RF Trip Compensation for Beam Stability

ESLS RF Workshop – Max-IV – Oct 2015

RF&Linac Section - ALBA Accelerators Division

Angela Salom
Introduction and Motivation
- SR RF Plants
- ALBA LLRF
- RF Operation

Feed-Forward Loops for RF Trip Compensation
- Amplitude Modulation
- Phase Modulation
- Phase Step Modulation

Future Upgrade: Feedforward for Beam Loading Compensation

Conclusions
Introduction and Motivation
RF Parameters

$U_0$ 1.3 MeV/turn

$V_{\text{total}}$ 3.6 MV

$q \approx 2.5$

$f_s \approx 9$ kHz

$P_{RF}$ 960 kW

6 RF Plants of 160 kW at 500 MHz

2 IOT Transmitters per RF cavity. Power combined in CaCo

Dampy Cavity

- Normal Conducting
- Single cell, HOM damped
- 3.3 MΩ

Digital LLRF System based on IQ mod/demod
Main Characteristics

- Based on digital technology using a commercial cPCI board with FPGA
- Signal processing based on IQ demodulation technique
- Main loops: Amplitude, phase and tuning
- RF diagnostics: Circular buffer for post-mortem analysis (0.5s)
- Extra utilities
  - Automatic conditioning for cavities
  - Automatic cavities recovery

Loops Resolution and bandwidth (adjustable parameters)

<table>
<thead>
<tr>
<th></th>
<th>Resolution</th>
<th>Bandwidth</th>
<th>Dynamic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude Loop</td>
<td>&lt; 0.1% rms</td>
<td>[0.1, 50] kHz</td>
<td>30dB</td>
</tr>
<tr>
<td>Phase Loop</td>
<td>&lt; 0.1° rms</td>
<td>[0.1, 50] kHz</td>
<td>360°</td>
</tr>
<tr>
<td>Tuning</td>
<td>&lt; ± 0.5°</td>
<td>--</td>
<td>&lt; ± 75°</td>
</tr>
</tbody>
</table>
RF Operation

At present

- Running at 110mA with 2.6MV of RF Voltage in SR
- 2 or 3 RF Interlocks per week
- One RF Trip does not cause beam loss (enough over-voltage)
- Automatic recovery allows setting into operation a tripped plant with circulating beam

In Future

- SR Current will be increased up to nominal current 250mA (SR RF designed to withstand 400mA)
- With present available RF voltage, higher SR currents will lead to beam losses when an RF plant trips
- Solution: Active compensation of RF Trip disturbances
Active RF Trip Compensation
Analysis of Beam Survival after RF Failure

- **Cavity voltage** and **synchronous phase** drop and they start to oscillate with a frequency equal to synchrotron tune.
- **Beam** extracts more power from cavity.
- **Reverse power** of the cavity decreases.
- Amplitude of oscillations depend on beam current.
- Frequency oscillations depend on how much RF voltage is left.

Response of active cavities after RF Trip
Analysis of Partial Beam Loss after RF Failure

- Cavity voltage decreases and then there is an overshoot
- Synchronous phase decreases
- But, reverse power increases and power delivered to the beam decreases → Power extracted from the beam → Partial beam lost
- So, if behavior known, compensation can be applied before losing the beam
Feed-Forward Loops

✓ **Active compensation of disturbance: Theoretical results**

- Cavity Voltage oscillations after interlock measured
- Compensation activated for first periods (Amplitude modulation with frequency equal to synchrotron tune)
- Overlap of two responses
- Sum of two responses: theoretical result
  - Decrease of perturbations by a half

Response of 06A Cavity Voltage after stopping Cavity 10B – 60mA

✓ **Simulations done by J. Marcos to calculate optimum compensation**

- Analysis of Overall Cavity Voltage after trip applying compensation with different amplitudes
- **Optimum**: Compensation where no voltage overshoots were observed
Feed-Forward Loops: Amplitude Modulation

Initial conditions:
- 5 Active Cavities
- Total RF Voltage = 1.6MV (320kV per cavity)
- Ibeam = 60mA
- Fake Interlock created in one cavity

Analysis of Cavity Voltage of 06A after trip in 06B with amplitude compensations
- With no compensation: Beam lost
- With 3.5% compensation – 2mA lost
- With 4.0% compensation – 0.5mA lost
- With 4.5% compensation – Beam survived

Still 4.5% overdrive (1dB) could be high when working at higher current/power

Other compensation strategies analyzed
- phase modulation to compensate oscillations instead of amplitude modulation
- No overdrive needed
Feed-Forward Loops: Phase Modulation

Frequency Phase Modulation
- Amplitude of RF Drive kept constant
- Phase of RF Drive modulated to compensate longitudinal oscillations of beam
- Frequency equal to synchrotron tune
- Tested with beam, but not conclusive results. Further tests needed

Example of Frequency Phase Modulation
- Modulation Freq = 10kHz
- Phase Mod = 10°
- Decay time = 10ms
Phase Step Modulation

- Phase of RF Drive changed $\Delta \phi$ with a step which decreases with a decay time equal to damping time.
- Capable to compensate partial beam loss, but not total beam loss.
Feed-Forward Loops: Step Phase Modulation with beam

**Initial conditions:**
- 5 Active Cavities
- Total RF Voltage = 1.55MV (3x450kV + 1x200kV)
- Ibeam = 60mA
- Fake Interlock created in 200kV Cavity

**Analysis of Cavity Voltage of 06B after trip in 06A with phase step compensation**

- Beam loss partially compensated, but no conclusive results
- Further tests needed
✓ In Normal Operation: Effect of beam loading negligible
  - Revolution frequency ~ 1MHz
  - 90% Filling Pattern
  - 10 trains: 10 x (32 bunches + 12 empty buckets)

✓ Filling pattern modified to 1/3 to be able to measure beam loading effect
✓ Beam Loading measured with 1/3 filling pattern (60mA)

- Beam Phase modified by 5° due to beam loading effect
- Future upgrade: Phase modulation (feed-forward loop) to compensate this effect
- Needed to prove feasibility of this approach for CLIC collaboration
Conclusions

✔ RF Operation:
  - 2 or 3 RF interlocks per week
  - Beam survives after RF Trip with present configuration: 110mA – 2.6MV RF voltage

✔ RF Trip Compensation:
  - Amplitude Modulation can compensate beam loss due to RF Trip, but overdrive needed (higher stress to IOT)
  - Other RF Trip compensation approaches being studied (phase modulation and phase step modulation)
  - RF Trip compensation would allow increasing SR Current keeping RF Voltage and keeping beam availability when an RF Trip occurs

✔ Feed-Forward loops for beam loading compensation being studied
Thanks for your attention
Questions?