Automatic phase calibration for RF cavities using beam-loading signals

Jonathan Edelen

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  - Phase drift from the RFQ
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- Recalibration requires machine studies which reduces up-time
- Develop a scheme that uses beam-loading signals in the cavities to determine the synchronous phase of the beam parasitically to machine operation

Automatic calibration scheme

- Turn off feed-forward beam loading compensation and measure the beam loading transient
- Calculate the beam phase relative to the RF
- Adjust the cavity phase calibration accordingly
  - Note that this is for individually controlled cavities

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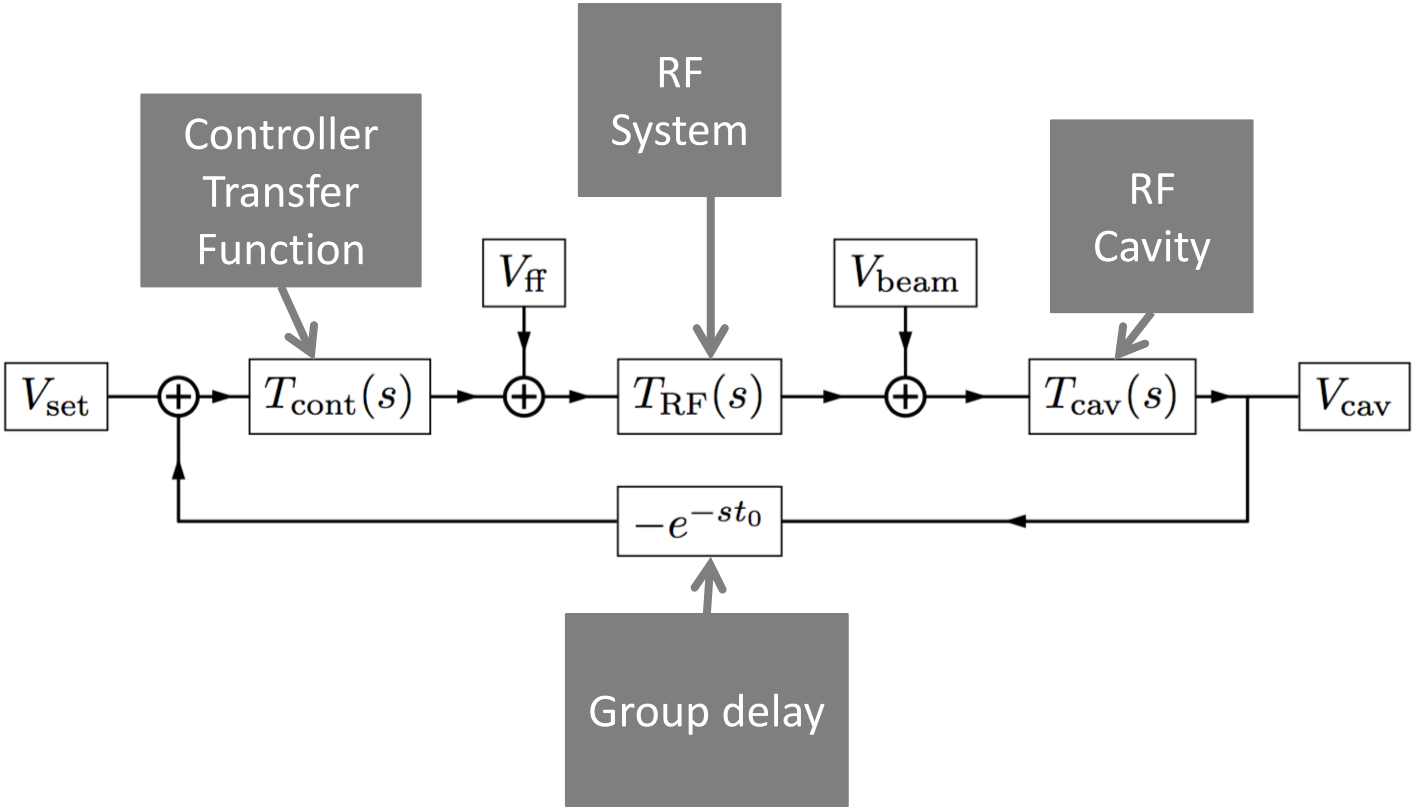
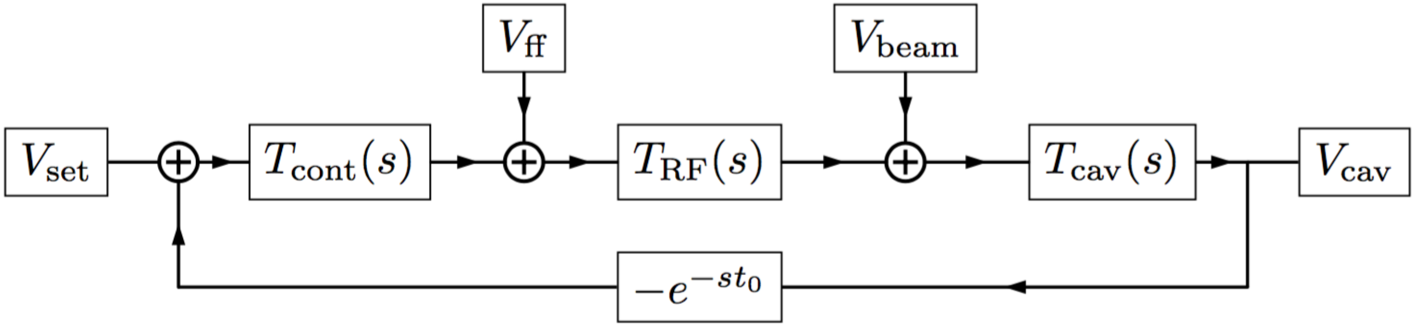
- Assumptions
  - Amplifiers are operating in the linear regime
  - Disturbances other than beam-loading (microphonics, LFD, etc.) are small or slow relative to the timescale of the response due to beam-loading
  - Loop phase and gain are calibrated

Block diagram of model



Block diagram of model



- Use the block diagram to compute the system transfer function

$$V_{\text{cav}} = \left(V_{\text{set}} T_{\text{RF}}(s) T_{\text{cont}}(s) + V_{\text{ff}} T_{\text{RF}}(s) + V_{\text{beam}}\right) \left(\frac{T_{\text{cav}}(s)}{1 + T_{\text{cav}} T_{\text{RF}}(s) T_{\text{cont}}(s) e^{-st_0}} \right)$$

- Beam loading is linearly independent from changes to the set-point and feed forward

Calculating Beam Phase

- Using the system transfer function model:

$$V_{\text{cav}} = (V_{\text{set}} T_{\text{RF}}(s) T_{\text{cont}}(s) + V_{\text{ff}} T_{\text{RF}}(s) + V_{\text{beam}}) \left(\frac{T_{\text{cav}}(s)}{1 + T_{\text{cav}} T_{\text{RF}}(s) T_{\text{cont}}(s) e^{-st_0}} \right)$$

- Casting in a simpler form

$$V_{\text{cav}} = V_{\text{set}} F(s) + V_{\text{ff}} G(s) + V_{\text{beam}} H(s)$$

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- Casting in a simpler form

$$V_{\mathrm{cav}} = V_{\mathrm{set}} F(s) + V_{\mathrm{ff}} G(s) + V_{\mathrm{beam}} H(s)$$

- Convert to time domain

$$V_{\mathrm{cav}}(t) = V(0) + \int_{-\infty}^{\infty} I_{\mathrm{beam}} I(t) H(t-\tau) d\tau$$

Calculating Beam Phase

- Using the system transfer function model:

$$V_{\rm cav}(t) = V(0) + \int_{-\infty}^{\infty} I_{\rm beam} I(t) H(t-\tau) d\tau$$

- Solve for beam current

Measurement

$$I^Q_{\rm beam} = \frac{\boxed{V^Q_{\rm cav}(t) - V^Q(0)}}{\boxed{\int_{-\infty}^{\infty} I(t) H(t-\tau) d\tau}}$$

Unknown function

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$$\phi_{\mathrm{beam}} = \tan^{-1}\left(\frac{I^{Q}_{\mathrm{beam}}}{I^{I}_{\mathrm{beam}}}\right)$$

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$$I_{\text{beam}}^{Q} = \frac{\boxed{V_{\text{cav}}^{Q}(t) - V^{Q}(0)}}{\boxed{\int_{-\infty}^{\infty} I(t) H(t-\tau) d\tau}}$$

Measurement

Unknown function

$$\phi_{\text{beam}} = \tan^{-1}\left(\frac{I_{\text{beam}}^{Q}}{I_{\text{beam}}^{I}}\right) = \tan^{-1}\left(\frac{V_{\text{cav}}^{Q}(t) - V^{Q}(0)}{V_{\text{cav}}^{I}(t) - V^{I}(0)}\right)$$

Calculating Beam Phase

- Using the system transfer function model:

$$V_{\text{cav}}(t) = V(0) + \int_{-\infty}^{\infty} I_{\text{beam}} I(t) H(t-\tau) d\tau$$

- Solve for beam current

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Measurement

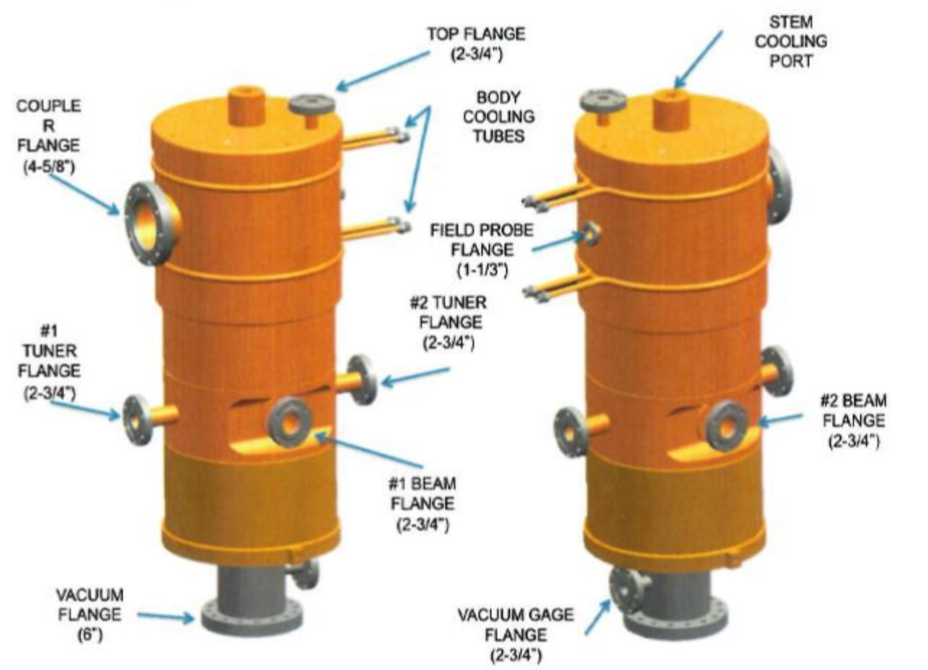
Unknown function

Can integrate to improve SNR

$$\phi_{\text{beam}} = \tan^{-1}\left(\frac{I^Q_{\text{beam}}}{I^I_{\text{beam}}}\right) = \tan^{-1}\left(\frac{\boxed{V^Q_{\text{cav}}(t)} - V^Q(0)}{\boxed{V^I_{\text{cav}}(t)} - V^I(0)}\right)$$

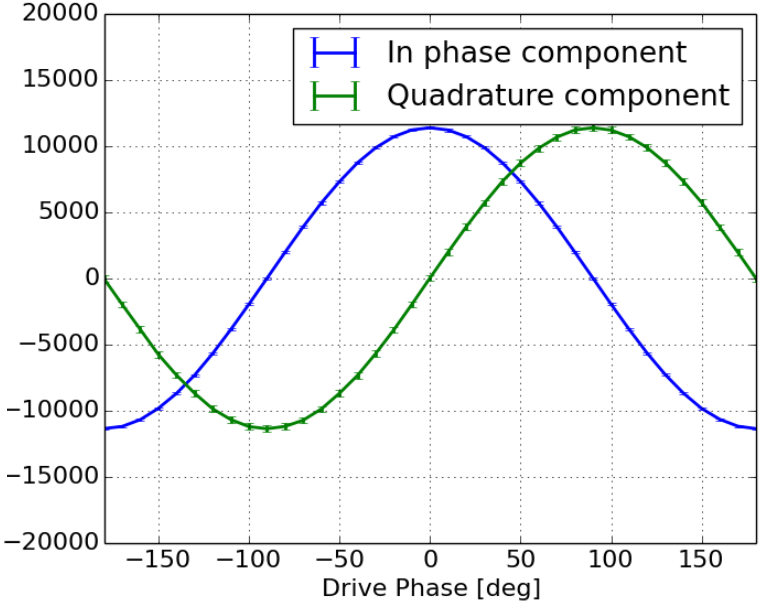
Proof of principle test: 162.5 MHz bunching cavity

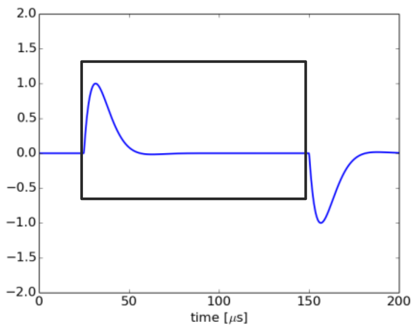
- 162.5 MHz cavities
  - 2 gap quarter wave resonator
  - Loaded Q ~5000
  - r/Q ~600
- Pulsed and CW operation
- Operating voltage is 50-100 kV (peak energy gain)
- Beam energy is 2.1 MeV
- Beam loading voltage is ~ 15 kV



Proof of principle results: ideal beam loading

- Perform a phase scan with feed-forward disturbance using the LLRF system
- Use the field in the cavity to calculate the phase of the disturbance
- Compare the calculated phase with the set phase of the disturbance





Measurements of cavity disturbance due to LLRF driven disturbance as a function of drive phase

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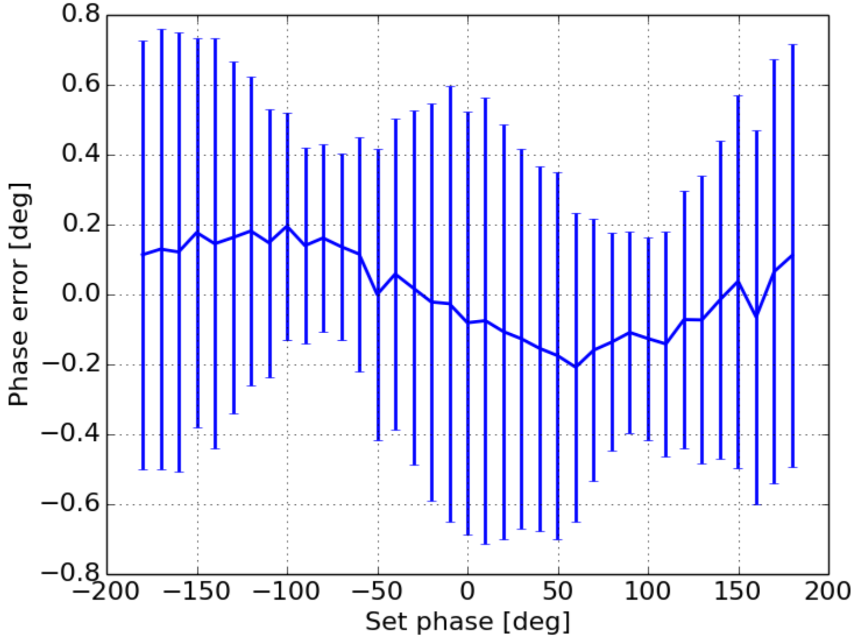

Difference between the calculated phase of the beam-like disturbance and the drive phase of the disturbance. Errors likely due to crosstalk.

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- The feed-forward disturbance should be a good approximation of a real beam loading disturbance
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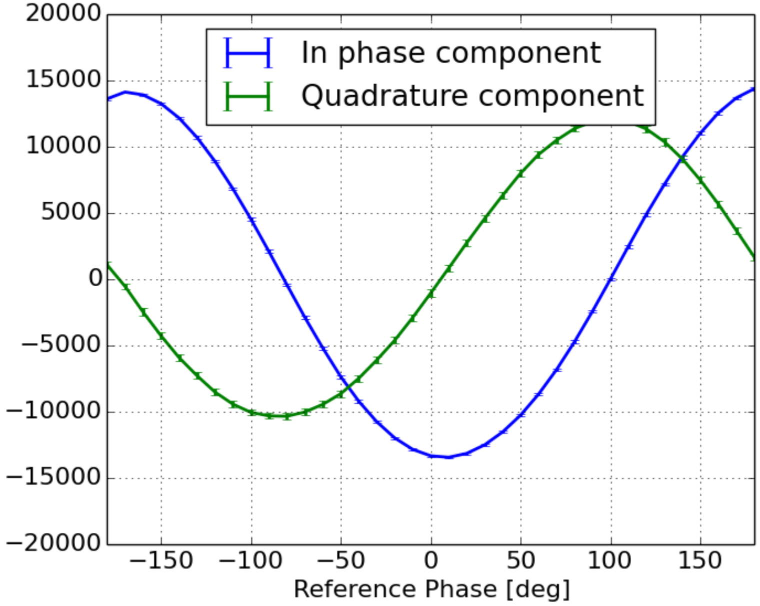
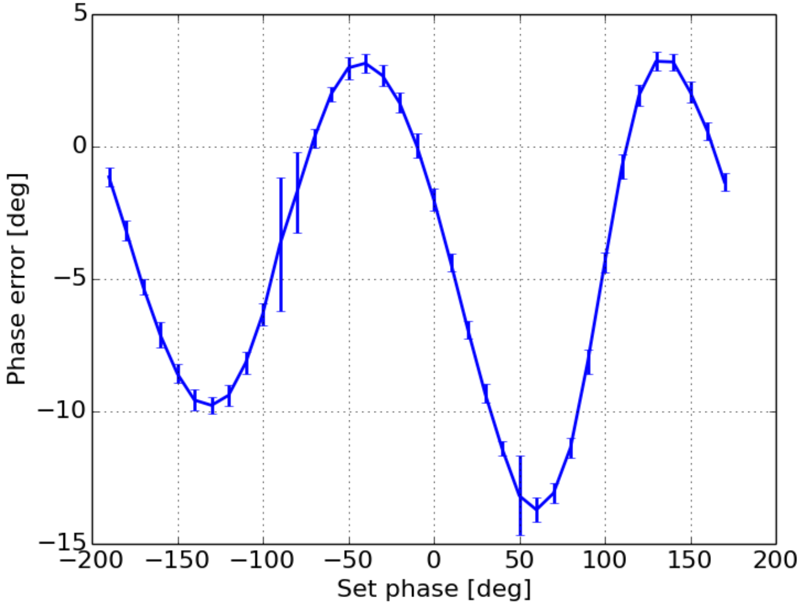
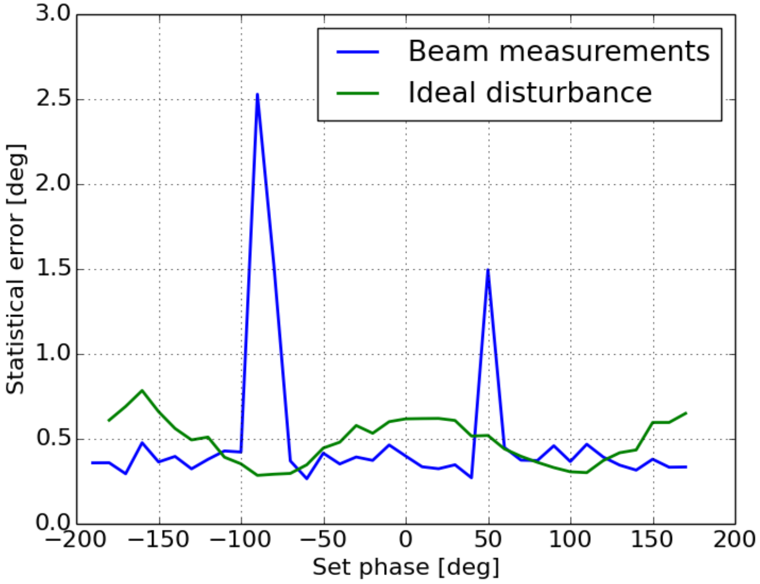
- The feed-forward disturbance should be a good approximation of a real beam loading disturbance
- Results with the feed-forward disturbance were promising
- However, tests with real beam-loading did not perform as expected





Proof of principle: real beam loading

- Statistical errors are similar for the two tests
  - Wobble in ideal disturbance suspected to be caused by cross talk
  - Large deviations in beam phase measurements cause by beam dropout



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- We have a technique that should in principle be able to determine the beam phase relative to the RF to approximately 0.5 degrees

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  - Unknown source of the errors: Low-beta effects, geometry issues?
  - Try testing on other cavities as well as analyze other signals

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- Future plans
  - Extend to amplitude calibration
  - Include detuning subtraction

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- Future plans
  - Extend to amplitude calibration
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- Open to suggestions and discussion

Thank you!