Evidence for Magnetic Relaxation in Coaxial Helicity Injection Discharges in the HIT–II Spherical Torus

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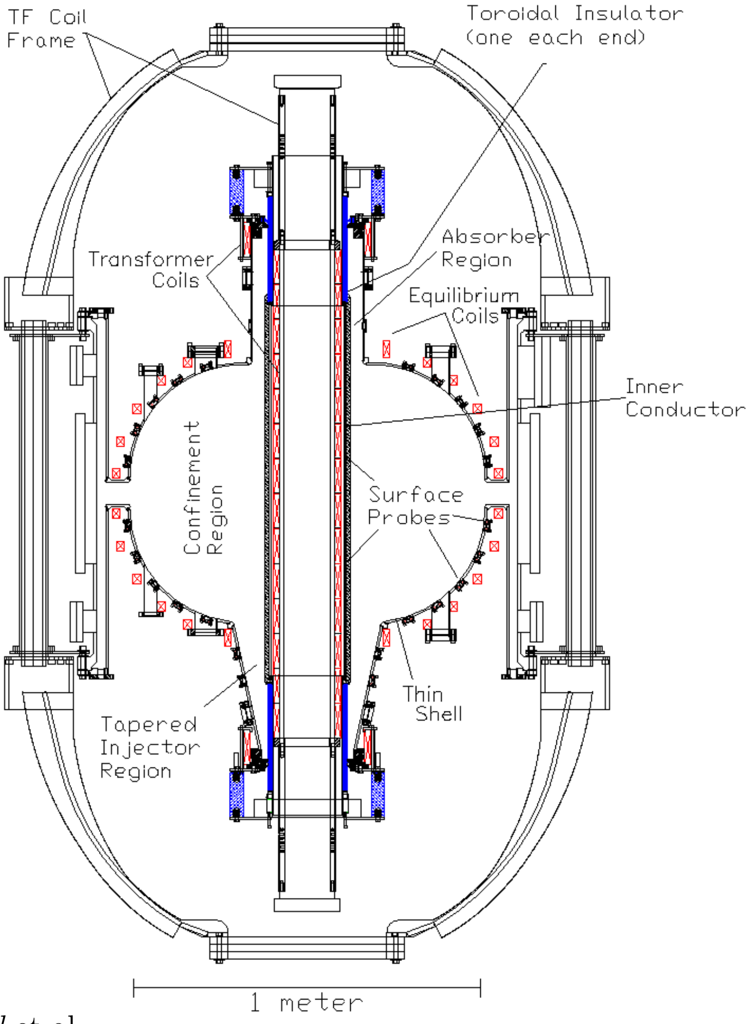
Summary

- New Coaxial Helicity Injection (CHI) regime on HIT–II
  - Toroidal plasma current I_p over 350 kA
  - I_p greater than I_{TF} in some discharges ($\leq 120\%$)
  - I_p can be up to 6 times the wrap-up current $q_a I_{\mathrm{INJ}}$
  - Internal magnetic measurements show:
    - Poloidal flux build-up and closed-flux core formation
    - Strongly paramagnetic at low TF
- Further CHI studies can be done using other STs:
  - Scaling relationship exists for the CHI injector current
  - Empirically, there is a threshold value of $\lambda_{\mathrm{INJ}} d$ for significant current and flux build-up

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 $\kappa = 1.75$
60 mWb Ohmic Flux Available

Active poloidal-flux boundary feedback control system (response time < 1 ms)

The HIT–II Spherical Torus

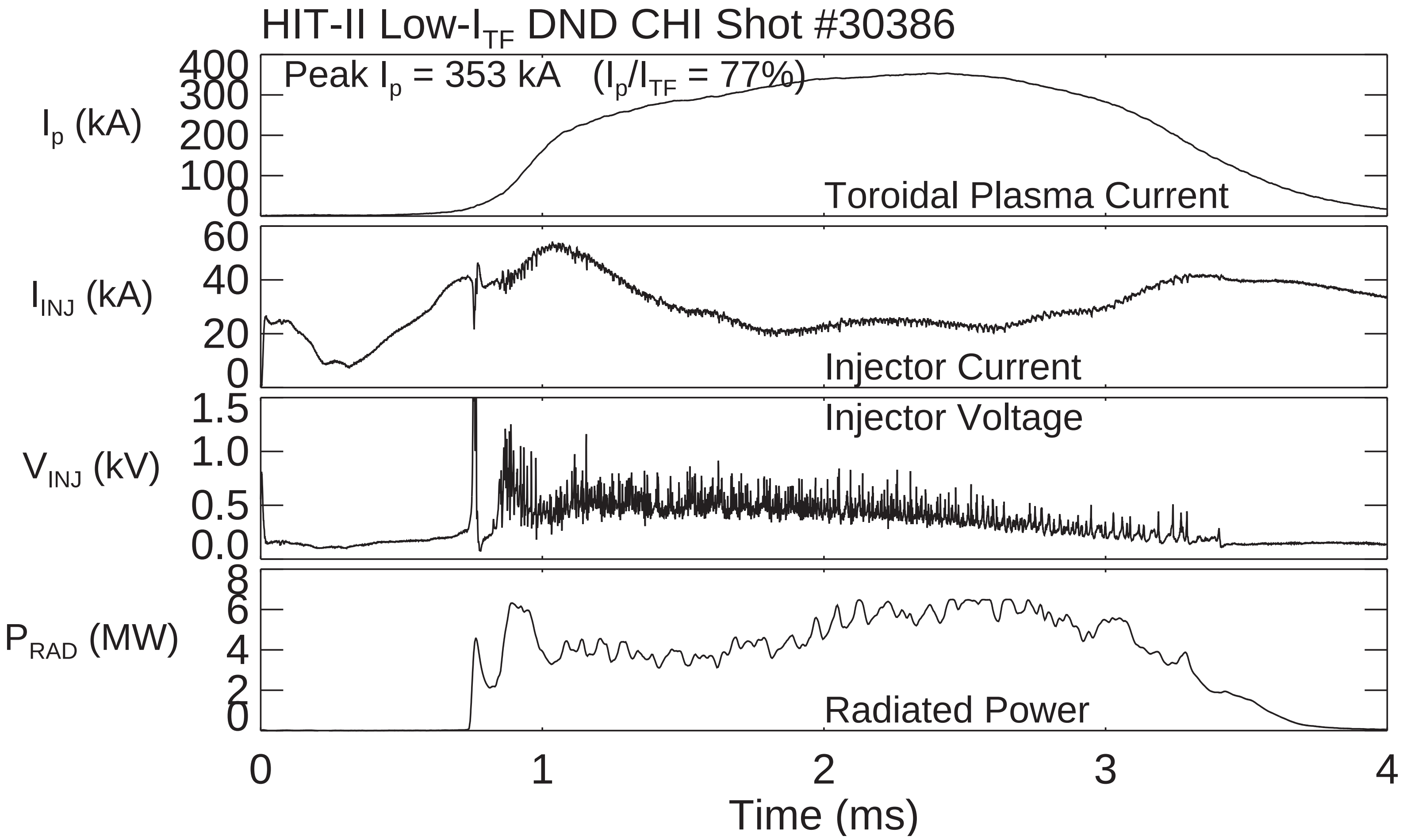
HIT–II plasma parameters achieved:

	Ohmic	CHI	CHI Startup
Pulse Length	60 ms	25 ms	40 ms
Peak Current	300 kA	350 kA	300 kA
Density $\bar{n}_e$	$\leq 5\times10^{19}$ m^{-3}	1–10$\times10^{19}$ m^{-3}	$\leq 5\times10^{19}$ m^{-3}

HIT diagnostic systems include:

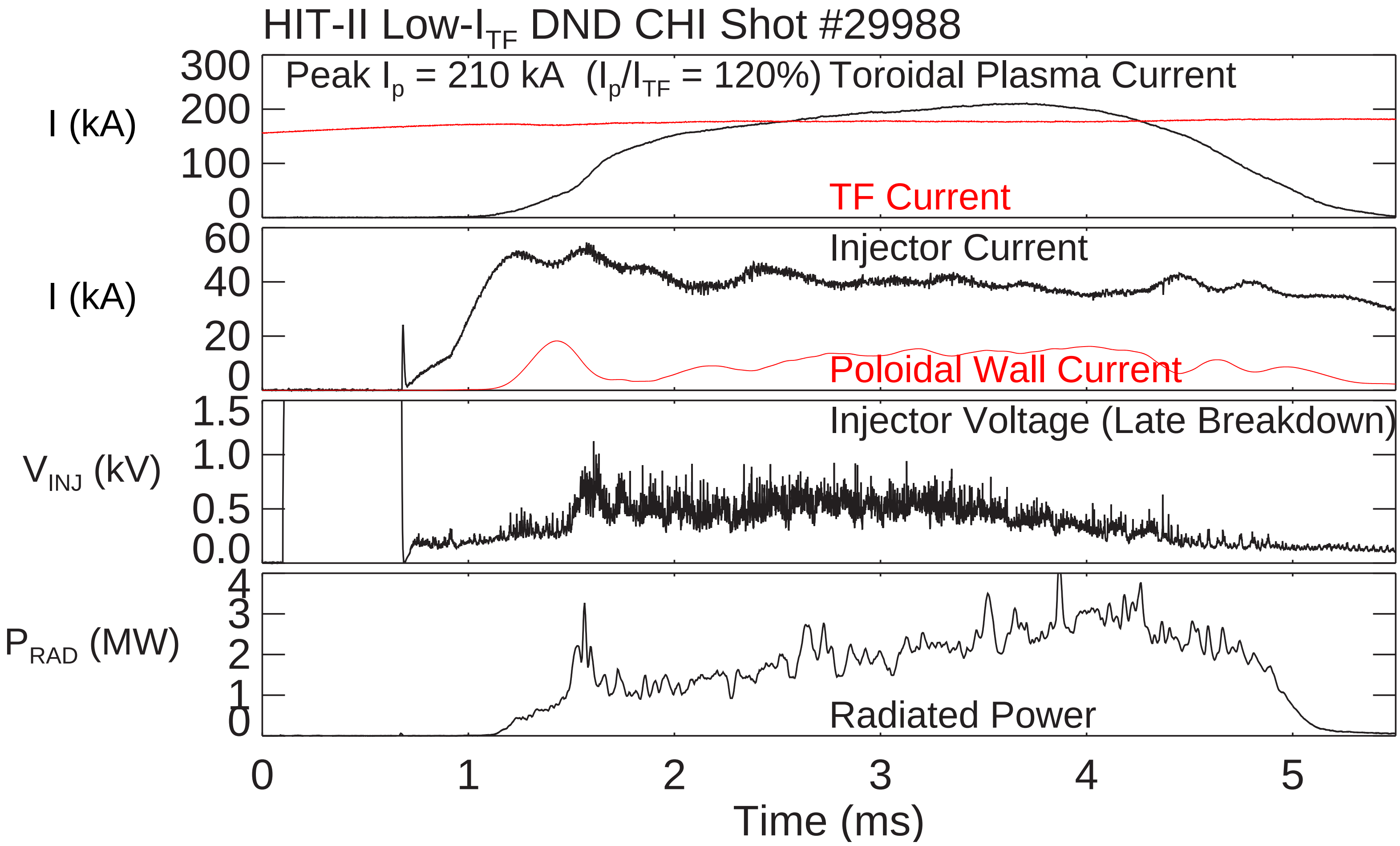
- Internal magnetic and Langmuir probes
- Scannable two-chord FIR interferometer
- 16-channel Ion Doppler Spectrometer, scannable single-chord
- Multi-point Thomson Scattering
- Pair of VUV spectrometers (OVI/OV ratio)
- H-α visible light detectors
- Surface magnetic triple probes
- Bolometer (total radiated power)
- SPRED
- Single-chord $\bar{\mathrm{Z}}_{\mathrm{eff}}$ measurement

CHI-driven I_p up to 353 kA



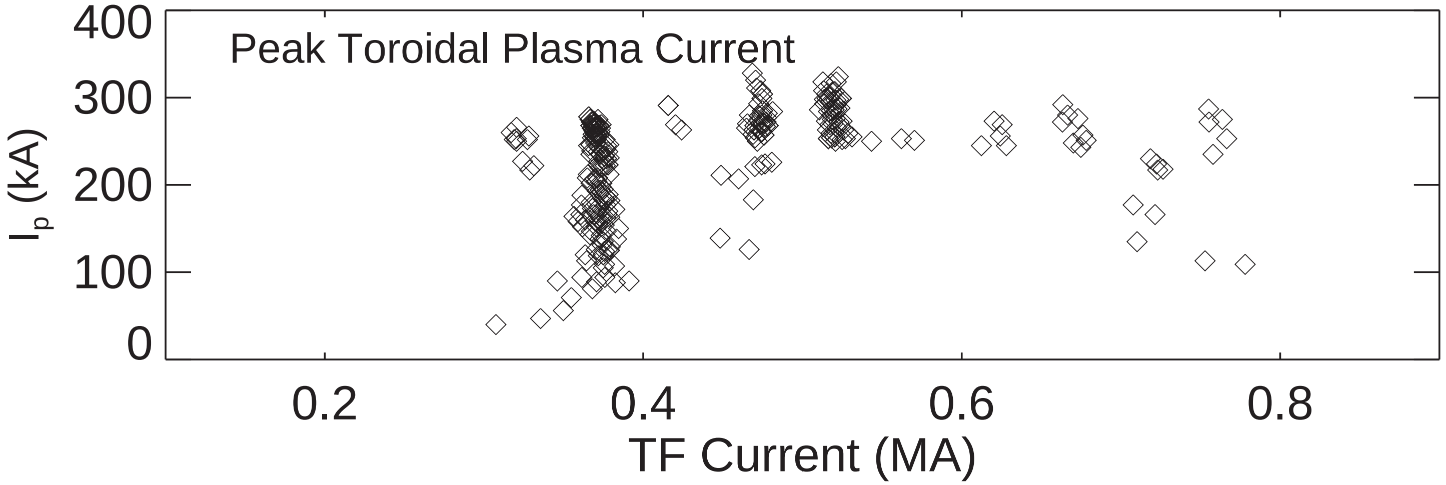
I_p is total (open- and closed-flux) toroidal plasma current.

CHI-driven I_p up to 120% of I_{TF}



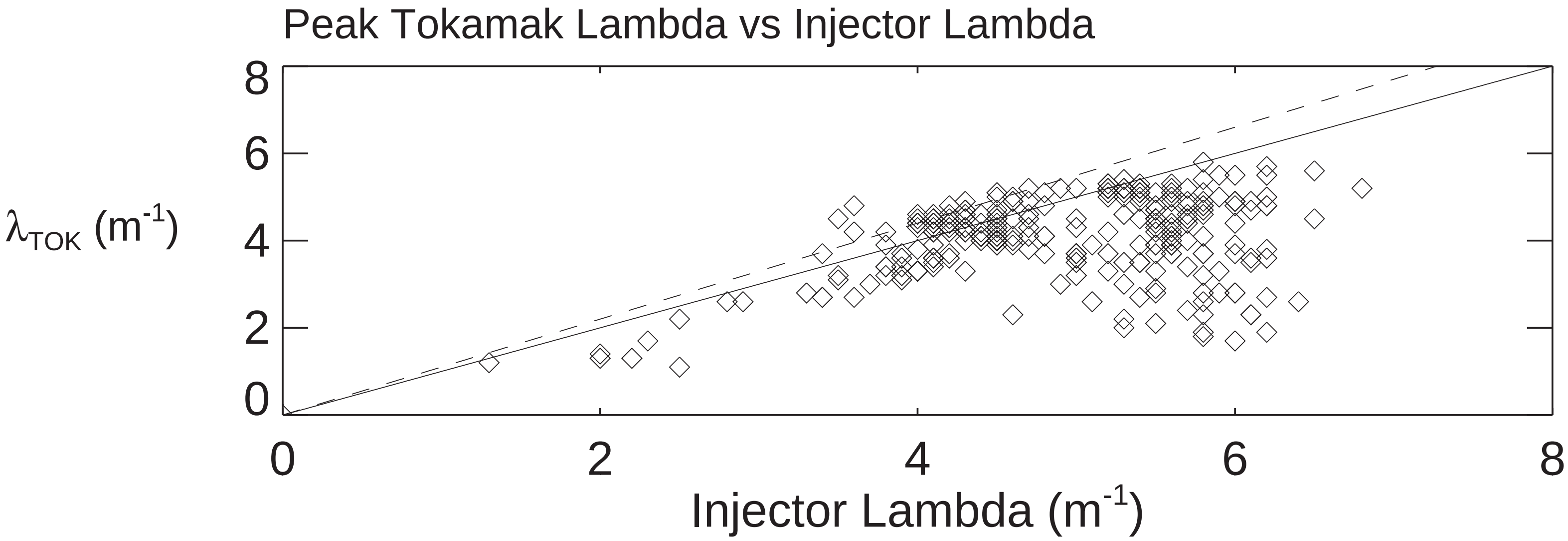
I_p is total (open- and closed-flux) toroidal plasma current.

Optimum I_{TF} for CHI-Driven I_p on HIT–II



- Peak plasma current I_p in 307 shots, versus corresponding I_{TF}
- I_p can be maximized for $I_{\mathrm{TF}} \approx 500$ kA
- Wall conditions can produce significant shot-to-shot variations, and can limit plasma performance early in a run campaign

CHI-Driven I_p Consistent With Taylor Relaxation

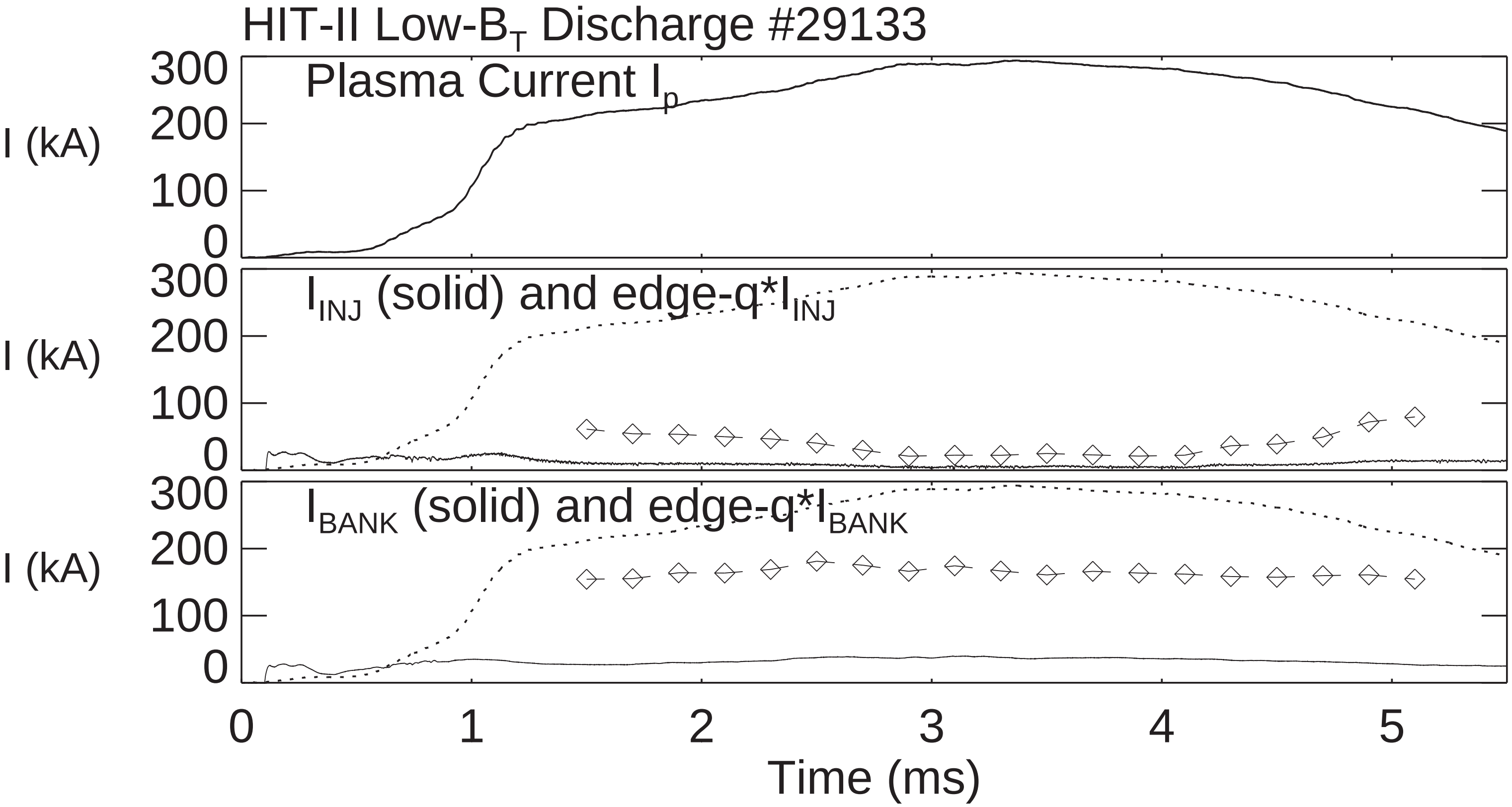


- Peak λ_{TOK} in 307 shots, versus post-formation λ_{INJ}

$$\text{where}\quad \lambda_{\mathrm{INJ}} \equiv \frac{\mu_0 I_{\mathrm{INJ}}}{\psi_{\mathrm{INJ}}} \quad\text{and}\quad \lambda_{\mathrm{TOK}} \equiv \frac{\mu_0 I_p}{\phi_{\mathrm{TF}}}$$

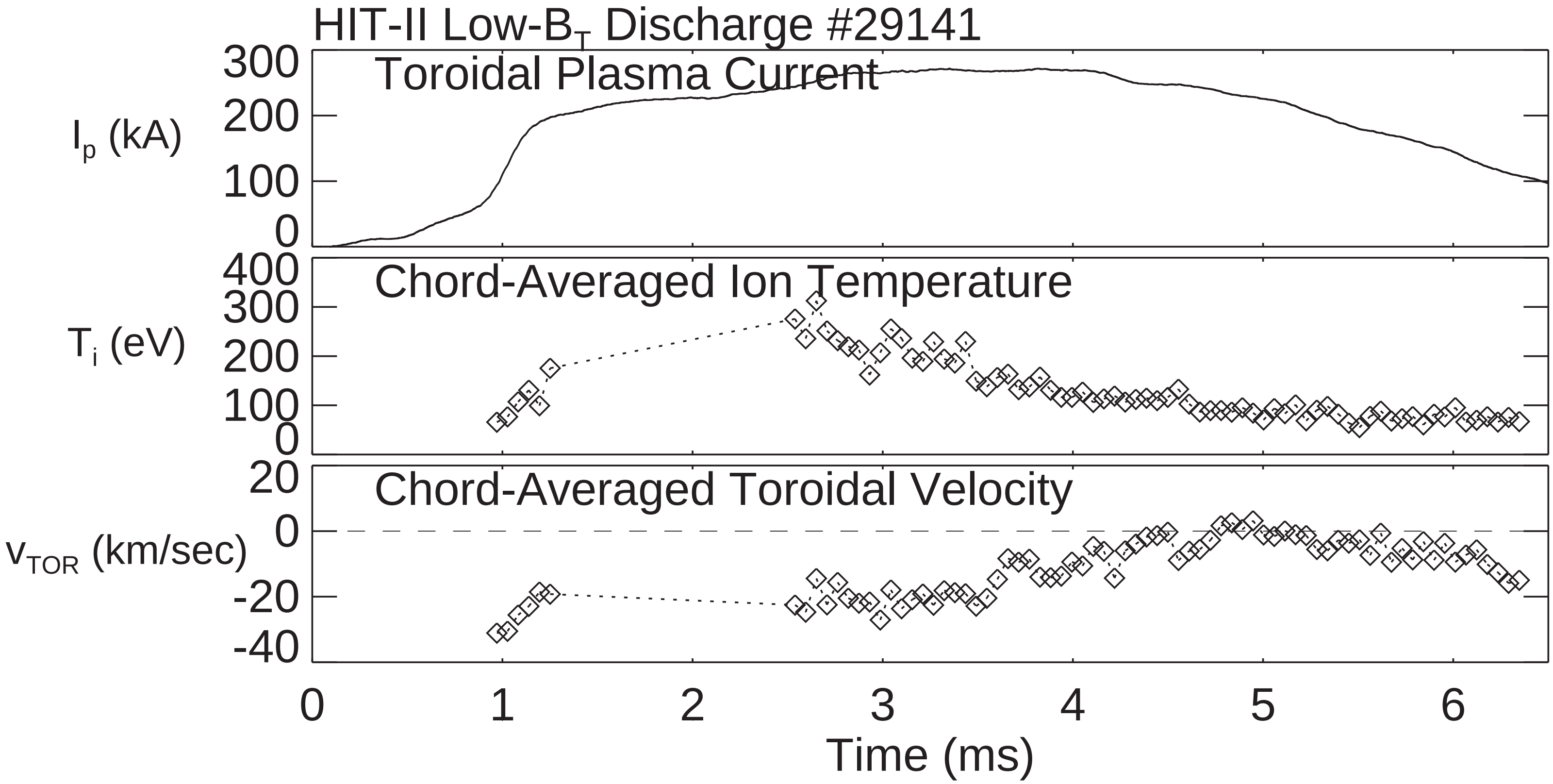
- Solid line is $\lambda_{\mathrm{TOK}}=\lambda_{\mathrm{INJ}}$, dashed line is $\lambda_{\mathrm{TOK}}=(1.1)\lambda_{\mathrm{INJ}}$
- Generally, $\lambda_{\mathrm{TOK}} \leq \lambda_{\mathrm{INJ}}$, which agrees with Taylor relaxation

I_p Up To 6 Times Wrap-up Current $q_a I_{\mathrm{INJ}}$



Discharge #29133: peak I_p was 290 kA, while $I_{\mathrm{TF}} \approx 470$ kA, for peak I_p/I_{TF} of 62%.
Peak $I_p/qI_{\mathrm{INJ}} \approx 6$, while peak I_p/qI_{BANK} is nearly 2.

IDS-Measured T_i up to 300 eV

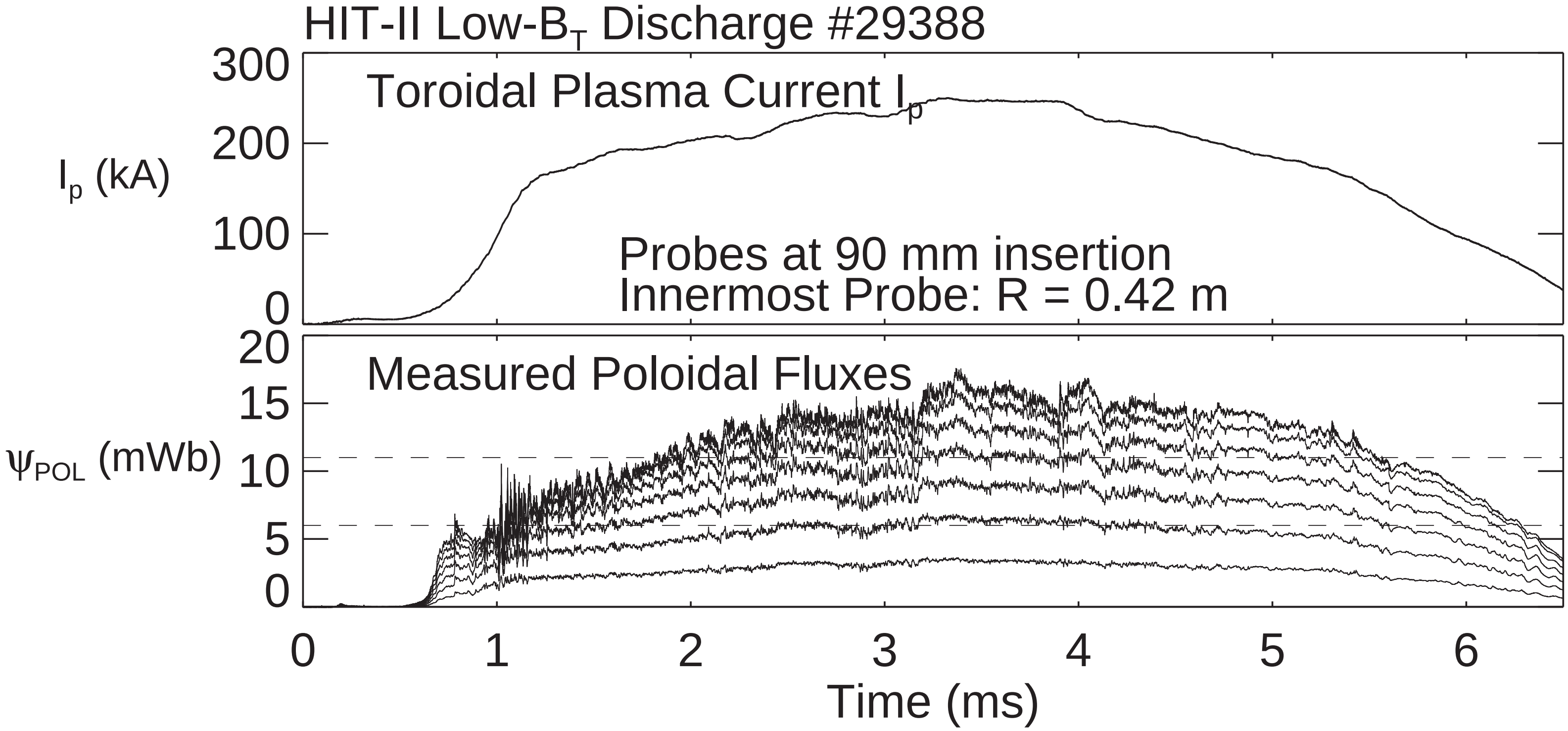


T_i and $\bar{v}_{\mathrm{TOR}}$ measured by single-chord Ion Doppler Spectroscopy,
tuned to `OV` emission (278 nm) on edge chord (impact parameter of 0.44 m).
Negative $\bar{v}_{\mathrm{TOR}}$ is counter to I_p.

Internal Magnetic Probe Array

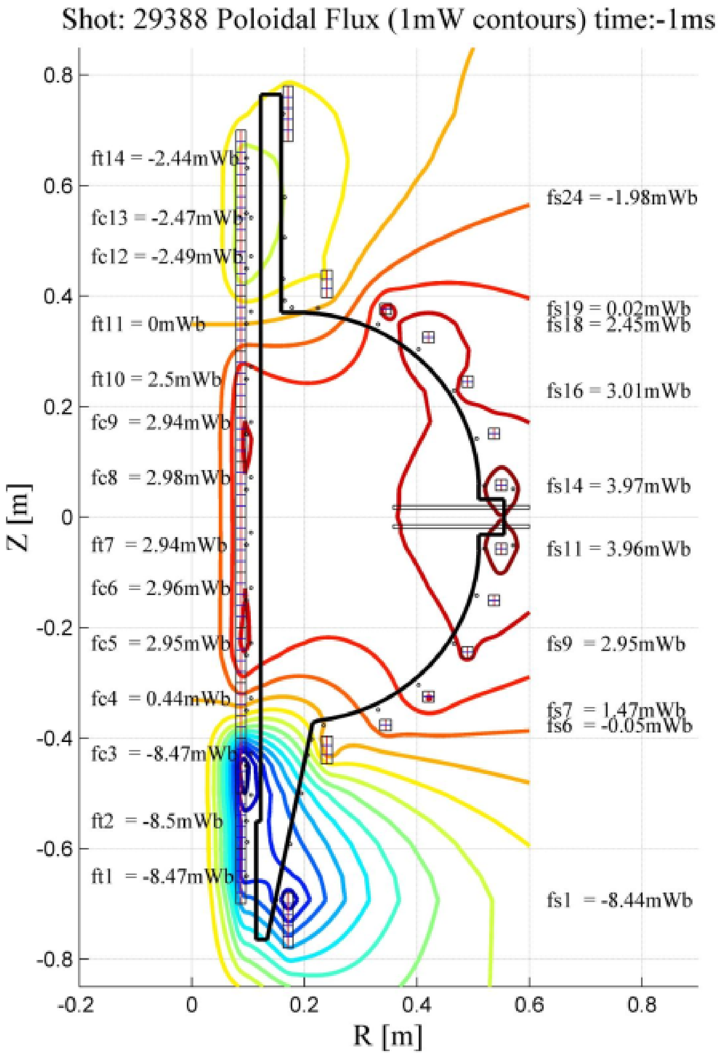
- Each probe "stem" contains 5 or 8 magnetic triple probes, with Boron-Nitride sheaths, stem axes spaced 35 mm apart
- Three probe stems are spaced poloidally and toroidally to enable calculations of the current density J
- Shallow probing (90 mm insertion) was found to be only slightly perturbing for these discharges
- Deeper probing (150 mm insertion) significantly degraded plasma performance, generally reducing peak I_p by 20%

Probes Show Poloidal Flux Generation



- Rapid rise in I_p corresponds to the “bubble-burst”, and probe-measured flux is simply the injector flux $\psi_{\rm INJ}$ (6.0 mWb, lower dashed line)
- Slow post-formation rise in I_p corresponds to increasing probe-measured flux.
- Peak measured flux is larger than the total vacuum flux that could be in the confinement region (∼11 mWb, upper dashed line)

Vacuum Fluxes for HIT–II CHI Shot #29388



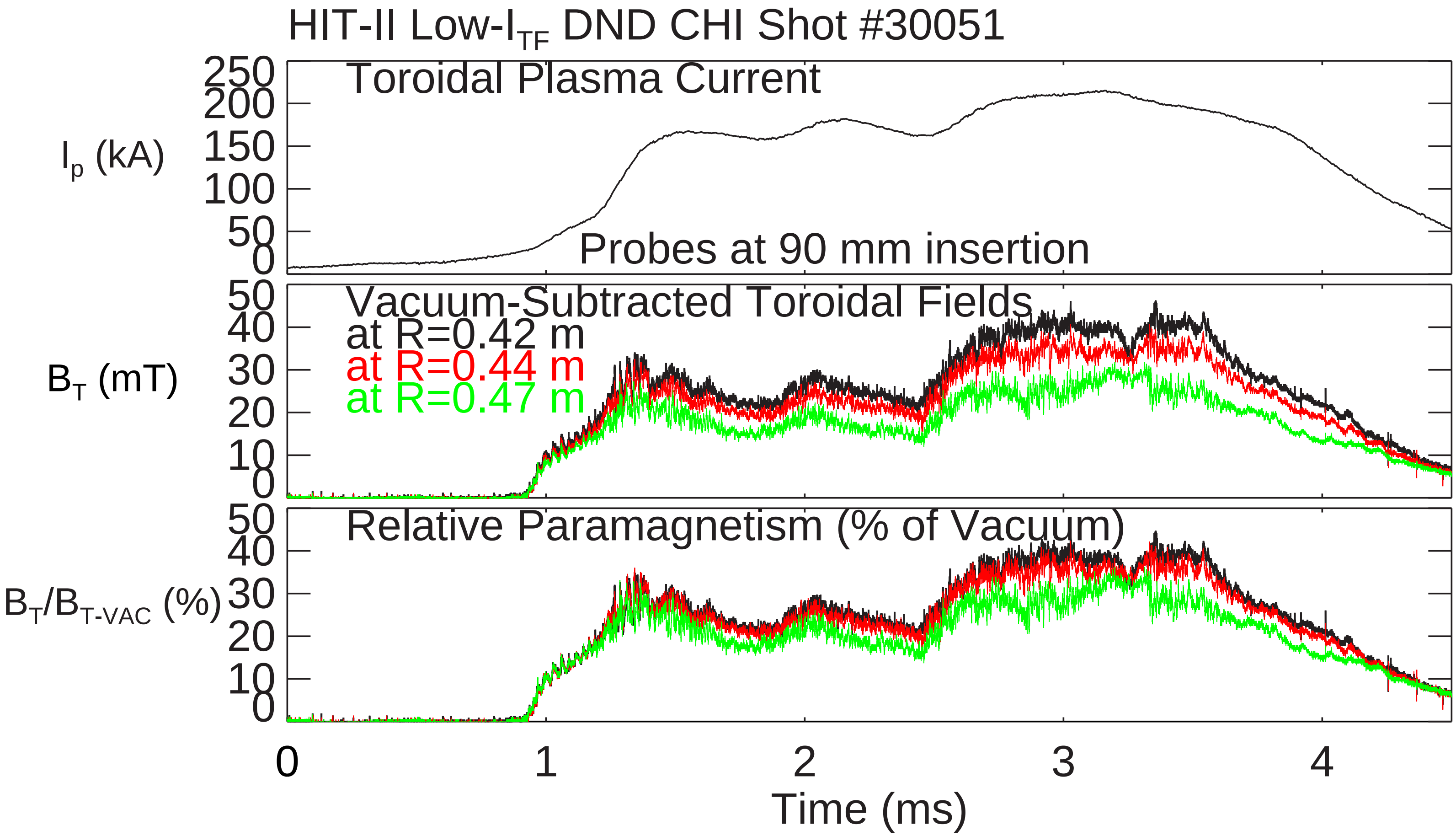
Discharge #29388 flux boundaries are Unbalanced Double-Null Divertor, with:

- Injector flux $\psi_{\mathrm{INJ}} = 6.0$ mWb
- “Absorber null flux” $\psi_{\mathrm{INJ}} = 2.5$ mWb
- Vertical flux up to 4.0 mWb at midplane

Internal magnetic probes can have up to 2 mWb of vertical flux behind the tips for 150mm insertion (as shown)

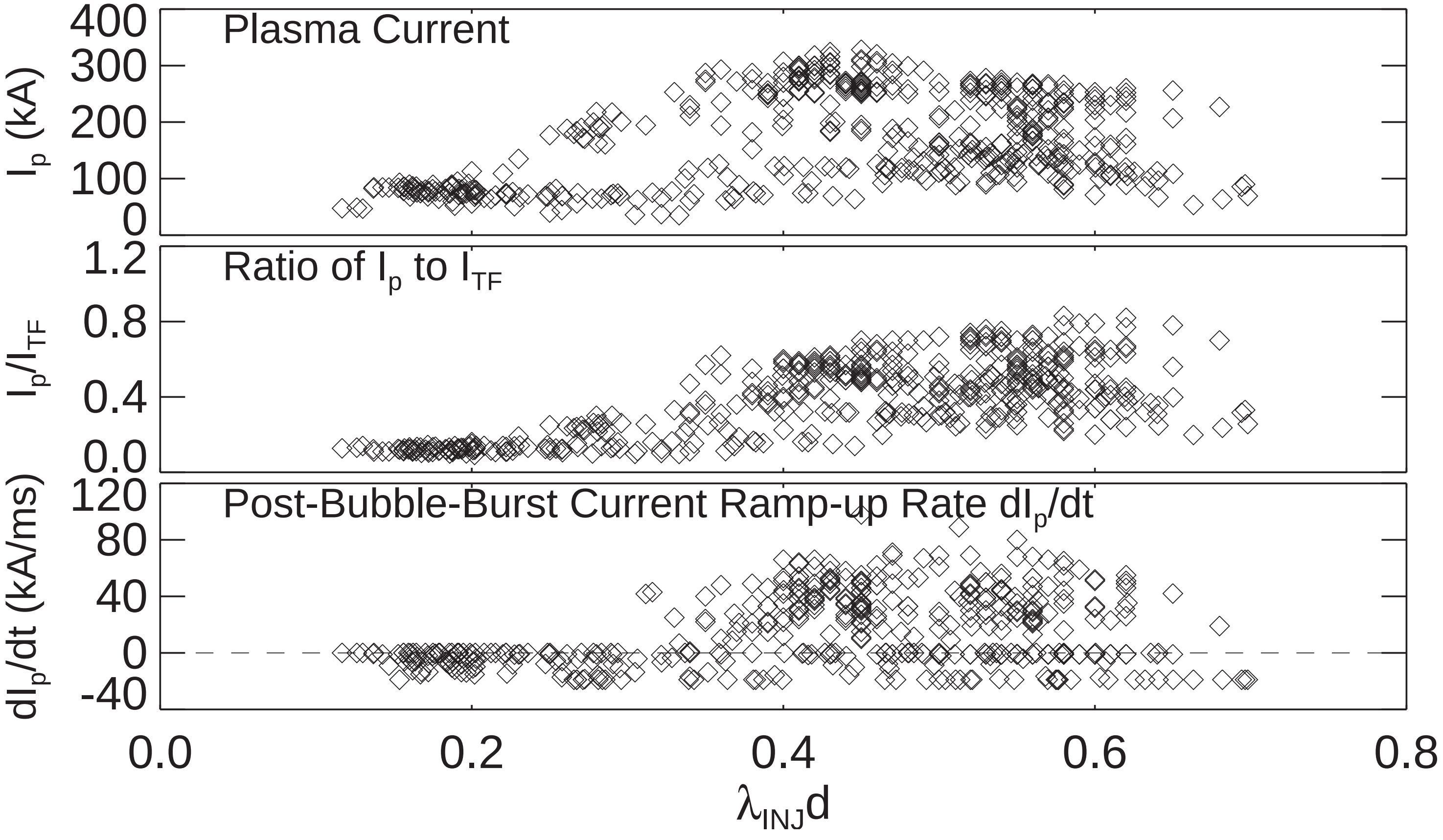
Open flux in confinement region may be up to 11 mWb for 90 mm insertion, assuming ψ_{INJ} is completely drawn out.

Low-TF Plasmas Can Be Strongly Paramagnetic



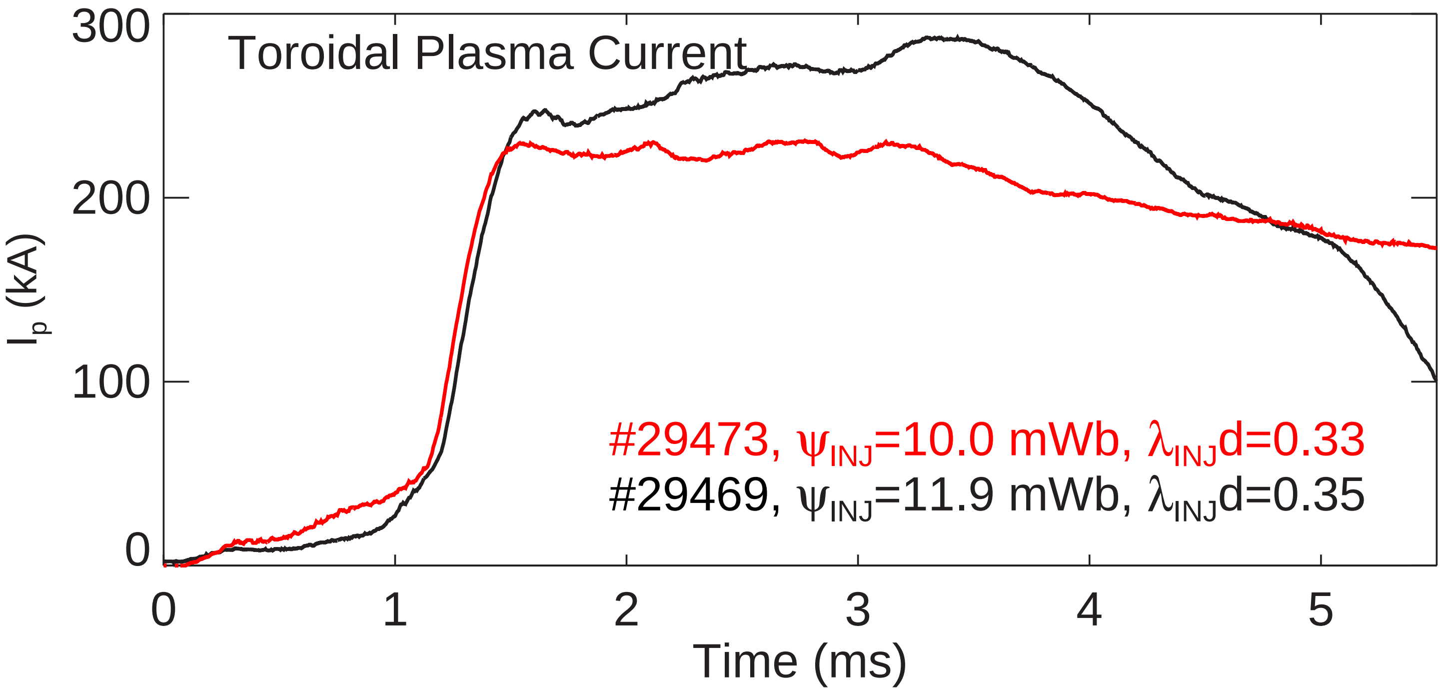
Paramagnetic toroidal fields reach 40% of the vacuum toroidal fields.

Current Ramp-up Correlates with Injector Field-Line Geometry



$\lambda_{\mathrm{INJ}}d$ is a dimensionless measure of field-line pitch in the injector
(points are 508 timeslices in 332 discharges)

Even for High B_T, Increasing $\lambda_{\text{INJ}}d$ Allows Relaxation and Current Build-Up



Shots with relatively high toroidal field ($I_{\text{TF}} \approx 800$ kA)

Relaxation Buildup Overcomes Resistive Decay When $\lambda_{\mathrm{INJ}} d$ Exceeds a Critical Value

- Relaxation rates vary with field-line geometry:
  Antiparallel field lines reconnect faster than parallel field lines.
  [Y. Ono *et al*, Phys. Fluids B **5**, 3691 (1993)]

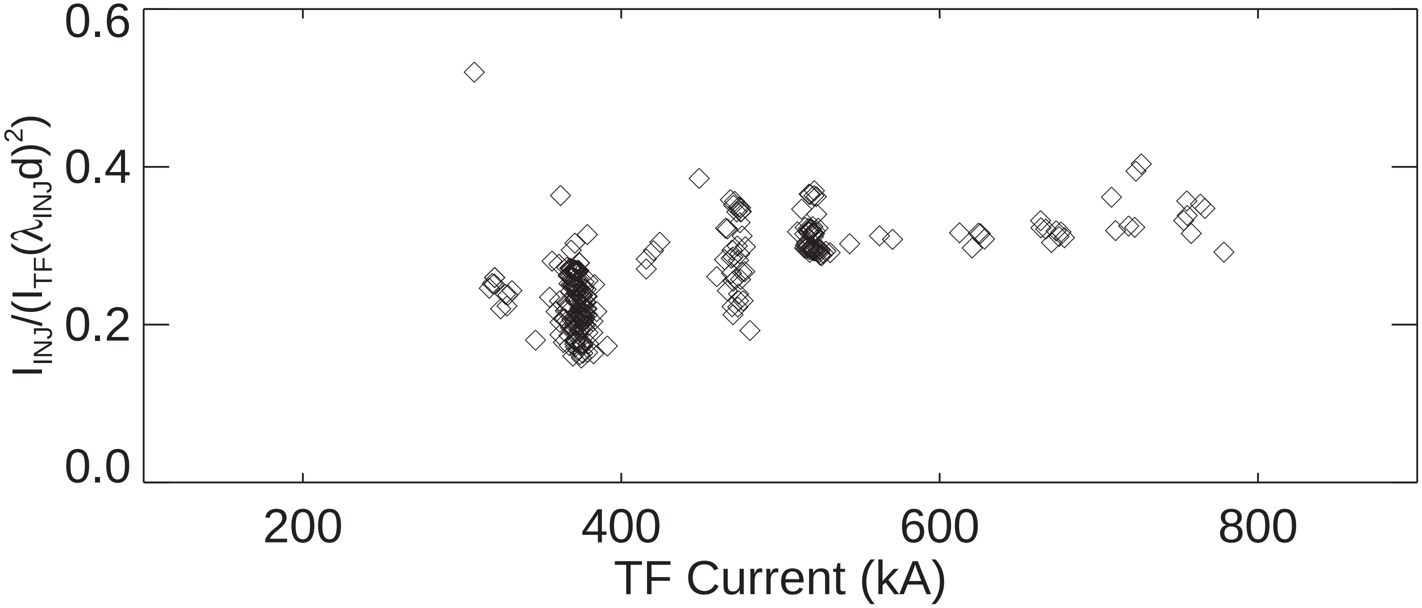
- Strong toroidal fields in a Spherical Tokamak
  ⇒ Fields are nearly parallel in the HIT–II injector
  ⇒ Slow magnetic relaxation rate

- Decreasing I_{TF} and/or increasing ψ_{INJ} will increase $\lambda_{\mathrm{INJ}} d$, or the magnetic field pitch in the injector region

- Empirically, there is a minimum value of $\lambda_{\mathrm{INJ}} d$ needed for significant buildup of the toroidal plasma current
  ⇒ Minimum relaxation rate needed to overcome resistive decay

- Critical value is $\lambda_{\mathrm{INJ}} d \approx 1/3$

CHI Injector Current Can Be Predicted Using a Semi-Empirical Formula



Points are 307 DND HIT–II CHI discharges, each at maximum λ_{TOK}.

As long as $I_{\mathrm{INJ}} \ll I_{\mathrm{TF}}$ and $d \ll a$,

$$I_{\mathrm{INJ}} \approx \frac{1}{3} I_{\mathrm{TF}} \left(\lambda_{\mathrm{INJ}} d\right)^2 \quad \text{or} \quad I_{\mathrm{INJ}} \approx \frac{3\psi_{\mathrm{INJ}}^2}{\mu_0^2 d^2 I_{\mathrm{TF}}}$$

Summary

- New HIT–II CHI operating regime has been explored:
  - Toroidal plasma current I_p over 350 kA
  - I_p greater than I_{TF} in some discharges ($\leq 120\%$)
  - I_p can be up to 6 times the wrap-up current $q_a I_{\mathrm{INJ}}$
  - Relatively high temperatures:
    IDS T_i typically 100-300 eV and MPTS T_e up to 100 eV
  - Internal magnetic measurements show:
    - Buildup of poloidal flux and formation of closed-flux core
    - Strongly paramagnetic at low TF (up to 40% of vacuum)
- Similar CHI studies can be performed on other STs:
  - I_{INJ} scaling demonstrated for wide range of TF
  - Current ramp-up occurs only if $\lambda_{\mathrm{INJ}} d$ exceeds $\sim 1/3$
    (Excess TF inhibits relaxation and current drive)
  - Plasma current builds up until $\lambda_{\mathrm{TOK}} = \lambda_{\mathrm{INJ}}$

Future Work

- Continue analysis of HIT–II data:
  - Discharges with variable injector geometry
    - ⋆ Do these discharges follow the field-pitch scalings?
  - More detailed probing results:
    - ⋆ Overall scalings?
    - ⋆ n=1 mode structure?
    - ⋆ Formation dynamics?
  - Correlate (if possible) other discharge features: Occasional HXR pulses, slow P_{RAD} oscillations
- EFIT equilibrium reconstructions, with and without fitting to internal probe measurements
- Do corresponding CHI studies on NSTX