Low-TF Steady-State CHI Discharges in NSTX: Toroidal Current and Poloidal Flux Buildup by Magnetic Relaxation

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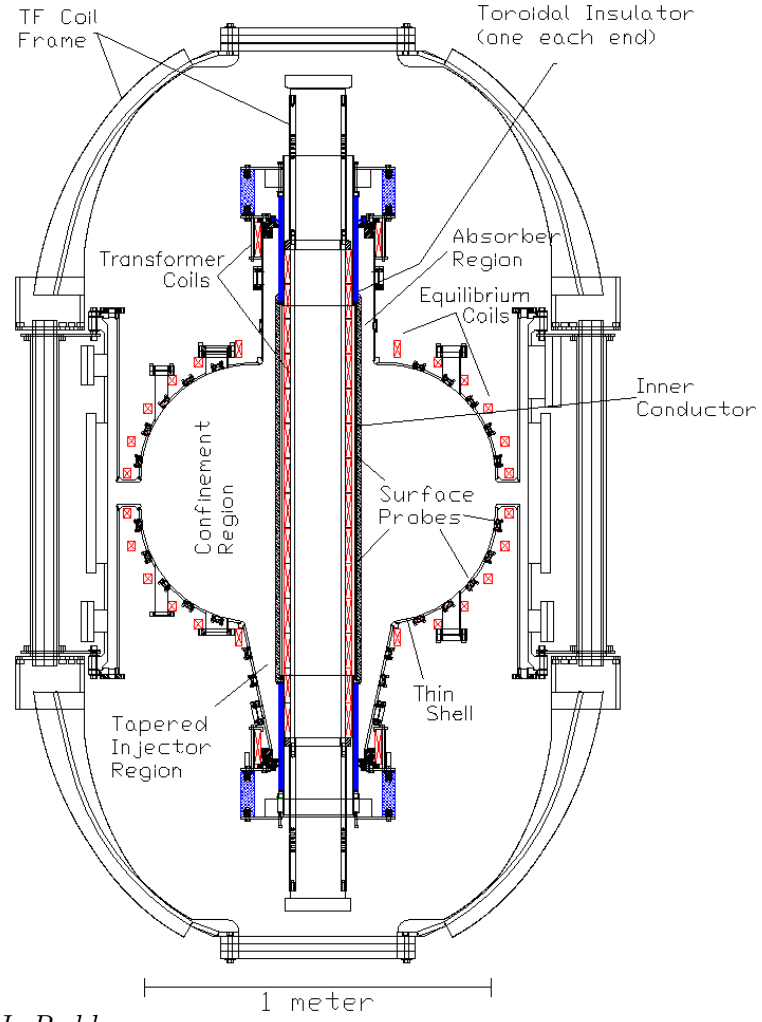
2004 NSTX Research Forum
Princeton Plasma Physics Laboratory
Princeton, NJ
Sept 22–24, 2004

Outline

- New CHI operating regime explored on HIT–II
  - Toroidal plasma current I_p over 350 kA
  - Plasma current increases until $\lambda_{\mathrm{TOK}} = \lambda_{\mathrm{INJ}}$
  - Threshold value of $\lambda_{\mathrm{INJ}} d$ for current build-up
  - Empirical scaling for injector current
- Propose to study this operating regime on NSTX
  - Better duration, volume-to-area ratio than HIT–II
  - Target parameter sets can be identified using a set of semi-empirical scalings
  - If these scaling relations hold, then can project to CHI-driven I_p much higher than 400 kA

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

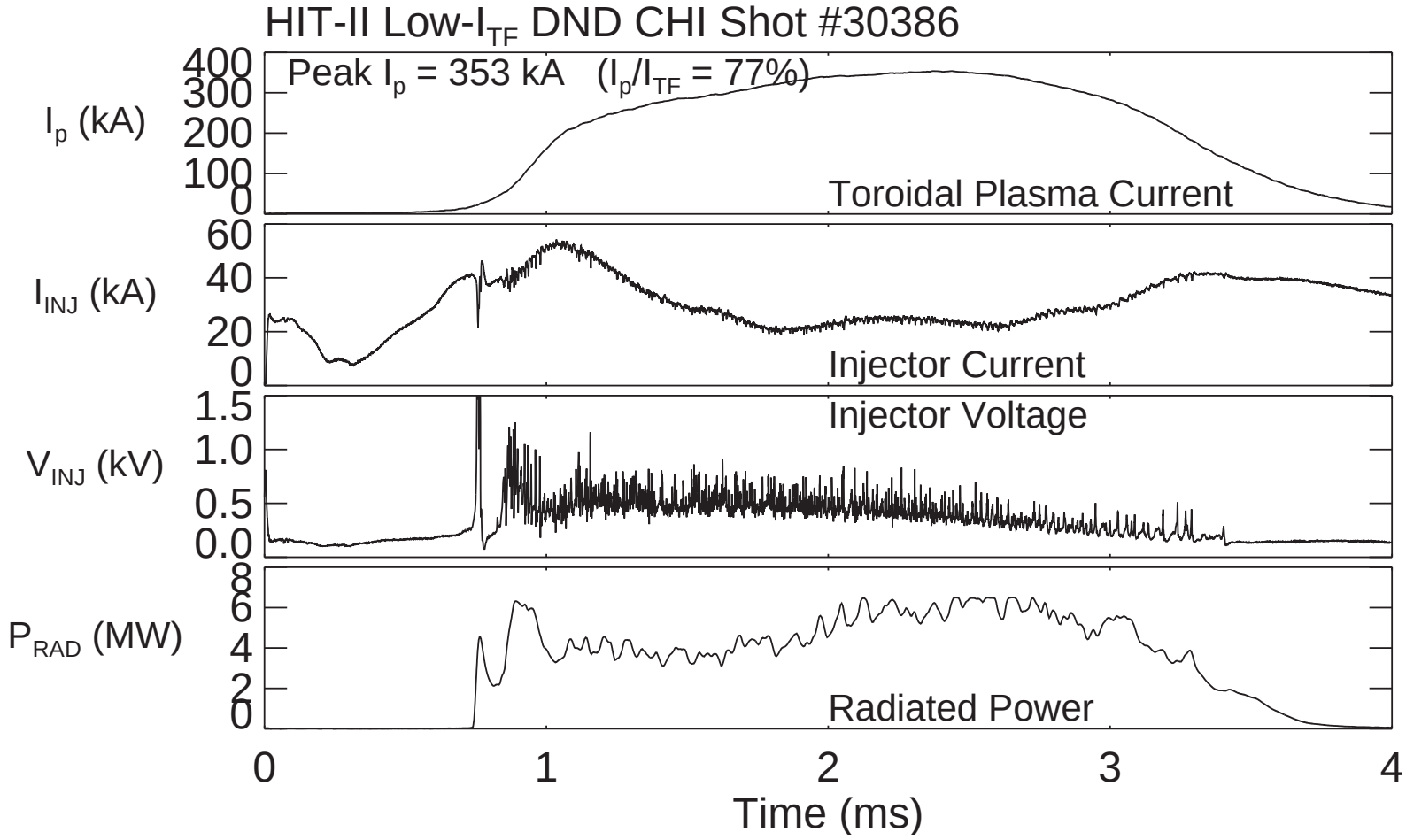
HIT–II plasma parameters achieved:

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

HIT diagnostic systems include:

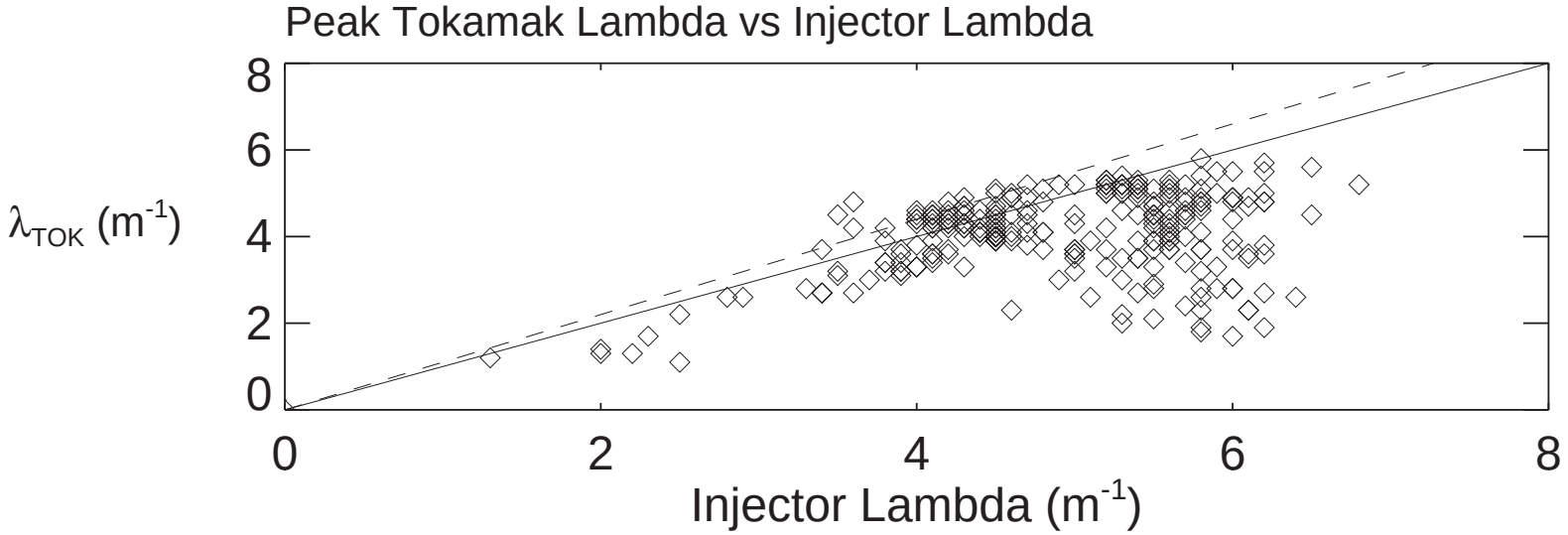
- Internal magnetic and Langmuir probes
- Scannable two-chord FIR interferometer
- 16-channel Ion Doppler Spectrometer, scannable single-chord
- Multi-point Thomson Scattering
- Pair of VUV spectrometers (OVI/OV ratio)
- H-α visible light detectors
- Surface magnetic triple probes
- Bolometer (total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

CHI-driven I_p up to 353 kA



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

CHI-Driven I_p Rises Until $\lambda_{\mathrm{TOK}} = \lambda_{\mathrm{INJ}}$

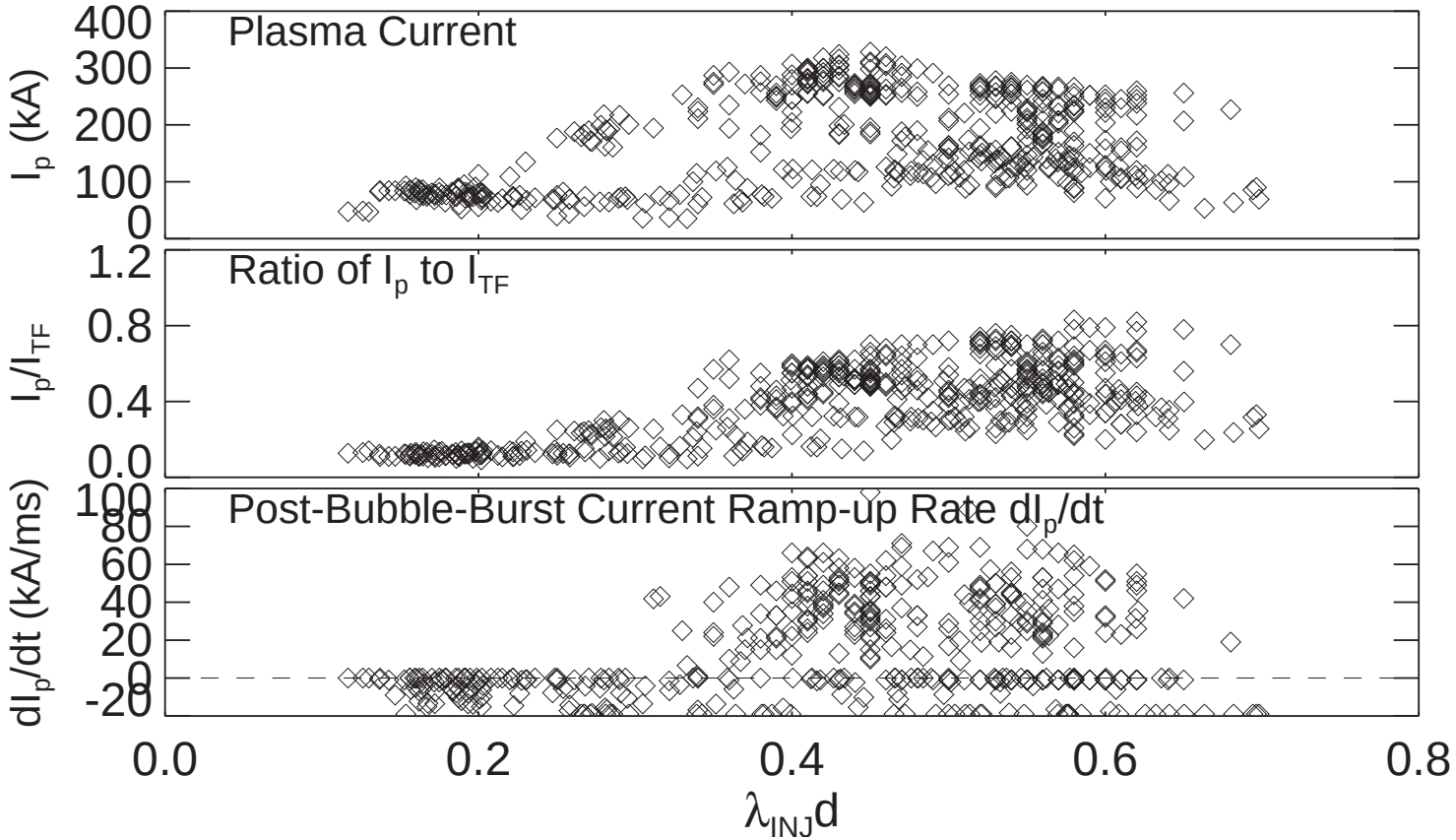


- Peak λ_{TOK} in 307 shots, versus post-formation λ_{INJ}

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

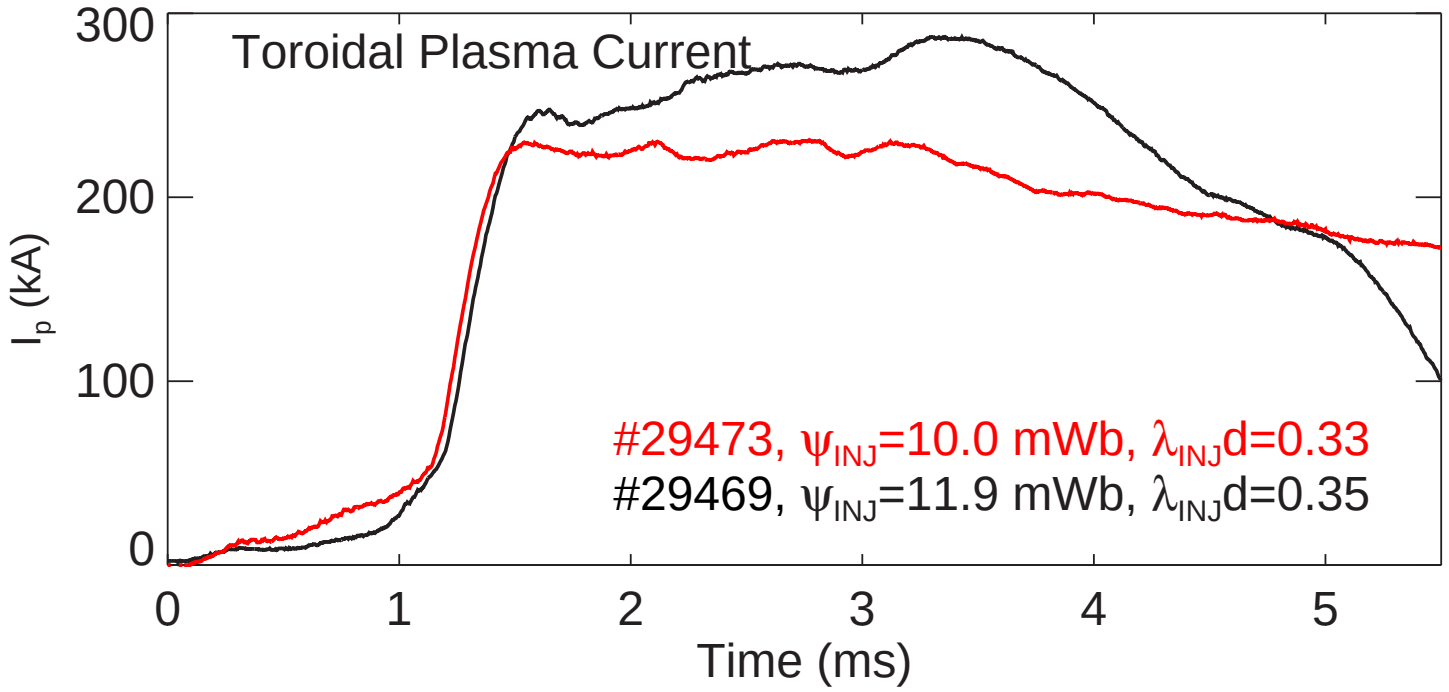
- Solid line is λ_{TOK}=λ_{INJ}, dashed line is λ_{TOK}=$(1.1)\lambda_{\mathrm{INJ}}$
- Generally, $\lambda_{\mathrm{TOK}} \leq \lambda_{\mathrm{INJ}}$, consistent with Taylor relaxation

Current Ramp-up Occurs Only When $\lambda_{\mathrm{INJ}}d$ Exceeds Critical Value



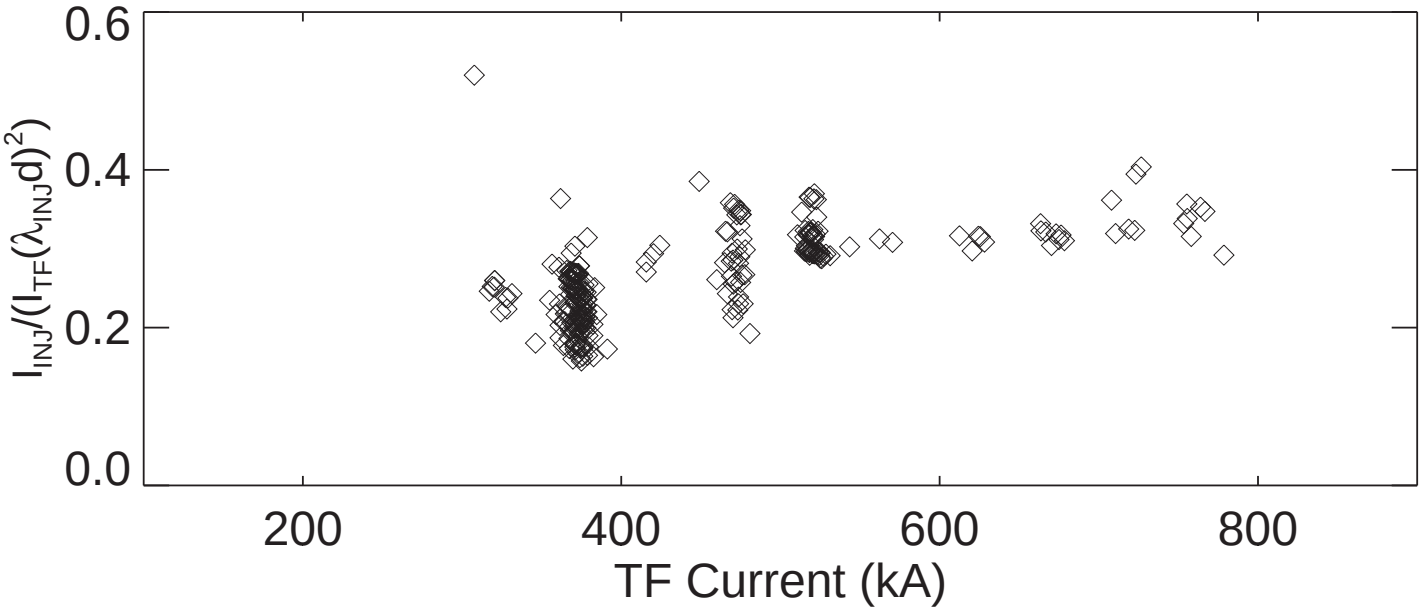
$\lambda_{\mathrm{INJ}}d$ is a dimensionless measure of field-line pitch in the injector
(points are 508 timeslices in 332 discharges)

Small Increases in $\lambda_{\mathrm{INJ}}d$ Can Allow Relaxation and Current Build-Up



Two shots with relatively high toroidal field ($I_{\mathrm{TF}} \approx 800$ kA)

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 $d \ll a$,

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

Low-TF CHI Operations on NSTX

- In general, I_{INJ} is expressed as a function of d, ψ_{INJ} and I_{TF}.

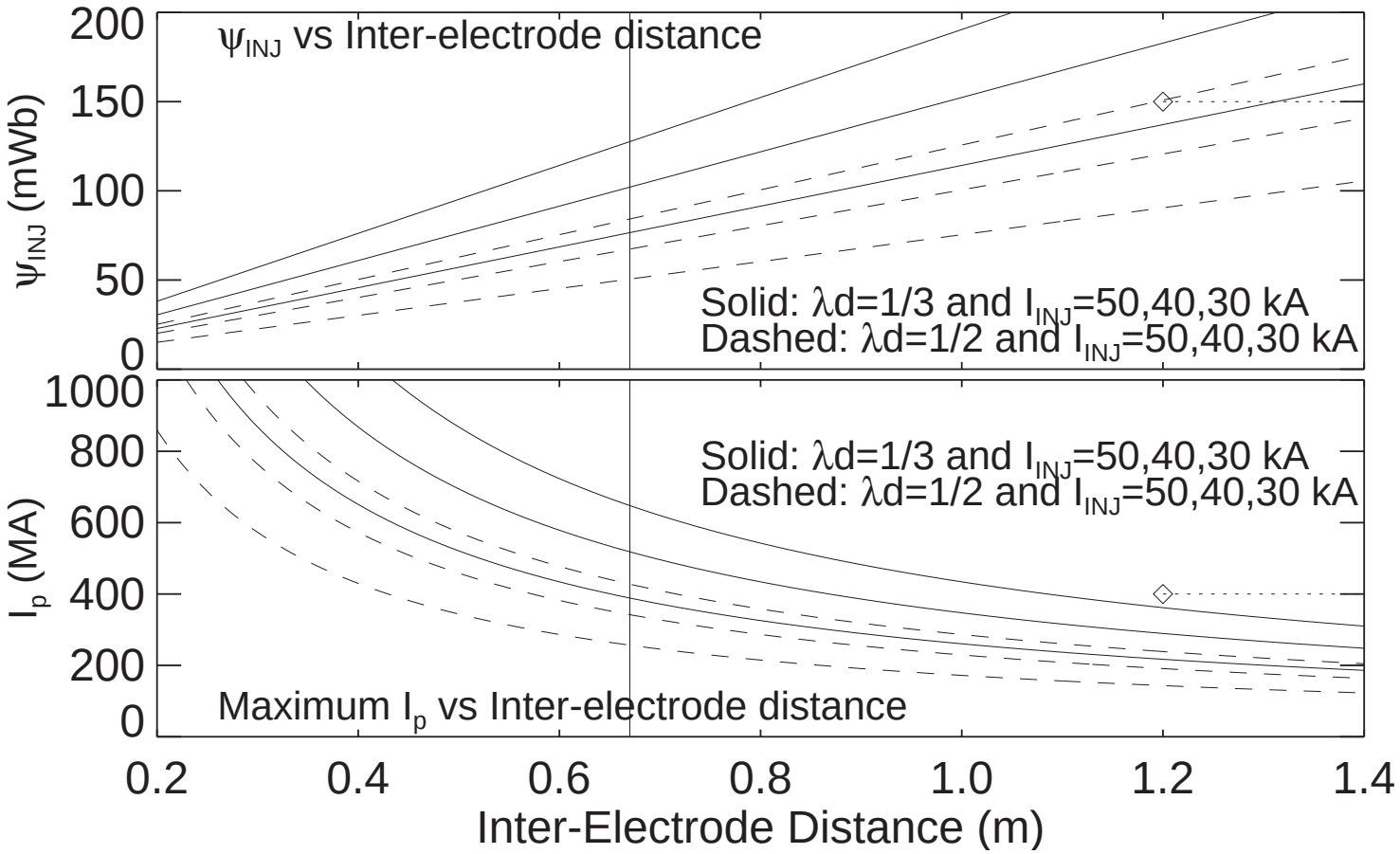
  However, in NSTX CHI experiments, I_{INJ} is constrained,
  d is determined by injector flux control, and
  $\lambda_{\mathrm{INJ}} d$ should be kept at or above the threshold value of 1/3.

- Using the preceding equations (and $\lambda_{\mathrm{TOK}} = \lambda_{\mathrm{INJ}}$), one can obtain ψ_{INJ}, I_{TF} and peak I_p in terms of I_{INJ}, d and $\lambda_{\mathrm{INJ}} d$:

$$\psi_{\mathrm{INJ}} = \frac{\mu_0 d I_{\mathrm{INJ}}}{(\lambda_{\mathrm{INJ}} d)} \quad , \quad I_{\mathrm{TF}} = \frac{3 I_{\mathrm{INJ}}}{(\lambda_{\mathrm{INJ}} d)^2} \quad \text{and} \quad I_p \leq \frac{3 L I_{\mathrm{INJ}}}{\mu_0 (\lambda_{\mathrm{INJ}} d) d}$$

  where L is related to TF coil inductance ($\approx 1.2\ \mu$H).

Significant Improvement as d is Decreased



The diamonds indicate conditions in NSTX CHI discharge #106488, at time t=334 ms (where $d \geq 1.2$ m $\gg a$).

NSTX Low-TF CHI Scenarios

In all scenarios, use time-varying flux boundaries to reach steady state:

1. Initial injector flux has large magnitude and wide footprint, allowing the feedback system to keep control of the discharge.
2. Narrow the flux footprint and reduce ψ_{INJ}, in order to hold I_{INJ} approximately constant (also hold I_{TF} constant).
3. Reach final steady state with parameters listed below:

Plasma Parameters	#106488 t=334 ms	Target Shot #1 $I_{\mathrm{INJ}} = 37$ kA	Target Shot #2 $I_{\mathrm{INJ}} = 45$ kA
$\lambda_{\mathrm{INJ}} d$	0.23	0.33	0.40
Inter-electrode Dist	$\geq$1.2 m	0.40 m	0.40 m
Injector Current	28 kA	37 kA	45 kA
Injector Flux	150 mWb	57 mWb	57 mWb
TF Current	1.0 MA	1.0 MA	0.85 MA
Toroidal Field	0.30 T	0.30 T	0.25 T
Plasma Current	400 kA	780 kA	790 kA
I_p/I_{TF}	0.4	0.78	0.93

Summary

- New CHI operating regime explored on HIT–II
  - Toroidal plasma current I_p over 350 kA
  - Plasma current increases until $\lambda_{\mathrm{TOK}} \approx \lambda_{\mathrm{INJ}}$
  - Threshold value of $\lambda_{\mathrm{INJ}} d \approx 1/3$ for current build-up
  - Simple scalings allow accurate prediction of I_{INJ}, if inter-electrode distance is less than the minor radius
- Proposing to study this operating regime on NSTX
  - Better duration, volume-to-area ratio than HIT–II
  - Some target parameter sets have been identified, with projected CHI-driven plasma currents up to 800 kA, and without unreasonably taxing NSTX