# LLRF Comments on the RF cluster and Distributed RF schemes

Shin Michizono (KEK)
Brian Chase (FNAL)
Stefan Simrock (DESY)

- Klystron cluster / Distributed rf schemes
- Operational gain and bandwidth
- Power and Ql control
- Possible control system @klystron cluster
- High availability @ 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 $\leq 0.1\%$ |

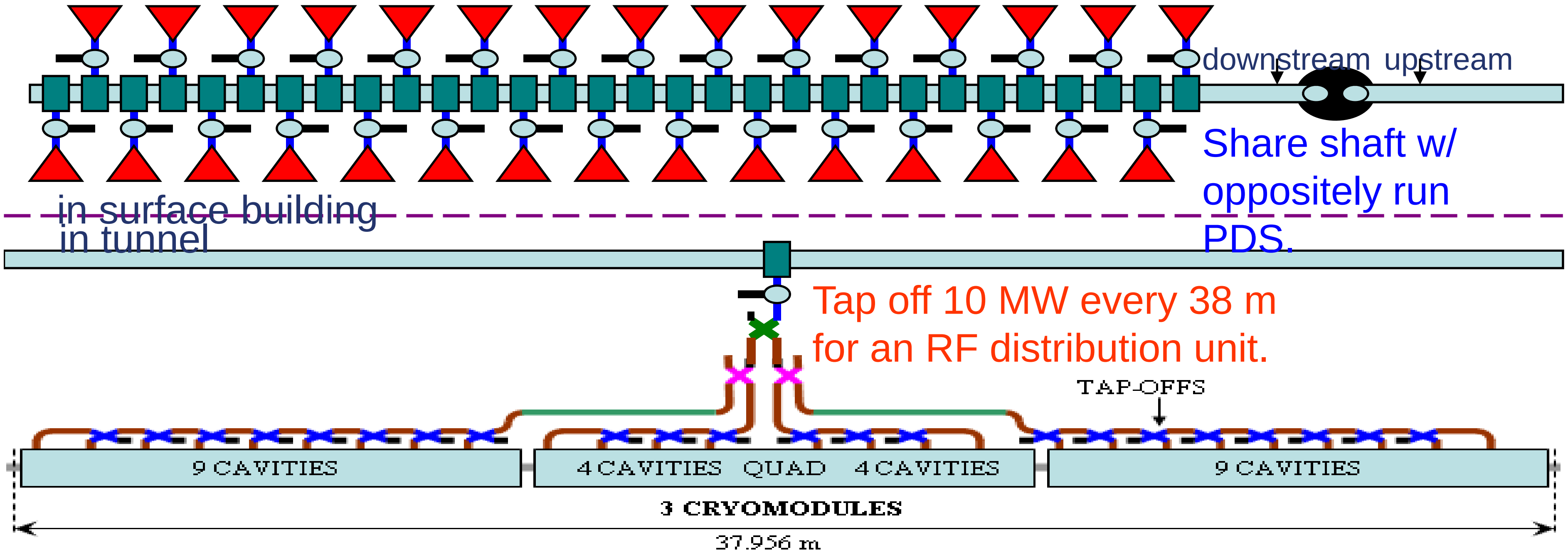
# Klystron cluster

- The configuration of klystron cluster introduces total 10~15us latency.

  -> larger latency than our current model (<1us)

  - 3.5us (rf transmission)
  - 1us (ADC detection at each 26 cavities in the tunnel and conversion to optical signal of 26 vector sum)
  - 6us (optical transmission)
  - 1us (conversion and vector sum of 27 units)
  - 1us (DAC outputs to 27units)

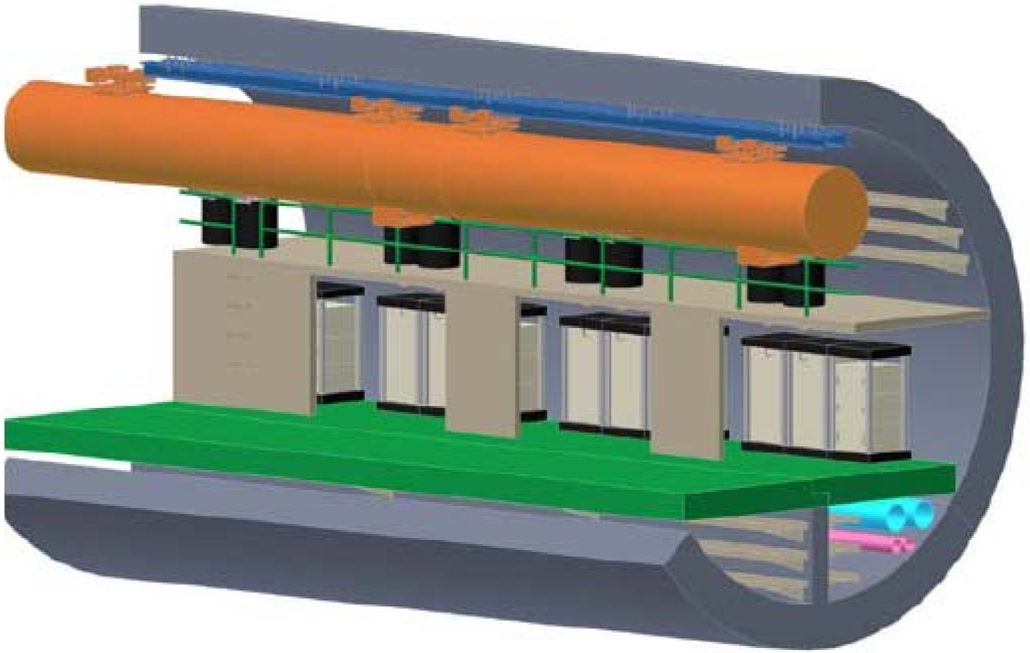
- LLRF detectors will be located in the tunnel (and process each 26 cavities).

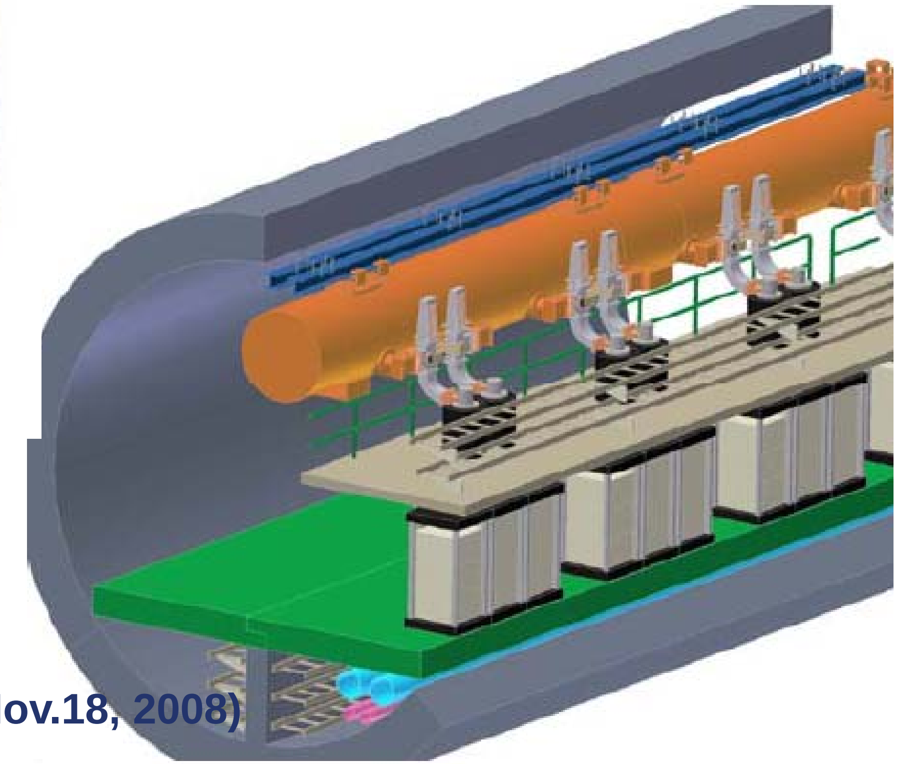



With extra transmission loss, feeds ~27 RF units = 1.026 km. (shaft serves 2.052 km)

# Distributed rf scheme

- One rf unit drives single or 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 (and process each 26 cavities).





# 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 | 1 or 2 |
| No. of vector sum | 26 | 26 | 780 | 1 or 2 |
| Ql and power distribution control | Necessary | Necessary | Difficult | No need |
| No. of llrf cable /rf | ~80 | ~80 | ~80*30 or fast optical cables | 3 or 6 |
| Loop delay | ~1 us | ~1 us | ~10 us | ~0.3 us |

- Operational gain?
- Operational bandwidth?
- Power and Ql control?
- High availability?

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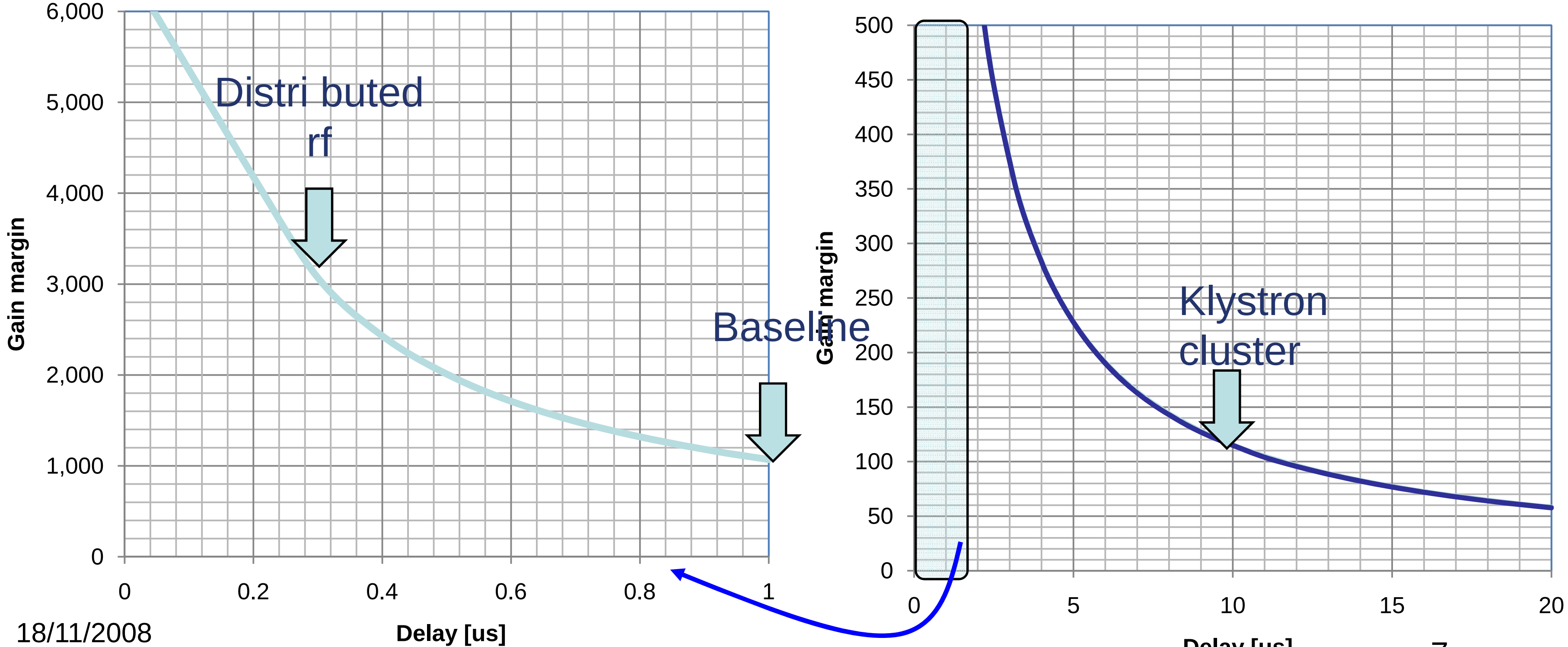
# Operational gain

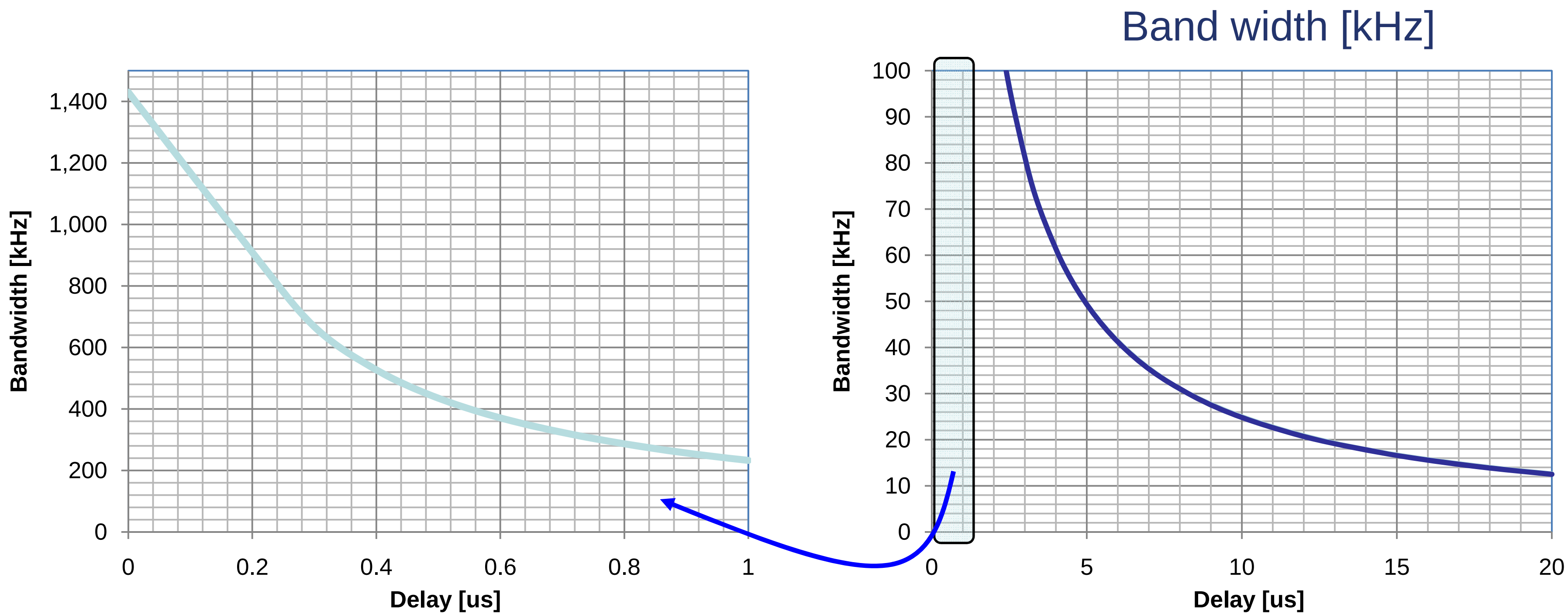
- Error is only compressed by a factor of gain
- Gain margin is calculated from Bode-plot.

- 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)



# Operational bandwidth (without beam)

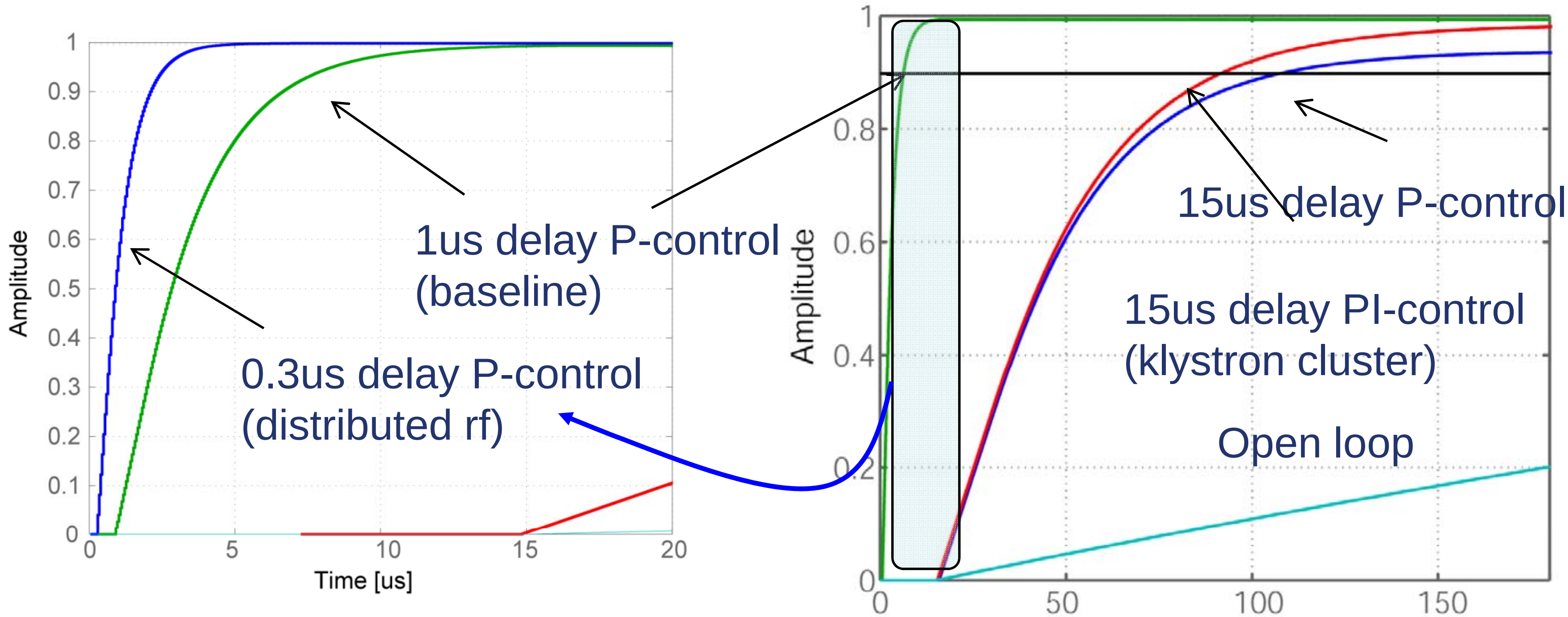



| Latency | 0.3us | 1us | 10us | 15us | 15us PI |
|---|---|---|---|---|---|
| operation gain | 600 | 200 | 25 | 15 | 15 |
| bandwidth [kHz] | 700 | 230 | 25 | 17 | 17 |

- Bandwidth becomes ~700 kHz in case of distributed rf scheme
- Bandwidth is <20 kHz at klystron cluster.

# Step response of llrf control (w/o beam)

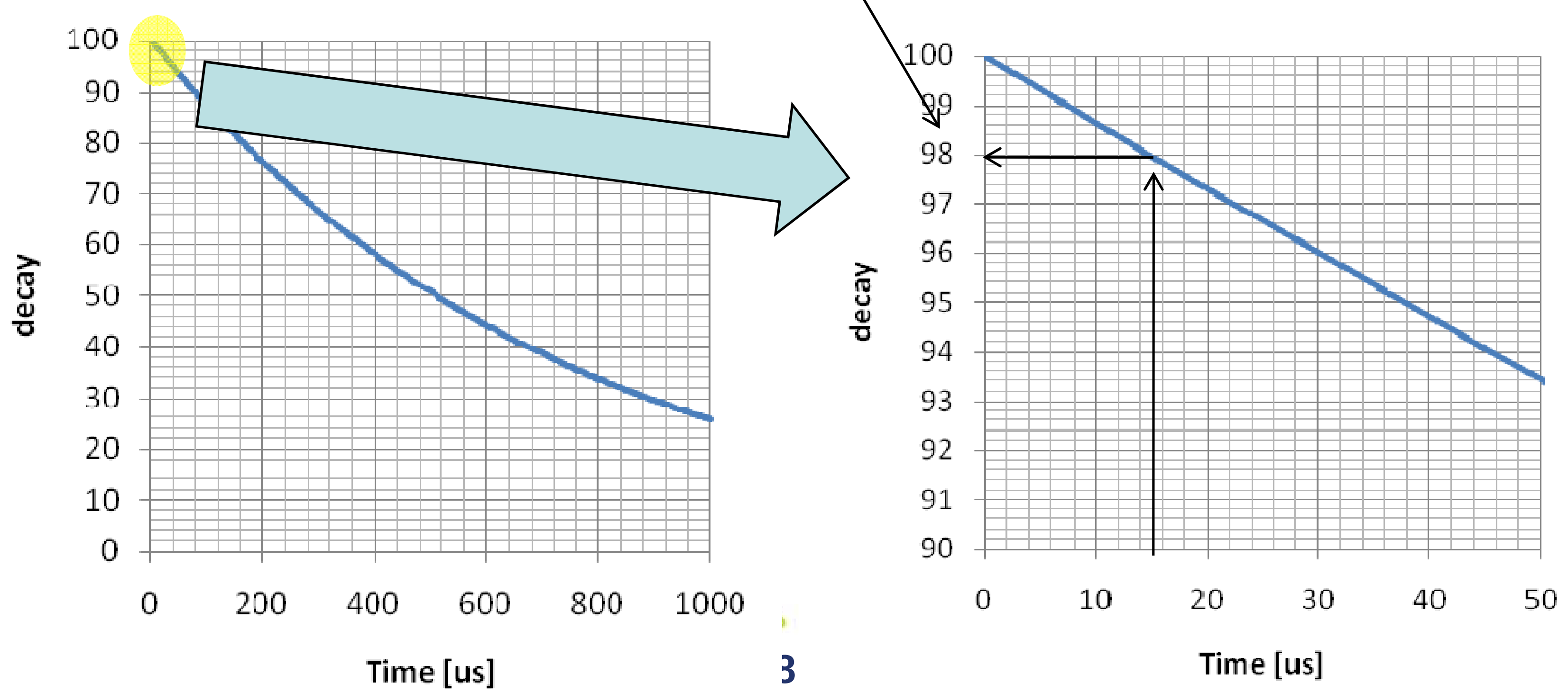
- Fast response will be offered in case of short delay of 0.3 us at distributed rf scheme.
- We can expect faster response with beam condition due to the lower QI.




| Latency | 0.3us | 1us | 15us | 15us PI |
|---|---|---|---|---|
| scheme | Distributed rf | baseline | Klystron cluster | |
| Proportional gain | 600 | 200 | 15 | 15 |
| Integral gain | 0 | 0 | 0 | 15,000 |
| 90% Settle time [us] | 2 | 6 | 100 | 80 |
| Saturation value | 99.8% | 99.5% | 93.3% | 100% |

# FB latency and llrf performance @klystron cluster

- Assumption
  - Cavity Q:3e6 -> decay time constant=462us and f1/2=217Hz
  - All signals change in this time constant
  - After 15us of blind time, system changes 2% of perturbation (still large even though the time constant is slow).
- Example : Kly HV change (1%, 12 deg. in phase) during rf operation.
  - Cavity phase changes by 0.24 deg. (=12*2%) far from our goal of <0.1deg.
- 15us FB loop delay (blind time for fluctuation detection) is large.



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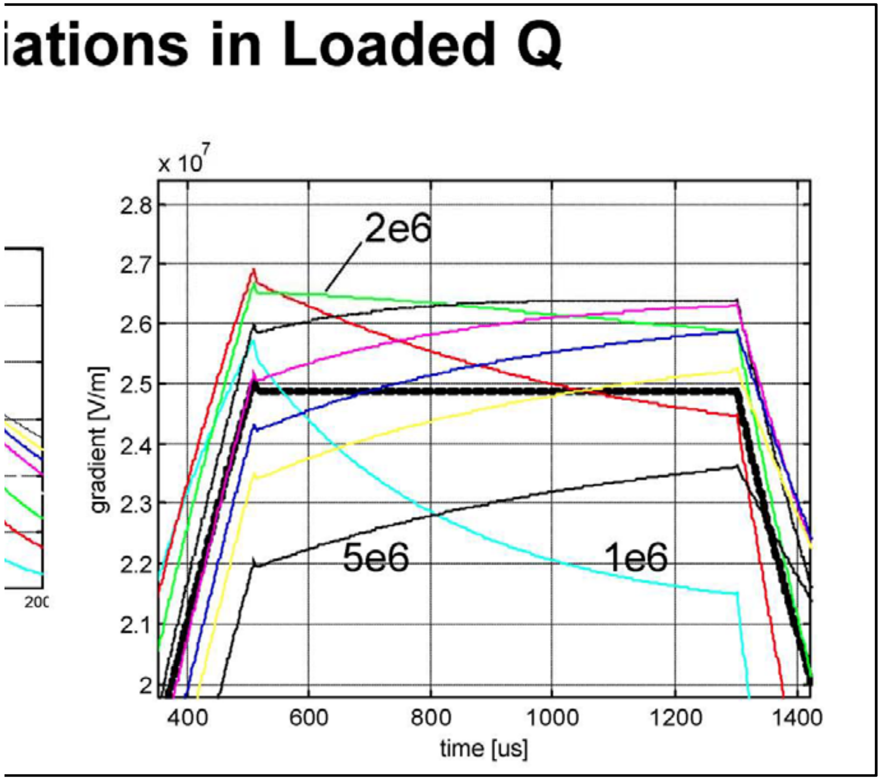
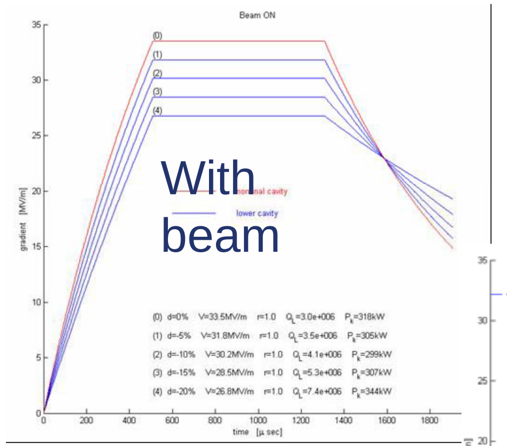
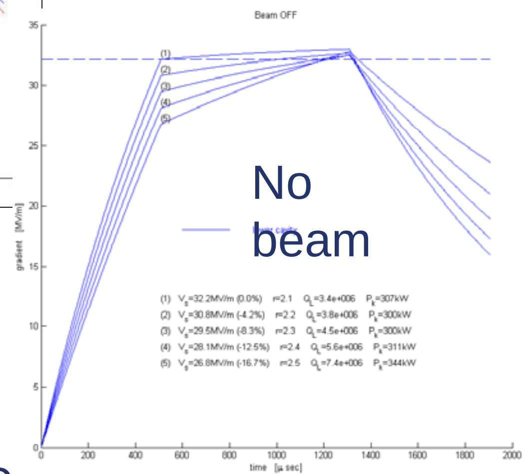
# Power and Ql control




- Vector sum control under restrict quench limit requires power and Ql control

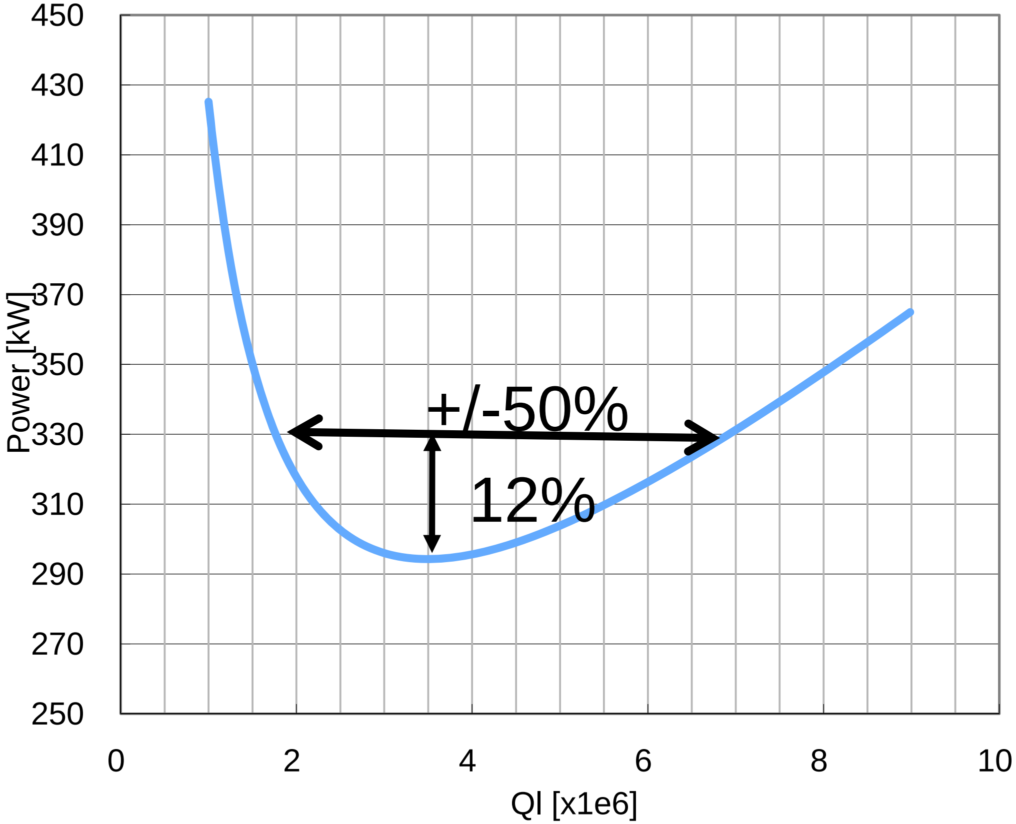
Klystron cluster:

- 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)***

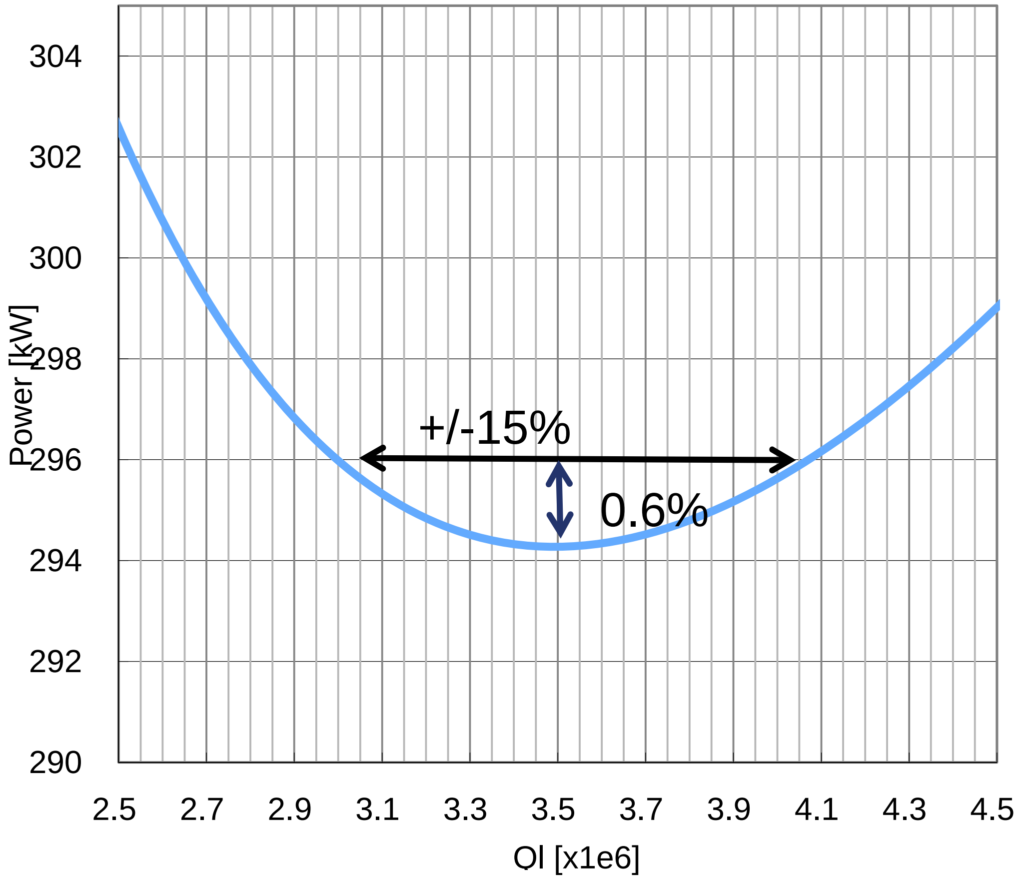
# Power, Ql control (baseline & klystron cluster)




Baseline & klystron cluster:

■ In case of rf power and Ql control, additional 12% rf power is necessary at +/-50% coupling control for flatten 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***

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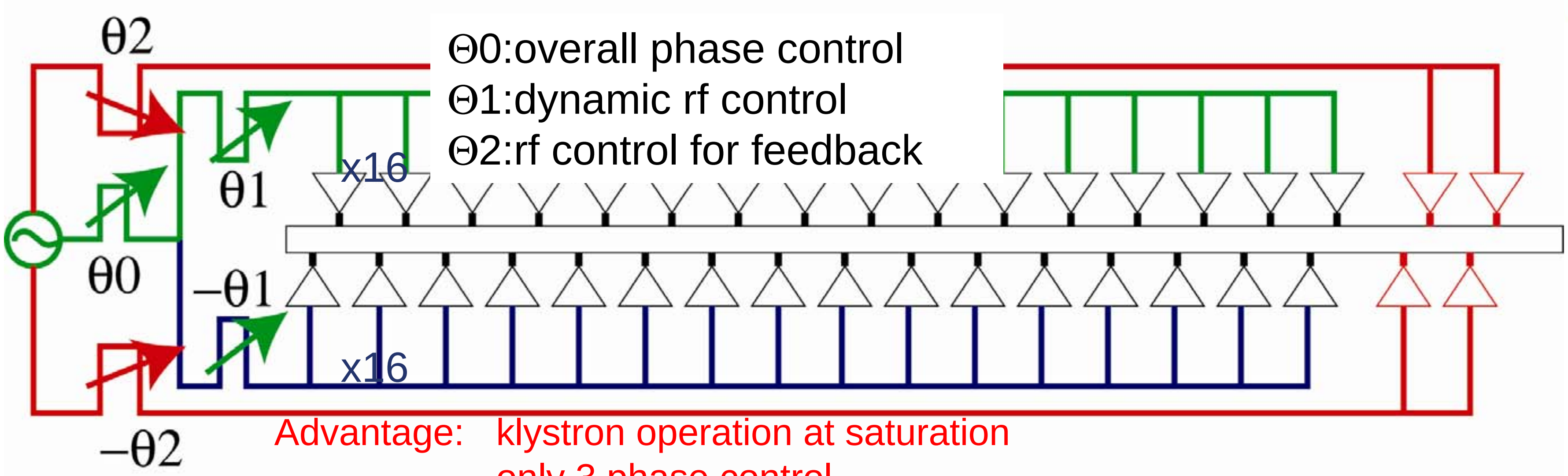
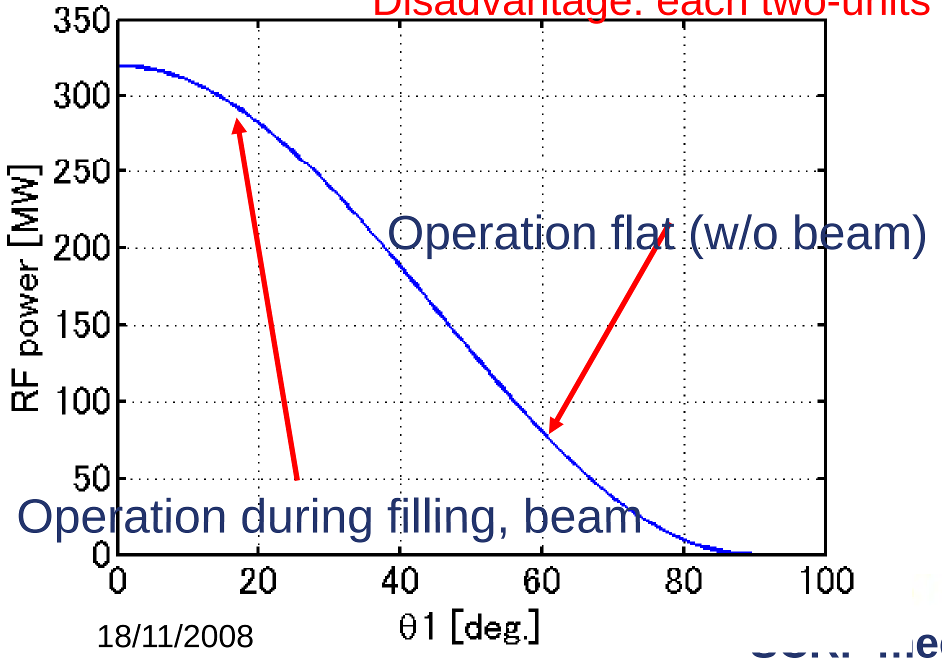
# Example of field control (36kly. 300MW op.)

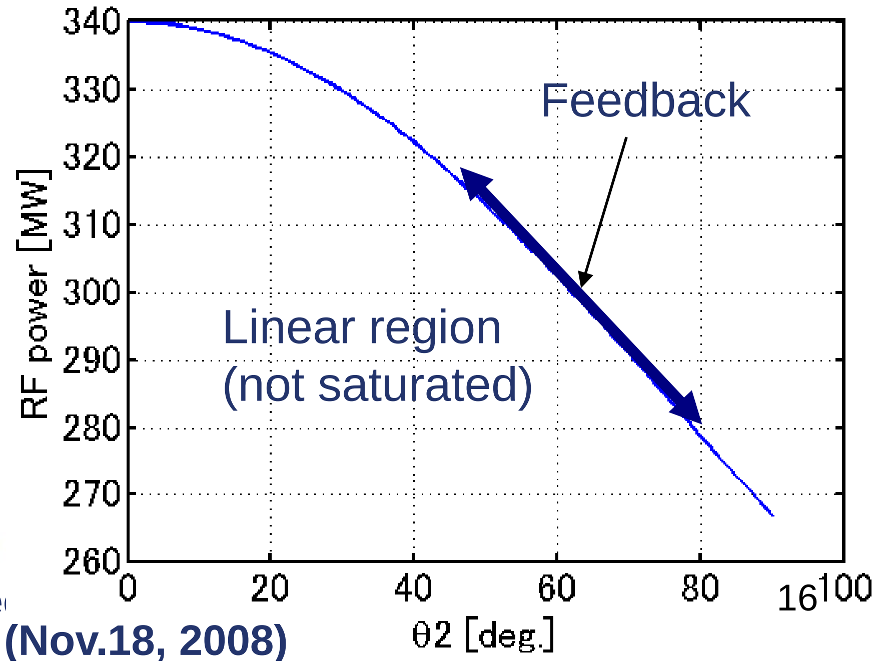



Θ0:overall phase control
Θ1:dynamic rf control
Θ2:rf control for feedback

Advantage: klystron operation at saturation
only 3 phase control

Disadvantage: each two-units should be operated at same power



# Summary of Klystron cluster

## 1. Field regulation

- field regulation worse but may be still ok
- higher stability of all subsystems required
- robust against perturbations or parameter changes significantly reduced
- operational field/current limits will be lower
- difficulties with feedforward due to delay between rf and beam (upstream rf distribution)
- should use fast klystron loops to reduce HLRF errors.

## 2. Availability

- exception detection and handling severely limited
- hot spare concept cannot be implemented

## 3. Operational

- Cannot simply turn on-off (or by-pass or manipulate) individual rf stations for commissioning, operational or diagnostic purposes.
- Setting up linac cannot be done by incrementally adding or controlling rf stations
- Operation close to performance limit (cavity quench, field emission, klystron saturation) will become much more challenging.

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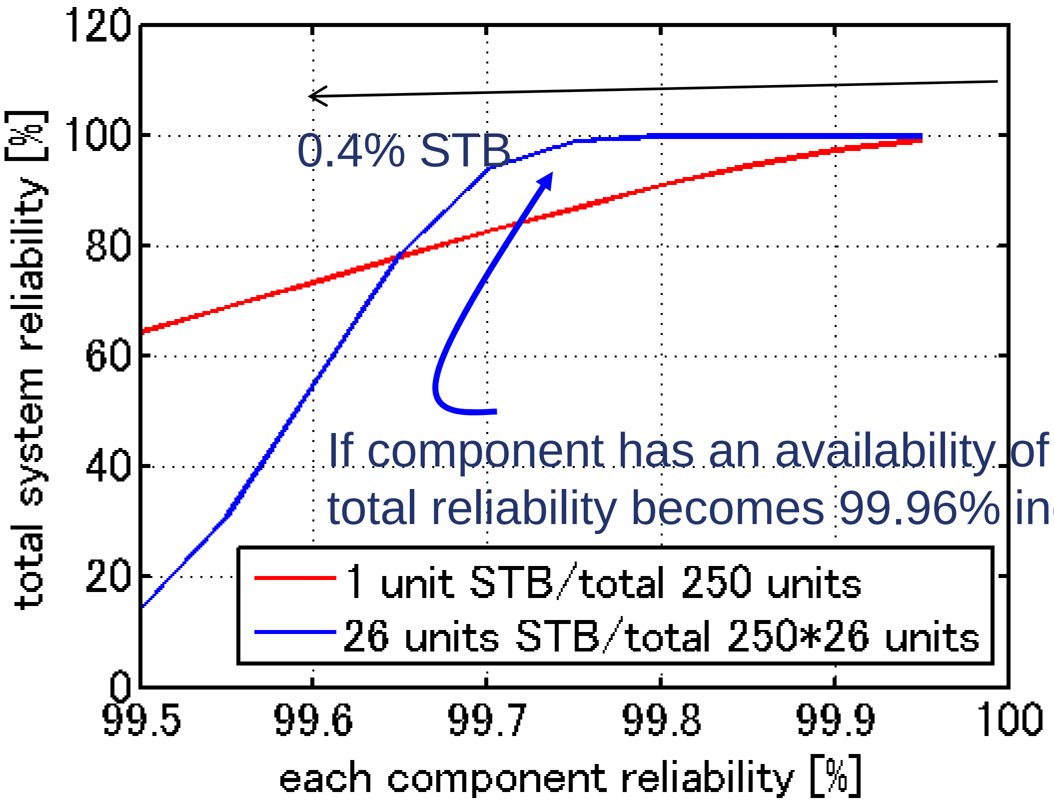
# High Availability @ distributed rf

Assumption:
There is a 0.4% stanby cavities (1/250:corresponding to raughly 1 rf unit in baseline and 26 units in single cavity driver).

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

$${}_N C_m = \frac{N!}{(N-m)!\,m!}$$

p: each rf unit reliability
Ptotal: total reliability
Baseline: N=250,m=1
Single drive: N=250*26=6,500, m=26




If component has an availability of 99.8%,
total reliability becomes 99.96% incase of 26cav.STB.

# High Availability @ distributed rf (2)

- Each rf unit has a reliability of 99.8%? Maybe yes.

: 99.8% corresponds to 20 min./week, 5 hrs/yr (5,000 hrs op.)

From the experience of KEKB injector linac (60 units, 7,000 hrs operation/yr.), the downtime of the unit is<5min./week.

- In addition, we can neglect one cavity failure. (because its energy contribution is negligibly small (0.015%).

 -> We can make some diagnostics even during luminosity operation!

 -> Exception handling becomes quite simple.

 (Fast recovery of beam energy is not necessary even when quench or rf failure happen.)

# Summary of distributed rf

## LLRF performance

- shorter latency results in higher FB gain (robustness)
- higher FB operation (aiming the FB gain of ~1000)

## Operability

-simpler cavity control (flat field obtainable near below quench without worrying about Ql and P control scheme)
- LLRF diagnostics become possible even during luminosity operation.

## HA/Robustness

- higher availability owing to the flexible selection of stand-by cavity

## Exception handling

- No need for fast recovery (because each unit has small energy contribution)

## Other advantages/disadvantages

- Reduce the length of rf cables (less cost, less phase rotation)
- Omit fast optical link between llrf board s(for vector sum)
- Omit phase-shifter, tunable coupler in waveguide and cavity
- Need IQ modulator (in each rf unit) (but the devise is cheap)

# Comparison of llrf configurations

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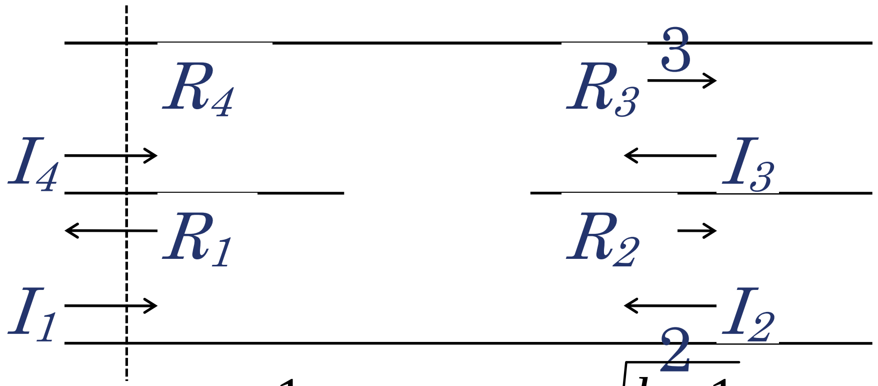
|---|---|---|---|---|
| No. of tunnels | 2 | 1 | 1 | 1 |
| LLRF unit | Service tunnel | Beam tunnel | Beam tunnel | Beam tunnel |
| Cavity/ rf unit | 26 | 26 | 780 | 1 or 2 |
| No. of vector sum | 26 | 26 | 780 | 1 or 2 |
| No. of llrf cable /rf | ~80 | ~80 | ~80*30 or fast optical cables | 3 or 6 |
| Loop delay | ~1 us | ~1 us | ~10 us | ~0.3 us |
| Typical FB gain | ~100 | ~100 | ~20 | ~1,000 |
| Ql and power distribution control | Necessary | Necessary | Difficult | No need |
| Each cavity field flatness | Bad | Bad | Worse | Best or better |
| Robustness | Good | Good | Not good | Better |
| Exception handling | Not easy | Not easy | Quite complicated | Easy |

# Appendix: directional coupler




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

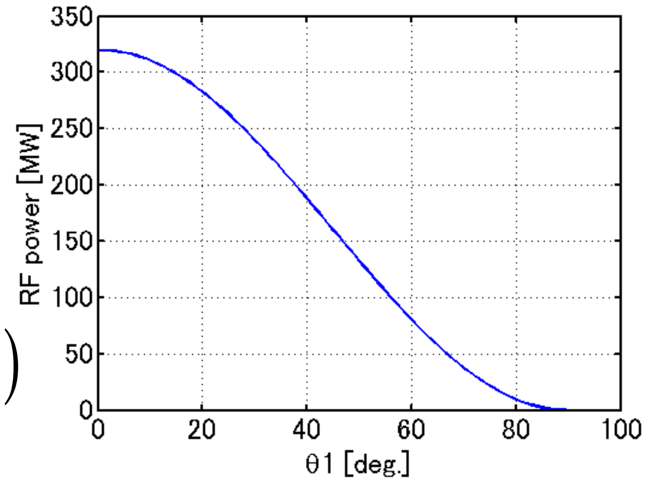
$$C_k = \frac{1}{\sqrt{k}}; \sqrt{1-C^2} = \sqrt{\frac{k-1}{k}}$$

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

If #1~#16:θ & #17~#32:-θ

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

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




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