Model Based Verification

for Multi-Cavity LLRF Control Systems

Burak Dursun, *Andrea Bellandi, Cagil Gumus, Christian Schmidt, Julien Branlard, Lukasz Butkowski, Martin Hierholzer, Max Herrmann, Sven Pfeiffer*

LLRF Workshop, Gyeongju, Republic of Korea, 26.10.2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

European XFEL

DESY.

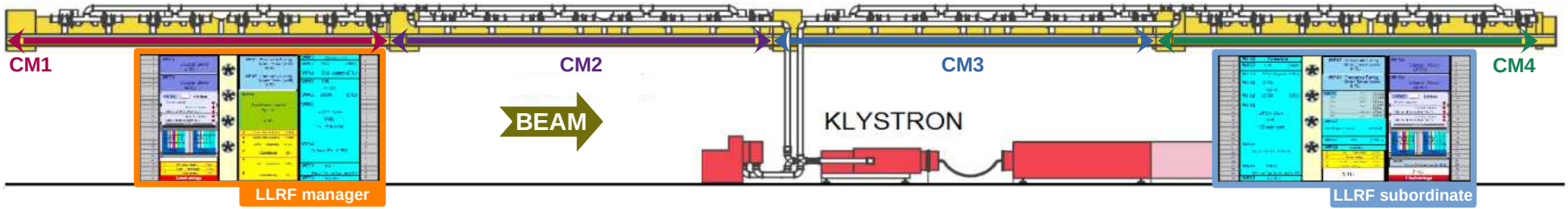
Model Based Verification

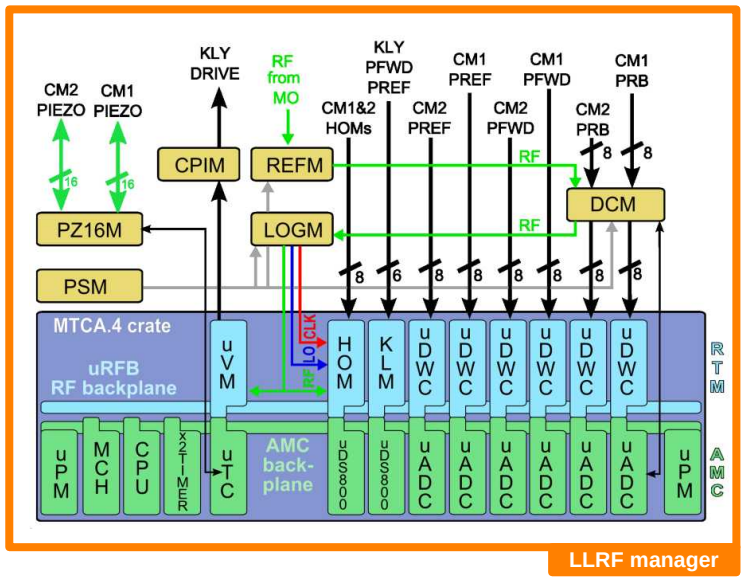
for Multi-Cavity LLRF Control Systems

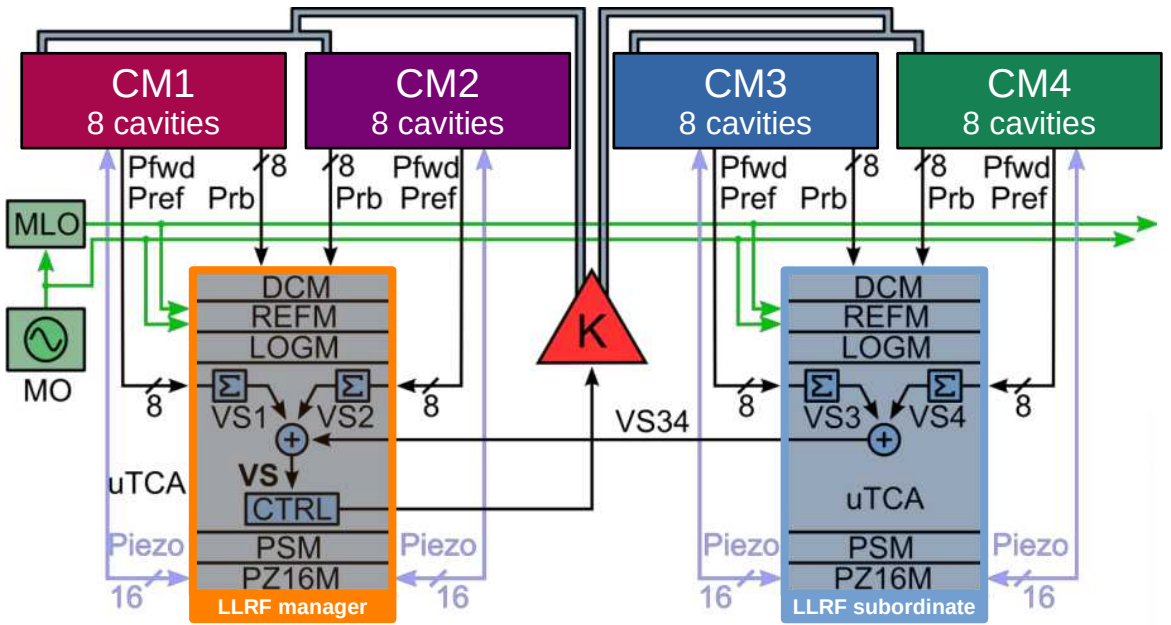
- System Description
- Development Workflow
- Problem Definition
- Model Based Solution
- Status and Future Work

Multi-Cavity LLRF Control Systems

Plant and Hardware







Multi-Cavity LLRF Control Systems

Firmware

> Large number of sensor channels

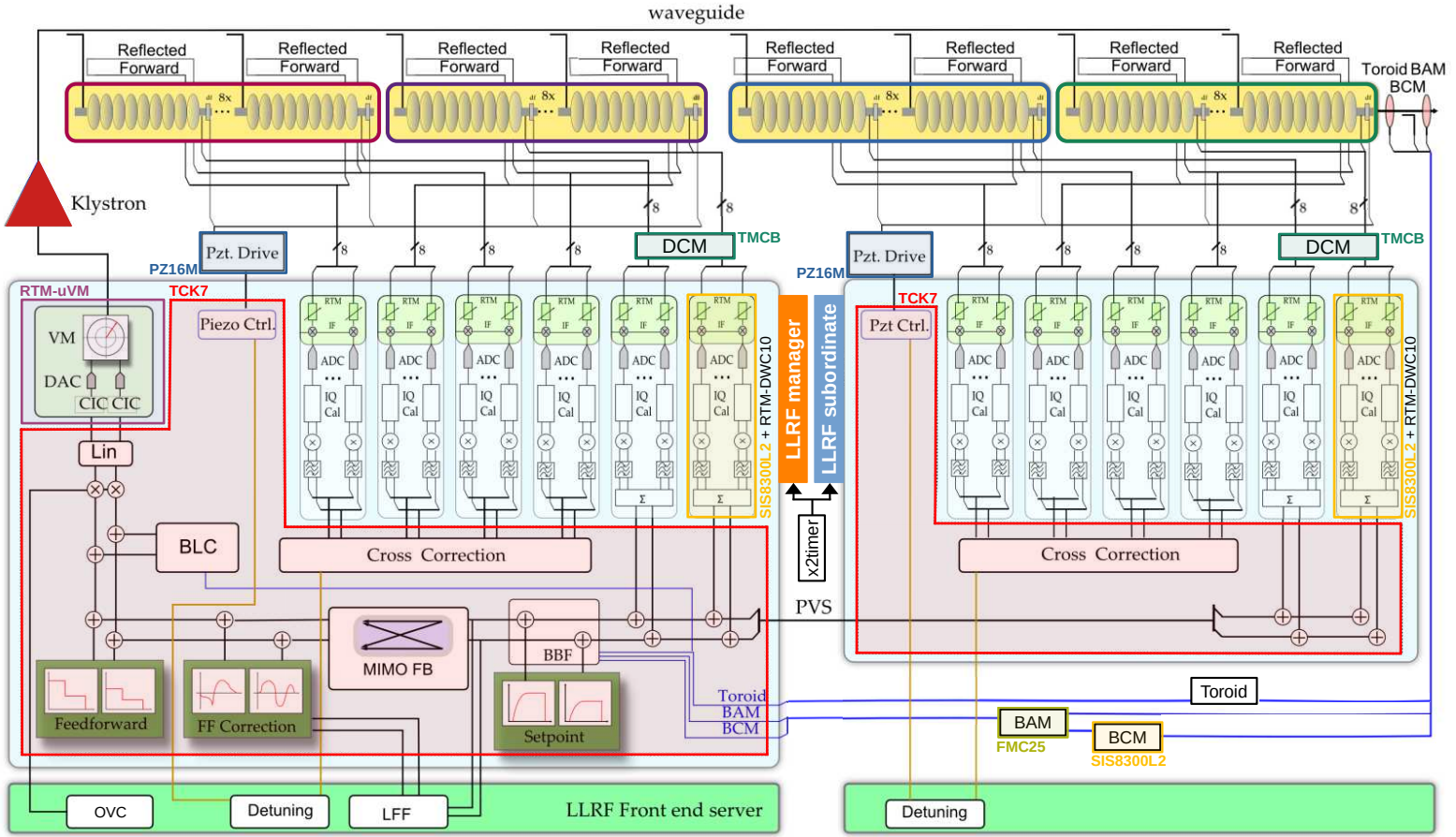
> Distributed architecture

> Control action at 9 MHz with ~ 1 µs latency

> Design optimization for quantization error to achieve tight regulation parameters

> 20+ years support for various hardware

- **TCK7** (Kintex 7)
- **SIS8300L2** (Virtex 6)
- **RTM-uVM** (Spartan 6)
- **PZ16M** (Spartan 6)
- **TMCB** (Spartan 6)
- **FMC25** (Virtex 5)



Multi-Cavity LLRF Control Systems

Software

LLRF Ctrl

> Slow feedback control implementation

> Manipulate fast feedback control (firmware)

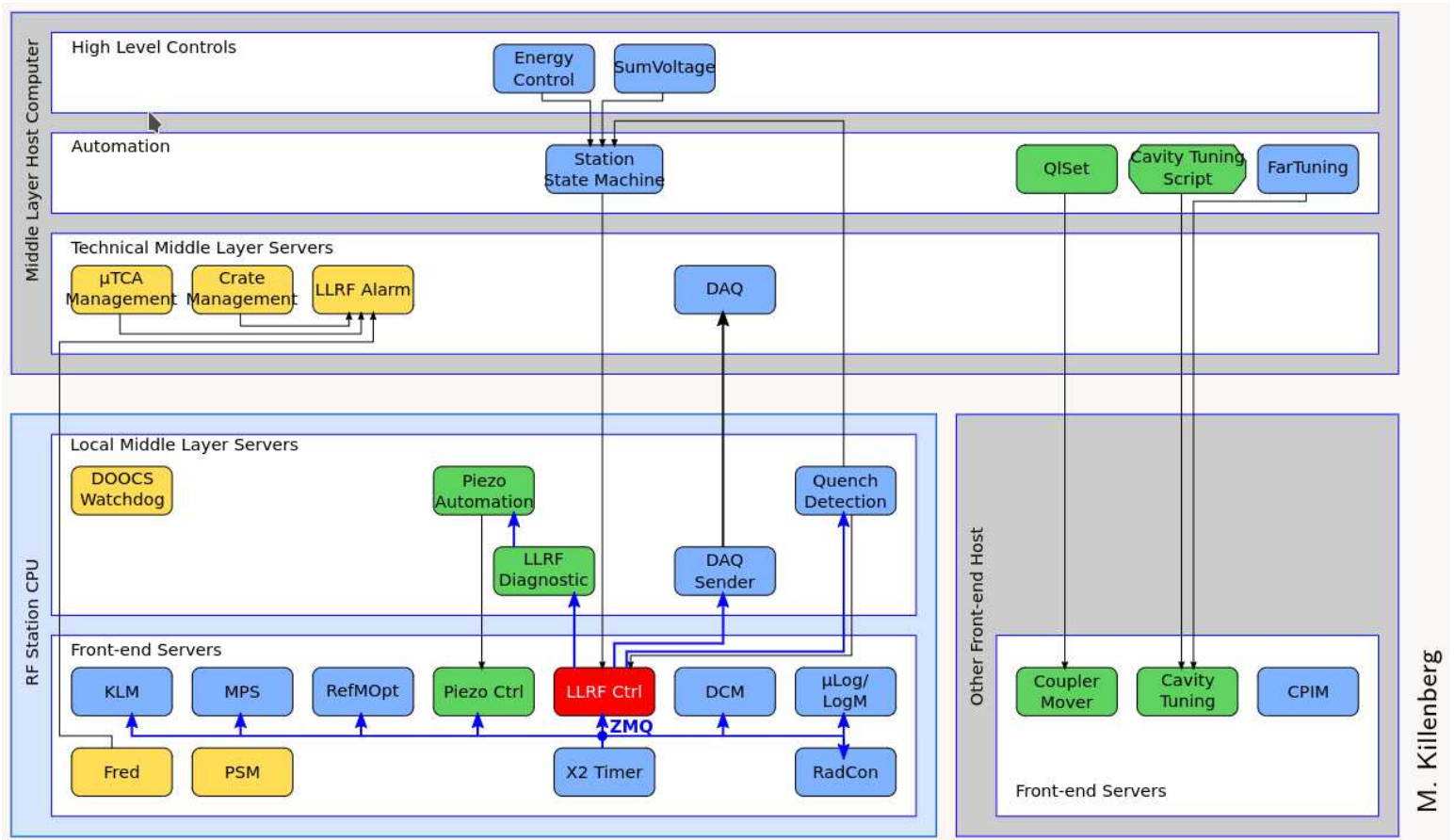
> Generate control tables (setpoint, feedforward, gain) for firmware

> Monitor sensor data and states of the controller

> Manipulate parameters of hardware/firmware

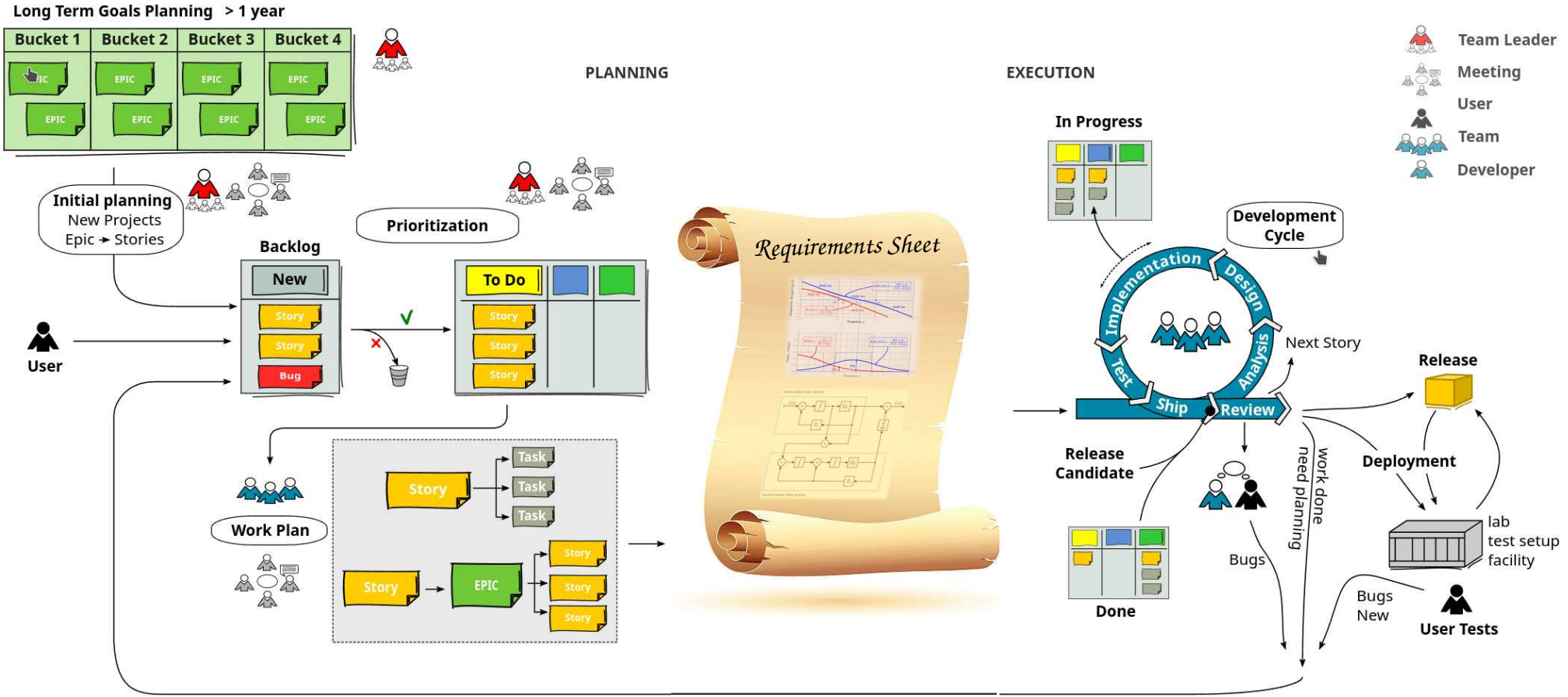
> Interface with **DOOCS.**

doocs.desy.de
github.com/ChimeraTK



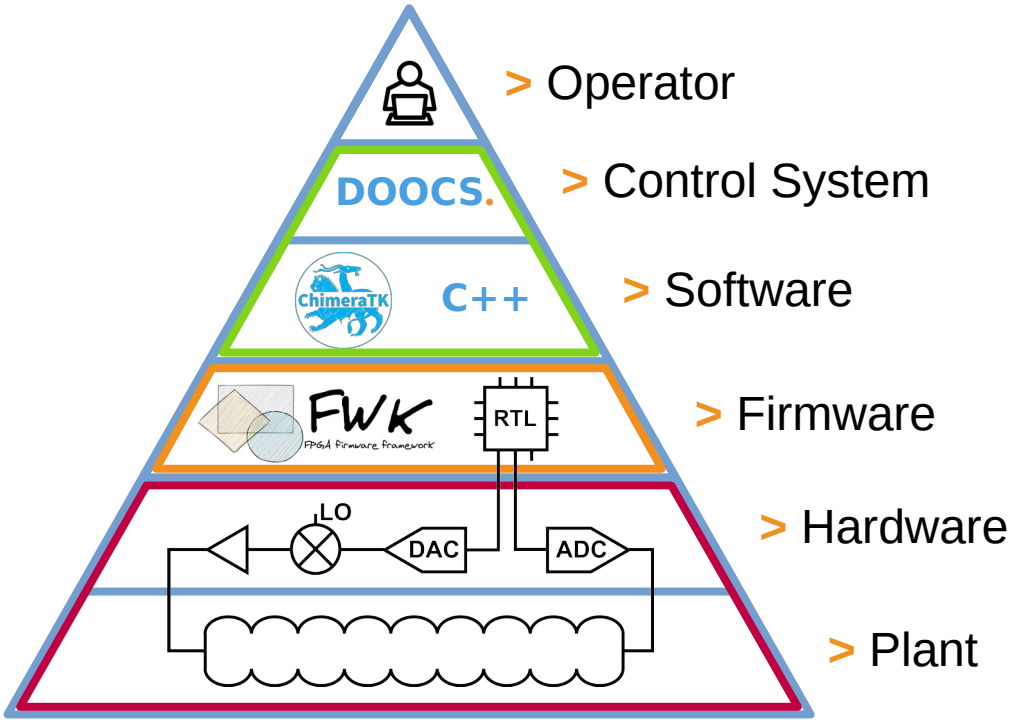
Development Worklow

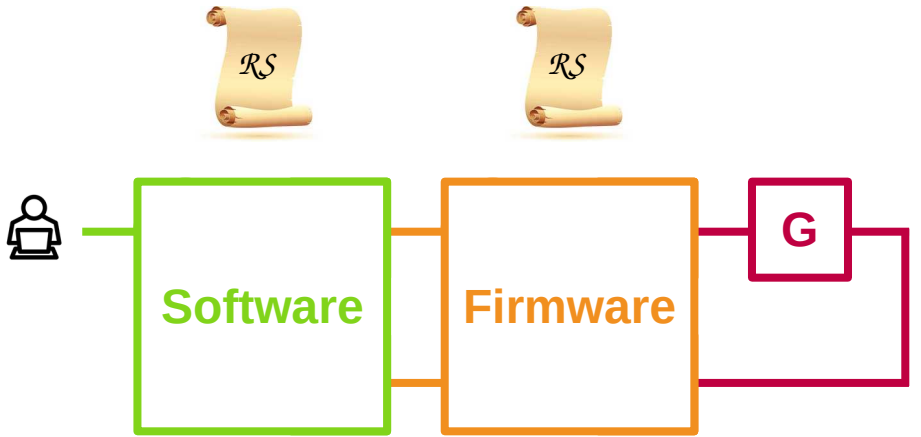
Requirements Specification



Development Worklow

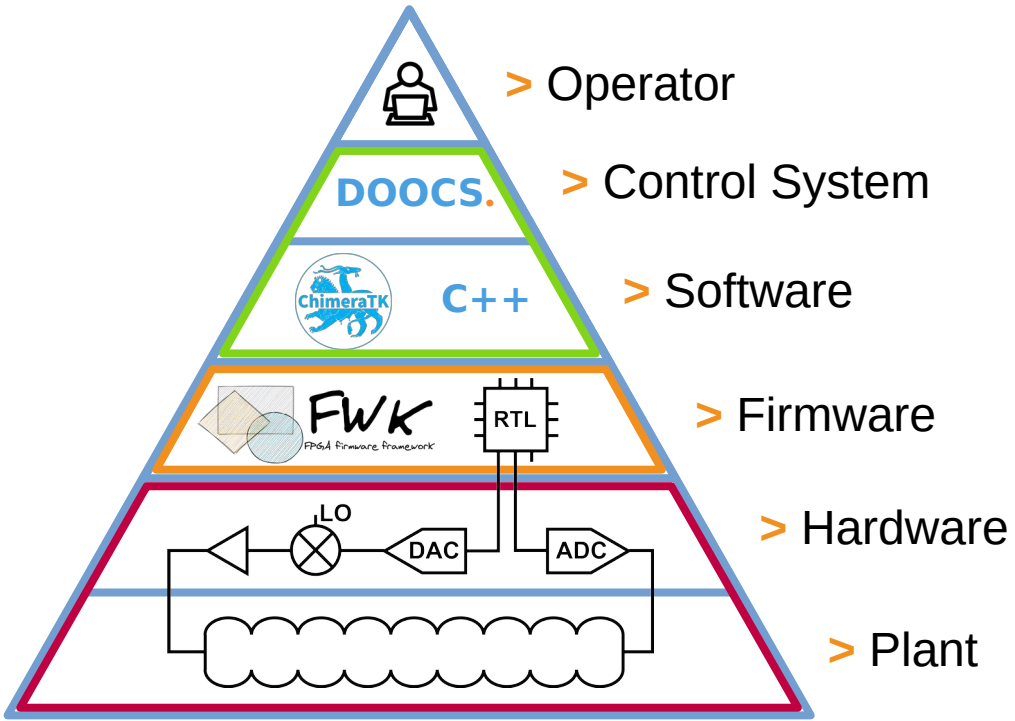
Algorithm Developer Perspective

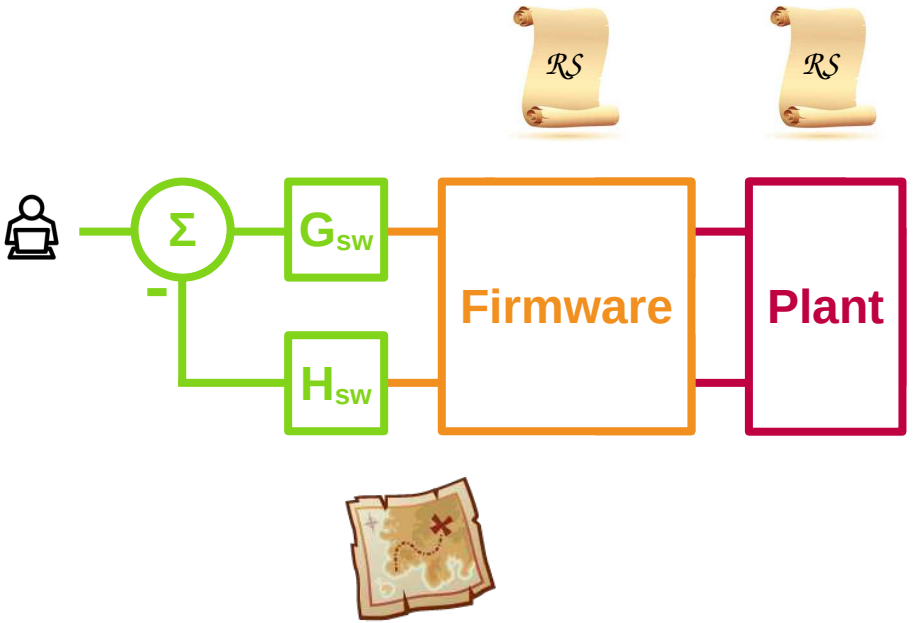




Development Worklow

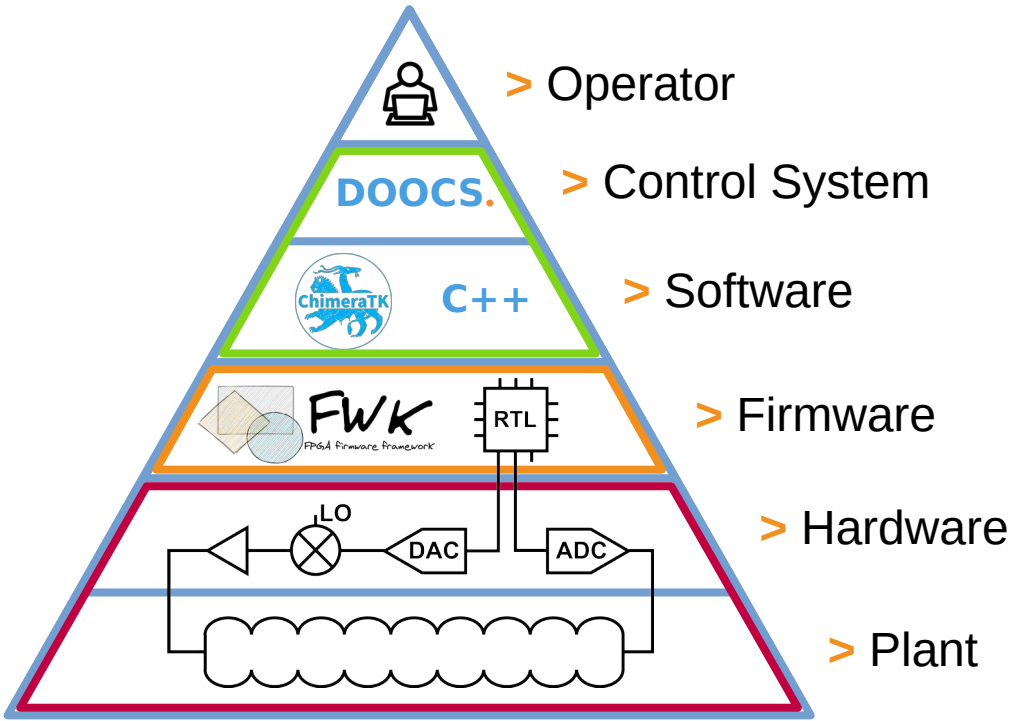
Software Developer Perspective

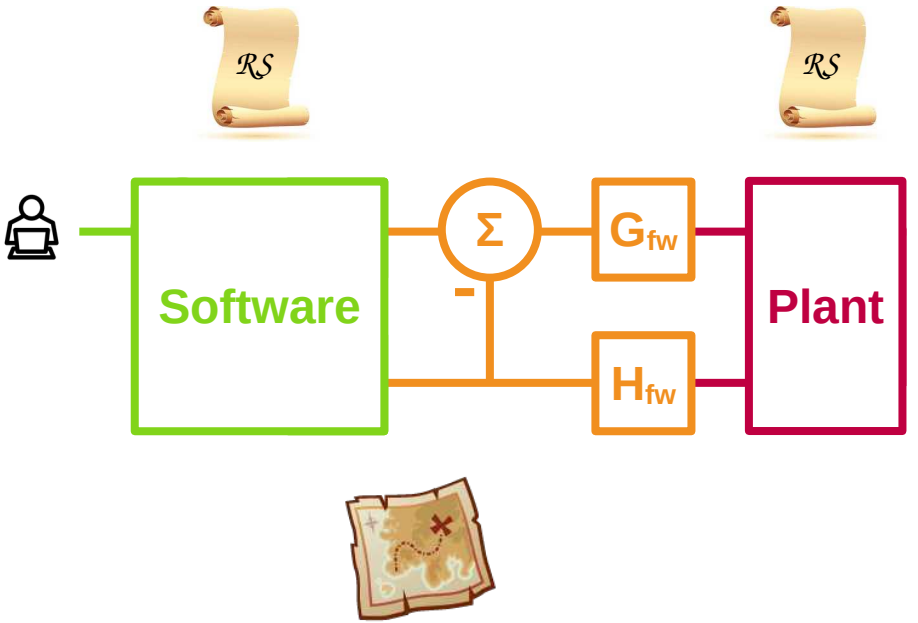




Development Worklow

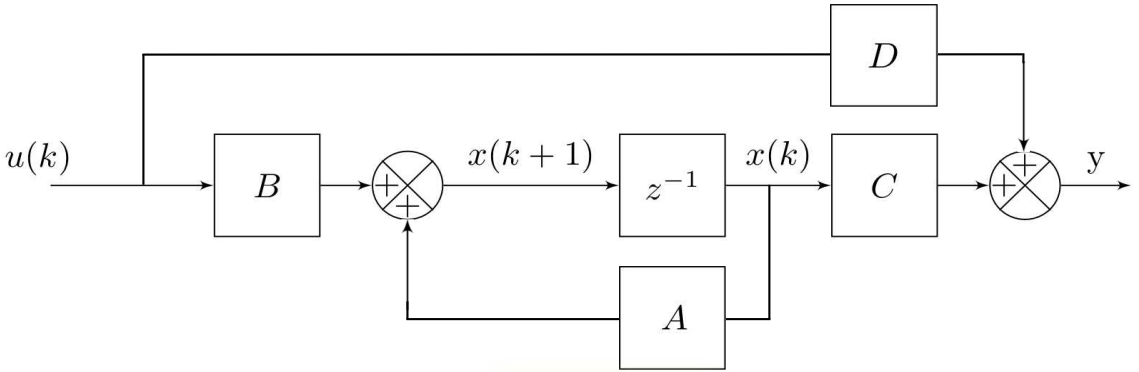
Firmware Developer Perspective





Problem Definition

on Realization of a Controller in State Space



$$x(k+1) = Ax(k) + Bu(k)$$
$$y(k) = Cx(k) + Du(k)$$

where

$x(k) \in R^n$ is the state vector

$y(k) \in R^q$ is the output vector

$u(k) \in R^p$ is the input vector

$A \in R^{n \times n}$ is the state matrix

$B \in R^{n \times p}$ is the input matrix

$C \in R^{q \times n}$ is the output matrix

$D \in R^{q \times p}$ is the feedforward matrix

$\mathcal{RS}$

p = q = 1

n = 4

u = 18 bits

y = 18 bits (sat)

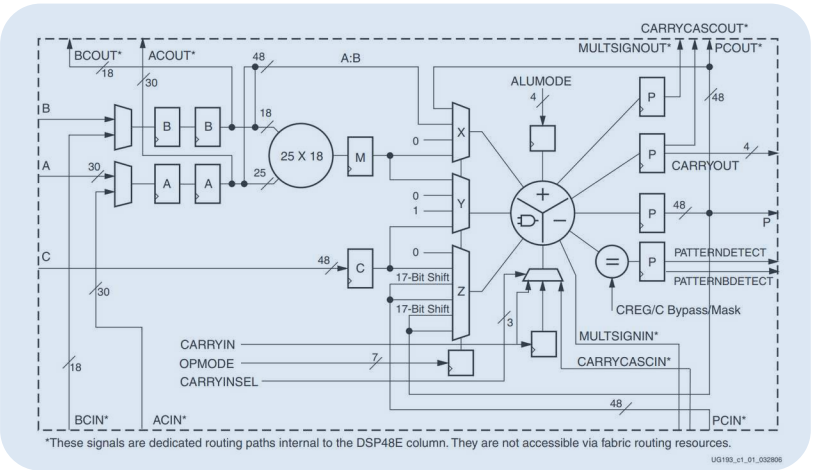
coef = 25 bits

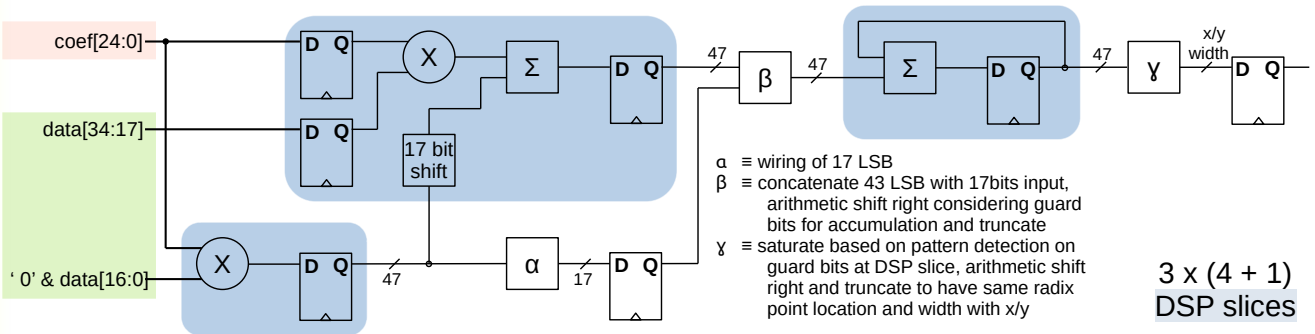
$coef_{int}$ = 1 bit

x > 32 bits (sat)

$T_s = 9 \times T_{clk}$

$$\begin{bmatrix} x(k+1) \\ y(k) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x(k) \\ u(k) \end{bmatrix}$$

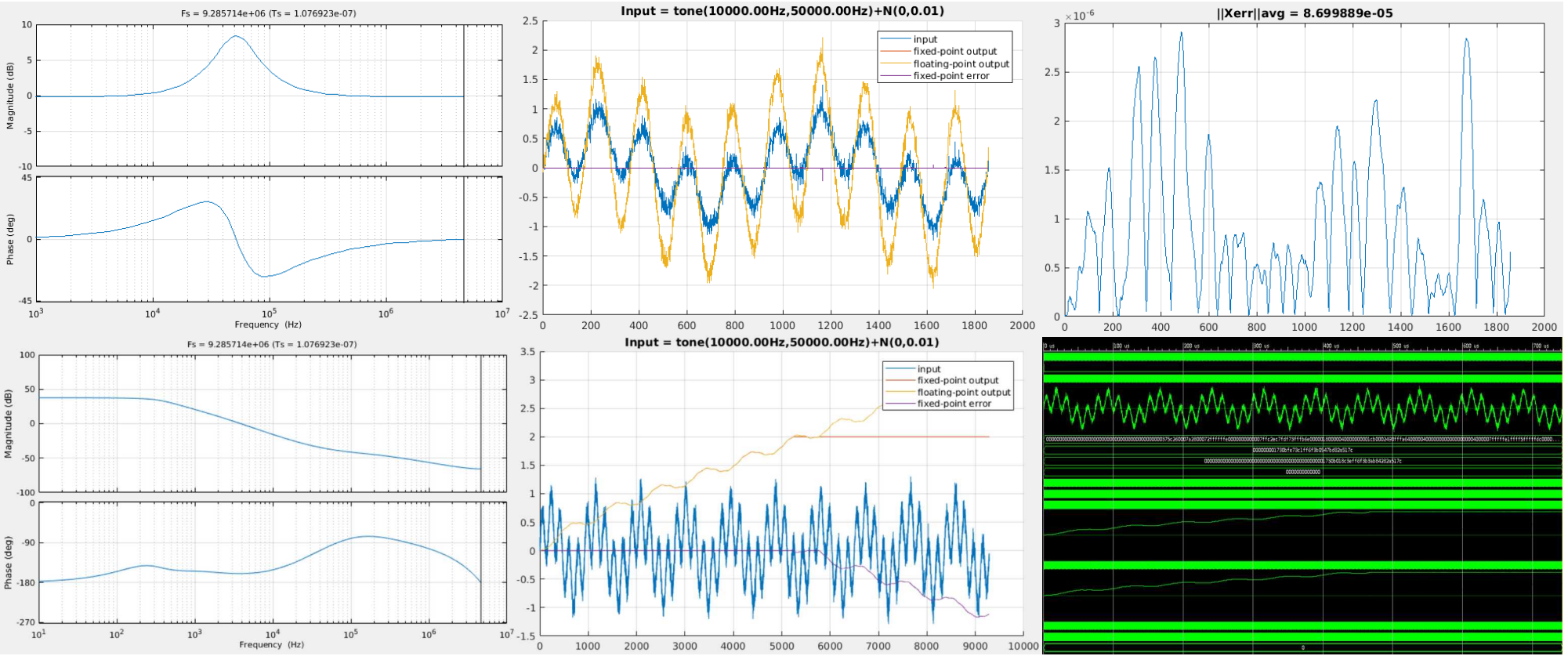




3 x (4 + 1) DSP slices

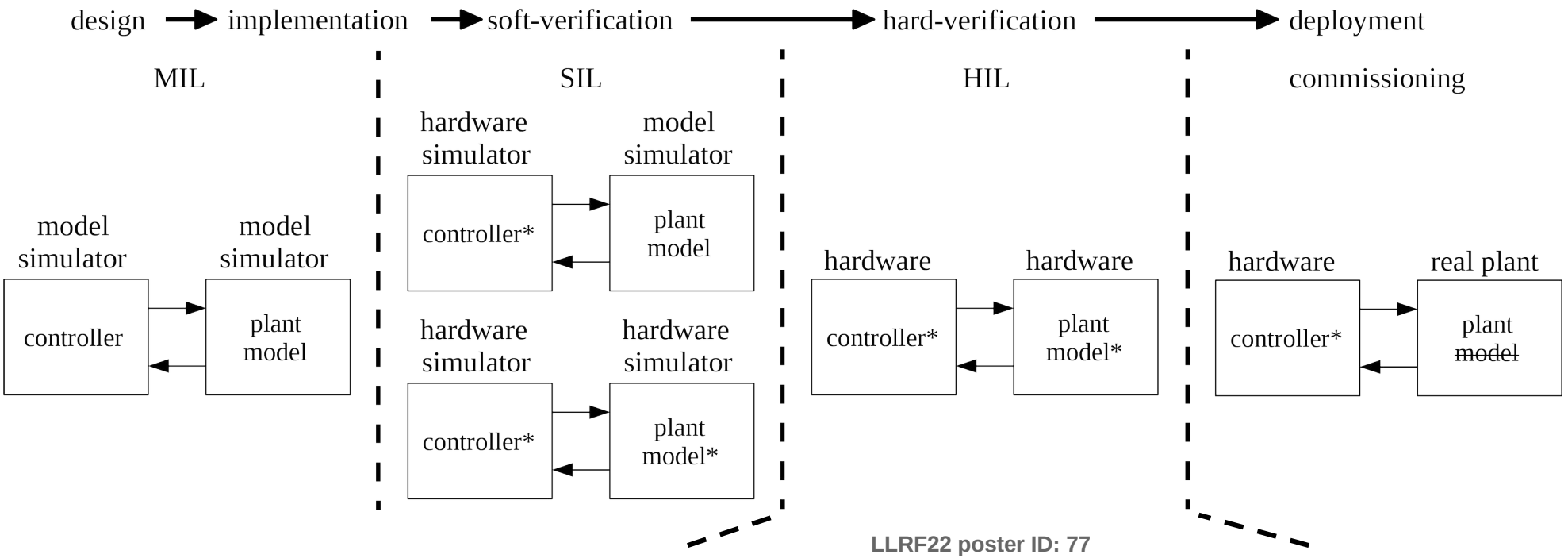
An Effective but Tedious Solution

Bit and Cycle Accurate Modeling



Model Based Design

As a Complete Workflow



LLRF22 poster ID: 77

The Self Excited Loop Cavity Field Controller and The Cavity Simulator Implemented in MTCA.4 System

L. Butkowski, C. Gümüs, J. Branlard
Deutsches Elektronen-Synchrotron (DESY) Hamburg, Germany

* implemented design

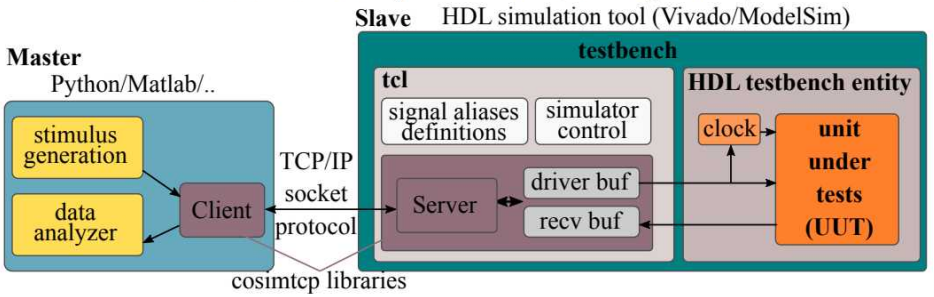
Co-Simulation

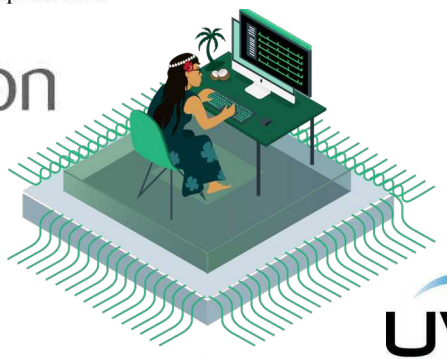
An Alternative to Manual Modeling of Design Behavior

17th Int. Conf. on Acc. and Large Exp. Physics Control Systems ICALEPCS2019, New York, NY, USA JACoW Publishing
ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-WEPHA023

CO-SIMULATION OF HDL USING PYTHON AND MATLAB OVER Tcl TCP/IP SOCKET IN XILINX VIVADO AND MODELSIM TOOLS

Ł. Butkowski*, B. Dursun, C. Gumus, M. K. Karakurt
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany



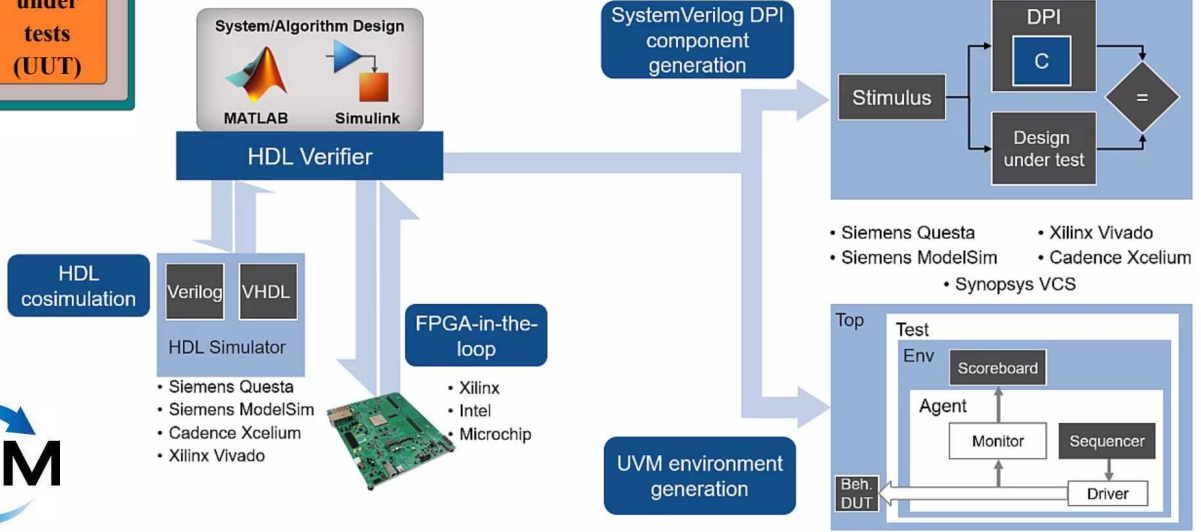


github.com/pyuvm

External Language Interfaces for HDL

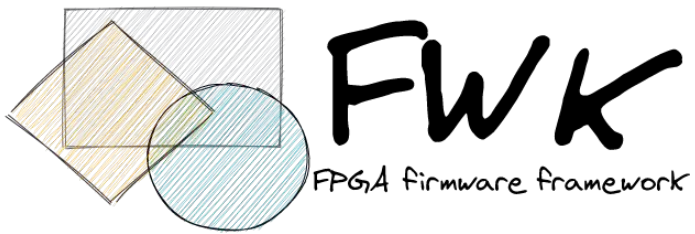
(System)Verilog
- VPI (Verilog 2005, PLI 2.0)
- DPI

VHDL
- VHPI (2008, 2019)
- FLI (ModelSim, Questa)
- VHPIDIRECT (GHDL)
- VFFI / VDPI (202X)

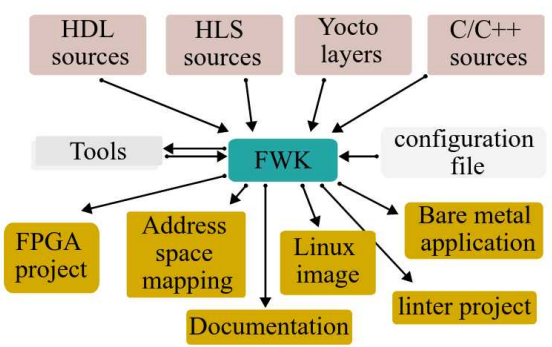


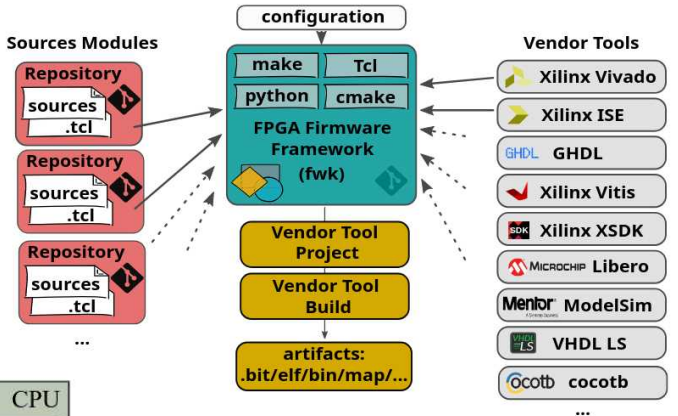
DESY.MSK.FWK

An Open Source Firmware Development Framework



repo: gitlab.desy.de/fpgafw/fwk
doc : fpgafw.pages.desy.de/docs-pub/fwk





THE DESY OPEN SOURCE FPGA FRAMEWORK

L. Butkowski*, A. Bellandi, B. Dursun, C. Gümüs, K. Schulz,
M. Büchler, N. Omidsajedi, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

MO4AO03

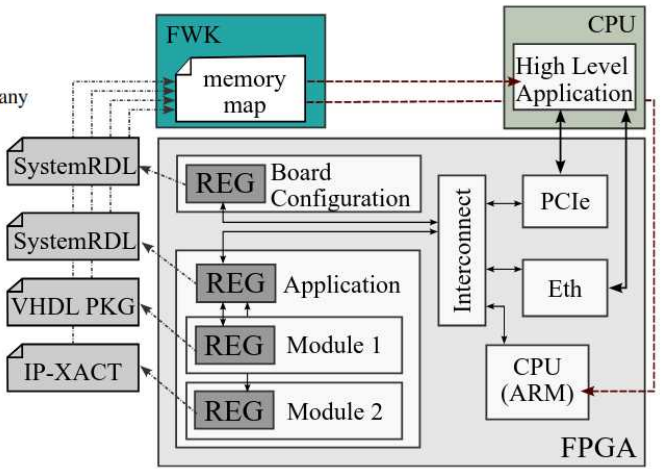
ICALEPCS CAPE TOWN SOUTH AFRICA 2023

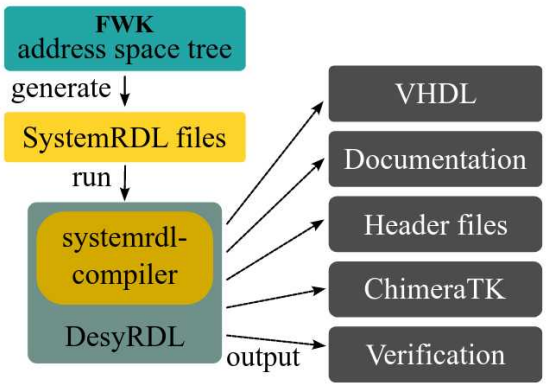
WEPGF074

ICALEPCS 2015
International Conference on Accelerator & Large Experimental Physics Control Systems

FPGA FIRMWARE FRAMEWORK FOR MTCA.4 AMC MODULES

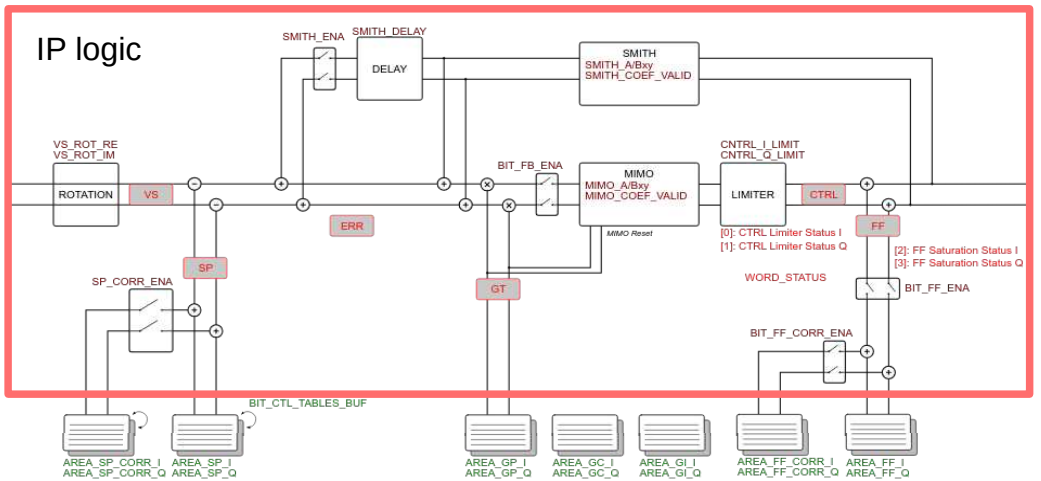
Lukasz Butkowski, Tomasz Kozak, Bin Yang, DESY, Hamburg, Germany
Paweł Prędki, DMCS, Lodz University of Technology, Lodz, Poland
Radoslaw Rybaniec, ISE, Warsaw University of Technology, Warsaw, Poland

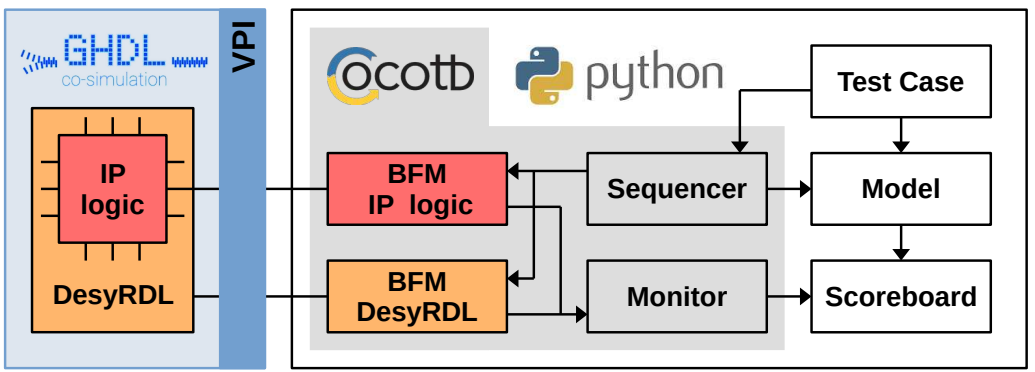


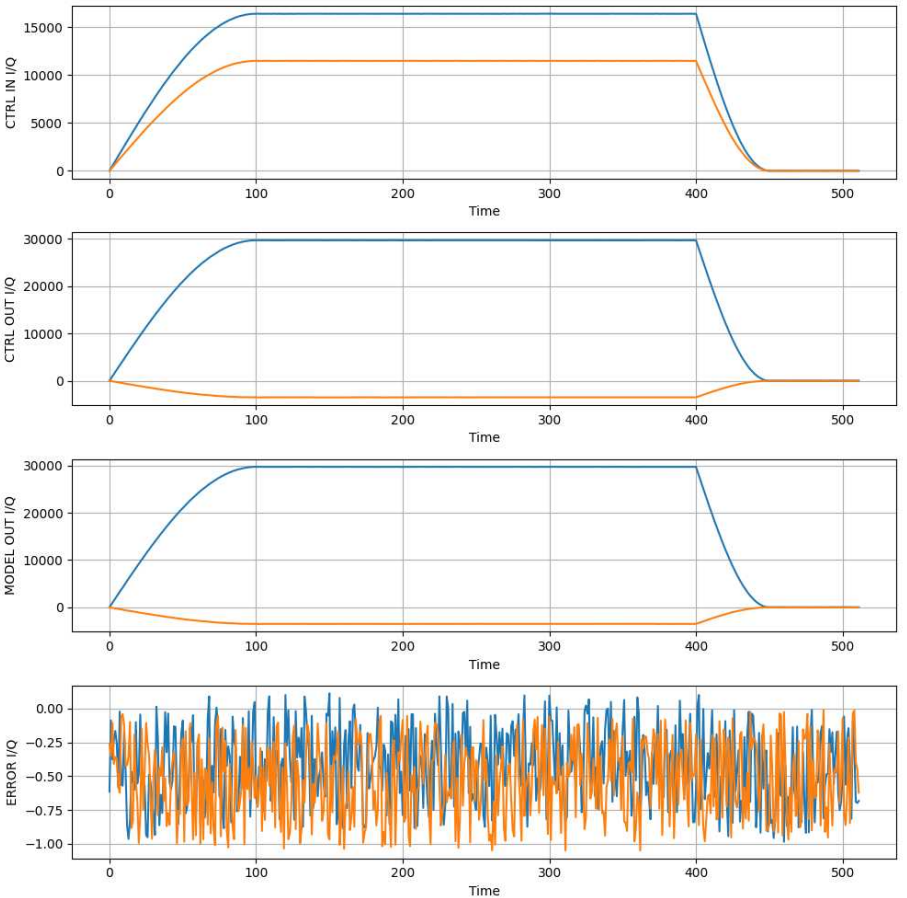


Open Loop Verification

of the core FPGA IP for LLRF control

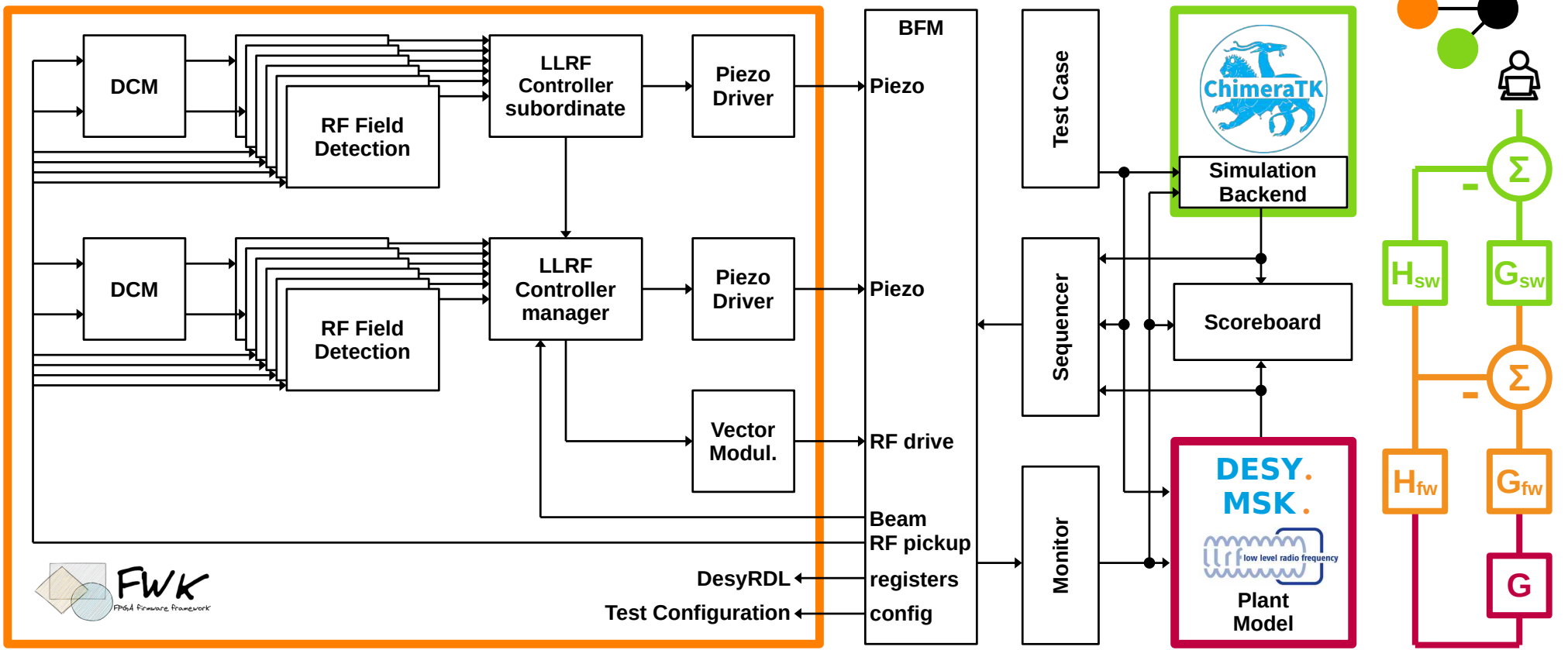






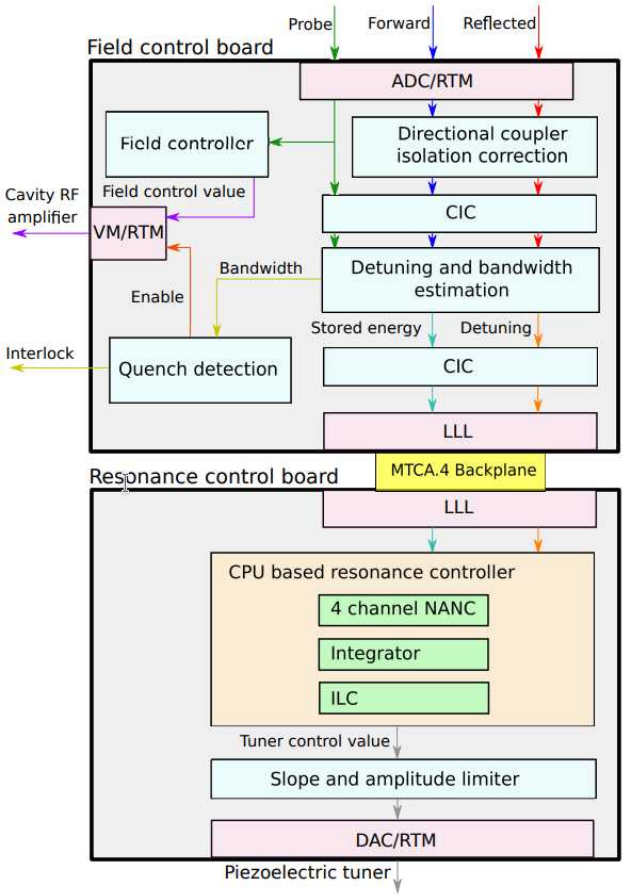
Closed Loop Verification

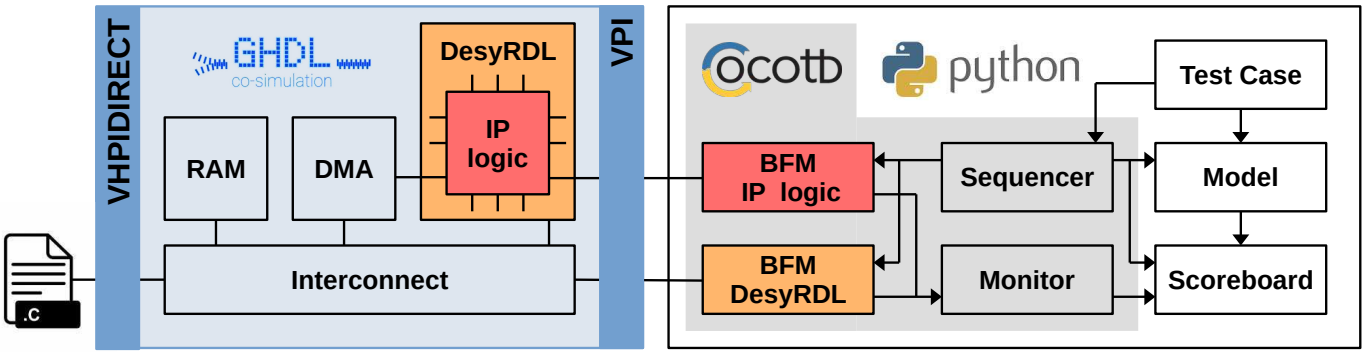
of Multi-Cavity LLRF Control System



Future Work

Co-Simulation for Co-Processing





14th International Particle Accelerator Conference,Venezia JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: doi/jacow-ipac2023-thpa090/index.html

A MTCA.4-BASED RESONANCE CONTROLLER FOR SUPERCONDUCTING CAVITIES

A. Bellandi*, M. Buechler, L. Butkowski, B. Dursun, C. Gumus, J. Branlard,
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Thank you.

Model Based Verification
for Multi-Cavity LLRF Control Systems

LLRF Workshop
Gyeongju, Republic of Korea, 26.10.2023

DESY.
Deutsches
Elektronen-Synchrotron

www.desy.de

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

MSK.
Maschine Strahlkontrollen

Burak Dursun
burak.dursun@desy.de
+49 40 8998 1738

LOW LEVEL RADIO FREQUENCY WORKSHOP 2023
LLRF2023

European XFEL

DESY.