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 QI control
- Possible control system @klystron cluster
- LLRF layout @ distributed rf
Required stability

- L1rf 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.

<table>
<thead>
<tr>
<th>Location</th>
<th>Phase (degree)</th>
<th>Amplitude (%)</th>
<th>limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>correlated</td>
<td>uncorr.</td>
<td>correlated</td>
</tr>
<tr>
<td>Bunch Compressor</td>
<td>0.24</td>
<td>0.48</td>
<td>0.5</td>
</tr>
<tr>
<td>Main Linac</td>
<td>0.35</td>
<td>5.6</td>
<td>0.07</td>
</tr>
</tbody>
</table>
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 27 units)

- 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

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

- Operational gain?
- Power and Ql 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: $3 \times 10^6$ and decay time constant = 462us and $f_{1/2} = 217$Hz
  - 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. (= $12 \times 3\%$) far from our goal of 0.1deg.
  - Need to relax the rf stability requirements.

![Graph showing decay over time]
Stability and FB loop delay@G=55

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

Stable @ 1.5us delay

unstable @ 5.8us delay
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 QI control

Variations in Loaded Q

- Vector sum control under restrict quench limit requires power and QI 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 QI control)

TILC09 (Apr. 20, 2009)
Power, QI control (baseline & klystron cluster)

Baseline & klystron cluster:
- In case of rf power and QI control, additional 12% rf power is necessary at +/- 50% coupling control for flattening the rf field under beam loading.

19/04/2009

TILC09 (Apr. 20, 2009)
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.)

- **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

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![Graphs showing RF power vs. Θ1 and Θ2](TILC09 (Apr. 20, 2009))

- **Operation flat (w/o beam):** RF power vs. Θ1
- **Operation during filling, beam:** RF power vs. Θ2
- **Feedback:** Linear region (not saturated)
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)
- 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.)

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>Cluster</th>
<th>DRFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crates/26cav.</td>
<td>1 large crate (ATCA, VME, )</td>
<td>1(ATCA, VME, )</td>
<td>3 small cheap crates (uTCA, …)</td>
</tr>
<tr>
<td>FPGA board</td>
<td>3</td>
<td>3(+sum)</td>
<td>13</td>
</tr>
<tr>
<td>Clock distribution</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Downconverters</td>
<td>~100</td>
<td>~100</td>
<td>~100</td>
</tr>
<tr>
<td>IQ modulators</td>
<td>1</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>Typical rf cable length</td>
<td>25 m</td>
<td>10 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Number of racks</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Total costs</td>
<td>100%</td>
<td>113%</td>
<td>99%</td>
</tr>
</tbody>
</table>
## Summary of llrf systems

<table>
<thead>
<tr>
<th></th>
<th>Klystron cluster</th>
<th>DRFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB performance</td>
<td>Not good</td>
<td>Better</td>
</tr>
<tr>
<td>Ql and power</td>
<td>Difficult</td>
<td>No need</td>
</tr>
<tr>
<td>Each cavity field</td>
<td>Worse</td>
<td>Best or better</td>
</tr>
<tr>
<td>Exception handling</td>
<td>Quite complicated</td>
<td>Easy</td>
</tr>
<tr>
<td>LLRF cost</td>
<td>Similar to baseline</td>
<td>13% expensive than baseline</td>
</tr>
</tbody>
</table>

- 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

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

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

\[ I_{rf\_w\_beam} = 2I_{rf\_w\_o\_beam} \text{ (in case of on - resonance)} \]
Appendix: directional coupler

\[ C_k = \frac{1}{\sqrt{k}} \cdot \sqrt{1-C^2} = \sqrt{\frac{k-1}{k}} \]

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

If #1~#16: \( \theta \) & #17~#32: \( -\theta \)

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

\[ P_{out} = \left( \sqrt{32}V_1 \cos \theta \right)^2 = 320 \cdot \cos^2 \theta [MW] \]
Assumption:
There is a 0.4% standby cavities (1/250:corresponding to roughly 1 rf unit in baseline and 13 units in DRFS).

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

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

$$\binom{N}{m} = \frac{N!}{(N-m)!m!}$$

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