Energy Efficiency and Availability Improvement in Control and Operation of Superconducting Cavities

Rihua Zeng, Olof Troeng
RF Group, Accelerator Division, ESS ERIC
Automatic Control Department, Lund University
HB 2016, Malmö, July 7, 2016
Outline

• Energy Efficiency and Availability in Accelerator

• Challenges to Achieve Higher Efficiency and Availability

• Advanced Technologies makes it possible

• Some consideration/progress at ESS
**SRF Cavity at SNS (Sang-ho Kim)**

- **Grid power**: 73 kW
- **HVCM input**: 71.6 kW
- **HVCM output**: 67 kW
- **HVCM output for RF gate**: 61.5 kW
- **Transformer, switch, etc.**: 1.4 kW
- **HVCM loss**: 4.6 kW
- **HVCM settling time**: 5.5 kW
- **Available RF**: 40 kW
- **Filling and LLRF settling**: 9.0 kW
- **Copper loss**: 0 kW
- **Mismatching (detuning, Qex, etc.)**: 1.4 kW
- **Control margin or unused**: 6.9 kW
- **To beam**: 22.5 kW

**Grid power input:**
- HVCM 73 kW
- Electricity for cooling system: 5 kW
- Cryogenic plant: 38.3 kW

**Efficiency**: 19.5%
Availability

Distinguish in two aspects:

– Enhance reliability in design and development stage (careful design, redundancy, high reliable key components, flexibility)

– Fault tolerance in operation stage: a mitigation strategy to the failures
Future Large Scale Accelerators
(Erk Jensen, CWRF2016)

ILC $\text{e}^+\text{e}^-$: Pulsed, 1.3 GHz, $P_{RF}$ total = 88 MW

FCC $\text{e}^+\text{e}^-$: CW, 0.8 GHz, $P_{RF}$ total = 110 MW

CLIC $\text{e}^+\text{e}^-$: Pulsed, 1.0 GHz, $P_{RF}$ total = 180 MW
To Achieve Higher Efficiency and Availability

Break through operation limitations:

– to work at nonlinearities

– to work close to limitation

– to change operation point quickly and correctly.
The Challenges

• **System is usually optimized at designed operating point, while**

• **RF dynamics and cavity dynamics were/are often black box**
  - Cavity pass band modes
  - Lorentz force detuning at different cavity field levels
  - Lorentz force to cavity tuning transfer function
  - Piezo tuner to cavity tuning transfer function (time domain, or frequency domain)
  - Moto tuner to cavity tuning transfer function
  - Microphonics spectrum
  - System open loop matrix
  - System closed loop matrix
  - Cavity field behaviour close to and at quench
  - Multipacting in cavity and power coupler
  - Fast fault detection and fault recovery
  - Power amplifier input-output characteristics (power and phase) at different modulator voltage
  - Modulator ripple frequency and amplitude
  - Circulator characteristics (return loss, frequency) under different power consumption, different reflection power, and working temperature
  - Power amplifier bandwidth variation at different output power level
  - Driver amplifier and power amplifier delay, rise time and falling time under different power level
  - Phase drift in cables due to temperature or humidity changes
Insight into RF & Cavity Dynamics

• Rely heavily on high precision and online diagnostic of basic cavity parameters:
  – Cavity voltage
  – Synchronous phase
  – QI
  – Detuning
  – R/Q

\[ \dot{V}(t) = (-\omega_{1/2} + i\Delta\omega(t)) V(t) + \kappa_g I_g(t) + \kappa_b I_b(t) \]

• Rely heavily on high precision and online diagnostic of critical parameters in RF power chain
Advanced Technologies Makes It Possible
(Anders Johansson)

Pre-Amp

Klystron or Tetrode

PSU modulator

Circulator

Power Grid

Load

Potential Inner Loop

LLRF system (FPGA based):
PI-controller

Phase Reference
352.21 or 704.42 MHz

Master Oscillator
(Not part of LLRF)

Master Oscillator
(Not part of LLRF)

LLRF system (CPU based):
IOC

1...10

Warning/Errors

LLRF system (FPGA based):
Monitoring & Storing

LLRF system (Standalone HW):
Local oscillator

Pz Ctrl fine grain tuning

Pz Ctrl coarse grain tuning

Motion control

PIO

Circulator

Cavity

Load

LLRF system (FPGA based):
Monitoring & Storing

LO

LLRF system (FPGA based):
Monitoring & Storing

LO

LLRF system (CPU based):
IOC

LLRF system (FPGA based):
Monitoring & Storing

LO

LLRF system (CPU based):
IOC

Master Oscillator
(Not part of LLRF)

Phase Reference
352.21 or 704.42 MHz

Master Oscillator
(Not part of LLRF)

LLRF system (CPU based):
IOC

Master Oscillator
(Not part of LLRF)
The Goal at ESS
The Last Thing to Overcome

Online beam phase measurement
Phase Scan vs. Transient Beam Loading

- **Phase Scan**

  $$V_b(t) = -\left( \frac{1}{2} V_{b0} e^{-(t-nT_b)/\tau} + V_{b0} e^{-(t-(n-1)T_b)/\tau} + V_{b0} e^{-(t-(n-2)T_b)/\tau} + \cdots + V_{b0} e^{-(t-T_b)/\tau} + V_{b0} e^{-t/\tau} \right)$$

- **Transient Beam Loading**
## Phase Scan vs. Transient Beam Loading

<table>
<thead>
<tr>
<th>Accuracy and parameter used</th>
<th>Phase scan – signature matching</th>
<th>Transient beam loading – drift beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>±2.4%</td>
<td>±4%</td>
</tr>
<tr>
<td>Phase</td>
<td>±1°</td>
<td>±1°</td>
</tr>
<tr>
<td>Pulse length</td>
<td>&lt;20μs</td>
<td>&gt;50μs</td>
</tr>
<tr>
<td>Beam current</td>
<td>&lt;20mA</td>
<td>&lt;20mA</td>
</tr>
<tr>
<td>Rep. rates</td>
<td>1Hz</td>
<td>1Hz</td>
</tr>
</tbody>
</table>
Improved Transient Beam Loading Method at DESY

• Rather than suffering from poor signal to noise ratio (SNR in some case <10dB), strong signal and clear information is observed

Build constant cavity field without beam:
\[ V_{\text{cav},1} = V_g \]

Pulse beam comes:
\[ V_{\text{cav},2} = V_g + V_b \]

\[ V_b = V_{b, r} + jV_{b, i} \]
Online Beam Phase Measurement

At filling time (no beam):
\[ V_{cav,1} = V_g \]

During beam pulse:
\[ V_{cav,2} = V_g + V_b \]

\[ V_b = V_{b,r} + jV_{b,i} \]
Online Beam Phase Measurement

MOPL025

TRANSIENT BEAM LOADING BASED CALIBRATION FOR CAVITY PHASE AND AMPLITUDE SETTING

Rihua Zeng*, European Spallation Source ERIC
Olof Troeng†, Lund University, Sweden

\[ \dot{V}(t) = \left(-\omega_1/2 + i\Delta\omega(t)\right)V(t) + \kappa_g I_g(t) + \kappa_b I_b(t) \]

and let the measured terms in the time derivative of \( V_m \) form the regressor matrix,

\[
X = \begin{bmatrix}
V_m(t_1) & t_1 V_m(t_1) & I_g(t_1) & \Gamma(t_1) \\
V_m(t_2) & t_2 V_m(t_2) & I_g(t_2) & \Gamma(t_2) \\
\vdots & \vdots & \vdots & \vdots \\
V_m(t_N) & t_N V_m(t_N) & I_g(t_N) & \Gamma(t_N)
\end{bmatrix}
\]

where

\[
\Gamma(t_k) = \begin{cases}
0 & \text{before beam start} \\
1 & \text{after beam start}
\end{cases}
\]

Then the relation

\[ y = X\theta \]

is approximately satisfied for some parameter vector

\[ \theta = [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4]^T, \]

where \( \theta_4 \) is the beam phase that we are looking for.

The least squares estimate of \( \theta \) is given by

\[ \theta_{LS} = (X^TX)^{-1}X^Ty. \]
Opportunities and Challenges

- Build upon Existing High precision and online RF measurement: QL, detuning, klystron, circulator characteristics, etc..

\[
\text{slope: } -\frac{1}{\tau}
\]

Field decay: \( \sim e^{-t/\tau} \)

\[
\tau = \frac{Q_L}{\pi \cdot f}
\]

Rel. error < 1%

Loaded Q

\[
\text{slope: } \frac{d\phi}{dt}
\]

Phase with respect to LO

\[ \Rightarrow \Delta\omega = \frac{d\phi}{dt} = 2\pi \cdot \Delta f \]

Rel. error < 2 Hz

Detuning

S. Simrock
Opportunities and Challenges

- **Build upon Advanced Hardware:**

<table>
<thead>
<tr>
<th>Error type</th>
<th>Required range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current variation during pulse</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>High frequency ripple in beam current (&gt;1kHz)</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Beam current variation from pulse to pulse</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>High frequency modulator ripple (&gt;1kHz)</td>
<td>&lt;0.02%</td>
</tr>
<tr>
<td>Feedforward matching error for beam loading</td>
<td>&lt;30ns</td>
</tr>
<tr>
<td>Microphonics induced cavity detuning (including resonant case)</td>
<td>&lt;100Hz</td>
</tr>
<tr>
<td>QL spread (deviation from optimal value (zero reflection))</td>
<td>&lt;30%</td>
</tr>
<tr>
<td>SNR from IQ detection (digital domain)</td>
<td>&gt;75dB</td>
</tr>
<tr>
<td>SNR from phase reference system (including MO)</td>
<td>&gt;70dB</td>
</tr>
</tbody>
</table>

![Graph showing detuning at different directivities](image)

![Graph showing generator current I&Q input and output](image)
Opportunities and Challenges

• It is promising

• Uncertainties in reality.

• Interactive learn from practice (data, experiment)

• Guided by modeling (expressing uncertainty in a precise, quantitative and controlled way)
Learning from Practice: 
Integrate Data, Modeling and Tests

- A methodology to integrate RF measurement, modeling and data/database, to really identify detailed dynamics
Thanks!