RF Power Requirements for Cavity Field Regulation (LLRF)

Shin Michizono, KEK

Brian Chase FNAL

Stefan Simrock DESY

- RF power overhead and its budget
- Perturbations and rf dissipation
- Case study: one cavity breakdown or Piezo failure
- Ql and VTO optimization
- Treaty points between LLRF and HLRF
- Questionnaire to HLRF

Background (required stability)

- Llrf stability requirements (@ ML and BC) are < 0.07%, 0.24deg.
- In order to satisfy these requirements, FB with proper FF control will be carried out.

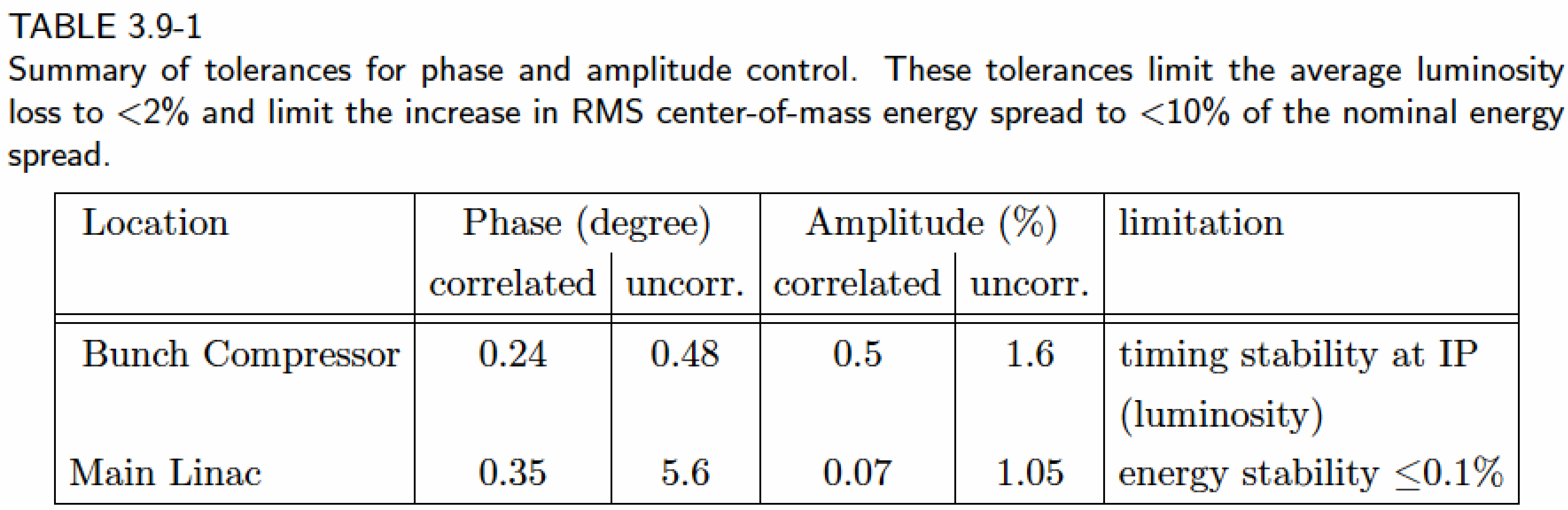


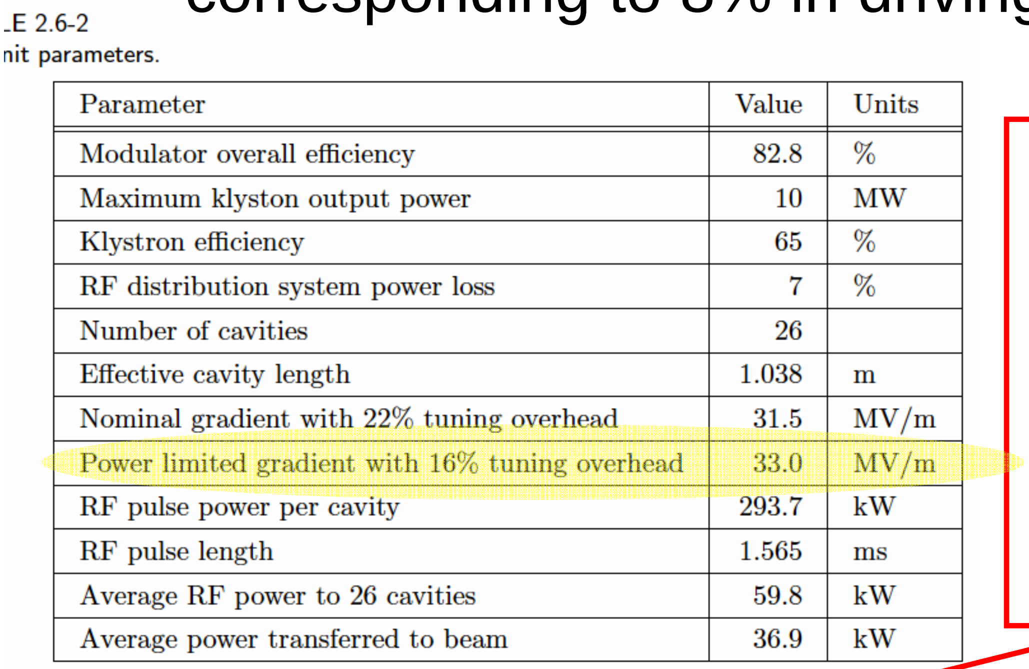
TABLE 3.9-1

Summary of tolerances for phase and amplitude control. These tolerances limit the average luminosity loss to <2% and limit the increase in RMS center-of-mass energy spread to <10% of the nominal energy spread.

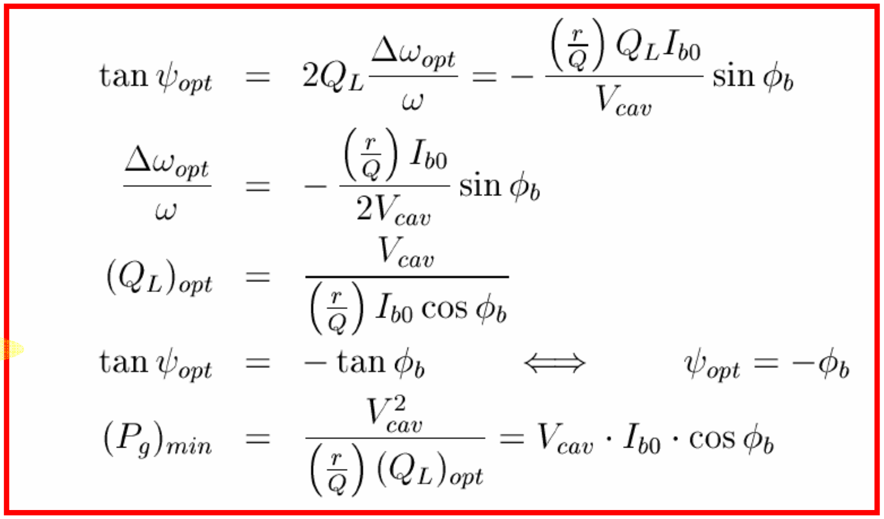
Location	Phase (degree)		Amplitude (%)		limitation
	correlated	uncorr.	correlated	uncorr.	
Bunch Compressor	0.24	0.48	0.5	1.6	timing stability at IP (luminosity)
Main Linac	0.35	5.6	0.07	1.05	energy stability $\leq 0.1\%$

Background (llrf tuning overhead)

- As in RDR, llrf tuning overhead is only 16% in power. corresponding to 8% in driving amplitude.


LE 2.6-2
nit parameters.

Parameter	Value	Units
Modulator overall efficiency	82.8	%
Maximum klyston output power	10	MW
Klystron efficiency	65	%
RF distribution system power loss	7	%
Number of cavities	26	
Effective cavity length	1.038	m
Nominal gradient with 22% tuning overhead	31.5	MV/m
Power limited gradient with 16% tuning overhead	33.0	MV/m
RF pulse power per cavity	293.7	kW
RF pulse length	1.565	ms
Average RF power to 26 cavities	59.8	kW
Average power transferred to beam	36.9	kW



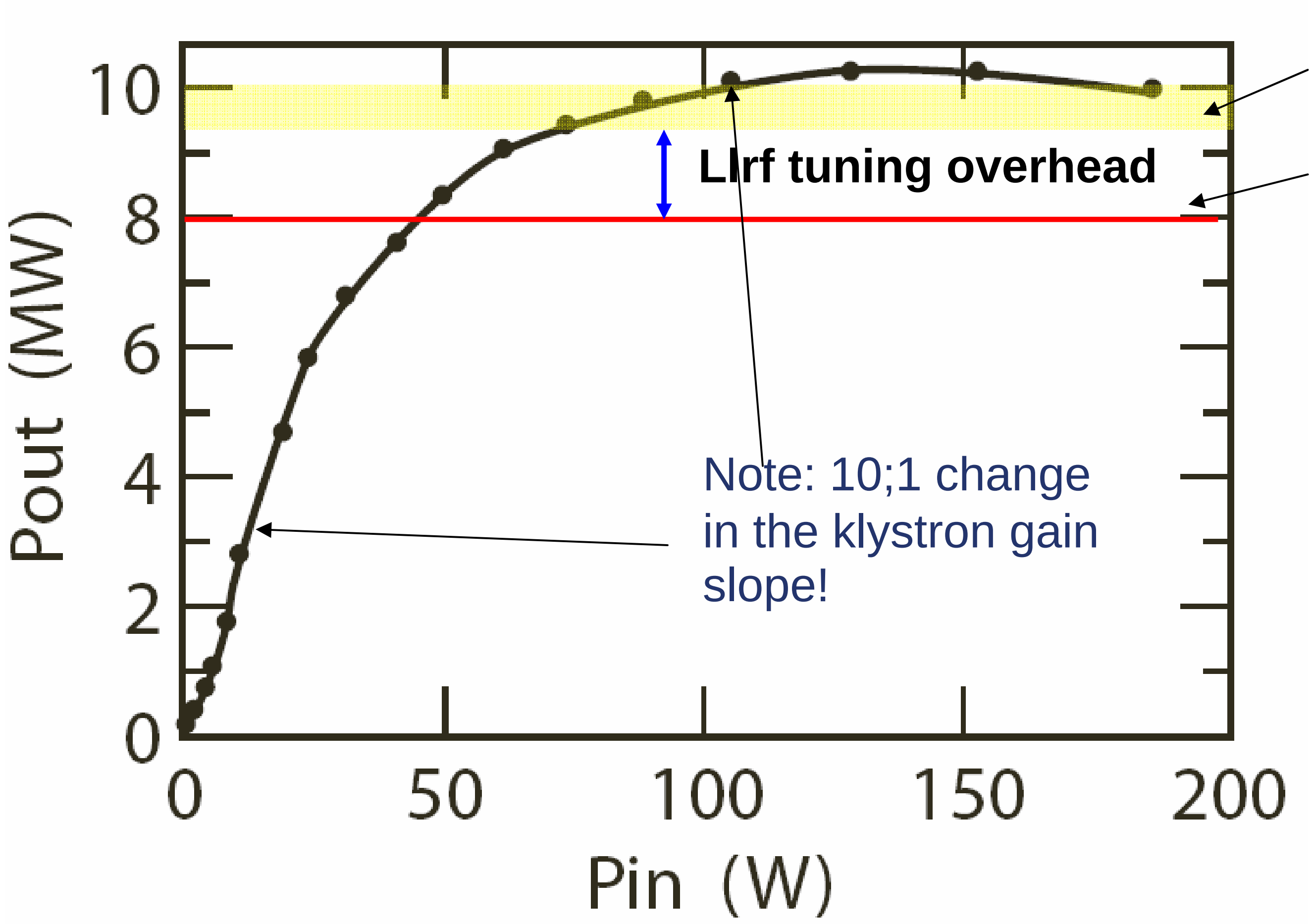
$$\begin{aligned}
\tan\psi_{opt} &= 2Q_L\frac{\Delta\omega_{opt}}{\omega} = -\frac{\left(\frac{r}{Q}\right)Q_L I_{b0}}{V_{cav}}\sin\phi_b \\
\frac{\Delta\omega_{opt}}{\omega} &= -\frac{\left(\frac{r}{Q}\right)I_{b0}}{2V_{cav}}\sin\phi_b \\
(Q_L)_{opt} &= \frac{V_{cav}}{\left(\frac{r}{Q}\right)I_{b0}\cos\phi_b} \\
\tan\psi_{opt} &= -\tan\phi_b \qquad \Longleftrightarrow \qquad \psi_{opt} = -\phi_b \\
(P_g)_{min} &= \frac{V_{cav}^2}{\left(\frac{r}{Q}\right)(Q_L)_{opt}} = V_{cav}\cdot I_{b0}\cdot\cos\phi_b
\end{aligned}$$

- Under optimal Ql and detuning, Pg becomes minimum.

Pg= 33 MV/m*1.038 m *9 mA *cos(5deg.)*26 cav.= 7.98 MW ~ 8 MW
RF loss (7%) -> available rf power= 9.3 MW
Llrf overhead = 9.3/7.98 -1 ~16%

Llrf Operating Point

- As in RDR, llrf tuning overhead is only 16% in power. corresponding to 8% in driving amplitude. (too narrow!)



Waveguide loss (7%)

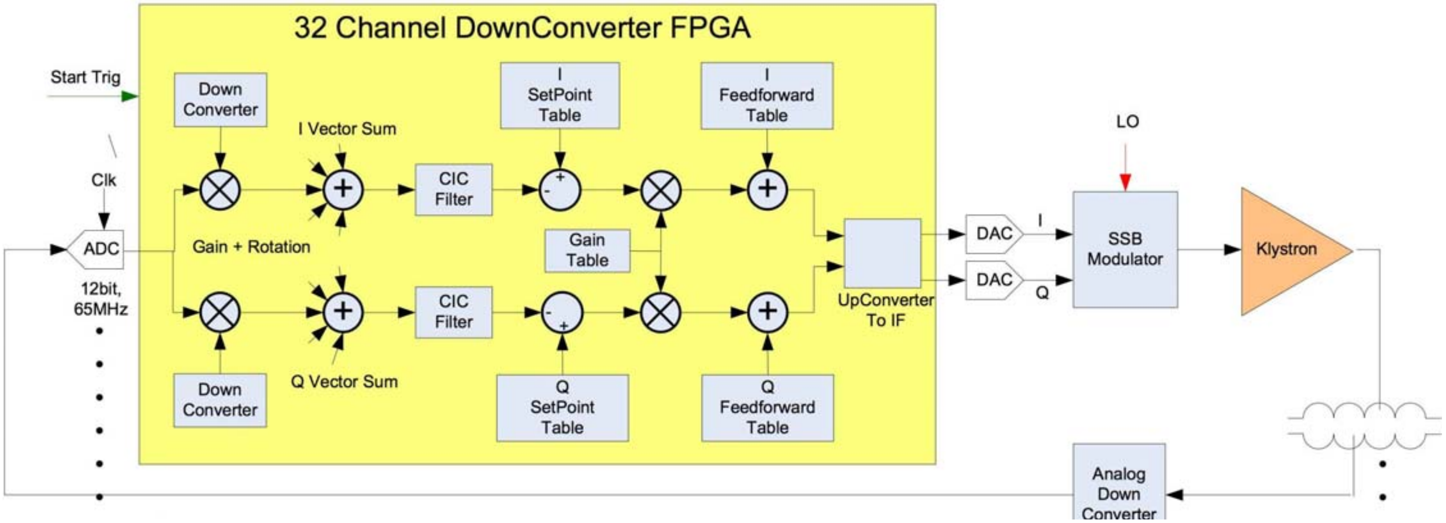
Llrf tuning overhead

operation
(~8 MW @33 MV/m)

Note: 10;1 change in the klystron gain slope!

Power Overhead Budget

- llrf overhead (16% @33 MV/m op.) is used for
    - 1% (beam current compensation) (1% fluctuation)
    - 2.5% (HLRF) (1% HV fluctuation)
    - 2% (detuning; microphonics+Lorentz force)
    - 10.5% Feedback headroom



- Current FB control consists of feed forward and proportional FB.
- Having proportional gain of Pgain, fluctuations can be suppressed 1/Pgain.

(10% fluctuation and Pgain=100, -> 0.1% stability)

- In case of *x*% error, rf amplitude increase x/100*Pgain

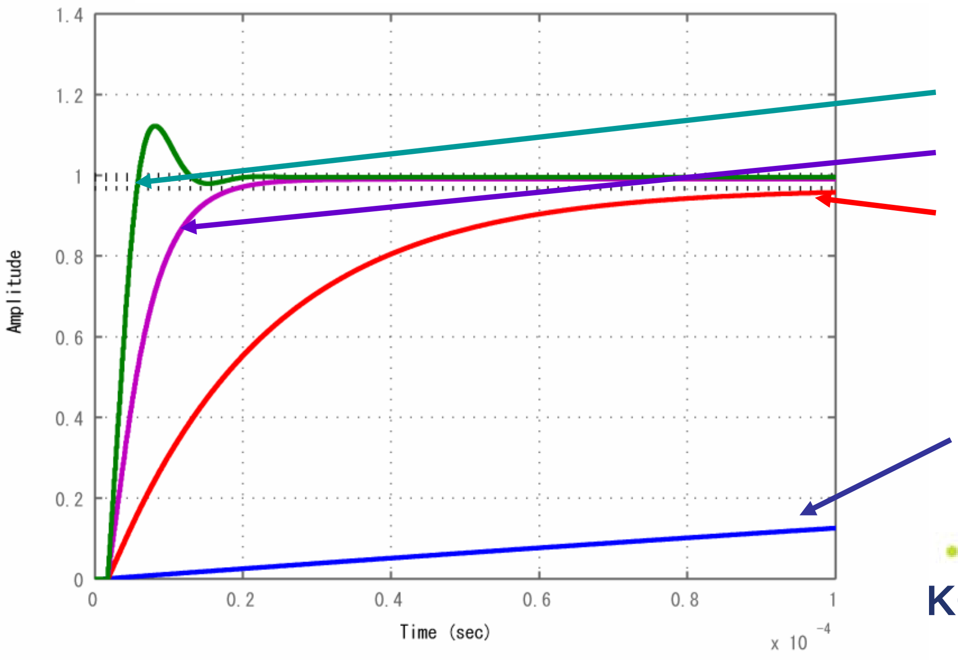
(0.05% error and Pgain=100, -> 5% additional amplitude (10% in power)

- Thus 10% is minimum headroom for linear feedback operation.

Slew Rate Limit

- If there is an error present, then the RF system must add energy to recover. (Additional power depends on Proportional gain.)
- Any time the klystron and therefore the control loop are saturated there will be no regulation of any disturbance such as beam loading.
  - **If multiple stations are saturated then amplitude errors will be correlated.**

Step response at Ql=3e6 and Tdelay=1 us.



PGain=200 settling time ~6 us

PGain=100 settling time ~18 us

PGain=30 settling time ~100 us

PGain=1

For higher gain operation, we need more rf headroom.

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Perturbations

- In order to evaluate llrf stability (and satisfy llrf requirements), we need further information
  - electron beam stability : <+/-1% (?)   Frequency distribution?
  - positron beam stability : <+/-1% (?)

-> 1% increase caused 1% more rf power.

  - damping ring rf stability : <0.3%, 0.3deg.rms (?)
  - preciseness of beam current monitor at damping ring : <+/- 0.5% (This will be used for FF table at ML)

-> This precise beam current information is necessary for beam loading compensation.

  - accuracy of Ql and RF distribution at HLRF : <1% (?)

-> We will benefit from measured distribution losses and setting accuracy of Ql and power splitters.

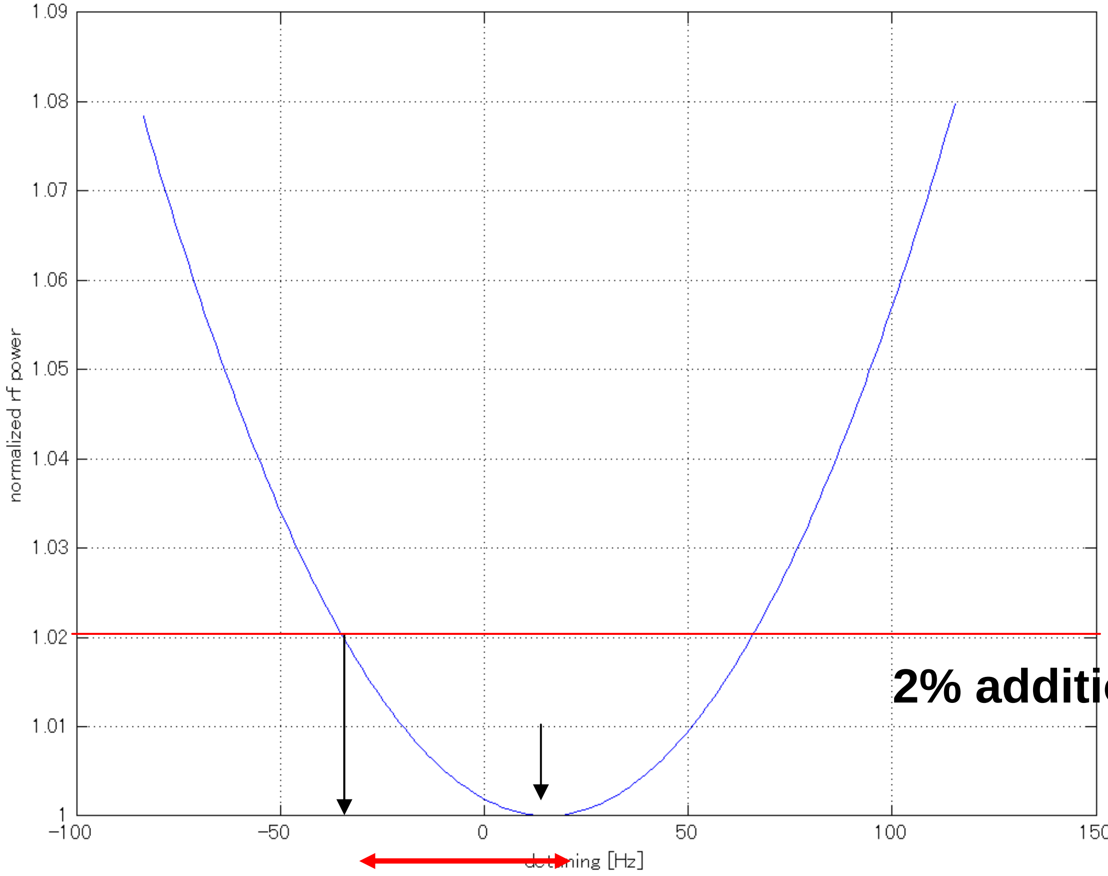
  - microphonics level at cavities : <10 Hz (?)
  - Lorentz force detuning with correction : <+/-50 Hz (?) (including microphonics)

-> +/-50 Hz detuning causes +/-2% additional rf power.

  - Cavity gradient spread in an RF Unit

-> As much as 4% additional RF power.

Detuning v.s. RF Power



2% additional power

50 Hz

- 50 Hz detuning requires additional 2% rf power

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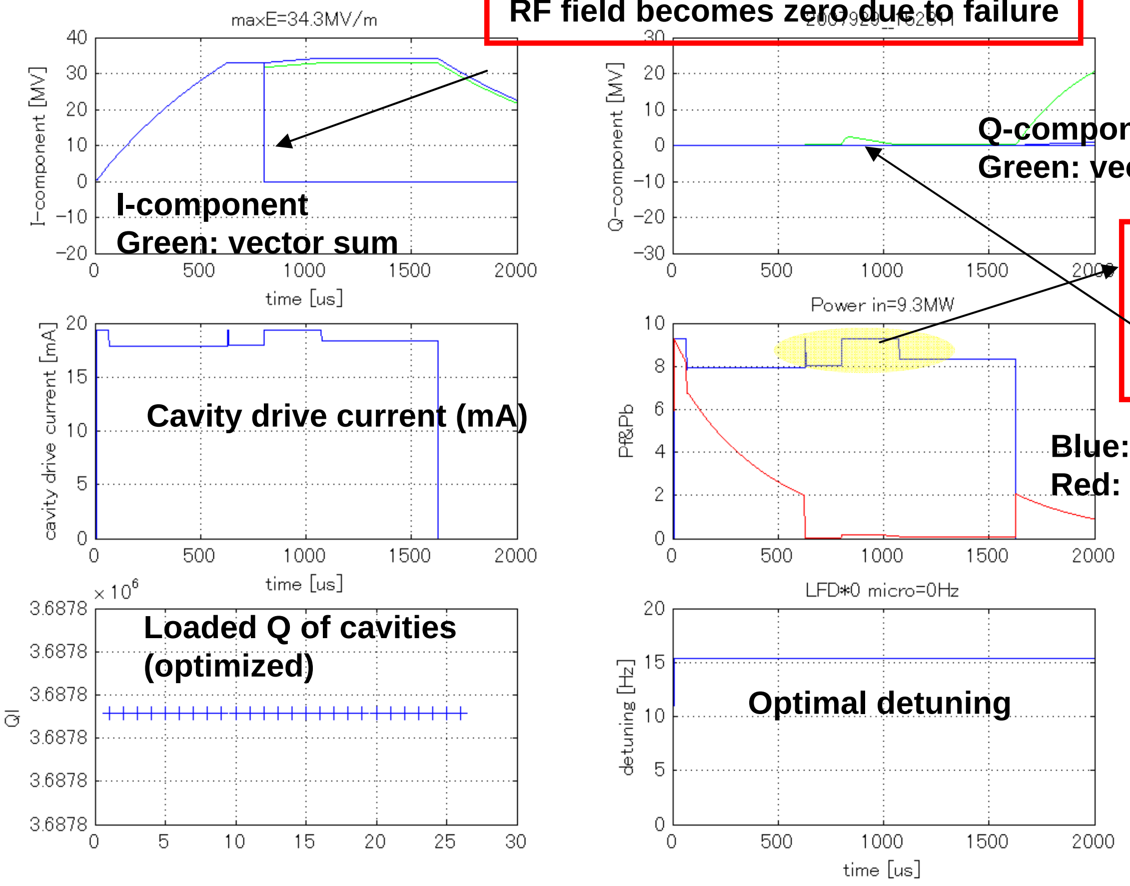
RF stability with one cavity failure

- If one of 26 cavities completely failed during rf operation, other 25 cavities have to compensate during rf operation.



RF field becomes zero due to failure

I-component
Green: vector sum

Q-component
Green: vector sum

RF power increase from 8 MW to 9.3 MW (upper limit (10 MW *93%))
Due to the limitation of rf power, vector sum is not stable.

Cavity drive current (mA)

Blue: forward rf power [MW]
Red: reflection power [MW]

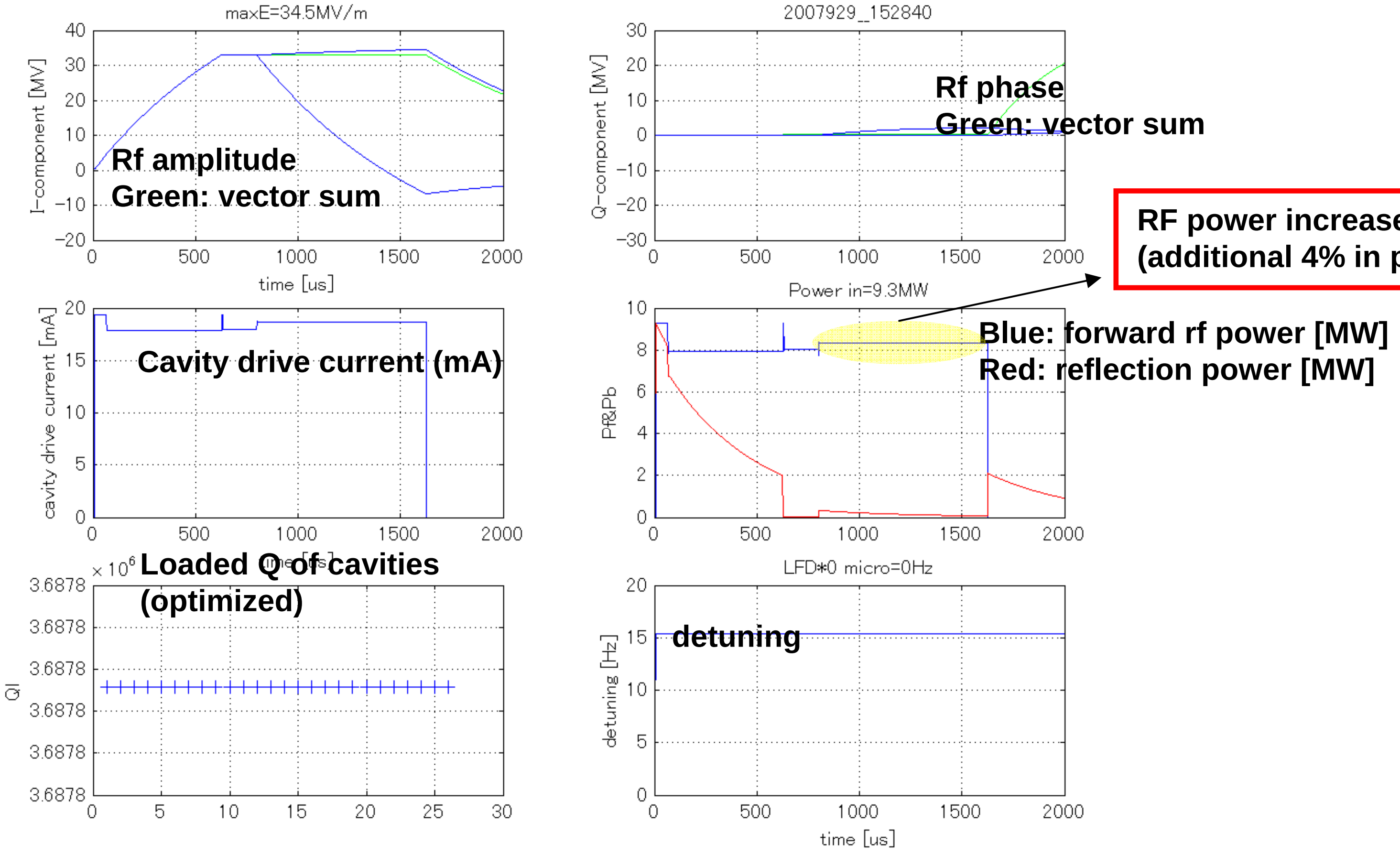
Loaded Q of cavities (optimized)

Optimal detuning

- *9.3 MW is not enough for fast decrease in rf power.*

RF stability with one cavity failure

- If one of 26 cavity input stops, other 25 cavities have to compensate during rf operation.



Rf amplitude
Green: vector sum

Rf phase
Green: vector sum

Cavity drive current (mA)

Blue: forward rf power [MW]
Red: reflection power [MW]

Loaded Q of cavities (optimized)

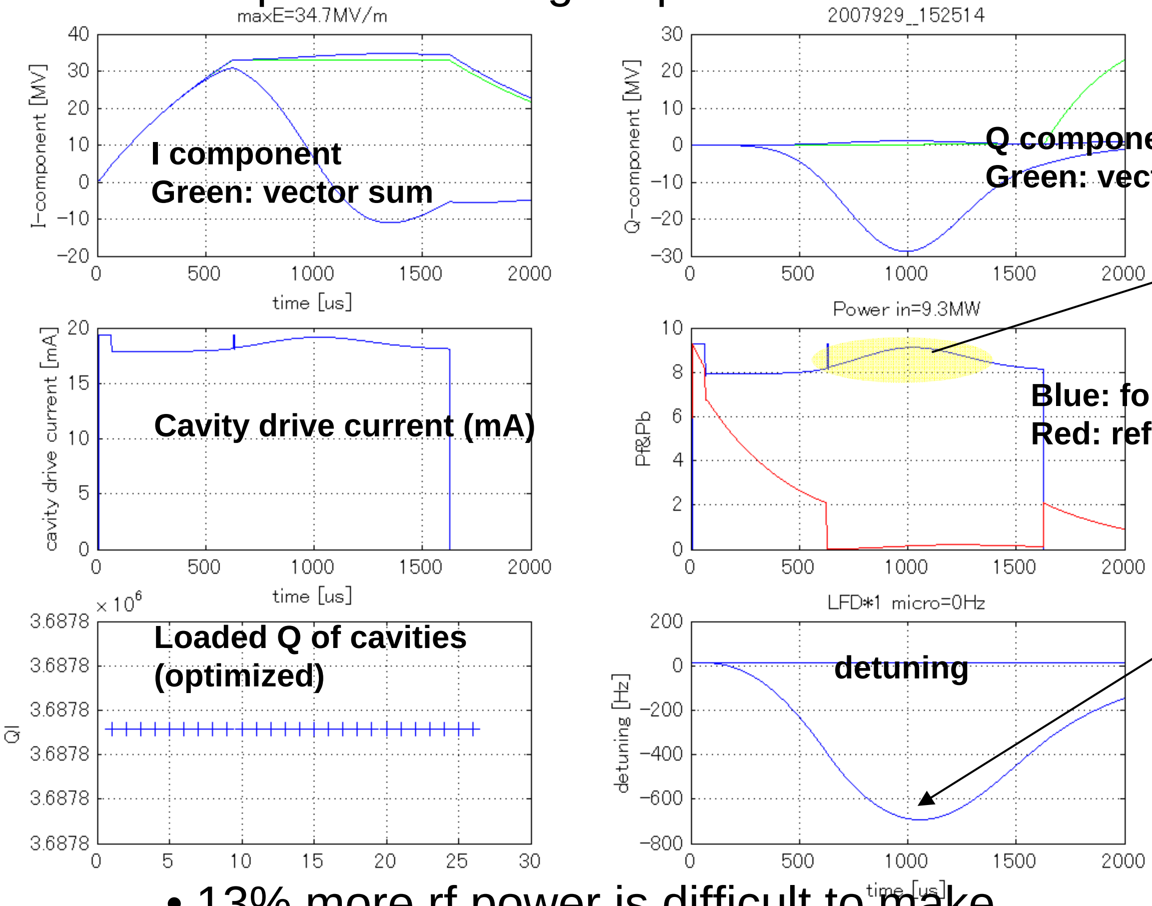
detuning

RF power increase from 8 MW to 8.35 MW (additional 4% in power)

- In case of slow rf decay, llrf can sustain vector sum rf field by FB.

Failure in LFD Piezo Control

- If one of 26 cavities failed detuning control, other 25 cavities have to compensate during rf operation.



I component
Green: vector sum

Q component
Green: vector sum

Cavity drive current (mA)

Blue: forward rf power [MW]
Red: reflection power [MW]

Loaded Q of cavities (optimized)

detuning

RF power increase from 8 MW to 9.15 MW (additional 13% in power)

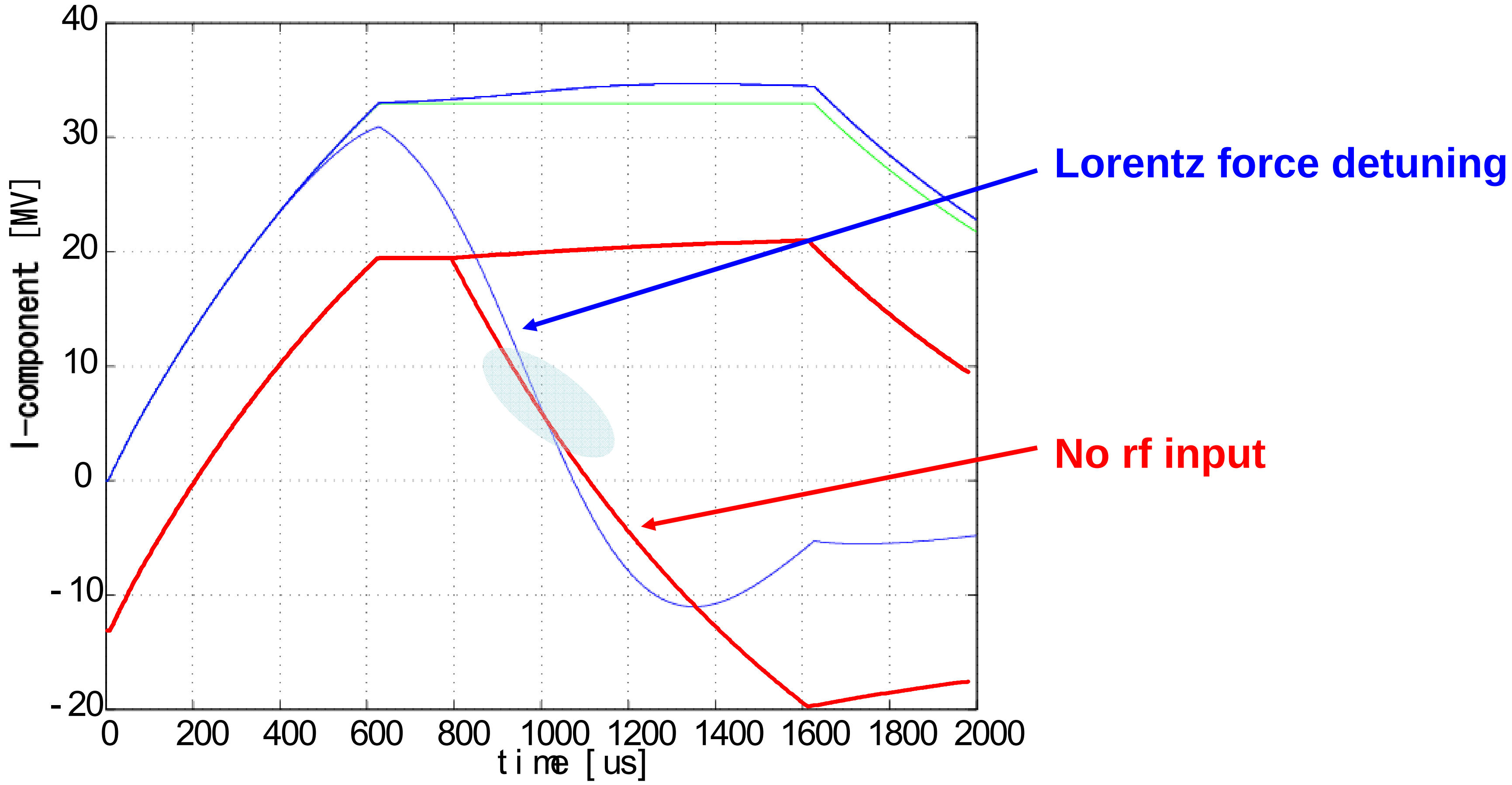
Un-compensated cavity (-700 Hz detuning)

- 13% more rf power is difficult to make.

-> LLRF cannot satisfy requirements even in the case of one cavity Piezo tuner failure.

Why we need more rf power at piezo failure?

- Cavity drive current is used for “filling” and “to maintain rf gradient”.
- In case of “Piezo mis-control”, rf gradient change is more rapid than “no rf input”, and *the driving current is used also for “cavity filling”.*



Case study: Piezo failure

- ***If Piezo tuner does not work during rf pulse,***

(a) When we have enough power overhead

i. We can continue operation during the pulse and check the failure during rf operation.
ii. If piezo failure is caused by HV supply, we can replace it with rf operation.

(b) When we do not have enough power overhead

i. RF stability does not satisfy the requirements during the first rf pulse.
ii. So we have to detune the cavity and change vector sum set-table (because number of sum decreases.)
iii. Diagnose the reason of failure off-line
iv. If piezo failure is caused by HV supply, replace it.
v. Lower the rf gradient (in order to guarantee the rf stability even if the Piezo control still fails) and change set-table for 26 cavities.
vi. Operate with 26 cavities
vii. If the failure is completely repaired, we can increase the set-point to the previous value.

-> Smaller power overhead brings a lot of complicated works to do during beam operation.

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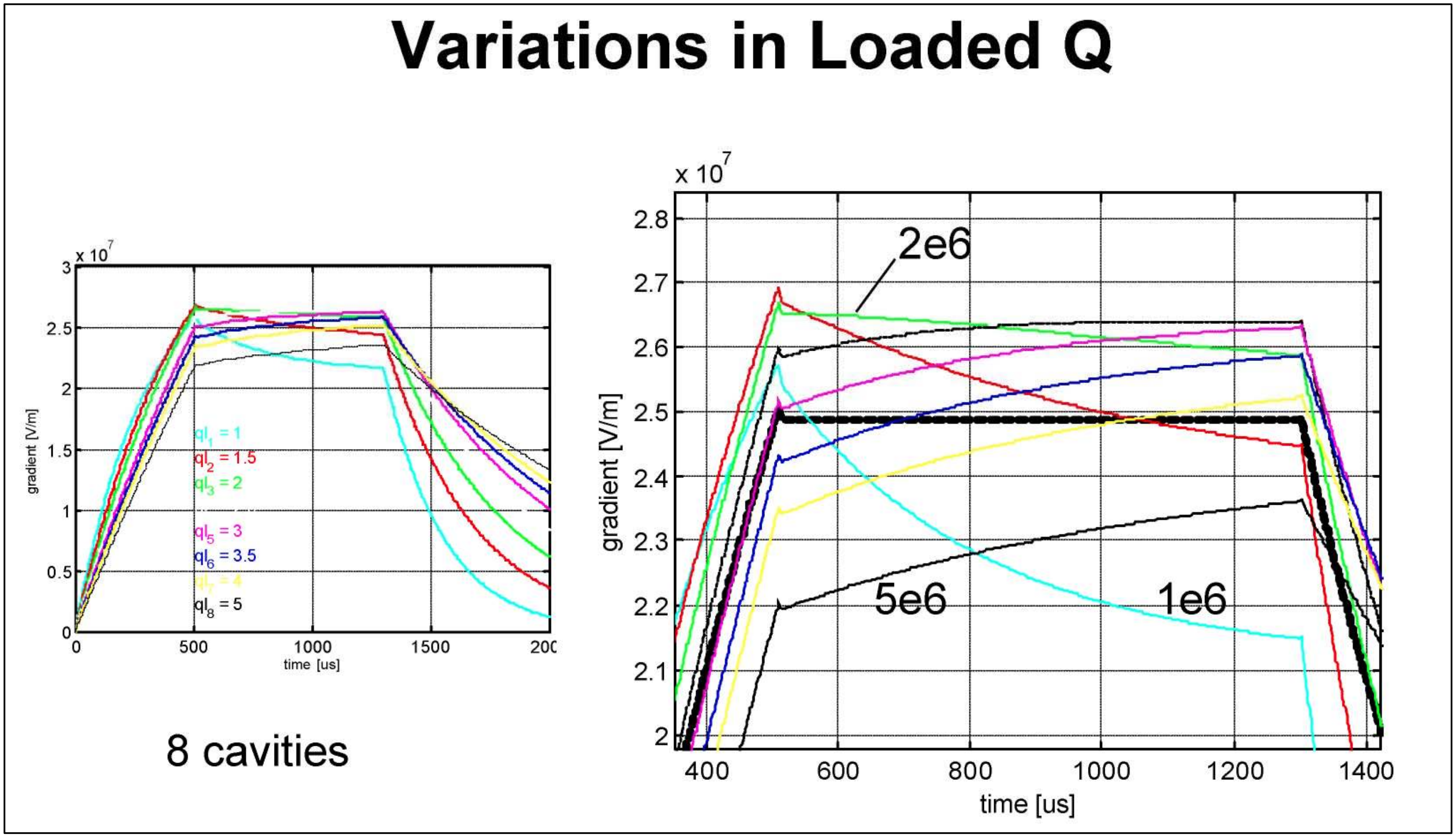
Operation at Different Gradients



Variations in Loaded Q

8 cavities

Variety of Ql results in the increase of rf field during rf pulse.

Strategy for lower gradient cavity

- Each cavity has ***a minimum performance of 35 MV/m*** during cavity mass-production acceptance testing. (RDR p. III-3)

-> ***At the beginning, we can operate at same rf field gradient (in principle).***

- If some cavities can not operate at 31.5~33 MV/m after long time operation, these cavities should be controlled in some strategy.

Example: one cavity operation limit is 28 MV/m other 25 cavity-limit is 33 MV/m

(1) Conventional vector sum control:

Operation point decreases to 28 MV/m (average 28 MV/m) or one cavity detuned (average 33*25/26= 31.7 MV/m)

Advantage: simple

Disadvantage: we can not make use of the lower threshold cavity.

(2) Bane, Adolphsen, Nantista (PAC07): Ql and rf distribution control

Operation point can be 28 MV/m and 33 MV/m (average 32.8 MV/m)

Advantage: maximum usage of all the cavities with flat rf field during beam pulse

Disadvantage: complicated (motorized variable power tap-offs (VTO) and Ql are necessary), optimal Ql and VTO depend on beam current. -> When there is no beam (or short pulse beam), rf field increase with time at lower gradient cavity.

(3) Bane, Adolphsen, Nantista (PAC07): Ql control

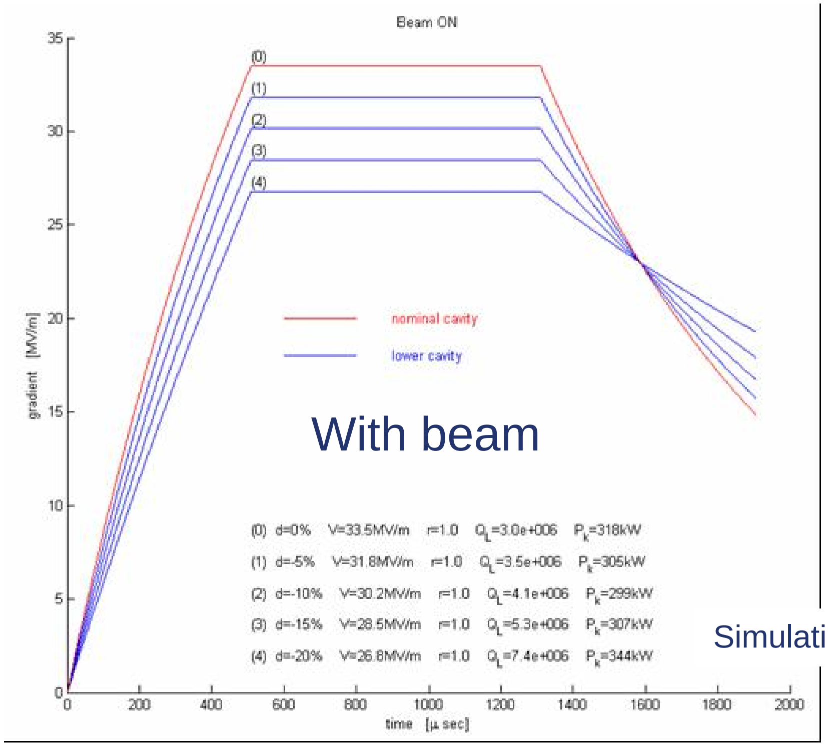
Operation point can be 28 MV/m and 33 MV/m (average 32.8 MV/m)

Advantage: more simple compared with (2)

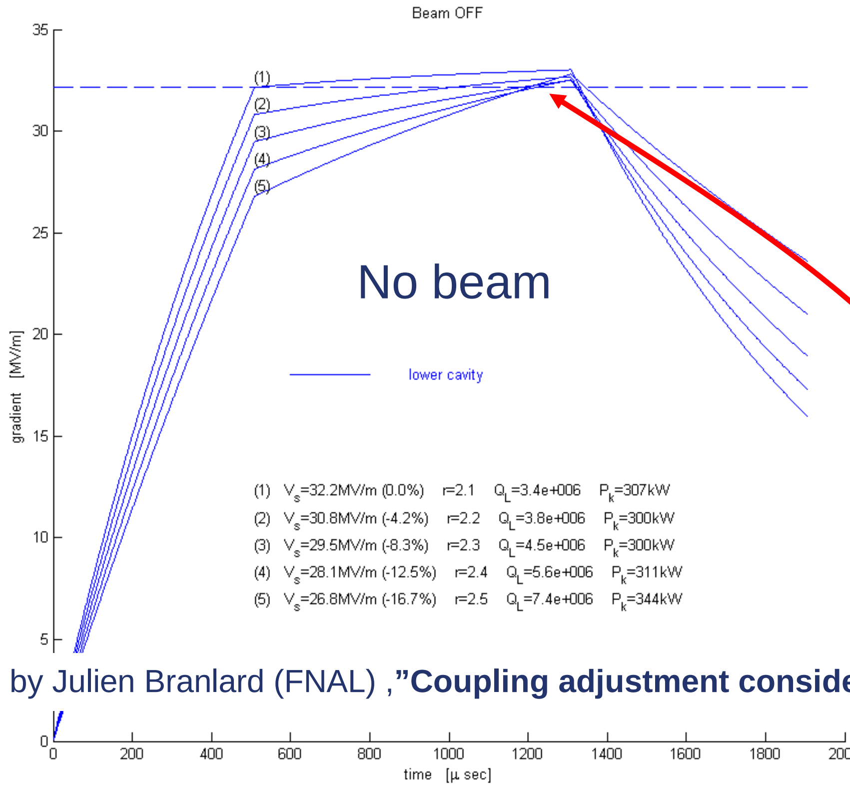
Disadvantage: We can not use simple vector sum control.

Operation with Cavities at Different Gradients

Loaded Q and VTO control



With beam



No beam

Simulation by Julien Branlard (FNAL) ,**”Coupling adjustment considerations”**

- RF field profile depends on beam condition (on/off/long/short …).
- Especially, lower gradient cavity’s field increase in case of no-beam.
- Prepare two (or more) FB modes and switch them depending on beam.

…But when unexpected beam-loss takes place (by MPS,PPS), lower gradient cavity will be quenched.

Only loaded Q control

The RF unit voltage gain will not be completely flat along the bunch train (it will also, in general, not be monotonic).

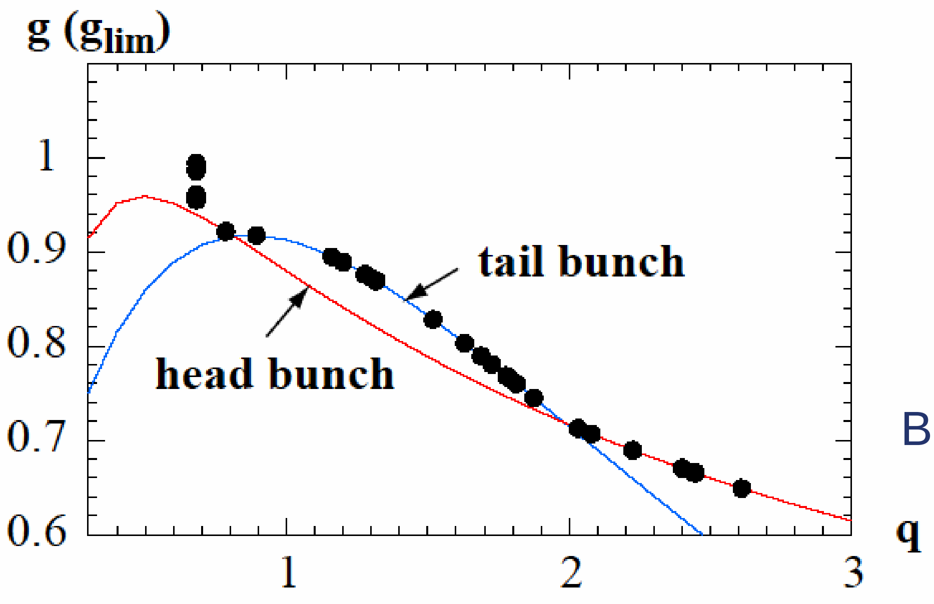
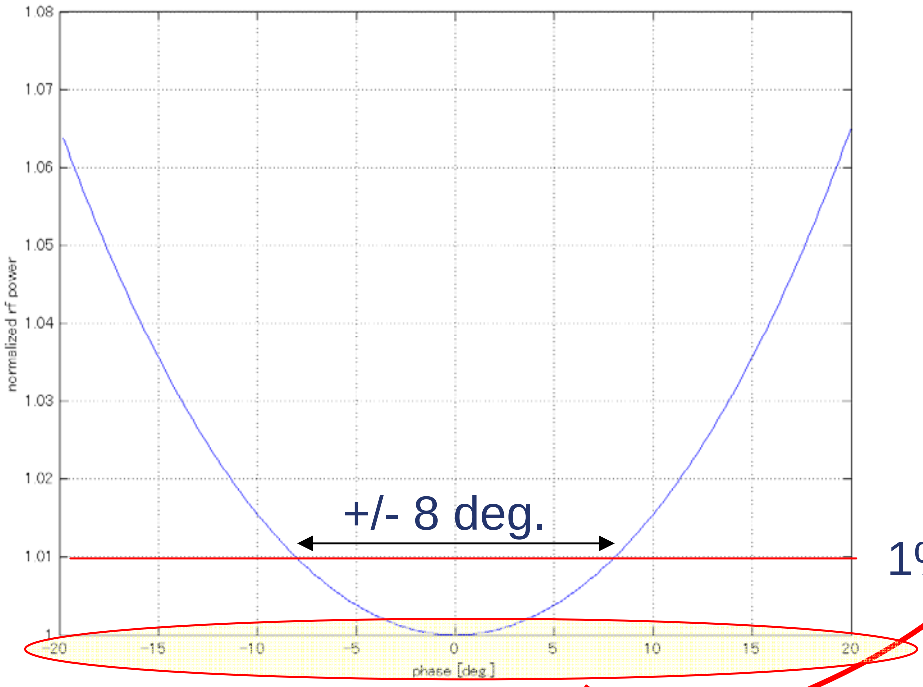


Figure 3: 1-p, individual q's: For one seed, where optimized $p = 0.92$ and $\tau_b = 0.885$: gradient g *vs.* q for the head (red) and tail (blue) bunch in the train. Also plotted are $(g_{lim})_i$ *vs.* optimized q_i for the 26 cavities (plotting symbols). For this seed $\delta_{loss} = 2.8\%$.

Bane, Adolphsen, Nantista (PAC07)

Required rf power under variation of waveguide length

$$\Rightarrow P_g \approx \frac{V_{cav}^2}{\left(\frac{r}{Q}\right) Q_L} \frac{1}{4} \left\{ \left(1 + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \cos\phi_b \right)^2 + \left(\frac{\Delta f}{f_{1/2}} + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \sin\phi_b \right)^2 \right\} \quad (A.27)$$



1% extra power

$$V_{cav}^{'} = \frac{V_{cav}}{\cos\phi}$$

$$\begin{aligned}
\tan\psi_{opt} &= 2Q_L \frac{\Delta\omega_{opt}}{\omega} = -\frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \sin\phi_b \\
\frac{\Delta\omega_{opt}}{\omega} &= -\frac{\left(\frac{r}{Q}\right) I_{b0}}{2V_{cav}} \sin\phi_b \\
(Q_L)_{opt} &= \frac{V_{cav}}{\left(\frac{r}{Q}\right) I_{b0} \cos\phi_b} \\
\tan\psi_{opt} &= -\tan\phi_b \qquad \Longleftrightarrow \qquad \psi_{opt} = -\phi_b \\
(P_g)_{min} &= \frac{V_{cav}^2}{\left(\frac{r}{Q}\right)(Q_L)_{opt}} = V_{cav} \cdot I_{b0} \cdot \cos\phi_b
\end{aligned}$$

- Phase variation between cavities (due to the waveguide expansion under rf dissipation) requires more rf power.
- In vector sum control, +/- 8 deg. variation in cavity requires extra 1% rf power.
- +/-3 deg. variation requires 0.15% additional power (negligible small).

Recommendations

- The specification for Modulator regulation needs to be better defined and probably be tightened up
- Both the cavity power couplers and power splitters(3-stub tuners) need to be motorized if there will be cavities operating at different gradients
- Selection of cavities with similar quench limits for RF units is highly desirable from the RF control viewpoint.
- Continued R&D effort into the control of LFD and microphonics (or stiffer cavities) is key to operation at high gradients
- Study minimum control overhead during high beam current tests at FLASH

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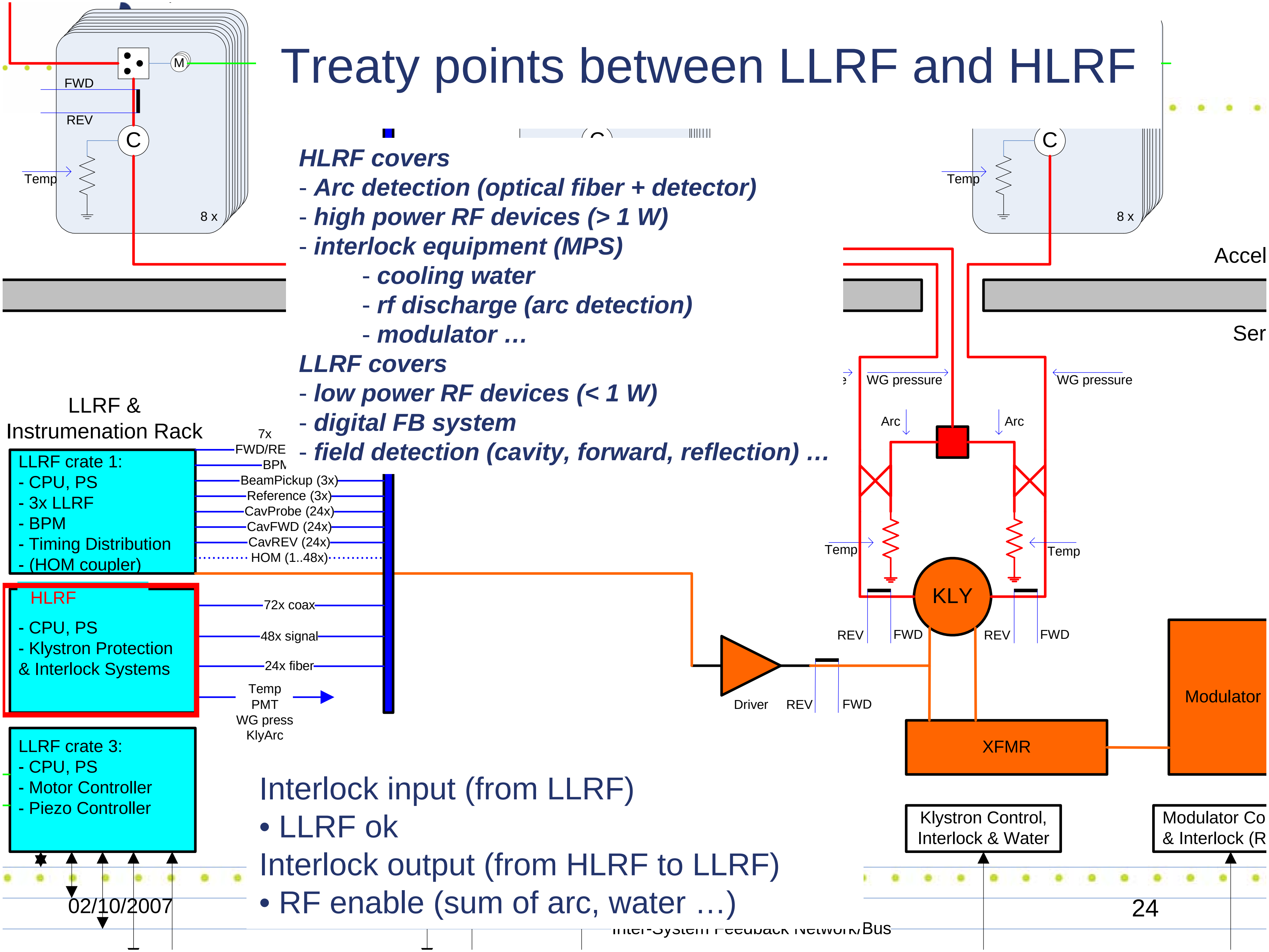
Treaty points between LLRF and HLRF



HLRF covers

- ***Arc detection (optical fiber + detector)***
- ***high power RF devices (> 1 W)***
- ***interlock equipment (MPS)***
  - ***cooling water***
  - ***rf discharge (arc detection)***
  - ***modulator …***

LLRF covers

- ***low power RF devices (< 1 W)***
- ***digital FB system***
- ***field detection (cavity, forward, reflection) …***

Interlock input (from LLRF)

- LLRF ok

Interlock output (from HLRF to LLRF)

- RF enable (sum of arc, water …)

Questionnaire to HLRF

LLRF team would like to have a document of replies to these questions.

(1) High voltage flatness during rf pulse (or klystron output (<+/-2.5%) and phase (<+/-5 deg.)?)

(2) Strategy of “manual” loaded Q and tap-off (VTO) setting in beam tunnels.

Example)

1) determine operational gradient of each cavity
2) set load Q and tap-off to optimized value

(3) Procedure of optimization on Ql and VTOs commissioning from 0 to 9 mA.

-> How do you set Ql and VTOs? (conventional or Ql/VTO control?)

(4) How much the residual errors of loaded Q and tap-off control (<+/-3%?)?

Ref)

- 10% residual error in loaded Q induces 4% higher cavity field (need further simulations)
- 10% residual error in rf distribution induces 8.5% higher cavity field (need further simulations)
- Roughly 3%rms residual errors in loaded Q and tap-off coupling causes 3% rms more rf power. (need further simulations)

-> need *motor control of 3-stub tuner and VTO* for fine tuning & less rf dissipation.

(5) We hope HLRF group will confirm the waveguide loss (7%) from klystron to input coupler *experimentally* in order to guarantee the LLRF tuning overhead.

-> In the Friday ML meeting, it revealed that 8.54% loss (@10 MW or nominal operation power?) would be expected instead of 7%.

We do not agree the higher rf loss at waveguide because our overhead would be suppressed.

Summary

- In order to satisfy stability requirements under severe llrf tuning overhead, suppressions of perturbations are essential.
  Beam current, **cavity detuning**, rf distribution and so on.

- LLRF team will continue RF simulation based on proper parameters.

- LLRF team want to know the real power overhead.

- We do *not* like the idea that "all unknown issues (such as rf waveguide loss, klystron maximum operation power, modulator stability,…) would be included this llrf overhead."

- Shortage of the llrf overhead results in the lower gradient operation !!

Thank you

Spare slides

RF power estimation

Steady state rf dissipation at a cavity.

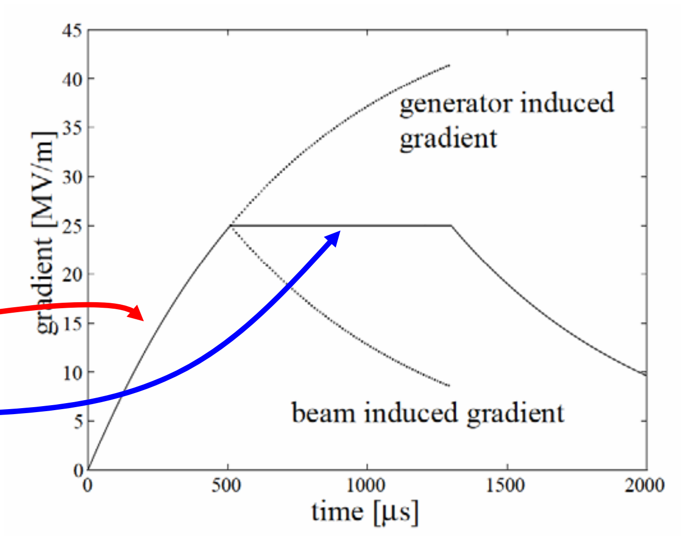
$$\Rightarrow P_g \approx \frac{V_{cav}^2}{\left(\frac{r}{Q}\right) Q_L}\,\frac{1}{4}\left\{\left(1+\frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}}\cos\phi_b\right)^2+\left(\frac{\Delta f}{f_{1/2}}+\frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}}\sin\phi_b\right)^2\right\} \quad \text{(A.27)}$$

General description including transition state

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix} . \quad (3.49)$$

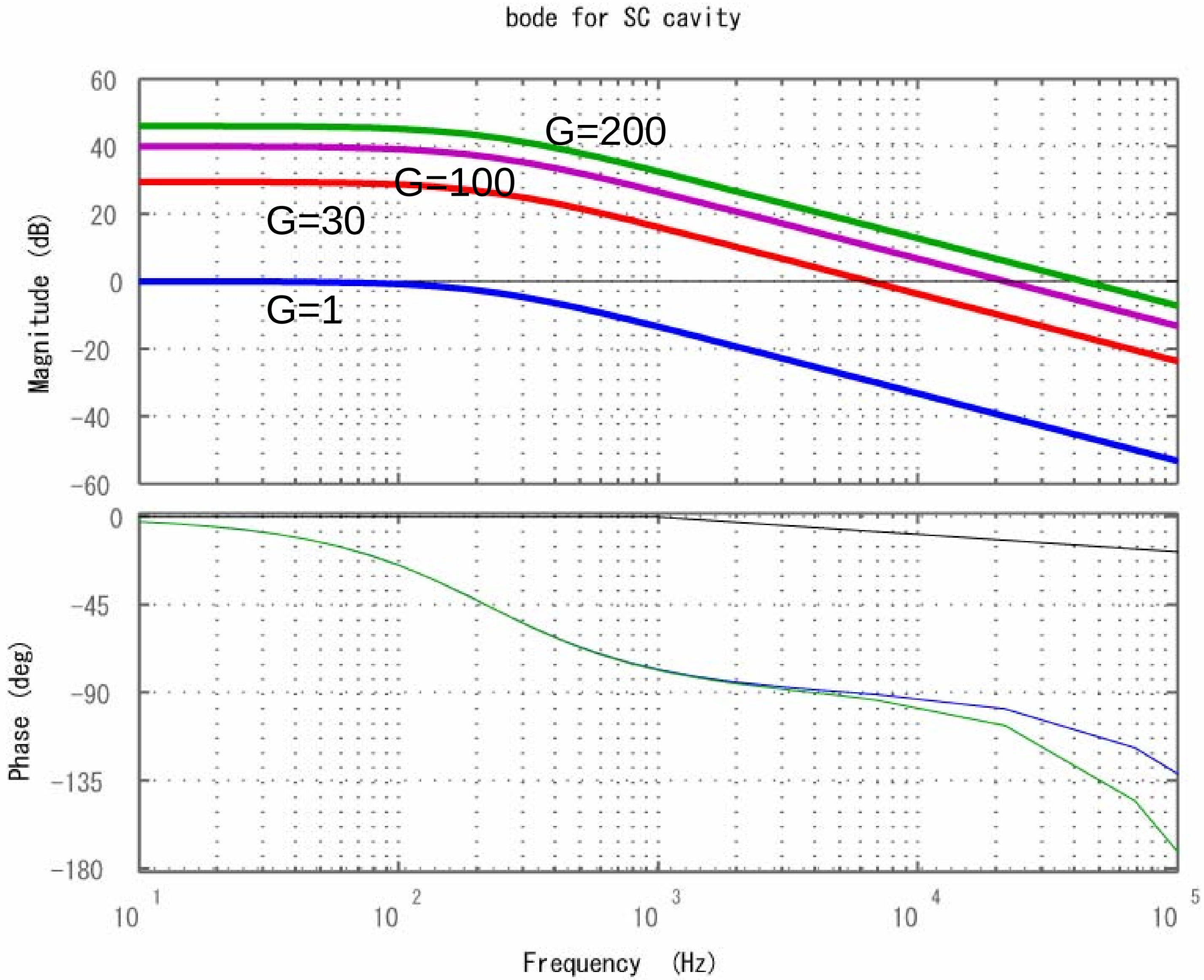
$$I_r = I_{gen/real} + I_{beam/real} ; I_i = I_{gen/imag} + I_{beam/imag}$$

$$P_g = \frac{1}{4}\left(\frac{R}{Q}\right) Q_l \left(I_{gen/real}{}^2 + I_{gen/imag}{}^2\right)$$



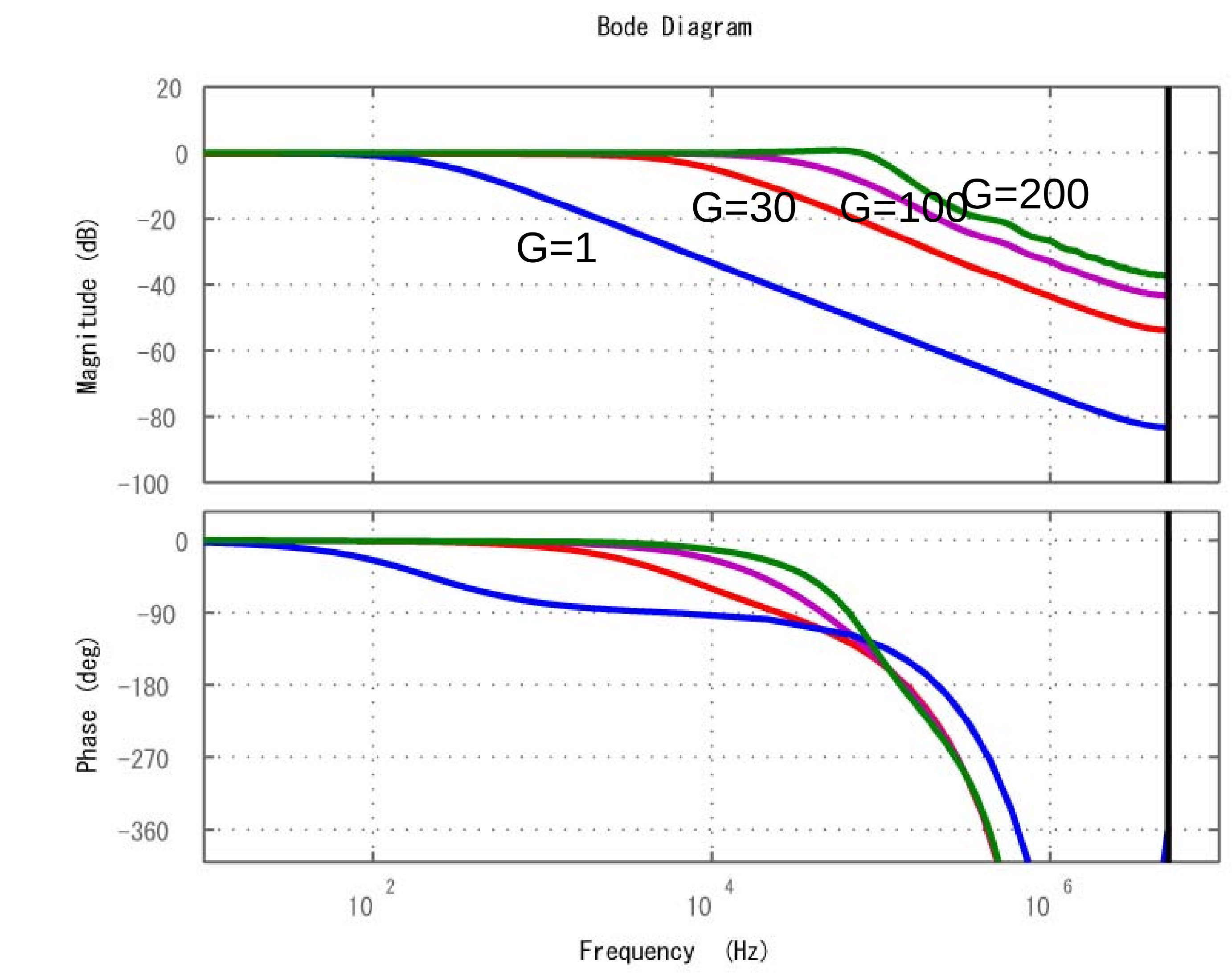
Simple case: 9 mA (0deg.) beam with optimal Ql.
18 mA for filling (transient),
18 mA under beam loading (steady state)
9 mA without beam (steady state)
Twice drive current (x4 power) is used for cavity filling
If rapid field increase is required, filling power becomes larger.

Open loop characteristics



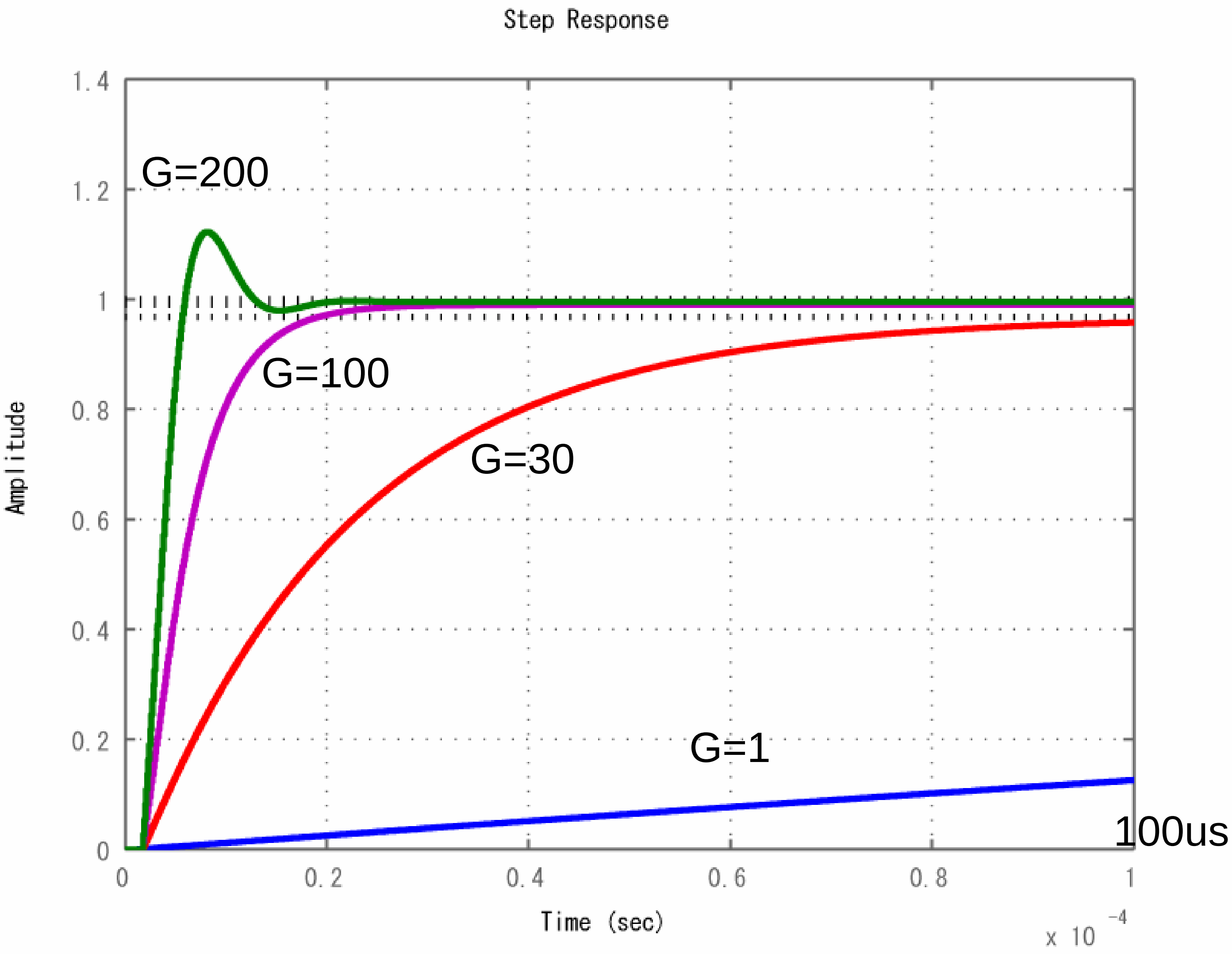
Parameters:
Ql=3e6
Delay=1us

Frequency response (w/ FB)



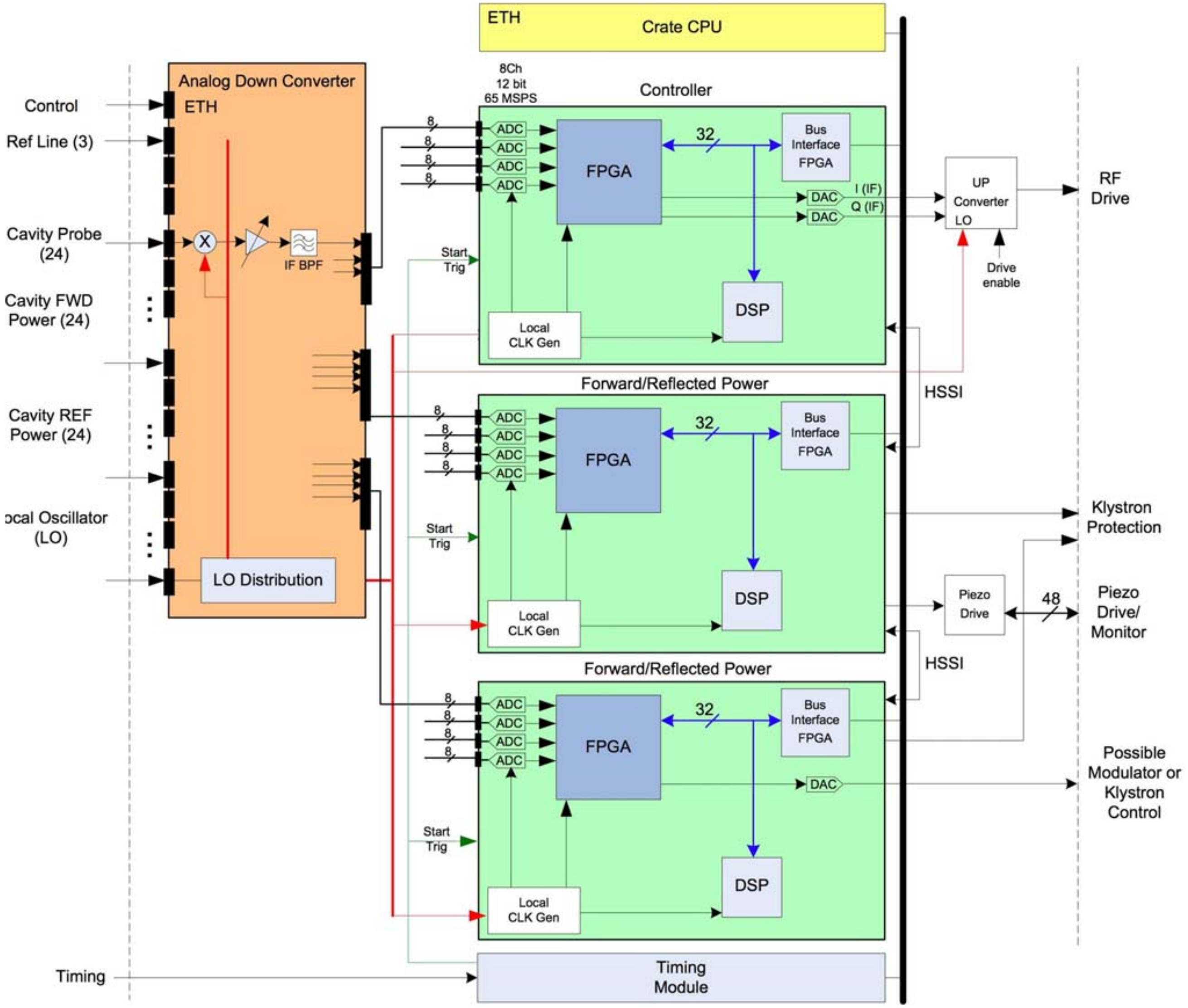
Larger bandwidth with larger FB gain.

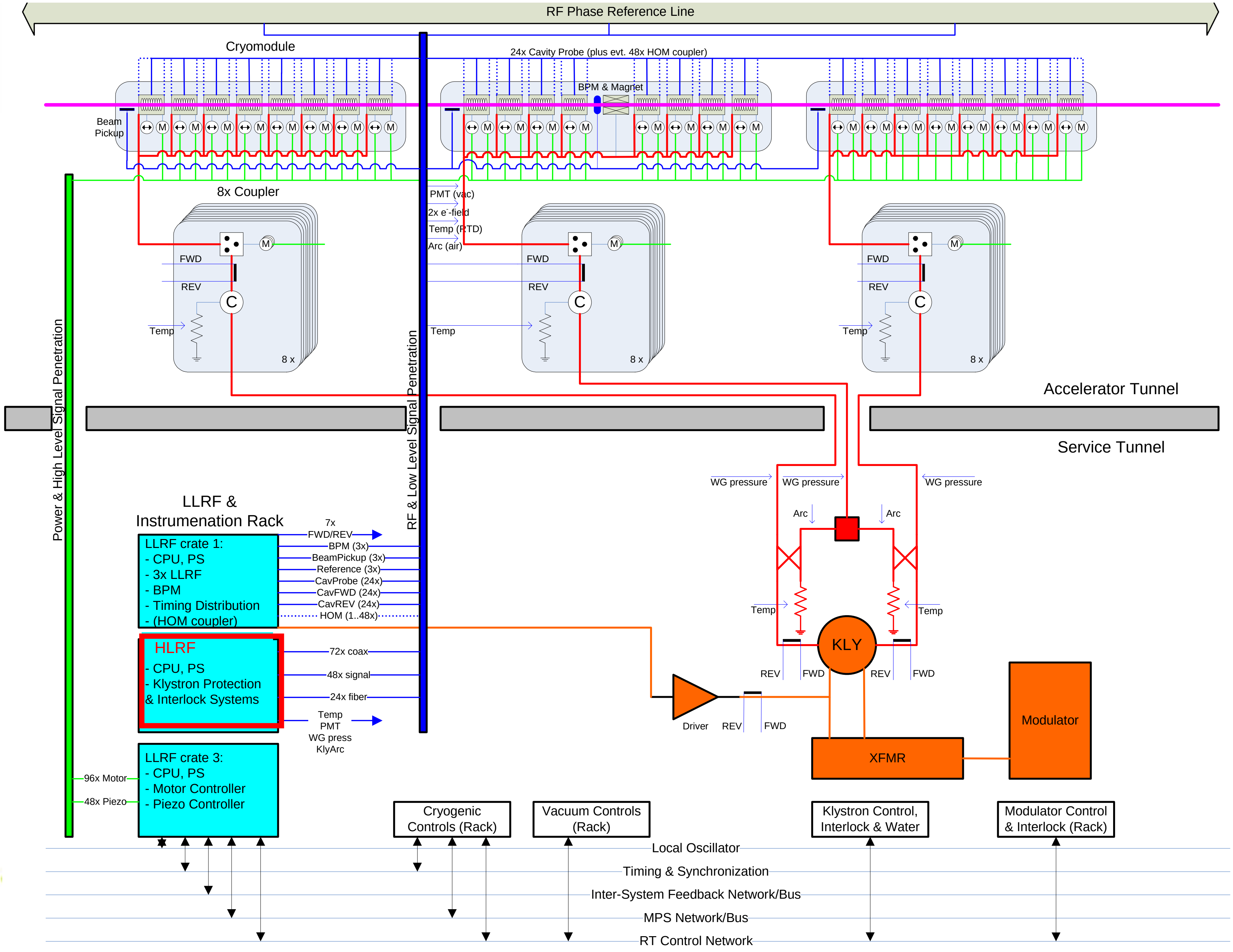
Step response



Faster response at high gain (but larger drive will be necessary).
Fast FB needs larger driving power.

LLRF Rack Detail




RF Phase Reference Line
Cryomodule
24x Cavity Probe (plus evt. 48x HOM coupler)
BPM & Magnet
Beam
Pickup
M
8x Coupler
PMT (vac)
2x e⁻-field
Temp (RTD)
Arc (air)
FWD
REV
C
Temp
8 x
Accelerator Tunnel
Service Tunnel
Power & High Level Signal Penetration
RF & Low Level Signal Penetration
WG pressure
WG pressure
WG pressure
Arc
Arc
Temp
Temp
KLY
REV
FWD
REV
FWD
Driver
REV
FWD
XFMR
Modulator
LLRF &
Instrumenation Rack
LLRF crate 1:
- CPU, PS
- 3x LLRF
- BPM
- Timing Distribution
- (HOM coupler)
7x
FWD/REV
BPM (3x)
BeamPickup (3x)
Reference (3x)
CavProbe (24x)
CavFWD (24x)
CavREV (24x)
HOM (1..48x)
HLRF
- CPU, PS
- Klystron Protection
& Interlock Systems
72x coax
48x signal
24x fiber
Temp
PMT
WG press
KlyArc
LLRF crate 3:
- CPU, PS
- Motor Controller
- Piezo Controller
96x Motor
48x Piezo
Cryogenic
Controls (Rack)
Vacuum Controls
(Rack)
Klystron Control,
Interlock & Water
Modulator Control
& Interlock (Rack)
Local Oscillator
Timing & Synchronization
Inter-System Feedback Network/Bus
MPS Network/Bus
RT Control Network