NSTX

Measurements of Plasma Diamagnetism in NSTX

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Abstract

A system has been installed in NSTX to measure the toroidal flux displaced by the plasma by integrating the total voltage applied to the toroidal field (TF) coil and subtracting the self-inductive and resistive components, which are up to two orders of magnitude larger than the diamagnetic flux. A precision analog integrator with fixed coefficients is used to remove the bulk of the resistive and inductive coil flux, thereby reducing the dynamic range of the resulting flux analog. The residual coupling arising from the thermal change in TF resistance and the small direct couplings to the poloidal field windings are removed by software.

Provided that the TF pulse has a flattop beginning before and ending after the plasma current pulse, a measurement of the plasma diamagnetism accurate to 2mWb can be obtained with a time resolution of 2ms. At the nominal NSTX toroidal field, 0.3T on axis, this corresponds to an uncertainty of roughly 2.5kJ in the plasma kinetic energy in the transverse degrees of freedom. The diamagnetic flux can be used as a constraint in the analysis of the plasma equilibrium with the EFIT code.

The 1 Minute Summary

- Measurements of diamagnetic flux help determine plasma energy
  - For low aspect-ratio, the interpretation requires an equilibrium code
- Insulating breaks for CHI and compact center stack prevent installing a dedicated loop in NSTX
- The diamagnetic flux is linked by the toroidal field coil but it is very small compared to the self-inductive and resistive flux of the coil
- We have installed a system to measure the TF flux accurately
  - Uses analog integrator and digital post-processing
- With this system, we can measure the diamagnetic flux with an uncertainty of about 2mWb in normal NSTX plasmas
- These measurements are being used as an additional constraint in EFIT analyses of the NSTX plasma equilibrium

Diagnostics Installed Aug 2001

* In operation • In commissioning phase [Collaborating institution]

Confinement Studies

- * Magnetics for equilibrium reconstruction
- *** Diamagnetic flux measurement**
- * Thomson scattering (10 ch., 60Hz)
- * 2 mm interferometer (single chord)
- * VB detector (single chord)
- * Bolometer array (midplane tangential)
- * X-ray crystal spectrometer ($T_i(0)$, $T_e(0)$)
- * X-ray pulse height analyzer
- * Charge Exchange Recombination Spectroscopy (CHERS): T_i & v_ϕ (18 ch.)
- * Neutral particle analyzer (central chord)
- • Electron Bernstein wave radiometer
- • FIReTIP 119µm interf'r/polarim'r (2 ch) [UCD]

MHD/Fluctuations

- * High-n and high-frequency Mirnov arrays
- * Soft x-ray arrays (3) [JHU]
- * Edge reflectometer [UCLA]
- * Edge fluctuation imaging [LANL]
- * Fast ion loss probe

Plasma Monitoring

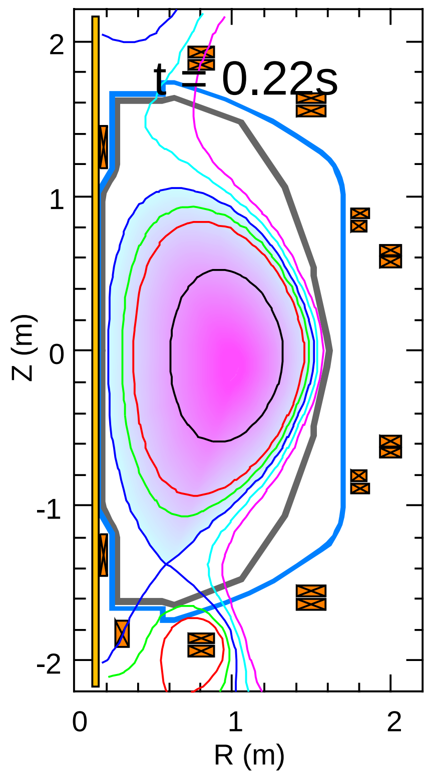
- * Fast visible camera [LANL]
- * VIPS-1: Visible spectrometer (reticon)
- * VIPS-2: Visible spectrometer (CCD)
- * SPRED: UV spectrometer (CCD)
- * GRITS: VUV spectrometer [JHU]
- * Fission chamber neutron measurement
- * Fast neutron measurement
- * 1-D CCD H_α camera [ORNL]
- * Visible filterscopes (H_α, OII, CII) [ORNL]
- * Scrape-off layer reflectometer [ORNL]
- • Locked mode coils
- • IR camera

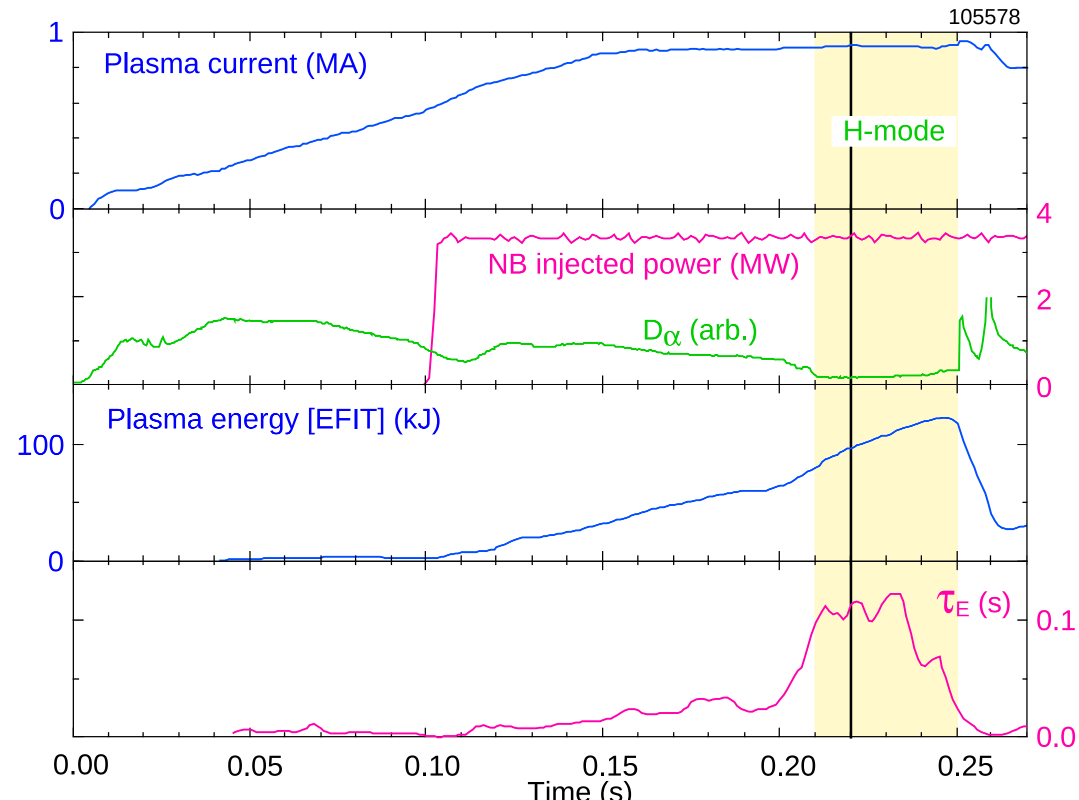
External Magnetic Diagnostics for EFIT Analysis

- B-field coils, flux loops and coil currents provide basic data for EFIT
  - Least-squares solution of G-S equation with parametrized profiles

  ⇒ configuration and global plasma parameters as functions of time

- Without internal measurements some ambiguity remains between β_p, l_i





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Diamagnetic Flux Yields Plasma Perpendicular Energy

Basic equilibrium relation *[e.g. Lao et al., Nucl.Fusion **25** (1985) 1421]*

$$W_\perp = \int_\Omega p_\perp dV = \int_\Omega \frac{B_{tv}^2 - B_t^2}{2\mu_0} dV + \int_\Gamma \frac{B_p^2}{2\mu_0} [(R - R_t)\,\mathbf{e}_R + Z\,\mathbf{e}_Z] \cdot d\boldsymbol{S}$$

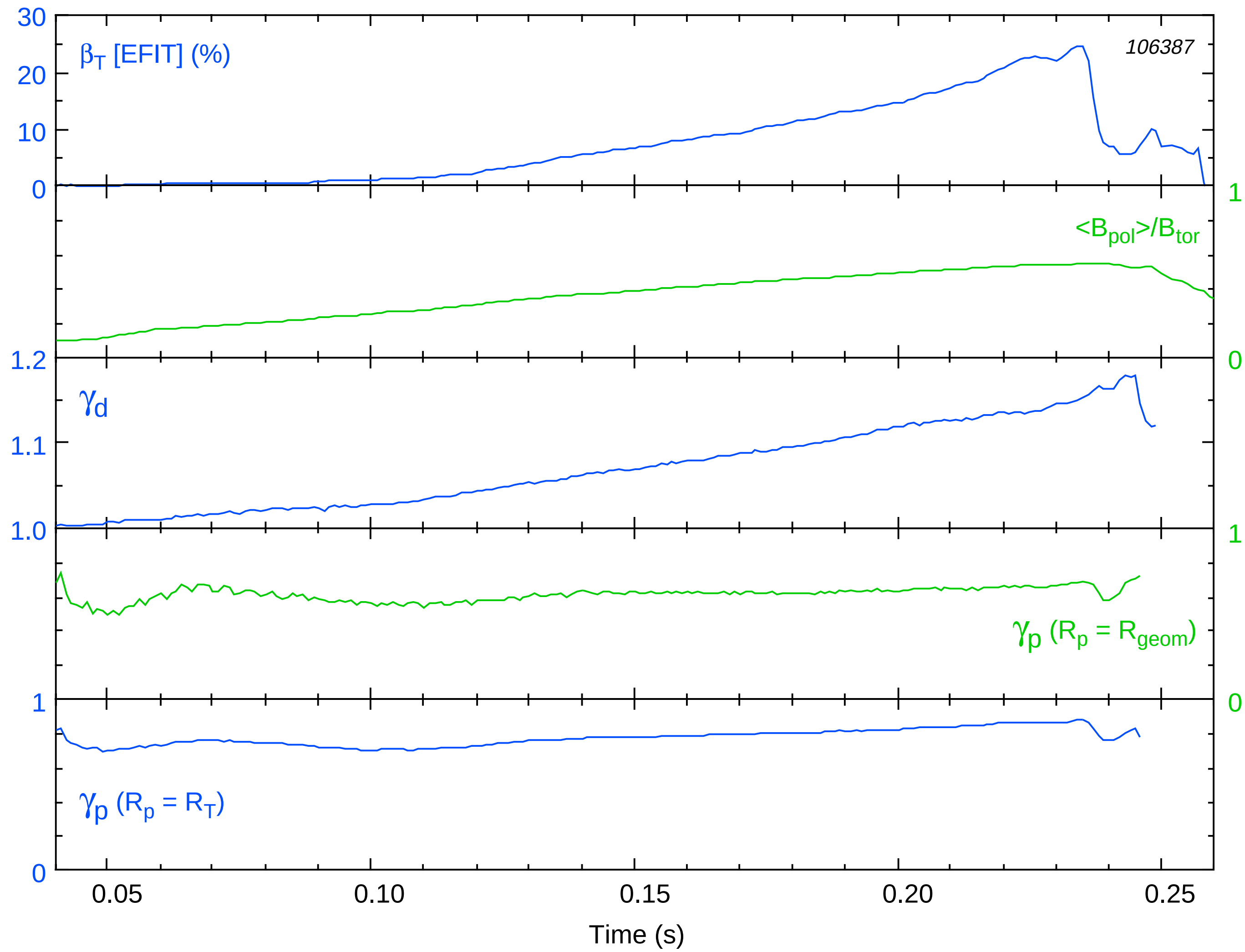
$$= I_t\, \phi_d\, \gamma_d + \tfrac{1}{4}\mu_0\, R_p\, I_p^2\, \gamma_p$$

where

- $W_\perp$, $p_\perp$: plasma energy and pressure perpendicular to the toroidal field
- B_{tv}, B_t: vacuum and actual toroidal field in the plasma region
- B_p: poloidal field;
- Ω, dV: plasma volume and its element
- Γ, $d\boldsymbol{S}$: plasma bounding surface and its vector element
- $\mathbf{e}_R$, $\mathbf{e}_Z$: unit radial (R) and major axial displacement (Z) vectors;
- R_t: curvature weighted average major radius
- I_t, I_p: toroidal field coil threading current and plasma current
- ϕ_d: toroidal flux displaced by the plasma from an encircling loop
- R_p: representative plasma major radius
- γ_d, γ_p: coefficients; γ_d, $\gamma_p \rightarrow 1$ for high aspect-ratio circular plasma

Low aspect-ratio Introduces Significant Changes

- Since $B_p \sim B_t$ and the cross-section in NSTX is shaped, both γ_d, $\gamma_p \neq 1$



Challenges for a Diamagnetic Measurement in NSTX

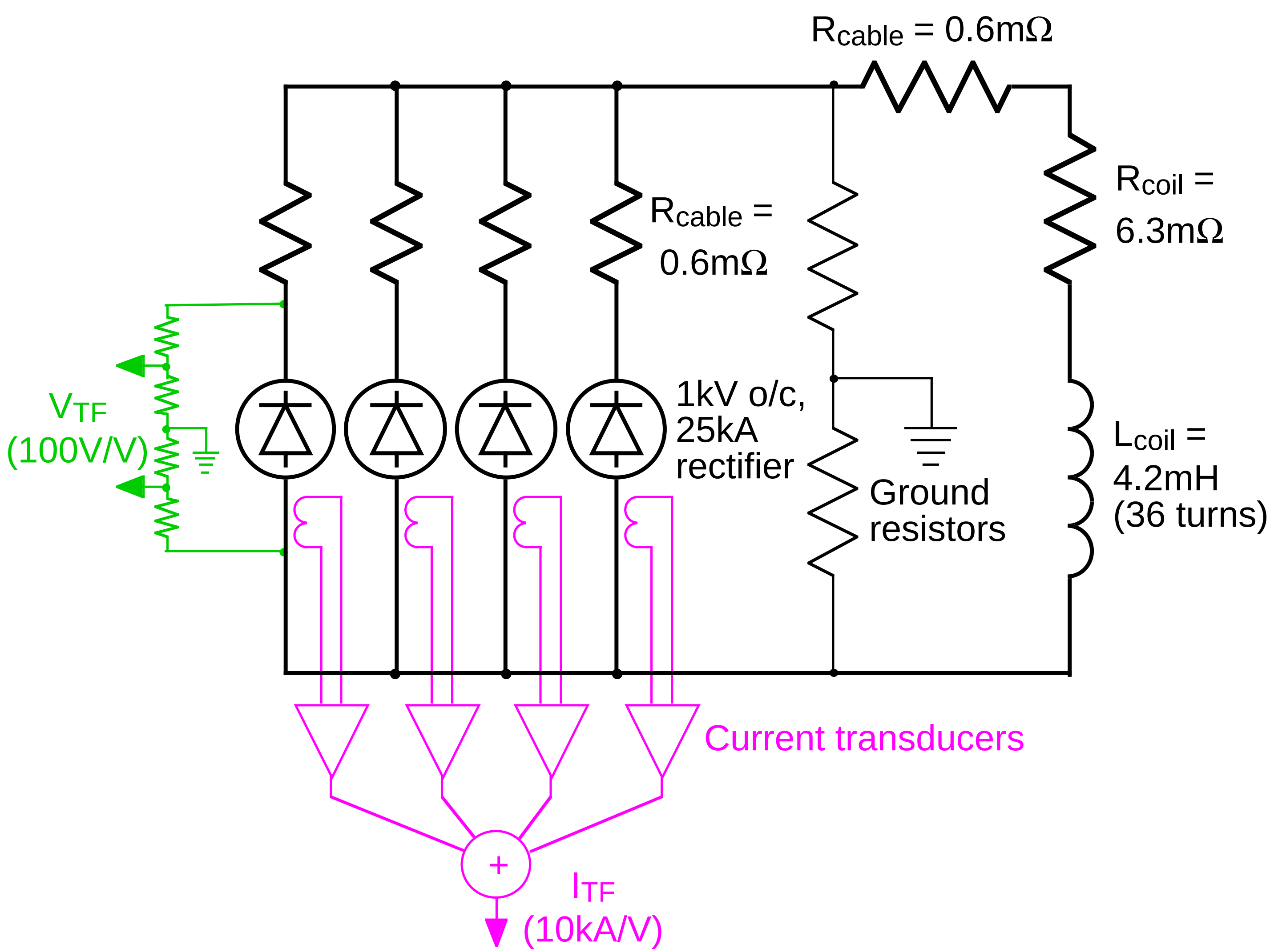
- Poloidal breaks for CHI prevent using internal loop for toroidal flux
  - Breaks allow rapid penetration of toroidal flux for external loop, *but*
- No room in center stack for loop with adequate isolation and stability
- Try using the TF coil itself to measure flux displaced by plasma
  - Method used on PDX [P. Thomas, report PPPL-1979 (1983)]

$$N_{TF}\phi_d = -\int_0^t V_{TF}\,dt' + L_{TF}I_{TF} + \int_0^t R_{TF}I_{TF}\,dt' + \sum_j M_{TF:j}I_j + \sum_{PF} M_{TF:PF}I_{PF}$$

N_{TF}: number of turns in TF coil (36)
V_{TF}, I_{TF}: coil terminal voltage and current
L_{TF}, R_{TF}: coil inductance and resistance (as functions of time)
$I_{PF}, M_{TF:PF}$: PF coil currents and their mutual inductances to the TF
$I_j, M_{TF:j}$: Currents in structure driven by dI_{TF}/dt and mutual inductances

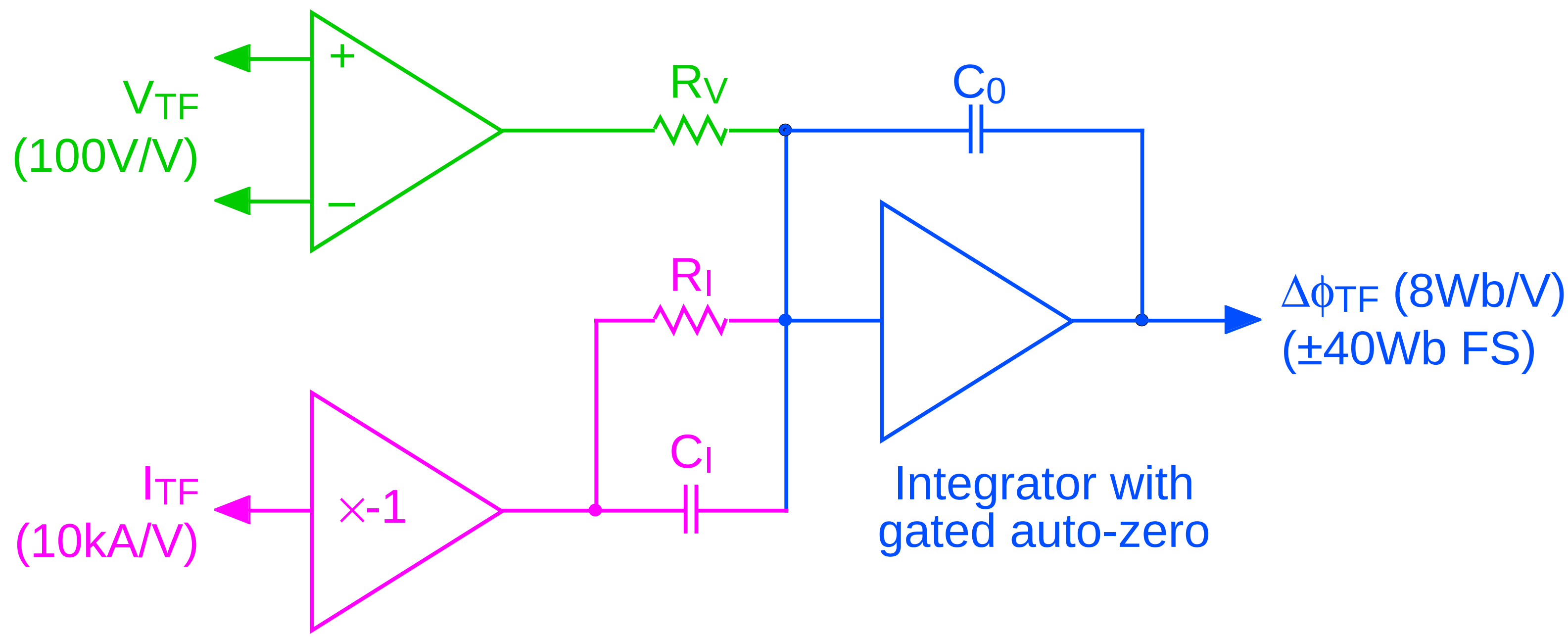
- ϕ_d ~ 0.1Wb while $L_{TF} I_{TF}$ ~ 200Wb and $\int R_{TF}I_{TF}dt'$ ~ 150Wb in a 0.4s pulse
  - Very accurate compensation and modelling of the TF is needed

NSTX Toroidal Field Coil Circuit and Diagnostics



- Precision DC current transducers make measurement possible

Analog Circuit Integrates Coil Voltage and Removes First-Order Self-Inductive and Resistive Flux Terms



1) $100[V/V]R_V C_0 = 8[s]$
2) $100[V/V]R_V C_I/10^4[A/V] = L_{TF0}$
3) $R_I C_I = L_{TF0}/R_{TF0}$

- All input signals received differentially
- High stability components used throughout

Thermal Resistance Change of TF

- Adiabatic resistive heating of conductor carrying current $I(t)$ (A)

$$R(t) = R(0)\exp\left[\frac{\alpha}{SA^2}\int_0^t I^2(t')dt'\right]$$

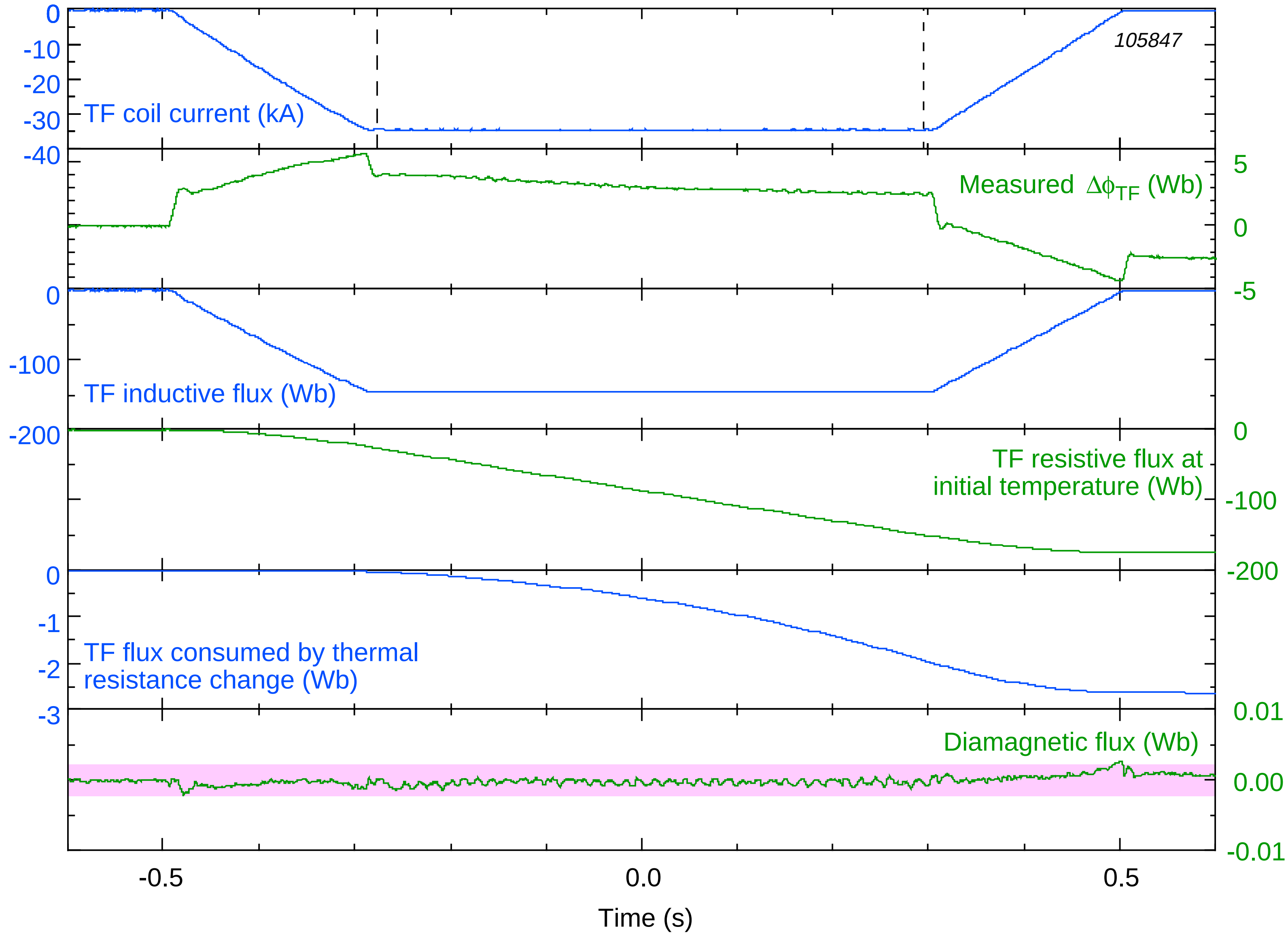
$R(t)$: resistance; α (ΩmC^{-1}): temperature coefficient of resistivity;
S ($Jm^{-3}C^{-1}$): volume specific heat; A (m^2): cross-section area.

  - Inner legs of TF coil can rise from 10°C to 90°C during a TF pulse
  - Causes non-linear increase in resistive flux during TF flattop

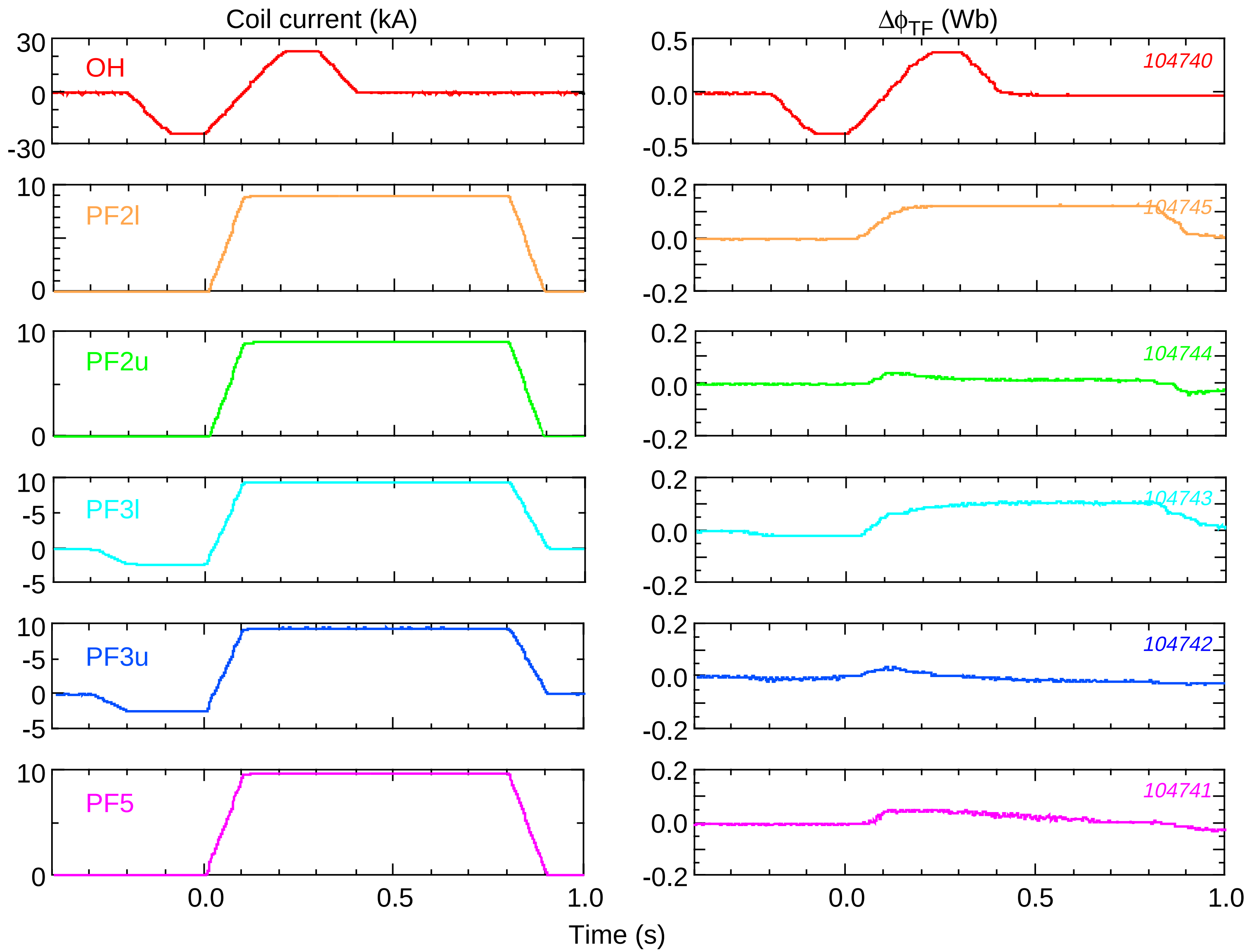
$$\phi_{res}(t) = \int_0^t I_{TF}(t')\left\{R_{TF0} + R_{IL0}\left[\exp\left(4.5\times 10^{-11}\int_0^{t'} I_{TF}^2(t'')\,dt''\right) - 1\right]\right\} dt'$$

- Must also account for effects of:
  - Water already in the cooling channels (~6% decrease in ΔR_{TF})
  - Inflowing cooling water (~4% $\times$ t_{pulse}[s] decrease)
  - Diffusion of heat into insulation (~4% $\times$ $\sqrt{t_{pulse}}$[s] decrease)
- Fit to data implies ΔR is about 90% of adiabatic expectation

TF Characteristics are Well Modelled During Flattop



PF Couplings Measured in Single-Field Test Shots



PF Couplings Originate In TF Connections

- Measured PF/TF mutual inductances >1µH:

OH	(R = 0.13m, solenoid, 960 turns):	16.5 µH
PF2l	(R = 0.80m, Z = -1.89m, 28 turns):	13.6 µH
PF3l	(R = 1.49m, Z = -1.59m, 30 turns):	10.3 µH
PF5	(R = 2.00m, Z = ±0.62m, 48 turns):	4.3 µH

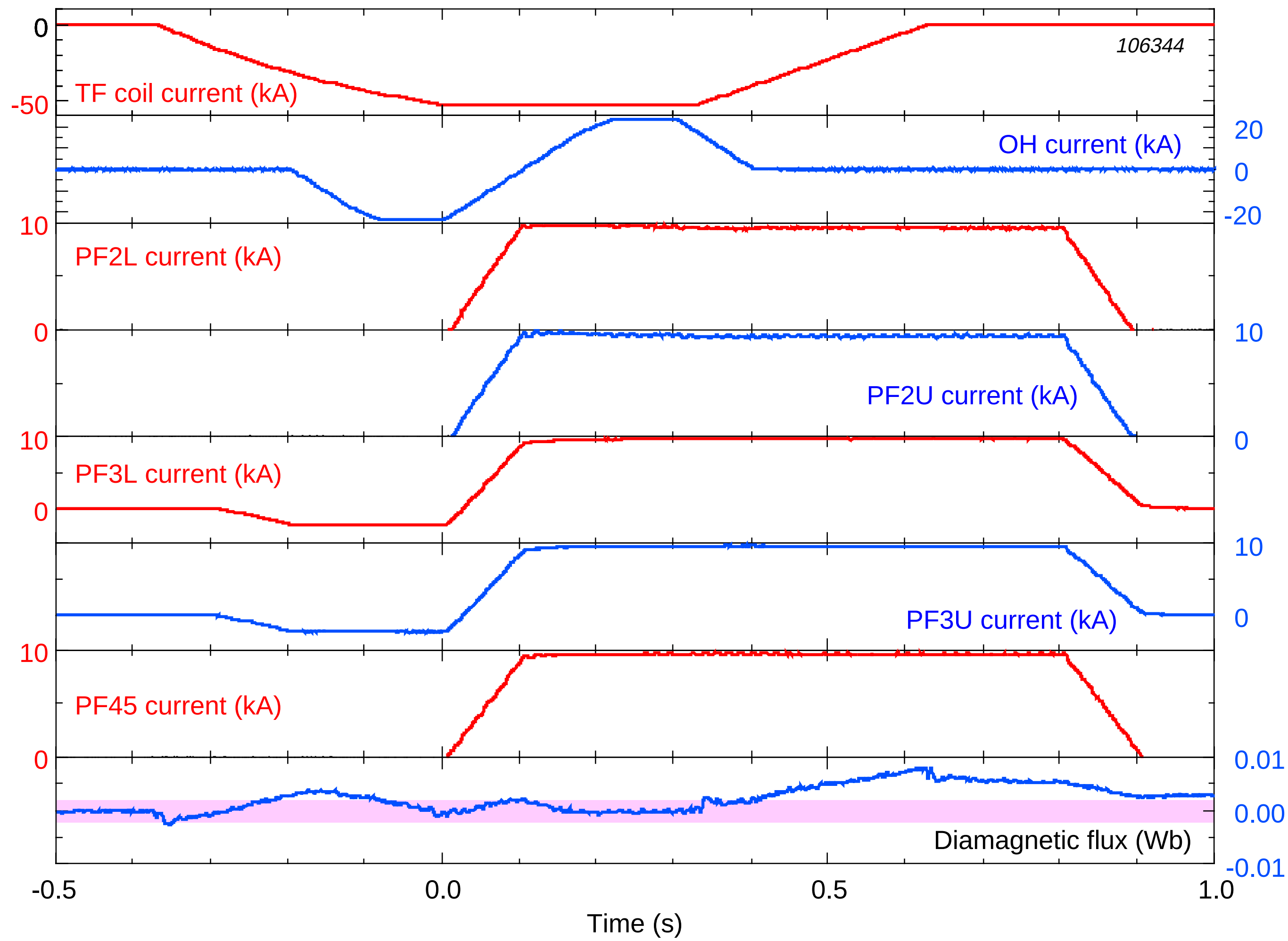
  - These coils generate significant field through TF interconnections and buswork at bottom of machine

- Measuring direct plasma current coupling to TF requires reversing I_p/I_{TF}
  - In a low-β plasma ($W_\perp << {}^1/_4\, \mu_0 R_p I_p^{\,2}$), displaced TF flux is

$$\Delta\phi_{TF} = N_{TF}\phi_d + M_{TF,p}I_p = \left[\tfrac{1}{4}\mu_0\left(\gamma_p/\gamma_d\right)R_p / I_t\right]I_p^2 + M_{TF,p}I_p$$

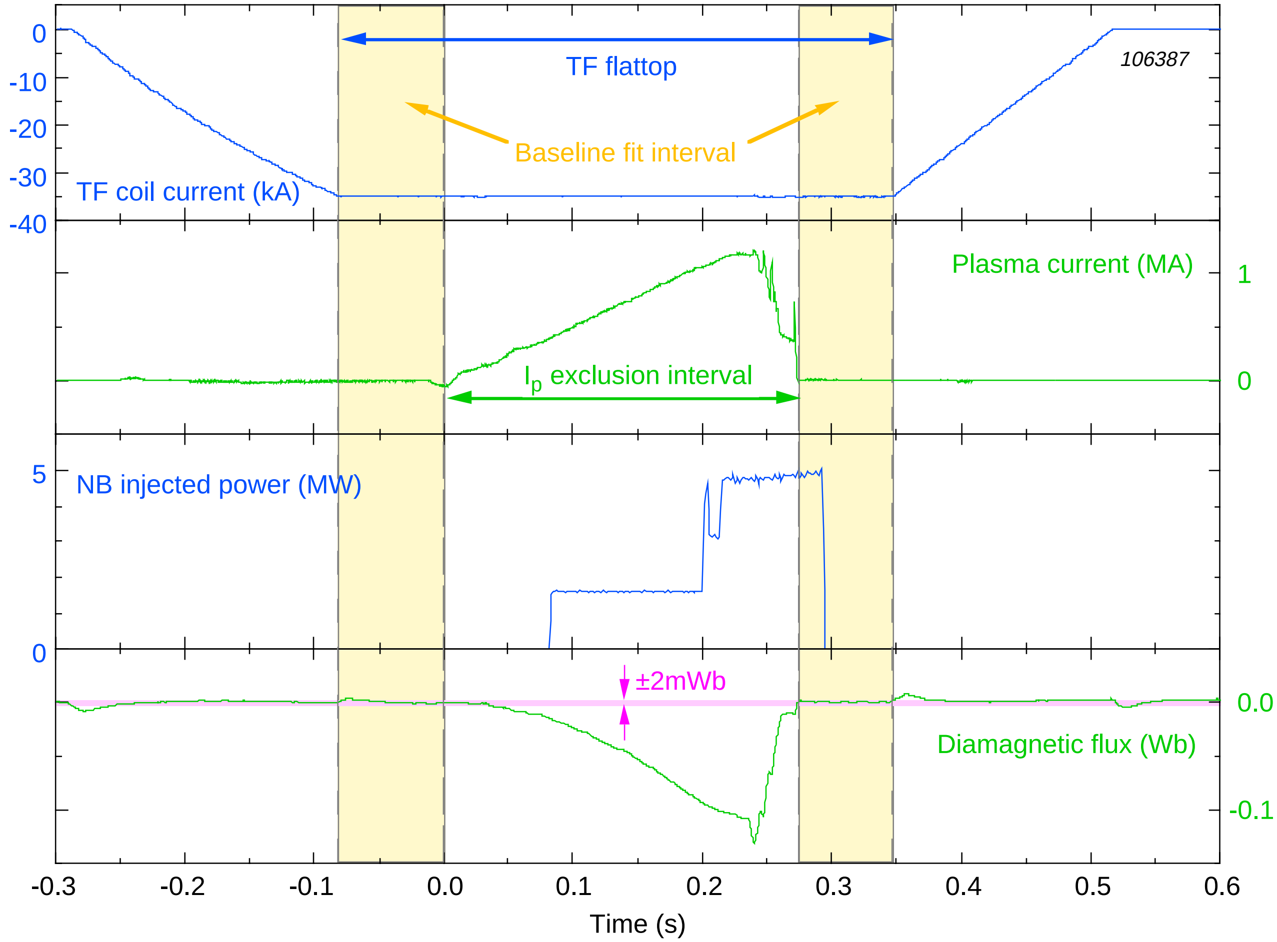
  - This has not yet been done
  - Estimate from PF5 coupling is that direct I_p coupling is small, <0.1 µH
    - $\Delta\phi_d$ < 3 mWb for I_p < 1.2 MA

Uncertainty of 2mWb Achieved for Diamagnetic Flux in Combined TF/PF Shots During TF Flattop



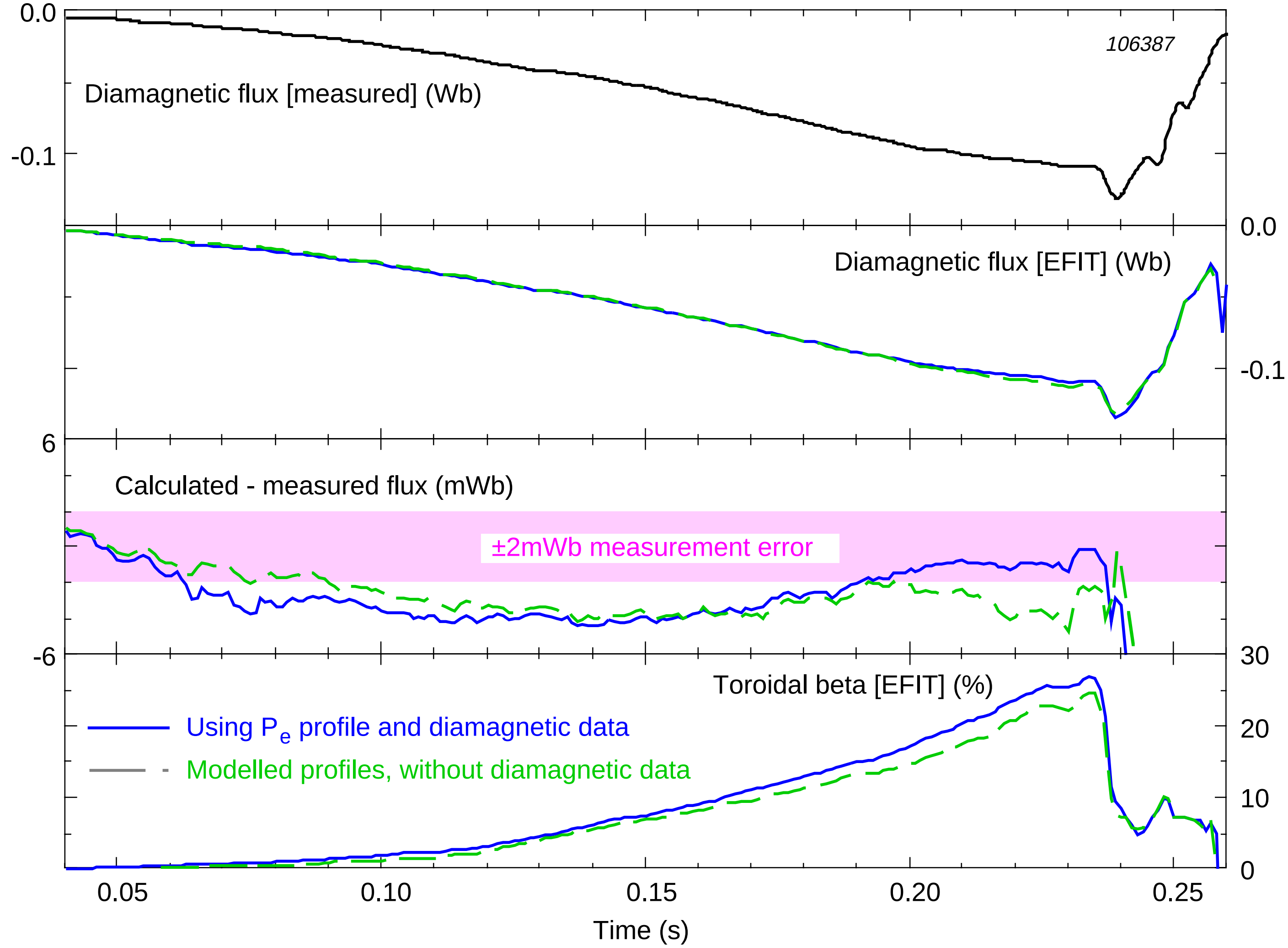
- ♦ Drift during TF rampdown caused mainly by power supply imbalance

In Plasma Shots, Fit Residual Resistive TF Flux During TF Flattop When Plasma Current Absent

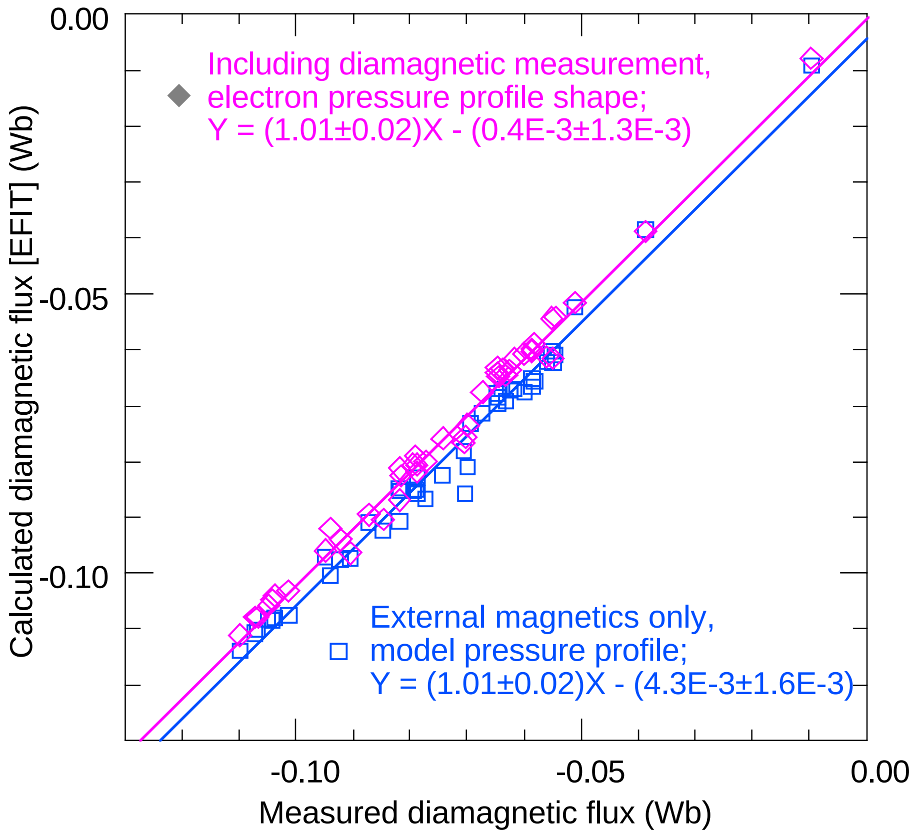


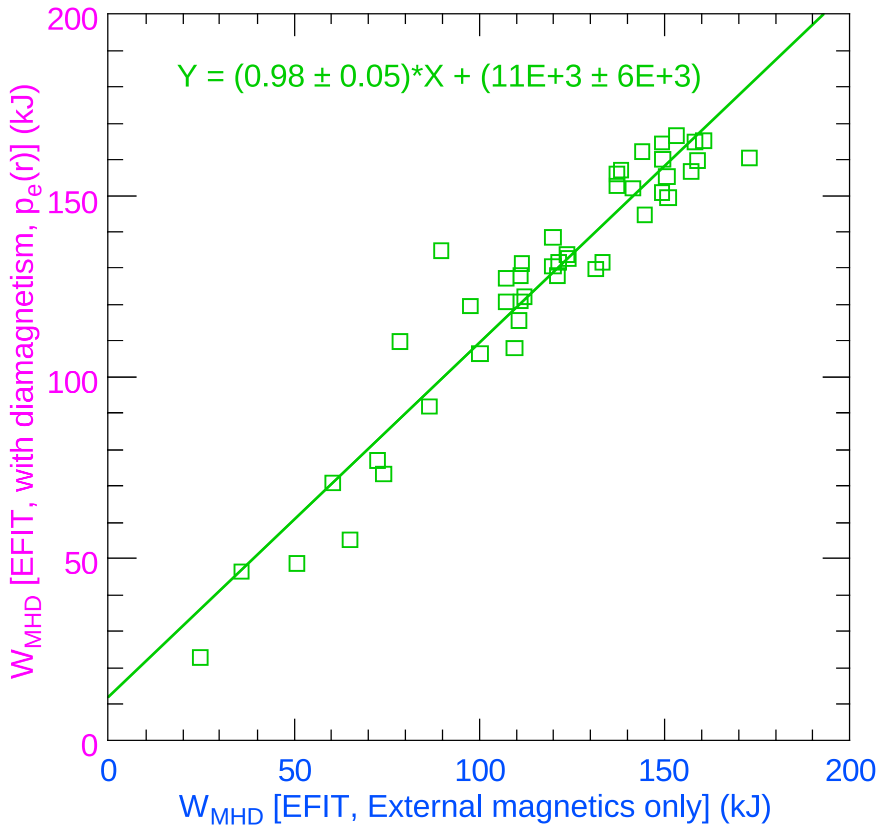
- Fit coefficient of resistive flux varies by about 1% with temperature of air-cooled buswork; coefficient of inductive flux varies by <0.1%

Diamagnetic Flux and Pressure Profile Shape Provide Additional Constraints for EFIT



EFIT Analysis Constrained by Diamagnetic Flux and Using Measured Form for Pressure Profile Available for Most High-β Shots





- Measurement will be extended to higher-field shots when longer TF flattop is available or compensation fit can be extended into TF ramp

Summary

- ♦ It has proved feasible to use the TF coil to measure the diamagnetic flux displaced from the plasma in NSTX.
- ♦ A hybrid analog/digital measurement system has been adopted to remove the TF self-inductive and resistive flux
  - High precision divider for coil voltage and coil current measurements
  - High stability differential analog integrator with input coefficients trimmed to reduce residual flux in TF-only shots
  - Single-coil shots determine couplings and thermal model for TF coil
- ♦ A measurement uncertainty of about ±2mWb has been achieved in suitable shots
  - Measurement presently depends on fitting remaining variable flux terms during TF flattop outside the plasma current interval
  - May be possible to improve residual coupling model
- ♦ Measurement increases confidence in the EFIT analysis for NSTX