Modeling the LLRF Control of a Multi-Cavity RF Station for Project X

using ferrite vector modulators

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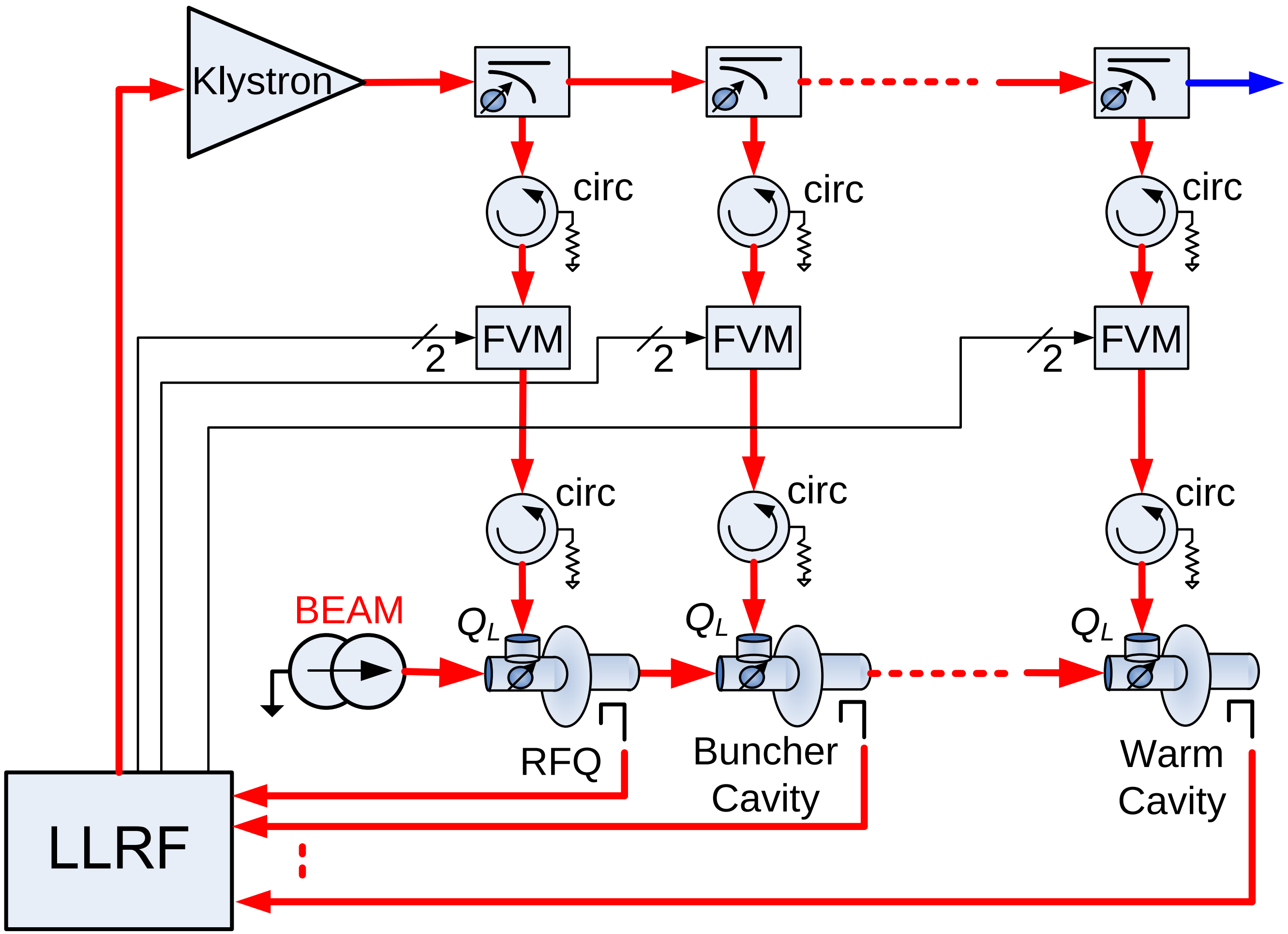
Outline

- Problem statement + scope
- Model
  - Cavity
  - Ferrite Vector Modulator (FVM)
- RF control and beam compensation
  - Using Klystron FF + FVM
- Path forward

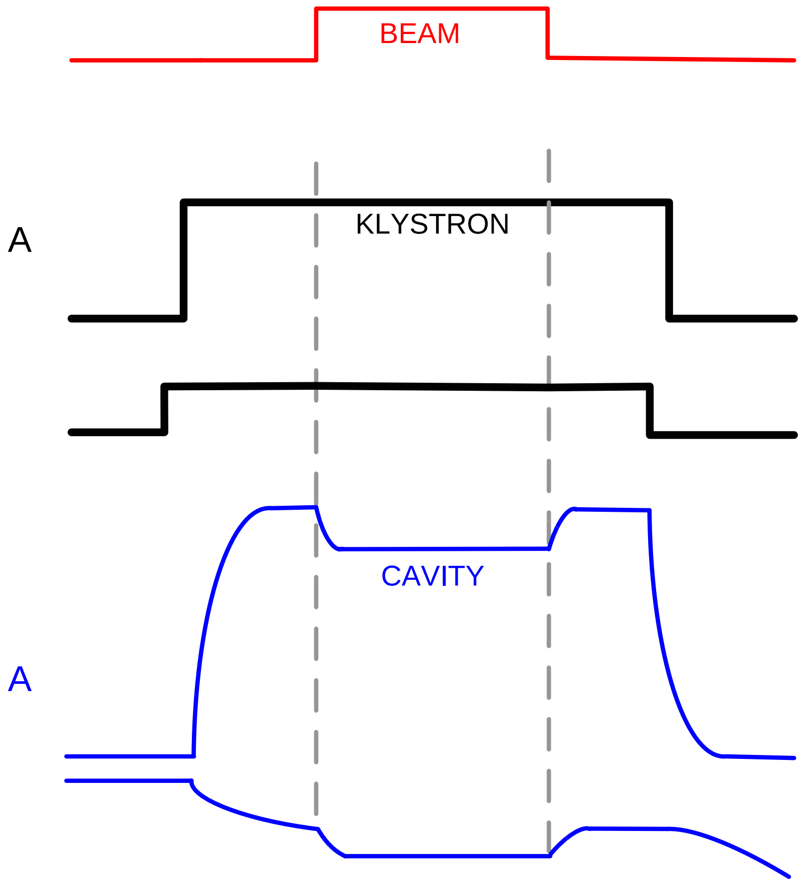
HINS – Project X front end



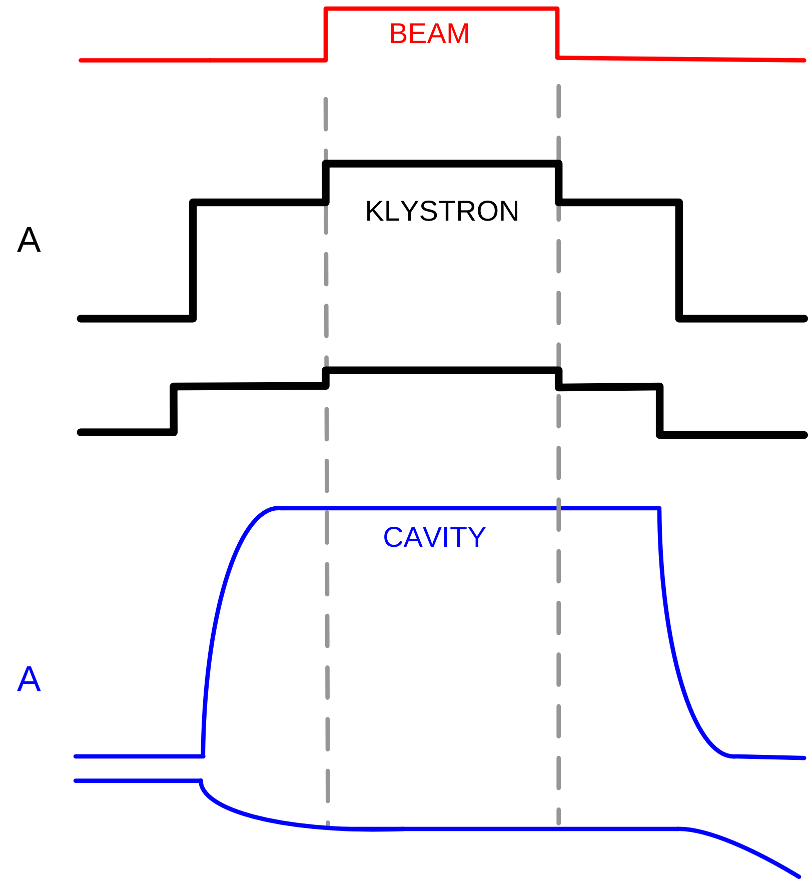
- HINS
  - High Intensity Neutrino Source
  - 30 MeV H$^-$ linac
  - 25 mA beam
  - 325 MHZ
- Warm section
  - 2.5 MW klystron
  - 1 RFQ
  - 2 buncher cavities
  - 16 room temperature cavity
- Cold section
  - superconducting cavities

Beam compensation

during steady state



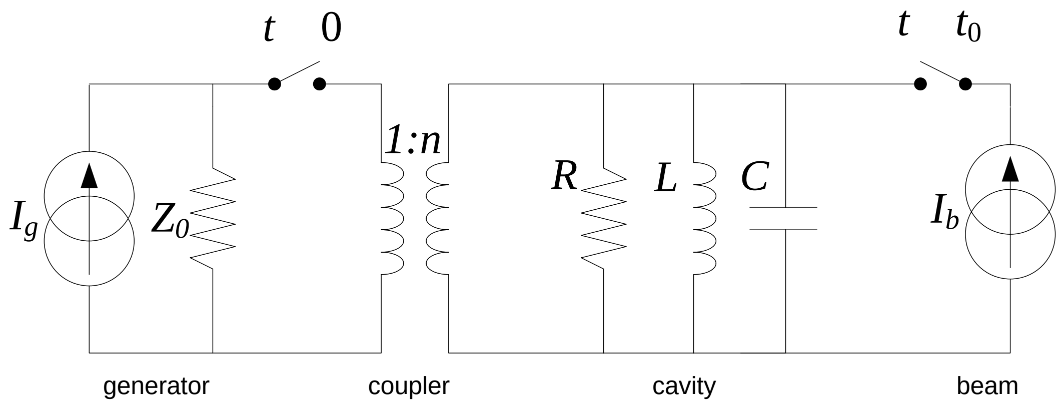
A/Φ beam loading



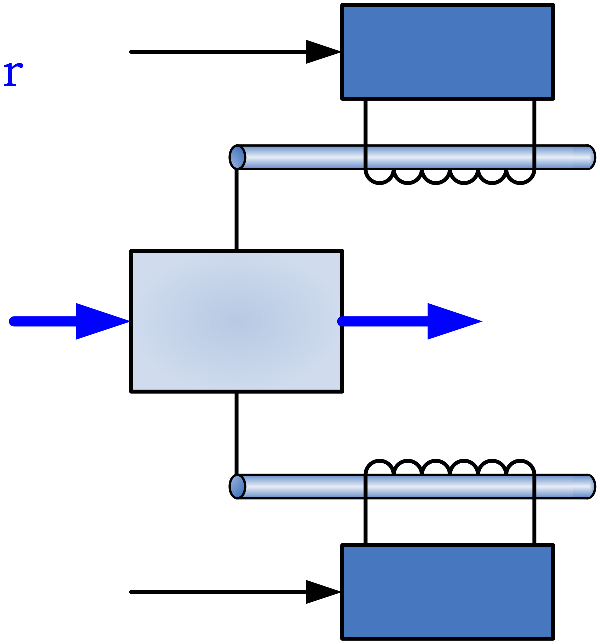
use A/Φ modulation to compensate for beam loading

Simulation Model

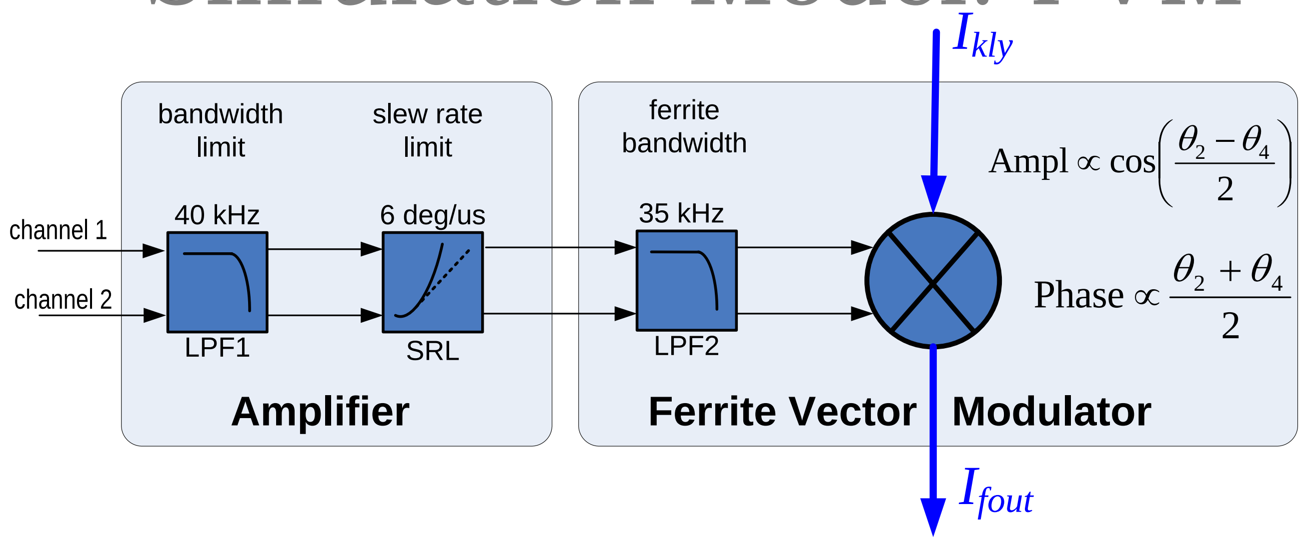
cavity



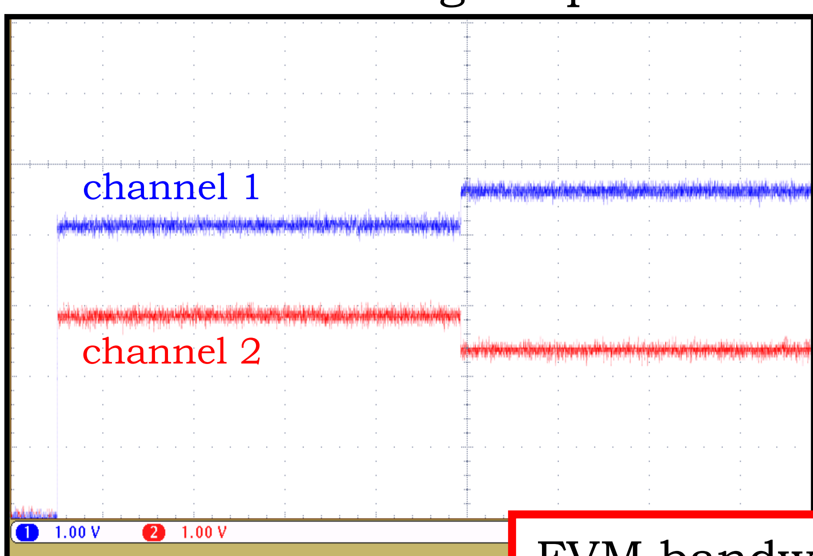
ferrite vector modulator



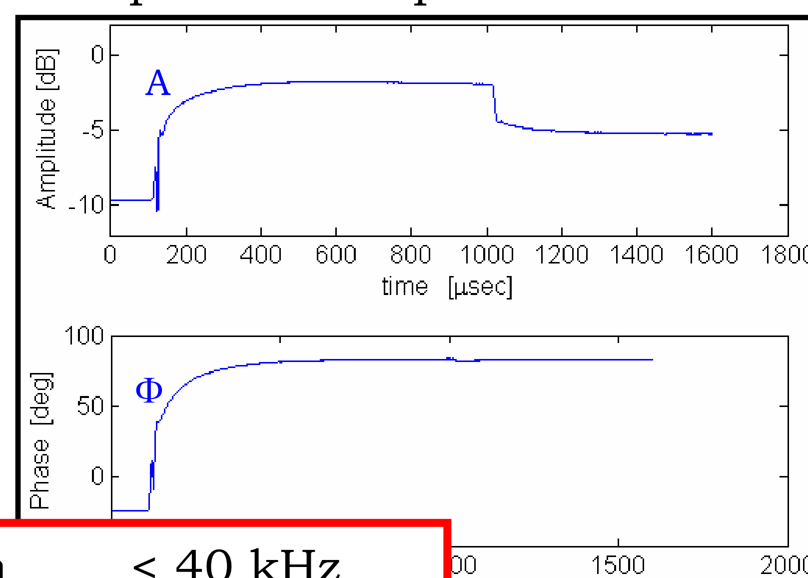
Simulation Model: FVM



control voltage request

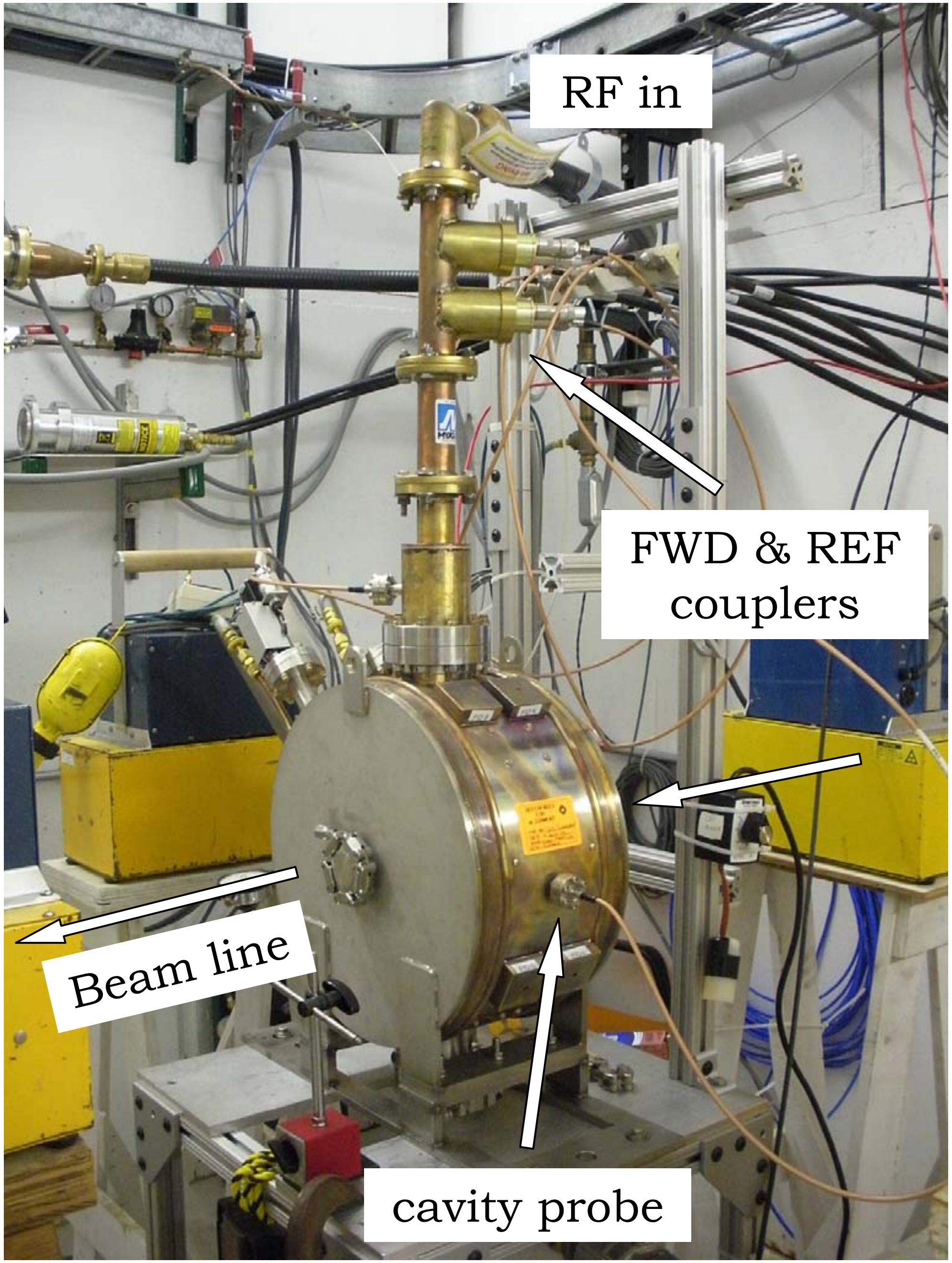


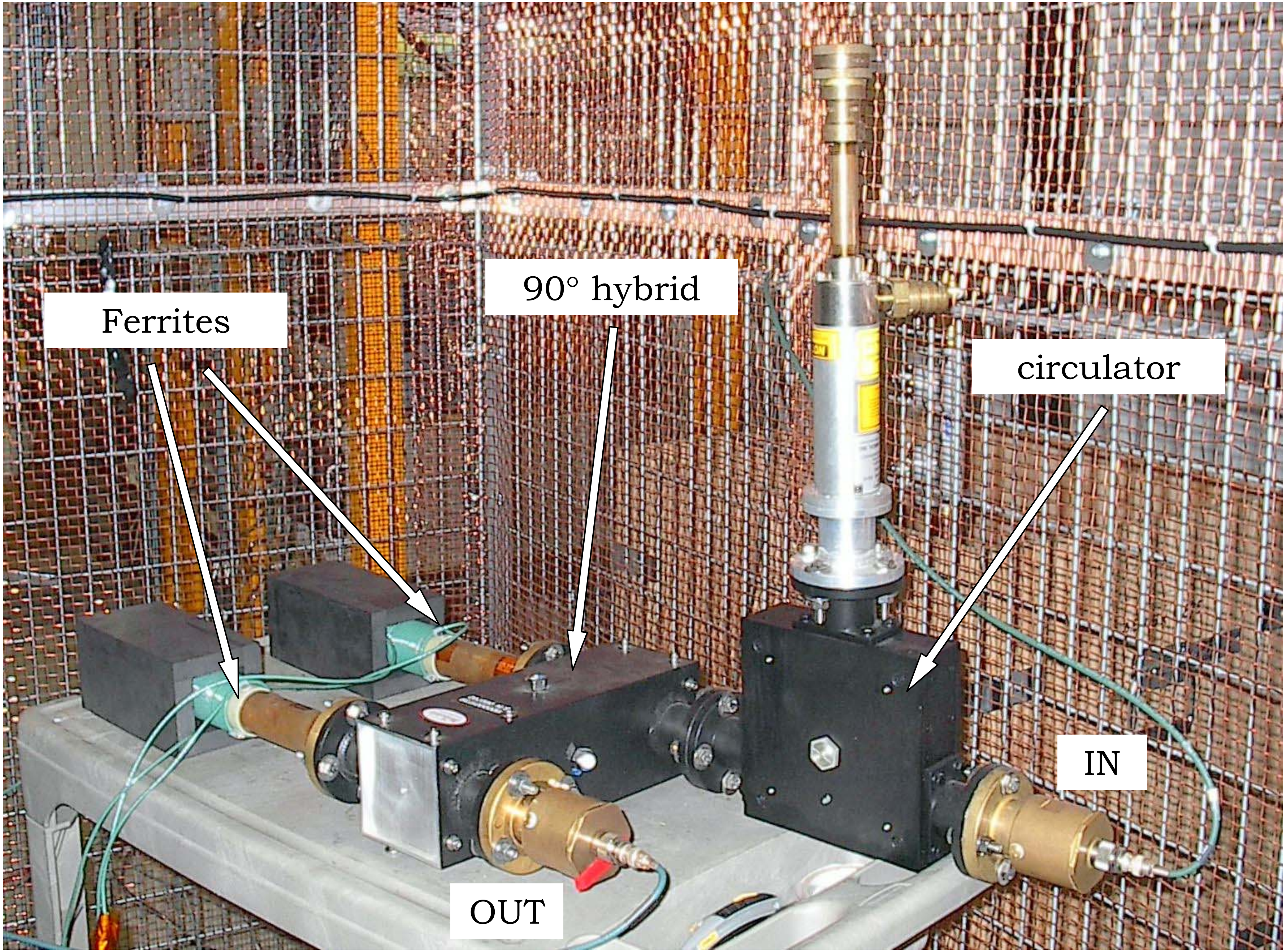
amplitude and phase modulation



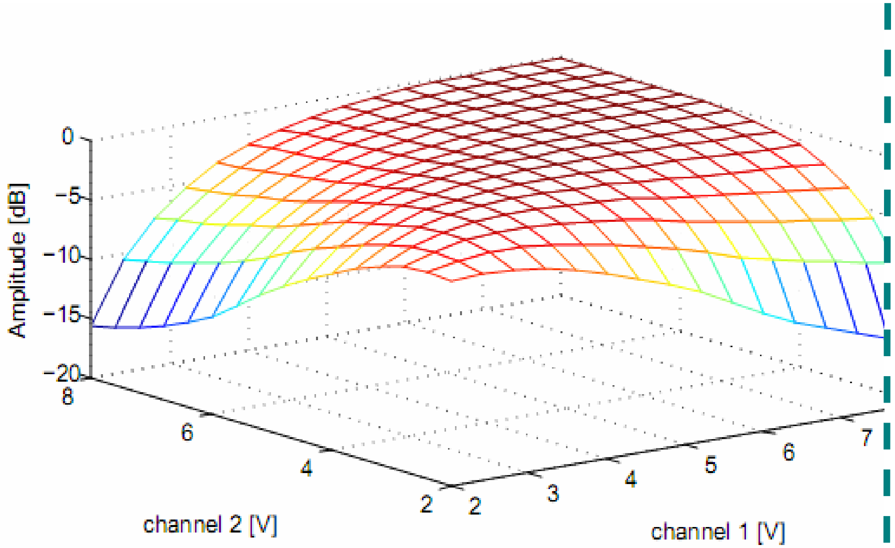
FVM bandwidth < 40 kHz
Klystron bandwidth > 2 MHz

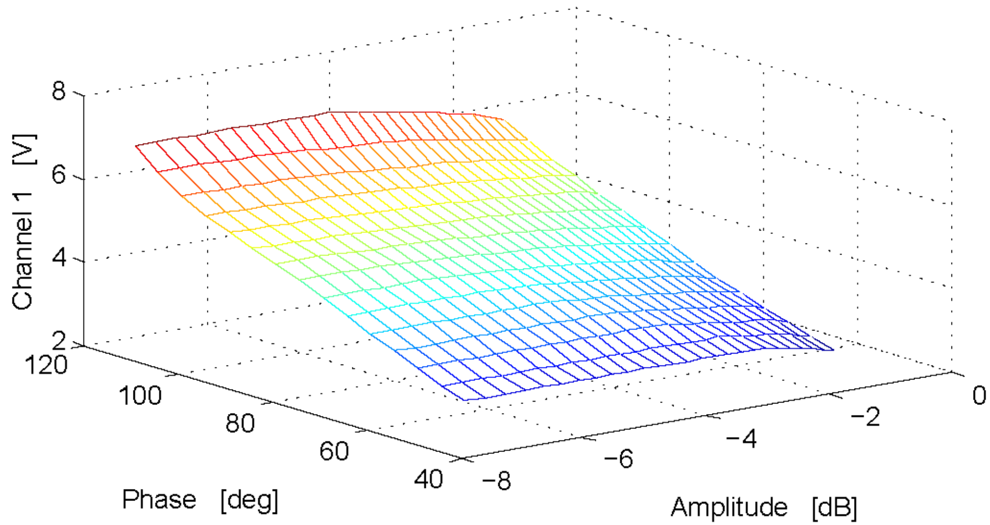
Fermilab PAC09


RF in
FWD & REF couplers
Beam line
cavity probe


Ferrites
90° hybrid
circulator
IN
OUT

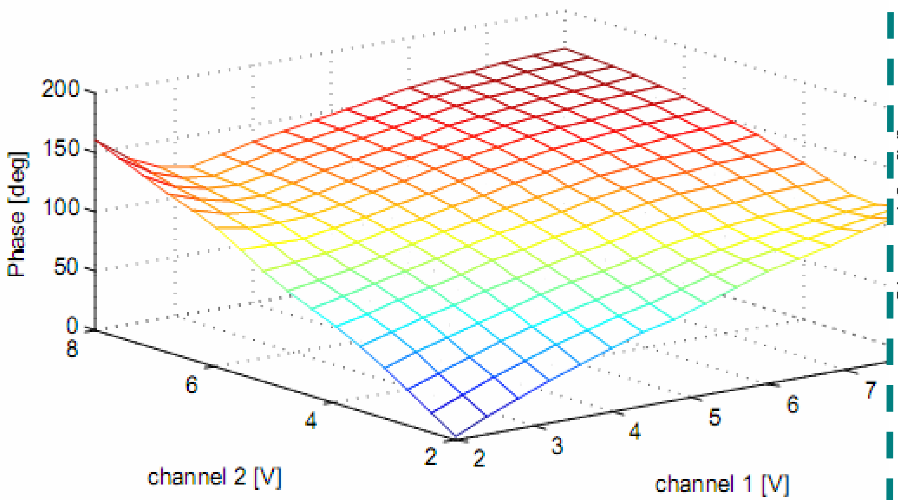
Controlling the FVM

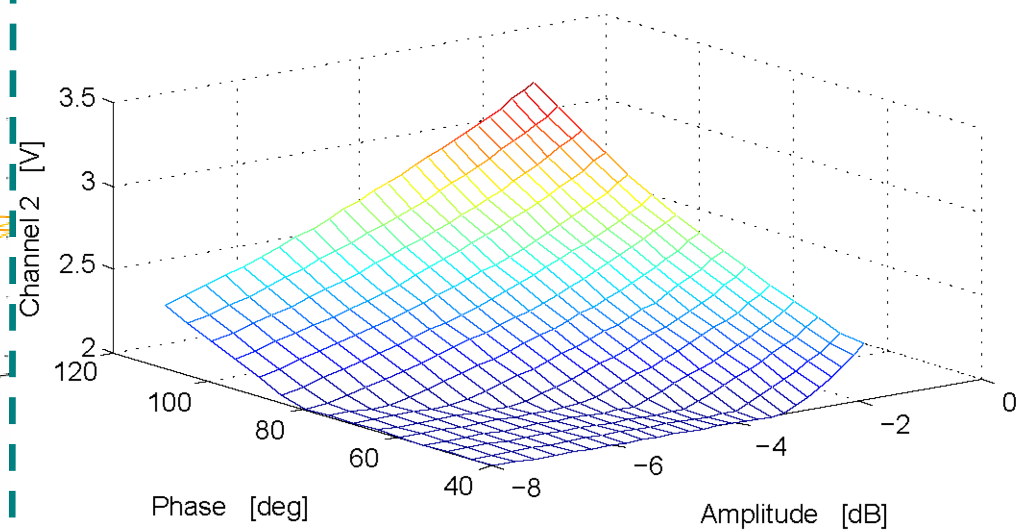




measured modulation domain

modulation control domain



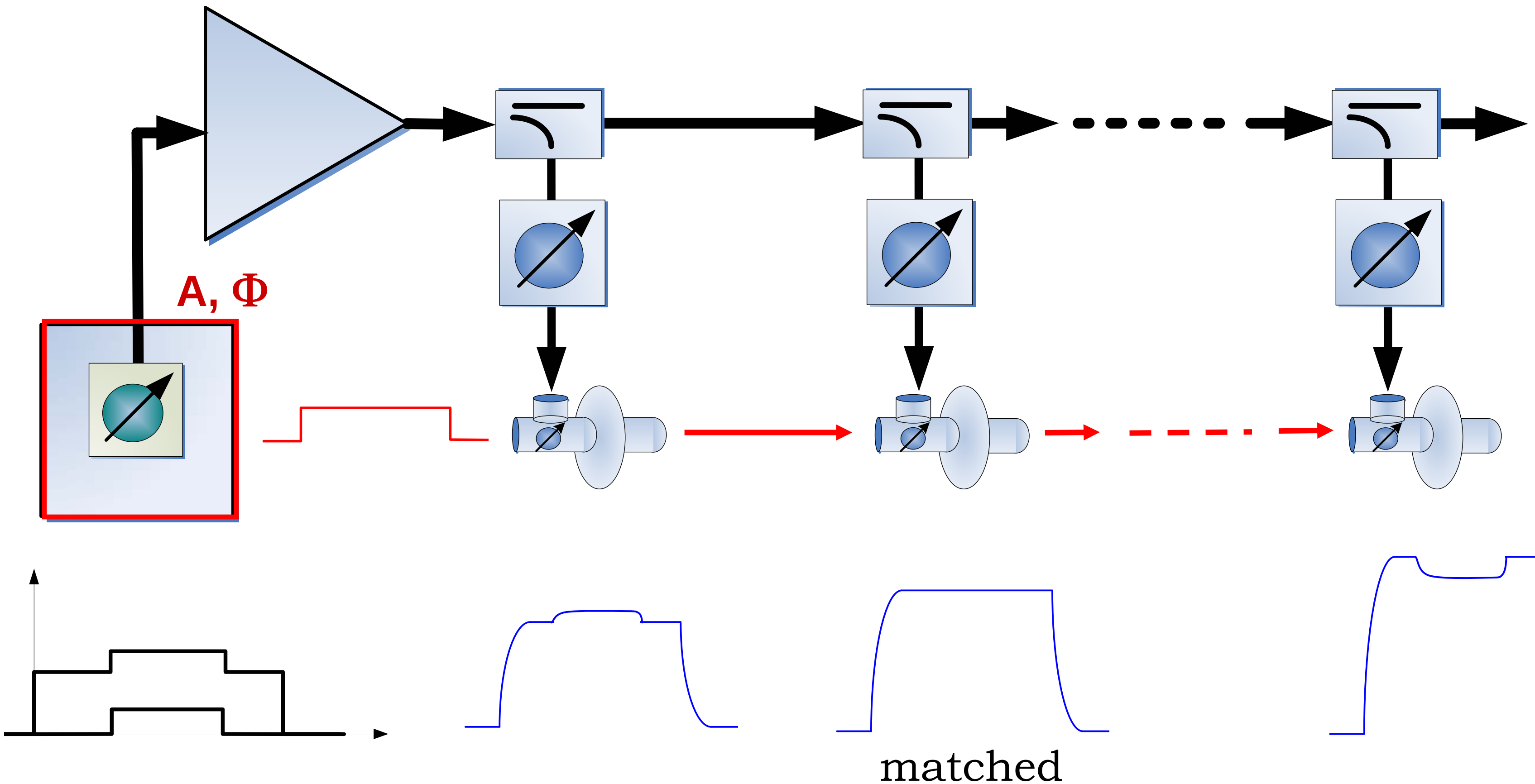


Control algorithm

1. Compute klystron *A* and Φ (initial conditions: cavities tuned for $P_{REF}=0$)

→compensate beam loading for one cavity

→ zero reflected power for one cavity



Control algorithm

1. Compute klystron *A* and Φ (initial conditions: cavities tuned for P_{REF}=0)
   - → compensate beam loading for one cavity
   - → zero reflected power for one cavity

2. Before RF pulse, tune FVMs for all cavities
   - → power amplitude coupling, α
   - → power phase coupling, ψ

$$\alpha = \frac{I_b}{I_k} \frac{1}{\sqrt{1 + A^2 - 2A\cos\Phi}}$$

$$\Psi = \Phi s + \Phi + \cos^{-1}\left[\frac{A - \cos\Phi}{\sqrt{1 + A^2 - 2A\cos\Phi}}\right]$$

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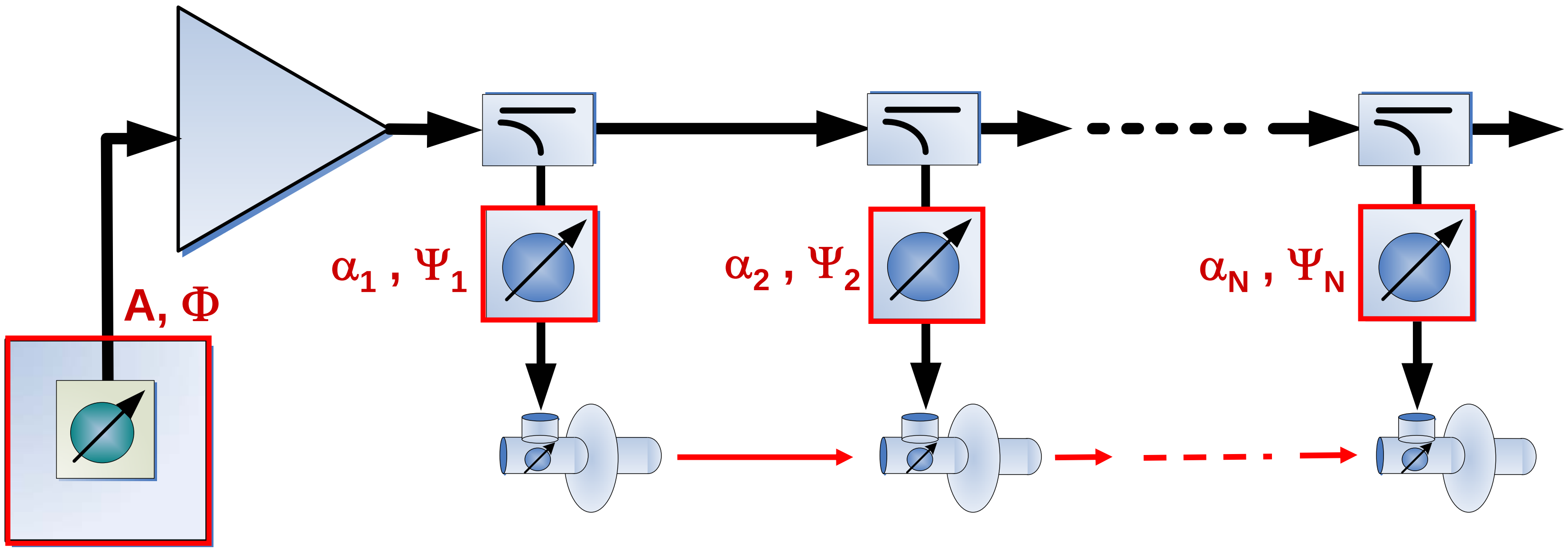

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   → zero reflected power for one cavity

2. Before RF pulse, tune FVMs for all cavities
   → power amplitude coupling, α
   → power phase coupling, ψ

3. Before RF pulse, tune cavities
   → loaded Q_L
   → cavity detuning, $\Delta\omega$

$$Q_L = \frac{2Vcav}{I_b\, R/Q} \frac{\sqrt{1 + A^2 - 2A\cos\Phi}}{\cos\Psi}$$

$$\Delta f = \frac{f0}{2Q_L} \tan\Psi$$

Control algorithm

1. Compute klystron *A* and Φ (initial conditions: cavities tuned for P_{REF}=0)
   → compensate beam loading for one cavity
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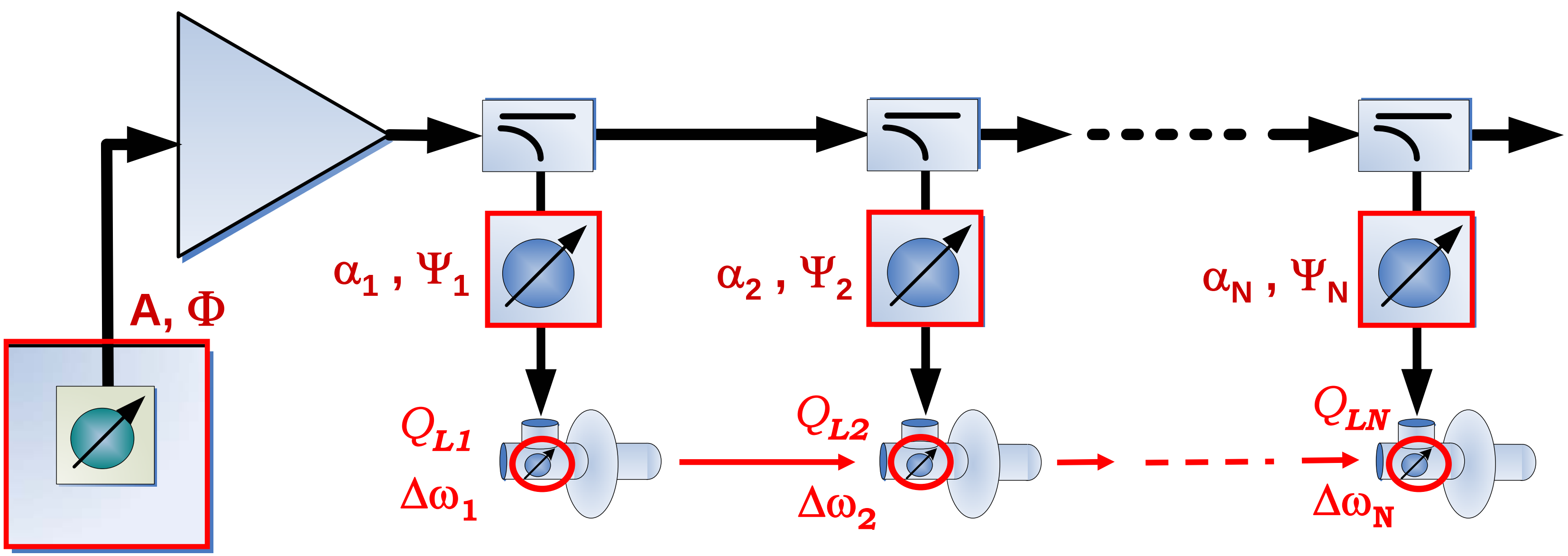


Control algorithm

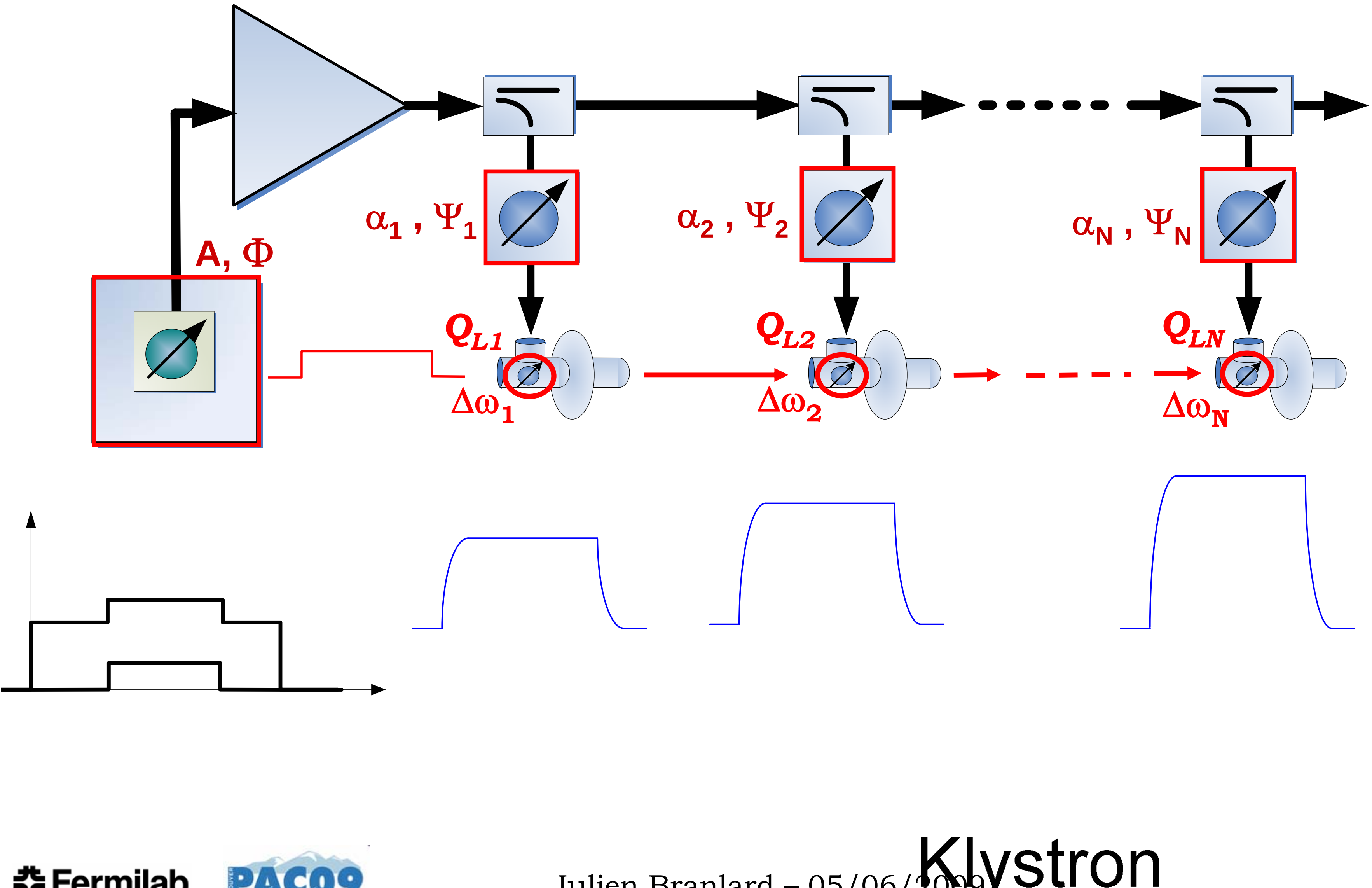
1. Compute klystron *A* and Φ (initial conditions: cavities tuned for $P_{REF}=0$)
   → compensate beam loading for one cavity
   → zero reflected power for one cavity

2. Before RF pulse, tune FVMs for all cavities
   → power amplitude coupling, α
   → power phase coupling, ψ

3. Before RF pulse, tune cavities
   → loaded Q_L
   → cavity detuning, $\Delta\omega$

4. RF pulse
   → at beam arrival time, klystron modulation *A*, Φ
   → nothing else changes

Control algorithm

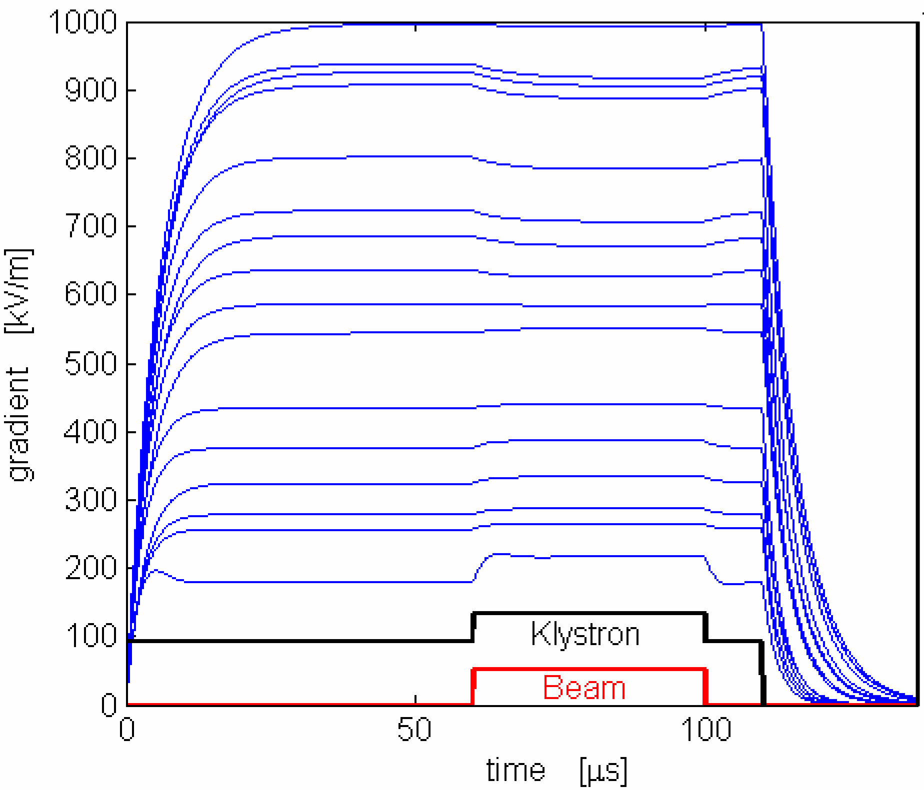


RF control: beam loading compensation

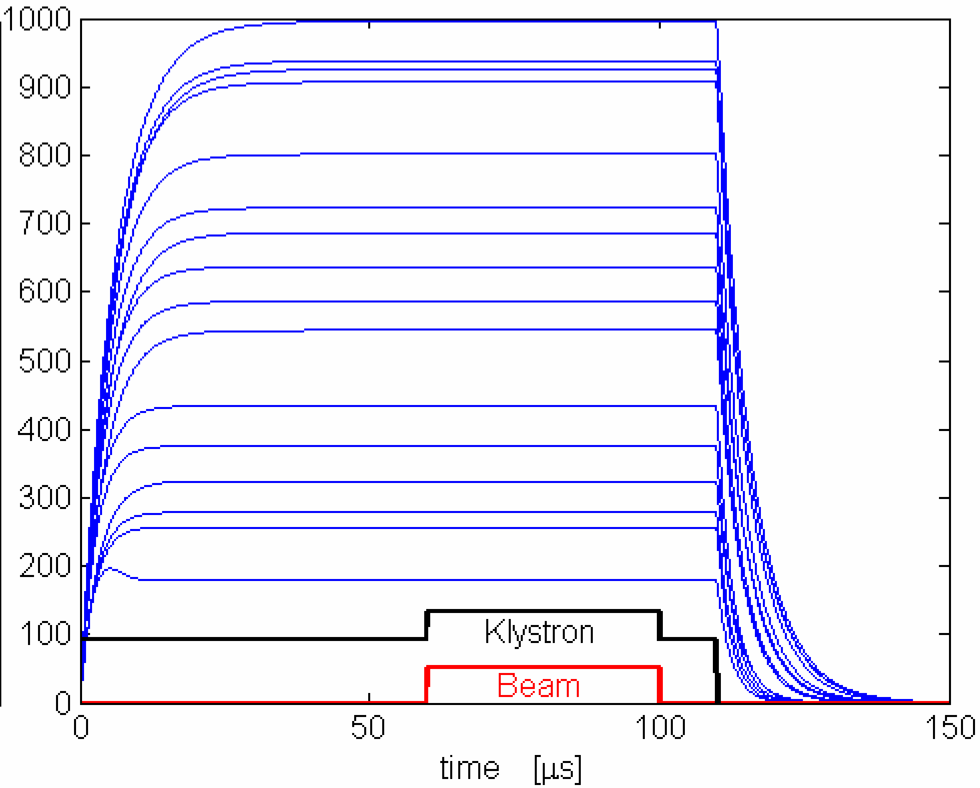
Using FF klystron amplitude and phase modulation

➔ Verification using a time dependent simulation

no FVM tuning



with FVM tuning



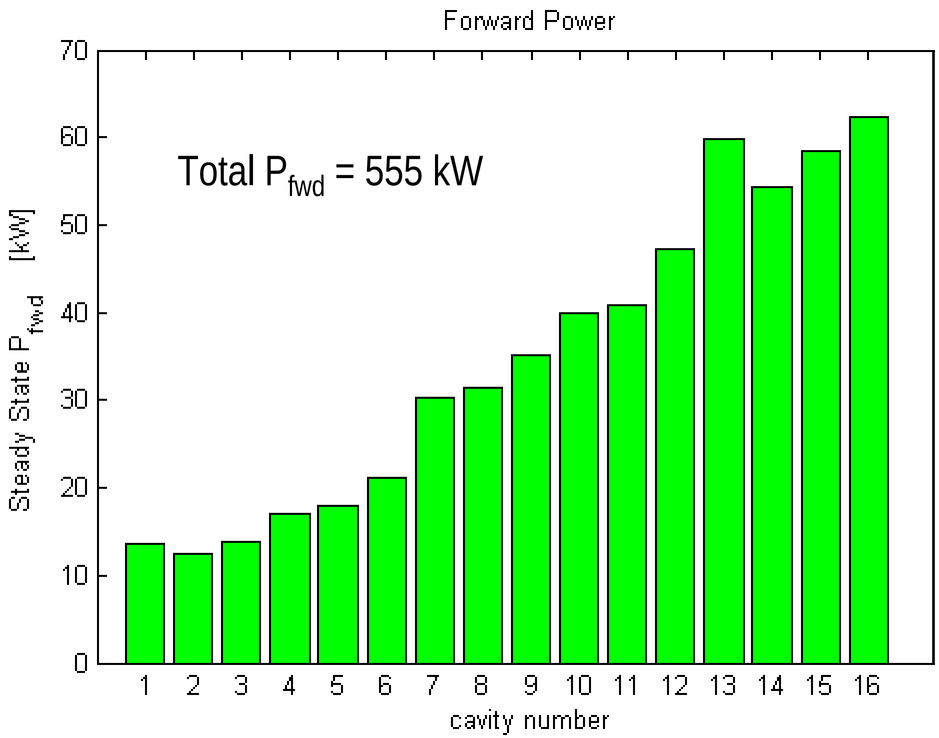
HINS – 16 cavity warm section

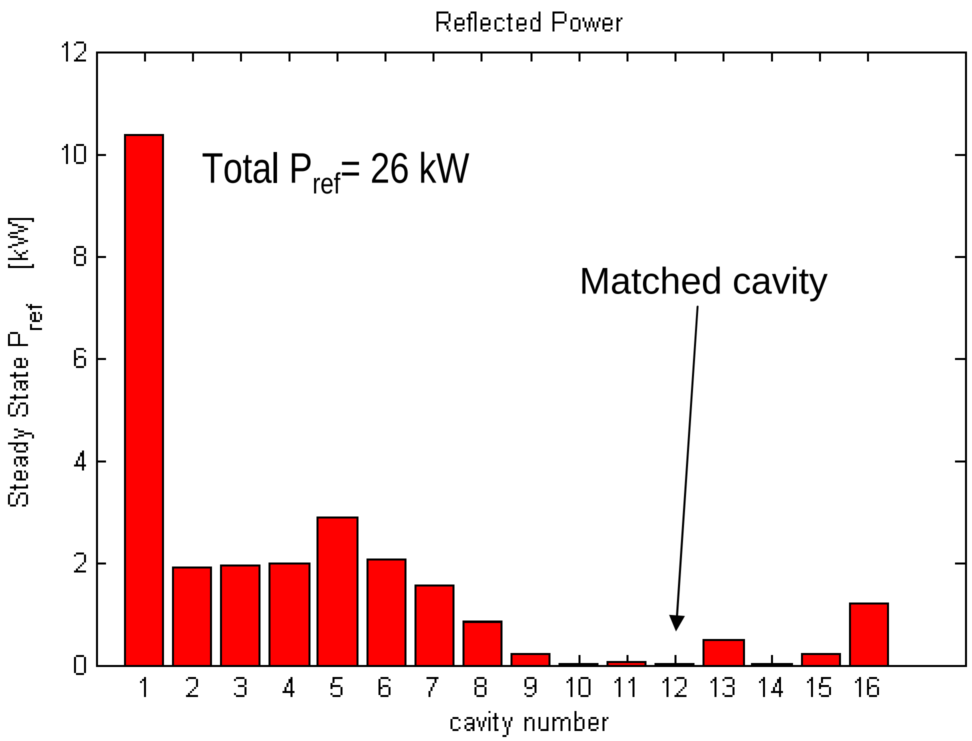
RF control: beam loading compensation

Using FF klystron amplitude and phase modulation

➔ Power analysis

Steady state power during beam loading





Path forward

- Steady state transfer function of the FVM has been measured and interpolated over the modulation range.
- An inverse transfer function has been developed to linearize RF control
- An approach has been developed to handle beam loading transients using a combination of klystron FF and individual cavity tuning
  (optimizing high klystron bandwidth to alleviate FVM burden)
- Model improvements include individual FB on FVM
- Implementation to drive 6 cavities with beam in near future (1½ year)

Thank you!

Back-up slides

Control algorithm

1. For 1 cavity, compute klystron A and Φ
   - → compensate beam loading for one cavity
   - → zero reflected power for one cavity

2. Before RF pulse, tune FVMs for all cavities
   - → power amplitude coupling
   - → power phase coupling

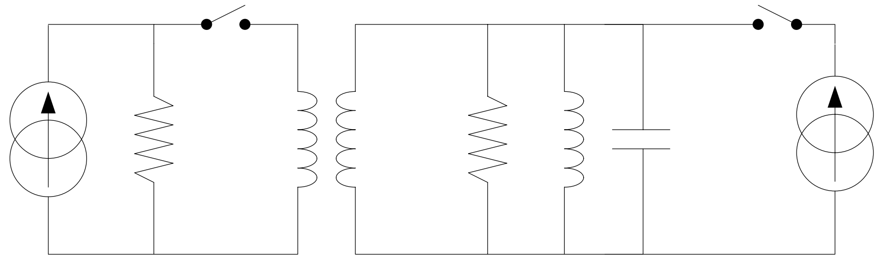
$$\alpha = \frac{I_b}{I_k} \frac{1}{\sqrt{1 + A^2 - 2A\cos\Phi}} \qquad \Psi = \Phi s + \Phi + \cos^{-1}\left[\frac{A - \cos\Phi}{\sqrt{1 + A^2 - 2A\cos\Phi}}\right]$$

3. Before RF pulse, tune cavities
   - → loaded Q_L
   - → cavity detuning

$$Q_L = \frac{2Vcav}{I_b\, R/Q} \frac{\sqrt{1 + A^2 - 2A\cos\Phi}}{\cos\Psi} \qquad \Delta f = \frac{f0}{2Q_L}\tan\Psi$$

4. RF pulse
   - → at beam arrival time, klystron modulation A, Φ
   - → nothing else changes

Simulation Model: cavity



Solving the RLC electrical model of a cavity → 2nd order differential equation

$$\ddot{\mathbf{V}}(t) + \frac{\omega_0}{Q_L}\dot{\mathbf{V}}(t) + \omega_0^2\mathbf{V}(t) = \frac{\omega_0 R_L}{Q_L}\dot{\mathbf{I}}(t)$$

1st order solution to the equation above:

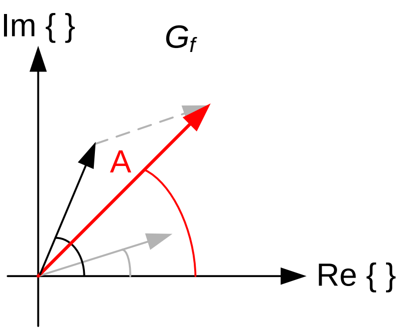
$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix}$$

$V_{cav} = (V_r + j.V_i)$ is a function of the cavity detuning $\Delta\omega$, the cavity half bandwidth $\omega_{1/2}$, the cavity loaded resistance R_L and the current inside the cavity $I_t = I_g + I_b = (I_r + j.I_i)$

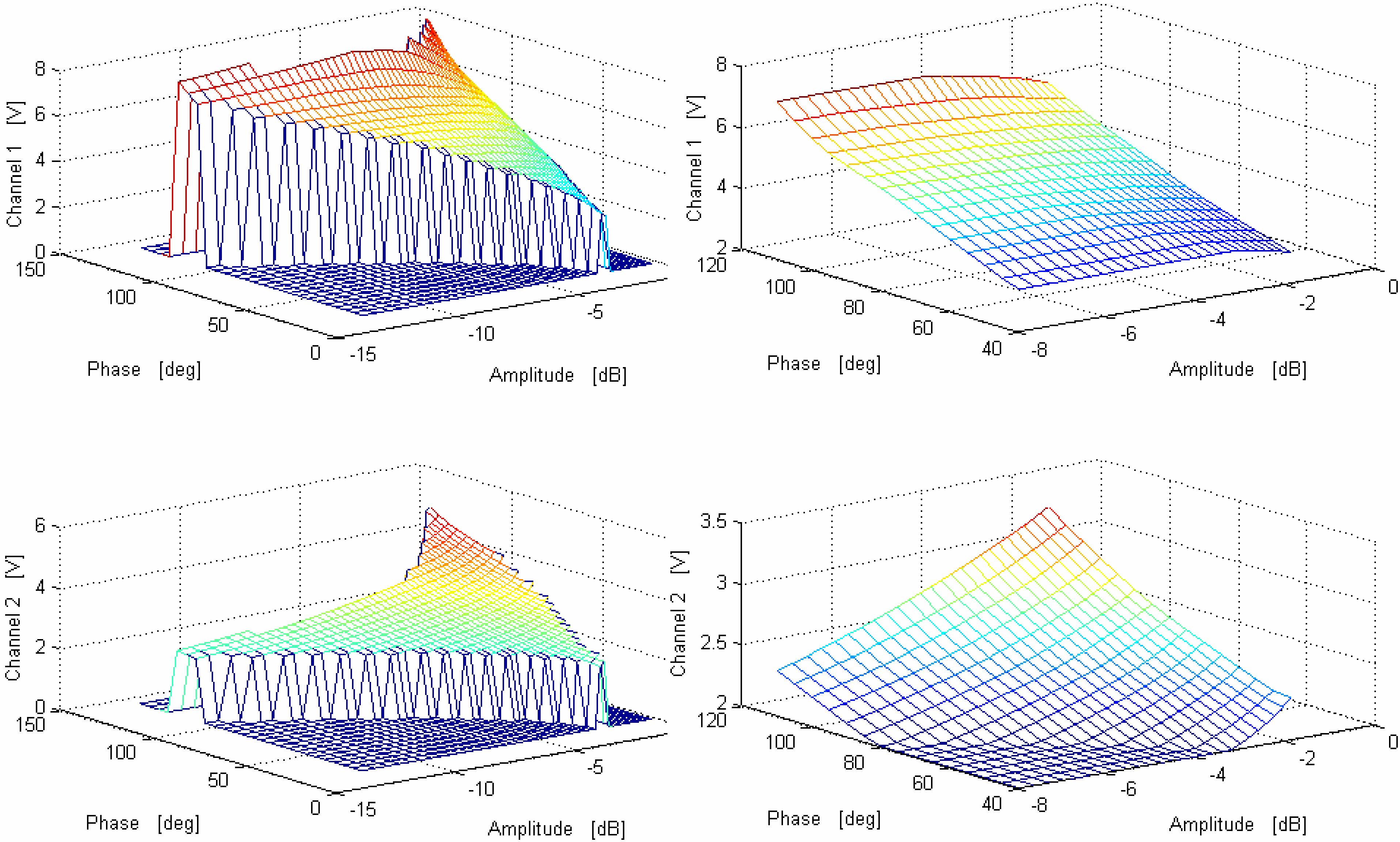
I_g

Simulation Model: FVM

- each cavity has its own: Q_0, V_0, Φ_s, ψ, Q_L
- P_{fwd} A/Φ modulation is unique to each cavity
- using one FVM for each cavity

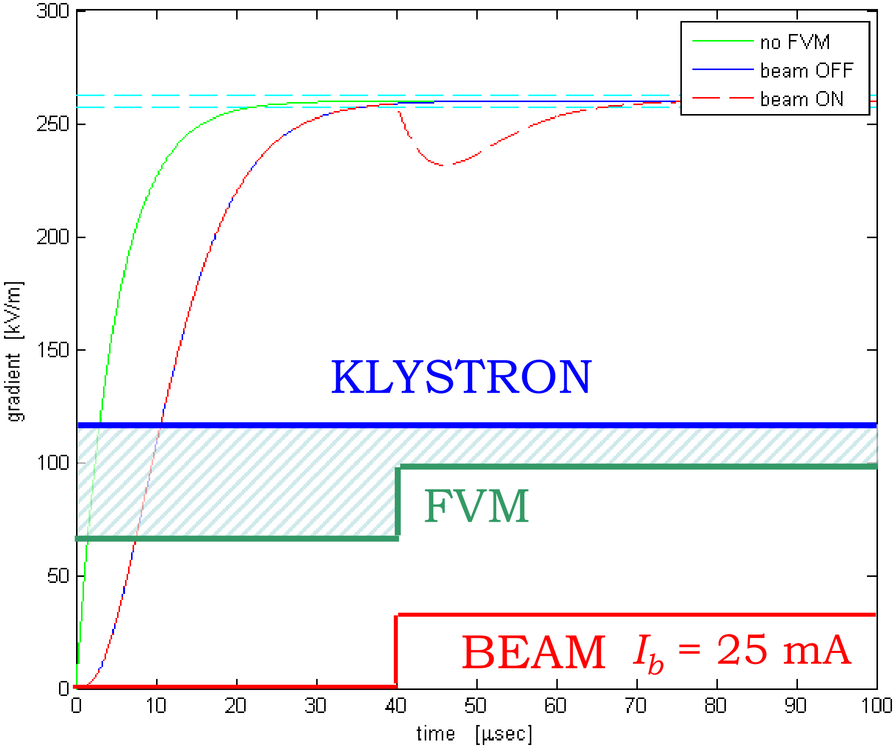


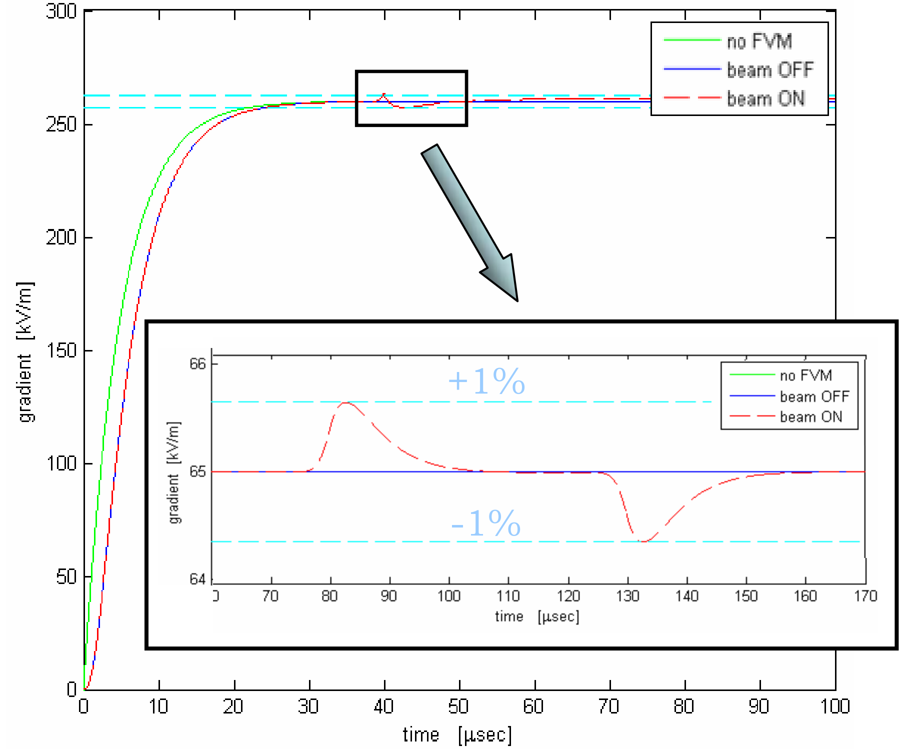
Controlling the FVM: domain limitations



RF control: beam loading compensation:

FVM only





- "warm" cavity Q_L ~ 5000
- rise time τ ~ 30 usec
- beam arrival during steady state
- slow FVM response time

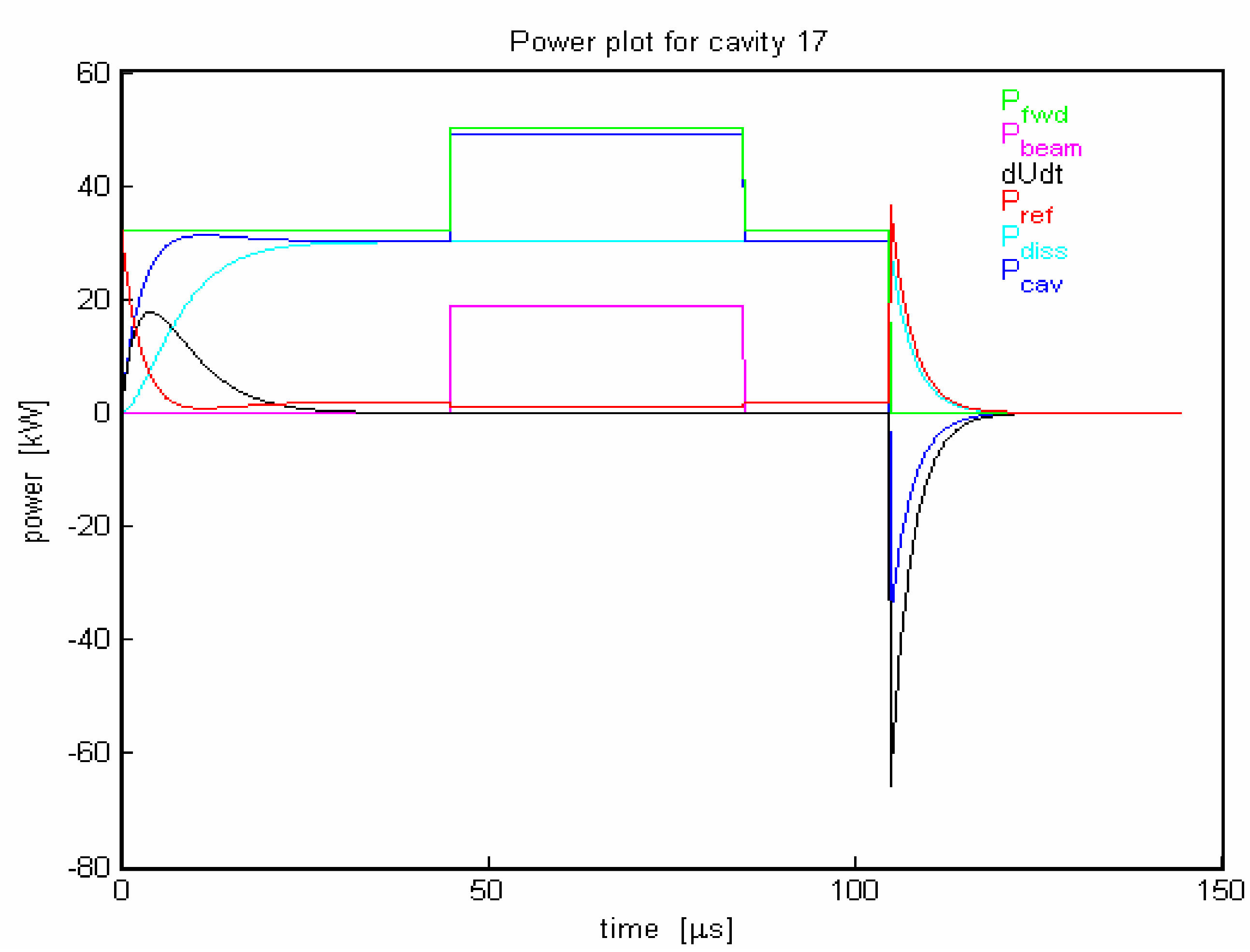
- ramping beam over 50 μsec
- anticipate FVM response
- introduce pole cancellation
- ability to regulate beam loading ±1% amplitude

RF control: beam loading compensation

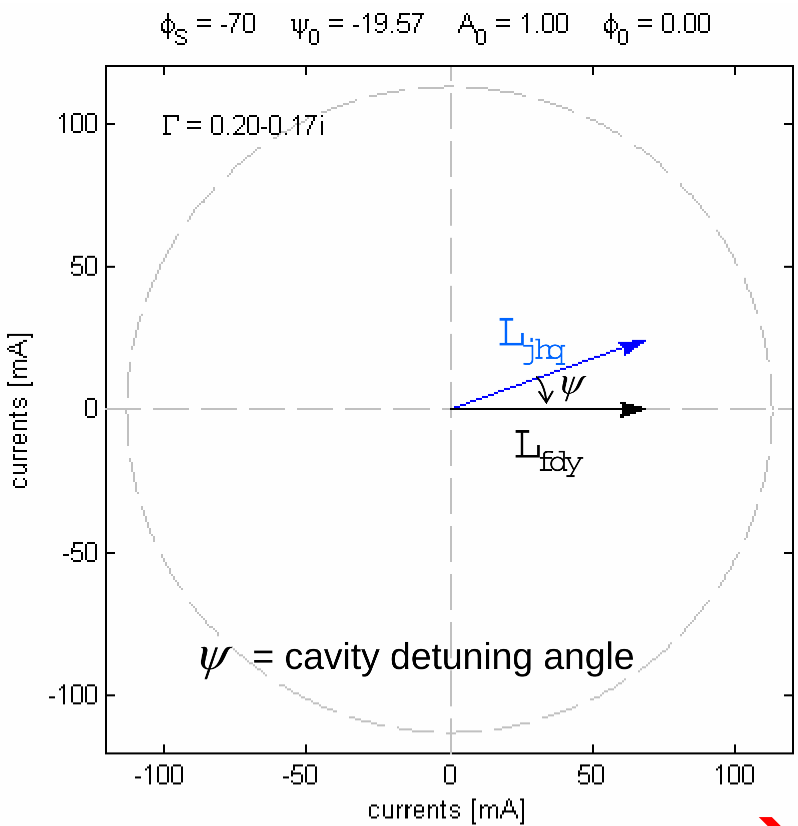
Using FF klystron amplitude and phase modulation

→ Power analysis

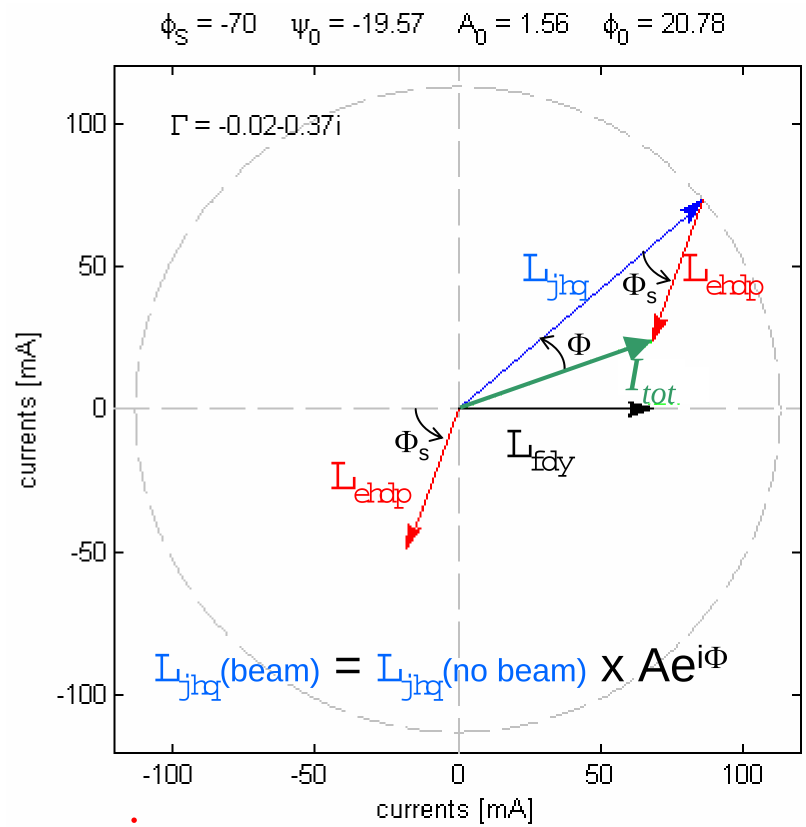
Power variations during a pulse



RF control: beam loading compensation
Using FF klystron amplitude and phase modulation



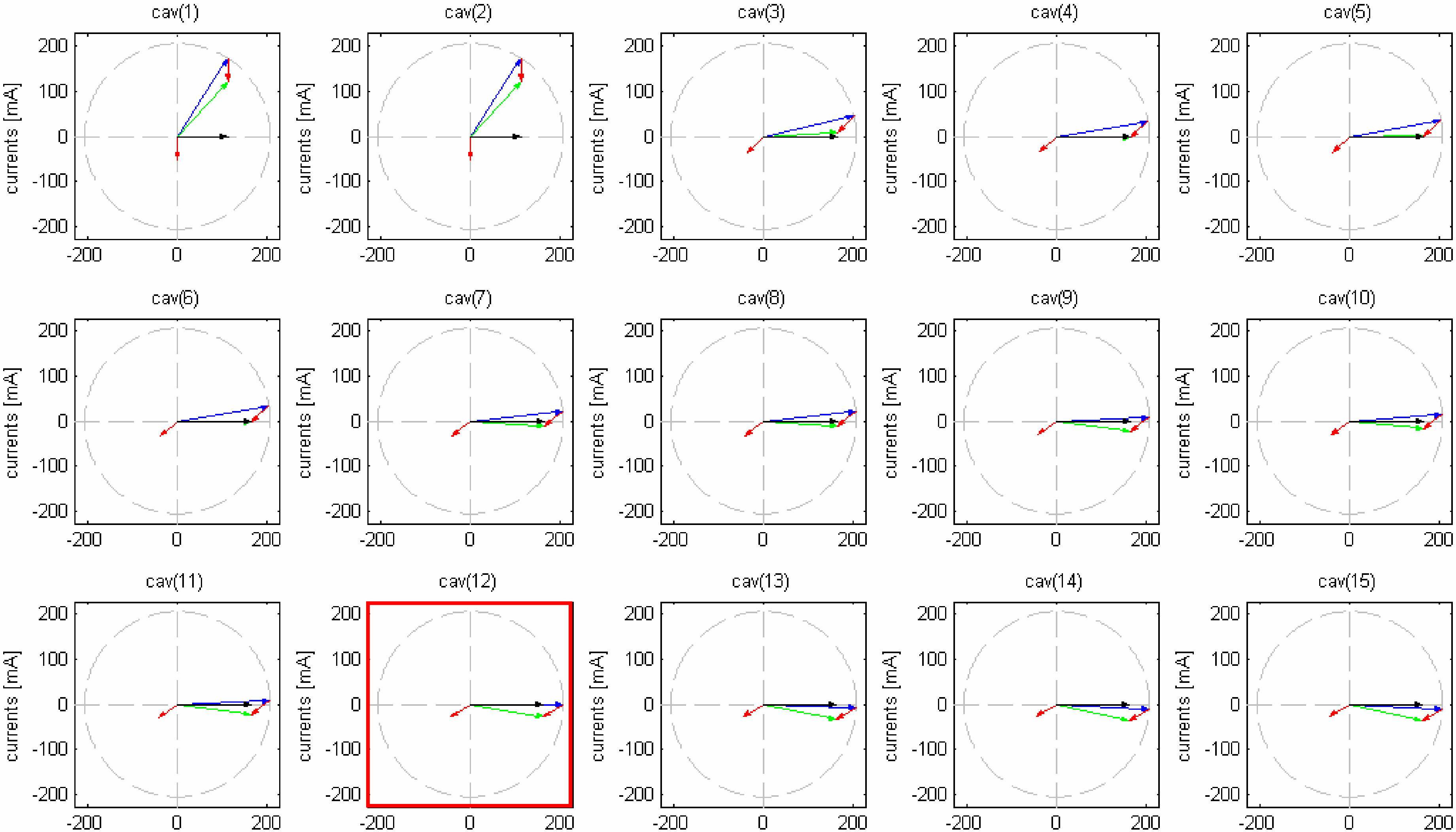
Beam OFF

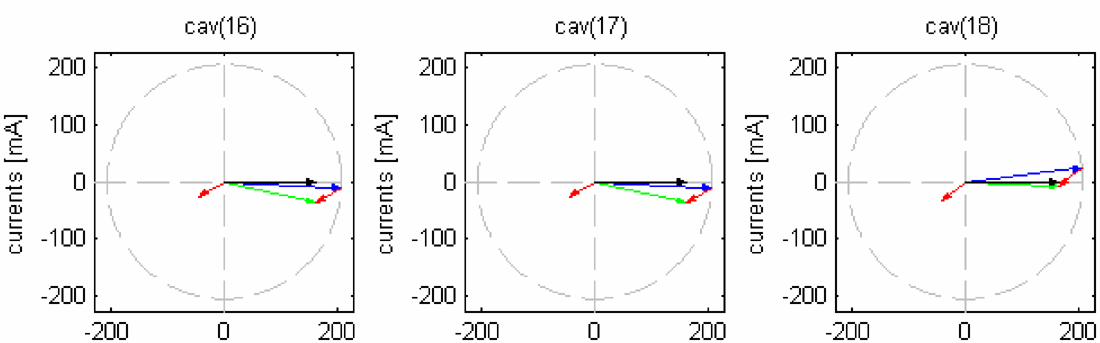


Beam ON

➔ No dynamic use of FVM

Assuming nominal beam loading, there is no need to modulate the klystron forward power using the ferrite vector modulator if Lwrw(beam OFF) = Lwrw(beam ON)





18 normal conducting cavities

Cavity 12 is matched ($P_{ref} = 0$)

A = 1.25 , $\Phi = 10°$

Total P_{fwd} = 480 kW

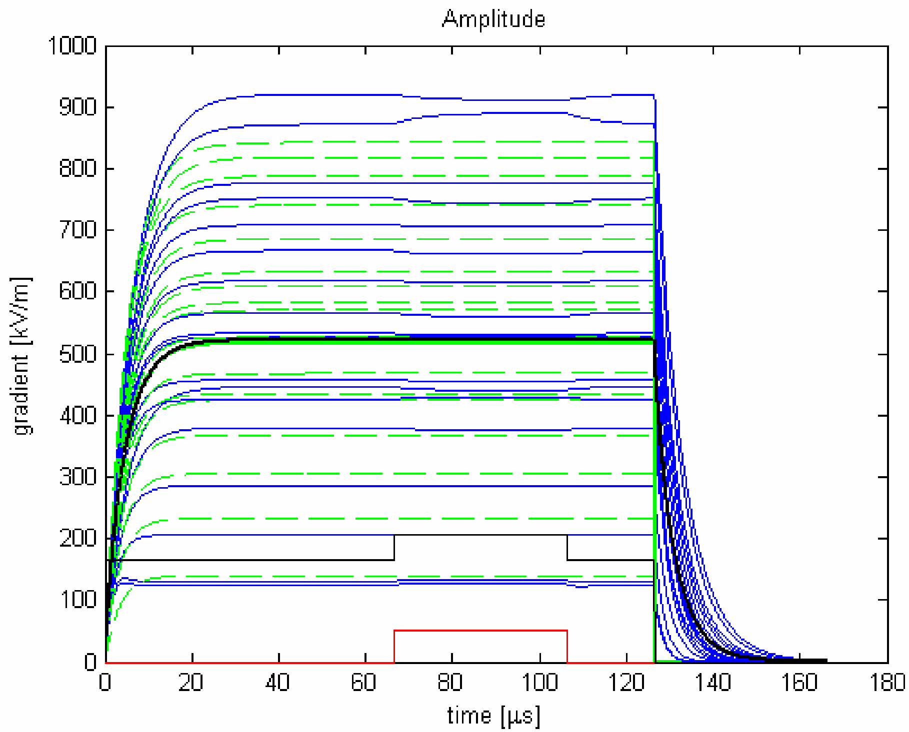
Total P_{ref} = 6.85 kW

Introducing variations in detuning ($\delta\omega$) and in loaded Q (δQL)

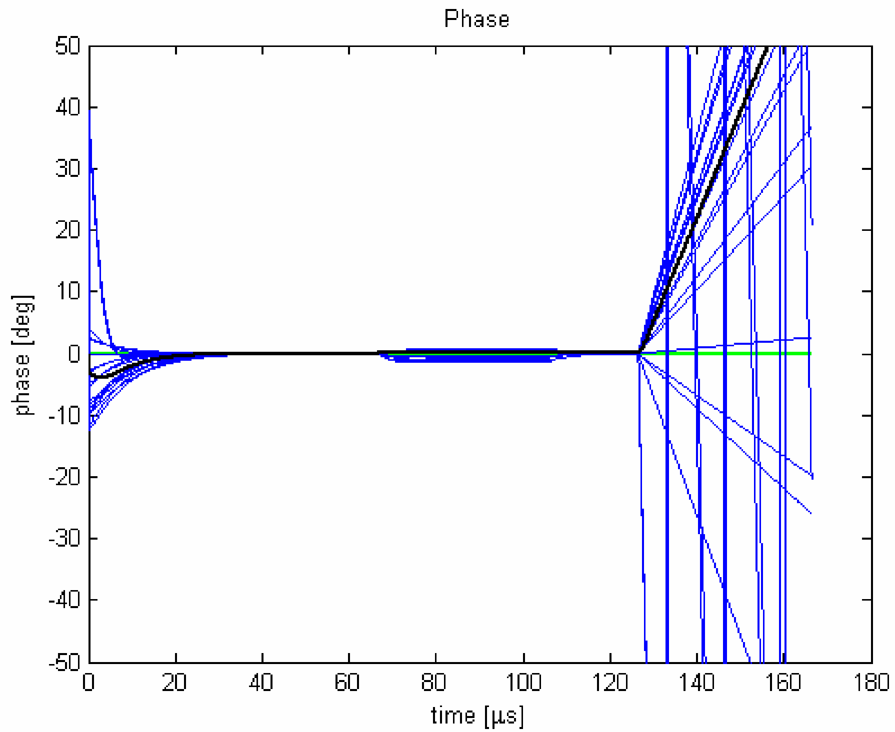
$\delta\omega$ = 2π x 2.5kHz (~6%)

δQ_L = 500 (~12%)

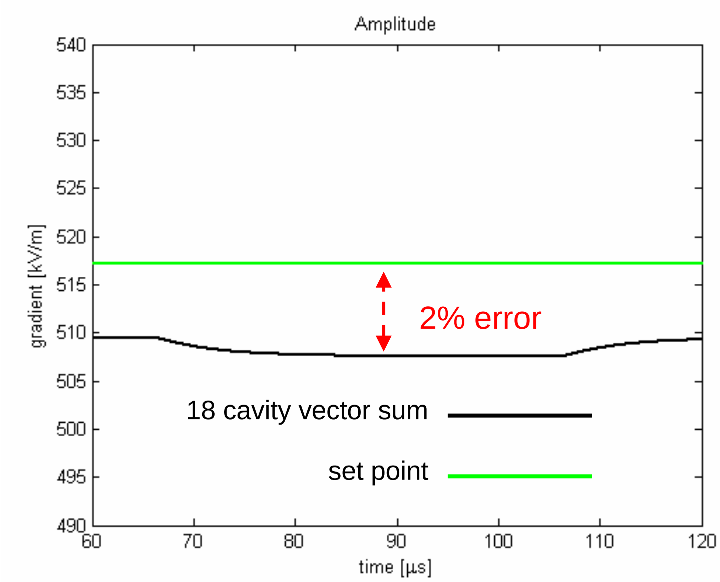
vector sum amplitude error: 2%



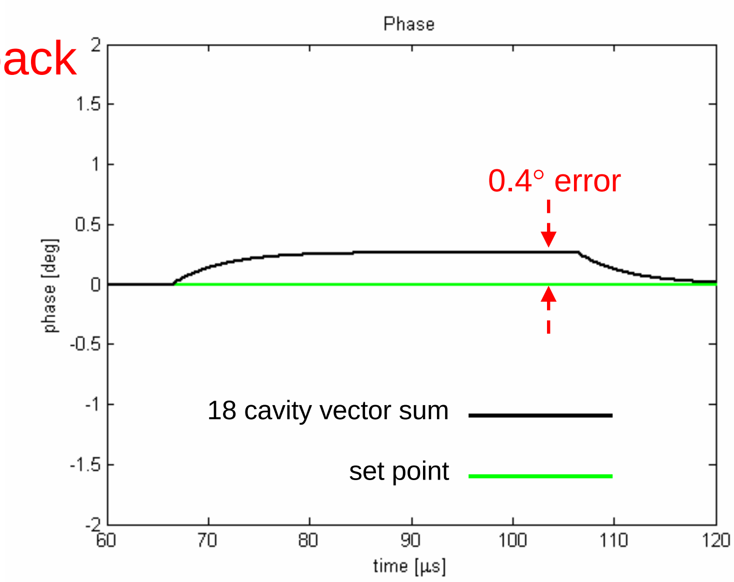
vector sum phase error: 0.5°

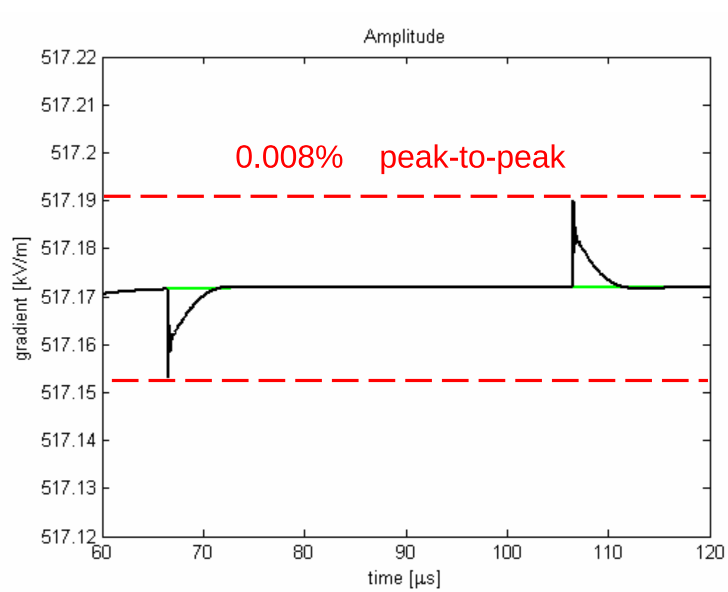


Introducing feedback



no feedback

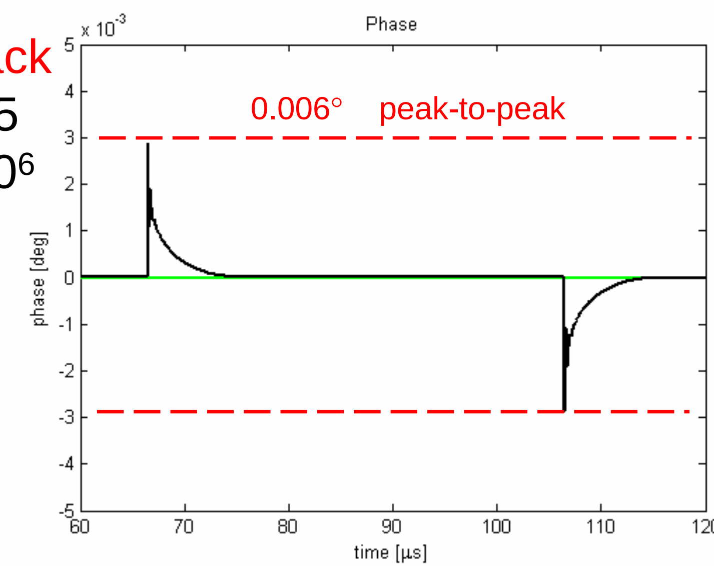




with
PI feedback

$K_P = 1.5$

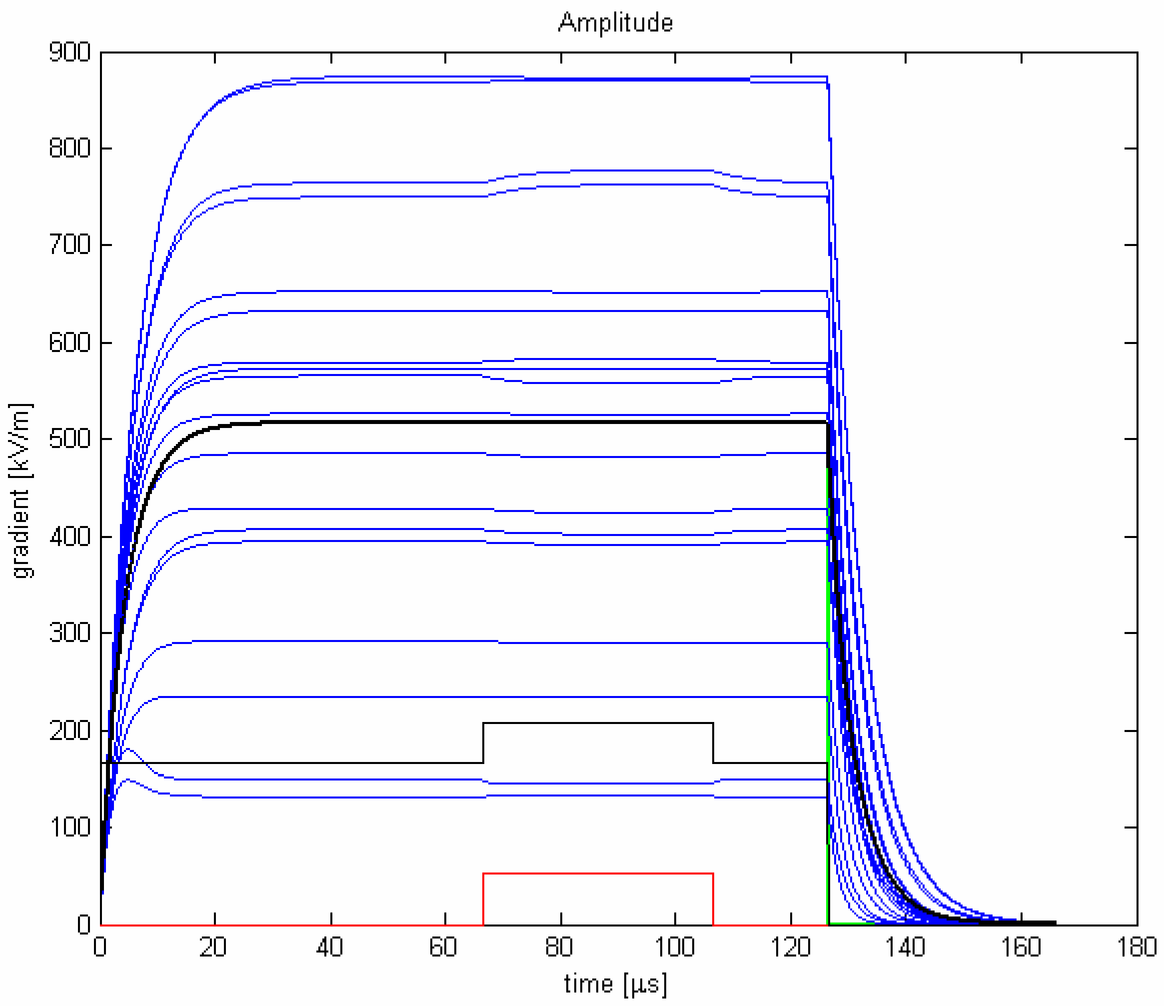
$K_I = 10^6$



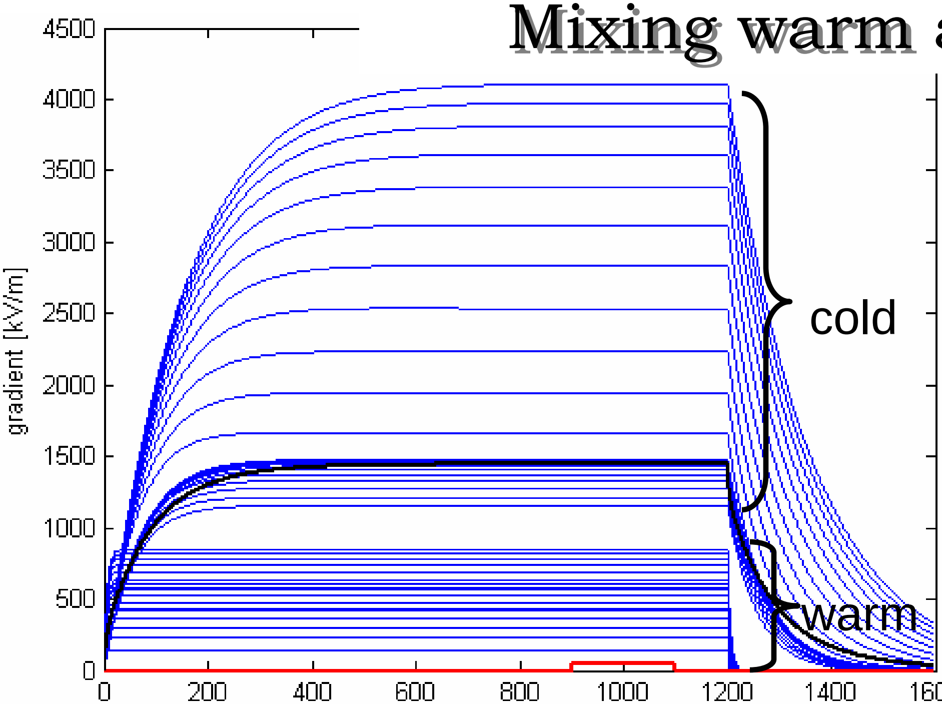
Introducing feedback

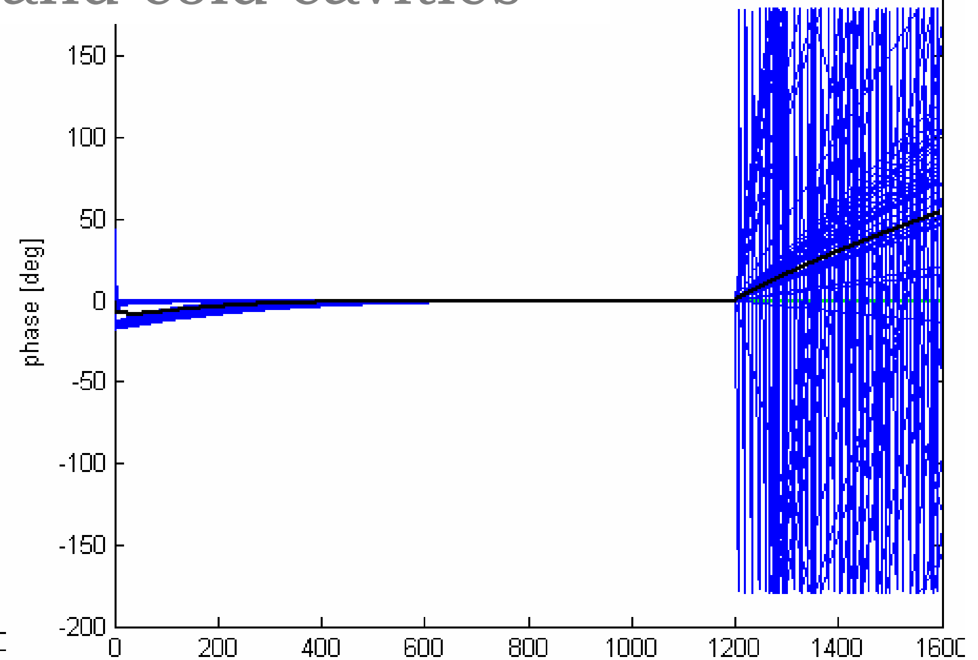
FB is on V_{sum} only

→ Individual cavities might still show beam loading



Mixing warm and cold cavities





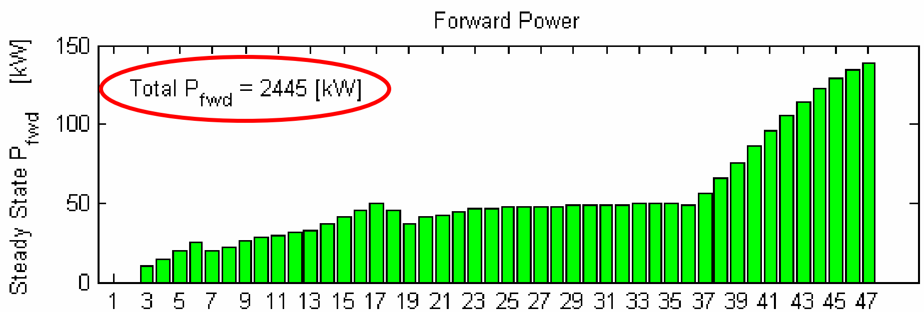
beam ON (900 usec)

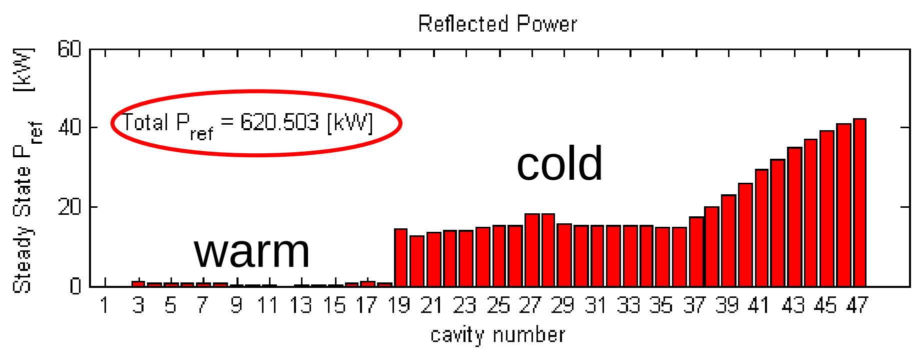
Fill time ~ **600-700 usec**

Total $\mathbf{P_{fwd}}$ **= 2.5 MW**

Total **Pref = 620 kW**

P_{ref} matched for cavity #12





Fermilab PAC09