Data Analysis of LLRF Measurements at FLASH

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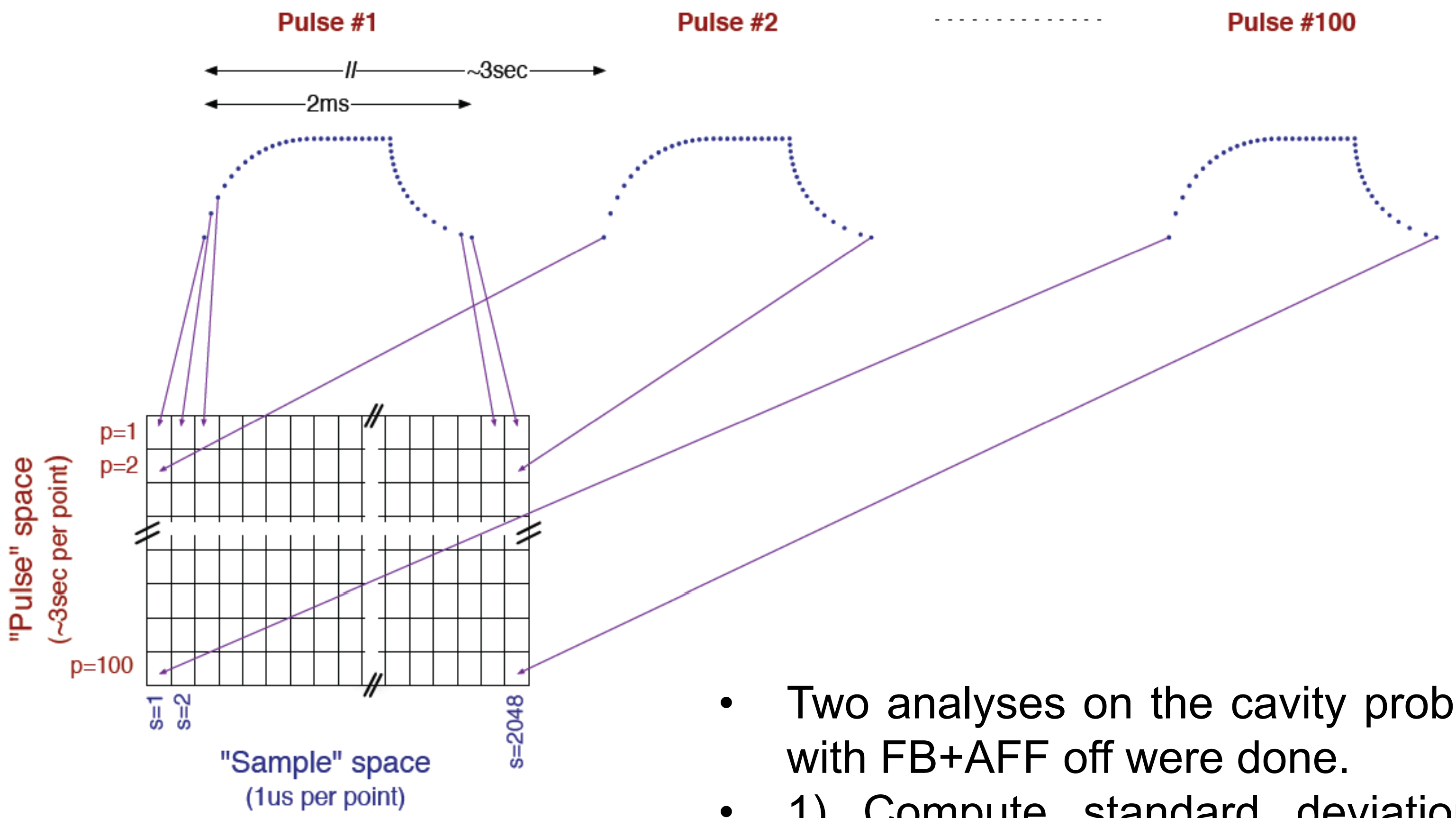
Motivation and Introduction

- Motivation: analyze FLASH LLRF real time data (they have an impressive DAQ system), measure the system stability, determine the electronic noise levels, gauge the perturbations to the system, etc.
- Data was collected on Sep 17, 08 for the following 3 setups:
  - No beam, FB off, AFF off.
  - No beam, FB on, AFF off.
  - No beam, FB on, AFF on.
- For each set of measurements, the phase and amplitude waveforms (both from the cavity input and pickup couplers) of all cavities in the three cryomodules (ACC4-ACC6) were recorded simultaneously for 100 pulses (one every 3 sec).
- Data and analyzing scripts can be found at http://public.me.com/carwardine.

Time Domain Analysis

- Calibrated the input forward signal at first flattop in MV/m (assuming the cavity probe signal is calibrated correctly).
- Averaged sets of 4 points to eliminate the 250 kHz LLRF signal leakage effect.
- Computed the standard deviation at each time step for the 100 pulses in each set of measurements.
- The standard deviation before the RF turns on is a measure of electronic noise, while the standard deviation when the RF is on includes the rf jitter. To compute the jitter, the noise contribution was subtracted in quadruture.
- This method was used to analyze the vector sum, input forward and cavity probe signals.

Frequency Domain Analysis


Pulse #1
Pulse #2
Pulse #100
~3sec
2ms
p=1
p=2
p=100
"Pulse" space
(~3sec per point)
s=1
s=2
s=2048
"Sample" space
(1us per point)

This method was only used for probe signal analysis.

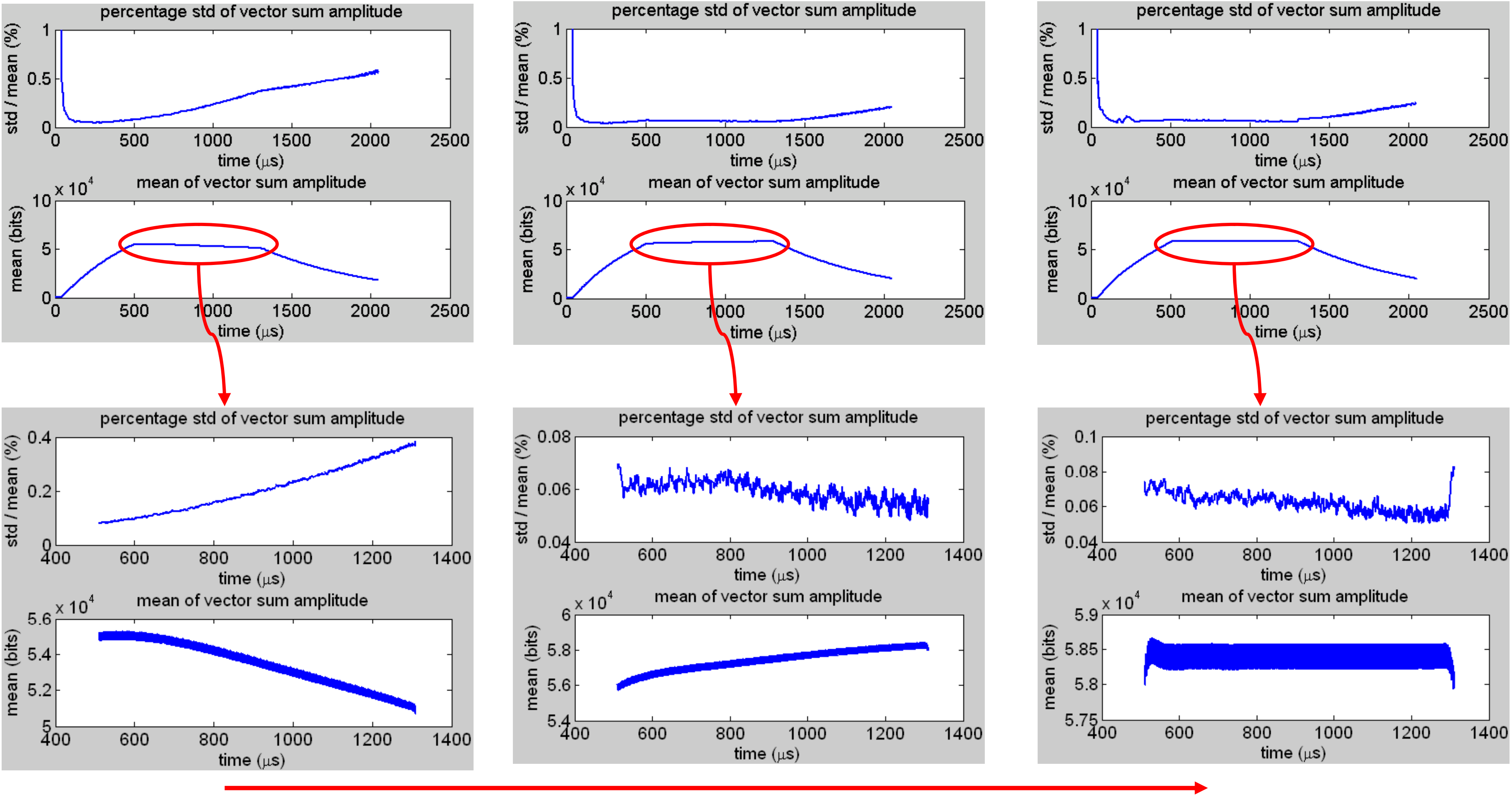
- Two analyses on the cavity probe flat top data with FB+AFF off were done.
- 1) Compute standard deviation of 'Pulses' versus 'Sample' time.
- 2) Compute FFT of the 'Pulses' at two fixed sample times (beginning and end of the flattop).

Outline of Key Findings

- The FB + AFF controls work well to flatten the vector sum amplitude and phase.
- Input RF very stable (~ 0.1% level) with FB and AFF off.
- Jitter on cavity probe signals dominated by variations in pulse-to-pulse cavity detuning profile.
  - Jitter essentially random pulse to pulse with large cavity to cavity variations (probably uncorrelated).
  - Jitter does not scale simply with gradient^2 (in 14-24 MV/m range) – suggests large variations in mechanical stiffness (factor 2 difference).

Vector Sum Amplitude

FB Off / AFF Off / No Beam   FB On / AFF Off / No Beam   FB On / AFF On / No Beam



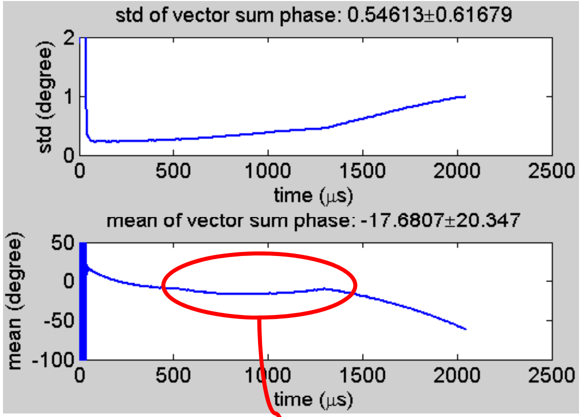
Flat top amplitude percentage standard deviation is decreased by factor 2-6.
FB can decrease the percentage std, AFF can flat the flat top amplitude.

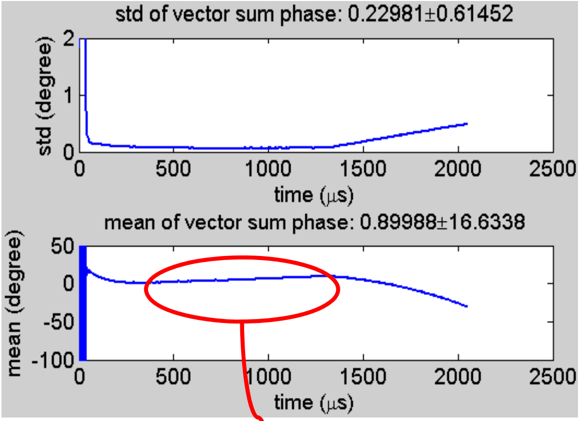
Vector Sum Phase

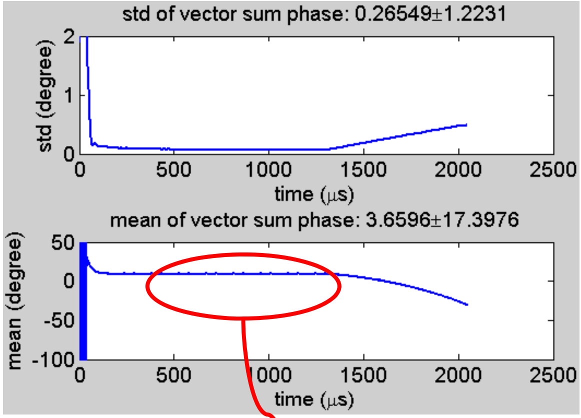
FB Off / AFF Off / No Beam

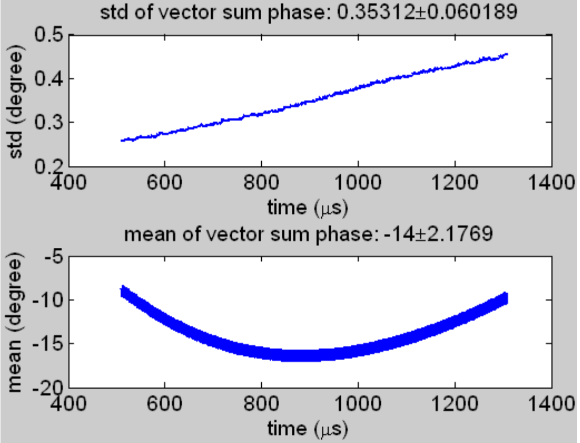
FB On / AFF Off / No Beam

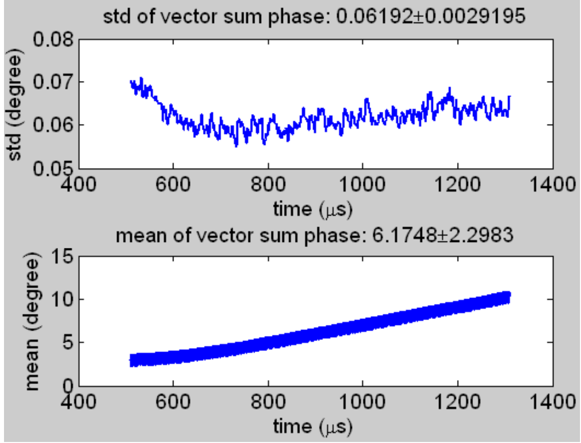
FB On / AFF On / No Beam

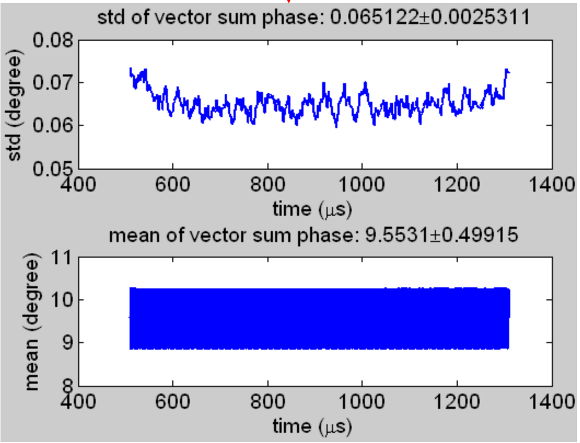












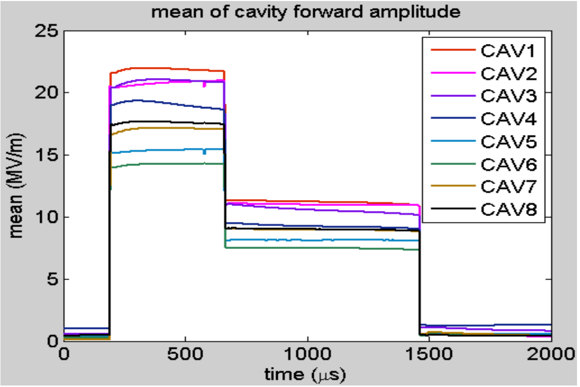
The phase standard deviation is decreased by factor 3-7.
FB can decrease the phase std, AFF can flat the flat top phase.

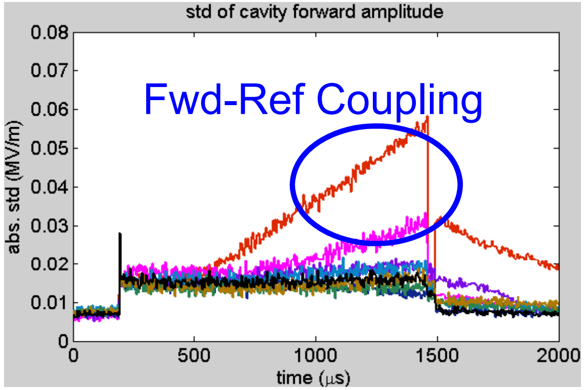
For. and Refl. Signals

- Input signals not calibrated (i.e., amplitude not proportional to gradient), noisy (electronic) and some contain 250 kHz leakage.
- Significant reflected-to-forward signal coupling (i.e., signals not all the same shape – could not de-convolute them perfectly).
- Reflected signals indicate significant initial detuning (i.e. reflected amplitude is not zero near end of first flattop) – expect ~ 300 Hz LFD over 1 ms at these gradients.
- FB+AFF off amplitude very stable pulse to pulse: ~ 0.07% RMS in first flattop and 0.15% RMS in second, which may be larger due to ref-fwd coupling or if jitter dominated by noise on common RF drive (i.e. independent on RF amplitude).
- FB On, AFF Off: input signal shape change as expected for detuning (i.e. no piezo compensation).
- FB On, AFF On: Adds strange shape to first flattop and increase jitter.

ACC6 Input Mean and Std

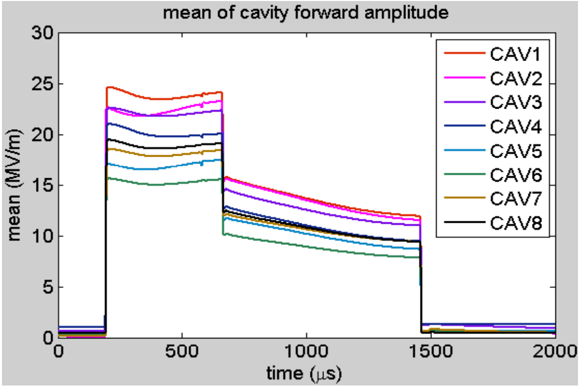
FB Off / AFF Off / No Beam

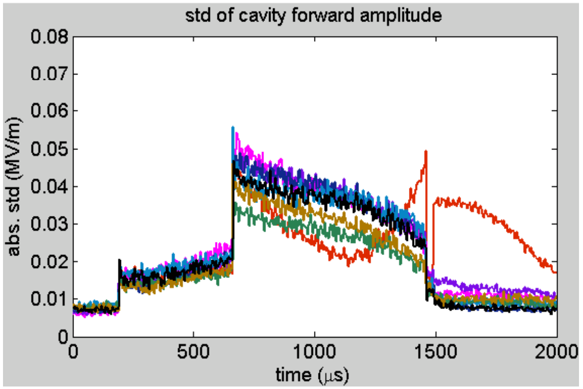




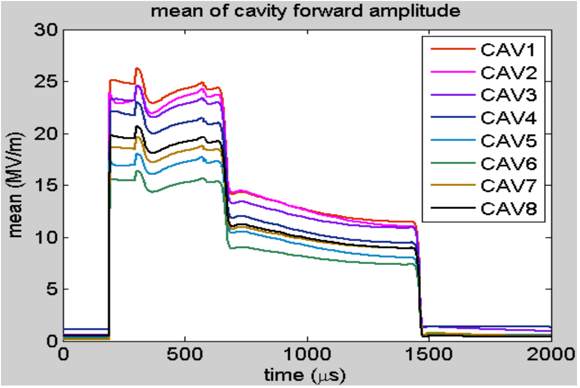
Fwd-Ref Coupling

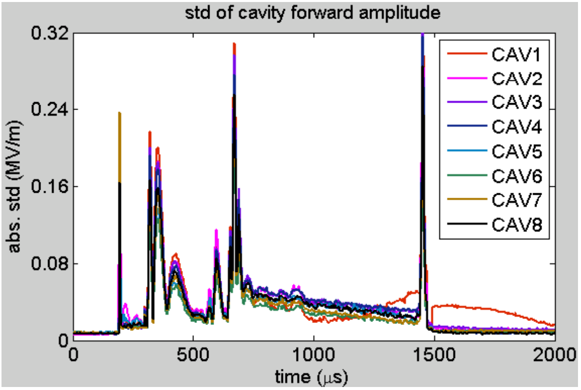
FB On / AFF Off / No Beam





FB On / AFF On / No Beam

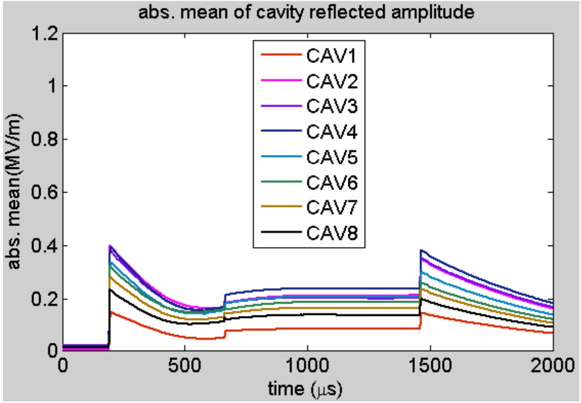




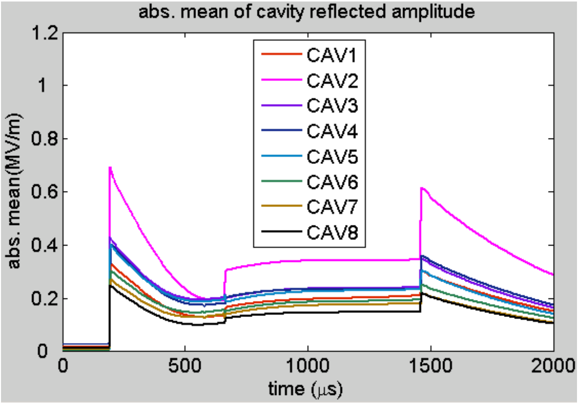
Refl. RF from Cavities

FB Off / AFF Off / No Beam

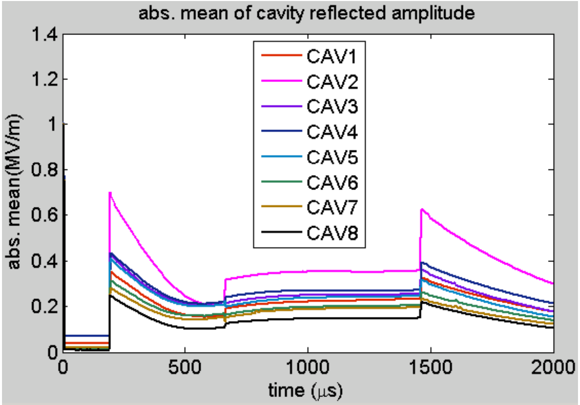
ACC4

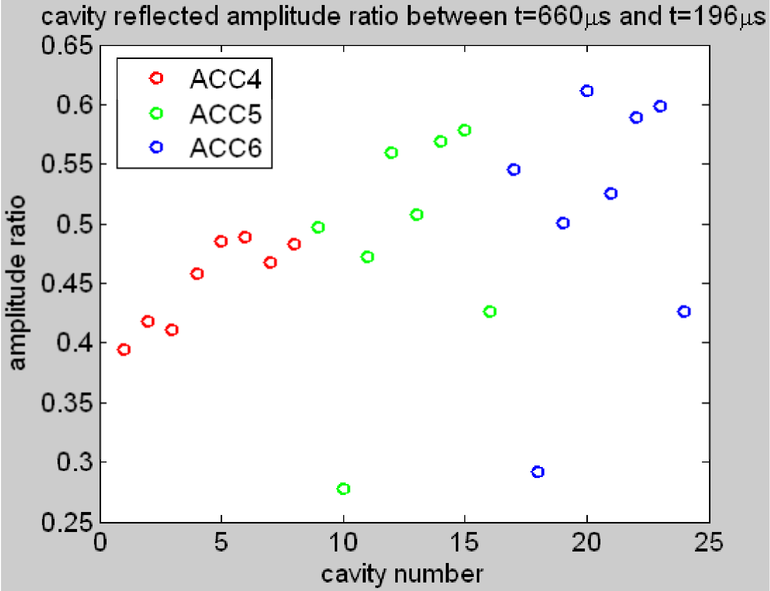


ACC5



ACC6



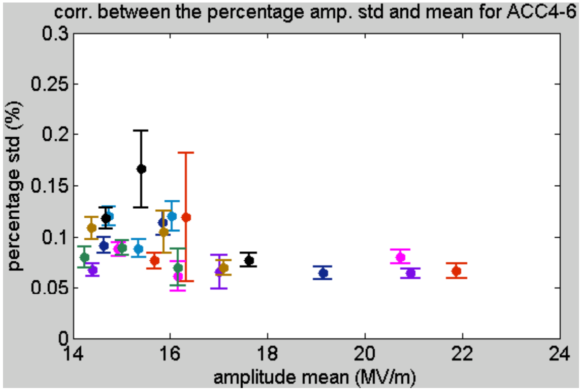


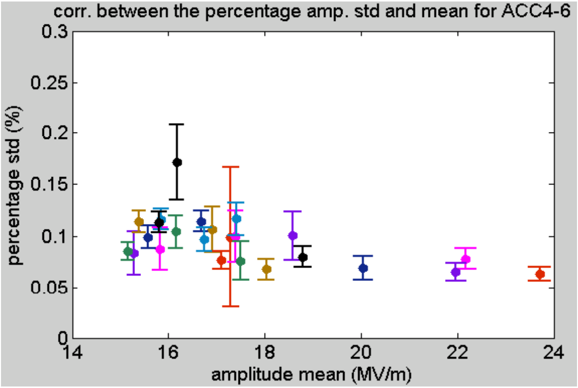
These plots suggest the cavities are running fairly far off-resonance.

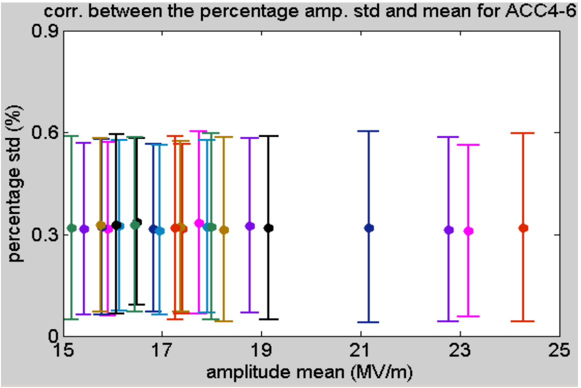
Forward Flat in ACC4-6

1st Forward Flat in ACC4-6

FB Off / AFF Off / No Beam FB On / AFF Off / No Beam FB On / AFF On / No Beam

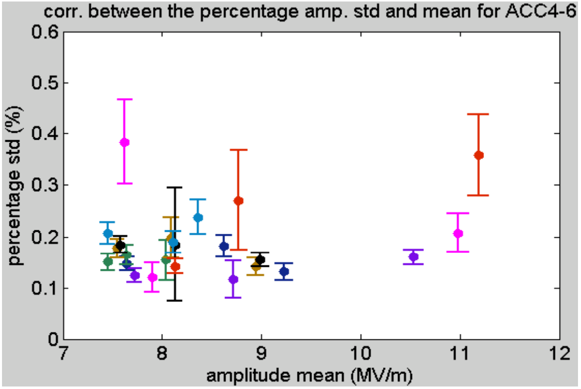


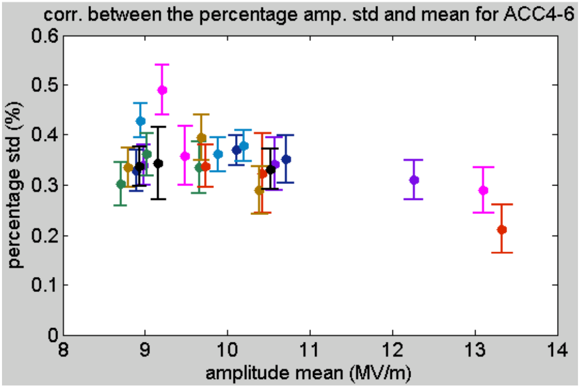


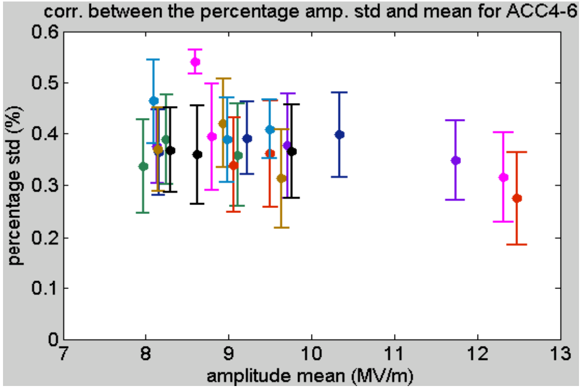


2nd Forward Flat in ACC4-6

FB Off / AFF Off / No Beam FB On / AFF Off / No Beam FB On / AFF On / No Beam





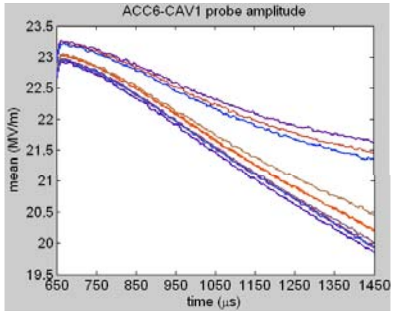


Cavity Probe Signals

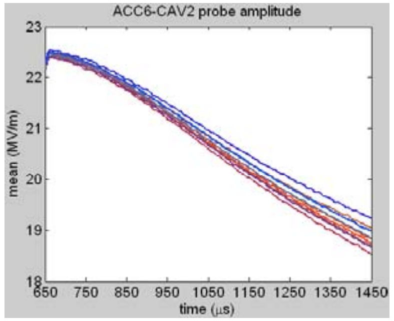
- See smooth pulse-to-pulse variations in probe signal shape that grow along the pulse, suggesting jitter is an integrated effect and not dominated by fast changes in Q (as in dark current and multipacting).
- Jitter is a few tenths of percent at beginning of flattop and grows up to 4% by end of flattop.
- Higher gradient cavities have higher jitter in general, but it does not scale simply with gradient^2.
- Jitter at flattop end correlates well with detuning variation just after RF shut-off, suggesting that variations in pulse-to-pulse detuning is driving the probe signal jitter.
- Jitter essentially random pulse to pulse with large cavity to cavity variations (uncorrelated between cavities).
  - See some peaks in FFT spectrum but they do not contribute significantly to jitter.

Probe Signals for Flattop

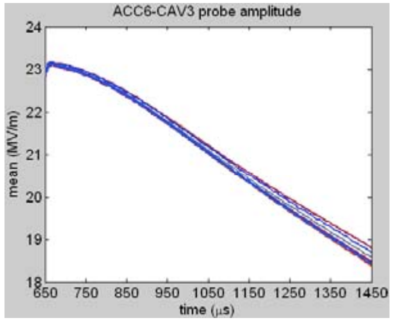
ACC6 FB Off / AFF Off / No Beam



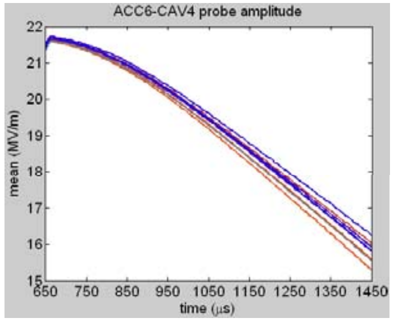
CAV1



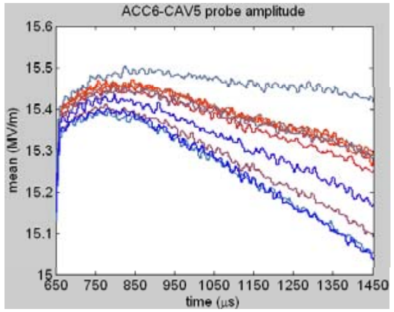
CAV2



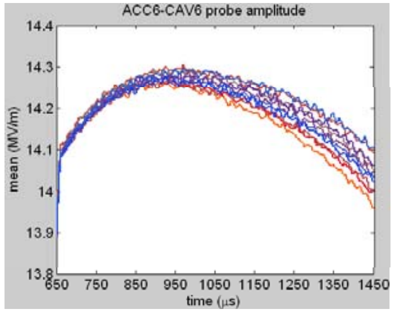
CAV3



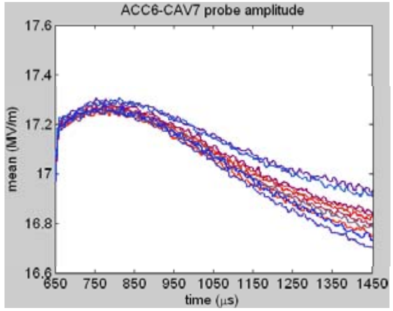
CAV4



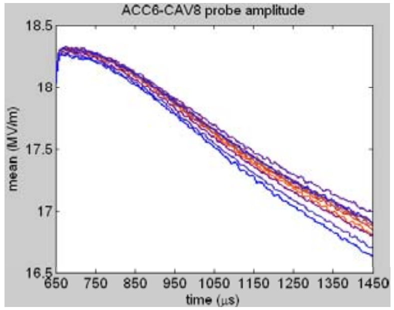
CAV5



CAV6



CAV7

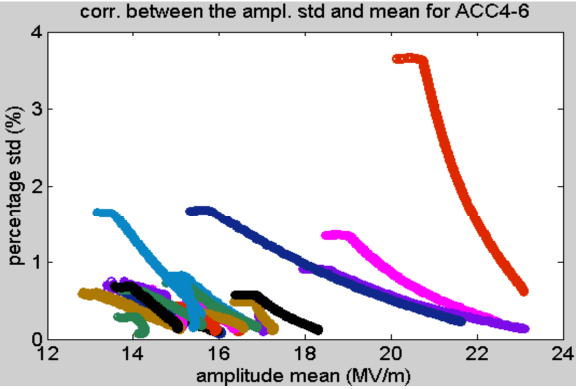


CAV8

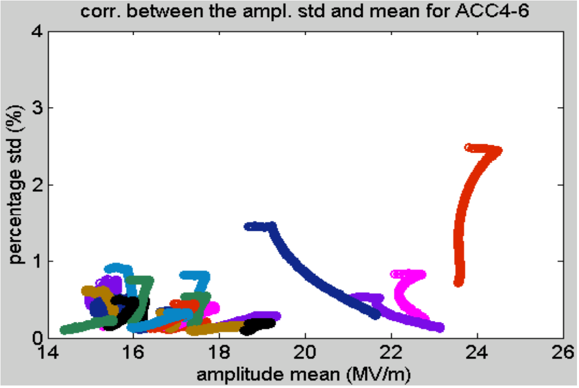
Probe Signal Std for ACC4-6

Std -vs- Gradient along Flattop for each Cavity

FB Off / AFF Off / No Beam



FB On / AFF Off / No Beam



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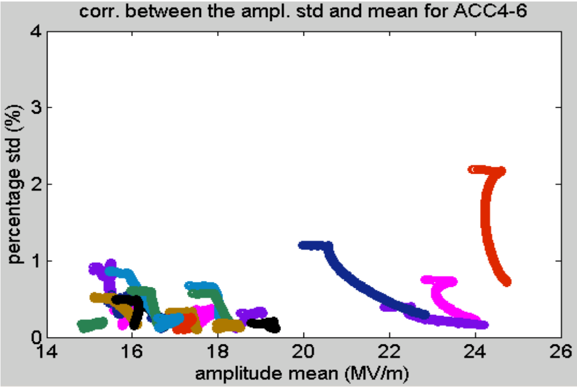
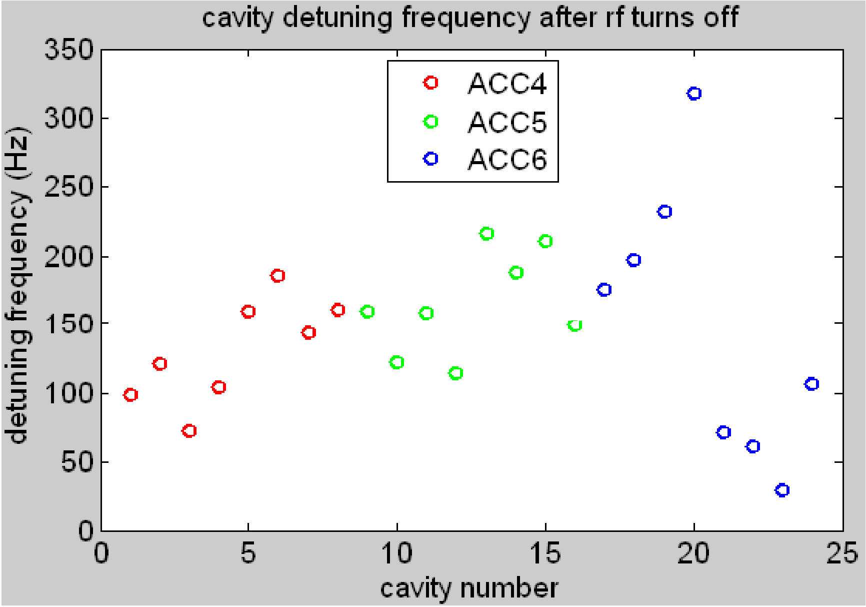
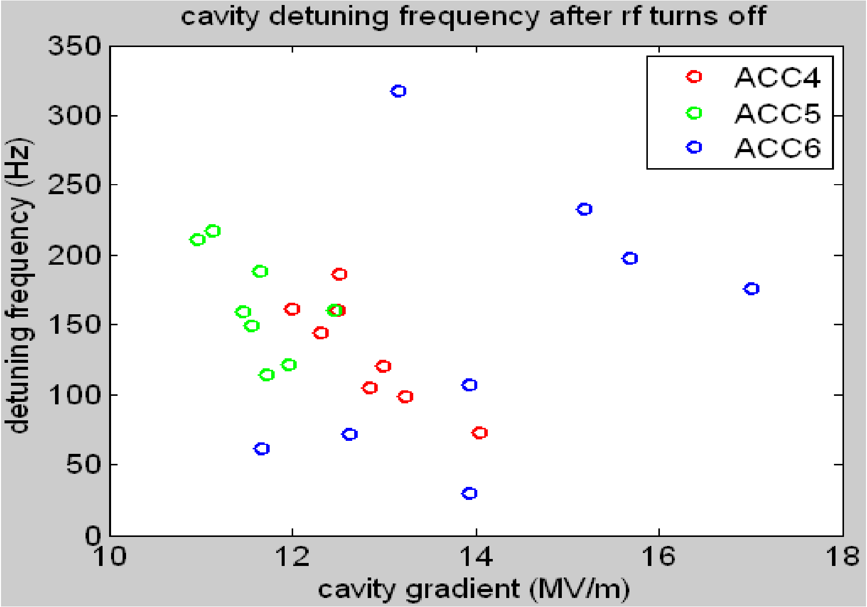


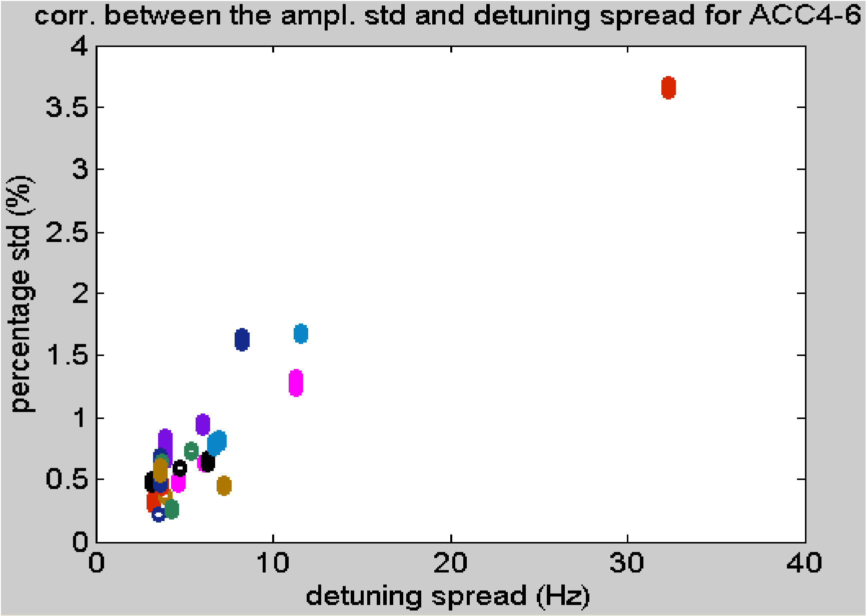
Detuning after RF Off

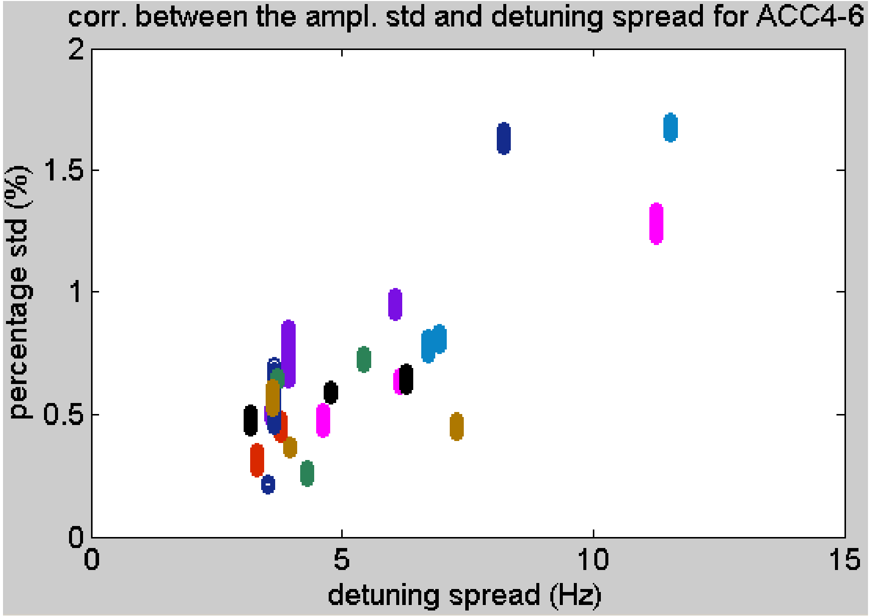
FB Off / AFF Off / No Beam





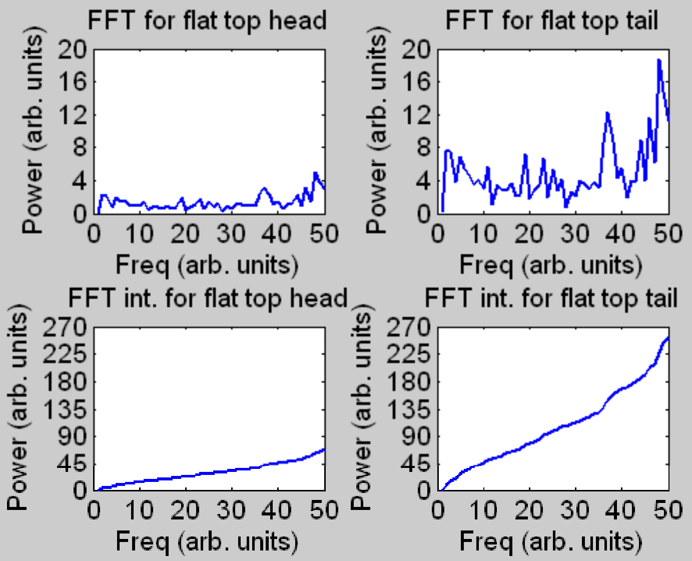
Corr. of Jitter Std & Detuning Std



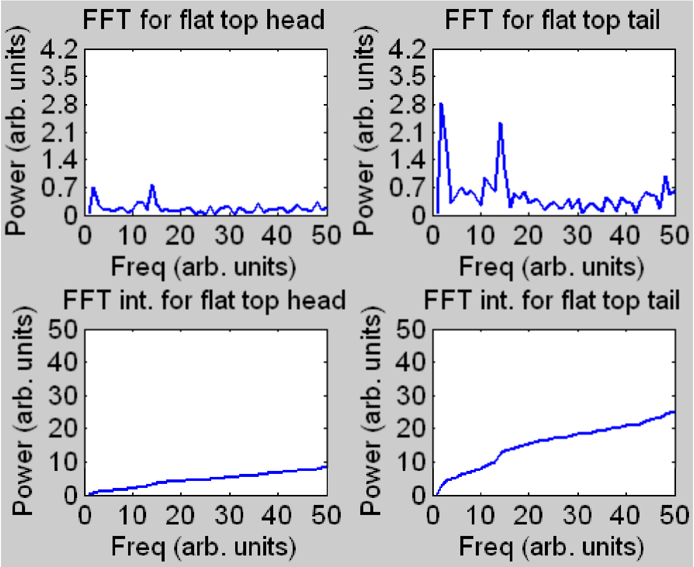


FFTs of Probe Signal Jitter

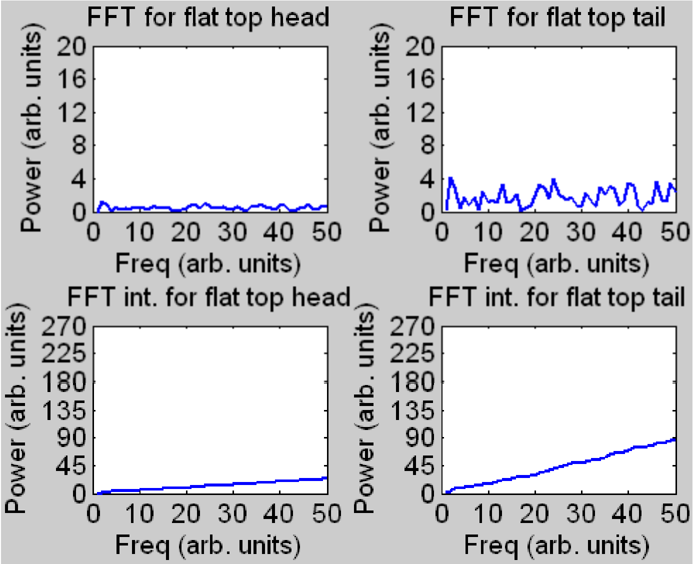
ACC6-CAV1



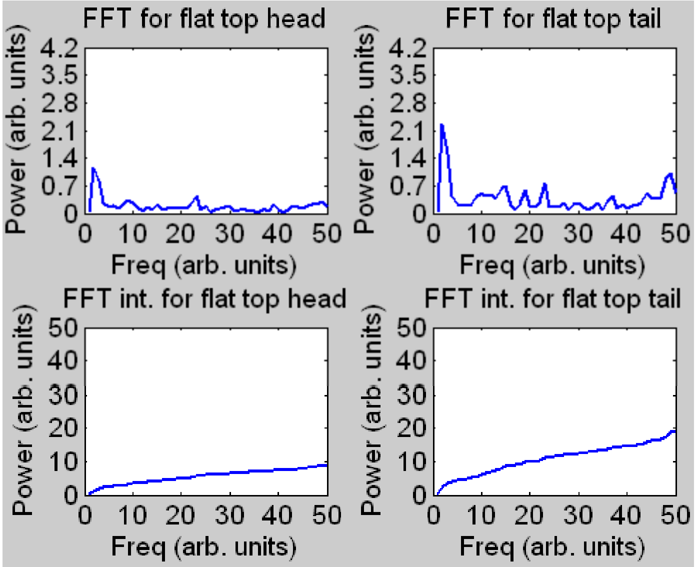
ACC4-CAV3



ACC6-CAV2



ACC4-CAV7



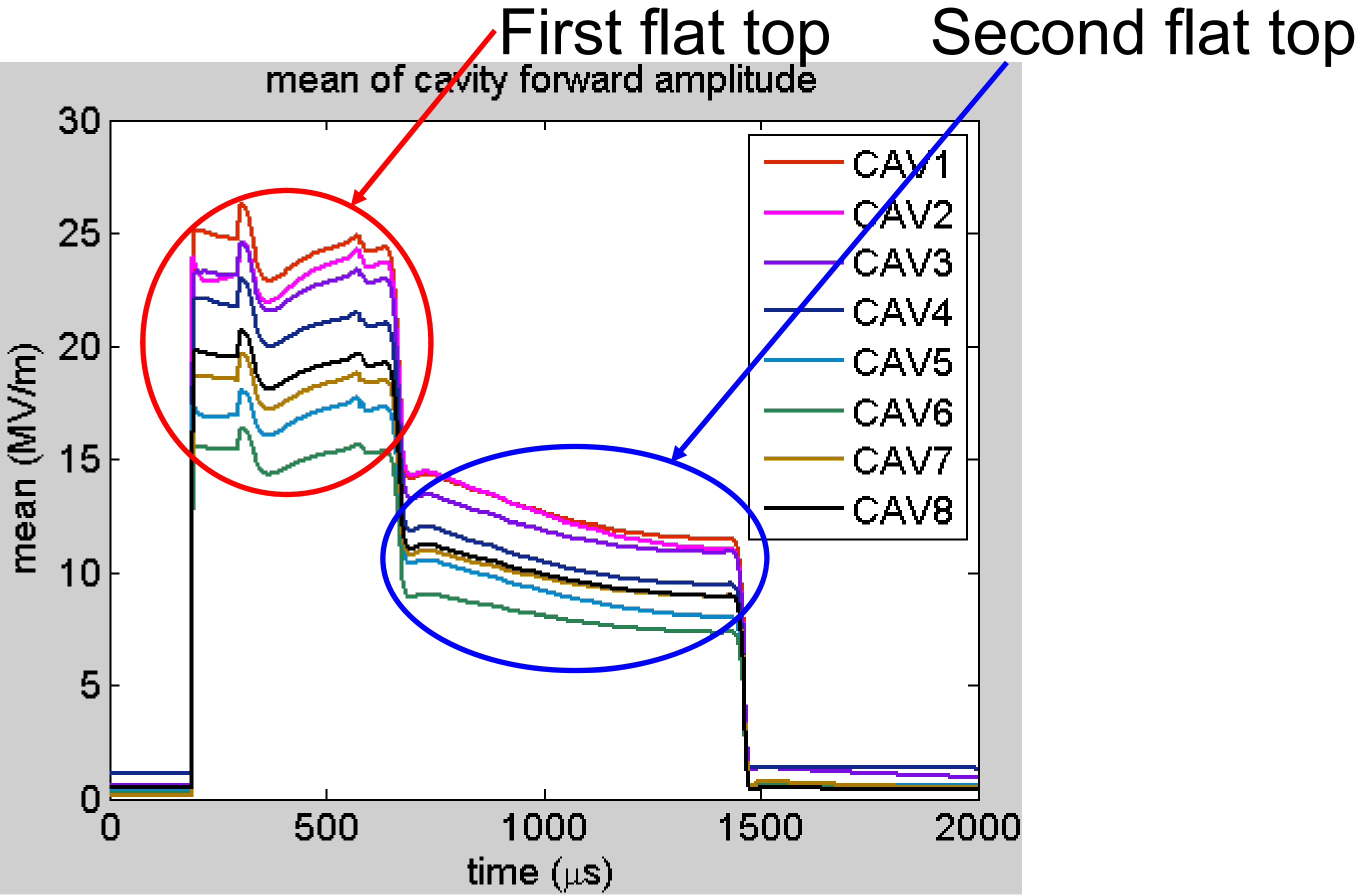
Acknowledgement

- Thanks John Carwardine (ANL) and Michael Davidsaver (FNAL) for help with the data collection.
- Thanks colleagues from DESY (Nicholas Walker, Stefan Simrock, Valeri Ayvazyan, Zheqiao Geng etc.), ANL (John, Carwardine), FNAL (Brain Chase) and KEK (Shinichiro Michizono) for many helpful discussions.

Thanks!

Backup Slides

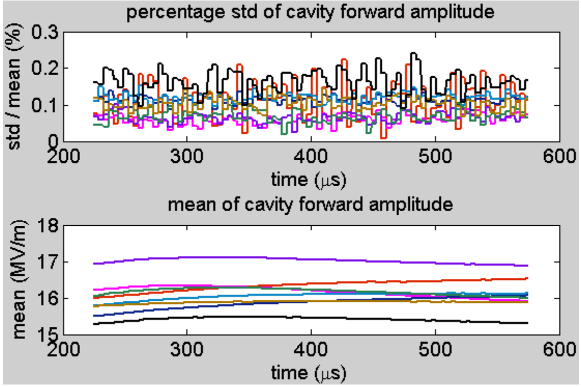
Definition for Forward Signal



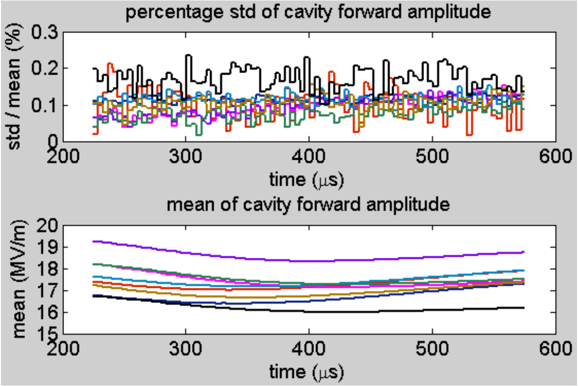
Typical input signal for cavities in ACC6 with FB+AFF on
(mean for 100 pulses)

1st Forward Flat in ACC4

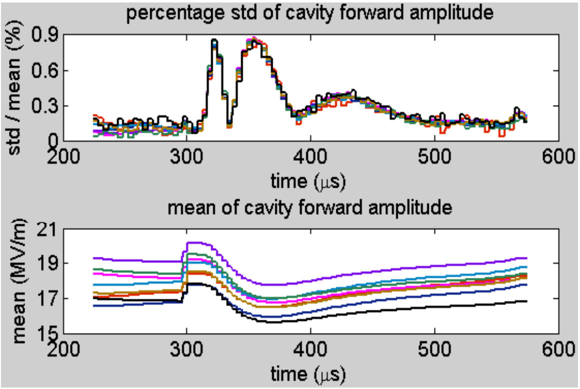
FB Off / AFF Off / No Beam



FB On / AFF Off / No Beam

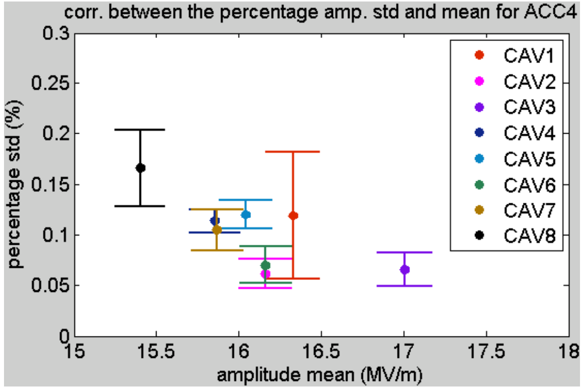


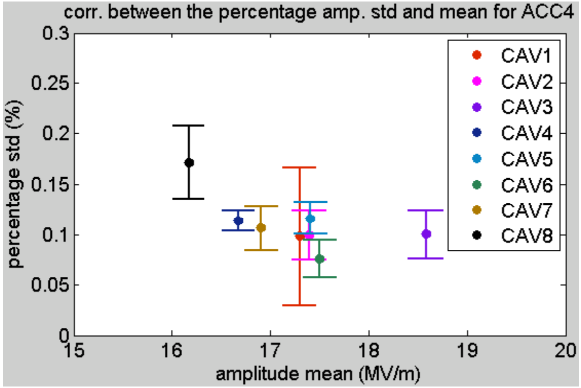
FB On / AFF On / No Beam

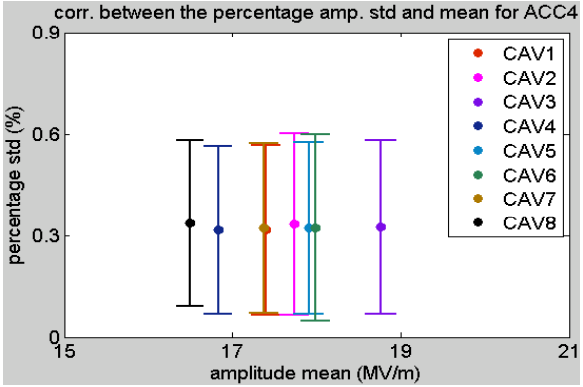


Note the vertical scale!

Only 1st flat top fractional jitter is shown below! Noise effect is eliminated roughly!



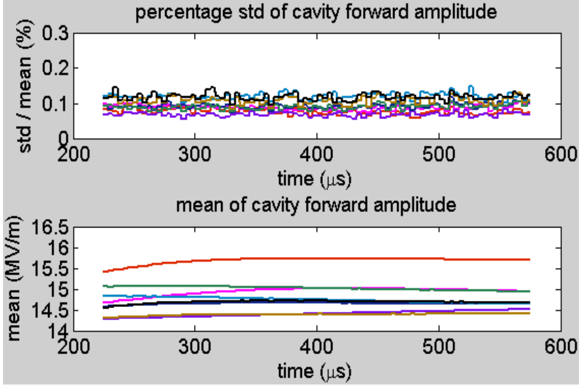




Note the vertical scale!

1st Forward Flat in ACC5

FB Off / AFF Off / No Beam



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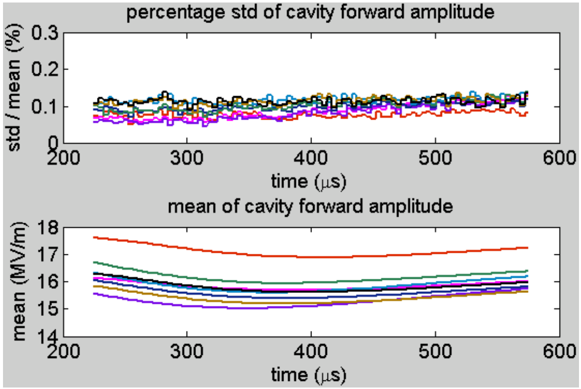
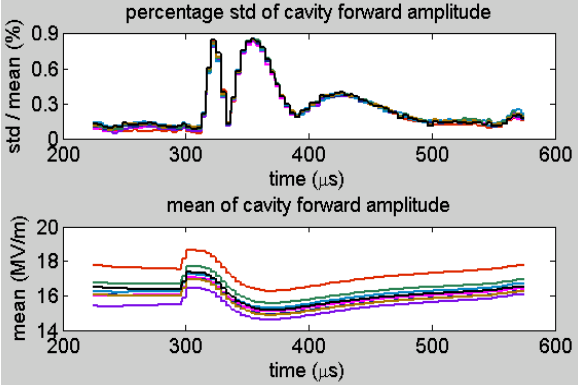
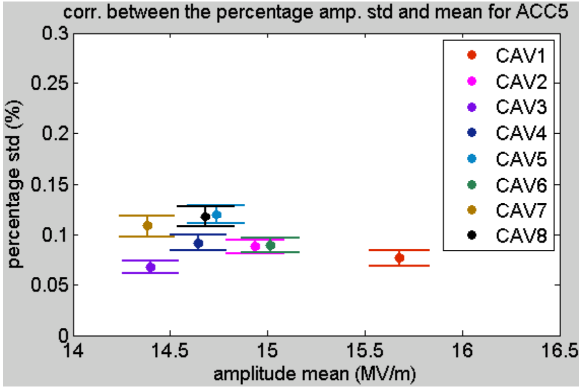


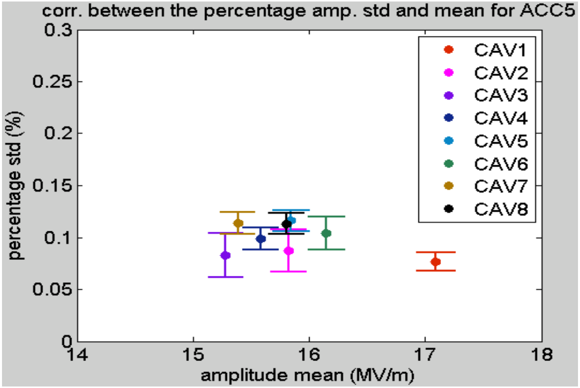
FB On / AFF On / No Beam

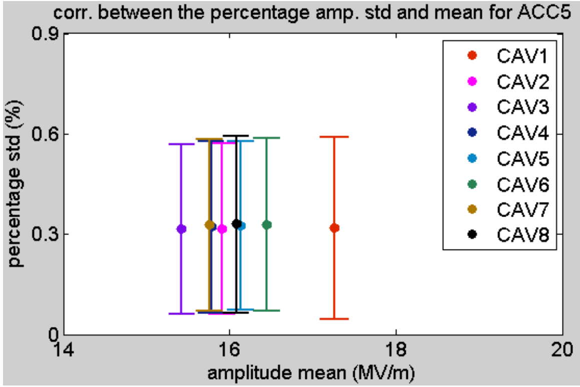


Note the vertical scale!

Only 1st flat top fractional jitter is shown below! Noise effect is eliminated roughly!



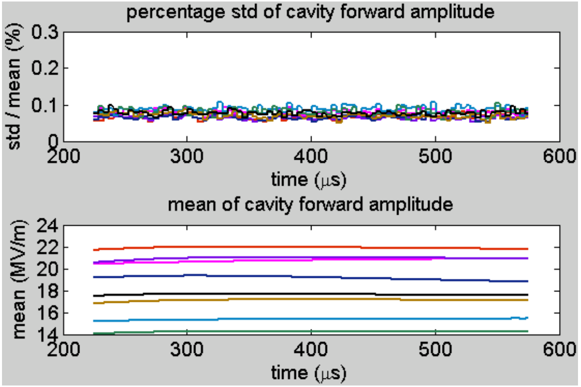




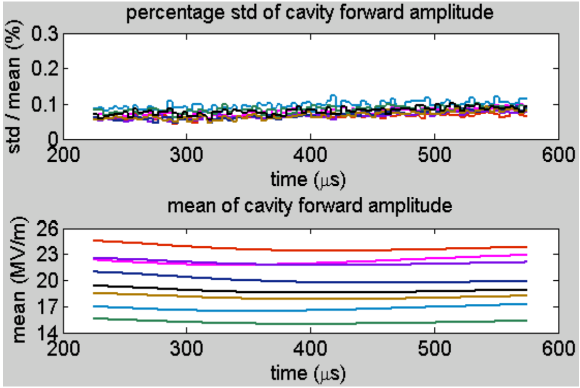
Note the vertical scale!

1st Forward Flat in ACC6

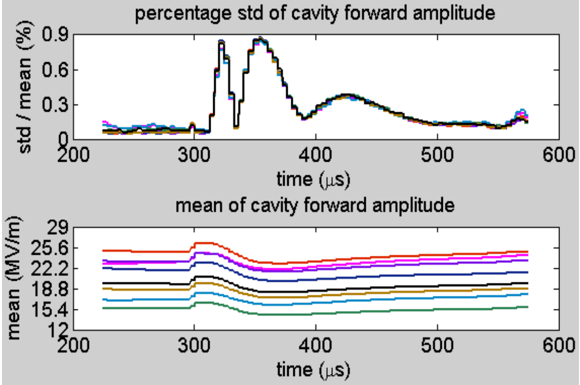
FB Off / AFF Off / No Beam



FB On / AFF Off / No Beam

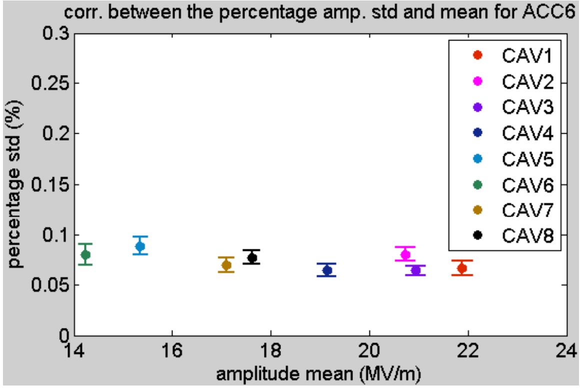


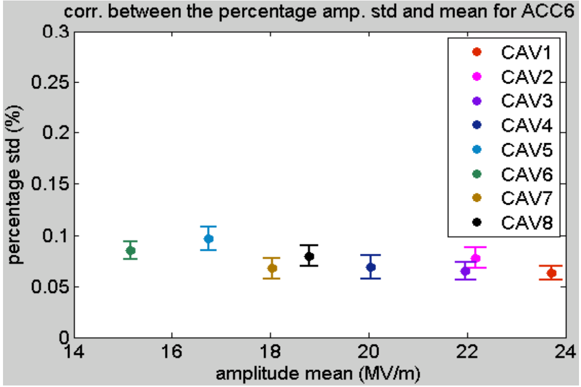
FB On / AFF On / No Beam

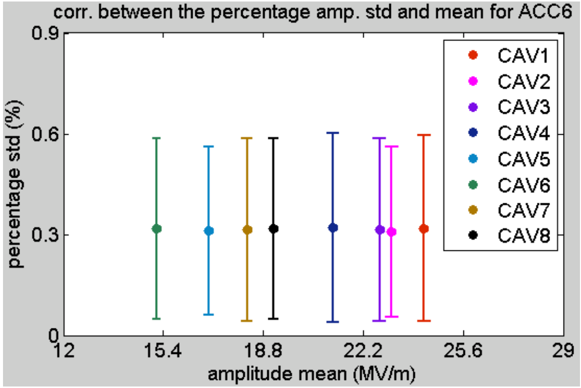


Note the vertical scale!

Only 1st flat top fractional jitter is shown below! Noise effect is eliminated roughly!



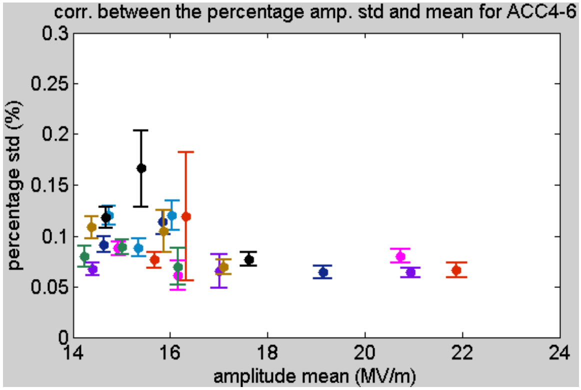




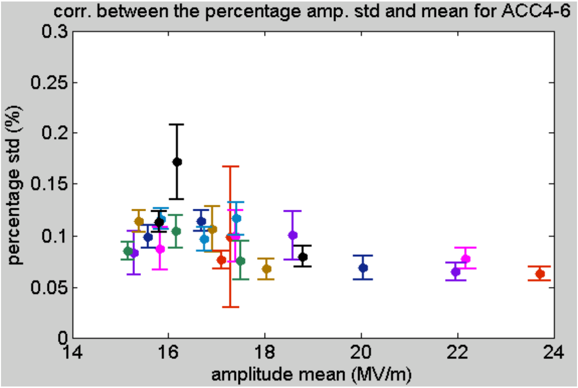
Note the vertical scale!

1st Forward Flat in ACC4-6

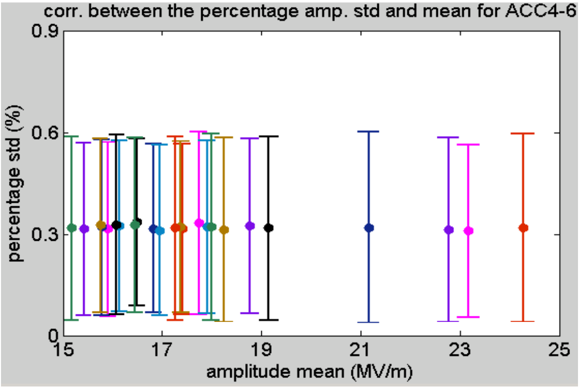
FB Off / AFF Off / No Beam



FB On / AFF Off / No Beam



FB On / AFF On / No Beam



Note the vertical scale!

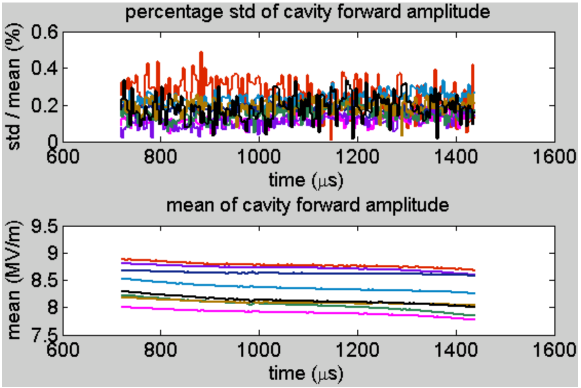
Only 1st flat top fractional jitter is shown below! Noise effect is eliminated roughly!

The fractional jitter on the 1st input flat top rf amplitude is about 0.05-0.2% with FB and AFF off.

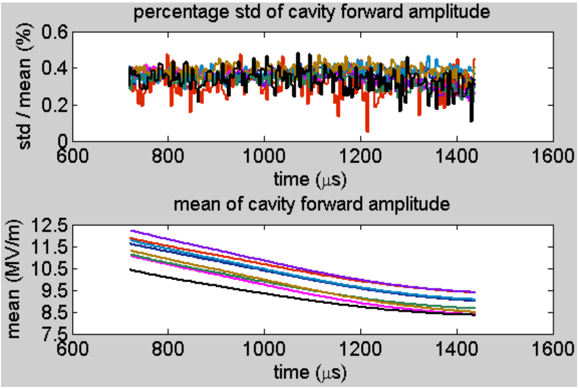
The cause of the large fractional jitter and the strange transient bump on the 1st input RF flat top with FB+AFF on might be that the AFF is turned on part way up the fill (Brain Chase, FNAL). Suggestions are to ramp up AFF gain in a linear way to reach full gain at flattop. Further development on AFF is still needed.

2nd Forward Flat in ACC4

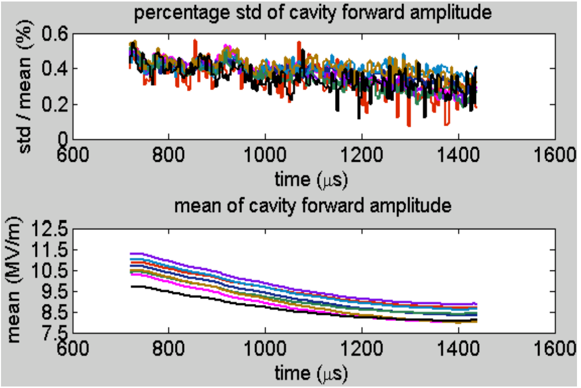
FB Off / AFF Off / No Beam



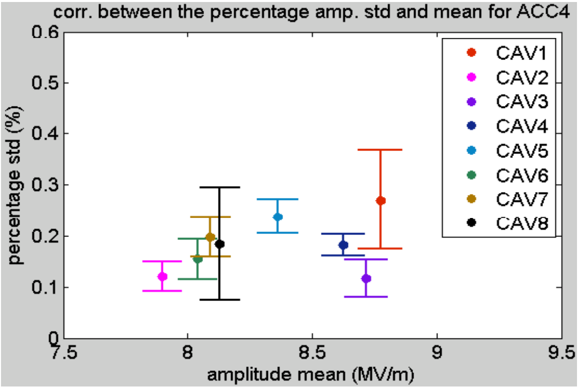
FB On / AFF Off / No Beam

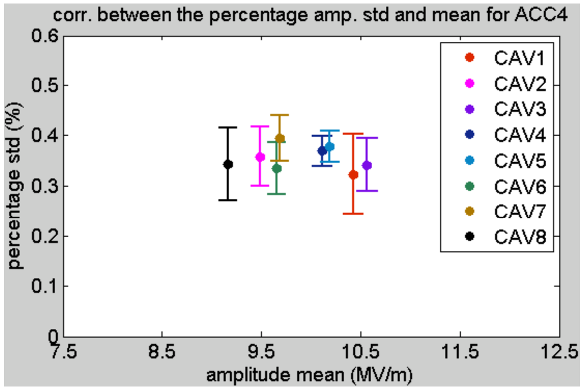


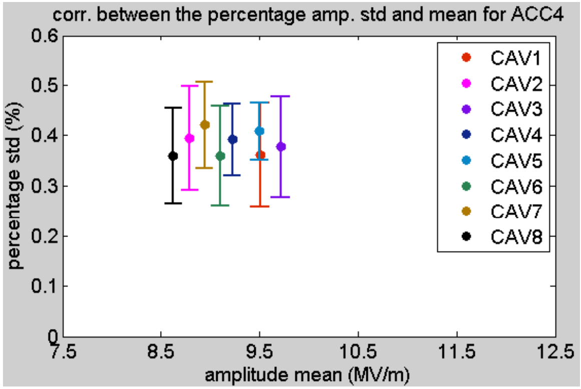
FB On / AFF On / No Beam



Only 2nd flat top fractional jitter is shown below! Noise effect is eliminated roughly!

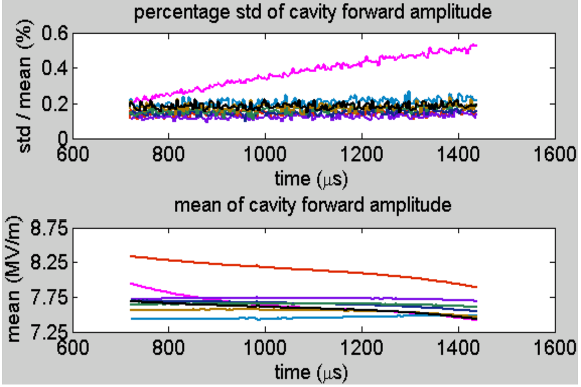




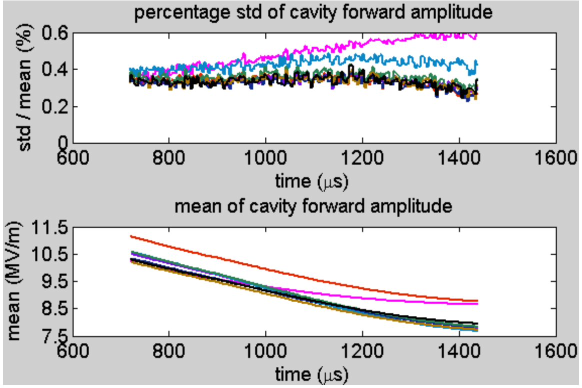


2nd Forward Flat in ACC5

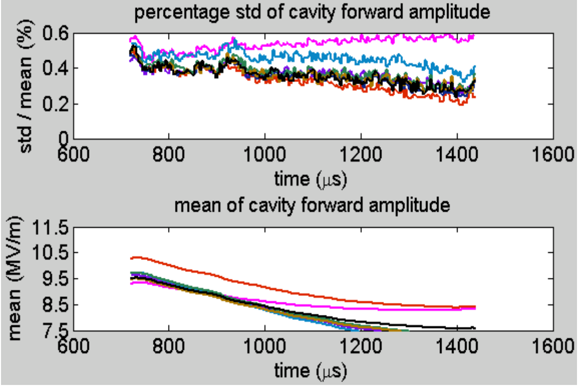
FB Off / AFF Off / No Beam



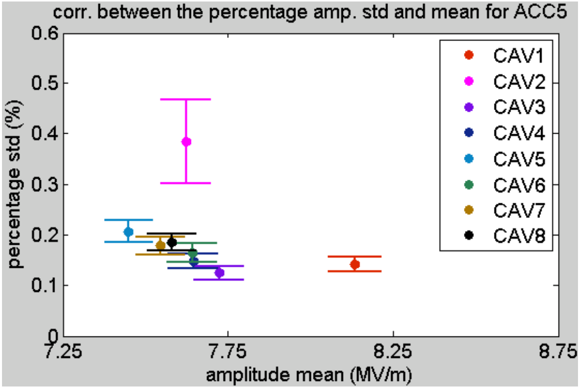
FB On / AFF Off / No Beam

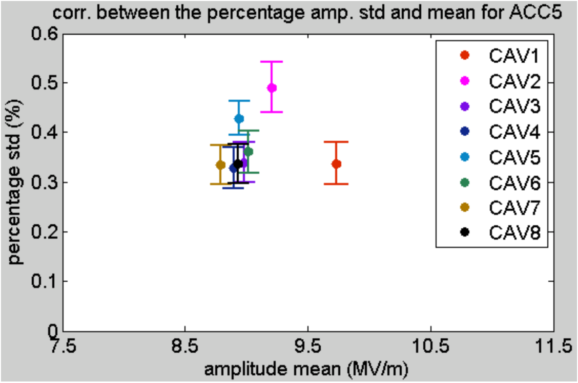


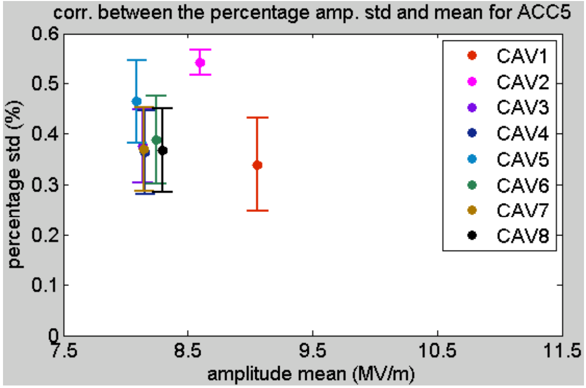
FB On / AFF On / No Beam



Only 2nd flat top fractional jitter is shown below! Noise effect is eliminated roughly!

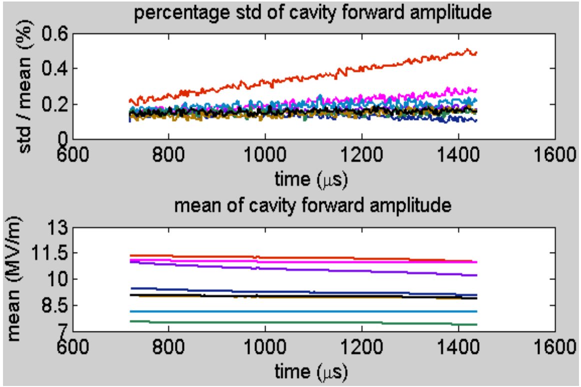




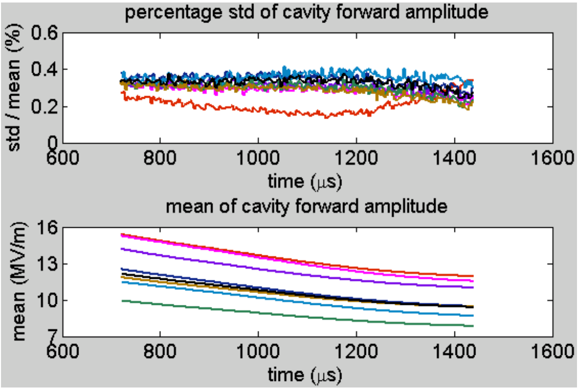


2nd Forward Flat in ACC6

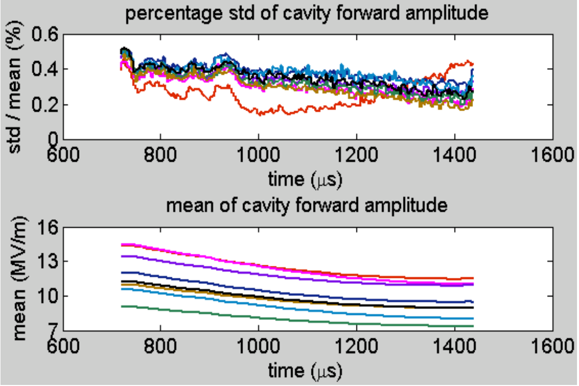
FB Off / AFF Off / No Beam



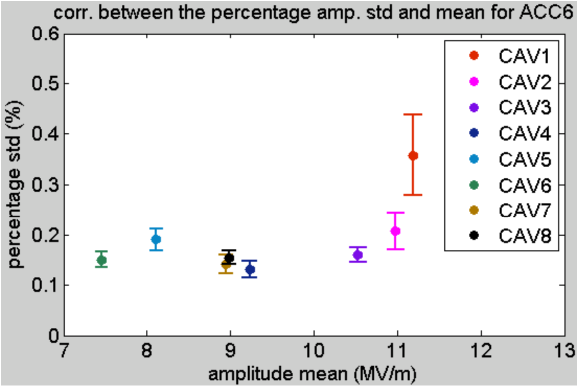
FB On / AFF Off / No Beam

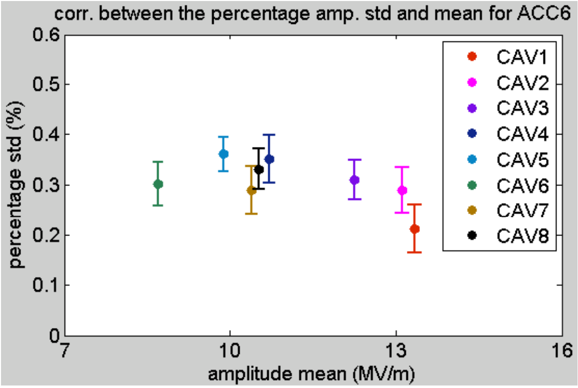


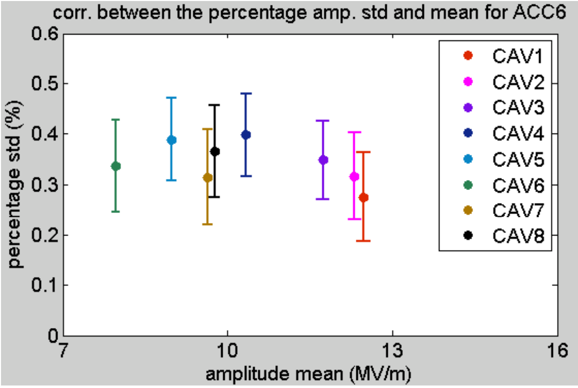
FB On / AFF On / No Beam



Only 2nd flat top fractional jitter is shown below! Noise effect is eliminated roughly!

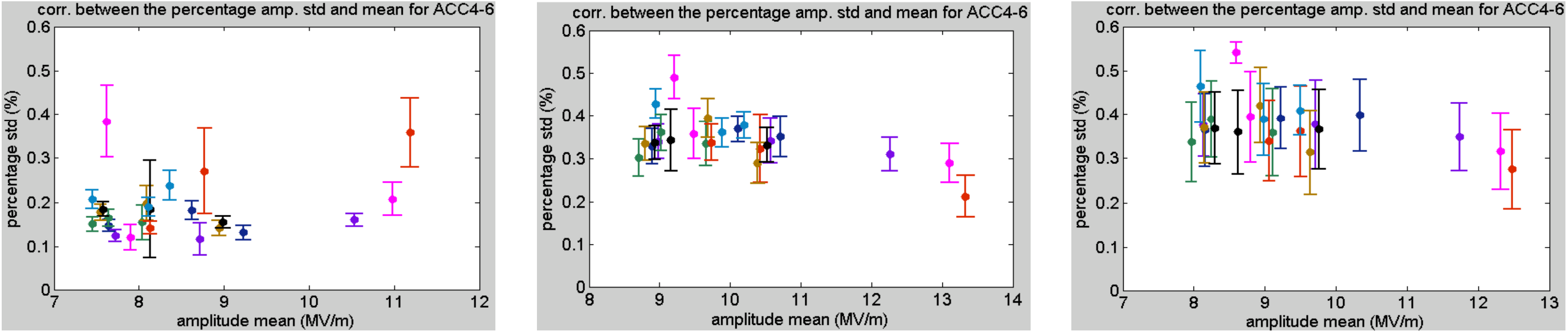






2nd Forward Flat in ACC4-6

FB Off / AFF Off / No Beam FB On / AFF Off / No Beam FB On / AFF On / No Beam



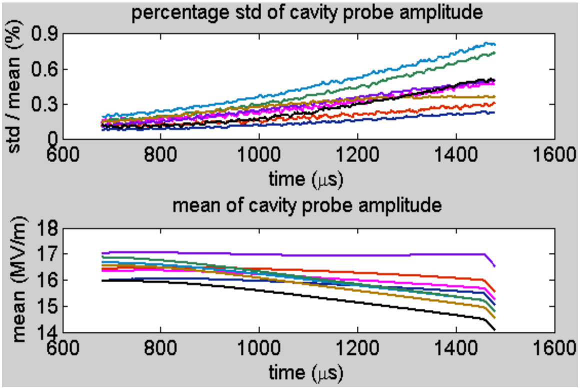
Only 2nd flat top fractional jitter is shown below! Noise effect is eliminated roughly!

The fractional jitter on the 2nd input flat top RF amplitude is about 0.07-0.47% with FB and AFF off. It seems both FB and AFF will introduce a large fractional jitter for the 2nd input RF flat top amplitude.

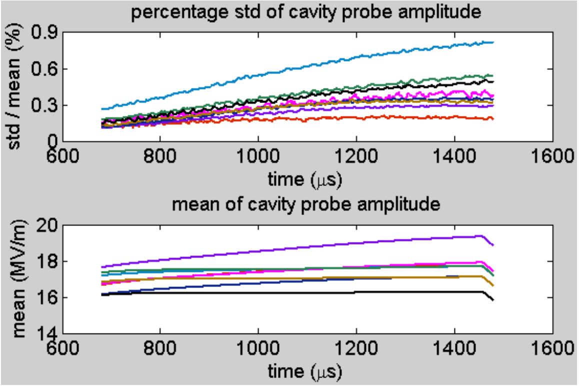
The fractional jitter for the 2nd input flat top with FB+AFF off is about factor 2 of that for the 1st flat top (the RF amplitude for the 2nd flat top is roughly half of that for the 1st flat top). It seems the jitter is dominated by some effect not related with the RF amplitude, which might come from the electronic noise.

Cavity Probe in ACC4

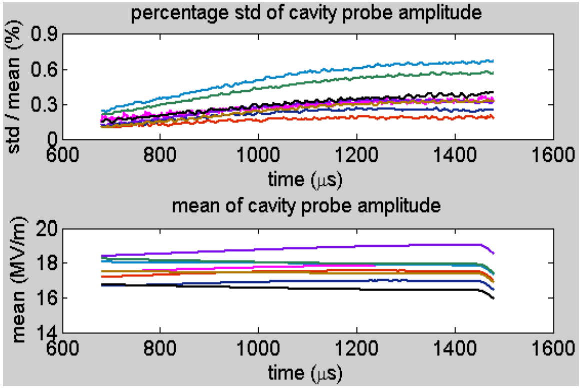
FB Off / AFF Off / No Beam



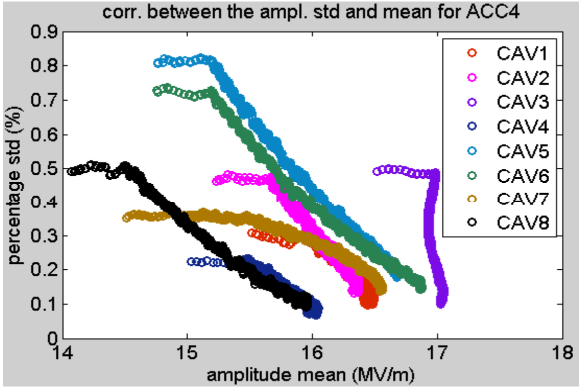
FB On / AFF Off / No Beam

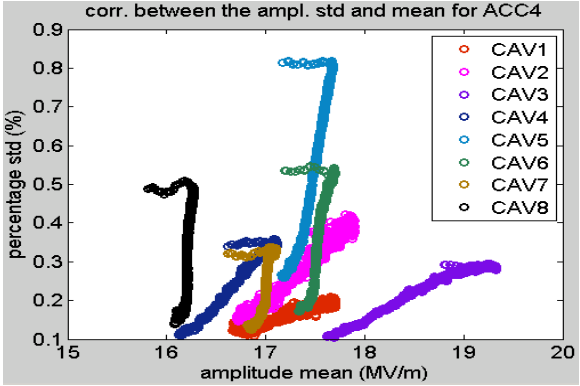


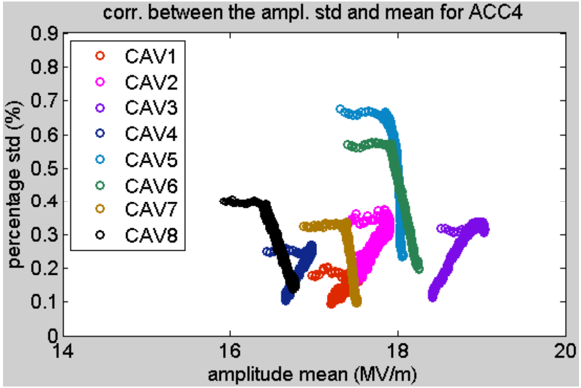
FB On / AFF On / No Beam



Only flat top is shown here! Noise effect included!





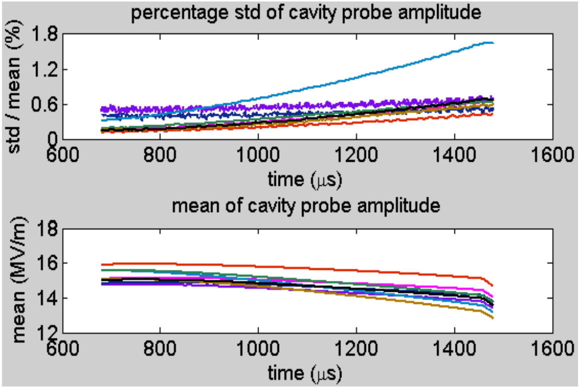


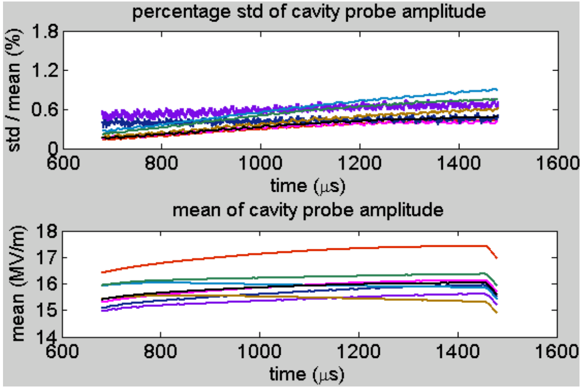
Cavity Probe in ACC5

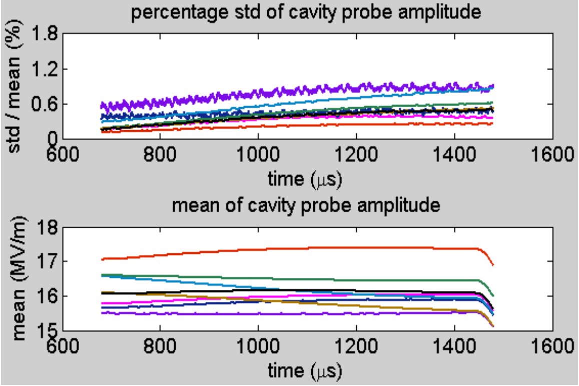
FB Off / AFF Off / No Beam

FB On / AFF Off / No Beam

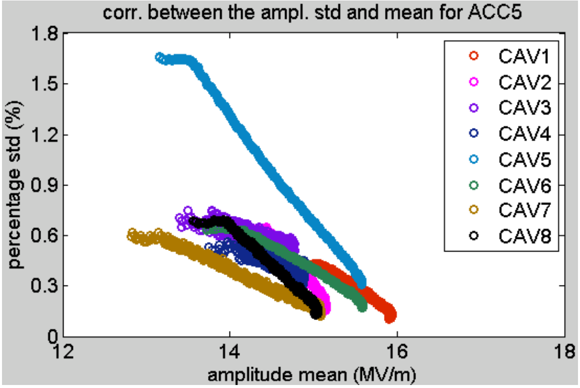
FB On / AFF On / No Beam

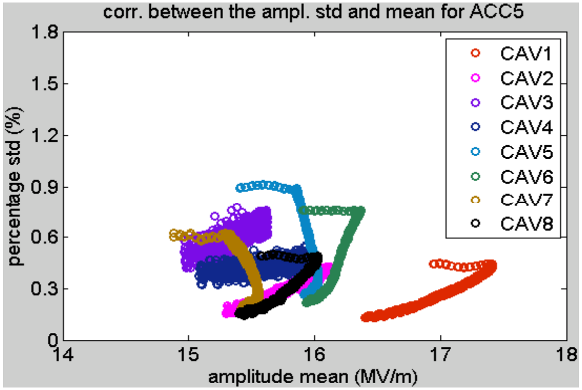


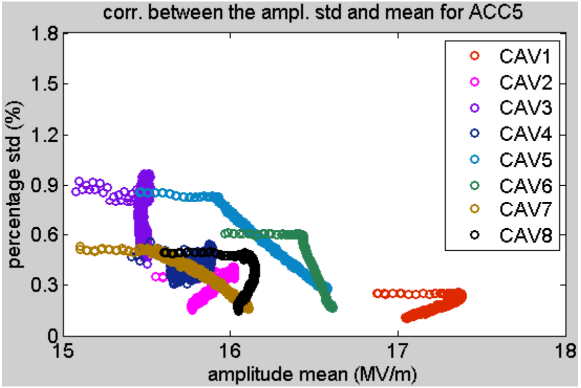




Only flat top is shown here! Noise effect included!

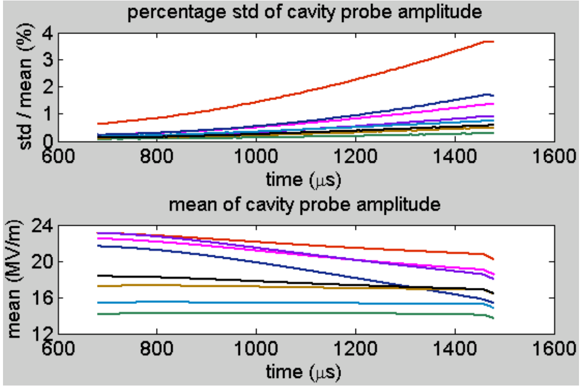




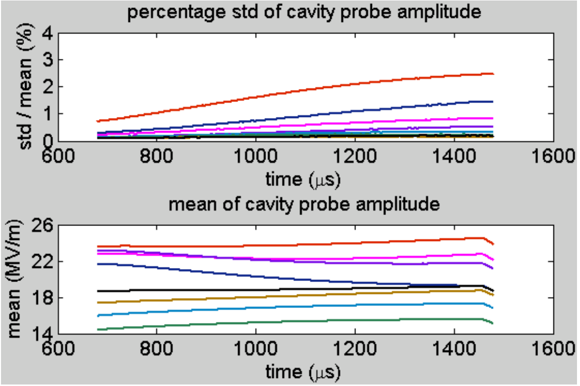


Cavity Probe in ACC6

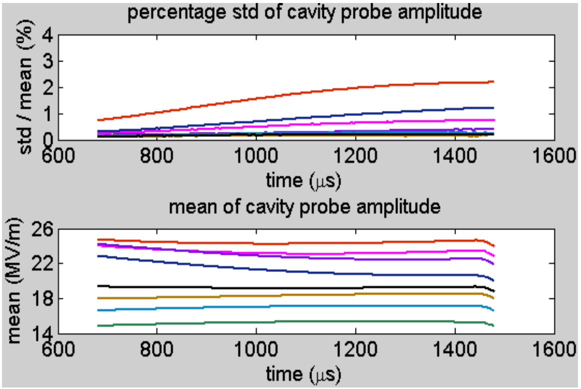
FB Off / AFF Off / No Beam



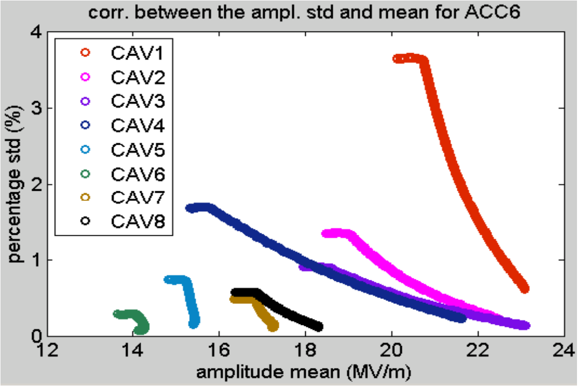
FB On / AFF Off / No Beam

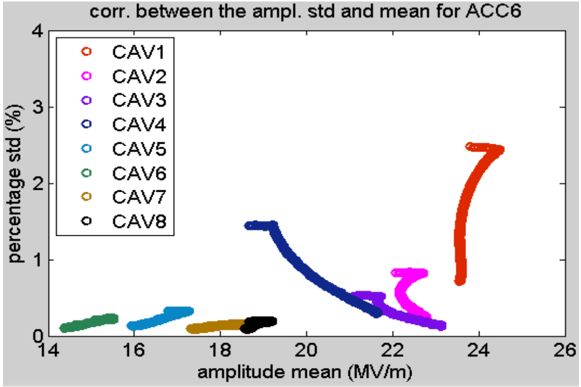


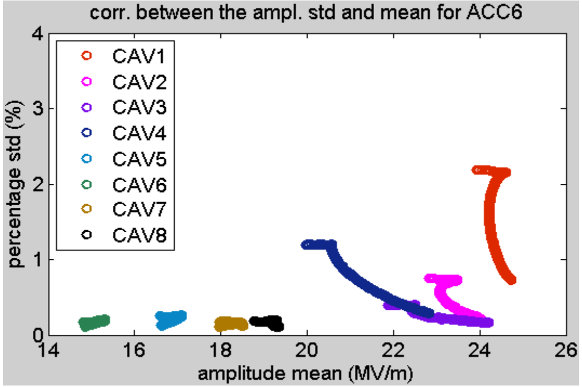
FB On / AFF On / No Beam



Only flat top is shown here! Noise effect included!





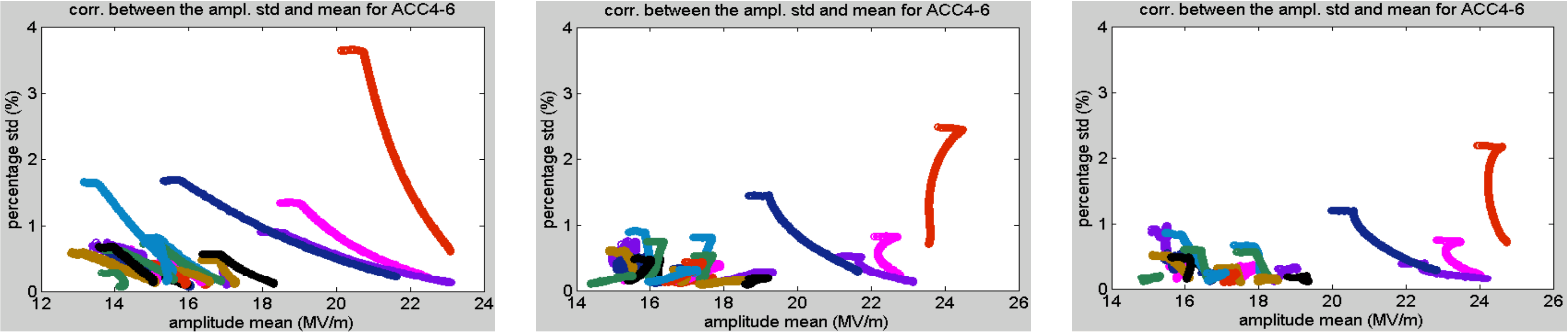


Cavity Probe for ACC4-6

FB Off / AFF Off / No Beam

FB On / AFF Off / No Beam

FB On / AFF On / No Beam



Only flat top is shown here! Noise effect included!

FB+AFF can reduce the cavity probe fractional jitter and flatten the cavity flat top to some extent.

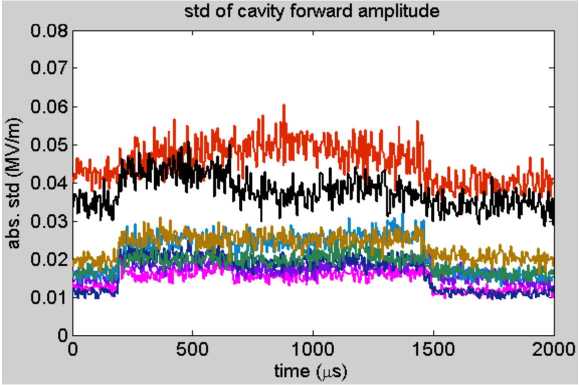
Dark current effect may exist (after further study, this possibility was eliminated) or some cavities are very sensitive to the Lorentz detuning variation effect (confirmed by further study).

Conclusions and Questions

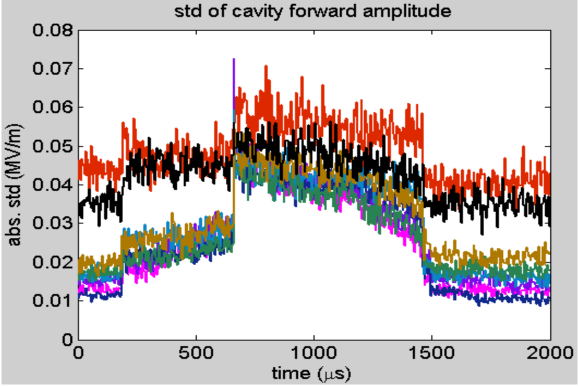
- The cavity input rf amplitude jitter (FB off, AFF off) appears to be very small (0.05%-0.2%) for the 1st flat top. Even with noise effect, the jitter is still smaller than 0.6%.
- The FB + AFF controls work well to flatten the vector sum amplitude and phase, although AFF adds strange bumps to the rf waveform at the 1st flat top and is the main cause of rf jitter – the AFF might be turned on part way up the fill (Brain Chase, FNAL). Suggestions are to ramp up AFF gain in a linear way to reach full gain at flattop. Further development on AFF is still needed.
- The fractional jitter for the 2nd input flat top is about factor 2 of that for the 1st flat top (which they should be same theoretically). Since the RF amplitude for the 2nd flat top is roughly half of that for the 1st flat top, it seems the jitter is dominated by some effect not related with the RF amplitude, which might come from the electronic noise.
- The cavity probe signals are particularly interesting as their jitter is much larger (up to 4% with noise) than that of the input rf, and grows along the pulse. Either some of the cavities are very Lorentz detuning sensitive or dark currents are generating the jitter in the higher gradient cavities – this really needs to be understood as it has major implications for XFEL and ILC.

Whole Pulse for ACC4

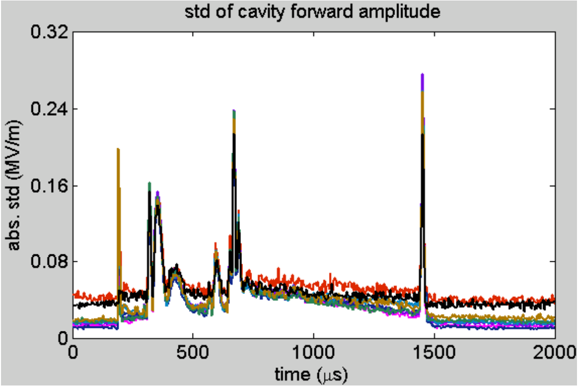
FB Off / AFF Off / No Beam



FB On / AFF Off / No Beam

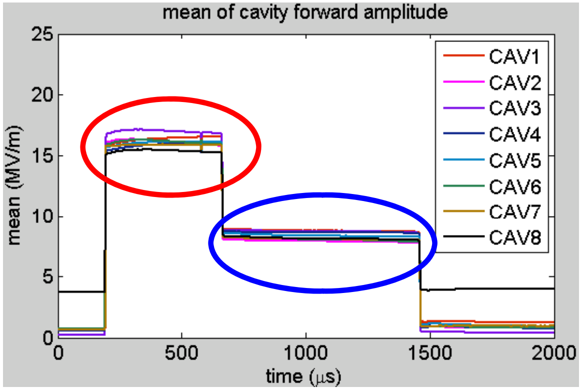


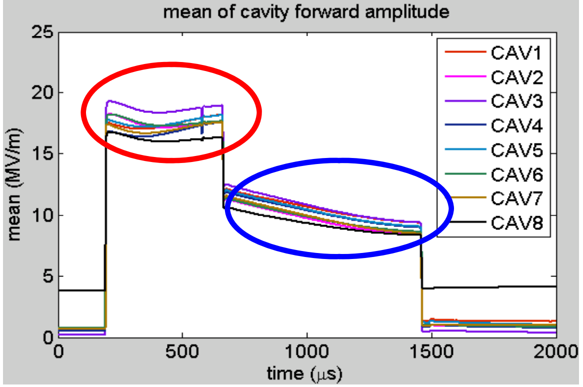
FB On / AFF On / No Beam

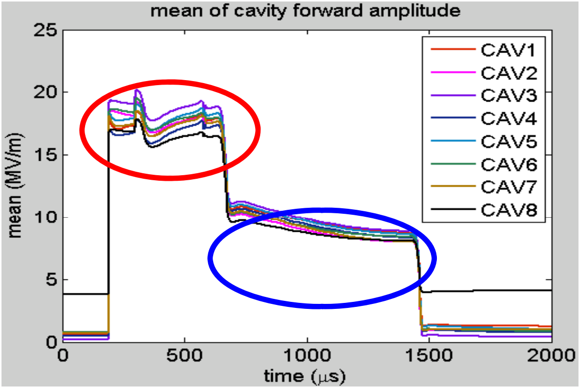


Note the vertical scale!

The signal in the red circle is first flat top, that in blue circle is second flat top.

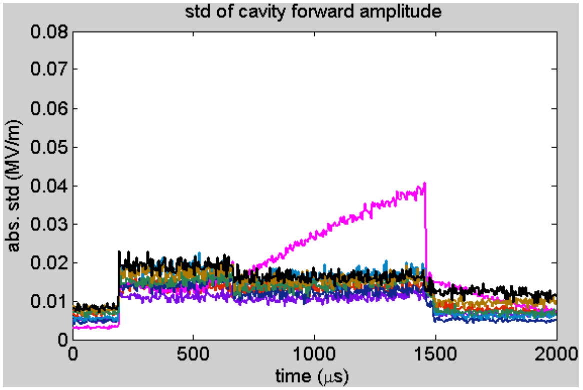


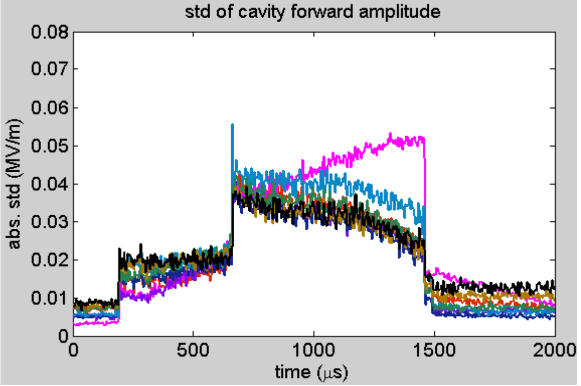


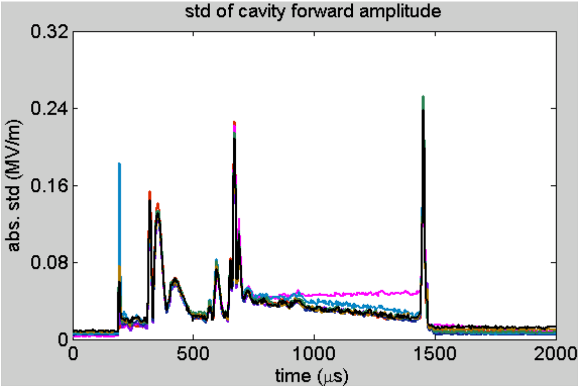


Whole Pulse for ACC5

FB Off / AFF Off / No Beam FB On / AFF Off / No Beam FB On / AFF On / No Beam

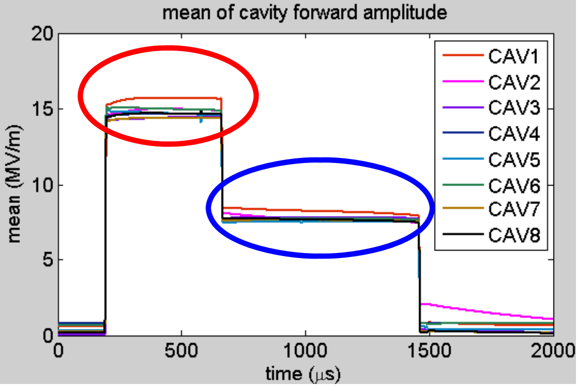


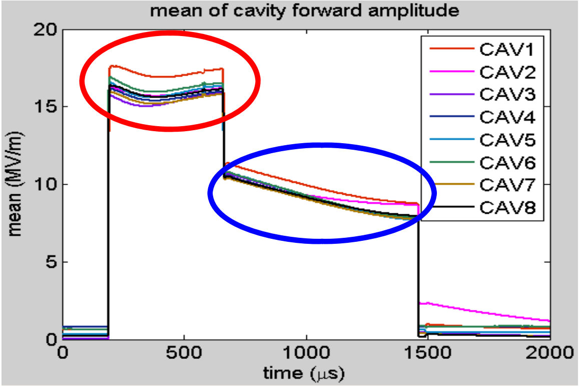


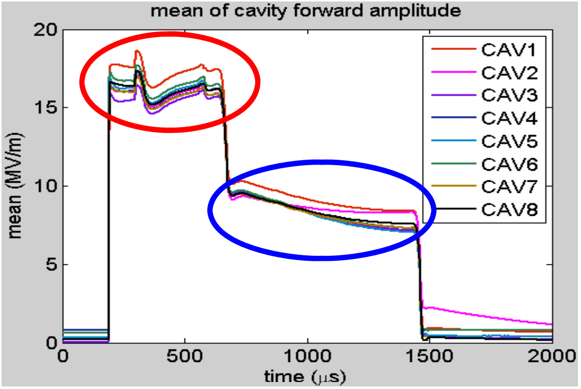


Note the vertical scale!

The signal in the red circle is first flat top, that in blue circle is second flat top.

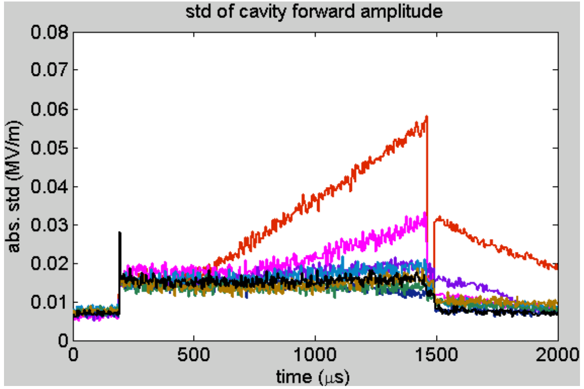


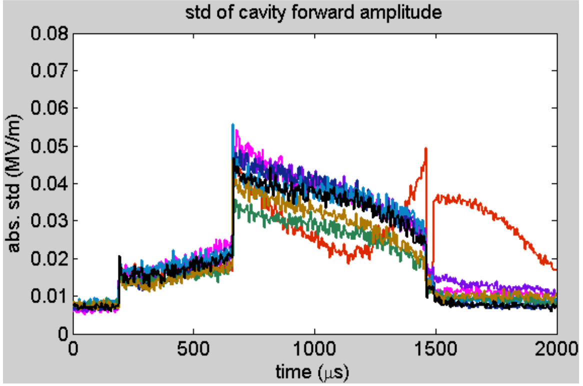


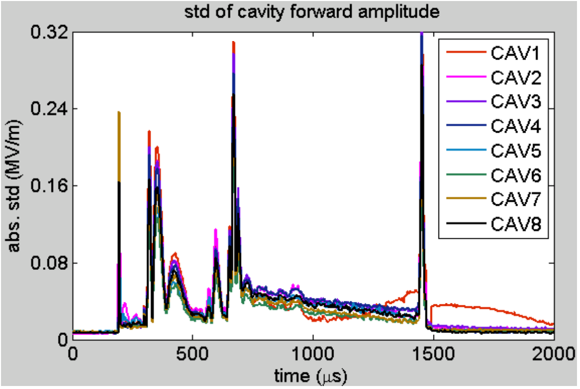


Whole Pulse for ACC6

FB Off / AFF Off / No Beam FB On / AFF Off / No Beam FB On / AFF On / No Beam

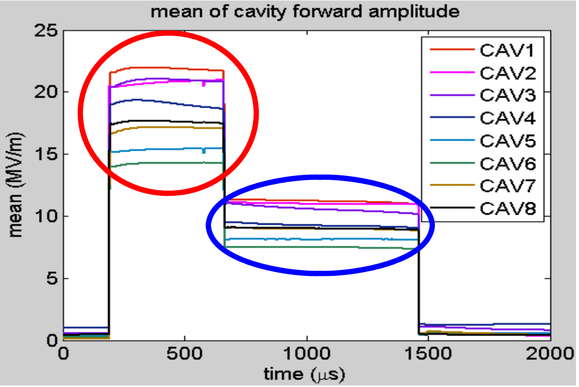


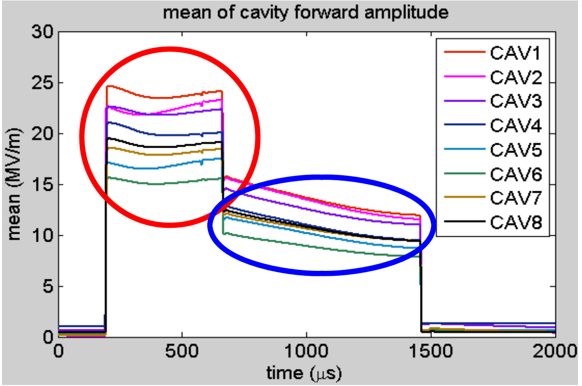


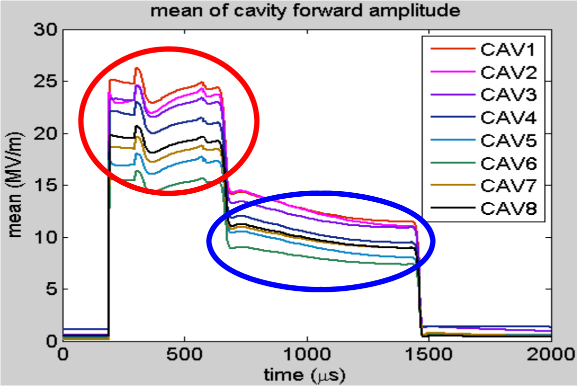


Note the vertical scale!

The signal in the red circle is first flat top, that in blue circle is second flat top.





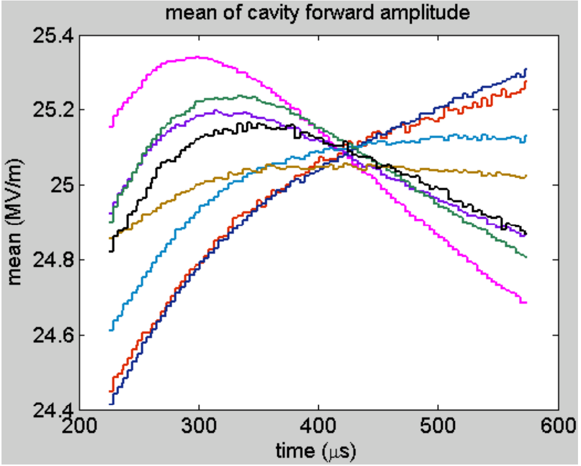


1st Input Forward Flat

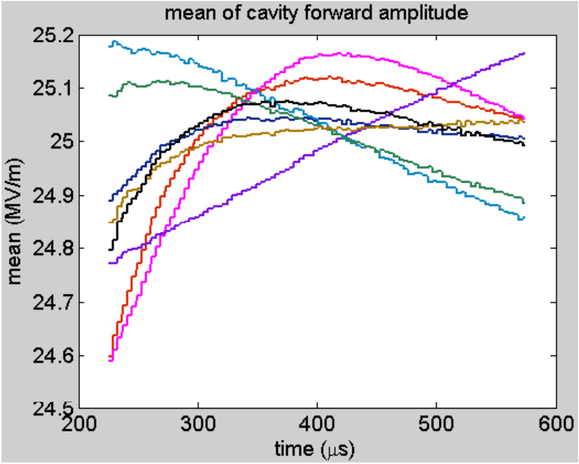
FB Off / AFF Off / No Beam

Normalized to the same average amplitude!

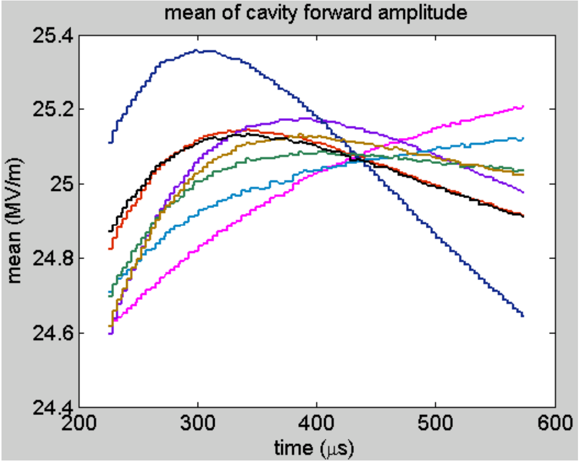
ACC4



ACC5



ACC6



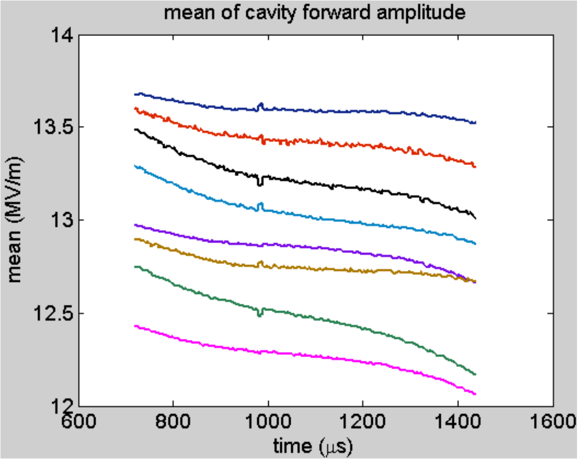
The cause of the slight difference of the forward flat top shape for different cavities is that the forward input signal as detected is the sum of forward signal plus the reflected signal times F-R isolation. The isolation may be as low as 20dB on some channels (Stefan Simrock, DESY). HLRF requirements for power coupler isolation need to be discussed. Maybe 35dB is realistic starting point.

2nd Input Forward Flat

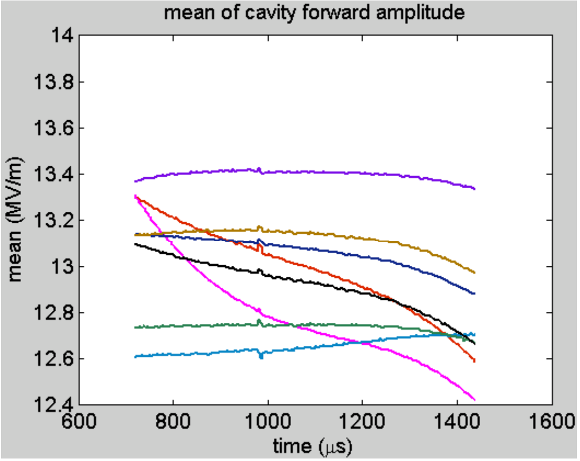
FB Off / AFF Off / No Beam

Normalized to the same average amplitude!

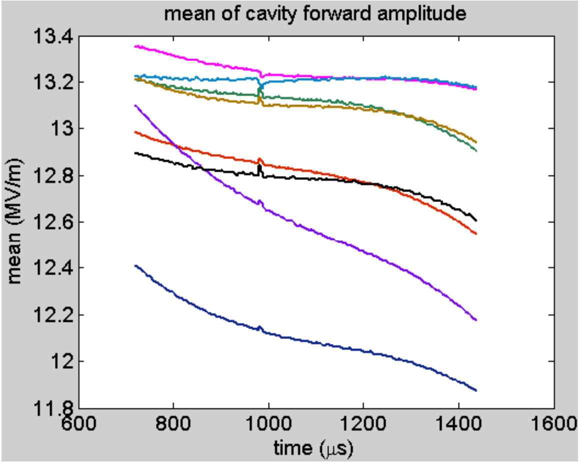
ACC4



ACC5



ACC6

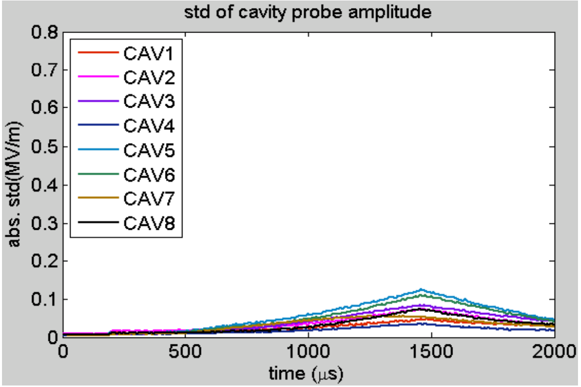


The cause of the slight difference of the forward flat top shape for different cavities is that the forward input signal as detected is the sum of forward signal plus the reflected signal times F-R isolation. The isolation may be as low as 20dB on some channels (Stefan Simrock, DESY). HLRF requirements for power coupler isolation need to be discussed. Maybe 35dB is realistic starting point.

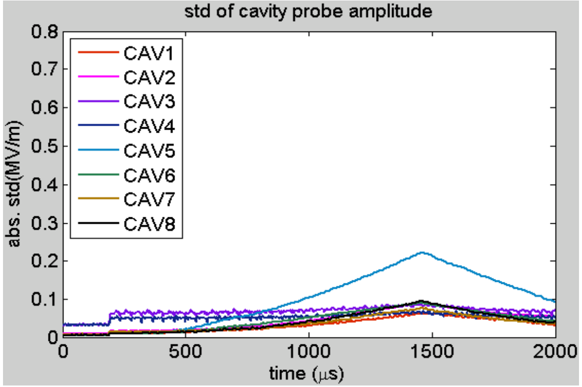
Cavity Probe Abs. Std

FB Off / AFF Off / No Beam

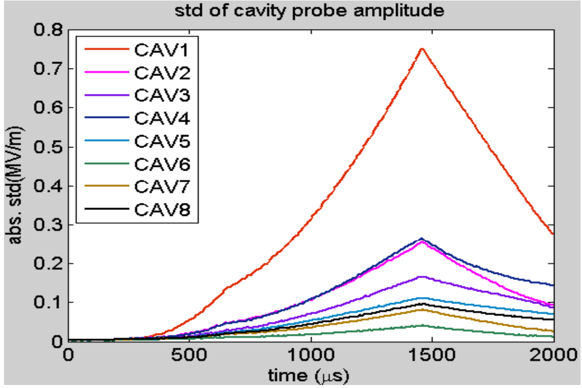
ACC4



ACC5



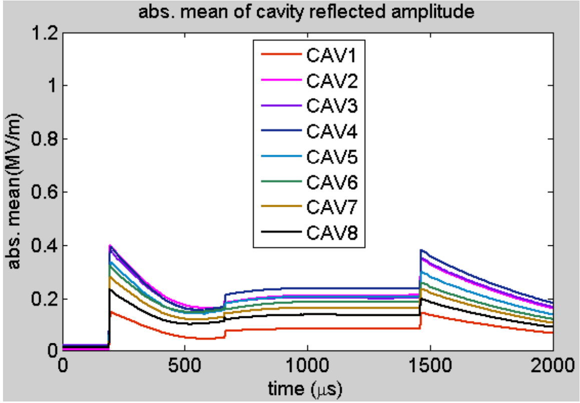
ACC6



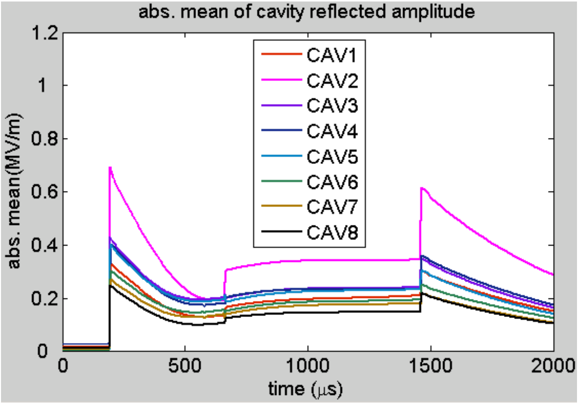
Cavity Reflected Abs. Mean

FB Off / AFF Off / No Beam

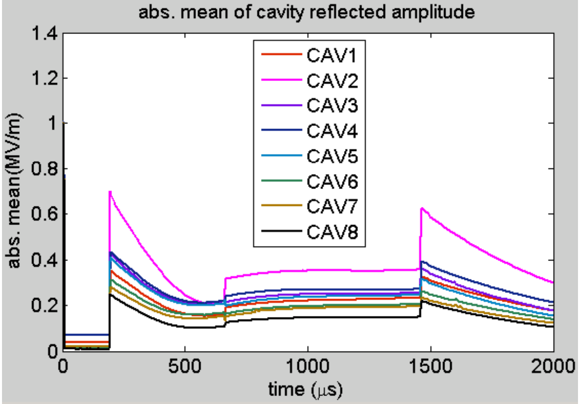
ACC4

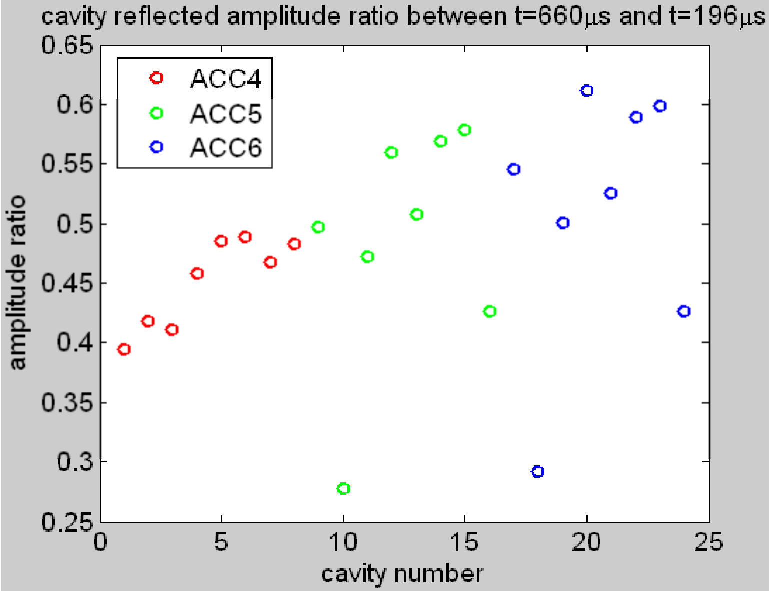


ACC5



ACC6



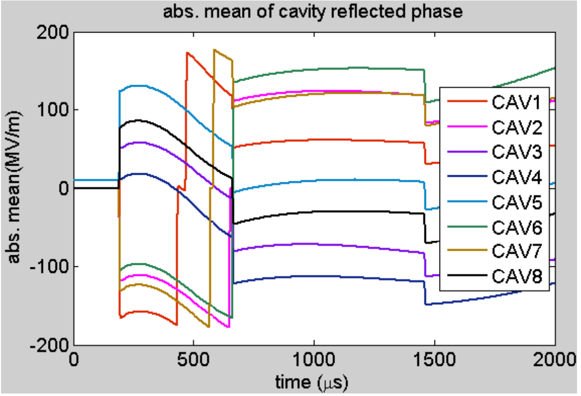


These plots suggest the cavities are running fairly far off-resonance!

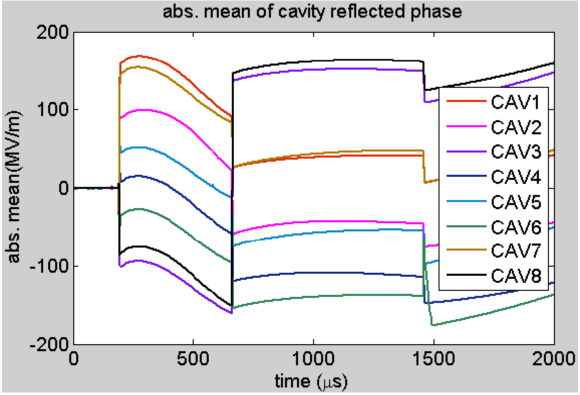
Cavity Reflected Abs. Phase

FB Off / AFF Off / No Beam

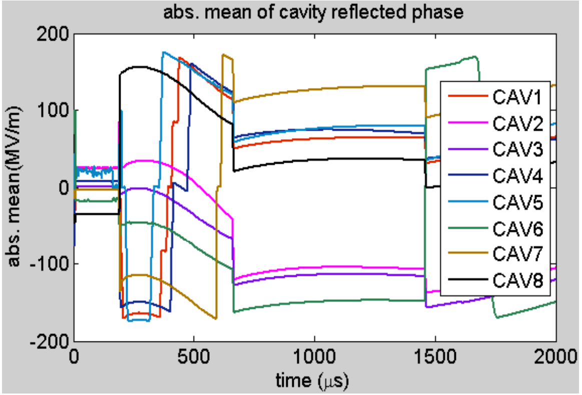
ACC4



ACC5

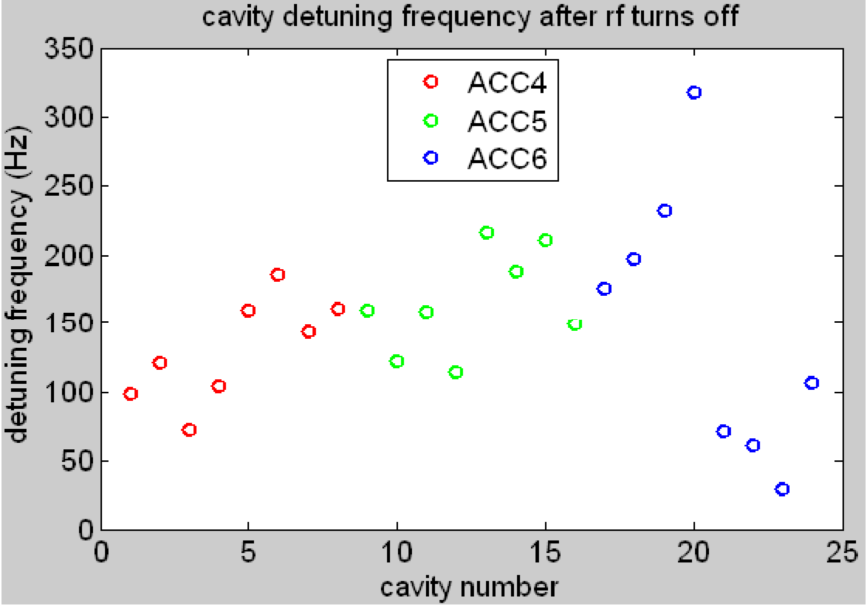


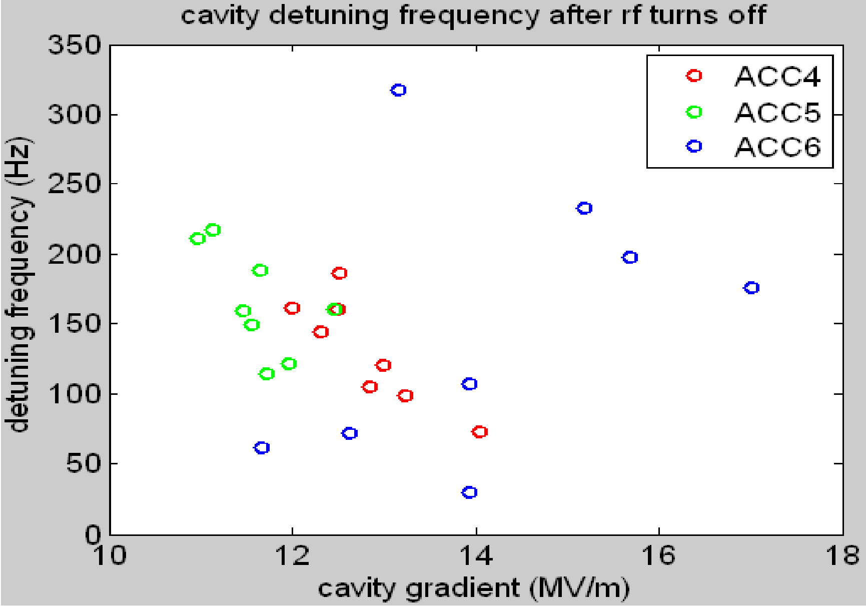
ACC6



Detuning after RF Off

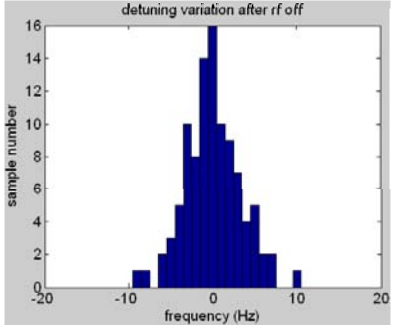
FB Off / AFF Off / No Beam



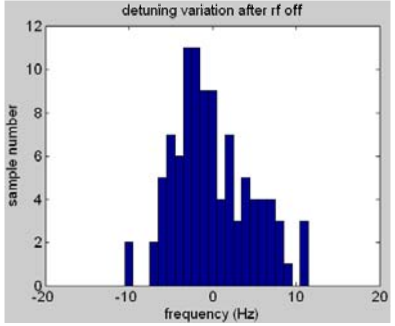


Detuning Variation for RF Off

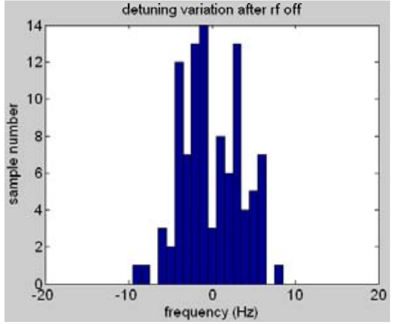
ACC4 FB Off / AFF Off / No Beam



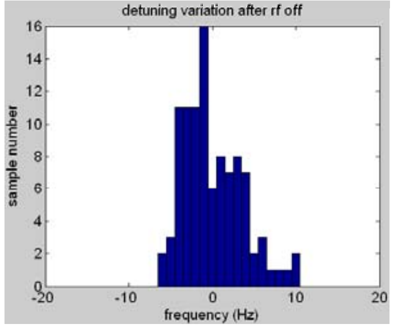
CAV1
σ=3.3Hz μ=99Hz



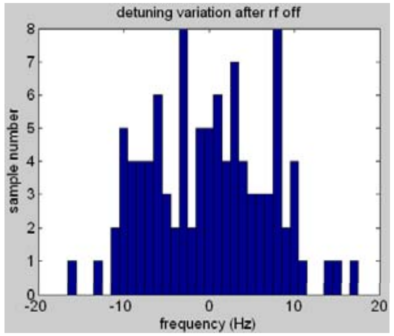
CAV2
σ=4.6Hz μ=121Hz



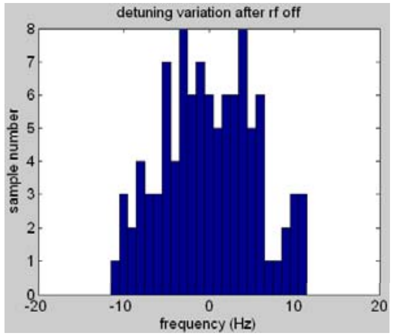
CAV3
σ=3.6Hz μ=73Hz



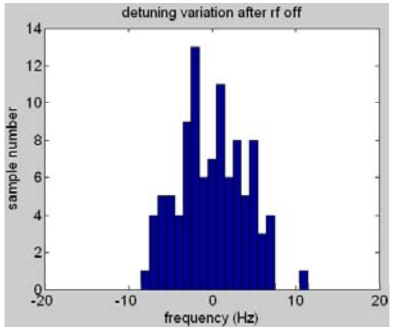
CAV4
σ=3.5Hz μ=104Hz



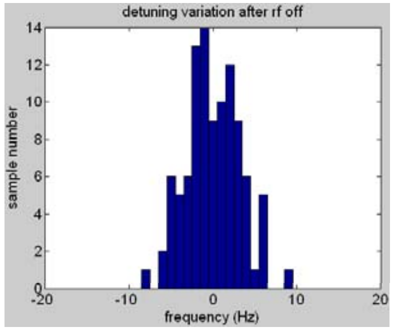
CAV5
σ=6.9Hz μ=160Hz



CAV6
σ=5.4Hz μ=186Hz



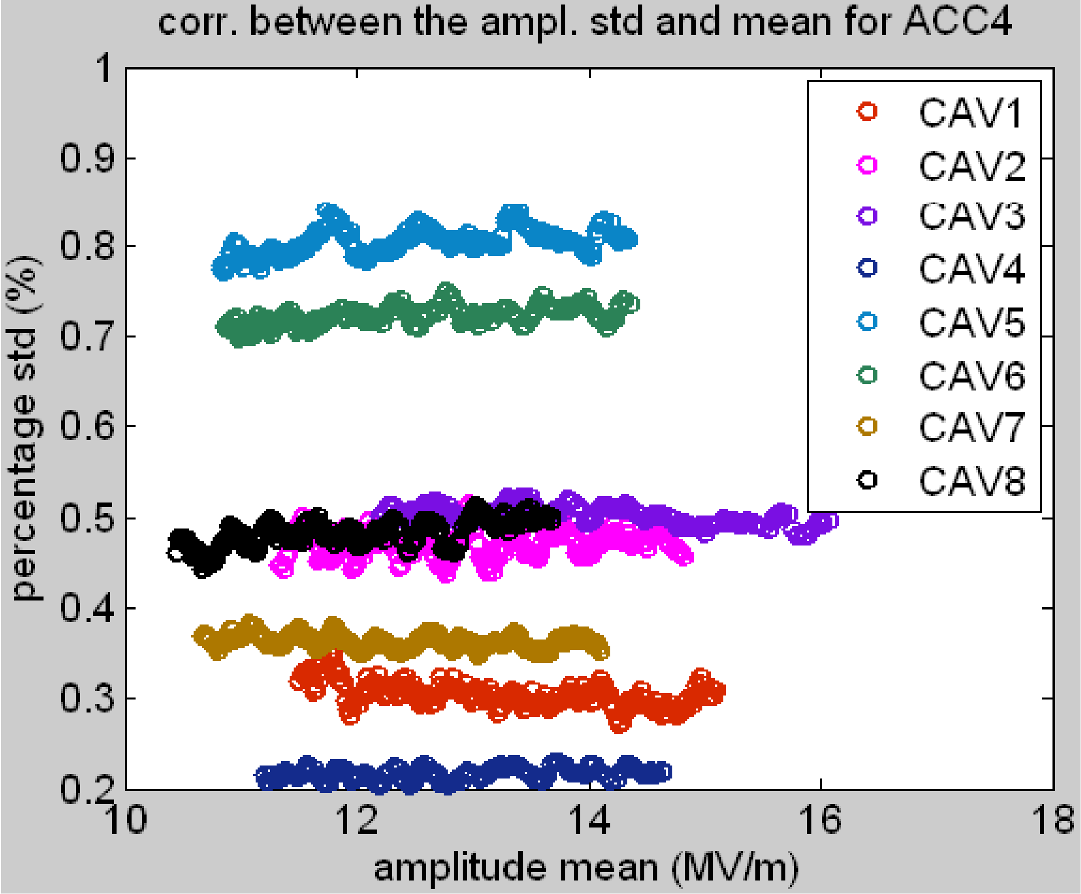
CAV7
σ=4.0Hz μ=144Hz



CAV8
σ=3.2Hz μ=162Hz

Probe Std for RF Off

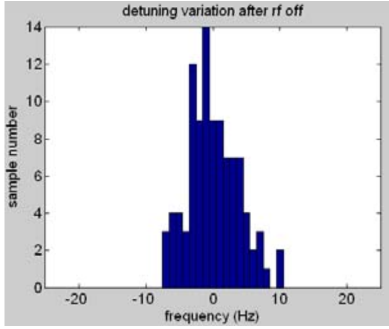
ACC4 FB Off / AFF Off / No Beam



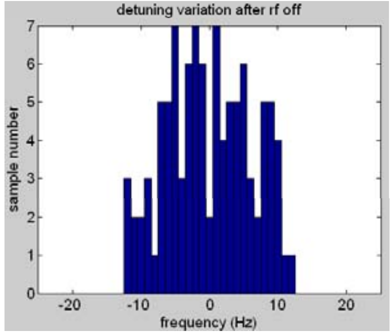
SLAC
NATIONAL ACCELERATOR LABORATORY

Detuning Variation for RF Off

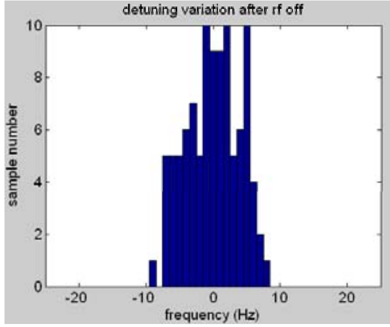
ACC5 FB Off / AFF Off / No Beam



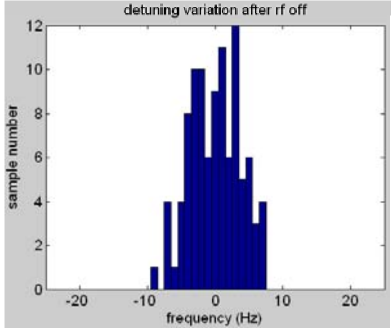
CAV1
σ=3.8Hz μ=160Hz



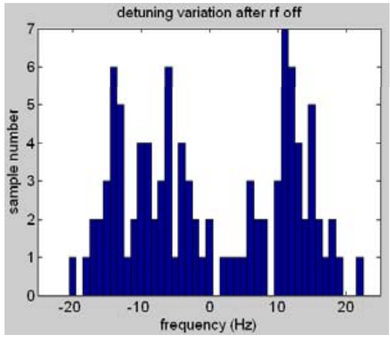
CAV2
σ=6.2Hz μ=122Hz



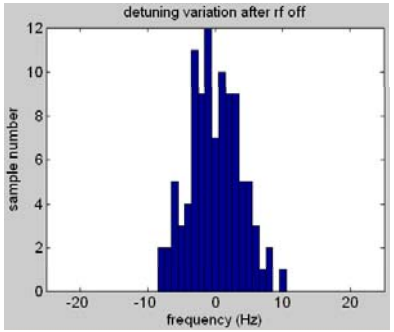
CAV3
σ=3.9Hz μ=160Hz



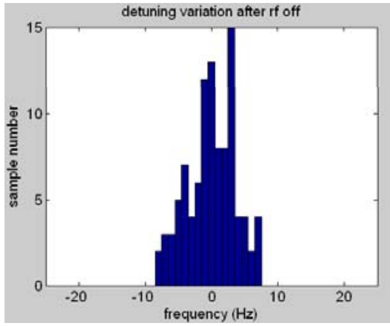
CAV4
σ=3.7Hz μ=114Hz



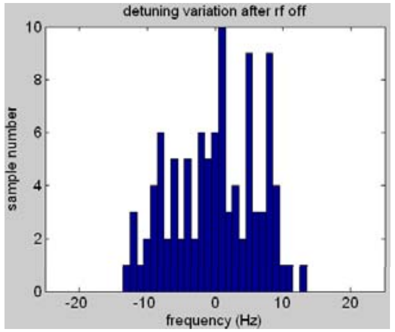
CAV5
σ=11.5Hz μ=217Hz



CAV6
σ=3.7Hz μ=189Hz



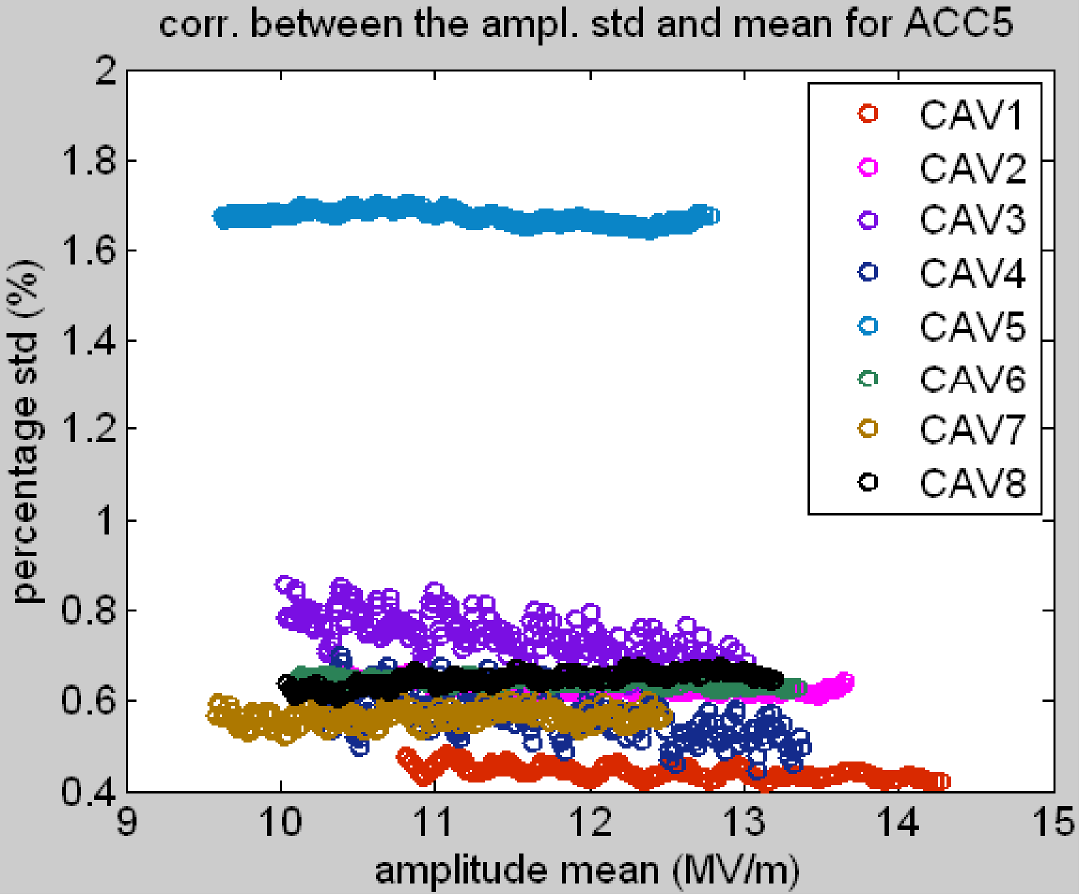
CAV7
σ=3.6Hz μ=211Hz



CAV8
σ=6.3Hz μ=149Hz

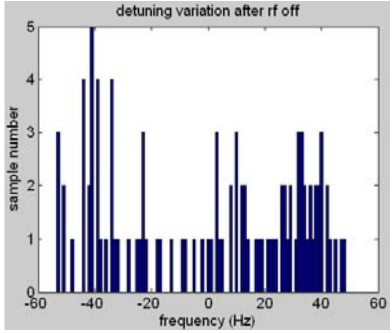
Probe Std for RF Off

ACC5 FB Off / AFF Off / No Beam

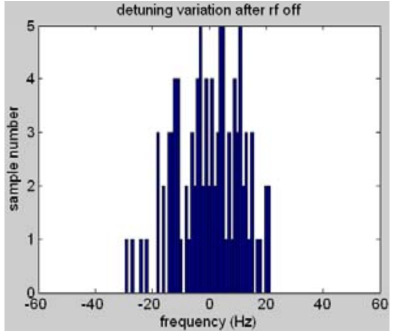


Detuning Variation for RF Off

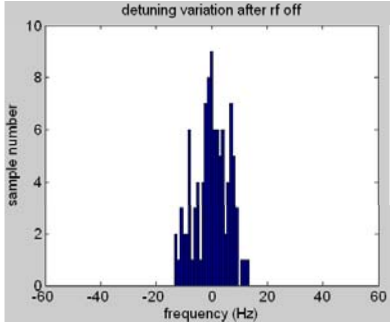
ACC6 FB Off / AFF Off / No Beam



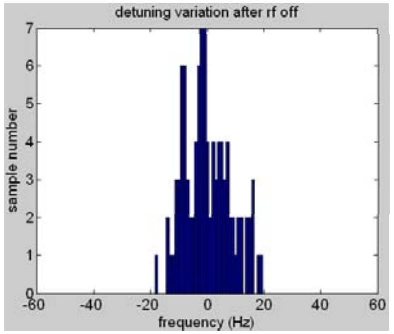
CAV1
σ=32.3Hz μ=177Hz



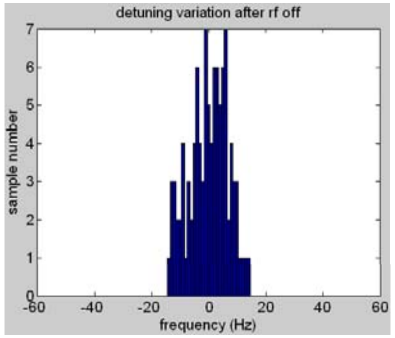
CAV2
σ=11.3Hz μ=197Hz



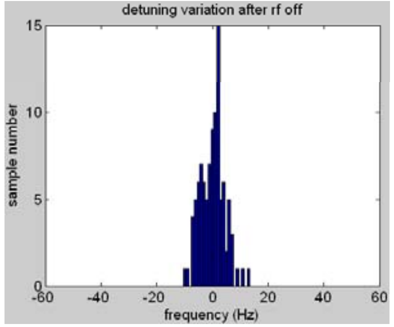
CAV3
σ=6.1Hz μ=232Hz



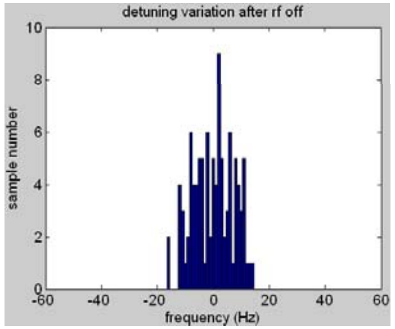
CAV4
σ=8.2Hz μ=318Hz



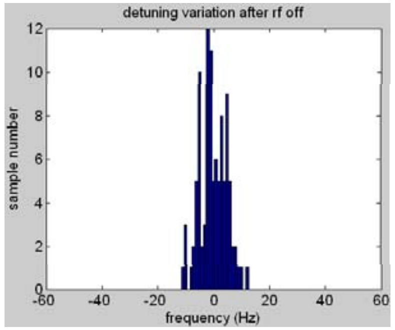
CAV5
σ=6.7Hz μ=72Hz



CAV6
σ=4.3Hz μ=62Hz



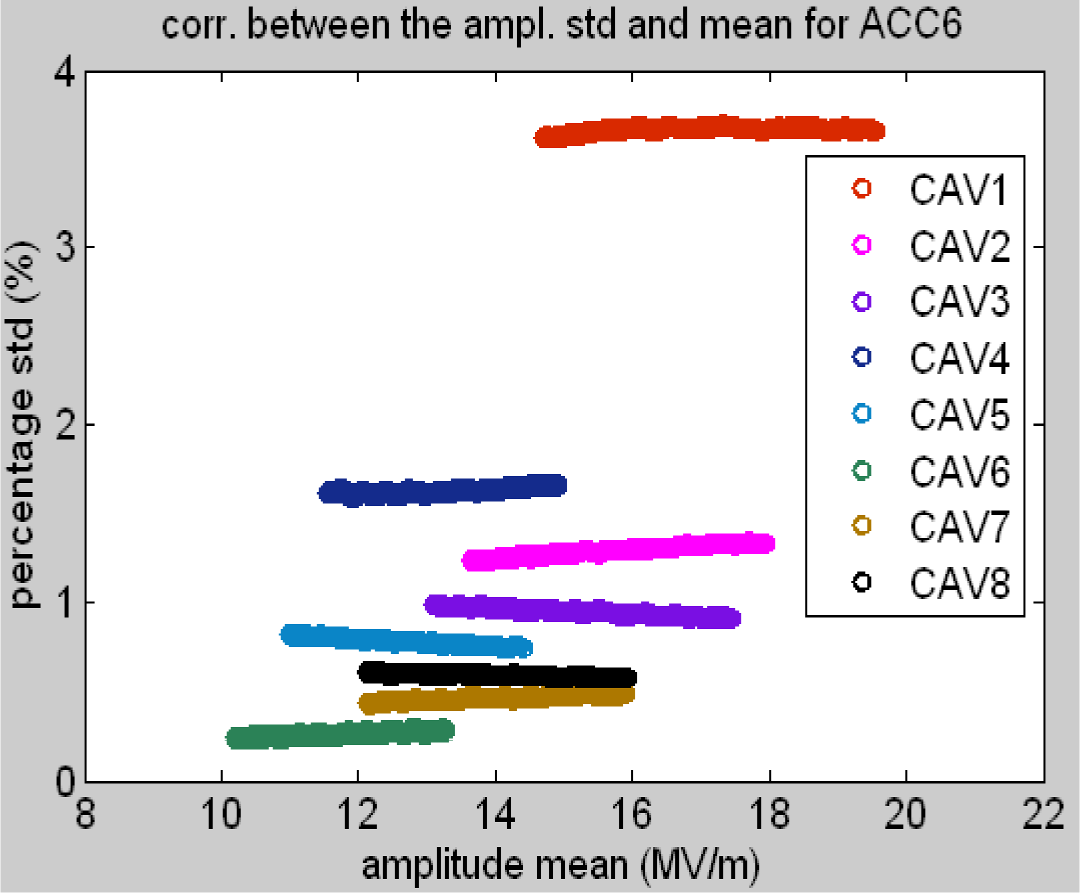
CAV7
σ=7.3Hz μ=30Hz



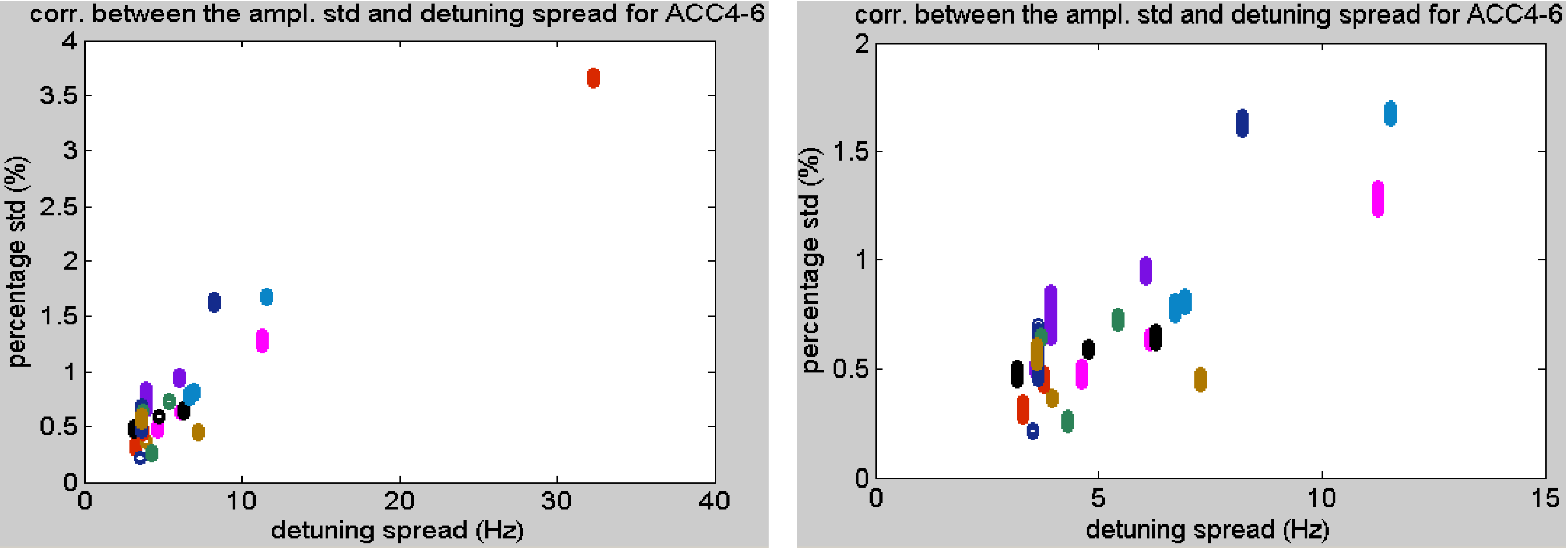
CAV8
σ=4.8Hz μ=107Hz

Probe Std for RF Off

ACC6 FB Off / AFF Off / No Beam

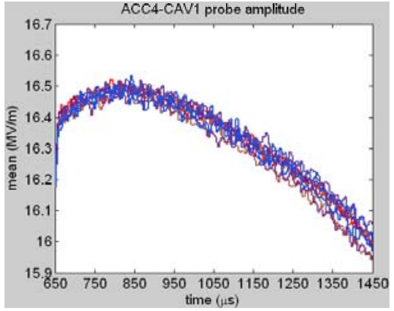


Corr. of Std and Detuning Std

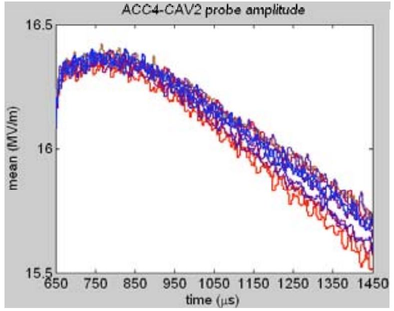


Dark Current Investigation

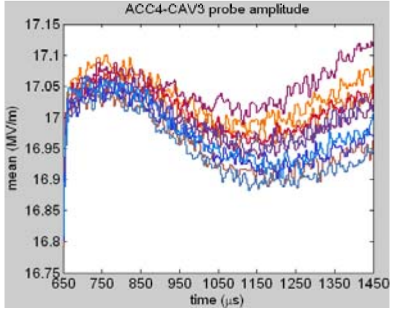
ACC4 FB Off / AFF Off / No Beam



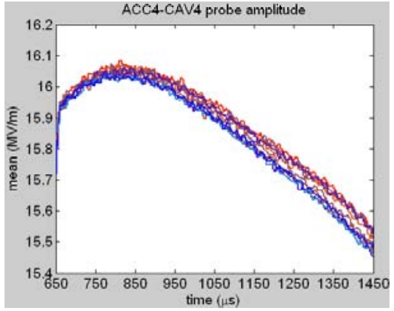
CAV1



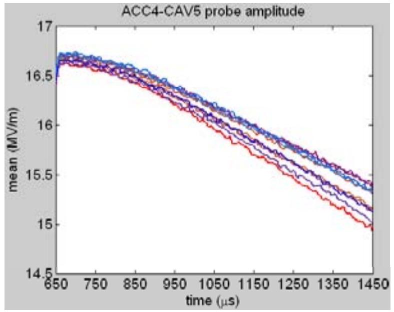
CAV2



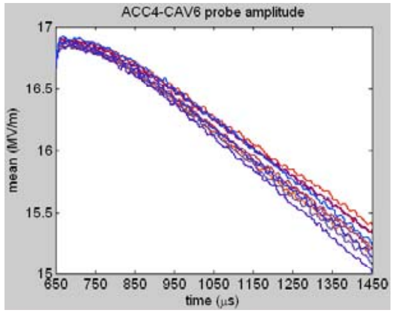
CAV3



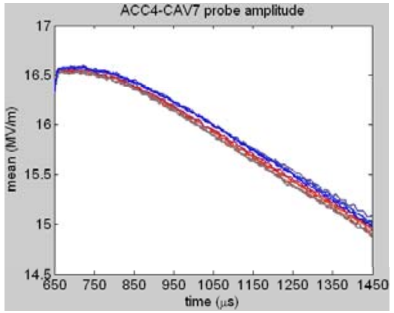
CAV4



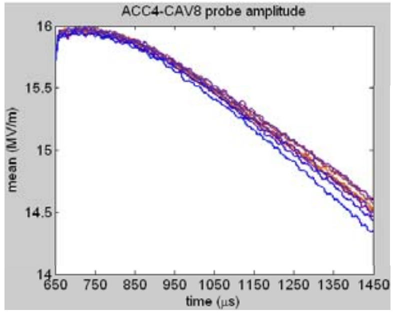
CAV5



CAV6



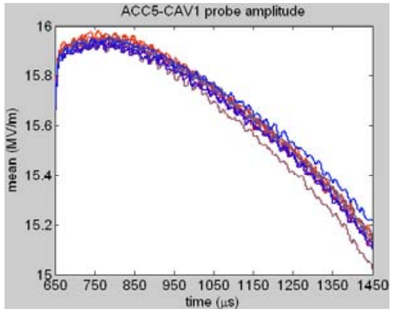
CAV7



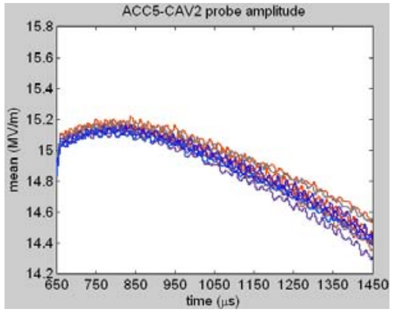
CAV8

Dark Current Investigation

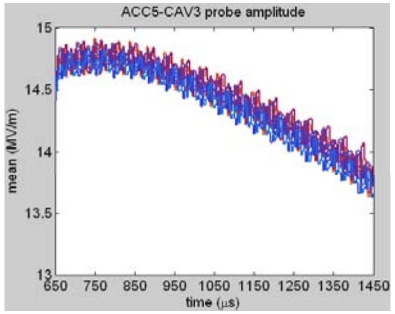
ACC5 FB Off / AFF Off / No Beam



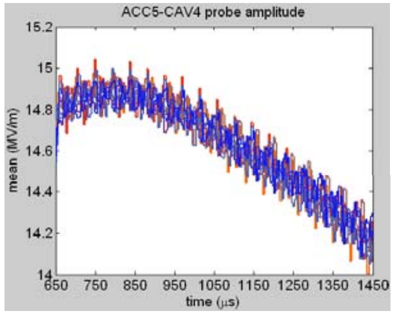
CAV1



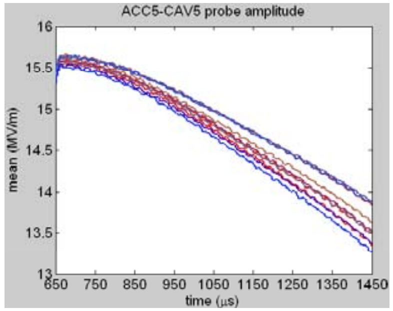
CAV2



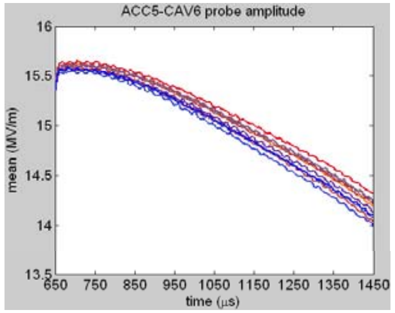
CAV3



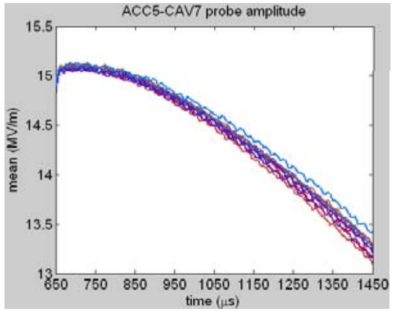
CAV4



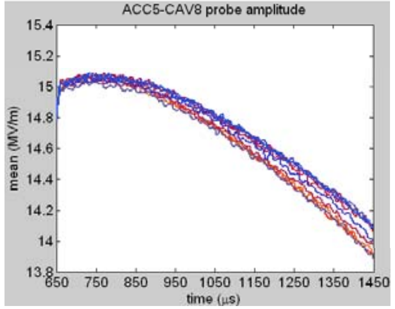
CAV5



CAV6



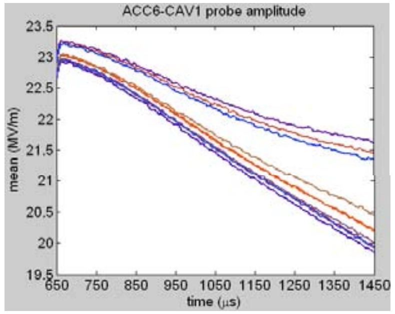
CAV7



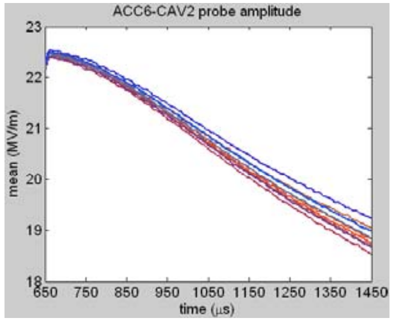
CAV8

Dark Current Investigation

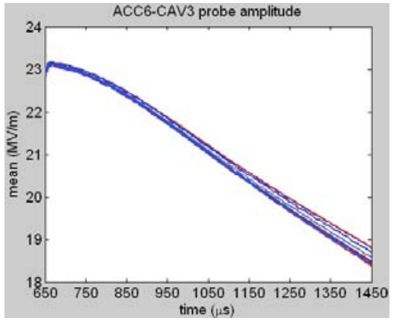
ACC6 FB Off / AFF Off / No Beam



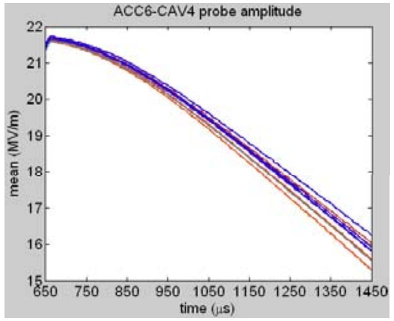
CAV1



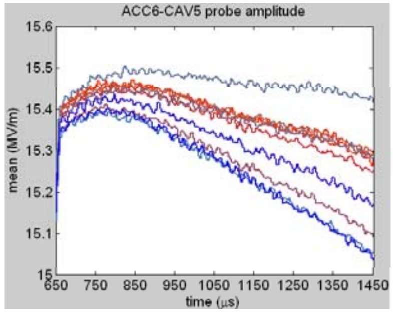
CAV2



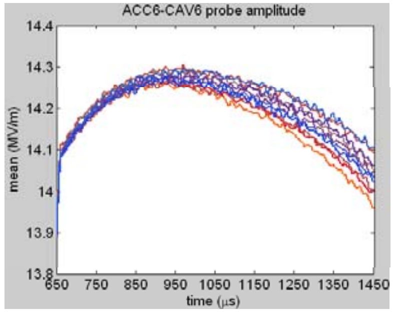
CAV3



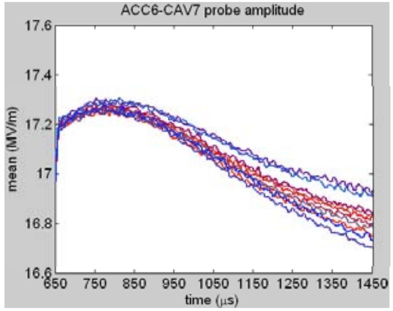
CAV4



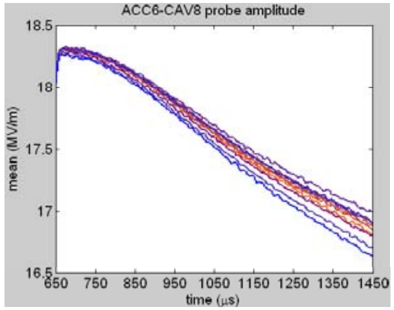
CAV5



CAV6



CAV7



CAV8

ACC4-CAV1

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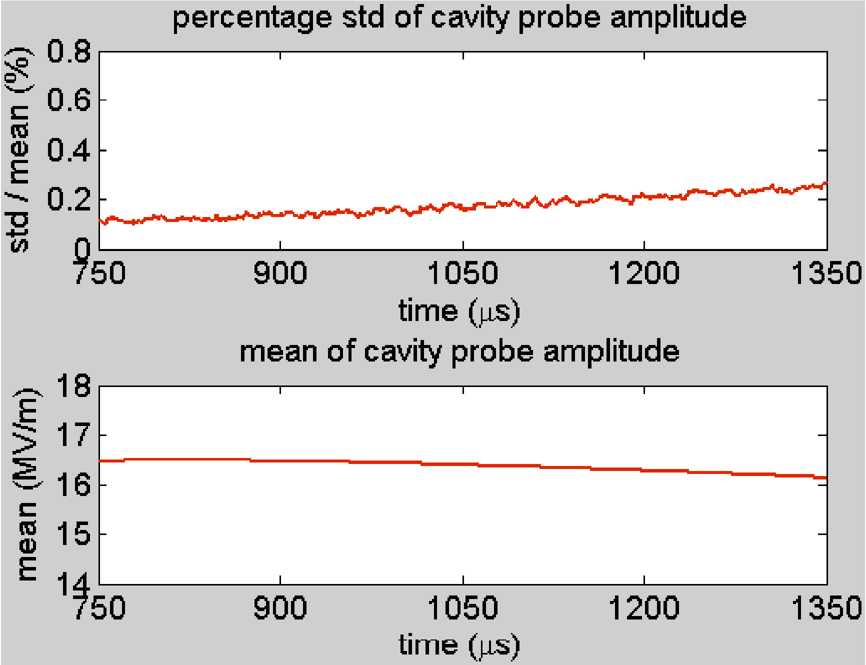

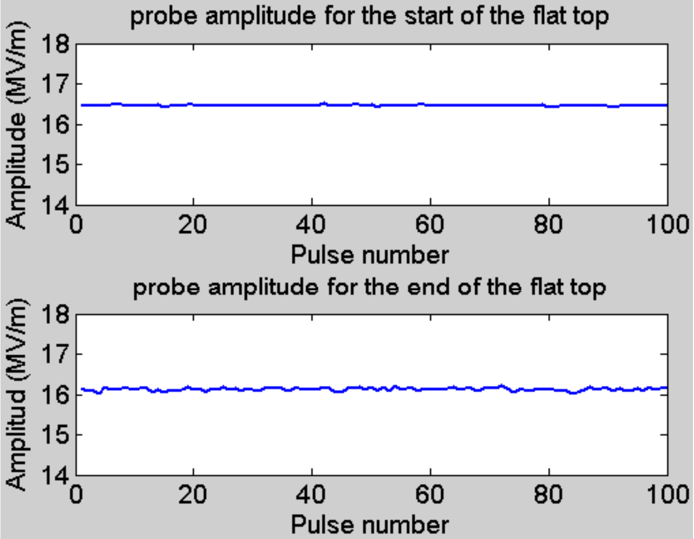

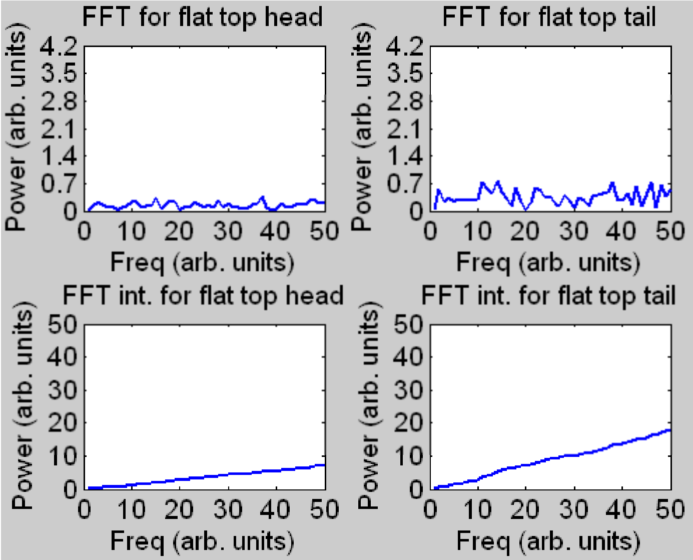

ACC4-CAV2

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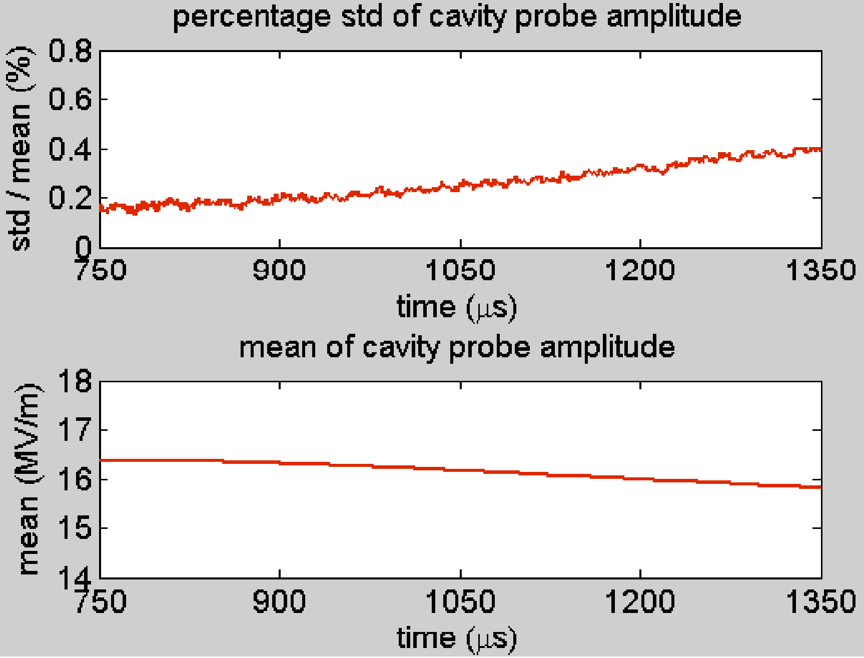

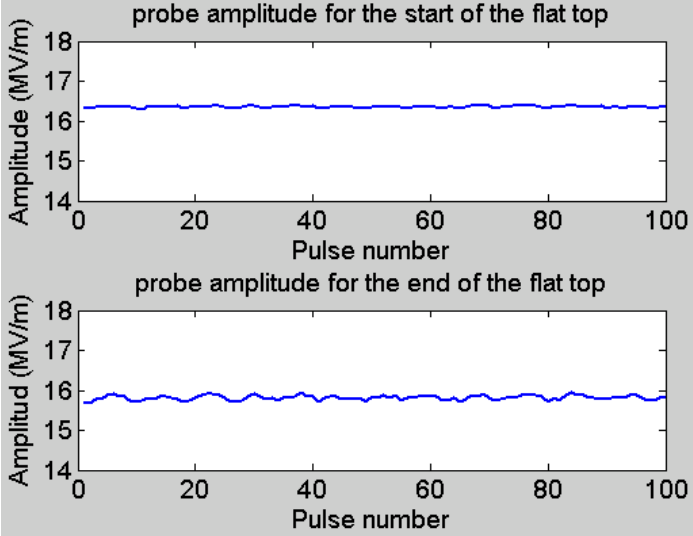

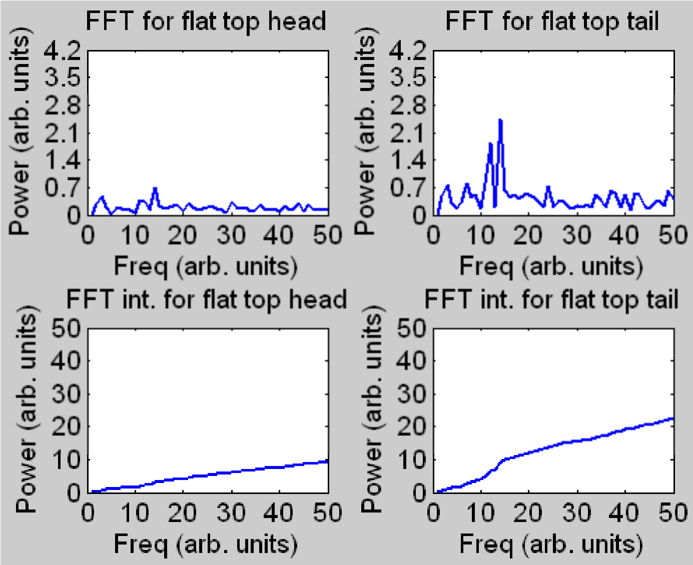

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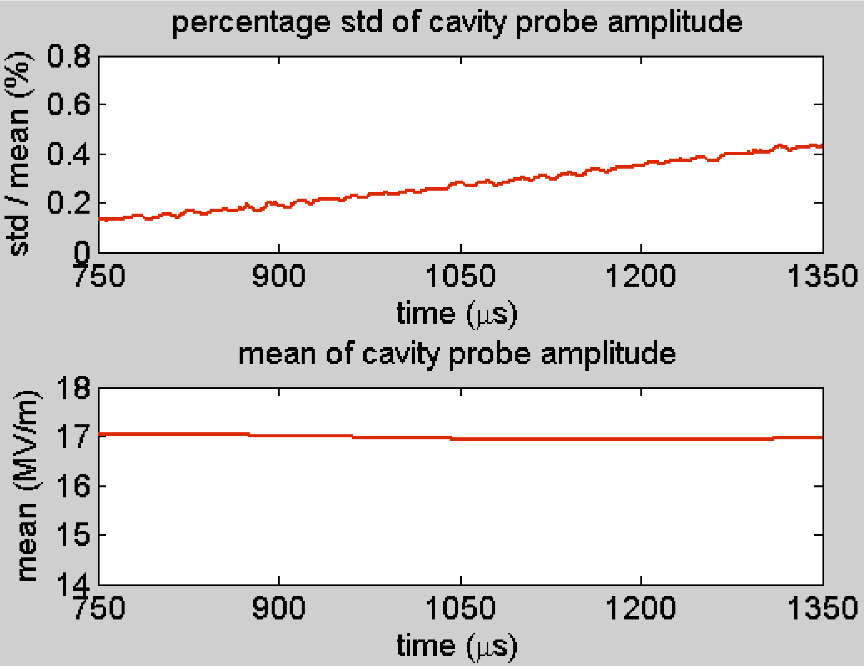

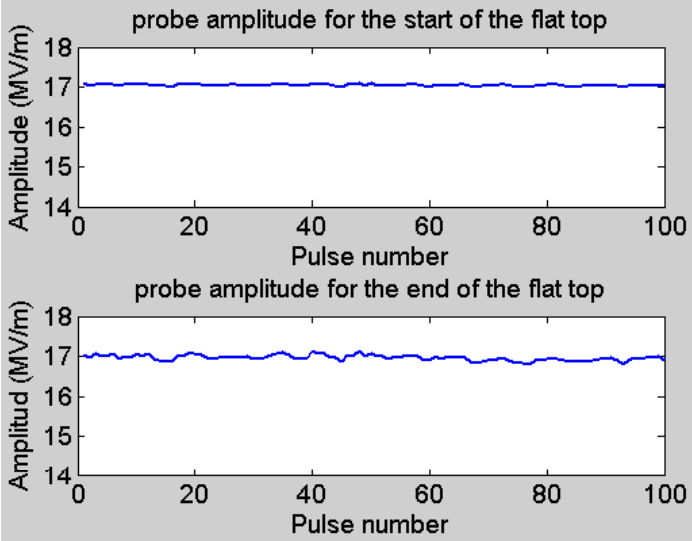

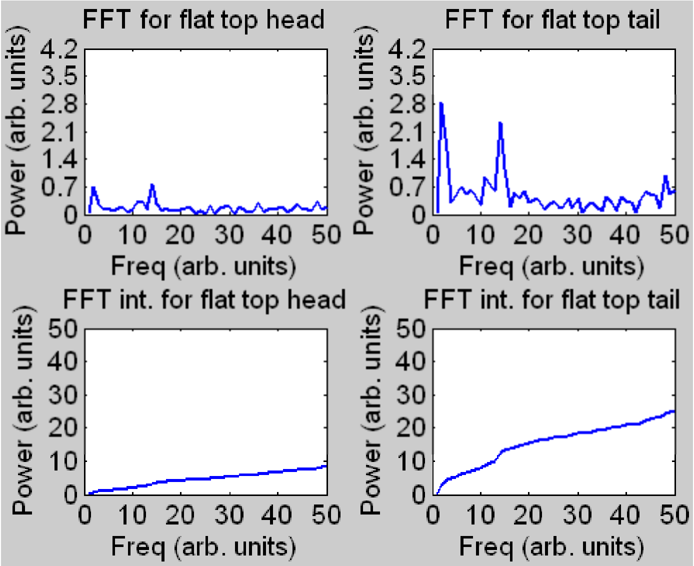

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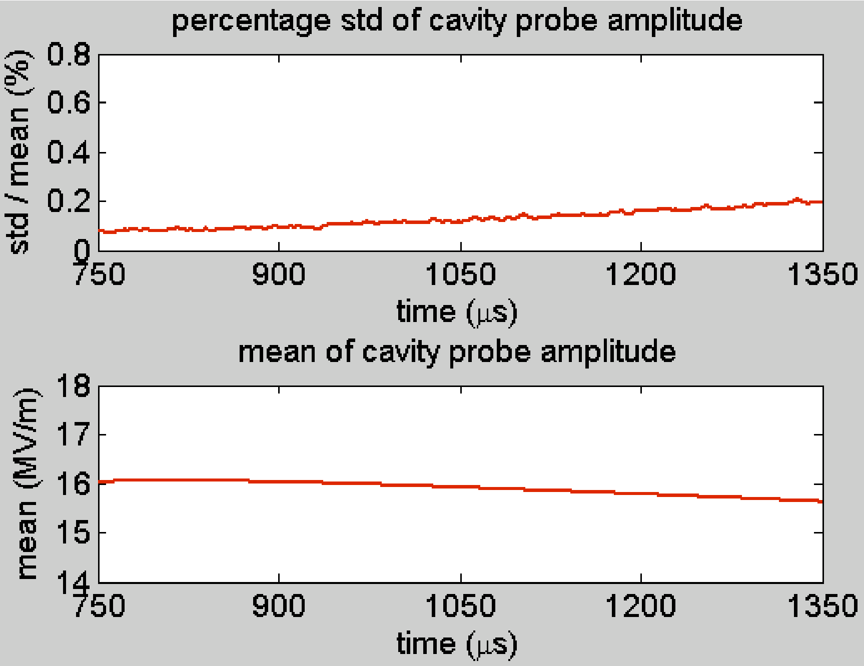

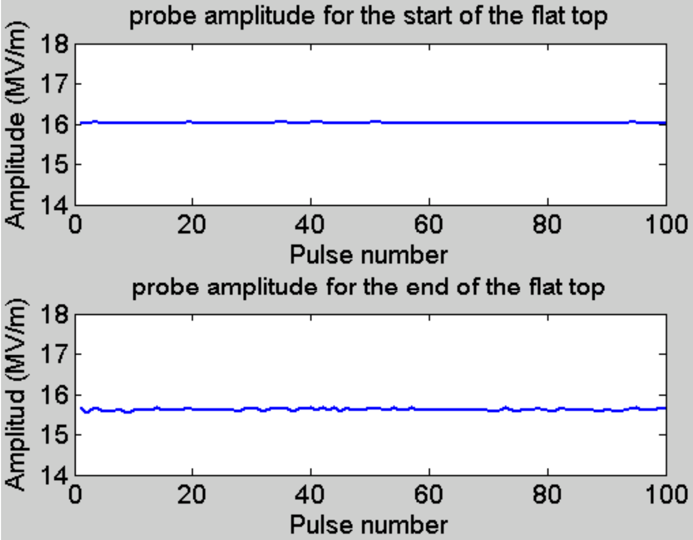

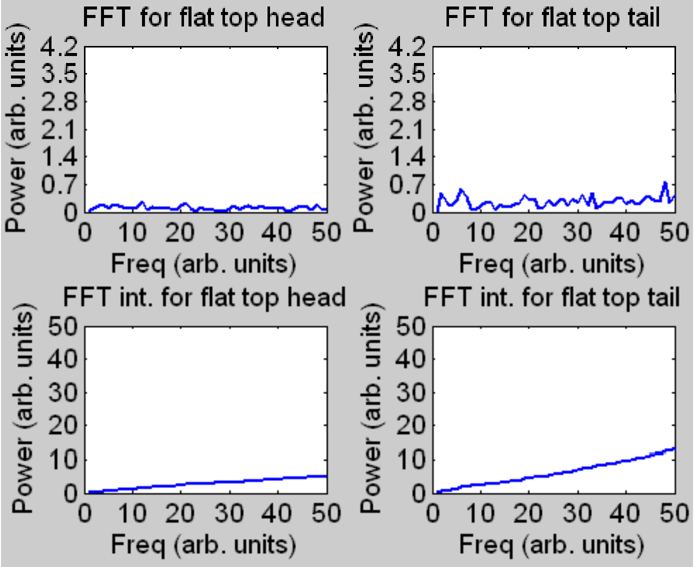

ACC4-CAV5

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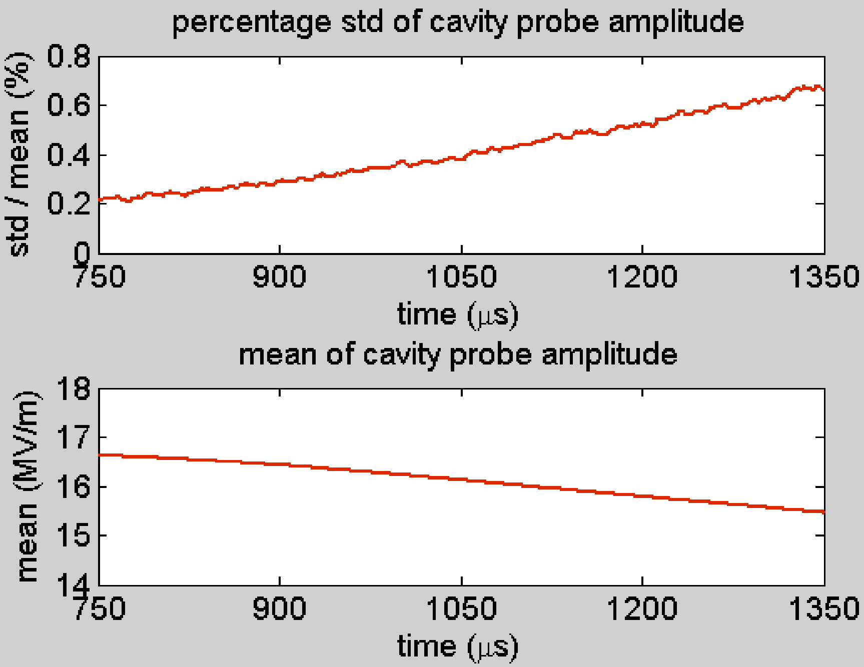

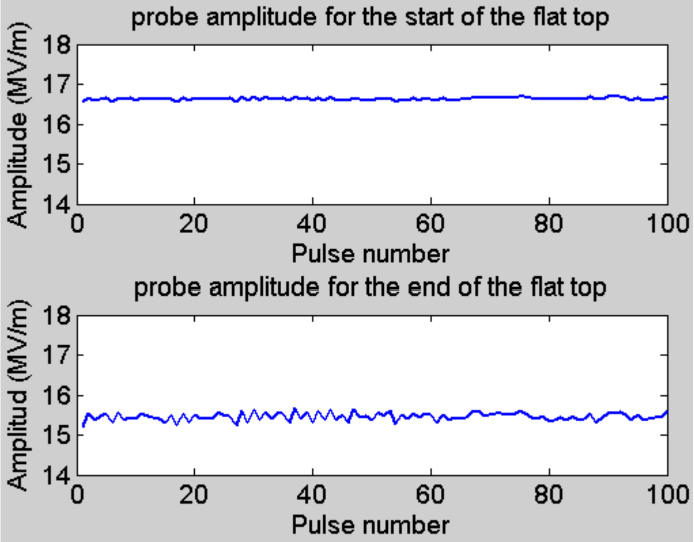

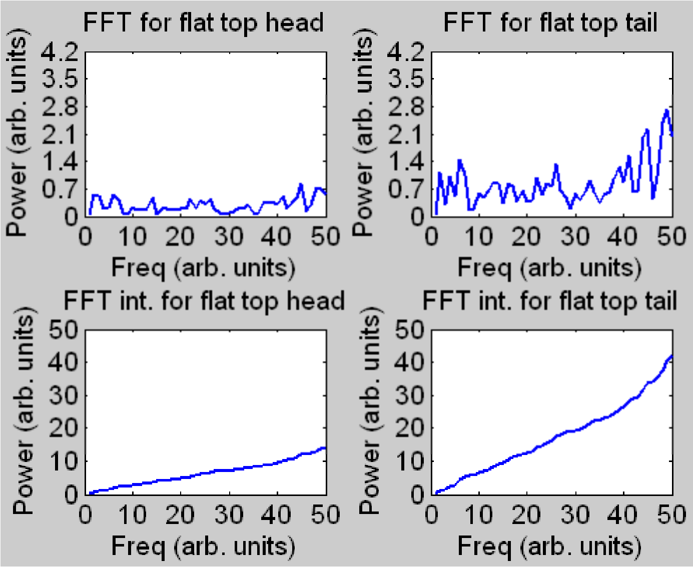

ACC4-CAV6

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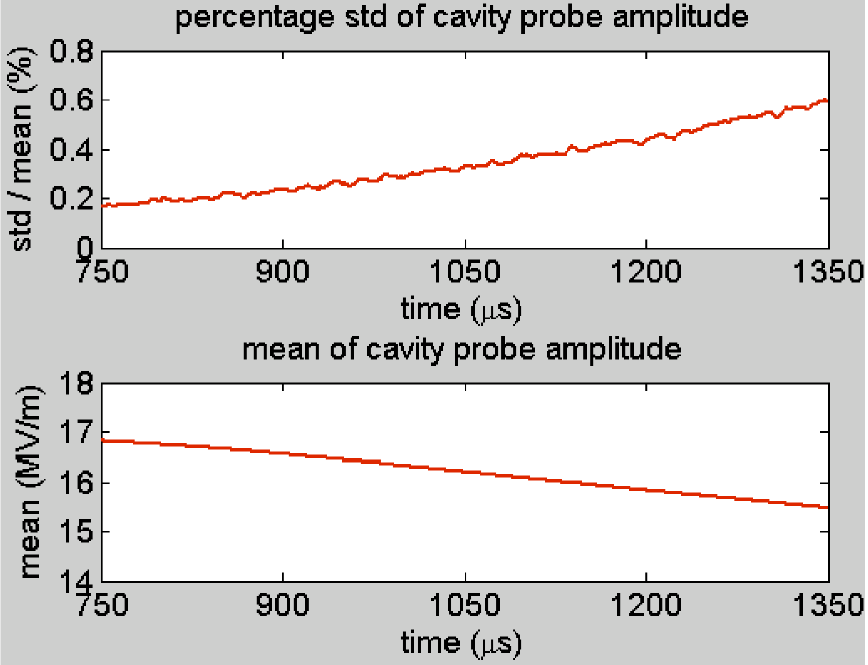

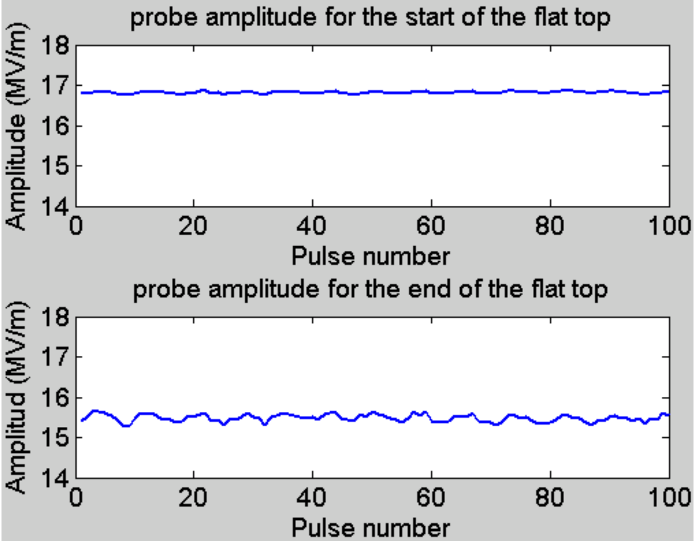

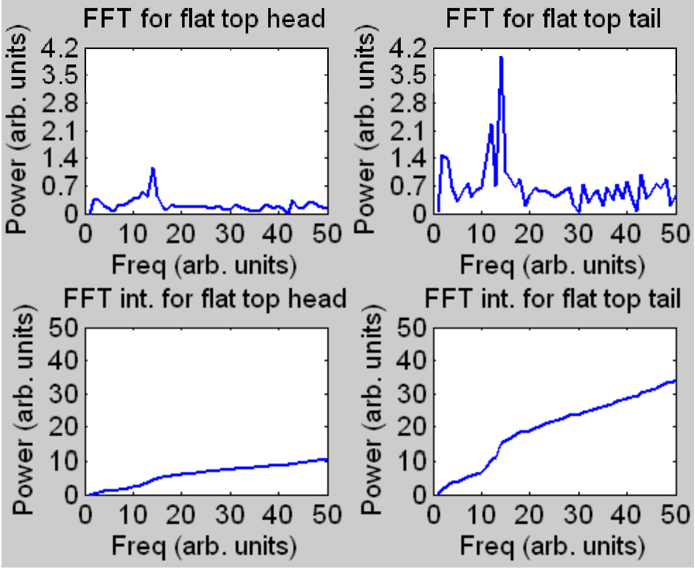

ACC4-CAV7

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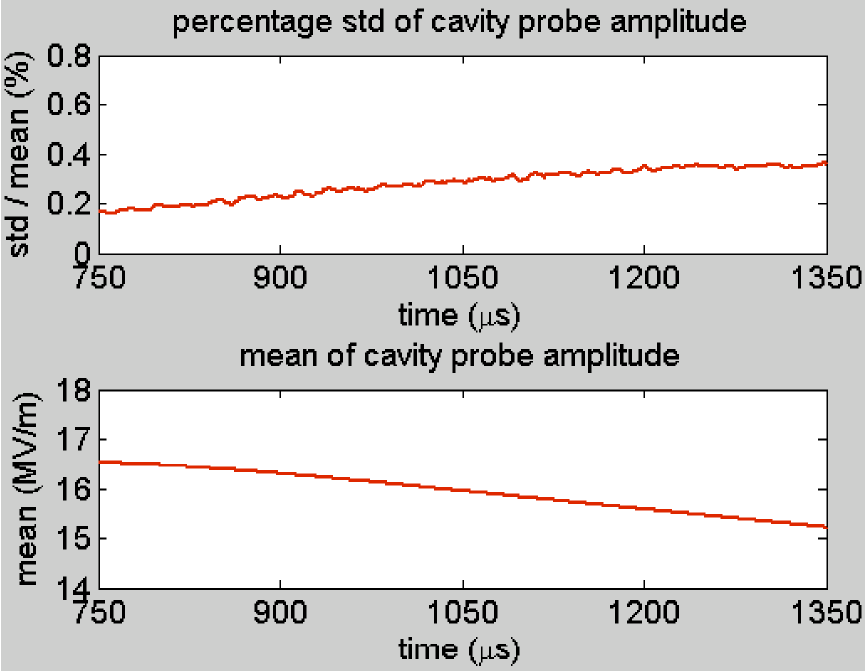

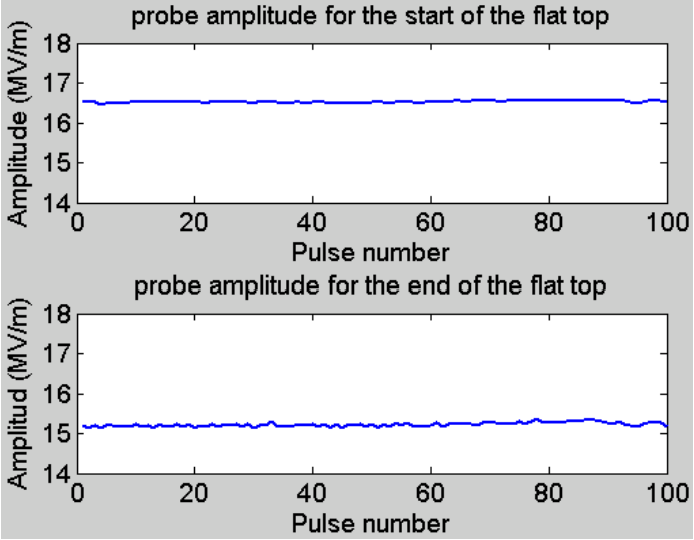

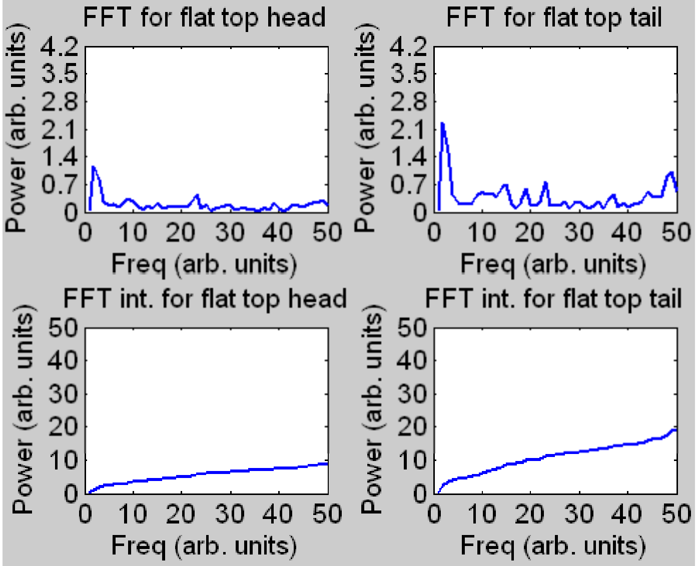

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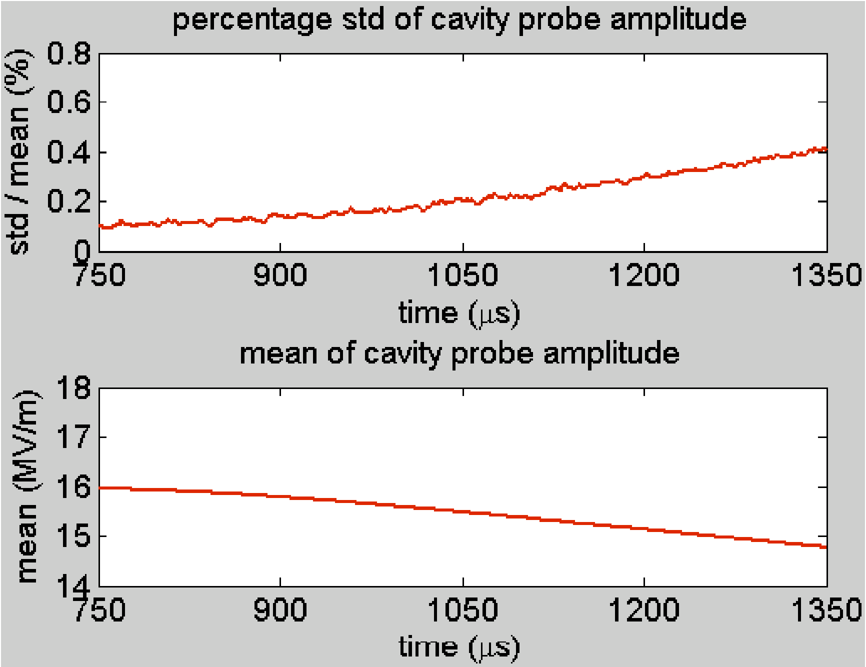

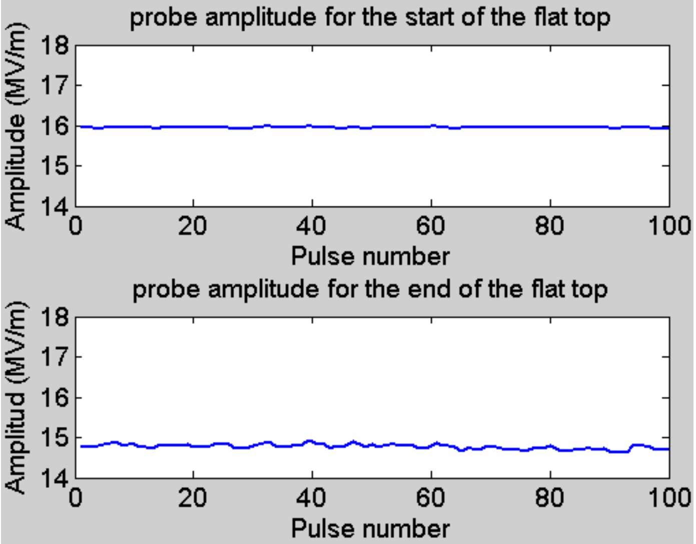

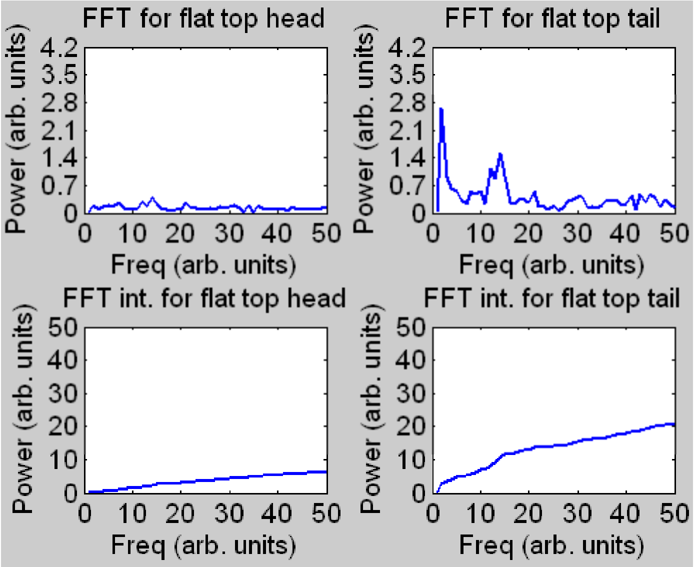

ACC5-CAV1

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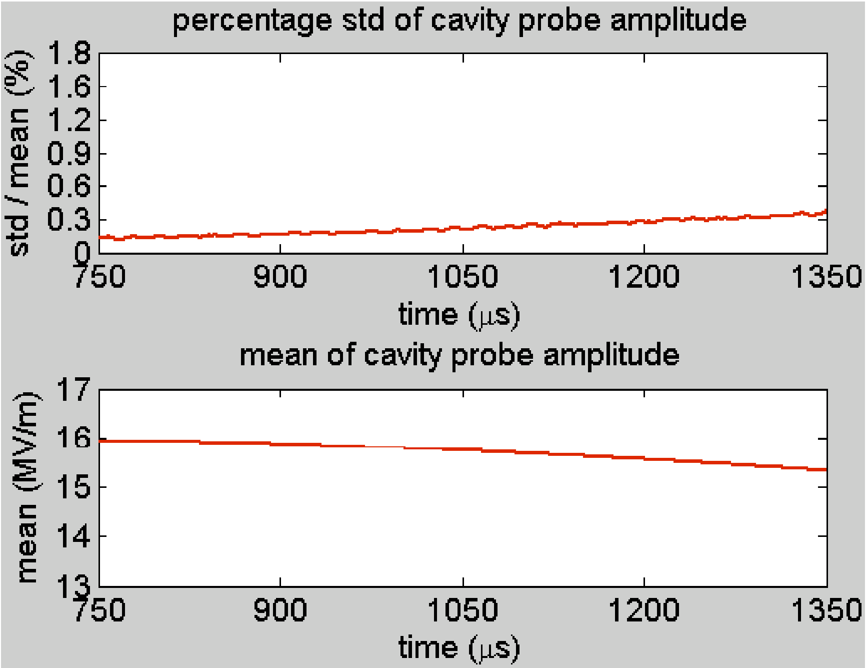

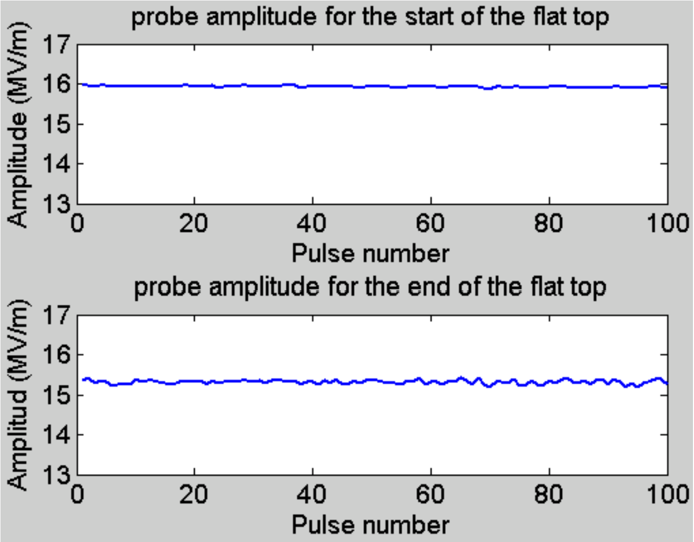

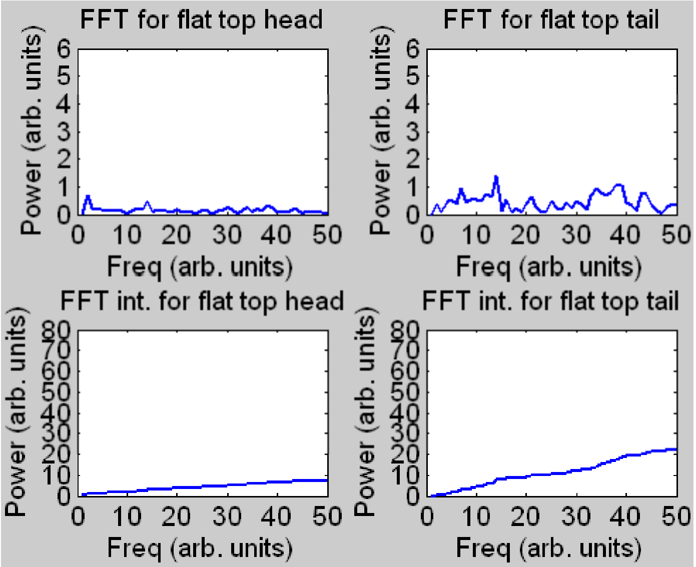

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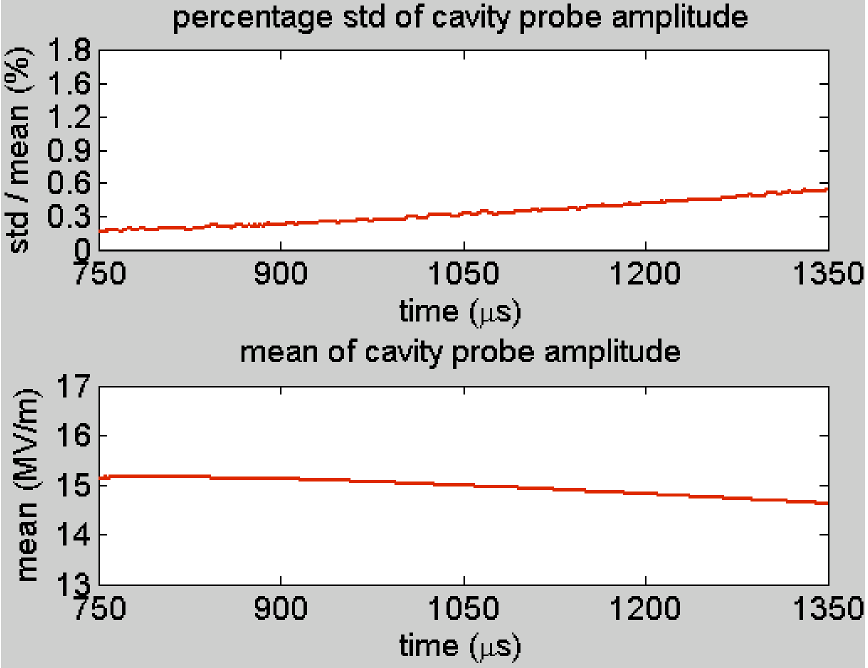

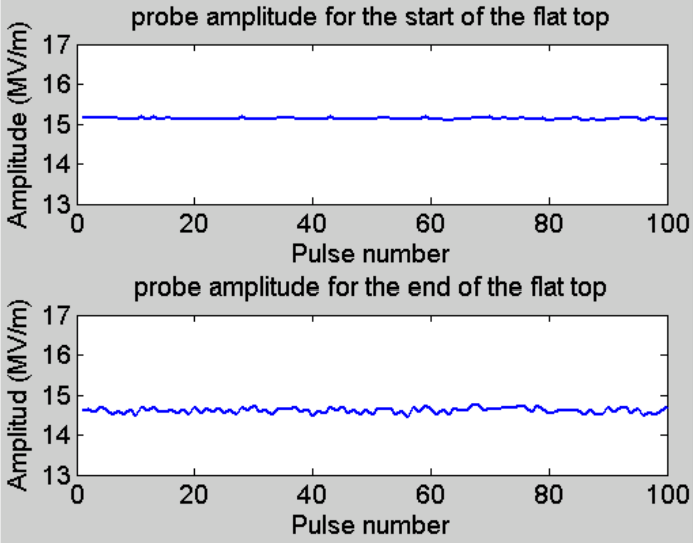

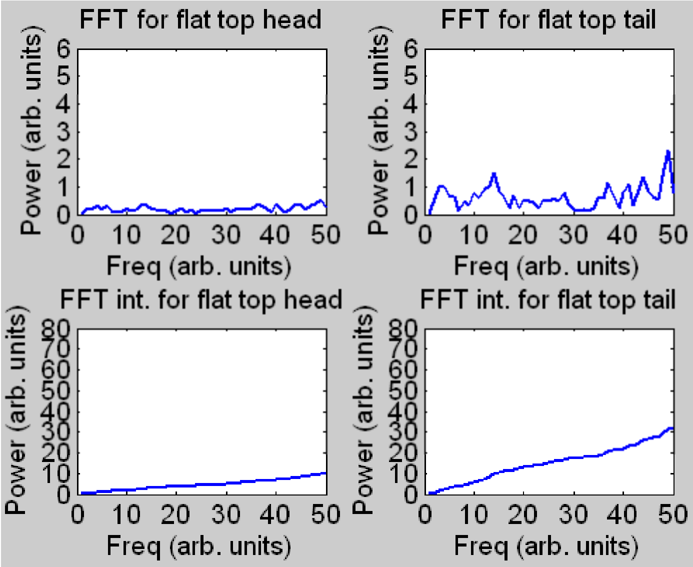

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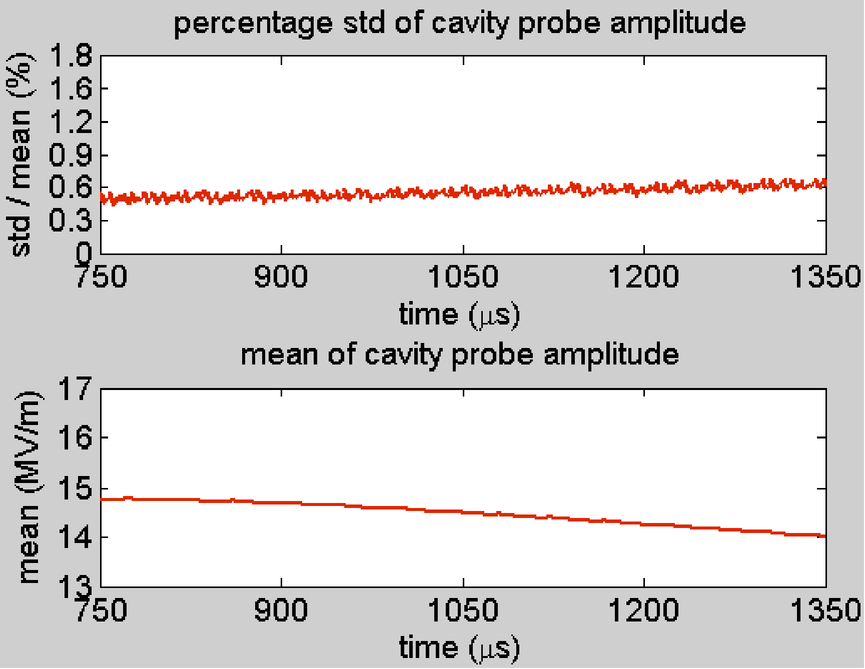

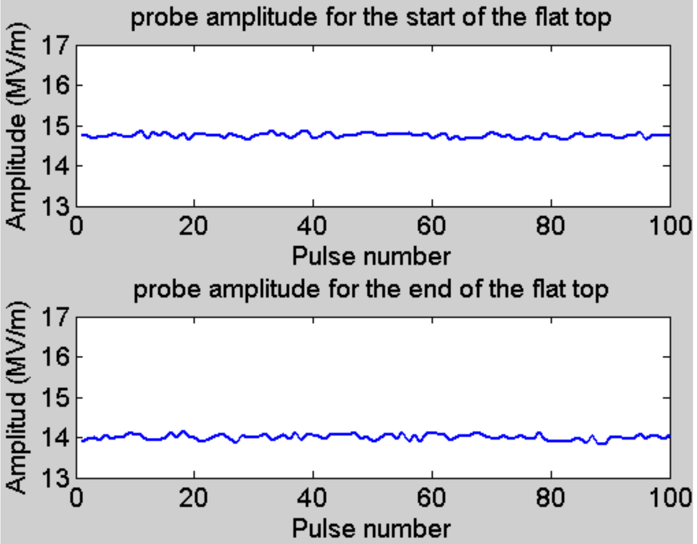

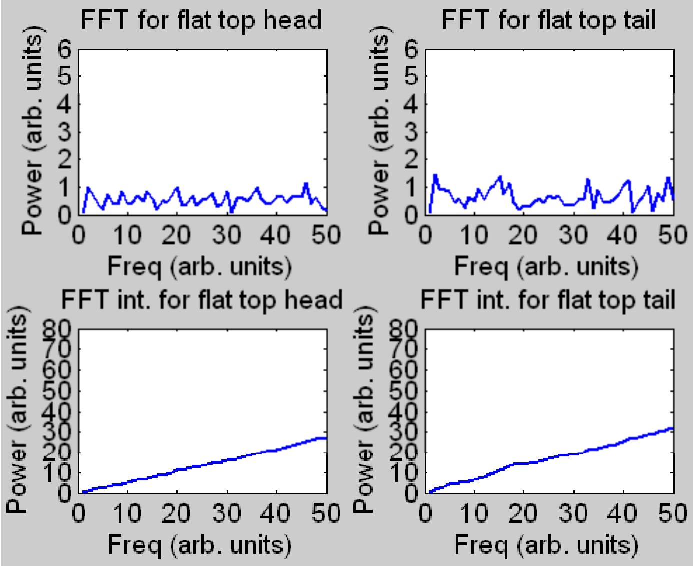

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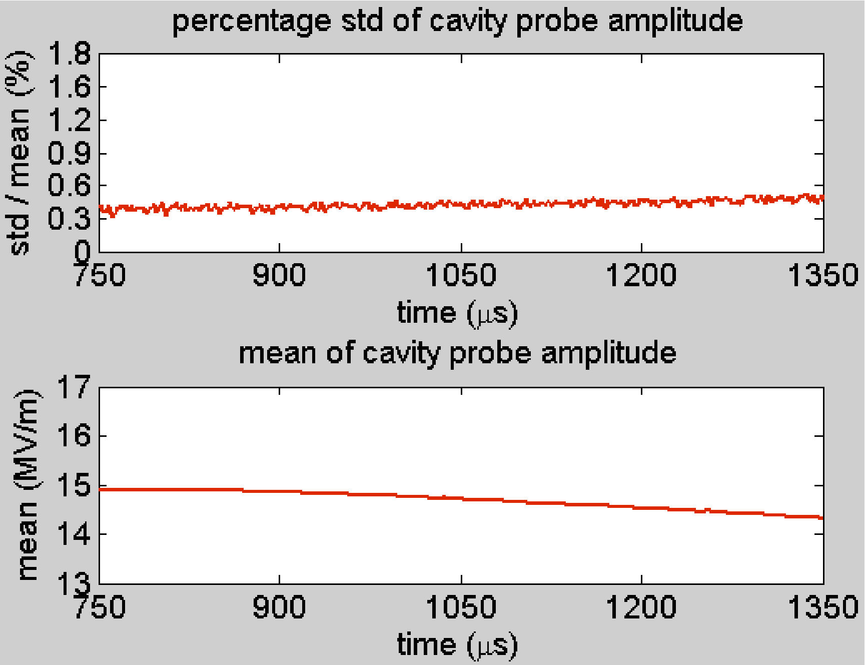

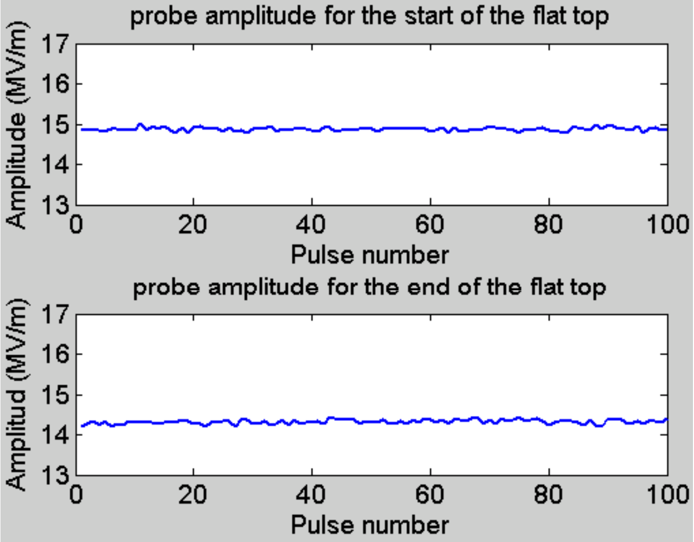

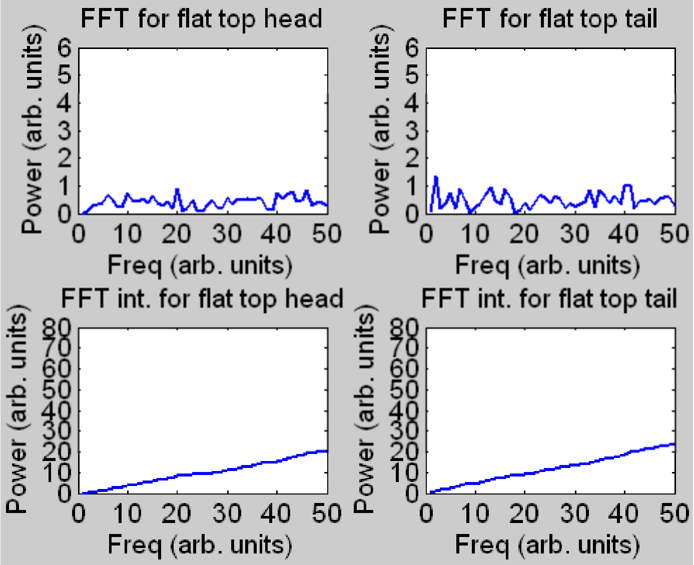

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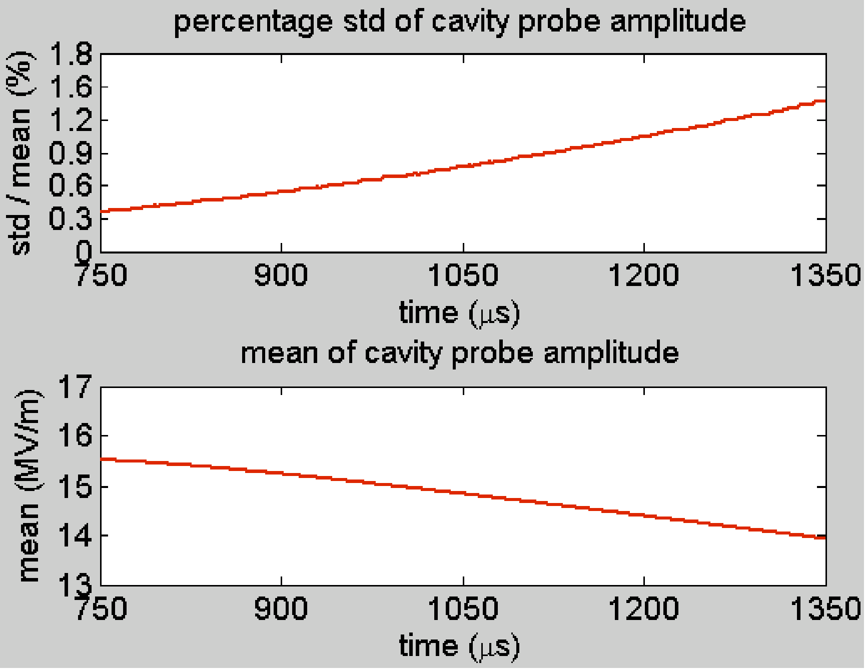

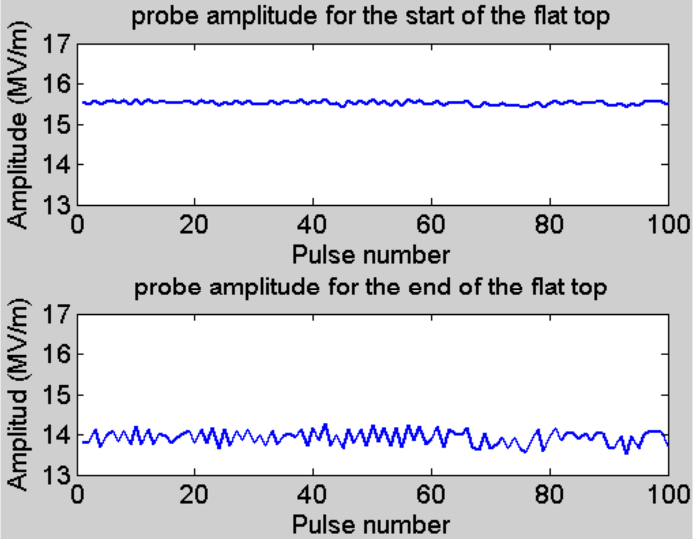

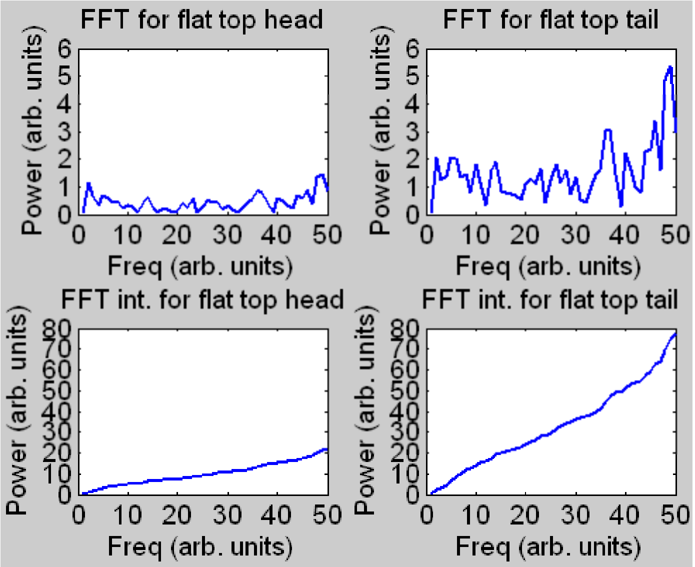

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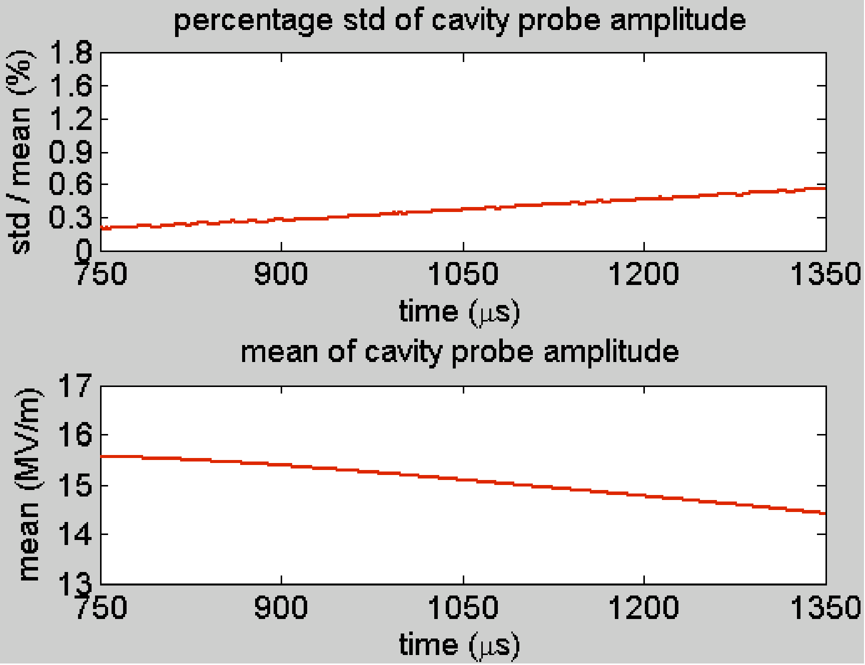

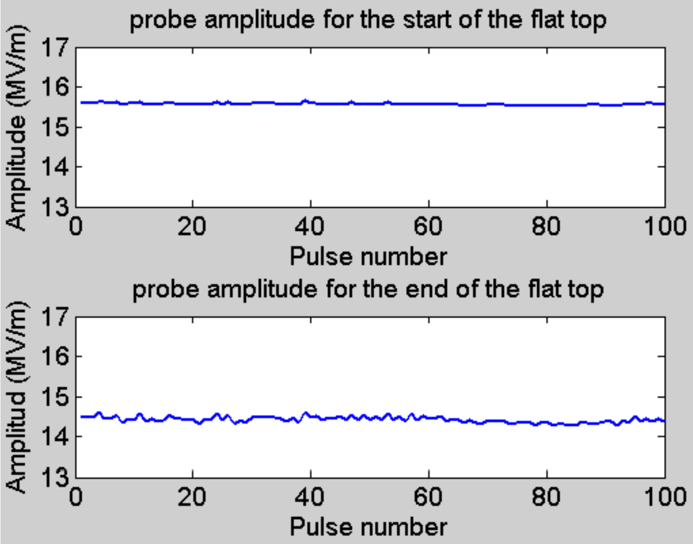

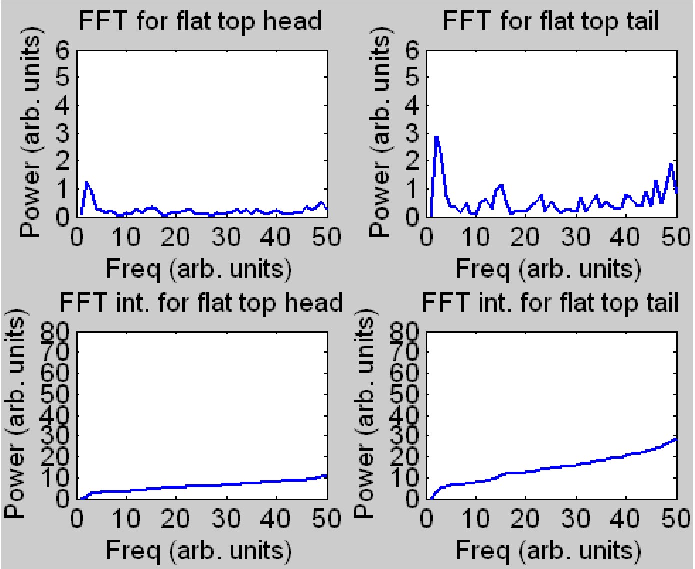

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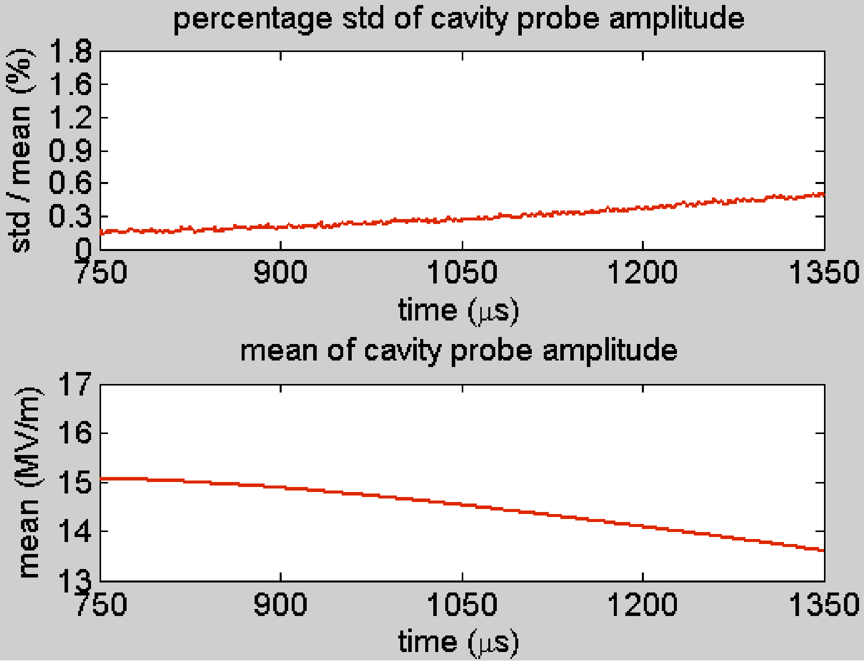

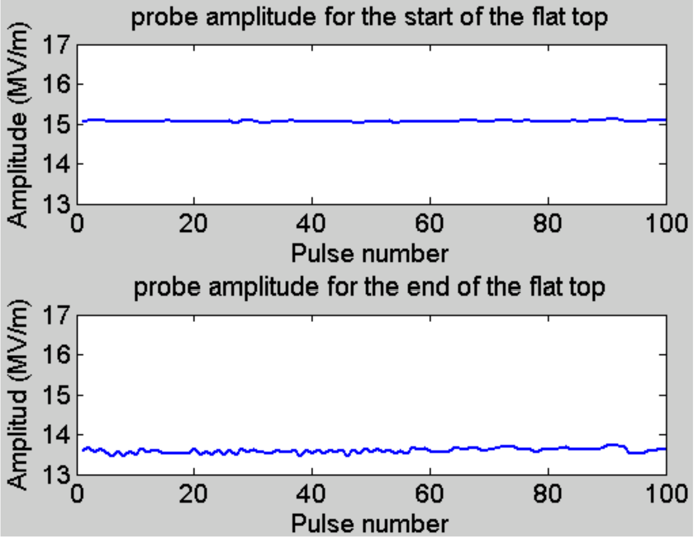

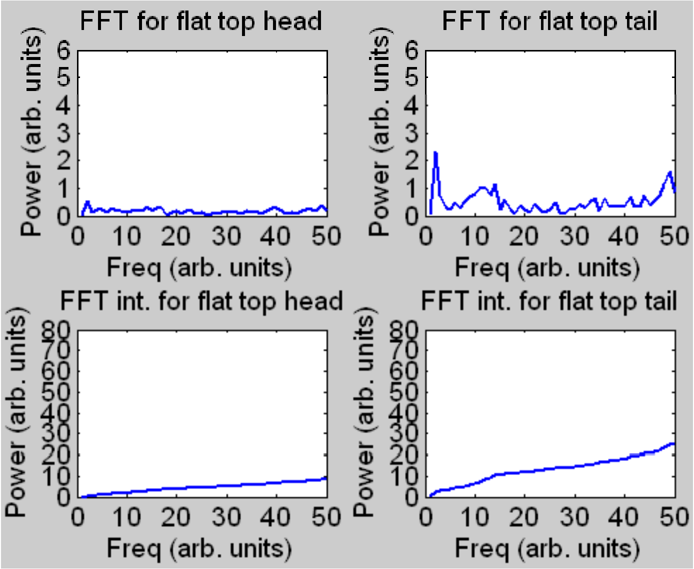

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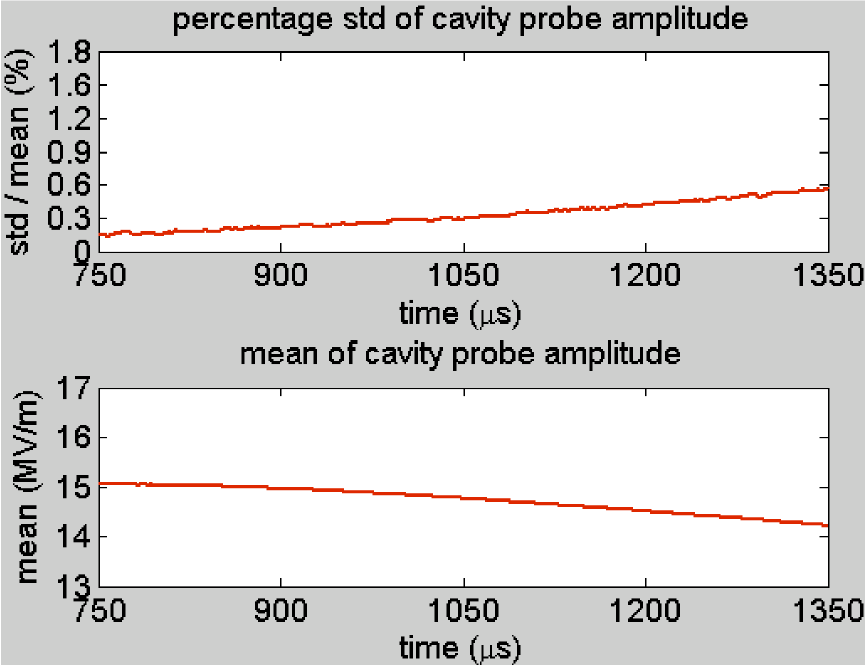
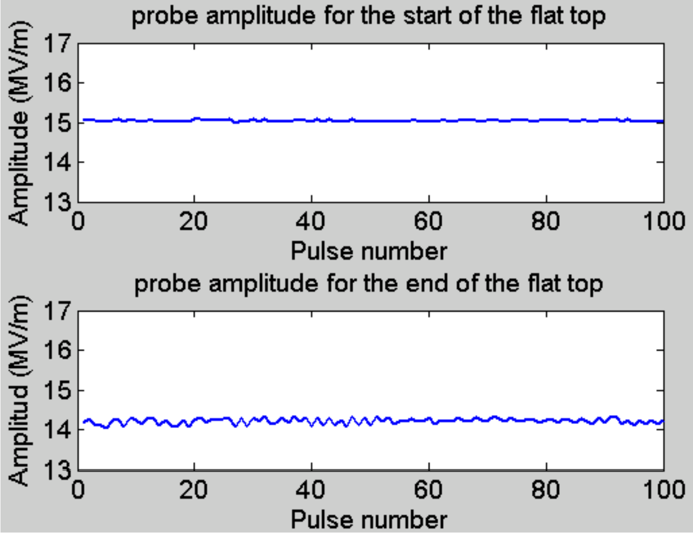
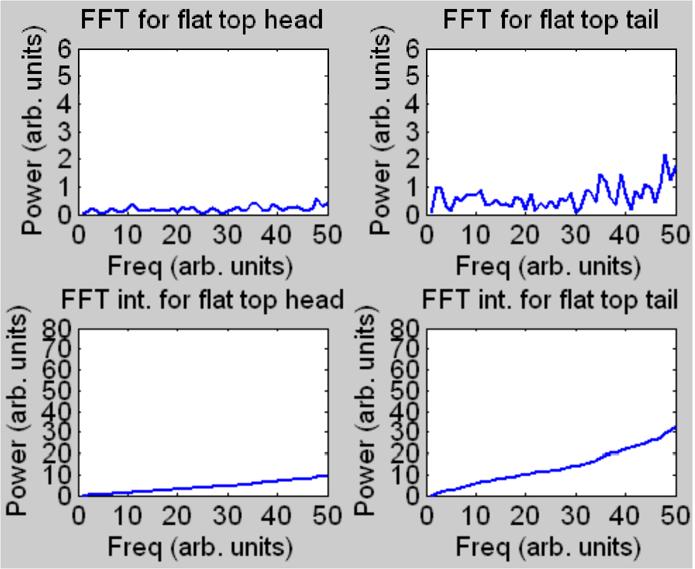
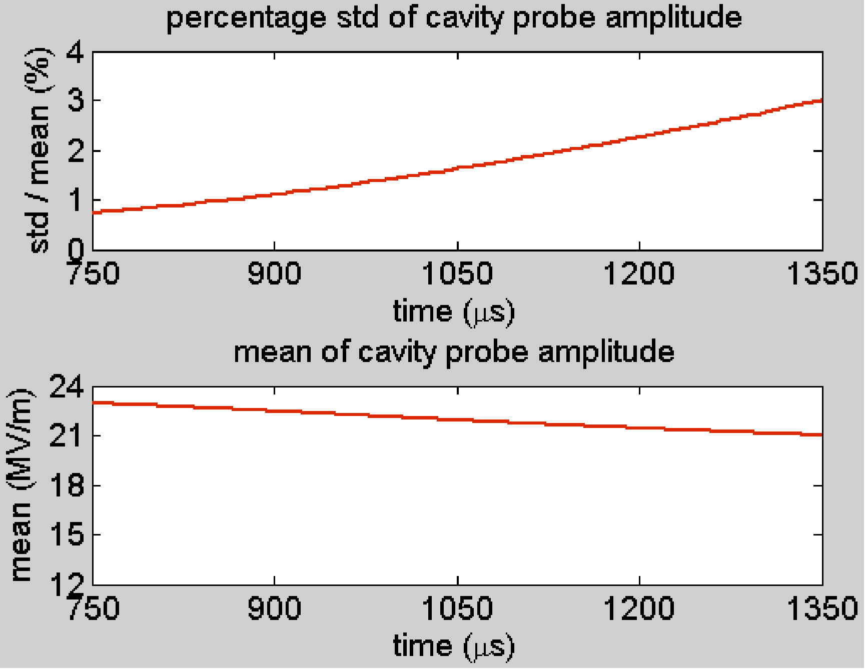


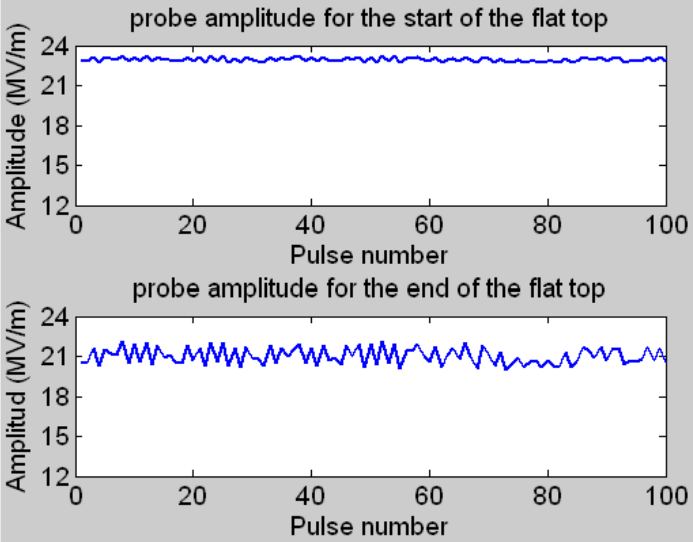


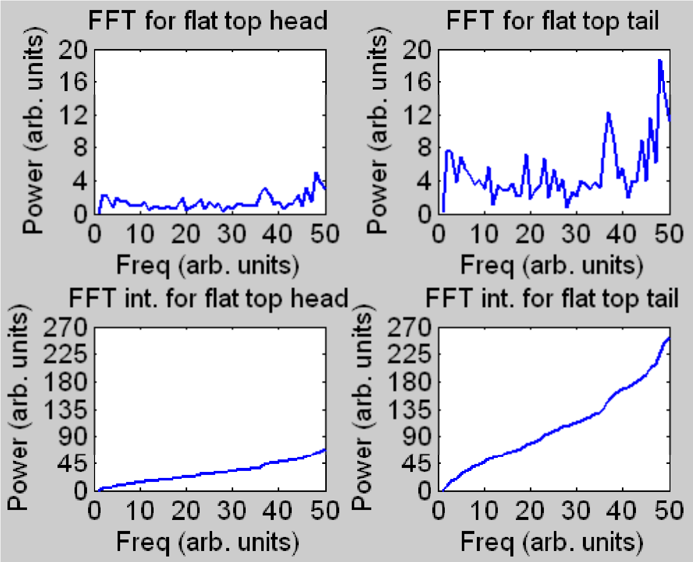


ACC6-CAV1

Here we use sample number 750 indicates start of the flat top, while 1350 indicates the end of the flat top.







ACC6-CAV2

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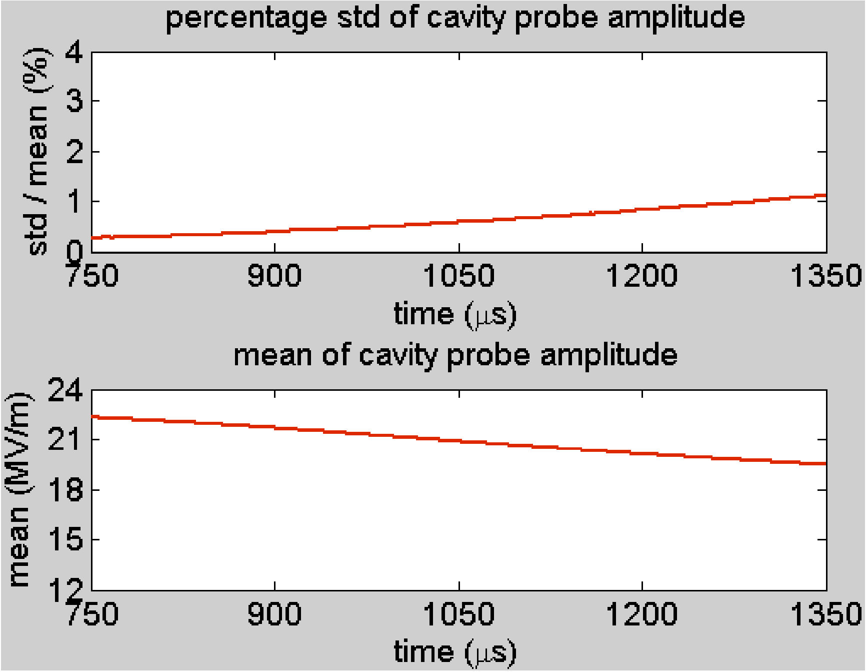

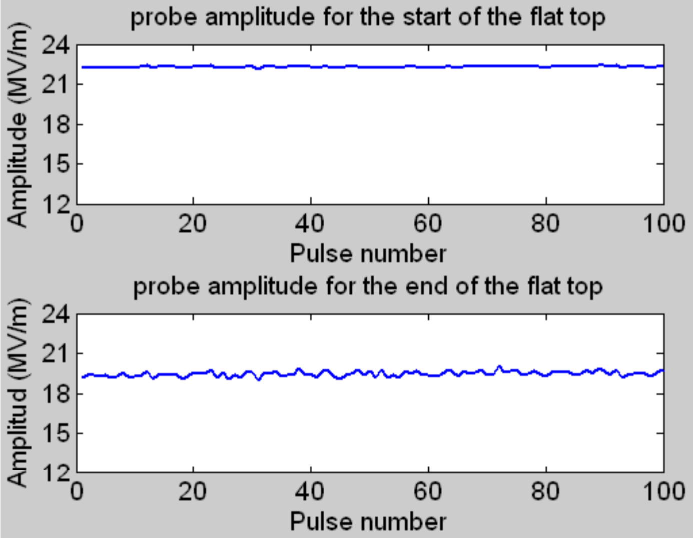

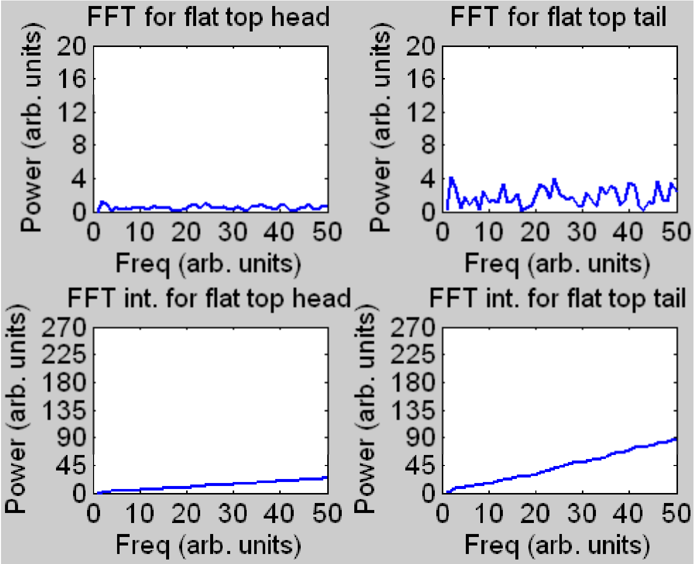

ACC6-CAV3

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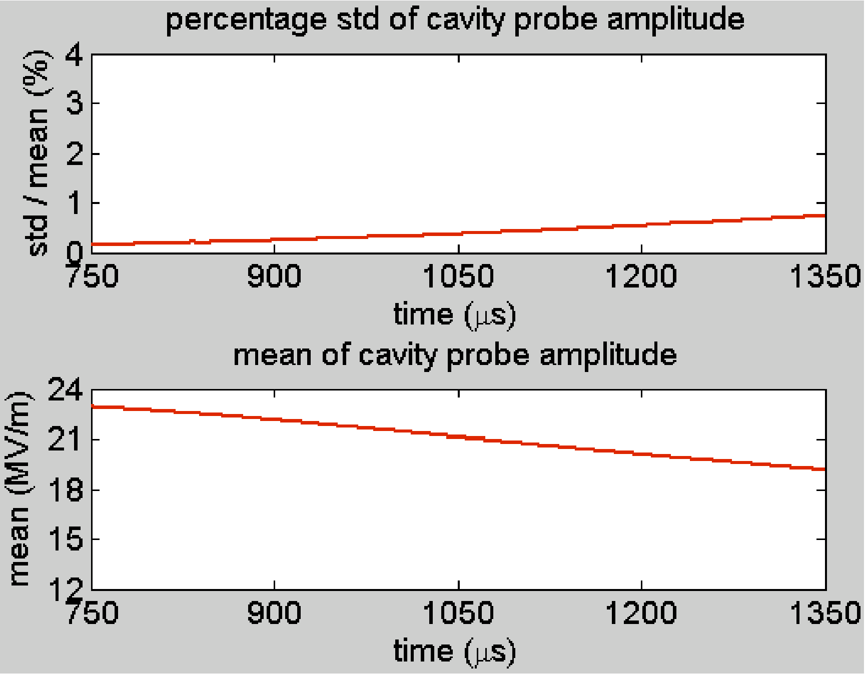

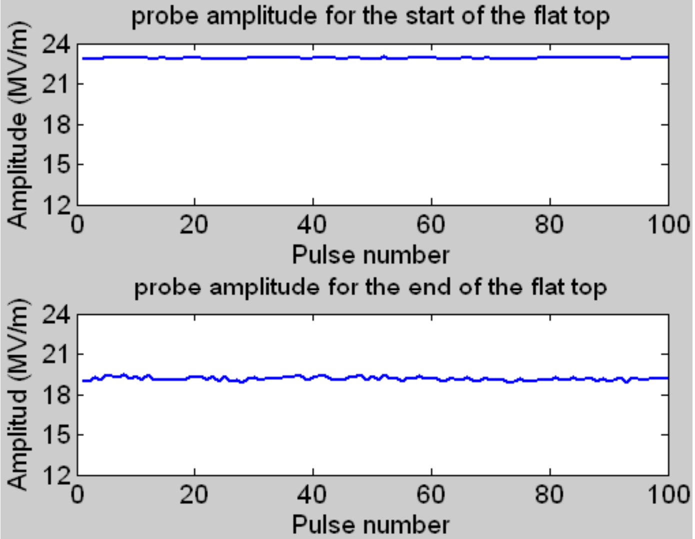

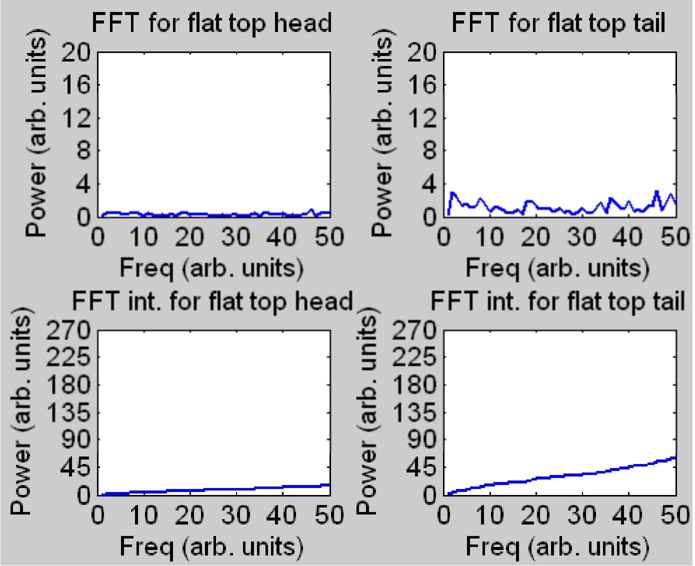

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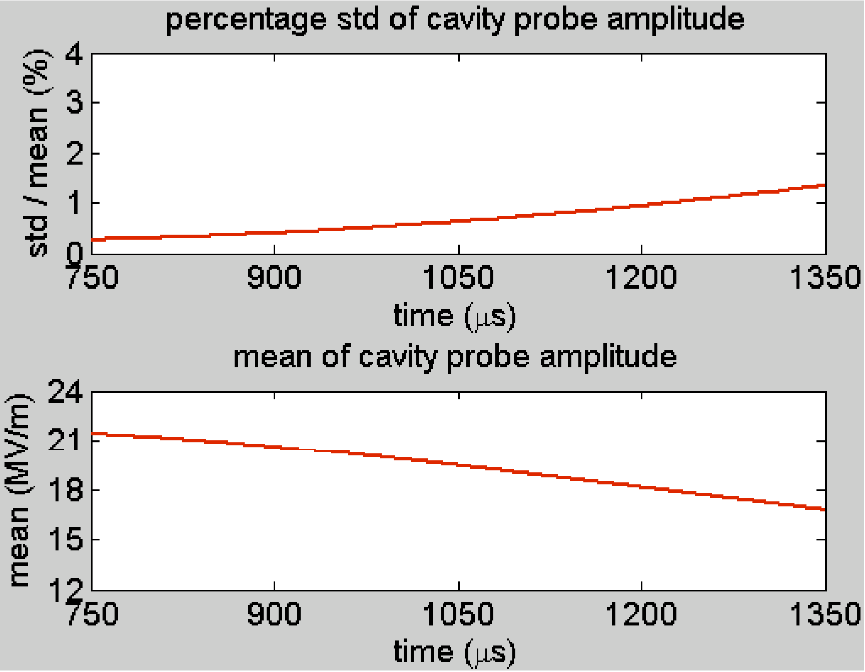
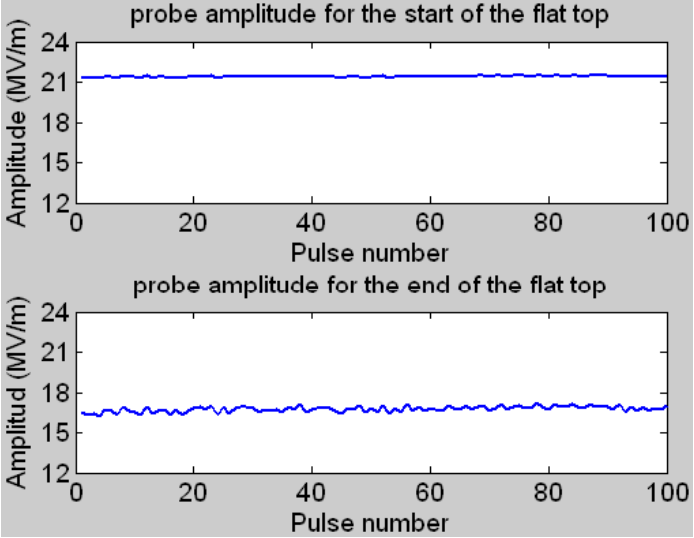
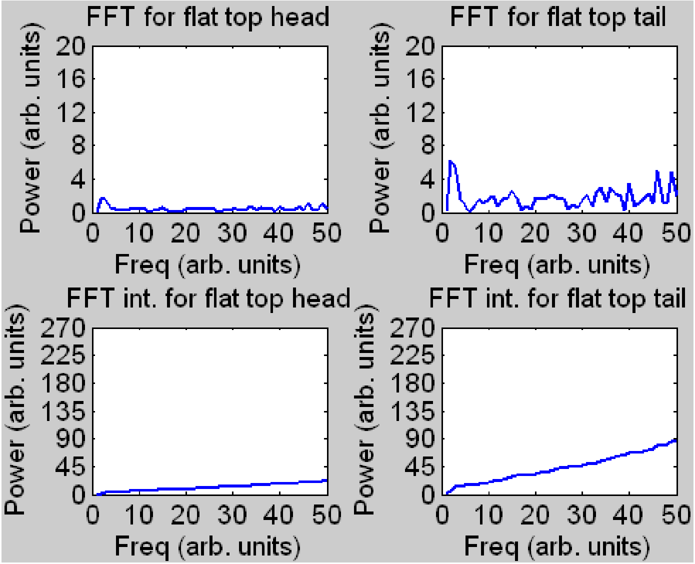
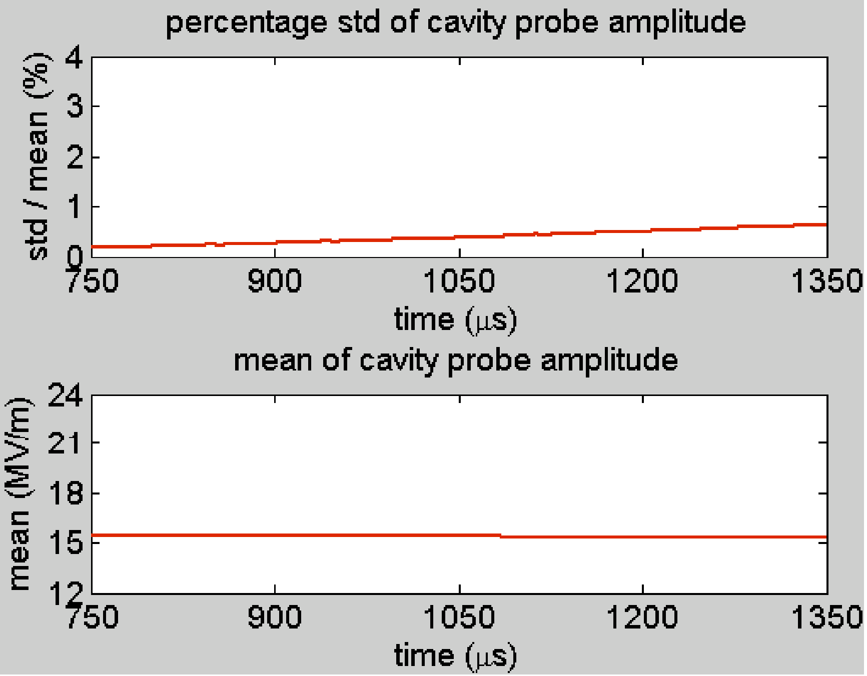


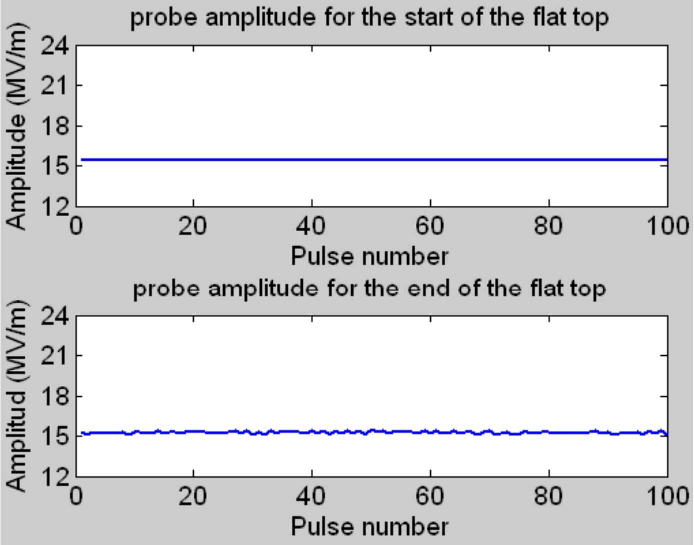


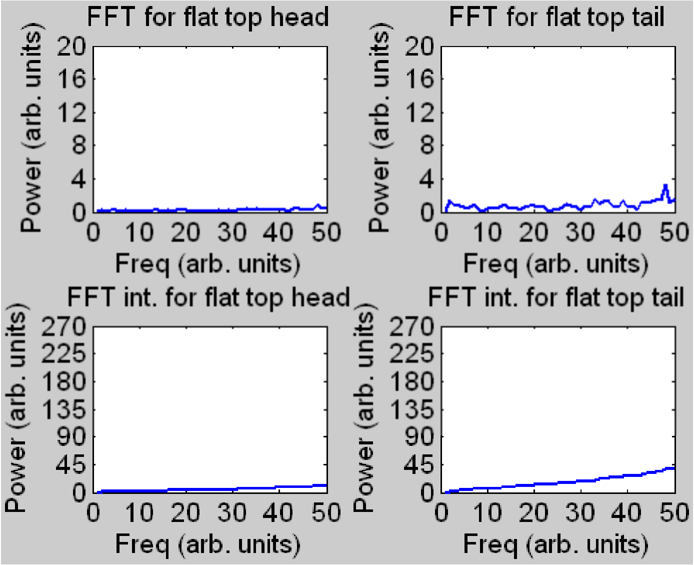


ACC6-CAV5

Here we use sample number 750 indicates start of the flat top, while 1350 indicates the end of the flat top.







ACC6-CAV6

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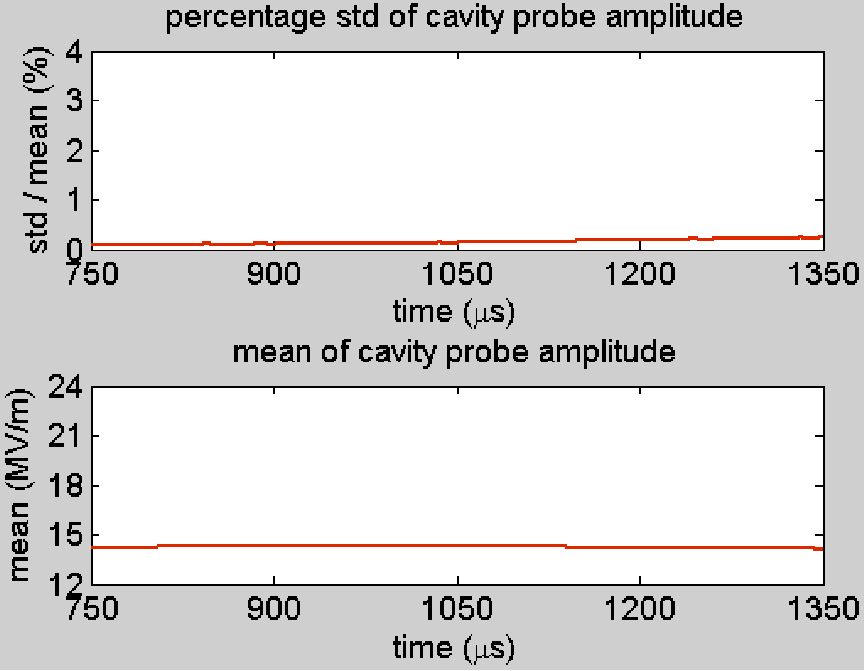

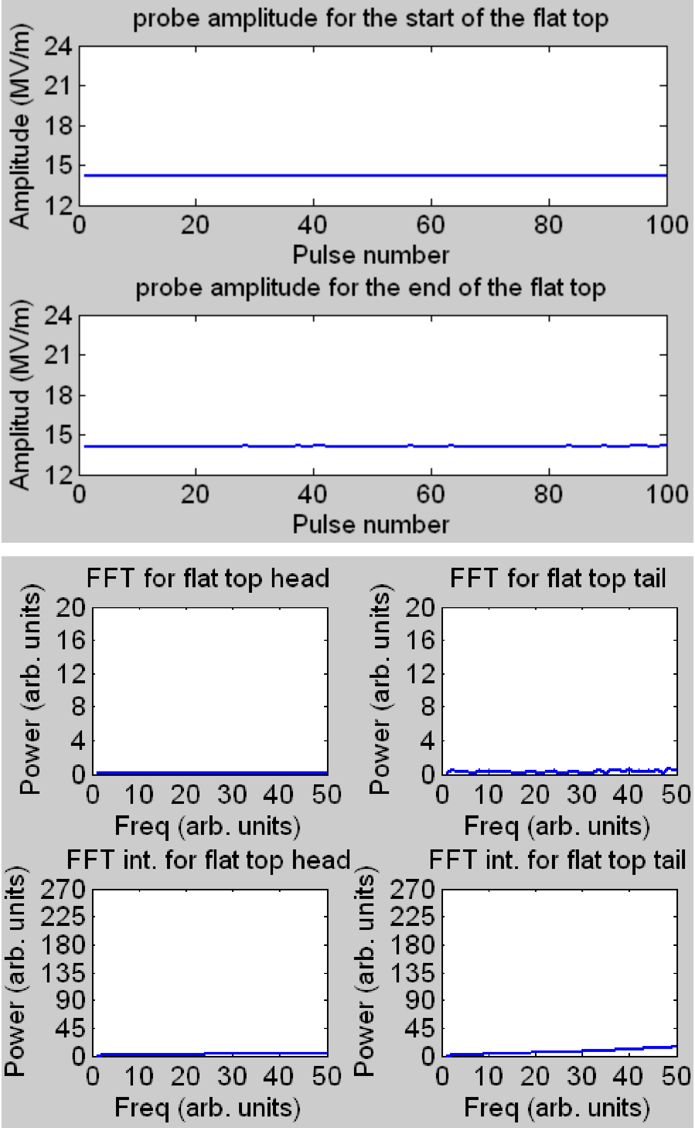

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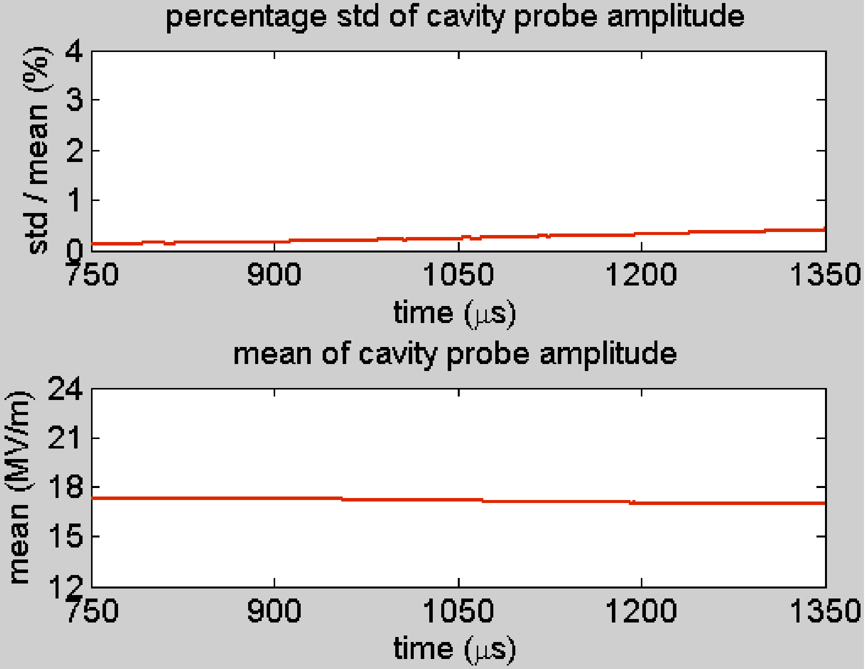
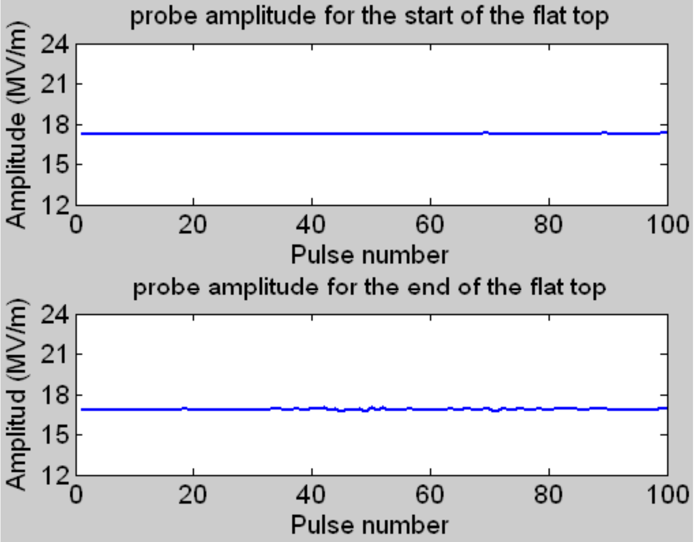
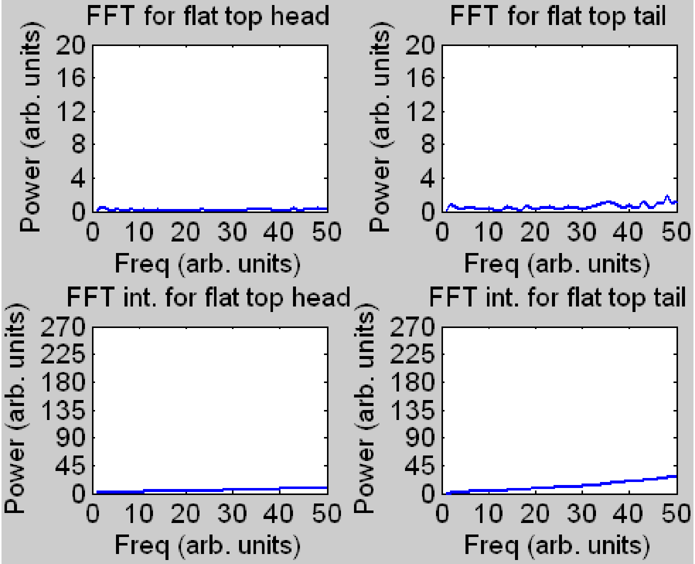
ACC6-CAV7

Here we use sample number 750 indicates start of the flat top, while 1350 indicates the end of the flat top.

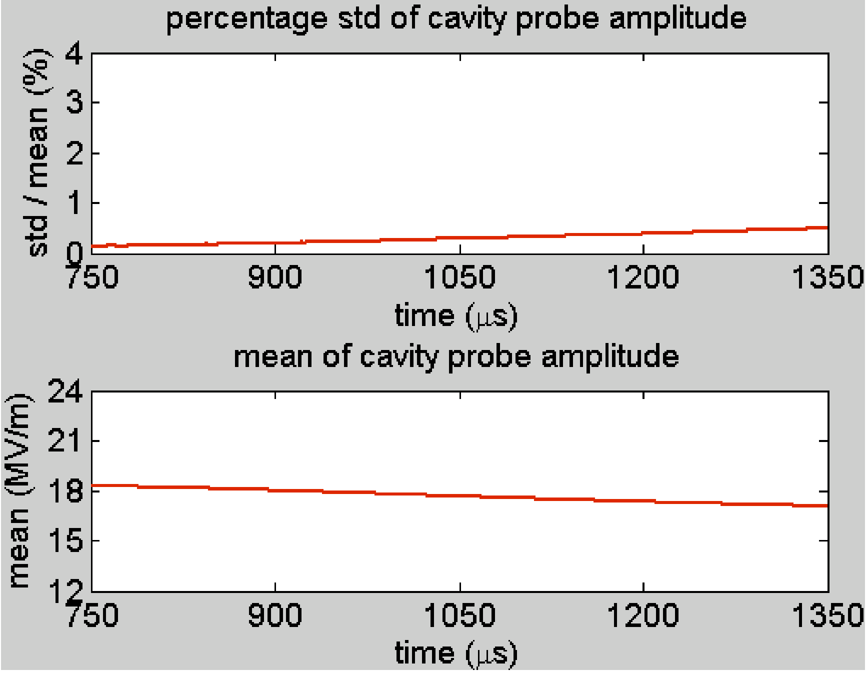


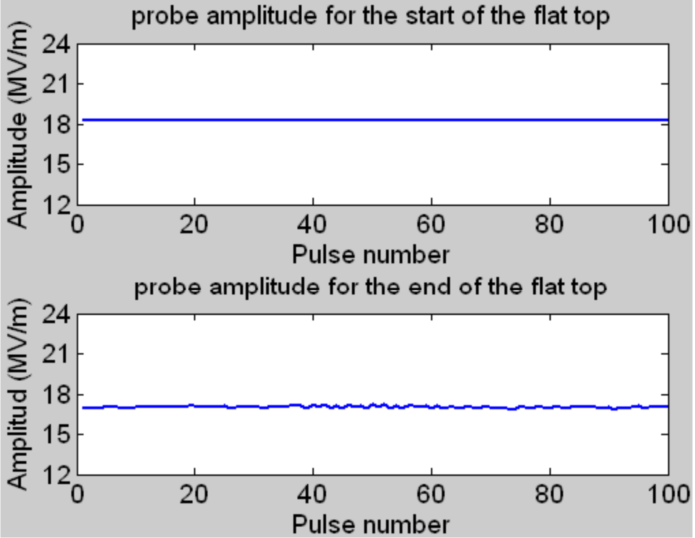


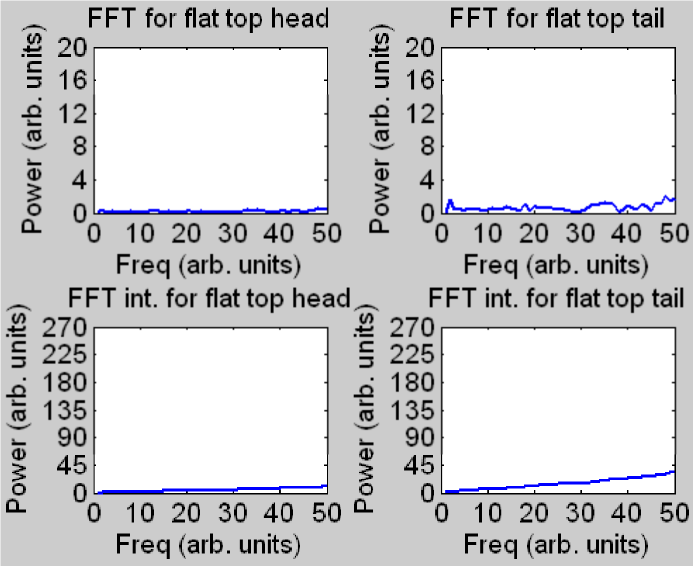


ACC6-CAV8

Here we use sample number 750 indicates start of the flat top, while 1350 indicates the end of the flat top.







Some Conclusions

- From the non-integral power spectrum, we can see there is clearly something going on at 10-15 frequency units (ACC4-2, 3, 6, 8) and at ~40 frequency units (ACC4-5, ACC5-2, 5, 6, 8, ACC6-1). The effect of ~40 frequency units seems bigger than that of ~10-15 units (one particular example is the effect of ~40 frequency units on ACC6-1). However, the contribution of them to the total integral power spectrum is relatively small, only about ~10-30%.
- The enormous signal on the spectrum for ACC6-1 would be consistent with the information that this cavity is unstable (Valeri Ayvazyan).
- Big amplitude deviation usually comes with large gradient tilt along the RF pulse flat top. The deviation of the flat top end is usually bigger than that of the start.