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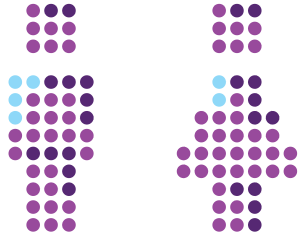
Belgian Nuclear Research Centre

TEST CAMPAIGN AT 2K OF THE BETA 0.35 SPOKE CRYOMODULE PROTOTYPE WITH A MTCA.4-BASED LOW LEVEL RF SYSTEM PROTOTYPE WITHIN THE MYRRHA/MINERVA R&D

W. De Cock - 06/12/2023

12th MicroTCA Workshop for Industry and Research



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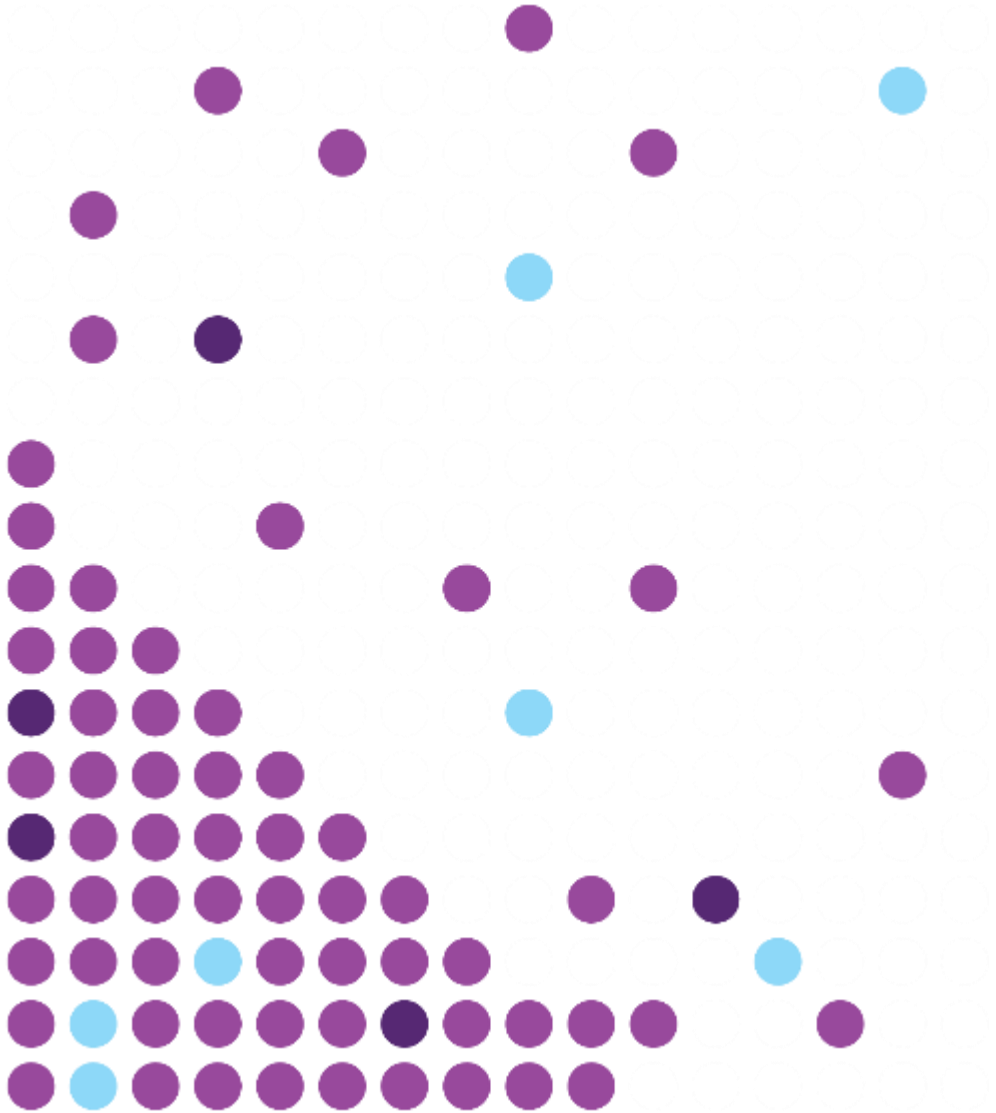
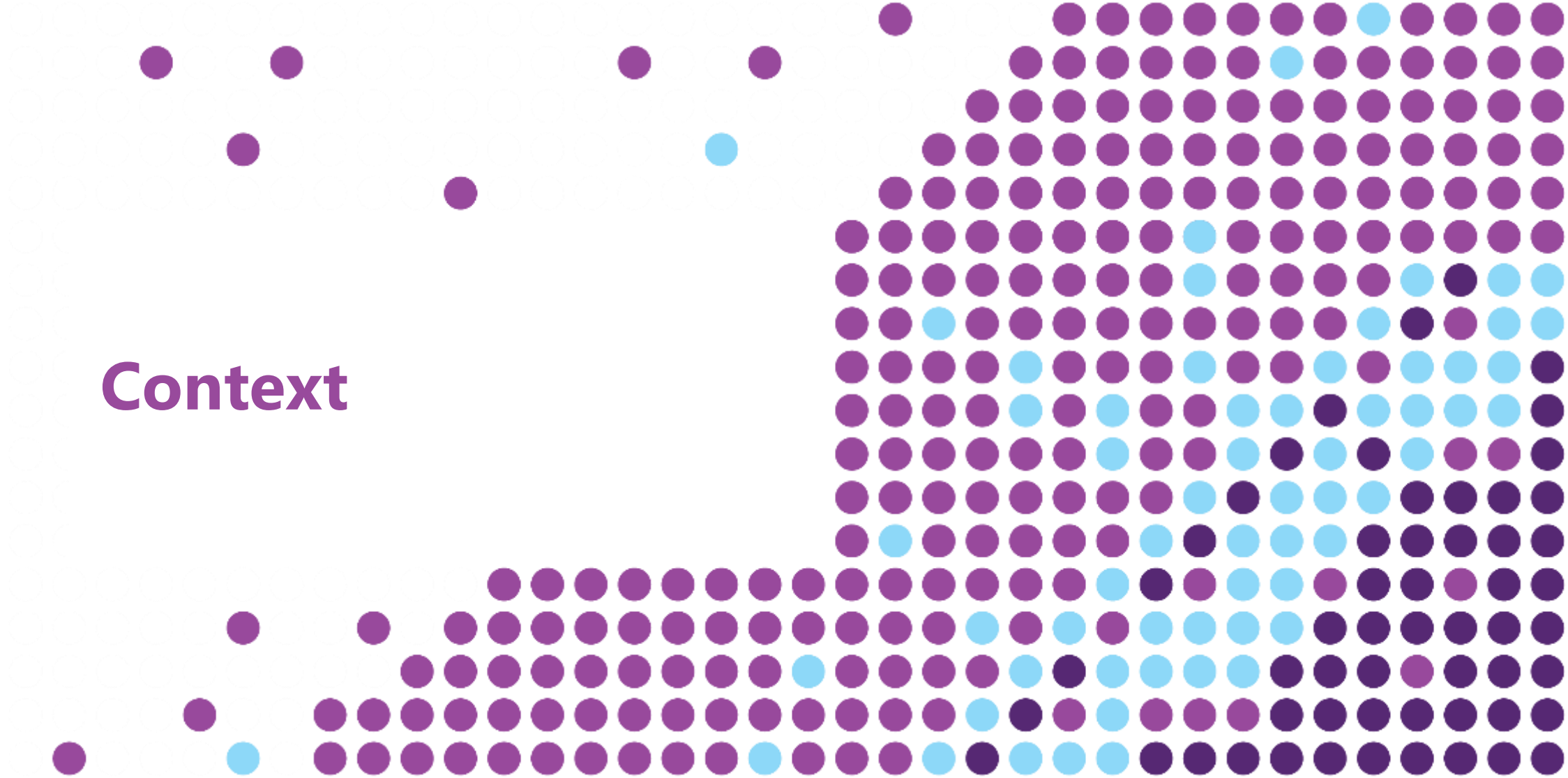
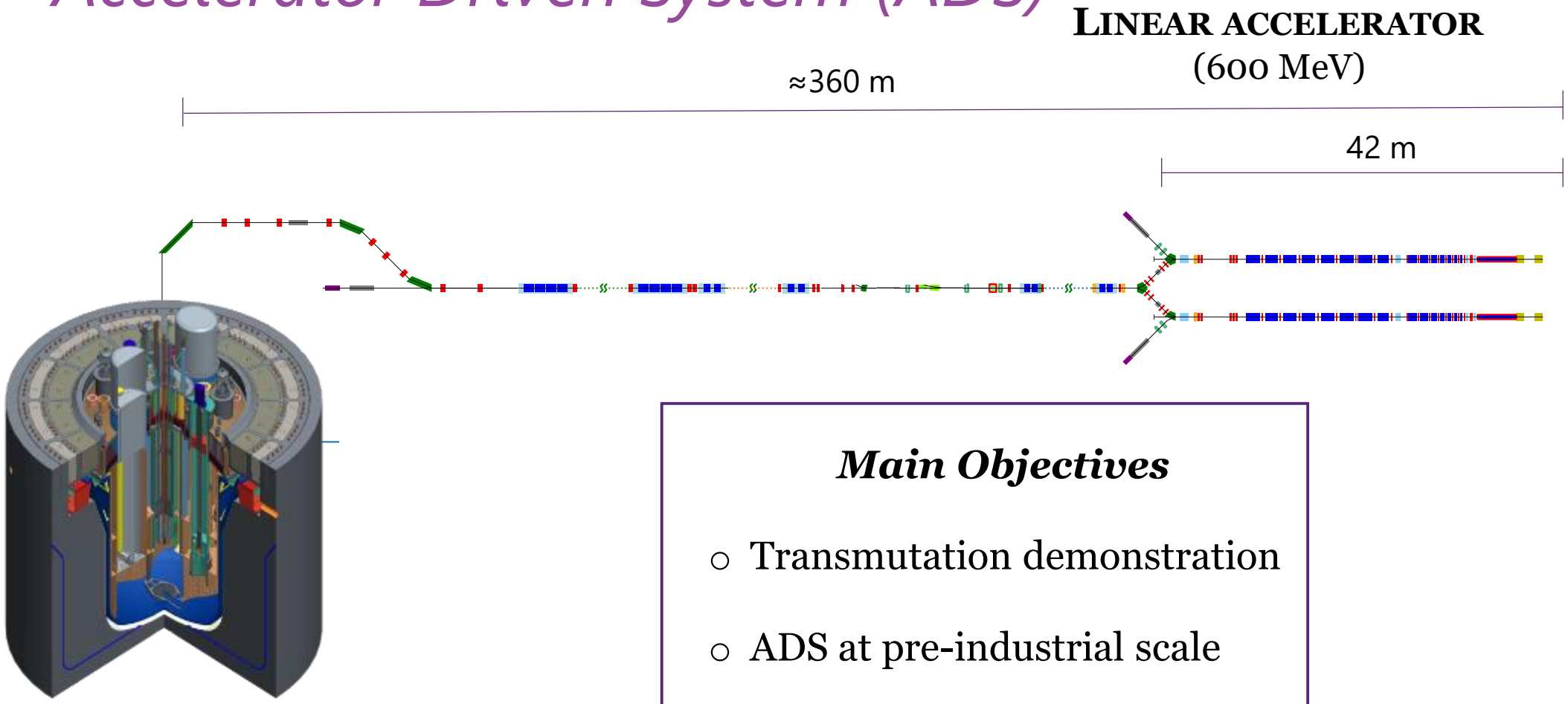
The presented work was made possible by the collaboration/ open source from ESS



Context



MYRRHA
Accelerator Driven System (ADS)



Main Objectives

- Transmutation demonstration
- ADS at pre-industrial scale
- Flexible irradiation facility

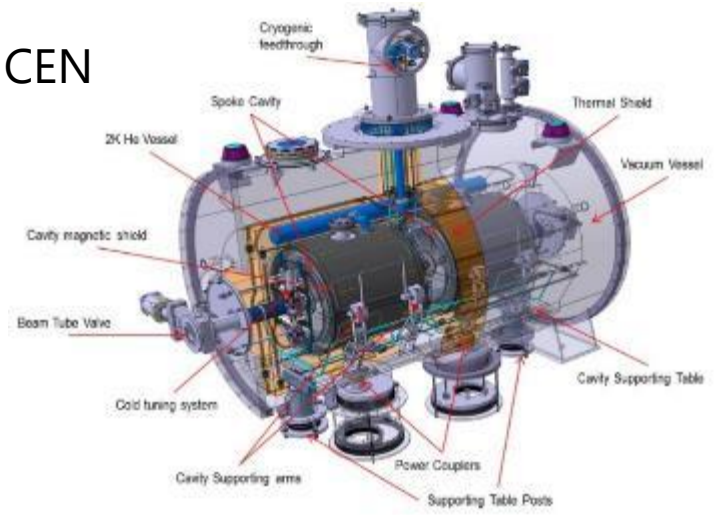
MINERVA ACCELERATOR MAIN SPECIFICATIONS

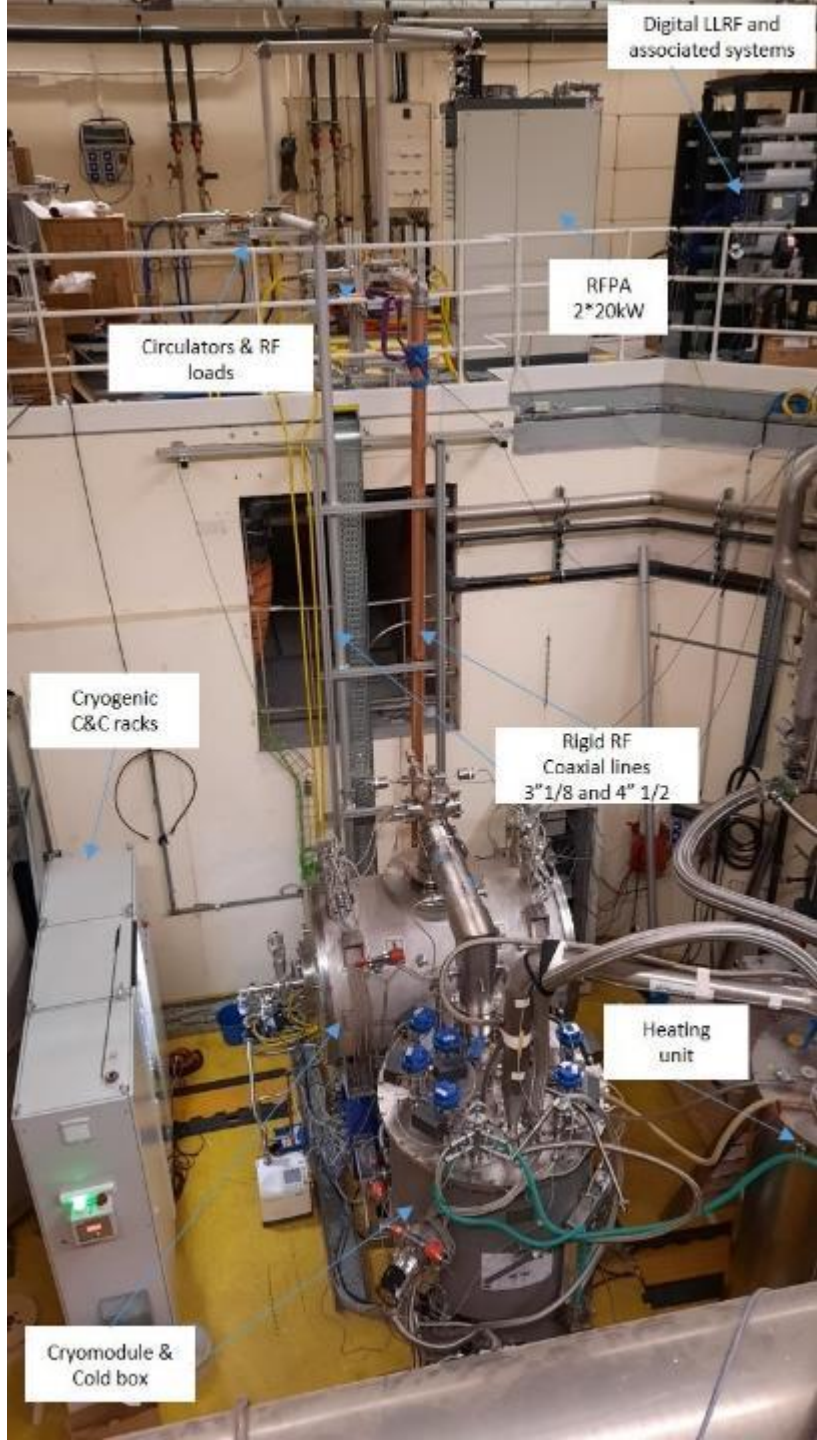
- Protons
- 4 mA
- CW operation with pulses to adapt beam power on targets & 250Hz target switching
- 176.1 MHz normal conducting injector up to 17MeV
- 352.2 MHz super conducting linac up to 100 MeV
- Possibility to later extend to 600 MeV (704 MHz)
- 3s fast fault compensation coordinated by central system
  - <10 beam trips of >3s per 90 day run (Beam trips must be resolved within 3 seconds to be transparent to the reactor)

Cryomodule Test Area at Orsay

SupraTech platform, IJCLab

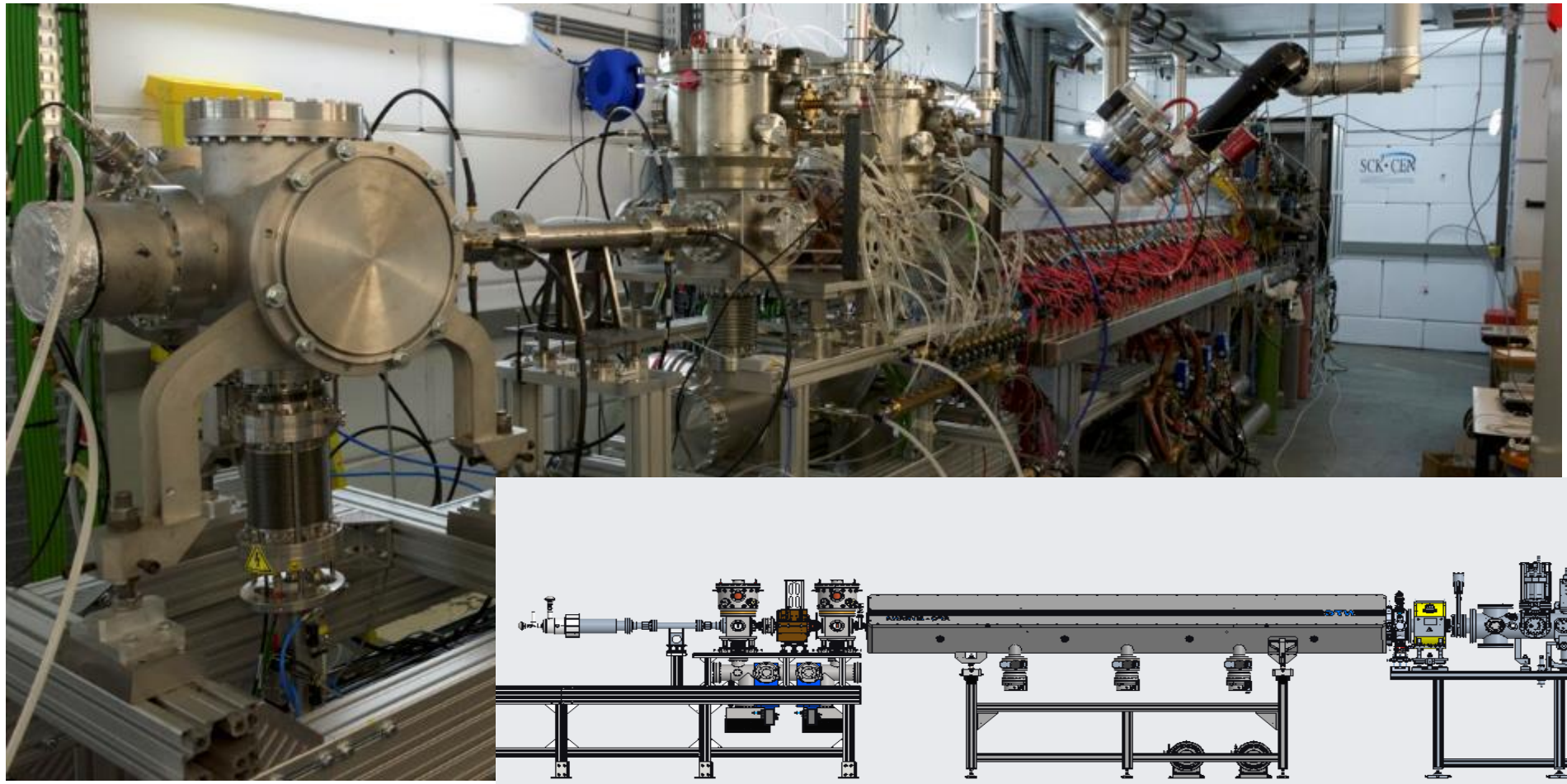
- R&D on the design, construction and test of a fully equipped cryomodule prototype for 352.2MHz LINAC section using single spoke cavities
- IJCLab: cryomodule, cavity tuner and LLRF control developed by IJCLab
- RF power couplers and C&C board for the Cold Tuning System (CTS) by LPSC
- EPICS based control system by SCK CEN





Injector Test Area at Louvain-La-Neuve

ITS, SCK CEN

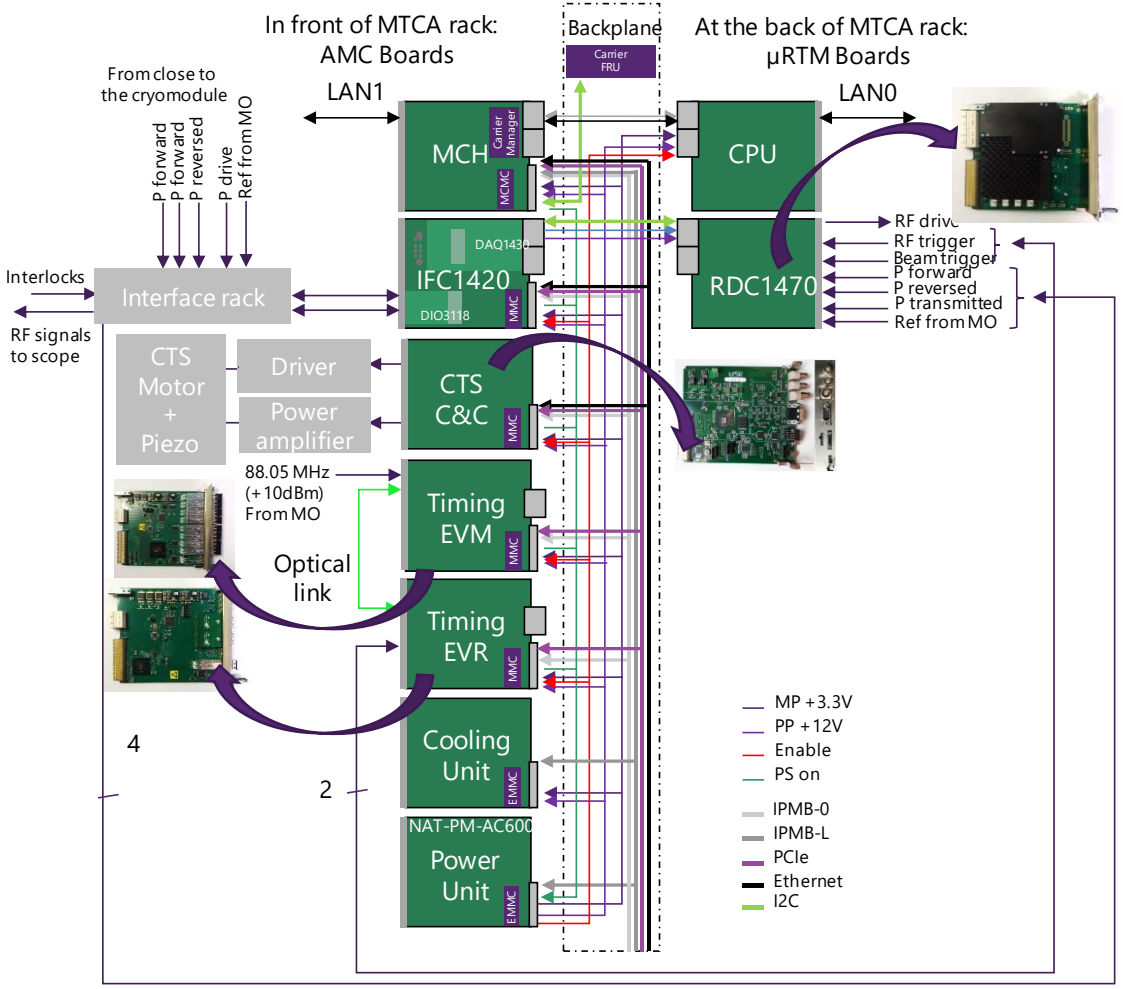


LLRF System

Low Level RF System

Hardware Architecture

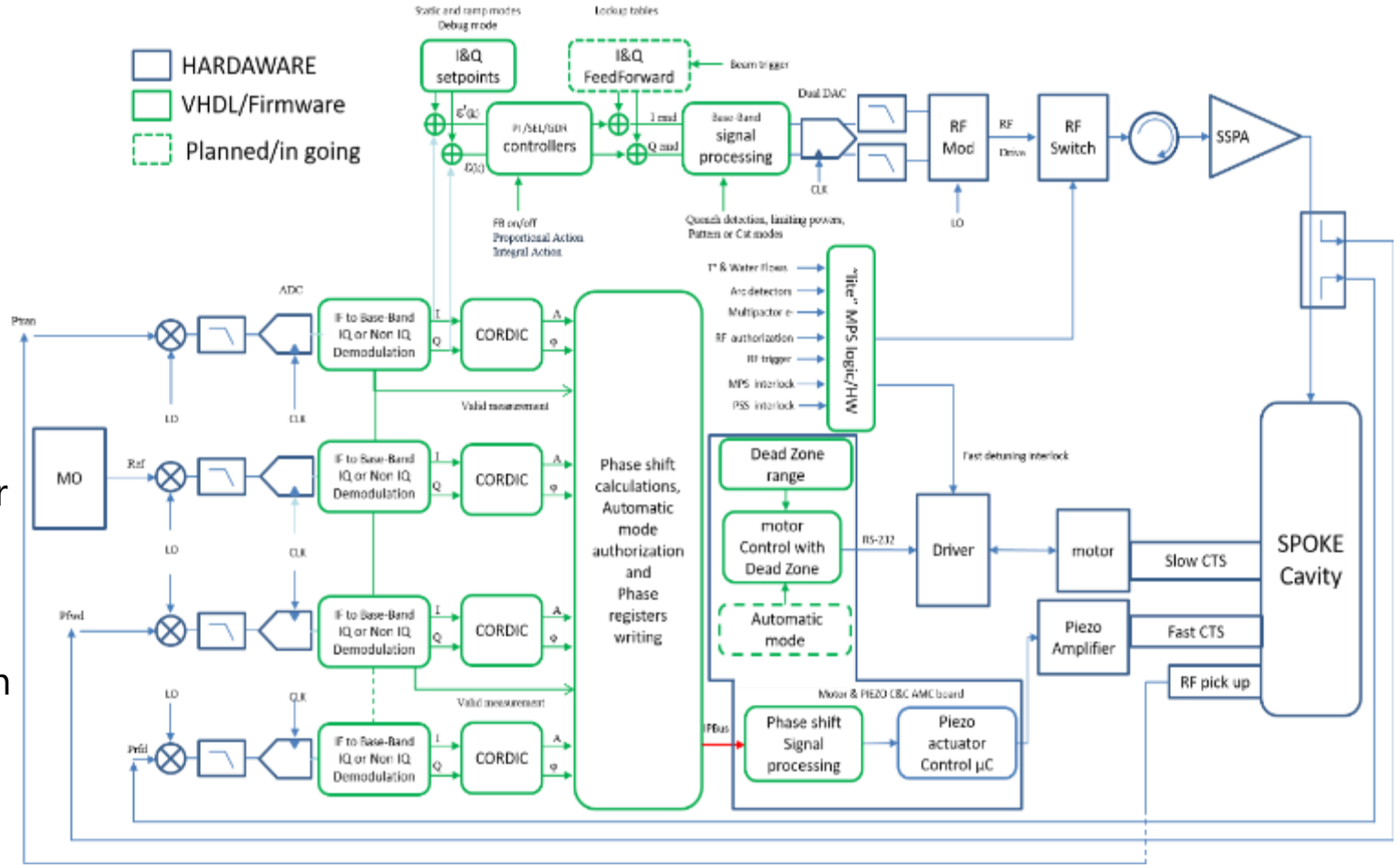
- amplitude and phase stabilities of the accelerating field: ±0.2% and ±0.1° respectively.
- MTCA.4-based:
  - 2 crates (1 per cavity): NATIVE-R5
  - main board: IFC1420
  - µRTM prototype board: RDC1470 developed in collaboration with IOXOS Technologies.
  - C&C CTS board developed by LPSC
  - Timing: MRF EVM/EVR distributed via backplane
- Operation:
  - QWRB cavity field regulation at 176.1MHz, with beam.
  - Two single SPOKE cavities at 352.2MHz during Cryomodule tests



LLRF

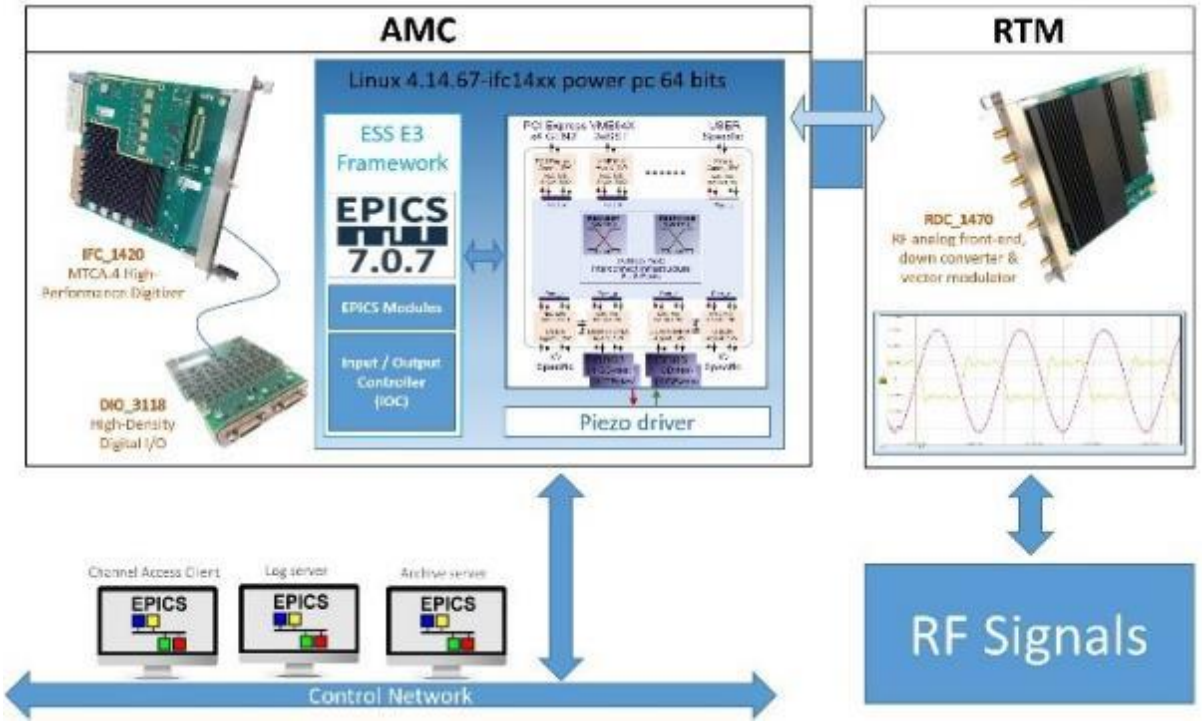
Firmware Architecture

- Two types of demodulation,
  - classic I/Q demodulation (44MHz IF signals sampled at 176.1MHz)
  - NON IQ demodulation (9 samples on 2 IF periods).
- Three operation modes:
  - A Proportional Integral (PI) corrector
  - A Self Excited Loop (SEL)
  - A Generator Driven (GDR)
- Phase shift calculation, power limitation and Quench detection functions using CORDIC, conversions in Phase and Amplitude



EPICS Development

Control System Architecture

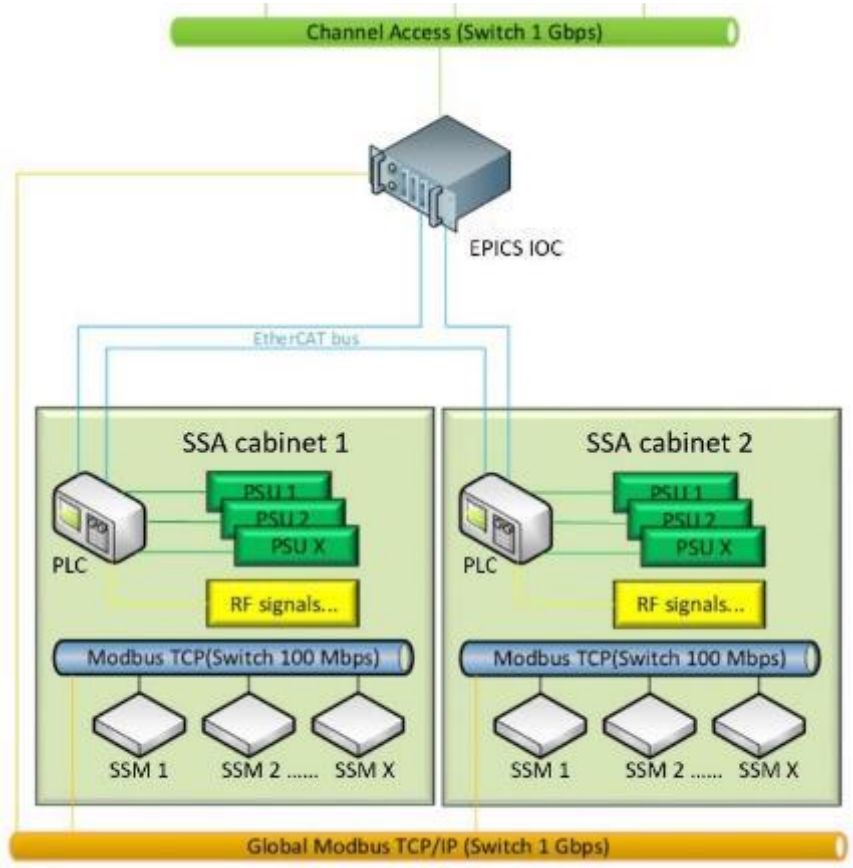


LLRF

- EPICS Input-Output Controller (IOC) implemented on a IOxOS IFC 1420 board, using ESS E3 framework
- Collaborative work with the IOXOS Technologies team in order to control the RF front-end board and to adapt the TOSCA libraries .
- Multifunctional IOC associated to the FPGA firmware.
  - LLRF regulation on the cavity
  - Real oscilloscope which returns data in the form of trigged buffers with a precision of +/- 12 ns between each measurement.
  - Buffers are archived via EPICS channel access (CA) for retrospective analysis.

- Piezo driver installed on the IOxOS OS communicating with the CTS C&C card.
  - C++ Hardware Access Library (uHAL) which provides an API for IPbus reads, writes, and transactions.
  - Compiled for 64-bit Power PC architecture
  - Runs independent of the EPICS layer and realizes the data exchange with an update rate which can be chosen by configuration.
  - Registers exchange can also be configured using an xml file.

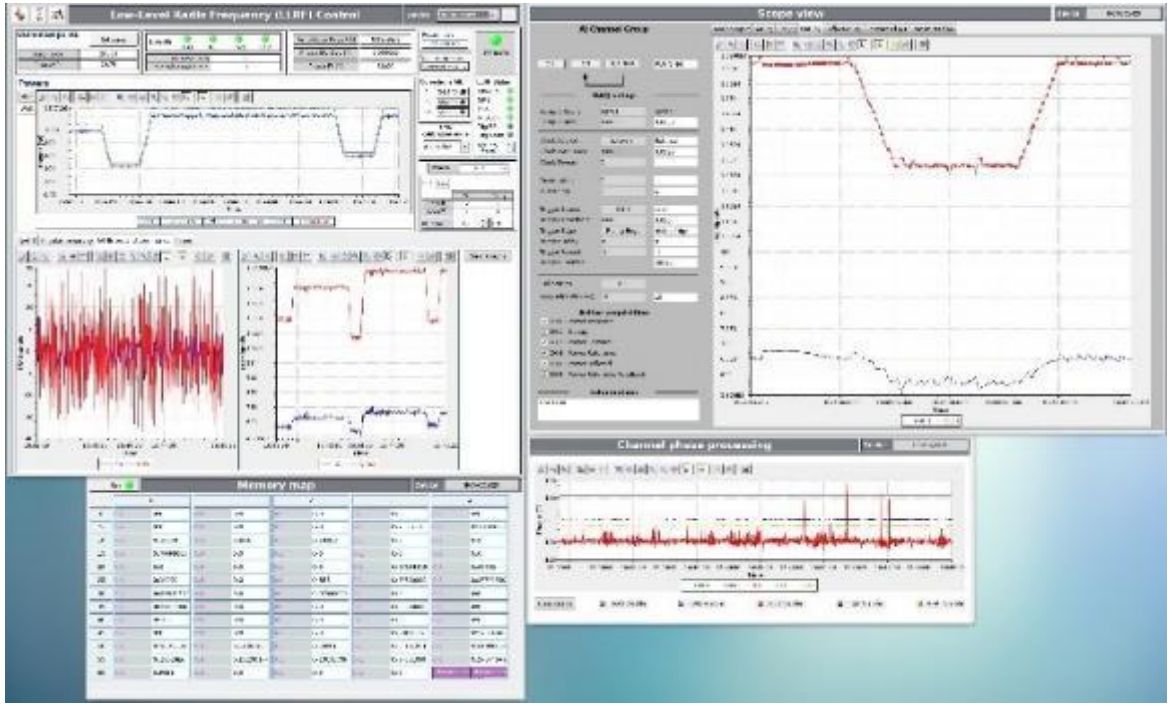
Control System Architecture



Solid-State Amplifiers

- Driven by the LLRF boards (µRTM) and synchronized via PTP protocol.
- Data can be recovered in the form of triggered buffers sent to the archivers via EPICS.
- One SSA cabinet holds:
  - 1-to-n Solid State Module(s) (SSM)
  - 8 power supply units (PSU).
  - 1 PLC
- SSM data is directly pulled through Modbus communication by the IOC, remaining data is pulled from the amplifier PLC through Ethercat bus communication.
- Post-processing function is supported with circular buffers as in the LLRF system.
- EPICS IOCs running on PC with CentOS .

Control System Architecture



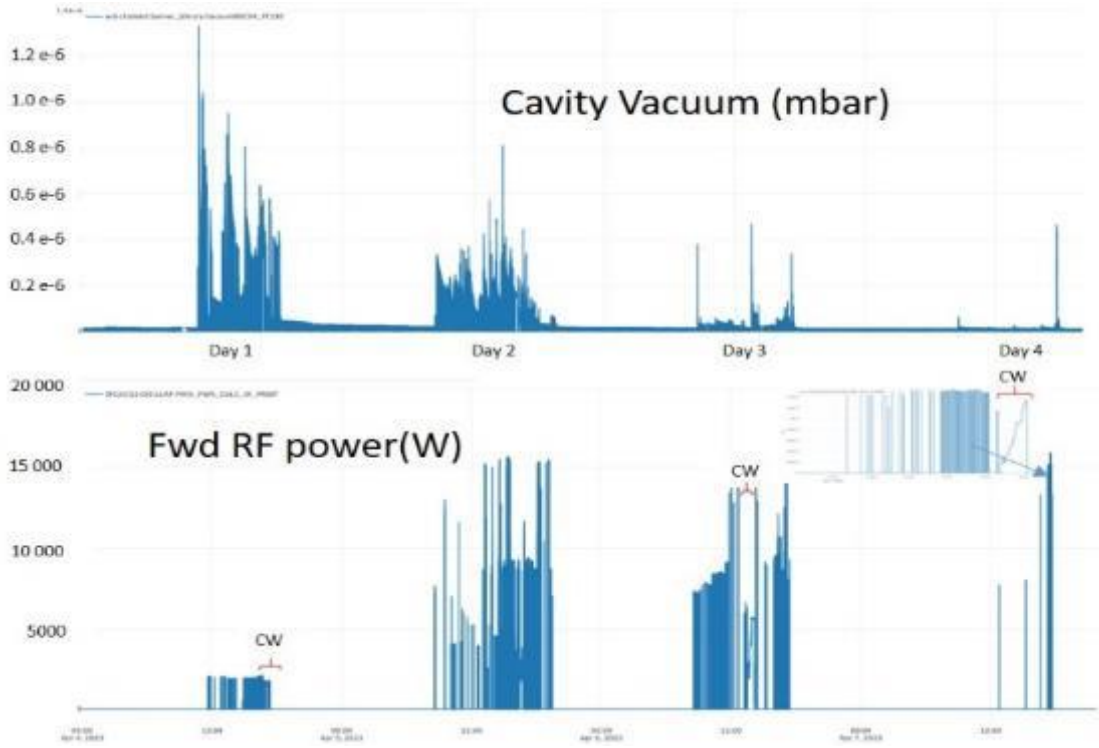
Graphical User Interface

- Realized with Control System Studio 4.6.1.25 (CSS)
- Configuration files to start the LLRF system easily and to manage several similar hardware boards in parallel.
- Possible to change the configuration on-line for specific functions.
- automatic high-level functions (e.g. frequency tuning) are implemented using the EPICS sequencer
- Main EPICS modules: archiver, sequencer, pvAccess/CA

Results of the test campaign

Test Campaign

RF Power Couplers at 300K and 4K

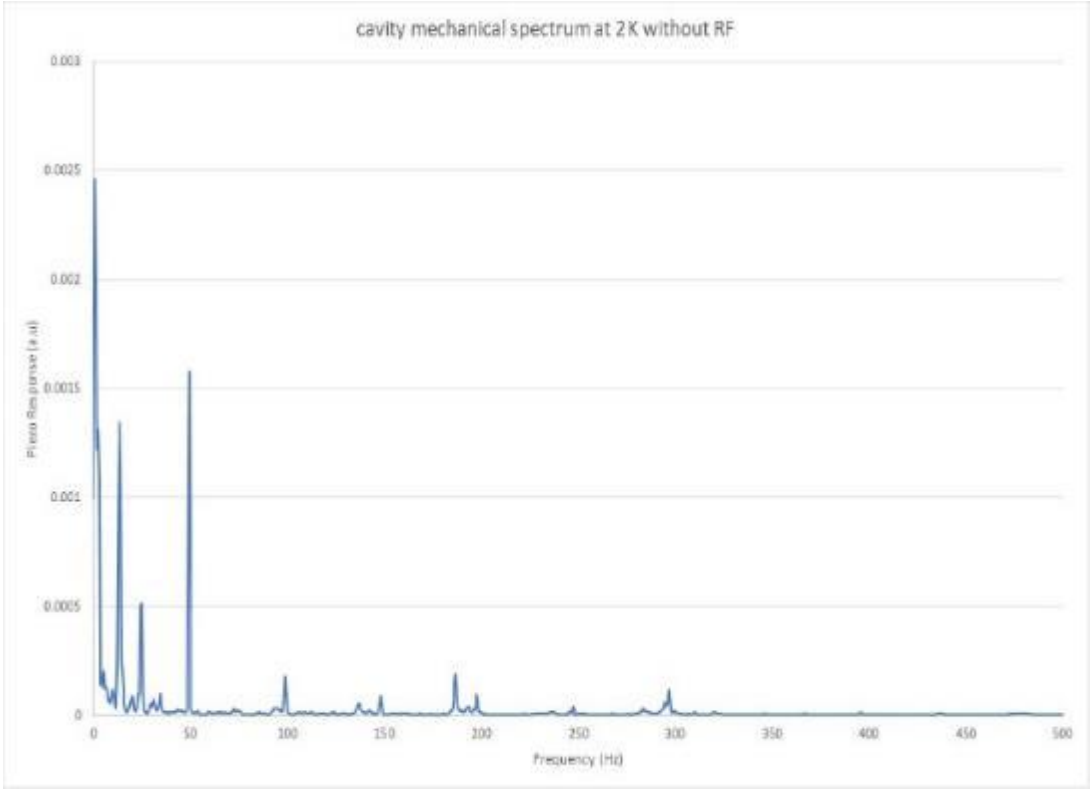


- RF power conditioning at 14kW CW
  - 2 Couplers
  - LLRF system in GDR and Pulsed mode using the MRF timing system.
  - RF pulses ranging from 10µs @16Hz to 99.9ms @ 1Hz.
  - Conditioning out of the bandwidth with first step below the multipacting level
- First RF power coupler, 4 days at 300K to reduce the e- pick up current due to the multipacting effect.
- Second RF power coupler, just one day of conditioning has canceled the e- pick up current.
- At 4K, the cryogenic pumping effect made conditioning easier.

Test Campaign

CTS at 2K

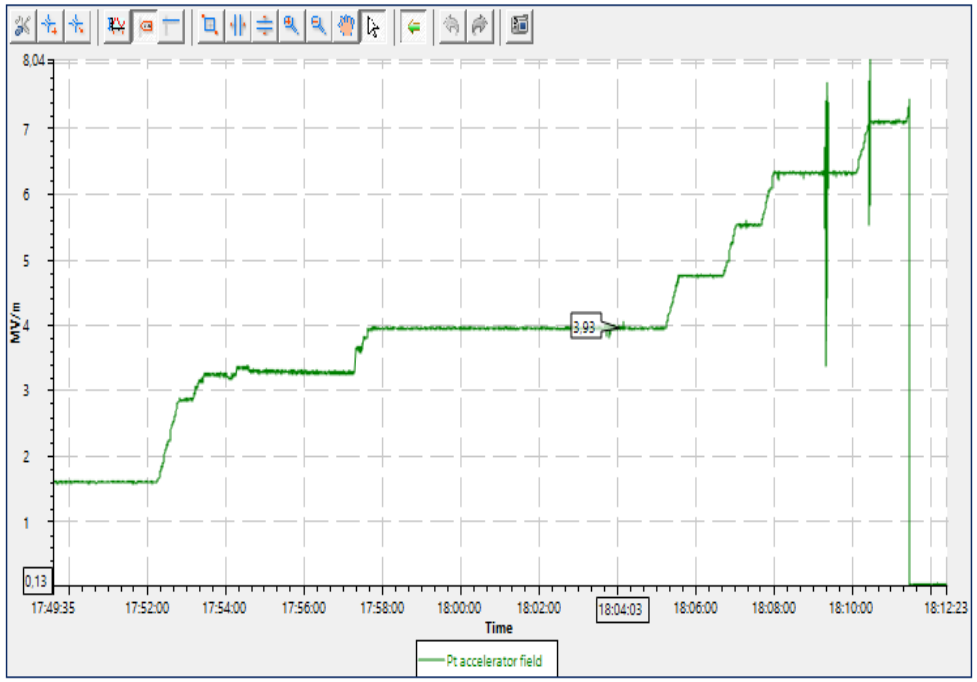
- LLRF system in GDR mode for tuning the cavity at the accelerator reference frequency = 352.2MHz.
- SEL loop tested in IQ demodulation mode.

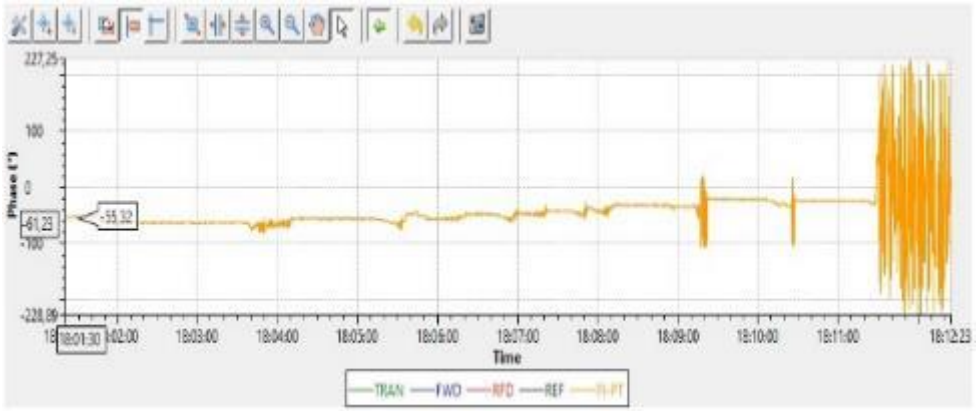


Test Campaign

Spoke Cavities

- Increase of the accelerator field without a frequency regulation (OL)
- Slow RF power increase using a ramp and a manual tuning to compensate for Lorentz forces.
- Manual tuning using the mechanical cavity spectrum transformed to a “little music”
- Phase shift between the forward and transmitted signals calculated with FPGA. Communicated via supervision and IPBUS to the CTS C&C board.
- Stepper motor position changes can be observed as well as Quench and the RF OFF interlock.

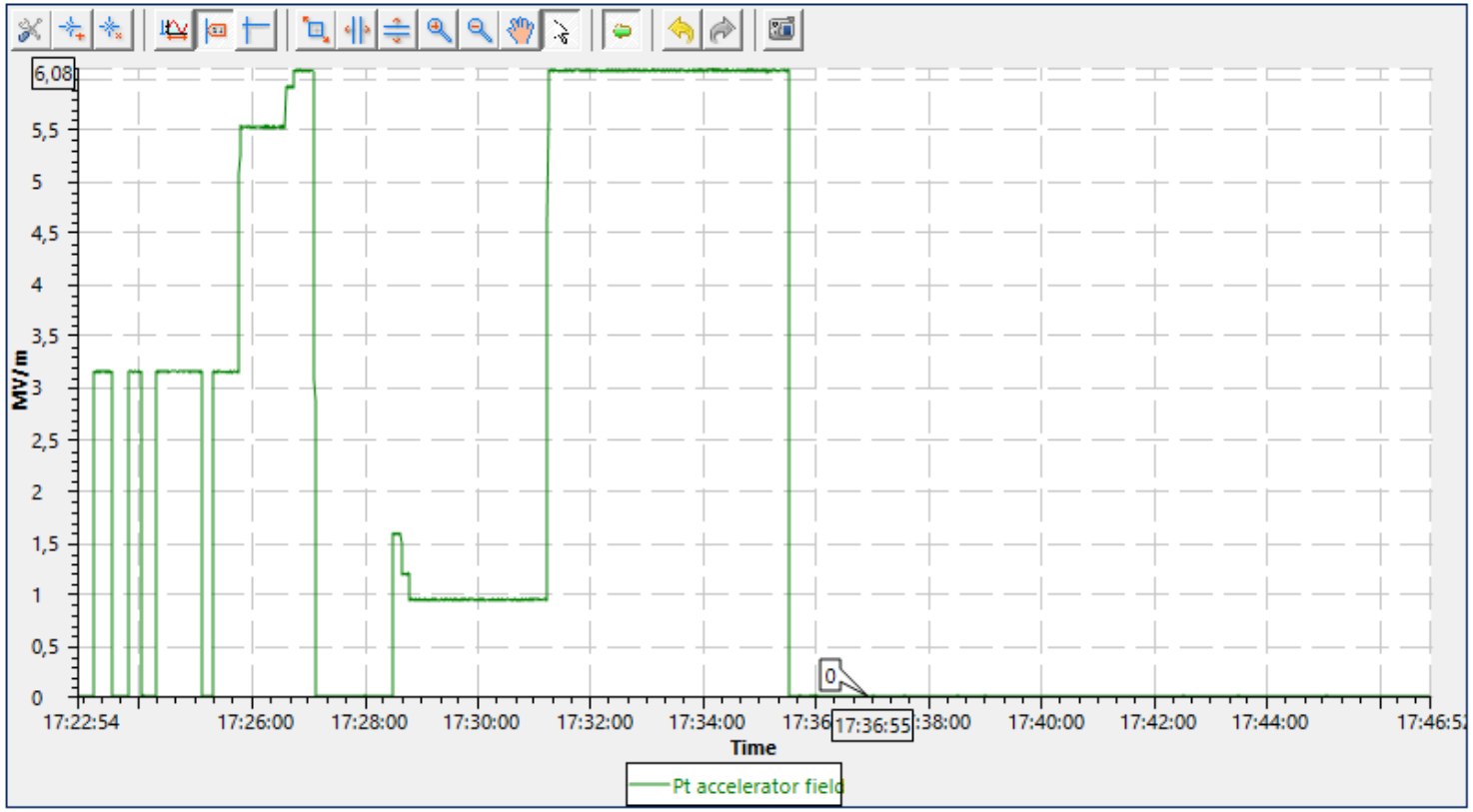




Test Campaign

Spoke Cavities – Fault Tolerance Test

- First cavity field changing from 1MV/m to 6MV/m with the second cavity detuned out of band
- Switch within 1 second with field and frequency regulation on the fist cavity.
- Compliant with the fault tolerance strategy



Conclusions

- MTCA4 based LLRF system validated successfully at 176MHz on the injector prototype (two QWRB cavities) with beam.
- Currently being validated at 352.2MHz with superconducting cavities at 2K
- Planned improvements (firmware and software):
  - Second version of the RF AFE μRTM board prototype (IOxOS RDC1470) → more flexibility and functionality.
  - R&D on integrating White Rabbit (WR) for timing and accelerator reference signals.
- "Lessons learned" are incorporated in the final design of the accelerator

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