Low-Level RF

S. Simrock, DESY
Outline

• Scope of LLRF System

• Work Breakdown for XFEL

• LLRF Design for the VUV-FEL

• Cost, Personpower and Schedule
RF Systems for XFEL

- RF Gun
- Injector
- 3rd harmonic cavity
- Main Linac
## Scope of RF Control

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>total number of klystrons / cavities</td>
<td>~ 30/ 1,000</td>
</tr>
<tr>
<td>per rf station (klystron):</td>
<td></td>
</tr>
<tr>
<td># cavities / 10 MW klystron</td>
<td>~ 32</td>
</tr>
<tr>
<td># of precision vector receivers (probe, forward, reflected power)</td>
<td>~ 100</td>
</tr>
<tr>
<td># piezo actuator drivers / motor tuners</td>
<td>~ 32/32</td>
</tr>
<tr>
<td># waveguide tuner motor controllers</td>
<td>~ 32</td>
</tr>
<tr>
<td># vector-modulators for klystron drive</td>
<td>1</td>
</tr>
<tr>
<td>Total # of meas. / control channels</td>
<td>3,000 / 3,000</td>
</tr>
</tbody>
</table>
RF Control Requirements

• Maintain **Phase** and **Amplitude** of the accelerating field within given tolerances to **accelerate** a charged particle beam
  - up to 0.01% for amplitude and 0.01 deg. for phase

• Minimimize **Power** needed for control

• RF system must be **reproducible, reliable, operable, and well understood.**

• Other performance goals
  - **build-in diagnostics** for calibration of gradient and phase, cavity detuning, etc.
  - provide **exception handling** capabilities
  - meet performance goals over wide range of operating parameters
Requirements RF Control

• Reliable
  • not more than 1 LLRF system failure / week
  • minimize LLRF induced accelerator downtime
  • Redundancy of LLRF subsystems
  • ...

• Operable
  • “One Button” operation (State Machine)
  • Momentum Management system
  • Automated calibration of vector-sum
  • ...

• Reproducible
  • Restore beam parameters after shutdown or interlock trip
  • Recover LLRF state after maintenance work
  • ...
Requirements RF Control

• Maintainable
  • Remote diagnostics of subsystem failure
  • “Hot Swap” Capability
  • Accessible Hardware
  • ...

• Well Understood
  • Performance limitations of LLRF fully modelled
  • No unexpected “features”
  • ...

• Meet (technical) performance goals
  • Maintain accelerating fields - defined as vector-sum of 32 cavities - within given tolerances
  • Minimize peak power requirements
  • ...
Architecture of digital RF Control

- Master oscillator
- Vector modulator
- RF switch
- Klystron
- Isolator
- RF power transmission
- Waveguide tuner
- Beam pickup
- ADC
- DAC
- FPGA
- DSP
- Downconverter
- Clock
- Rep. rate
- Digital feedback
- Master oscillator
- Vector modulator
- RF switch
- Klystron
- Isolator
- RF power transmission
- Waveguide tuner
- Beam pickup
- ADC
- DAC
- FPGA
- DSP
- Downconverter
- Clock
- Rep. rate
- Digital feedback

Local server (VME)
Main frame (client)
Network
Linac RF Subsystems

A. Frequency generation
   (1) Stable reference frequency oscillator
   (2) Phase locked Oscillator (various frequencies)
   (3) Power supply
   (4) Diagnostics
   (5) Control system interface

B. Frequency and Reference Phase Distribution
   (1) Phase stable transmission line
   (2) Temperature stabilization
   (3) Power distribution (directional couplers)
   (4) Phase stability monitoring and correction

C. Cavity Field Control
   (1) Detectors for accelerating field
      (a) downconverter
      (b) A&P detector
      (c) I/Q detector
   (2) Controllers for klystron drive
      (a) A&P modulator
      (b) vector-modulator
   (3) Digital Feedback/Feedforward
      (a) Fast analog IO (ADC/DAC)
      (b) Signal Processors (FPGA,DSP)
   (4) Feedback/Feedforward Algorithms
   (5) Interlock system
   (6) Diagnostics
   (7) Interface to control system

D. High Power Amplifier
   (1) RF power source
   (2) Power supply
   (3) Interlocks
   (4) Diagnostics
   (5) Interface to control system

E. Power Transmission System
   (1) Transmission line (coaxial, waveguide)
   (2) Circulator, Isolator
   (3) Power dividers
   (4) Directional coupler (Monitor)
   (5) Waveguide (coaxial) window
   (6) Pressurisation system

F. Accelerating System
   (1) Cavity
   (2) Fundamental Coupler
   (3) Higher Order Mode Coupler

G. Cavity Frequency Tuning System
   (1) Cavity tuner (fast and/or slow)

H. Machine Protection System

I. Personnel Safety System

J. Control System Interface
**LLRF Control Algorithms**

**A. FIELD CONTROL ALGORITHMS**

1. **Feedback**
   - (a) PID filter
   - (b) Kalman filter
   - (c) adaptive filters
   - (d) optimal controller

2. **Feedforward**
   - (a) beam loading compensation

3. **Beam based feedbacks**
   - (a) rf phase feedback
   - (b) beam energy feedback
   - (c) bunch length feedback

4. **Exception handling**
   - (a) quench detection and handling
   - (b) error from beam loading

**B. LLRF System Measurement Algorithms**

1. **Loop phase rotation matrix**
2. **Field calibration rotation matrix**
   - (based on rf, beam based transients, and spectrometer)
   - (a) gradient calibration
   - (b) phase calibration
3. **Vector-sum calculation**
4. **Meas. of incident phase (vector-sum !)**
5. **Beam phase measurement**
6. **forward/reflected power calibration**
   - (a) correct for directivity of couplers
7. **Cavity detuning**
   - (a) average during pulse
   - (b) detuning curve during pulse
8. **Loaded Q**
LLRF Control Algorithms

D. High level procedures
(1) Adaptive feedforward
   (a) response matrix or T.F. based
   (c) robustness
   (d) different beam modes
(1) System identification
   (a) beam phase and current
   (b) loaded Q
   (c) incident phase
(3) Waveguide tuner control
(4) Momentum management system
(5) Field control parameters optimization
(6) Operation at different gradients
(7) Operation at the performance limit
   (a) maximize availability
   (b) maximize field stability
(8) Hardware diagnostics
(9) On-line rf system modelling
(10) Automated fault recovery
(11) Finite state machine

C. Cavity Resonance Control
(1) Slow tuner
   (a) maintain average resonance frequency (pre-detuning)
   (b) maximize tuner lifetime
(2) Fast tuner (ex. piezoelectric tuner)
   (a) dynamic Lorentz force compensation
   (b) microphonics control
   (c) minimize rf power required for control

E. Other
(1) RF System Database
   (a) calibration coefficients
   (b) subsystem characteristics
(2) Alarm and warning generation
(3) Control System functions
Beam Based Calibration

- Good beam required to get sufficient signal (8nC, 30µs, 15MV/m)
- Preliminary calibration (to 10%)
- Gradient calibration (to 3-5%)
Beam Induced Transient Detection Hardware
Measurement Results

Measurement results of calculated beam phases from captured single bunch induced transients for 3 different bunch charges. Measurements at cavity 3 module ACC1. Expected value ≈ -10°.

Measurement of 3nC single bunch induced transient (phase calibrated for direct beam phase calculation).

<table>
<thead>
<tr>
<th>Charge [nC]</th>
<th>Phase [deg]</th>
<th>Phase error [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-12,326</td>
<td>-2,326</td>
</tr>
<tr>
<td>2</td>
<td>-11,3168</td>
<td>-1,3168</td>
</tr>
<tr>
<td>3</td>
<td>-13,0406</td>
<td>-3,0406</td>
</tr>
</tbody>
</table>
System Identification (1)

\[ \dot{V} = \begin{bmatrix} -\omega_{1/2} & \Delta \omega \\ \Delta \omega & -\omega_{1/2} \end{bmatrix} \dot{V} + R \omega_{1/2} (\dot{I}_G + \dot{I}_B) \]

Differential Equation

\[ \dot{V} = \begin{bmatrix} -\omega_{1/2} & \Delta \omega \\ \Delta \omega & -\omega_{1/2} \end{bmatrix} \dot{V} + R \omega_{1/2} (\dot{I}_G + \dot{I}_B) \]
System Identification (2)

1st Order ID on Cavity 7

Single Pulse Detuning Measurement

$V_{\text{acc}}$

$\Delta \omega(t)$

$\Delta f/Hz, \Delta f Hz^2, V^2/2MV^2$

- force $P_f$ to be zero at end of pulse by subtraction of $d_t^*P_r$ (complex)
- the whole shape changes

Correct for directivity of couplers

Beam phase of 4 cavities for different phase of $V_{\text{acc}}$
Exception Handling

- Cavity quench detection mechanism (algorithms)
- Exception handling procedure

ACC1* at high gradient

1-st quench in Cavity 2
Eacc=19 [MV/m]

2-nd quench in Cavity 6
Eacc=21 [MV/m]

3-rd quench in Cavity 1
Eacc=24 [MV/m]
Drift ACC1 (cryomodule before BC) at TTF

**Energy Jitter**
- Energy drift: 0.072% ± 0.028%
- Jitter: 0.077%

**Time Jitter**
- Jitter: 1 ps
- Duration: 30 min
Active Compensation of Lorentz Force Detuning (1)

Piezo-Actuator:
- $l = 39$ mm
- $U_{\text{max}} = 150$ V
- $\Delta l \approx 4$ to $5 \ \mu\text{m}$ at 2K
- $\Delta f_{\text{max, static}} \approx 500$ Hz

He-tank + cavity

Tuning mechanism
Active Compensation of Lorentz Force Detuning (2)

9-cell cavity operated at 23.5 MV/m

Lorentz force compensated with fast piezoelectric tuner
Digital Control at the TTF

1.3 GHz master oscillator

vector modulator

klystron

1.3 GHz power transmission line

cryomodule 1

1.3 GHz field probe

1.3 GHz + 250 kHz

250 kHz clock

$\frac{1}{f_s} = 1 \text{ MHz}$

ADC

$\sum_{a-b}(a-b)$

vector-sum

digital low pass filter

DSP system

feed forward table

gain table

setpoint table

MAC mtg, May 05

Stefan Simrock

DESY
C67 DSP board
Digital Feedback Hardware

Gun and ACC1

ACC2, ACC3, ACC4 & ACC5
Cost

• Cost estimate based on experience with TTF and VUV-FEL

• Cost reduction for 30 systems possible but cost increase for design which is compatible with operation in tunnel ==> basically no change in cost expected

• Further cost reduction should be discussed after meeting technical and operational performance requirements in prototype in VUV-FEL
Personpower

• Personpower based on
  - detailed work breakdown structure
  - experience at JLAB with 25+ people in LLRF group
  - Note: Scope of LLRF significantly larger than for CEBAF

• For digital rf systems, most of the personpower is needed software development.
Summary

• Challenging task to control the fields to 0.01% in amplitude and 0.01 deg. in phase

• Main challenges for the LLRF system for the ILC are
  - Operability, Reliability, Reproducibility, Maintainability

• Most personpower will be invested in intelligent software

• Similar electronics is needed for other subsystems (ex. beam diagnostics). ==> Collaboration beneficial.

• Test facilities are available to evaluate new concepts