LLRF simulation update

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IN2P3/LPSC Grenoble

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Introduction

- In the XIV SuperB General Meeting a frequency domain simulation was presented, BUT:
  - Difficulty to access to the temporal response
  - How to include the non-linearities (klystron, preamplifier)?
  - Effect of the gap transient on cavity voltage, power demand?
  - Effect of the operating point on the loop stability (detuning, position on the klystron saturation curve, ...)?
- Need a time domain model!
- Using ideas developed for PEP2 $\rightarrow$ model under construction

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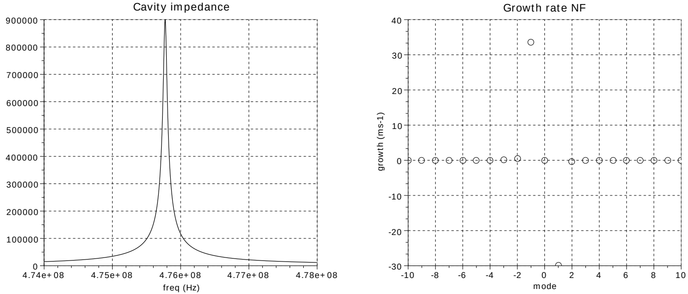
Instabilities and cavity impedance

- Instabilities growth rates proportionnal to the cavities impedance:

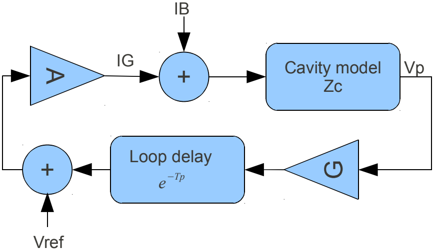
$$\tau_l^{-1} \approx \frac{eI_B F_{rf} \alpha}{2EQ_s} \left[Re\ Z_c(\omega_{rf} + l\omega_{rev} + \omega_s) - Re\ Z_c(\omega_{rf} - l\omega_{rev} - \omega_s) \right]$$

- Applying this to the detunned cavity impedance yields:



- Mode -1 growth rate is 33 ms^{-1} (baseline LER)
- Exceed the radiation damping rate (LER damping time =20.3 ms) $(1/\tau_{-1})/(1/\tau_d) \sim 670$

Direct RF feedback (1/2)



Expected impedance reduction

$$Z_{fbk}(\omega) = \frac{Z(\omega)}{1 + GAe^{-jT\Delta\omega} Z(\omega)}$$

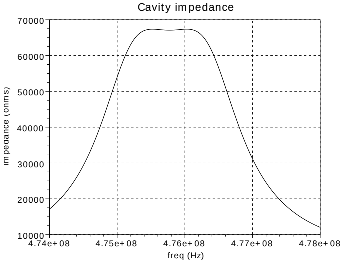
- In theory the highest gain GA is desired:
  - Maintain loop stability $\rightarrow$ Phase Margin is impacted by loop delay
  - Canonical value of PM $= \pi/4$ yields

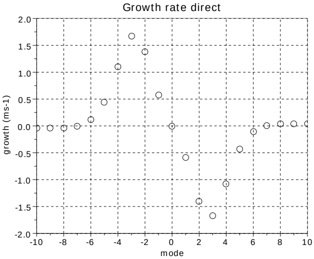
$$GAR \leq \frac{Q}{\omega_r} \frac{\frac{\pi}{4T} + 2\omega_r}{1 + \omega_r \frac{4T}{\pi}} = G_{max}AR$$

  - Impedance reduction limited by the loop delay T

Direct RF feedback (2/2)

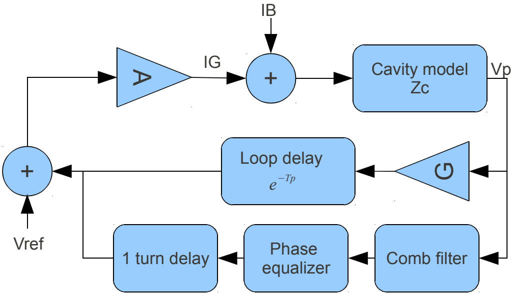
- Plots with loop gain $= 1.3 \times G_{max}AR$ (flat response) and T=440 ns (PEP2 delay value)





- Maximum impedance decreased by a factor of 12.8
- -1 Mode is damped by a factor of 20
- Side effect: other modes growth rates are increased!
- More impedance reduction is needed

Comb filter feedback principle

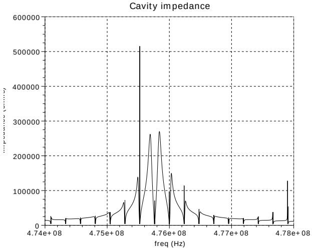


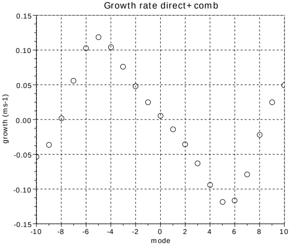
- Overcome loop delay limitation
- Correction applied with one turn delay
- Minimize impedance at certain frequencies

- Attenuation needed at synchrotron sidebands → dual peaked comb filter
- Out of klystron bandwidth, large dephasing → loop instability
  - Requires precompensation of the dephasing → phase equalizer
- Limitation comes from the gain margin of 10 dB at $\phi = \pi$
- The higher the comb gain the narrower the bandwidth
  - Must still cover the synchrotron bandwidth!

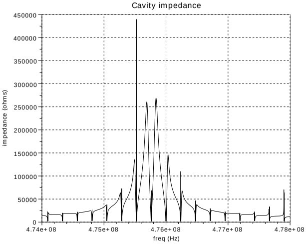
Frequency domain simulations

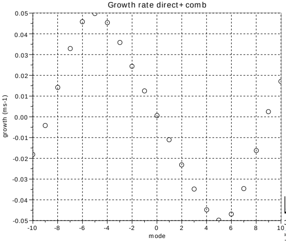
K=63/64

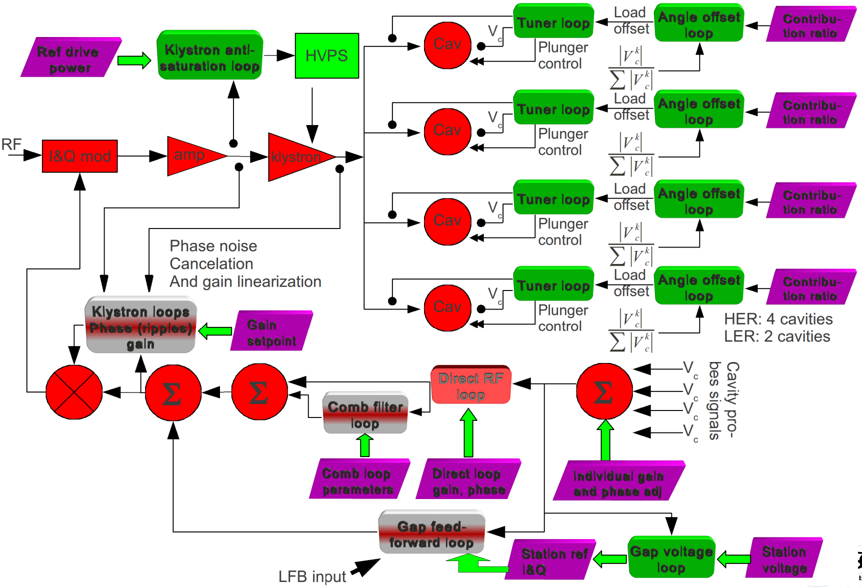




K=127/128
33 $ms^{-1} \rightarrow$
0.05 ms^{-1}







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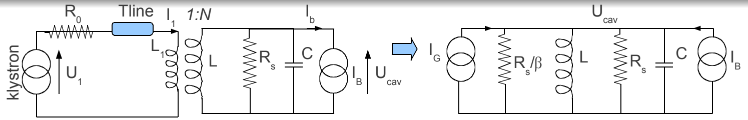
Coupled cavity model



- Inductive coupling:
  - $n^2 = \frac{Z_2}{Z_1} = \frac{L}{L_1}$
  - $n = \frac{U_{cav}}{U_1} = \frac{I_1}{I_2}$
  - $\beta = \frac{R_s}{n^2 R_0}$
- $R_l = \frac{R_s}{(1+\beta)}, \; Q_l = \frac{Q}{(1+\beta)},$ $\omega_r = \frac{1}{\sqrt{LC}}$
- $Y(\omega) = \frac{\beta+1}{R_s} + j\left(\omega C - \frac{1}{\omega L}\right)$
- $Z(s) = \dfrac{R_l \frac{\omega_r}{Q_l} s}{s^2 + \frac{\omega_r}{Q_l} s + \omega_r^2}$
- $\dfrac{d^2 V_c}{dt^2} + \dfrac{\omega_r}{Q_l}\dfrac{V_c}{dt} + \omega_r^2 V_c = \dfrac{R_l \omega_r}{Q_l}\dfrac{dI_c}{dt}$

- High intensity beam → cavity voltage perturbed by I_B
- Objective: maintain constant V_C
  - I_G contribution should compensate I_B
  - Modulation of I_B → modulation I_G

Cavity baseband model

- For faster simulation, cavity model is ported at baseband and modeled as a set of 2 complex equations

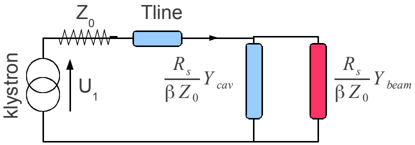
$$\frac{dV_{cr}}{dt} = -\frac{\omega_r}{2Q_l} V_{cr} - \Delta\omega V_{ci} + R_l \frac{\omega_r}{2Q_l} I_r \qquad (1)$$

$$\frac{dV_{ci}}{dt} = \Delta\omega V_{cr} - \frac{\omega_r}{2Q_l} V_{ci} + R_l \frac{\omega_r}{2Q_l} I_i \qquad (2)$$

- Using state space representation (easy to implement in simulators)

$$\frac{d}{dt}\begin{bmatrix} V_{cr} \\ V_{ci} \end{bmatrix} = \begin{bmatrix} -\frac{\omega_r}{2Q_l} & -\Delta\omega \\ -\Delta\omega & -\frac{\omega_r}{2Q_l} \end{bmatrix} \begin{bmatrix} V_{cr} \\ V_{ci} \end{bmatrix} + R_l \frac{\omega_r}{2Q_l} \begin{bmatrix} I_r \\ I_i \end{bmatrix} \qquad (3)$$

Klystron load - reflected power



- $Y_{cav} = \frac{1}{R_s} + j\frac{Q}{R}\delta$
- Where $\delta = \frac{\omega}{\omega_r} - \frac{\omega_r}{\omega} \approx 2\frac{\omega - \omega_r}{\omega}$
- $Y_{beam} = \frac{I_b}{V_{cav}} e^{j\phi_s}$

- Reflection coefficient $\rho = \frac{\beta - 1 - \frac{R_s I_b}{V_{cav}}\cos\phi_s - jR_s\left(\frac{\delta Q}{R} + \frac{I_b}{V_{cav}}\sin\phi_s\right)}{\beta - 1 - \frac{R_s I_b}{V_{cav}}\cos\phi_s + jR_s\left(\frac{\delta Q}{R} + \frac{I_b}{V_{cav}}\sin\phi_s\right)}$
- β optimized for nominal current $\beta = \left(1 + \frac{R_s|\vec{I_B}|}{|\vec{V_{cav}}|}\cos\phi_s\right)$
- Cavity optimal tuning $\delta = -\frac{R}{Q}\frac{I_b}{V_{cav}}\sin\phi_s = -N_c\frac{R}{Q}\frac{I_b}{V_{acc}}\sin\phi_s$
- Klystron delivered power $P_{out} = P_{FWD} + P_{REF} = \frac{V_{FWD}^2}{Z_0} + \frac{V_{REF}^2}{Z_0}$
- $I_g = \frac{1}{n}\frac{V_{FWD}}{Z_0}$, where $n = \sqrt{\frac{R_s}{\beta Z_0}}$

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Beam/cavity interaction

Longitudinal dynamics

- Oscillations around the synchronous phase described by:
  $$\ddot{\tau}_n + 2d_r\dot{\tau}_n - \alpha\frac{eV_{rf}(\tau_s + \tau_n) - U_0}{E_0 T_{rev}} = 0$$
  - τ_s is the synchronous particle time arrival
  - τ_n the time deviation of the bunch n from the synchronous time
- One equation per bunch! But mode count = bunch count
- $\Rightarrow$ Use macro bunches (30 instead of 978 bunches for LER baseline)

Macro-cavity

- One klystron supplying one macrocavity is considered:
- $V_{acc} = N_c \times Z_{cav} \times [I_{beam} + I_g]$
- Simulation performed at baseband, each bunch features:
  - An amplitude (used to model gap transient)
  - A phase ϕ ($= \phi_s + \phi_n = \omega_{rf}\tau_s + \omega_{rf}\tau_n$)

Beam dynamics in state space representation

- Equation in Laplace domain:

$$\tau_n = \alpha \frac{eV_{rf}(\tau_s + \tau_n) - U_0}{E_0 T_{rev}} \frac{1}{p^2 + 2d_r p} \quad (4)$$

- State space:

$$\frac{dx(t)}{dt} = \begin{bmatrix} -2dr & 0 \\ 1 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} (eV_{rf}(\tau_s + \tau_n) - U_0) \quad (5)$$

$$\tau_n = \begin{bmatrix} 0 & \frac{\alpha}{E_0 T_{rev}} \end{bmatrix} x(t) \quad (6)$$

Where $V_{rf}(\tau_s + \tau_n)$ is the in-phase (I) part of the cavity voltage at the macrobunch arrival time

- Macrobunch current phase: $\phi_n = \omega_{rf} \tau_n$

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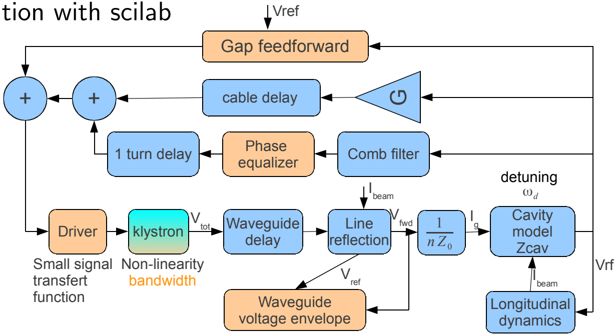
Time domain simulation

- Simulation with scilab



- Effect of non optimal detuning (klystron power)
- Klystron non-linearity effect (can be corrected in the FPGA)
- Small signal driver transfer function (was non linear in PEP2)
- Blocks in orange are not modeled yet (see next slide)

Time domain simulation

Blocks not yet simulated

- Klystron BW $\rightarrow$ phase equalizer (number of damped modes)
- Waveguide voltage envelope, simulate beamloss at full detuning
- Gap feedforward to limit the gap transient effect
- Driver small signal transfer function (see next slide)

Loops not simulated

- Cavity tuning loops (slow, fixed detuning $\Delta\omega$ is used per simulation)
- Gap voltage loop (slow, minimizes the error at fundamental RF between gap and Vref)
- Klystron anti saturation loop (slow, fixed working point)
- Klystron phase noise cancellation loop

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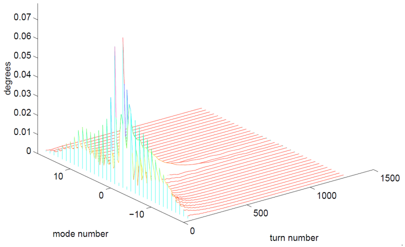
Expected benefit

- Growth/damping rates → for each turn, FFT of the recorded bunch phases

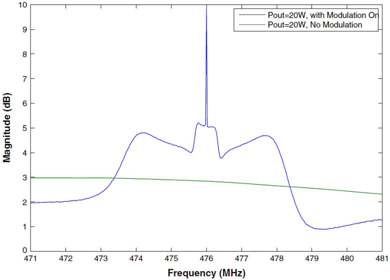


Extracted from R. Tighe, RF feedback simulation results for PEP-II, PAC95

- Gap feed forward can be tested/adjusted
- Reflected power monitoring (during uncorrected gap transient or beam loss)
- Effect of non-optimal detuning

Lesson from PEP2, watch the driver!

- Influence of the klystron driver, tested with a two tones modulation (RF carrier + small signal)



Extracted from Phys.Rev.ST Accel.Beams 13:052802,2010

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Conclusion

- A tool to understand operational limitation (non-linear effects, non optimal detuning, ...)
- Simulation building blocks are ready
- Technical implementation in progress
- All blocks can be adapted with real system response (driver, klystron BW and saturation, ...)
- Availability of the klystron transfer function (it was measured for PEP2)?
- Using frequency domain simulation, the highest growth rate was about $0.05\,\text{ms}^{-1}$, to be compared to time-domain simulation as the model complexity increases

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