LUT participation in the software and firmware tools design, preparation and delivery for ESS superconducting cavities testing and LLRF operation support

Wojciech CICHALEWSKI, Kacper KŁYS, Grzegorz JABŁOŃSKI, Rafał KIEŁBIK, Wojciech JAŁMUŻNA, Wojciech TYLMAN, Dariusz MAKOWSKI, Aleksander MIELCZAREK, Radosław TOMALA

That work has been supported by the Ministry of Science and Higher Education Republic of Poland, agreement no. 2023/WK/11

SPAS'26, Cracow, Poland 21.10.2026

- Project title:

SOFTWARE FOR SUPERCONDUCTING CAVITIES CHARACTERISATION AND THE ESS TEST STAND 2 CRYOMODULE PROGRAMME,

- Based on:

THE IN-KIND CONTRIBUTION AGREEMENT SIGNED BETWEEN EUROPEAN SPALLATION SOURCE ERIC (ESS ERIC) AND LODZ UNIVERSITY OF TECHNOLOGY (TUL)

- Project beginning:
  - **08-09.04.2024 (Project kick-off meeting)**

- Project end date:
  - **30.03.2026 (According to the last application to the MoSaHE),**

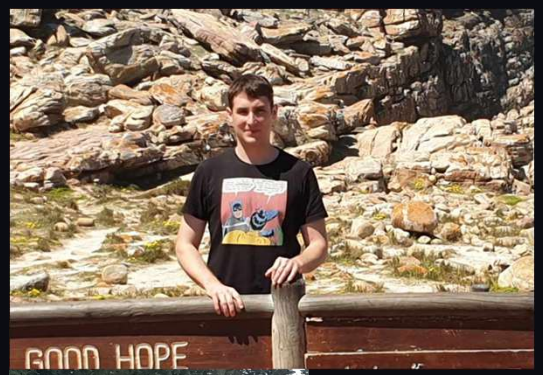
- Project supported by Polish funding agency:
- *Ministry of Science and Higher Education.* Agreement No: *Nr 2023/WK/11*

Ministerstwo Nauki i Szkolnictwa Wyższego











Name	SW dev.	FW dev.	integration	Testing
Wojciech CICHALEWSKI	+		+	+
Grzegorz (Wojciech) JABŁOŃSKI		+	+	+
Wojciech JAŁMUZNA	+	+		
Rafał KIEŁBIK		+		
Kacper KŁYS	+		+	+
Wojciech TYLMAN	+			



Main contributions

- Provide complete set with four piezo system.
- Prepare, develop, evaluate, deliver, test and deploy software (and/or possibly firmware) solutions providing functionality needed for superconducting cavities testing and characterization at the ESS Test Stand 2.
- Prepare, develop, evaluate, deliver, test and deploy software (and/or possibly firmware) solutions supporting resonators operation (configuration, monitoring and management), especially related to the Piezo Drivers (PD) provided by TUL-DMCS.

Project structure

- Identified Work Units:

1. Software tools for superconducting cavities testing and characterization at the ESS Test Stand 2,

2. Software solutions supporting resonators operation especially related to the Piezo Drivers (PD),

3. Four piezo systems delivery for the TS2 operation



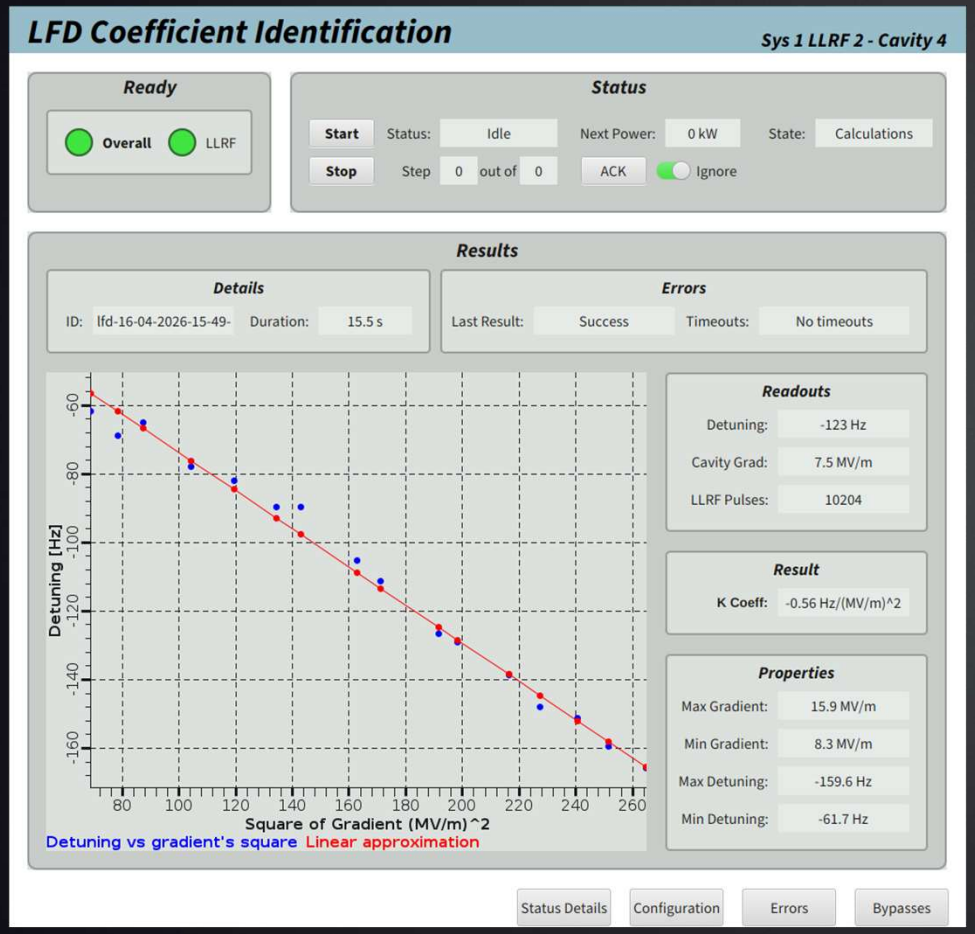




WU 1. Software tools for cavities testing and characterization at Test Stand 2

- 1.1. Tool for determining LFD static/dynamic coefficients
- 1.2. Tool for automated measurement of piezo range and polarity control
- 1.3. Identification of the longitudinal mechanical modes using PD
- 1.4. Pi-modes identification,
- 1.5. Cavity performance evaluation without beam
- 1.6. Piezo capacitance characterization,

WU 1. Tool for determining LFD static coefficients - Implementation



- Detuning measured for different cavity gradients level (open loop).
- The e3-lfdcoefficients module has a form of EPICS IOC wrapped into the e3 module.
- The process is controlled by a state machine written in SNL.
- Reads cavity gradient from LLRF IOC (max flattop value).
- Gets corresponding detuning from e3-cavityoperation IOC.
- Approximation done with GSL library.

WU 1. Tool for determining LFD static coefficients

LFD Coeff Identification

EUROPEAN SPALLATION SOURCE

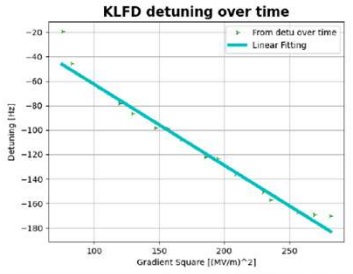
Date: 2026-04-16 15:47:49

Final result: success

USER: Aga
CAVITY_ID: 2
CRYO_MODULE_ID: 48
TEST_ID: lfd-16-04-2026-15-46-17-5
TEST_LENGTH: 15.1 s

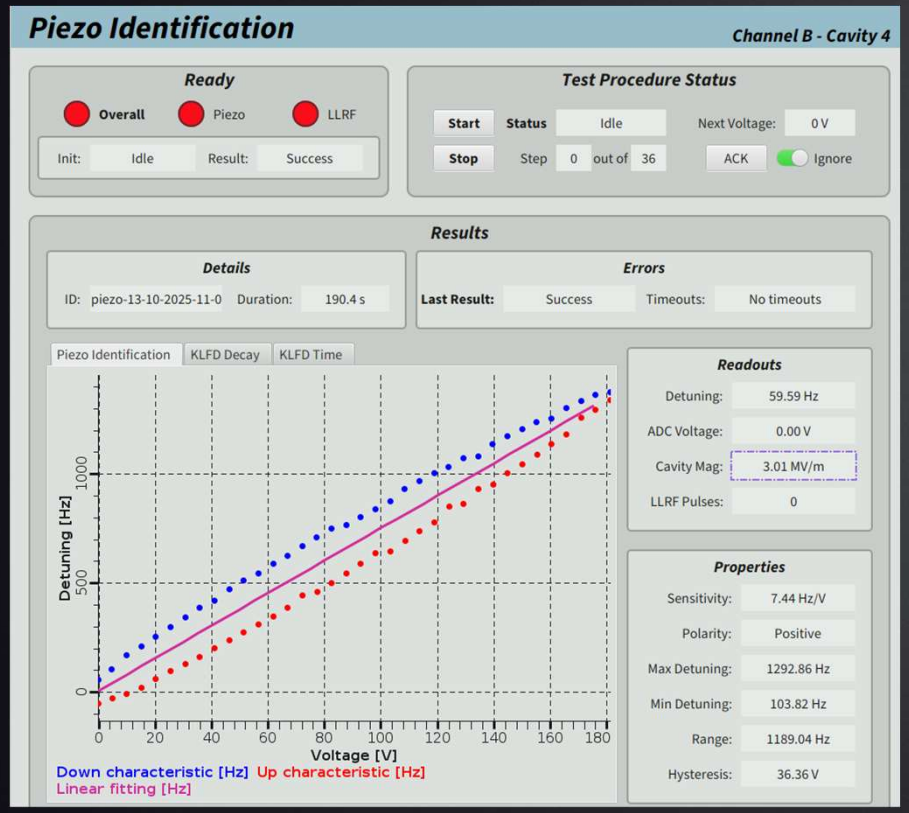
LFD Iden parameters

Name	Value
K Coeff	-0.66 Hz/(MV/m)^2
Max Detu	-169.15 Hz
Min Detu	-19.53 Hz
Max Grad	16.41 MV/m
Min Grad	8.68 MV/m



- Reports contain K_{LFD} coefficient value and the plot with measured characterization.
- Since CM34 – each cryomodule is tested in TS2.
- Results available in TS2 olog.
- 03.2026 – first characterization of linac – results (needs to be repeated)

WU 1. Tool for automated measurement of piezo range and polarity control - Implementation



- Scanning up and down the DC voltage component
- The **e3-piezoidentification** module has a form of EPICS IOC wrapped into the e3 module.
- There are two state machines implemented in an SNL language:
  - voltage ramping,
  - identification.
- Identified piezo parameters:
  - sensitivity,
  - polarity,
  - range,
  - hysteresis.

WU 1. Tool for automated measurement of piezo range and polarity control

Piezo Identification

EUROPEAN SPALLATION SOURCE

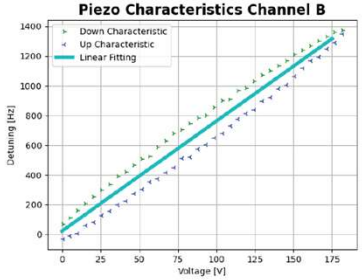
Date: 2026-04-16 14:15:58

Final result: success

USER: Aga
CAVITY_ID: 1
CRYO_MODULE_ID: 48
STACK: B
TEST_ID: piezo-16-04-2026-13-41-26-2
TEST_LENGTH: 184.5 s

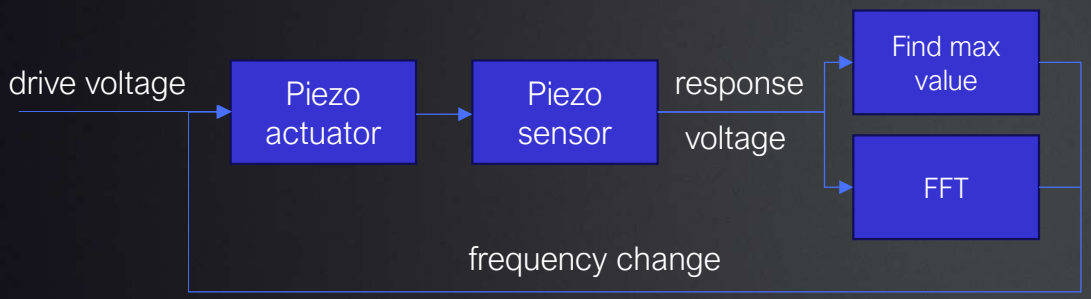
Piezo parameters

Name	Value
Sensitivity	7.39 Hz/V
Polarity	Positive [-]
Range	1177.48 Hz
Hysteresis	31.28 V



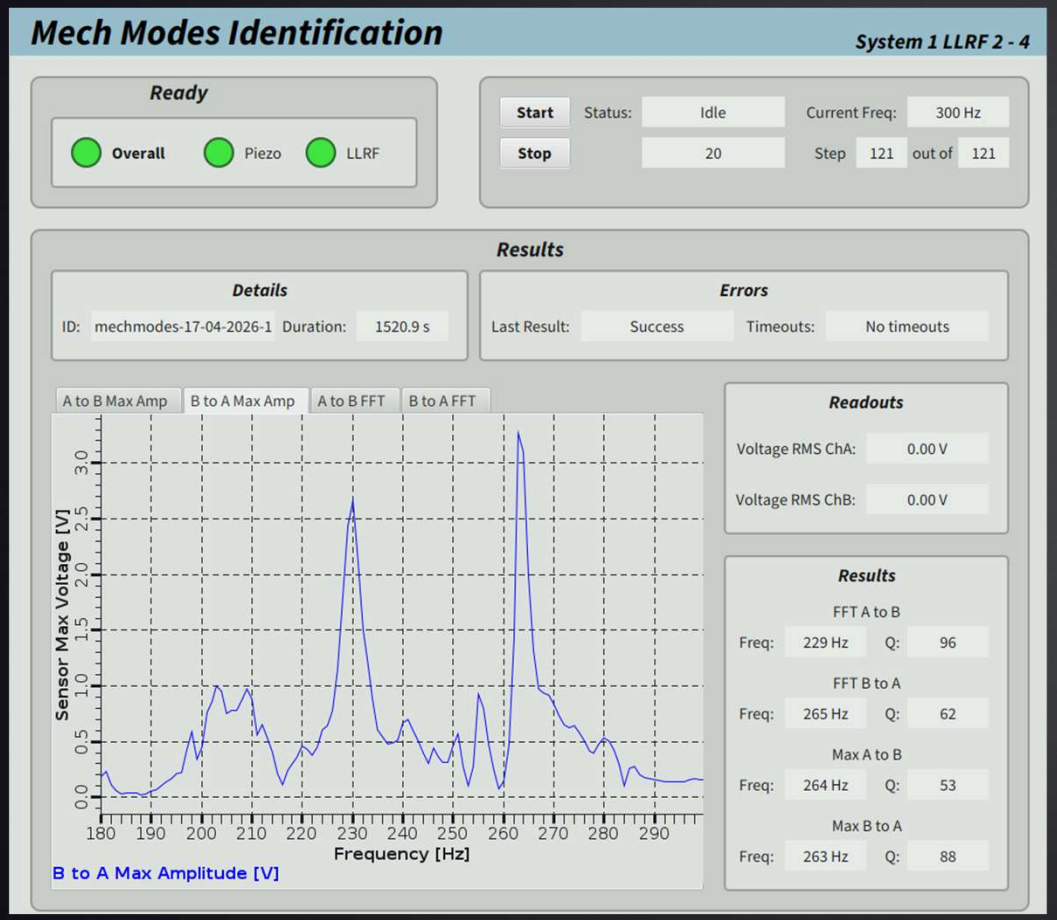
- The procedure can be launched for single channel or for both channels.
- Reports contain computed parameters and plots (for one or both channels).
- First measurement in TS2 – CM41, all results in the ESS dedicated logbook.
- 03.2026 – full characterization of the whole accelerator (all types of cavities) – results.

WU 1. Identification of the longitudinal mechanical modes using PD - Algorithm



- Three measurement modes: piezo A→B, piezo B→A, or bidirectional sweep.
- SNL state machine performs automated sine frequency sweep.
- Sensor response is recorded to identify resonance peaks
- FFT verifies excitation frequency and peak amplitudes.
- Results are plotted in the operator panel for comparison.

WU 1. Identification of the longitudinal mechanical modes using PD - Implementation



- The **e3-mechanicalmodes** module has a form of EPICS IOC wrapped into the e3 module.
- Q is calculated for the highest resonance peak.
- The „Max” method has better resolution (FFT is limited due to piezo number of samples and its sampling frequency).

WU 1. Identification of the longitudinal mechanical modes using PD

Mechanical Modes Identification

EUROPEAN SPALLATION SOURCE

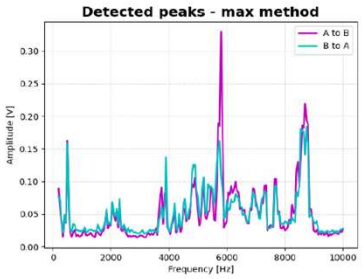
Date: 2026-04-22 12:14:50

Final result: success

USER: Kacper
CAVITY_ID: 1
CRYO_MODULE_ID: cm48
TEST_ID: mechmodes-22-04-2026-10-55-04-6
TEST_LENGTH: 2409.8 s

Mechanical Modes Iden parameters

Name	Frequency [Hz]	Q factor
Peak FFT A to B	500 Hz	5
Peak FFT B to A	500 Hz	5
Peak Max A to B	5800 Hz	58
Peak Max B to A	8750 Hz	25



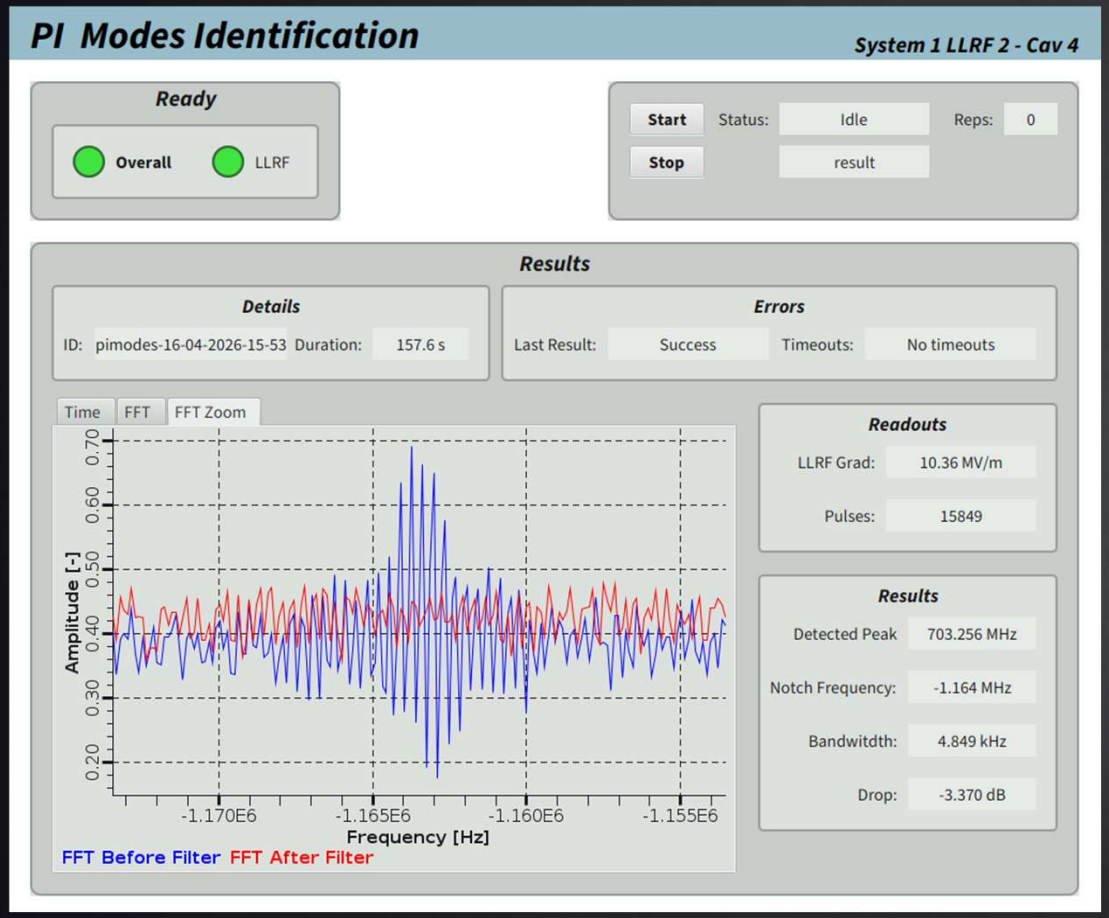
- Reports contain computed parameters and plots (for A to B and B to A).
- First measurement in TS2 – CM47, all results in the TS2 Olog.
- 12.2025 – 01.2026 – full characterization of the whole accelerator (all types of cavities) – results.

WU 1. Pi-modes modes identification - Algorithm



- Algorithm computes FFT amplitude spectrum and identifies the strongest mode peak
- Frequency range is divided into fragments to detect local maxima using thresholds.
- Peak selection is based on maximum amplitude and peak width analysis.
- Peak frequency and width are used to configure the LLRF notch filter.
- Current implementation supports detection of multiple highest peaks for future use.

WU 1. Pi-modes modes identification - Implementation



- The e3-cavitypimodes module has a form of EPICS IOC wrapped into the e3 module.
- The procedure is controlled by the SNL state machine.
- Works in the open loop and takes data from LLRF firmware internal channel (after filtration – before controller).

WU 1. Pi-modes modes identification - Algorithm

Cavity PI Modes Identification

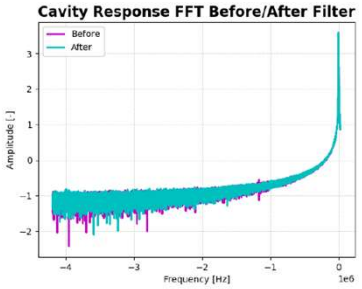
EUROPEAN SPALLATION SOURCE

Date: 2026-04-16 15:06:24

Final result: success

USER: Aga
CAVITY_ID: 3
CRYO_MODULE_ID: 48
TEST_ID: pimodes-16-04-2026-15-03-36-6
TEST_LENGTH: 37.6 s

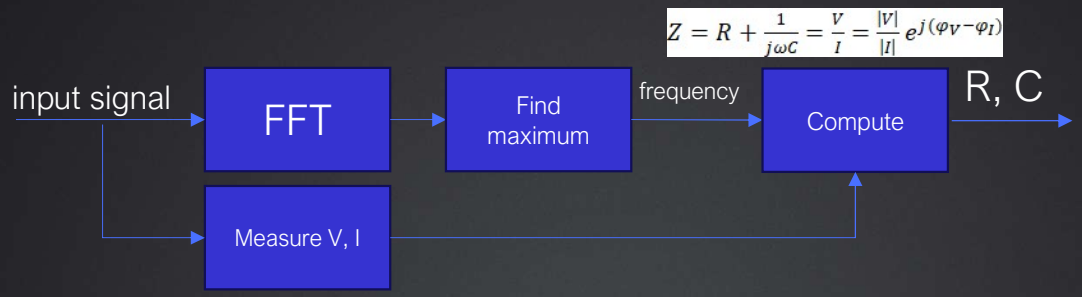
Cavity PI Modes Iden parameters	
Name	Value
Detected Peak	703.253 MHz
Notch Frequency	-1.167 MHz
Bandwidth	49.193 kHz
Signal Drop	-1.474 dB



- Reports contain calculated notch filter parameters and detected pi-mode frequency.
- First measurement in TS2 – CM34, all results in the TS2 Olog.
- 03.2026 – full characterization of the whole accelerator – results.

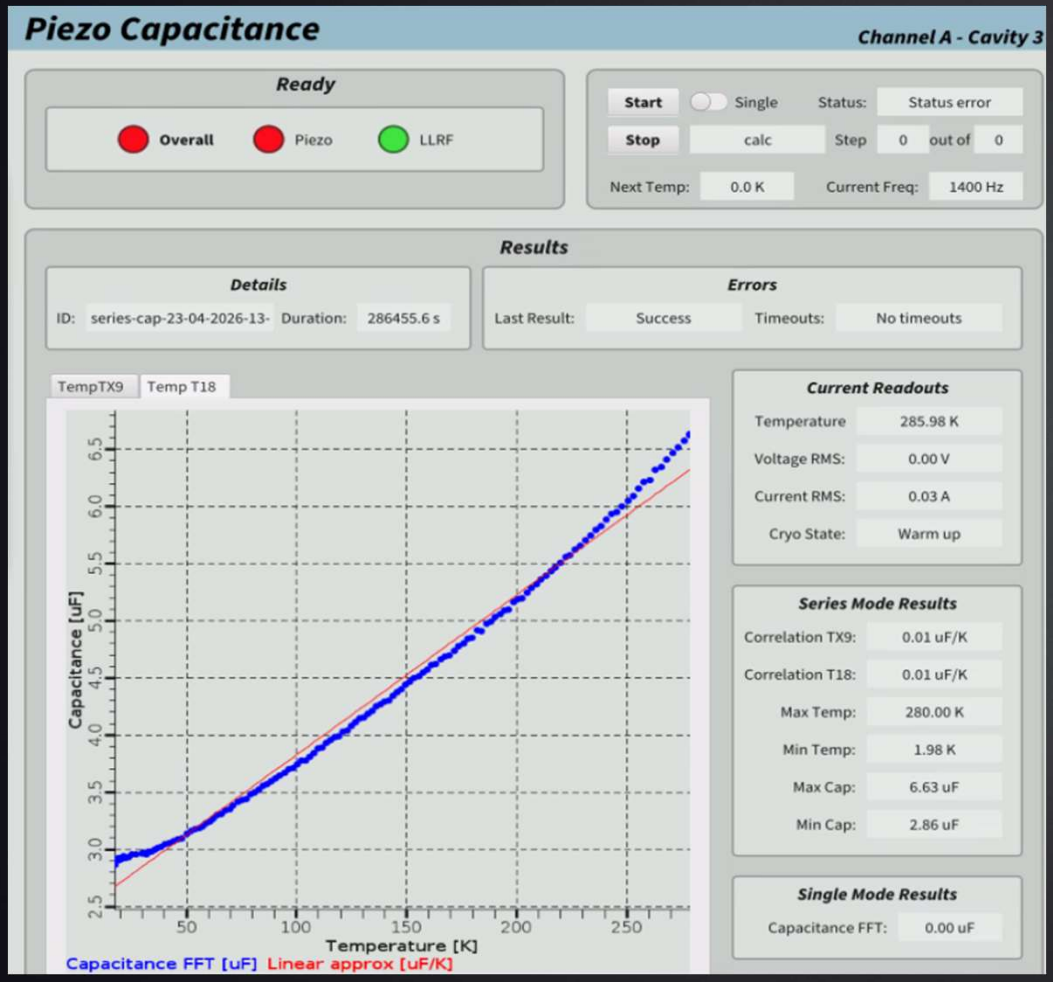
EUROPEAN SPALLATION SOURCE

WU 1. Piezo capacitance characterization - Algorithm



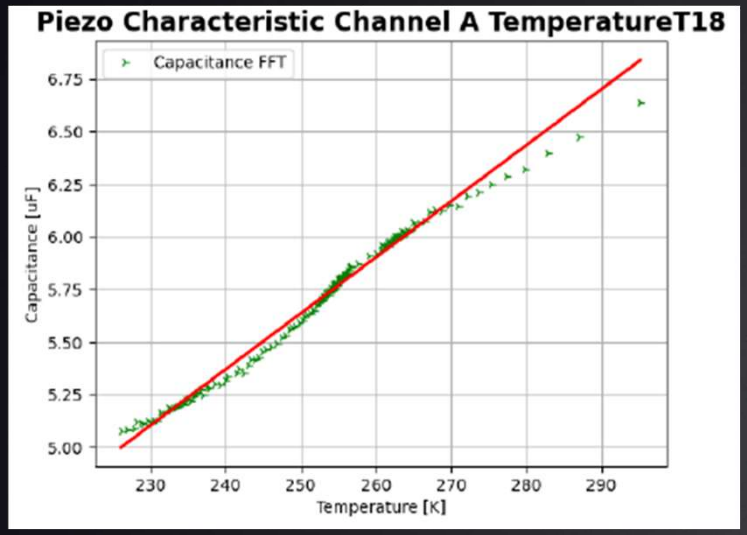
- Uses FFTW-based FFT to determine voltage and current phase and amplitude.
- Impedance is calculated from voltage-to-current ratio in a single acquisition.
- Algorithm identifies the excitation frequency from the highest FFT peak.
- Voltage and current phase information are used to compute impedance.
- Capacitance is derived directly from the calculated impedance.

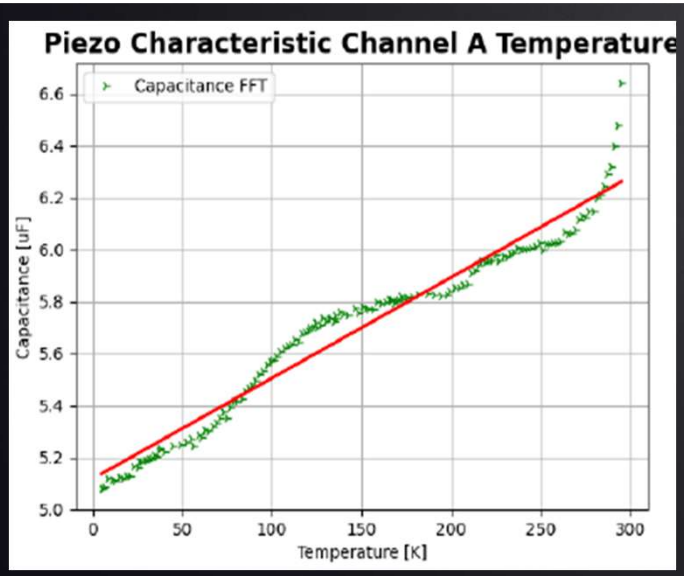
WU 1. Piezo capacitance characterization - Implementation



- The **e3-piezocapacitance** module has a form of EPICS IOC wrapped into the e3 module.
- The procedure is controlled by two SNL state machines.
- First one is responsible for voltage ramping, second for the procedure.
- Can be only used when LLRF is off.

WU 1. Piezo capacitance characterization





Final result: success

USER: MarekSkiba

CAVITY_ID: 2

CRYO_MODULE_ID: 48

STACK: A

TEST_ID: series-cap-30-03-2026-10-56-23-2

TEST_LENGTH: 96358.1 s

Piezo parameters

Name	Value
Correlation	3.88 nF/K
CorrelationT18	26.62 nF/K
Max Temperature	295.14 K
Min Temperature	4.99 K
Max Capacitance	6.64 uF
Min Capacitance	5.08 uF

- Reports contain two characteristics – TX9 and T18.
- First measurement in TS2 – CM39, all results in the TS2 Olog.
- From first linac cooldown – each accelerator action is registered.

WU 1. Cavity performance evaluation without beam

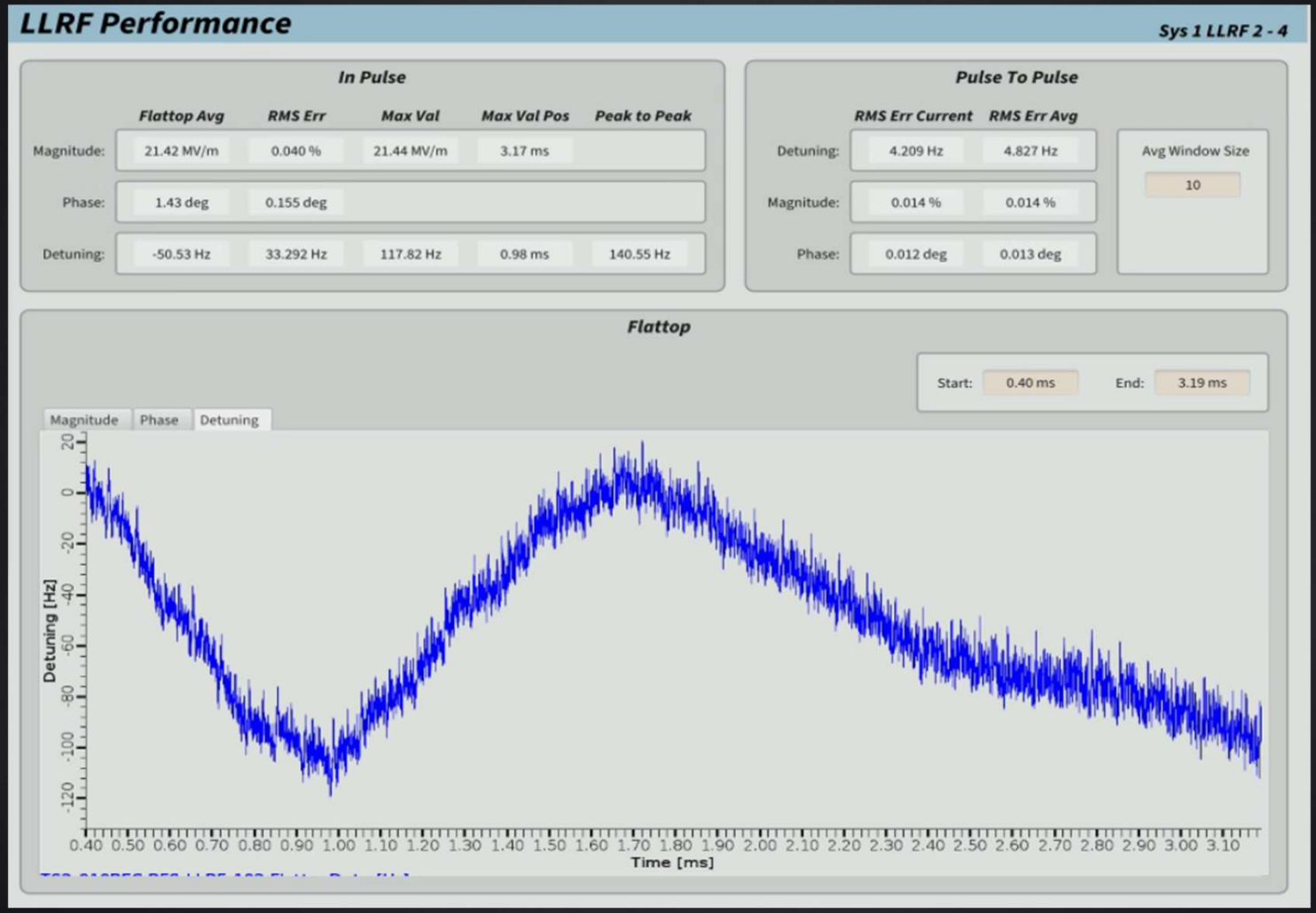
In pulse metrics (calculated over the flattop area of a single pulse) are as follows:

- amplitude, phase, detuning RMS error,
- amplitude, phase, detuning flattop average,
- amplitude and detuning max values and their position (corresponding time),
- detuning peak to peak.

The pulse-to-pulse metrics (comparing values of two subsequent pulses) are:

- amplitude, phase, detuning RMS error,
- moving average of amplitude, phase, and detuning RMS error.

WU 1. Cavity performance evaluation without beam



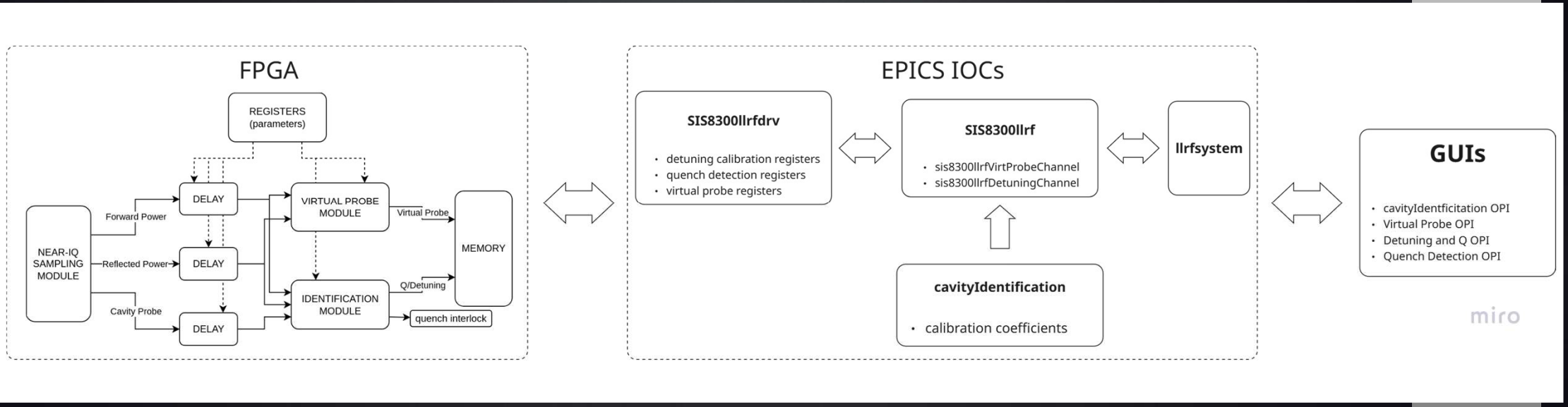
WU 2. Software solutions supporting resonators operation especially related to the Piezo Drivers

- ▸2.1. Cavity parameters identification (bandwidth and detuning) (integrated in the LLRF IOC)
- ▸2.2. Overall status monitoring (grad. phase, regulation performance, etc.)
- ▸2.3. Piezo capacitance measurement
- ▸2.5. Piezo range optimization
- ▸2.6. Forward and reflected power signal calibration (cross-talk reduction/directivity) verification
- ▸2.7. Virtual probe signal monitoring
- ▸2.8. Slow and Fast cavity quench detection



Software structure

- 3 layers:
  - Firmware layer
  - EPICS IOC layer
  - Graphical operator interface



New LLRF controller modules

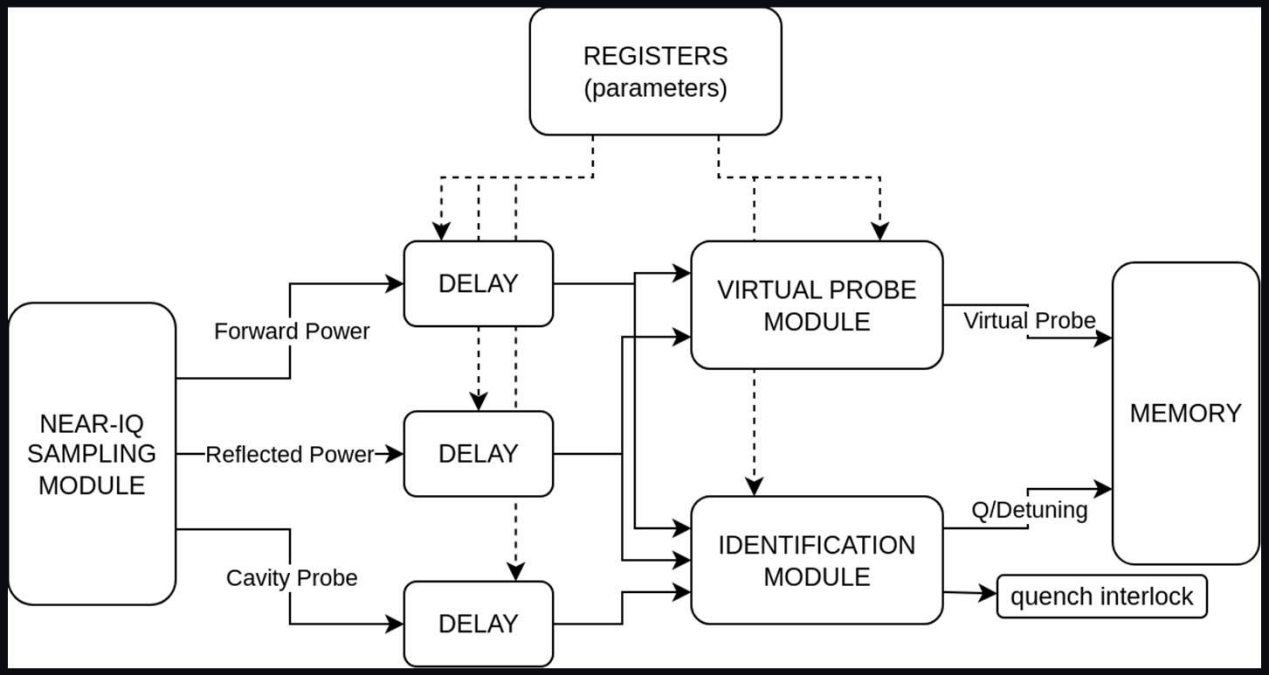
Cavity envelope equation

$$\dot{V} = (-\omega_{1/2} + j\Delta\omega)V + \frac{\rho\omega_0}{2}I$$

$$\dot{v}_{c,cal} + (\omega_{1/2} - j\Delta\omega)v_{c,cal} = \frac{2\beta}{\beta+1}\omega_{1/2}v_{f,cal}$$

Virtual Probe (from fwd and refl.)

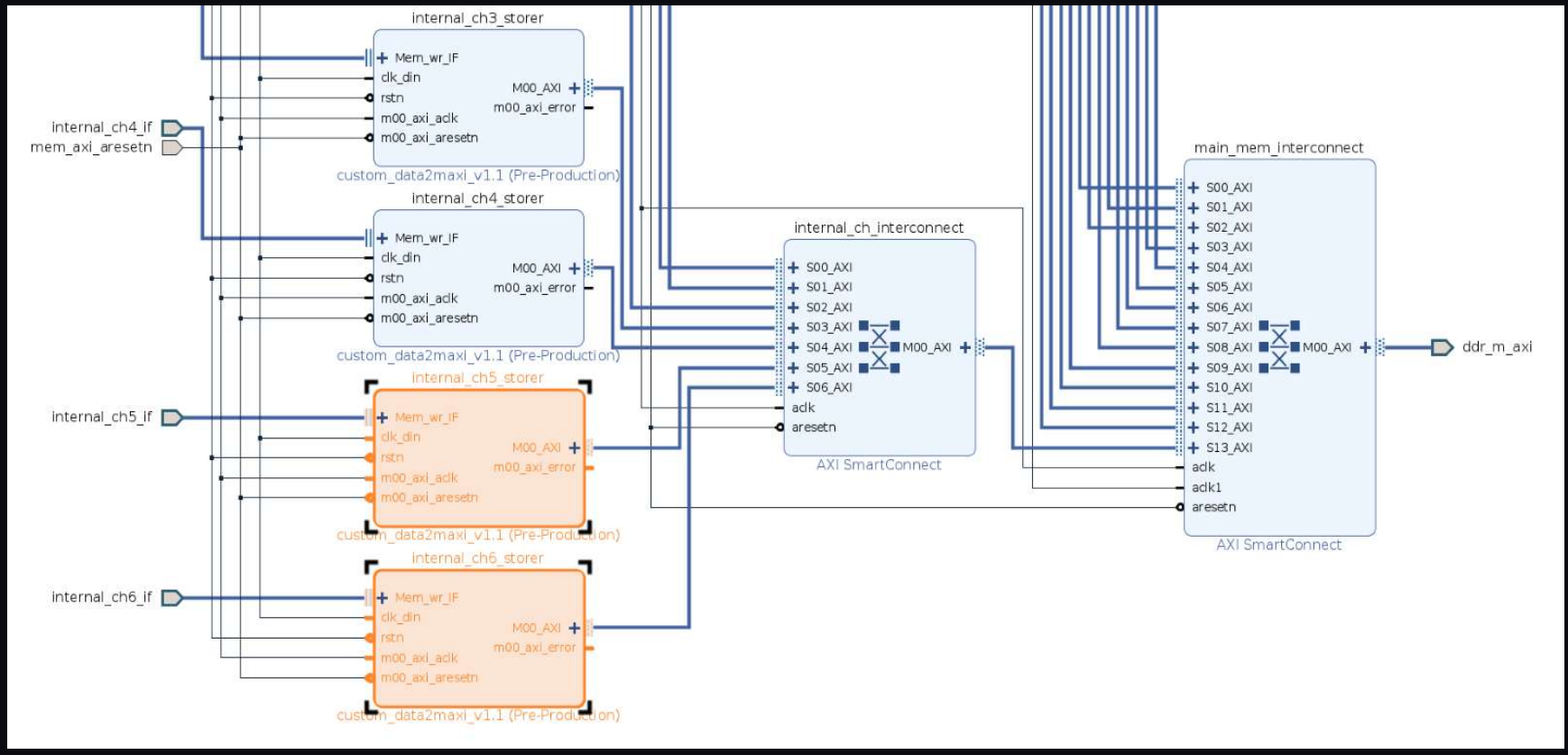
$$v_{c,cal} = v_{f,cal} + v_{r,cal}$$



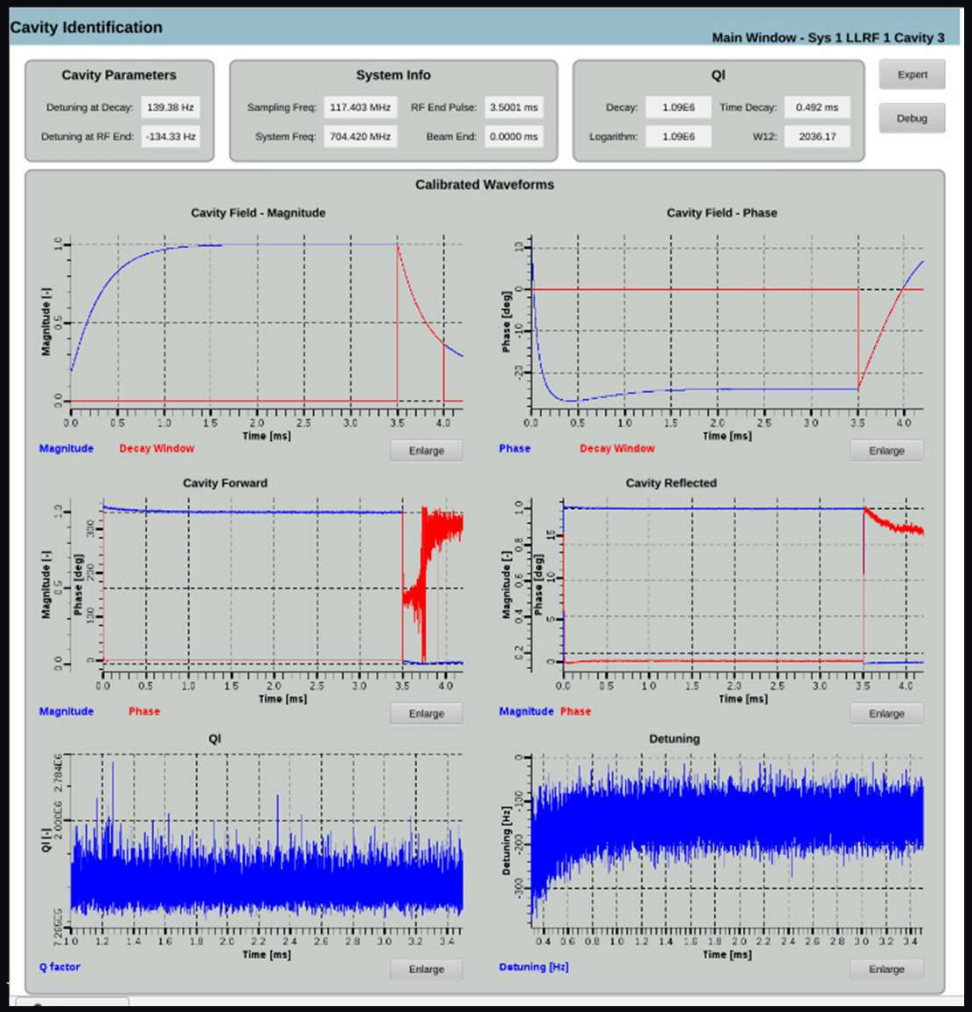
llrf_types_pkg.vhdl

```
781     );
782
783   type t_q_det_config is
784     record
785       w12_ext    : std_logic_vector(31 downto 0);
786       fwd_coef   : std_logic_vector(31 downto 0);
787       rfl_coef   : std_logic_vector(31 downto 0);
788       prb_coef   : std_logic_vector(31 downto 0);
789
790       delay         : std_logic_vector(31 downto 0);
791       window_length : std_logic_vector(31 downto 0);
792       config        : std_logic_vector(31 downto 0);
793       threshold     : std_logic_vector(31 downto 0);
794     end record;
795
796   constant Q_DET_CONFIG_DEFAULT : t_q_det_config := (
797     delay         => (others => '0'),
798     window_length => (others => '0'),
799     config        => (others => '0'),
800     threshold     => (others => '0'),
801
802     w12_ext  => (others => '0'),
803     fwd_coef => (30=>'1', others => '0'),
804     rfl_coef => (others => '0'),
805     prb_coef => (30=>'1', others => '0')
806   );
807
808   type t_virt_prb_config is
809     record
810       A     : std_logic_vector(31 downto 0);
811       B     : std_logic_vector(31 downto 0);
812       C     : std_logic_vector(31 downto 0);
813       D     : std_logic_vector(31 downto 0);
814       SCALE : std_logic_vector(31 downto 0);
815       DELAY : std_logic_vector(31 downto 0);
816     end record;
817
818   constant VIRT_PRB_CONFIG_DEFAULT : t_virt_prb_config := (
819     A =>     (30=>'1', others => '0'),
820     B =>     (         others => '0'),
821     C =>     (         others => '0'),
822     D =>     (30=>'1', others => '0'),
823     SCALE => (30=>'1', others => '0'),
824     DELAY => (         others => '0')
825   );
```

Two additional channels in LLRF controller memory interfaces

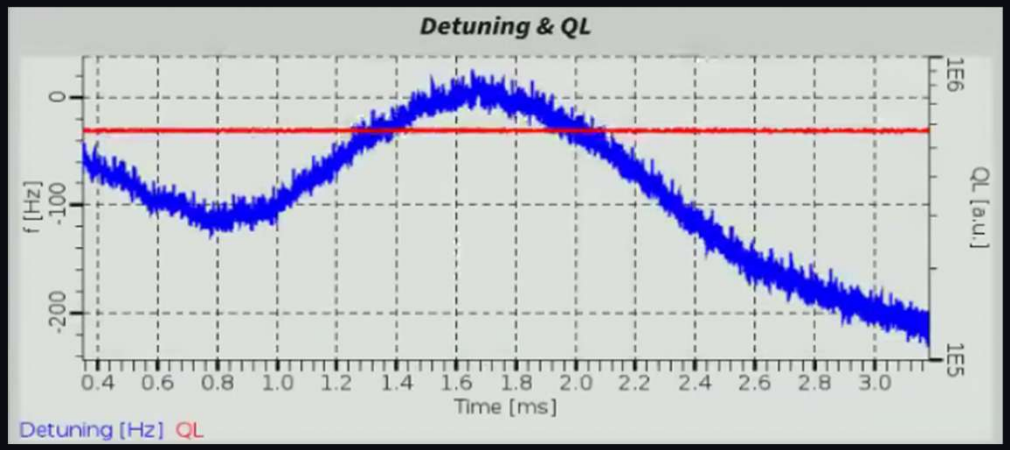


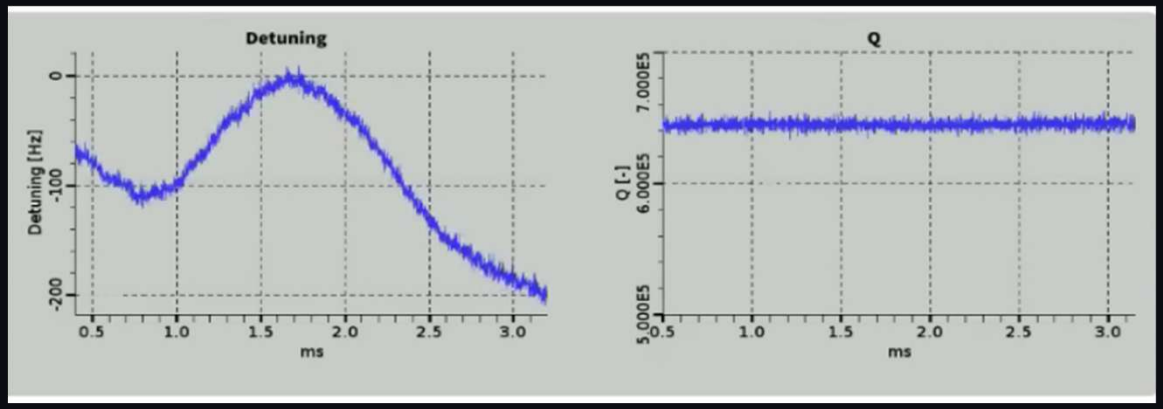
WU 2. Forward and reflected power signal calibration (cross-talk reduction/directivity) verification



- Calculates calibration coefficients to correct measured forward and reflected RF signals.
- Uses cavity pulse data and RF decay analysis to identify crosstalk and decouple both signals.
- Applies numerical methods to determine the full set of calibration coefficients.
- Reconstructs calibrated signals for online cavity diagnostics.
- Uses calibrated signals for detuning, loaded Q and virtual probe calculation.

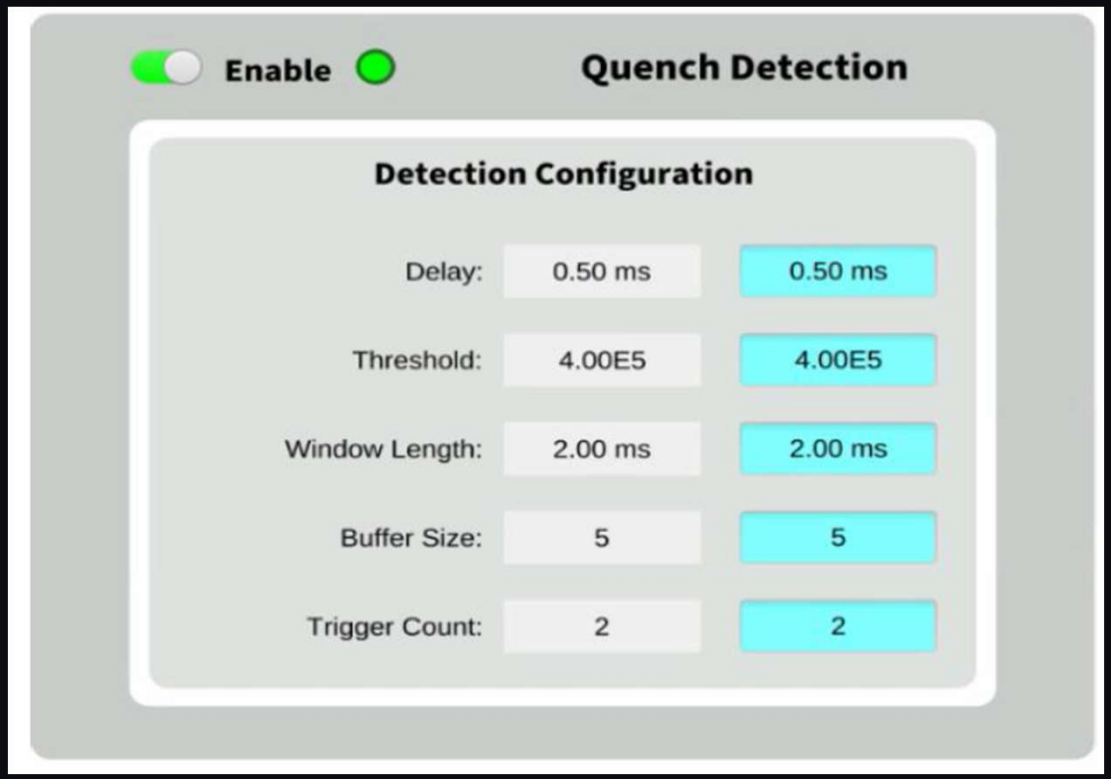
WU 2. Cavity parameters identification (bandwidth and detuning)





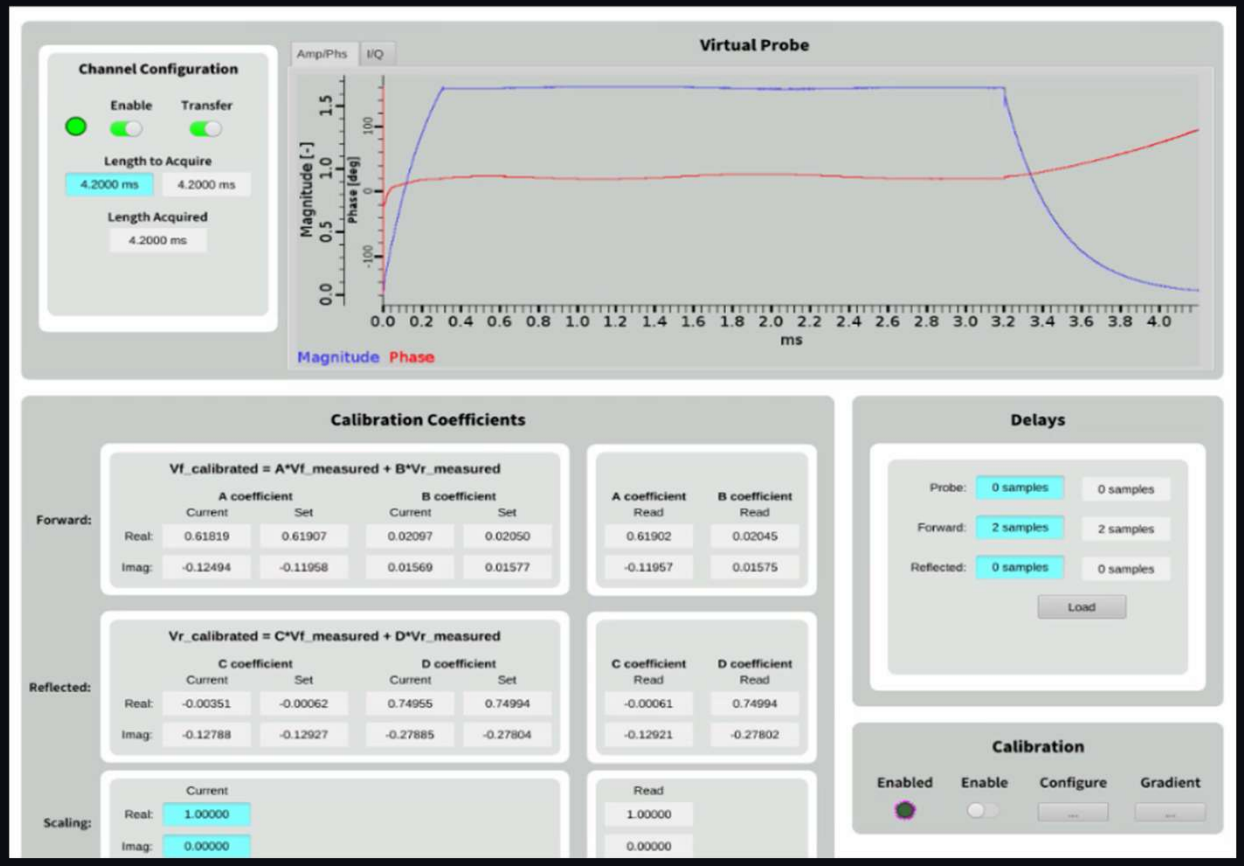
- Calibrated Vf and Vr are used to calculate Q and detuning.
- LLRF firmware has been extended with a new channel.
- Added to LLRF IOC – new classes with detuning and Q.
- Compared with existing software tool – e3-cavityoperations-ts2.

WU 2. Slow and Fast cavity quench detection



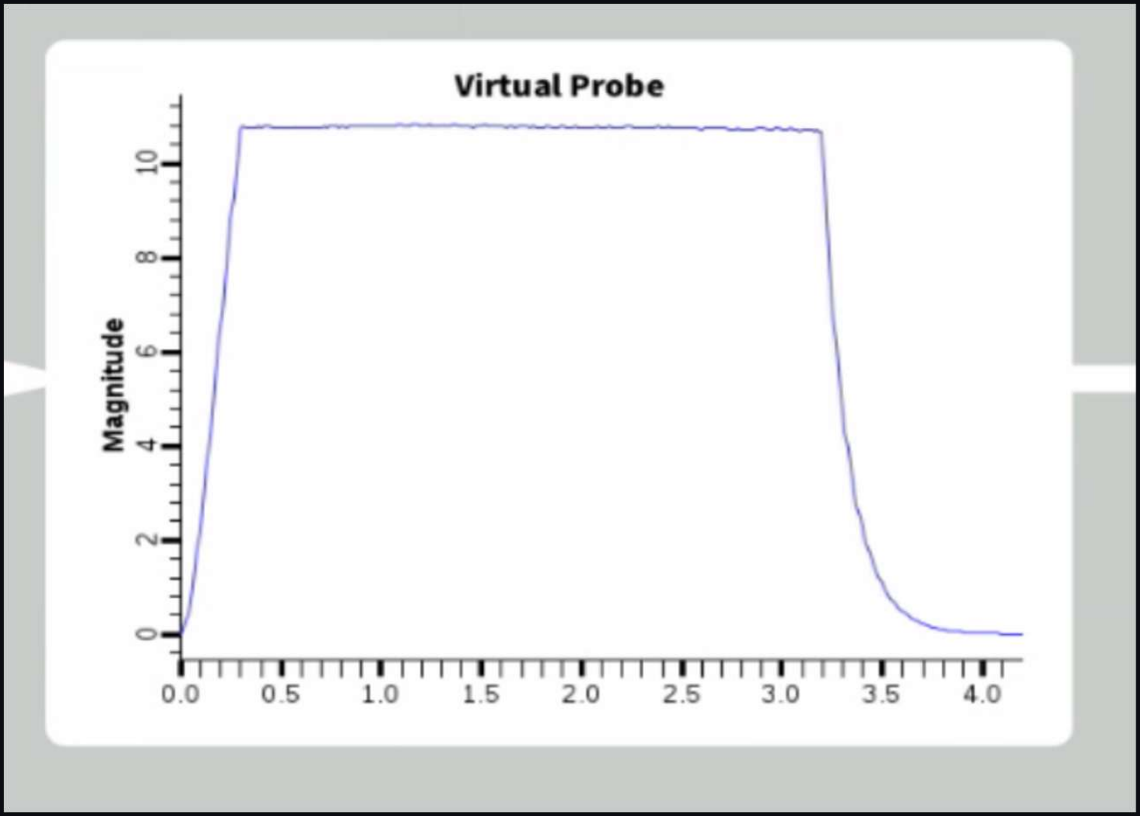
- Quench detection based on the sudden Ql drop (Energy loss),
- Configurable quench detection parameters in LLRF firmware,
- Sets RF start delay, detection threshold, and monitoring window for Q.
- Defines buffer size and number of violations required to trigger interlock.
- Allows enabling or disabling the detection system.
- Tested in TS2 – still requires verification on live system.

WU 2. Virtual probe signal monitoring



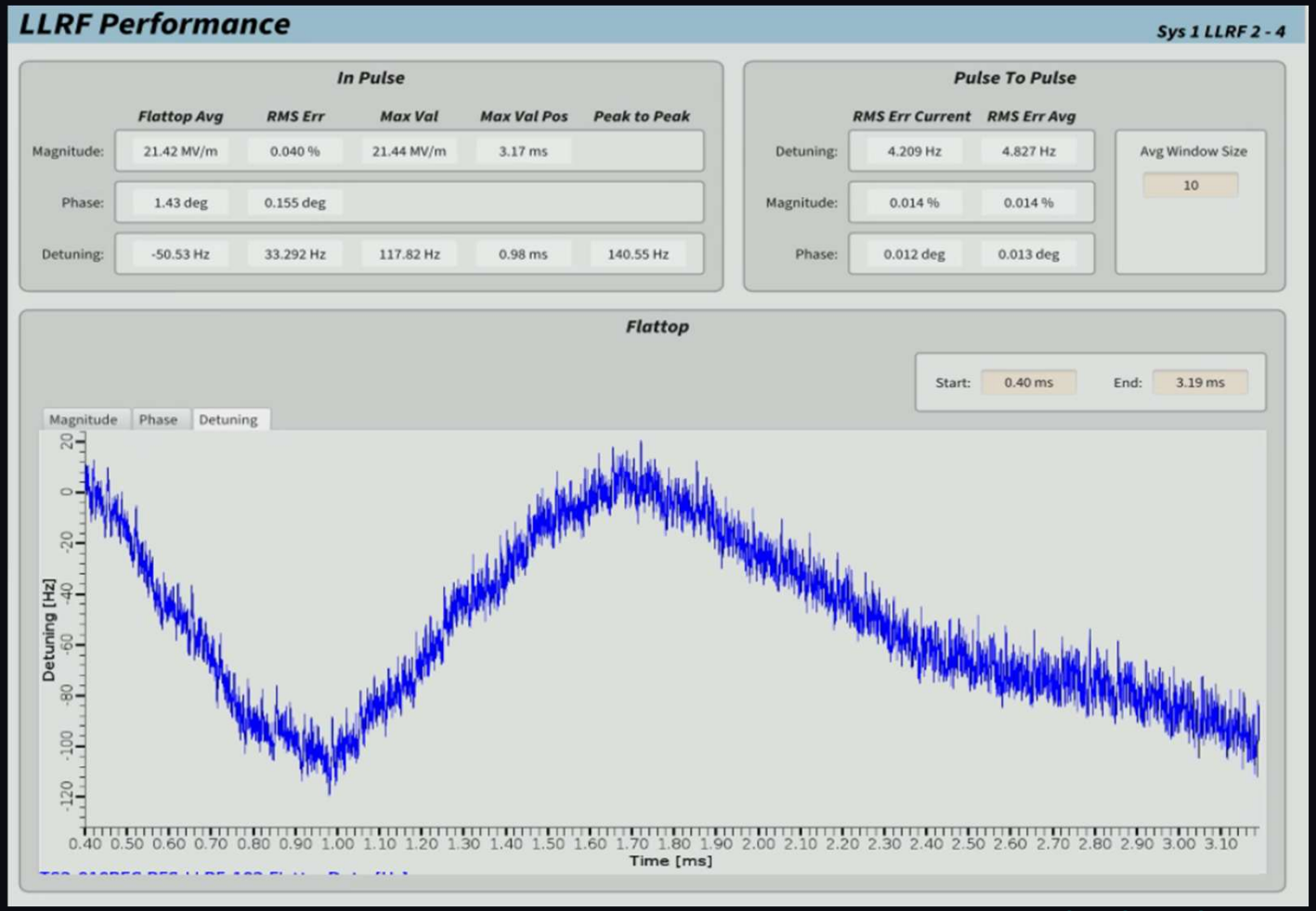
- Provides firmware-side computation of the virtual probe signal.
- Uses calibrated forward and reflected signals to reconstruct the virtual probe.
- Includes a configurable delay window to time-align signals.
- Allows optional calibration of the raw virtual probe signal using the same method as the cavity probe signal.

WU 2. Virtual probe signal monitoring

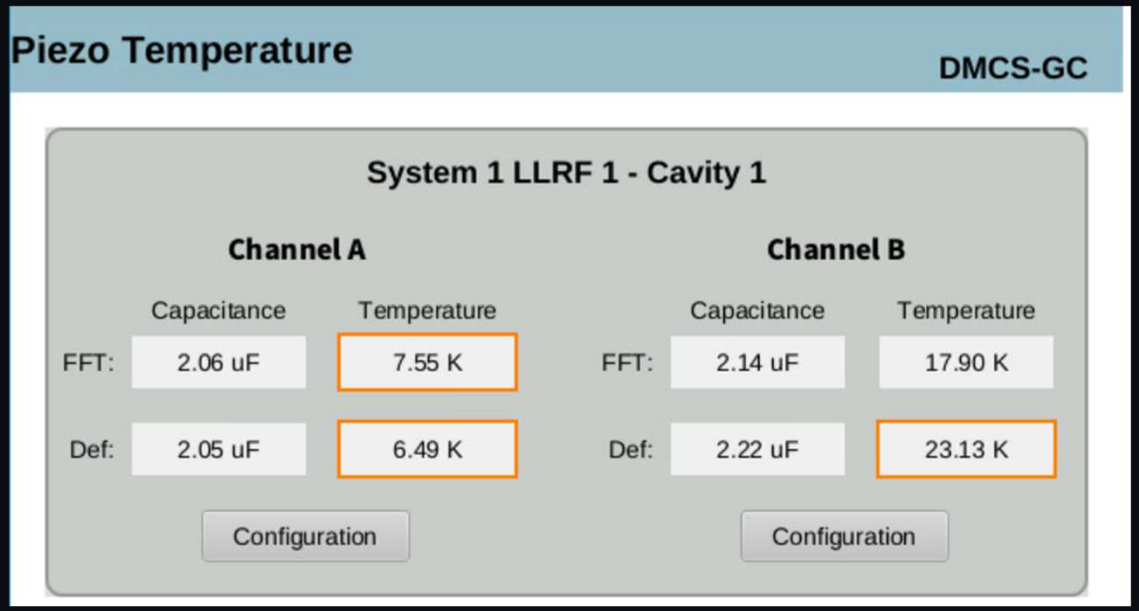


- Virtual probe signal compared with the cavity probe.
- LLRF firmware has been extended with a new channel.
- Added to the LLRF IOC as a new class.
- Tested in TS2 – still requires verification on live system.
- Can be further developed toward main probe substitution

WU 2. Overall status monitoring (grad. phase, regulation performance, etc.)

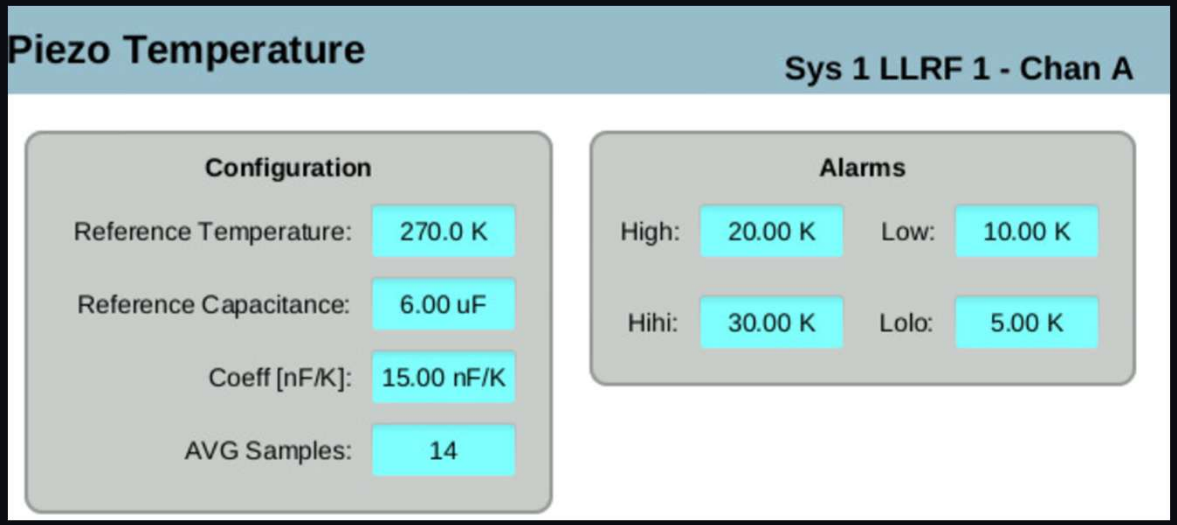


WU 2. Piezo capacitance measurement



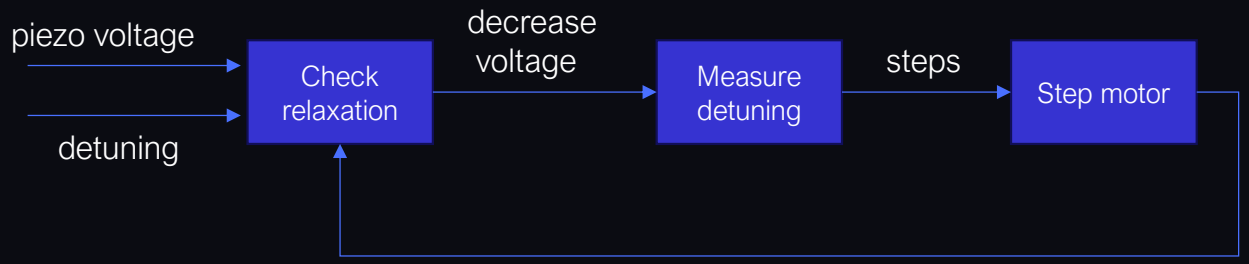
- Provides continuous monitoring of piezo capacitance and estimated temperature.
- Detects abnormal temperature increases indicating possible piezo degradation.
- Uses two calculation methods: FFT-based impedance analysis and time-domain definition method.

WU 2. Piezo capacitance measurement



- FFT method derives capacitance from impedance spectrum and converts it to temperature estimate.
- Definition method computes capacitance from current–voltage relationship
- Temperature is derived from calculated capacitance in both approaches.

WU 2. Piezo range optimization



- Delivers information if piezo actuator can be relaxed (its DC component can be reduced).
- The relaxation target is configurable (target + margin).
- Adjustable piezo sensitivity (Hz/V) and step motor sensitivity (Hz/step).
- Each step motor position change requires user's confirmation.
- Requires careful tests in the TS2 (tested only with motor simulator).

WU 3. Four piezo systems delivery for the TS2 operation

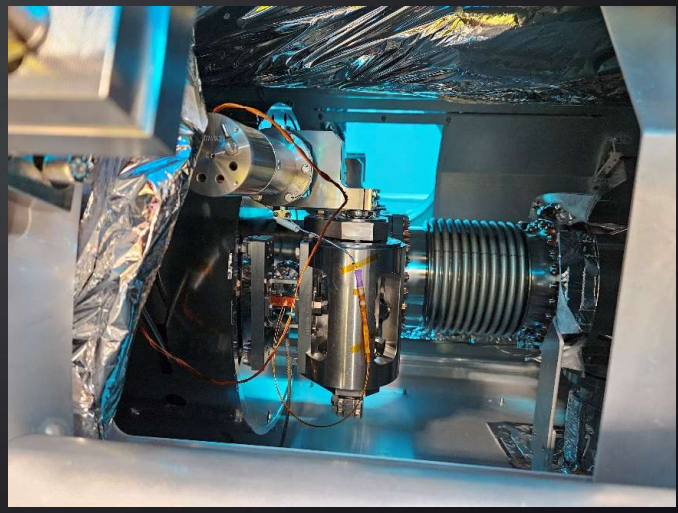
- WU Scope:

3.1. Piezo driver, PD power supply and AMC board production and purchase

3.2. Delivery and installation

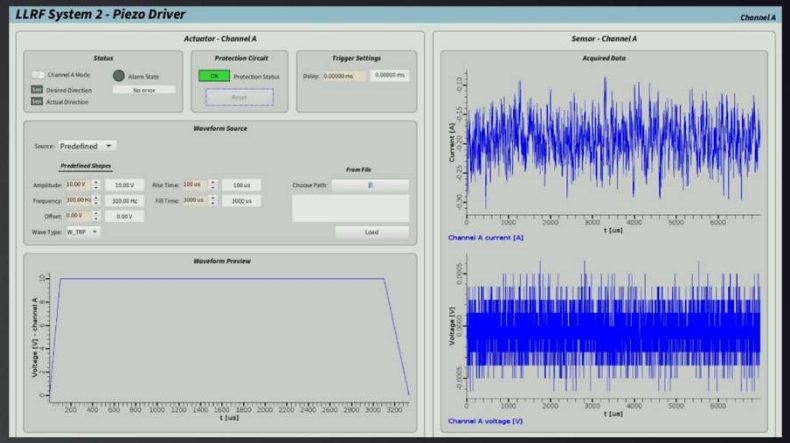
3.3. Integration and commissioning

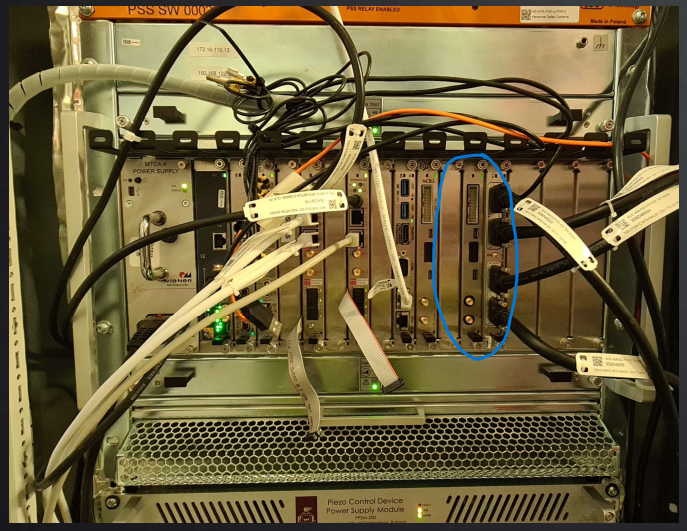


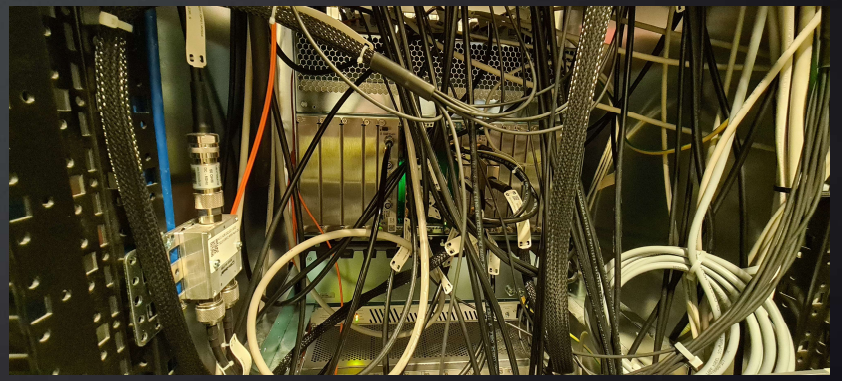


WU 3. Four piezo systems delivery for the TS2 operation

- Four piezo driver systems delivered and installed at TS2,
- Successfully operated since now,
- Missing RTM carrier modules borrowed from the H-Beta installation batch from RF group







Summary

- Main Goal: TS2 support in superconducting cavities characterization and operation, together with piezo driver hardware production and integration – *achieved,*
- *Funds provided* by *Ministry of Science and Higher Education* Republic of Poland 12.2023 – 03.2026,
- Three work units - *completed*:
  - Software tools for superconducting cavities testing and characterization at the ESS Test Stand 2,
  - Software solutions supporting resonators operation especially related to the Piezo Drivers (PD),
  - Four piezo systems delivery for the TS2 operation
- Characterization tools deployed for all RF systems in the linac and TS2,
- Documentation provided in the form of the confluence pages,
- SW and FW modules provided - local ESS repositories

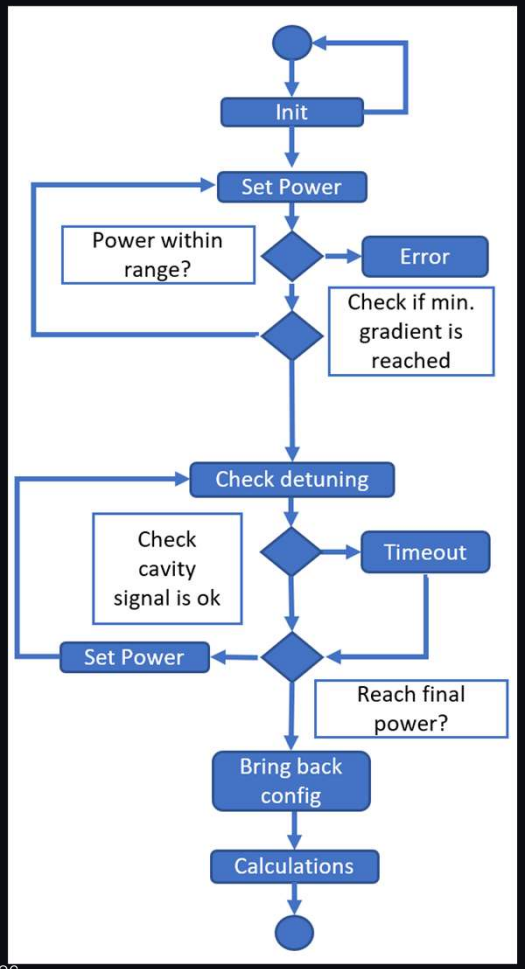




Thank You

That work has been supported by the Ministry of Science and Higher Education Republic of Poland, agreement no. 2023/WK/11

WU 1. Tool for determining LFD static/dynamic coefficients - Algorithm



Initialization
Load parameters, check system readiness, clear previous results.

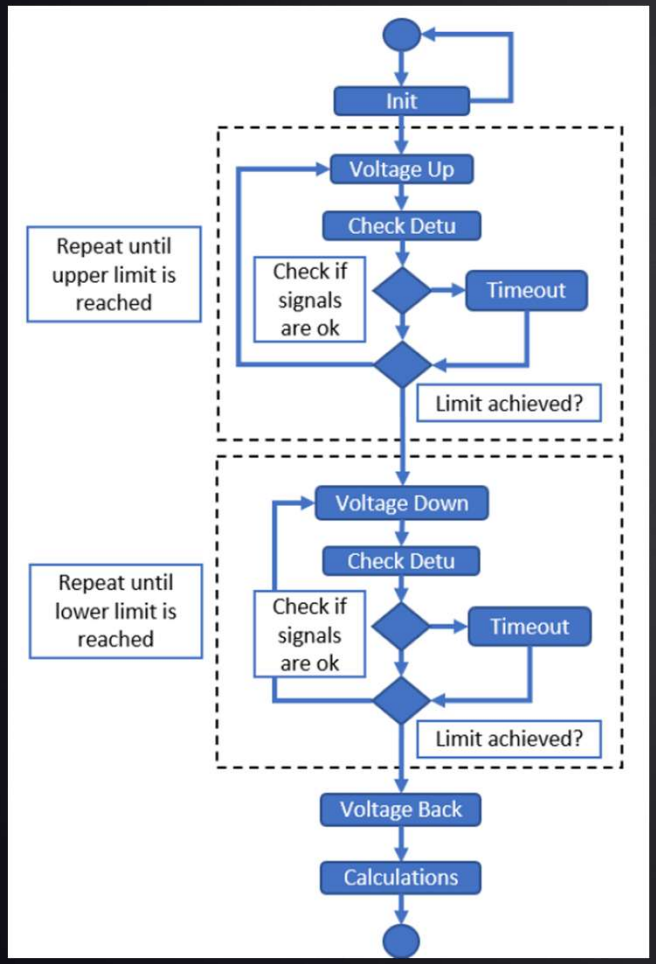
Gradient & Detuning Scan
Increase power stepwise and measure average detuning.

Permit & Timeout Control
Wait for user confirmation and handle low-gradient timeouts.

Power Recovery
Restore original pulse power settings after the scan.

Coefficient Calculation
Compute LFD coefficient and evaluate test success.

WU 1. Tool for automated measurement of piezo range and polarity control - Algorithm



Initialization
Load parameters, verify IOC readiness, clear previous results.

Voltage Sweep & Detuning Scan
Sweep piezo voltage up and down while measuring average detuning.

Permit & Channel Synchronization
Wait for user approval and synchronize both piezo channels if needed.

Timeout & Error Handling
Manage low response or voltage errors through timeout recovery.

Parameter Calculation
Calculate piezo range parameters and evaluate test success.

Virtual Probe dedicated stop signal


```
    Turn of stopping VIRT_PRB with other stop signals, collect all required samples.

---------------------- hw/rtl/llrf_custom_logic_top.vhdl ----------------------
index d0c37d69..8acfc061 100644
@@ -1271,8 +1271,17 @@ begin
   end block;

   intern_daq : for i in 0 to NBR_INTERN_SIG_DAQ-1 generate
+    signal s_daq_stop : std_logic;
   begin

+    STOP: if i /= NBR_INTERN_SIG_DAQ-1 generate
+      s_daq_stop <= main_control_signals.rf_stop or main_control_signals.daq_stop or main_control_signals.interlock_active or force_intacq_stop_sync(i);
+    end generate;
+
+    NO_STOP: if i = NBR_INTERN_SIG_DAQ-1 generate
+      s_daq_stop <= '0';
+    end generate;
+
     daq_pipeline_intern : entity ess_common.esscom_daq_pipeline
       generic map (
         TDATA_IN_WIDTH  => 4,
@@ -1302,7 +1311,8 @@ begin
         clock_i           => clock_i,
         reset_n_i         => system_reset_n,
         daq_start_i       => internal_ch_ctrl(i).start,
-        daq_stop_i        => main_control_signals.rf_stop or main_control_signals.daq_stop or main_control_signals.interlock_active or force_intacq_stop_sync(i),
+        --~ daq_stop_i        => main_control_signals.rf_stop or main_control_signals.daq_stop or main_control_signals.interlock_active or force_intacq_stop_sync(i),
+        daq_stop_i        => s_daq_stop,
         nr_samples_i      => internal_ch_ctrl(i).acq_samples,
         new_sample_i      => internal_ch_data(i).valid,
         daq_active_o      => internal_ch_daq_active(i),
```

WU 2. Cavity parameters identification (bandwidth and detuning)

