Progress in determining ac coil – sensor couplings for 2012

By
J. M. Hanson

Acknowledgements
M. J. Lanctot, J. King, H. Reimerdes, E. Strait

Presented at
DIII-D Stability and Disruption Avoidance Group meeting
25 June 2012

DIII-D NATIONAL FUSION FACILITY

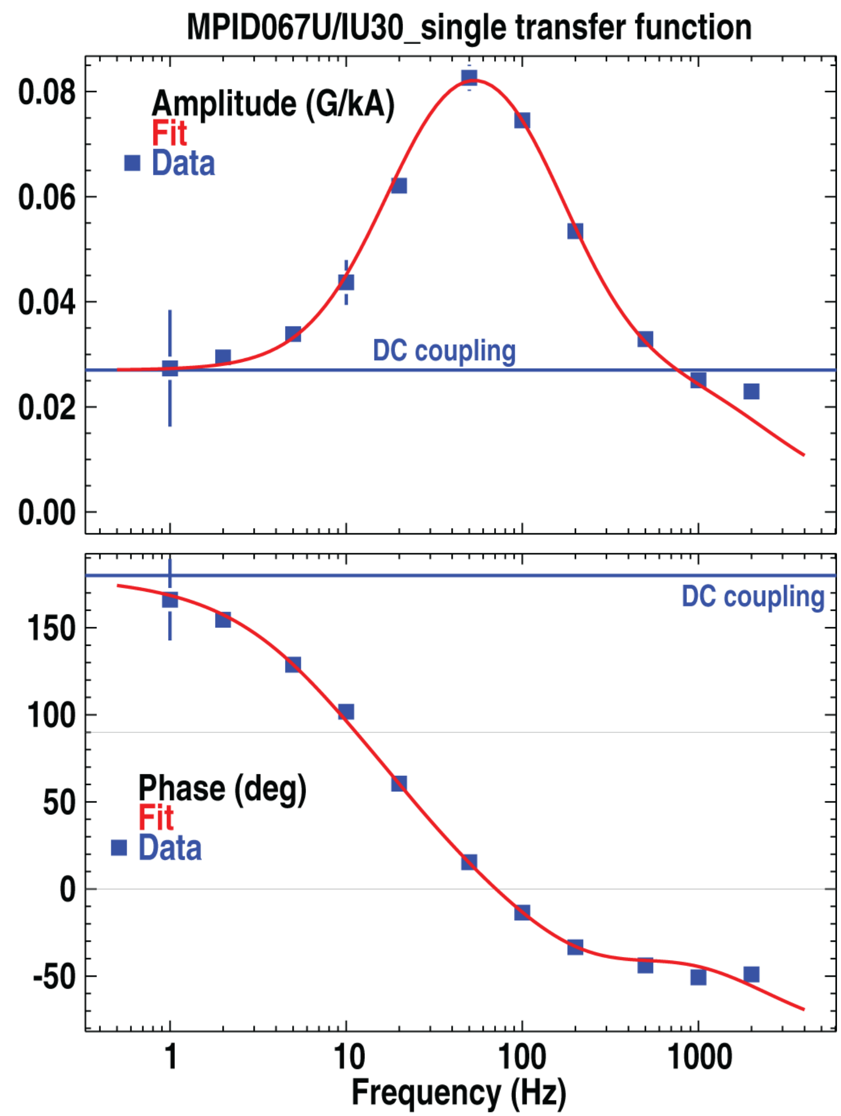
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Ac coil—sensor couplings used to calculate plasma response to applied perturbations

- **Vacuum couplings between DIII-D coils and magnetic sensors have non-trivial frequency dependencies**
  - Caused by induced eddy currents in passive conducing structures (*ie* DIII-D wall)
  - Couplings tend to have significant variation on RWM time-scales: 10 – 500 Hz.
- **Vacuum couplings measured yearly with applied ac coil waveforms**
- **Knowing the couplings allows computation of ac plasma response**

$$\delta B_s^{\text{plas}}(\omega) = B_s(\omega) - B_{sc}^{\text{vac}}(\omega)$$

- **Used for driven plasma response measurements, tested with RWM feedback** [L. Piron, *et al*, PPCF 2011]



Outline

1. Review transfer function model, ac compensation
2. Summary of 2012 measurements
3. Comparisons with 2009 and 2011
4. Accessing transfer function data

Frequency domain model used to fit ac coupling measurements

- Fit Fourier-analyzed data to rational function model

$$\frac{B^{\mathrm{sc}}(\omega)}{I^{\mathrm{c}}(\omega)} = \frac{(i\omega - z_1)(i\omega - z_2) \times \ldots}{(i\omega - p_1)(i\omega - p_2) \times \ldots}$$

- For a given coil waveform, coupling must be a convolution of the transfer function with the frequency content of the coil signal

$$B^{\mathrm{sc}}(\omega) = \frac{B^{\mathrm{sc}}(\omega)}{I^{\mathrm{c}}(\omega)} \int_{-\infty}^{\infty} I^{\mathrm{c}}(t) \exp(-i\omega t) \mathrm{d}t$$

$$B^{sc}(t) = \int_{-\infty}^{\infty} B^{\mathrm{sc}}(\omega) \exp(i\omega t) \mathrm{d}\omega$$

$$B^{\mathrm{plas}}(t) = B^{\mathrm{s}}(t) - B^{\mathrm{sc}}(t)$$

- **Problem:** must know the full time-series to Fourier transform. Not suitable for real-time analysis.

Bi-linear transform used to derive discrete, time-domain filters for ac compensation

- When working with discretely sampled data, can express the frequency-dependent delay between samples as

$$Z(\omega) = \exp(i\omega\delta t)$$

- Can interpret *Z* as a shift operator on the Fourier transform of a sampled signal

$$Z^{-j}\mathcal{F}(x_k) = \mathcal{F}(x_{k-j})$$

- Can invert the relationship between *Z* and ω (inverse bilinear transform)

$$i\omega = \frac{1}{\delta t}\log Z \approx \frac{2}{\delta t}\frac{1 - Z^{-1}}{1 + Z^{-1}}$$

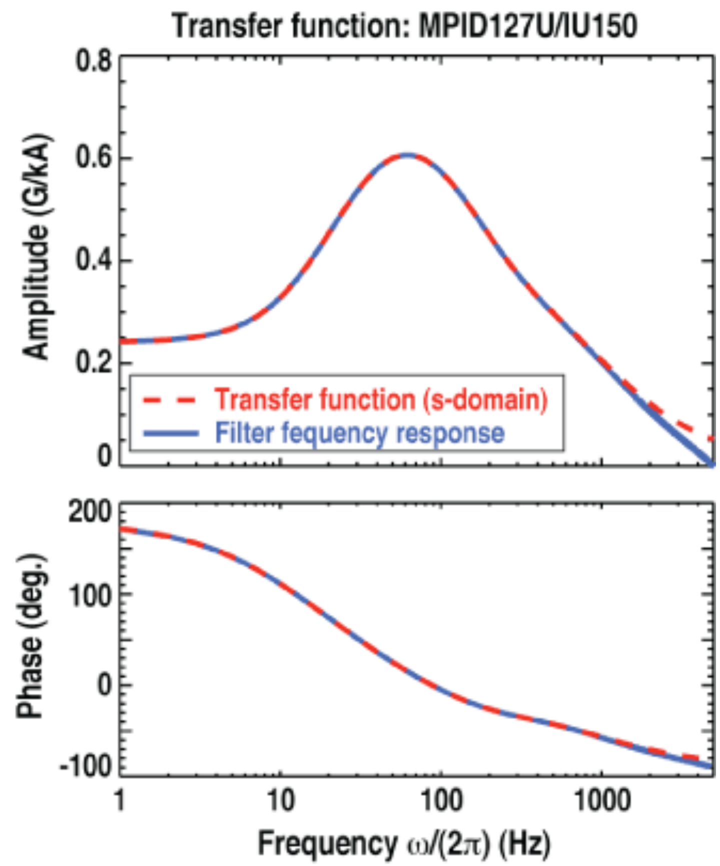
and substitute this into the transfer function expression to get a time-domain filter.

Time domain compensation is suitable for real-time and offline analysis

- We now have a representation of the transfer function in the discrete time domain

$$B^{sc}(t_k) = \sum_{j=0}^{N_{\text{zeros}}} a_j I^c(t_{k-j}) - \sum_{j=1}^{N_{\text{poles}}} b_j B^{sc}(t_{k-j})$$

- **Advantages:**
  - Only need a few prior time-steps – good for real-time.
  - In offline analysis, scales like *N*, rather than *N* log *N* as with the FFT.
- Approximation breaks down close to the Nyquist frequency, but we are normally concerned with much lower frequencies. Agreement is excellent for these.



Extensive set of ac coupling measurements made in April 2012.

- **In previous years, measured couplings between odd-*n* coil pairs and odd-*n* sensor pairs**
  - 9 coil pairs, 22 pair sensors -> 198 transfer functions
  - Adequate for $n = 1$ and $n = 3$ analysis, but useless for $n = 2$

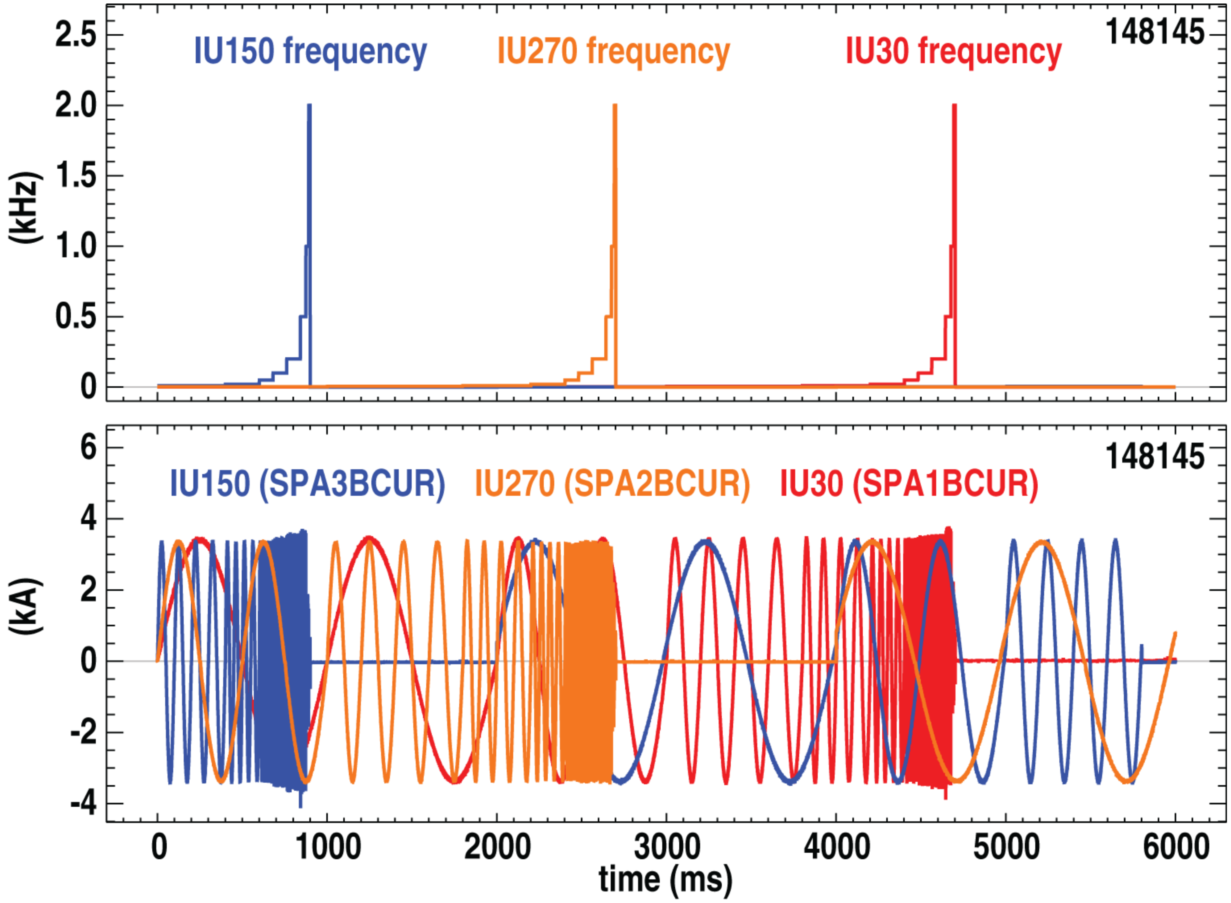
- **Starting in 2011, started measuring single-coil couplings as well and analyzing unpaired sensors**

- **In 2012: paired, unpaired C-coils, unpaired I-coils, analyzing 72 sensors**
  - ***This gives 1512 transfer functions.***

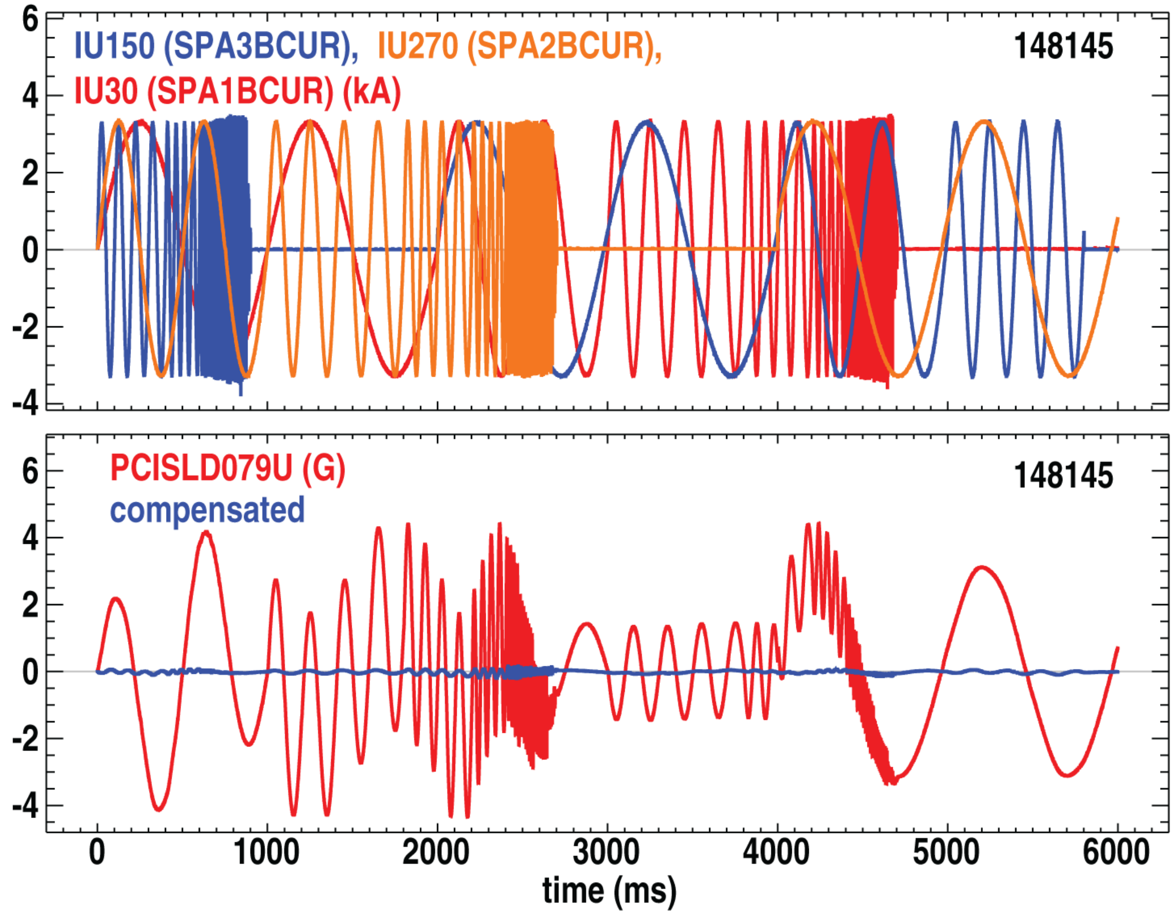
- **Attempting to make analysis semi-automatic**
  - Fourier analysis now fully-automatic. Added considerations of sensor bit-depth and sampling rates. Experimenting with controlling for linear drifts
  - Transfer function fit step now loops over number of free parameters to minimize χ^2 and rejects data that is too small to fit
  - All fits still checked individually

New measurement technique enables couplings to three coils to be obtained in one shot

- **Coils energized simultaneously, but at different frequencies**
  - Thanks to Ted for coming up with this idea!
  - Fourier analysis does a good job of untangling the couplings, as long as you keep track of what frequencies were applied when.

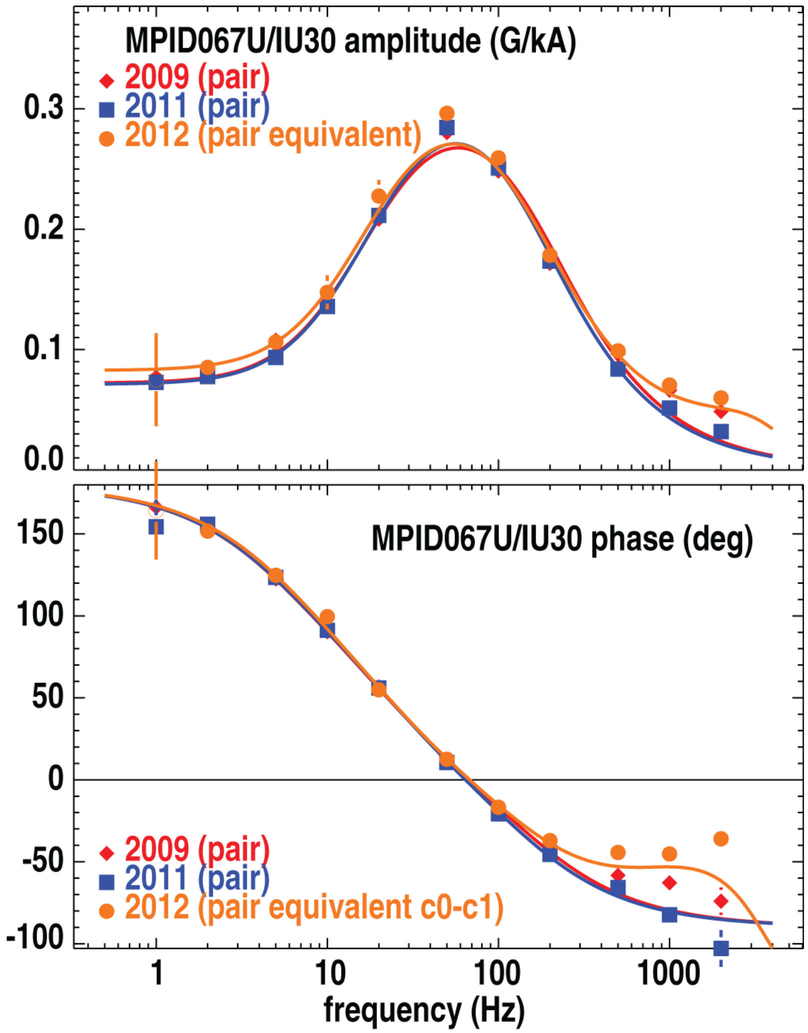


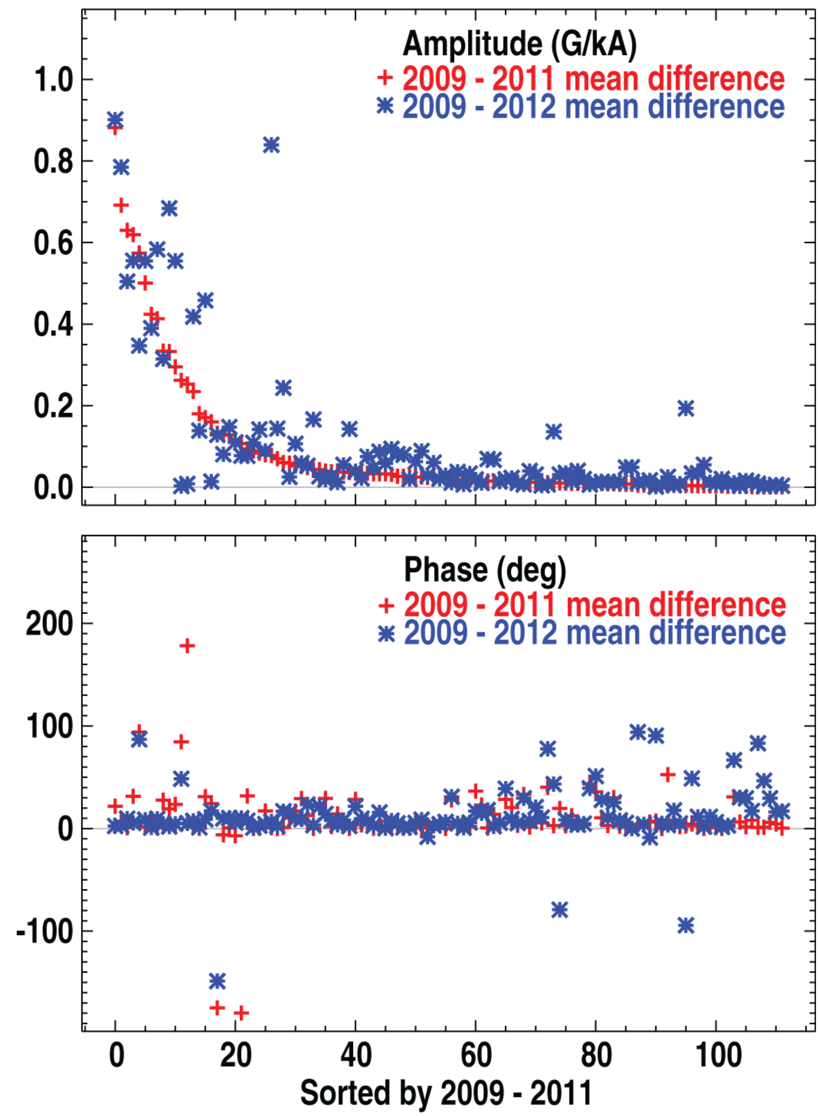
Compensation check shows multi-coil coupling measurements and analysis successful



- **Caveat: some filters have stability issues and should NOT be used yet (see list on final slide).**

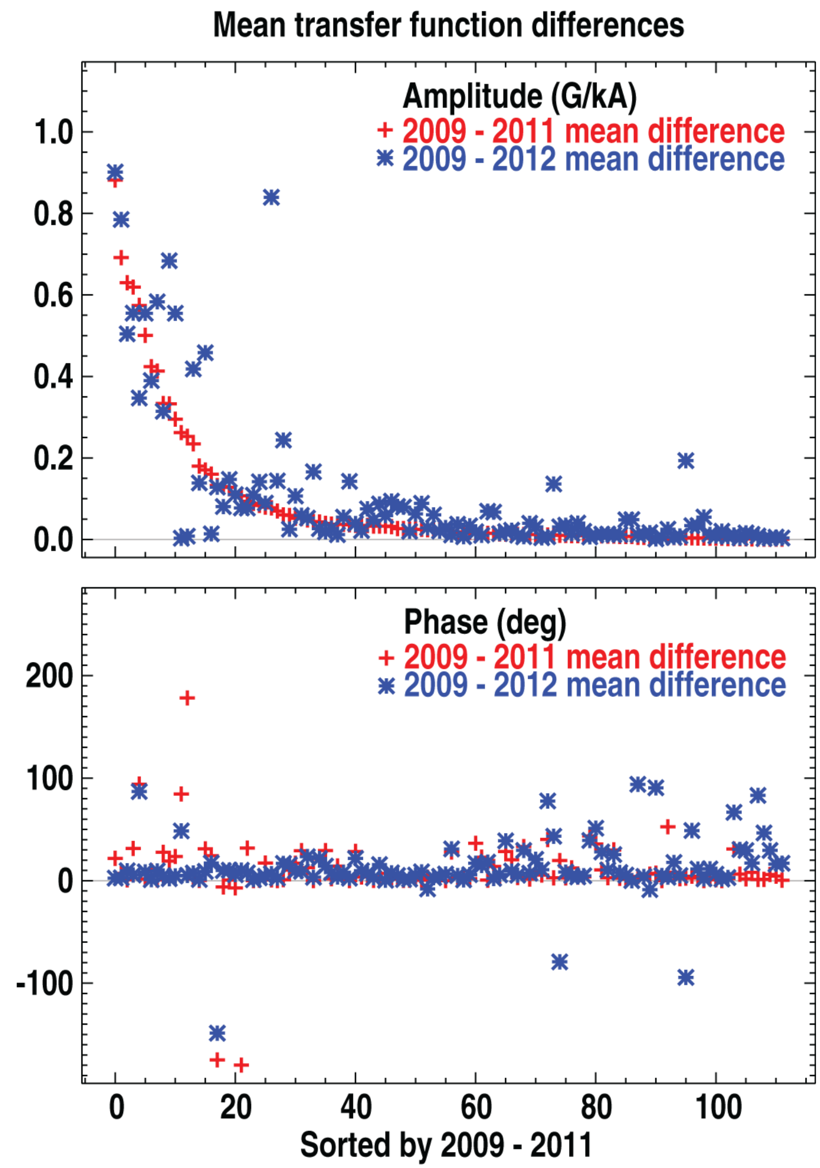
Comparisons with previous years shows minor deviations





Comparisons with previous years shows minor deviations

- **Note: 2009-2011 and 2009-2012 differences seem correlated.**
- **Largest 2009-2011 differences:**
  - ISLD199U/C199
  - ISLD139U/C139
  - ISLD079U/IU150
- **Largest 2009-2012 differences:**
  - ISLD199U/C199
  - UMPID157/IL30
  - UMPID097/IU150
- **Important: coil-pair "equivalents" transfers not as accurate for small couplings.**



DIII-D NATIONAL FUSION FACILITY

Transfer function data accessible by several means

- **IDL routines**
  - /u/hansonjm/idl/lib/rwm_compensation3.pro
    - Returns either transfer function or time-domain data for 2009 – 2012
    - Extensive documentation header
  - /u/hansonjm/idl/lib/plot_xfer.pro
    - Quick transfer function plotting routine
  - All required subroutines *should* be in /u/hansonjm/idl/lib/
- **HDF5 files**
  - Readable in IDL, Matlab, Python
  - Tree-like data structure containing all fit coefficients and fitted data
  - /u/hansonjm/var/data/transfers/tf2009.h5
  - /u/hansonjm/var/data/transfers/tf2011.h5
  - /u/hansonjm/var/data/transfers/tf2011_single.h5 (single coils)
  - /u/hansonjm/var/data/transfers/tf2012.h5
  - /u/hansonjm/var/data/transfers/tf2012_single.h5 (single coils)

Future work

- **Most 2012 couplings available, but some fits still need work**
  - See list on final slide
  - Coupling data recalculated with improved error bars and control for linear drifts
  - Next step is to recalculate transfer functions with improved technique:
    - Skip datasets with large errors (> 100%)
    - Minimize reduced χ^2 instead of χ^2

- **New strategy needed for dramatic increase in number of sensors in 2013**
  - Matlab frequency-domain fit algorithm still requires some human intervention.
    - Suspect some issues due to low measurement resolution
    - However, each fit is still inspected individually
  - Might be better to fit a dynamical time-domain model:

$$B^{sc}(t) = \sum_{j=0} a_j \frac{d^j}{dt^j} I^c(t) - \sum_{j=1} b_j \frac{d^j}{dt^j} B^{sc}(t)$$

  - Advantages: Linear model easier to fit with standard techniques. Generalizes to non-sinusoidal data. Can be mapped to transfer functions and discrete filters.

Extra slides

2012 ac vacuum shots

- **Odd-*n* C-coil pairs, April 12, 2012:**
  - 148121 C139
  - 148123 C79
  - 148124 C199

- **Unpaired I-coils, April 13, 2012:**
  - 148140 IL210, IL270, IL330
  - 148145 IU30, IU150, IU270
  - 148147 IU90, IU210, IU330
  - 148148 IL30, IL90, IL150

- **Unpaired C-coils, April 13, 2012:**
  - 148150 C79, C139, C199
  - 148152 C259, C19, C319 (only SPA currents available)

- ***SPA currents used for all analysis.*** *Pointnames available upon request.*

List of BAD 2012 fits/filters (do NOT use – yet)

- **All reconstructions of 2012 ac vacuum data checked. These were BAD:**

LMPID097/C139 pair (chaotic)
LISLD199/C139 pair (unstable)
MPI67B6/C139 pair
MPI67A4/C79 pair
MPI67B4/C79 pair
ESL199/C79 pair
LISL5/C199 pair
MISL4/IL330
UISL3/IU150
UISL6/IU210
MPI67B6/IL90
MISL4/IL30
MISL5/IL90
MISL6/IL150,IL90
LISL5/IL90
LISL6/IL150,IL30
ESL199/IL30
ESL259/IL90
ESL319/IL150
MPI66M157/C79,C139,C199 single (unstable, not clear which C-coil)
MPI66M340/C139 single
LISL1/C199 single

- ***Let me know if any of these fits are urgently needed***