HOM Data Analyses with Curve Fitting Method for TTF/FLASH

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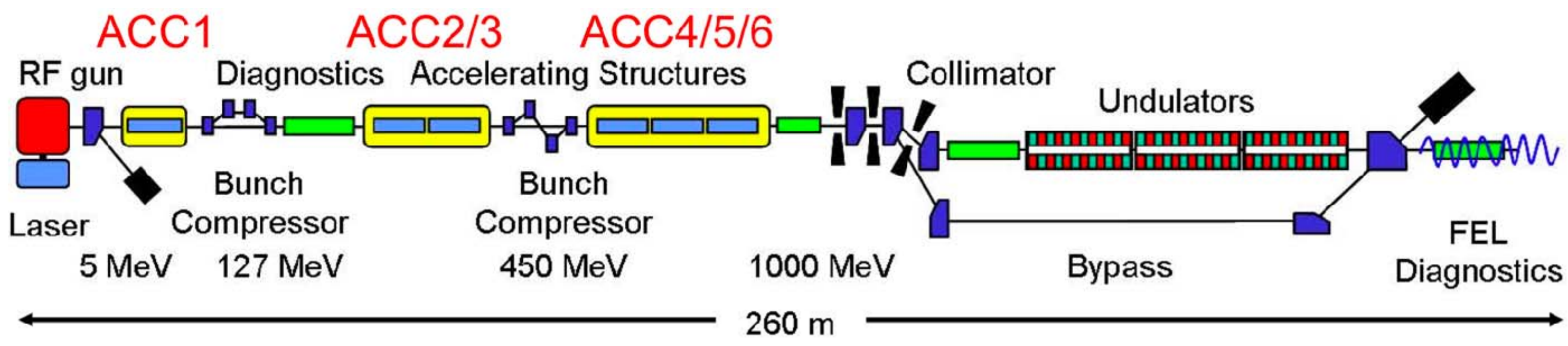
Topics

- FLASH overview & HOM data introduction
- Data acquisition & collection
- Dipole mode response & phase
- Data analyses with CF (Curve Fitting) method
  - FSF (First Step Fitting) for NB (Narrow Band) data
  - FSF for BB (Broad Band) data
  - SSF (Second Step Fitting) for NB data
- Conclusions & future plans

FLASH Overview



- World's only FEL facility for VUV and soft X-ray production.
- RF gun produced e^- bunches accelerated by SC Linac.
- 1nC bunch compressed at intermediate energies (ps→fs)
- Peak current increased from 50-80A to 1-2kA.
- 6 modules containing 8/1.3GHz/1m/9-cell SC cavities.
- ACC4/5/6 similar to an ILC rf unit, focuses for many studies.
- ACC4/5 are the focuses for both HOM meas. & analyses.

HOM Signals & Data Introduction

- Produced by beam passage through SC cavities.
- Collected for both NB (1.69-1.71GHz) & BB (0-6GHz).
- NB TE111-6 (6π/9-like) dipole mode (~1.7GHz) recorded in the 1st 40 cavities with 108MS/s by down-mix electronics.
- BB (monopole, dipole & quadrupole mixed together) only collected in the 1st cavity of ACC4 by scope with 20GS/s.
- Analyses done with SVD (Sigular Value Decomposition), no requirements for mode properties & beam optics.

S. Molloy et al. "High Precision Superconducting Cavity Diagnostics with High Order Mode Measurements", Physical Review Special Topics – Accelerator and Beams 9, 112802 (2006)

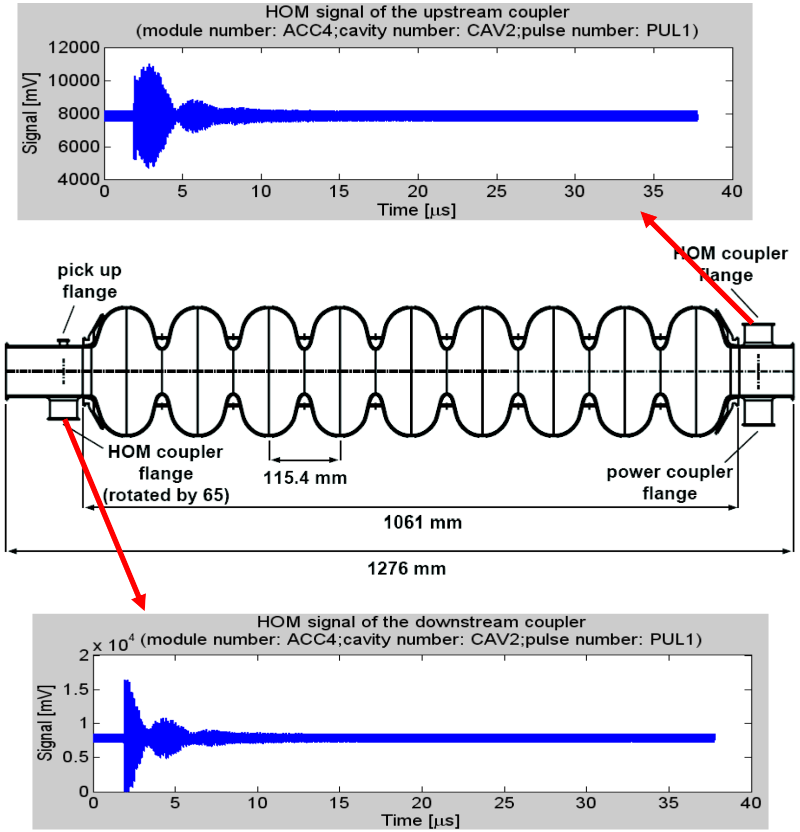
- Here one physical method based on CF will be presented, which determines both mode and cavity's properties.

Analyses Methodology Introduction

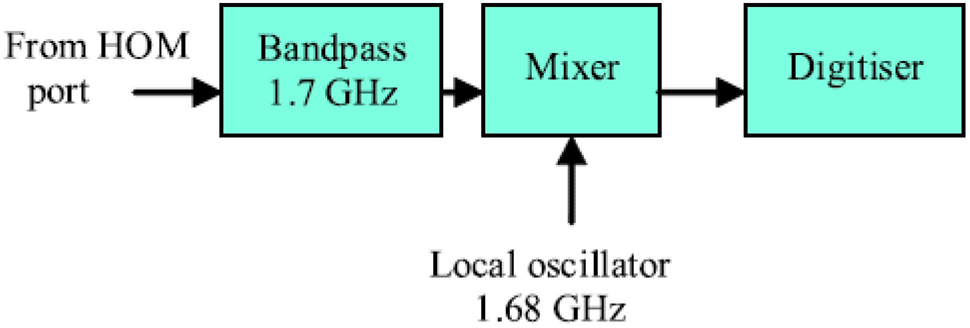
- Two basic steps need to be done.
- FSF (First Step Fitting)
  - Time domain to frequency domain data transformation.
  - Fit signal freq. spectrum to obtain modal information (e.g. *f*, *Q* and modes' phase and amplitude)
- SSF (Second Step Fitting)
  - Use the modes' phase and amplitude together with conventional BPM data to determine the dipole modes' polarization axes, relative centers, cavity tilts, etc.

Data Acquisition & Collection

TE111-6 Mode at Upstream coupler



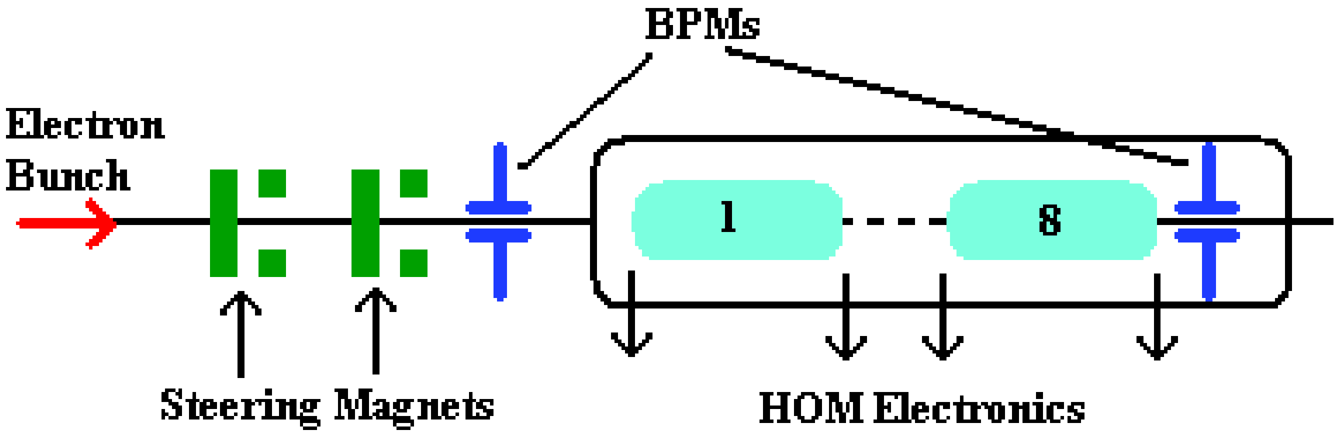
TE111-6 mode at downstream coupler



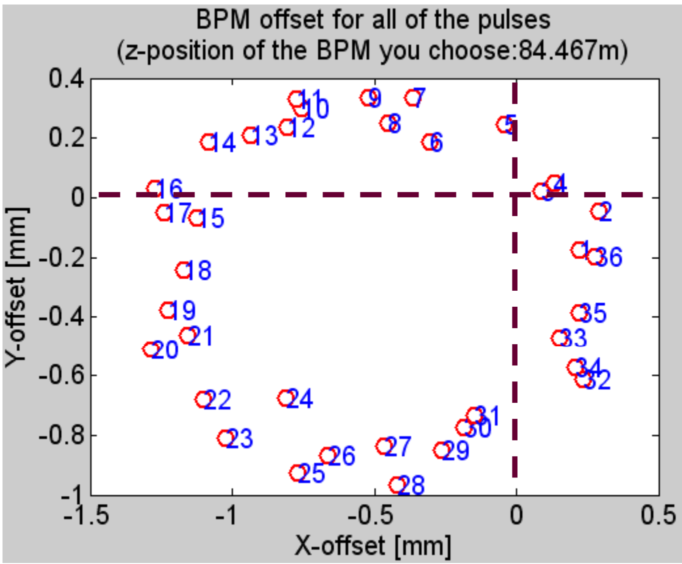
Schematic of the down-mix electronics for meas. of the strong TE111-6 dipole mode

S. Molloy et al. "High Precision Superconducting Cavity Diagnostics with High Order Mode Measurements", Physical Review Special Topics – Accelerator and Beams 9, 112802 (2006)

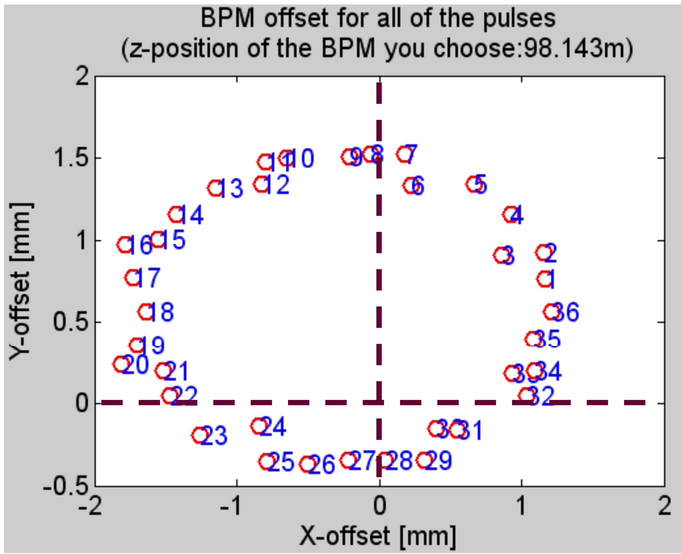
Data Acquisition & Collection



BPM17

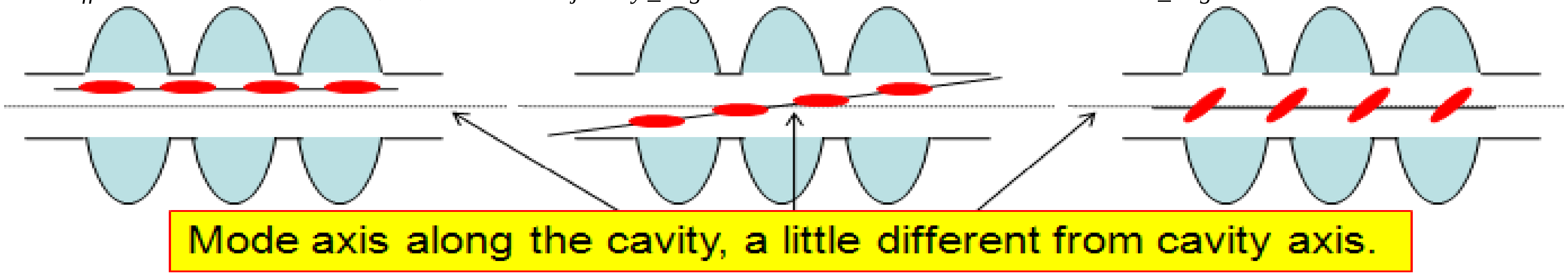


BPM18



Dipole Mode Response

$$V_{offset}(t) \propto x e^{-t/2\tau} \sin(\omega t) \qquad V_{tracjectory\_angle}(t) \propto \theta e^{-t/2\tau} \cos(\omega t) \qquad V_{tilt\_angle}(t) \propto -\alpha e^{-t/2\tau} \cos(\omega t)$$



Three ways to excite dipole modes

- Signal excited by pure offset (in phase or IP) is 90° out-of-phase from that induced by pure trajectory angle and pure bunch tilt (out phase or OP).
- Due to the very short bunch length (~50fs) in ACC4/5/6, the bunch tilt angle contribution can be ignored.

Dipole Mode Response

- The bunch trajectory angle contribution to the dipole mode signal is generally small (verified by simulation).
- Ignore the modes' Qs, dipole signal can be expressed as:

$$
\begin{aligned}
V_{HOM}(t) &= V_{offset}(t) + V_{trajectory\_angle}(t) + V_{tilt\_angle}(t) \\
&\approx V_{offset}(t) + V_{trajectory\_angle}(t) \\
&\approx \sqrt{\left(V_{offset\_amp}\right)^2 + \left(V_{trajectory\_angle\_amp}\right)^2}\cos(\omega_0 t + \varphi)
\end{aligned}
$$

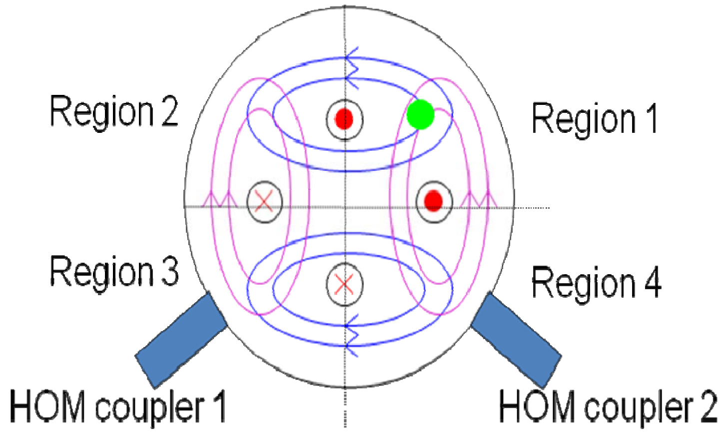
where $\varphi = \tan^{-1}(V_{trajectory\_angle\_amp} / V_{Offset\_amp})$. For more than one mode, we have

$$
V_{HOM}(t) = \sum_{n=1}^{\infty} A_n \cos\left(\omega_{0n} t + \varphi_n\right)
$$

Dipole Mode Phase

- Dipole modes appear in pairs with different polarizations, frequencies of which are nearly degenerate and are further split due to cell asymmetries and fabrication errors.

- For dipole signal excited with constant offset in region 1, phase difference of the two polarized signals will be 0^o at coupler 1 and 180^o at coupler 2 (suppose the two degenerate modes have almost same frequency and the time elapsed after the mode excitation is not long enough).
- If beam trajectory has some angle, the phase difference will deviate from 0^o or 180^o.



Different dipole mode polarizations

Verification by Simulation

- Dipole mode excited by pure angle has ~90^o phase difference from those excited by pure offset. Slight deviation from 90^o is caused by fundamental and high order mode couplers.
- Dipole mode amplitude excited by 1mrad trajectory angle is about 12% of that excited by 1mm pure offset.

Results calculated by Omega3P for dipole modes excitation in ILC TDR cavity

Case #	Y1 / mm	Y2 / mm	Vr / arb. units	Vi/ arb. units	Phase / °	DeltaPhase / °	|V| / arb. units
1	10	10	-0.674	0.164	166.3		0.693
2	-10	10	0.043	0.166	75.5	-90.8	0.171
3	-5	5	0.023	0.081	74.1	-92.2	0.084
4	0	20	-0.634	0.334	152.2	-14.1	0.717
5	V(Case 4) – V(Case 1)		0.040	0.171	76.8	-89.5	0.175

First Step Fitting

- Considering the finite Q of the dipole mode, the HOM signal in time domain can be expressed as,

$$\sum_{n=1}^{\infty} A_n \cos(\omega_{0n} t + \varphi_n) \exp(-\omega_{0n} t / 2Q_n)$$

$$\sum_{n=1}^{\infty} A_n \sin(\omega_{0n} t + \varphi_n) \exp(-\omega_{0n} t / 2Q_n)$$

$$\sum_{n=1}^{\infty} A_n Exp[j(\omega_{0n} t + \varphi_n)] \exp(-\omega_{0n} t / 2Q_n)$$

- The Fourier transform is a complex Lorentzian,

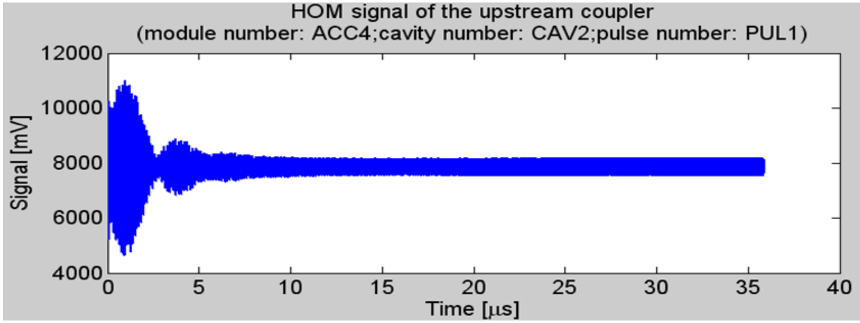
$$\sum_{n=1}^{\infty} A_n \frac{2Q_n(-2jQ_n\omega\cos(\varphi_n) + (-\cos(\varphi_n) + 2Q_n\sin(\varphi_n))\omega_{0n})}{4Q_n^2\omega^2 - \omega_{0n}(4jQ_n\omega + (1+4Q_n^2)\omega_{0n})}$$

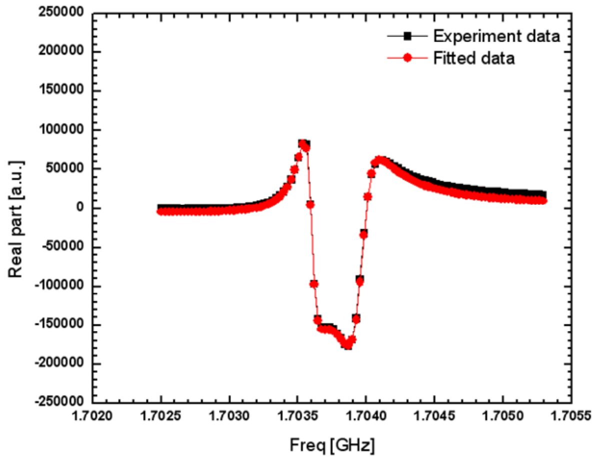
$$\sum_{n=1}^{\infty} A_n \frac{2Q_n(-2jQ_n\omega\sin(\varphi_n) - (2Q_n\cos(\varphi_n) + \sin(\varphi_n))\omega_{0n})}{4Q_n^2\omega^2 - \omega_{0n}(4jQ_n\omega + (1+4Q_n^2)\omega_{0n})}$$

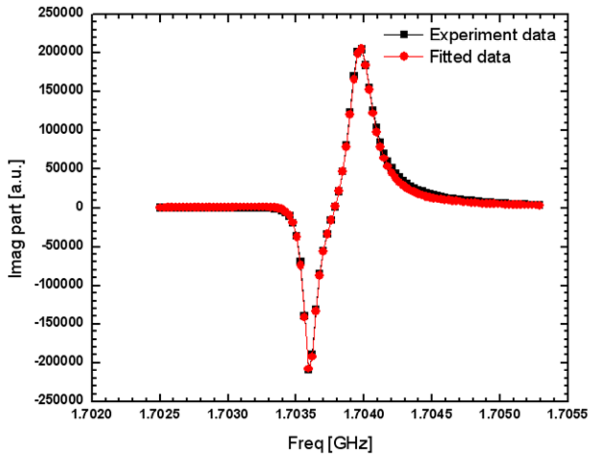
$$\sum_{n=1}^{\infty} A_n \frac{2jExp(j\varphi_n)Q_n}{-2Q_n\omega + (j+2Q_n)\omega_{0n}}$$

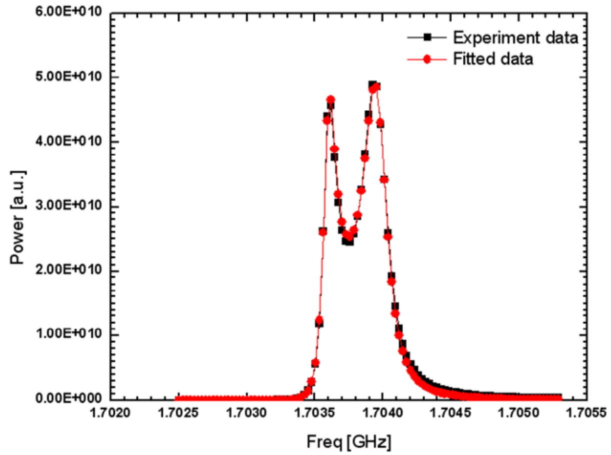
$$\sum_{n=1}^{\infty} \frac{A_n}{\omega - \omega_{0n} + \Gamma j}$$

Frequency Domain Fitting



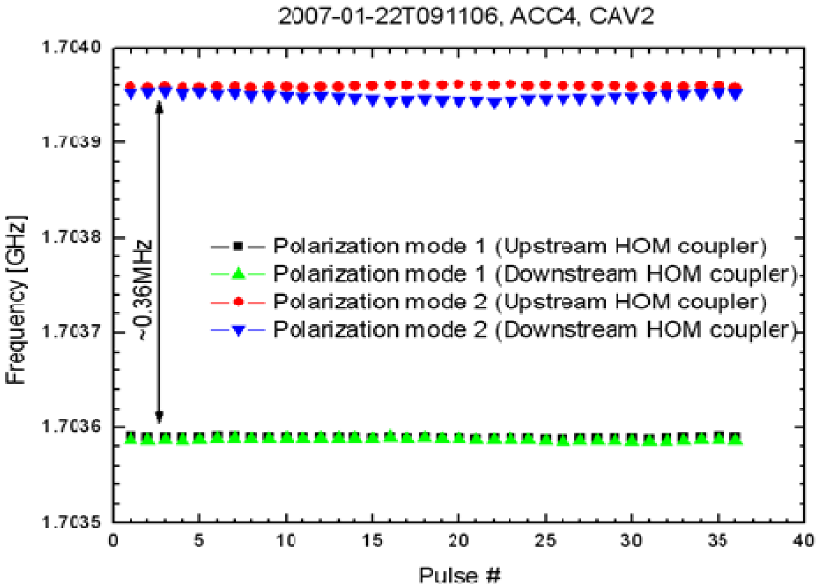


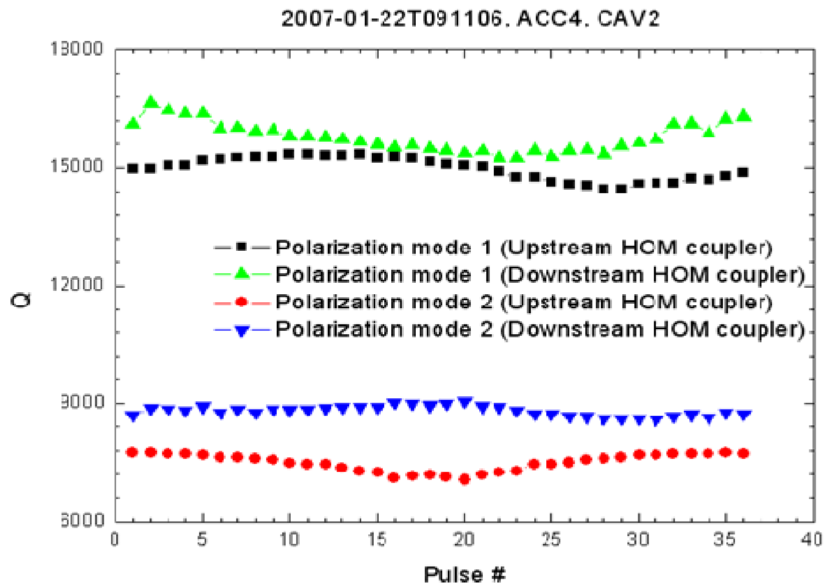




Early part data in time domain was cut off before transformation to frequency domain to eliminate the effect of the direct beam excitation and get one unique solution for each fitting.

First Step Fitting Results for NB Data





Up Mode 1: 1703.5892±0.0009MHz
Down Mode 1: 1703.5873±0.0011MHz
Up Mode 2: 1703.9593±0.0013MHz
Down Mode 2: 1703.9488±0.0032MHz

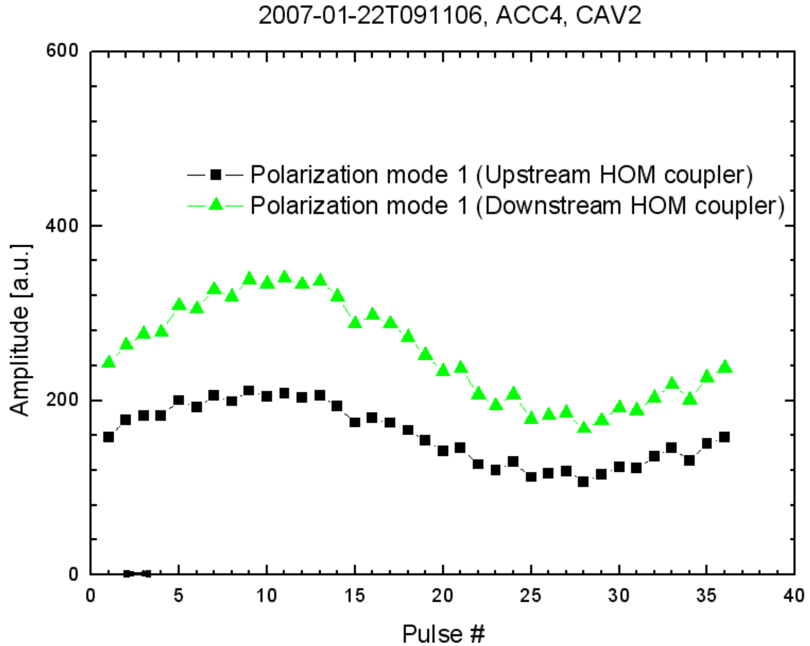
Up Mode 1: 14972±289
Down Mode 1: 15779±381
Up Mode 2: 7502±227
Down Mode 2: 8817±131

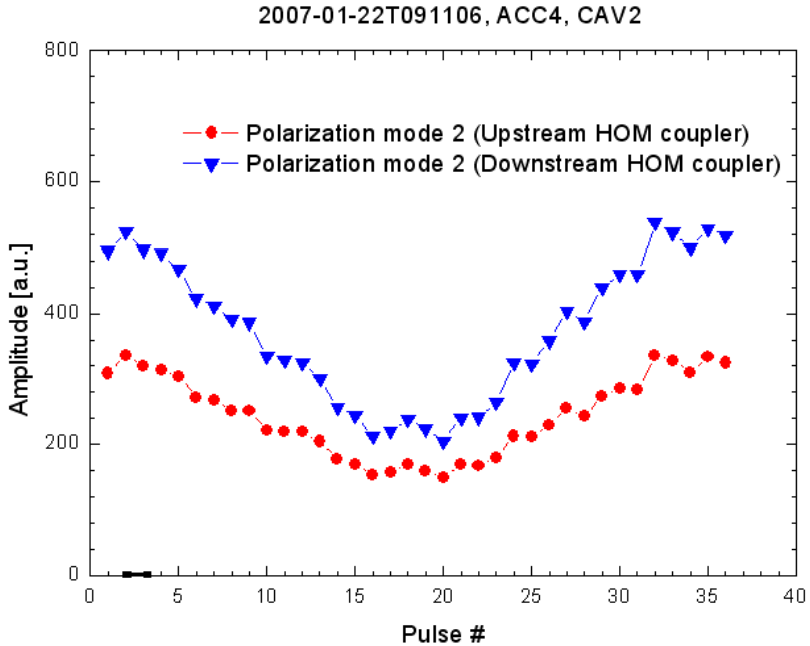
Fitting error of the frequency is about several kHz.

Fitting error of the Q is about several hundred.

First Step Fitting Results for NB Data

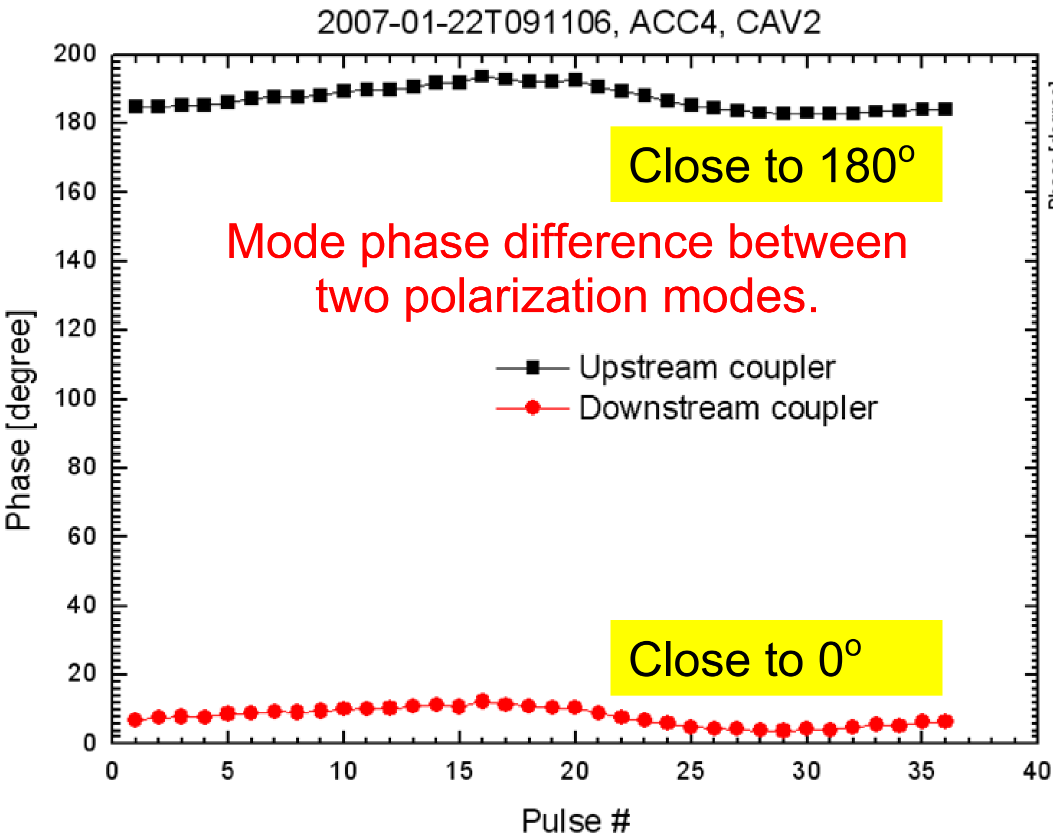
In order to reduce the systematic error, we do the fitting with same dipole frequency and Q, while different initial phase and amplitude for the 36 pulses. So 36×4+2+2=148 parameters need to be fit at the same time.

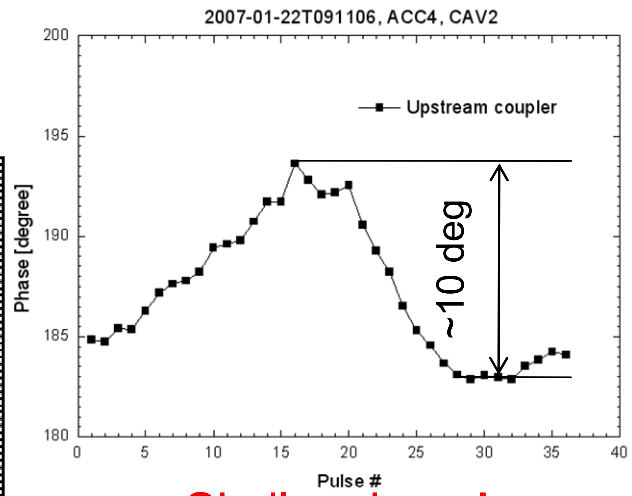




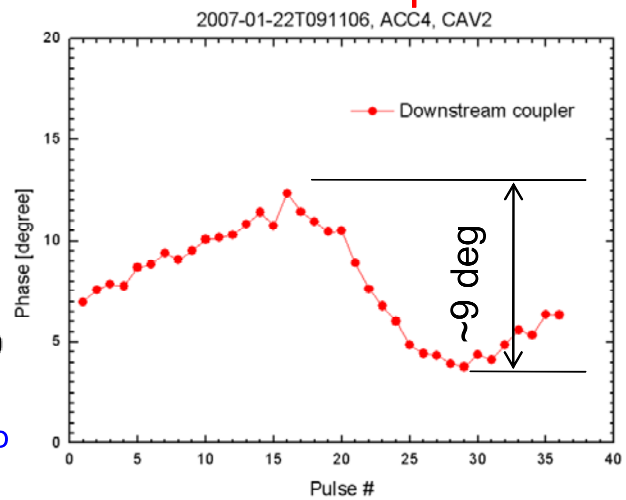
At both upstream and downstream coupler, the amplitude of the two polarization modes have similar shape. The amplitude variation of the polarization mode 1 is sine-like while mode 2 is cosine-like, indicating that the polarizations are about ~90^o apart azimuthally.

First Step Fitting Results for NB Data



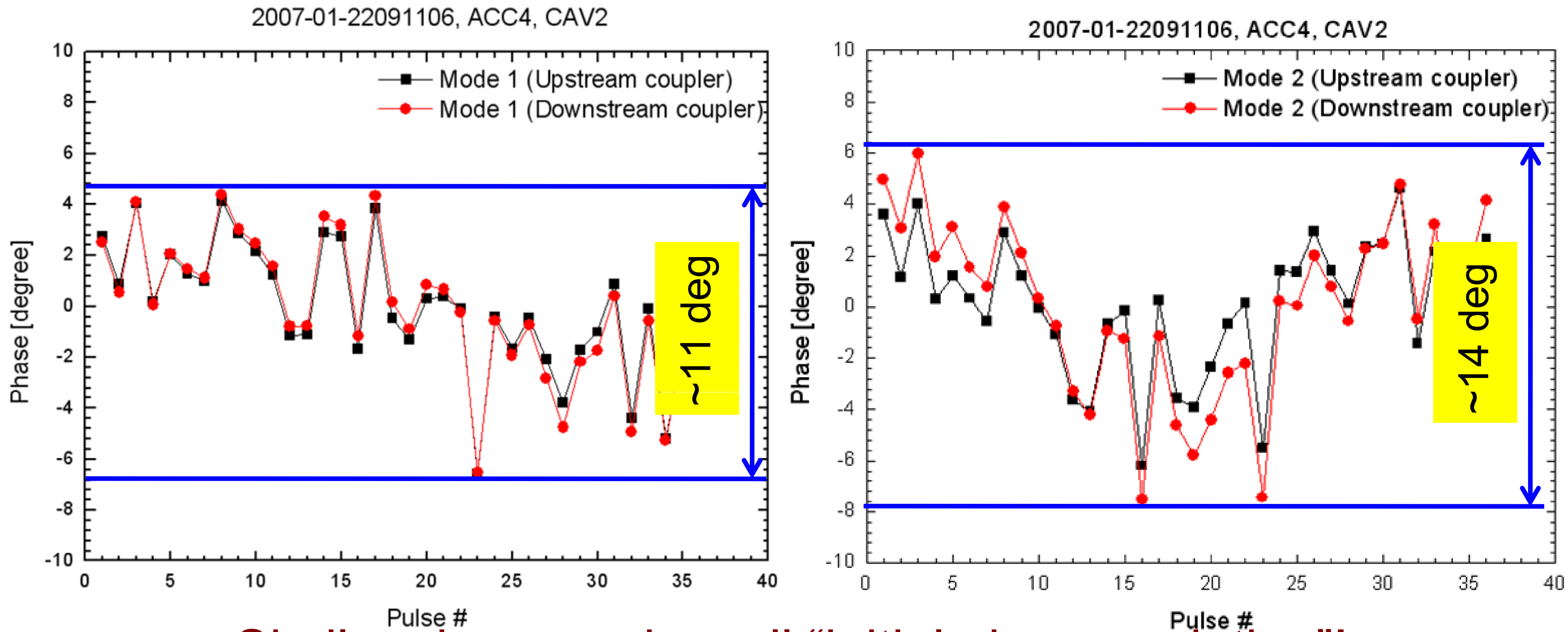


Similar shape!



Consistent with our expectation of ~0° and ~180° for pure offset except for small variations (~10°)!

First Step Fitting Results for NB Data

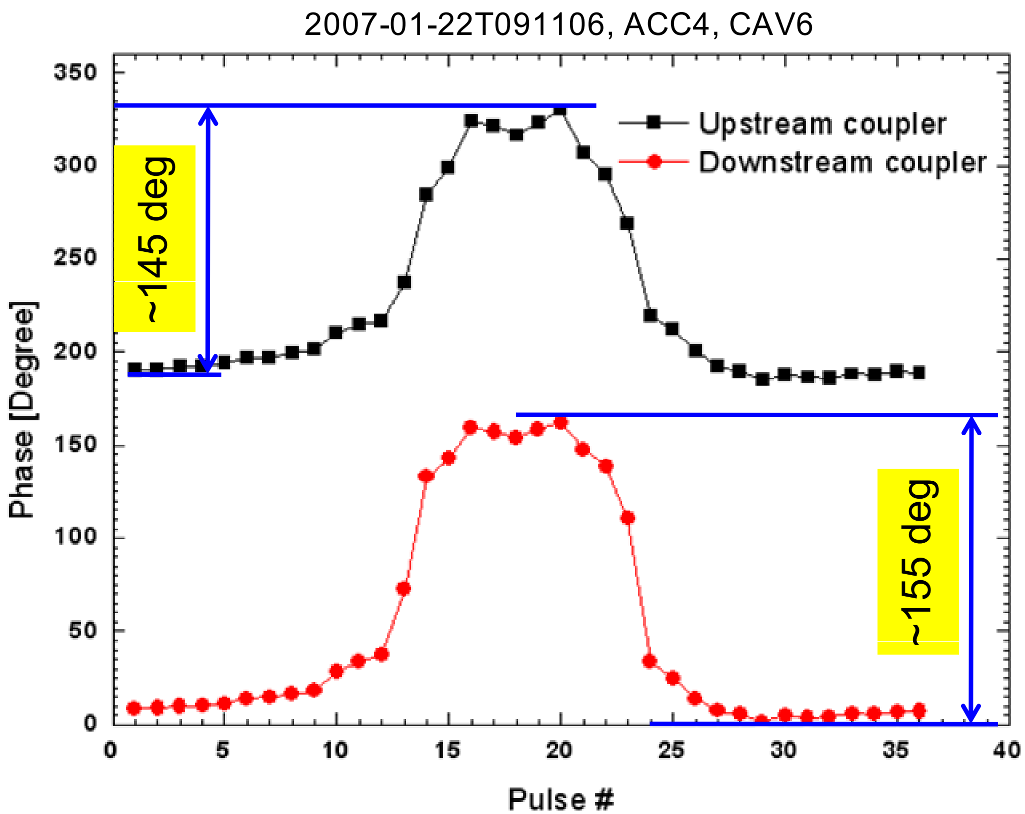


Similar shape and small "initial phase variation"!

Here mainly caused by beam timing variations for both modes.

This is not resulted from down-mix electronics, but caused by beam timing variations (possibly due to beam orbit effects in the two BC before this cavity, which is about 6 -10^{o} at 1.7GHz and can be roughly eliminated by time domain analysis of the raw signal data with 2-2.5^{o} error at 1.7GHz) and beam trajectory angle contribution (should be less than 10^{o} for fairly large offset and much larger than 10^{o} for relatively small offset).

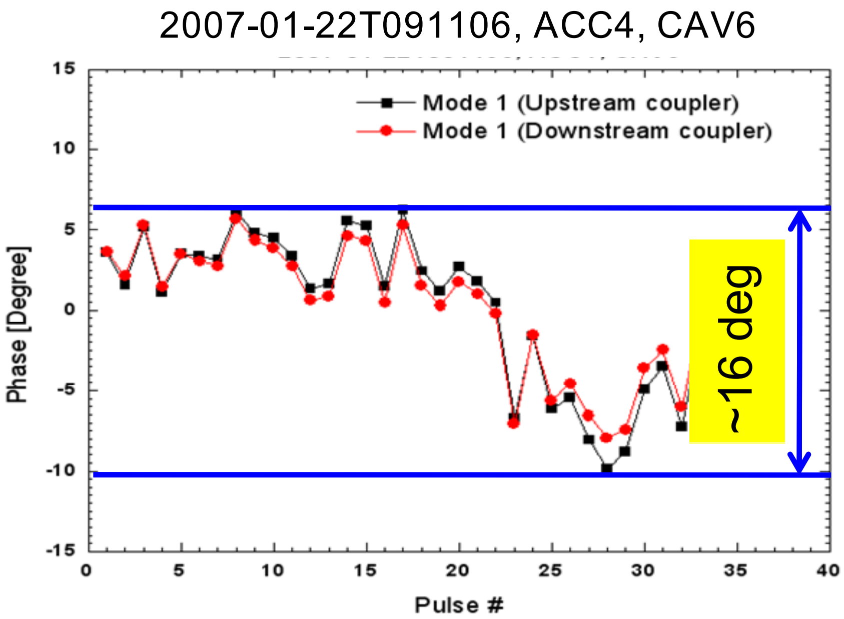
First Step Fitting Results for NB Data

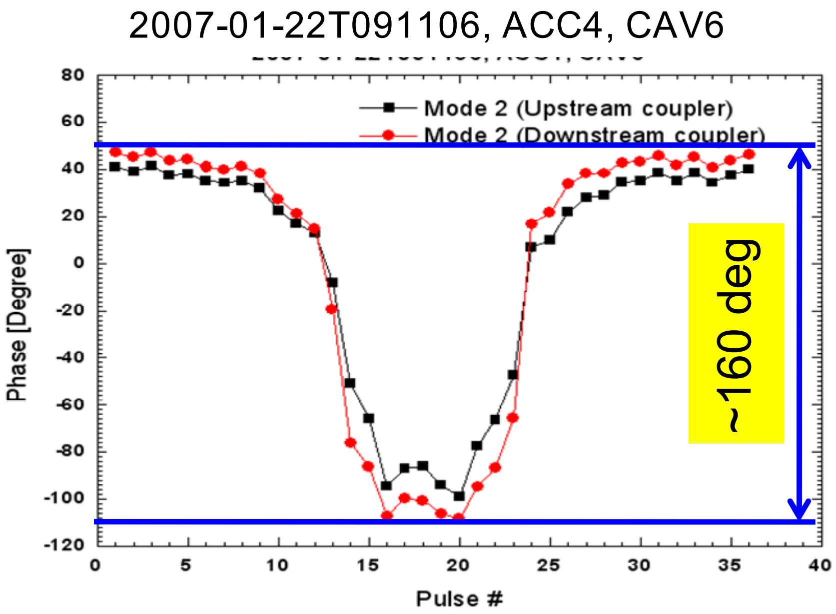


Fairly large phase difference between the two degenerate modes!

For other cavities in this data set, the beam passes closer to the mode center, and the phase variation is relatively large, indicating the existence of a finite OP component relative to the small IP component.

First Step Fitting Results for NB Data



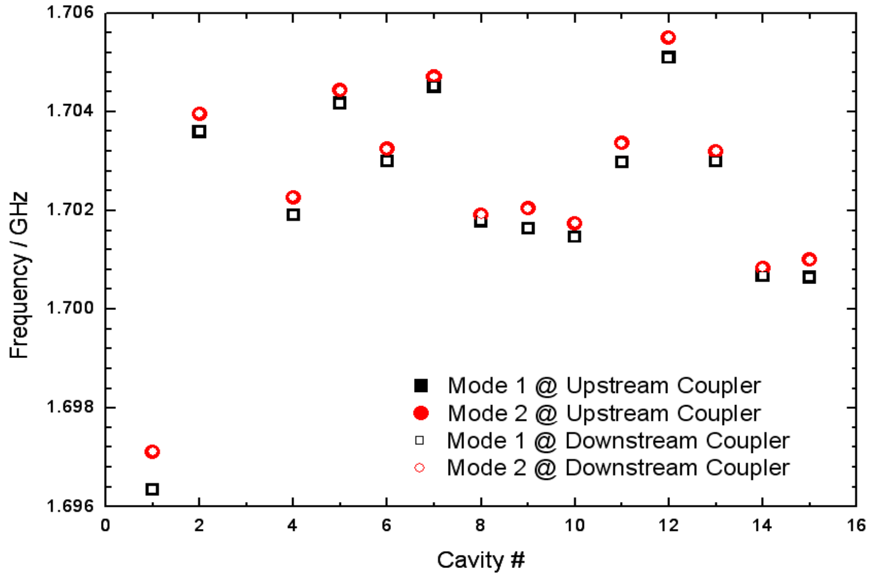


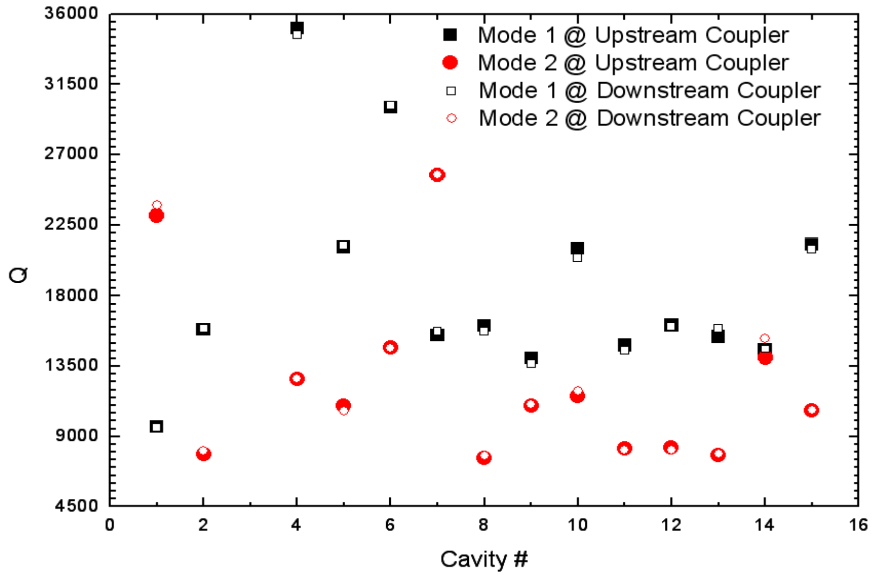
Similar shape and small "initial phase variation"!

Here for mode 1 mainly caused by beam timing variations, for mode 2 mainly caused by beam trajectory angle contribution.

First Step Fitting Results for NB Data

FSF results for cavities in ACC4&5 for dataset 2007-01-22T091106.mat





First Step Fitting Results for BB Data

- BB is consistent with NB in general. Slight difference on frequencies was caused by frequency resolution difference (~0.03MHz for NB and 0.05MHz for BB). Almost same Q's.
- BB data is more irregular than the NB data due to much noise, existence of many spurious modes and absenteeism of calibration tone.

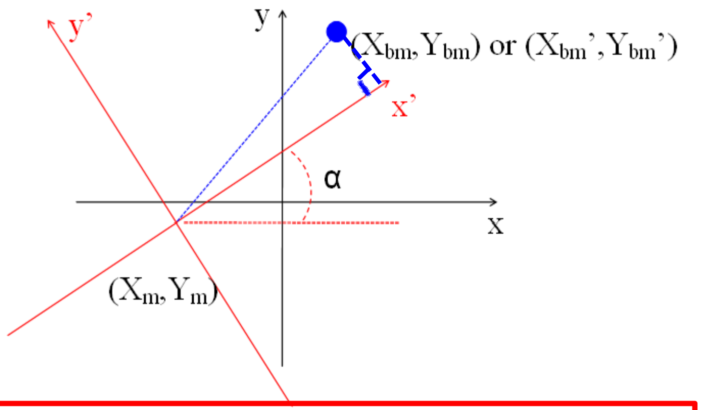
FSF results from both NB and BB for ACC4-CAV1 of dataset 2007-01-22T091106.mat

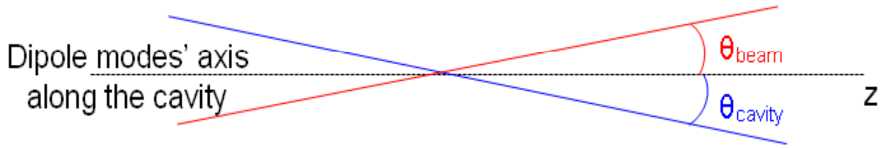
Coupler	Mode	Narrow Band	Broad Band
Upstream	Mode 1 Freq. / MHz	1696.346	1696.335
	Mode 2 Freq. /MHz	1697.107	1697.092
Downstream	Mode 1 Freq. / MHz	1696.345	1696.329
	Mode 2 Freq. / MHz	1697.108	1697.092
Upstream	Mode 1 Q	9672	9672
	Mode 2 Q	22931	22773
Downstream	Mode 1 Q	9620	9602
	Mode 2 Q	22592	21770

Second Step Fitting

- The amplitude (A) and phases (Φ) of dipole modes have been determined by FSF.
- For the SSF, the results from FSF are further analyzed in terms of the BPM readings at the ends of each 8-cavity module. In particular, they are fit to the beam position in the BPM coordinate system at the start, middle and end of a specific cavity, which are obtained through linear interpolation of the BPM readings.
- The beam timing jitter ($\Delta\Phi$) phase corrections can be very roughly obtained by time domain analysis of the raw signal.
- Using this information and the simulated normalized (relative to cal. tone) amplitude ratio ($A_{IP\_norm}/A_{op\_norm}=0.12mm/mrad$) of the IP and OP components, the dipole mode center (crossing point of two polarization axis), polarization angle, cavity tilt angle, IP and OP normalized amplitudes and cavity tilt angle can be obtained.

Second Step Fitting





$$A_{IP} = A\cos\left(\varphi - \varphi_{ref} + \Delta\varphi\right)$$

$$= \begin{cases} A_{IP-norm}\sqrt{\left(X_{bm} - X_m\right)^2 + \left(Y_{bm} - Y_m\right)^2} \times \sin\left(\tan^{-1}\left(\dfrac{Y_{bm} - Y_m}{X_{bm} - X_m}\right) - \alpha\right) & \left(X_{bm} - X_m\right) \geq 0 \\ A_{IP-norm}\sqrt{\left(X_{bm} - X_m\right)^2 + \left(Y_{bm} - Y_m\right)^2} \times \sin\left(\tan^{-1}\left(\dfrac{Y_{bm} - Y_m}{X_{bm} - X_m}\right) + \pi - \alpha\right) & \left(X_{bm} - X_m\right) \leq 0 \end{cases}$$

$$A_{OP} = A\sin\left(\varphi - \varphi_{ref} + \Delta\varphi\right)$$

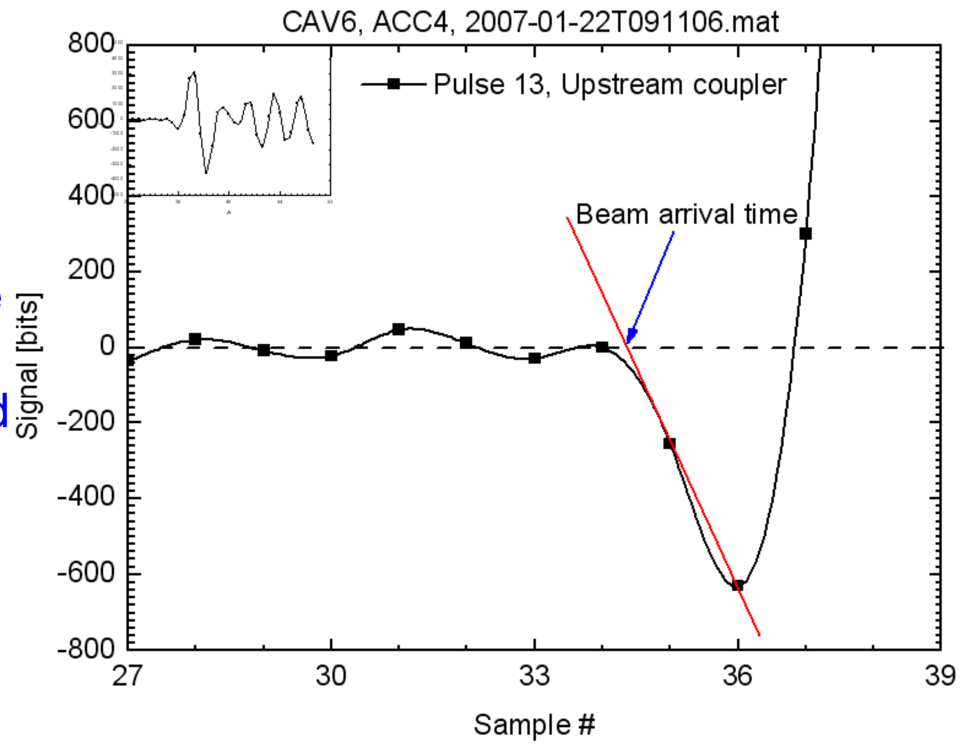
$$= A_{OP-norm}\tan\left(\theta_{beam} - \theta_{cavity}\right) = A_{OP-norm}\tan\left(\tan^{-1}\left(\frac{Y'_{be}}{Y'_{bs}}\right) - \theta_{cavity}\right)$$

$$= A_{OP-norm}\tan\left(\tan^{-1}\left(\frac{(Y_{be} - Y_{bs})\cos\alpha - (X_{be} - X_{bs})\sin\alpha}{L}\right) - \theta_{cavity}\right)$$

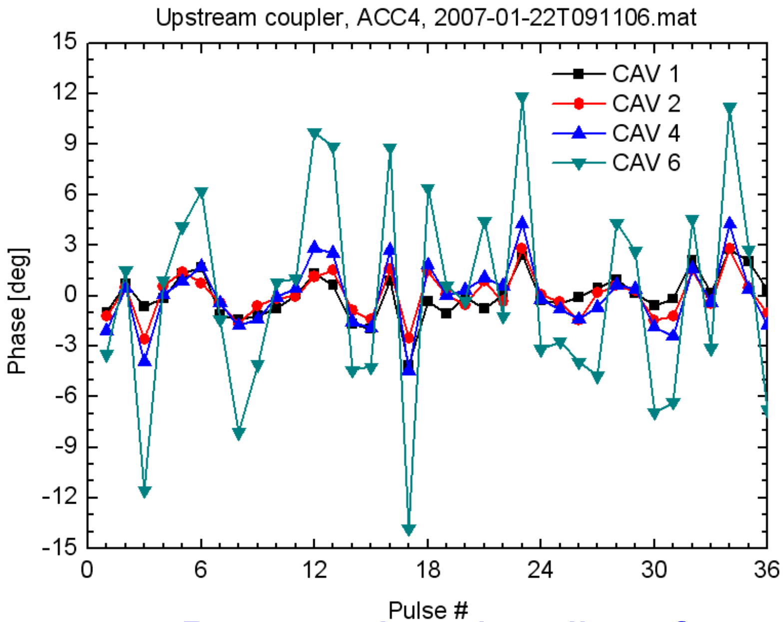
Beam Timing Jitter Determination

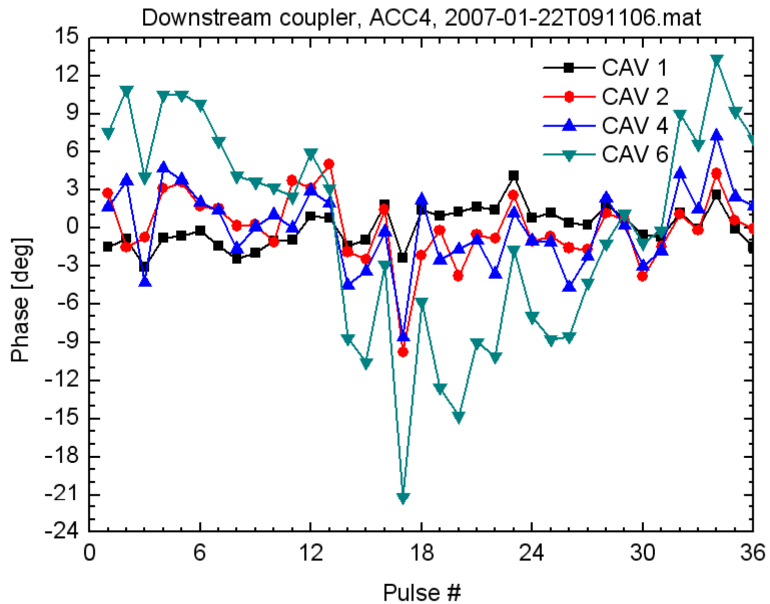
- HOM signal excitation always starts from 0 due to existence of transient state and can be decomposed to IP and OP components, no matter how large the OP component.
- It can be clearly seen that this method is not so precise; the maximum amplitude of noise (e.g., Samples 31 and 33) is about 5%-8% of that for the 1st HOM signal peak (sample 36), which can cause 3-4ps (2-2.5^{o} at 1.7GHz) beam arrival time jitter calculation error.

Linear interpolation example with a large OP component to calculate the beam arrival time roughly (calibration tone has been subtracted based on mode properties obtained from FSF)



Beam Timing Jitter Determination

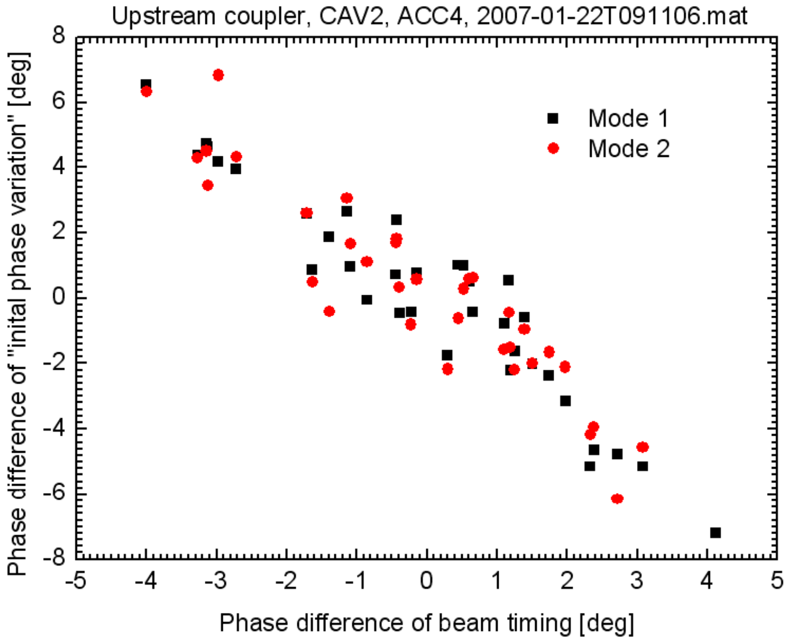


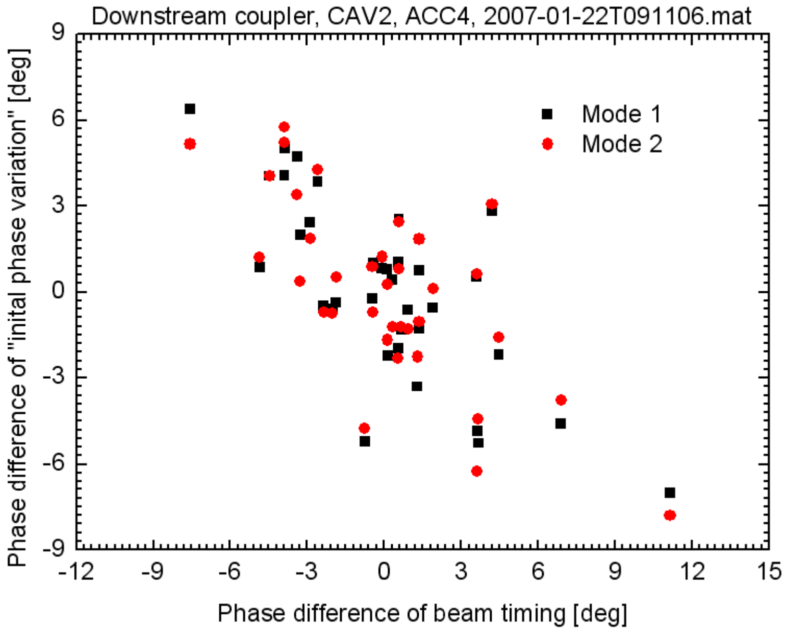


Beam arrival time jitter for some cavities in module ACC4 of dataset 2007-01-22T091106.mat.

- Consistence of 1^{st}, 2^{nd} and 4^{th} cavity in ACC4 suggests 10-16ps (6-10^{o} at 1.7GHz, peak to peak) beam timing jitter resulted from beam orbit effects in BC.
- Large deviation of 6^{th} cavity maybe resulted from large OP component, which increases the error and difficulty to estimate the beam arrival time correctly.
- Data collection for different cavity may not happen simultaneously.

Correlation of Jitter & “Initial Phase Variation”

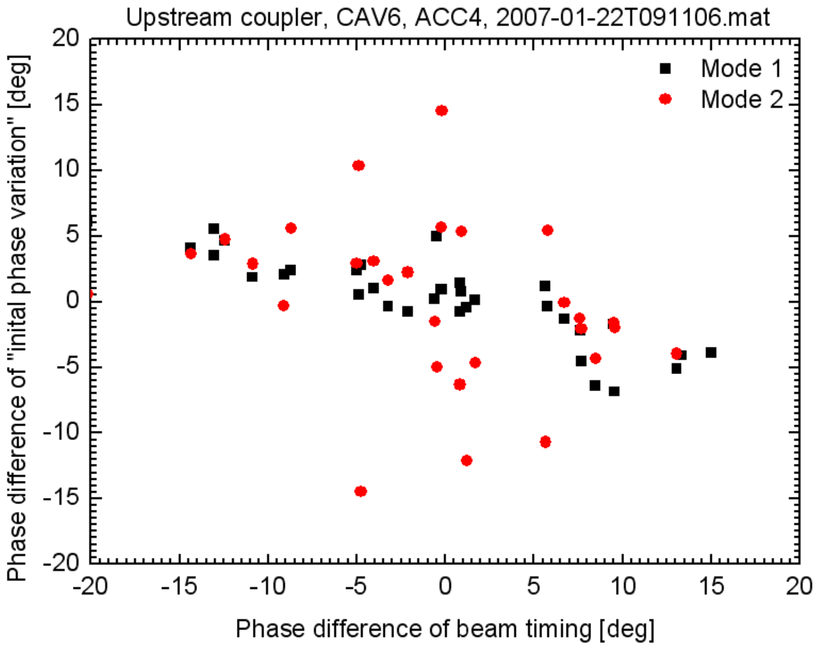


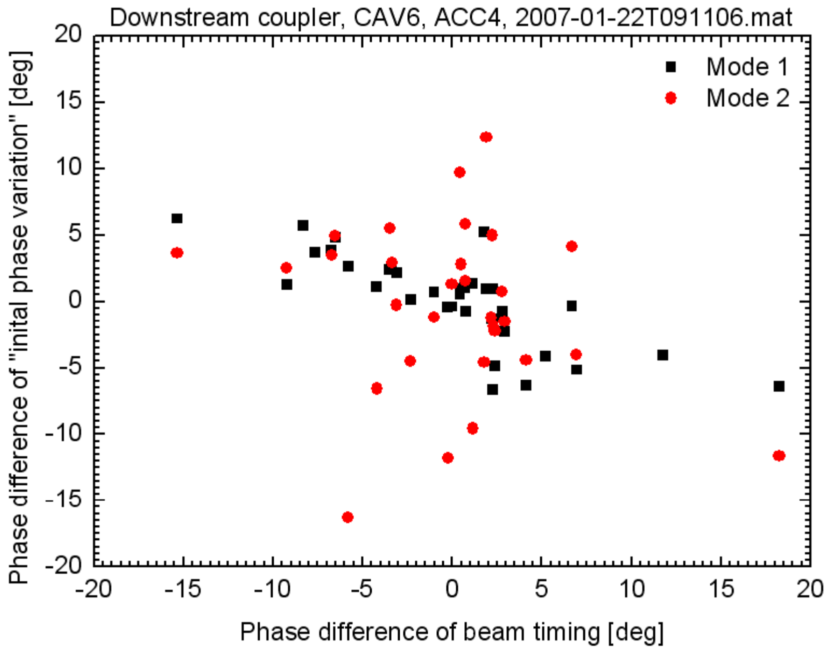


Correlation between the phase difference of the “initial phase variation” for neighboring pulses and that of beam jitter for 2nd cavity in module ACC4 of dataset 2007-01-22T091106.mat

Here clear correlation for both modes indicates that the “initial phase variation” is mainly caused by beam jitter. And the beam timing estimation at upstream coupler is better than that at downstream coupler.

Correlation of Jitter & "Initial Phase Variation"

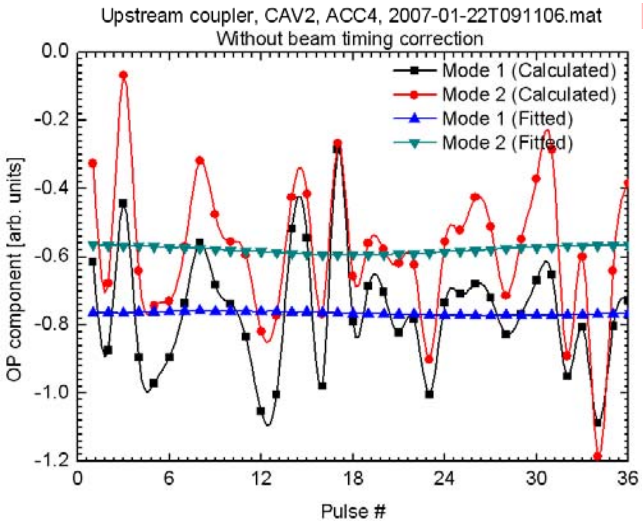


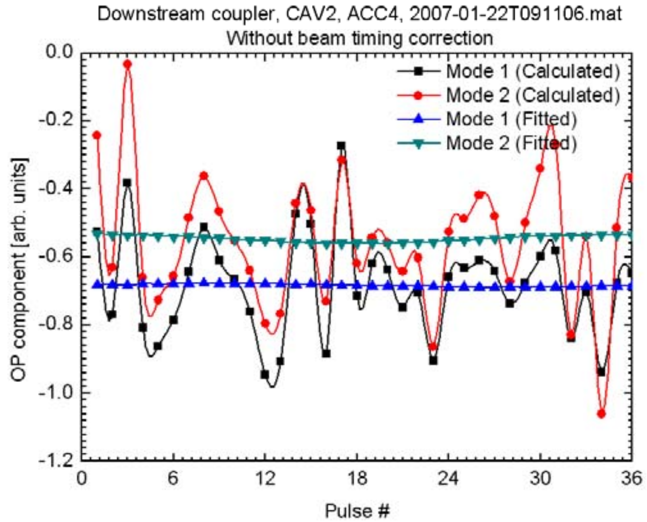


Correlation between the phase difference of the "initial phase variation" for neighboring pulses and that of beam jitter for 6th cavity in module ACC4 of dataset 2007-01-22T091106.mat

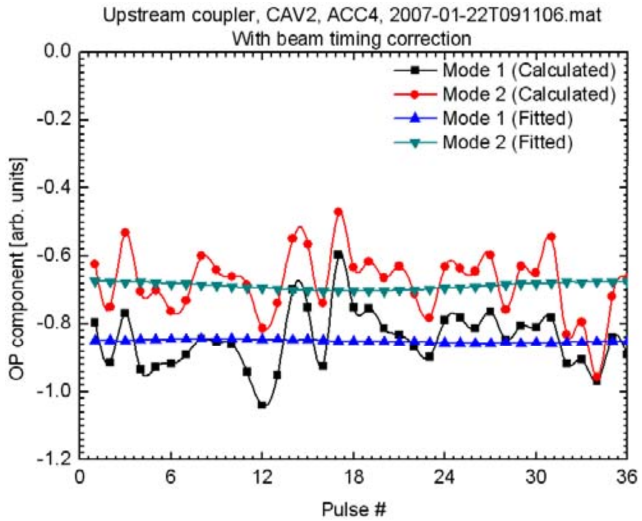
Here clear correlation for mode 1 indicates that the "initial phase variation" is mainly caused by beam jitter, while for mode 2 the OP component plays the main role to the "initial phase variation".

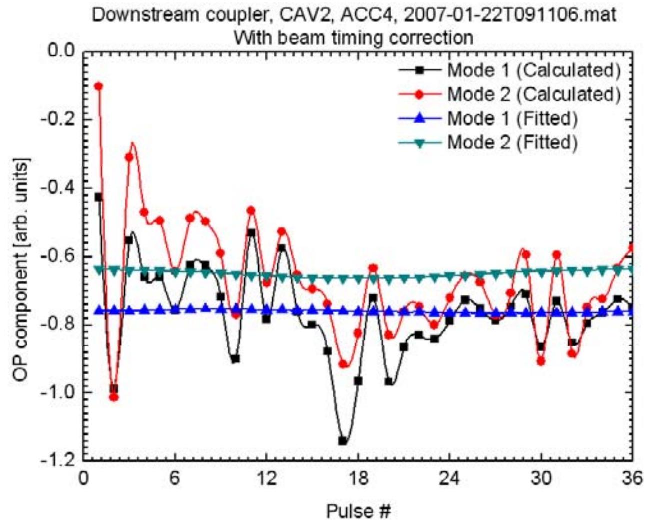
Fitting Results with/without Jitter Correction





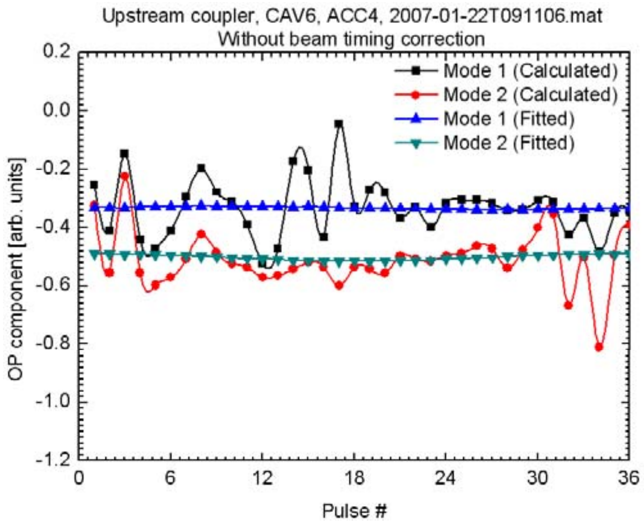
Correct elimination of beam timing jitter can greatly but not fully reduce the residue!

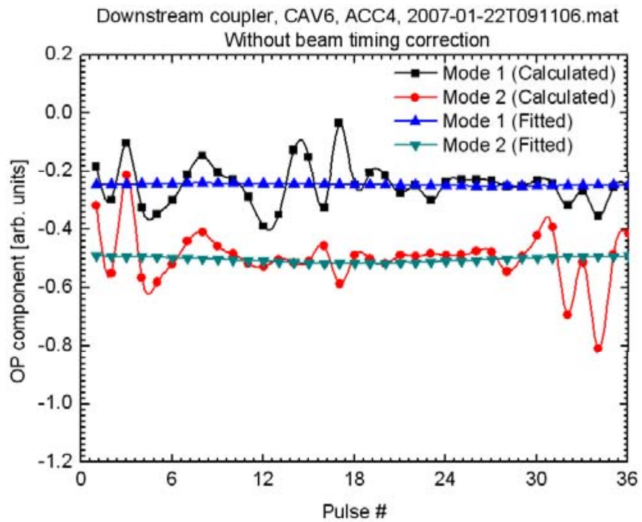




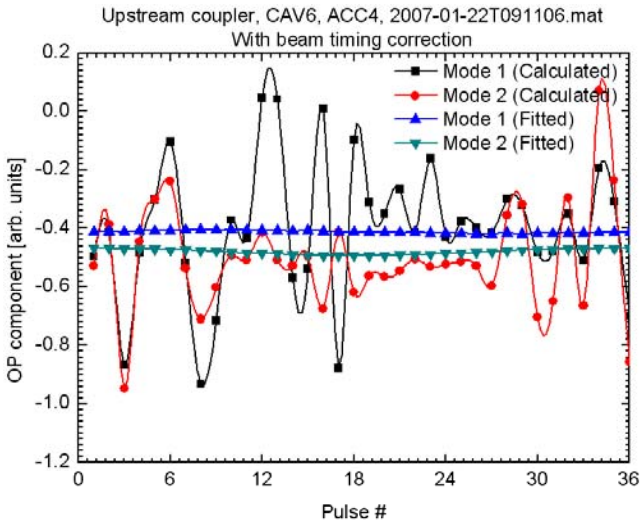
Only OP component fitting is shown, since jitter has small effect on IP component fitting due to the relatively large amplitude!

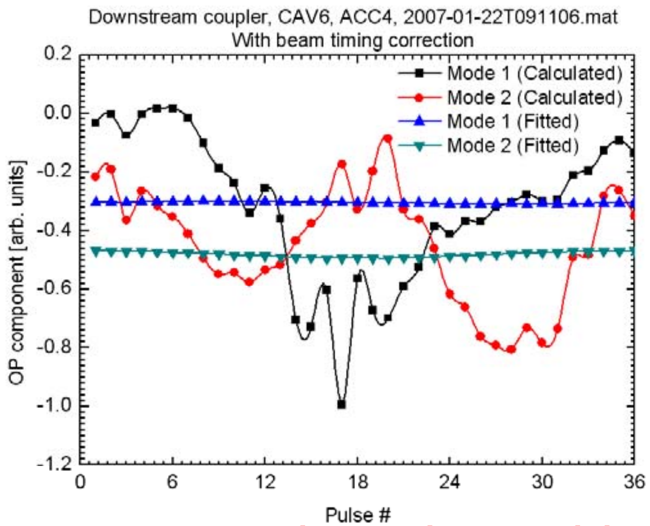
Fitting Results with/without Jitter Correction





Incorrect elimination of beam timing jitter can't reduce but increase the residue!





Beam jitter determination is very important to reduce the residue!

Second Step Fitting Results for NB Data

SSF results for cavities in ACC4 & ACC5 ($A_{OP\text{-}norm}/A_{IP\text{-}norm}$=0.12mm/mrad)

Cavity #	Mode Center [mm]	Mode Pol. [deg]	Cavity tilt [mrad]	Cavity #	Mode Center [mm]	Mode Pol. [deg]	Cavity tilt [mrad]
4-1	(-3.20, -1.09)	(-21.75, 69.51)	(-1.26, 1.28)	5-1	(-0.17, 0.23)	(14.01, 109.71)	(-1.14, -0.66)
4-2	(-2.73, -2.21)	(1.70, 93.32)	(-2.17, 3.08)	5-2	(0.23, -0.40)	(3.59, 94.63)	(-1.32, 0.58)
4-3				5-3	(0.86, -0.13)	(7.09, 99.17)	(-1.69, 0.62)
4-4	(-1.88, -1.59)	(20.90, 111.58)	(-2.03, 1.73)	5-4	(1.38, -0.82)	(5.59, 98.28)	(-1.18, 0.94)
4-5	(-1.34, -1.43)	(1.69, 93.20)	(-3.18, 0.95)	5-5	(0.72, -0.51)	(-5.35, 82.70)	(-1.90, 1.75)
4-6	(-1.09, -0.98)	(3.41, 94.15)	(-2.07, 1.44)	5-6	(0.68, -0.35)	(-54.23, 29.63)	(1.64, -0.29)
4-7	(-0.18, -0.94)	(-15.79, 73.08)	(-1.19, 3.00)	5-7	(0.79, -0.65)	(-1.86, 87.02)	(-0.97, 1.15)
4-8	(-0.12, -0.36)	(-22.61, 68.97)	(-0.24, 2.29)	5-8			

In realistic case, the mode polarization direction is not always horizontal or vertical (existence of x-y coupling, can't be ignored), which will affect the beam dynamics. The mode center is not always (0,0), which need to be considered in the beam dynamics simulation.

Here the cavity tilt can only be a reference due to its dependence on $A_{OP\text{-}norm}/A_{IP\text{-}norm}$, which can be determined by experiments precisely.

Conclusions

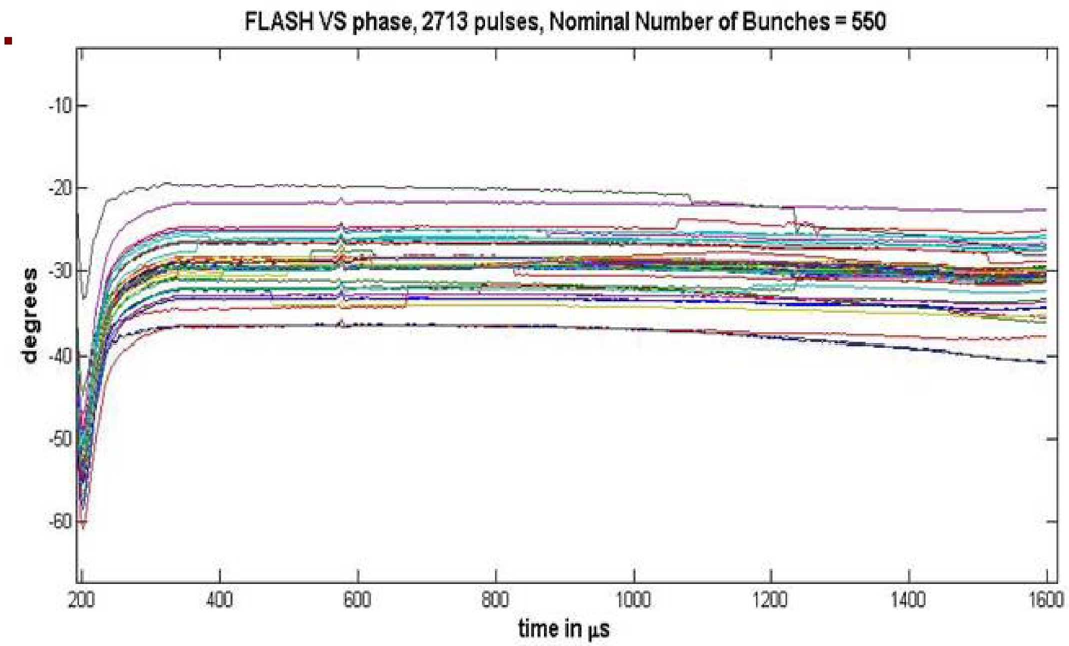
- It has been shown that a frequency domain fitting method can be used to extract dipole mode information, and these results can then be used to determine relative mode polarizations, centers and cavity tilts.
- The accuracy of this method depends on the external BPM system and the down-mix electronics.
- Beam timing jitter of 10-15ps (peak to peak) were found, likely from bunch compressor induced beam orbit effects. This is very important to reduce the fitting results' residue.
- The fitting results from both NB and BB show very good consistence.

Conclusions

- 20^o peak-to-peak phase jitter at 1.3GHz for consecutive 2713 pulses was found in recent TTF/FLASH 9mA operation studies. Although this jitter is fairly larger than the 6-10^o jitter at 1.7GHz we found for consecutive 36 pulses (<<2713 pulses), it is still an evidence for existence of beam timing jitter.

Phase jitter found in TTF/FLASH 9mA studies

G. Cancelo et al., TTF/FLASH 9mA Studies and Results, LCWS/ILC 08, Chicago, USA, 2007.11



Future Plans

- To precisely eliminate the beam jitter effect and get more precise modal information, we can measure one additional monopole mode signal (no OP components exist and can be used to determine the beam jitter). And all of the signals should be collected simultaneously to eliminate any undesired effects.
- Measure $A_{OP\text{-}norm}/A_{IP\text{-}norm}$, which is very important for determination of cavity tilts relative to the dipole modes.

Thanks for your attention!