An LLRF perspective on LLRF - Beam Physics interaction

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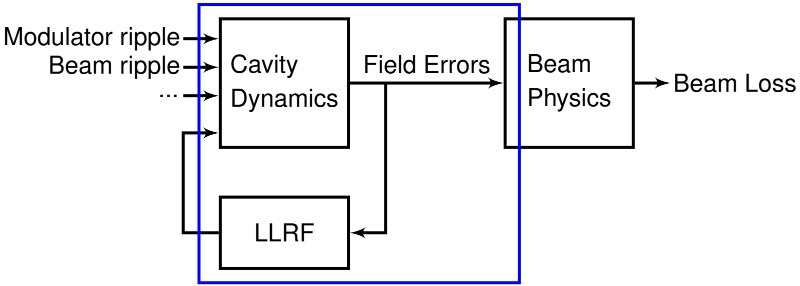
Overview

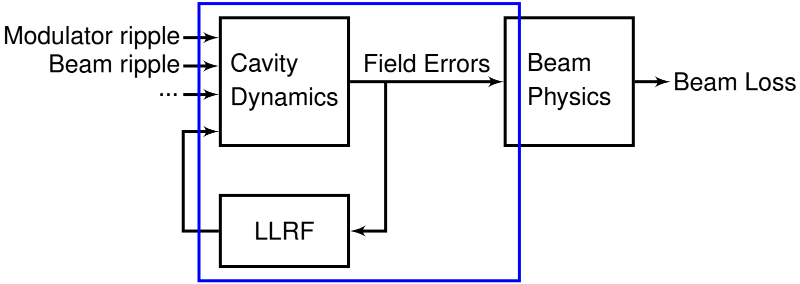


Problems and suboptimality often originate from interfaces

Requirements on field errors should reflect what affects beam loss

LLRF system reduces impact of the disturbances -
It does not remove them

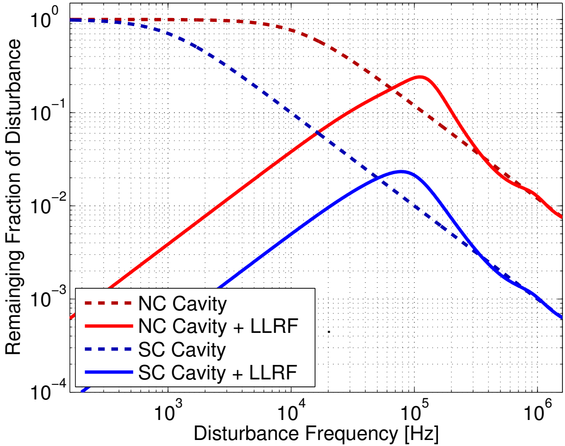
Overview



Outline

- Disturbance Rejection of LLRF
- What really matters to the beam?
- Some remarks and summary

Disturbance Rejection vs Frequency

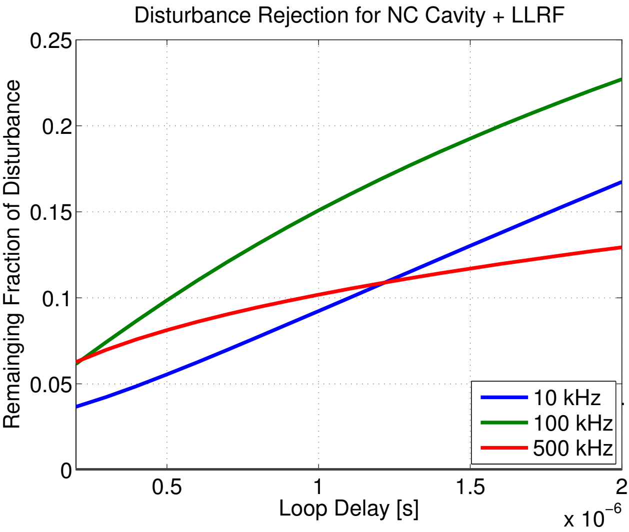


Ability to reject disturbance depends its on frequency!

Frequencies around 100 kHz are worst!

Cavity Bandwidths 12 kHz and 1 kHz, 1 μs loop delay, PID controller

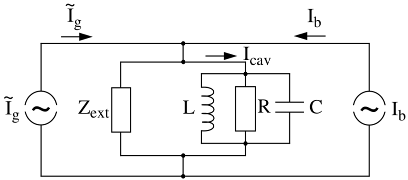
Disturbance Rejection vs Loop Delay



Performance is limited by loop delay

Cavity Bandwidth 12 kHz, 1 μs loop delay, PID controller

Cavity Model [Schilcher 1998]



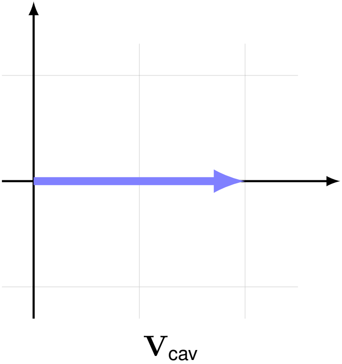
$$\frac{d}{dt}\begin{bmatrix} V_{\text{Re}} \\ V_{\text{Im}} \end{bmatrix} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{bmatrix}\begin{bmatrix} V_{\text{Re}} \\ V_{\text{Im}} \end{bmatrix} + \begin{bmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{bmatrix}\begin{bmatrix} I_{\text{Re}} \\ I_{\text{Im}} \end{bmatrix}$$

- $\mathbf{V}$ - cavity voltage
- $\mathbf{I} = 2\mathbf{I_g} + \mathbf{I_b}$ = beam current + generator current
- $\omega_{1/2}$ - cavity bandwidth
- $\Delta\omega$ - detuning of the cavity

or

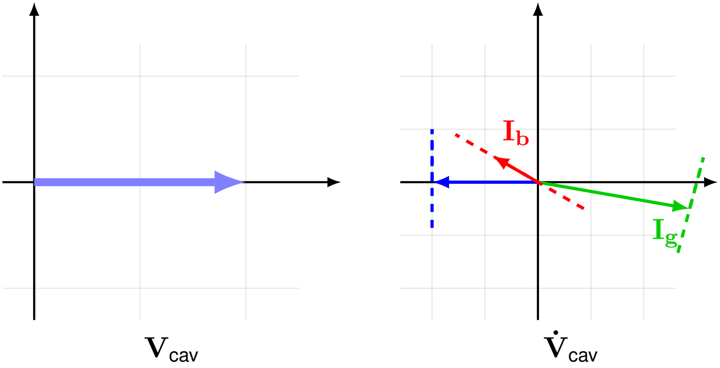
$$\dot{\mathbf{V}}_{\text{cav}} = (-\omega_{1/2} + i\Delta\omega)\mathbf{V}_{\text{cav}} + 2\omega_{1/2}R_L\mathbf{I}_{\text{g}} + \omega_{1/2}R_L\mathbf{I}_{\text{b}}$$

Basic cavity dynamics



$$\dot{\mathbf{V}}_{\text{cav}} = (-\omega_{1/2} + i\Delta\omega)\mathbf{V}_{\text{cav}} + 2\omega_{1/2}R_L\mathbf{I}_{\text{g}} + \omega_{1/2}R_L\mathbf{I}_{\text{b}}$$

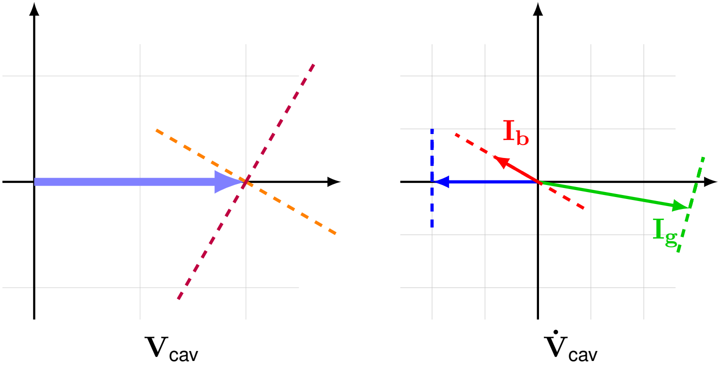
Directions of disturbances



Linearize (beam ripple affects amplitude of $\mathbf{I_b}$,
modulator ripple affects phase of $\mathbf{I_g}$):

$$\delta\dot{\mathbf{V}}_{\mathbf{cav}} = (-\omega_{1/2} + i\Delta\omega)\delta\mathbf{V}_{\text{cav}} + 2\omega_{1/2}R_L\delta\tilde{\mathbf{I}}_{\mathbf{g}} + \mathbf{B}_{\text{detuning}}\Delta\omega + \mathbf{B}_{\text{beamrip}}\Delta I_b + \mathbf{B}_{\text{modrip}}\Delta V_{\text{modrip}}$$

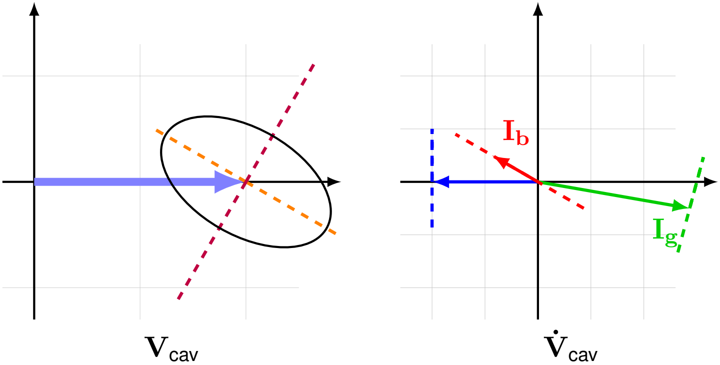
What matters to the beam



Transferred Energy $\propto$ $\quad \mathrm{Im}\left\{\mathbf{V}_{\mathsf{cav}} \cdot \mathbf{I}_{\mathbf{b}}^{*}\right\} = V_{\mathsf{cav}} I_b \cos(\phi_b - \phi_{\mathsf{cav}})$

Longitudinal Focusing $\propto$ $\quad \mathrm{Im}\left\{\mathbf{V}_{\mathsf{cav}} \cdot \mathbf{I}_{\mathbf{b}}^{*}\right\} = V_{\mathsf{cav}} I_b \sin(\phi_b - \phi_{\mathsf{cav}})$

What matters to the beam



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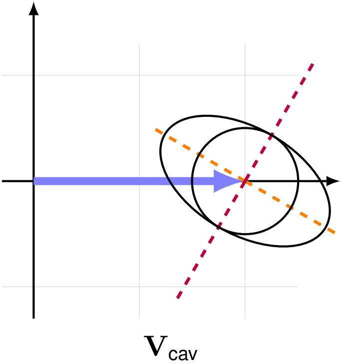
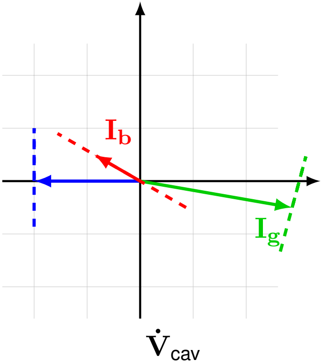
What matters to the beam

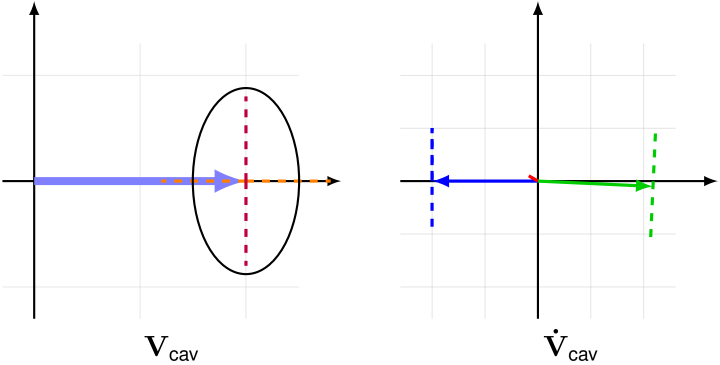




Transferred Energy $\propto$ $\mathrm{Im}\left\{\mathbf{V}_{\mathsf{cav}} \cdot \mathbf{I}^*_{\mathbf{b}}\right\} = V_{\mathsf{cav}} I_b \cos(\phi_b - \phi_{\mathsf{cav}})$

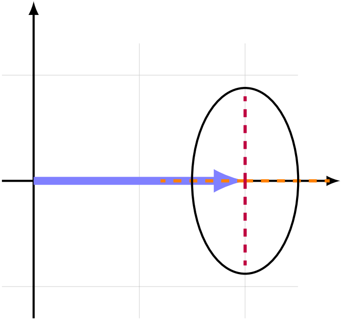
Longitudinal Focusing $\propto$ $\mathrm{Im}\left\{\mathbf{V}_{\mathsf{cav}} \cdot \mathbf{I}^*_{\mathbf{b}}\right\} = V_{\mathsf{cav}} I_b \sin(\phi_b - \phi_{\mathsf{cav}})$

Comparison: Small beam Loading

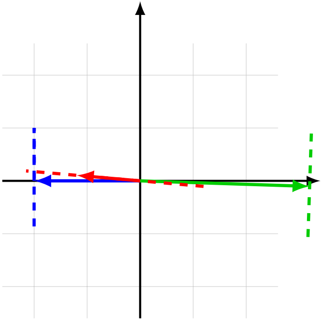


Small beam loading, disturbance due to modulator ripple only affects cavity phase $\Rightarrow$ amplitude and phase requirements are OK

Comparison: Relativistic particles



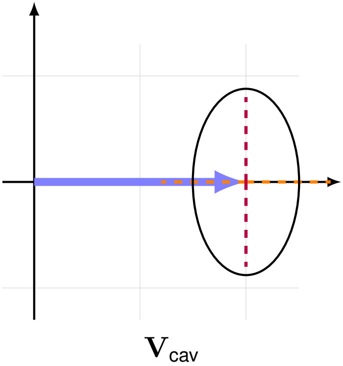
$\mathbf{V}_{\text{cav}}$



$\dot{\mathbf{V}}_{\text{cav}}$

Disturbance due to modulator ripple affects mostly cavity amplitude, disturbance due to modulator ripple only affects cavity phase $\Rightarrow$ amplitude and phase requirements are OK

Implicit assumption on errors

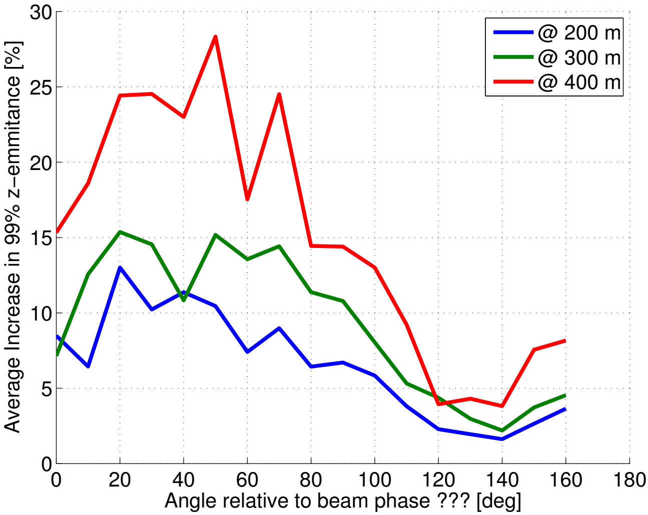


(x %, x°) requirement corresponds to an ellipse! (0.01, 0.017 (rad))

Consequences of Alternative Error Definitions

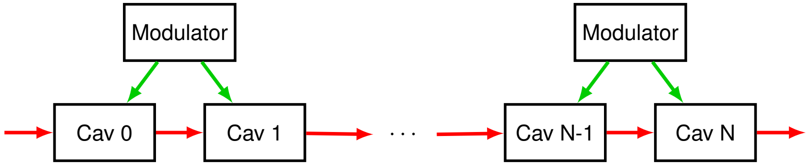
- Errors in terms of Transferred Energy and Longitudinal Focusing are not harder to compute - just scalar product
- Advantage with specifying errors in Gained Energy and Longitudinal Focusing: Less conservative design. Relaxed requirement on modulator or ion source.

Example of TraceWin simulation



Average increase in 99 % z-emmitance due to 0.3 % error in different directions.

Cavity-cavity correlation



Field errors due to beam ripple are correlated between all cavities

Modulator will cause correlated errors between the cavities it supplies

Correlated errors may cause more severe problems than uncorrelated ones as discussed by Jean-Luc yesterday (?)

Static field errors

In the beam physics simulations static field are large compared to dynamic error, $\approx 1\%$ (static) vs $\approx 0.2\%$ (dynamic)

As Didier mention, the situation is not clear. How are static errors correlated? How to Correct them?

Seems important to take into account.

Design for time of flight measurements to correct static errors have not yet been fixed.

What can be done to reduce field errors

- Improve LLRF
  - Improve Hardware (shorter loop delay)
  - Feedforward from disturbances
- Improve Ion Source (Hard)
- Improve Modulators (Quite hard)
- (Improve Calibration Procedure)

Summary

- Disturbance rejection depends on disturbance frequency and loop delay
- Requirements on field error should reflect impact on beam loss
  - Disturbances enter in specifc directions
  - Errors in gained energy and longitudinal focusing matters to the beam NOT amplitude and phase
  - The impact is on ion source and modulator requirements
  - Some errors will be correlated from cavity to cavity

Feedback and discussions are most welcome!

Thanks!

Thanks to the following people for providing input to the presentation

- Mamad Eshraqi @ ESS
- My supervisors Bo Bernhardsson, Anders J Johansson and Rolf Johansson @ Lund University
- Many more ...

References I

[0] Schilcher, Thomas (1998). “Vector sum control of pulsed accelerating fields in Lorentz force detuned superconducting cavities”. PhD thesis. DESY.