CHI Injector Scalings in a Spherical Tokamak

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Summary

- Empirical scaling studies for CHI injector current $I_{\rm INJ}$ and toroidal plasma current I_p have been conducted on the Helicity Injected Torus (HIT–II) device. Extensive scans over:
  - Injector flux $\psi_{\rm INJ}$
  - TF current $I_{\rm TF}$
  - Effective inter-electrode distance d
- Experimentally, found that:
  - $I_{\rm INJ}$ and I_p scale as expected with $\psi_{\rm inj}$ and $I_{\rm TF}$. I_p is independent of $I_{\rm TF}$!
  - Injector geometry: Two classes of CHI discharges:
    - If d is large compared to a, the injector impedance is non-dynamic, suggesting resistive current sheet
    - If d is small, then impedance is dynamic
- Poloidal wall current is significant.
- There is an optimum injector flux geometry.

Model for ST CHI Discharges

- A CHI discharge remains in the injector unless the injector current passes a threshold:
  the bubble-burst current.

- Above bubble-burst, the injector flux is drawn into the confinement region, and the steady-state injector current will be clamped to the bubble-burst value.

- For large A, this bubble-burst I_{inj} is

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

  where χ is a dimensionless number, ψ_{inj} is the injector flux, d is the inter-electrode distance, and I_{TF} is the current generating the TF.

- References:
  Jarboe, *Fusion Technology* **15**, 7 (1989), and
  Nelson *et al.*, *Nuclear Fusion* **34**, 1111 (1994)

Model for ST CHI Discharges

- CHI-generated plasma is assumed to be force-free:

$$\nabla \times \vec{B} = \lambda \vec{B}$$

- Define λ for the injector and tokamak regions:

$$\lambda_{\rm inj} \equiv \frac{\mu_0 I_{\rm inj}}{\psi_{\rm inj}} \quad \text{and} \quad \lambda_{\rm tok} \equiv \frac{\mu_0 I_p}{\psi_{\rm TF}}$$

- Assume that $I_{\rm inj}$ is equal to bubble-burst, and that

$$\lambda_{\rm inj} = \lambda_{\rm tok}$$

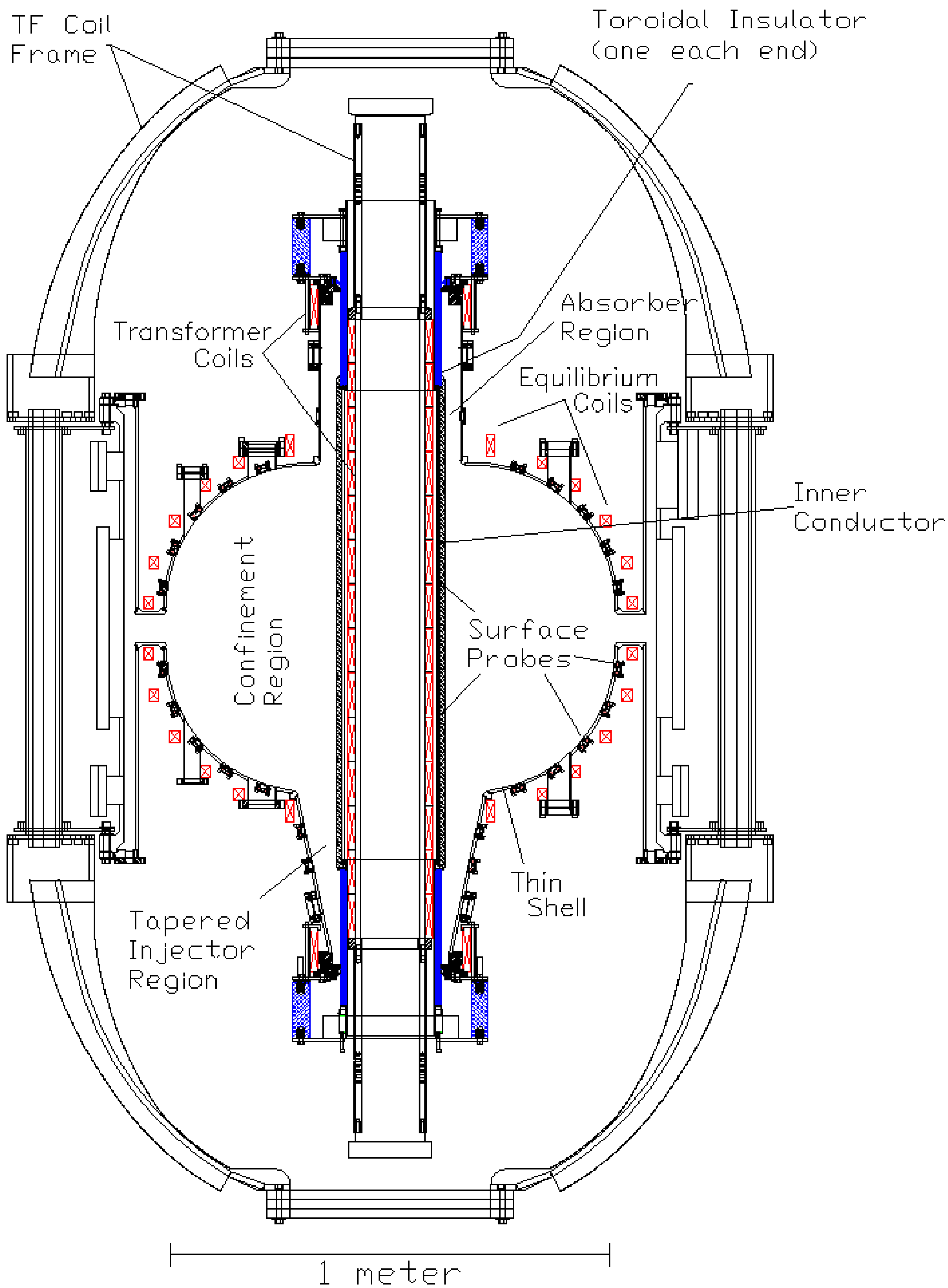
  Then, the CHI-driven plasma current is

$$I_p = \left(\frac{\chi^2 S_{\rm TF}}{\mu_0}\right)\left(\frac{\psi_{\rm INJ}}{d^2}\right)$$

  where $S_{\rm TF}$ is a parameter with units of length, determined by the geometry of the device

- So, from these arguments, we expect:
  - Injector current proportional to $\psi_{\rm inj}^2$ and $1/I_{\rm TF}$
  - Plasma current independent of $I_{\rm TF}$, but proportional to $\psi_{\rm inj}$

The HIT–II Spherical Torus



The HIT–II Spherical Torus

- HIT–II Engineering Parameters:

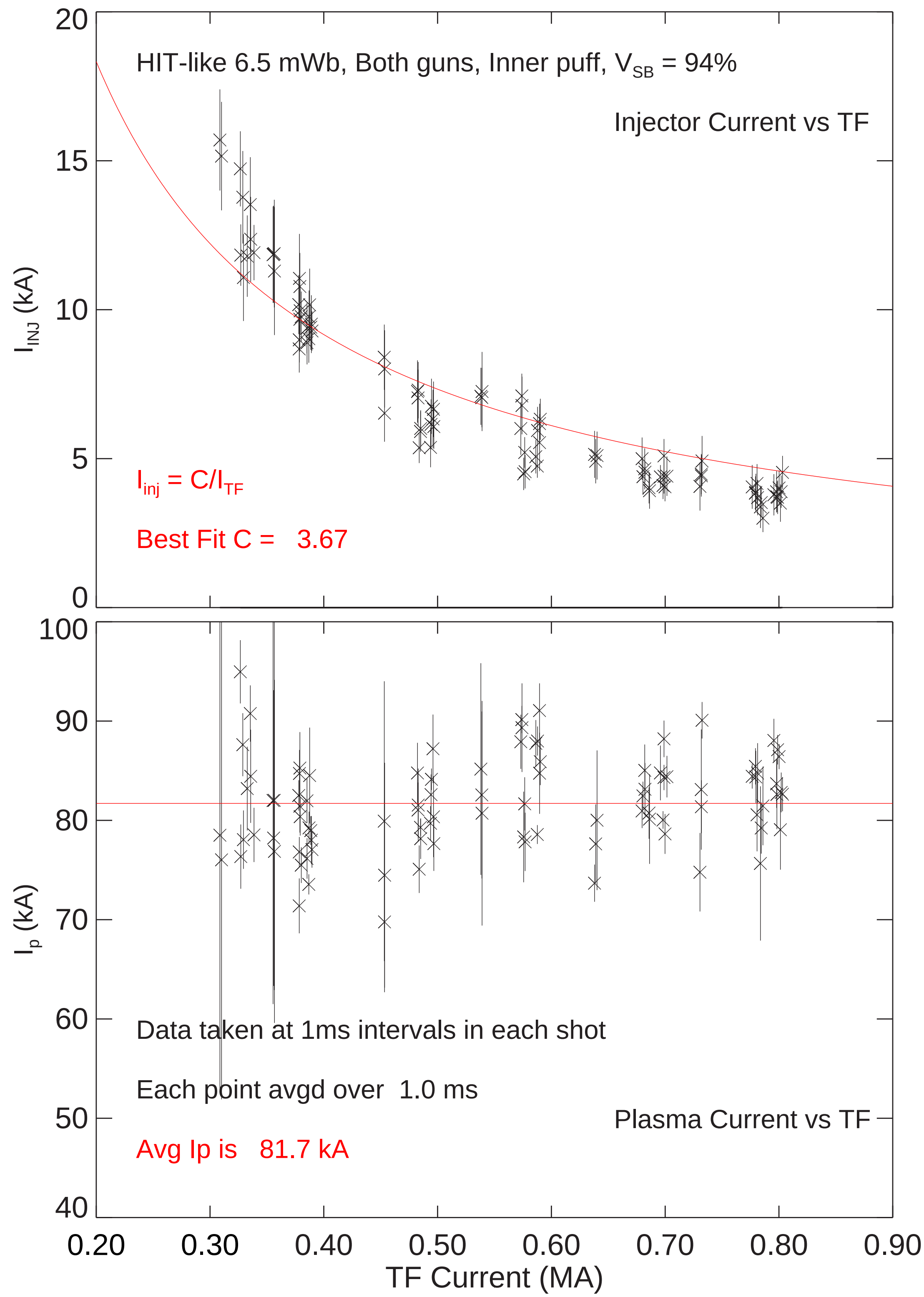
Major Radius R	0.3 m
Minor Radius a	0.2 m
Aspect Ratio A	1.5
Elongation κ	1.75
Ohmic Flux Available	60 mWb

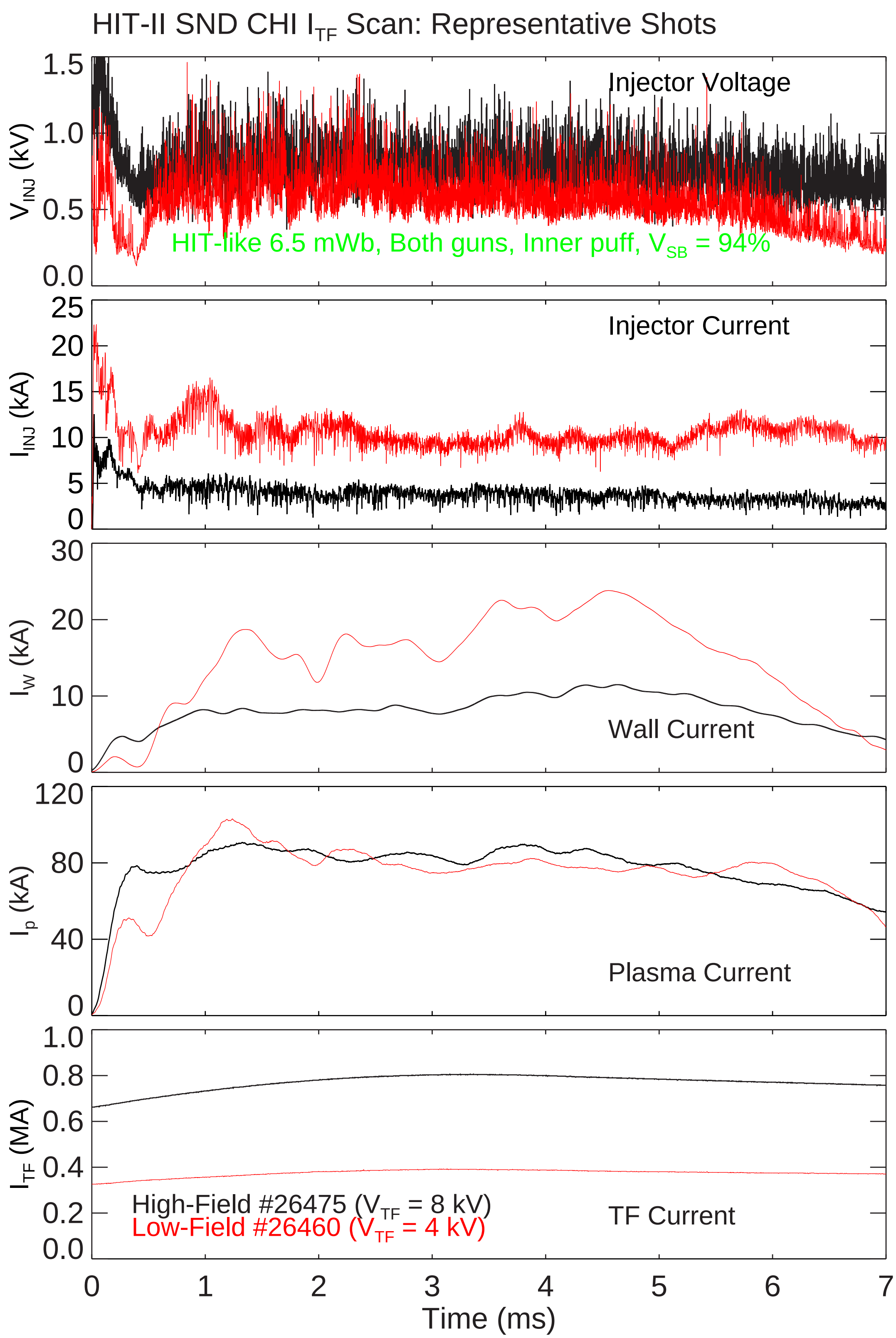
- HIT–II Achieved Plasma Parameters:

Parameter	Ohmic	CHI	CHI Startup
Pulse Length	60 ms	25 ms	40 ms
Peak Current	240 kA	240 kA	290 kA
Density $\bar{n}_e$	$\leq 5\times10^{19}$ m^{-3}	1–6$\times10^{19}$ m^{-3}	$\leq 5\times10^{19}$ m^{-3}

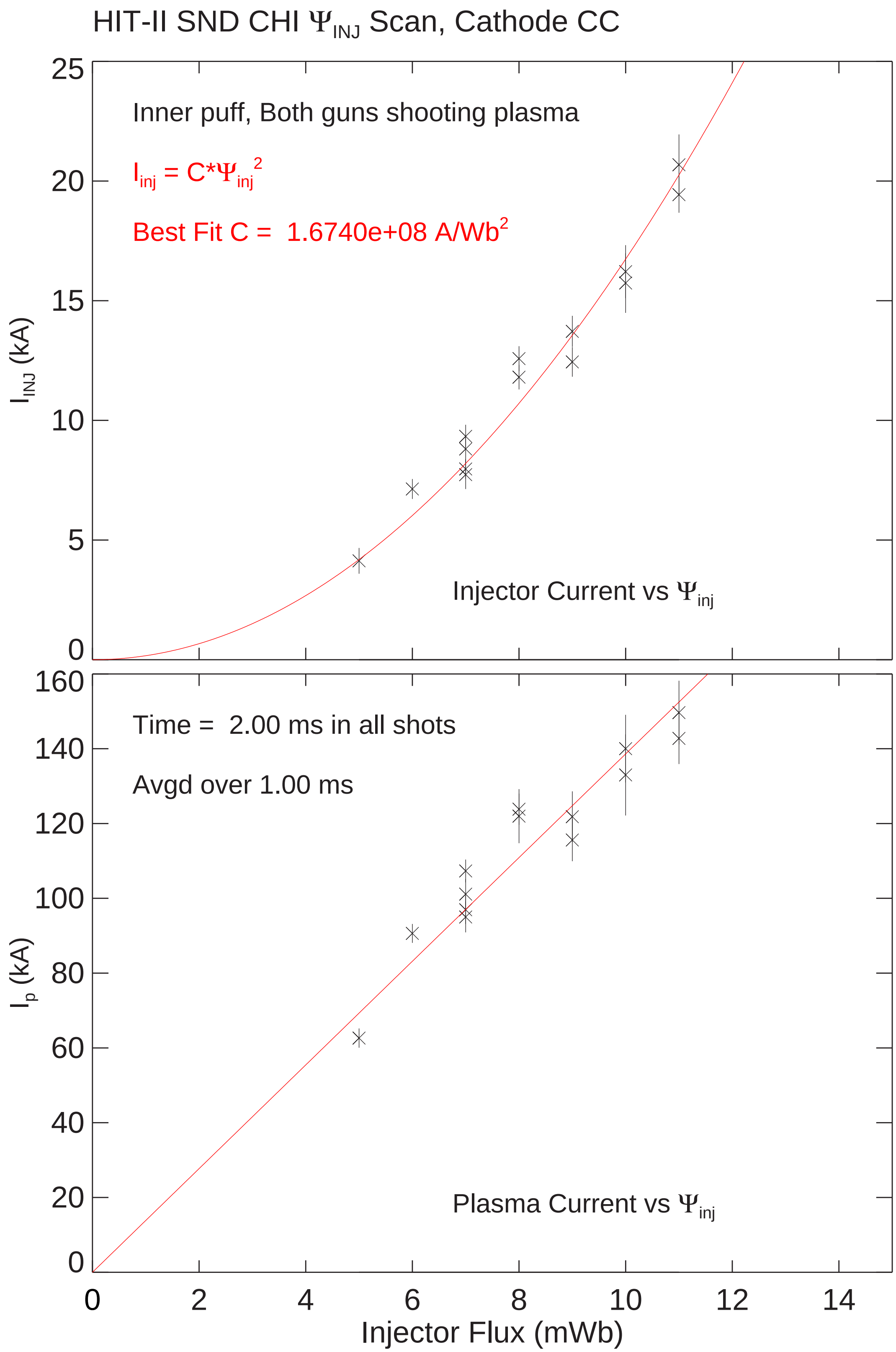
- HIT diagnostics include:
  - Multi-point Thomson Scattering
  - Scannable two-chord FIR interferometer
  - Scannable single-chord 16-channel Ion Doppler Spectrometer
  - Multi-chord soft X-ray (SXR) camera
  - Pair of vacuum-UV (VUV) spectrometers (OVI/OV ratio)
  - Single-chord average-Z_{eff} measurement
  - H-α visible light detectors
  - Surface magnetic triple probes (poloidal wall current)
  - Bolometer (total radiation emission)
  - Internal magnetic and Langmuir probes
  - SPRED
  - Transient Internal Probe (TIP)

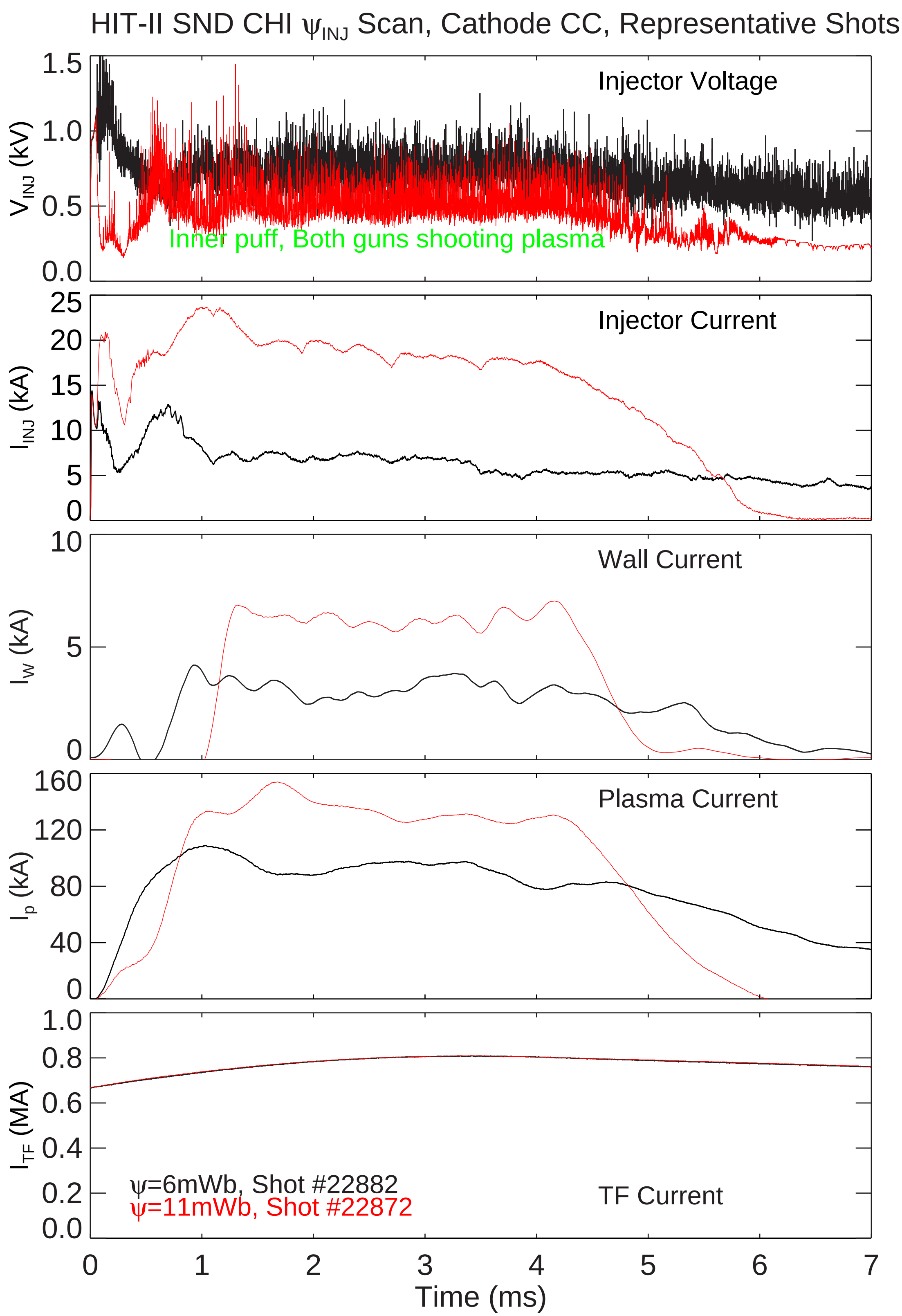
I_p is Independent of I_{TF}

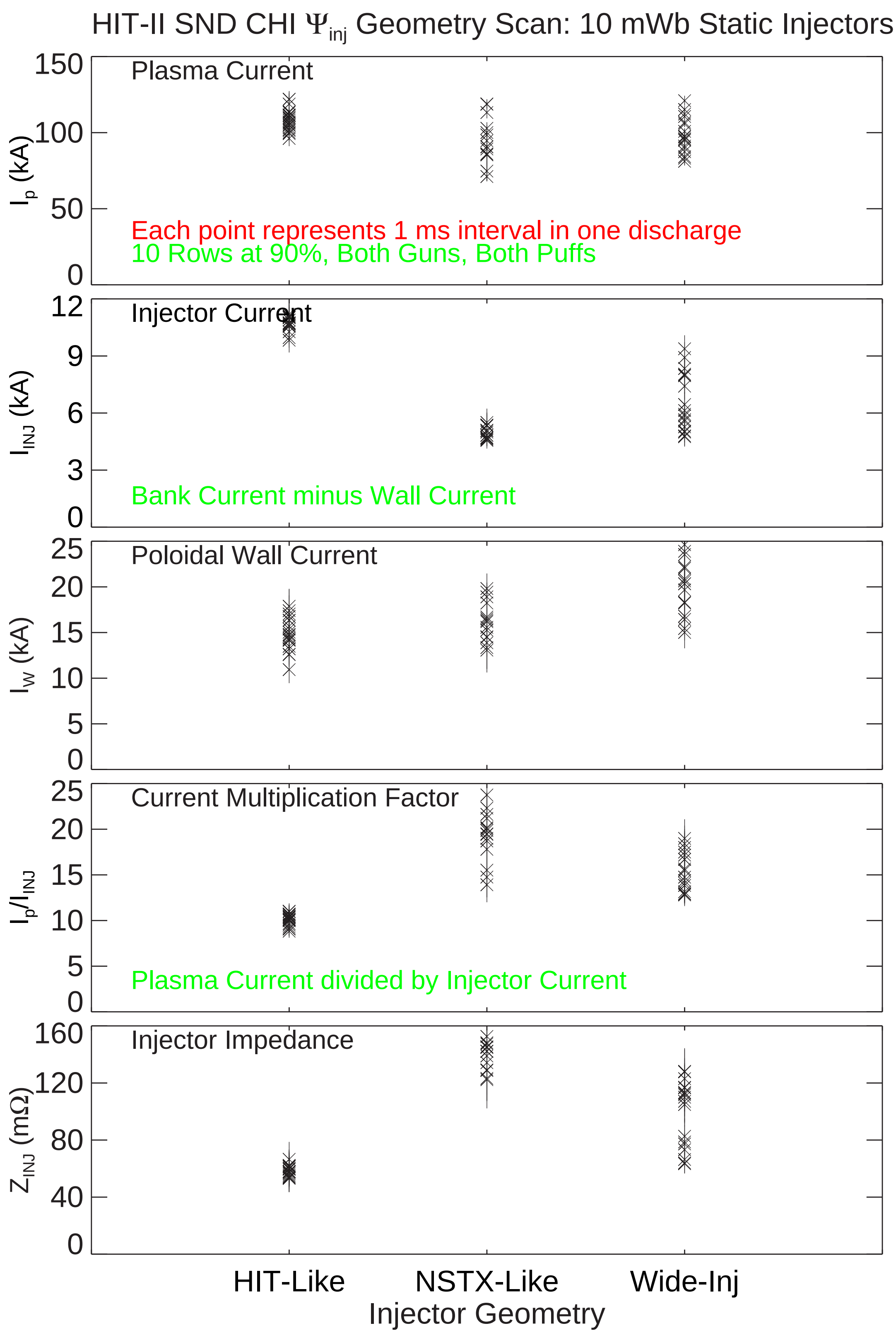




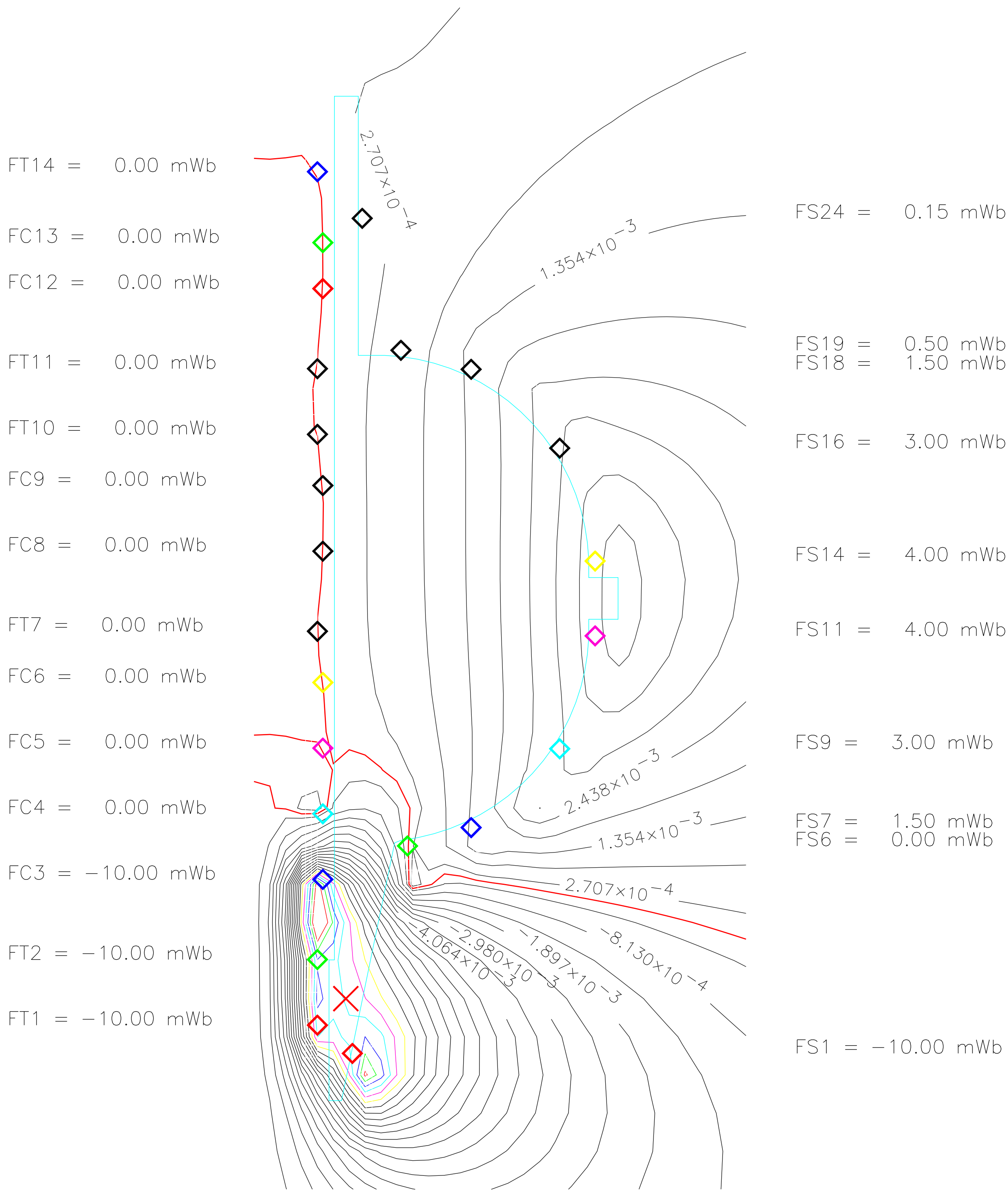
HIT-II SND CHI I_TF Scan: Representative Shots
Injector Voltage
V_INJ (kV)
1.5
1.0
0.5
0.0
HIT-like 6.5 mWb, Both guns, Inner puff, V_SB = 94%
Injector Current
I_INJ (kA)
25
20
15
10
5
0
30
20
10
0
I_W (kA)
Wall Current
120
80
40
0
I_p (kA)
Plasma Current
1.0
0.8
0.6
0.4
0.2
0.0
I_TF (MA)
High-Field #26475 (V_TF = 8 kV)
Low-Field #26460 (V_TF = 4 kV)
TF Current
0
1
2
3
4
5
6
7
Time (ms)

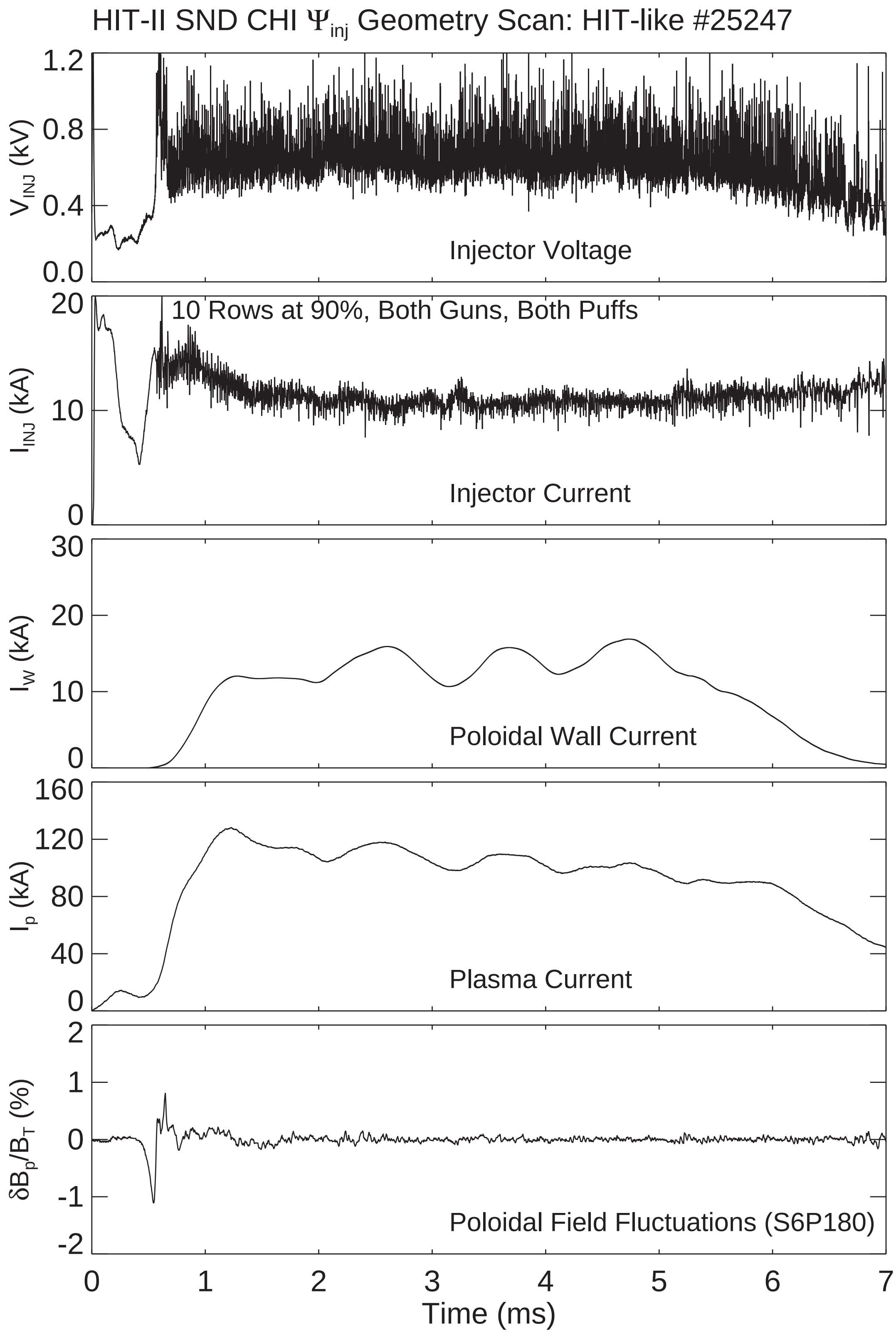

HIT-II SND CHI Ψ_INJ Scan, Cathode CC
Inner puff, Both guns shooting plasma
I_inj = C*Ψ_inj^2
Best Fit C = 1.6740e+08 A/Wb^2
Injector Current vs Ψ_inj
I_INJ (kA)
25
20
15
10
5
0
Time = 2.00 ms in all shots
Avgd over 1.00 ms
Plasma Current vs Ψ_inj
I_p (kA)
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
Injector Flux (mWb)


HIT-II SND CHI ψINJ Scan, Cathode CC, Representative Shots
Injector Voltage
VINJ (kV)
Inner puff, Both guns shooting plasma
Injector Current
IINJ (kA)
Wall Current
IW (kA)
Plasma Current
Ip (kA)
ITF (MA)
ψ=6mWb, Shot #22882
ψ=11mWb, Shot #22872
TF Current
Time (ms)

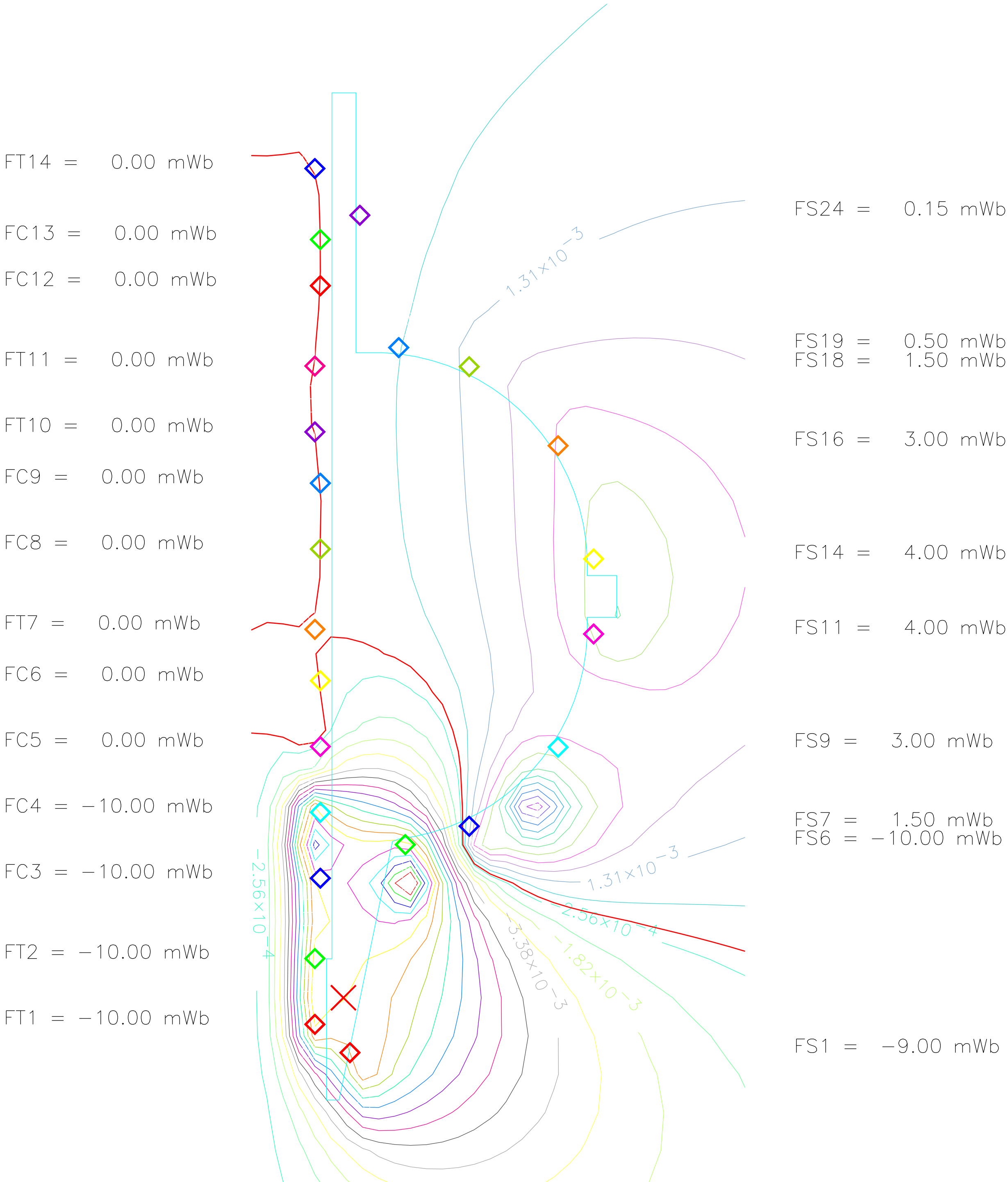

HIT-II SND CHI Ψinj Geometry Scan: 10 mWb Static Injectors
Plasma Current
Ip (kA)
Each point represents 1 ms interval in one discharge
10 Rows at 90%, Both Guns, Both Puffs
Injector Current
IINJ (kA)
Bank Current minus Wall Current
Poloidal Wall Current
IW (kA)
Current Multiplication Factor
Ip/IINJ
Plasma Current divided by Injector Current
Injector Impedance
ZINJ (mΩ)
HIT-Like
NSTX-Like
Wide-Inj
Injector Geometry

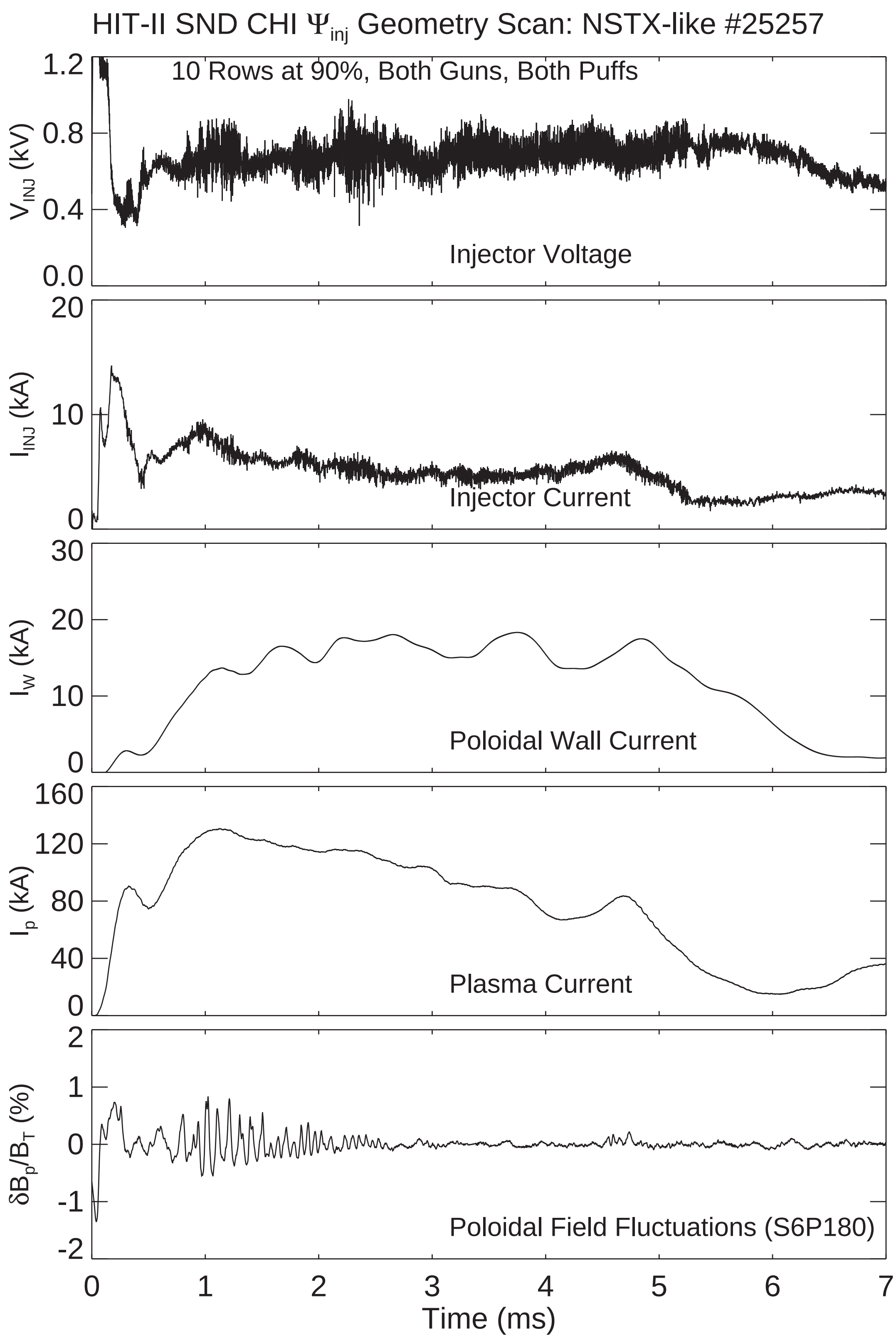
“HIT-like” Vacuum Flux



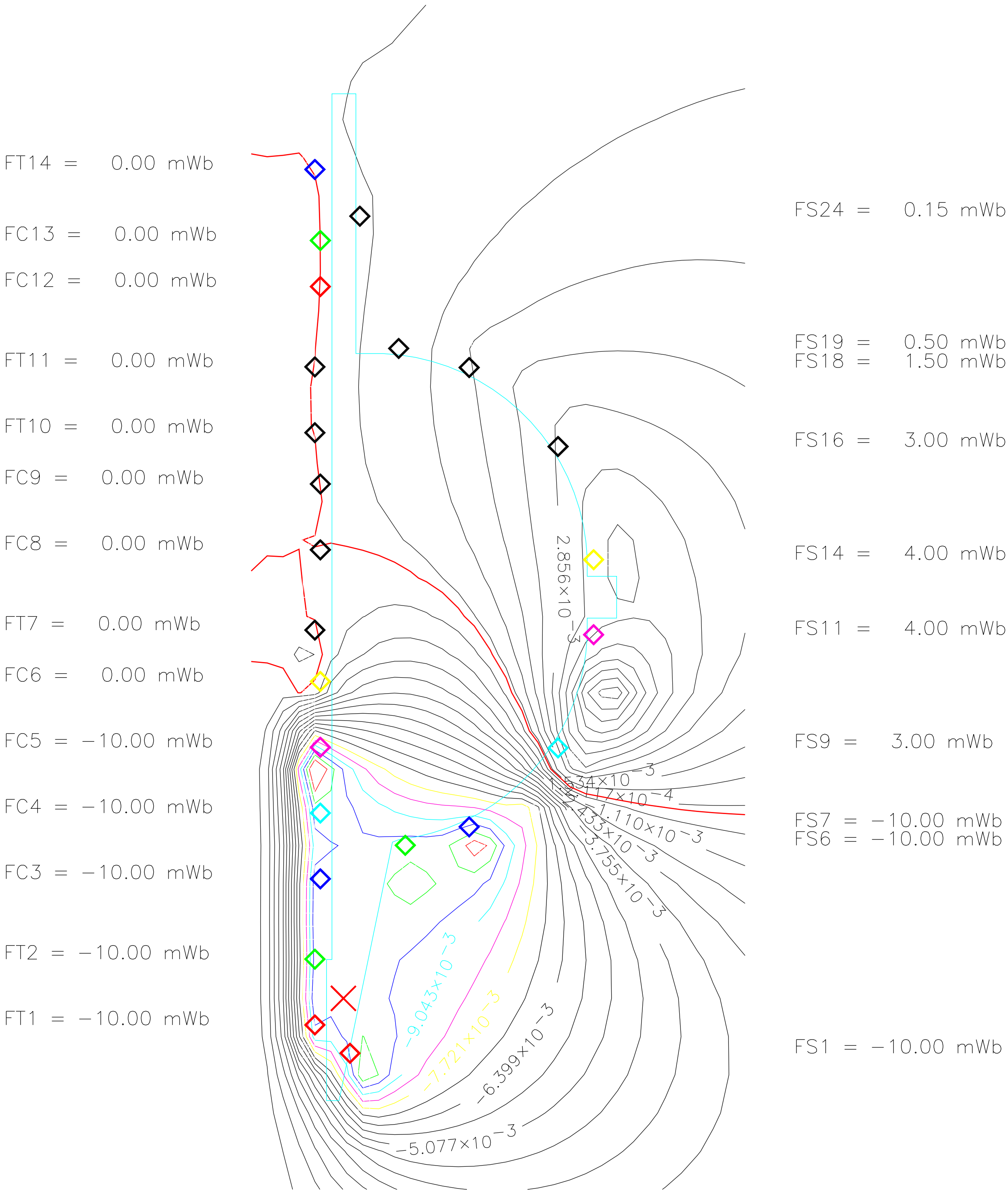

HIT-II SND CHI Ψinj Geometry Scan: HIT-like #25247
VINJ (kV)
Injector Voltage
10 Rows at 90%, Both Guns, Both Puffs
IINJ (kA)
Injector Current
IW (kA)
Poloidal Wall Current
Ip (kA)
Plasma Current
δBp/BT (%)
Poloidal Field Fluctuations (S6P180)
Time (ms)

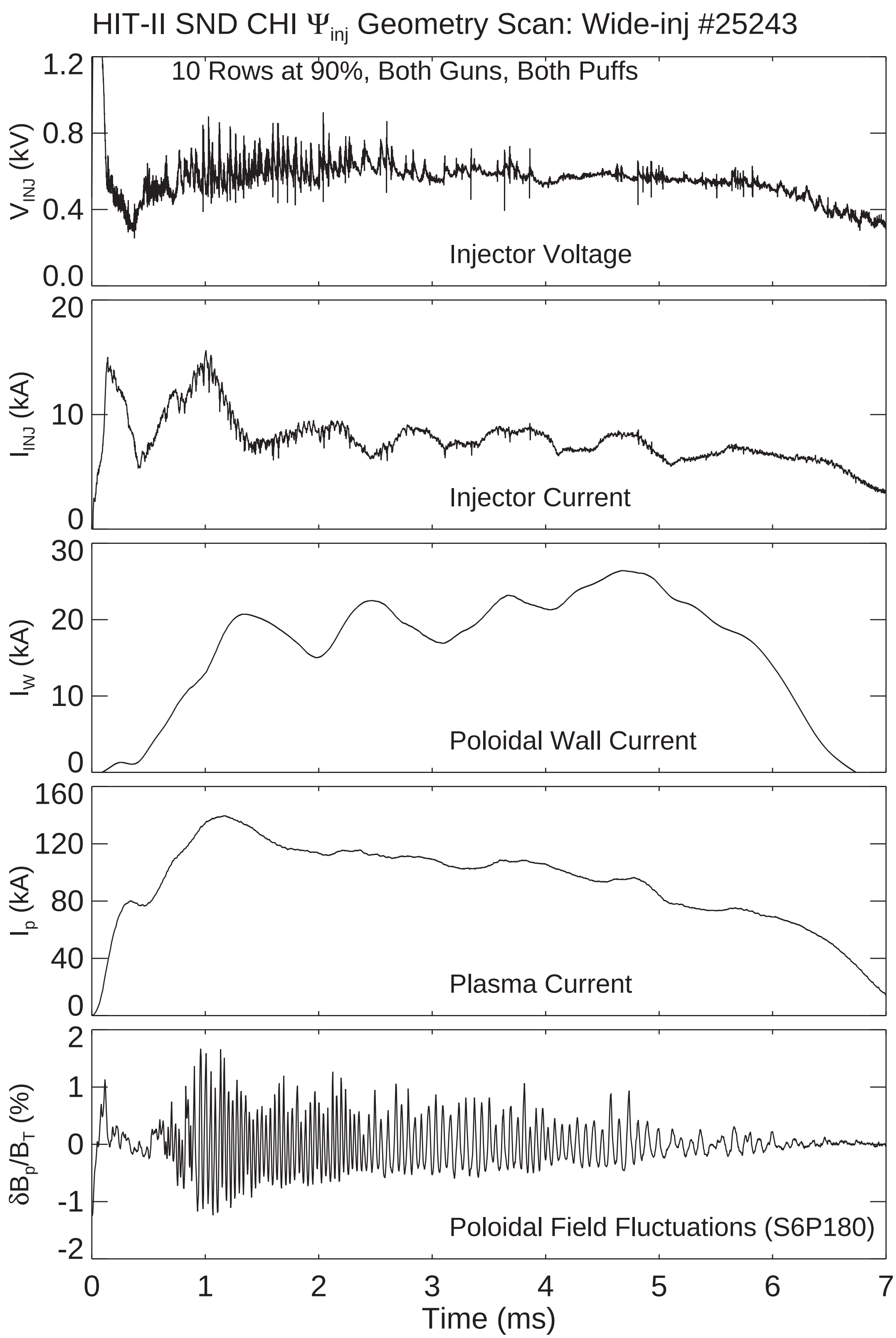
"NSTX-like" Vacuum Flux




HIT-II SND CHI Ψinj Geometry Scan: NSTX-like #25257
10 Rows at 90%, Both Guns, Both Puffs
VINJ (kV)
1.2
0.8
0.4
0.0
Injector Voltage
IINJ (kA)
20
10
0
Injector Current
IW (kA)
30
20
10
0
Poloidal Wall Current
Ip (kA)
160
120
80
40
0
Plasma Current
δBp/BT (%)
2
1
0
-1
-2
Poloidal Field Fluctuations (S6P180)
0
1
2
3
4
5
6
7
Time (ms)

“Wide-Injector” Vacuum Flux




HIT-II SND CHI Ψinj Geometry Scan: Wide-inj #25243
10 Rows at 90%, Both Guns, Both Puffs
V_INJ (kV)
Injector Voltage
I_INJ (kA)
Injector Current
I_W (kA)
Poloidal Wall Current
I_p (kA)
Plasma Current
δB_p/B_T (%)
Poloidal Field Fluctuations (S6P180)
Time (ms)

Significance for CHI on NSTX

- Improving CHI plasma performance:
  - Use the optimum injector flux geometry.
  - I_{TF} and ψ_{INJ} chosen to optimize I_p and/or I_{INJ} within experimental constraints (*e.g.*, injector power supply)
  - Poloidal wall current measurement may be needed
- Appearance of dynamic CHI discharges:
  - Previously, NSTX CHI plasmas have been in the wide-injector configuration (resistive, rather than dynamic impedance).
  - With improved absorber and coils, NSTX should now be able to form and sustain CHI plasmas with a narrower injector (and a dynamic impedance).
  - Significant amounts of closed flux are only expected in CHI plasmas with dynamic impedance.

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