Automatic phase calibration for RF cavities using beam-loading signals

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LLRF 2017 Workshop (Barcelona)
18 Oct 2017
Introduction

- How do we meet $10^{-4}$ energy stability for PIP-II?
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- Assume we can calibrate phase and amplitude to ±0.5° and ±1% respectively
- We have shown in simulation that we can correct for calibration errors using beam-based feedback on the last 6 cavities in the LINAC
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  – Temperature drift in the cables
  – Phase drift from the RFQ
  – Other sources of calibration change or drift
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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

Controller
Transfer
Function

RF System

RF Cavity

Group delay

$V_{\text{set}}$ → $T_{\text{cont}}(s)$ → $T_{\text{RF}}(s)$ → $T_{\text{cav}}(s)$ → $V_{\text{cav}}$

$V_f$ → $V_{\text{beam}}$

$-e^{-st_0}$
Use the block diagram to compute the system transfer function

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

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

- Using the system transfer function model:

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- 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

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

- Convert to time domain

\[ V_{\text{cav}}(t) = V(0) + \int_{-\infty}^{\infty} I_{\text{beam}} I(t) H(t - \tau) d\tau \]
Calculating Beam Phase

- Using the system transfer function model:

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

- Solve for beam current

\[ I_{\text{beam}}^{Q} = \frac{V_{\text{cav}}^{Q}(t) - V^{Q}(0)}{\int_{-\infty}^{\infty} I(t)H(t - \tau) d\tau} \]
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\[
\phi_{\text{beam}} = \tan^{-1}\left(\frac{I_{\text{beam}}^{Q}}{I_{\text{beam}}^{I}}\right)
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Measurement

Unknown function

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

Unknown function

Can integrate to improve SNR

\[ \phi_{\text{beam}} = \tan^{-1} \left( \frac{I_{\text{beam}}^Q}{I_{\text{beam}}^I} \right) = \tan^{-1} \left( \frac{V_{\text{cav}}^Q(t) - V_{\text{cav}}^Q(0)}{V_{\text{cav}}^I(t) - V_{\text{cav}}^I(0)} \right) \]
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
Proof of principle results: ideal beam loading

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- Use the field in the cavity to calculate the phase of the disturbance

- Compare the calculated phase with the set phase of the disturbance

Difference between the calculated phase of the beam-like disturbance and the drive phase of the disturbance. Errors likely due to crosstalk.
Proof of principle: real beam loading

- The feed-forward disturbance should be a good approximation of a real beam loading disturbance
- Results with the feed-forward disturbance were promising
Proof of principle: real beam loading

- 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

![Graph showing phase error and component analysis.](image-url)
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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- Open to suggestions and discussion
Thank you!