NSTX-U

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Layered low-pass magnetic sensor compensations for real-time mode identification in tokamaks

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DIII-D
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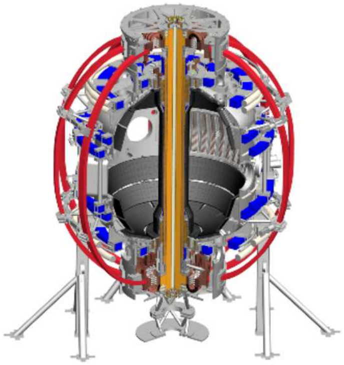


Presentation outline

- Demonstration and tuning of layered low-pass (LLP) compensations:
  - LLP algorithm goals and merits
  - Numerical formulation
  - NSTX-U compensation example
  - Determining the compensation coefficients (DC3D/AC3D, DC2D, AC2D)
- Cross-machine portability and algorithmic improvements:
  - Demonstration of vacuum field pickup compensation on DIII-D
  - Improving AC2D compensations with chirped PF coil training shots
- Mode identification:
  - Numerical formulation
  - NSTX-U mode identification example (both offline and real-time)
  - DIII-D mode identification example (offline)

Features of the layered low-pass compensation algorithm

- What is the layered low-pass (LLP) compensation algorithm?
  - The goal is to remove all vacuum field pickup (both DC and AC) from 3D magnetic sensor difference pairs → isolates plasma-generated fields
  - AC pickup is compensated by low-pass filtering (LPF) the loop voltage that the coils apply to passive conducting structures

    → Use multiple LPF time constants → multiple low-pass 'layers'
  - After isolating the plasma-generated fields, conduct mode identification:

    → Facilitates locked mode detection and dynamic mode control
  - Generalized python implementation facilities cross-machine portability

- Merits of the LLP algorithm:
  - The same compensation techniques are applied to all vacuum field sources (i.e., both 2D coils and 3D coils)
  - Compensation is very fast (seconds to execute per sensor array)
  - Conducted entirely in the time domain → tailor-made for real-time

Numerical formulation of the layered low-pass algorithm

- Compensation coefficients, G, capture the contribution from each source, S, to a given signal, δB
- DC sources are either a coil current or the average local magnetic field
- AC sources represent currents induced in passive structures
- AC sources are approximated as low-pass filtered (LPF) driving voltages (either $\partial_t I_{\text{coil}}$ or V_{loop})
- Multiple low-pass time constants, τ, are applied to each AC source to account for superposed currents
  → **'Layered low-pass' approach**

$$\delta B^i_{\text{comp}} = \delta B^i_{\text{raw}} - \delta B^i_{\text{DC}} - \delta B^i_{\text{AC}}$$

$$\delta B^i_{\text{DC}} \equiv \sum_j^{N_{\text{DC}}} G^{ij}_{\text{DC}} \, S^j_{\text{DC}}$$

$$\delta B^i_{\text{AC}} \equiv \sum_j^{N_{\text{AC}}} \sum_k^{N_\tau} G^{ijk}_{\text{AC}} \, S^{jk}_{\text{AC}}$$

$$S^j_{\text{DC}} = \begin{cases} I^j_{\text{coil}} & , \ \text{DCTF/PF/3D} \\ \langle B_{\text{P/R}} \rangle & , \ \text{BP2D/BR2D} \end{cases}$$

$$S^{jk}_{\text{AC}} = \begin{cases} \text{LPF}\left(\partial_t I^j_{\text{coil}} \,|\, \tau^k_{\text{AC}}\right) & , \ \text{ACTF/PF/3D} \\ \text{LPF}\left(V^j_{\text{loop}} \,|\, \tau^k_{\text{AC}}\right) & , \ \text{ACVL} \end{cases}$$

Layered low-pass compensation levels

Compensation	Description
DCTF	Direct pickup from the main toroidal field coil
DCPF	Direct pickup from the axisymmetric poloidal field coils
DC3D	Direct pickup from the non-axisymmetric field coils
BP2D / BR2D	Axisymmetric magnetic field compensation to account for sensor gain mismatches
ACTF	Indirect pickup from currents induced by the main toroidal field coil
ACPF	Coil-current-based compensation for indirect pickup from currents induced by the axisymmetric poloidal field coils
ACVL	Loop-voltage-based compensation for indirect pickup from currents induced by the axisymmetric PF coils and by the plasma
AC3D	Indirect pickup from currents induced by non-axisymmetric coils

Diagram of 3D coils and sensors in NSTX-U and DIII-D

Place holder

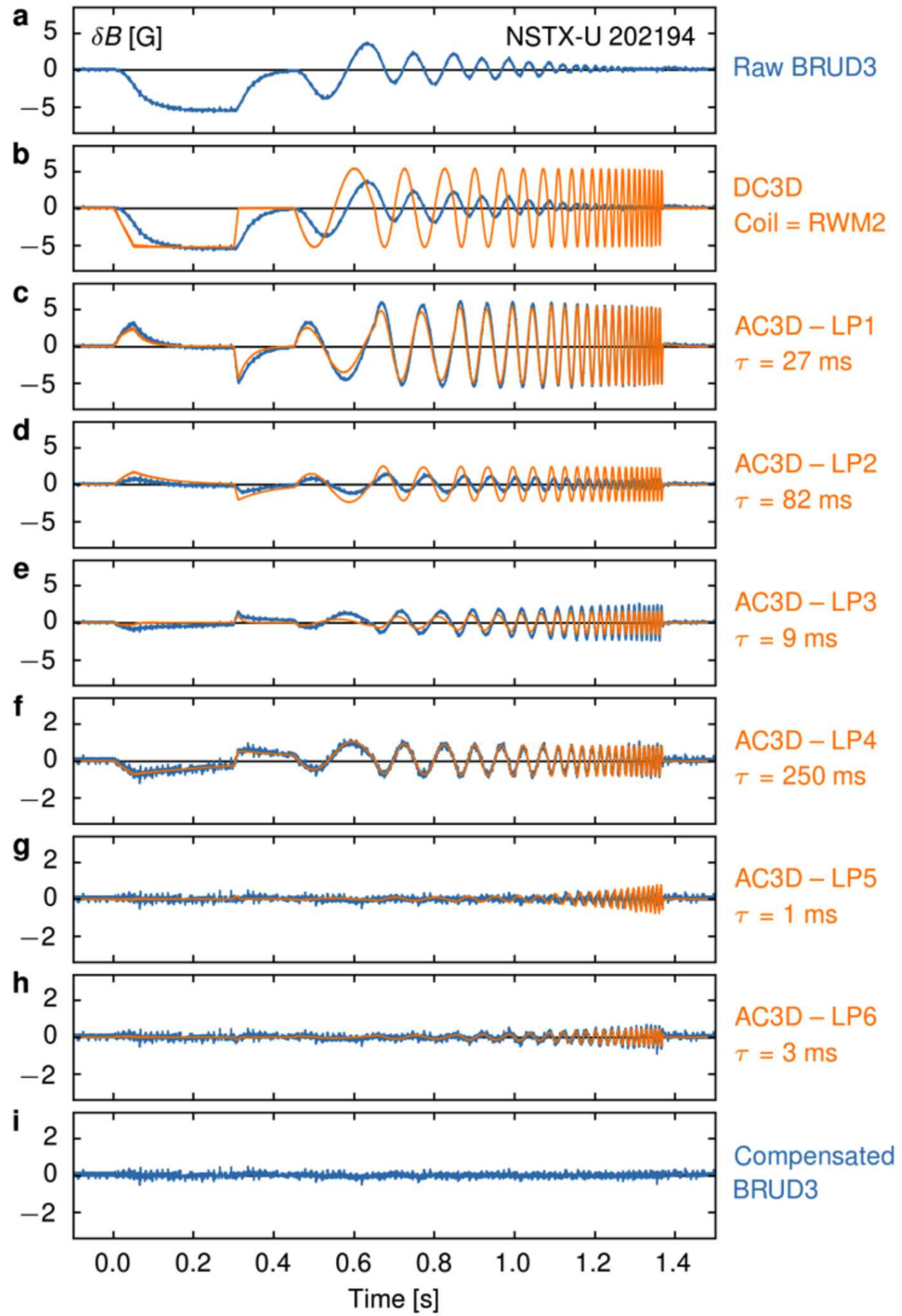
Example of layered low-pass sensor compensation

a A chirped current pulse on the RWM2 coil in NSTX-U generates a vacuum response on the BRUD3 radial field sensor difference pair

b Removing just the DC3D contribution amplifies rather than cancels the AC3D response

c-h Six low-pass (LP) layers with LPF time constants of τ = 1–250 ms successfully compensate out the AC3D response

i The original ~5 G response is compensated down to the noise threshold (< 0.1 G)



Determining the LLP coefficients: DC3D & AC3D

- Acquire a 'training shot' for the jth 3D coil (such as the RMW2 example from the previous slide)
- Construct a source matrix, **S**, with one row for each time point of the training data and one column for each source term ($N_t \times N_\tau$+1)
- Construct a coefficient vector, **g**, of length N_τ+1 that holds the compensation coefficients
- Construct a data vector, **b**, of length N_t that holds the training data from the ith sensor

Take the pseudo-inverse of **S** (**S**$^+$) to identify the coefficients, **g**, that best fit the training data, **b**:

$$\mathbf{b}^i_{3D} = \mathbf{S}^j_{3D} \cdot \mathbf{g}^{ij}_{3D}$$

$$\mathbf{g}^{ij}_{3D} = \left(\mathbf{S}^j_{3D}\right)^+ \cdot \mathbf{b}^i_{3D}$$

$$\mathbf{S}^j_{3D} = \begin{bmatrix} S^j_{\mathrm{DC3D}}(t_1) & S^{j1}_{\mathrm{AC3D}}(t_1) & \cdots & S^{jN_\tau}_{\mathrm{AC3D}}(t_1) \\ \vdots & \vdots & \ddots & \vdots \\ S^j_{\mathrm{DC3D}}(t_{N_t}) & S^{j1}_{\mathrm{AC3D}}(t_{N_t}) & \cdots & S^{jN_\tau}_{\mathrm{AC3D}}(t_{N_t}) \end{bmatrix} \quad \mathbf{g}^{ij}_{3D} = \begin{bmatrix} G^{ij}_{\mathrm{DC3D}} \\ G^{ij1}_{\mathrm{AC3D}} \\ \vdots \\ G^{ijN_\tau}_{\mathrm{AC3D}} \end{bmatrix} \quad \mathbf{b}^i_{3D} = \begin{bmatrix} \delta B^i_{\mathrm{raw}}(t_1) \\ \vdots \\ \delta B^i_{\mathrm{raw}}(t_{N_t}) \end{bmatrix}$$

Optimizing the LPF τ values maximizes LLP performance, but optimization only needed when using relatively few layers

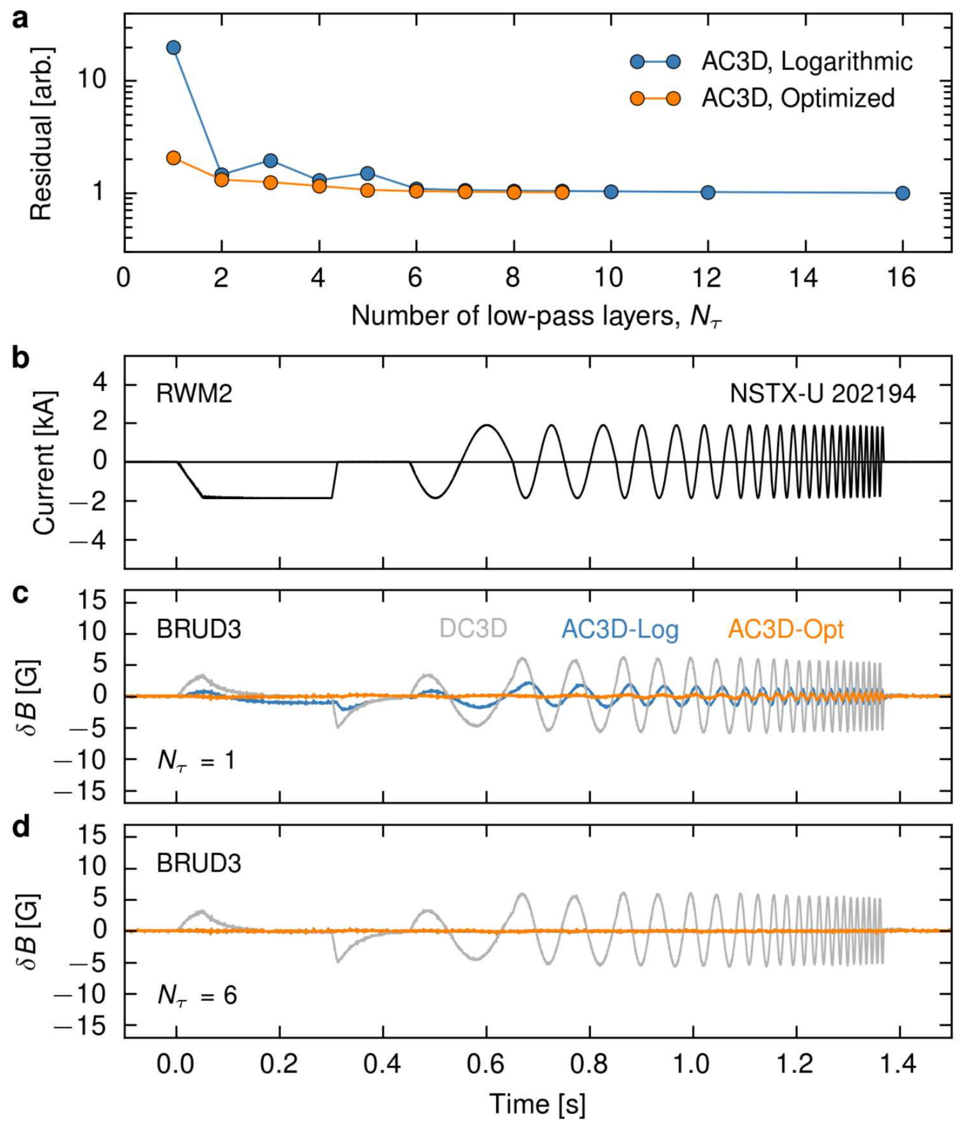
a Residual of compensated data for logarithmically distributed and optimized τ values versus the number of low-pass layers, N_τ

Here, τ optimization improves LLP performance for $N_\tau < 6$

b RWM2 coil current for the training shot, NSTX-U 202194

c Comparison of LLP performance for optimized vs. logarithmically distributed τ values with $N_\tau = 1$

d Comparison of LLP performance for optimized vs. logarithmically distributed τ values with $N_\tau = 6$



Mismatched sensor gains in sensor difference pairs require additional DC axisymmetric field compensation

- Assemble a DC2D source matrix where each row (except the last row) represents a single-coil training shot
- If the sensor gains are mismatched in a sensor difference pair, then a 2D field will generate a spurious signal
- To compensate for the 2D field, include the avg. poloidal and radial fields in the last two columns of the DC source matrix
- Use a quiescent plasma shot in the last row of the DC source matrix to break the degeneracy of the pseudo-inverse
- Construct AC2D matrices as with AC3D; can combine into global $\mathbf{S}_{\mathrm{2D}}$ matrix

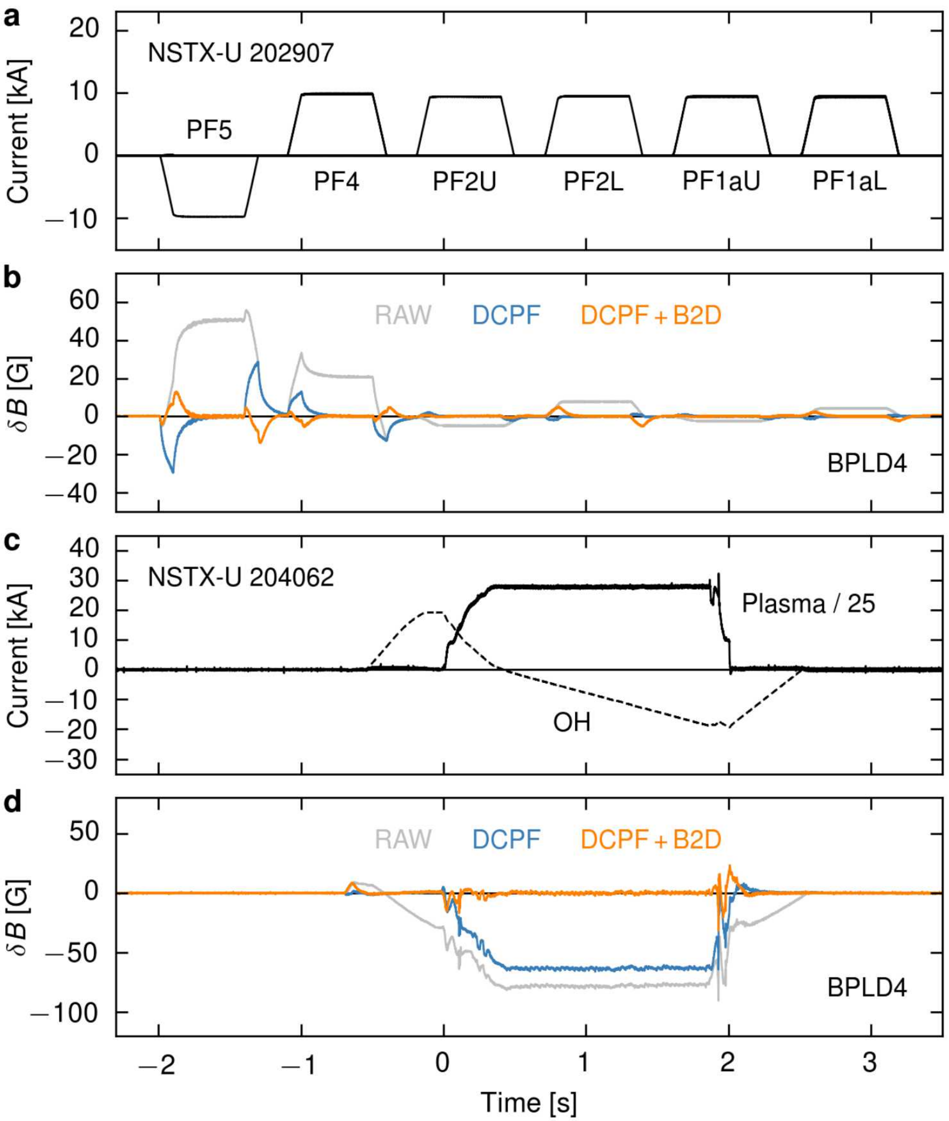
$$\mathbf{S}_{\mathrm{DC2D}} = \begin{bmatrix} I_{\mathrm{TF}} & 0 & \cdots & 0 & \langle B_{\mathrm{P}} \rangle & \langle B_{\mathrm{R}} \rangle \\ 0 & I_{\mathrm{PF}}^{1} & \cdots & 0 & \langle B_{\mathrm{P}} \rangle & \langle B_{\mathrm{R}} \rangle \\ 0 & 0 & \ddots & 0 & \langle B_{\mathrm{P}} \rangle & \langle B_{\mathrm{R}} \rangle \\ 0 & 0 & \cdots & I_{\mathrm{PF}}^{N_{\mathrm{PF}}} & \langle B_{\mathrm{P}} \rangle & \langle B_{\mathrm{R}} \rangle \\ I_{\mathrm{TF}} & I_{\mathrm{PF}}^{1} & \cdots & I_{\mathrm{PF}}^{N_{\mathrm{PF}}} & \langle B_{\mathrm{P}} \rangle & \langle B_{\mathrm{R}} \rangle \end{bmatrix}$$

$$\mathbf{S}_{\mathrm{AC2D}}^{j} = \begin{bmatrix} S_{\mathrm{AC2D}}^{j1}(t_1) & \cdots & S_{\mathrm{AC2D}}^{jN_{\tau}}(t_1) \\ \vdots & \ddots & \vdots \\ S_{\mathrm{AC2D}}^{j1}(t_{N_t}) & \cdots & S_{\mathrm{AC2D}}^{jN_{\tau}}(t_{N_t}) \end{bmatrix}$$

$$\mathbf{S}_{\mathrm{2D}} = \begin{bmatrix} \mathbf{S}_{\mathrm{DC2D}} & \vdots & \vdots & \vdots \\ \vdots & \mathbf{S}_{\mathrm{AC2D}}^{1} & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \mathbf{S}_{\mathrm{AC2D}}^{N_{\mathrm{2D}}} \end{bmatrix}$$

Axisymmetric field compensations (BP2D/BR2D) eliminate spurious DC field pickup due to sensor gain mismatches

- **a** Coil currents from an NSTX-U PF coil training shot
- **b** DC flattop pickup in the PF coil training shot is compensated out using either the DCPF matrix or the DCPF + B2D matrix
- **c** Coil and plasma current from a quiescent plasma training shot
- **d** The DCPF-only compensations leave a residual signal due to the plasma-generated axisymmetric fields → Residual eliminated by DCPF + B2D compensations



NSTX-U AC2D (ACPF / ACVL) compensations are imperfect
ACVL converges faster (is more efficient) than ACPF

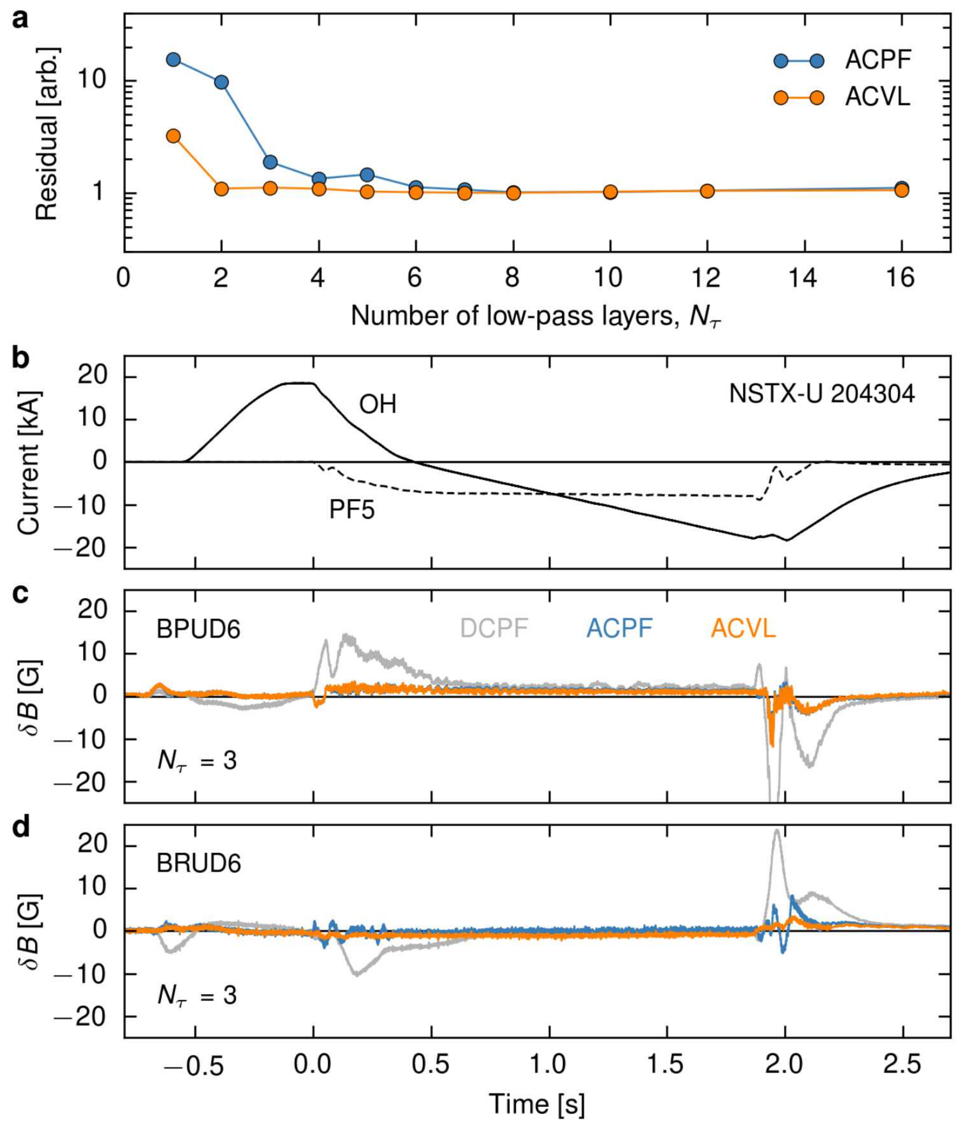
a Residual of compensated data for ACPF ($\partial_t I_{coil}$) and ACVL (V_{loop}) compensations versus N_τ

The ACVL compensations converge faster than the ACPF compensations → V_{loop} is a direct measure of inductive drive

b Coil currents in a plasma-like vacuum shot on NSTX-U

c-d Comparisons of ACPF and ACVL compensations for a B_P and a B_R sensor

Imperfect AC2D compensations due to poor training waveforms?



The LLP algorithm has excellent cross-machine portability Example: Rotating 3D vacuum fields on DIII-D

Flexible python framework developed to facilitate cross-machine portability of LLP compensations

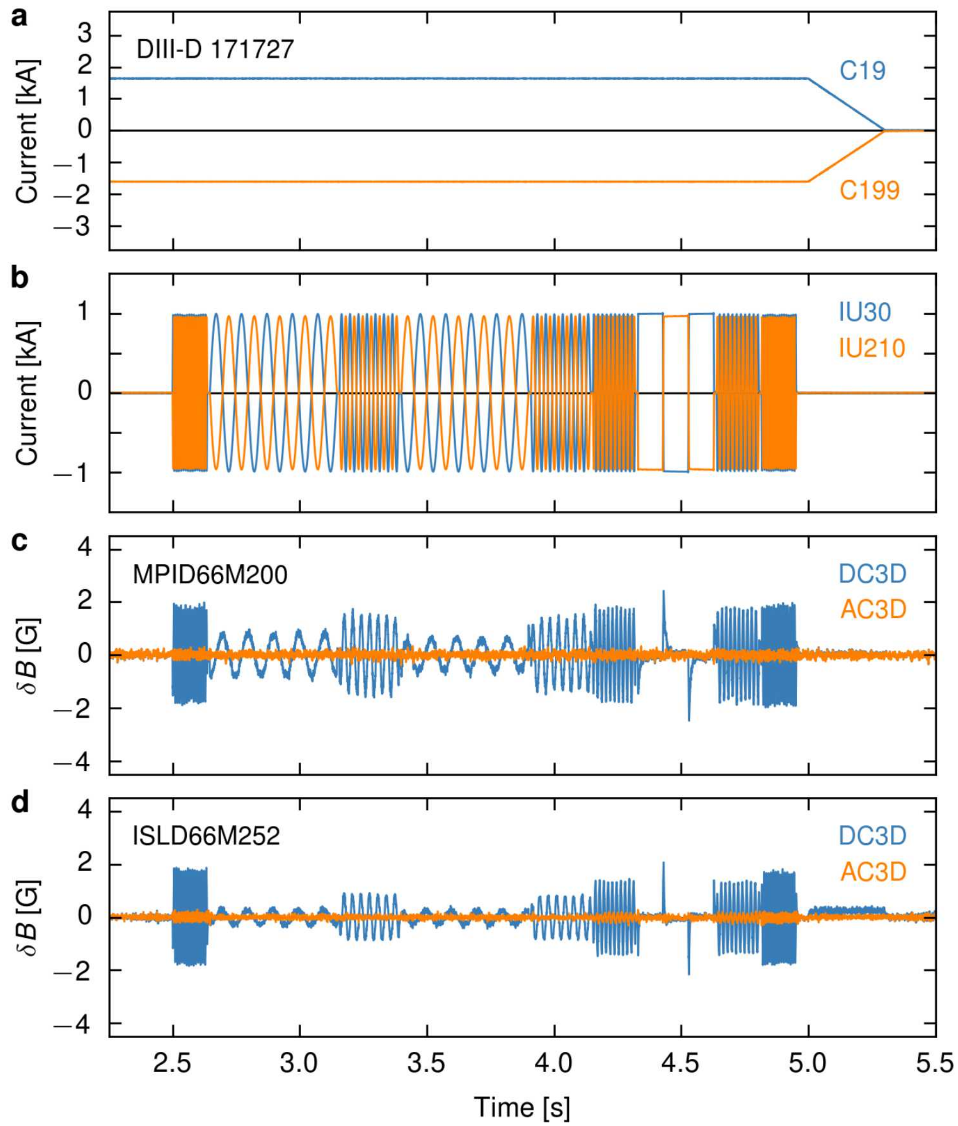
Example: Rotating 3D field vacuum shot on DIII-D (171727)

a C-coil currents (ex-vessel, 3D)

b I-coil currents (in-vessel, 3D)

c-d Comparisons of DC3D and DC3D + AC3D compensations for a B_P sensor (MPID66M) and a B_R sensor (ISLD66M)

Excellent compensations achieved with DC3D + AC3D algorithm



Chirped PF coil training shots improve the AC2D (ACPF) compensations on DIII-D

Traditional AC2D training shots rely on the rise and fall of square waves

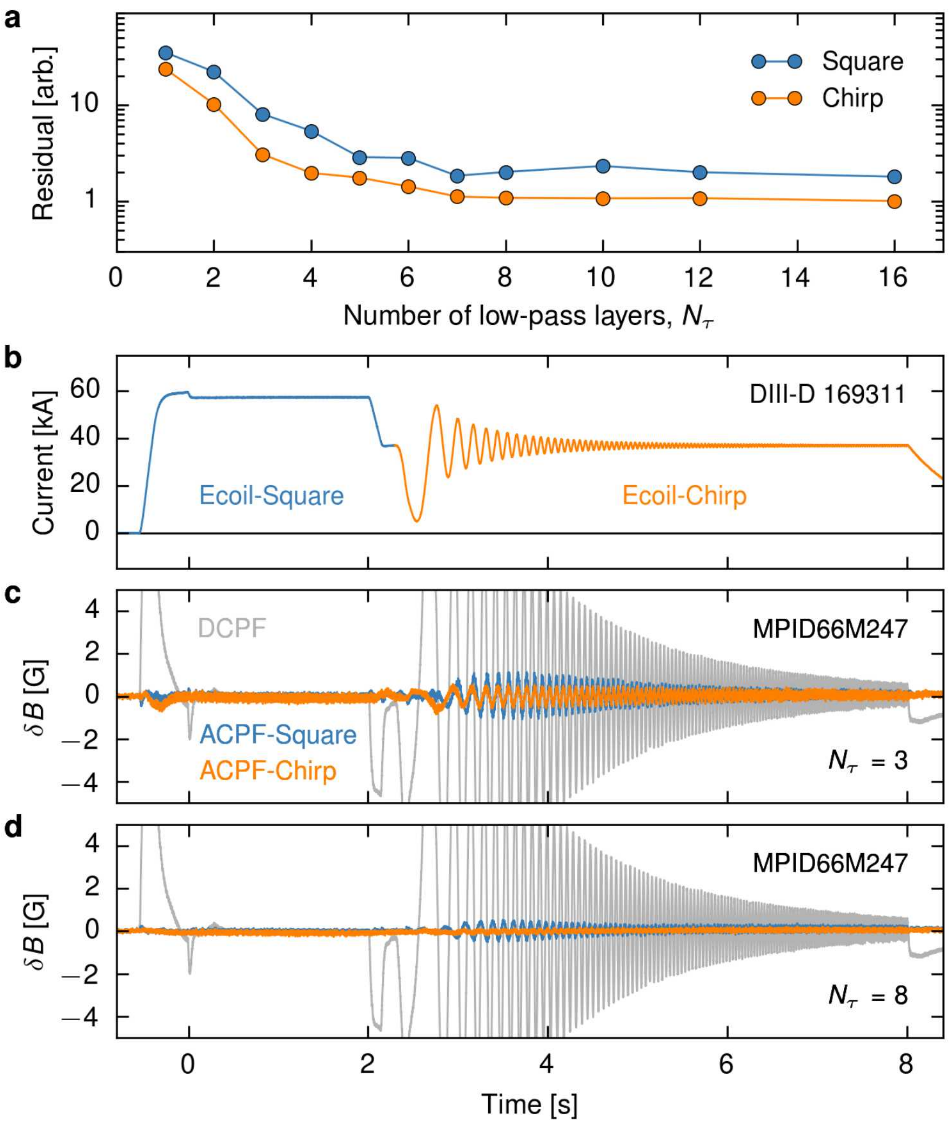
Chirped F- and E-coil shots were acquired on DIII-D to provide higher-bandwidth training data

a Residuals show that chirp-based compensations consistently outperform square wave comps.

b E-coil pulse with square wave and chirped components

c-d Square wave and chirp-based comps. for $N_\tau = 3$ and $N_\tau = 8$

Chirp-based ACPF compensations with $N_\tau = 8$ are highly effective



Mode identification from compensated data

- Fit Fourier amplitudes and phases to the data at each time point:

$$\delta B = \sum_{n=1}^{n_{\max}} |\delta B_{\mathrm{n}}| \cos\left(n\phi - \phi_{\mathrm{n}}\right)$$

$$= \sum_{n=1}^{n_{\max}} \left[a_{\mathrm{n}} \cos\left(n\phi\right) + b_{\mathrm{n}} \sin\left(n\phi\right)\right]$$

$$|\delta B_{\mathrm{n}}| = \sqrt{a_{\mathrm{n}}^2 + b_{\mathrm{n}}^2}$$

$$\phi_{\mathrm{n}} = \arctan\left(b_{\mathrm{n}}/a_{\mathrm{n}}\right)$$

- Define a mode ID matrix, **M**, based on the toroidal locations of the sensor difference pairs. Take the pseudo-inverse to find the mode coefficients, **c**:

$$M_{\mathrm{cn}}^{i} = \cos\left(n\phi_{\mathrm{A}}^{i}\right) - \cos\left(n\phi_{\mathrm{B}}^{i}\right)$$

$$M_{\mathrm{sn}}^{i} = \sin\left(n\phi_{\mathrm{A}}^{i}\right) - \sin\left(n\phi_{\mathrm{B}}^{i}\right)$$

$$\mathbf{d} = \mathbf{M} \cdot \mathbf{c}$$

$$\mathbf{c} = \mathbf{M}^{+} \cdot \mathbf{d}$$

$$\mathbf{M} = \begin{bmatrix} M_{\mathrm{c1}}^{1} & M_{\mathrm{s1}}^{1} & \cdots & M_{\mathrm{cn_{max}}}^{1} & M_{\mathrm{sn_{max}}}^{1} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ M_{\mathrm{c1}}^{N_{\mathrm{sens}}} & M_{\mathrm{s1}}^{N_{\mathrm{sens}}} & \cdots & M_{\mathrm{cn_{max}}}^{N_{\mathrm{sens}}} & M_{\mathrm{sn_{max}}}^{N_{\mathrm{sens}}} \end{bmatrix} \qquad \mathbf{c} = \begin{bmatrix} a_{\mathrm{n=1}} \\ b_{\mathrm{n=1}} \\ \vdots \\ a_{\mathrm{n=n_{max}}} \\ b_{\mathrm{n=n_{max}}} \end{bmatrix} \qquad \mathbf{d} = \begin{bmatrix} \delta B_{\mathrm{comp}}^{i=1} \\ \vdots \\ \delta B_{\mathrm{comp}}^{i=N_{\mathrm{sens}}} \end{bmatrix}$$

Offline and real-time mode identification in NSTX-U
Example: $n = 1$ mode locking

The 3D (RWM) coils are ramped in an $n = 1$ pattern starting at 0.7 s

The plasma locks at t = 0.949 s

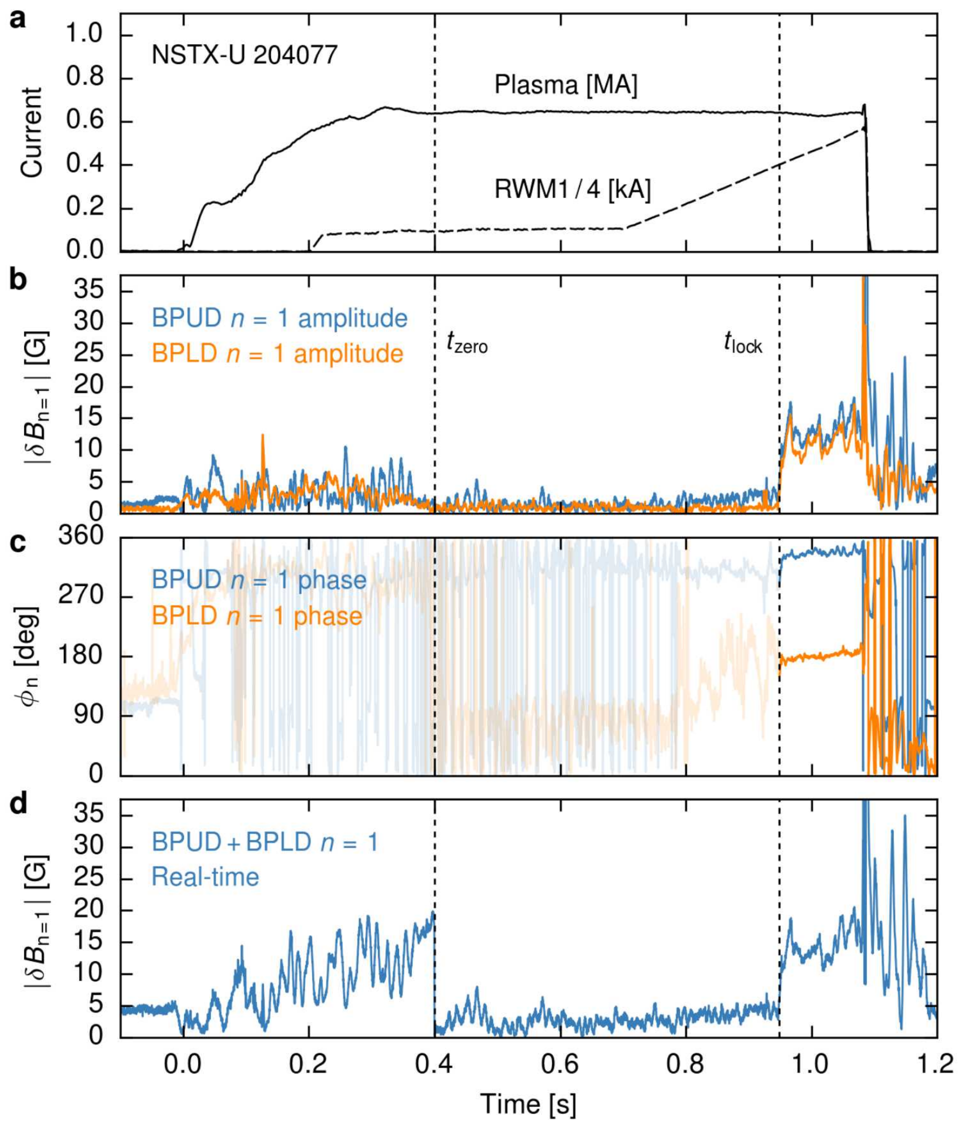
The sensors are 're-zeroed' at 0.4 s to maximize sensitivity in the flattop

a Plasma and 3D coil currents

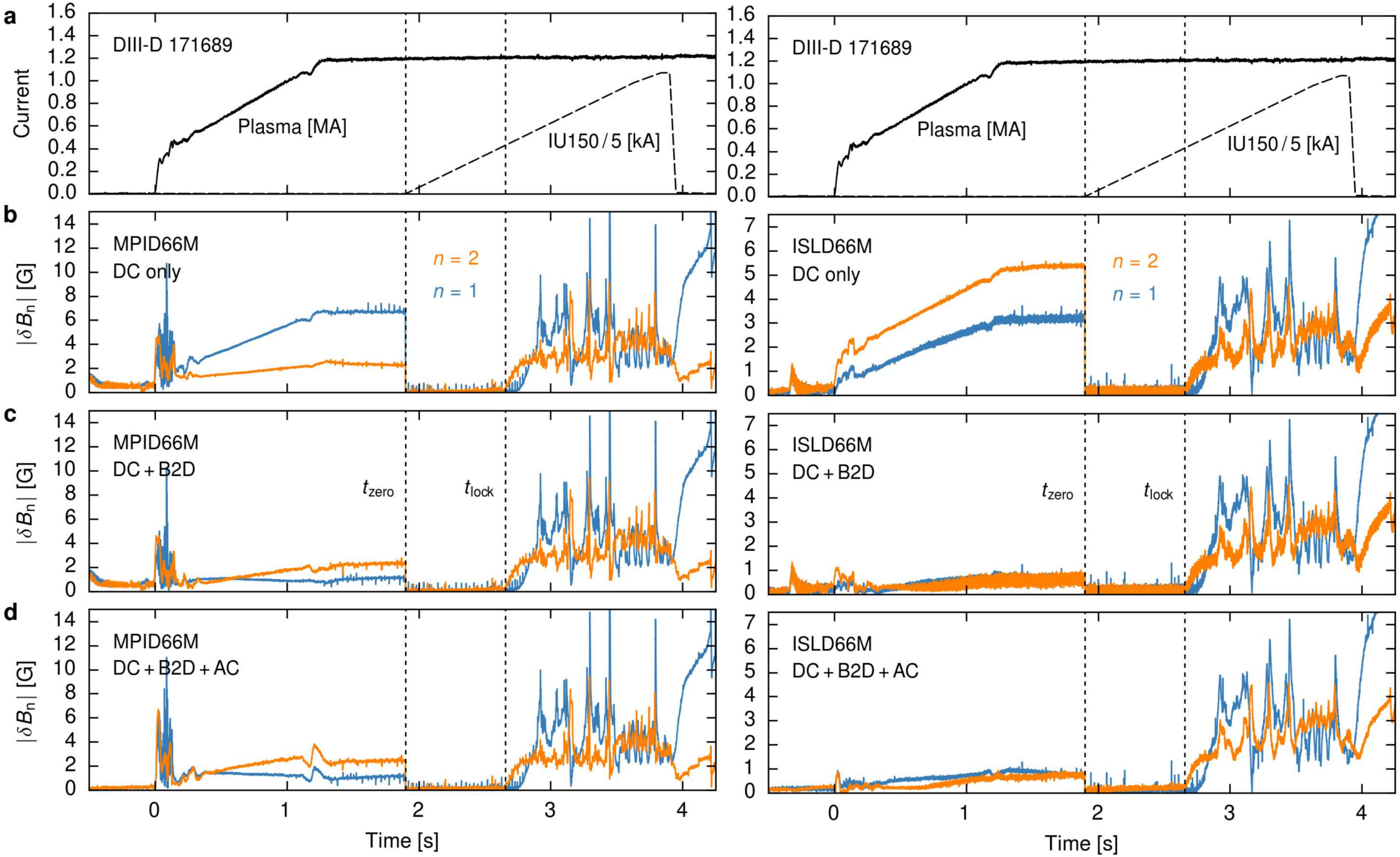
b Mode locking observed in both BPUD and BPLD $n = 1$ amplitudes

c The $n = 1$ phases after mode onset are locked (and toroidally offset)

d Mode ID was conducted in real-time on this shot. Though the compensations are not well tuned, the locked mode is still identified.



Mode identification also implemented for DIII-D (offline) Example: n = 2 mode locking



Summary and future plans

- Layered low-pass compensations have been implemented on NSTX-U and on DIII-D:
  - Satisfactory vacuum field compensation achieved in both machines
    - LLP compensations could replace dedicated vacuum field shots on DIII-D
  - Offline and real-time mode identification demonstrated in NSTX-U
    - Real-time mode ID enables locked mode detection and dynamic mode control
  - BP2D/BR2D compensations are key for DC2D compensations
  - Chirped PF coil shots in DIII-D improve AC2D compensations

- Path forward:
  - Acquire chirped PF coil shots on NSTX-U to improve AC2D compensations
  - Update NSTX-U real-time algorithm to include an arbitrary number of layers
  - Implement LLP algorithm in OMFIT for broad distribution (already in python)
  - Implement real-time algorithm on DIII-D for improved mode ID and mode control