LLRF Comments on the RF cluster and Distributed RF schemes

Shin Michizono (KEK)

- Klystron cluster / Distributed rf schemes
- Operational gain and feedback stability
- Power and Ql control
- Possible control system @klystron cluster
- LLRF layout @ distributed rf

Required stability

- Llrf stability requirements (@ ML and BC) are < 0.07%, 0.24deg.
- Each error source should be <1/3 of requirements (<0.02%, 0.08deg.)

TABLE 3.9-1

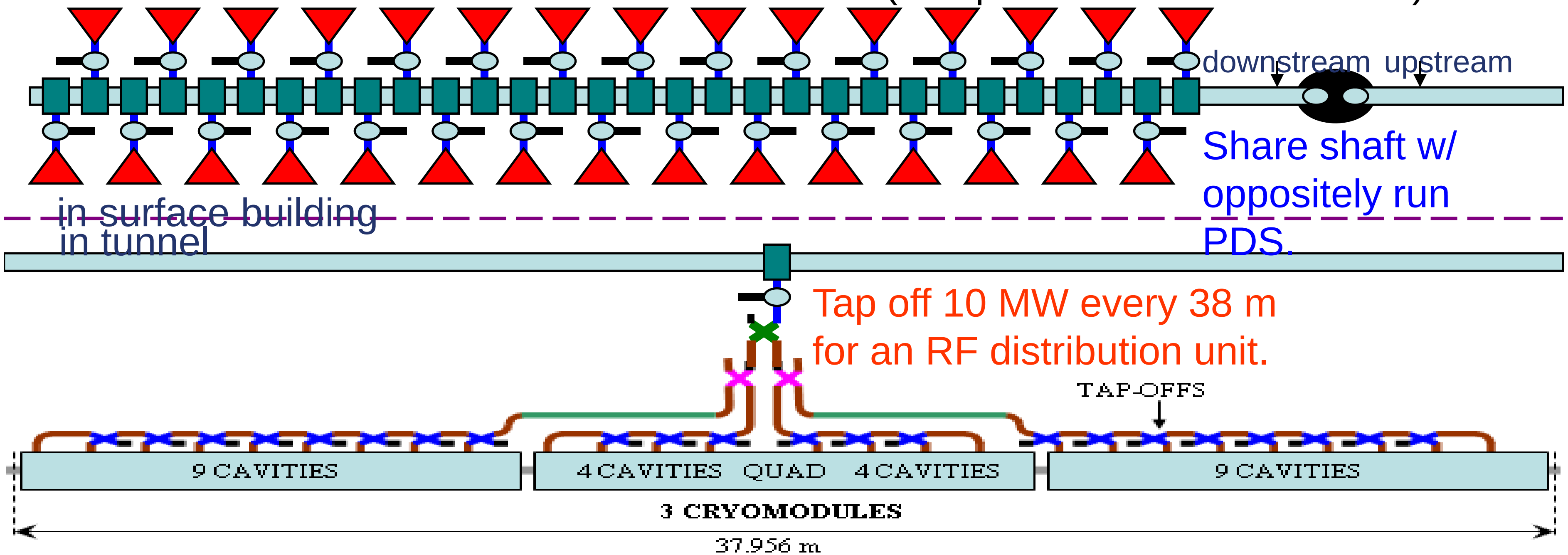
Summary of tolerances for phase and amplitude control. These tolerances limit the average luminosity loss to <2% and limit the increase in RMS center-of-mass energy spread to <10% of the nominal energy spread.

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 $\leq 0.1\%$

Klystron cluster

- The configuration of klystron cluster introduces total 8~10us latency.
  -> larger latency than our current model (<1us)
  - 3.5us (rf transmission)
  - 0.5us (ADC detection at each 26 cavities in the tunnel and conversion to optical signal of 26 vector sum)
  - 3.5us (optical transmission)
  - 0.3us (conversion and vector sum of 27 units)
  - 0.2us (DAC outputs to 27units)

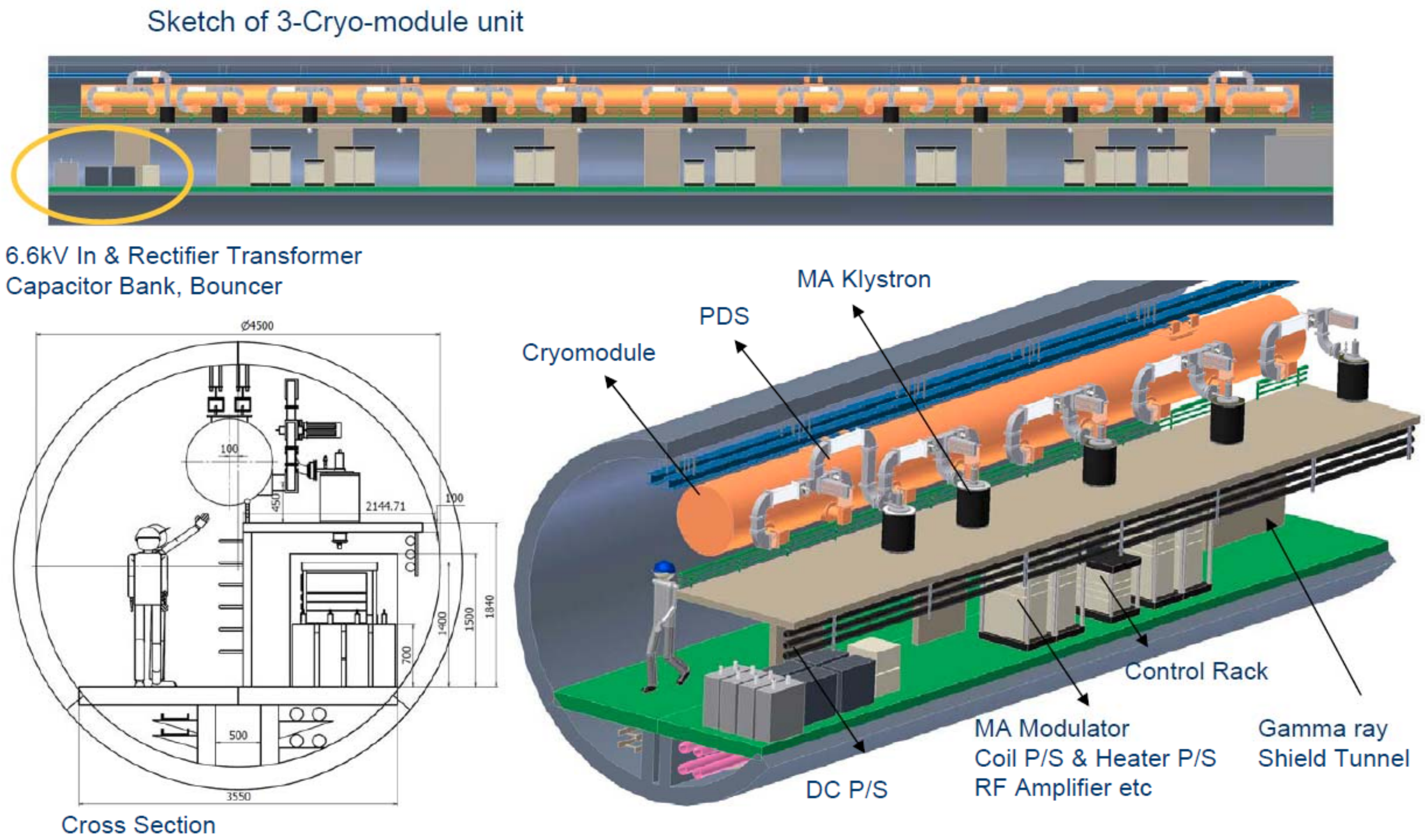
- LLRF detectors will be located in the tunnel (and process each 26 cavities).



With extra transmission loss, feeds ~27 RF units = 1.026 km. (shaft serves 2.052 km)

Distributed rf scheme (DRFS)

- One rf source drives two cavities.
- Since the rf source is located just around the cavity, FB loop would be <0.3 us.
- The LLRF performance would be best.
- LLRF detectors will be located in the tunnel.



Comparison of llrf configurations

	Baseline	Single tunnel	Klystron cluster	Distributed rf
No. of tunnels	2	1	1	1
LLRF unit	Service tunnel	Beam tunnel	Beam tunnel	Beam tunnel
Cavity/ rf unit	26	26	780	2
No. of vector sum	26	26	780	2
QI and power distribution control	Necessary	Necessary	Difficult	No need
No. of llrf cable /rf	~80	~80	~80*30 or fast optical cables	6
Loop delay	~1 us	~1 us	~10 us	~0.3 us

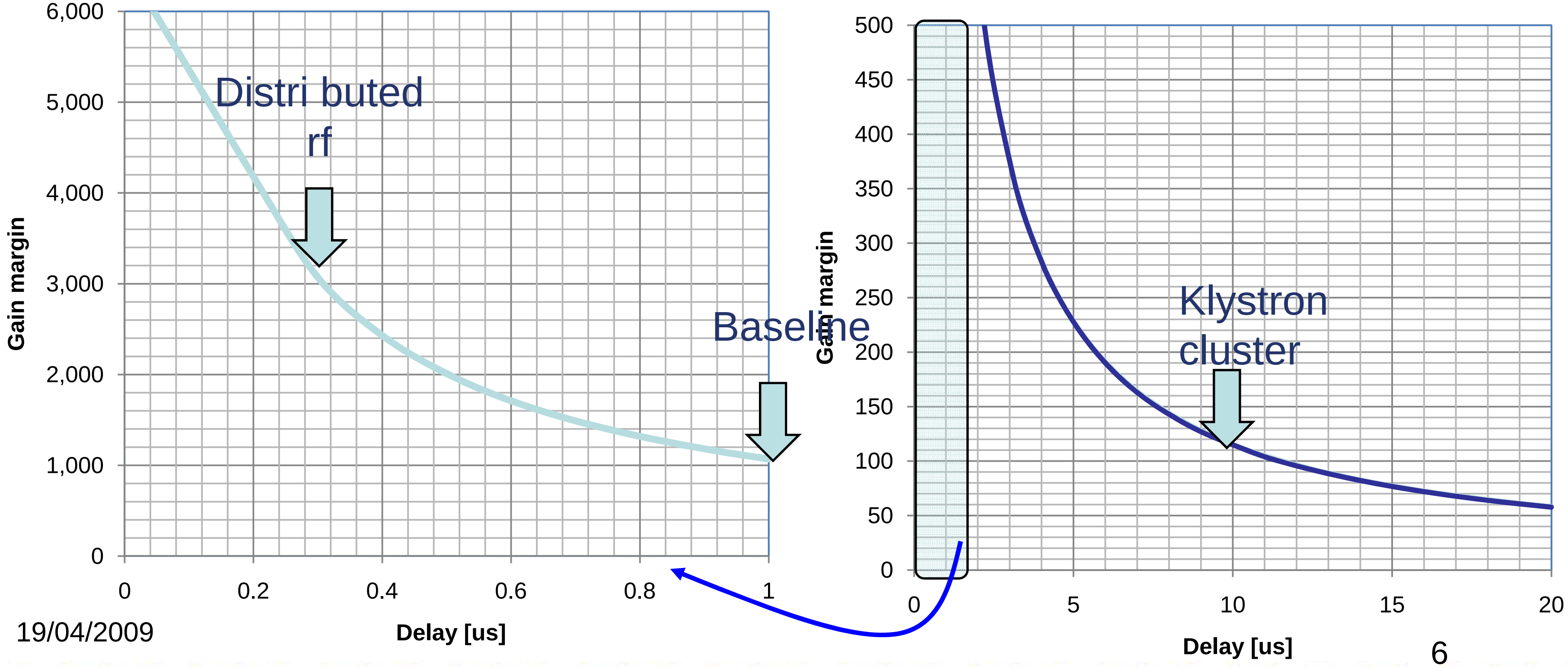
- Operational gain?
- Power and QI control?
- Cost?

Operational gain

- Error is only compressed by a factor of gain
- Gain margin is calculated from Bode-plot.

- Operational gain can become ~1000 in case of distributed rf owing to its short latency (such as total loop delay of 0.3 us).

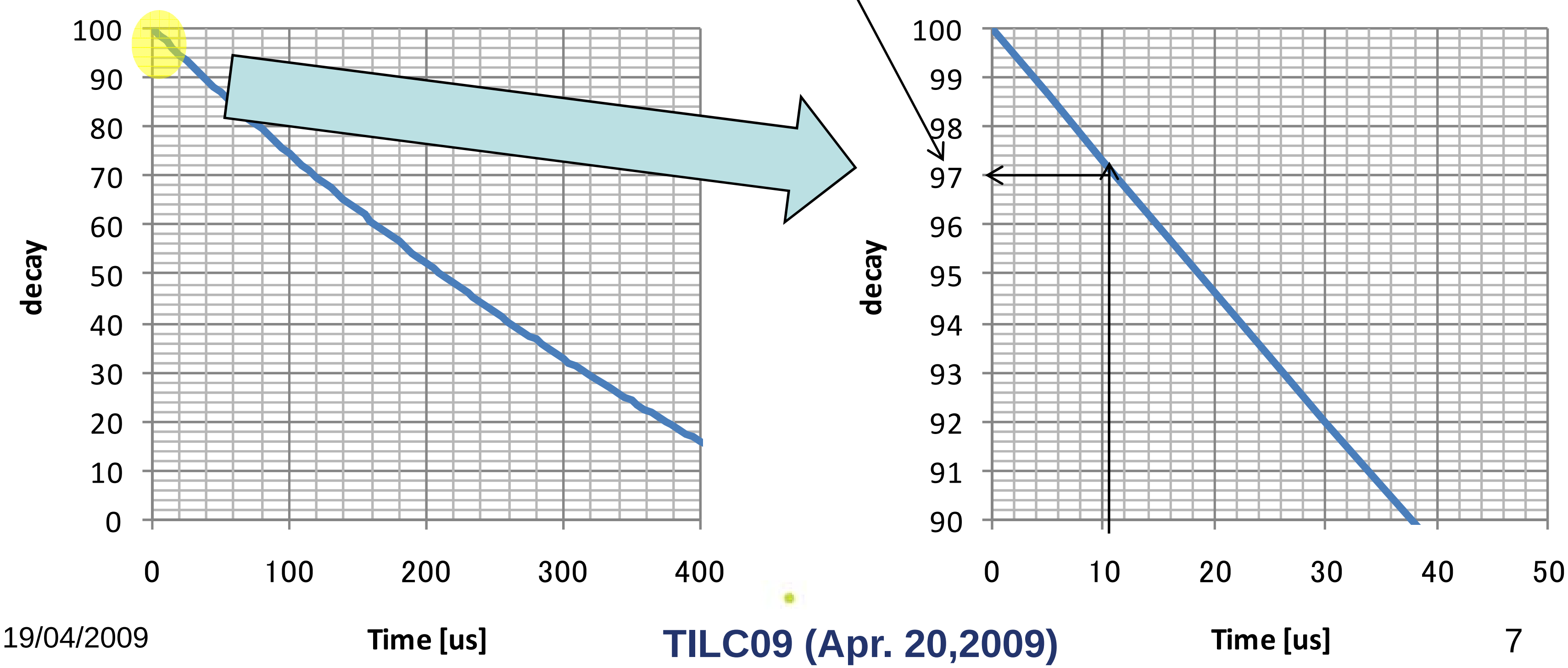
Gain-margin (Gain just before oscillation)



LLRF performance (with beam loading) @klystron cluster

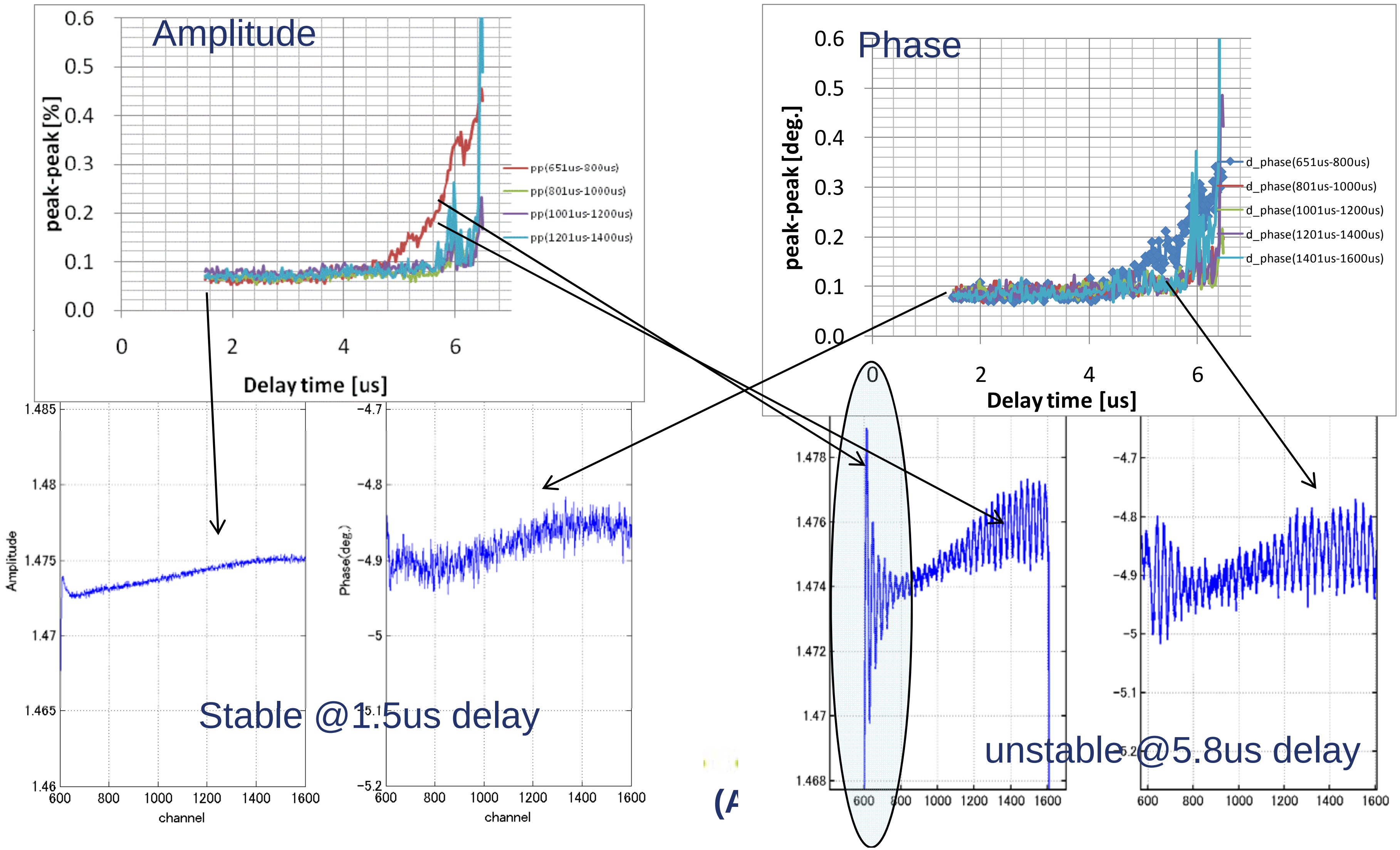
- Assumption
  - Cavity Q:3e6 and -> decay time constant=462us and f1/2=217Hz
  - After 10us of blind time, system changes 3% of perturbation (large even though the time constant is slow).
  - Since the input rf power is high (due to compensation of beam power), the cavity field is sensitive to rf power input. (rather than no-beam condition)

- Example : Kly HV change (1%, 12 deg. in phase) during rf operation.
  - Cavity phase changes by 0.36 deg. (=12*3%) far from our goal of 0.1deg.
- Need to relax the rf stability requirements.

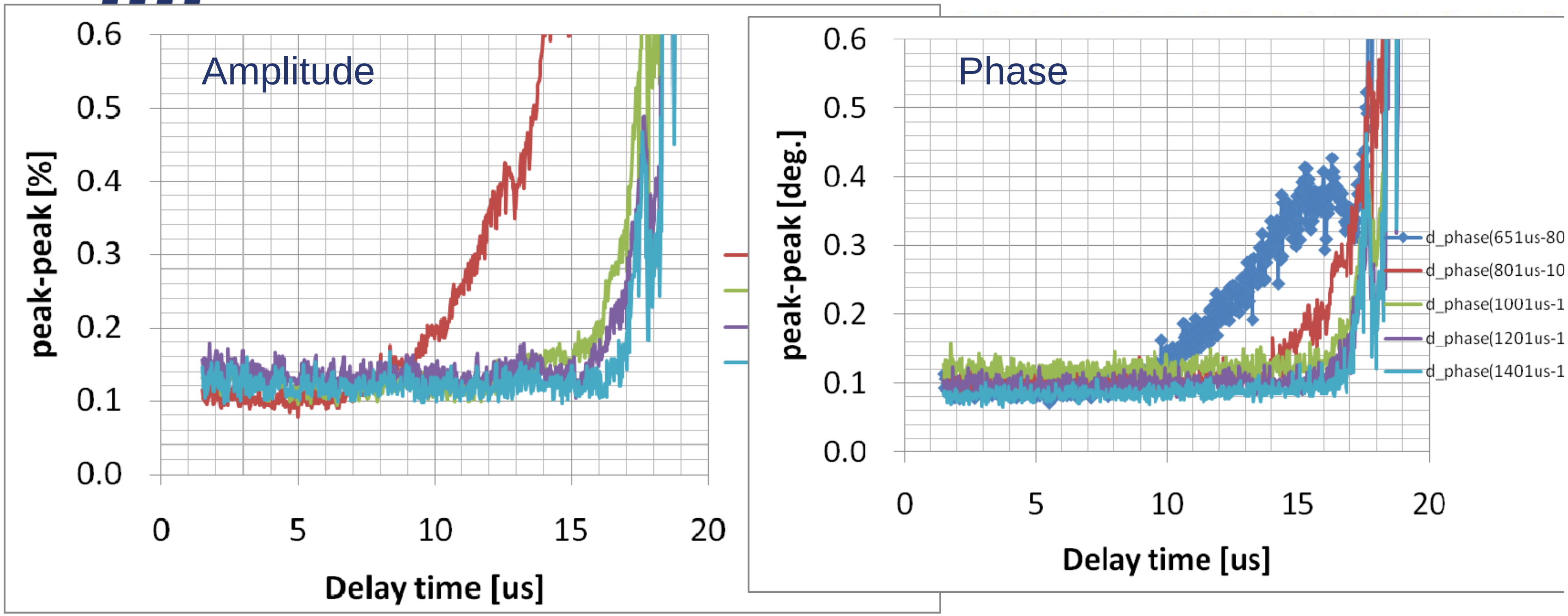


Stability and FB loop delay@G=55

- FB loop delay v.s. rf stability is measured at STF (4 cavity vector-sum control).

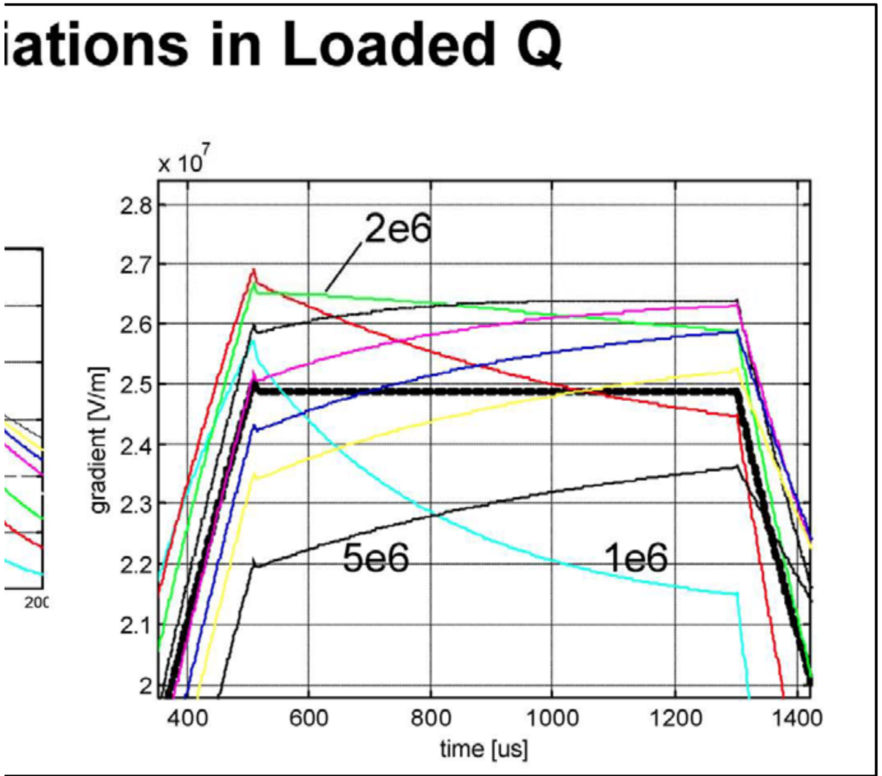


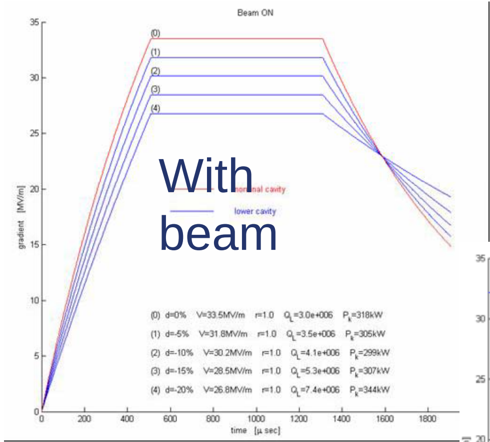
Stability and FB loop delay@G=22

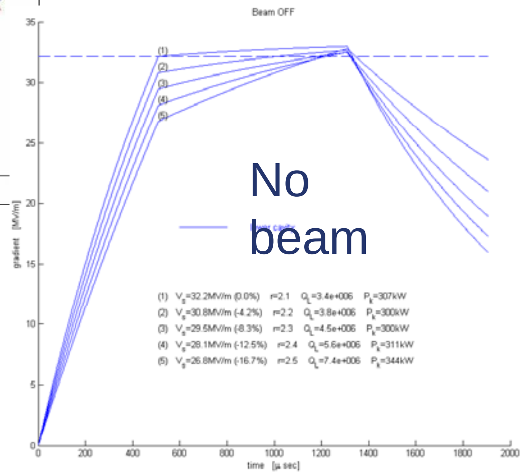


- At proportional gain of 55
  - stable delay limit is about ~5us.
- Proportional gain of 22
  - stable limit is about 10 us.

Power and Ql control

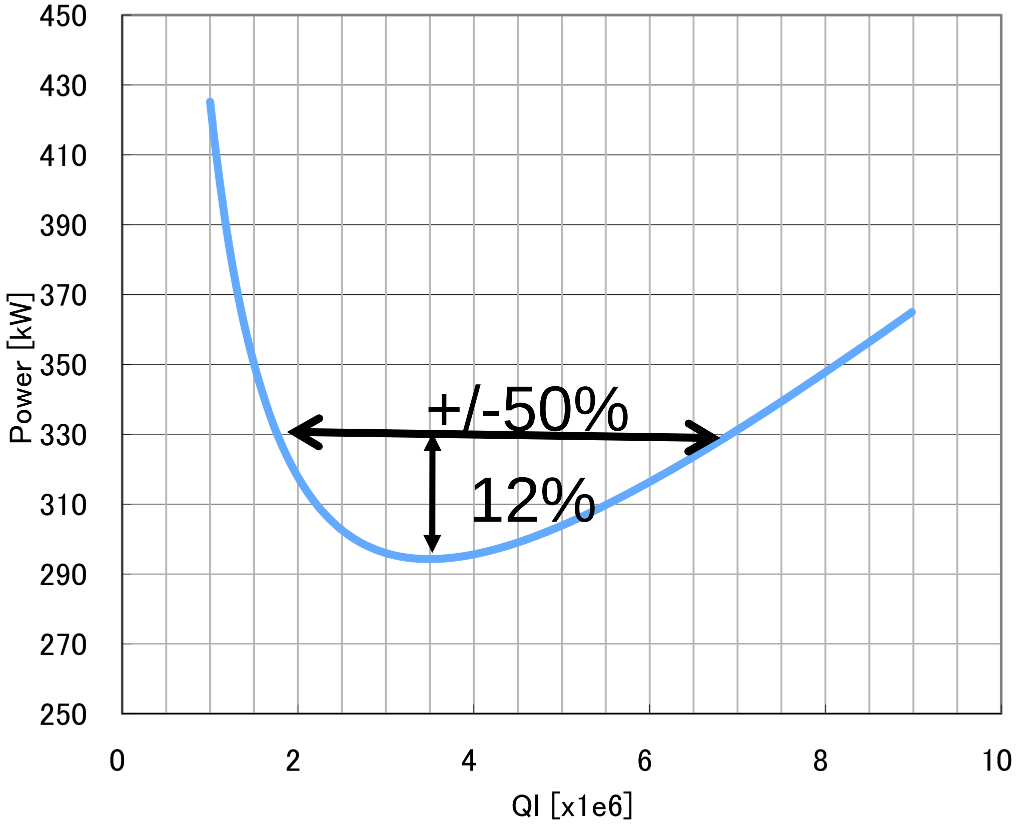






- Vector sum control under restrict quench limit requires power and Ql control
- Klystron cluster: Rather complicated because of >700 vector sum control
- Distributed rf:***Each cavity can be operated near the limit of quench.(No need for P and Ql control)***

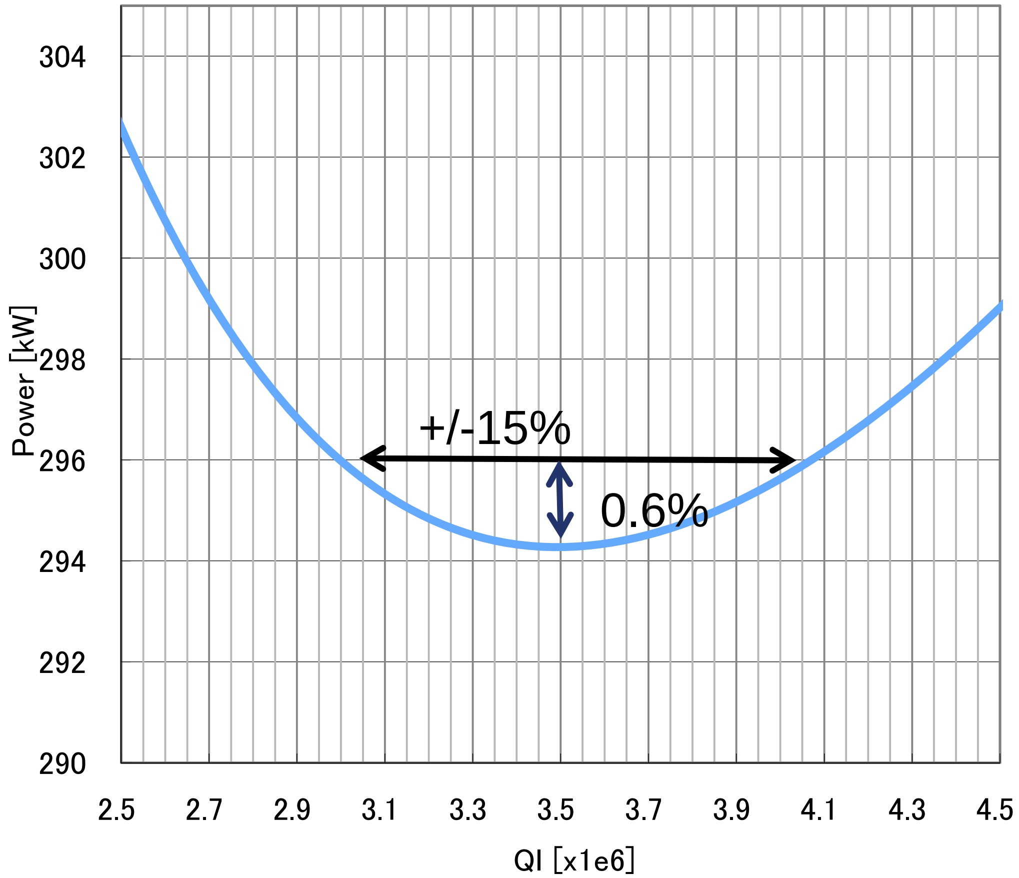
Power, Ql control (baseline & klystron cluster)



Baseline & klystron cluster:

■ In case of rf power and Ql control, additional 12% rf power is necessary at +/-50% coupling control for flattening the rf field under beam loading.

Power, Ql control (distributed rf)

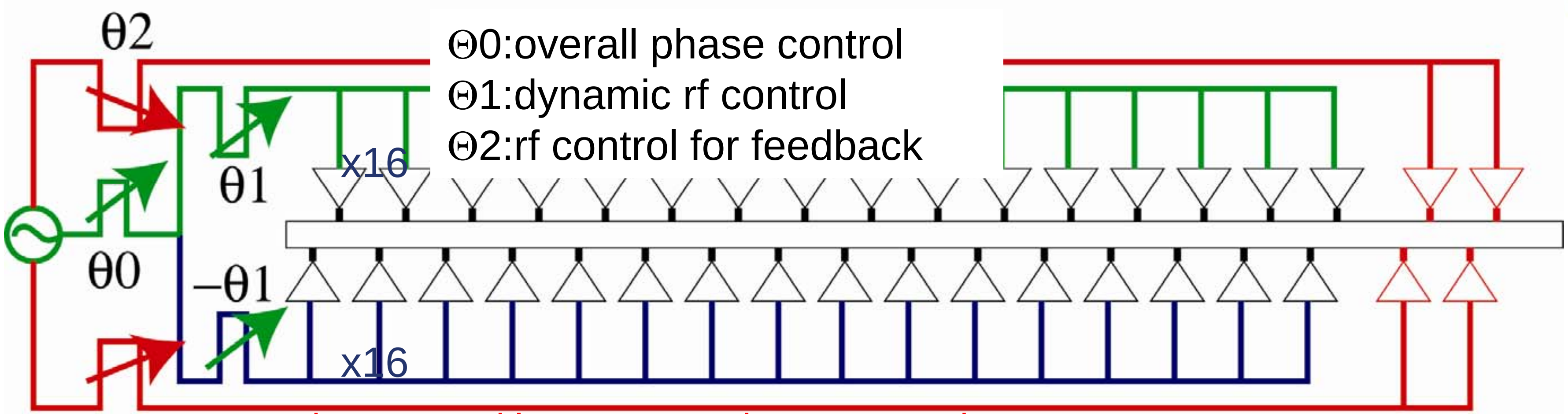


Distributed rf:

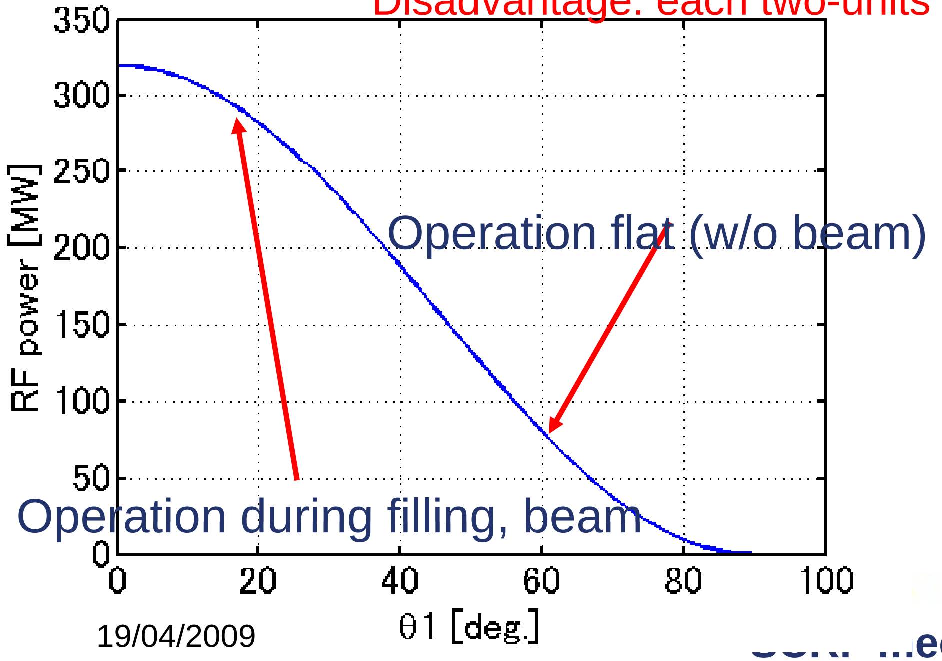
■ If the cavity coupler 's Q value within +/-15% to ideal Q value, the additional rf power is less than 0.6%

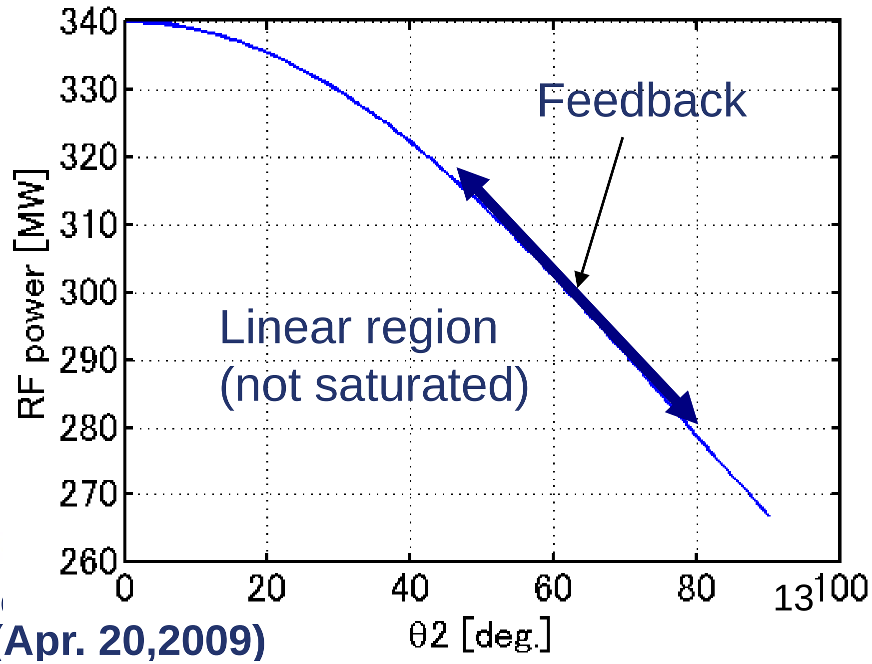
-> No need for variable coupler

Example of field control (36kly. 300MW op.)

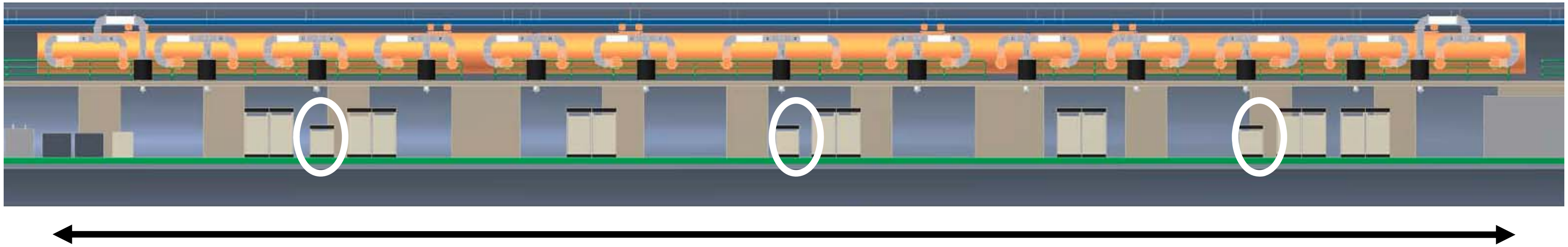


Advantage: klystron operation at saturation
only 3 phase control
Disadvantage: each two-units should be operated at same power



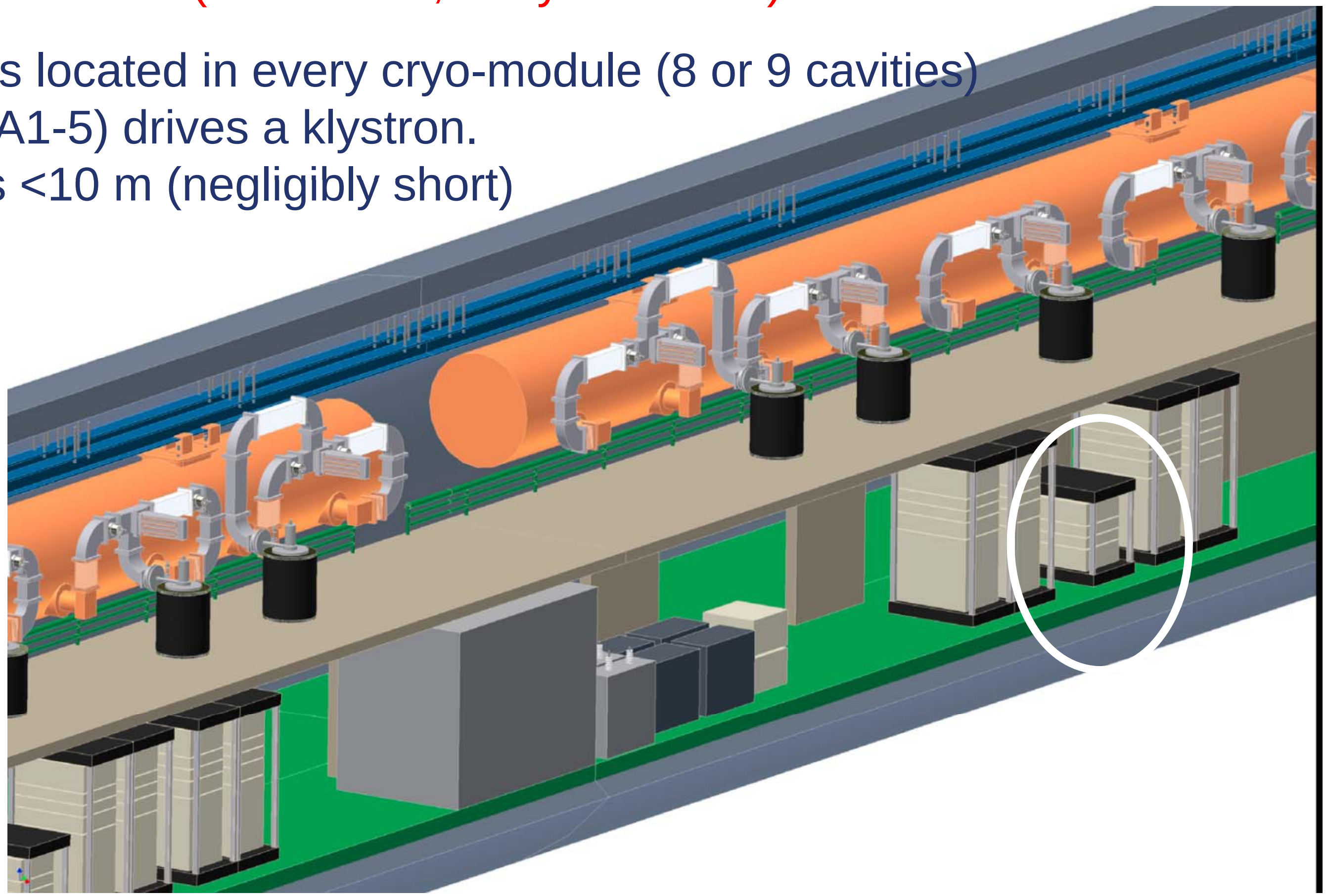


LLRF lack layout for DRFS

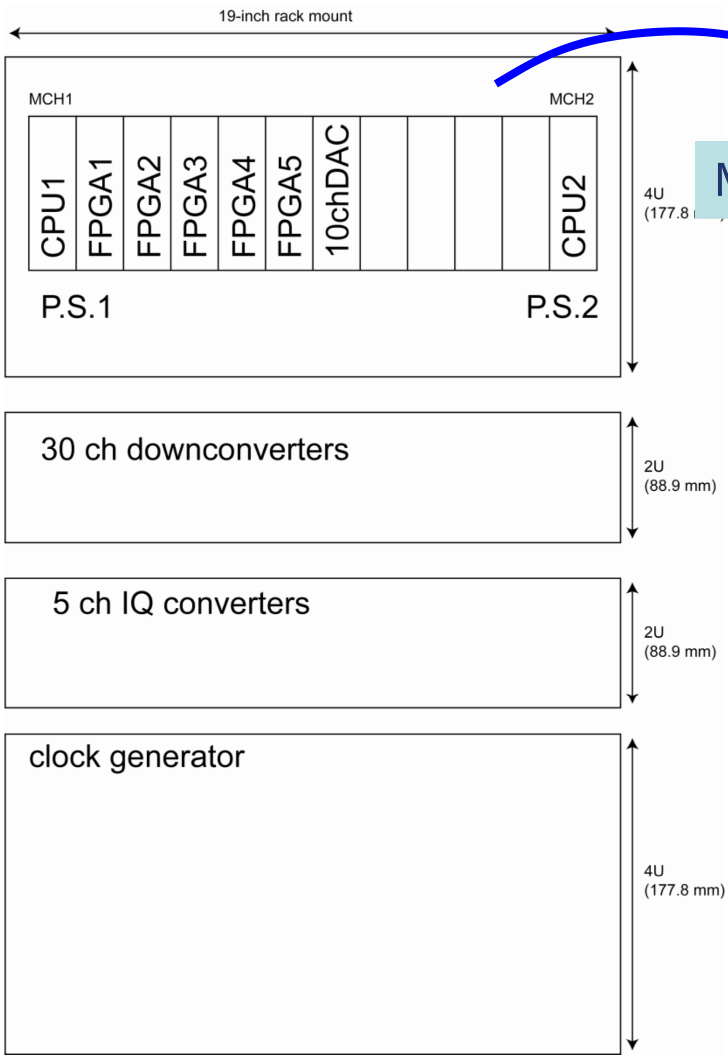


1 baseline unit (26 cavities, 3 cryomodules)

- 19 inch rack (total 16U) is located in every cryo-module (8 or 9 cavities)
- Each FPGA board (FPGA1-5) drives a klystron.
- Maximum cable length is <10 m (negligibly short)



LLRF lack layout for DRFS (2)

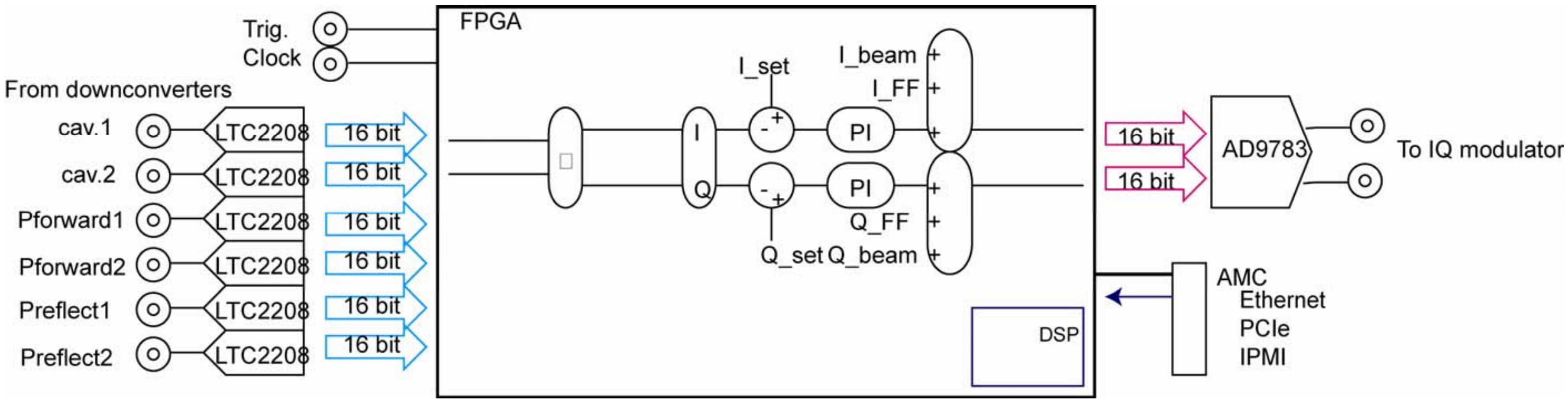


- Each FPGA board (FPGA1-5) drives a klystron.
- 10ch DACs are used for piezo drivers.
- 30 ch downconverters receive rf signals (cavity , forward and reflection power of each cavity)
- Clock generator creates clock and timing signals synchronized with master oscillator.

AMC FPGA board at DRFS

Commercial 8ch ADC (105MSps, 14bit) board by TEWS (developed by DESY)

- 6 ch ADCs + 2ch DACs board with FPGA will be used for this scheme.



Comparison of llrf components

- LLRF main cost drivers are crate, FPGA board, clock distribution and cables.
- Total costs are ~13% more expensive at DRFS compared with baseline.

(although cables are shorter, llrf stations (3 per. 26 cavities) cost more.)

	baseline	Cluster	DRFS
Number of crates/26cav.	1 large crate (ATCA, VME,)	1(ATCA, VME,)	3 small cheap crates (uTCA, …)
FPGA board	3	3(+sum)	13
Clock distribution	1	1	3
Downconvertes	~100	~100	~100
IQ modulators	1	1	13
Typical rf cable length	25 m	10 m	5 m
Number of racks	1	1	3
Total costs	100%	113%	99%

Summary of llrf systems

	Klystron cluster	DRFS
FB performance	Not good	Better
QI and power distribution control	Difficult	No need
Each cavity field flatness	Worse	Best or better
Exception handling	Quite complicated	Easy
LLRF cost	Similar to baseline	13% expensive than baseline

- In klystron cluster, rf stability requirements should be relaxed.
- Although the performance of llrf system will be better at DRFS, 13% more expensive (in llrf part).

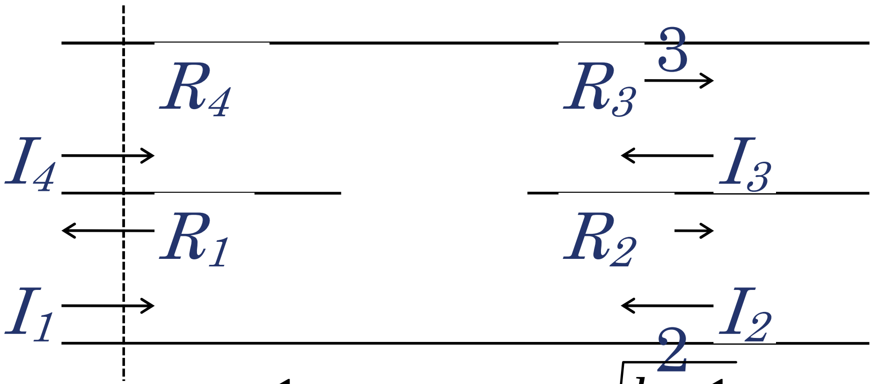
Appendix: RF response with beam

$$\dot{V}_{cav} + \left(\omega_{1/2} - j\Delta\omega\right)V_{cav} = \omega_{1/2} I_{rf\_w/o\_beam}$$

$$\dot{V}_{cav} + \left(\omega_{1/2} - j\Delta\omega\right)V_{cav} = \omega_{1/2}\left(I_{rf\_w\_beam} - I_{beam}\right)$$

$$I_{rf\_w\_beam} = 2I_{rf\_w/o\_beam} (in\, case\, of\ on - resonance)$$

Appendix: directional coupler



$$R=\begin{bmatrix} 0 & \sqrt{1-C^2} & jC & 0 \\ \sqrt{1-C^2} & 0 & 0 & jC \\ jC & 0 & 0 & \sqrt{1-C^2} \\ 0 & jC & \sqrt{1-C^2} & 0 \end{bmatrix} I$$

$$C_k=\frac{1}{\sqrt{k}};\sqrt{1-C^2}=\sqrt{\frac{k-1}{k}}$$

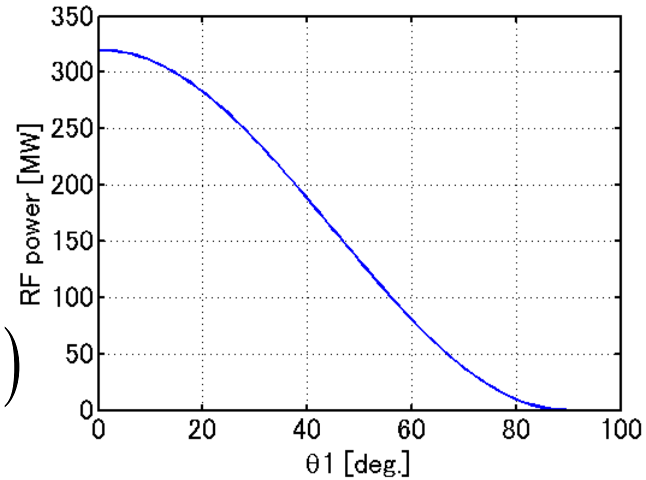
$$I_n=\frac{1}{\sqrt{n}}\sum_{k=1}^{n}V_k e^{j\theta_k}$$

If #1~#16:θ & #17~#32:-θ

$$I_{out}=\frac{1}{\sqrt{32}}\left(\sum_{k=1}^{16}V_k e^{j\theta_k}+\sum_{k=17}^{32}V_k e^{j\theta_k}\right)=\frac{V_1}{\sqrt{32}}\left(16e^{j\theta}+16e^{-j\theta}\right)$$

$$=\sqrt{32}V_1\cos\theta$$

$$P_{out}=\left|\sqrt{32}V_1\cos\theta\right|^2=320\cdot\cos^2\theta[MW]$$



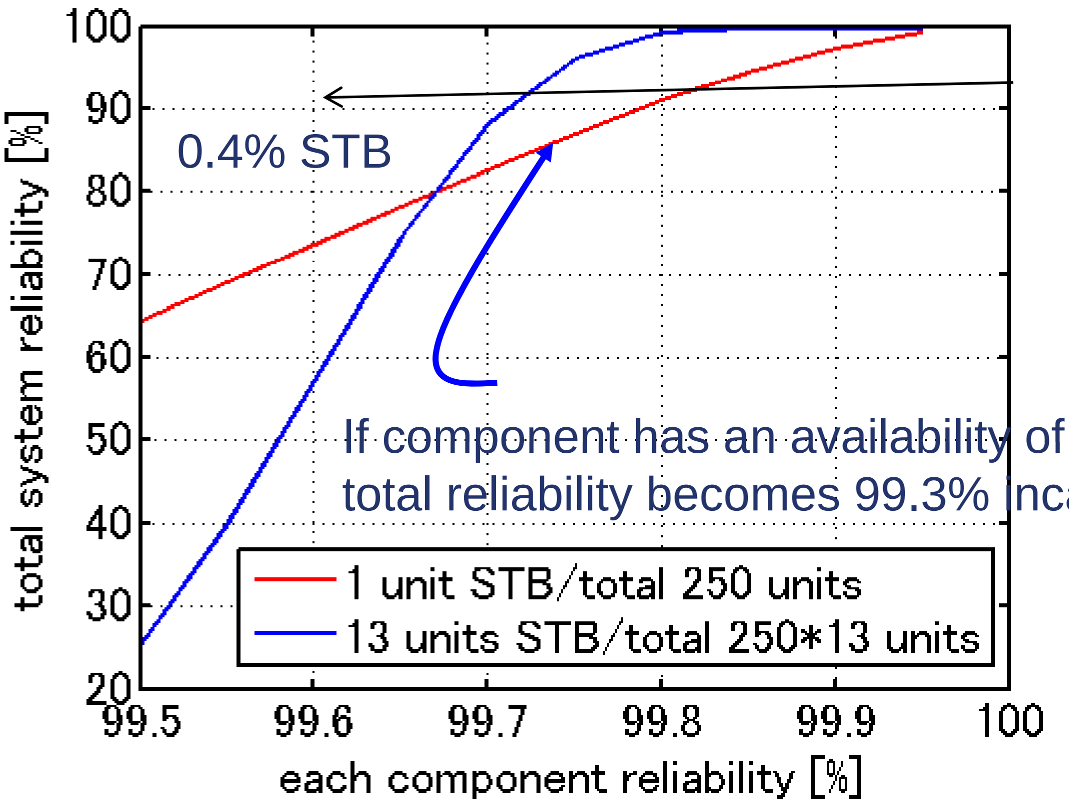
High Availability @ distributed rf

Assumption:
There is a 0.4% standby cavities (1/250:corresponding to roughly 1 rf unit in baseline and 13 units in DRFS).

$$P_{total} = p^{N} + \sum_{k=1}^{m} {}_{N}C_{m}\, p^{N-k} (1-p)^{k}$$

$${}_{N}C_{m} = \frac{N!}{(N-m)!\,m!}$$

p: each rf unit reliability
Ptotal: total reliability
Baseline: N=250,m=1
DRFS: N=250*13=3,250, m=13



If component has an availability of 99.8%,
total reliability becomes 99.3% incase of 13 rf units STB.