LLRF for S1 and ilc

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- LLRF for ilc commissioning and operation
- Questionaire
- LLRF for S1 operation

For ilc

Actual LLRF tuning overhead

- RF power budget
  - cavity input 8.02 MW (33 MV/m * 1.038 m * 26 cav. * 9 mA)
  - reflection from waveguide system 1% (VSWR~1.2)
  - non-optimal coupling 2% (if over-coupling x1.3)

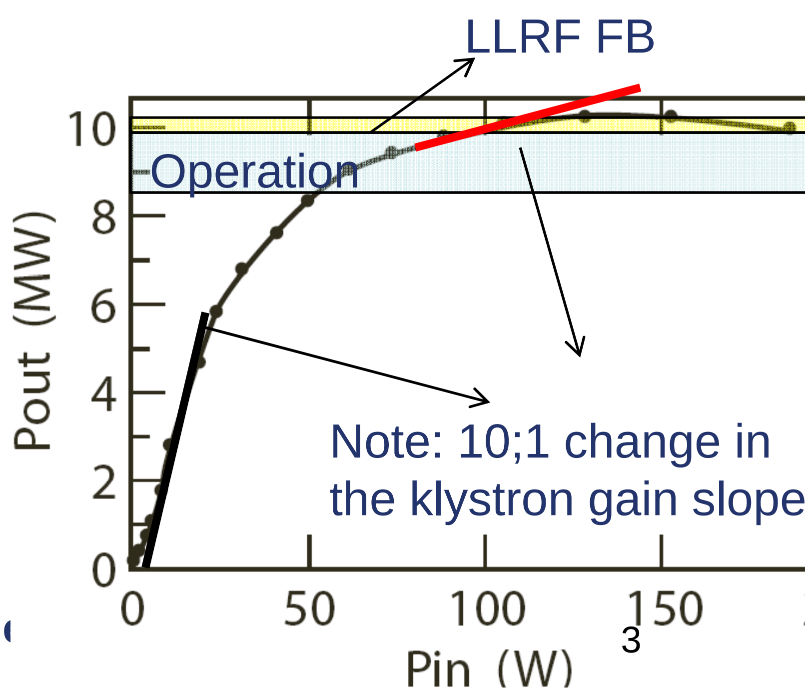
(We should also consider the rf-output reduction due to the rf reflection to klystron)

  - rf loss 8.54% (should be minimized!)
  - beam fluctuation 1% (should be compensated by fast feedforward)
  - modulator ripple 2.5% (pulse-to-pulse +/- 0.5%HV ripple)
  - cavity detuning 2% (*40 Hz* ***peak*** of Lorentz force and microphonics)
- Remained rf power:

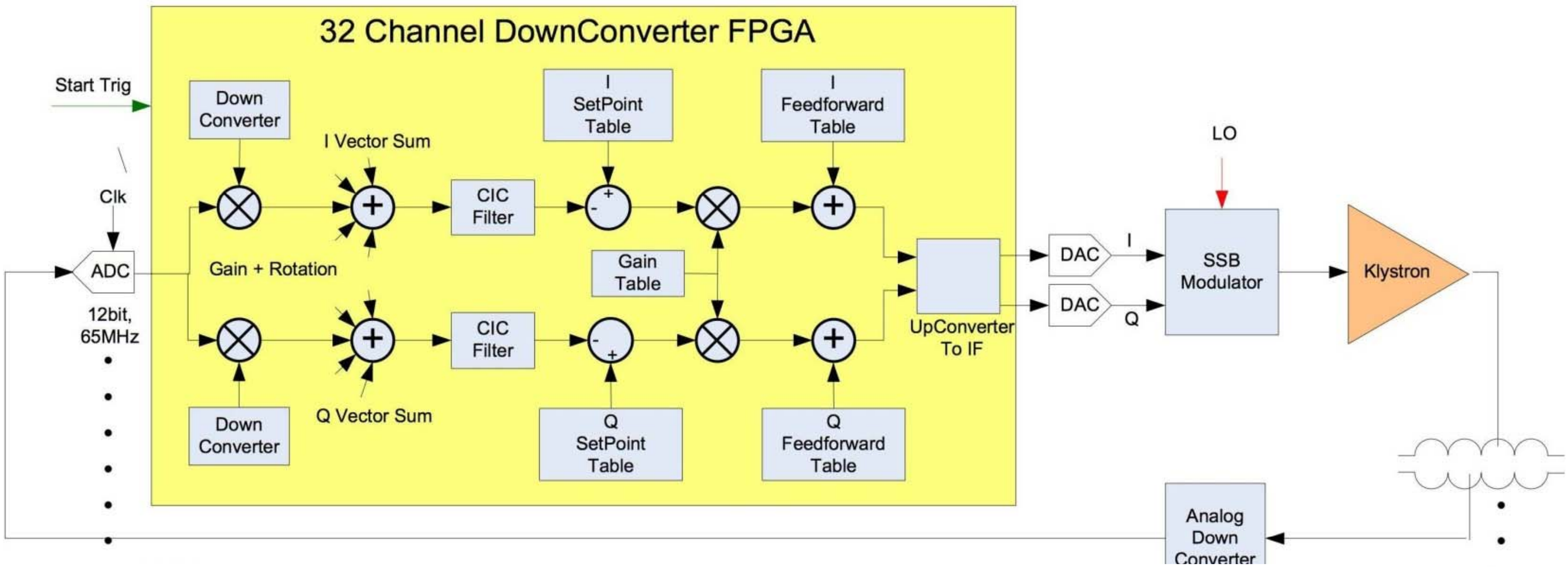
10 MW – 8.02 MW*(1.01 * 1.02 * 1.01* 1.025 * 1.02)/(1-0.0854)=0.47MW

- LLRF feedback overhead
  - 8.02* (1.01 * 1.02 * 1.01 * 1.025 * 1.02* X)/(1-0.0854)=10

  -> X=1.049 (5%) ***(2.5% in amplitude)***
  - The overhead is used for field regulation.
  - Performance of the field stability depends on
    - feedback gain
    - additional rf power
- Strategy for cavity quench or mistuning should be considered.



Power Overhead Budget



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

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

Brief History of “CCR” from BCD

	Vmax,Vave	Ibeam	# cavities
BCD	35 MV/m, 31.5 MV/m	9.5 mA	24
CCR#20	33.5 MV/m, 31.5 MV/m	9.5 mA	26
RDR	33 MV/m, 31.5 MV/m	9 mA	26

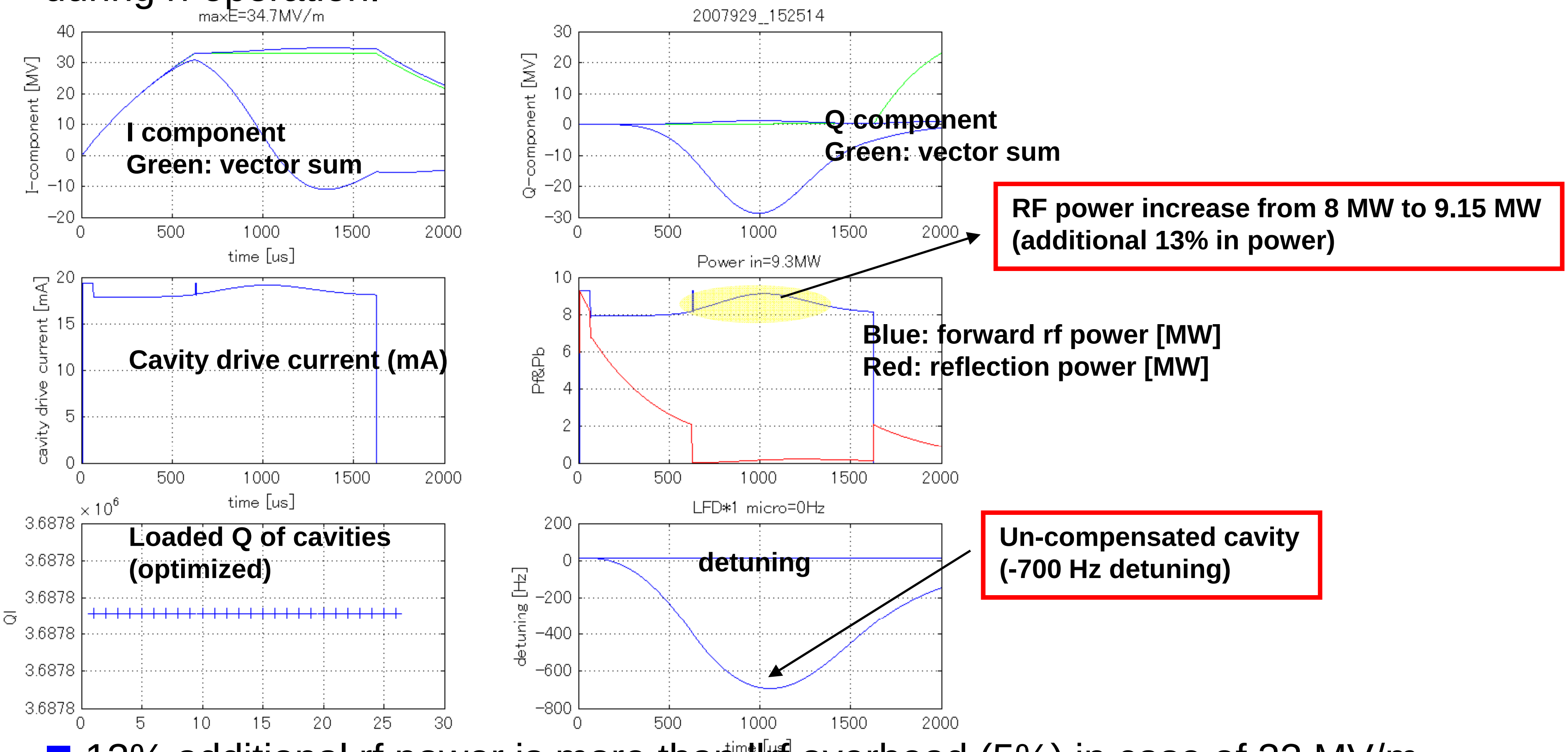
- At CCR(Change configuration request) #20, llrf team estimated some fluctuations. (beam, rf loss,…)
- We opposed to CCR#20 because of the less llrf tuning overhead.

33.5 MV/m * 9.5 mA * 1.038 m = 330.3 kW (Cavity Input Power)
* 26 Cavities
* 1 / 0.95 (Distribution Losses with WR770/WR650)
* 1 / 0.90 (Tuning Overhead)
= 10.0 MW

- *Increased power consumption (such as distribution loss, coupling loss), the situation became worse than CCR#20.*

Failure in LFD Piezo Control

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



- 13% additional rf power is more than llrf overhead (5%) in case of 33 MV/m.

-> Vector-sum gradients cannot be sustained even at one cavity Piezo tuner failure.

Case study: Piezo failure

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

(a) When we have enough power overhead

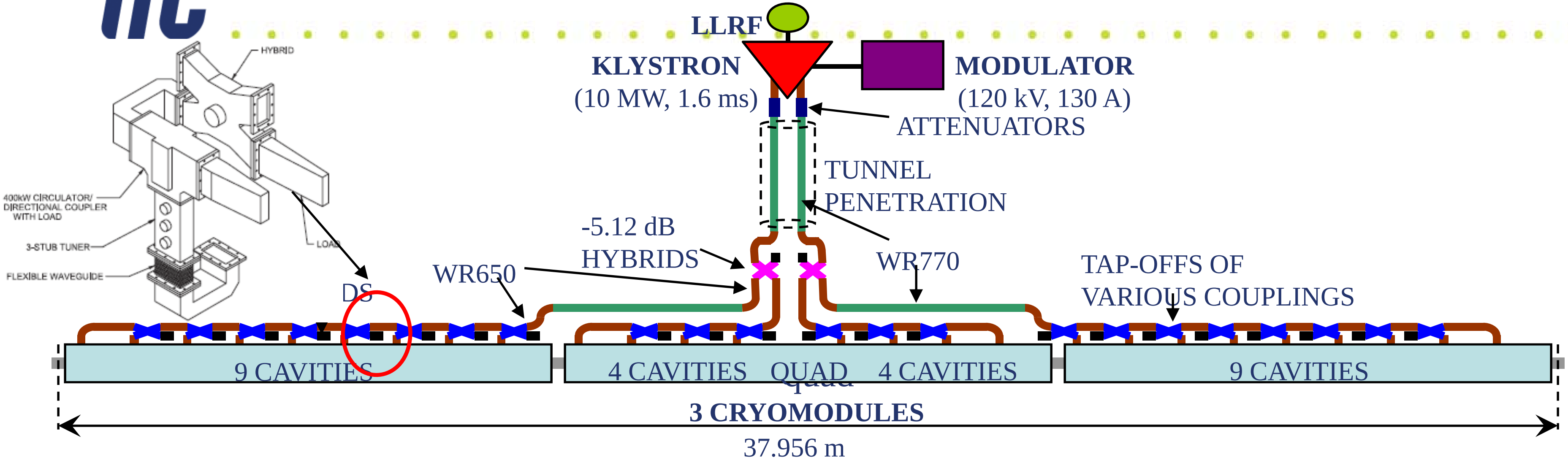
i. We can continue operation during the pulse and check the failure during rf operation.
ii. If piezo failure is caused by HV supply, we can replace it with rf operation.

(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.*

Questionnaire to HLRF and ML (1)



(1) 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 based on the low power data

(2) 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?)

(3) 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.

Questionnaire to HLRF and ML (2)

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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

By Christopher Nantista (SLAC)
Main Linac – KOM, Fermilab September 28, 2007

Waveguide Attenuation

Take: .0078 dB/m for WR650 and .0053 dB/m for WR770 (11.6% above theoretical)*.

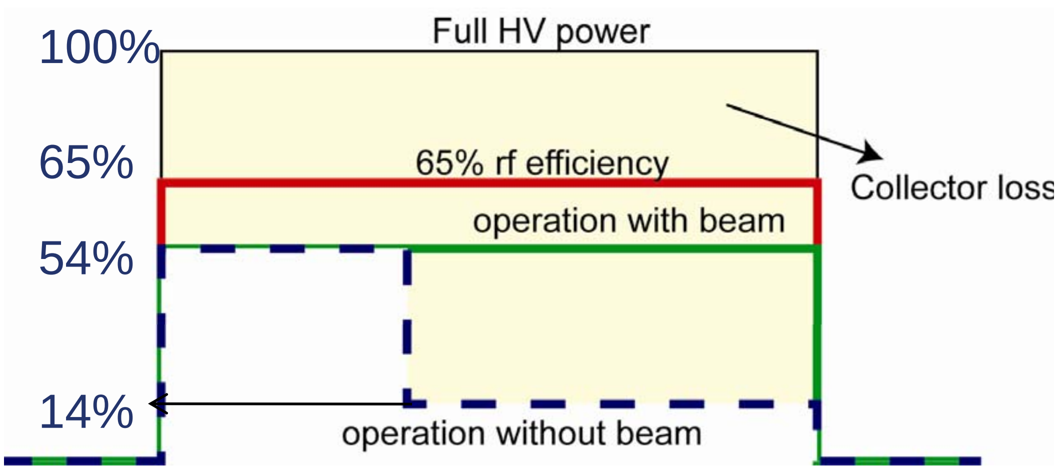
Horizontal run through penetration (~1.5m+6.75m+~3m = 11.25m WR770):	.0596 dB	(1.36%)
Up & down/back & forth, both tunnels (~9m WR650):	.0702 dB	(1.60%)
Average tunnel run to cryomodule (6.0m×9/13 = 4.15m WR770):	.0220 dB	(0.505%)
Average longitudinal run along cryomodule (1.376m**×3.23 = 4.44m WR650):	.0347 dB	(0.795%)
Circulators:	.10 dB	(2.28%)
Other feed components (bends, phase shifter, directional coupler):	.020 dB	(0.459%)
Flex waveguides (3×0.027dB):	.081 dB	(1.85%)
TOTAL Waveguide Loss:	.3875 dB	(**8.54%**)

- Under optimal Ql and detuning, klystron output becomes minimum.
-> In other words, additional losses will take place in non-optimal configuration.

- We hope HLRF group will confirm the waveguide loss (7% or 8.54%) from klystron to input coupler *experimentally* in order to guarantee the LLRF tuning overhead.
-> If the rf loss in waveguides are higher than expected, improvements of specification (field gradient, or beam current) will be necessary.

What should llrf do?

Power estimation:



Thermal Phase Shifts

almost ?

By Christopher Nantista (SLAC)
at Main Linac – KOM, Fermilab September 28, 2007

WR770 0.0446°/m/°C

	max. available, no atten. power flow	approx. length	from Katalev's plot ΔT	Δφ
penetration	5 MW (770)	11.25 m	11° C*	5.52°
up & down	5 MW (650)	9 m	19° C	8.62°
to cryomodule	3.46 MW (770)	6 m	8° C*	2.14°
to 2nd & 3rd feeds	2.88 MW (650) avg.	2.75 m	12° C	1.66°
to 4th & 5th feeds	2.11 MW2.75 m avg.	9° C	1.25°	
to 6th & 7th feeds	1.35 MW avg.	2.75 m	6° C	0.83°
to 8th & 9th feeds	577 kW avg.	2.75 m	3° C	0.42°
feed	384 kW	3 m	2° C	0.30°

14.44° common shift

6.3° max. diff structure to structure

20.7° max. total klystron to structur

*Scaled with power dissipation and inversely with perimeter for WR770
(may get much hotter in penetration without cooling)

- diode power (15.4 MW = 10 MW/0.65) -> 120 kW loss @ kly. collector
- operation (with beam) 8.4 MW @ 31.5 MV/m -> 55 kW loss @ kly. Collector
- operation (without beam) 8.4 MW & 2.1 MW -> 86 kW loss @ kly. Collector

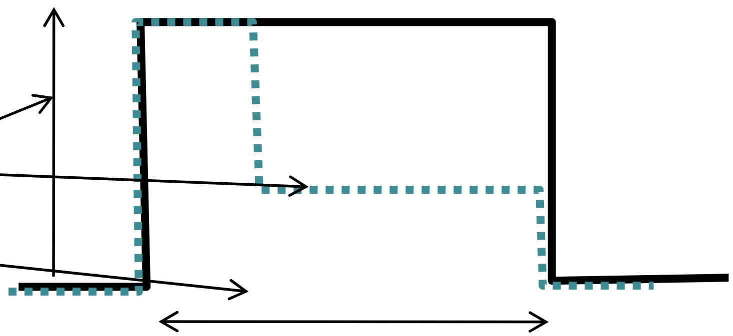
What should llrf (or trigger) do?

- beam off: change HV width in order to avoid excess klystron collector loss(?)
  -> temperature change at waveguide leading to phase drift!!
- rf conditioning: change repetition(?) or control the HV width(?)
- slow LLRF compensation by adaptive FF will be necessary for suppress the effect of phase-shift.

Adaptive feed-forward (FF) with intelligence

- Feed-forward (FF) is useful to suppress the repetitive error
- Feedback (FB) works for the suppression of non-repetitive error.

- In order to compensate the slow drift (by microphonics, thermal drifts), Adaptive feed forward will be the powerful method for field regulation.
- Adaptive feed forward is
  - to refresh the feed forward table periodically
  - like a pulse-to-pulse feedback
  - useful to reduce the repetitive error
- Adaptive feed-forward requires
  - beam information
  - rf width information
  - field level information



Example)

If “Quench” takes place, we eliminate these pulses from FF table generation

If “beam off” takes place, ….

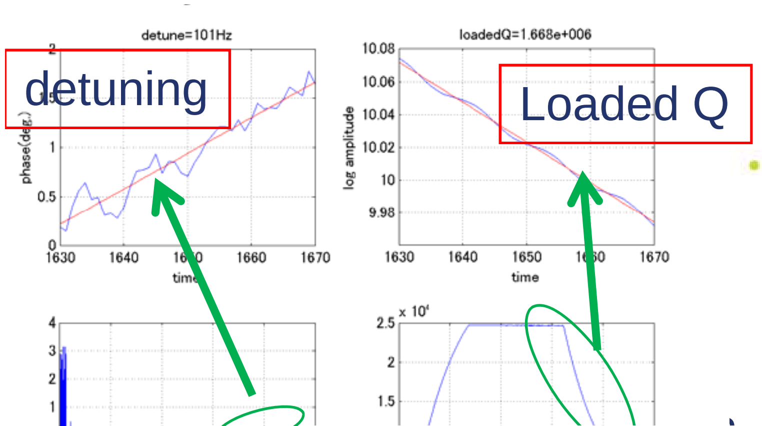
Automation and High Availability (information for software development)

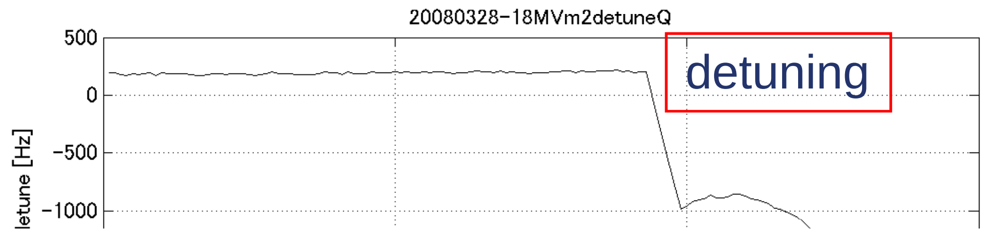
- "For the 4 RF systems at FLASH an rf expert must presently be almost all times available in case of changes in machine settings or if exceptions (for example cavity quenches) occur. *This will not be tolerable for the XFEL and ILC.*" by Stefan Simrock
- Automation study should be considered and more information will be necessary.
  Examples)
  - How do we detect "Quench"? (from rf ? Or from cryo?)
  - Does llrf have to watch dynamic detuning compensation? (if compensation is not enough, does llrf have to inform it to some machine?)
  - How do we compensate phase drift? (need intelligent adaptive FF?)
  - Does llrf have to change rf pulse-width and set-point (in case without beam)?
  - …
- These automation software development is not easy because the debugging is only possible at test facility.

- LLRF also needs more information for "high availability".
  Examples)
  - What should llrf do when "Quench"? (detune the cavity or stop rf/beam?)
  - What should llrf do when "Piezo failure"? (could not sustain stable op.)

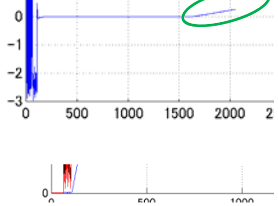
Quench detection

(150 pulses (30 sec.) before rf off)

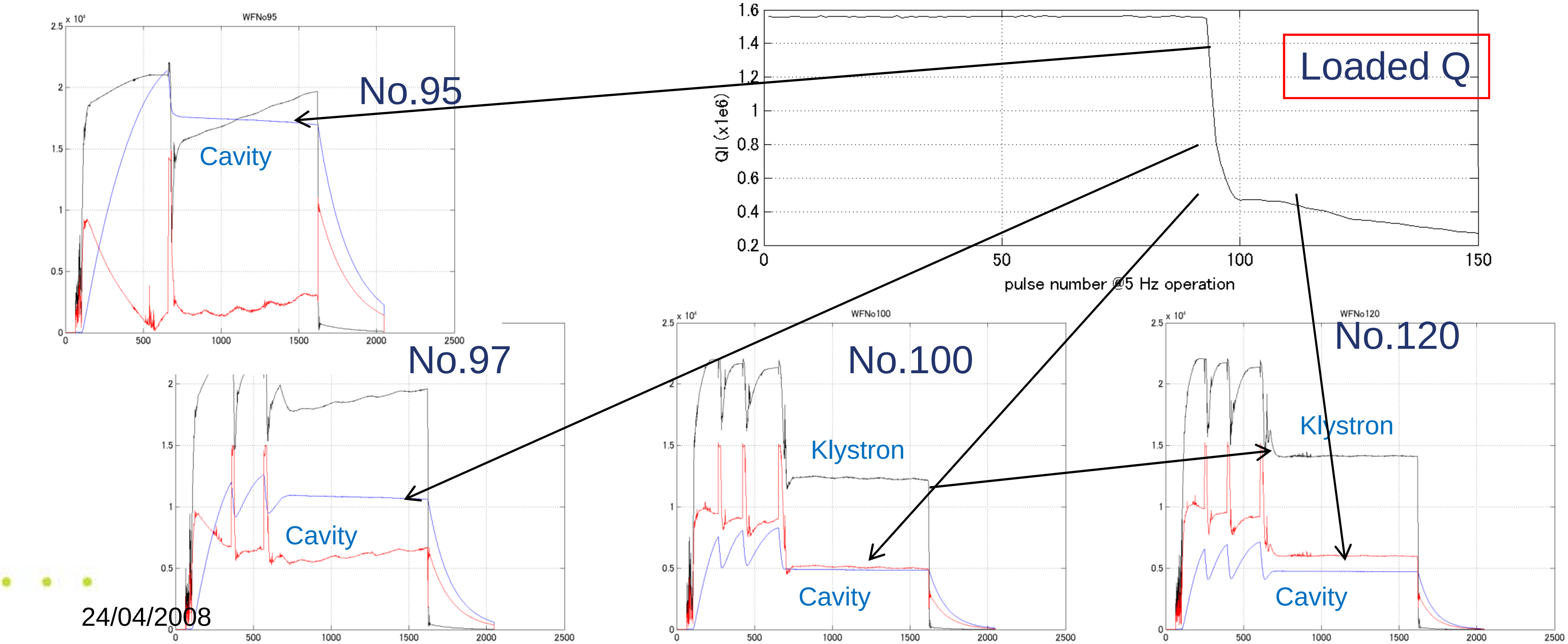




-Detuning and Loaded Q are calculated from decay curve after the pulse.



- LLRF should detect the degeneration of Loaded Q and stop rf?



24/04/2008

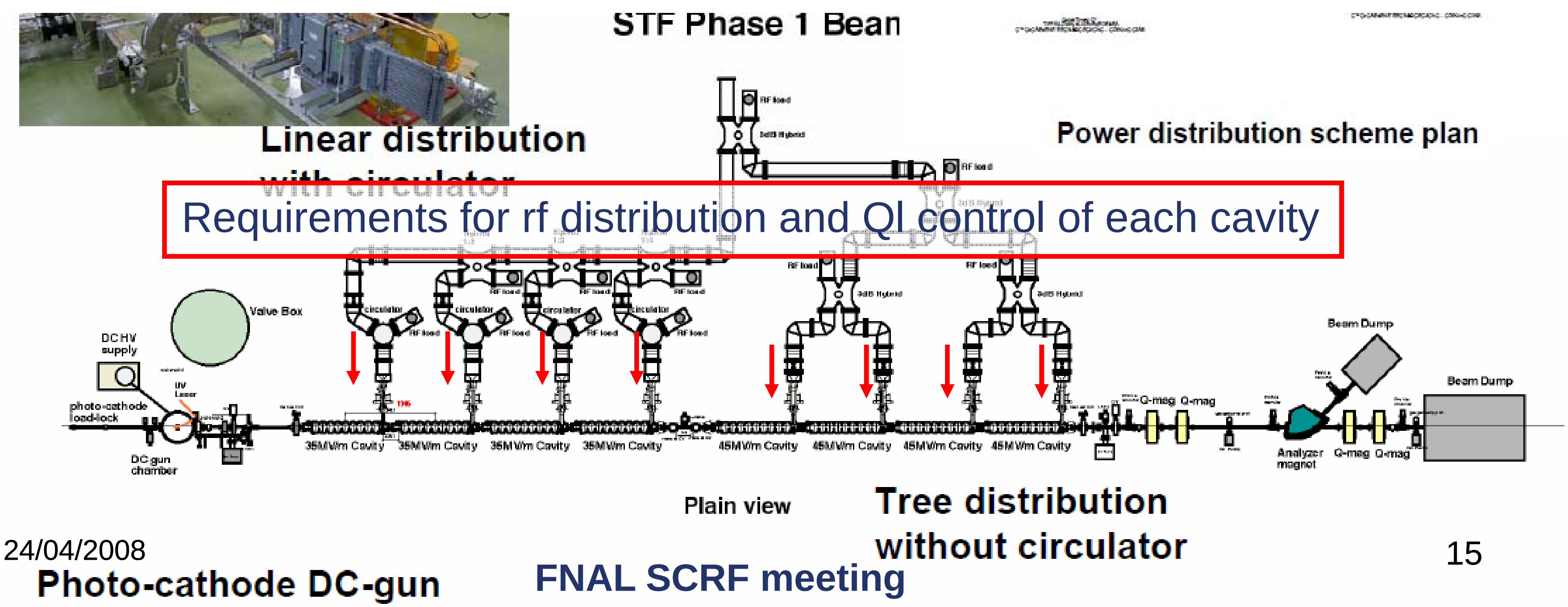
For S1 at KEK

Consideration of S1 at STF

- Eight cavities will be installed.
- Since we have 2 rf sources, 4 cavities (at least) will be driven by each rf source.

(Assumption)

- *Average gradient should be 31.5 MV/m.*
- *Cavities are operated without beam (no beam loading).*
- *Cavity operating gradient can depend on the performance of each cavity and it ranges from 28.5 MV/m to 34.5 MV/m.*
- *Loaded Q of each cavity varies +/-15%.*
- *RF distribution ratio can be controlled by fine tuning (to some extent).*

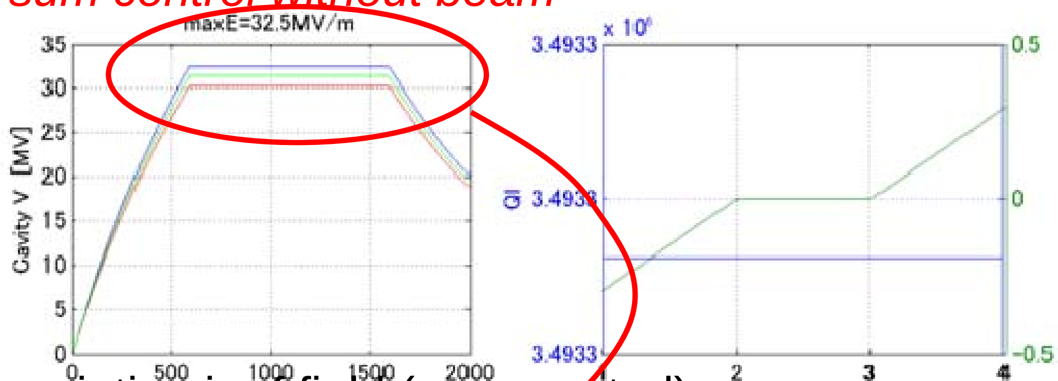


Requirements for rf distribution and Ql control of each cavity

Rf distribution and cavity field gradient

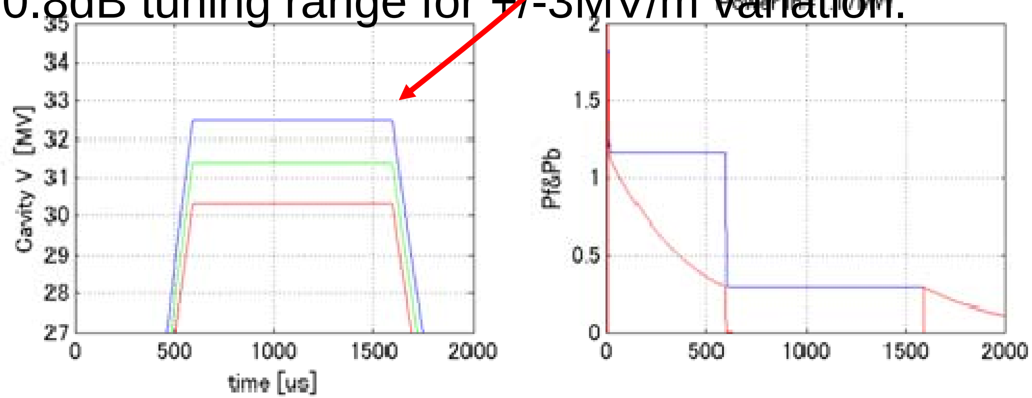
(simulation assumption)

- *4 cavities are driven.*
- *All cavities have same loaded Q (no variation).*
- *Rf distribution to cavities are -6.3dB, -6dB, -6dB, -5.7dB.*
- *Vector sum control without beam*



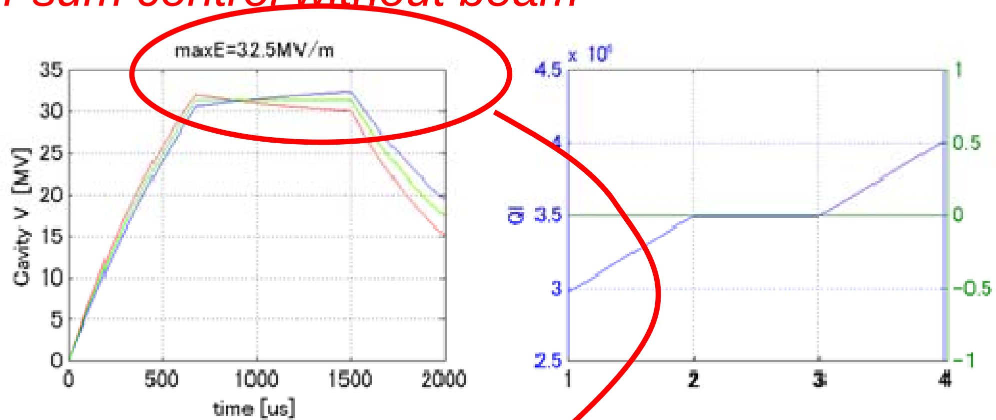
- +/-0.3dB variation in rf field (as expected).

-> need +/-0.8dB tuning range for +/-3MV/m variation.

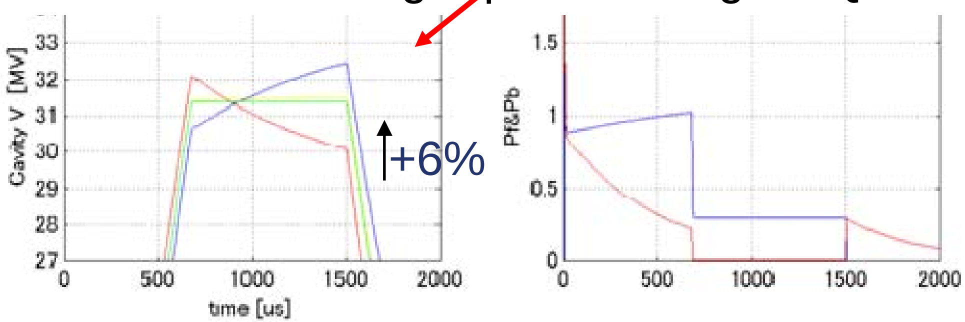


Ql variation and cavity field gradient

- *All cavities have same rf distribution (-6dB).*
- *Loaded Q variation of the cavities are -15%,0%,0% and 15%.*
- *Nominal loaded Q is 3.49e6.*
- *Vector sum control without beam*



- +6% increase in rf field during rf pulse for higher Ql



- **Ql control by 3-stub will be necessary.**

Thank you

Backup slides

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.

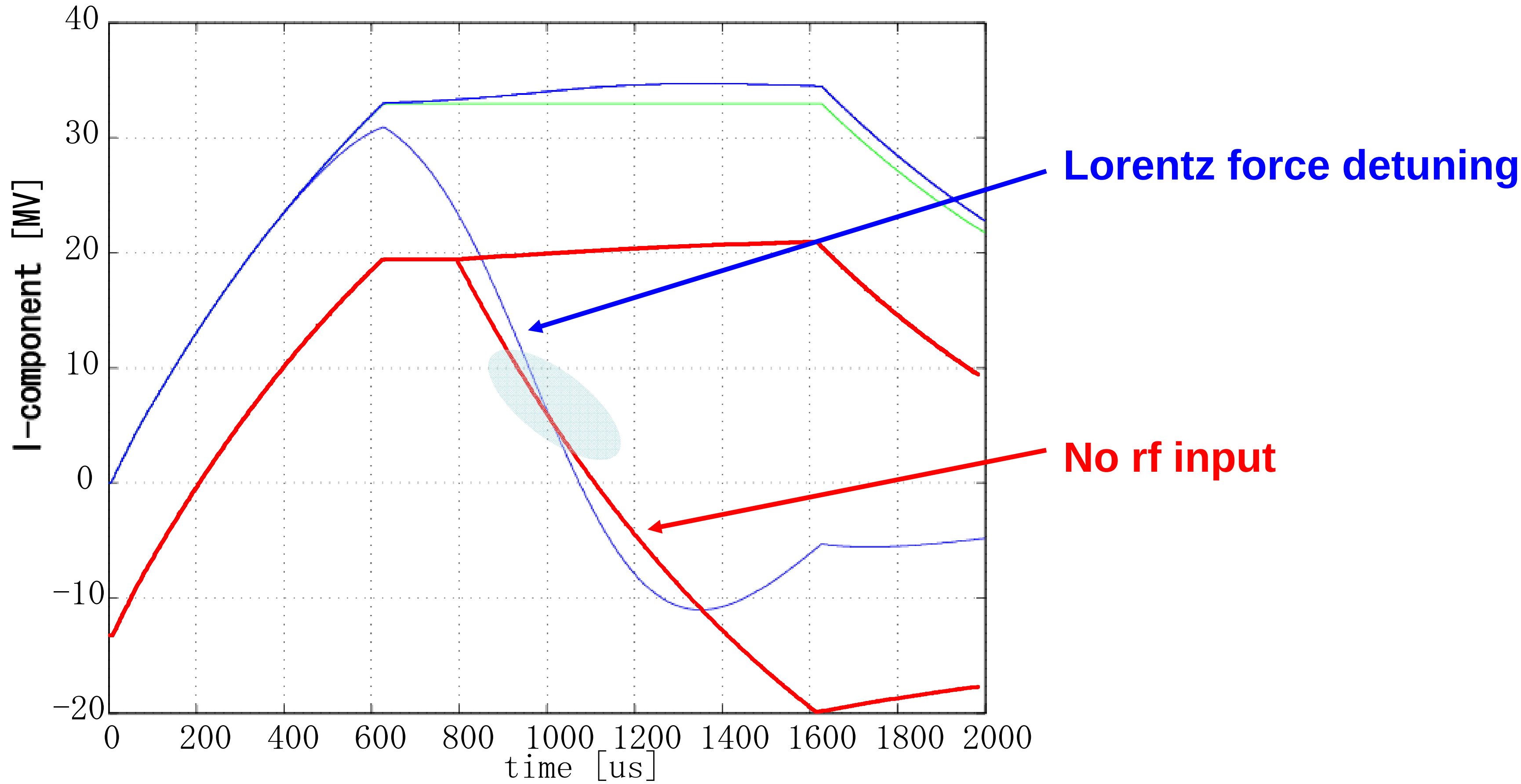
TABLE 3.9-1

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.

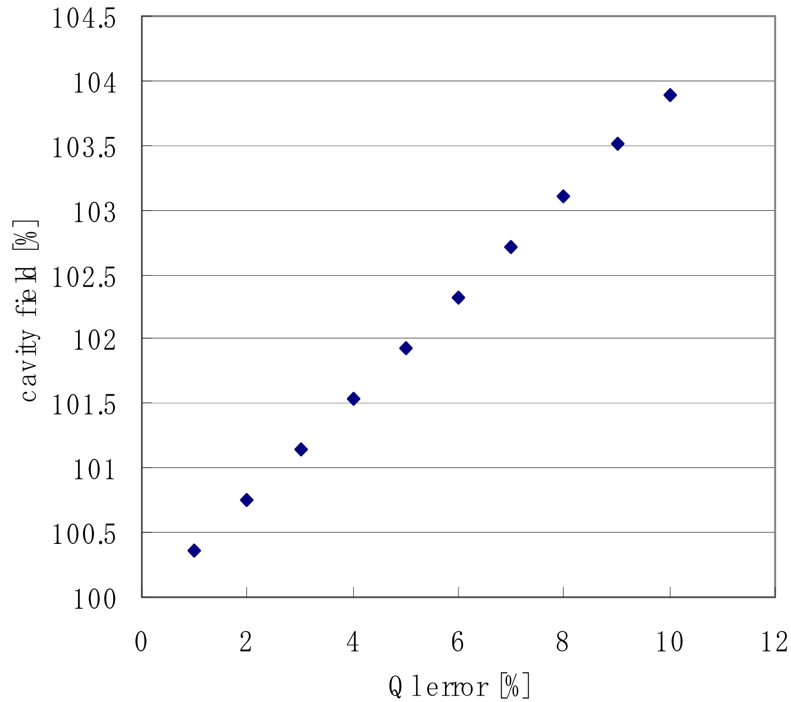
Location	Phase (degree)		Amplitude (%)		limitation
	correlated	uncorr.	correlated	uncorr.	
Bunch Compressor	0.24	0.48	0.5	1.6	timing stability at IP (luminosity)
Main Linac	0.35	5.6	0.07	1.05	energy stability $\leq 0.1\%$

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".*



Ql variation and cavity field gradient (2)

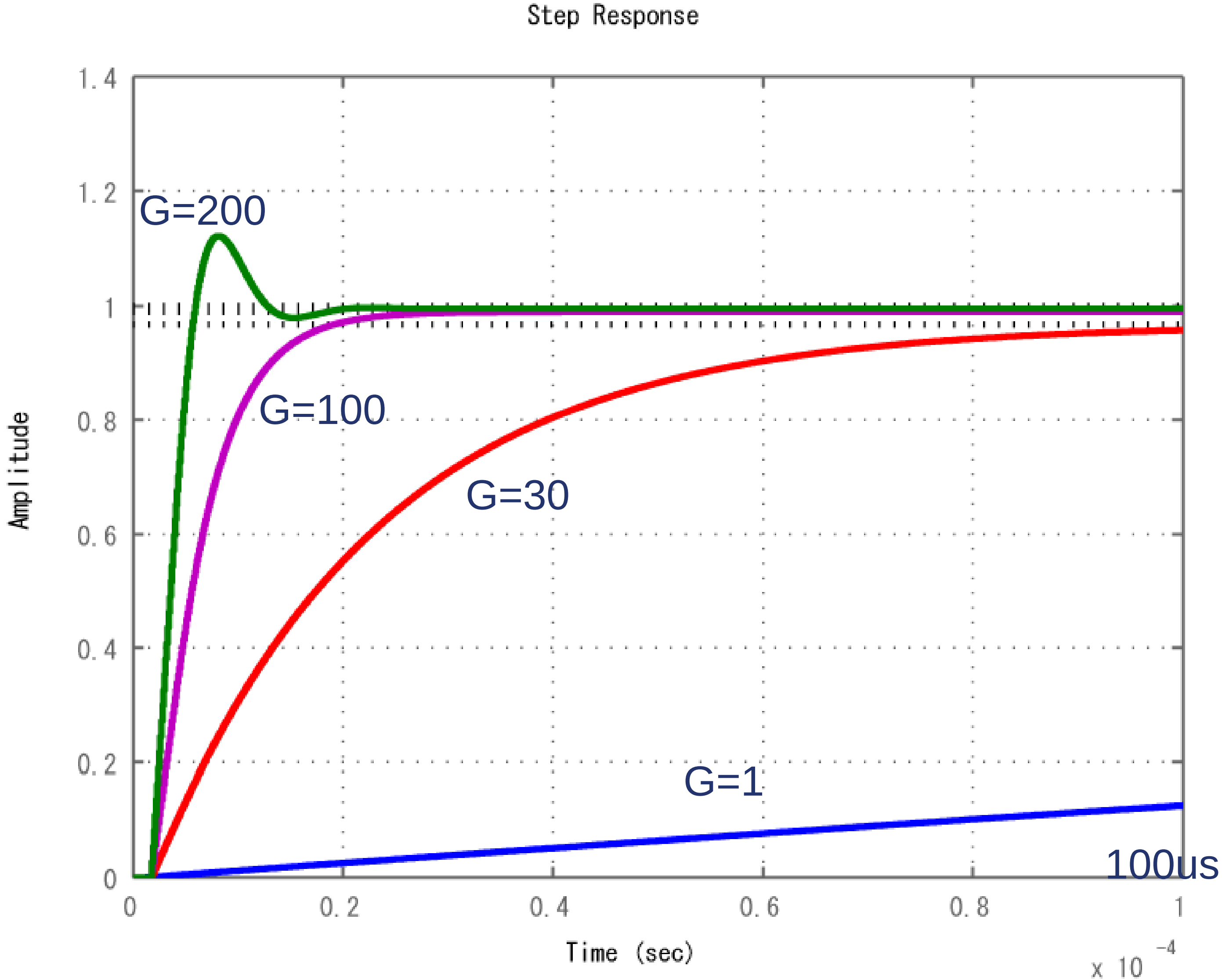


■ If the 6% field increase (+2MV/m) will not acceptable, external Ql control system by such as 3-stub should be installed.

(summary)

■ need rf input control of +/-0.8 dB and Ql control by 3-stub.

Step response



Faster response at high gain ***<u>(but larger drive will be necessary).</u>***
Fast FB needs larger driving power.

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)

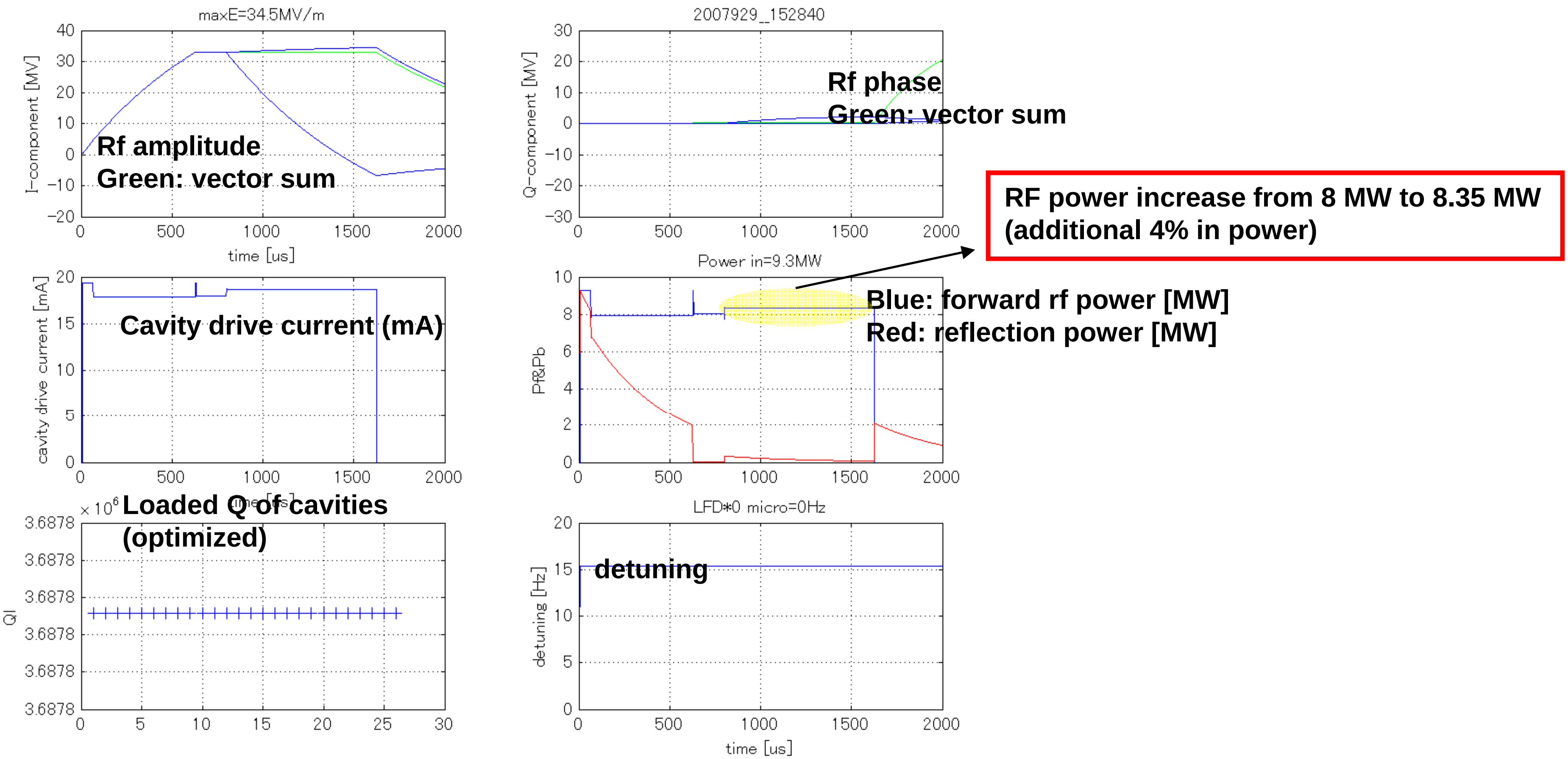
-> This precise beam current information is necessary for beam loading compensation.

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

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

RF stability with one cavity failure

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



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