Current Drive Mixing Experiments on the Helicity Injected Torus (HIT-II)

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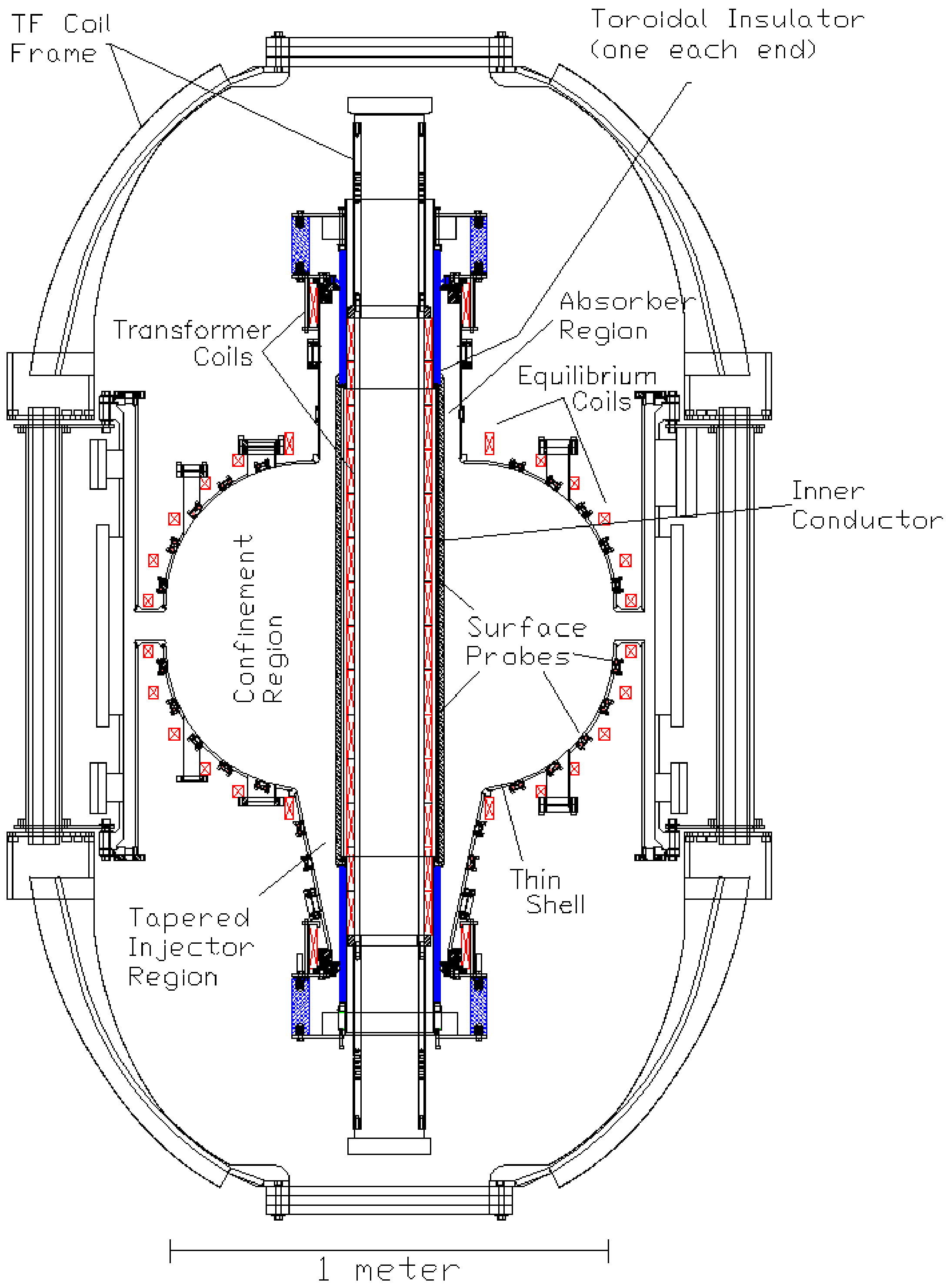
Summary

- HIT-II is a modest ST (major radius 0.3 m, minor radius 0.2 m, on-axis toroidal field up to 0.5 Tesla), but has demonstrated toroidal plasma currents of up to 250 kA, using a combination of CHI and Ohmic.
- Recent HIT-II experiments have demonstrated robust noninductive startup using CHI, with handoff to Ohmic current drive.
  - Highest I_p measured on HIT-II: 250 kA
  - Significant transformer Volt-second savings
  - EFIT indicates high plasma pressures
  - Sawtooth observations correlate with EFIT
- The Helicity Injected Torus with Steady Inductive helicity injection (HIT-SI) is under construction.

The HIT-II Spherical Torus



The HIT-II Spherical Torus

- HIT-II Engineering Parameters:

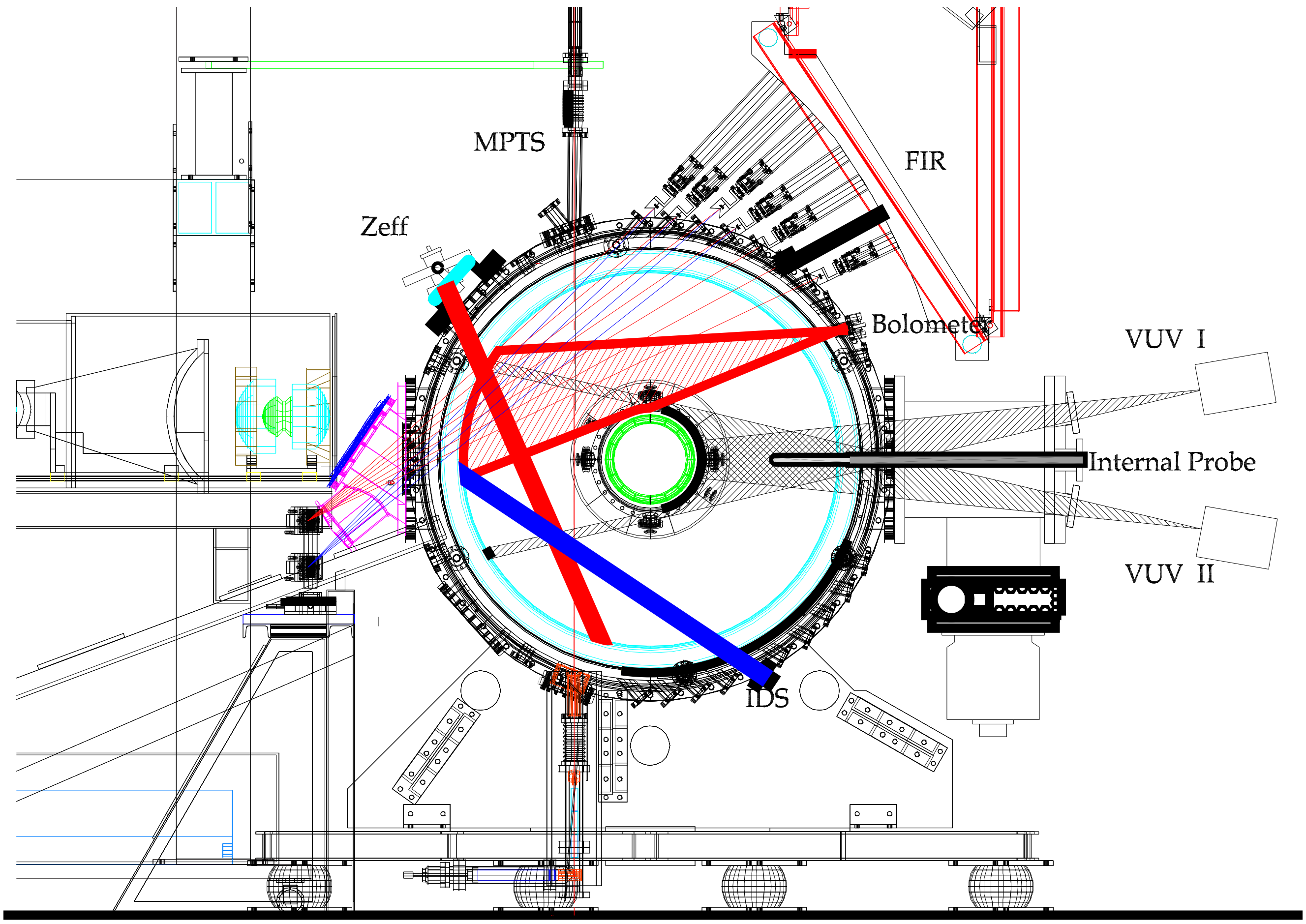
Major Radius R	0.3m
Minor Radius a	0.2m
Aspect Ratio A	1.5
Elongation κ	1.75
Ohmic Flux Available	60 mWb

- HIT-II Achieved Plasma Parameters:

Parameter	Ohmic	CHI	CHI+OH
Pulse Length	60 ms	25 ms	40 ms
Peak Current	200 kA	240 kA	250 kA
Density $\bar{n}_e$	$\leq 5\times10^{19}$ m^{-3}	1–6$\times10^{19}$ m^{-3}	$\leq 5\times10^{19}$ m^{-3}

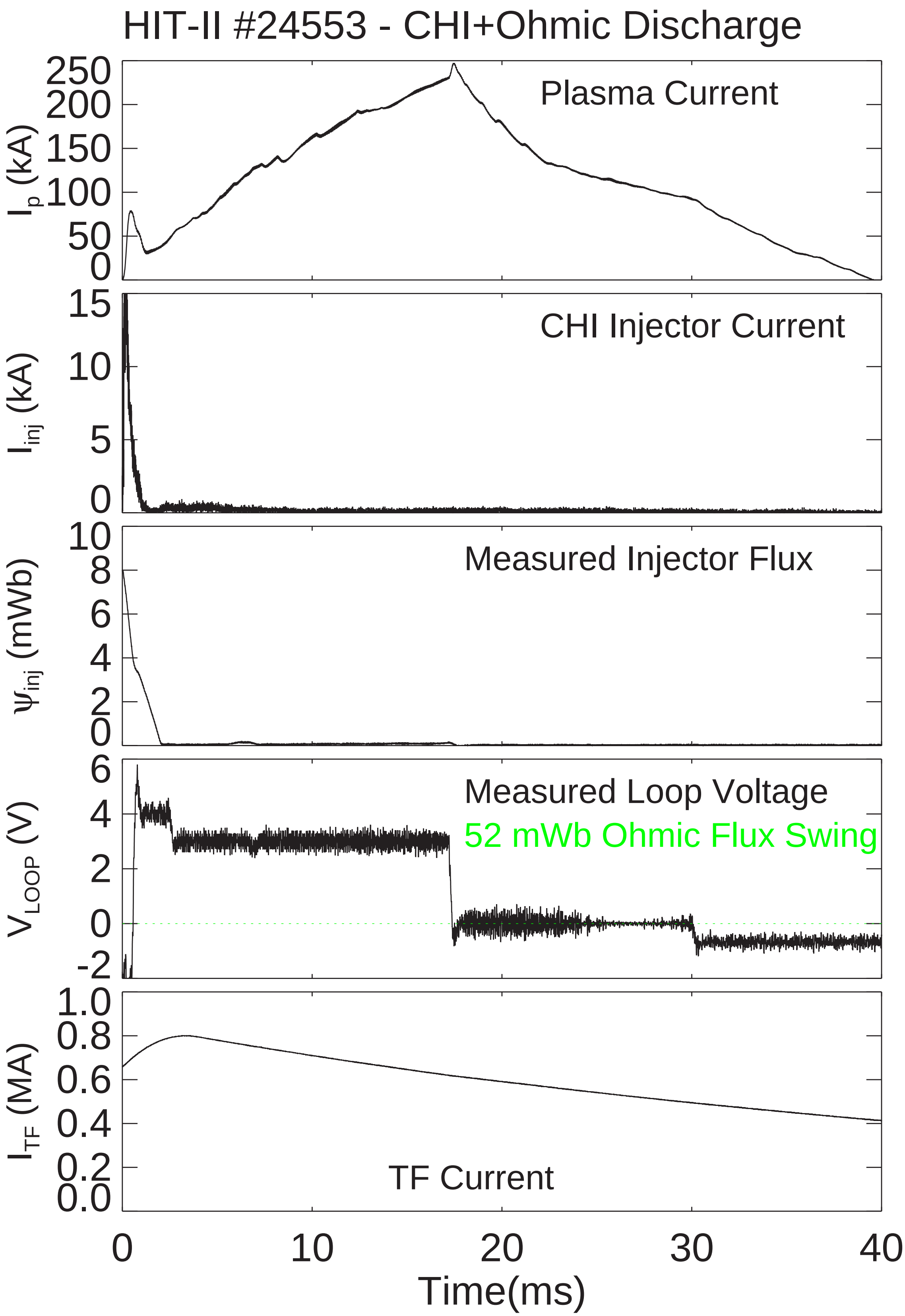
- HIT diagnostics include:
  - Multi-point Thomson Scattering
  - Scannable two-chord FIR interferometer
  - Scannable single-chord 16-channel Ion Doppler Spectrometer
  - Pair of vacuum-UV (VUV) spectrometers (OVI/OV ratio)
  - Single-chord average-Z_{eff} measurement
  - H-α visible light detectors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

Overview of HIT Midplane Diagnostics

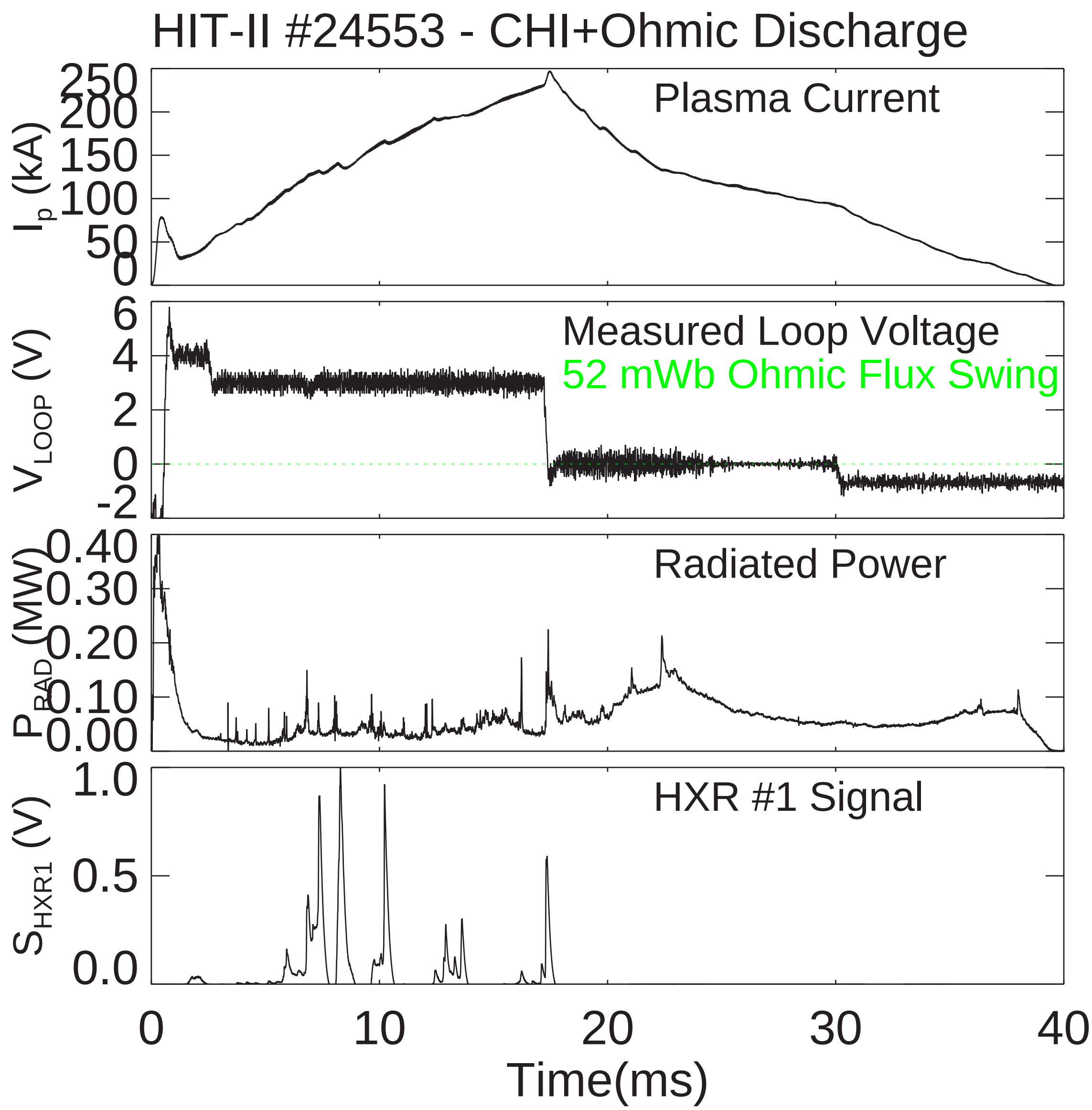


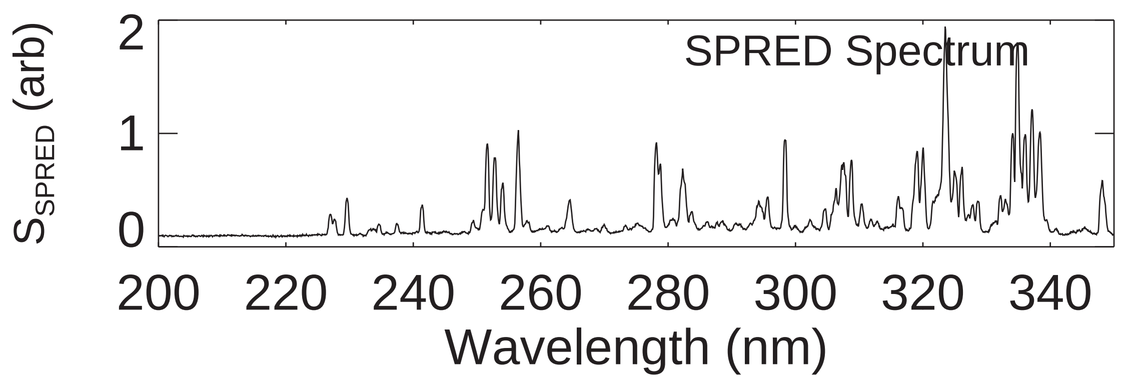
CHI Startup of Ohmic HIT-II Plasmas

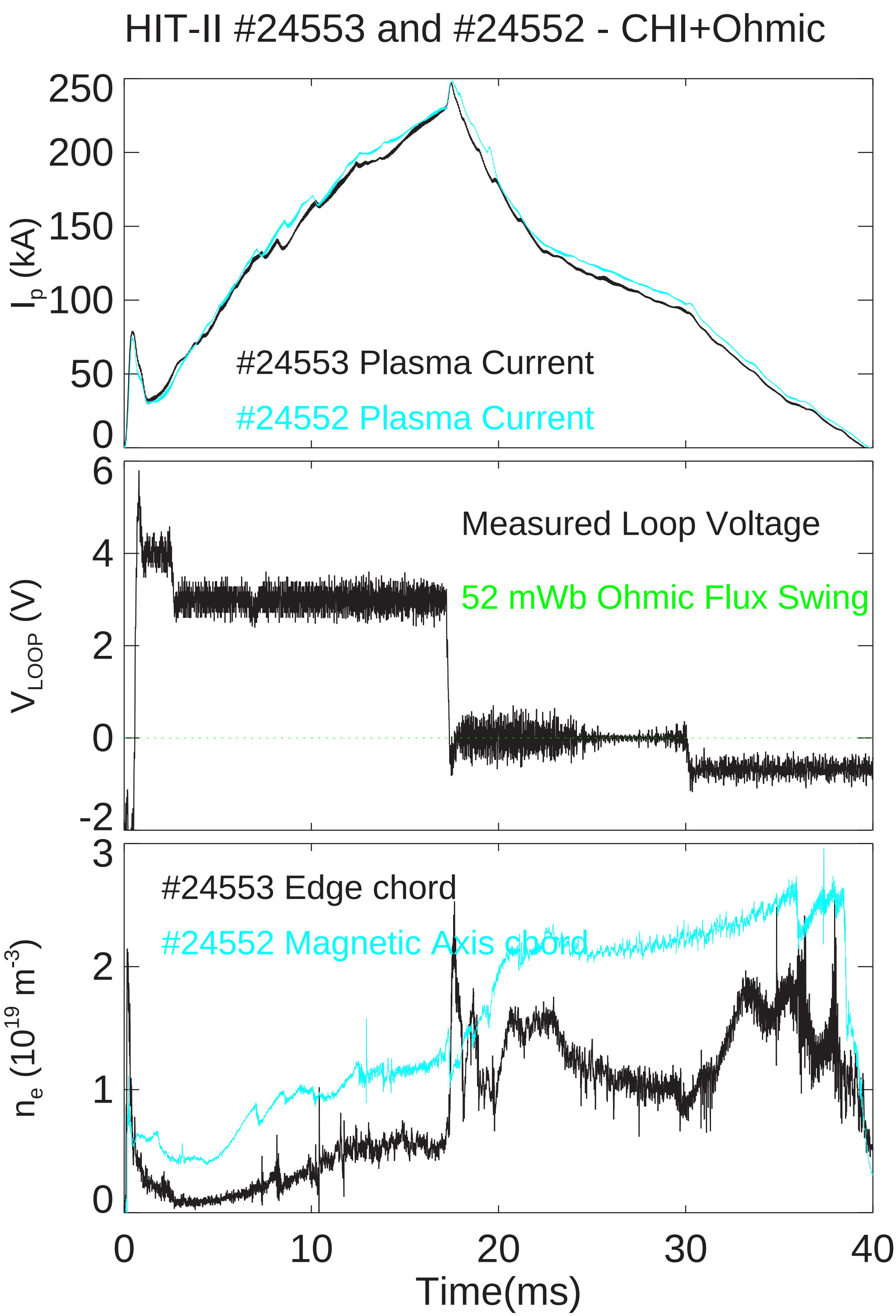
- Recent HIT-II experiments have used a CHI pulse to ionize and form a seed ST for Ohmic current drive:
  1. Discharge begins as typical CHI plasma (high voltage, low capacitance Formation Bank)
  2. Injector flux rapidly brought to zero (8 mWb of flux, ramped down in a few ms)
  3. As injector flux vanishes, apply Ohmic drive
- Discharge features:
  - CHI+Ohmic plasmas have I_p up to 250 kA, higher than any previous HIT-II Ohmic plasma
  - Significant transformer Volt-second savings over Ohmic-only operation
  - Interferometry scans show that:
    * CHI-phase plasma is thin current sheet near wall
    * Ohmic-phase plasma fills confinement region and has a peaked density profile

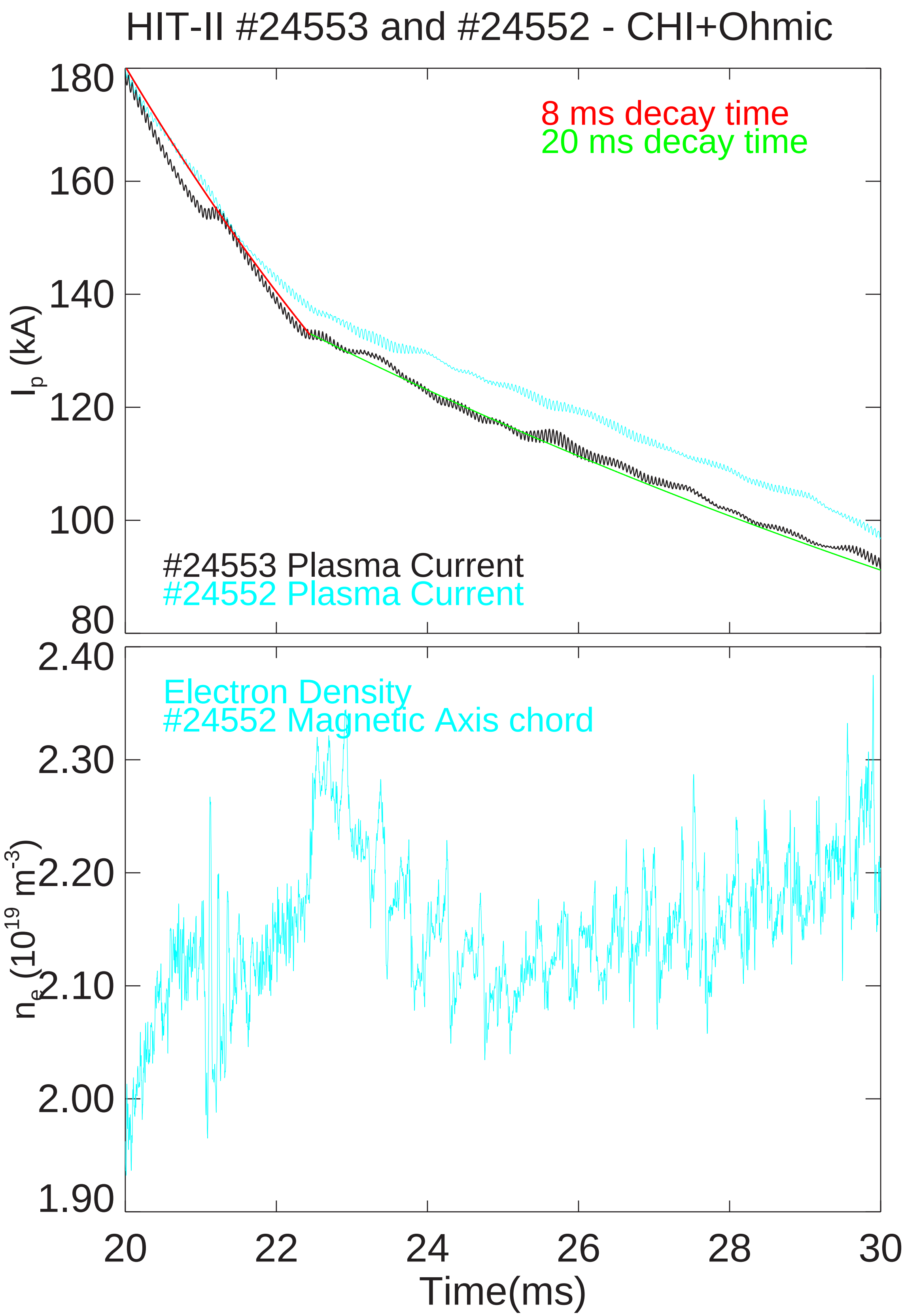


HIT-II #24553 - CHI+Ohmic Discharge
Plasma Current
I_p (kA)
250
200
150
100
50
0
CHI Injector Current
I_inj (kA)
15
10
5
0
Measured Injector Flux
Ψ_inj (mWb)
10
8
6
4
2
0
Measured Loop Voltage
52 mWb Ohmic Flux Swing
V_LOOP (V)
6
4
2
0
-2
I_TF (MA)
1.0
0.8
0.6
0.4
0.2
0.0
TF Current
0
10
20
30
40
Time(ms)


HIT-II #24553 - CHI+Ohmic Discharge
Plasma Current
Ip (kA)
250
200
150
100
50
0
Measured Loop Voltage
52 mWb Ohmic Flux Swing
VLOOP (V)
6
4
2
0
-2
Radiated Power
PRAD (MW)
0.40
0.30
0.20
0.10
0.00
HXR #1 Signal
SHXR1 (V)
1.0
0.5
0.0
0
10
20
30
40
Time(ms)


SPRED Spectrum
SSPRED (arb)
2
1
0
200
220
240
260
280
300
320
340
Wavelength (nm)


HIT-II #24553 and #24552 - CHI+Ohmic
250
200
150
100
50
0
I_p (kA)
#24553 Plasma Current
#24552 Plasma Current
6
4
2
0
-2
V_{LOOP} (V)
Measured Loop Voltage
52 mWb Ohmic Flux Swing
3
2
1
0
n_e (10^{19} m^{-3})
#24553 Edge chord
#24552 Magnetic Axis chord
0
10
20
30
40
Time(ms)


HIT-II #24553 and #24552 - CHI+Ohmic
8 ms decay time
20 ms decay time
#24553 Plasma Current
#24552 Plasma Current
Electron Density
#24552 Magnetic Axis chord
I_p (kA)
n_e (10^{19} m^{-3})
Time(ms)
180
160
140
120
100
80
2.40
2.30
2.20
2.10
2.00
1.90
20
22
24
26
28
30

EFIT Reconstruction of HIT-II Discharges

- EFIT reconstructions of HIT-II discharges are undergoing continual improvement. Presently, HIT-II EFITs utilize:
  - Toroidal plasma current, diamagnetic flux and current on the driven flux (I_{inj})
  - 24 poloidal flux loops
  - 18 Rogowski segments measuring poloidal field
  - 19 poloidal magnetic surface probes
  - Realistic estimates for measurement errors
- The fit functions are of the following form:

$$FF_1'(y) = \gamma_{10} \quad \text{(below the X-point)}$$

$$FF_2'(y) = \gamma_{20} + \gamma_{21} y \quad \text{(above the X-point)}$$

$$p'(y) = \alpha_0(1 - y)$$

  where

$$y \equiv \frac{\psi - \psi_{axis}}{\psi_{abs} - \psi_{axis}}$$

  and ψ_{abs} is the poloidal flux in the absorber region
- Qualitatively, reconstructions fit measurements acceptably. Quantitatively, overall error $\leq 10^{-4}$, but $\chi^2 \ll 64$.
- In the near future, HIT-II EFITs will also utilize:
  - 24 F-coil currents (code is being verified)
  - 12 surface $I_{\mathrm{inj}}(\psi)$-probes
  - Multi-point Thomson scattering data
  - Internal magnetic probing data

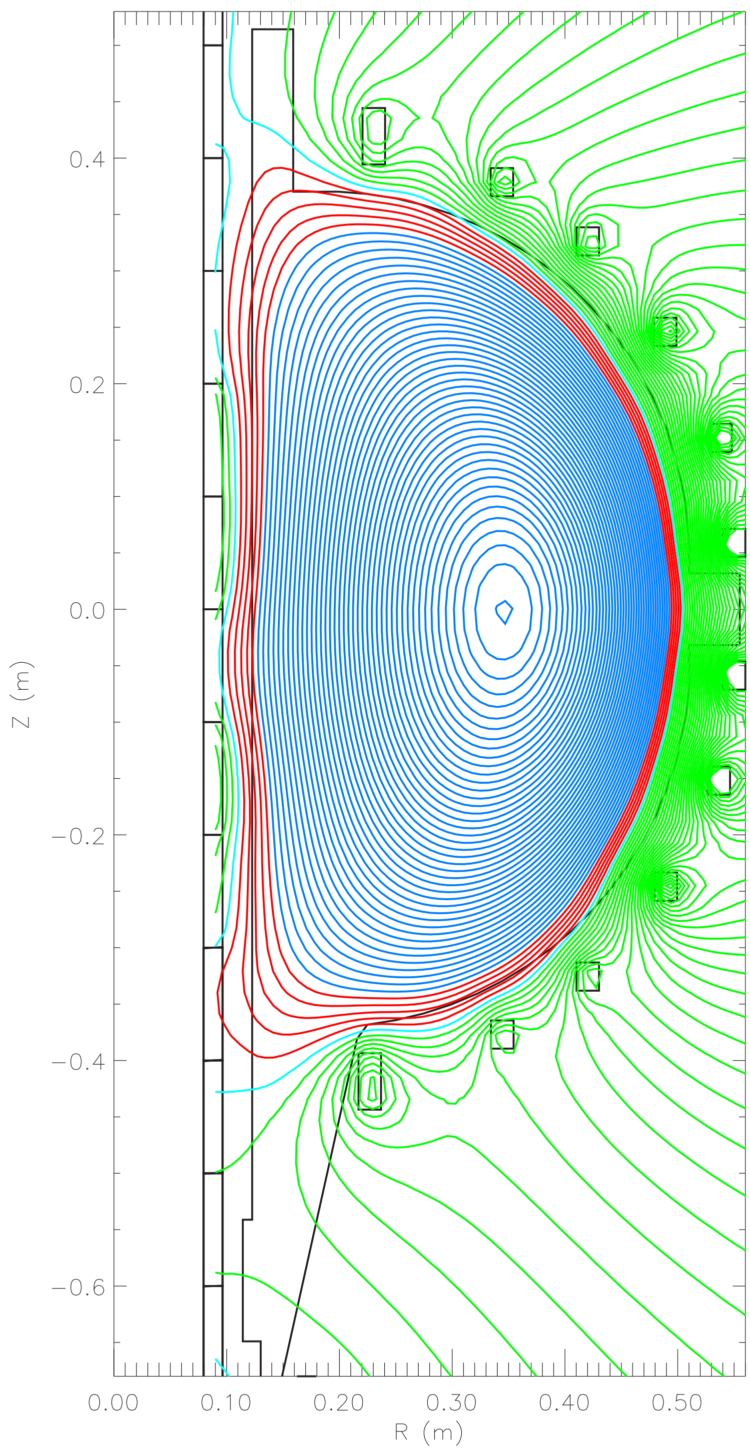
HIT-II #24553 CHI+Ohmic Results from EFIT Analysis

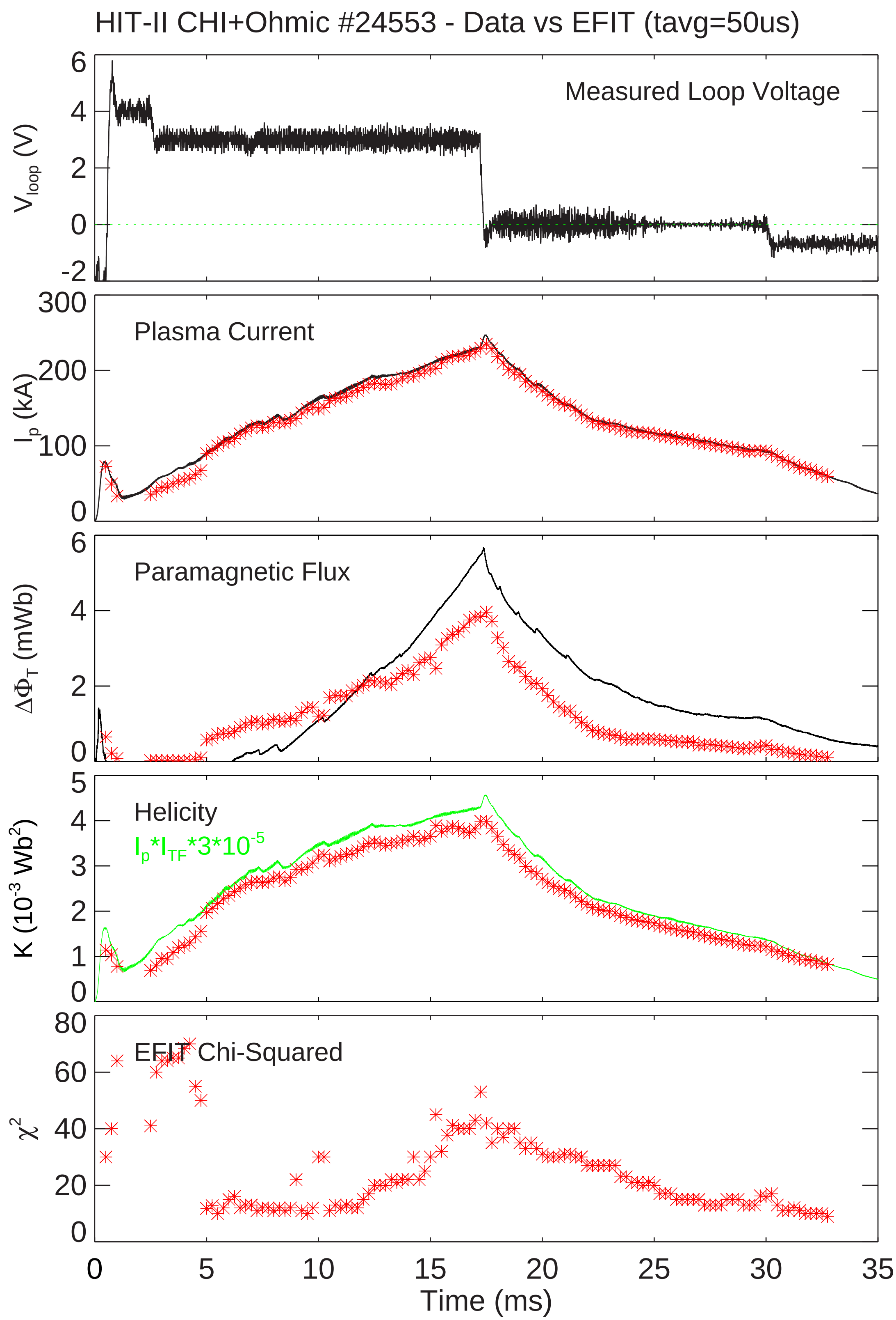
Discharge #24553 has best HIT-II plasma performance:

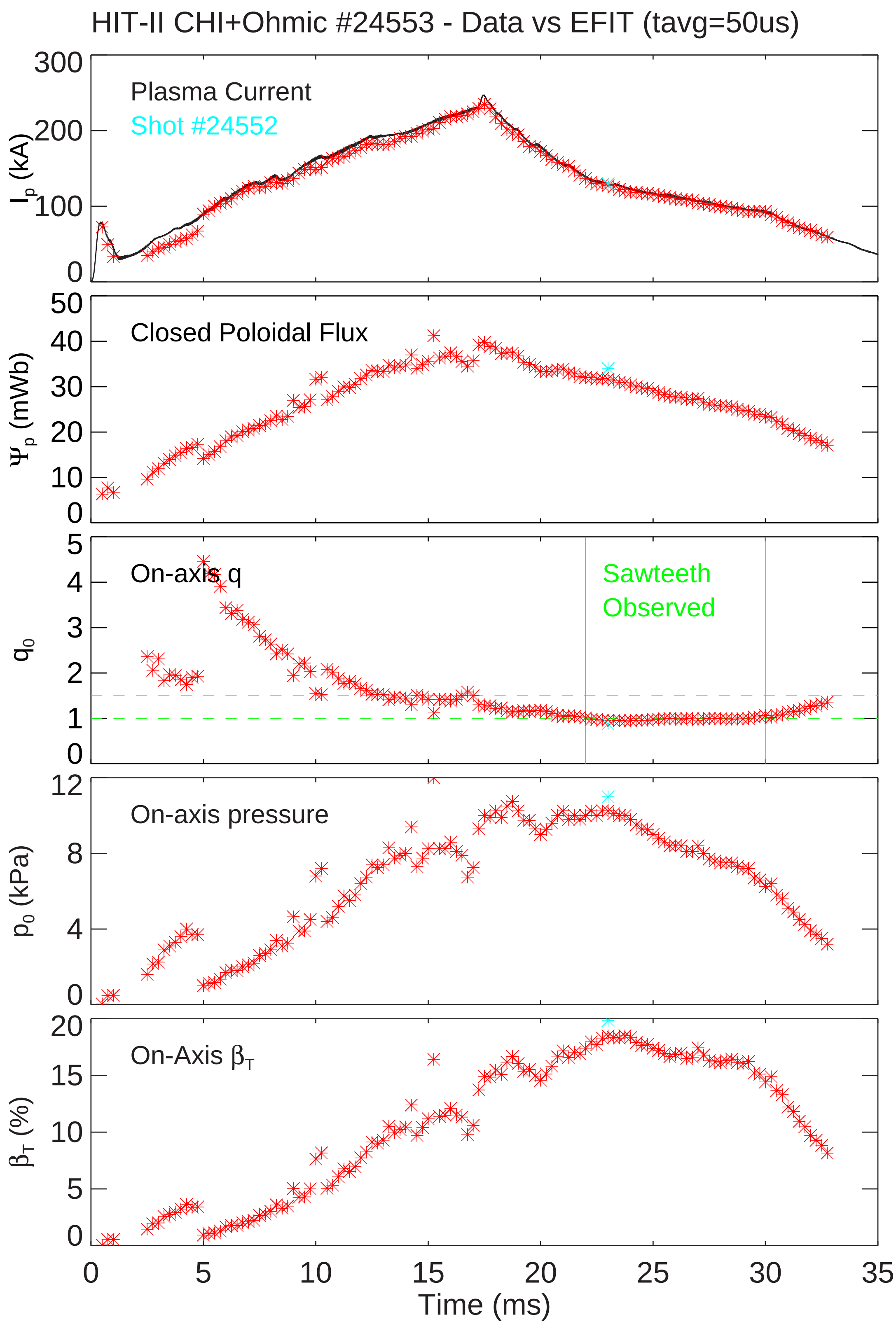
- Peak toroidal plasma current of 250 kA
- Current decay time of up to 20 ms
- Peak closed poloidal flux of 40 mWb, using 52 mWb Ohmic flux swing
- $q_0 < 1$ period correlates with observed sawteeth
- $\beta_p \approx 1.5$ and on-axis $\beta_T \approx 18\%$

Poloidal Flux Contours for HIT-II #24553 (CHI+OH) at t=17.5 ms

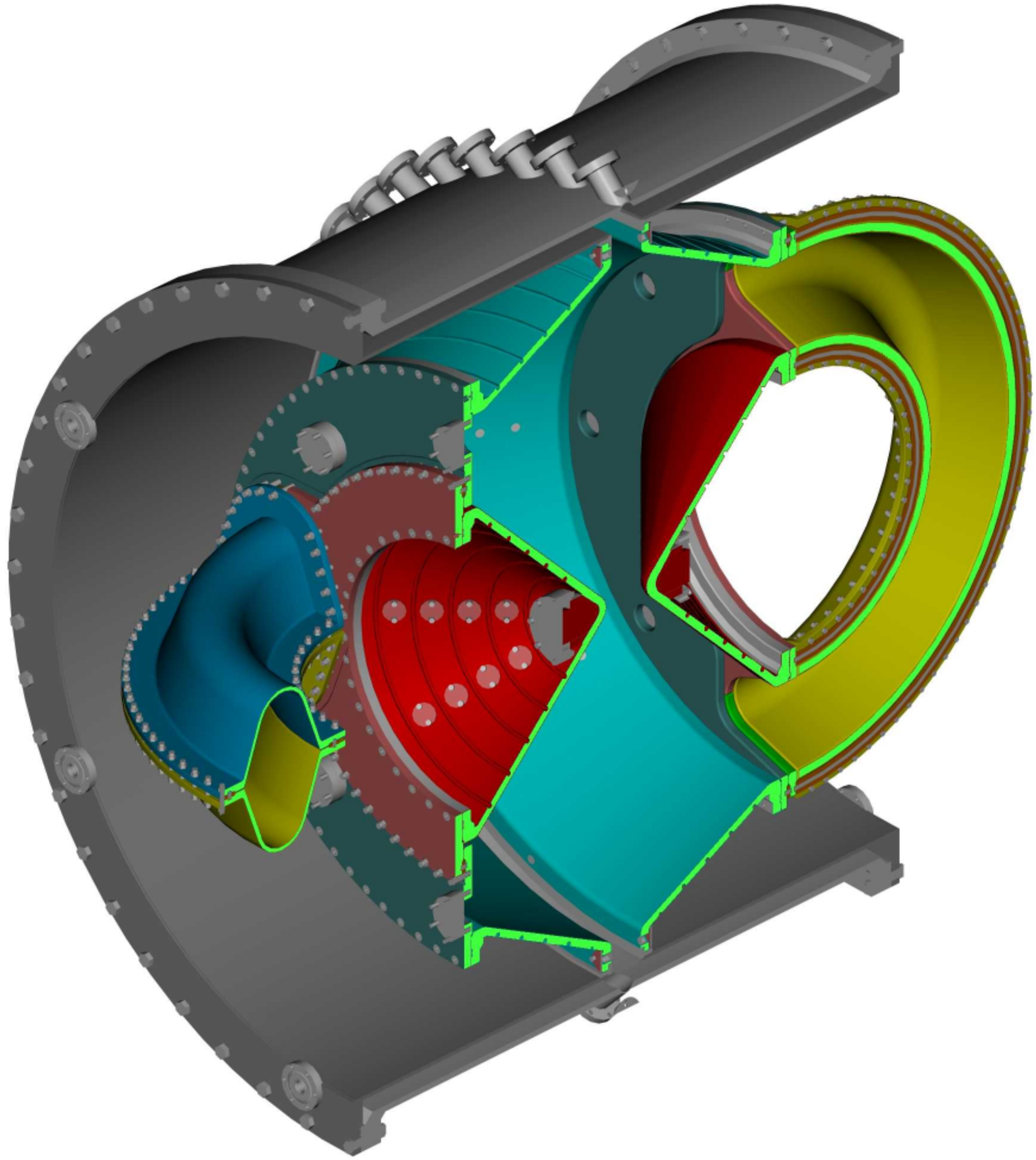
from EFIT reconstruction




HIT-II CHI+Ohmic #24553 - Data vs EFIT (tavg=50us)
Measured Loop Voltage
V_loop (V)
Plasma Current
I_p (kA)
Paramagnetic Flux
ΔΦ_T (mWb)
Helicity
I_p*I_TF*3*10^-5
K (10^-3 Wb^2)
EFIT Chi-Squared
χ^2
Time (ms)


HIT-II CHI+Ohmic #24553 - Data vs EFIT (tavg=50us)
Plasma Current
Shot #24552
Ip (kA)
300
200
100
0
Closed Poloidal Flux
Ψp (mWb)
50
40
30
20
10
0
On-axis q
Sawteeth
Observed
q0
5
4
3
2
1
0
On-axis pressure
p0 (kPa)
12
8
4
0
On-Axis βT
βT (%)
20
15
10
5
0
0
5
10
15
20
25
30
35
Time (ms)

The Proto-SI Device:
Design Cross-section



The Proto-SI Device: Under Construction