General Automation of LLRF Control for Superconducting Accelerators

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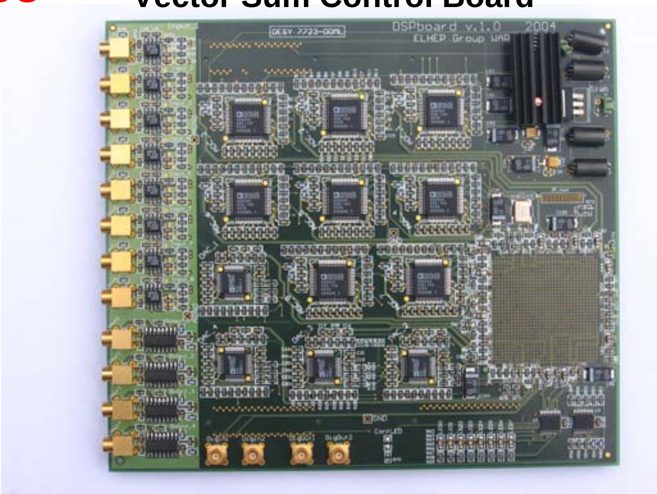
Overview

- Introduction
- Requirements towards automation
- Finite State Machines (FSM) for automation
- General LLRF automation using FSMs
- VUV-FEL FSM and procedures implementation
- Outlook

Introduction

- LLRF (control) requirements
  - Field quality for special purpose machines
    - 0.01 deg phase, 10^-4 amplitude for XFEL
  - Manageability for large scale systems
    - More than 20.000 cavities in ILC
  - Availability for user facilities
    - Short time windows for experiments
  - Flexible RF structures
    - Gradient / phase profile inter- or intrapulse
- Devices become digital now
  - Digital devices ease diagnosis
  - Therefore: flexibility at the cost of complexity

2004 VUV-FEL 8-Channel FPGA Vector Sum Control Board



Requirements for Automation

- Ease operators job, reduce operation errors
  - A large number of machine-errors is caused by the operators themselves
- Be applicable on top of existing infrastructure
  - An a priori consideration of automation is nice but unrealistic due to the large number of subsystems
- Accomplish operators acceptance
- Transparency for subsystem experts
- Expandability and adaptability for subsystem experts
- Deal with several ways of bypassing the automation
- There will certainly be some killer-applications
  - Start-up and shut-down, interlock-reset, parameter-tweaking

Automation-Wishlist vor VUV-FEL

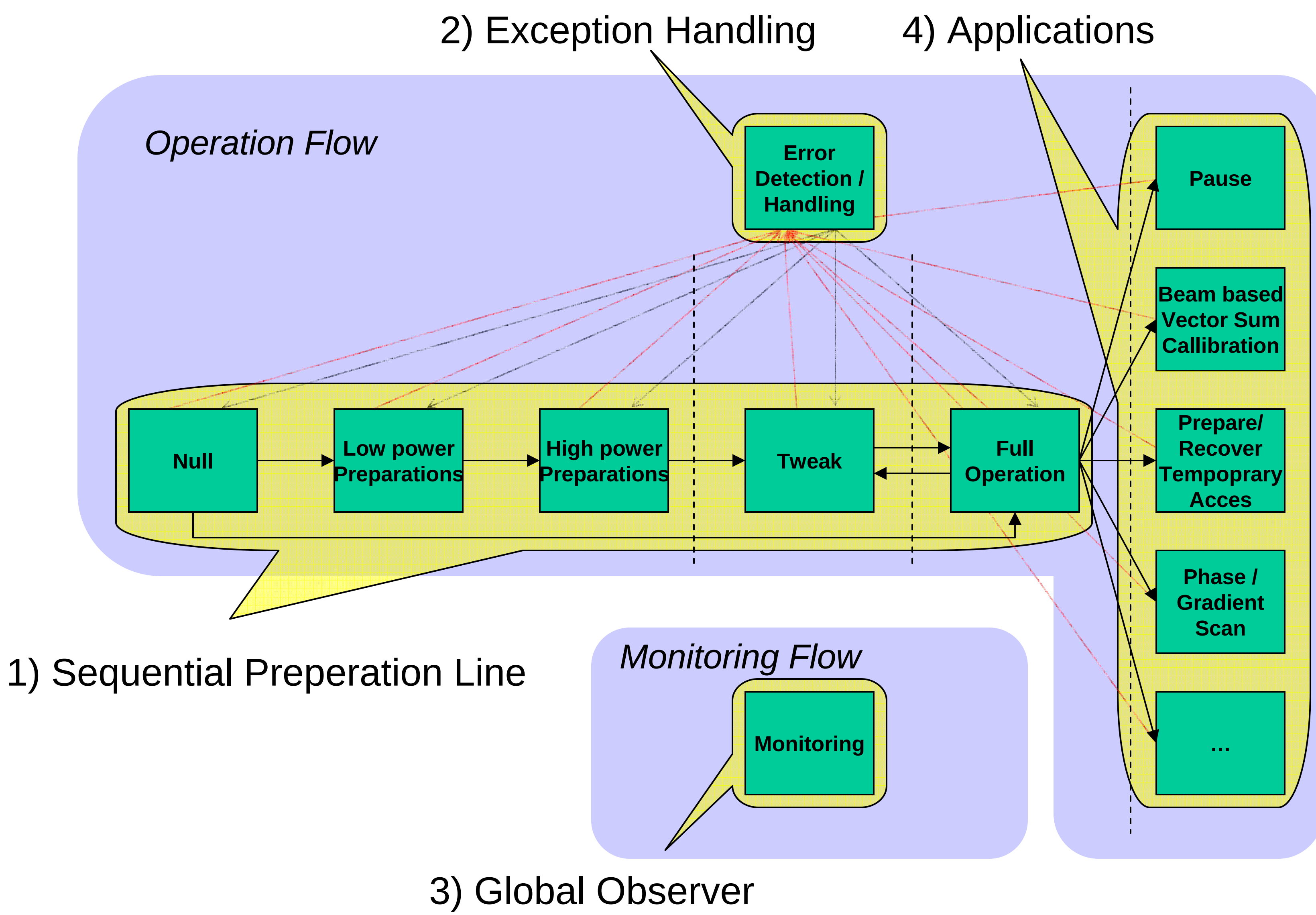
1. Offset Calibration
2. Loop Phase Determination
3. System Gain Determination
4. Predetuning of Vectorsum Estimation
5. Tuning of the Cavities
6. Adapt Feedforward
7. Synchronize ADCs of one RF Station
8. Calibrate DSP Matrices
9. Monitor Data Quality
10. Consistency Check
11. Interlock Reset
12. Calculate Detuning and Bandwidth
13. Adjustment of Waveguide Tuner
14. Momentum Management
15. Exeption Handling
16. Save and Restore Settings
17. History
18. Calibration of Forward and Reflected Power
19. Beam Phase Measurement
20. LO-Generator-Optimization
21. Track Frequency of RF Gun during Warm-Up
22. Klystron Linearization
23. Kryo Heatload Calculation
24. Hardware Diagnostics
25. Database with Calibrations
26. Database with Operational Limits
27. Adjustment of Amplitude and Phase
28. Close the Loop and increase Feedback Gain

- Surely incomplete list of tasks to be performed by automation system
- Procedures, provided by experts, will play a central role within the automation
- Need for clearly defined procedure trigger and its result

FSMs for Automation

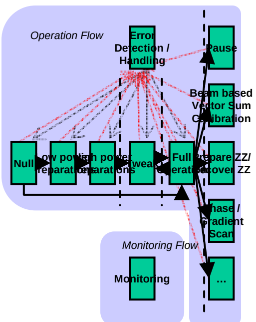
- Graphical way of managing complex subsystems
- The real world is considered a “State-Machine”, the software-implementation can just model a subset of all real states (design process is important)
  - Very transparent if states properly chosen
- Fairly used in industry
  - However: industrial FSMs forsee access to the hardware only through the FSM. In accelerators, there will certainly be frequent requests for bypassing the FSM
- Plug-and-play capability (modularity)
- Implementation can be done for example by using Matlab stateflow toolbox or the DOOCS FSM implementation

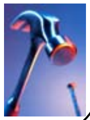
General LLRF FSM Proposal: Top Level View



VUV-FEL LLRF FSM Concept: Procedures

FSM-Layer	Intermediate (Interface) Layer	Application Layer	Hardware





FSM-Layer
- FSM Framework
- No knowledge of machine
- Generic for different RF stations

Intermediate (Interface) Layer
- Easy configurable
- No machine knowledge
- Accessible by experts

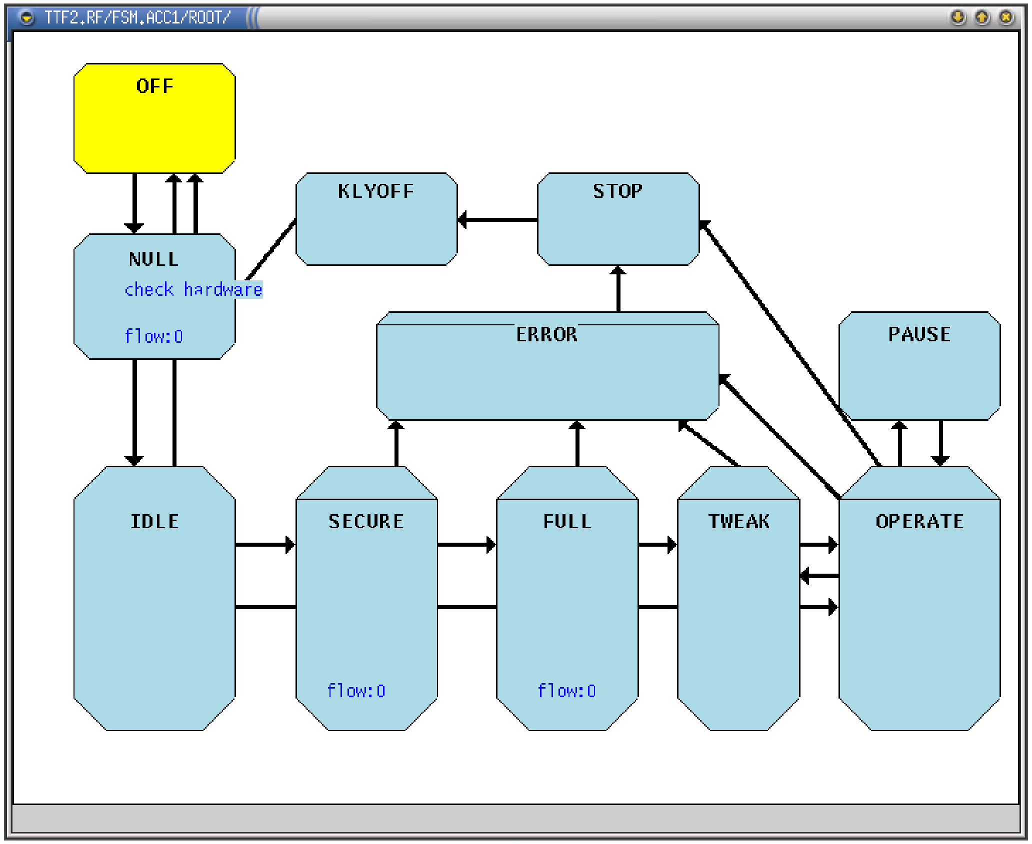
Application Layer
- Knows machine
- Ideally: fire and forget
- Can also be used as expert tools

- Network capable communication
- For DOOCS-FSMs: rpc calls

- Simple, low traffic protocol
- Unix pipes? Shared memory?

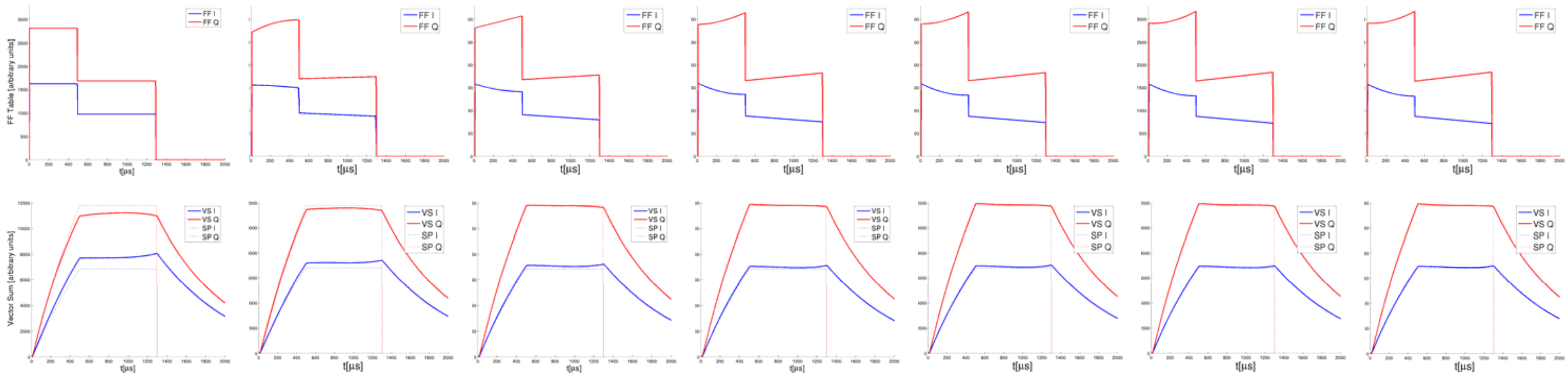
Middle layer can also be state machines or special purpose servers…

VUV-FEL LLRF FSM



- FSM is already equipped with some of the procedures
- Test phase and not in use during normal operation
- Implemention uses DOOCS FSM generator (automatic code generation)

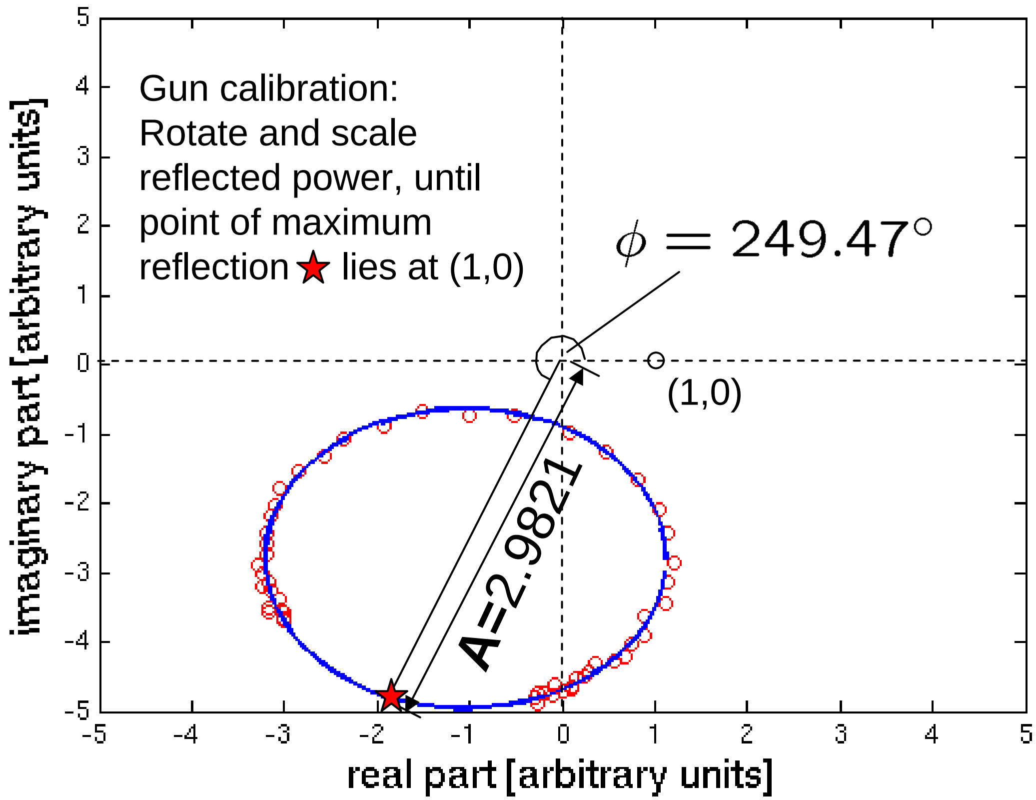
Implemented Procedures: Adaptive Feedforward



- In-Phase and Quadrature component are shown.
  Upper: controller output, lower: vectorsum readback
- Iterative algorithm that applies a simplified cavity differential equation to the error signal
- Low calculation time (<2s on VME-Sun) per iteration, converges after a few Iterations
- Compensates for Lorentz-Force detuning and system-nonlinearities

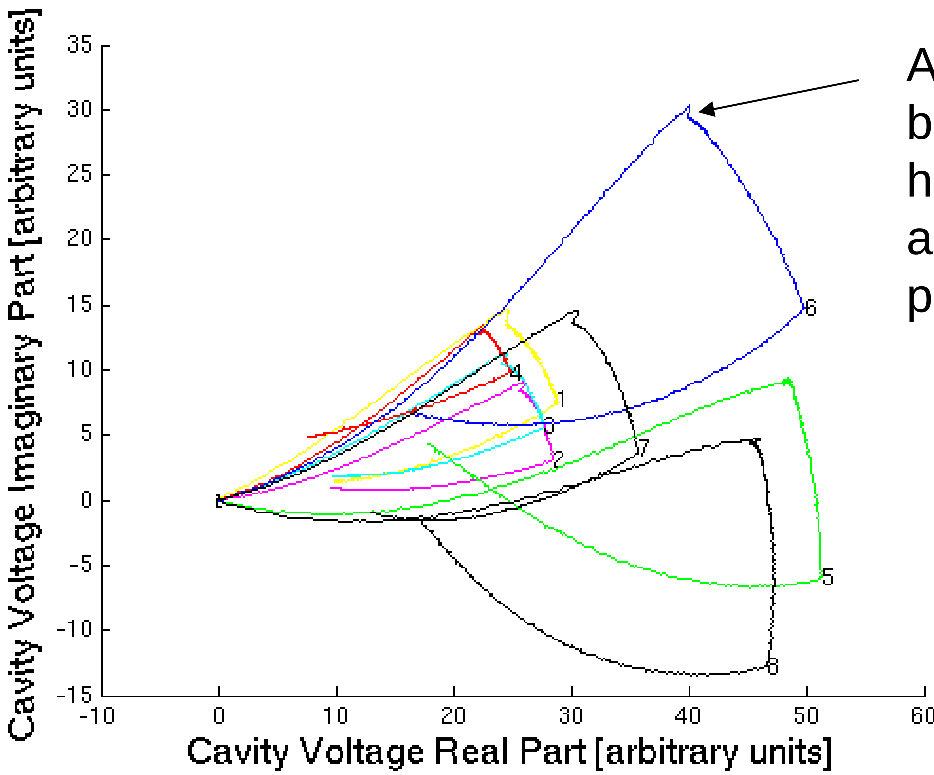
Implemented Procedures: Probeless Gun Calibration

Reflection-Coefficient for Gun-Temperature Scan (T=50.6..65.6°) with Fitted Circle



- Probeless normalconducting photoinjector at VUV-FEL,
  Cavity Voltage=Forward Amplitude-Reflected Amplitude after calibration
- Application part of the FSM

Implemented Procedures: Vector-Sum Calibration



After calibration, beam transients have same amplitude and phase

- At VUV-FEL with 30μs@1mA: ~1.5º and 2% resolution
- Application part of FSM

Implemented Procedures: Parameter Estimation

- Offset-Determination *1) Sequential Preparation Line*
  - Binary search for optimal offsets at controller output
- Resonance frequency tuning *1) Sequential Preparation Line*
  - Not yet tested
- System gain and loop phase *1) Sequential Preparation Line*
  - "Loop phase" does not apply for A-ϕ-control
  - Derived from cavity envelope equation in lowpass approximation

Summary and Outlook

- Our digital world demands for more automation (and vice versa)
- Automation will not replace an operator with a full understanding of the machine
- Requirements include soft-facts like operator acceptance and hardware-expert maintainability
- Finite State Machines are an established automation concept
- At VUV-FEL, all “expert parameters” were successfully and reproducible set automatically
- At VUV-FEL, a basic FSM with a number of automatic procedures has been successfully evaluated