Director's Review of the Project X Cost Range Estimate: Low Level RF

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Project X Director's Review
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Outline

- Scope of Estimated Work
- Boundary Conditions /Assumptions
- Basis of Estimate
- Technical Risks/Associated Cost Exposure
- Potential Technical Revisions
- Role of Outside Collaborators
- Summary

Scope of Estimated Work

- The primary global function of the RF Control System is to regulate the RF fields in all accelerating cavities to maintain required beam energy and emittance
  - Global regulation requires information from beam based instrumentation and sector vector sums created from multiple stations
    - Exception handling for events such as a quenched cavity
  - Cavity field regulation is performed by the local LLRF system which controls a klystron and two cryomodules
  - Cavity phase regulation is in relation to a Master Oscillator signal via the phase Reference line
- A local LLRF system
  - Receives program requests from global control and localized real-time beam based feedback
  - Demodulates over 60 RF signals from the cryomodules, RF, and beam pickups
  - Provides Cavity Field regulation by control of the klystron drive and the Ferrite Vector Modulators the RF drive fast and slow cavity tuners
  - Provides Cavity Resonance control with motorized and piezo cavity tuners
  - Provides self calibration and diagnostics

Boundary Conditions & Assumptions

- LLRF interface to other systems
  - Control and Timing system
    - The primary Control System interface is via Ethernet connection to the crate level CPU. This connection scaler settings and reading, alarms and limits and waveform capture
    - LLRF provides synchronous reference clock signals to the Distributed Timing system and receives "LlrfStartTrigger" (active high LVDS)
  - HLRF and station interlocks
    - LLRF provides the drive signal to the klystron drive amplifier (10dBm FS)
    - LLRF receives HLRF signals from Drive amp. And several waveguide forward and reflected power signals. (10dBm FS @ receiver)
    - LLRF provides a "LlrfReady" signal (active high LVDS)
    - Receives an "RfInhibit_n" (active low 50 Ohm)
  - Machine Protection system
    - LLRF provides a "GradientRegulated" signal (undefined interface)
    - LLRF provides a "RfTrip" signal (undefined interface)

Boundary Conditions & Assumptions

- LLRF interface to other systems
  - Cryomodule
    - LLRF receives forward, reflected, and cavity transmitted RF signals
    - LLRF drives stepping motors and piezo actuators
  - RF protection system
    - LLRF provides cavity RF signals
  - Instrumentation and Diagnostic
    - LLRF provides RF Phase Reference signals to diagnostic systems
    - LLRF receives beam phase signals from beam detectors

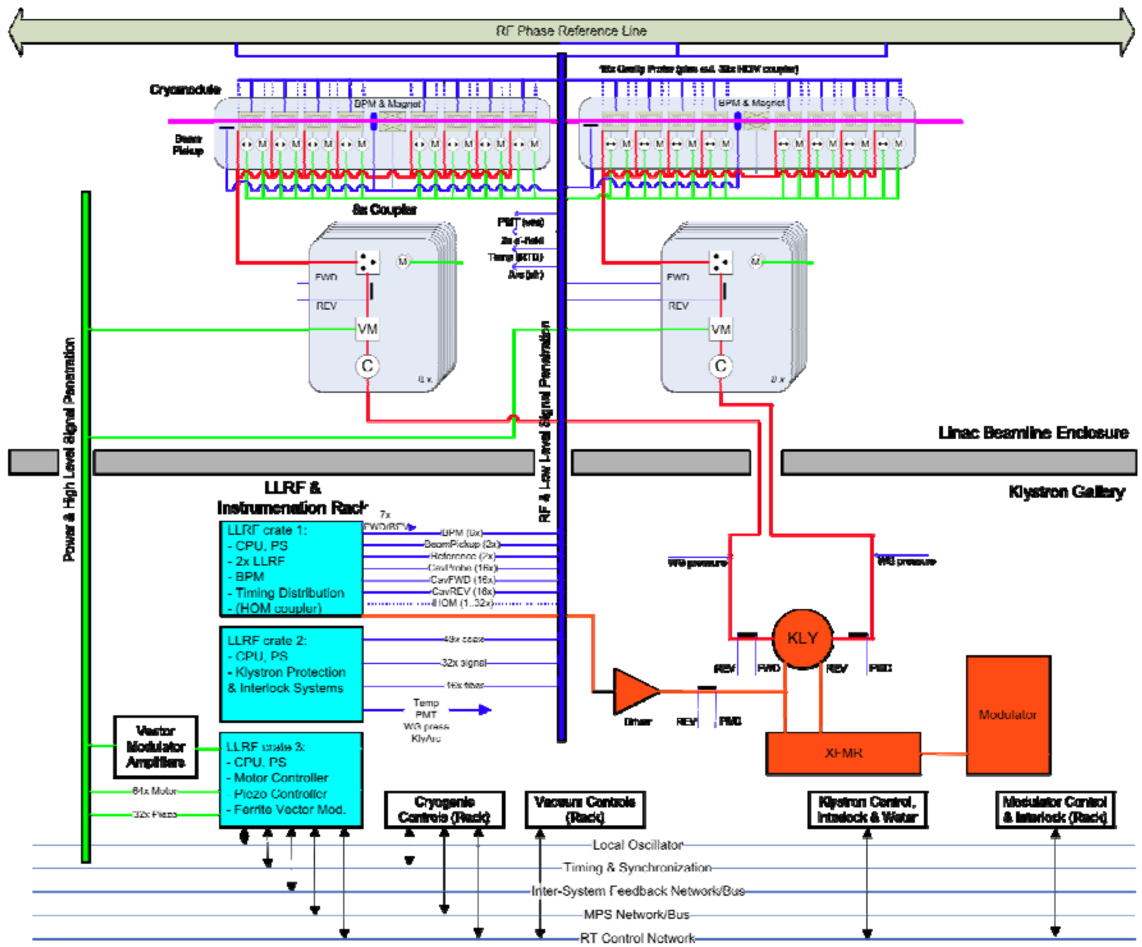
Boundary Conditions & Assumptions

- Anticipated inputs from other efforts
  - Much development work will be done within the current HINS and NML projects. Current activities include A0, HTS, CC2, HINS, NML, ILC
  - We expect to gain from the experience of our collaborators
- Presently not expecting major changes to the Main Injector LLRF system
- Electrician and other trade work is not included

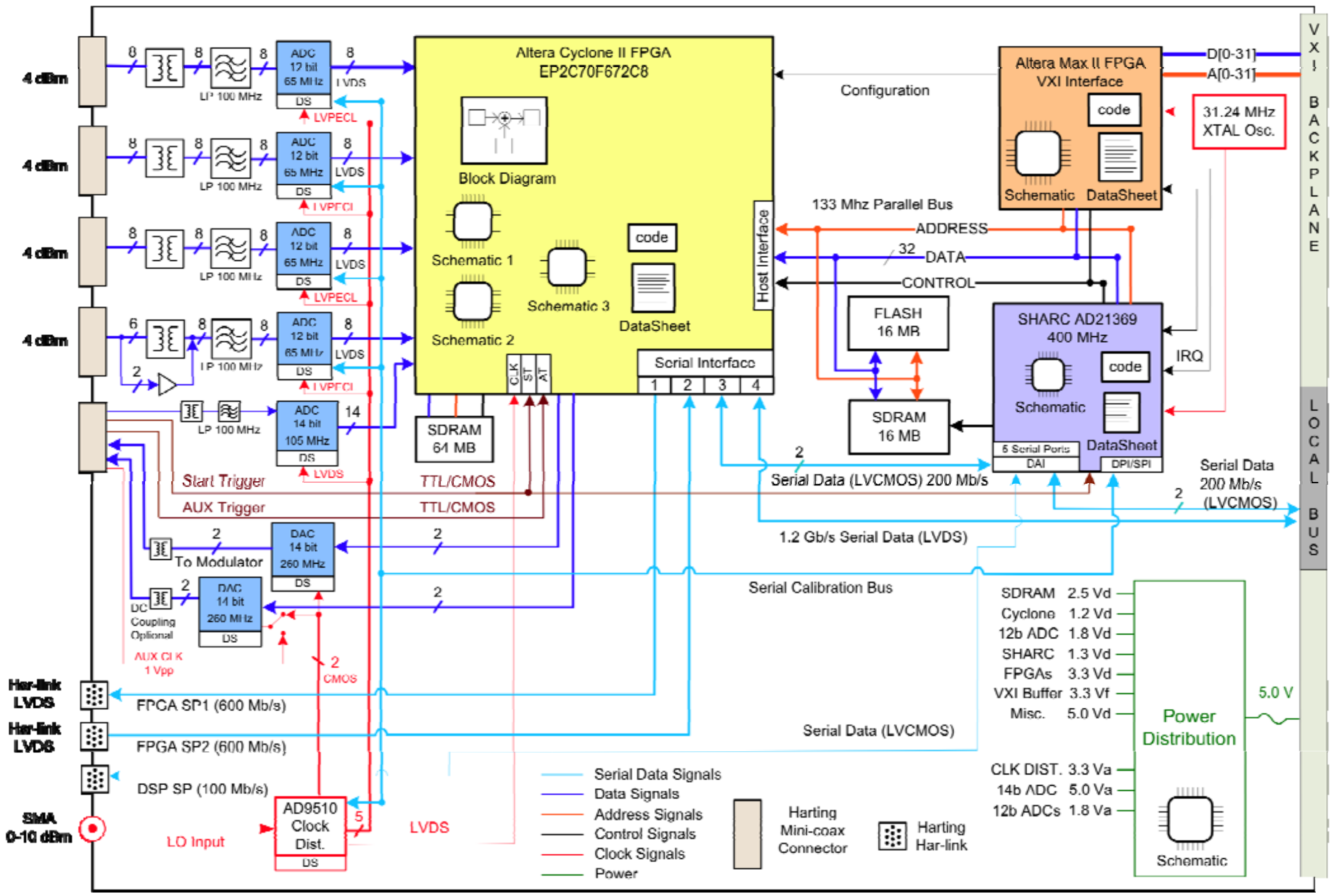
Project X LLRF: assumptions

- Main Linac: LLRF equipment will reside in the Klystron Gallery
- Small variation in R/Q of cavities - needed for beam based calibration
- Negligible ground motion over the length of the linac
- Internal hardware and software design with outsourced manufacturing
- There will be sufficient RF power headroom for regulation
- LLRF will not be a part of the personnel protection systems
- LLRF will be a secondary system in the machine protection systems
- The ILC construction LLRF Group will have control over most decisions that affect system costs

Project X RF Station with 2 Cryo-modules

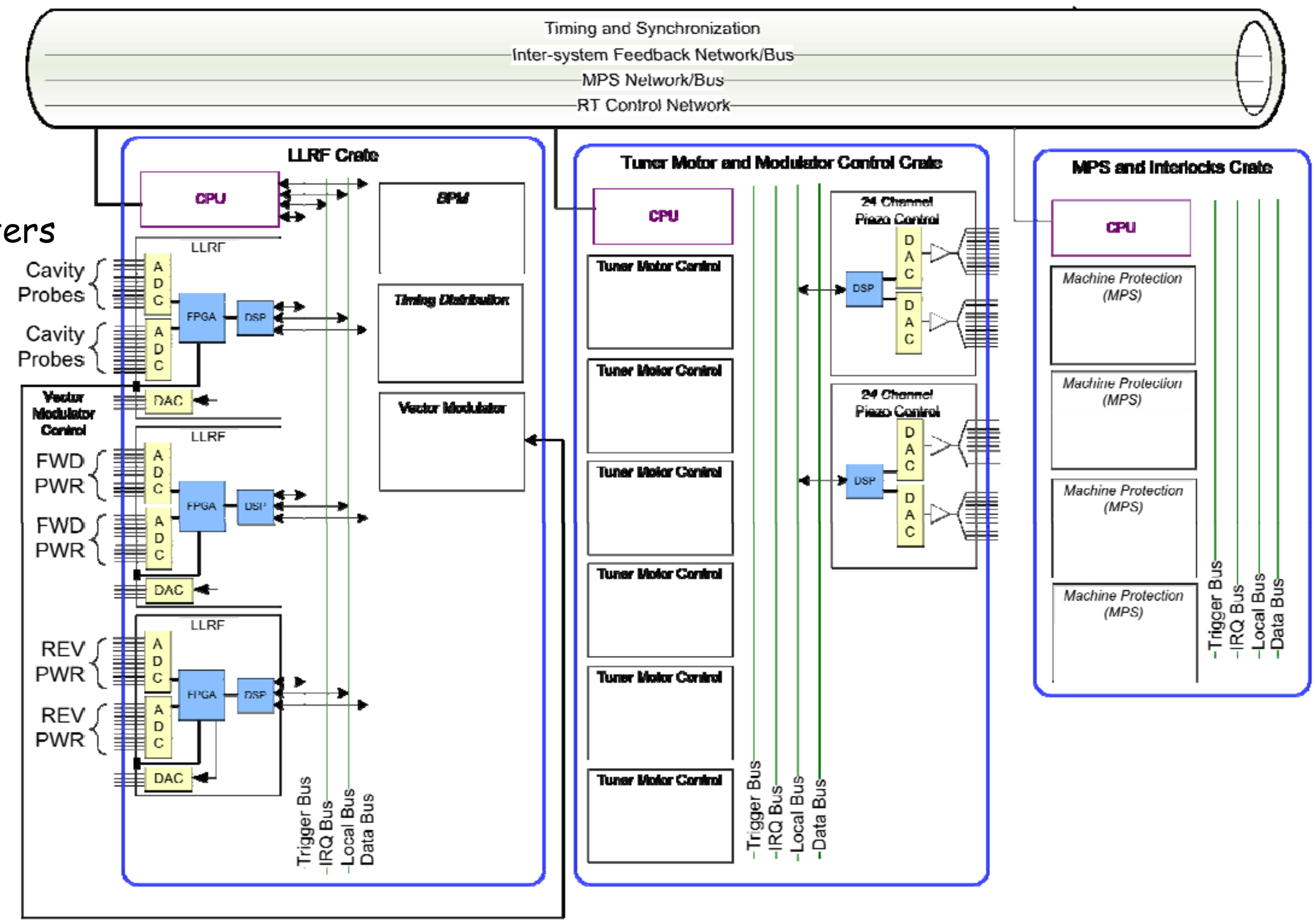


MFR Block Diagram



LLRF Rack Detail

Down-converters not shown



Project X Basis of Estimates

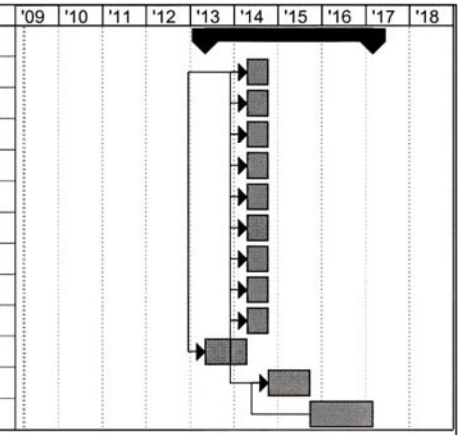
- Review of existing systems SNS, Jlab, DESY, KEK, FNAL
- Vender quotes on BOMs with production quantities
  - Receiver - FNAL prototype BOM
  - Controller - FNAL prototype BOM
  - Cable - quote from vendor
  - Piezo controller, vector modulator controller, drive amplifier, phase reference - best estimate
  - Final costs may be lower with a true bidding process
  - See paper documents for details
- Prototypes of major components
- Estimate of uncertainty ~ 30%
  - Copper, steel, management structure and requirements, high reliability requirements, present design level

Basis of Estimate

Cost Summary for Project X - LLRF			
	# RF Stations	Cost / Station (k $)	Total Cost (k $)
325 MHz Warm Cavities	1	$ 116.69	$ 117
325 MHz Cold Cavities	7	$ 126.02	$ 882
1300 MHz Beta=0.81	4	$ 90.02	$ 360
1300 MHz Beta=1	19	$ 90.02	$ 1,710
LLRF Total Station Cost	31		$ 3,069
Cable plant			$ 305.51
Master Oscillator			$ 75.00
Local Oscillator&Dist.			$ 63.20
Synchonizaton to MI			$ 80.00
Phase Reference Line			$ 215.08
Global Energy Controller			$ 50.00
Machine protection			$ 155.00
	Total LLRF System Cost ($k)		**$ 3,858**

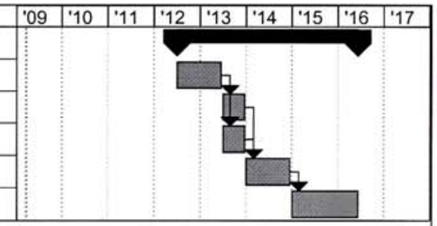
LLRF Gantt Chart

ID	WBS	Task Name	Duration	Start	Finish	Cost
1	**1.3.5**	**1.3GHz LLRF and Global LLRF Systems**	**1000 days**	**Mon 5/6/13**	**Fri 3/3/17**	**$3,013,790.00**
2	1.3.5.1	Beta = 0.81 LLRF Stations	125 days	Mon 4/21/14	Fri 10/10/14	$360,000.00
3	1.3.5.2	Beta = 1 LLRF Stations	125 days	Mon 4/21/14	Fri 10/10/14	$1,710,000.00
4	1.3.5.3	Cable Plant	125 days	Mon 4/21/14	Fri 10/10/14	$305,510.00
5	1.3.5.4	Master Oscillator	125 days	Mon 4/21/14	Fri 10/10/14	$75,000.00
6	1.3.5.5	Local Oscillator and Distribution	125 days	Mon 4/21/14	Fri 10/10/14	$63,200.00
7	1.3.5.6	Synchronization to MI	125 days	Mon 4/21/14	Fri 10/10/14	$80,000.00
8	1.3.5.7	Phase Reference Line	125 days	Mon 4/21/14	Fri 10/10/14	$215,080.00
9	1.3.5.8	Global Energy Controller	125 days	Mon 4/21/14	Fri 10/10/14	$50,000.00
10	1.3.5.9	Machine Protection	125 days	Mon 4/21/14	Fri 10/10/14	$155,000.00
11	1.3.5.10	1.3 GHz LLRF Final Design	250 days	Mon 5/6/13	Fri 4/18/14	$0.00
12	1.3.5.11	1.3 GHz LLRF Fab/Assy/Test	250 days	Mon 10/13/14	Fri 9/25/15	$0.00
13	1.3.5.12	1.3 GHz LLRF Installation & Checkout	375 days	Mon 9/28/15	Fri 3/3/17	$0.00



325MHz Gantt

ID	WBS	Task Name	Duration	Start	Finish	Cost
1	**1.2.9**	**325MHz LLRF**	**1028 days**	**Tue 7/3/12**	**Thu 6/9/16**	**$999,000.00**
2	1.2.9.1	325 MHz LLRF Final Design	250 days	Tue 7/3/12	Mon 6/17/13	$0.00
3	1.2.9.2	325 MHz Warm Cavities	125 days	Tue 7/2/13	Mon 12/23/13	$117,000.00
4	1.2.9.3	325 MHz Cold Cavities	125 days	Tue 7/2/13	Mon 12/23/13	$882,000.00
5	1.2.9.4	325 MHz LLRF Fab/Assy/Test	250 days	Fri 1/3/14	Thu 12/18/14	$0.00
6	1.2.9.5	325 MHz LLRF Installation & Checkout	375 days	Fri 1/2/15	Thu 6/9/16	$0.00



Technical Risks

- Field regulation of multiple cavities from a single RF power amplifier using Ferrite Vector Modulators with hadron beams
  - Requires precise field control of each cavity's amplitude and phase
    - ➢ 325 MHz coaxial modulators & 1300 MHz waveguide modulators
      - Power handling
      - Control Bandwidth
- Resonance control of spoke resonator cavities
- Regulation with low Klystron power overhead
  - Nonlinear behavior including AM to PM coupling
- Viability of low cost phase reference line and long run fiber
- The RD&D plan addresses all of these risks
    - ➢ For LLRF concerns, only FVMs are a large cost risk to the project
      - Simulations look promising

Potential Technical Revisions

- State of the art RF electronics changes rapidly and will affect circuit and possibly system topology. A ten years extrapolation into the future is a stretch but the sign of cost change is generally in our favor
    - Crate standards including possibly no crate
    - Direct sampling of RF signals
    - Radiation hardness of components – sample at the cryomodule
    - Technology for fiber and copper reference distribution
    - Next generation FPGAs and ADCs. Maybe new technology
  - No big cost drivers
- LLRF role in MPS is presently a best guess
  - Design decisions could be expensive

Collaborators

- We are currently working with Alessandro Ratti and Larry Doolittle from LBNL. This will develop with a completed MOU
- Ongoing collaboration with ILC groups from KEK and DESY
- Ongoing collaboration with Argonne
- Close ties with JLAB
- Internal collaboration at Fermilab from AD, CD, and TD

Summary

- The basic generation of LLRF hardware and software is becoming well understood. We can build it and make it work
- LLRF is a low cost and fairly low risk system on its own
  - It can be made into an effective controller
- Project X has several innovative technologies that may challenge regulation
  - Driving many cavities from one klystron by using Ferrite Vector Modulators
  - SRF Spoke Resonators in pulsed RF configuration
- RD&D at HINS and NML are critical to Project X LLRF development

- Thank You!

Project X LLRF Equipment: Uncertainty

- Electronics are based on Communication technology which is rapidly changing at close to a Moore's Law rate
  - Technology changes may yield major system topology upgrades
    - This may lower costs
- Cable costs
  - Raw copper cost fluctuations
    - Costs likely to go up
  - Exact cable routing is not complete
- Some module design specifications are not complete
  - Costs are best engineering guesses
    - Moderate cost effect
- LLRF role in MPS is undefined
  - Design decisions could be expensive

Other comments

- I have included Drive amplifiers for 325 MHz
- Machine protection is mostly a placeholder
- 325 MHz does not have interlocks
- Some cables are double counted in LLRF and HLRF
- Phase Reference line estimate may be low R&D is needed

LLRF Equipment: WBS Dictionary (snip)

(See ILC docdb #300)

- Downconverter:
  – Primary down-conversion from 1.3 GHz to IF for cavity probe, cavity forward and reflected power, beam pickup and phase reference signals. Also includes high-density cable patch panel, clock signal for LLRF digitizer boards and vector modulator for klystron drive signal. Self diagnostic and calibration system are controlled over Ethernet.
- Cavity Simulator:
  – The cavity simulator provides remote diagnostics of the llrf control, support of software algorithm development, and training of operators without risk of destroying hardware. Furthermore the real time cavity simulator allows studiers to check what happens if operational parameters are changed.
- LLRF System Crate:
  – This crate including power supply and crate controller CPU will house the boards processing signals for all LLRF specific signals, cavity probe, forward and reflected power, beam pickup and phase reference signals. The boards within this crate will also generate the LLRF drive signal for the vector modulator. The crate will also house a BPM processing board and a timing receiver board.

LLRF activities for Project X at CD

- ESECON controller
  - Hardware
    - We have 10 working boards.
      - 3 at A0 photoinjector
      - 1 for HTS at Meson lab.
      - 1 for CCII at NML.
  - Firmware
    - All basic modules are working.
    - The firmware work will continue adding new blocks such as klystron linearization, beam loading compensation, a more sophisticated control, automation and calibration, etc
  - Software
    - We will support DOOCS operation and some level of development. It would be nice to migrate ESECON to the main Controls software for Project X.
  - Commissioning, operations and studies
    - Will be supported.

LLRF activities for Project X at CD

- Real Time Simulator (RTS)
  - The RTS currently supports 4 cavities.
  - The current simulator models include superconducting and normal conducting cavities, individual cavity synchronous phases and beam loading conditions.
  - Future work:
    - Expand the RTS to simulate a full Project X RF unit and Project X front end LINAC.
    - Improve the user interface.

- Off line simulations
  - CD will complement AD effort in off line simulations for Project X.
  - CD will team up together with AD/LLRF to develop common models for the existing Matlab off line LLRF simulator.

LLRF activities for Project X at CD

- LLRF models
  - Complement AD/LLRF effort in modeling the LLRF problem for Project X.
  - Develop a machine parameter configuration to optimize RF fields in the cavities.
  - Calibration procedures.
  - Analyze and incorporate RF disturbances into the models.
  - Collaborate with TD in their Lorentz force detuning modeling.

- LLRF Control
  - Advance in the development of control algorithms.
  - Incorporate new control algorithms in the off line and real time simulations.
  - Implement the algorithms in firmware and measure results on field.

- Support Project X management
  - Support costing and documentation for reviews.
  - Participate of meetings and workshops.
  - Publish results.