LLRF Plans for XFEL for 2006

S. Simrock, DESY

Major Projects for 2006

- Define WBS and Assemble Teams
- Write LLRF Requirements Document
- Develop conceptual Design
- Develop many LLRF Control Algorithms (FPGA,DSP, CPU)
- Evaluate SIMCON 3.1 at VUV-FEL
- Automation of LLRF Control

Milestones 2006

Operation of ACC1 with SIMCON 3.1	July 06
Operation of RF Gun with SIMCON 3.1	July 06
SIMCON 3.1 Operational at PITZ RF Gun	Mar 06
SIMCON 3.1 at FNAL	Mar 06
XFEL LLRF Requirement Document	Nov 06
Concept for Packaging (Standardisation for Crates etc.)	July 06
On-line gamma/neutron dosimetry in VUV-FEL (5x)	Mar 06
Operation of klystron 4+5 with FSM	Mar 06
On-line diagnostics LLRF at VUV-FEL	Mar 06
Transient meas. ACC1 in operation	July 06
Prototype of new downconverter with new IF scheme	Mar 06
Prototype of 8-channel downconverter with ADC , FPGA	July 06
Fiber optic reference system in operation	April 06

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 ...

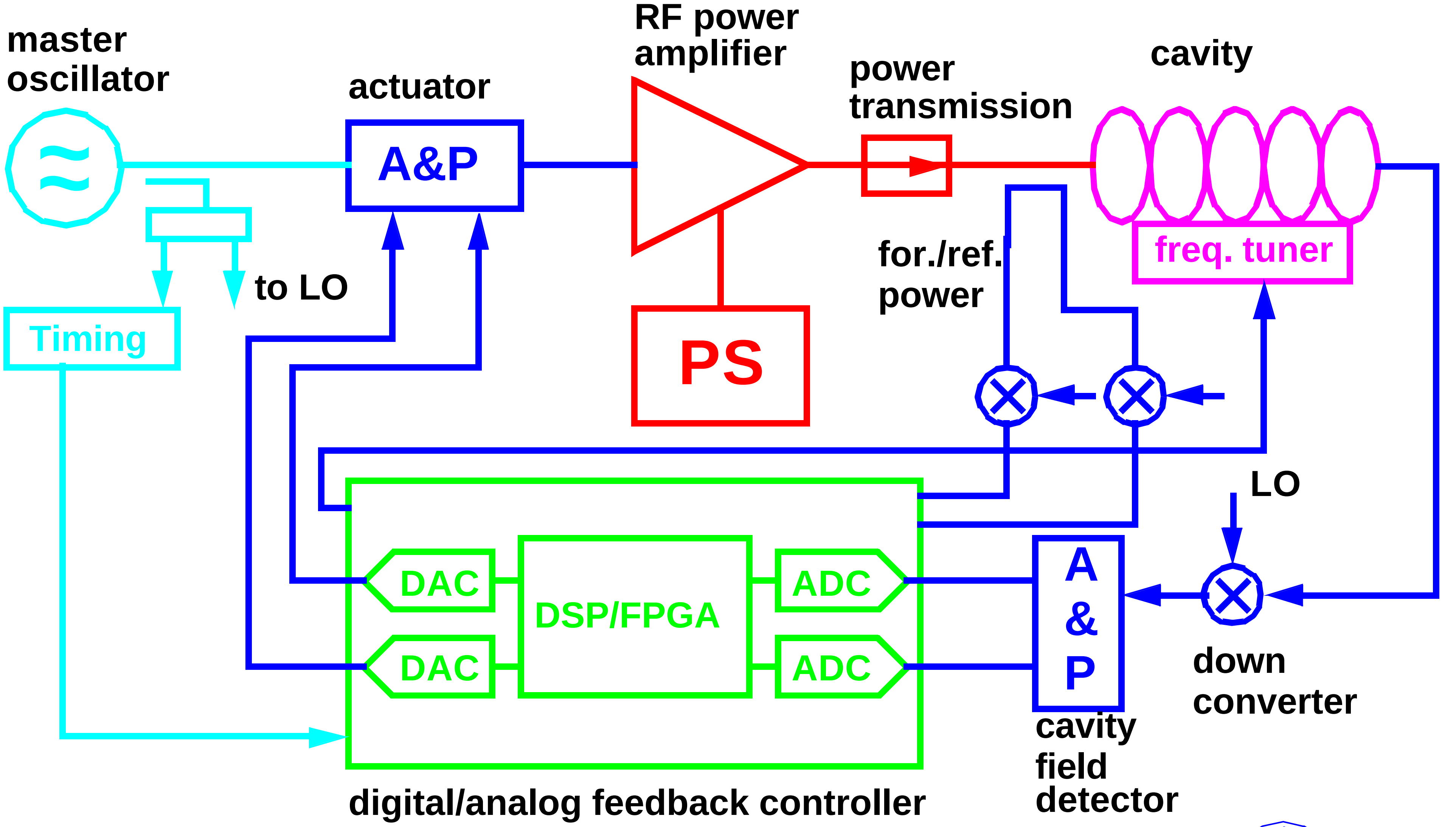
Highlights

- 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 ...)

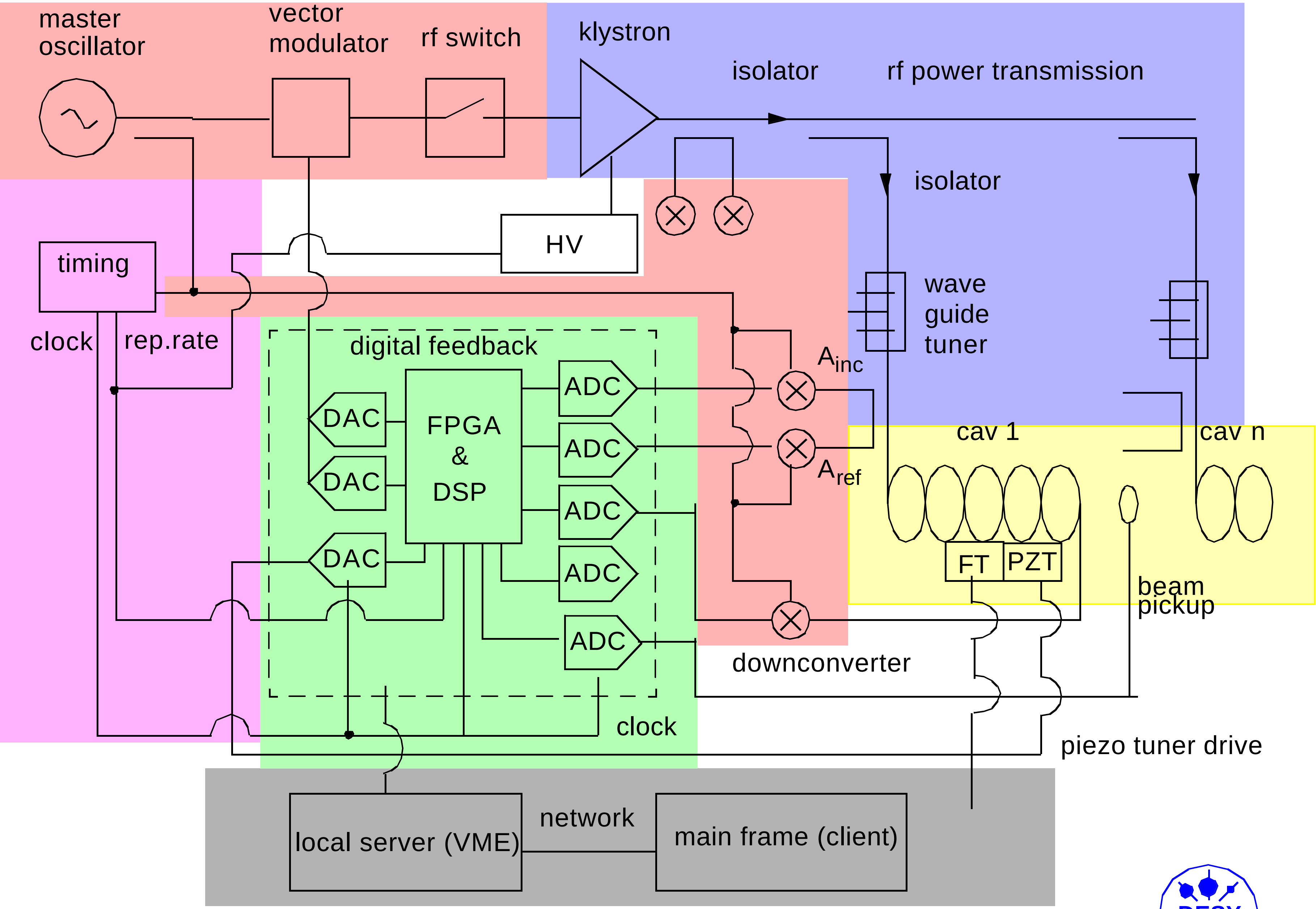
- Cost and Reliability (DESY ...)
- Radiation Effects on Electronics (ALL)

RF System Architecture (1)

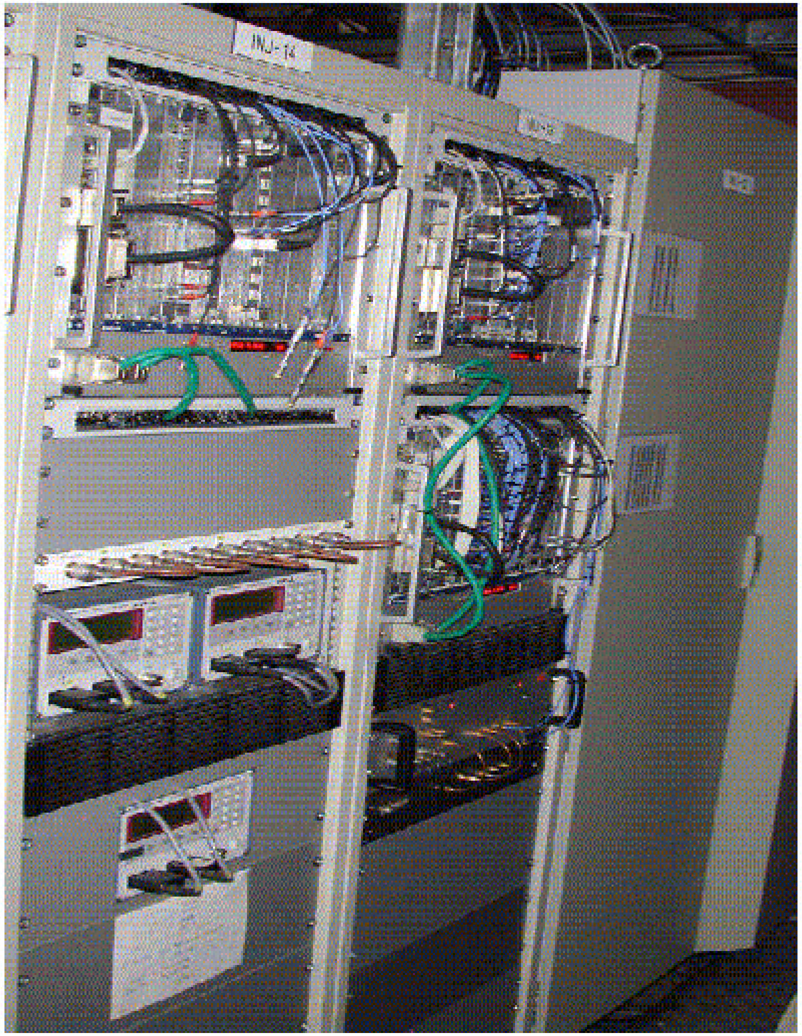


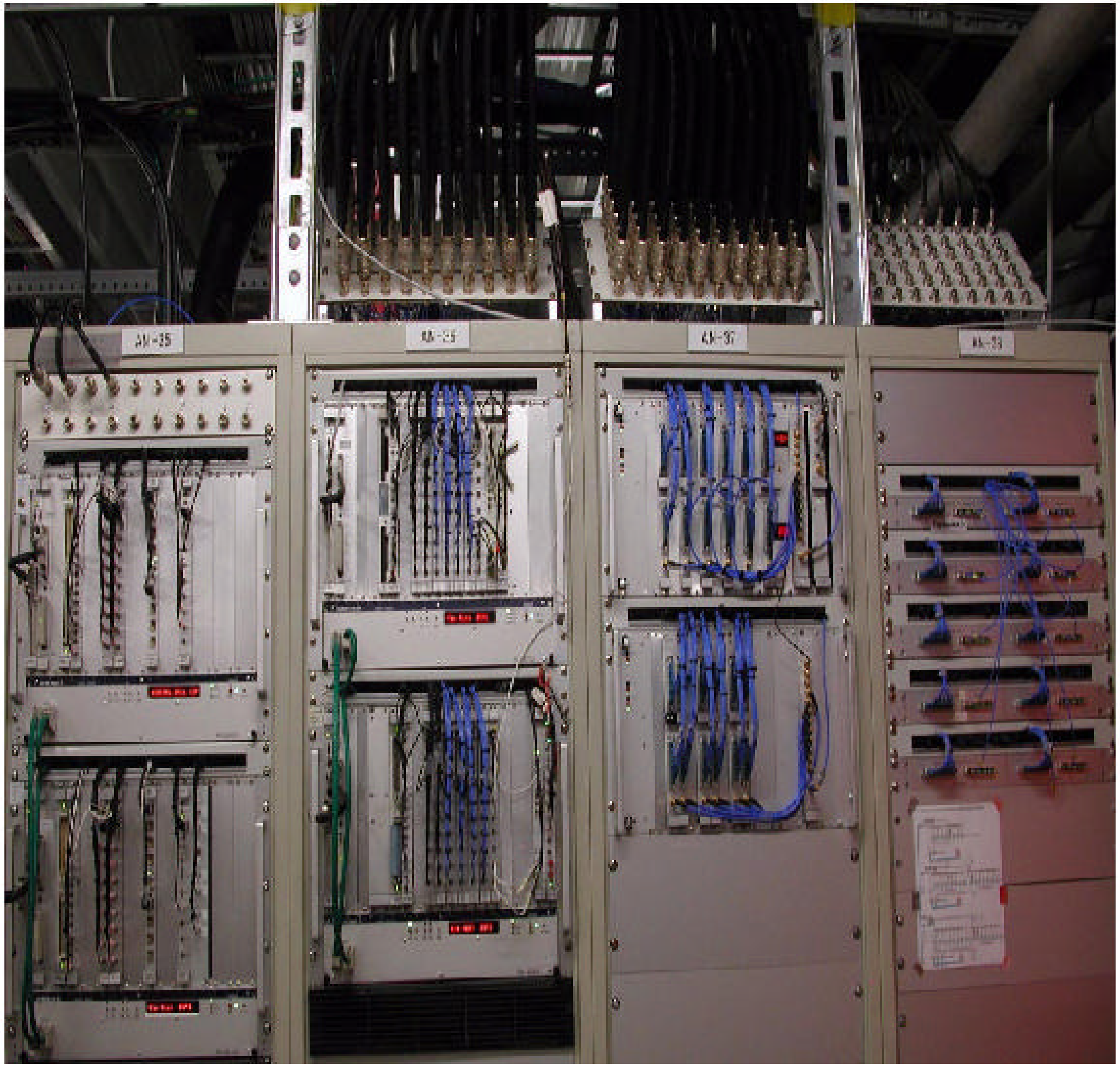
digital/analog feedback controller

RF System Architecture (2)



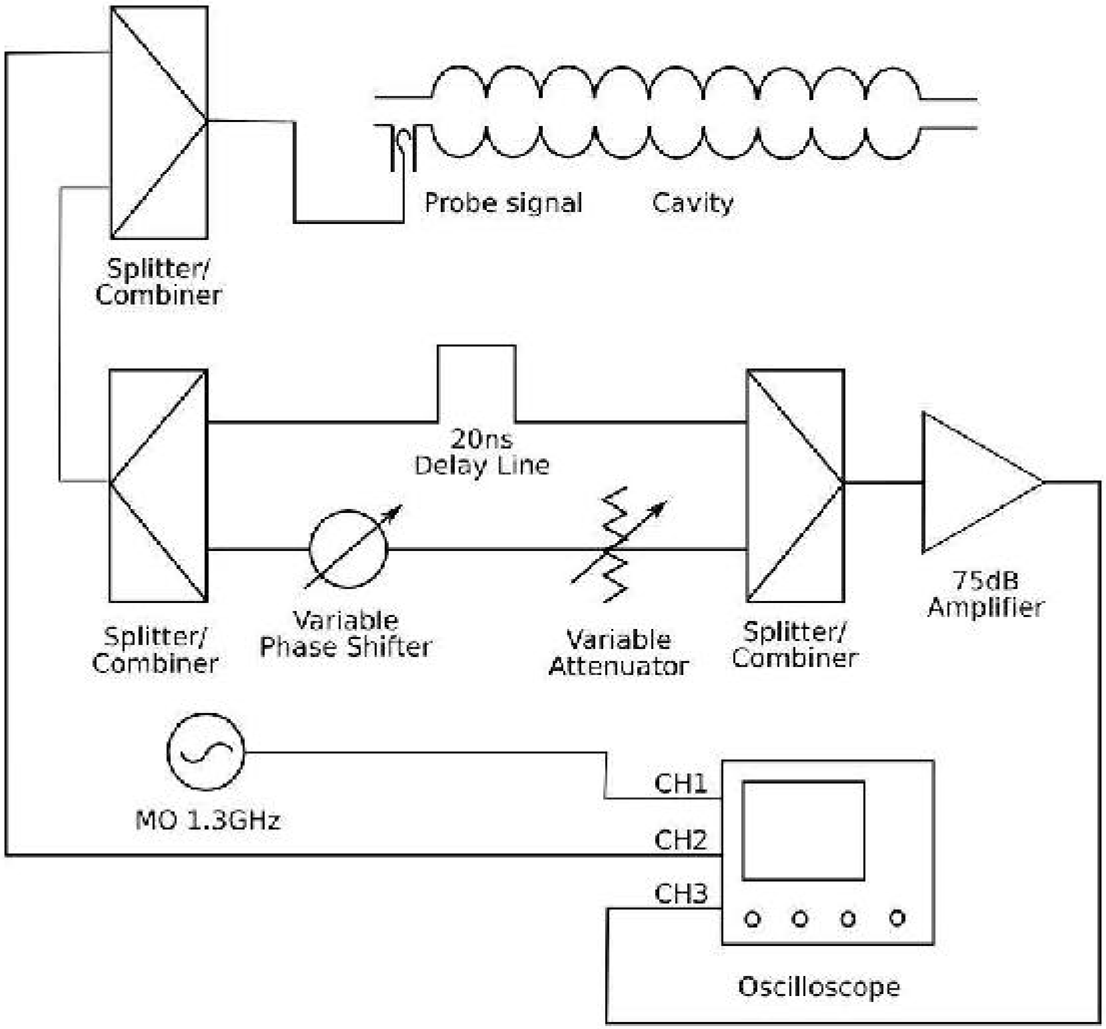
LLRF at the VUV-FEL





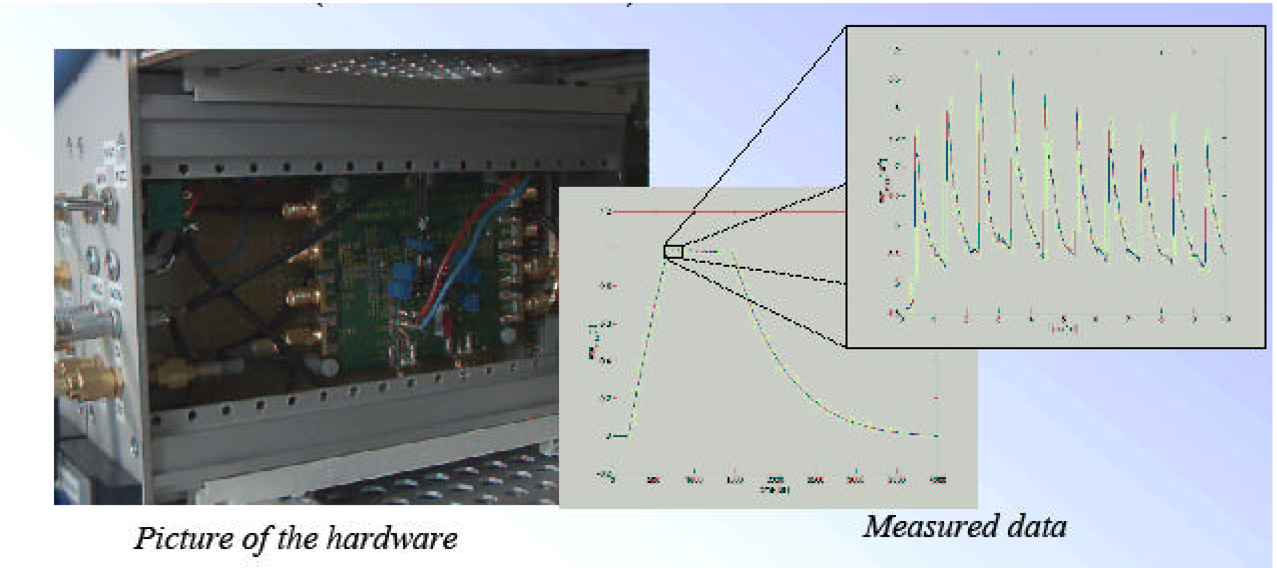
Single Bunch Transient Detection (1)

- 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

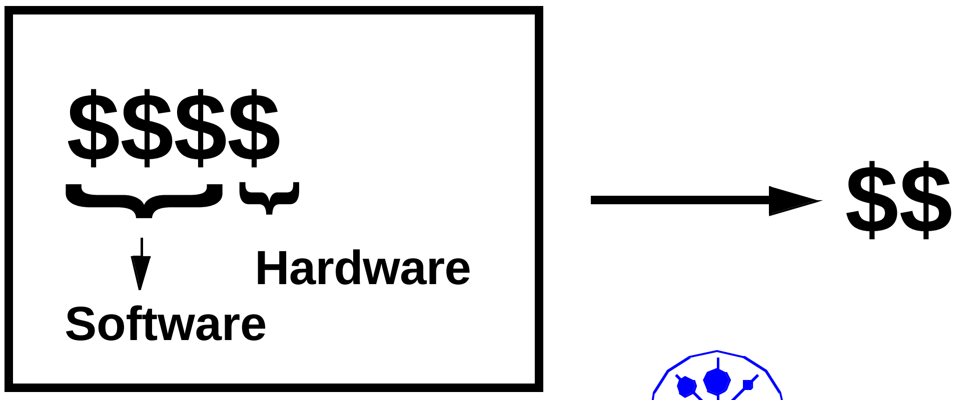
Performance ↑

Reliability ↑

Operability ↑

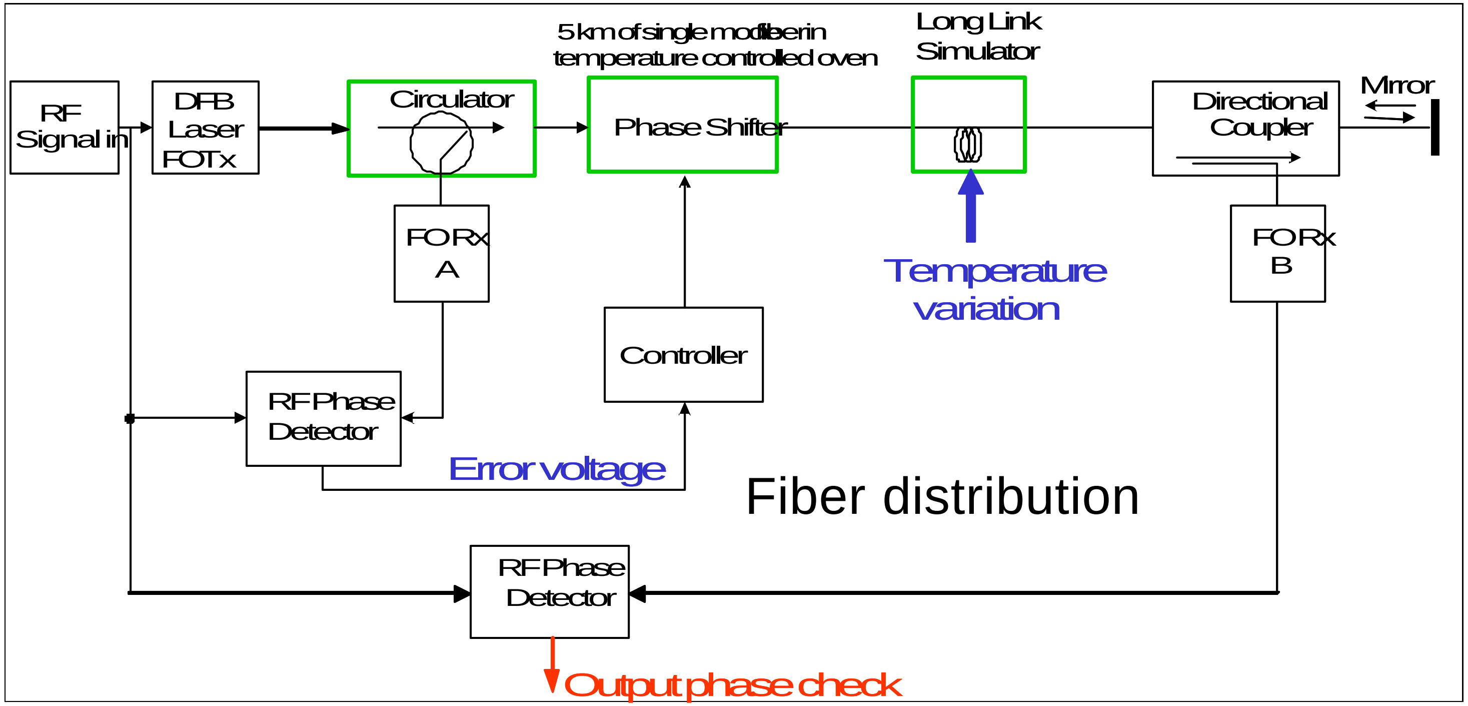
Maintainability ↑

AND



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.



RF Signal in

DFB Laser FOTx

Circulator

5 km of single mode fiber in temperature controlled oven

Phase Shifter

Long Link Simulator

Directional Coupler

Mirror

FORx A

FORx B

Temperature variation

Controller

RF Phase Detector

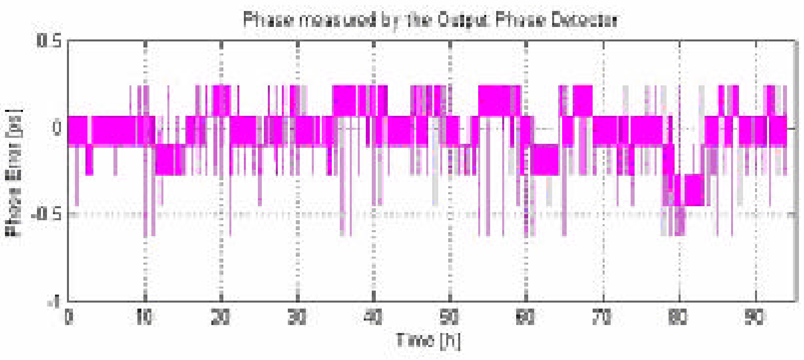
Error voltage

Fiber distribution

RF Phase Detector

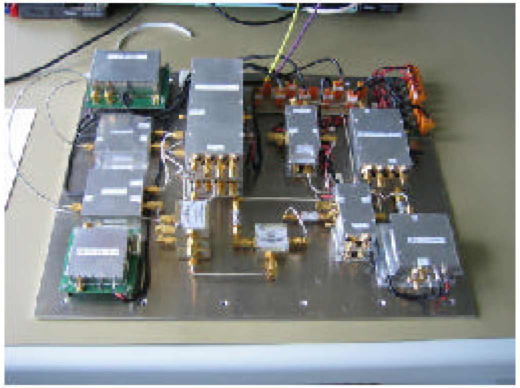
Output phase check

Highly stable frequency distribution (2)

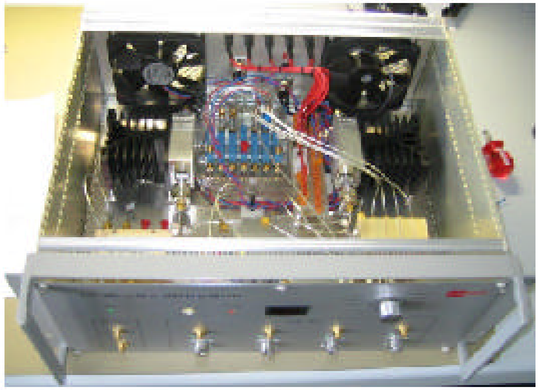


- Climate chamber for evaluation of temperature sensitivity of subsystems
- Short and long term error suppression

LOW POWER PART

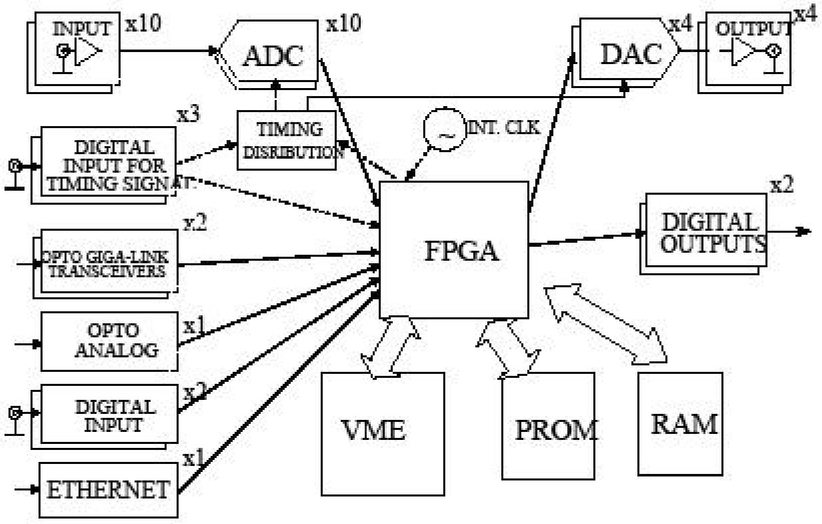


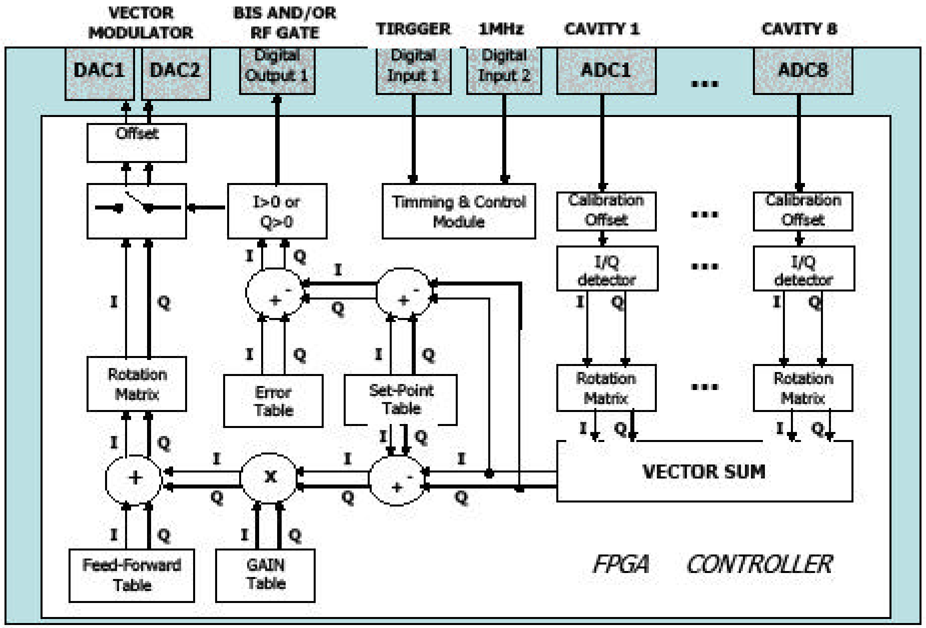
81 MHz POWER PART



- Master Oszillator with output for many frequencies

3rd Generation FPGA based RF Control (1)



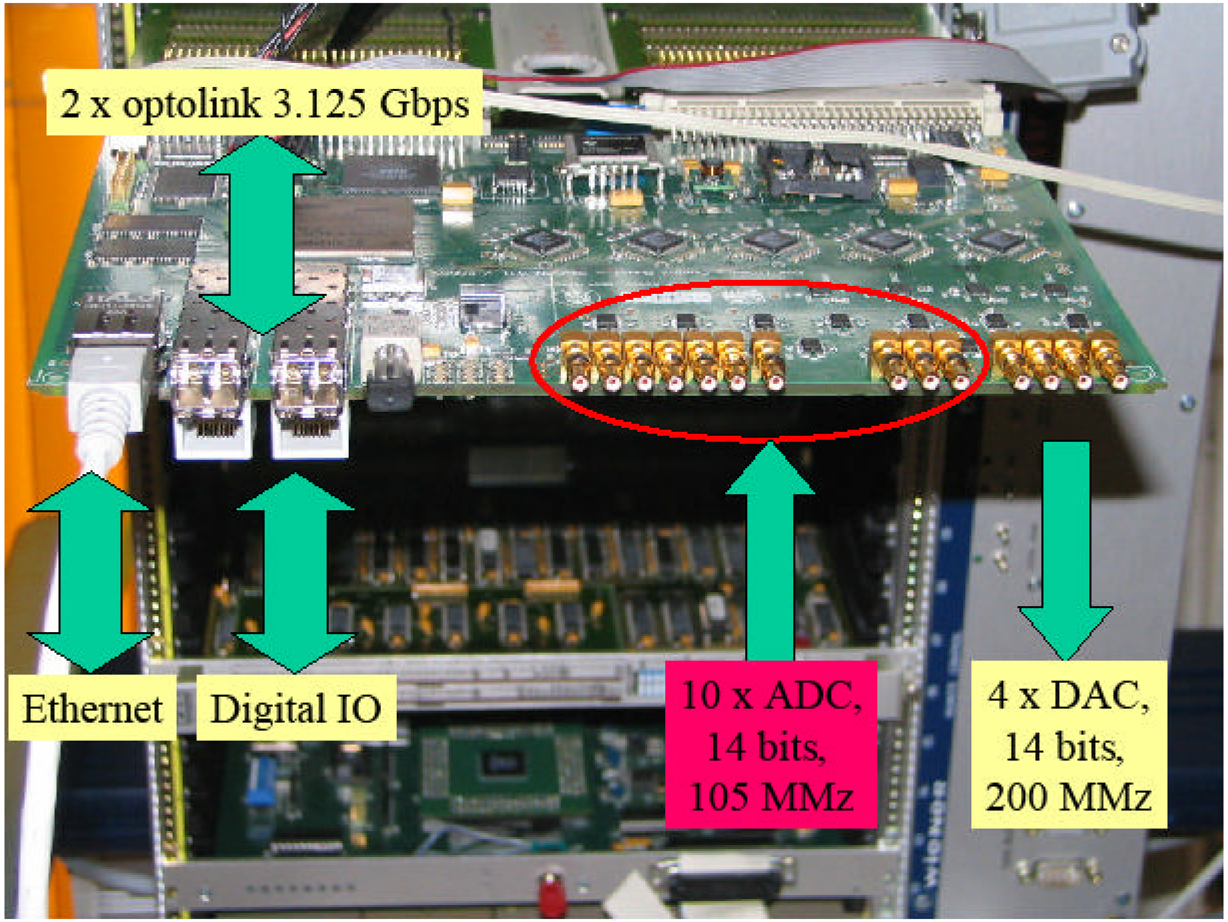


- Digital rf feedback systems for superconductind real time data processing
  - from a large number (up to 128) of ADC input channels and a smaller number (up to 64) DAC output channels.
- The latency from ADC clock to DAC output including all necessary data processing
  - should not exceed a few hundred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

3rd Generation FPGA based RF Control (2)

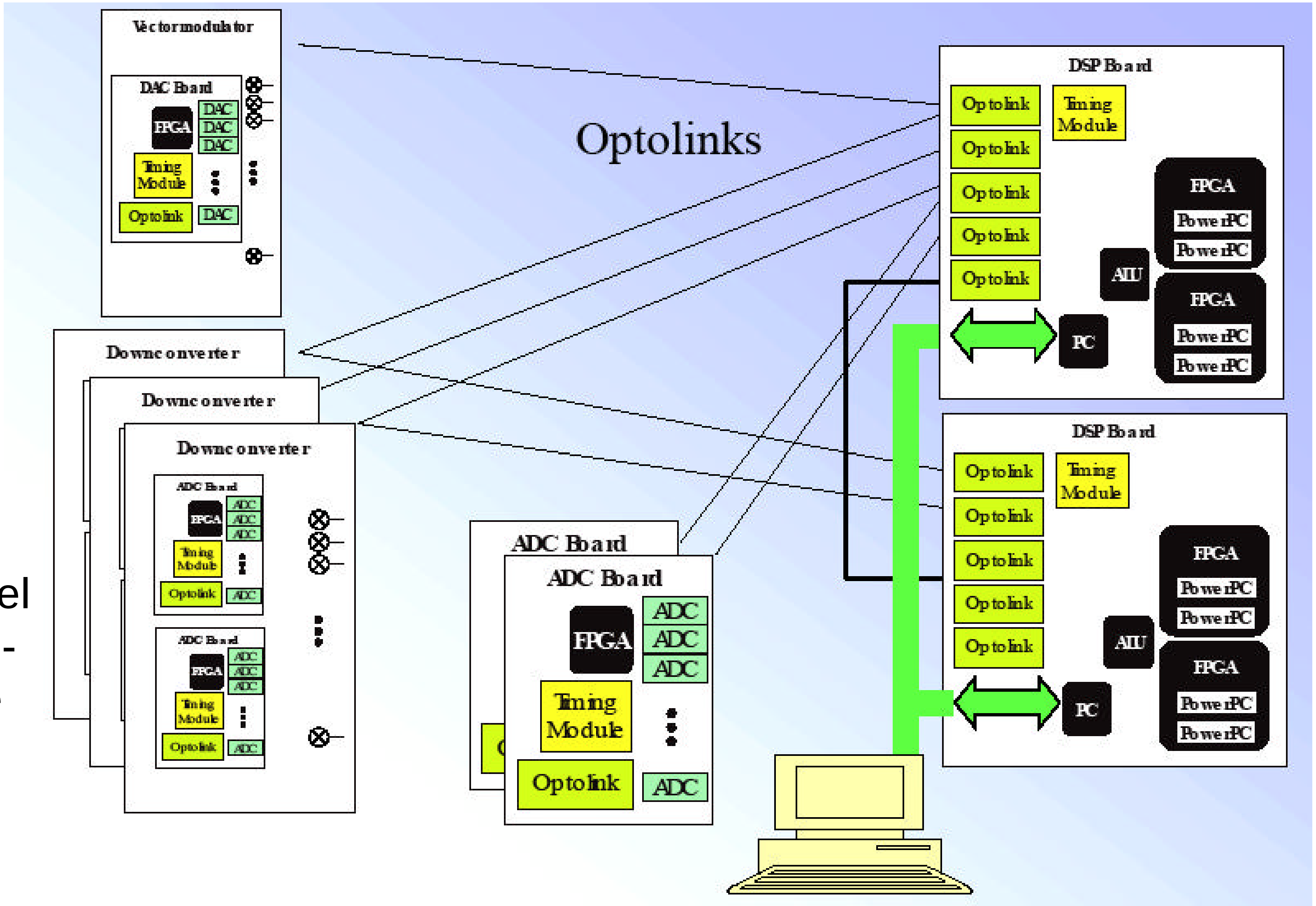
- FPGAs are well suited for this type of hardware due to their the large number of I/O pins, large number of logic cells, and large number of multiplier cores which allow parallel processing of data.

- Goal is to explore the feasibility of realization of digital feedback and feedforward algorithms, complex application algorithms, exception handling and built-in diagnostics



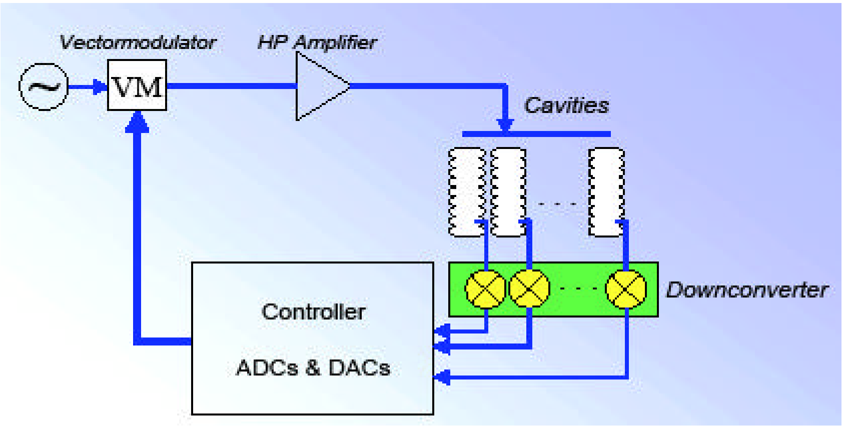
3rd Generation FPGA based RF Control (3)

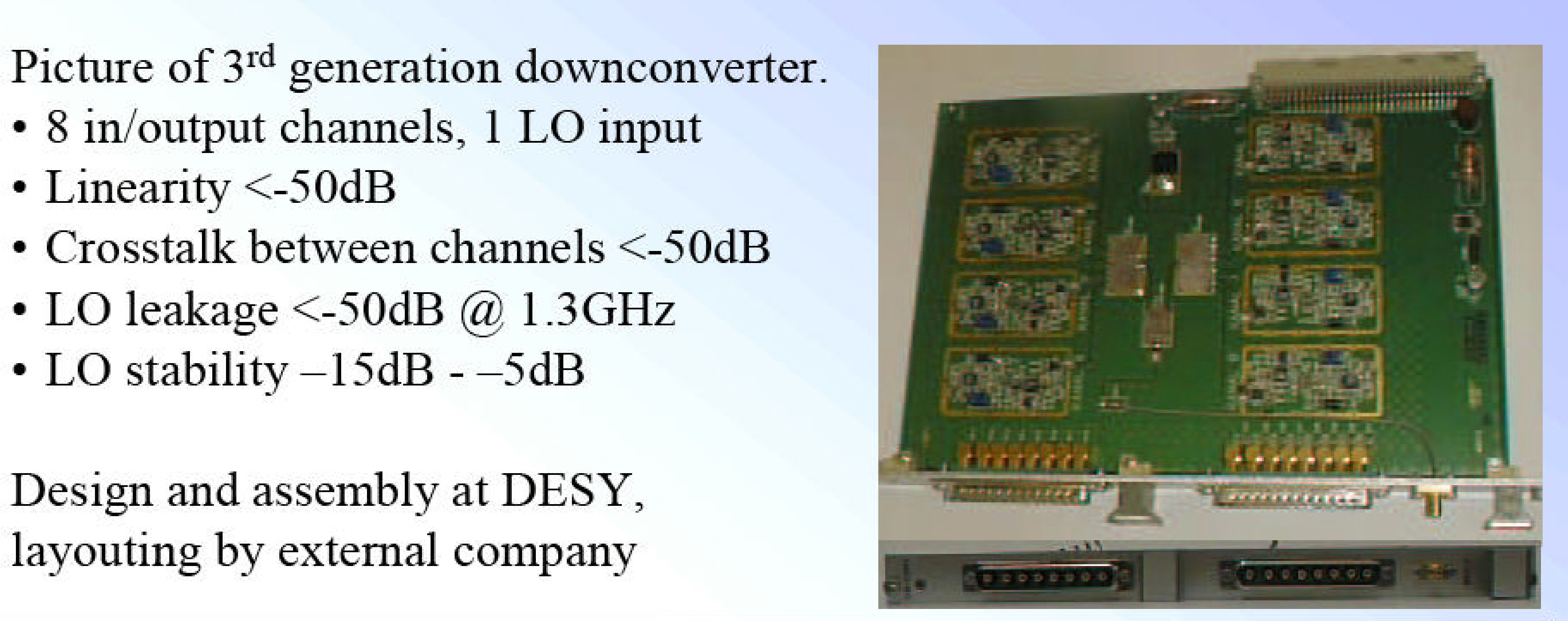
- In future more distribution of subsystems connected by optical Gigalinks
- Example: Downconverters with analog I/O and preprocessing
- Issues for single tunnel operation are maintenance and moderate radiation levels



Multichannel downconverter (1)

- Develop low cost and compact high-performance multichannel downconverter





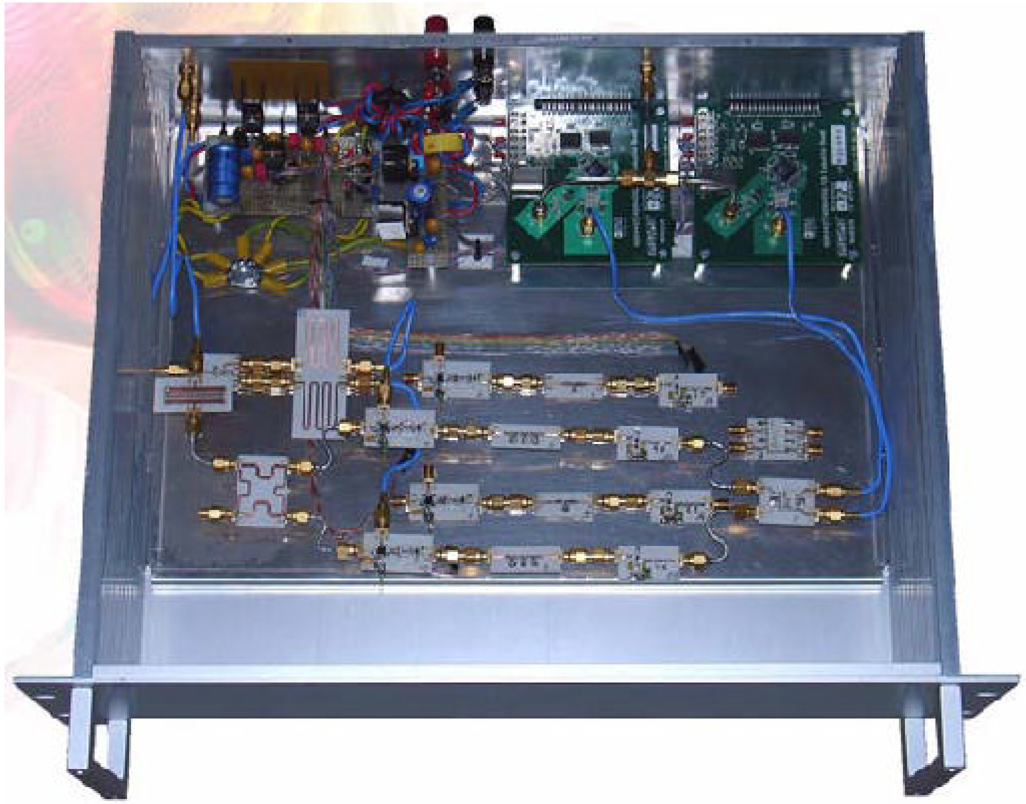
Picture of 3rd generation downconverter.

- 8 in/output channels, 1 LO input
- Linearity <-50dB
- Crosstalk between channels <-50dB
- LO leakage <-50dB @ 1.3GHz
- LO stability –15dB - –5dB

Design and assembly at DESY, layouting by external company

Multichannel downconverter (2)

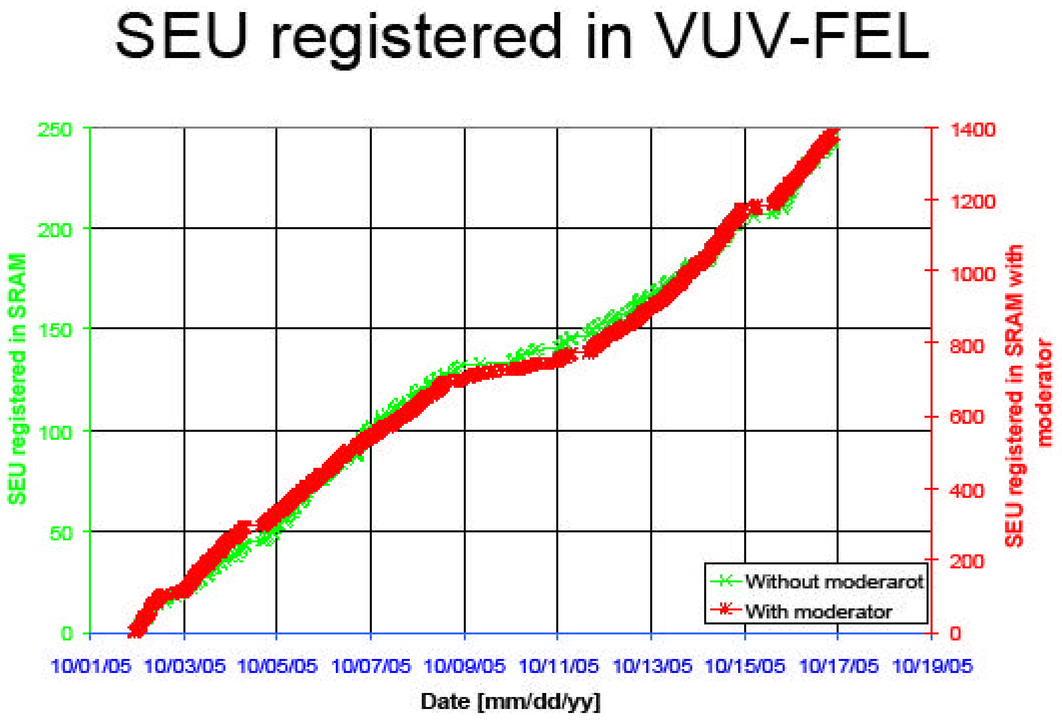
- Should include
  - - remote controlled attenuators at rf inputs
  - - RF outputs for transient detection
  - - input for rf calibration signals



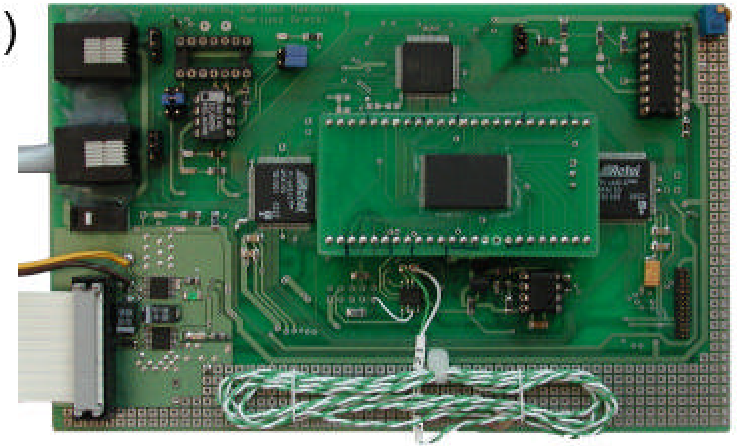
- Optional:
  - - ADCs and FPGA for preprocessing on board and optical Gigalink to connect to main processor for control

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

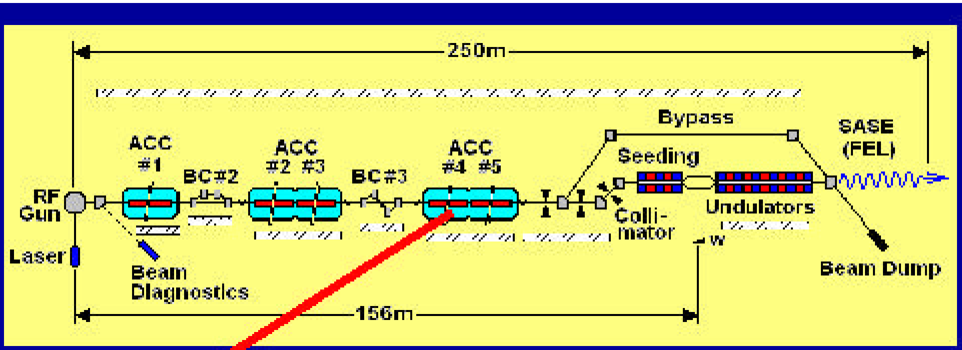
a)

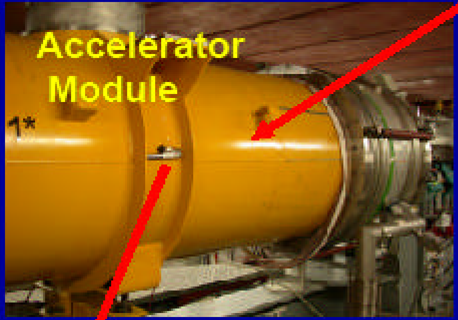


b)

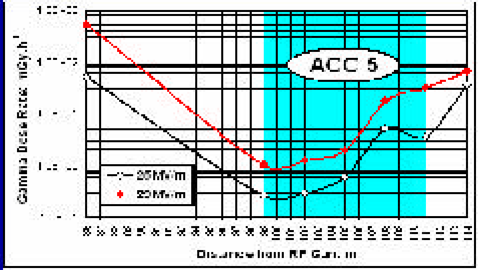
Study rad. effect on electronics (2)

- 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.

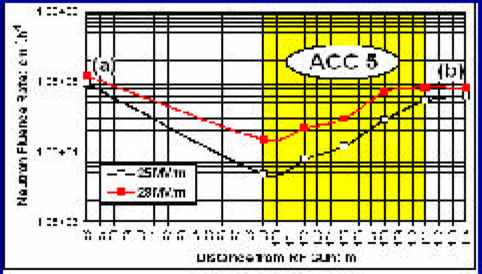




Neutron/Gamma Dosimeter pairs



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

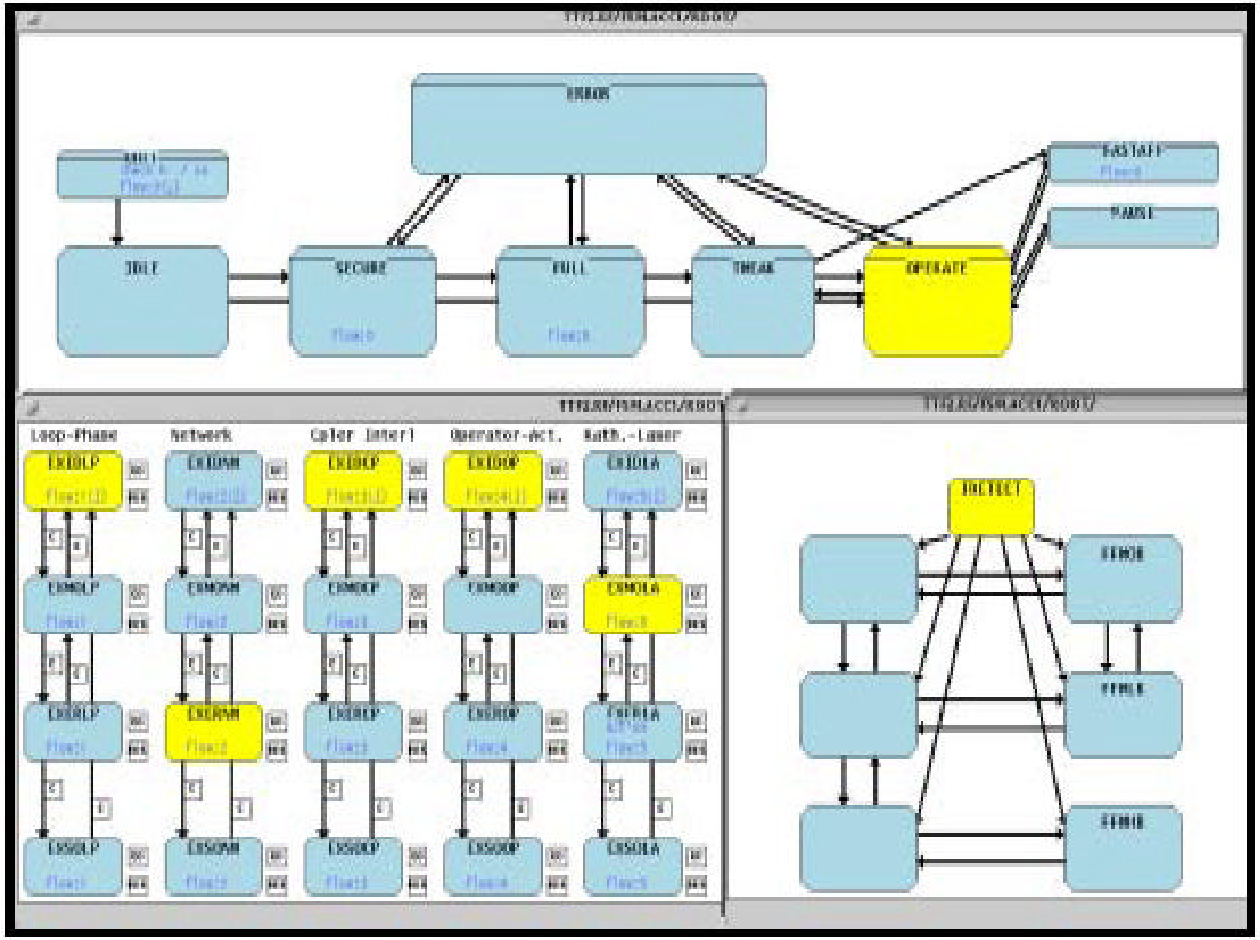


Neutron Fluence Rate along the module tank, 0.5m from the module axis evaluated with BDPND Superheated Emulsion (Bubble) dosimeters.

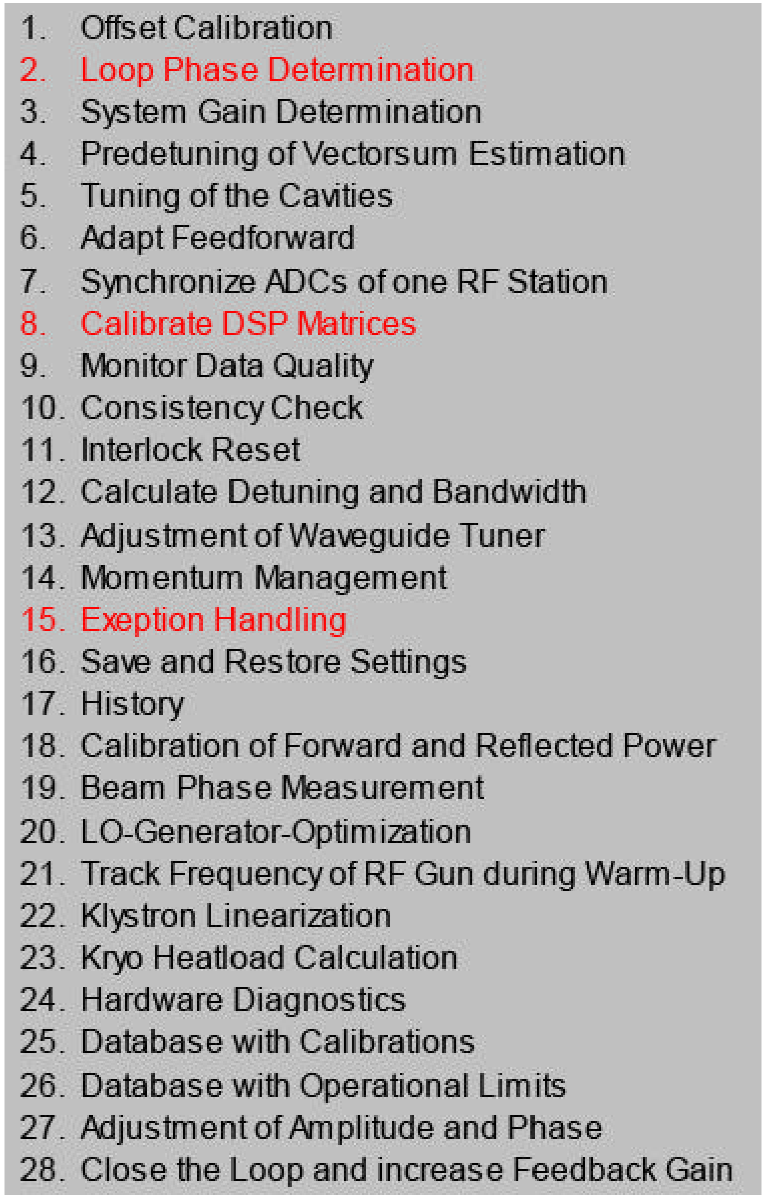
Finite State Machine (1)

- 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)

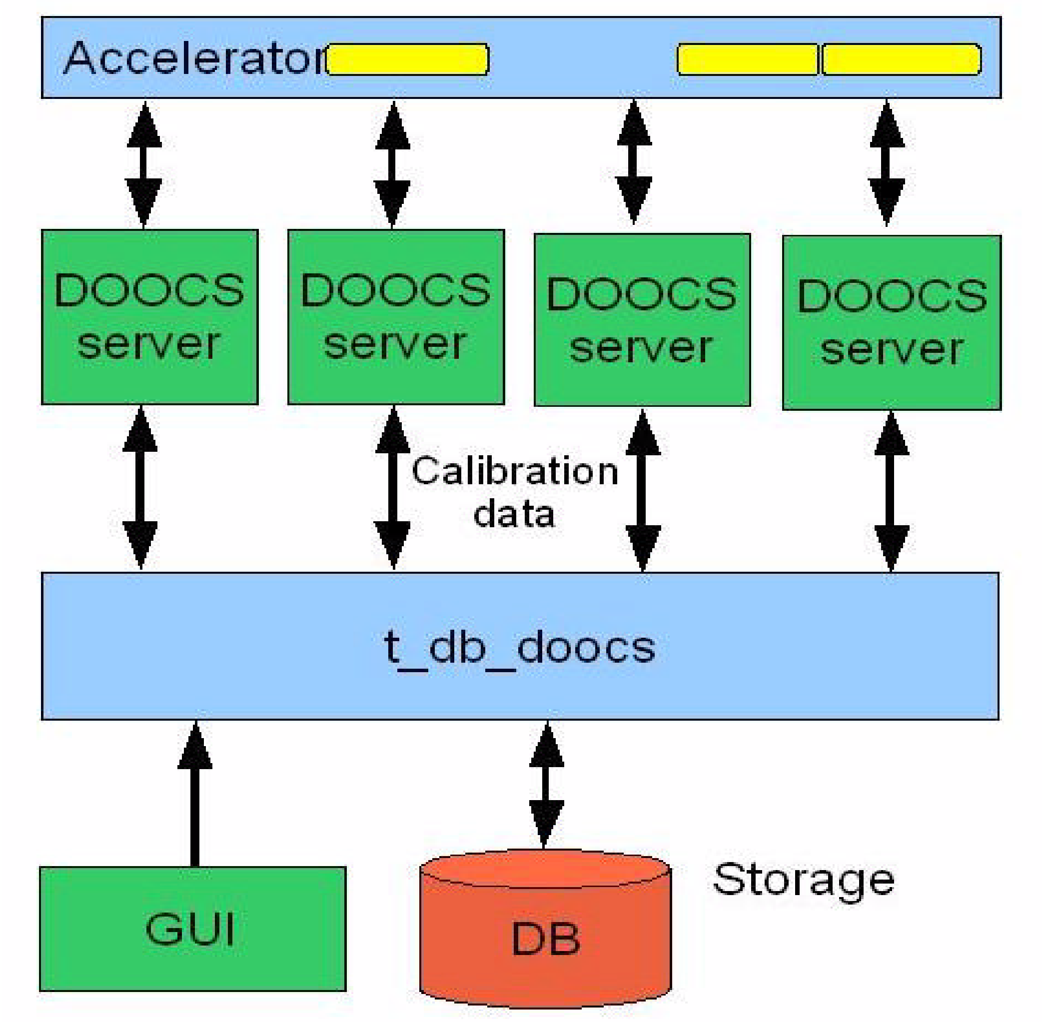


1. Offset Calibration
2. Loop Phase Determination
3. System Gain Determination
4. Predetuning of Vectorsum Estimation
5. Tuning of the Cavities
6. Adapt Feedforward
7. Synchronize ADCs of one RF Station
8. Calibrate DSP Matrices
9. Monitor Data Quality
10. Consistency Check
11. Interlock Reset
12. Calculate 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.

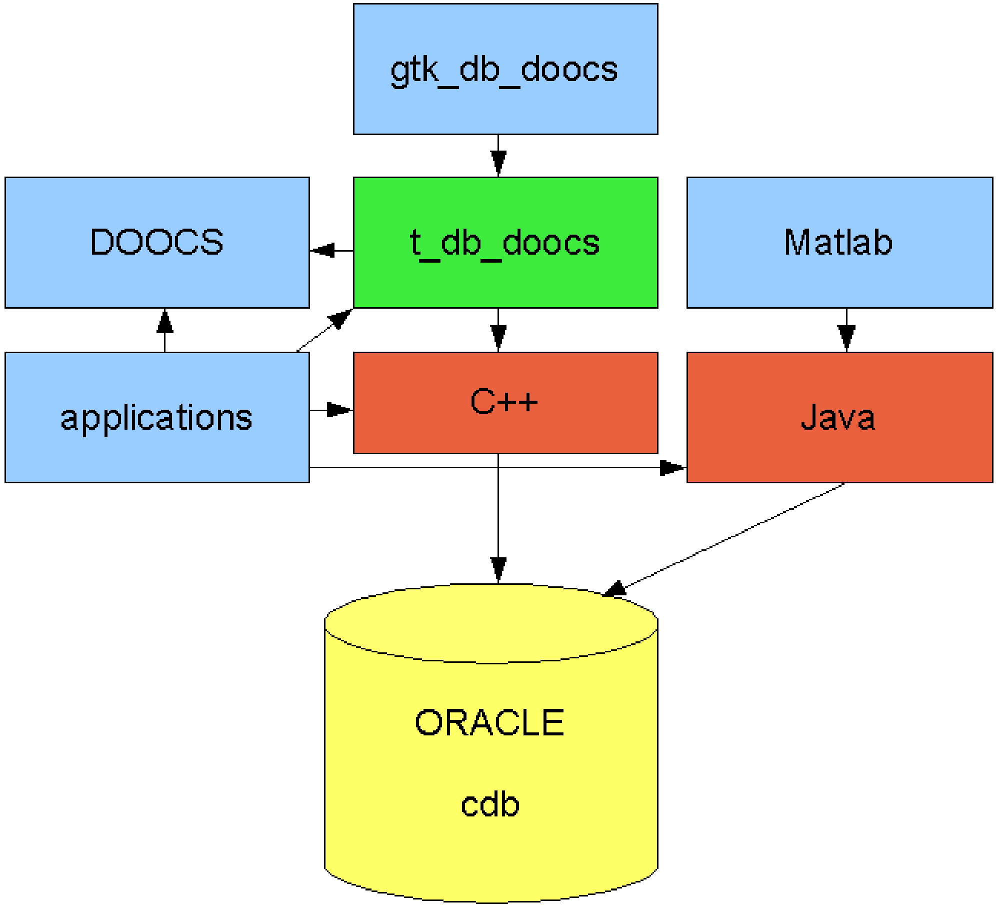
- Then the above functionality will be implemented as FSM server in DOOCS and the required application programs will be developed.

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)



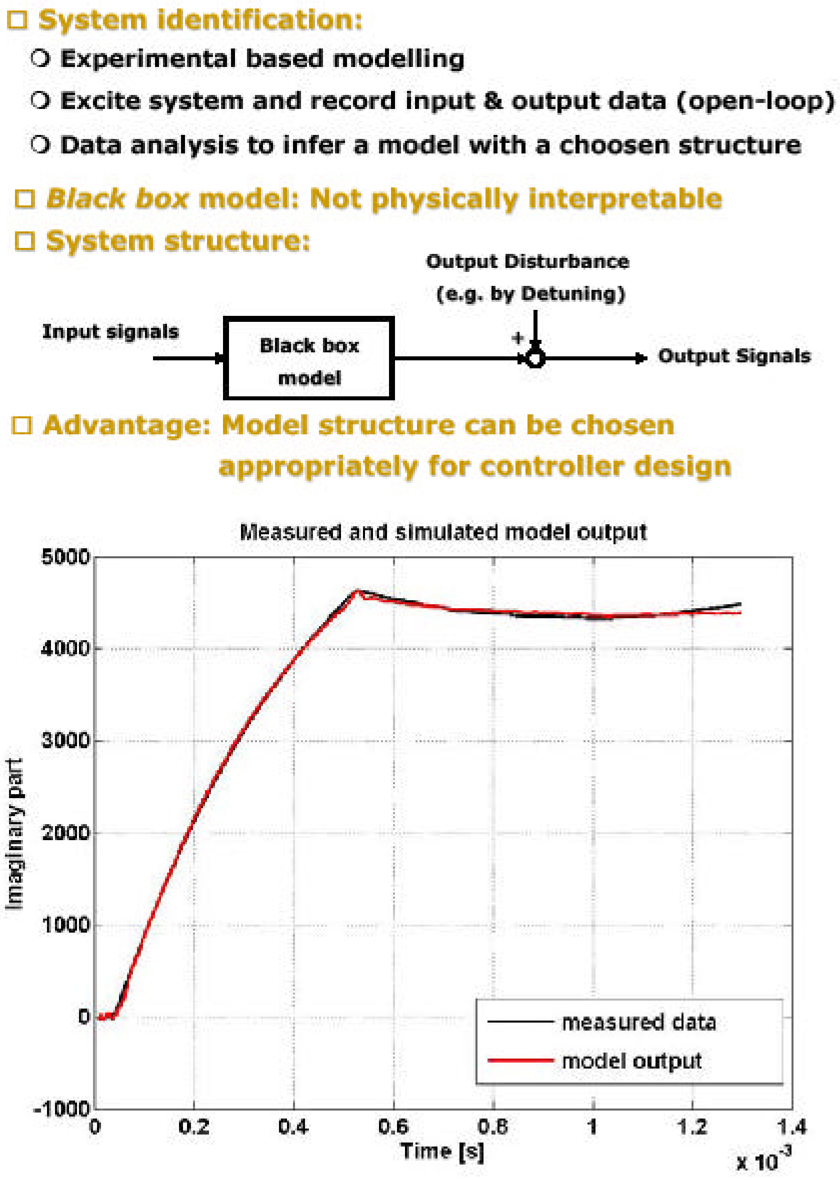
Data flow diagram

- Solution:
  - application of commercial database engine
  - database structure adapted to accelerator requirements
  - interface compatible with DOOCS
- Implemention:
  - 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 choosen structure

☐ ***Black box* model: Not physically interpretable**

☐ **System structure:**

☐ **Advantage: Model structure can be chosen appropriately for controller design**

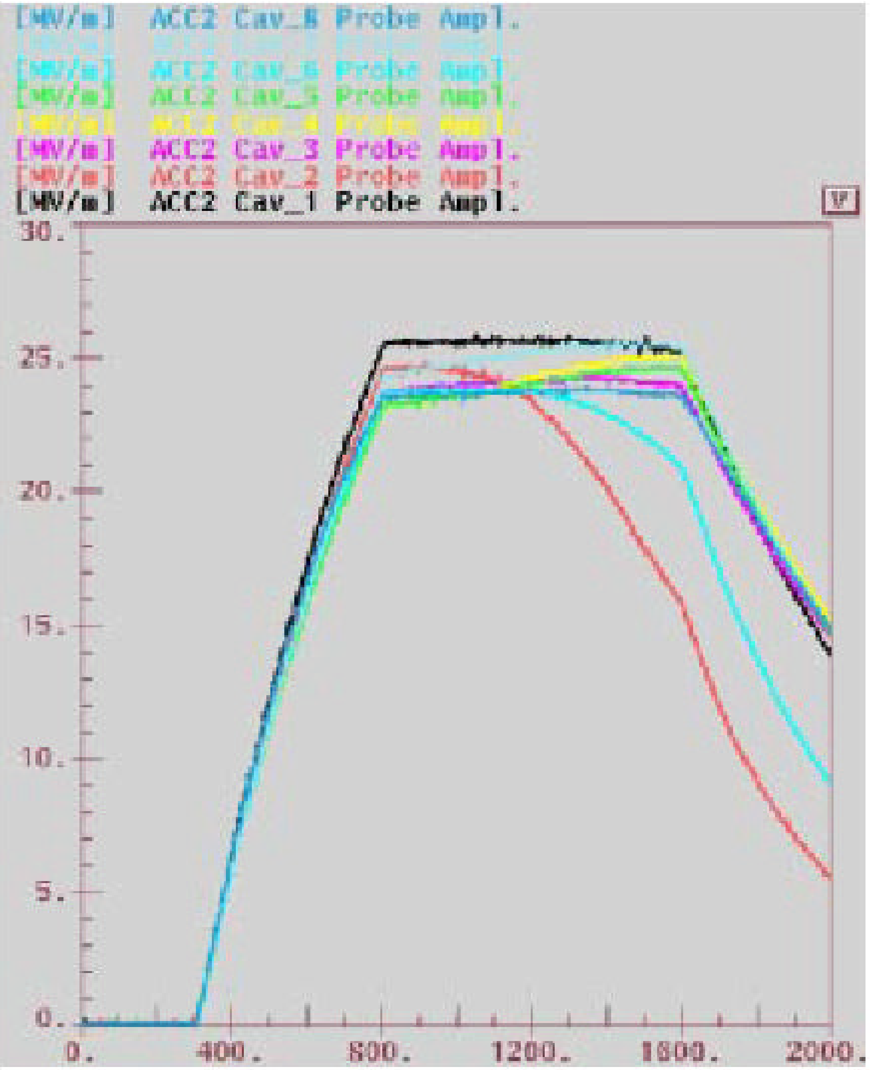
Measured and simulated model output

Exception handling

- Operation of superconducting cavities close to the performance limit will increase the trip rate due to the machine protection system.

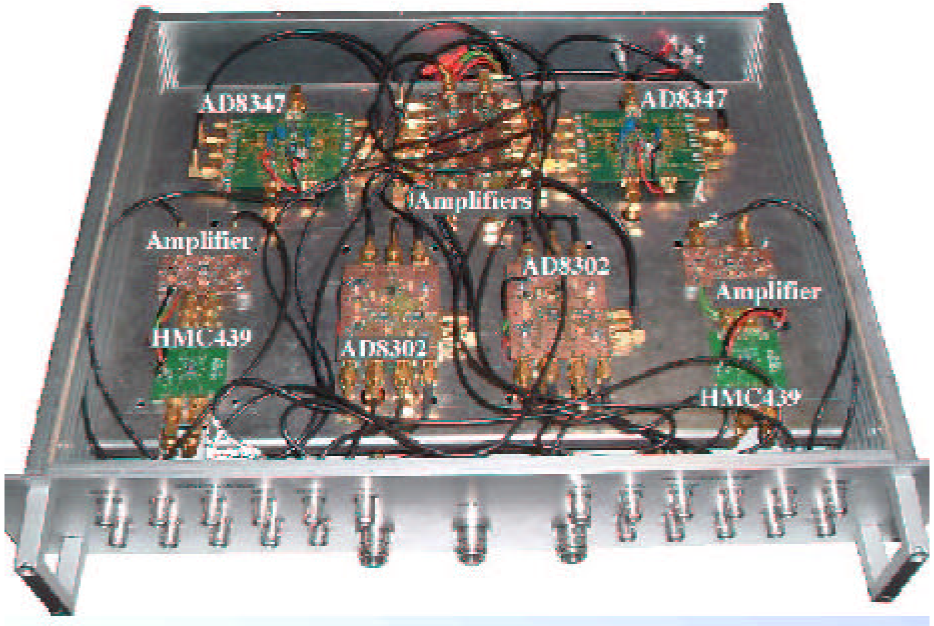
- Typical trips include couplers sparcs, cavity quench, klystron sparcs or other faults caused by operation with high power.

- Prototype system evaluated successfully at the VUV-FEL with long pulse operation



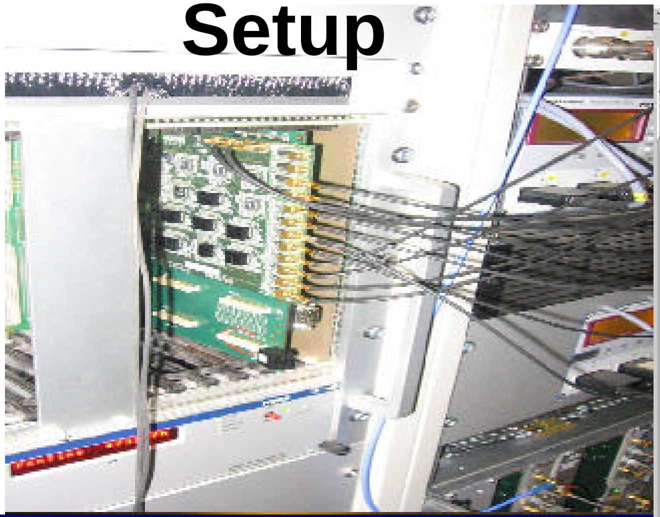
Robust RF Gun RF Control

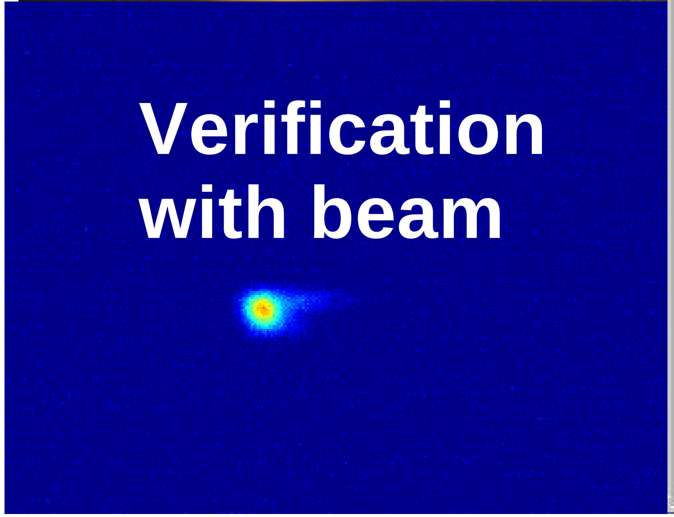
- The normalconducting RF gun requires special control considerations such as
  - low latency in the feedback loop
  - control for temperature of the of the rf gun resonator
  - and interlock scheme.
- Due to the lack of a field probe, the cavity field must be determined by a precision measurement of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



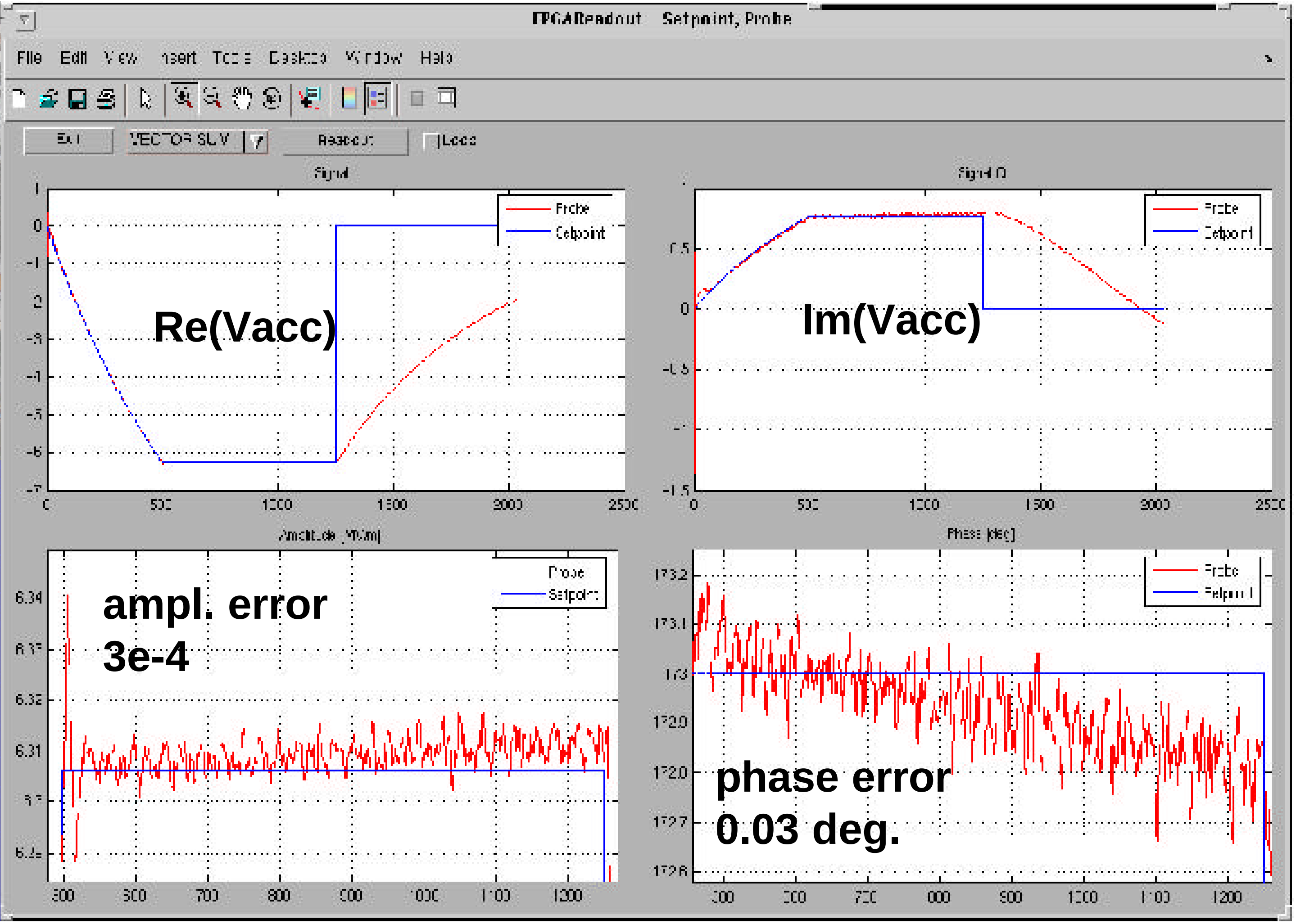
Performance of LLRF Verified at VUV-FEL with Beam

Setup





Verification with beam



Re(Vacc)

Im(Vacc)

ampl. error 3e-4

phase error 0.03 deg.

Table 1: LLRF Work Breakdown

				Subsystems and Tasks	**RP[1]**	**KP[2]**	**Team Members**	**Other Groups**	Status
1	Basic tasks								
		Assemble LLRF team (with permant core of qualified experts)							
		Office space (including seminar rooms etc.)				FE	EV		
		Laboratory space and equipment				FE	EV		
		Safety (Documents and Training)			SS		SS, EV, MH, KB		
		Laborleitung			HW	TJ	HW, MH, TJ, BW		
		Teststands							
			with cavity simulator in digital lab		?	?	WK, HW, TJ, BW		
			at module teststand (or Chechia)			TF			
			in accelerator with beam						
		VUV-FEL Operations			VA		VA, AB, TF, HW, GM, WK, PPu		
		VUV-FEL Machine studies			EV		EV, all		
	Conceptual layout of LLRF System (architecture of LLRF)				SS	SS	core team		
	LLRF Requirements (technical, operation, etc.)				EV	SS	EV, Industrie		
	LLRF work breakdown structure					SS	core team		
	Project management plan (schedule, manpower, cost)					KB	Core team		
	RF Hardware								
		Master Oscillator and Freqency Distribution; Timing			HW	HW	HW, BL	KR + 2	
			Rack (temperature stabilized) and AC-power		TF	TF	TF		
			Oscillators and PLLs		HW	HW	HW,CZ,BL,FL, MH,KO		
				9, 27, 54, 108, 1300 MHz reference frequencies		HW	HW,		

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[1] Responsible Person
[2] Contact Person

				Synchronisation with GPS standard		MH	HB, MH		
				Packaging (Crate) and power supplies		TF	TF		
				Amplifiers and power splitters		HW	HW, GM		
				Patch panels, level adjustment, monitor outputs		TF	TF		
			Frequency Distribution		HW	HW	HW,CZ,BL,FL		
				coaxial distribution for drive (1300 MHz)		HW	TF		
				temperature stabilized distribution for LO		HW	HW, TF		
				driveline amplifiers		HW	HW, TF		
				directional couplers for driveline		HW	HW, TF		
				LO generation and distribution for down/up-converter		GM	HW, GM		
			Optical Master Oscillator and Fiber Distribution		AW	AW	AW, FL		
				Fiber master oscillator		AW			
				Fiber distribution systems		AW			
				Optical to RF conversion		AW	AW, FL		
				Integration with conventional M.O. and Distr.		AW	AW, FL, HW		
			Timing generation		?	KR	1, 2, TJ, KPR, TJ	MVP	
				Standard timing		KR	1 ,2		
				Clock generation ADC clock (81*4/9 MHz) LLRF		TJ			
				Trigger (various events)		KR			
				Integration with M.O.		?			
			Timing Distribution (global and local)			KR		MVP	
				Timing distribution					
		Up/downconverters, actuators and field detection			FL	GM	GM,MH,TF,FL		
			Patch panels for RF and LO signals			TF			
			Level adjustment to downconverter			GM	GM	MVP	
			Downconverter (Probe, forward- and reflected power)			GM	GM, FL,		
				Integration of downconverter, level adjustment, rf test signal input with ADC, FPGA, opto.link on one board	WG	WG	WG, TJ, MG, KP, WJ, FL, GM, KZ, BL, HW		

			IF signal conditioning		GM			
			Up-converter or vector-modulator	MH	MH	MH, HW, TJ		
			RF gate (with various inputs)		GM	GM		
			High performance field detectors for injector		FL	MH		
			Field detectors for RF gun		FL	MH		
			Phase noise modelling of synchronization		AW			
		Single bunch transient detector			PP	PP, MG		
		Wave guide tuner control (also power distribution ?)			?	?		
			or phase shifter and variable coupler					
	Digital Feedback Hardware				WG	WG, WJ, TJ, MG		
		FPGA carrier board with floating point processor						
		ADC mezzanine card (daughter board)						
		DAC mezzanine card (daughter board)						
		Gigalink interface (optical or coaxial)						
		Timing module						
		Digital I/O interface						
		Beam input for feedforward (current and phase)						
	Cavity simulator (32 cavities)				?	?		
	Monitor and diagnostic Hardware				?	?	MVP	
		ADC boards			KR		MVP	
		DAC boards			PV		FEA	
	Piezo tuner controller				LL	LL, PS	FLA, TUL	
		Piezo fixture			LL			
		Piezo Driver			?	?		
		Piezo power supply			?	?		
		Sensor and readout			?	?		

	Special hardware					?			
		Ferrite tuner + drive				?			
		Analog fiber optic link				?			
		Piezo tuner controller				?			
		Fundamental coupler Qext controller				?			
	General Software Issues								
		Architecture of Software							
			Platform Independent Drivers, Interfaces						
			Middleware (Interface between software, firmwarre and hard ware)						
		Tools used for programming							
			VHDL						
			C++						
			other programming languages						
		Choice of operating systems							
		Concept of exchanging sofware between collaborations							
	Digital Feedback Software					WK	WK,		
		FPGA/DSP (floating point CPU) code							
			Rotation matrix (field calibration)						
			state estimator						
			feedback algorithm						
			feedforward algorithm						
			exception handling						
			loop phase						
			quench detection						
			klystron linearization						
		FPGA/DSP server				PP			
			Load programs						
			Load parameters						

			Table generation						
		Monitor software				KR		MVP	
			Monitor probe, forward/reflected power						
		Application programs				AB			
			Adaptive Feedforward (synch. with beam)						
			System Identification						
			Loop phase						
			Detuning and loaded Q						
			Gradient and phase calibration						
			Beam phase measurement						
			Automated frequency tuning (motor tuner)						
			Piezo tuner control						
			Fundamental coupler Qext control						
			Exception handling						
		High level applications				AB			
			Momentum management						
			Momentum vernier feedback						
			Beam based gradient and phase feedback						
	Finite state machine (automated operation)					VA			
		rf system start-up							
		setting of operational parameters							
		beam loading compensation							
		cavity detuning							
		adjustment of loaded Q and incident wave							
		exception handling							
		Performance optimisation							
			rf field stability						
			maximum energy						

			minimal trip rate						
	Miscellaneous software								
		Power PC and DOOCS				PP	PP,JS,PK,JZ		
		VHDL				WK	WK,WJ,KB,TJ,MG,DM,WG,		
		Algorithm Development				AB	AB, EV,MH, GP, SS		
		RF System Diagnostics				TJ			
		Interlocks							
		Display Development (Operator Displays)				?			
		Cavity and coupler conditioning				?			
		Vertical teststand				?			
	Doocs property generation					PP			
		Faults							
		Warnings							
		Performance parameters							
		Status parameters							
	Doocs features								
		Save/restore settings							
		History							
		Database (data management for calibration etc.)							
		Hardware/software diagnostic tools				TJ			
	Procedures					VA	VA, EV, SS, MH		
		Commissioning procedures							
			Open loop operation						
			adjustment of frequency tuner						
			adjustment of loaded Q						
			closed loop operation						
			gradient and phase calibration						

			calibration of forward and reflected power						
		Operating procedures				VA	VA,EV,SS,MH		
			Turn-on of RF system						
			set-up for beam operation						
	Electronic design issues and standards								
		EMC and EMI				?			
			Grounding and shielding						
			Electromagnetic emissioning						
		Radiation immunity				?			
			Single event upset (neutrons)						
			Displacement damage						
			Total ionising dose						
			In-situ radiation dose measurement (neutrons and gamma)						
		Racks and Crates				TF			
			Airconditioned racks, hermetically sealed (dust)						
			Power only crate standard (backplane, connectors etc.)						
				Power supplies for crates					
			Control systeme standard crate (VME bus, ethernet etc.)						
		Cabling				TF			
			between boards, crates, racks, crossconnects, patch panels						
			between subsystems						
		Reliability				NP			
		Maintainability							
		Cost vs performance optimisation							
	RF system modelling					EV	EV,SS,MH,AB		
		Prediction of technical performance							
		Development of algorithms							
	Documentation								

		LLRF requirement document							
		LLRF specification							
		LLRF design							
		LLRF operations manual							
		LLRF users manual							
		LLRF trouble shooting manual							
Total									