
Advances in the Low Level RF Control (LLRF) for the VUV-FEL

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for the LLRF Team



Objectives of RF Control

- **Advance RF control technology** in the areas of hardware and software to **meet the requirements** for the **VUV-FEL**, and XFEL and ILC. Focus is on
 - **state-of-the-art technology**, pushing the envelope of performance
 - **compatibility with tunnel installation** (low maintenance, radiation tolerant)
 - **operability**, high degree of automation for large scale systems
 - **availability** and reliability optimization and cost reduction

Collaboration



DESY



WUT-ISE



TUL-DMCS



PSI

also worldwide participation by
FNAL, KEK, IHEP, ORNL, JLAB ...



Highlights

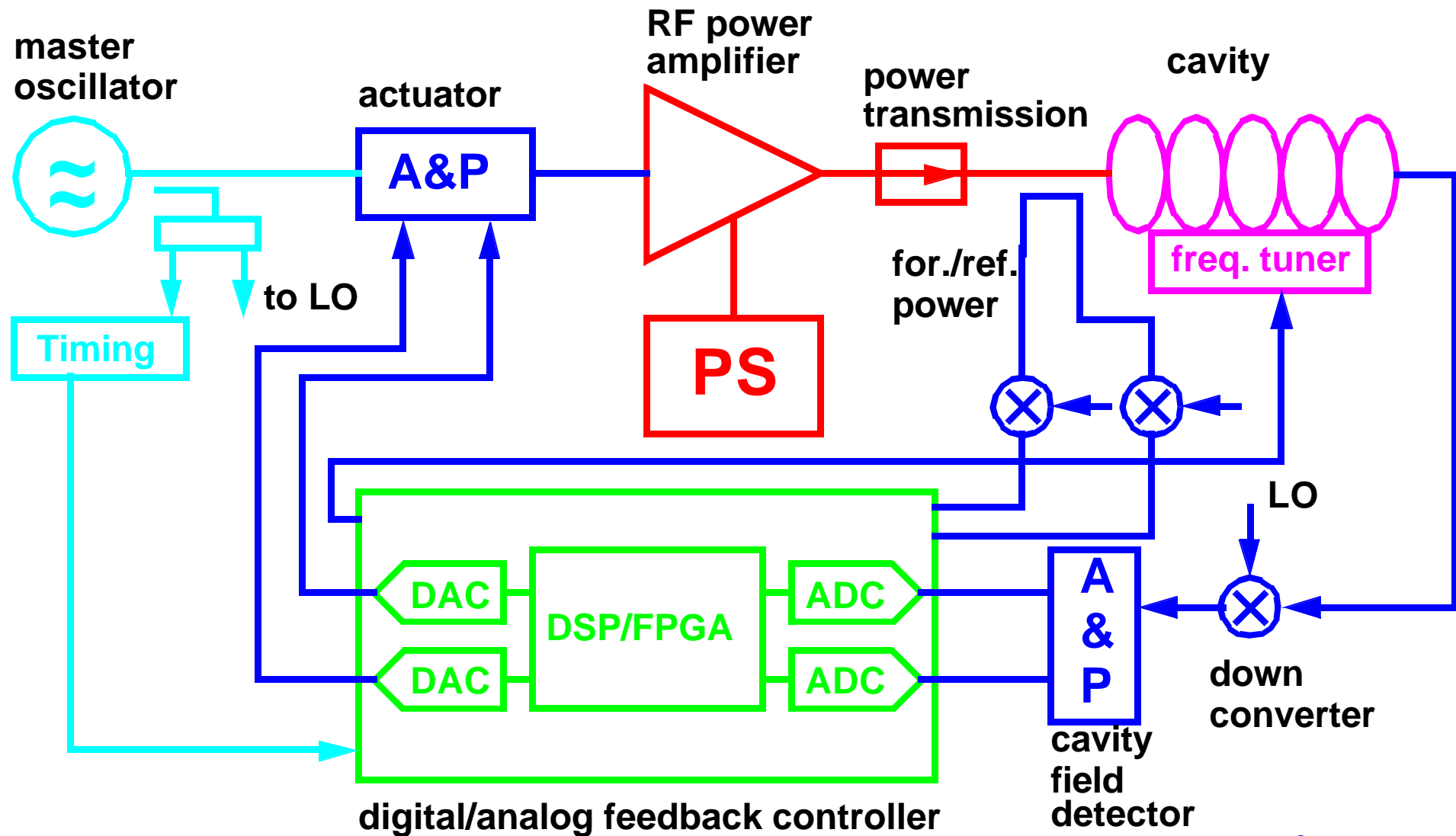
- **Third Generation RF Control (WUT-ISE ...)**
- **Single Bunch Transient Detection (TUL-DMCS ...)**
- **Multichannel Downconverter (WUT-ISE ...)**
- **Stable M.O. and Frequency Distribution (WUT-ISE ...)**
- **RF Gun Control (PSI ...)**

- **Automation of LLRF Control (TUL-DMCS ...)**
- **Exception handling (DESY ...)**
- **Data Management Development (TUL-DMCS ...)**
- **Control Optimisation (DESY ...)**

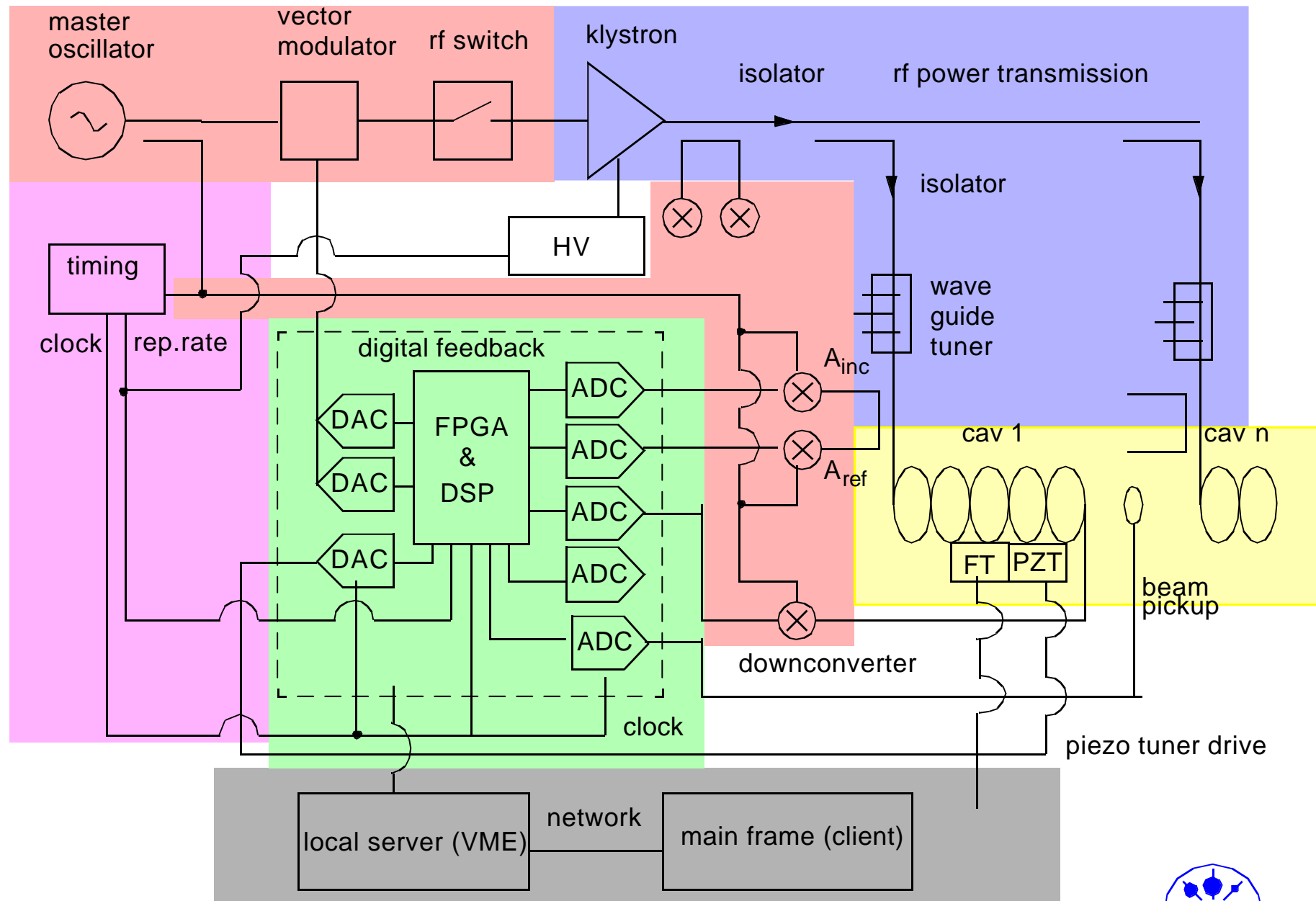
- **Cost and Reliability (DESY ...)**
- **Radiation Effects on Electronics (ALL)**



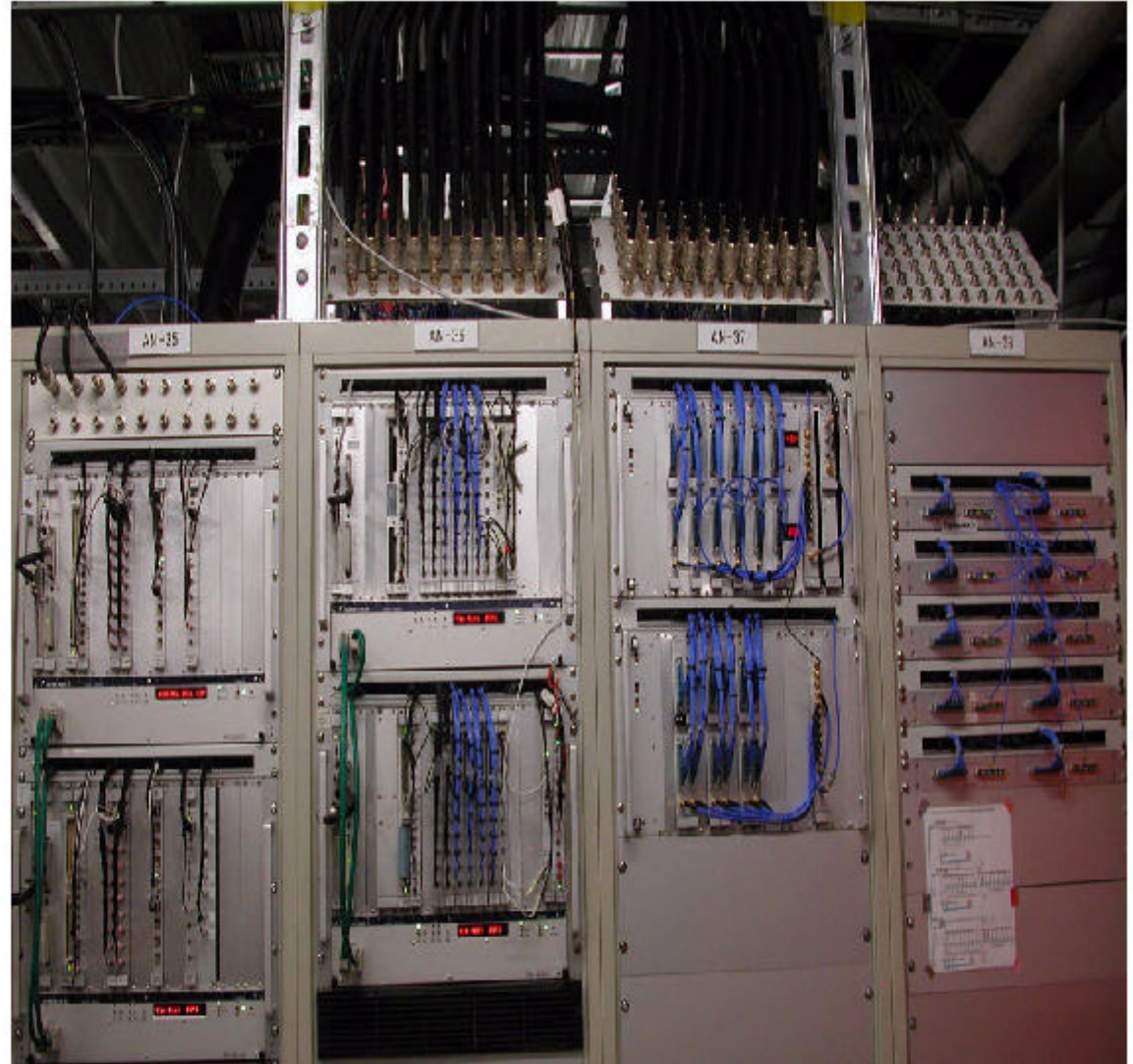
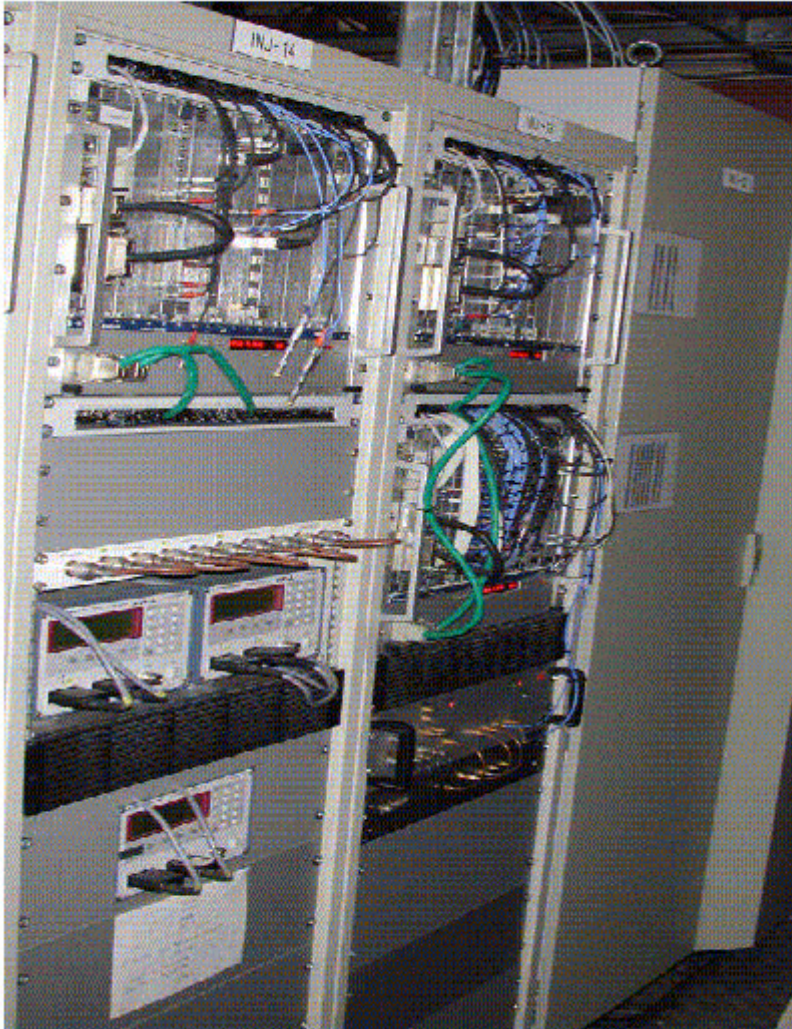
RF System Architecture (1)



RF System Architecture (2)

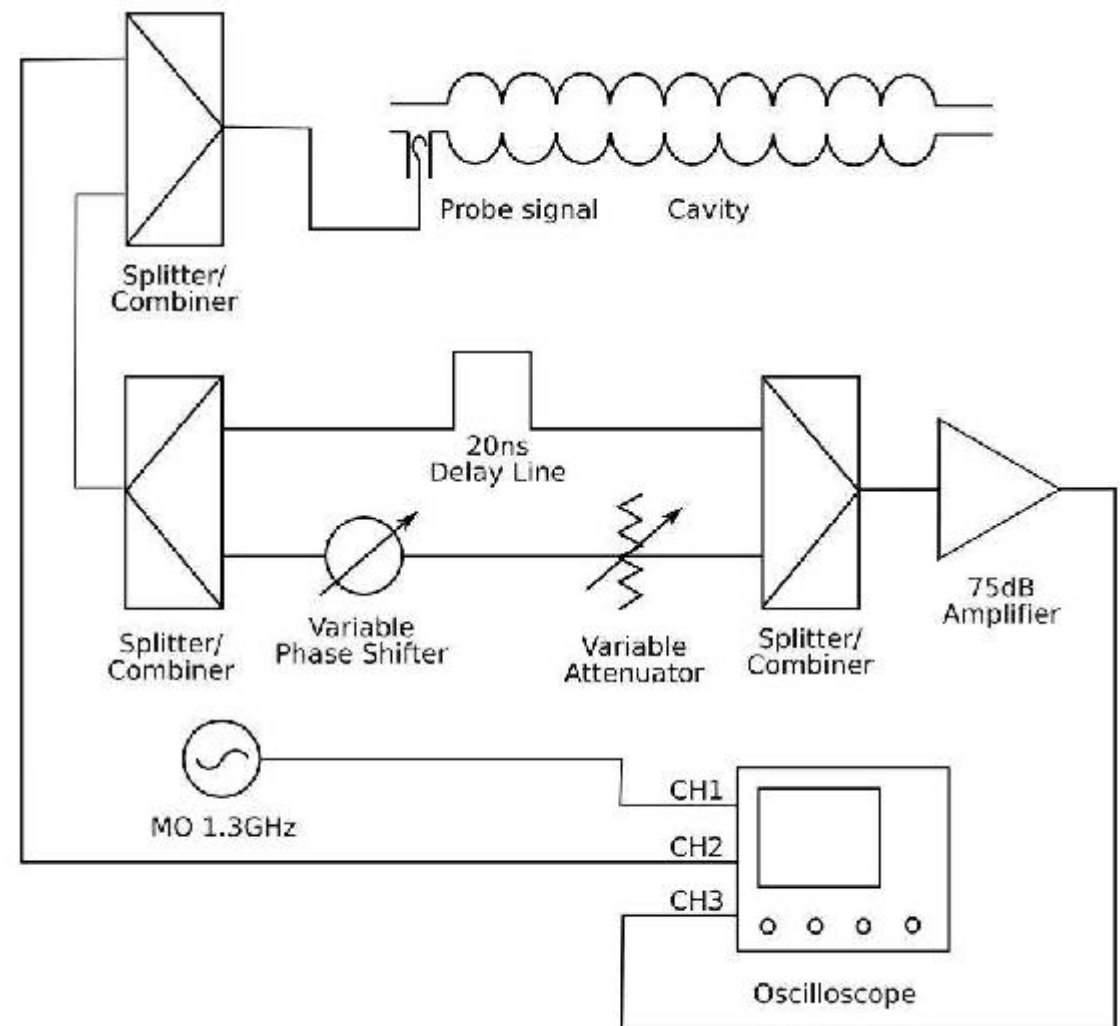


LLRF at the VUV-FEL



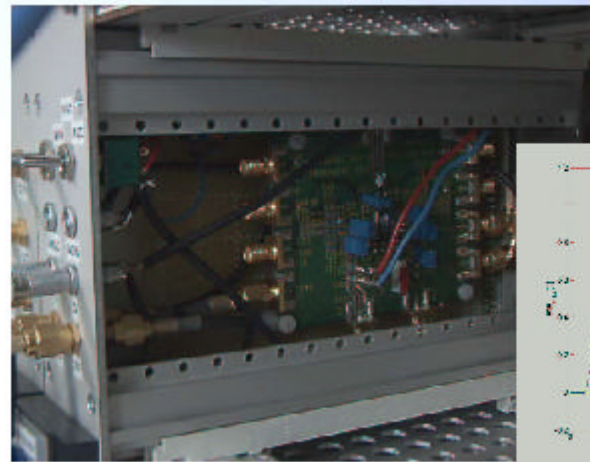
Single Bunch Transient Detection (1)

- Detection of transient of single bunch (1 nC)
 - with magnitude of about $2e-4$
 - with a resolution of a few percent in amplitude and few degrees in phase.
- Conceptual idea: subtract delayed probe signal from original probe signal and amplify error
 - Transient vector is detected by fast sampling scope

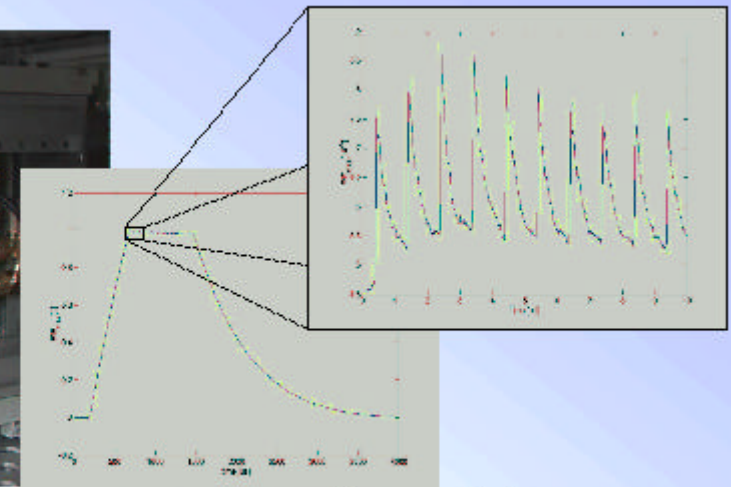


Single Bunch Transient Detection (2)

- This requires development of new hardware (microwave, analog, digital)
 - with high bandwidth and low noise



Picture of the hardware



Measured data

- Demonstrated required performance close to thermal noise limit.

Beam Phase Set Point	Measured Phase	Measured Magnitude	Measured Beam Phase Error
-90,0	-90,9	4,19E-04	0,9
-45,0	-48,2	4,37E-04	3,2
0,0	1,7	3,95E-04	-1,7
45,0	41,6	4,09E-04	3,4
90,0	44,9	1,19E-04	45,1
180,0	35,6	8,92E-05	144,4

Design Optimization, Cost and Reliability

- High performance design using digital processing (FPGAs) and telecommunication components.
- Reduce cost of LLRF system by application of COTS.
- Redundant design where necessary
- Reliability studies on prototypes include EMI, thermal, and radiation effects.
- Software design using modularity, standardization, good specifications and documentation
- Built-in diagnostics for hardware and software

Performance



Reliability



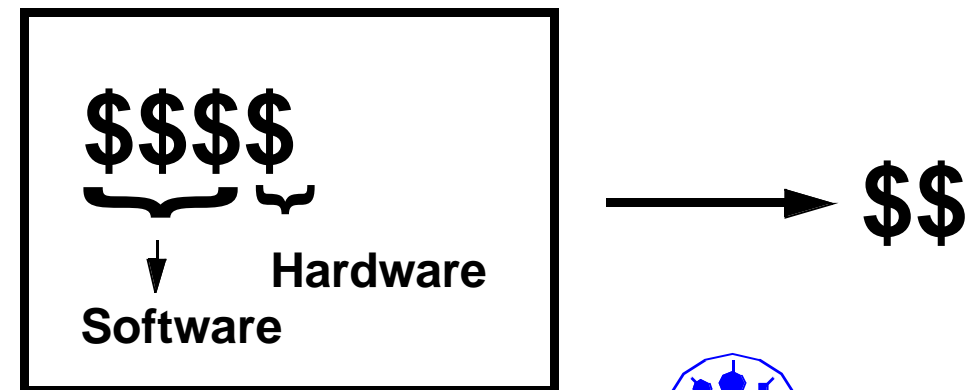
Operability



Maintainability

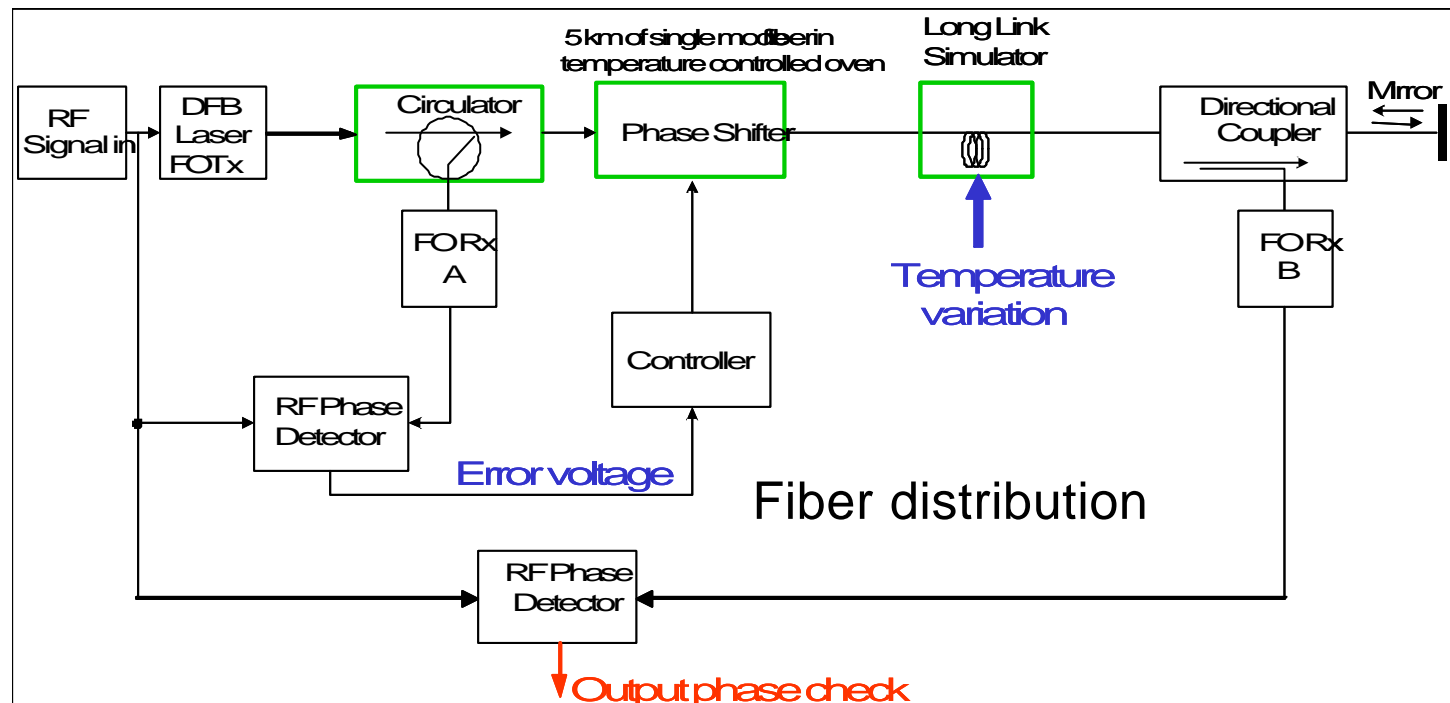


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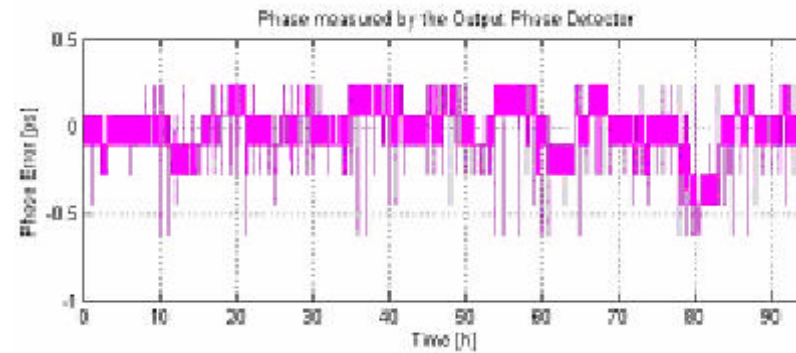


Highly stable frequency distribution (1)

- VUV-FEL, XFEL and ILC require a highly phase stable reference to
 - ensure that rf signals of laser, rf gun, and accelerating cavities are synchronized to better than 100 fs (short term) and 1 ps (long term)
- The proposed approach combines
 - a coaxial distribution system
 - with a fiber optic monitoring system.



Highly stable frequency distribution (2)

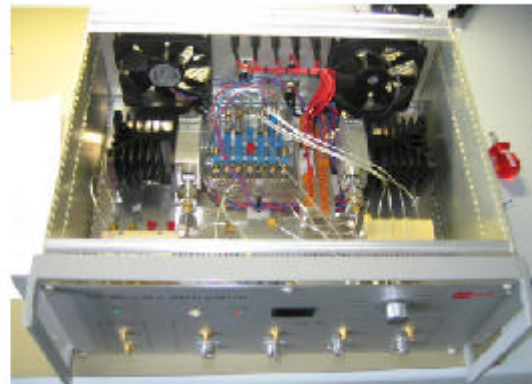


- Climate chamber for evaluation of temperature sensitivity of subsystems
- Short and long term error suppression

LOW POWER PART

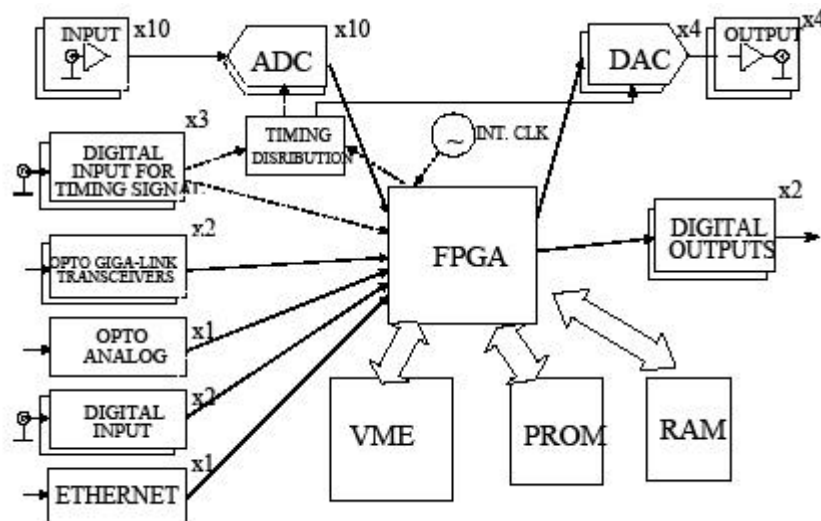


81 MHz POWER PART

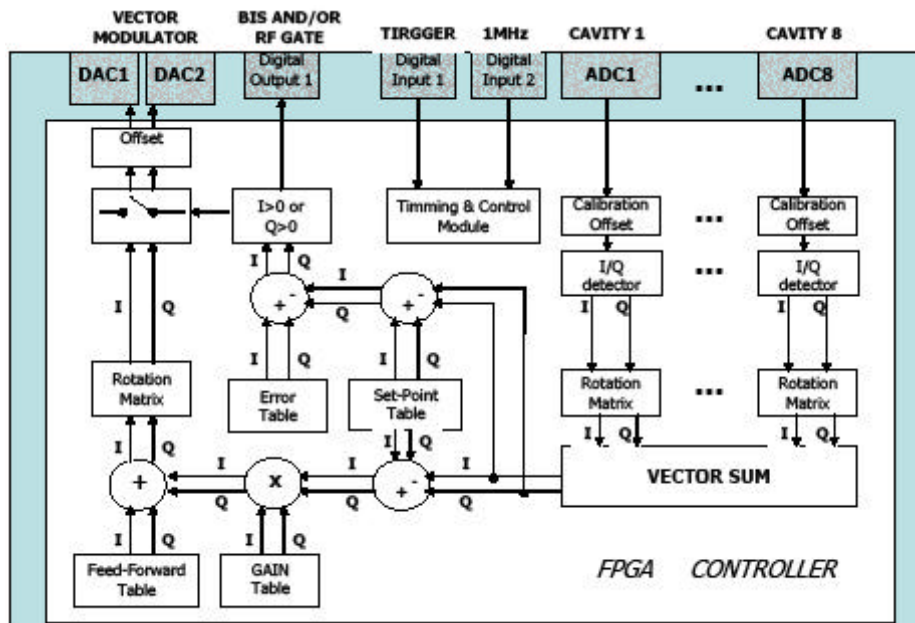


- Master Oszillator with output for many frequencies

3rd Generation FPGA based RF Control (1)

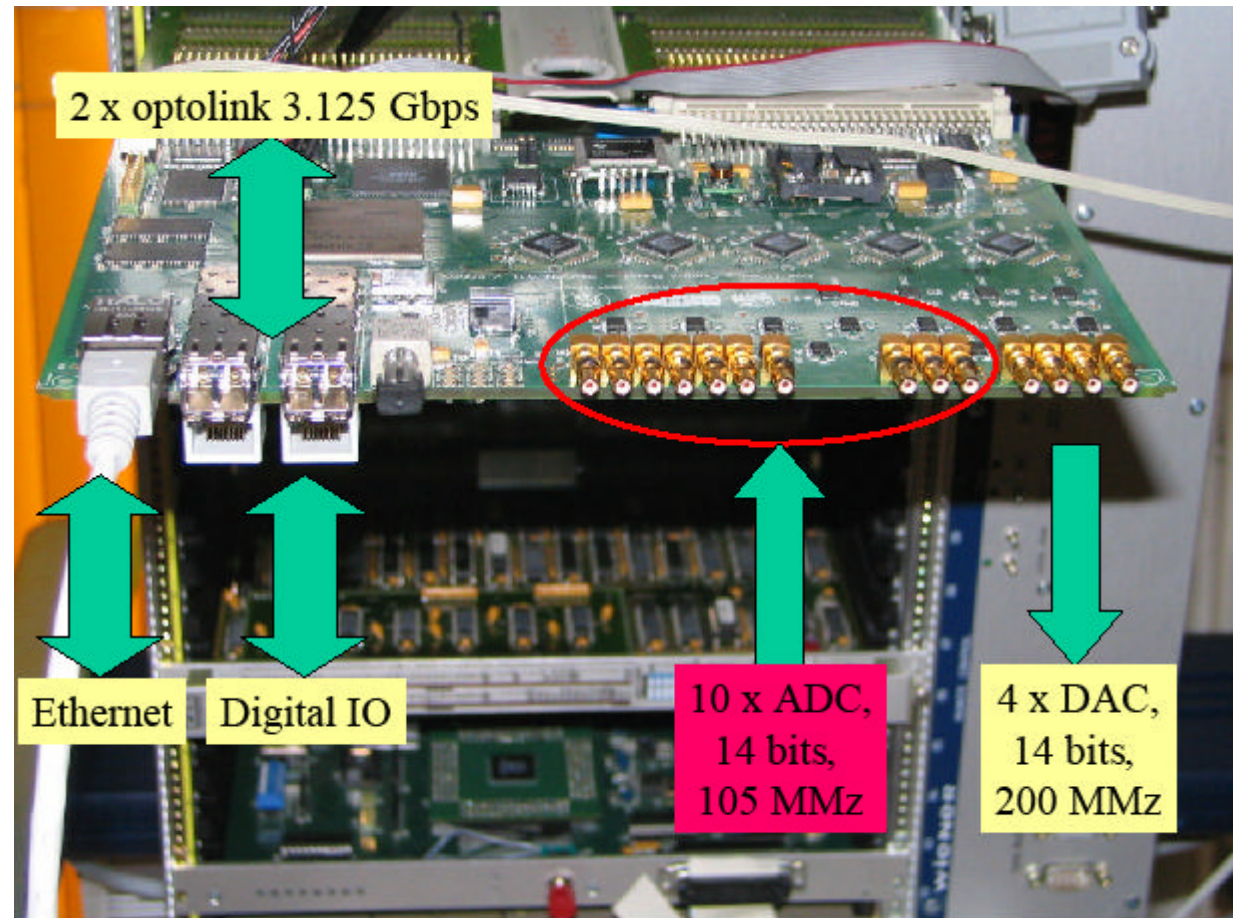


- Digital rf feedback systems for superconducting real time data processing
 - from a large number (up to 128) of ADC input channels and a smaller number (up to 64) DAC output channels.
- The latency from ADC clock to DAC output including all necessary data processing
 - should not exceed a few hundred nanoseconds.



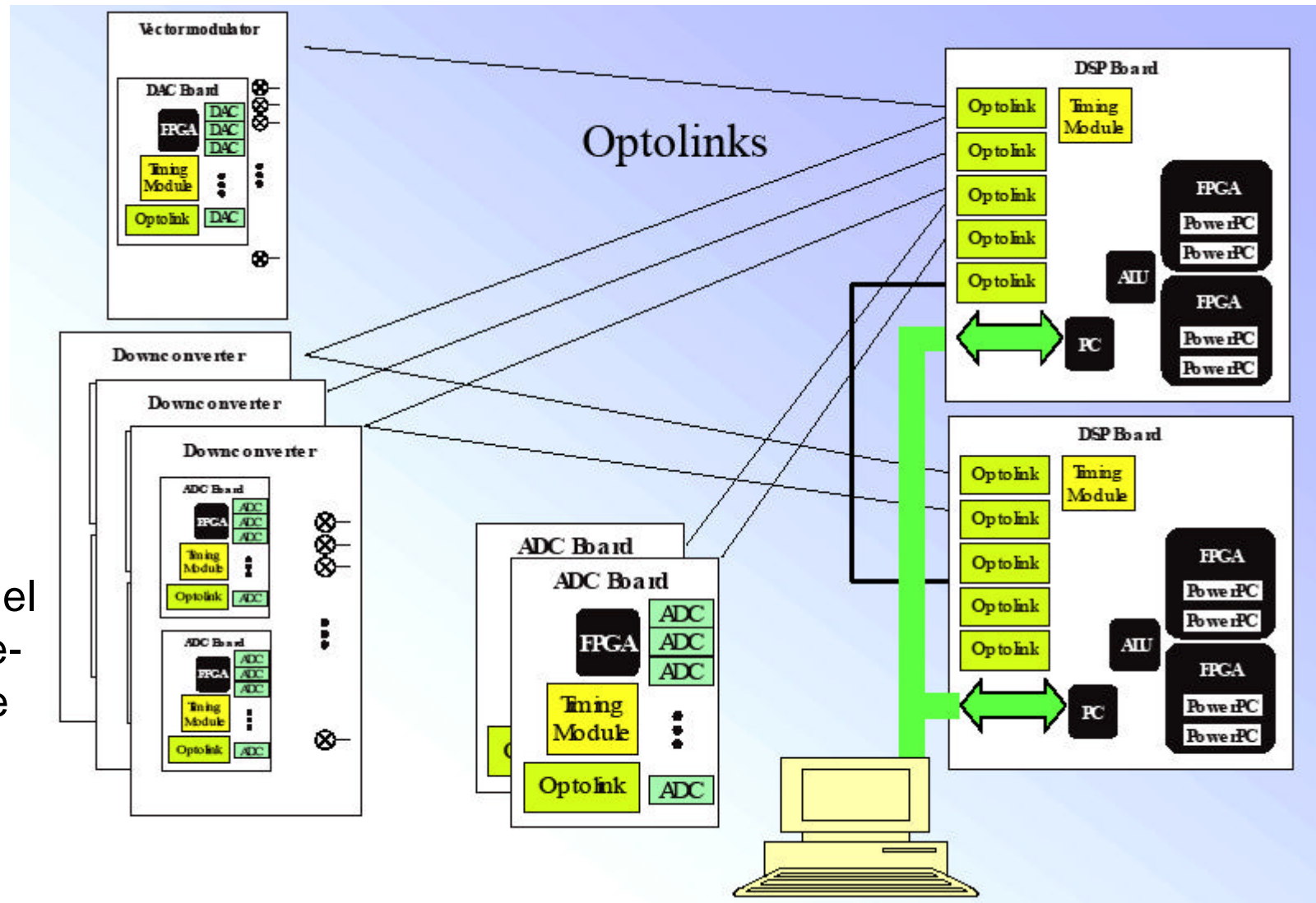
3rd Generation FPGA based RF Control (2)

- FPGAs are well suited for this type of hardware due to their the large number of I/O pins, large number of logic cells, and large number of multiplier cores which allow parallel processing of data.
- Goal is to explore the feasibility of realization of digital feedback and feedforward algorithms, complex application algorithms, exception handling and built-in diagnostics



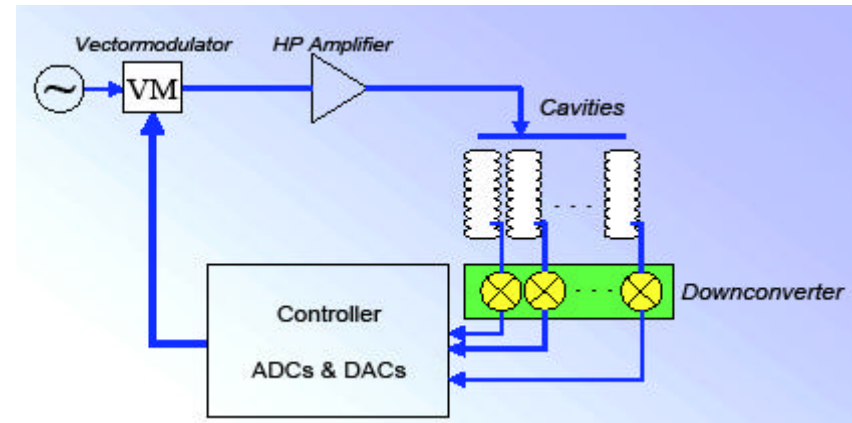
3rd Generation FPGA based RF Control (3)

- In future more distribution of sub-systems connected by optical Gigalinks
- Example:
Downconverters with analog I/O and preprocessing
- Issues for single tunnel operation are maintenance and moderate radiation levels



Multichannel downconverter (1)

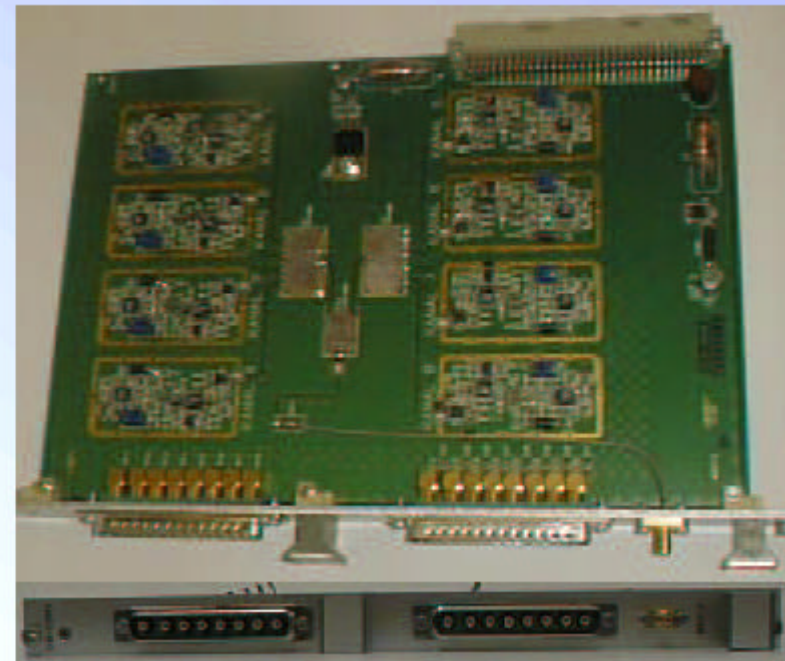
- Develop low cost and compact high-performance multichannel downconverter



Picture of 3rd generation downconverter.

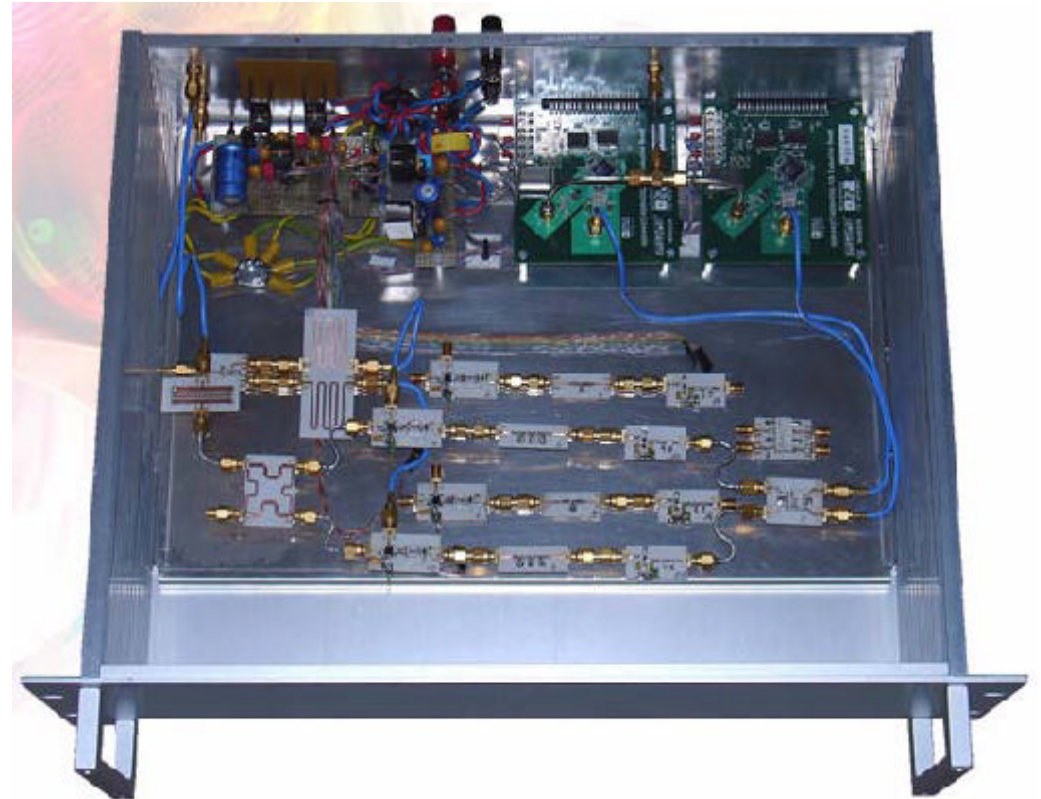
- 8 in/output channels, 1 LO input
- Linearity $< -50\text{dB}$
- Crosstalk between channels $< -50\text{dB}$
- LO leakage $< -50\text{dB}$ @ 1.3GHz
- LO stability $-15\text{dB} - -5\text{dB}$

Design and assembly at DESY,
layouting by external company



Multichannel downconverter (2)

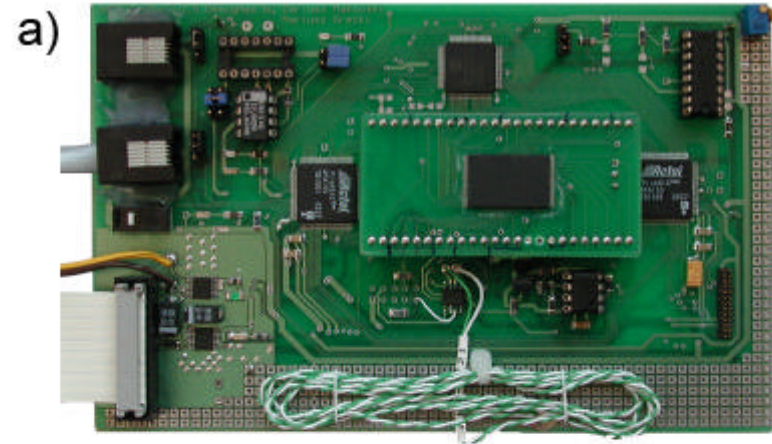
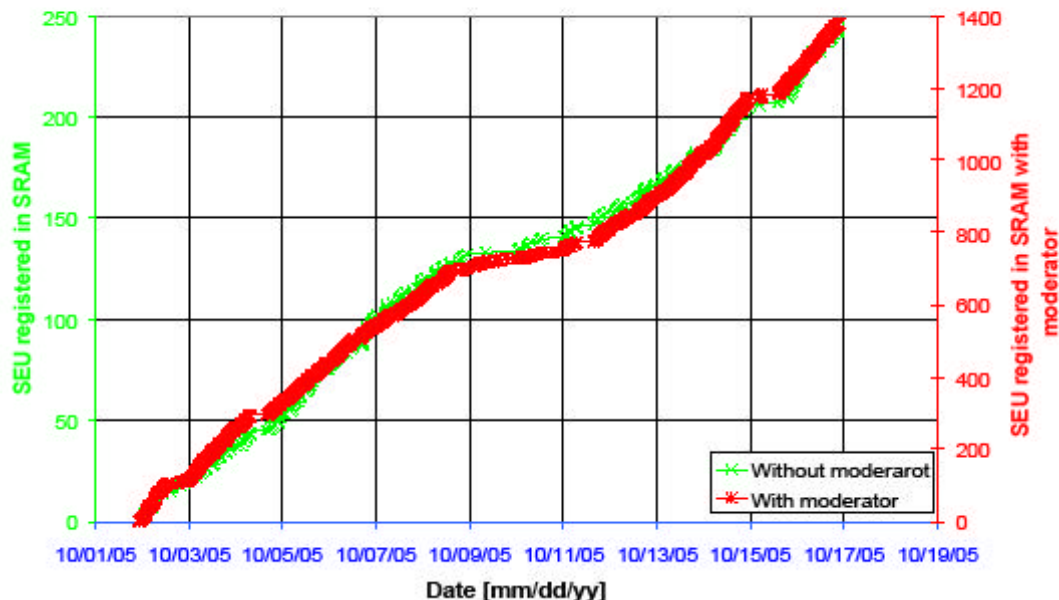
- Should include
 - remote controlled attenuators at rf inputs
 - RF outputs for transient detection
 - input for rf calibration signals
- Optional:
 - ADCs and FPGA for preprocessing on board and optical Gigalink to connect to main processor for control



Study rad. effect on electronics (1)

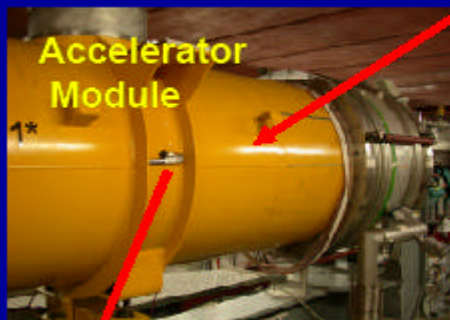
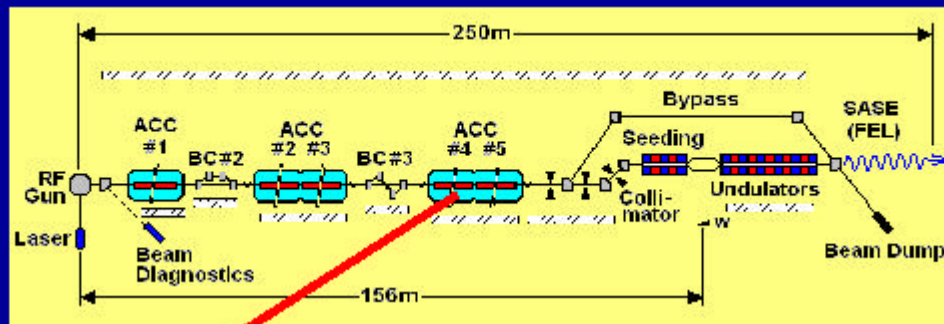
- On-line, calibrated neutron and γ Dosimetry
- Dosimetry based on SEU in semi-conductors. Calibration with TLDs and Bubble Dosimeters

SEU registered in VUV-FEL

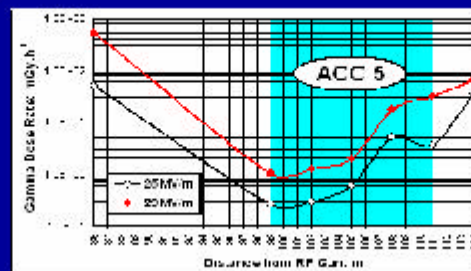


Study rad. effect on electronics (2)

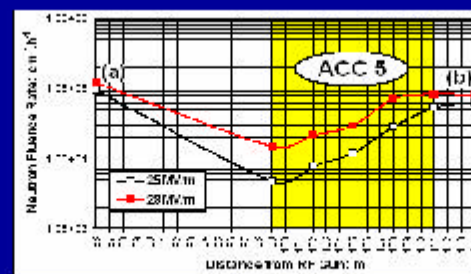
- Radiation impact studies include performance degradation in analog circuits, **single event effects** in digital electronics, **total ionizing dose** effects leading to complete failure, and **displacement** damage.



Neutron/Gamma Dosimeter pairs



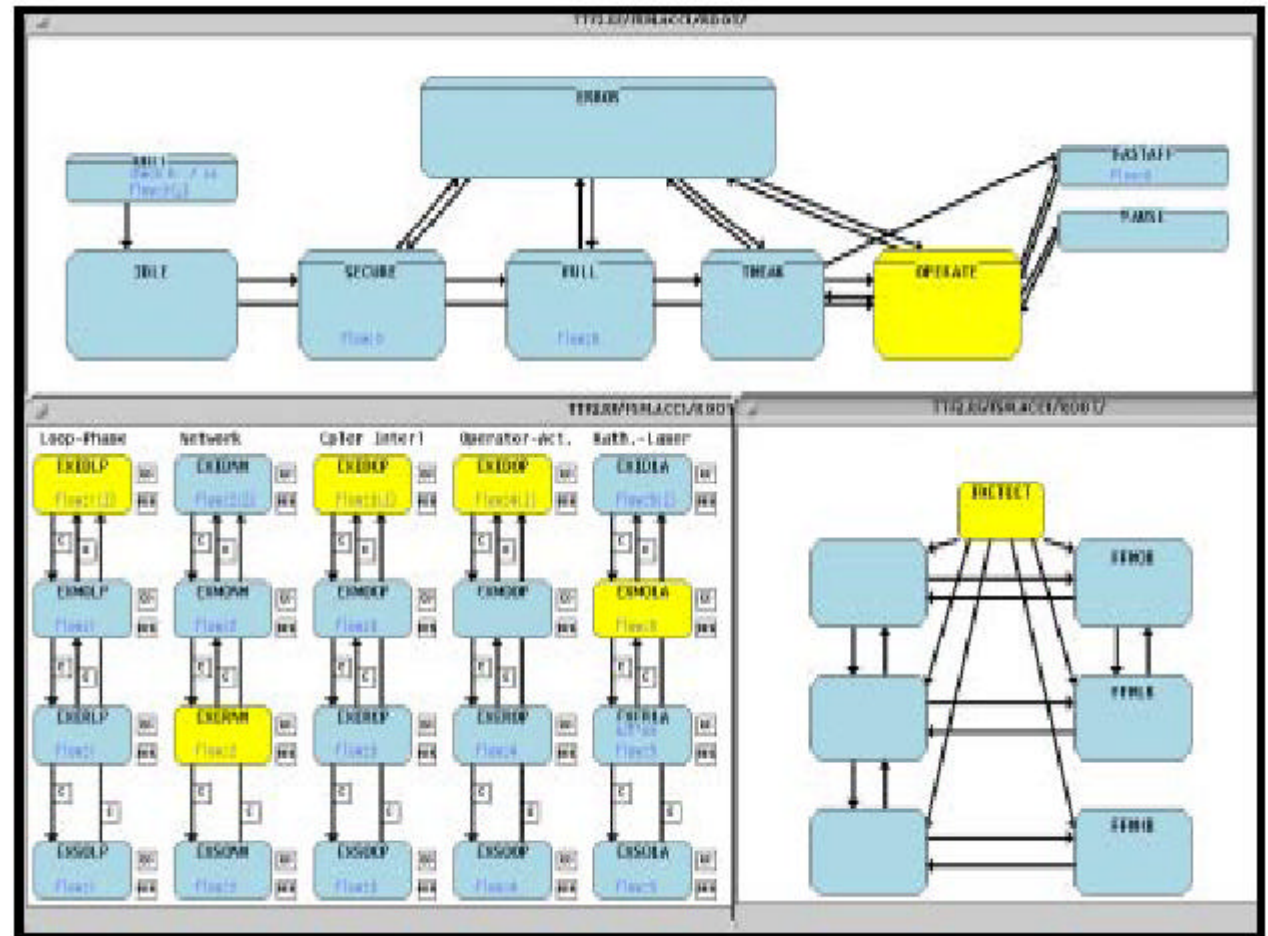
Gamma Dose Rate along the module tank, 0.5m from the module axis evaluated with PorTL (Al_2O_3) TLDs.



Neutron Fluence Rate along the module tank, 0.5m from the module axis evaluated with BDPND Superheated Emulsion (Bubble) dosimeters.

Finite State Machine (1)

- The automation of the LLRF system will be implemented in the framework of a finite state machine (FSM) which is a well established industrial standard.
- The first step will be the definition of the superstates, substates, flows, entry-, during-, and exit-procedures, entry conditions, timer and event triggered procedures etc..



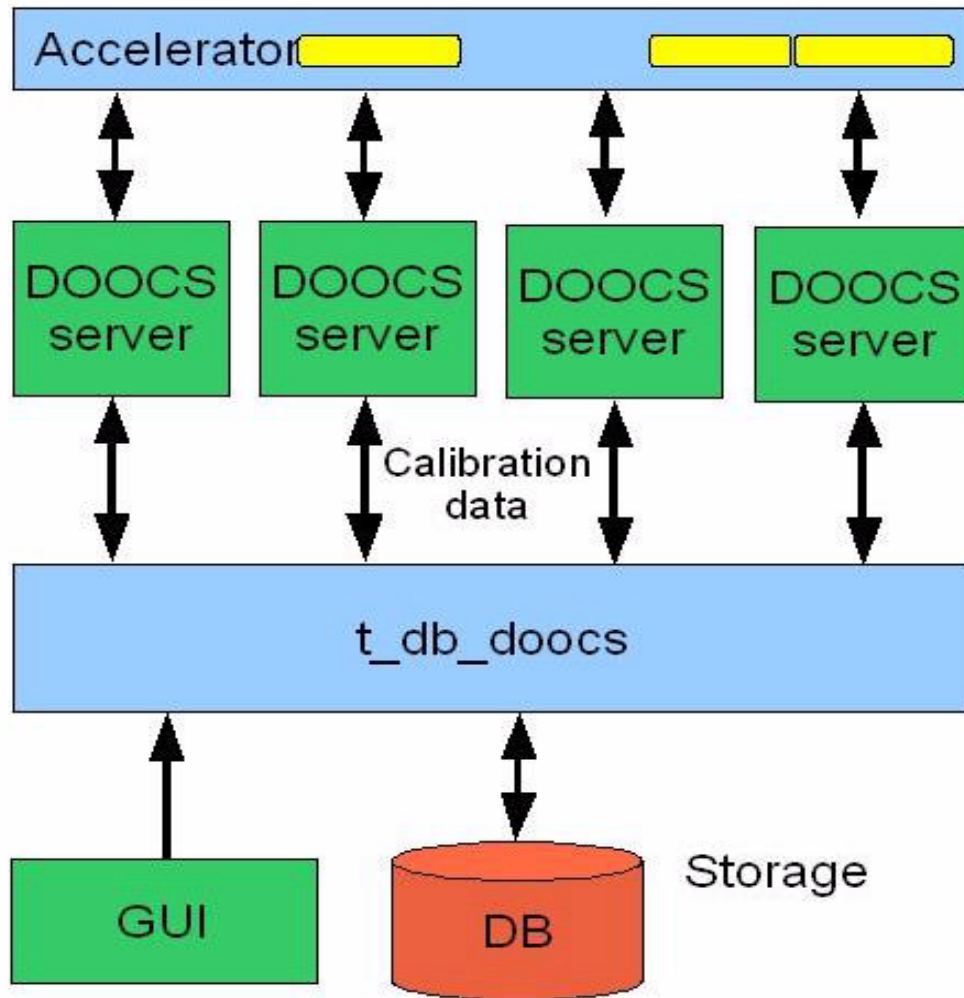
Finite State Machine (2)

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

- The next step is the description of the applications to be used by the FSM.
- Then the above functionality will be implemented as FSM server in DOOCS and the required application programs will be developed.

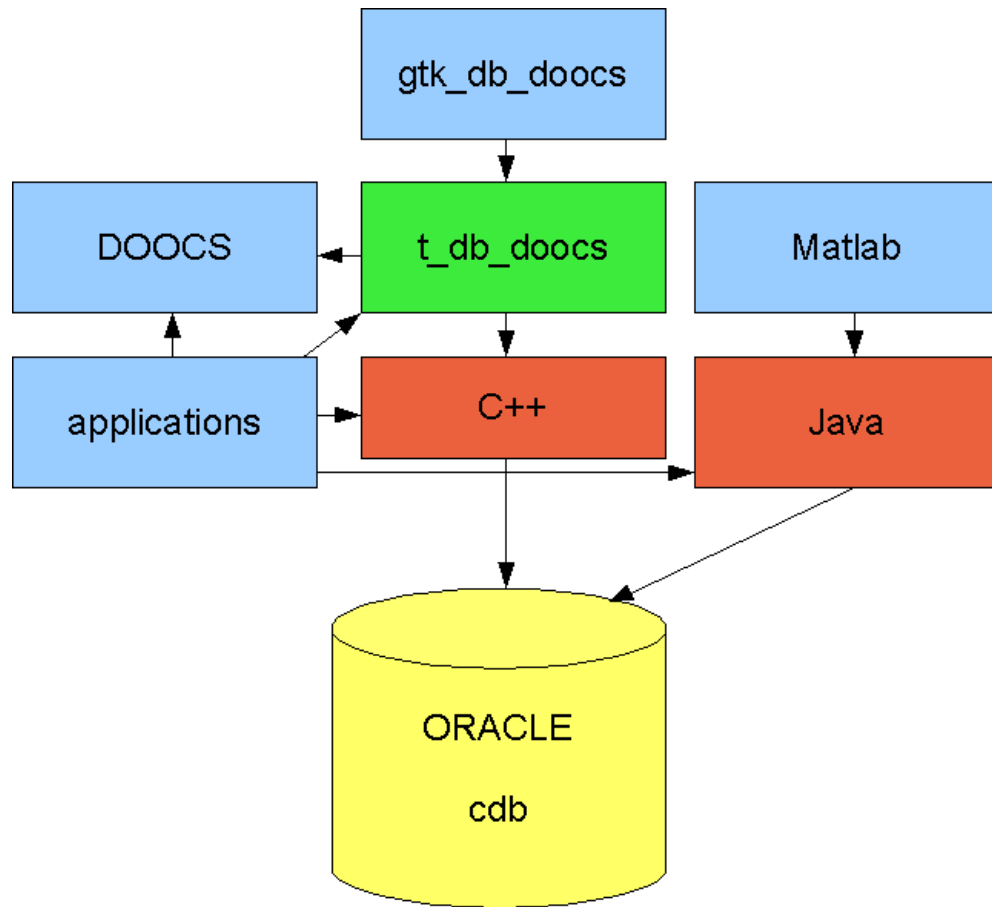


Data Management System (1)



- The operation of an accelerator requires
 - calibration of operating parameters,
 - characterization of subsystem components,
 - and documentation of the configuration
 - userfriendly data entry and access
- The data management system should be :
 - easy to maintain, and support reliable and reproducible operation of the accelerator

Data Management System (2)



Data flow diagram

- Solution:
 - application of commercial database engine
 - database structure adapted to accelerator requirements
 - interface compatible with DOOCS
- Implementation:
 - Oracle database engine
 - Table structure and datatypes
 - C++, Java, Matlab interface
 - Batch and GUI program interface

Development of optimal controller

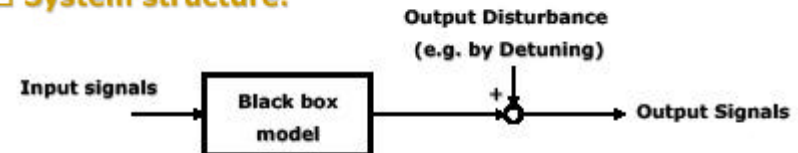
- Modern control theory has developed established methods for the design of optimal controllers.
- The optimal controller should guarantee best performance and robustness in presence
 - of beamloading,
 - Lorentz force detuning
 - and microphonics
 - while operating close to saturation of the klystron and the performance limit of cavities and couplers.

□ System identification:

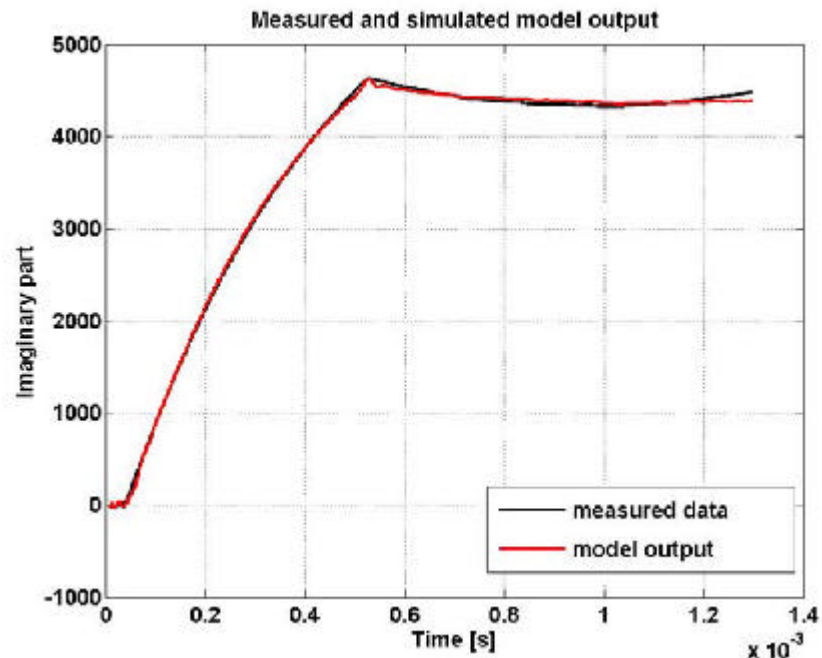
- Experimental based modelling
- Excite system and record input & output data (open-loop)
- Data analysis to infer a model with a chosen structure

□ Black box model: Not physically interpretable

□ System structure:

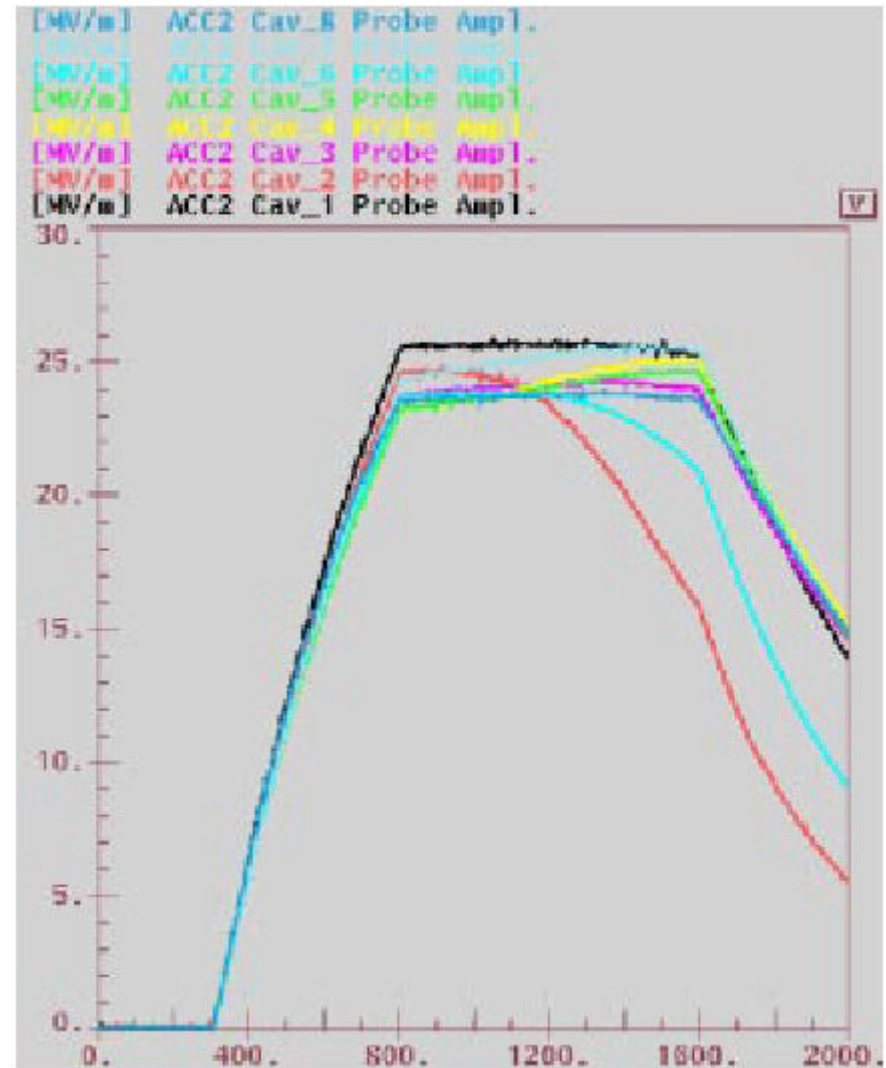


□ Advantage: Model structure can be chosen appropriately for controller design



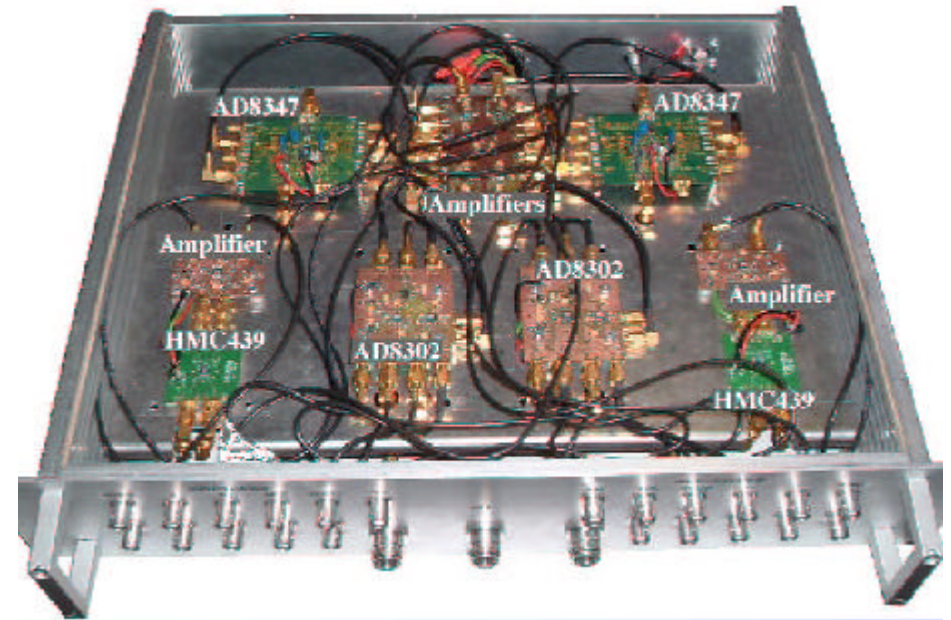
Exception handling

- Operation of superconducting cavities close to the performance limit will increase the trip rate due to the machine protection system.
- Typical trips include couplers sparks, cavity quench, klystron sparks or other faults caused by operation with high power.
- Prototype system evaluated successfully at the VUV-FEL with long pulse operation



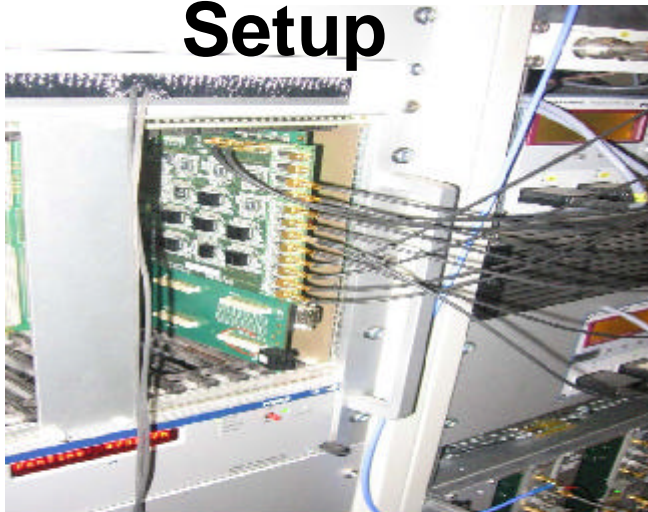
Robust RF Gun RF Control

- The normalconducting RF gun requires special control considerations such as
 - low latency in the feedback loop
 - control for temperature of the of the rf gun resonator
 - and interlock scheme.
- Due to the lack of a field probe, the cavity field must be determined by a precision measurement of incident and reflected wave.
- Detuning measured during field decay



Performance of LLRF Verified at VUV-FEL with Beam

Setup



Verification with beam

