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AC compensation of 3D magnetic diagnostic signals in DIII-D and NSTX-U for real-time application

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Magnetic sensor compensation can remove vacuum field pickup and isolate plasma-generated fields

- Plasma mode identification is essential in modern tokamaks:
  - Tailored plasma response and mode control often central to achieving high performance
  - Locked mode identification key to anticipating disruptions

- 3D fields produced by plasma modes are very small ($\delta B/B \sim 10^{-4}$):
  - Remove 2D field by electronically differencing two magnetic field sensors located at the same poloidal angle and radial location but different toroidal angles
  - Vacuum field pickup can pollute the remaining 3D signal

- Sensor compensations can remove vacuum field pickup:
  - DC pickup generated by vacuum field coils is easily removed
  - AC pickup generated by induced vessel currents is more difficult

Outline

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Method

DC and AC compensations are combined to remove the vacuum field pickup generated by various sources

- The raw measured signal δB_{RAW} is compensated for both the DC and the AC pickup from every energized coil

$$\delta B_{COMP} = \delta B_{RAW} - \delta B_{DC} - \delta B_{AC}$$

- The DC pickup from a single coil is proportional to the current in the coil

$$\delta B_{DC} = \sum_{i}^{N_{COIL}} g_{DC}^{i} I_{COIL}^{i}$$

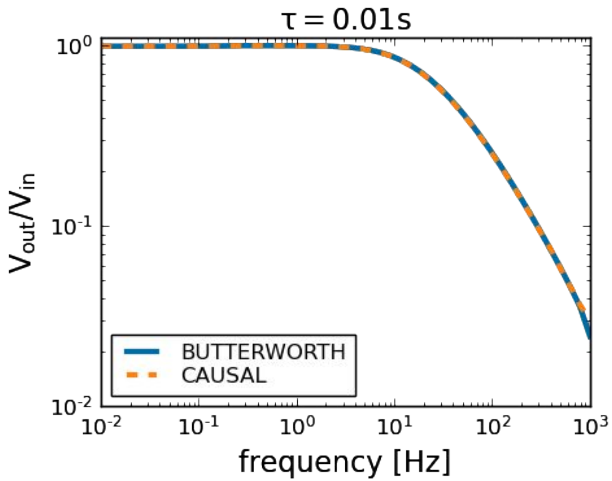
- The AC pickup from a single coil is proportional to the sum of the induced current in the passive structures

$$\delta B_{AC} = \sum_{i}^{N_{COIL}} \sum_{j}^{N_{\tau}^{i}} g_{AC}^{ij} LPF\left(\frac{\partial I_{COIL}^{i}}{\partial t}, \tau_{ij}\right)$$

- A first order low pass Butterworth filter is used offline, while a causal filter defined as:

$$Y_{OUT}(t) = \frac{Y_{OUT}(t-\Delta t)\cdot\tau + Y_{IN}(t)\cdot\Delta t}{\tau + \Delta t}$$

is used in real time. Δt is the sampling rate.



SVD used to calculate the AC gains for a given set of taus

- Single coil vacuum shots are used to calculate the coupling between the coil and the sensors

- g_{DC} is easily calculated using a step waveform for the coil current

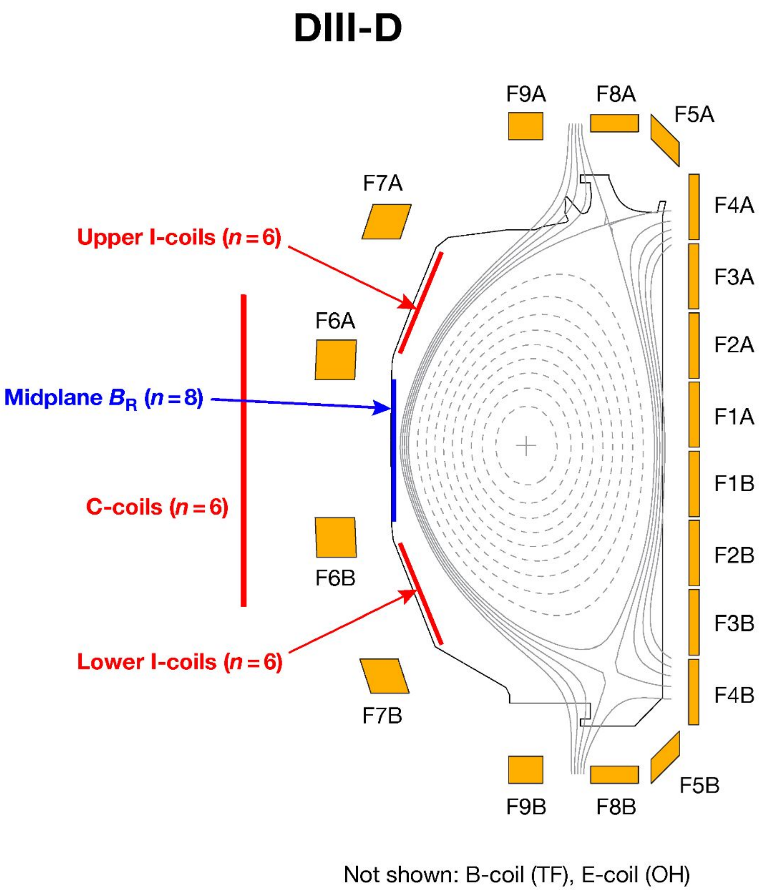
- The set of g_{AC} for a given set of τ is calculated minimizing **S·g=b**, where

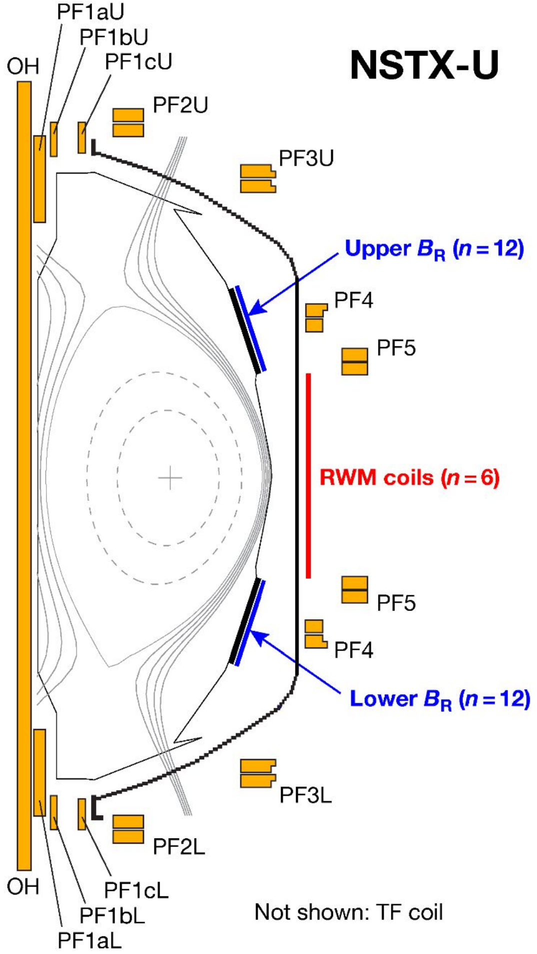
$$\mathbf{S} = \begin{bmatrix} LPF(\frac{\partial I_{COIL}}{\partial t}, \tau_0)(t_0) & \dots & LPF(\frac{\partial I_{COIL}}{\partial t}, \tau_N)(t_0) \\ \vdots & \ddots & \vdots \\ LPF(\frac{\partial I_{COIL}}{\partial t}, \tau_0)(t_M) & \dots & LPF(\frac{\partial I_{COIL}}{\partial t}, \tau_N)(t_M) \end{bmatrix} \qquad \mathbf{g} = \begin{bmatrix} g(\tau_0) \\ \vdots \\ g(\tau_N) \end{bmatrix} \qquad \mathbf{b} = \begin{bmatrix} (\delta B_{RAW} - \delta B_{DC})(t_0) \\ \vdots \\ (\delta B_{RAW} - \delta B_{DC})(t_M) \end{bmatrix}$$

- The calculation is done computing the (Moore-Penrose) pseudo-inverse of **S** using its singular-value decomposition

Examples

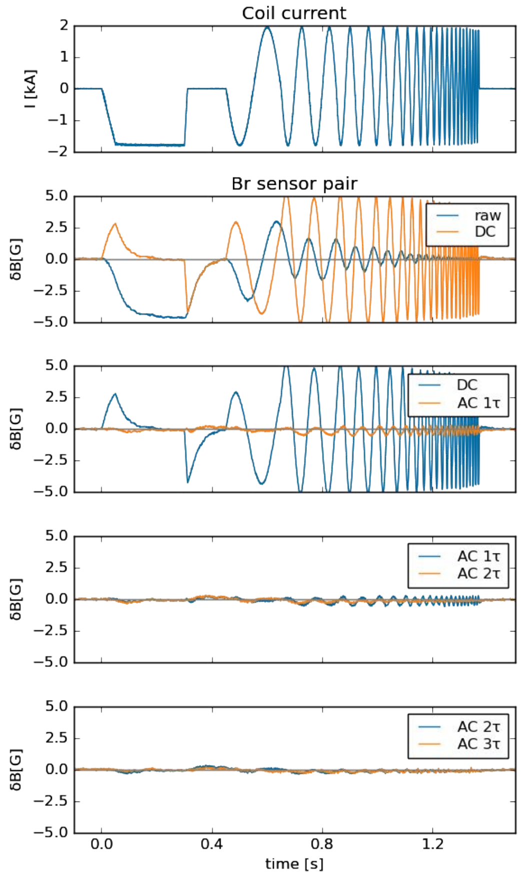
The DIII-D and the NSTX-U machine





Removing vacuum pickup from 3D coil fitting multiple time constants in NSTX-U ...

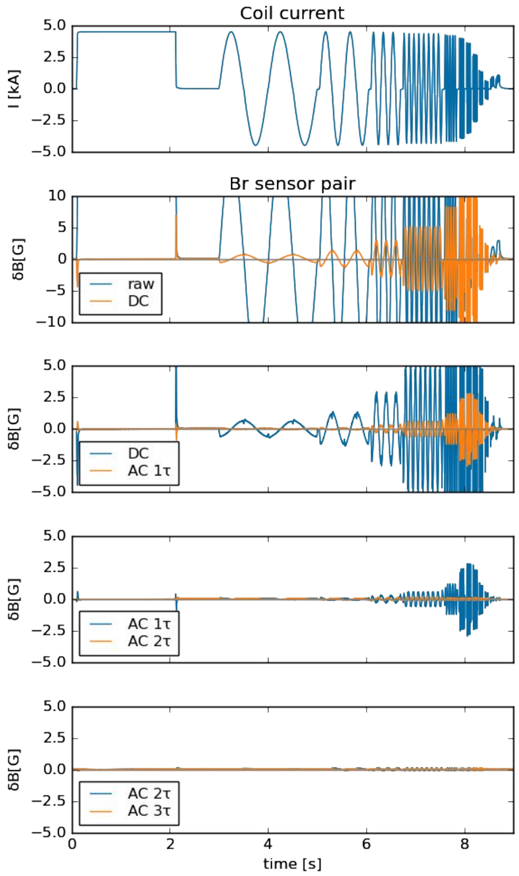
- Single coil discharges are performed to evaluate the vacuum field pick-up
- A step is used to evaluate the DC vacuum pick-up
- A frequency sweep is used to evaluate the AC vacuum pick-up
- Using one time constant reduces the vacuum pick-up of an order of magnitude
- Multiple time constants make the vacuum pickup comparable to the signal noise



NSTX-U

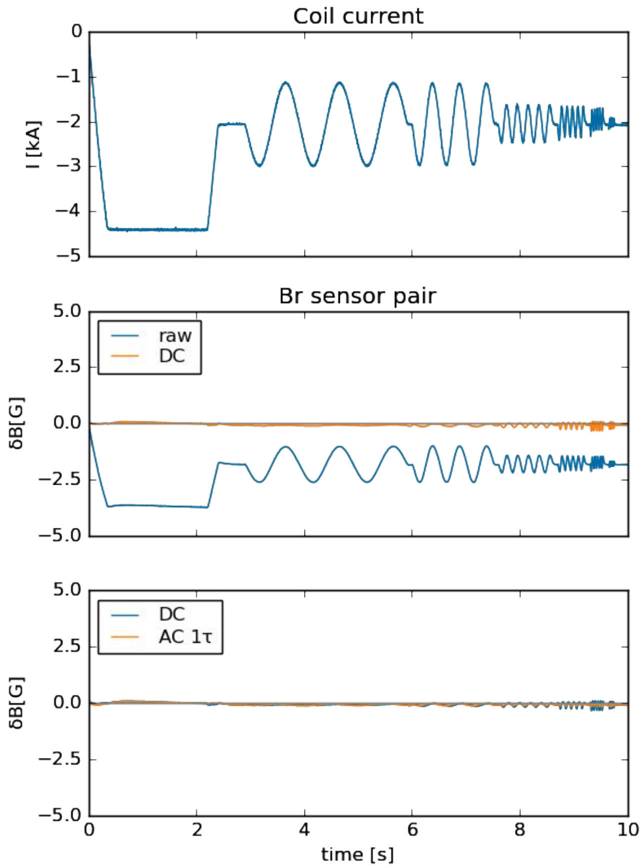
… and in DIII-D

- Similar single coil discharges are performed to evaluate the vacuum field pick-up
- A discrete frequency scan is used to evaluate the AC vacuum pick-up
- The DC compensation reduces the pickup at low frequencies, but amplifies it at higher frequencies
- Multiple time constants reduce the vacuum pickup of about 2 order of magnitudes



The same compensation can be applied to the vacuum pickup from 2D coils

- Due to unavoidable misalignments, 3D sensors are affected by vacuum pickup also from 2D coils
- Also in this case a discrete frequency scan is used to evaluate the AC vacuum pick-up
- The DC compensation reduces the pickup
- AC compensation further reduces the vacuum pickup



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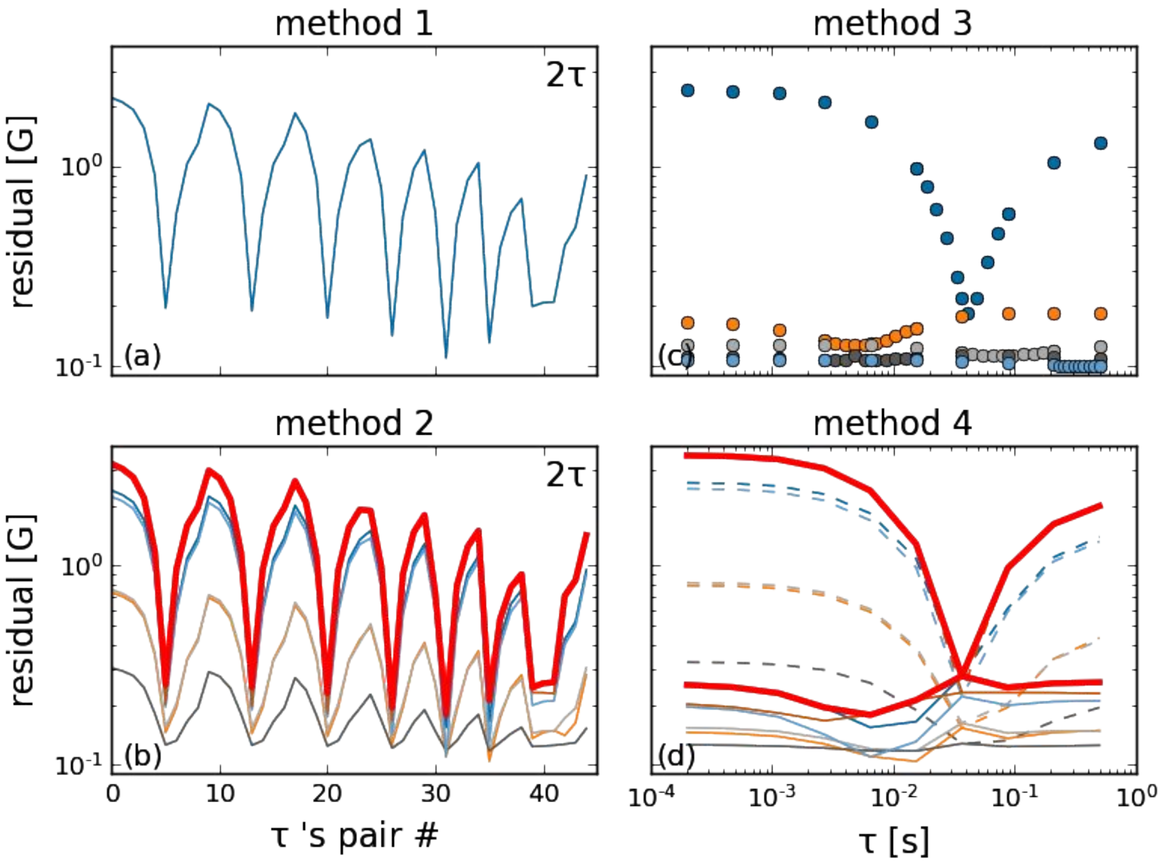
Optimizations

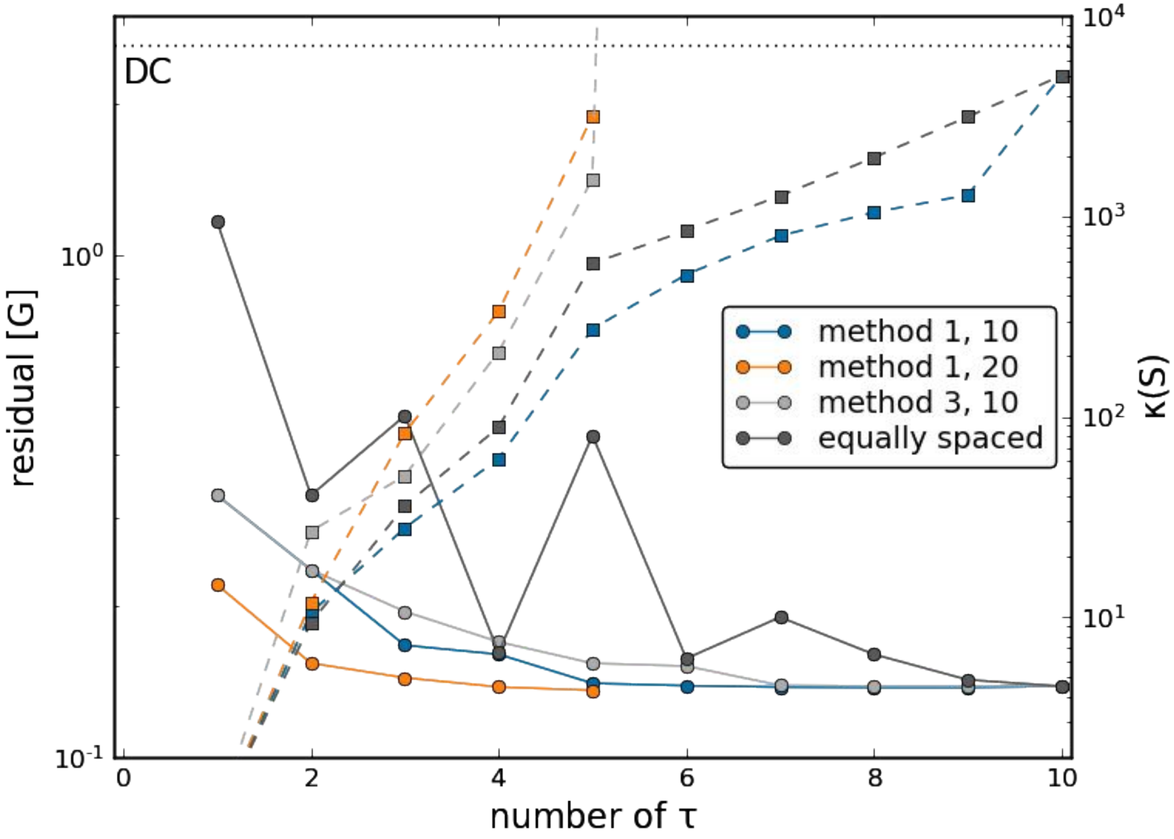
Different optimization methods are tested to choose the time constants



- Standard deviation of the signal used as figure of merit to optimize the choice of time constants
- The range of τ explored goes from 2x sampling rate to ½ the time interval considered
- Several optimization methods explored:
  - Pick *N* τ and explore all possible combinations
  - Chose one τ at a time
  - Chose the same τ for an array of sensors given a coil

NSTX-U

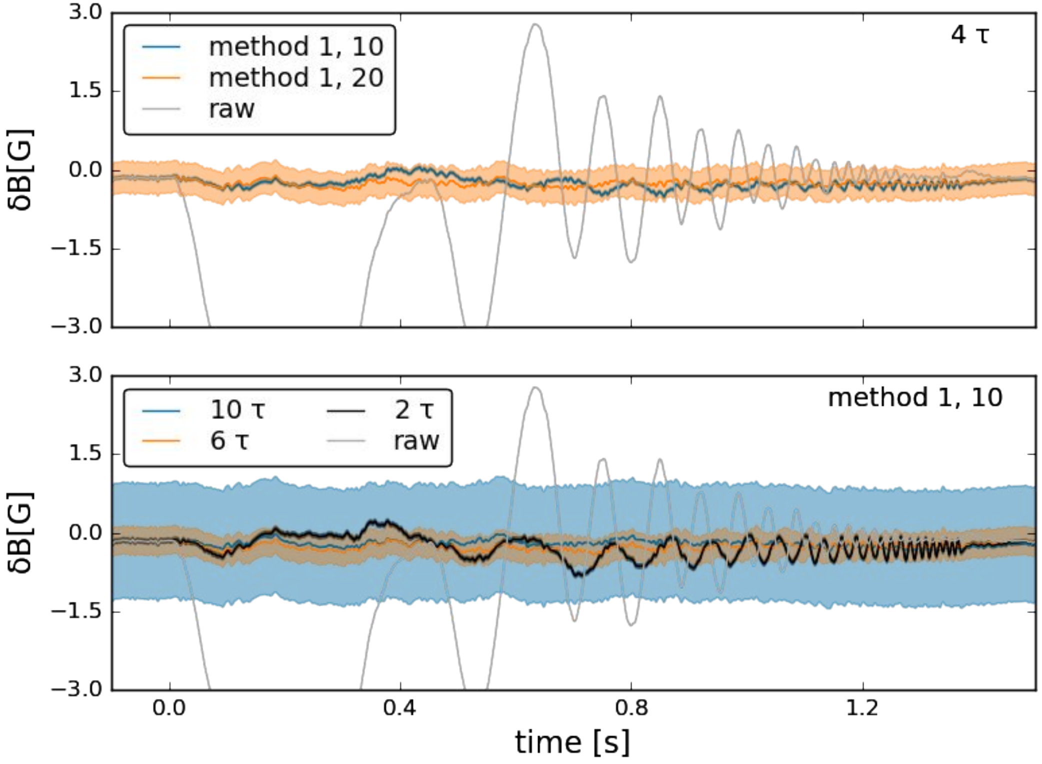
A few optimized time constants are enough to reduce the vacuum pickup to noise level



- A single τ reduces the vacuum pickup by an order of magnitude
- A large number of τ increases the uncertainties in the compensation

NSTX-U

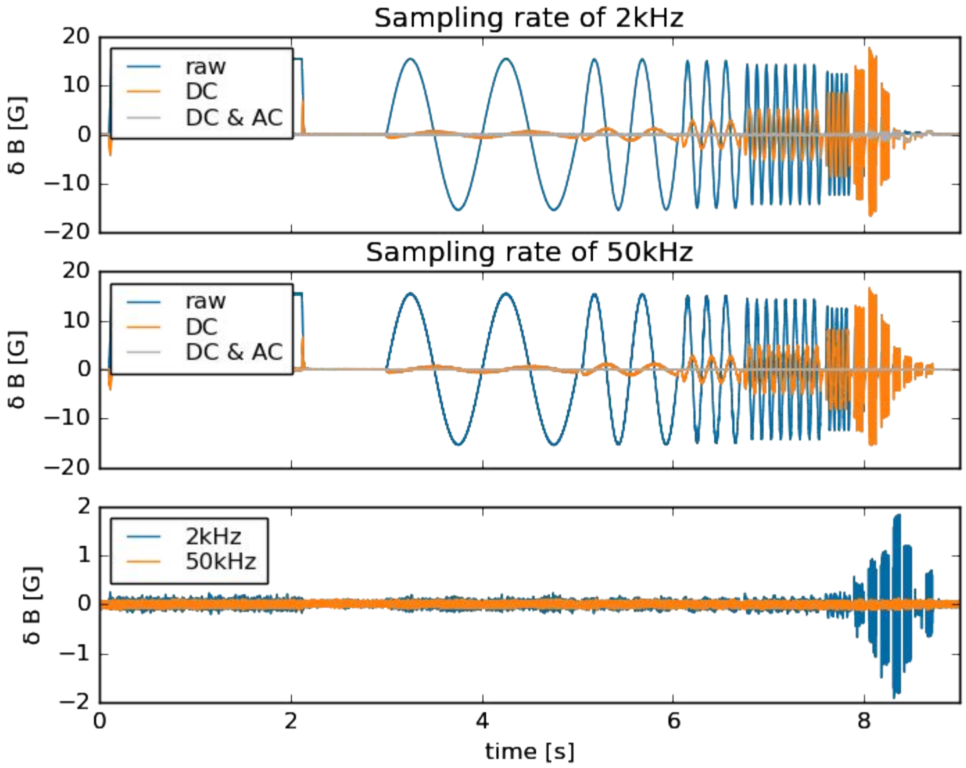
The choice of the time constants has an impact on the uncertainties



- τ close to each other can improve the compensation for the training shot but degrading it for its applications
- A good compensation is a compromise between compensation performances and uncertainties

Coil current sampling rate is a limitation for the correction of the higher frequencies

- In DIII-D the coil current for the 3D coils is digitized at 2 sampling rates
- The AC compensation calculated using the higher sampling rate shows a better correction especially at high frequencies



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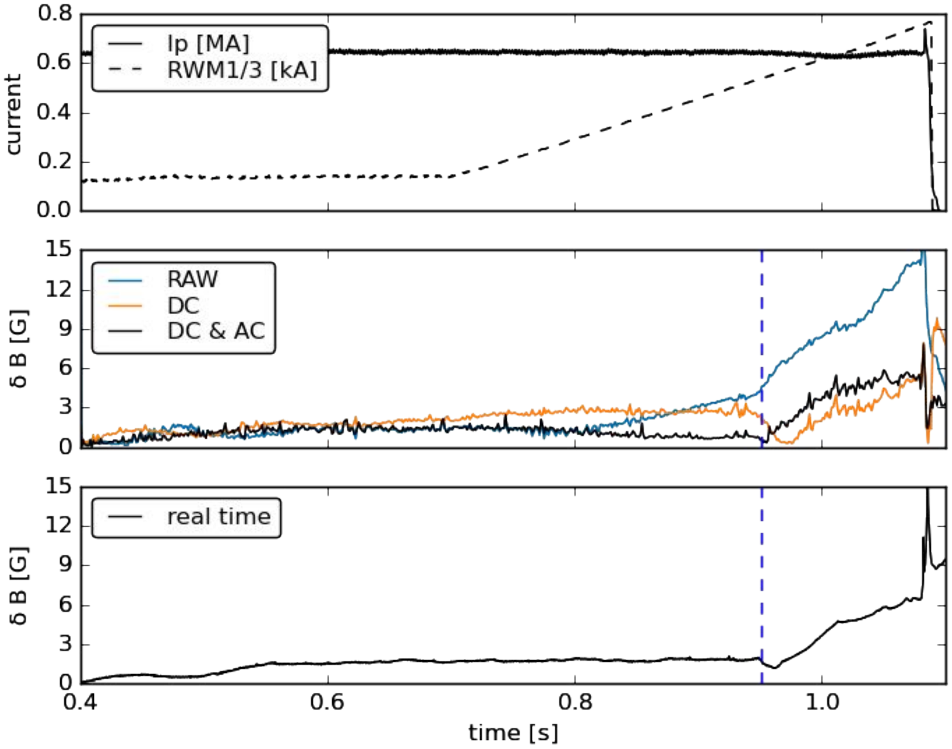
Applications

Compensated signals allow for the timely detection of locked mode onset

- The 3D (RWM) coils are ramped in an n = 1 pattern, and the plasma locks at t = 0.949 s
- Mode locking is clearly observed in the DC & AC compensated signal
- Mode locking is observed also in real-time.



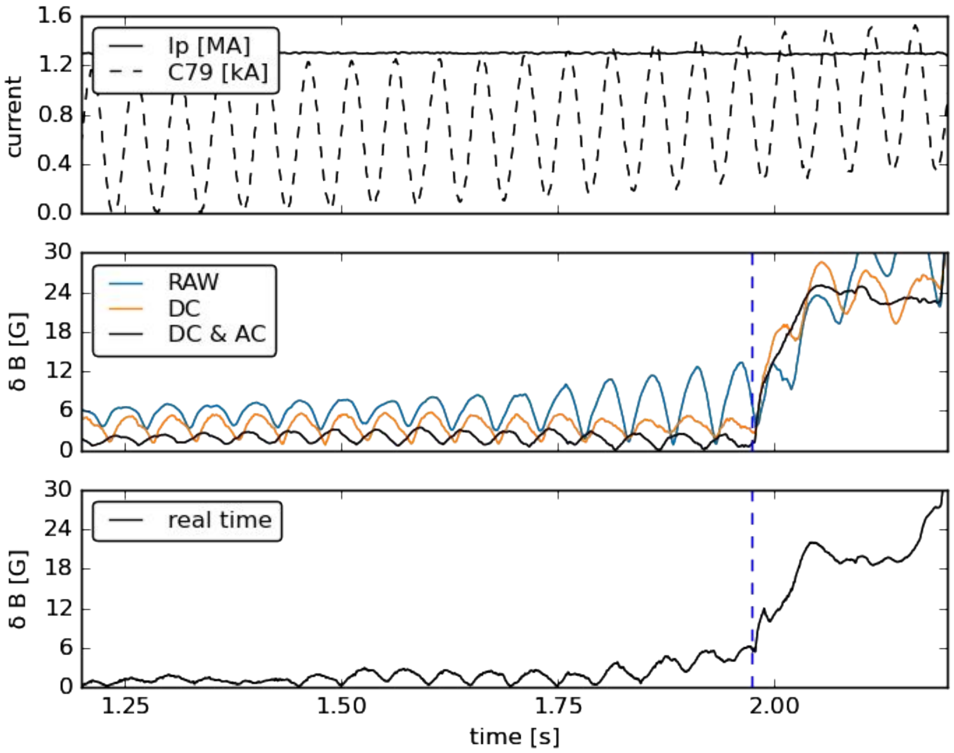
NSTX-U

… also during the application of oscillating 3D fields

- The 3D (C) coils are ramped in a rotating n = 1 pattern and the plasma locks at t ~ 1.9 s

- Mode locking onset is clearly observed in the compensated signals

- Simulated real-time AC compensation and mode ID was conducted. Though the compensation coefficients can be improved, mode locking is observed.



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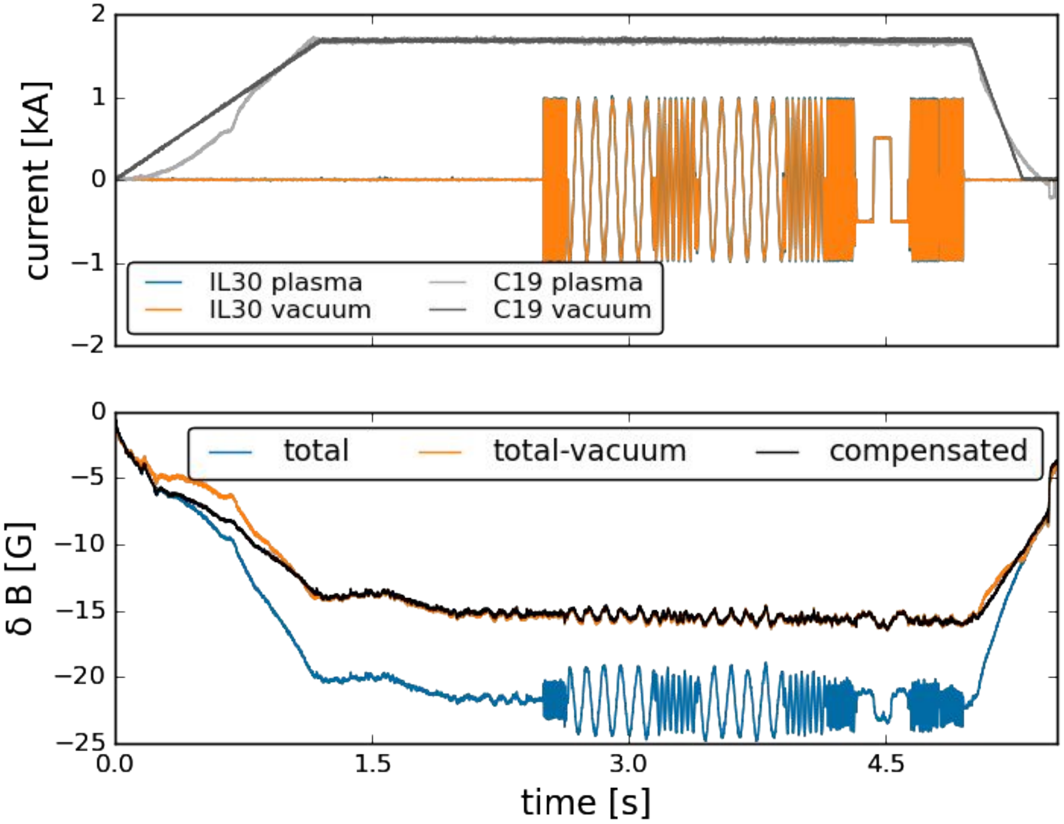
Compensated signals allow to measure the plasma response without the need for repeated vacuum discharges

- The 3D (C&I) coils are deployed for error field mitigation and to study the plasma response
- The shot was repeated without plasma to extract from the 3D measurement only the plasma component
- AC compensation allows to obtain the same result without requiring a repeated shot without plasma



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Summary

- Time domain AC compensation based on layered low pass filtering of coil currents showed to be effective and suitable for real time applications both in NSTX-U and DIII-D
- Few optimized time constants allow the vacuum pickup to be reduced to noise level
- Real-time mode locking detection and plasma response extraction were demonstrated

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