7/6/2009, V1.1

CONCEPTUAL LLRF DESIGN FOR THE EUROPEAN XFEL

Abstract

The LLRF System for the superconducting cavities of the European X-FEL must support amplitude and phase stability of the accelerating fields of up to 0.01% and 0.01 deg. respectively. The stability must be achieved in pulsed operation with one klystron driving 32 cavities in 25 rf stations in the main linac, the rf station for the rf gun, the first accelerating module and the 3.9 GHz harmonics system with 12 cavities. This goal can only be achieved with low noise downconverters for field detection, high gain feedback loops and sophisticated adaptive feedforward techniques. State-of-the art technology including analog multipliers for downconversion, 100 MHz ADCs with high a resolution up to 16 bit, and high performance data processing with FPGAs with a few hundred nanosecond latency allow to meets these goals. The large number of more than 100 input channels per rf station (including probe, forward and reflected signal of each of the 32 cavities) and more than 34 output channels combined with the tremendous processing power requires a distributed architecture using fast communication links to enable low latency protocols for data exchange.

The LLRF applications software must support procedures for subsystem commissioning, beam commissioning, and initial operation. Later upgrades are planned which will improve operability and availability of the rf system. Therefore the framework of automation must be developed in an early stage of the design. To support the required real time pulse-to-pulse event detection handling at pulse repetition rates of up to 30 Hz, the XFEL control system provide the necessary real time capability.

The development, construction, commissioning and operation with an international team requires excellent documentation of the requirements, designs and acceptance tests. For the RF control system of the XFEL a formal system engineering approach has been established. Systems engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals. The new system modelling language SySML has been chosen to facilitate the system engineering and to document the system. SysML uses 9 diagram types to describe the structure and behavior of the system. The hierarchy of the diagrams allows individual task managers to develop detailed subsystem descriptions in a consistent framework.

In order to ensure that the LLRF system fulfils the requirements of all stakeholders of the system the following documents have been prepared for the conceptual design and need to be signed by all stakeholders:

- Overview of the LLRF System for non-experts
- Stakeholder analysis
- High level user requirements
- LLRF system requirements
- Conceptual design including interface definitions, requirements coverage, and quality management plan

INTRODUCTION

The LLRF system for the XFEL is responsible for the longitudinal stability of the accelerated electron beam in terms of beam energy, bunch compression and arrival time. It comprises 25 rf stations in various linac sections (see figure 2):

- RF Gun (1.3 GHz, normalconduction 1+1/2 cell cavity , electron bunch generation)
- I1 (1 rf station, 1.3 GHz, 5 MW klystron, 8 sc-cavities)
- 3rd harm. sys. (1 rf station, 3.9 GHz, 1 klystron, 12 sc-cavities)
- L1 (1 rf station, 1.3 GHz, 10 MW klystron driving 32 sc-cavities)
- L2 (3 rf stations, 1.3 GHz, 3x 10 MW klystron driving 32 sc-cavities)
- L3 (21 rf stations, 1.3 GHz, 21x 10 MW klystron driving 32 sc-cavities

The requirements for the field stability are derived from the desired beam properties which are a peak current of 5kA (bunch compression of a factor of 100), a bunch to bunch and pulse to pulse energy stability of 1e-4 and an arrival time of less than 10 femtoseconds. Since the bunch compression takes place in the injector the most stringent requirements are in the injector section. A summary of the pulse to pulse requirements are listed in Table 1. The drift requirements of longer time periods (minutes to hours) are relaxed by a factor 2-5. .

Table 1: Field stability requirements (rms, pulse-to-pulse) at different locations

Accelerator Section		**RF Station**	**Gradient range [MV/m]**	**Amplitude stability [%]**	**Phase stability [deg.]**	**Remarks**
I1	Gun	1.3GHz	50-60	0.01	0.01	4 probe signals
I2	Injector	1.3GHz	20-25	0.003	0.005	-20 deg.
I3	Harmonic	3.9GHz	0, 10-15	0.005	0.03	-160 deg.
L1	Injector Linac	1.3 GHz	10-15	0.03	0.03	
L2	Booster	3 x 1.3 GHz	15-20	0.03	0.03	Each rf station
L3	Main Linac	20x1.3 GHz	0, 10-25	0.1	0.1	Each rf station

In the uncontrolled case, the cavity field errors are dominated by beam loading, lorentz force detuning and microphonics. While repetitive errors can be suppressed by feedforward techniques to the level of 1% for amplitude and 1 deg. for phase, feedback with a gain of the order of 100 is needed to achieve the required low errors shown in table 1.

The control of the cavity fields is accomplished with the scheme shown in figure 1. A klystron drives 32 cavities through a waveguide distributions systems which includes circulators to prevent damage to the klystron from the reflected power. High power phase shifter allow for individual adjustment of the incident wave to each cavity. Also forward and reflected power to each cavity is measured to providing information for calibration and diagnostics. Each cavity is equipped with a field probe for the measurement of the cavity field. Mechanical frequency tuners allow for control of the cavity resonance frequency. In the controller, the downconverted field vectors are ditigized, the vector-sum is calculated and subtracted from the measured vector-sum. The resulting error signal is amplified and filtered before it drives the vector-modulator which controls the vector-sum in a negative feedback configuration. Feedforward is added to the drive signal to compensate repetitive field error components.

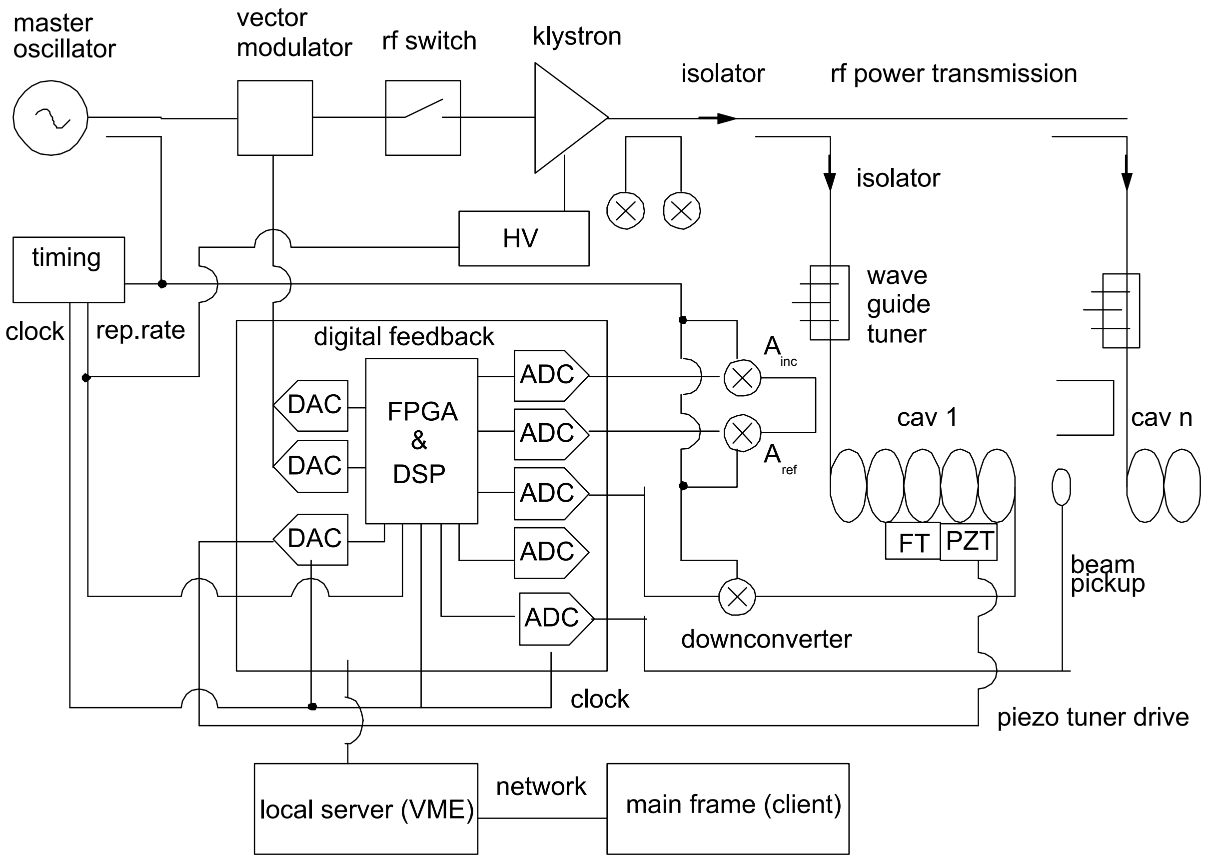

Figure 1: Architecture of the LLRF control system for one rf station.

Several sensors and actuators are available for fast and slow control of the cavity field.

The Sensors for field control at each rf stations are

- Cavity field probe signals
- Forward power signal for each cavity
- Reflected power signal for each cavity
- Total forward and reflected power for klystron
- Piezo sensors integrated with fast piezo tuner
- Other sensor signals
    - Bunch charge and beam current (toroids)
    - Beam energy of each bunch at exit of I1, L1,L2 and L3
    - Bunch compression at exit of I1, L1, L2, L3
    - Bunch arrival time at exit of I1, L1, L2, L3
    - HV measured at klystron
    - Coupler and klystron sensor signals

The actuators for field control at each rf station are

- Vector-modulator for fast control of incident wave (bandwidth > 1 MHz
- RF gate for fast rf inhibit (reaction time < 1 us)
- Slow Resonance frequency tuner based on stepper motor (+- 300 kHz, 100 Hz/sec)
- Fast frequency tuner based on piezo actuator (+-200 Hz, 100 Hz/ms)
- Higher power phase shifter for incident wave to each cavity (+-30 deg.)

- Variable coupler for loaded Q adjustment (1e6 – 1e7)
- Other control parameters:
  - Klystron high voltage
  - Klystron timing
  - LLRF timing
  - Beam inhibit
  - RF Gun temperature

The LLRF System, accelerator instrumentation, and control system constitutes a significant part of electronics in the XFEL tunnel. The operational goal of more than 90% uptime imposes an availability of more than 99.9% on the llrf system which is not achievable with current approaches considering that the tunnel is only accessible during one short maintenance period per month. The design must be fault tolerant to avoid interruptions in operation due to single-point failures and provide a large tolerance to single event upsets (SEUs) as a result of moderate levels of neutron radiation. Total ionizing dose levels will be managed with the use of built-in dosimetry which allow to manage gradient distributions to minimize local dose rates. This present both a hardware and a software challenges, as well as a severe challenges to the design with respect to cost as well as high availability (HA). Industrial standard solutions are preferred which lead to the choice of ATCA and uTCA as an attractive alternative to the presently employed VME and cPCI standard.

Other criteria for the choice of the standard are the desire for modularity which allows to combine several boards with different functionality to the desired system. This will simplify maintenance and reduce maintenance cost. Fast Gigabit Ethernet (GbE) communication links between the boards within a crate and between crates are required to support low latency real time feedback systems and transfer of large amounts of data between systems.

Other considerations include scalability, maintainability, and remote diagnostics. Since the hardware is a major investment and cannot be replaced frequently, it must support future hardware and software upgrades. This means that spare IO channels and adequate computational capacity must be included in the original design.

LLRF SYSTEM CONCEPT FOR THE EUROPEAN XFEL

The LLRF system for the XFEL will consist of 25 rf stations which are connected by various networks (see figure 2). High bandwidth uplinks at each rf station allow to send all relevant pulse data to the DAQ system. A private LLRF network is guarantees real time pulse-to-pulse response. This network also connects to critical other systems such as special diagnostics for beam feedbacks, the high power rf systems, the timing systems, the rf gun laser system, and the machine protection system. For intra pulse feedbacks and decisions dedicated optical Gigalinks are available from each rf station to a central location in the injector service building.

The automation server will be realized as middle layer server connected to the private LLRF network to enable global decision making between and possibly even during the 1 ms pulses. The data rates of all rf stations to the DAQ system are expected to be of the order of 500 MB/s.

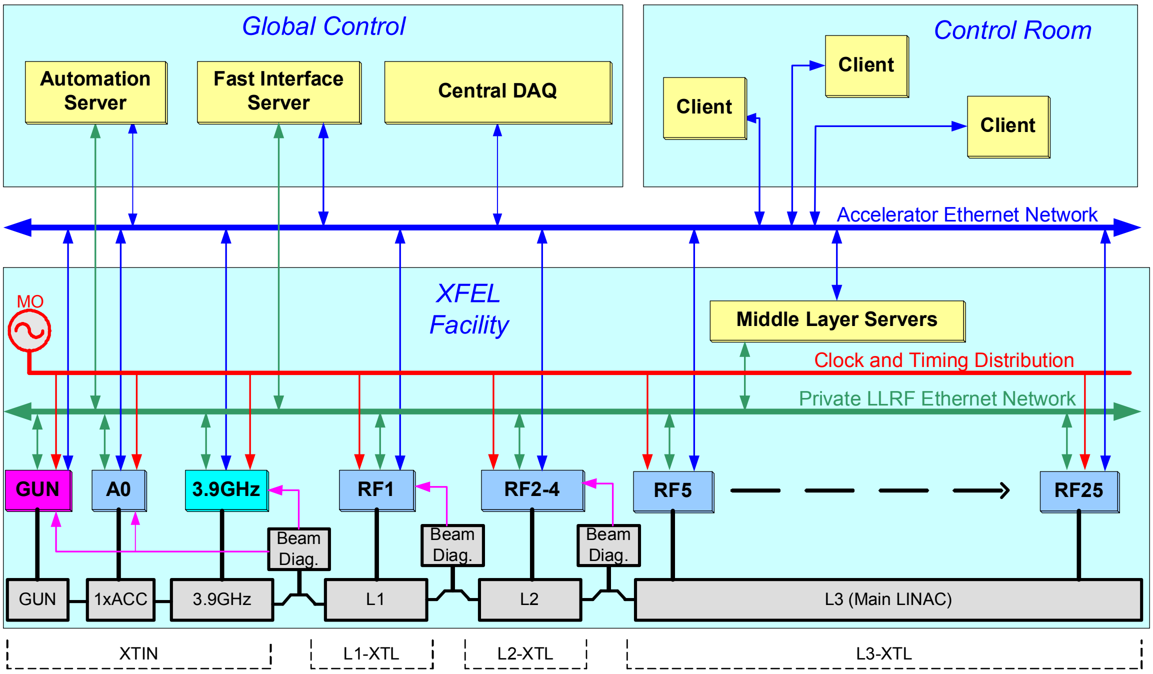

Figure 2: Global control concept for the 25 rf stations

HARDWARE ARCHITECTURE OF ONE RF STATION

The rf control system for one rf station consisting of a 10 MW klystron driving 32 cavities in 4 cryomodules must provide control of the vector-sum of all cavities with a stability of the order of 2e-4 for amplitude and up to 0.01 deg. in phase at 1.3 GHz. The feedback system requires individual field measurements from which the vector-sum is calculated as well as forward and reflected power measurements from which cavity detuning and beam phase are derived and which are used for system diagnostics. To support a low latency in the feedback loop of less than 1 us, 100 MHz ADCs with 14-bit resolution and DACs both with few cycle conversion times as well as a low latency processing unit based on large FPGAs are required. The field detection is accomplished by downconversion of the cavity probe signal at 1.3 GHz to an IF frequency of about 50 MHz which is sampled by the ADC from which the field vector is calculated. A vector-modulator driven by a DAC allows fast control of the incident power in amplitude and phase. Piezotuner support fast cavity tuning to compensate Lorentz force detuning.

The proposed architecture for the LLRF system of one rf station is shown in figure 3. The ATCA Crates placed in a semi-distributed configuration close to the cryomodules accommodate field detection boards with downconverters, ADCs and FPGA for processing the partial vector-sum of 8 cavities. The same boards are also used for the measurement of forward and reflected power. The boards are connected by low latency links to allow for real time algorithms which calculate cavity detuning, beam phase and other derived measurements required as input for various algorithms. Also installed in this crate is a processor board which takes care of the shelf management and can be used to implement a control system front end server supplying the necessary parameters to the individual boards. A timing receiver provides event triggers and clocks necessary for operation. Piezo drivers allow fast control of the cavity resonance frequency using piezo actuators for control.

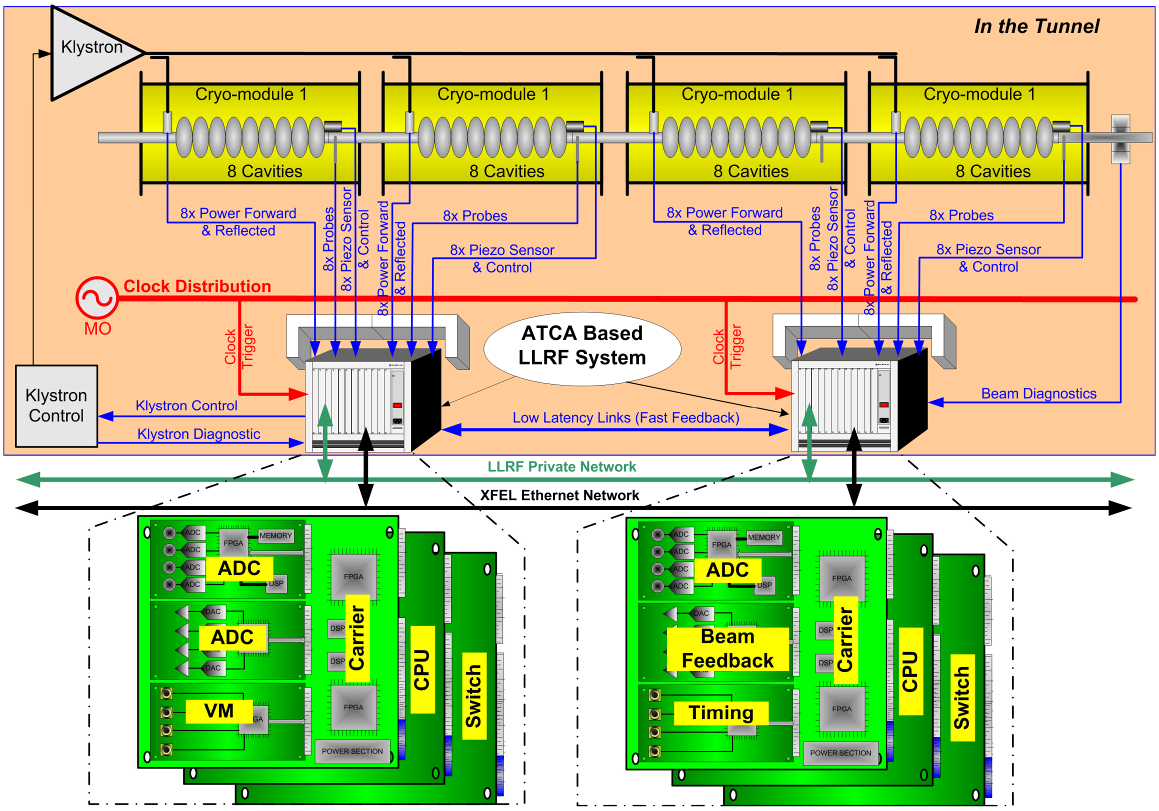

Figure 3: Hardware architecture for the LLRF System

In the middle the two pairs of cryomodules of one rf station are sets of 2 and 3 racks which house the main control electronics. A control system crate based on the ATCA standard accommodates a processor board with FPGAs and DSPs in which the main rf control algorithms are implemented. Low latency links are used to send the data from the front-end crate to the main processor board.
The middle layer servers and client computers are installed in the service buildings and control room. The servers for global automation of the LLRF systems and the clients providing the interface for the operators are also located here.

SOFTWARE ARCHITECTURE

The main requirements for the LLRF applications are 2 knob operation for amplitude and phase of each rf stations. The implementation of the 2 knob operation implies the implementation of 59 function divided in 11 functional groups. These are:

- Measurements
- Calibration
- Field Control
- Cavity Res. Control
- Subsys. Character.
- Subsystem Control
- Exception Detection
- Exception Handling
- LLRF Diagnostics
- Global RF Control
- System Functions

The framework for the implementation for LLRF software must also support

- low latency algorithms
- distributed algorithms
- beam based feedback
- remote control

- modularity of algorithms (interface !)
- exception handling
- build-in diagnostics
- redundancy
- data storage
- SEU immunity

The low latency in the feedback algorithm is supported by the massive parallel processing in the FPGAs. However the algorithm must be kept simple to achieve it goal. Complex algorithms requiring floating point calculations such as adaptive feedforward, system identification and piezo tuner control can be implemented on floating point DSP processors since the latency requirements are not as stringent. The server for automation of operation can be implemented on a middle layer server CPU since the timing requirements are not as critical.

The distribution of the modular algorithms requires well defined interfaces to ensure simplicity in trouble shooting, maintainability, and upgradeability. Low latency links will use in-house protocols while commercial link protocols are available for links with high bandwidth which do not require the low latency. It will be challenging to distribute the algorithms on the various processing platforms since detailed specifications are not yet available and depend also on the available allocation of resources. For fast global feedback algorithm including beam based feedback, the number of analog and digital IO channels must also be determined.

Redundancy can be achieved with algorithms which provide the same results from other signal sources. It is for example possible to calculate the cavity field from forward and reflected power although the measurement error is larger. Any discrepancy between the independent derived signals will flag potential errors in hardware or algorithms.

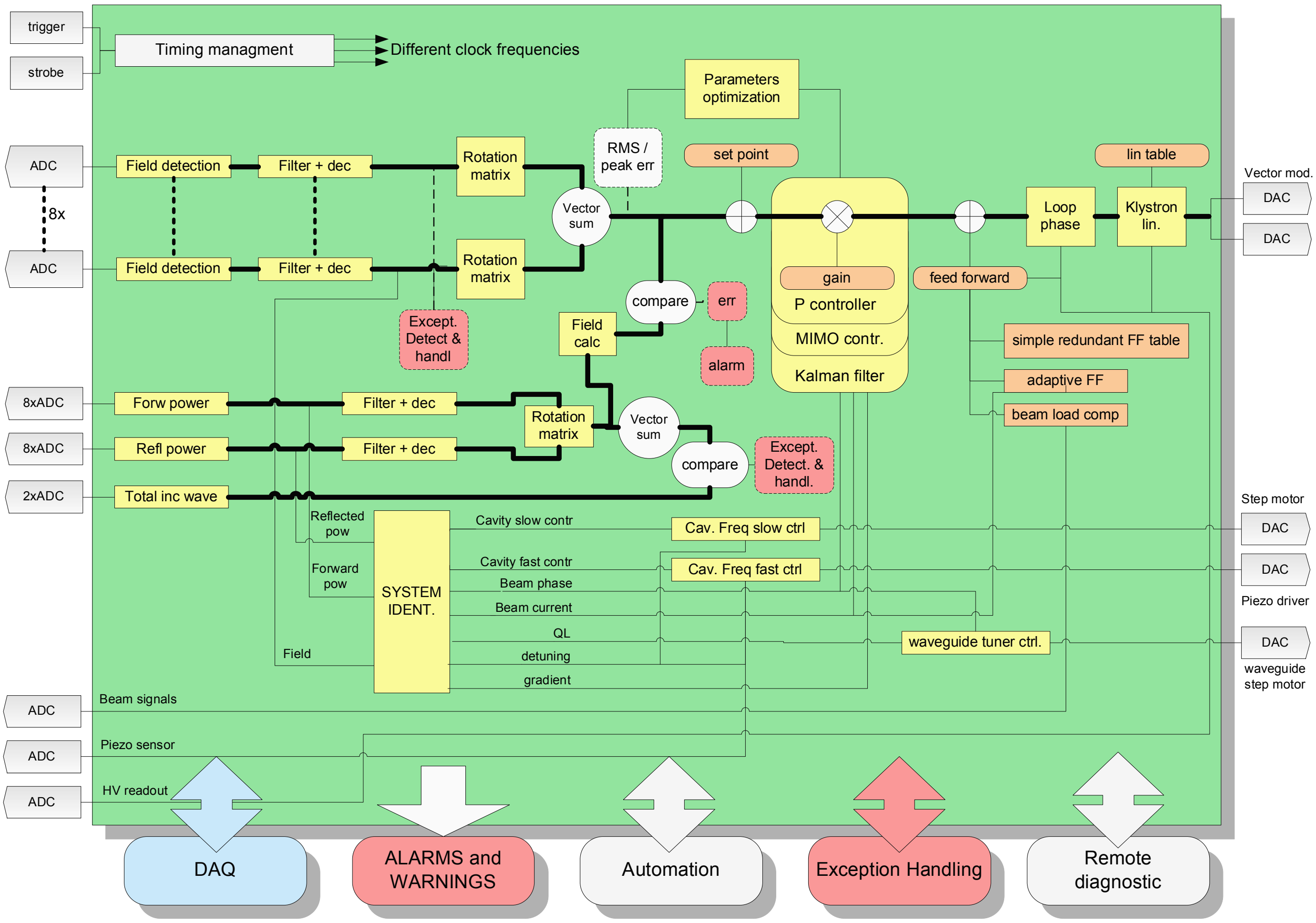

Figure 4: Architecture of the LLRF Software

Data storage is provided locally on most processor boards and will be distributed to the central servers between pulses for further signal processing.

Single event up-set immunity can be achieved by triple modular redundancy (TMR) methods which will be used only in small sections of the hardware. This part of the electronics is responsible to check for signal integrity and switch to the redundant feedforward if necessary.

Automation of operation will be essential for the control of almost 1000 cavities to ensure simplicity of operation and high availability. Therefore the front end hardware and software must support all features required for automation. Examples are measurement and setting of the following quantities:

- Field vector measurement
- Loop phase and loop gain
- Loaded Q and cavity detuning
- Beam phase and beam induced voltage
- Calibration of cavity field and phase
- Vector-sum calibration
- Calibration of forward and reflected wave
- Beam loading compensation
- Klystron linearization
- Exception detection and handling
- rms field errors
- Warnings and alarms

It is desirable to implement the algorithms as close a possible to the hardware to reduce network traffic. However often it is more convenient to implement algorithms and applications at middle layer server or as client applications simplify the programming (in C or C++) and later upgrades as well as maintainability. Also good documentations is essential to achieve these goals and support the exchange of algorithm within collaborations. The tools for software development should be standardized to facilitate the exchange of software.

For the algorithm and application development it is important to define signals, algorithms and interface in an early stage so that the work can be distributed in modules to the different groups working on the implementation. For example it will be possible to implements procedures for automation if the interfaces and available signals are known well in advance.

MASTER OSCILLATOR AND FREQUENCY DISTRIBUTION

Due to difficulty of modeling the sensitivity of beam energy, beam arrival time, and bunch compression to phase noise and phase drifts in the various accelerator sections a simplified model combined with experimental results from the FLASH facility including the MO and PRDS [2] lead to the requirements for the XFEL.

The stability requirements for the 1300 MHz RF signal is summarized in Table 1. Requirements for other frequencies are similar.

Table 1: Stability requirements at 1300 MHz

Location	Short Term Stability	Long Term Stability
Injector	10 fs	100 fs
Booster Section (L1 and L2)	30 fs	300 fs
Main Linac (L3)	100 fs	1 ps (1 second) 2 ps (1 hour) 10 ps (1 day)
Cavity BPM’s	500 fs	1 ps

The XFEL synchronization system frequency scheme is based on decimal (important change comparing to the FLASH accelerator) system. The MO reference frequency will be equal to 10 MHz and will be multiplied by integer numbers (eg. X10, x130) to obtain other frequencies. Due to the length of the accelerator and the high cable losses at 1300 MHz a distribution frequency of 100 MHz was chosen. At the destinations all other needed frequencies such as 1300 MHz are derived from the 100 MHz.

The overview of the subsystems requiring RF phase reference signals is shown in figure 5. Only a few devices are located in the injector area but their stability requirements are the strongest, see (Table 1).

The main user of the phase reference signals is the LLRF system located at 25 RF Stations (RFS) in the injector area, booster and main linac. Each RFS will consist of 4 cryomodules containing each 8 superconducting cavities. The LLRF system has therefore to process 4 * 8 * 3 = 96 signals (field probe, forward- and reflected power for each cavity) at each RFS. These signals are downconverted by mixers to an IF of 50 MHz. For this purpose a 1350 MHz phase stable LO signal has to be generated locally at each RF station. Additionally a frequency of 1300 MHz is needed for the input of the vector modulator to drive the klystron.

In the undulator section of the XFEL, about 130 cavity BPM's (used for diagnostic purposes of the beam position within the beam line) are synchronized at 100 MHz. The synchronization accuracy is less demanding than for the linac but the distribution line will be about 1500 m long in up to 5 parallel photon tunnels.

In the experimental area, some photon experiments may require a better then 1 picosecond long term phase stable RF reference. The details still have to be worked out. Until now no detailed data can be provided on required frequencies, power levels and locations.

SUMMARY

For the conceptual design of the LLRF system for the European XFEL the systematic approach of requirements engineering has been chosen. Starting with a stakeholder analysis all relevant user requirements have been captured and converted to system requirements. Based on the system requirements a conceptual design is proposed which includes the interfaces to other subsystems.

The LLRF concept is based on the Advanced TCA standard which support high speed serial interconnects in the crate and between crates. This standard fulfils also the requirements on high availability, scalability and modularity as well as compatibility with the uTCA standard chosen for the XFEL control system. Future upgrades in terms of operability and availability can be accomplished by software upgrades and do not require a change of hardware. A global control concept has been developed which fulfils the pulse to pulse real time requirements of the XFEL.

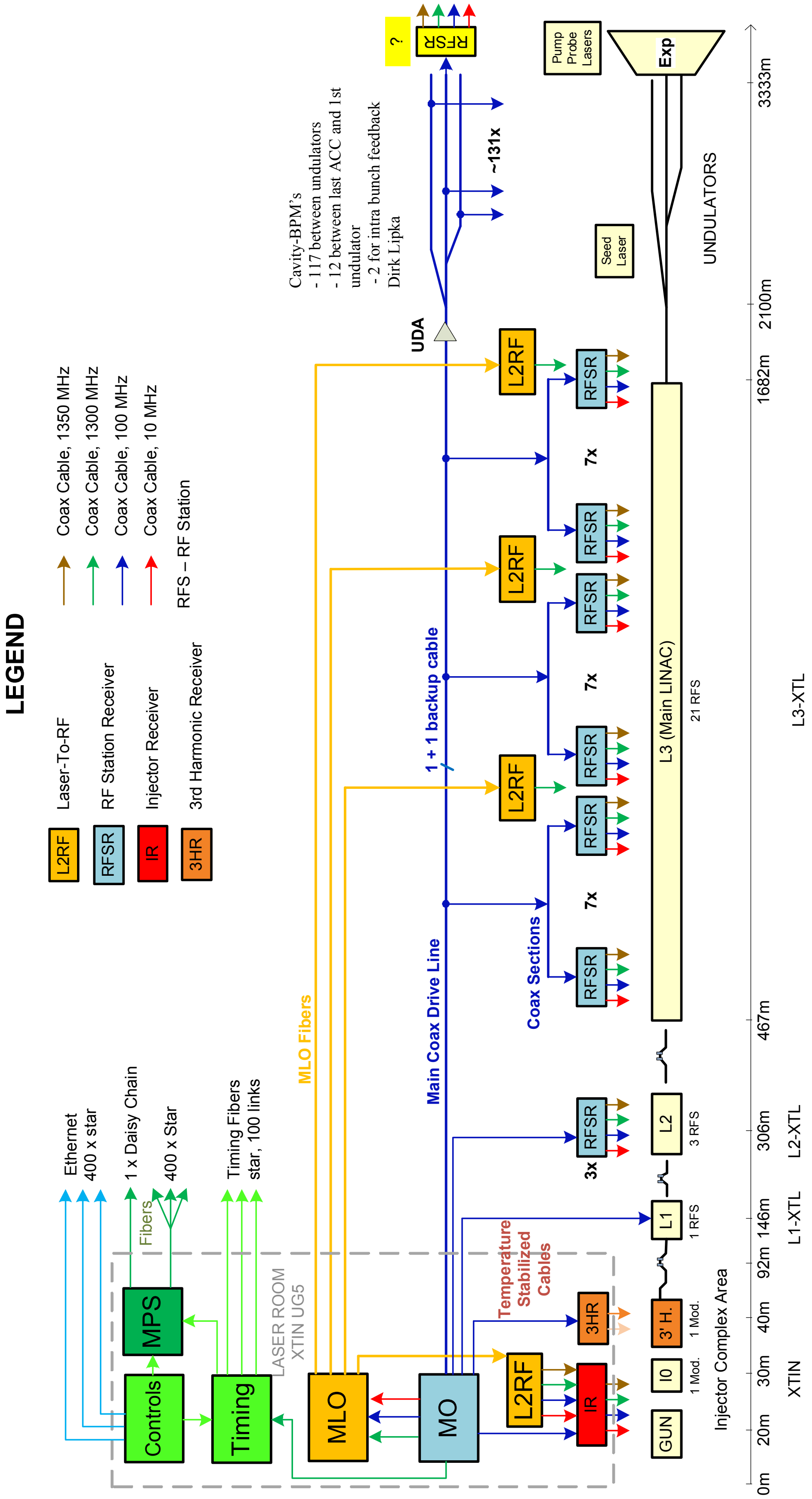

Figure 5: Master Oscillator and Frequency distribution to LLRF and other accelerator subsystems

Other material:

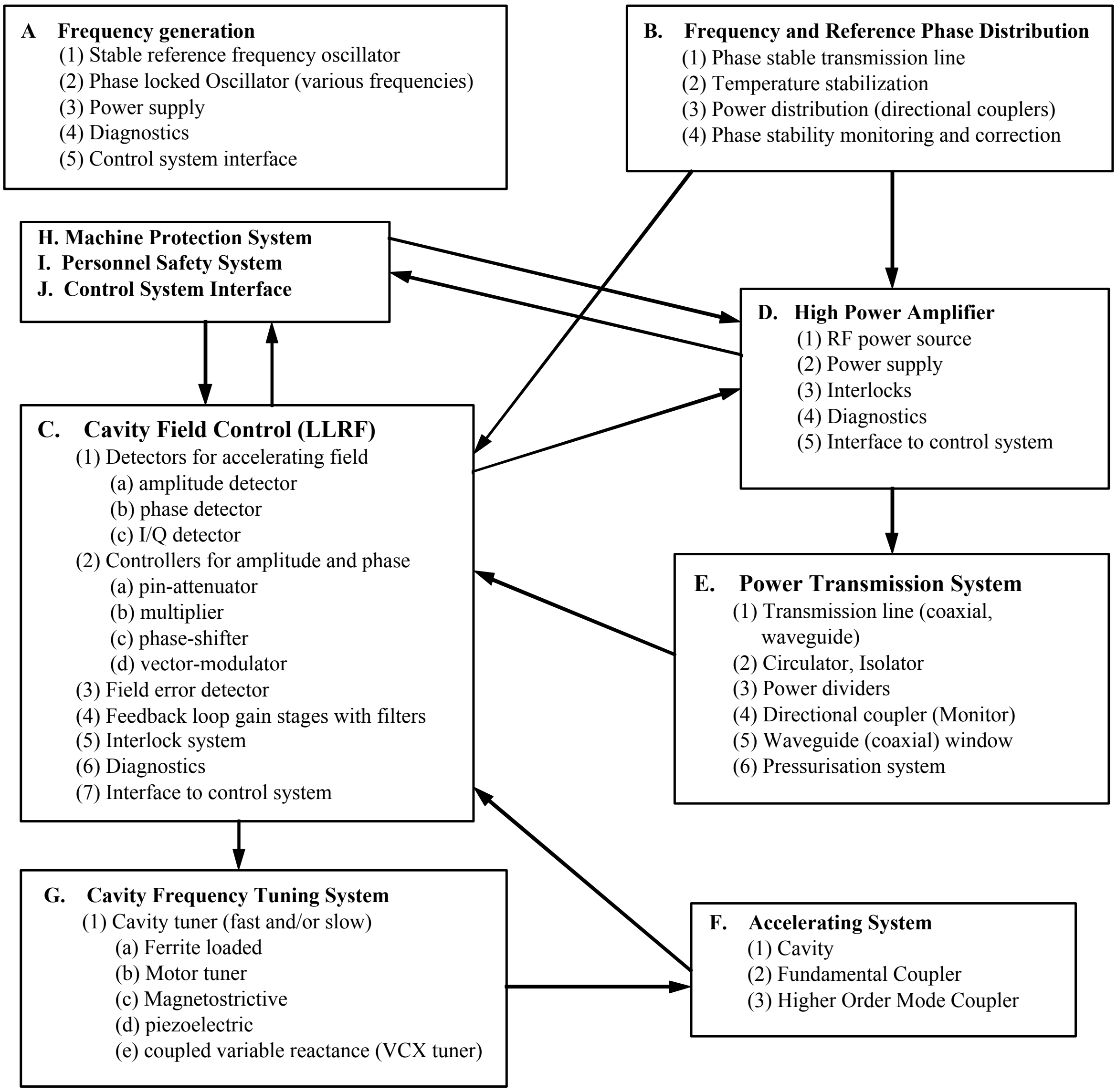

Figure x: Breakdown of RF Control Subsystems and some choices for implementation

A. FIELD CONTROL ALGORITHMS

- (1) Feedback
  - (a) PID filter
  - (b) Kalman filter
  - (c) adaptive filters
  - (c) Smith predictor
  - (d) optimal controller
- (2) Feedforward
  - (a) beam loading compensation
  - (b) beam energy feedback
  - (c) bunch length feedback
- (3) Klystron linearization
- (4) Exception handling
  - (a) quench detection and handling

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) Measurement of incident phase (vector-sum !)
- (5) Beam phase measurement
- (6) forward/reflected power calibratio
  - (a) correct for directivity of couplers
- (7) Cavity detuning
  - (a) average during pulse
  - (b) detuning curve during pulse
- (8) Loaded Q

C. Cavity Resonance Control

- (1) Slow tuner
  - (a) maintain average resonance frequency
  - (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

D. High level procedures

- (1) Adaptive feedforward
  - (a) response matrix based
  - (b) transferfunction based
  - (c) robust
  - (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

E. Miscellaneous

- (1) RF System Database
  - (a) calibration coefficients
  - (b) subsystem characteristics
- (2) Alarm and warning generation
- (3) Automated fault recovery
- (4) Finite state machine

Figure y: Algorithms and procedures required for an automated digital LLRF system