LONG TERM BEAM PHASE MONITORING BASED ON HOM SIGNALS IN SC CAVITIES AT FLASH.

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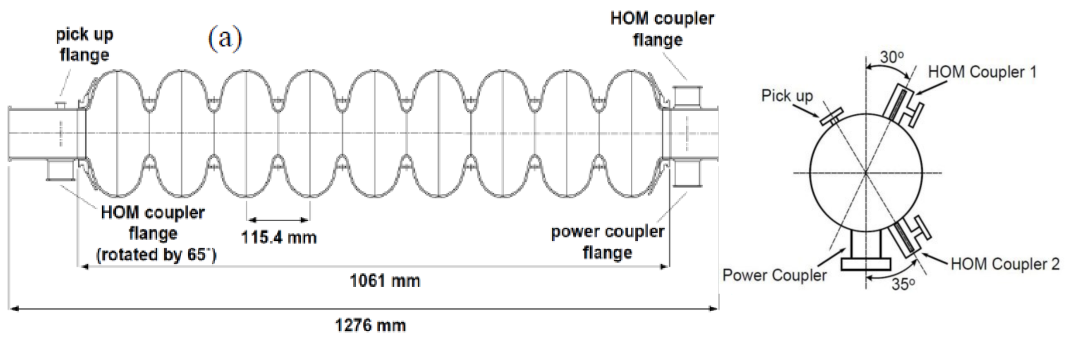
Introduction

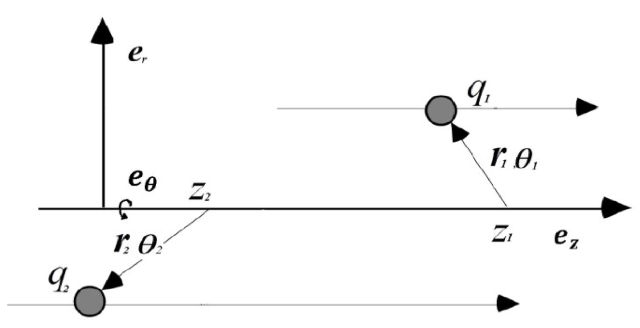
– The accelerating RF fields in superconducting cavities must be controlled precisely in FEL (Free Electron Laser) facilities to avoid beam energy spread and arrival time jitter. Otherwise the beam quality is degraded. The LLRF (Low Level Radio Frequency) system controls the RF field and provides a highly stable RF reference. A new type of beam phase determination technique based on beam-excited HOMs (Higher Order Modes) in cavities has been implemented. The two special couplers installed at both ends of each cavity, pick up the signals containing both the leakage of the accelerating field and the HOM signals. Therefore the signals can be used to calculate the beam phase directly with respect to the RF phase. We analysed the factors which may affect the result of the beam phase on a long-term based on an experimental platform at FLASH. Some phase drifts between the HOM-BPhM (Beam Phase Monitor) and the LLRF system phase measurement were observed and the reason will be further studied.



Section drawing of the TESLA cavity with one power coupler, one pickup probe and two HOM couplers.

HOM-BPhM Principle

— Longitudinal Wake Potential

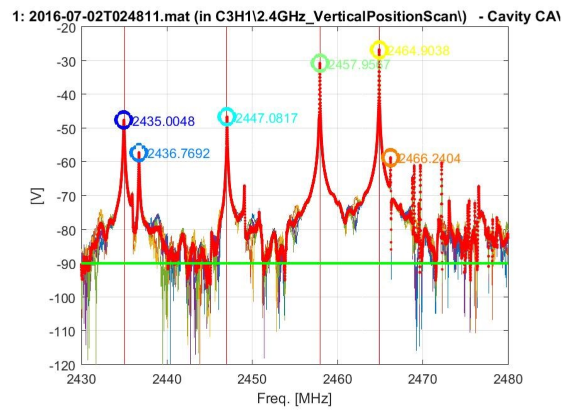


$$W_{\parallel} \cong -\sum_n \omega_{0n} \left(\frac{R}{Q}\right)^{(0n)} \cos\left(\frac{\omega_{0n} s}{c}\right) H(s) \boldsymbol{e}_z,$$

Longitudinal wake potential from Monopole modes:
For small beam offsets, the monopole modes are approximately independent of the beam offset of the leading bunch, and have no azimuthal dependence on the transverse position .

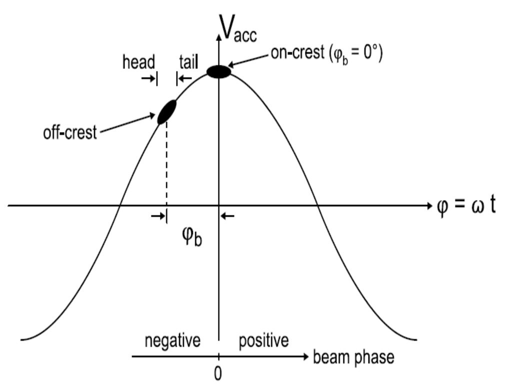
— Monopole Modes

- Including accelerating mode at 1.3GHz (with R/Q =511 Ohms).
- The 2nd monopole mode band TM011 (~ 2.4 GHz) are used to determine the beam phase.



— Beam Phase Concept

- The RF field should reach its maximum when the beam passes through the cavity.
- We define the beam phase according to the time difference between these two instants: when the beam passes the cavity and when the accelerating gradient in the cavity is maximum.
- The point of maximal accelerating voltage is called "on-crest".
- In ACC1, the beam is accelerated about 5 degrees "off-crest" to induce a bunch energy profile to meet the requirement for longitudinal compression in the bunch compressor section

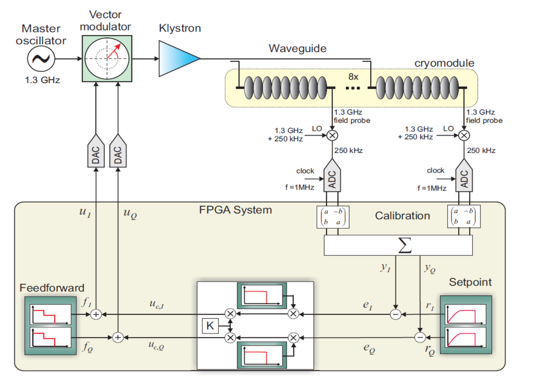


LLRF System

— Brief Introduction

- The Low Level Radio Frequency (LLRF) system is responsible for regulation of the accelerating field in the cavities used for a particle accelerator. This includes the generation of control signals, timing and synchronization, signal acquisition and digital signal processing.
- The LLRF system can be divided into analog and digital sections, as indicated in the figure. The analog part is the part to be controlled, while the digital part includes the controller and the corresponding data acquisition system.

Reference: C. Schmidt, **PhD thesis**, 2010.

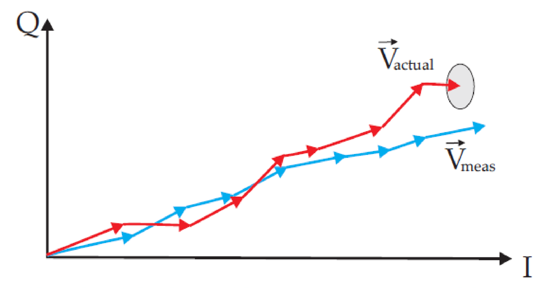


Schematic view of the current LLRF control system.

— Vector-Sum Control

- The accelerating voltage vector of the whole ACC-module is obtained by measuring the field vector of each single cavity and calculating the field vector-sum of all cavities in one module .
- The control system acts onto the vector-sum and keeps it constant, while each single cavity field within the vector-sum can fluctuate.
- The precision of VS control is below 0.01% for amplitude and 0.01° for phase .
- The vector-sum system needs fewer klystrons, and therefore can reduce the cost.
- The disadvantage of the vector-sum is that the single cavities are not individually controlled. The actual situation in each cavity is underdetermined.

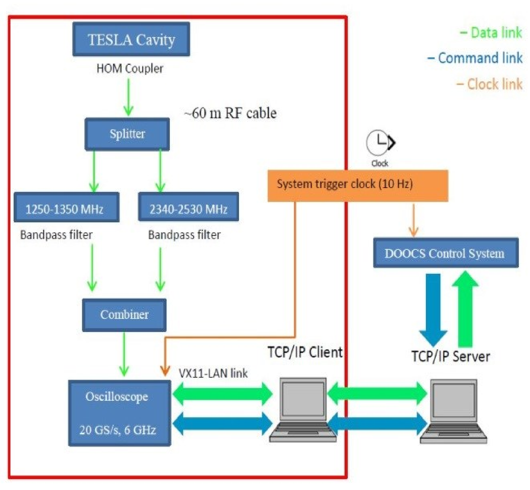
Reference: T. Schilcher, **PhD thesis**, 2007



Sketch of the basic idea of vector sum calibration with measurement and estimation errors.

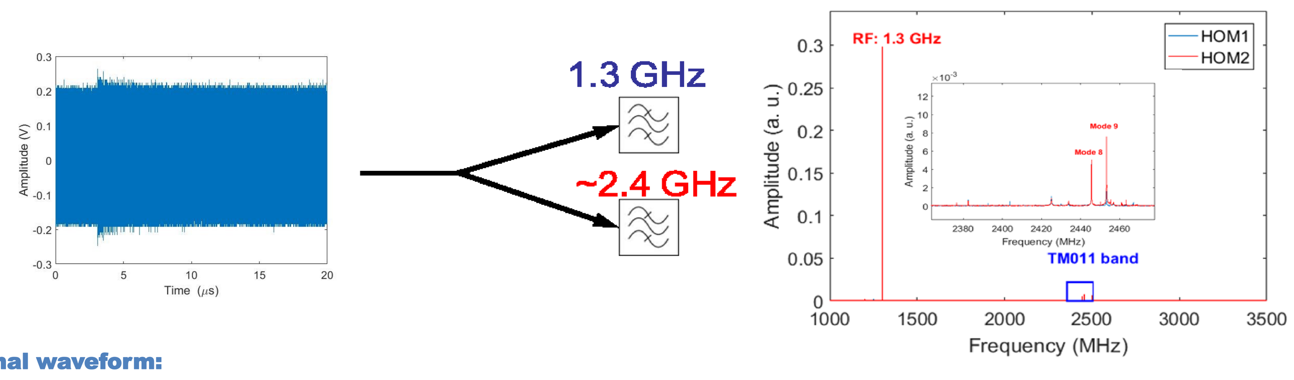
Beam Phase Measurement

— Measurement Setup



- The two HOM couplers on each cavity deliver the signal for the two channels used for beam phase measurement.
- The setup consists of two kinds of RF bandpass filters (one centered at approximately 1300 MHz with 100 MHz bandwidth and the other approximately 2435 MHz with 190 MHz bandwidth), combiner/splitter (5-2500 MHz), and a fast scope (Tektronix TDS6604B, 20 GS/s with 6 GHz bandwidth).
- One PC serves as a TCP/IP client and a second one as a server for collecting data from the control system.

— HOM Signal Processing



Signal waveform:

$$x(t) = a_0 + \sum_{n=1}^{N} (a_n \cos(\omega_n t) + b_n \sin(\omega_n t))$$

Fourier coefficients:

$$a_n = \frac{2}{T}\int_0^T x(t)\cos(\omega_n t)dt$$

$$b_n = \frac{2}{T}\int_0^T x(t)\sin(\omega_n t)dt$$

Mode amplitude and phase:

$$A_n = \sqrt{a_n^2 + b_n^2};\varphi_n = \arctan 2(a_n, b_n)$$

Beam phase:

$$\varphi_{beam} = \varphi_0 - \omega_0 \cdot \sum_n \frac{W_n \varphi_n}{\omega_n}$$

- The signal contains the RF leakage, the beam excited mode at 1.3 GHz and the beam excited TM011 mode.
- The SNR from the scope is about 10 dB.
- Mode 8 and mode 9 in TM011 band are excited strongly due to high R/Q (75 Ohms).

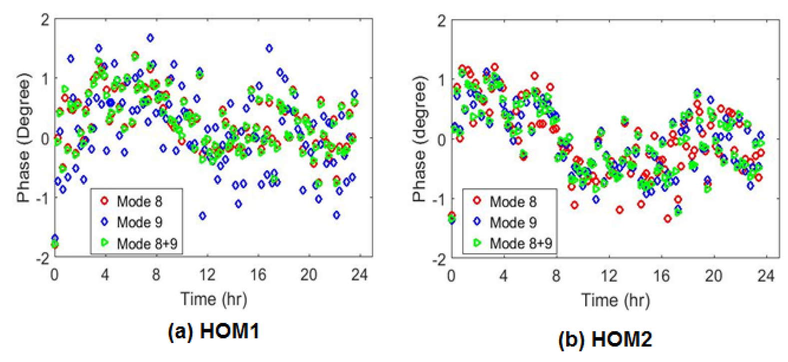
- The signal can be decomposed into a Fourier series of simple oscillating functions.
- φ_0 and ω_0 are the phase and angle frequency of the accelerating RF at 1.3 GHz, w_n is the weight factor of mode n according to its power.

Summary

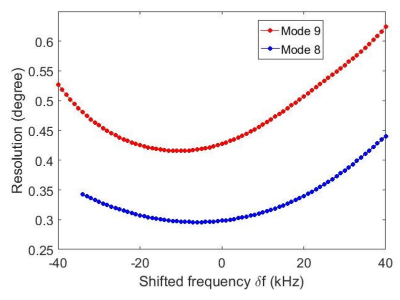
- The HOM-BPhM system gives good result for long term beam phase measurements. The noise level limits its performance.
- The HOM and the probe phase are comparable
- The RMS error of the beam phase difference between HOM1 and HOM2 observed is 0.41° .
- An electronics based on direct sampling, now under development, is expected to improve the resolution.

HOM-BPhM Results

— Measured Signal Analysis

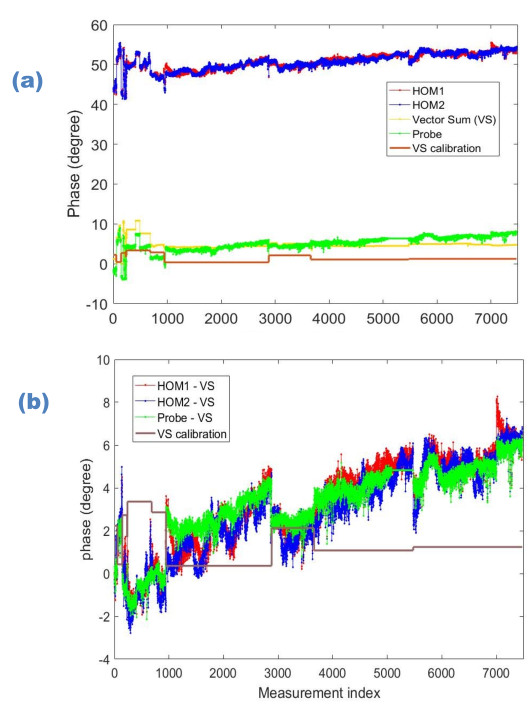


- Beam phase measurement by using mode 8 (red), mode 9 (blue) and both modes (green) from HOM (a) and HOM2 (b).
- The beam phase resolution, based on the two HOMs signals, is 0.298° for mode 8, 0.427° for mode 9 and 0.271° when using both.



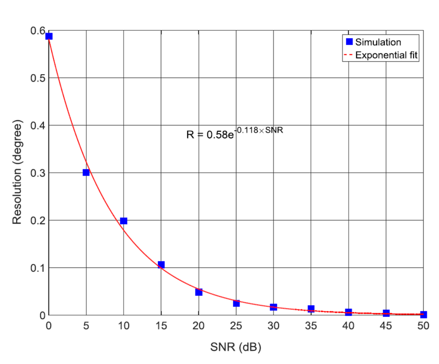
- Resolution dependence on the frequency shift of modes 8 and 9 with a step of 1 kHz. The centre frequency measured by a Real-time Spectrum Analyser (RSA) is 2.445481 GHz for mode 8 and 2.455319 GHz for mode 9.
- The minimum point corresponds to the mode frequency.

— Long-term Beam Phase Measurements

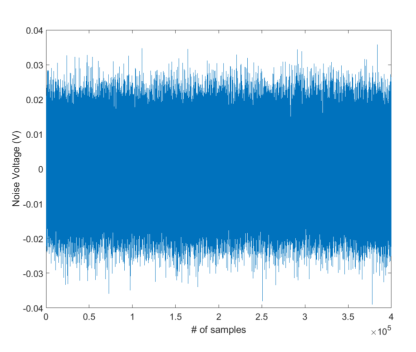


- (a) Long term phase measurement at FLASH. (b) Phase differences of the HOM phases and probe phase with respect to the VS phase.
- The HOM1 and HOM2 phases were measured in cavity 1 of ACC1 at FLASH with the HOM-BPhM system. The VS phase, probe phase and VS calibration phase were recorded from the control system.
- The HOM and probe phases initially have a similar evolution as the VS phase, but they drift away over time.
- The VS calibration affects the probe phase and beam phase.
- The HOM phase and probe phase are comparable.
- The RMS of the phase difference between HOM1 and HOM2 is 0.41°.

— Noise Analysis



Resolution dependence on the SNR and exponential decay fitting.



Noise waveform reconstructed by SVD method.

- The resolution of the HOM-BPhM system is highly dependent on the noise level according to a simulation study*.
- The simulation is based on a beam driven circuit model simulation.
- The noise can be estimated from the signal waveform by using SVD method.
- For 10 dB SNR, the expected resolution is 0.2°
- The measurement resolution is consistent with the simulation result.

*Reference: L. Shi, **Ph. D thesis**, 2015

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