Outlook of future studies to reach maximum gradient and current

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OVERVIEW

- What are the issues with each proposed RF Distribution scheme?
- Problems with changing RF pulse width
- 9mA solution at FLASH
- Automation
- Next steps
- Analytic solutions

What are the issues with each proposed RF Distribution scheme?

- Baseline
  - The tilts become worse with the spread of max cavity gradients
  - Best fit solutions require extra power overhead
  - Best overall solution from an RF control perspective is to sort cavities and match within RF Units
- KCS
  - Same issues as Baseline
  - Sorting may not be an option due to the large number of cavities in the unit
- DRFS
  - 2 or 4 cavity groups will be more sensitive to a single low cavity
  - Sorting is easy because of the small number of cavities in a unit
  - Reserve RF power is smaller on high gradient RF units

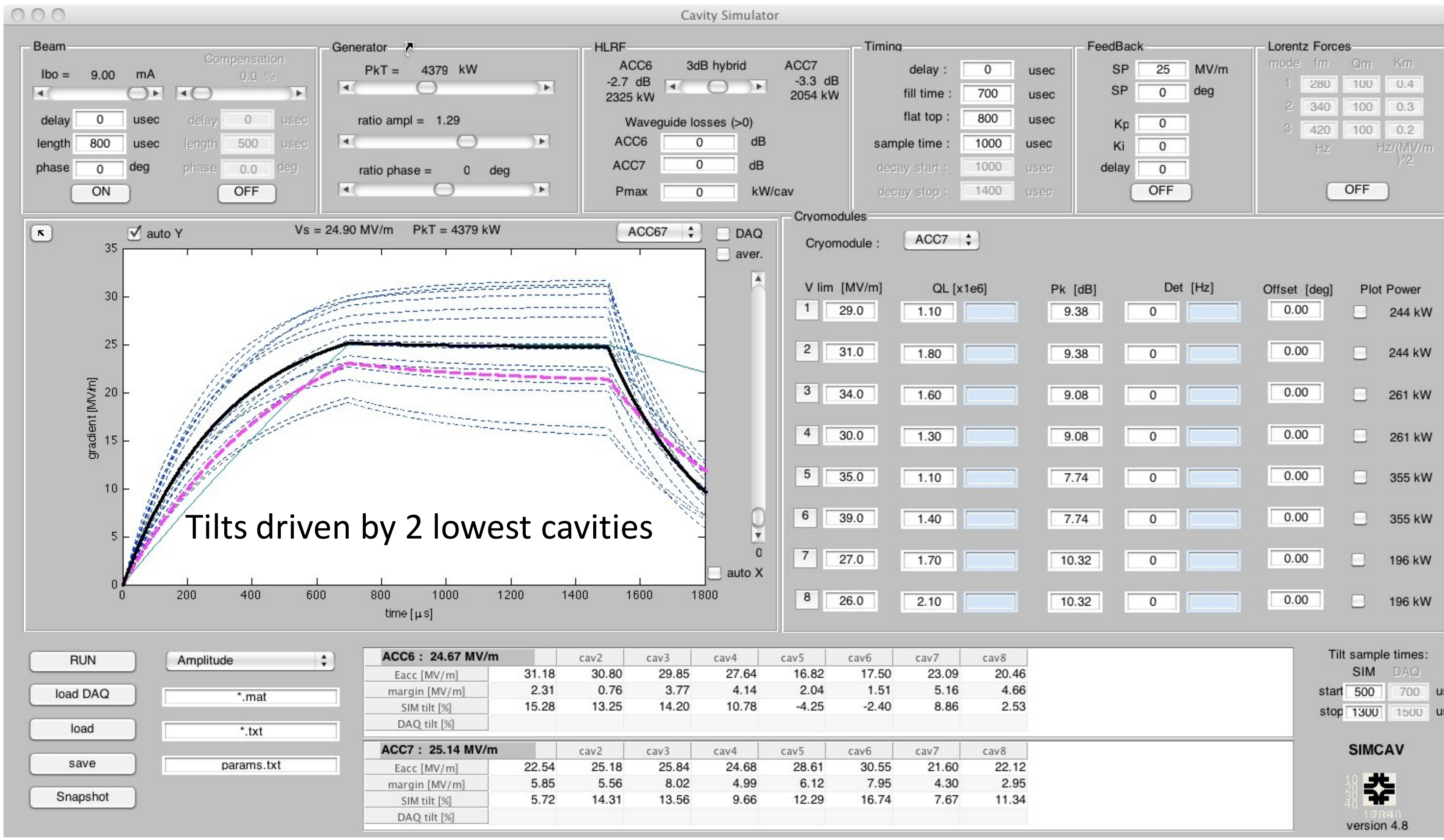
Effects of changing the RF pulse width as required by beam pulse width

- RF pulse length variation will affect the following systems
  - klystron, waveguide, LFD compensation, machine protection, cryogenics, instrumentation, adaptive FF, positron production, storage and cooling rings
  - Commissioning of RF systems can't be done at full gradient
  - Most of these can be engineered away – at the cost of operational complexity from lack of steady state operation

Configuration at FLASH for 9mA

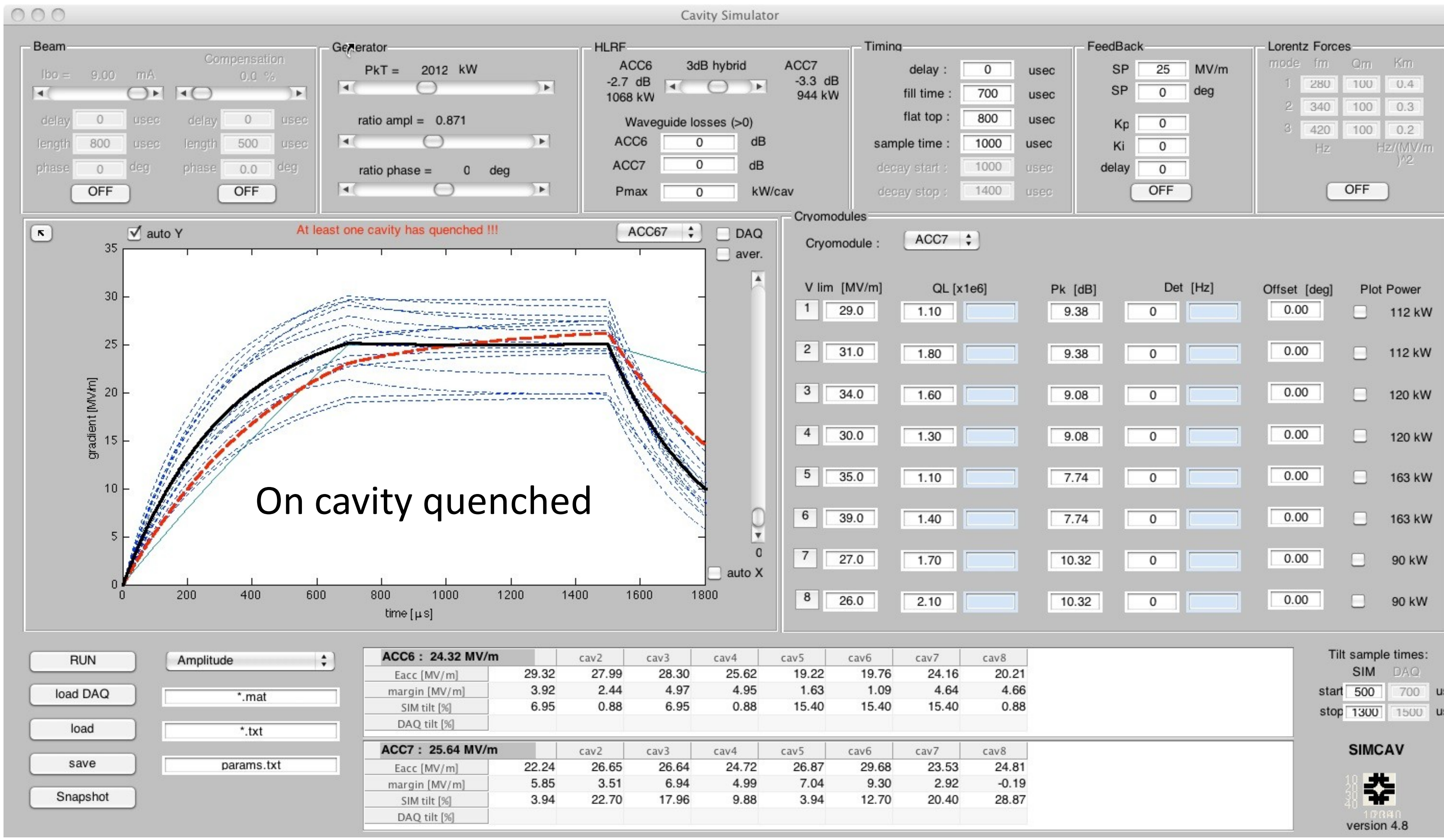
- It appears there is no solution to achieve 9mA current with flat gradients at FLASH using all cavities
- However
  - There are solutions if we allow some tilts
  - There may be solutions if the lowest gradient cavities are detuned from operation

Minimum Qs, 9mA Beam, 25 MV/m

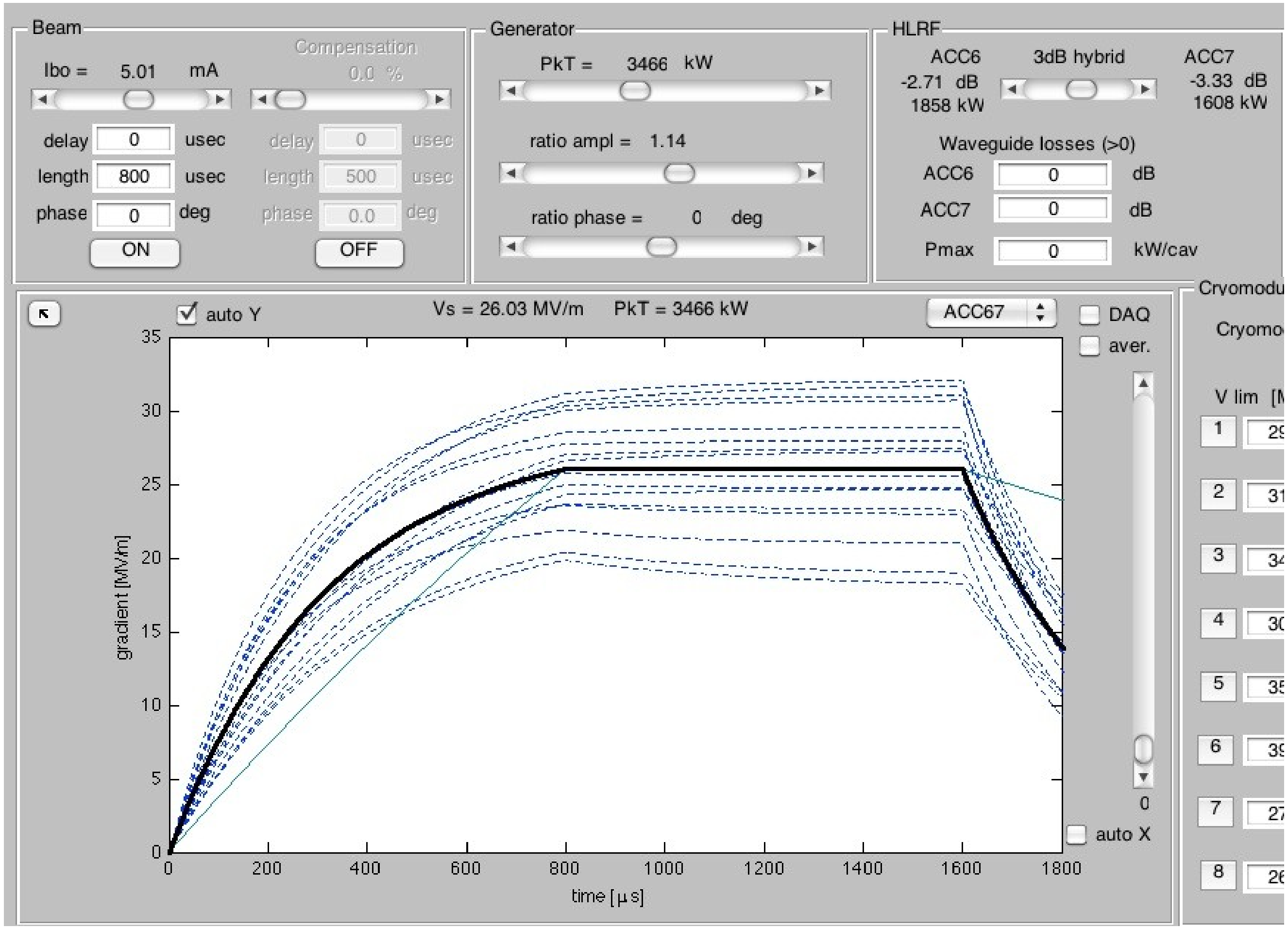


Qs are set at lowest values as measured in the last study

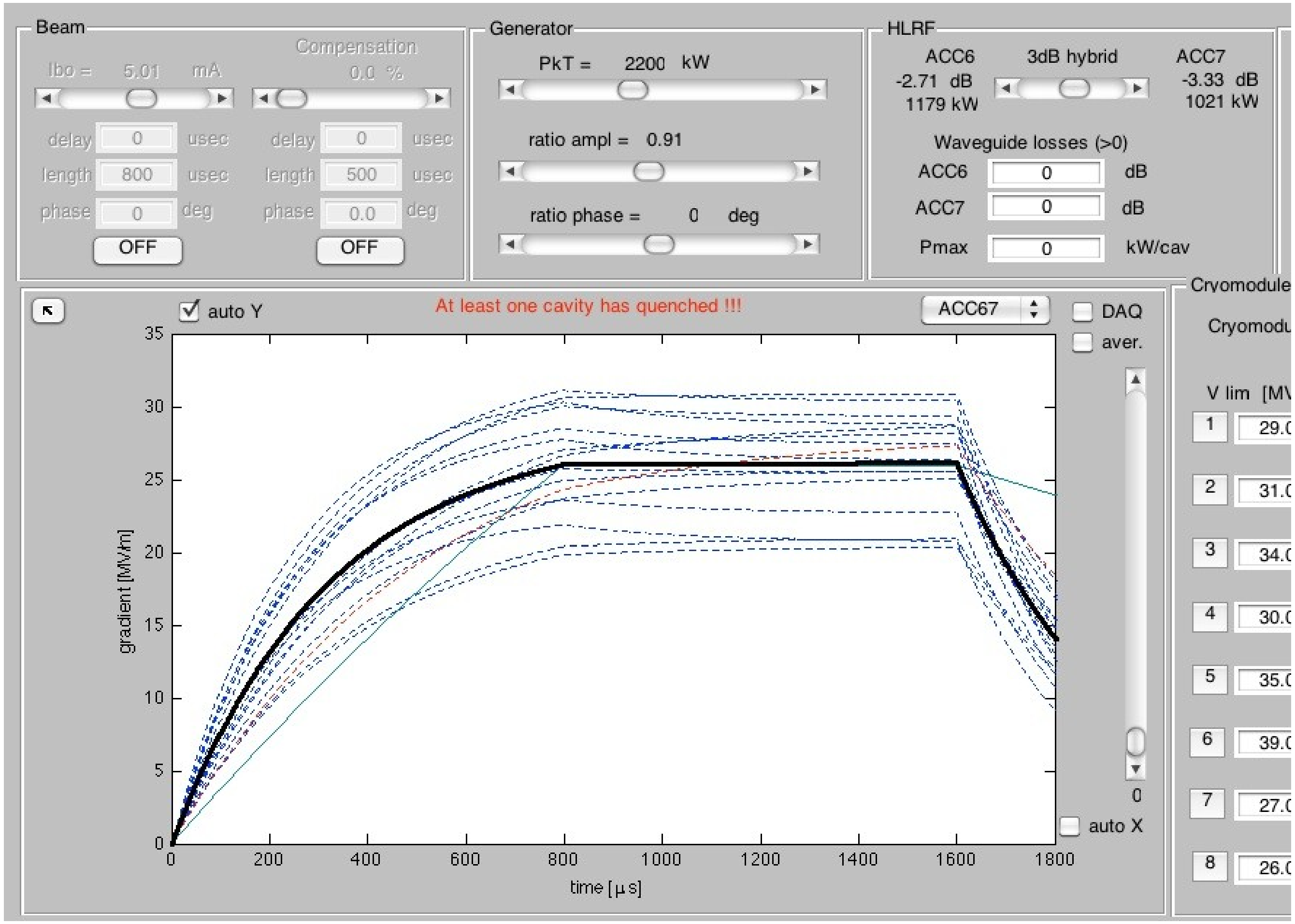
Minimum Qs, Beam Off



Setup for 5mA, 26 MV/m – Beam



Setup for 5mA, 26 MV/m – No Beam



Bringing up a linac

Traditional approach (i.e. FLASH)

1. Make target gradient with FF
2. Turn FB on
3. Compensate for LFD
4. Send a couple of pilot bunches (~10) (automated beam loading compensation)
5. Minimize losses
6. Gradually increase bunch length to full train (while minimizing beam losses)
7. Learning feed forward

One "possible" scenario for flat gradients

1. Bring cavity to their nominal gradient
   - ➔ typically: quench gradient -2-3 MV/m
2. Adjust Q_L so cavities are flat with beam
   - ➔ cavity will quench (because no beam)
3. Shorten pulse length to avoid quench
   - ➔ typically <200 usec for high beam currents Q_L's
   - ➔ can't see LFD effects (can't compensate for LFD)
   - ➔ can't walk pilot bunch across flat top
4. As you increase bunch length
   - ➔ increase flat top length
   - ➔ compensate for LFD
   - ➔ minimize losses
5. The LLRF quench monitoring system should
   - ➔ truncate the flat top length to prevent quenches
   - ➔ every time bunch train is shorter than expected

Slide - J. Branlard

Automation Needed for this Scheme

- Automate
  - Q measurement – settings
  - Resonance control (FNAL scheme?)
- Dynamic detuning measurements
- Linkage of RF pulse width, beam width and machine protection

Example Automation Loop to "Bring up a Linac"

- Identify desired gradient, beam current, pulse width
- Optimize cavity setup in model
- Automation controller loop
  - For(I_{beam} =0, 9, I_step)
    - For(t=0, t_final, t_step)
      - Set flattop = t
      - Measure (Q, detuning, forward and reverse power, field vector all cavities and vector sum)
      - Compare against model and determine errors
      - IF err exceed limits
        - Retune cavities
        - Test again
      - Else
        - Provide "RF OK (pulse width)" to machine protection
        - Compare beam loaded signals against model
        - IF pass, return to time loop
    - Return to beam loop
  - Beam loss and other exceptions will need to set "t" back to zero

Issues with this approach

- For a large machine, cavity tuning will need to be done in parallel or else the machine will never reach operational status
  - Sources of beam loss will be hard to trace to a single cavity or tuning action
  - Backlash and other non-linear controls will require sophisticated controllers
  - Tuning mechanisms are not designed for high duty factor movement

What to do next?

- Near and longer term - align efforts with FLASH 5 mA studies, NML and STF studies
  - Focus on LFD – getting the cavities flat
  - Automation of quench protection (predictive)
  - Automation of cavity Q adjustment
  - Automation of Lorentz Force Detuning
  - Measurements of dynamic detuning
  - Integration of cavity simulator into operations
    - (real-time data and real-time simulator)
  - Add cavity phase and detuning into the analytical equations

Analytical solution to the cavity tilt problem

- **Single Cavity Dynamic Equation:**

$$V_{cav_i}(t) = 2R_{L_i} I_{g_i}\left(1 - e^{-t/\tau_i}\right) \qquad t < t_0 \qquad (1)$$

$$V_{cav_i}(t) = 2R_{L_i} I_{g_i}\left(1 - e^{-t/\tau_i}\right) - 2aR_{L_i} I_{g_i}\left(1 - e^{-(t-t_0)/\tau_i}\right) - 2R_{L_i} I_b\left(1 - e^{-(t-t_0)/\tau_i}\right) + 2bR_{L_i} I_{g_i}\left(1 - e^{-(t-t_0)/\tau_i}\right) \qquad t > t_0 \qquad (2)$$

- Let's define *k*=a- *b* , and, $Q_L \cong \frac{2R_L}{(r/Q_0)}$ then equation (2) becomes:

$$V_{cav_i}(t) = Q_{L_i}(r/Q_0)\left[I_{g_i}\left(1 - e^{-t/\tau_i}\right) - kI_{g_i}\left(1 - e^{-(t-t_0)/\tau_i}\right) - I_b\left(1 - e^{-(t-t_0)/\tau_i}\right)\right] \qquad t > t_0 \qquad (3)$$

- K is the beam loading compensation ratio.
- This equation is only valid for detuning *Δω=0* and beam accelerated "on-crest".
- To get a flattop for $t > t_0$ (i.e. $V_{cavi}(t)$=constant) the t dependence in equation (3) must vanish for all $t > t_0$.

Analytical solution to the cavity tilt problem

- Solving for Q_{Li}

$$Q_{L_i} = \frac{\omega_c t_0}{2\ln\left(\frac{I_g \alpha_i}{kI_g \alpha_i + I_{b0}}\right)} \quad (4)$$

- Equation (4) has 3 “free” parameters I_g , k and t_0. (i.e. the total forward power, the beam loading compensation and the fill time). However, the free parameters are not so free because are constrained by the RF station energy and allowable Q’s (see next slide).

Analytical solution to the cavity tilt problem

The cavity voltages can be calculated by:

$$V_{cav_i}(t_0) = I_g (r/Q_0) Q_{L_i} \alpha_i \left(1 - e^{-t_0/\tau_i}\right) \qquad t = t_0 \qquad (5)$$

The desired vector sum by

$$V_{sum} = \frac{1}{N} \sum_{i=1}^{N} V_{cav_i}(t_0) \qquad (6)$$

And the desired total energy gain for 1.3GHz cavities operated "on-crest".

$$\Delta E_{RF} = \frac{(r/Q_0) I_g}{1.038} \sum_{i=1}^{N} Q_{L_i} \alpha_i \left(1 - e^{-\omega_0 t_0 / 2Q_{L_i}}\right) \qquad (7)$$

Analytical solution to the cavity tilt problem. Conclusions:

- The values of Q’s calculated by equation (4) not only need to be within the allowable Q’s but they must also satisfy equations (5) to (7).
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- During our shifts of Feb 2011 at FLASH the optimization was done by hand tuning, but a nonlinear system solver could be used to reach optimum Q values if they exist.
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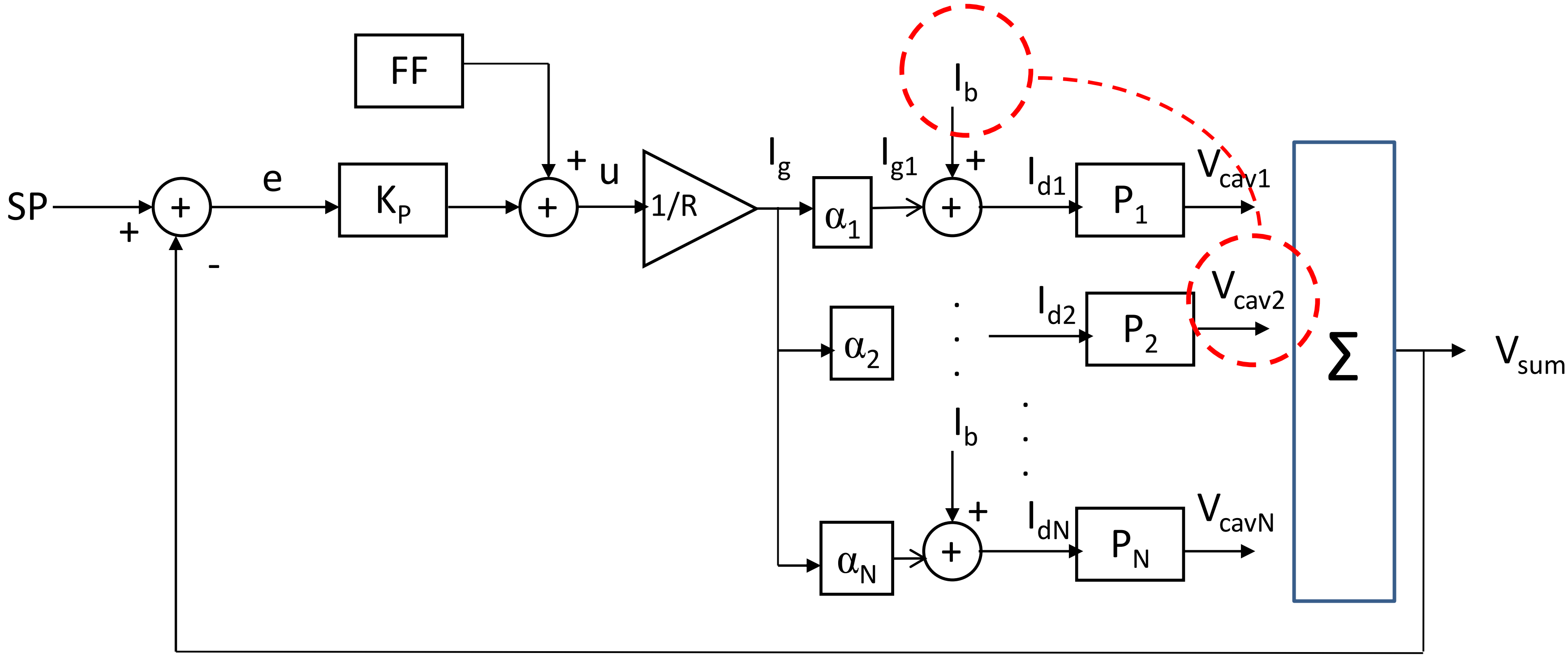
- These equations ONLY provide a solution to flattening of individual cavities, given that the solution exists, and for a given beam loading. Changing the beam loading will produce tilts. And, as is almost always the case, if the RF station is operated in closed loop mode, some cavities will approach or exceed their quenching limits.

Sensitivity to beam loading changes



- The RF loop is on the vector sum. However we are interested in individual cavity voltage variations as a function of changes in beam loading.

Sensitivity to beam loading

Gradient in cavity I as a function of beam loading and cavity transfer functions in closed loop:

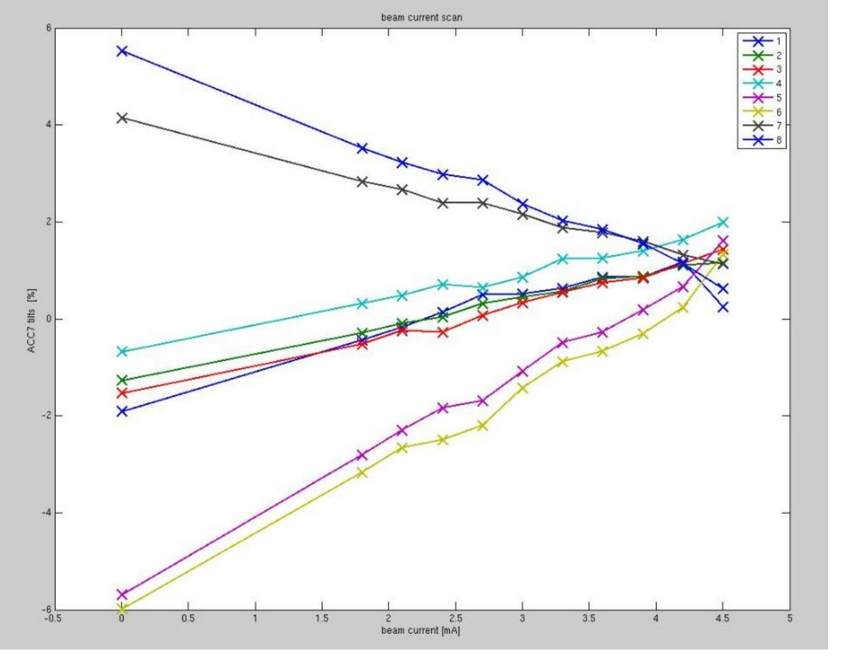
$$V_{cavi}(s) = I_b(s)T_i(s)\left[1 - \frac{\alpha_i \frac{Kp}{R}\frac{1}{N}\sum_{j=1}^{N} T_j(s)}{\left(1 + \frac{Kp}{R}\frac{1}{N}\sum_{j=1}^{N}\alpha_j T_j(s)\right)}\right]$$

(in frequency domain, Laplace transform)

Simplifying:

$$V_{cavi}(s) = I_b(s)T_{i\_CL}(s)$$

- The tilts have a linear dependence on change in beam loading, which was proved during the shifts of Feb 4-9, 2011



Sensitivity to beam loading

- From the last expression we can calculate the cavity tilts as a function of beam loading changes and cavity gradient spreads.
- I'm not done with this calculation but one can see that the tilts will be larger is the cavity spread is larger.