the closed flux plasma current that then resistively decays in time
 - About 0.2 MA produced on NSTX and 0.1 MA on QUEST [8, 14, 15]
- R. Raman, B.A. Nelson, M.G. Bell, et al., Phys. Rev. Letters, **97**, 175002 (2006)
K. Kuroda, R. Raman, T. Onchi, et al., Nuclear Fusion (Letter) **64** (2024) 014002.

What has been accomplished so far?

- 1) It has been successfully tested on three different Spherical Tokamaks of vastly different size and configuration

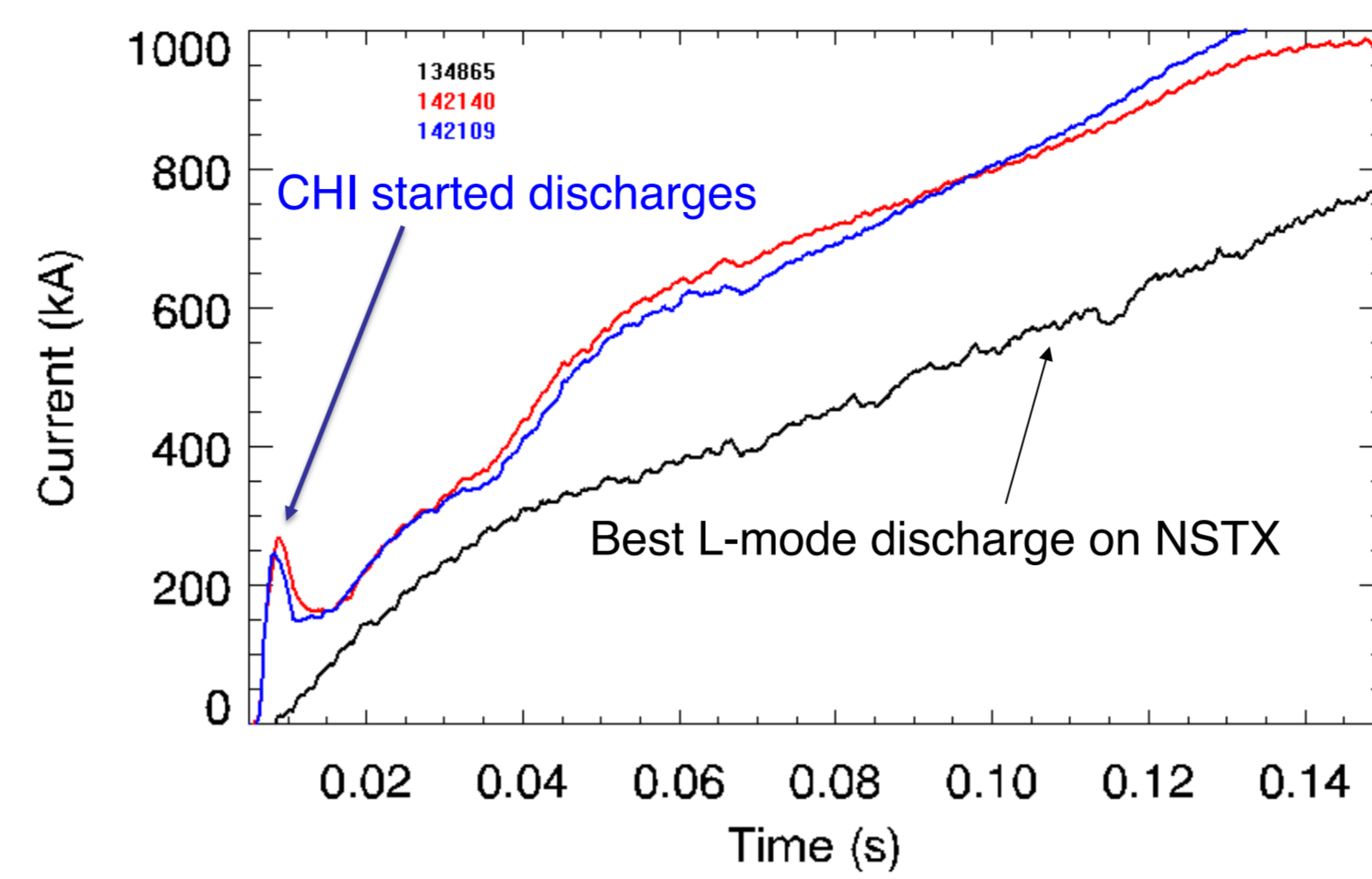
HIT-II (University of Washington)
NSTX (Princeton Plasma Physics Laboratory)
QUEST (Kyushu University)

Parameter	HIT-II	QUEST	NSTX	ST-FNSF
R_0 (m)	0.30	0.64	0.85	1.7
a (m)	0.20	0.40	0.68	1
$A = R_0/a$	1.5	1.6	1.25	1.7
B_0 (Tesla)	0.5	0.25	0.55	3
Electrode Config.	Closed Conical	Closed, 'U-shaped'	Open	Closed

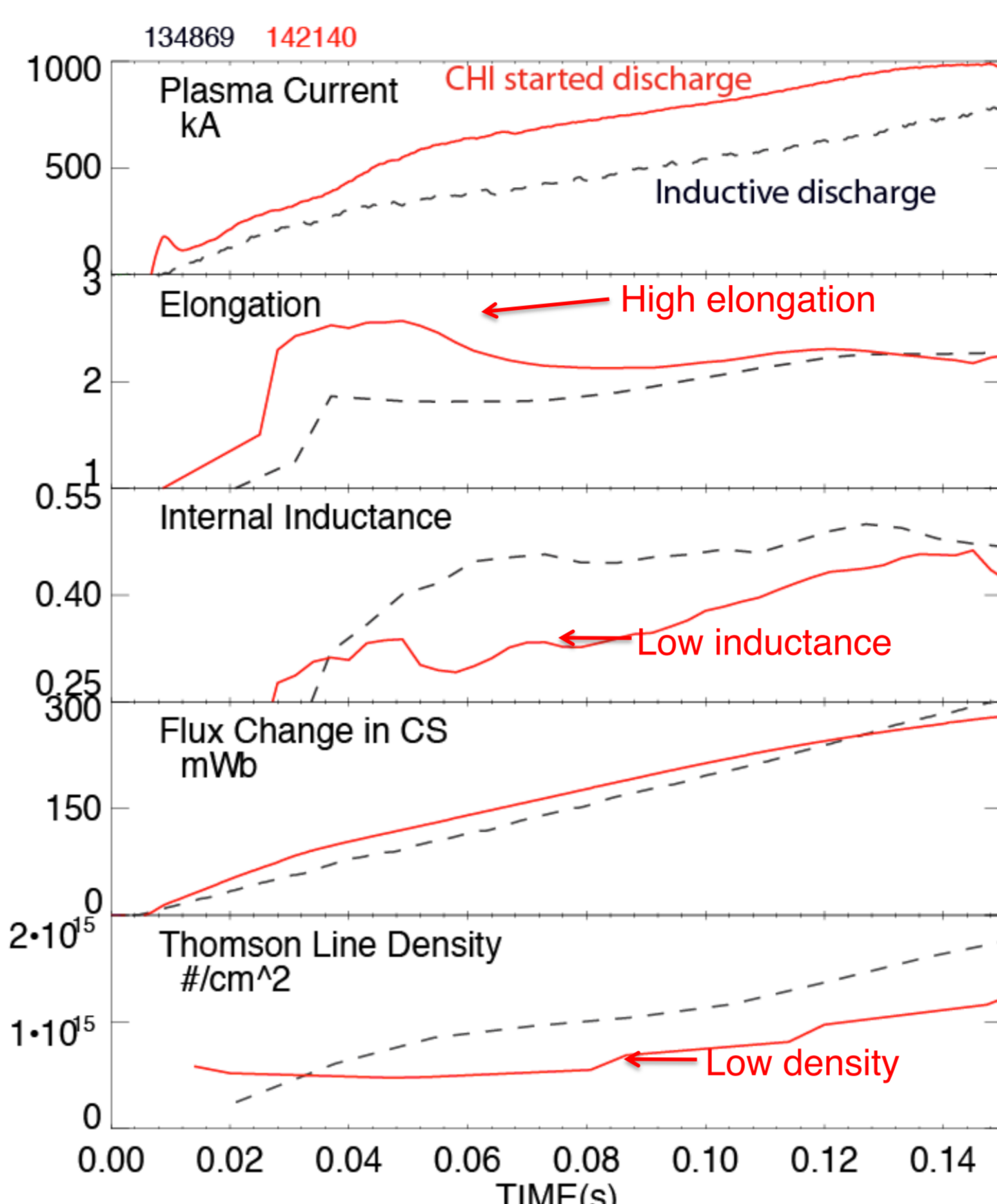


R. Raman, M. Ono, S.C. Jardin et al., PFCF **67** (2025) 095007

- 2) On NSTX L-Mode discharge ramps to 1MA requiring 50% more solenoid flux than a CHI started discharge

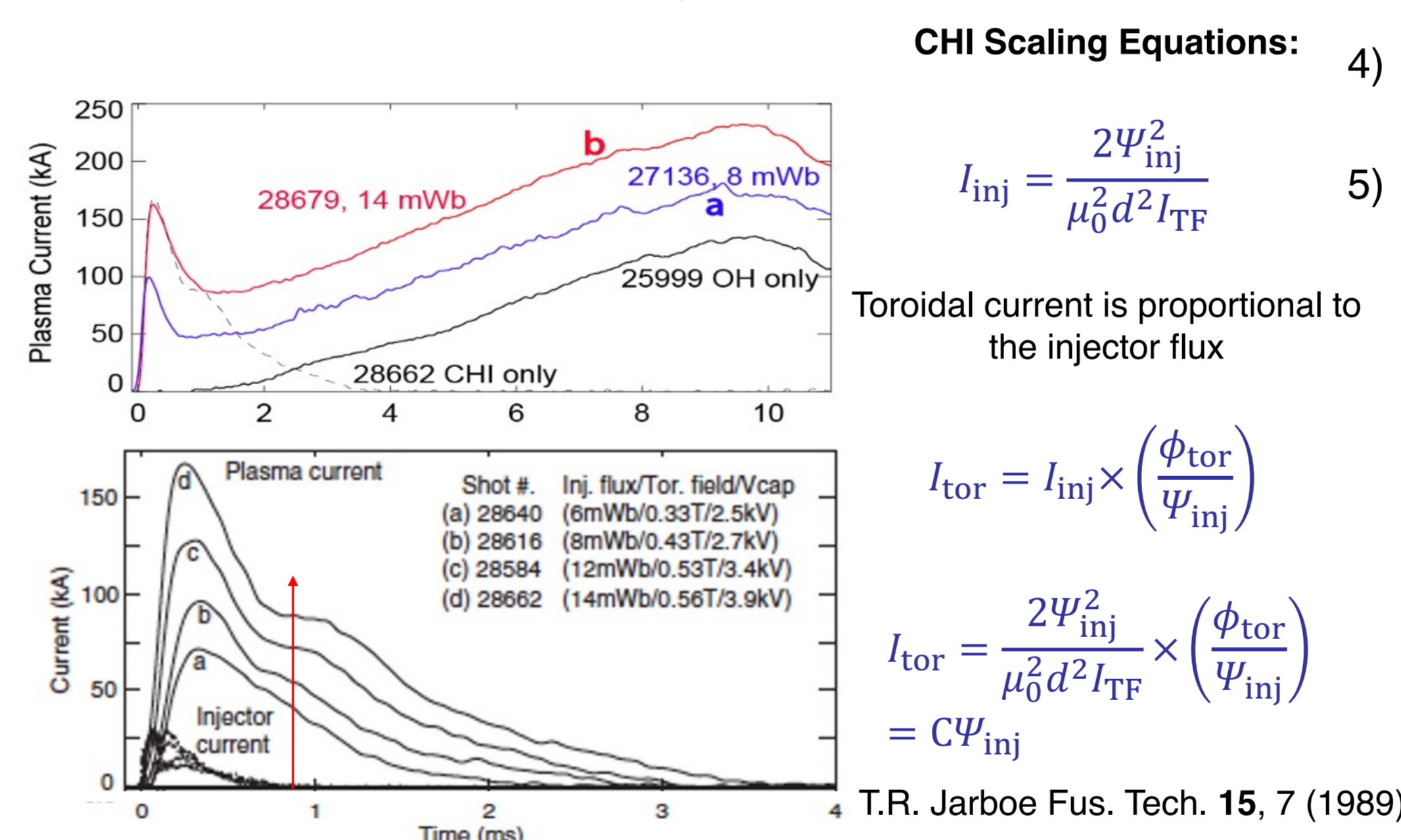


- 3) t-CHI discharge has profiles needed for Advanced Scenarios & for Non-Inductive Current Ramp-up



- t-CHI discharges have lower internal inductance, higher elongation, lower density, and can also be formed in a diverted configuration
- R. Raman, D. Mueller, T.R. Jarboe, et al., Phys. Plasmas **18**, 092504 (2011)

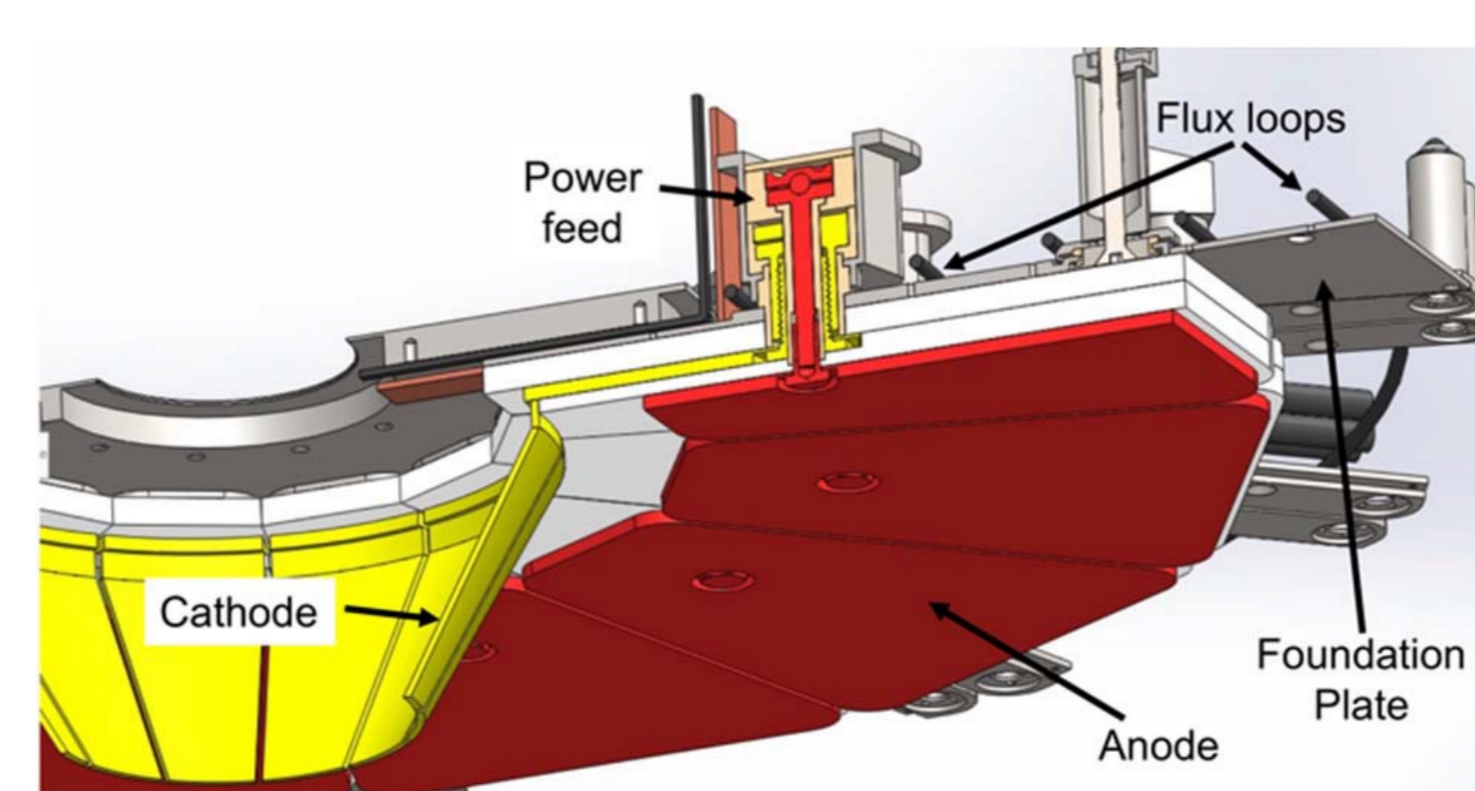
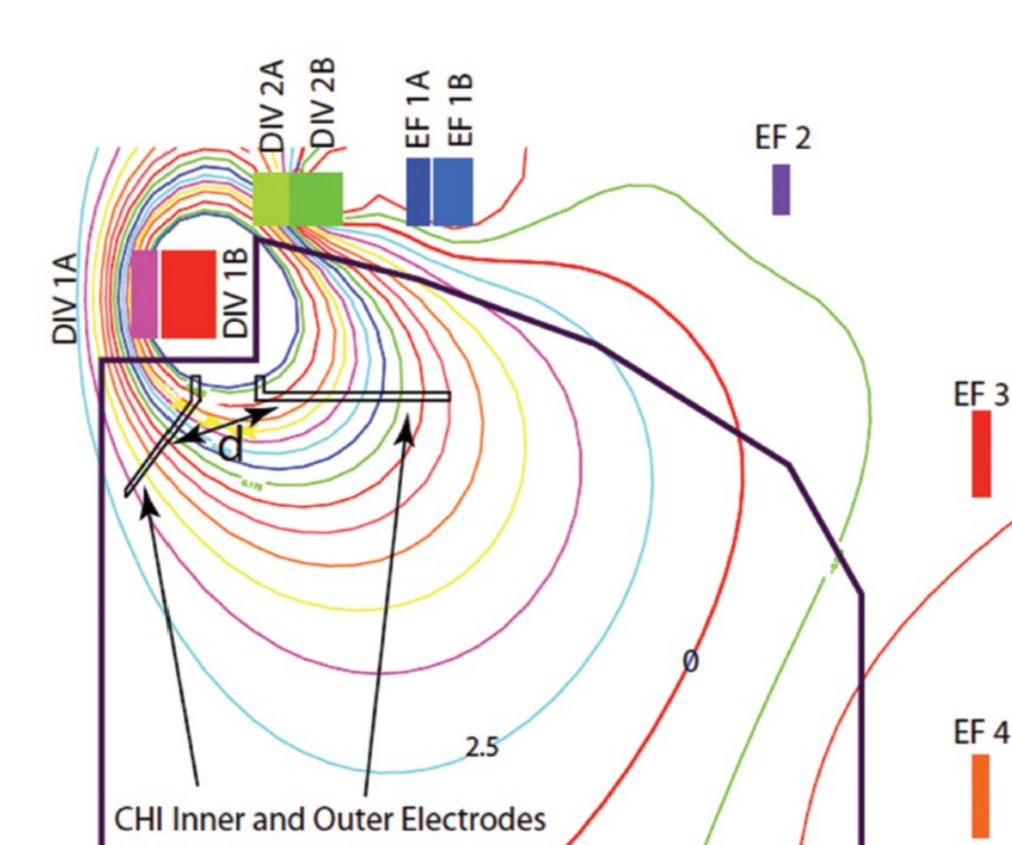
- 4) The CHI Current Generation Scaling is well understood. The Closed Flux Current increases with injector flux (i.e., the amount of current driven in the divertor coils)



- As injector flux in increases, the closed flux current increases [6, 8]
- Currents with higher closed flux ramp to proportionally higher final current with the same applied loop voltage (top frame)

R. Raman, T.R. Jarboe, R.G. O'Neill et al., Nucl. Fusion Lett. **45**, L15-L19 (2005).
R. Raman, T.R. Jarboe, B.A. Nelson, et al., Phys. Plasmas **11**, 2565 (2004).
K. Kuroda, R. Raman, T. Onchi, et al., Phys. Plasmas **32**, 0425506 (2025)

- 5) Pegasus-III will use a double biased electrode configuration

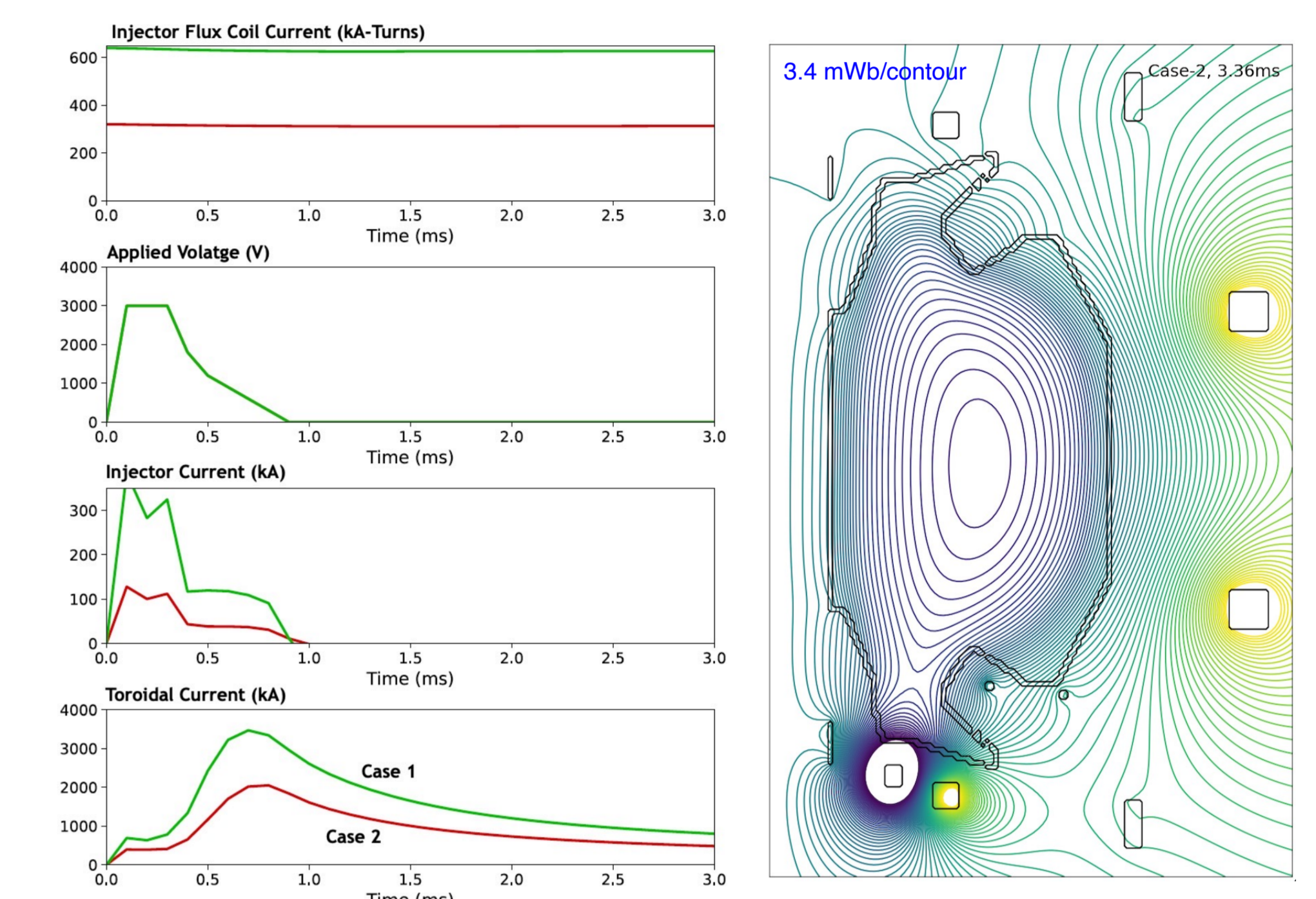


J. A. Reusch, R. Raman, et al., IEEE Trans. Plasma Science **50**, 4015 (2022)
R. Raman, K. Morgan, J.A. Reusch et al., Fusion Sci. Technol. **78**, 649 (2022)

What remains to be done?

- 1) The current generation scaling suggest the possibility of > 2 MA startup but extrapolation to that level would benefit from an intermediate level current startup demonstration
- 2) A test at about 0.5 MA current generation with transient CHI would reduce the extrapolation factor to about 2 to 3 for 1-2 MA current startup & provide a means to improve the ST-E1, STEP, STAR and FAST ST designs
- 3) Beyond that the possibility exists for several MA level current start-up

Conceptual design study for ST-40 indicates ~0.5 MA current generation potential (TSC simulations)



R. Raman, S. McNamara, M. Ono, et al., Design considerations for a transient CHI system for ST40, ISTW 2024, Oxford, UK, Oct. 21-24 (2024)

Possible Plan to increase the TRL Level of transient CHI start-up method from the present TRL of 5 to 6

- 1) Large scale demonstration of transient CHI on NSTX and QUEST places it at a TRL of 5
- 2) A 0.5 MA start-up on ST-40 would increase it TRL 6 (a prototype system)
- 3) A detailed design study for deploying a transient CHI system in ST40 is needed to assess the required modifications to the present ST40 vacuum vessel
- 4) The study should be detailed enough to estimate the cost and procurement time of the needed components
- 5) The study should also estimate the downtime for ST40 to install the needed components, the manpower needed, and the initial commissioning time

What are the scientific and engineering objectives?

- 1) 0.5 MA closed flux plasma startup (requires Li wall coatings)
- 2) Direct coupling of the transient CHI target to ECH or EBW current drive compared to a similar study with some inductive assist, and the achieved current profiles and plasma temperatures
- 3) How do the results from #3 impact the size of the solenoid needed in the ST-E1, STEP, STAR and FAST ST designs if those devices could benefit from 1 – 2 MA level current start-up using transient CHI?

Summary

- Transient CHI has generated 0.2 MA of closed flux current and when coupled to induction, ramps up to 1 MA with significant solenoid flux saving, including transitioning to H-mode discharges when neutral beams are injected
- QUEST has shown that a simple reactor-relevant biased electrode configuration can work just as well as the methods on NSTX and HIT-II that used toroidal vacuum insulators
- The plasma current scaling is simple and well understood
 - Plasma current is proportional to injector flux
 - Plasma current scaling supported by TSC and 3D resistive MHD simulations (NIMROD)
 - Plasma currents > 2 MA may be possible in a high-field ST reactor
 - Next-step experiments at 0.5 MA would significantly influence emerging reactor concepts such as ST-E1, STEP, STAR and FAST
 - ST40, which will be equipped with Li-wall coatings and high-power gyrotron is ideally positioned to carry out the needed studies that would increase the TRL of transient CHI from the present level of 5 to 6