Main Linac RF Power Requirements for Cavity Field Regulation (LLRF)

Brian Chase FNAL

Shin Michizono, KEK

Stefan Simrock DESY

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%

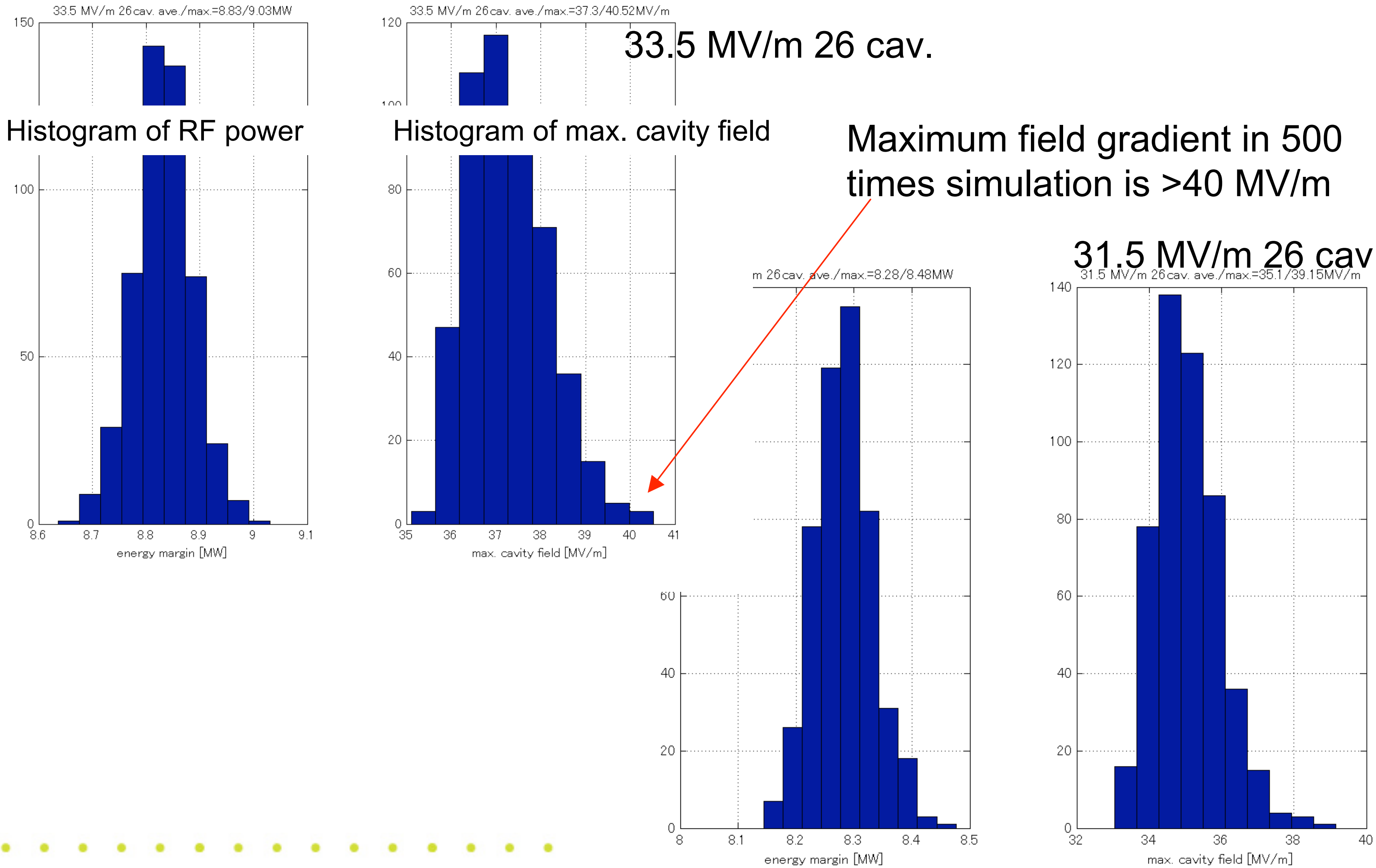
Background (llrf tuning overhead)

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

TABLE 2.6-2
RF unit parameters.

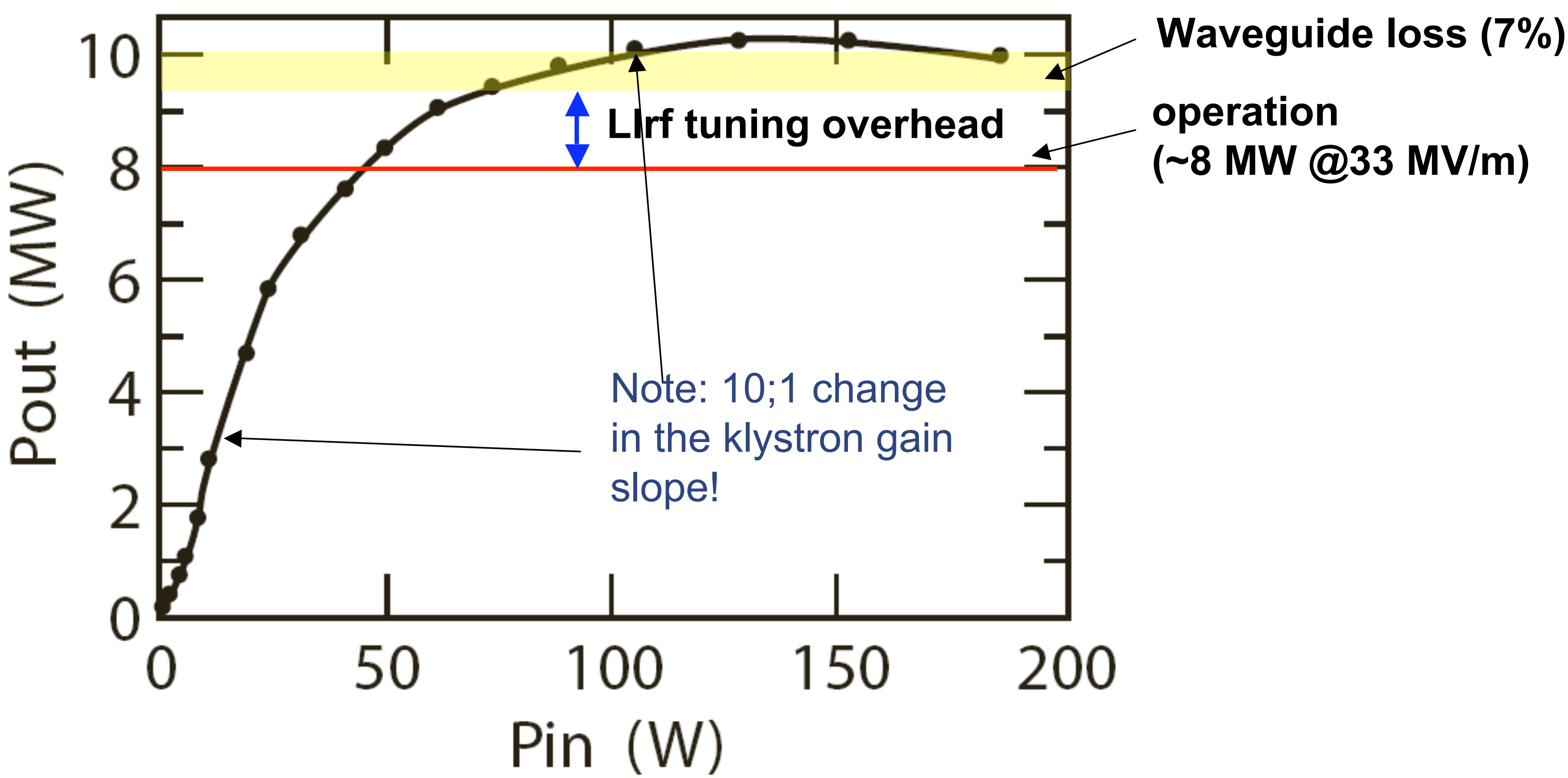
Parameter	Value	Units
Modulator overall efficiency	82.8	%
Maximum klyston output power	10	MW
Klystron efficiency	65	%
RF distribution system power loss	7	%
Number of cavities	26	
Effective cavity length	1.038	m
Nominal gradient with 22% tuning overhead	31.5	MV/m
Power limited gradient with 16% tuning 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

Histograms of cavity power and maximum cavity gradient @26 cav. system



Llrf Operating Point

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



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)

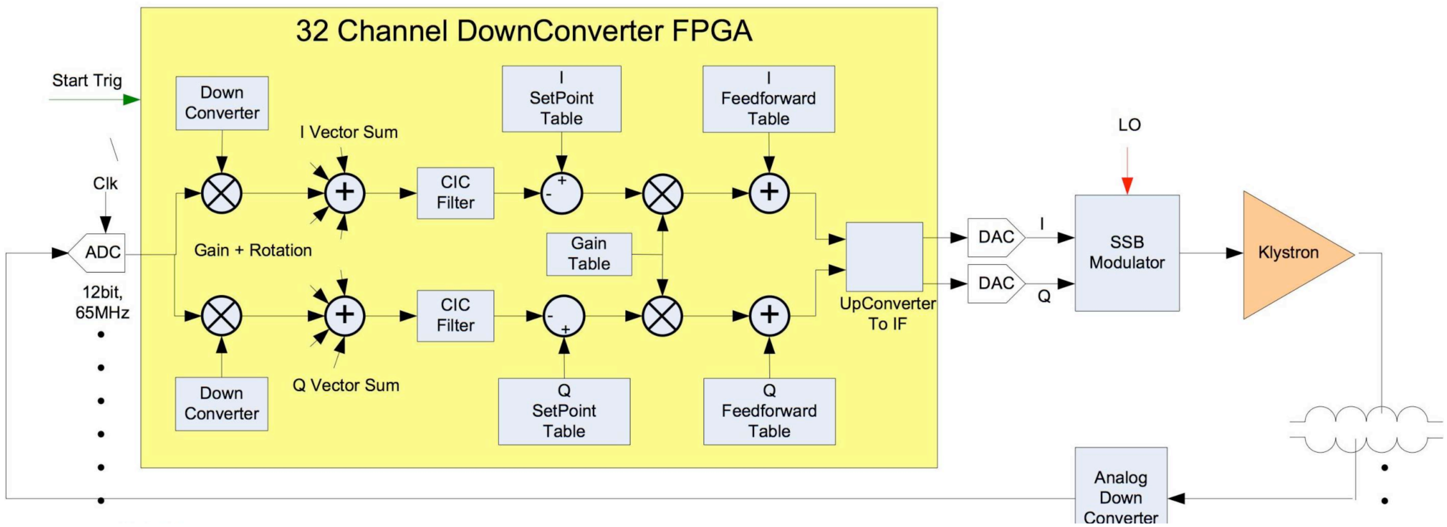
-> +/-50 Hz detuning causes +/-2% additional rf power.

  - Cavity gradient spread in an RF Unit

-> As much as 4% additional RF power.

Power Overhead Budget

- llrf overhead (18% @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.
- In case of proportional gain (Pgain), fluctuations can be suppressed 1/Pgain.

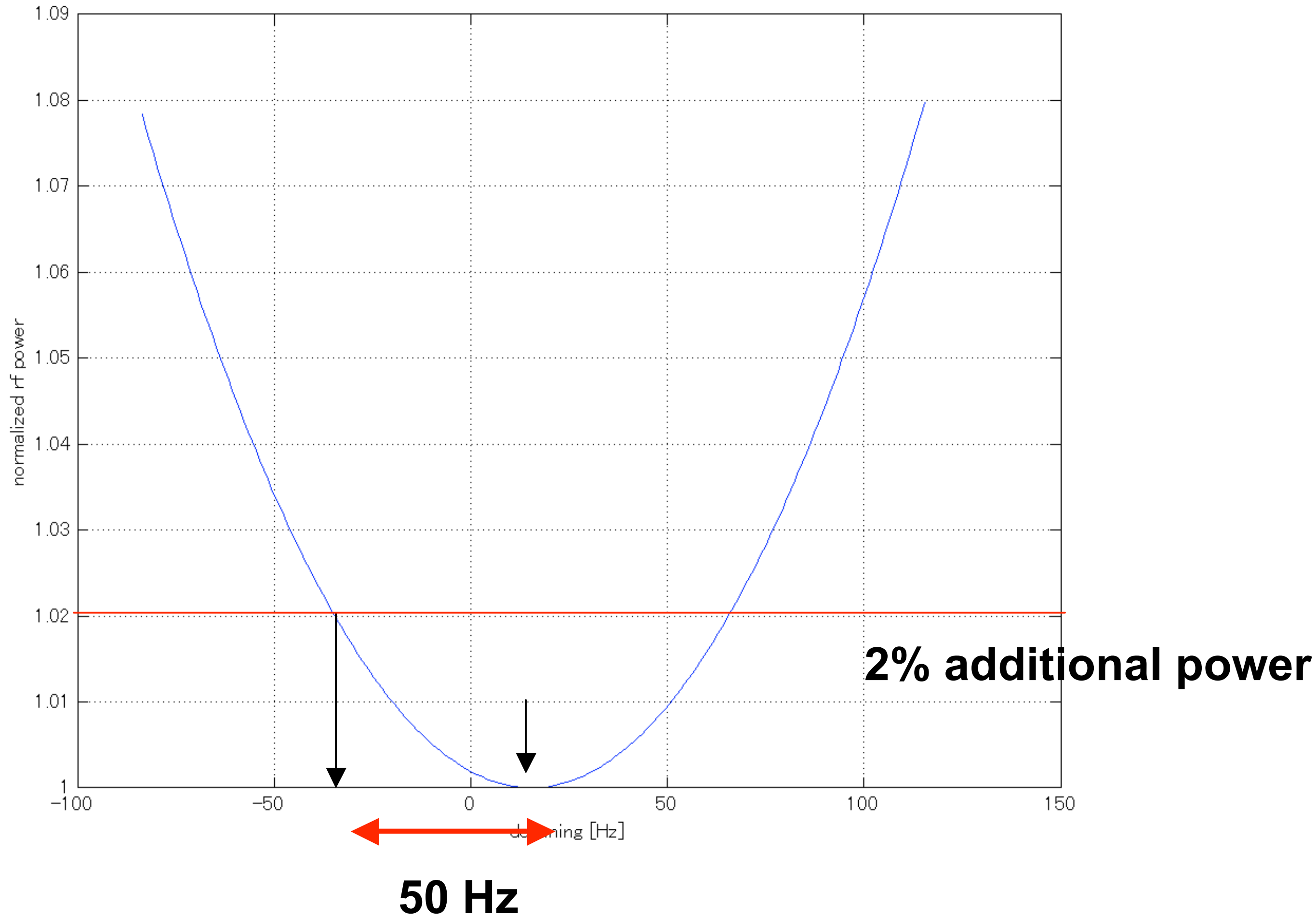
(10% fluctuation and Pgain=100, -> 0.1% stability)

- 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.

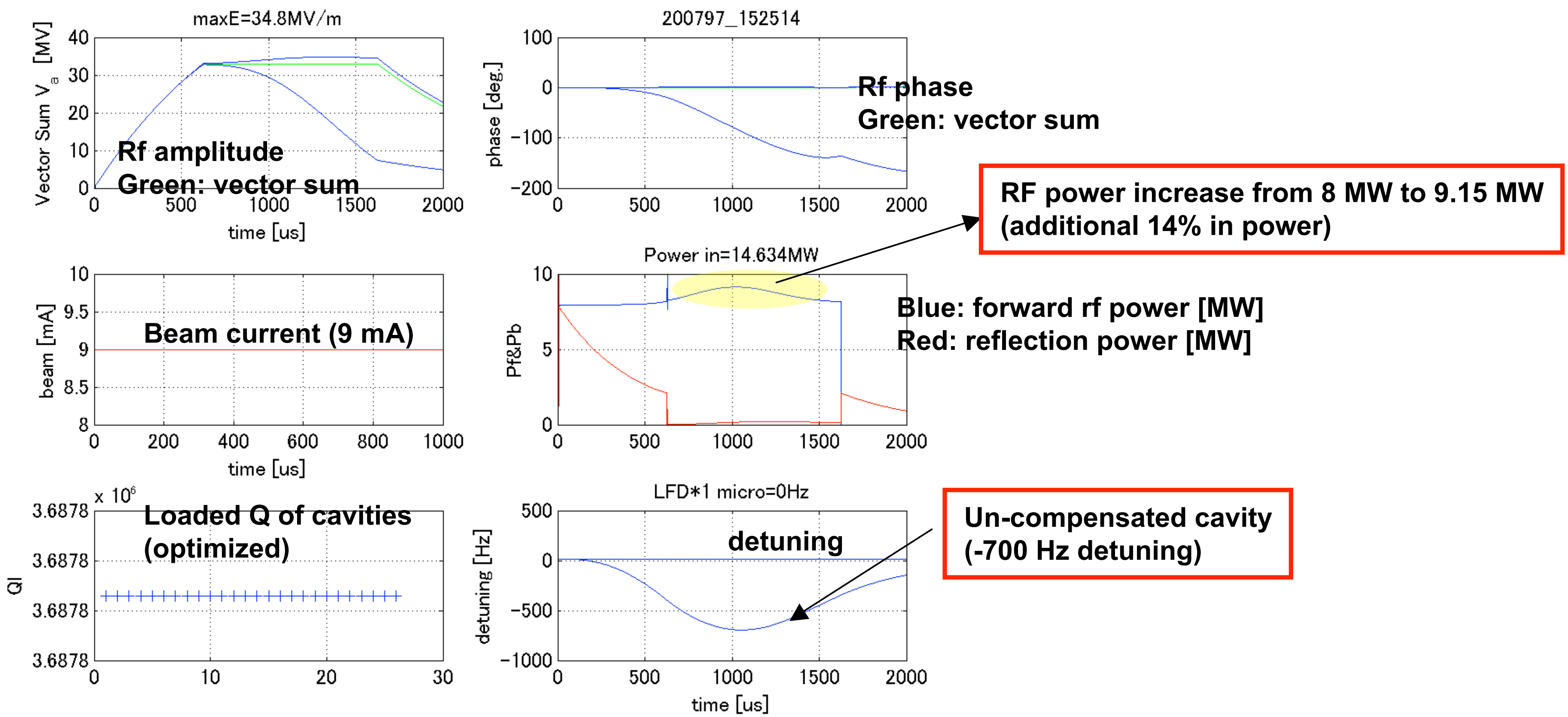
Detuning v.s. RF Power



- 50 Hz detuning requires additional 2% rf power

Failure in LFD Piezo Control

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

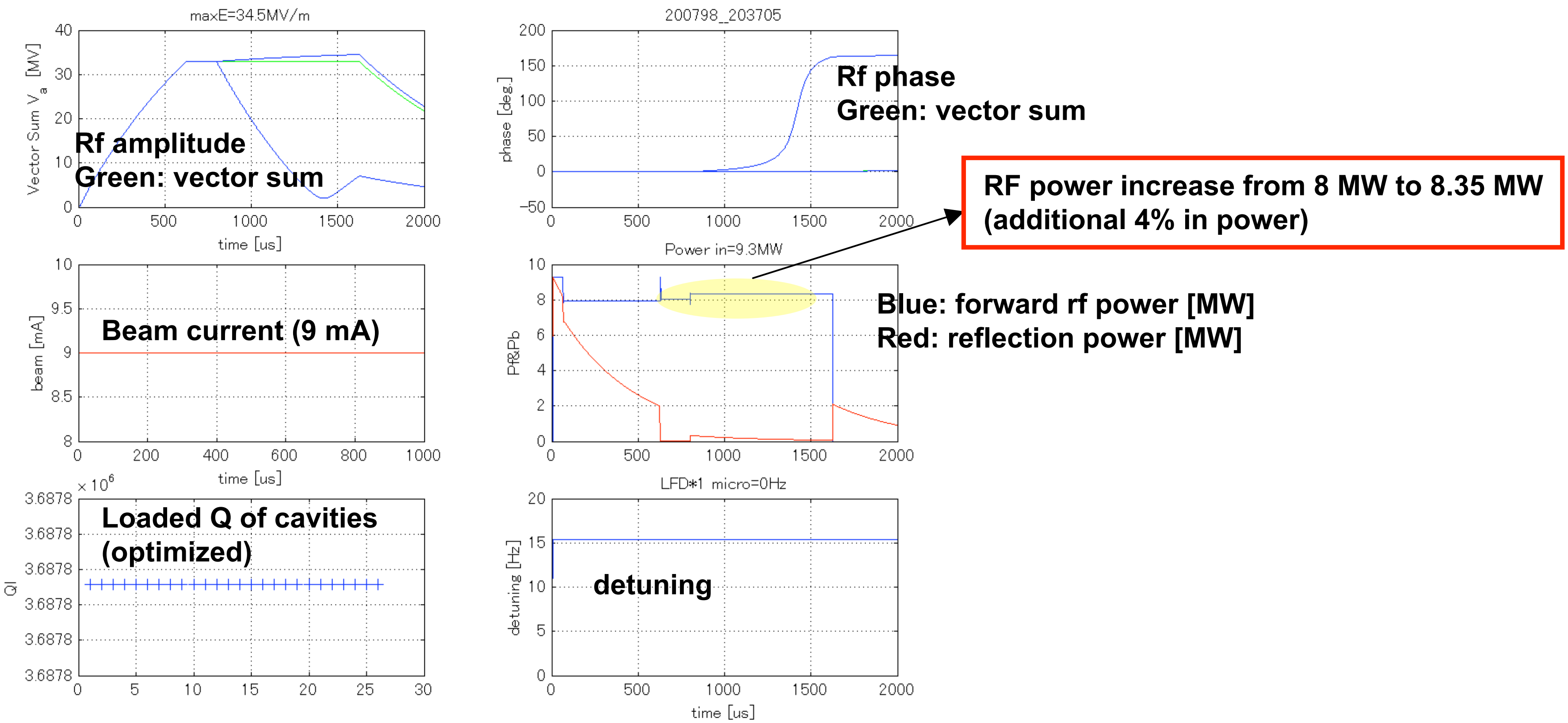


- 14% more rf power is difficult to make.

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

Cavity Failure

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



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

Slew Rate Limit

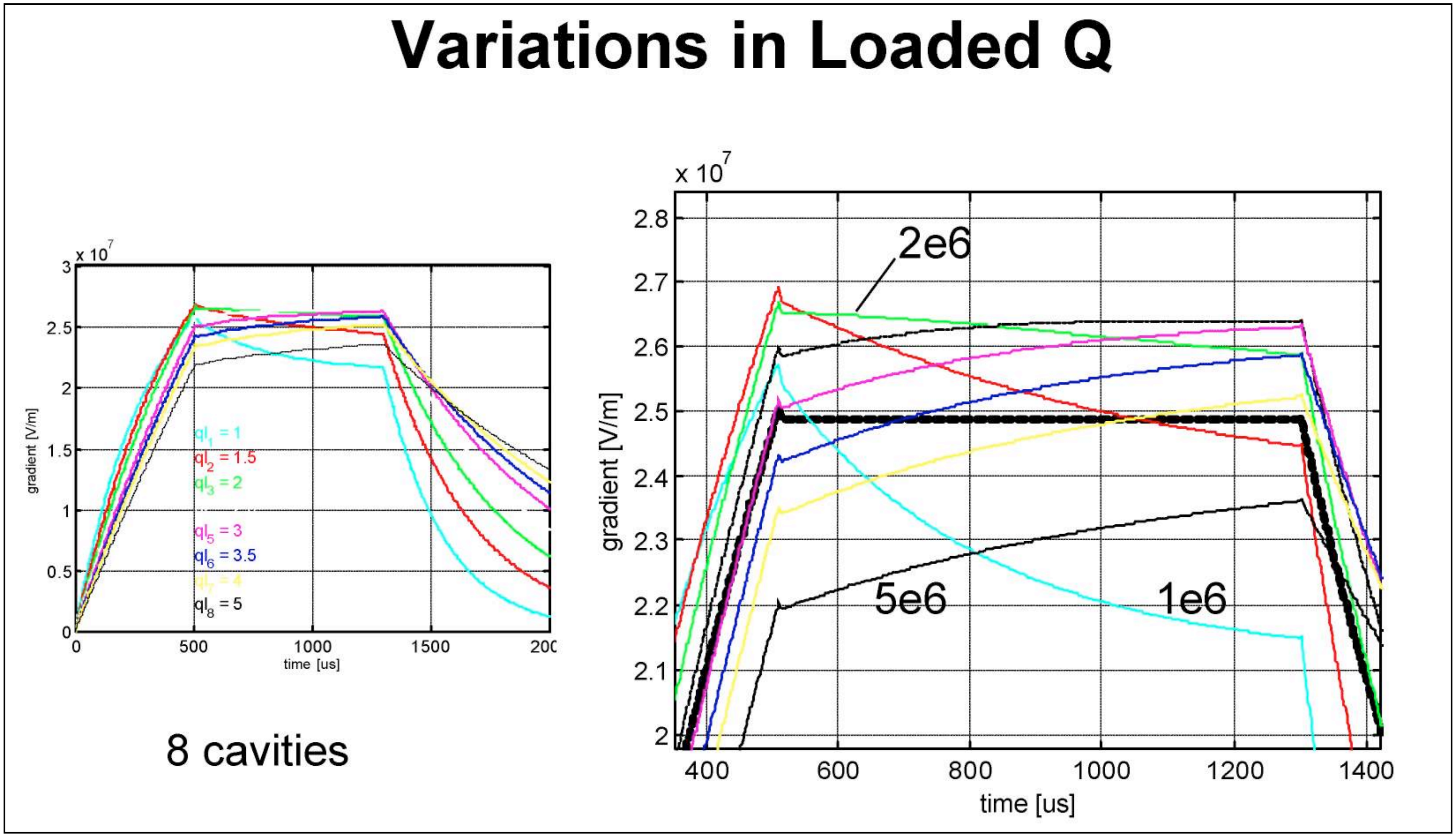
- If there is an error present, then the RF system must add energy to recover.
- Assume:
  - **a cavity BW/2 of 200Hz without beam and a beam loaded BW/2 of 100Hz**
  - **An error of 0.5% and 10% power overhead**
- It will take 100us or 10% of flattop to return to regulation
- Any time the klystron and 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.**

Unknowns for Simulations

- Quality of directional couplers(35dB?)
  - **Needed to adjust Ql and power taps**
- Procedure to adjust power taps
  - **Is this a one time set and forget?**
  - **Expected accuracy and stability**
- Klystron regulation
  - **Amplitude and phase with frequency spectrum**
- Real data on regulation of Lorentz Force Detuning at high gradients

Operation at Different Gradients

Variations in Loaded Q



Operation with Cavities at Different Gradients

Additional average power loss of 2.7%

PAC 07 "RF Distribution Optimization in the Main Linacs of the ILC"
Bane, Adolphsen, Nantista

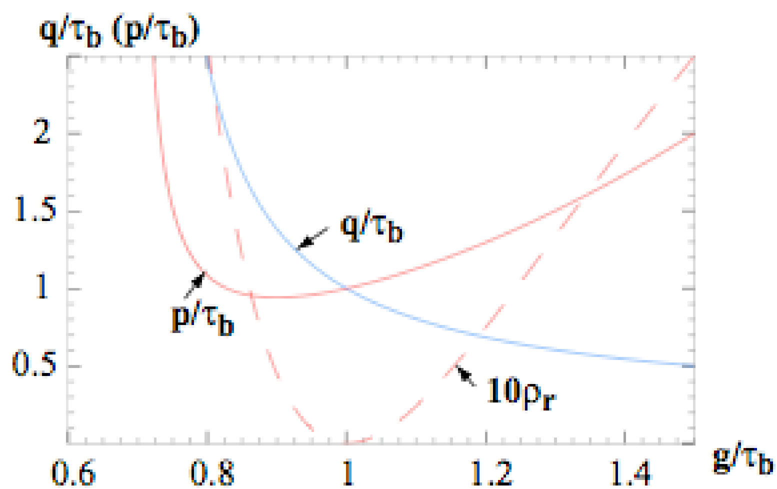


Figure 2: The values q/τ_b, input power p/τ_b, and reflected power ρ_r which yield a flat gradient, as functions of g/τ_b.

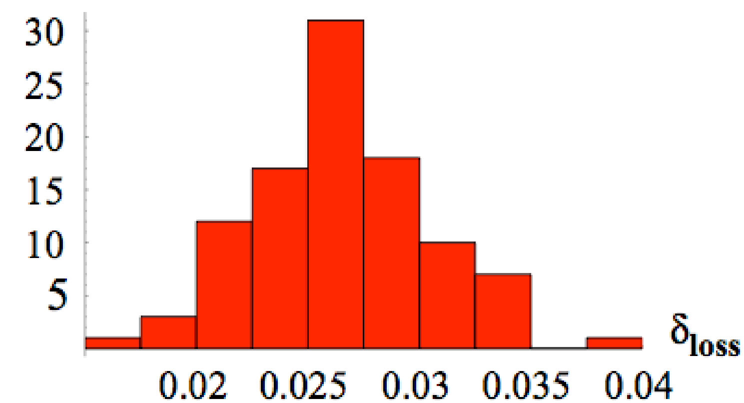
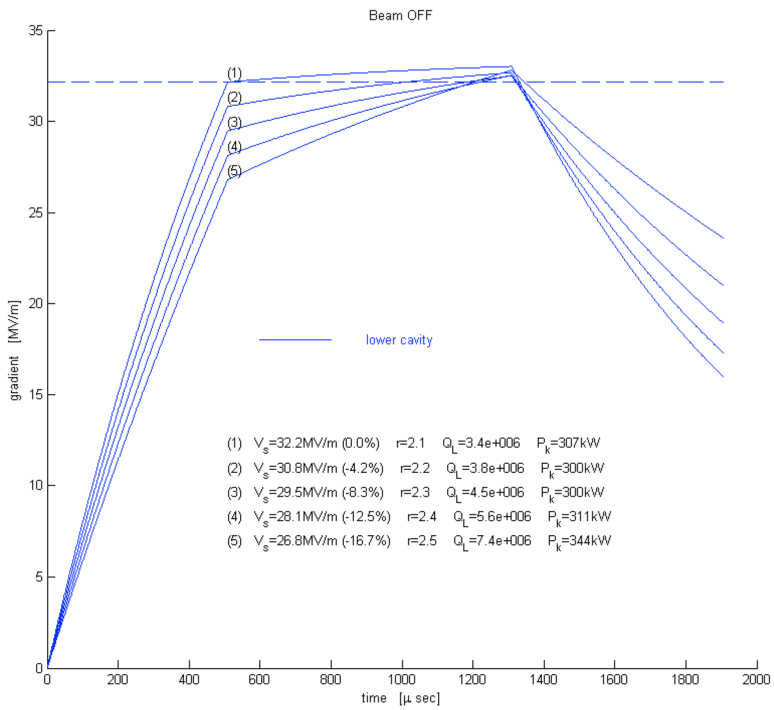


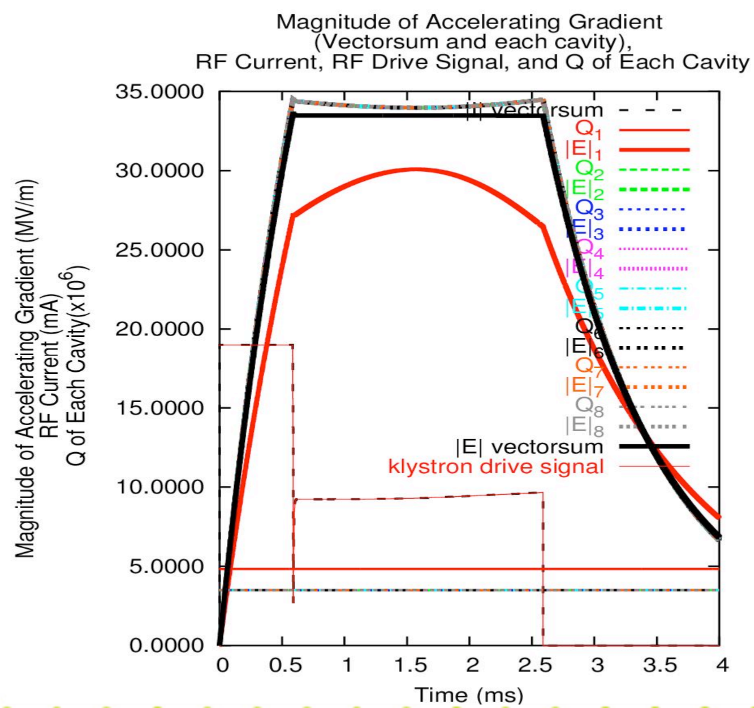
Figure 4: For optimized cases with 1 p and individual q's: histogram of δ_{loss} for 100 ensembles of 26 cavities.

Operation with Cavities at Different Gradients

Quench limits will prevent full pulse length operation with changes in gradient or beam current

Or, other schemes that involve detuning of the cavities will require more reflected power(loss)





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

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.

- Operation at 33 MV/m with a spread in cavity gradients will push the limits of the cavities, LFD compensation and field regulation

- More exotic regulation schemes such as global loops based on feedback from the IP or beam current regulation should be explored