Experience with beam-transient LLRF calibration in XFEL

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DESY-TEMF collaboration meeting

Rationale and Goals

- No direct ('classical') method of calibrating cavity probe signals in XFEL

- Calibration chain is complex and can change
  - In particular phase

- Understanding **maximum energy performance** in XFEL prompted more attention on LLRF calibration

- Solution: use beam-induced transient in cavities as calibration tool.
  - Beam-based calibration (BB-cal)

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- Basic method has been used for many years
  - Developed for FLASH, now used in XFEL
- Current goal is to develop a **robust**, **reproducible** and **non-invasive** approach to BB cal
  - Original FLASH methods are slow and invasive
- **Automation** tools now provide data acquisition for entire linac in <2 minutes
- Method can be routinely used during operations with little impact
- Used to monitor **calibration state**.

Approach 1

- Basic premise (Assumptions)
  - Assumption 1:
    Beam-induced transient voltage is the same in all cavities

    Valid for short pulses (t<<tau) for ~on-resonance cavities

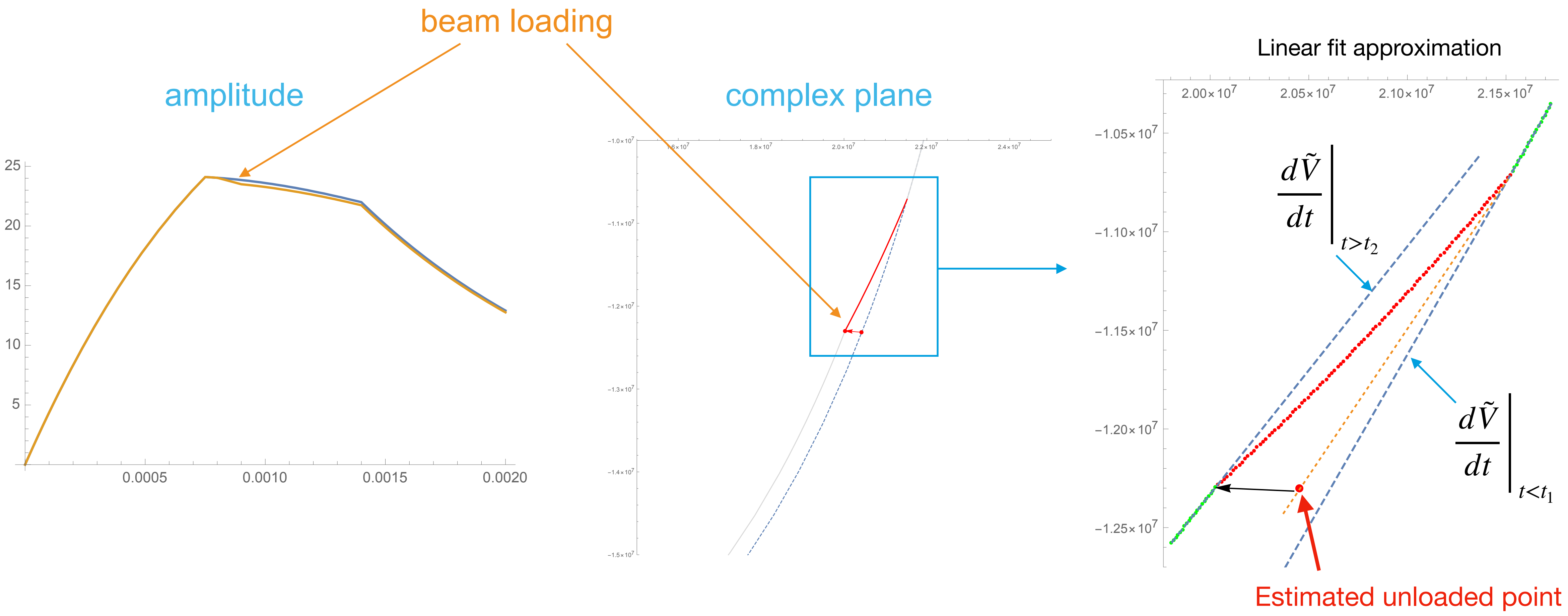
  - Assumption 2:
    Beam spectrometer absolute energy measurement at end of linac is accurate to ~1%

    Based on 'expert' opinion/ experience (but not verified)

First step: measure beam transient in all cavities

Approach 2: Beam Transient Measurement

simulated response in a TESLA cavity



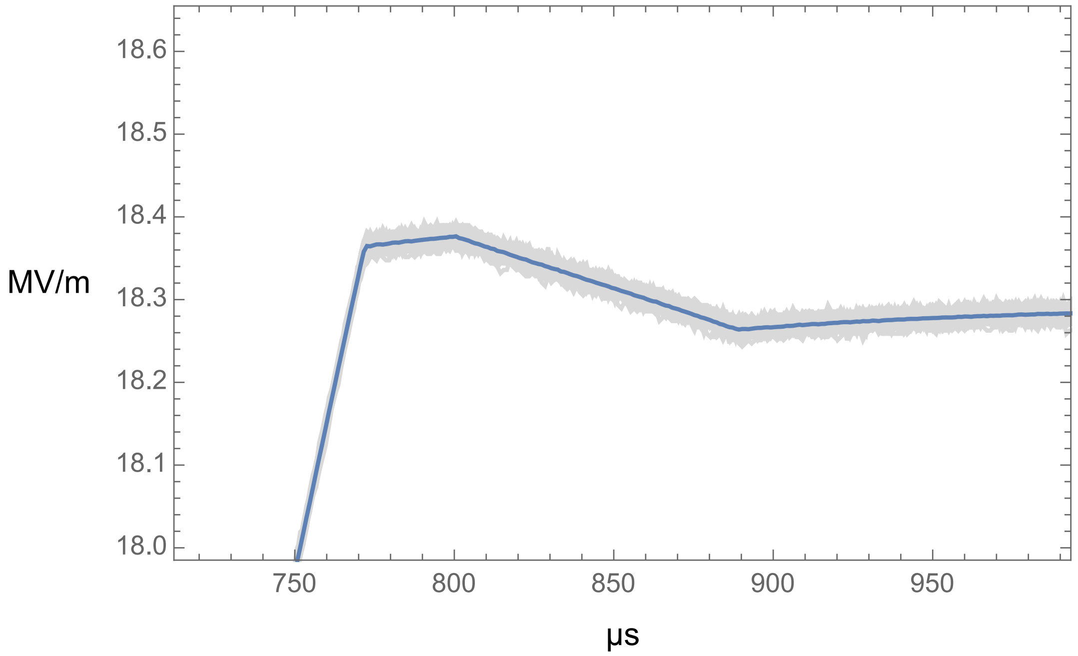
Typical transient amplitudes: 100 kV

In principle beam transients should be independent of the applied RF

Approach 3: Analysis

Understanding errors (random and systematic)

- S/N improved by averaging
  - Typically 300 consecutive pulses (30 seconds)
- Careful propagation and analysis of **statistical errors**
  - In general, all error bars shown are ±2 std error
  - Derived from averaging
- Understanding **systematic errors** is the remainder of this presentation.

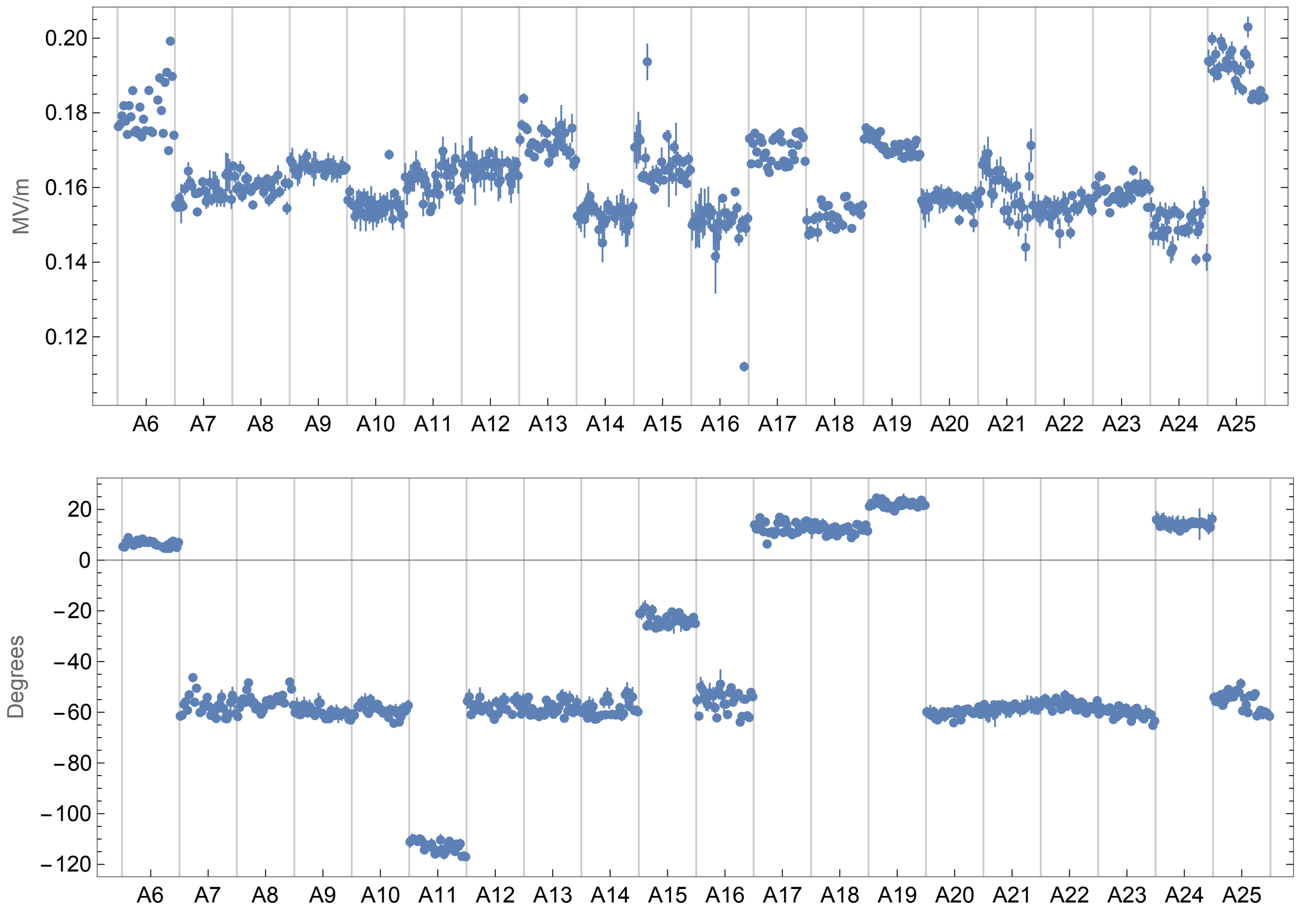


Calibration Algorithm

Procedure

- **Measure beam transients simultaneously in all cavities**
  - Short beam pulse (~200 bunches, t<100us)
  - LLRF system feedback and beam-loading compensation disabled during data acquisition
  - Simultaneously measure bunch energy at end of linac
    - Beam Energy Server (spectrometer)
- **Post-DAQ analysis**
  - Reconstruct beam transients
    - including statistical errors from averaging
  - Calculate probe signal complex calibration factors ***F*** to
    - Make all transient amplitudes equal
    - Zero transient phase (beam phase)
  - Apply ***F*** to probe recorded probe signals, and calculate linac energy gain.
  - Apply **global scale factor *G*** to make calculate energy gain equal to **measured beam energy**

Example transient measurement



Error bars ±2 std. errors

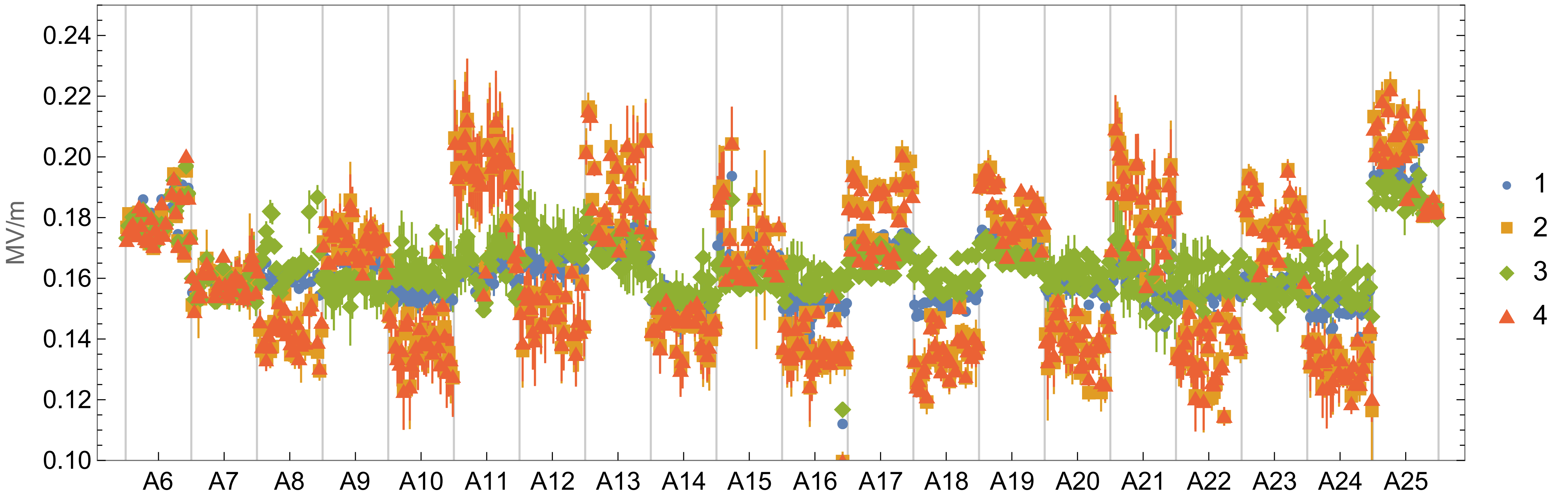
Understand systematic errors

- Statistical error can be arbitrarily reduced by averaging more pulses
- Simulations indicate that beam-RF phase and cavity detuning influence transient fits
  - Systematic errors
- Four datasets taken on 19.10.2020

Dataset	Energy	RF Voltage	RF Phase	Pulse charge	Pulse duration
	GeV		Degree	nC	µs
1	14.0	Low	22	51	89
2	14.0	High	44	29	67
3	17.6	High	0	30	67
4	14.0	High	44	29	67

High is typically 100MV per station higher than **Low**

Beam transient amplitudes

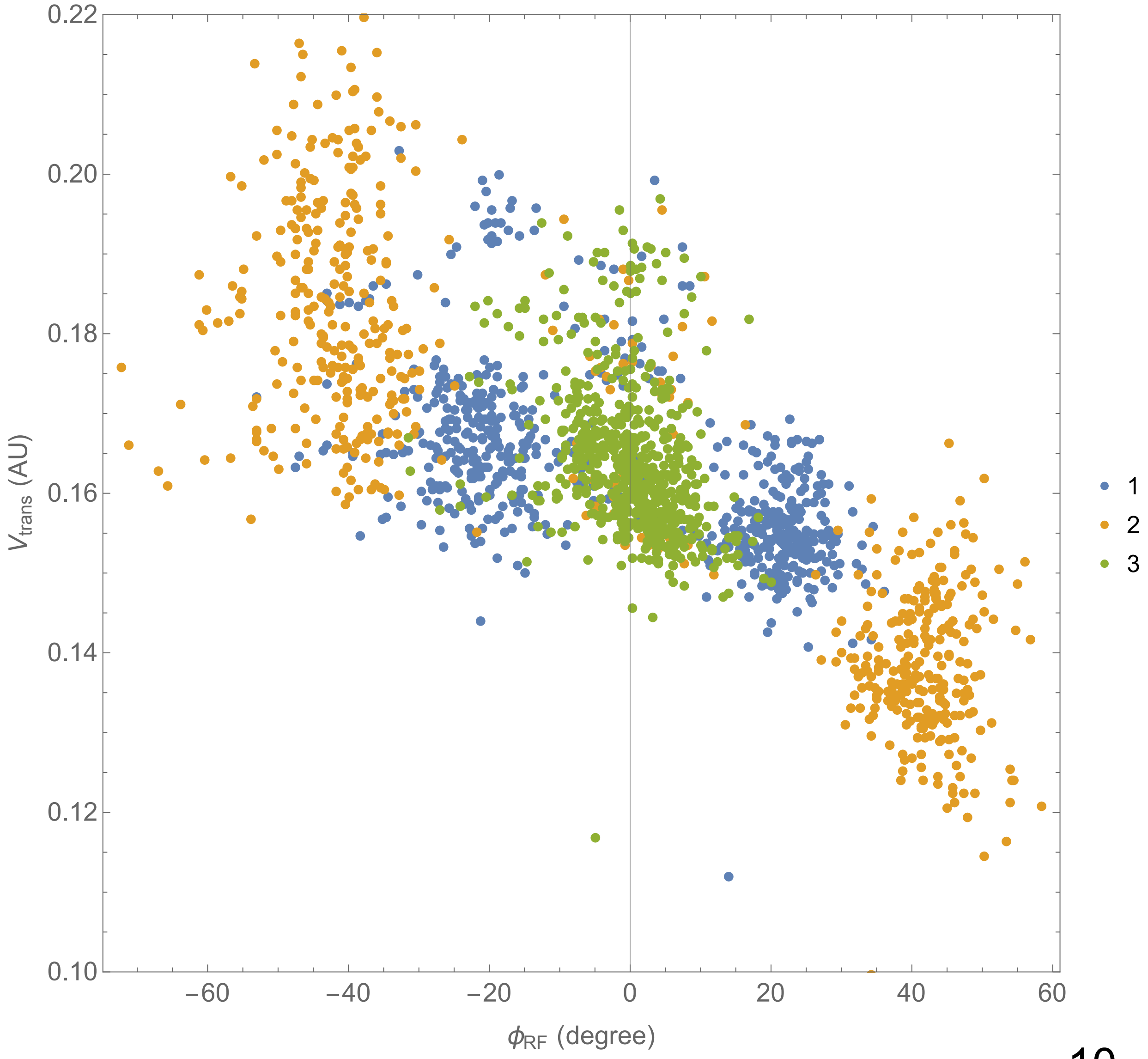


All datasets scaled to 51nC

Off crest datasets show correlation with RF phase

Transient amplitude - phase correlation

transients have been normalised
to 50.9 nC



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Transient amplitude - phase correlation

transients have been normalised
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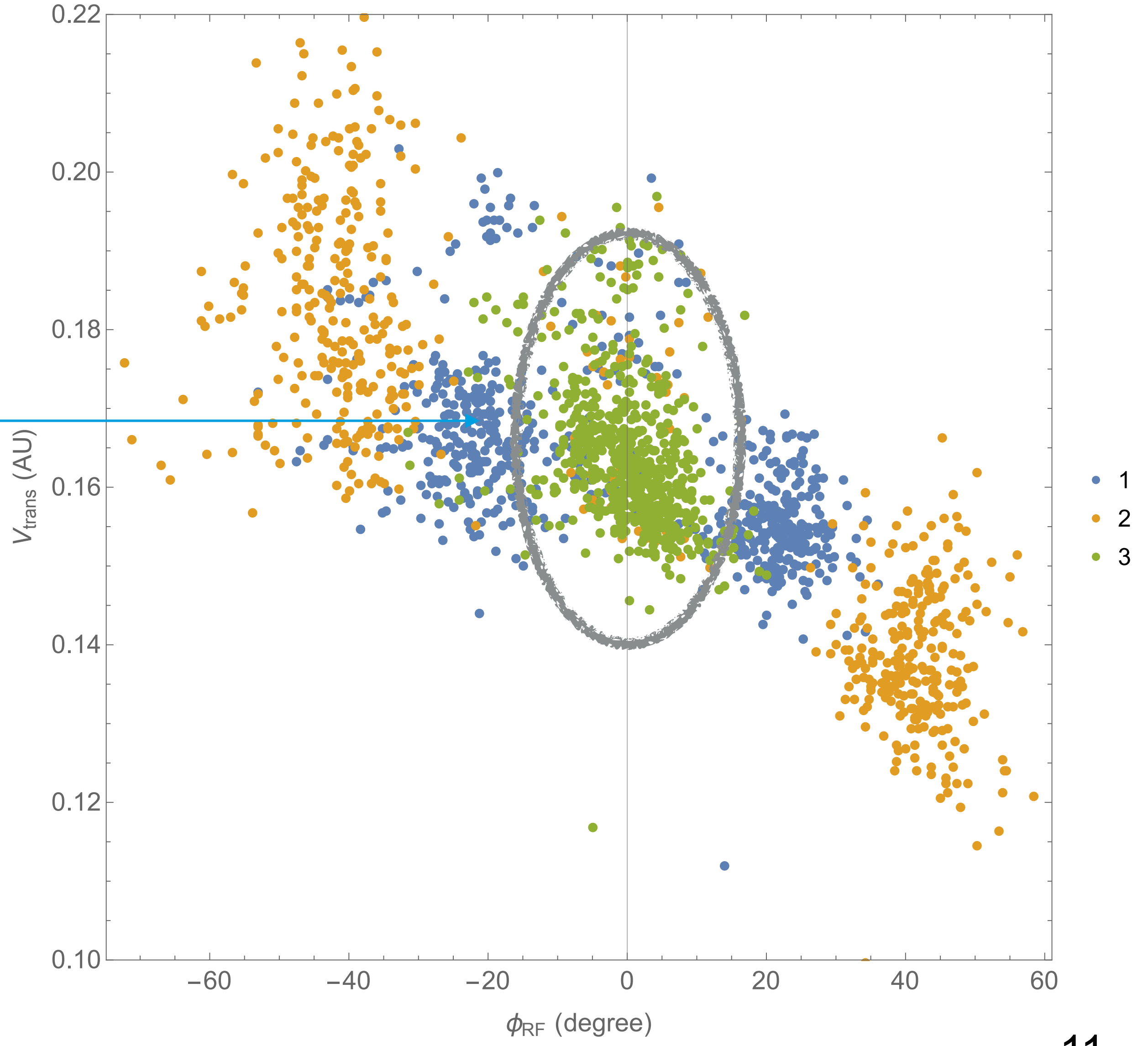
~ On crest dataset (3)



Transient amplitude - phase correlation

transients have been normalised
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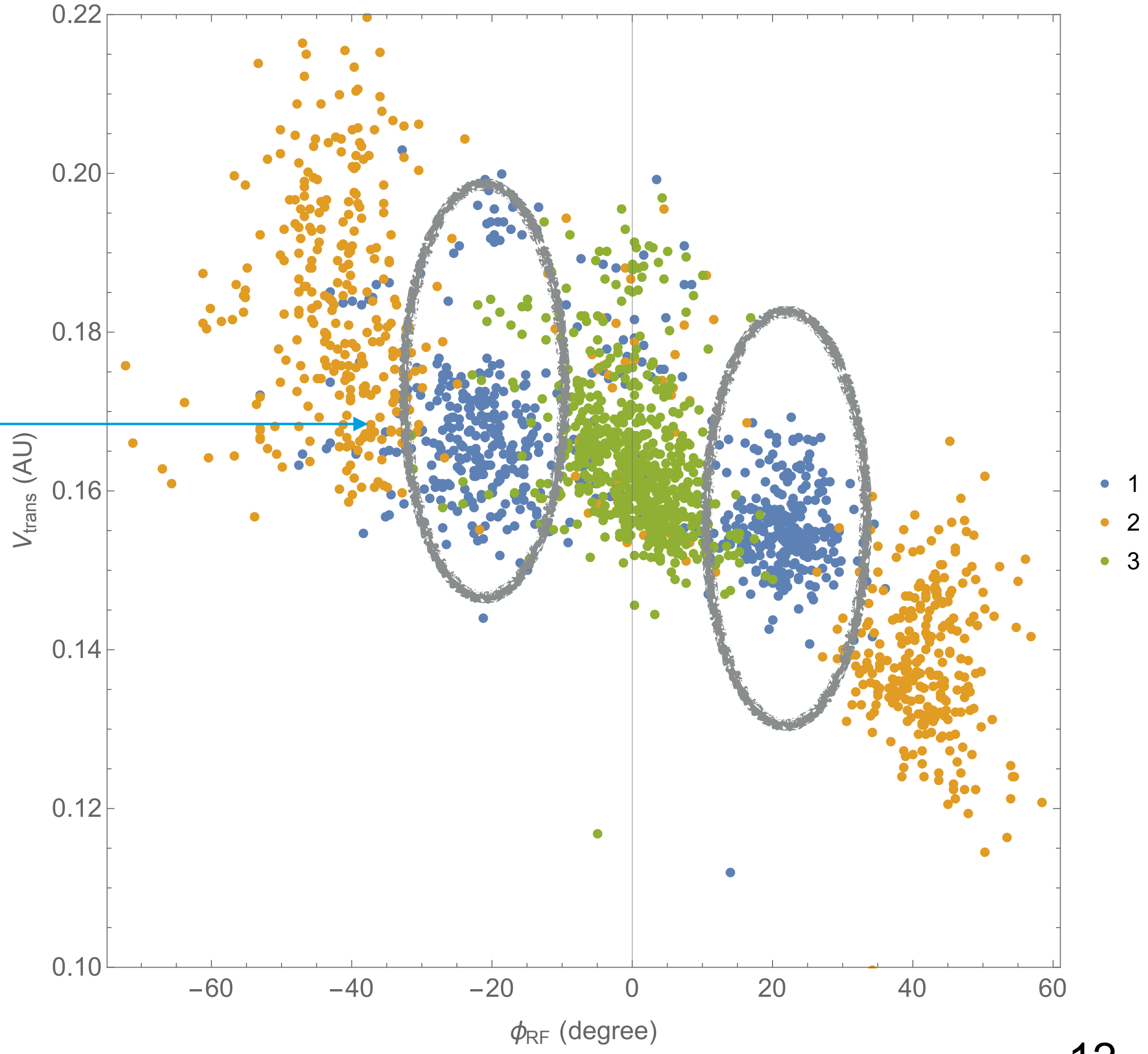
~ Off crest ±22° (1)



Transient amplitude - phase correlation

transients have been normalised
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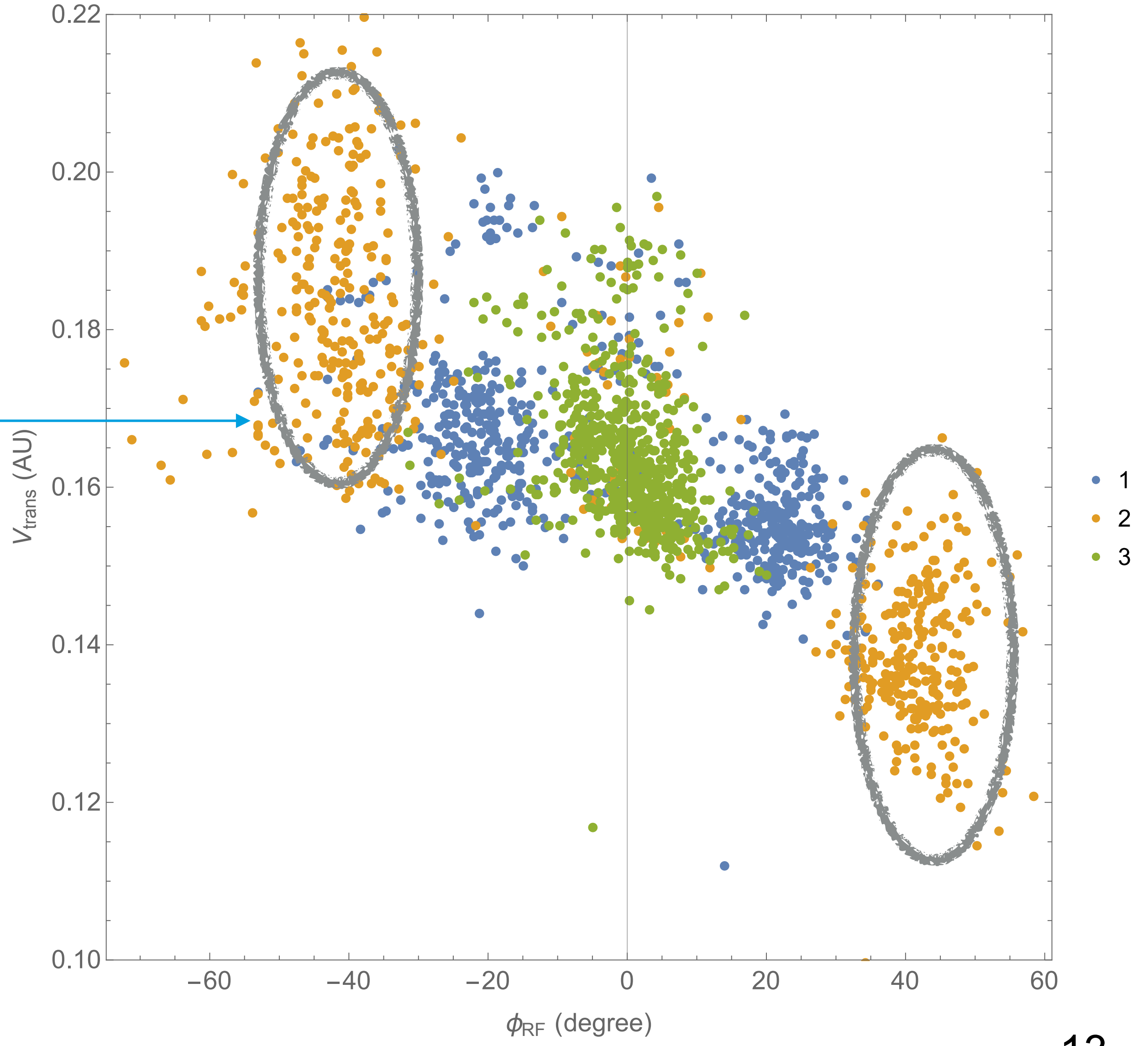
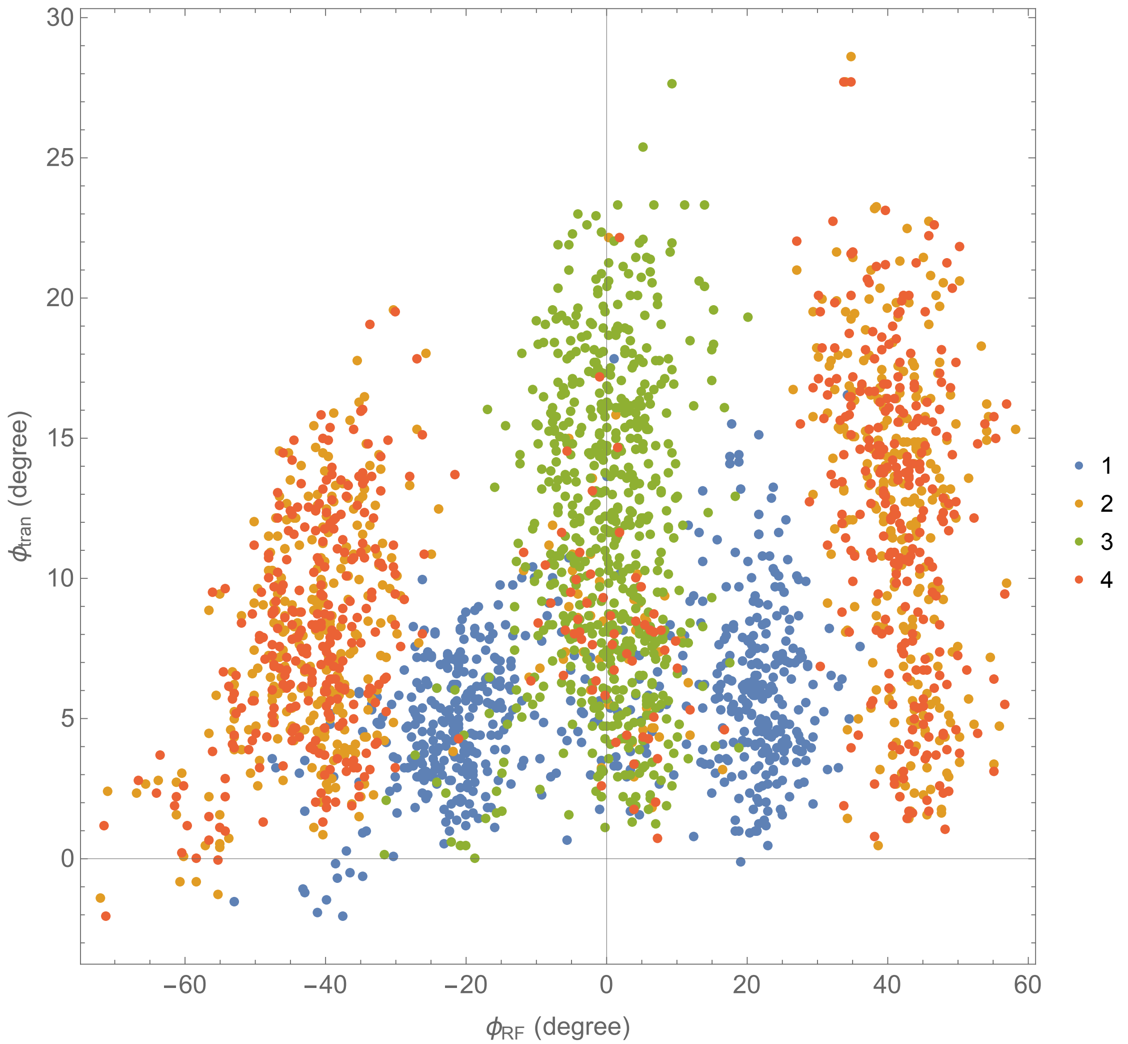
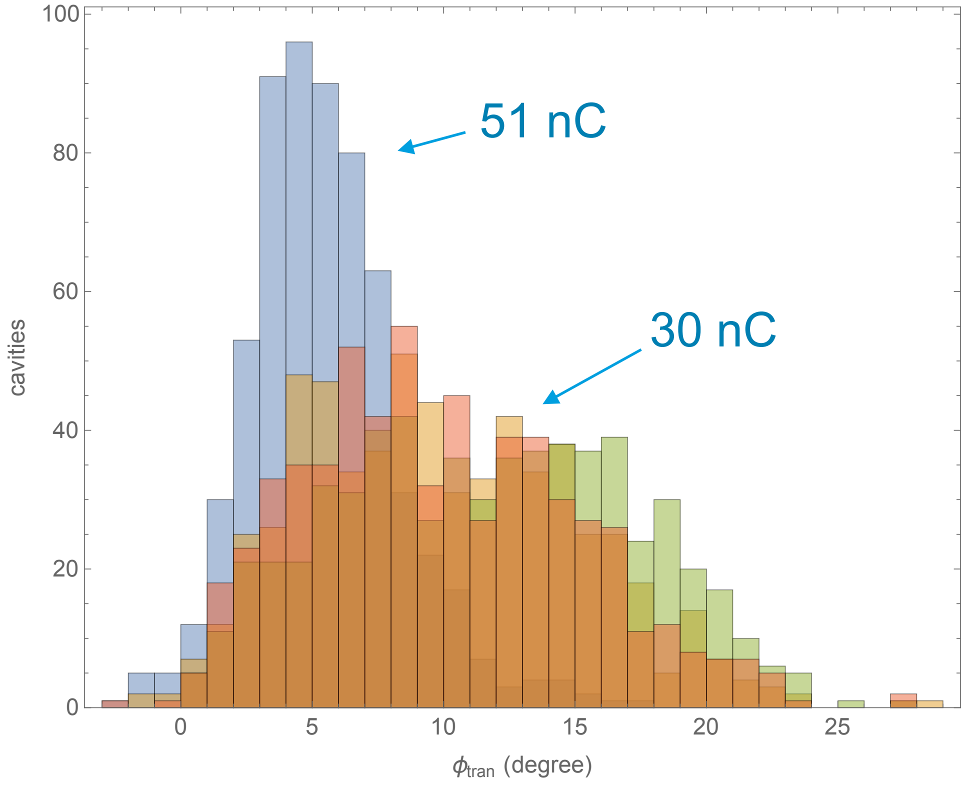
~ Far off crest ±44° (2)



Transient phase - RF phase correlation





- Correlation not so obvious
- Lower charge dataset (2,3 & 4) show broader distributions

Transient Amplitude — comparison to theory

$$V_{tran} \approx \pi f_0 Q_b \left(\frac{r}{Q}\right)\left(1 - \frac{1}{2}\pi f_0 \Delta t / Q_L\right)$$

after calibration normalisation

Dataset	Energy	RF Voltage	RF Phase	Pulse charge	Pulse duration	Vtran (theory)	Vtran (meas)	Rel. Diff.
	GeV		Degree	nC	µs	MV	MV	%
1	14.0	Low	22	51	89	0.21	0.19	-9 ±1
2	14.0	High	44	29	67	0.12	0.10	-15 ±3
3	17.6	High	0	30	67	0.12	0.11	-6 ±2
4	14.0	High	44	29	67	0.12	0.10	-14 ±2

Always systematically lower
Historical value: ~ -10%

Statistical Errors are ~ small

— Data very reproducible for a given RF setup

Dominated by Systematic Errors

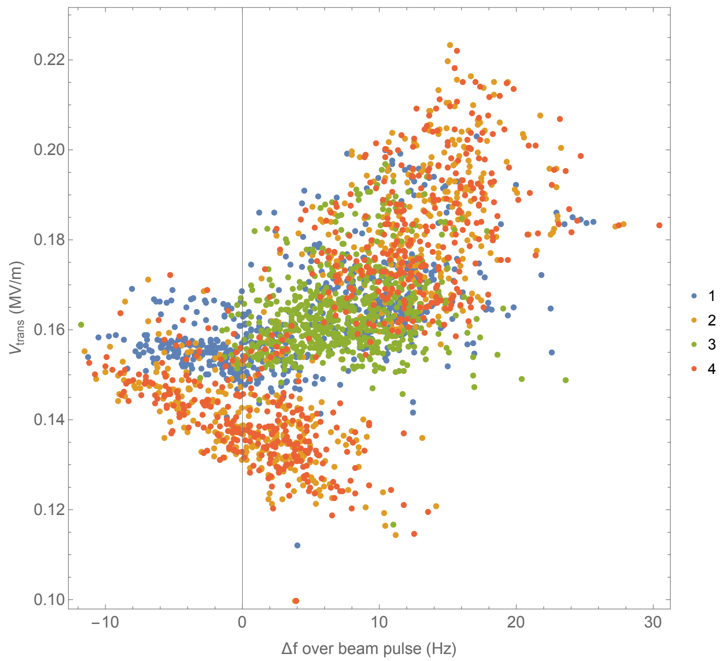
Why?

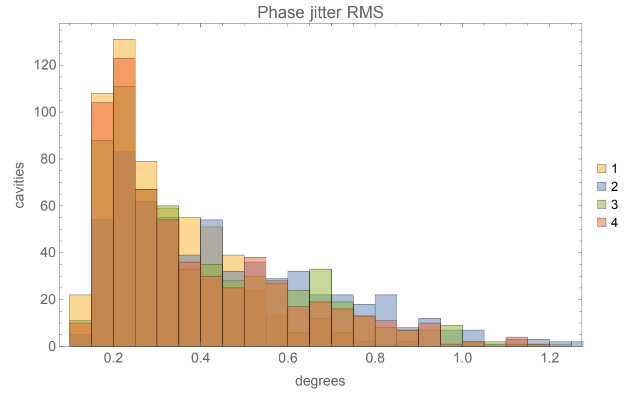
Data stability

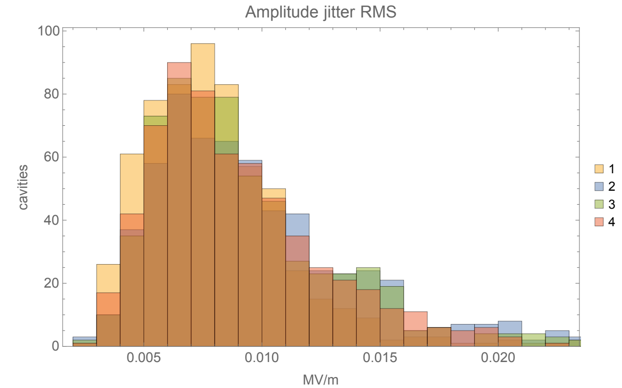
RF stability differences or other parameters differences

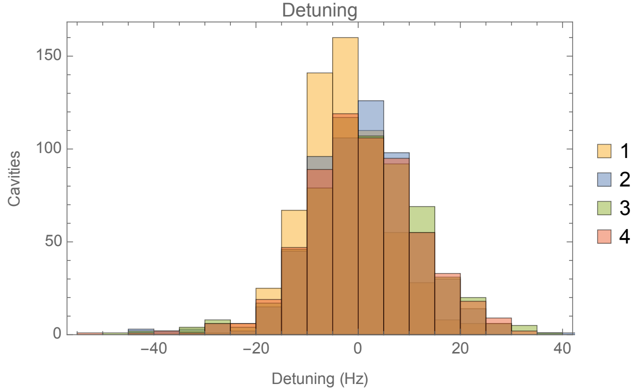
- Phase stability - OK (<1° rms)
- Amplitude stability - OK (<0.2 MV/m rms)
- Detuning - all OK (and similar)

- Delta detuning over beam pulse:









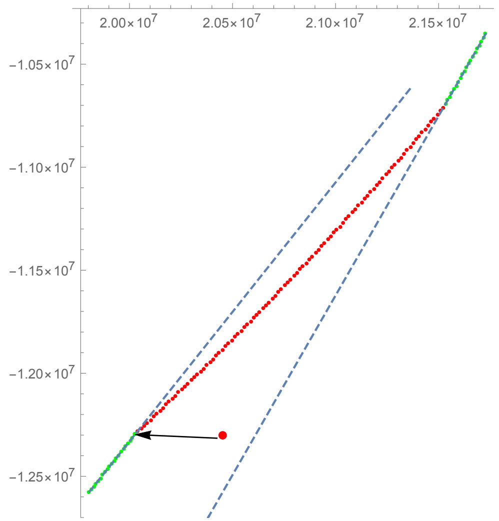
Raw transient fits

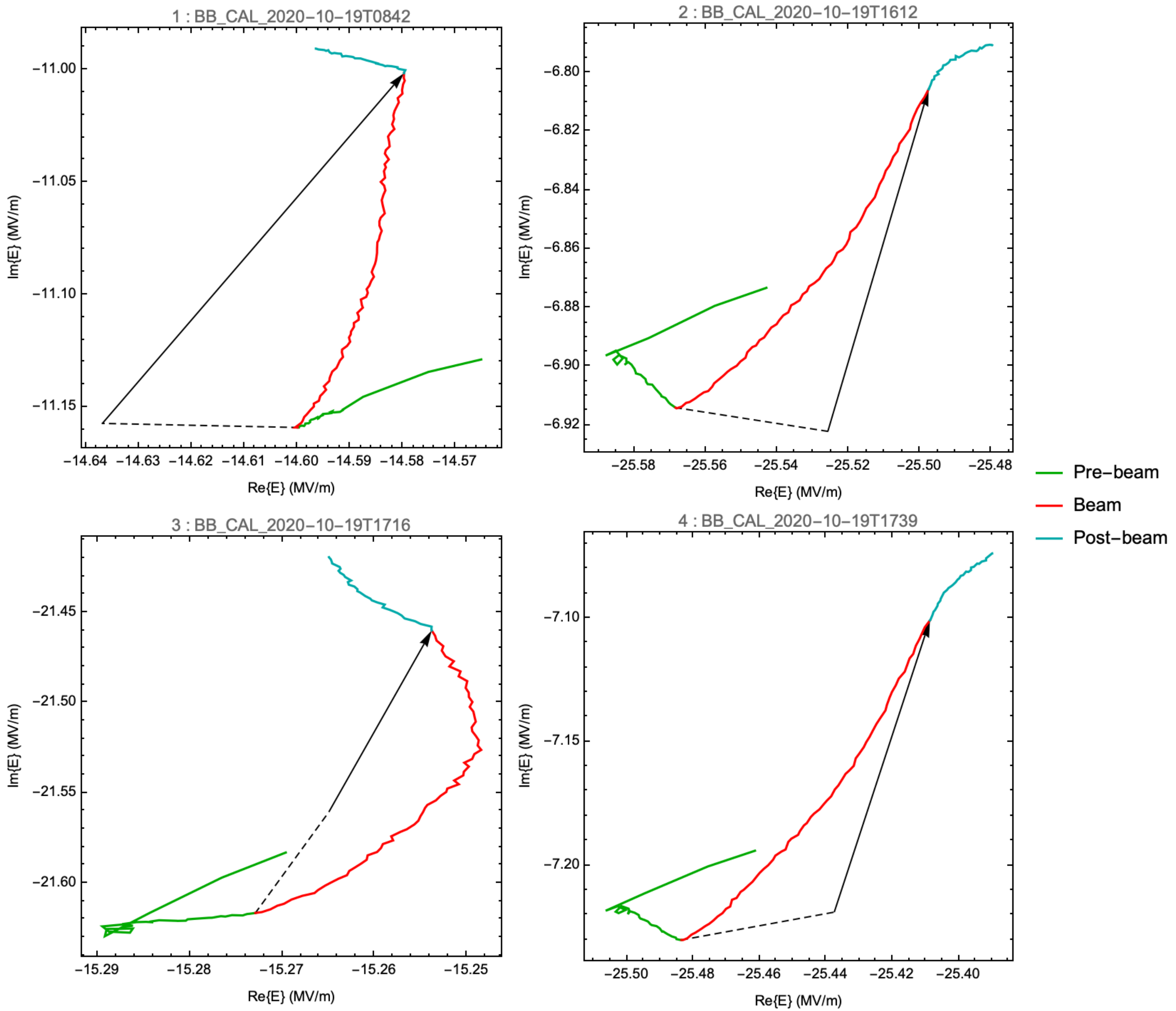
Example A11 M1 C7

probe voltage trace

from t = beam start - 20us
to t = beam end + 20us

CF simulation from slide 4





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Summary

- **Fast quasi-non-invasive data acquisition**
  - Allows routine data taking for monitoring

- **For a given RF set up, data is very reproducible**
  - Random errors are small for 300-point averaging
  - Useful for checking stability of calibration over time

- **Absolute calibration requires work**
  - Systematic errors dominate
    - Change in RF working point can affect results by tens of per cents
    - Simulations (not discussed) suggest systematic effects are smaller by up to factor of 10!
- **Next steps**
  - Re-check calculations for errors and consistency
  - Return to simulations to try and understand observed systematics
  - Take more data at higher charge at different RF phase.
    - Include ‘beam off’ data for direct subtraction method

Summary

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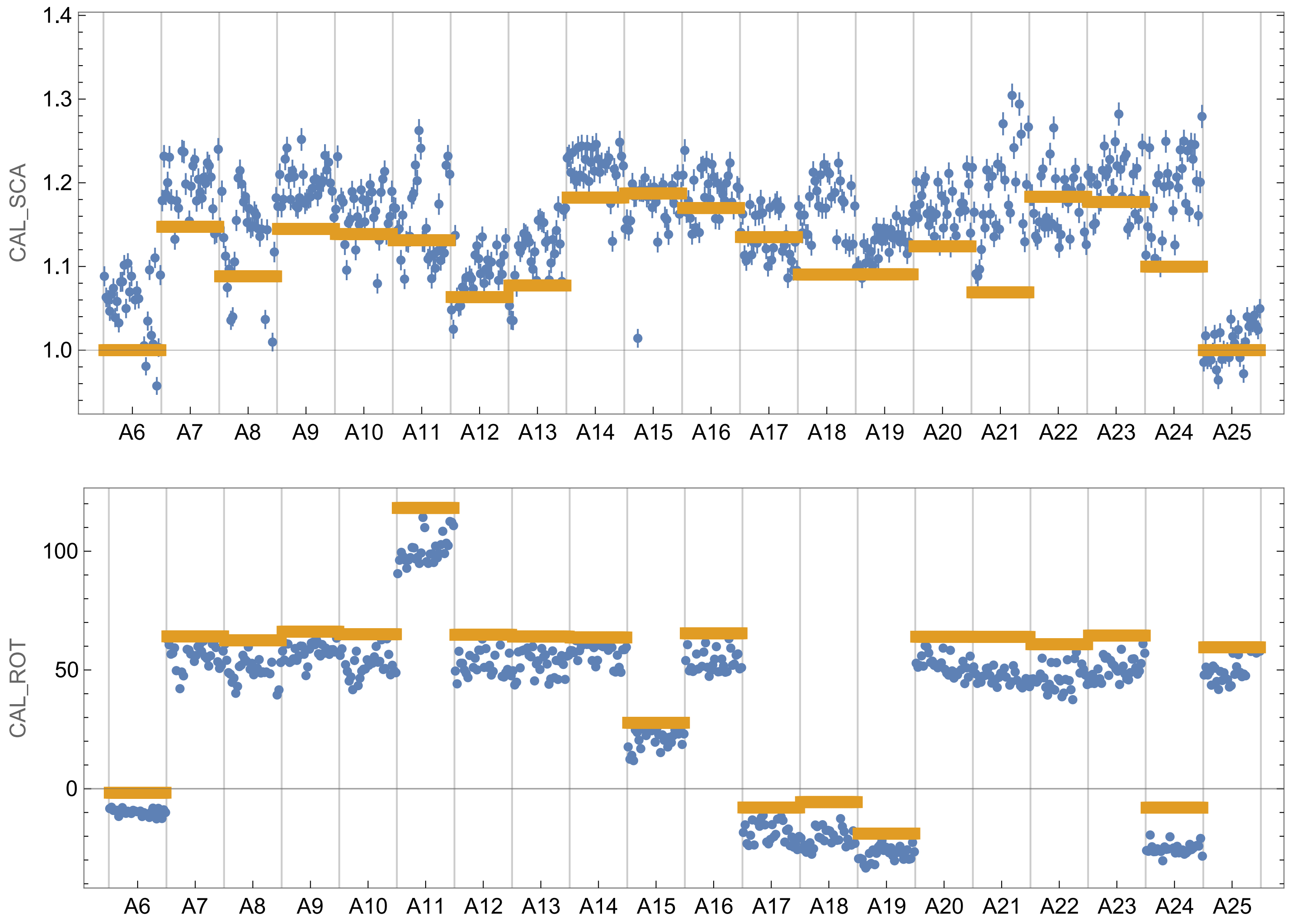
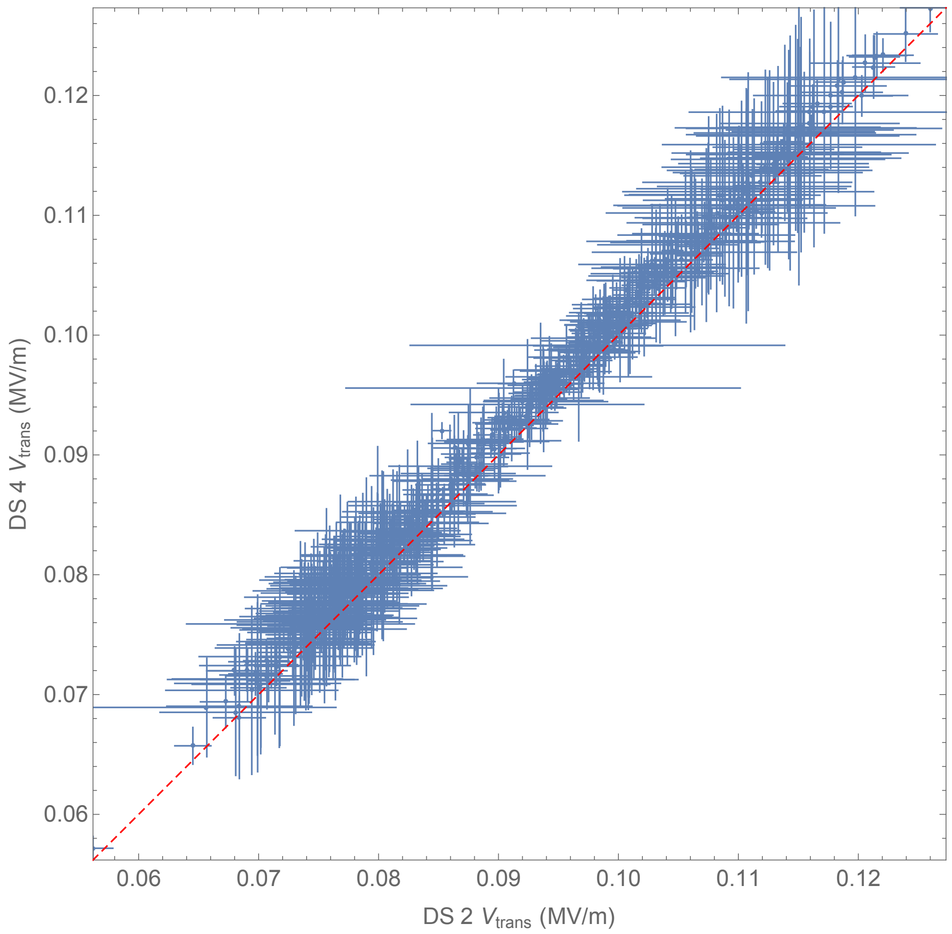
Thank you for your attention

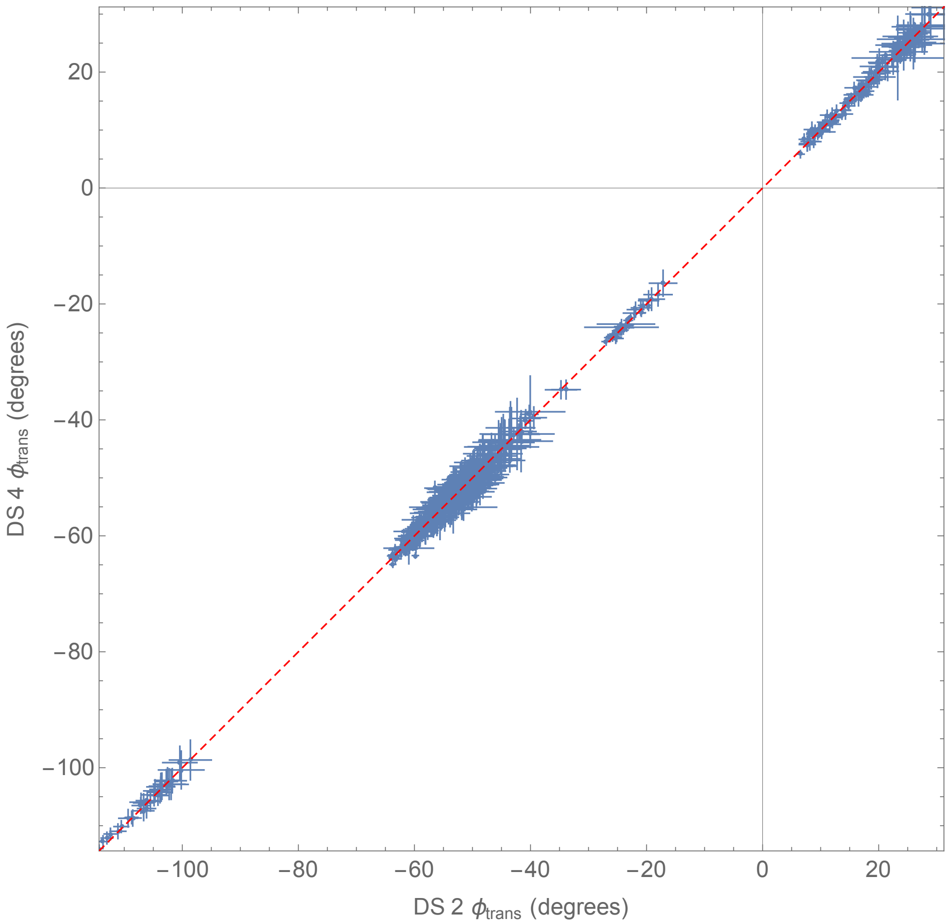
Probe calibration vs current VS.CAL (LLRF station calibration factors)



Consistency

Datasets 2 and 4 (same RF settings)





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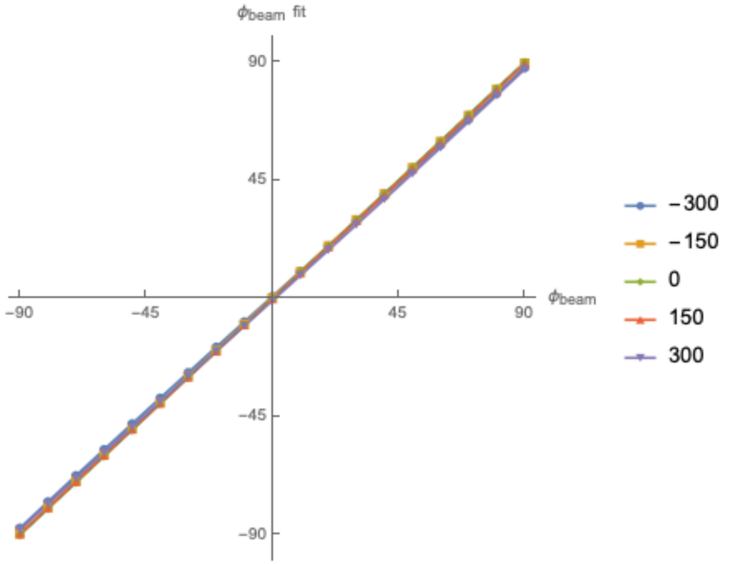
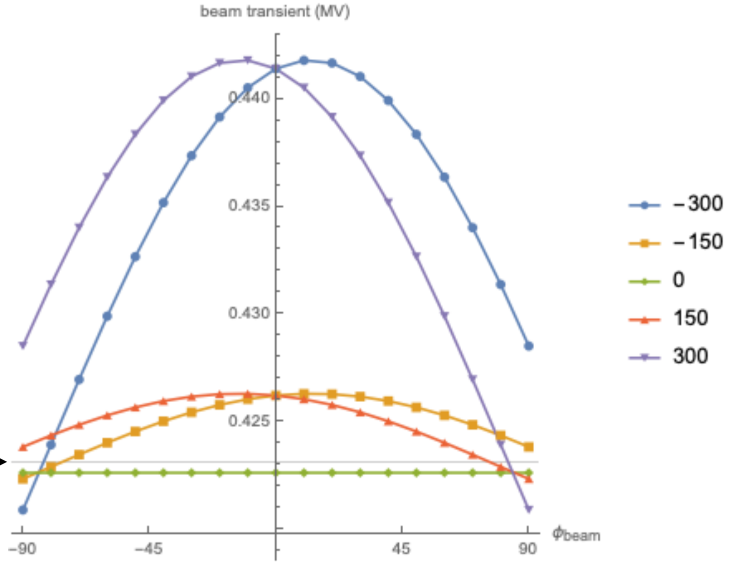
Calibration method - sensitivity to tune state and relative beam phase

Fitted phase vs true phase

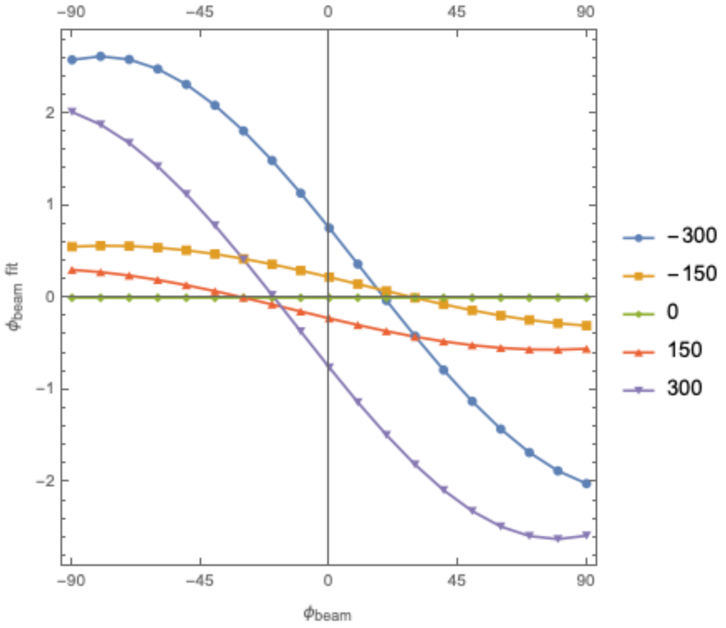


Fitted amplitude vs true phase

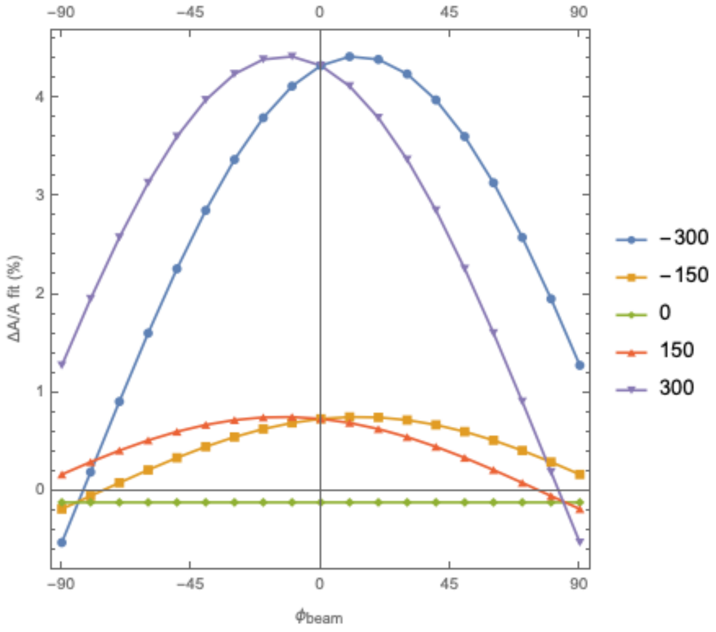
True amplitude



Absolute error (degrees)



Relative error (%)



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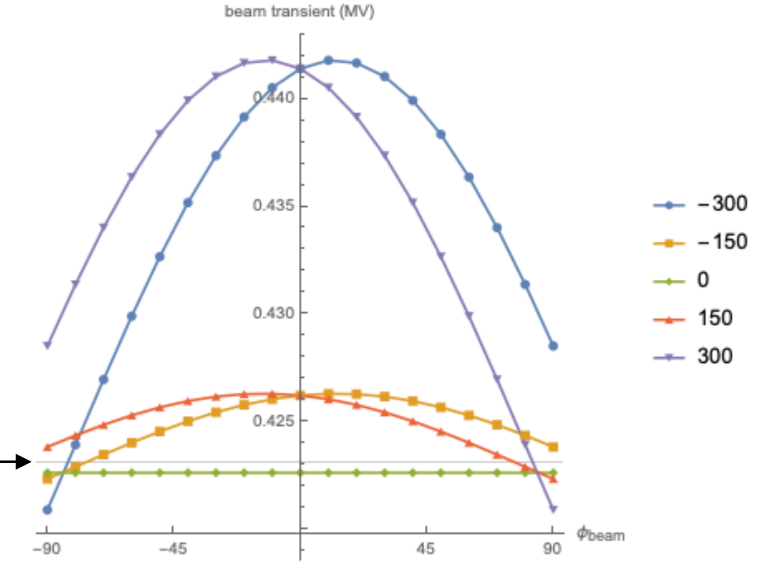
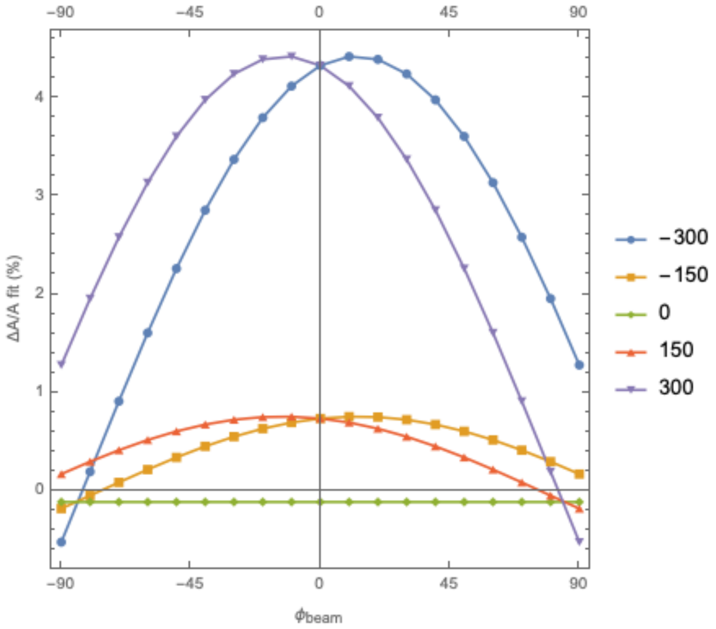


True amplitude



Relative error (%)

Simulation including random errors and LFD