The LLRF systems for elliptical cavities - from specification till successful installation

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- Warsaw University of Technology - WUT, Institiute of Electronic Systems - ISE
- National Center of Nuclear Science,
- Lodz University of Technology – LUT, Department of Microelectronics and Computer Science - DMCS

Profesor Andrzej Napieralski był wybitnym naukowcem w dziedzinie elektroniki i mikroelektroniki, założycielem Katedry Mikroelektroniki i Technik Informatycznych w Politechnice Łódzkiej.

Z żalem zawiadamiamy, że w dniu 29.09.2024 r.
zmarł przeżywszy 73 lat

Śp.

prof. Andrzej Napieralski

Msza Święta odbędzie się dnia 4.10.2024 o godz. 14.00
w Kaplicy cmentarnej Parafii Świętych Archaniołów Rafała i Michała
w Aleksandrowie Łódzkim.

O pogrzebie zawiadamia pogrążona w smutku Rodzina

Agenda

- ESS Project and superconducting cavities LLRF system
- The PEG polish in-kind project scope
- The MTCA hardware modules
- Other hardware modules
- Cavity simulator
- LLRF systems Integration and installation
- Summary

ESS Project and superconducting cavities LLRF system

European **S**pallation **S**ource – **E**uropean **R**esearch **I**nfrastructure **C**onsortium

The European Spallation Source Design
Roland Garoby et al 2018 Phys. Scr. 93 014001

Institution	Main deliverables
Aarhus Univ (DK)	Rastering system
Atomki (HU)	RF local protection system
Bergen University (NO)	Seconded staff
CEA Saclay (FR)	RFQ, elliptical cavities and cryomodules, diagnostics
DESY (DE)	Diagnostics
Elettra (IT)	Spoke RF sources, magnets, power converters, diagnostics
ESS-Bilbao (ES)	MEBT, warm linac RF, diagnostics
Huddersfield Univ (UK)	RF distribution, radiation protection
IFJ PAN (PL)	Manpower for installation
INFN Catania (IT)	Ion source, LEBT
INFN Legnaro (IT)	Drift tube linac
INFN Milan (IT)	Medium-beta elliptical cavities
IPN Orsay (FR)	Spoke cavities, cryo distribution
Lodz Univ of Techn (PL)	Low-level RF
Lund Univ (SE)	Low-level RF
NCBJ (PL)	Low-level RF, gamma blockers
Oslo Univ (NO)	Diagnostics
STFC Daresbury (UK)	High-beta elliptical cavities, vacuum
Tallinn Univ of Techn (EE)	IOT modulator development
Uppsala Univ (SE)	Tests of spoke cavities and cryomodules
Warsaw Univ of Techn (PL)	Phase-reference line, low-level RF
Wroclaw Univ of Techn (PL)	Cryogenic distribution

The PEG polish in-kind project scope

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- National Center of Nuclear Science,
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Funding agency: **Ministry of Education and Science**

Project duration:**10.2016 – 07.2025 (04.2024)**

ESS Project and superconducting cavities LLRF system

European **S**pallation **S**ource – **E**uropean **R**esearch **I**nfrastructure **C**onsortium

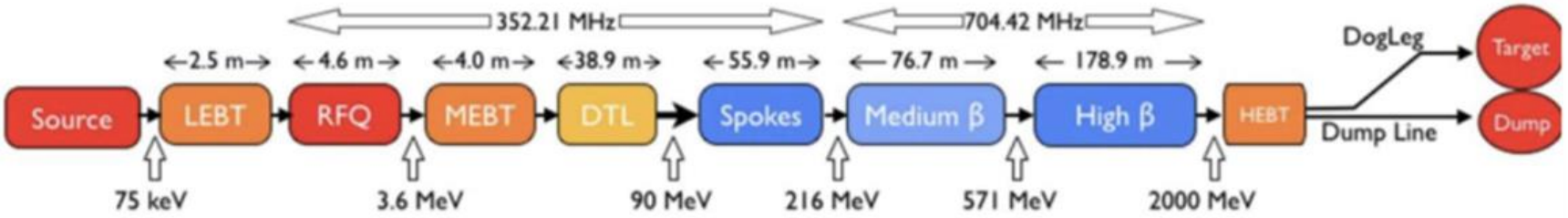

Table 19. Number of cavities, frequency and peak power level.

Linac section	Energy (MeV)	Freq. (MHz)	Number of cavities	Cavities per cryo-module	Geometric β	Temp. (K)	Max. RF power (kW)
Source	0.075	—	0	—	—	300	—
LEBT	0.075	—	0	—	—	300	—
RFQ	3.6	352.21	1	—	—	300	1600
MEBT	3.6	352.21	3	—	—	300	20
DTL	90	352.21	5	—	—	300	2200
Spoke	220	352.21	6	2	0.5 β_{opt}	2	330
Medium-β	570	704.42	36	4	0.67	2	870
High-β	2000	704.42	84	4	0.86	2	1100
HEBT	2000	—	0	—	—	300	—

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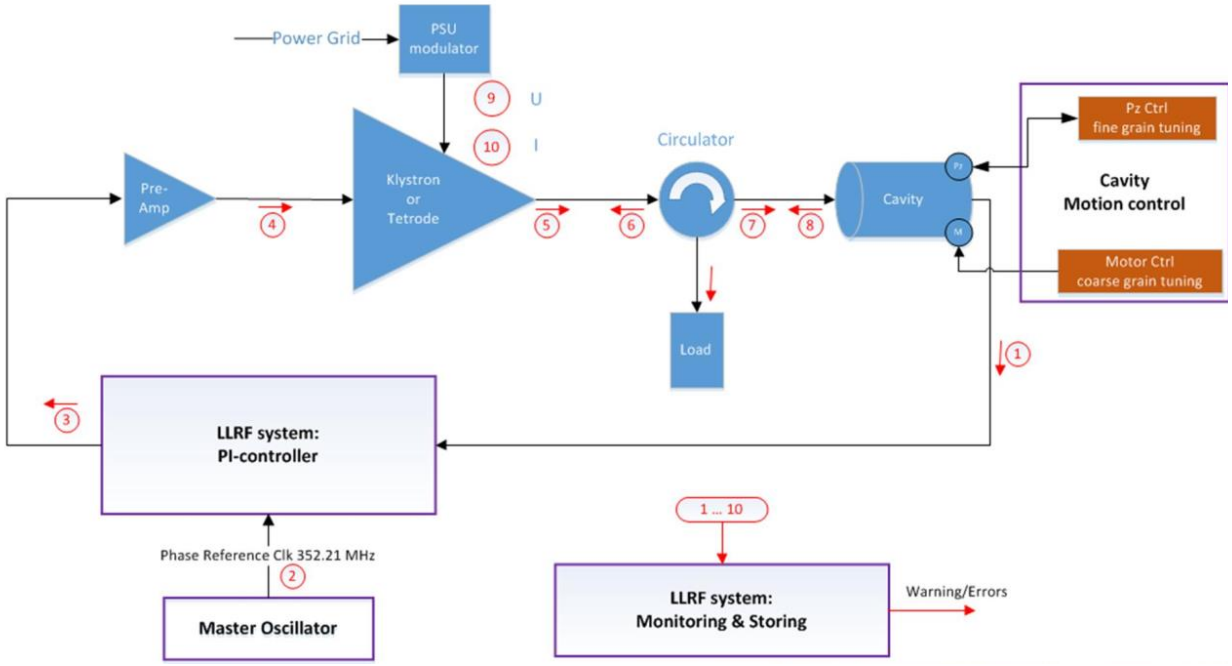
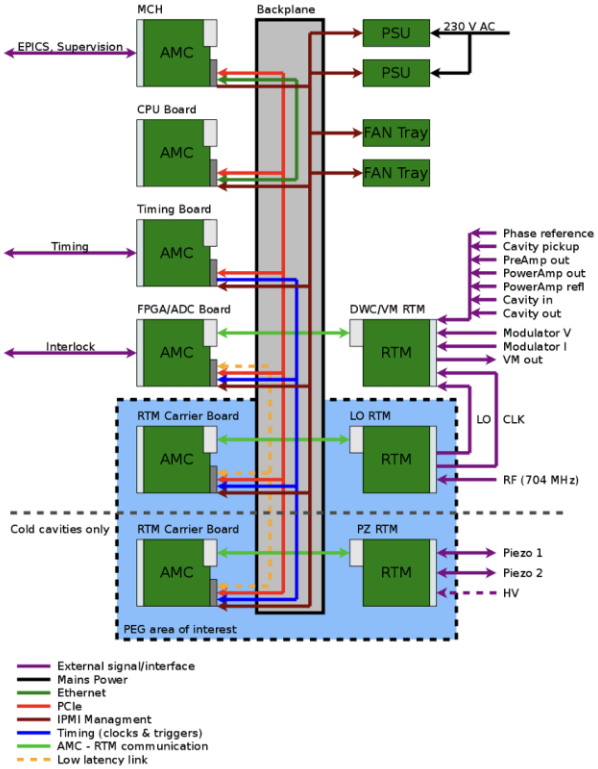
ESS Project and superconducting cavities LLRF system





Source: LLRF System for ESS Linac A. J. Johansson et. al.

The ESS Low Level Radio Frequency system:

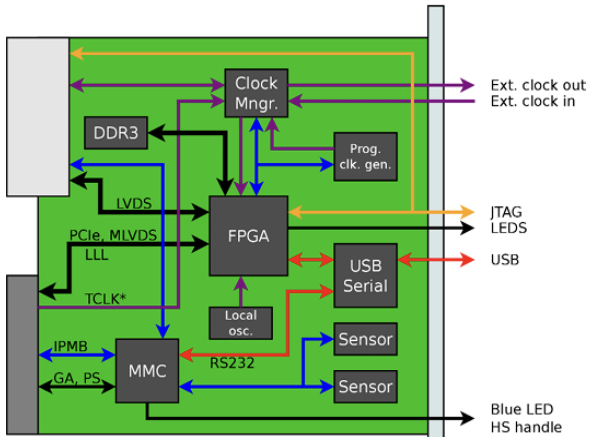
- Proposed and specified by the Lund University,
- Single cavity regulation, with PI controller and Feed-forward,
- Piezo-electric based fast frequency control integrated,
- Designed and build following MTCA.4 standard,

The PEG polish in-kind project scope

- Hardware components design, evaluation and production for M-Beta and H-Beta cavities control systems:
  - RTM Carrier board (for 120 LLRF systems),
  - RTM Piezo Driver (for 120 LLRF systems),
  - Local Oscillator board (for 120 LLRF systems),
  - PSS switch,
  - Pin diode,
  - Electron pick-up,
  - RF splitbox
- Reference LLRF system integration and evaluation,
- Hardware cavity simulator design and evaluation,
- LLRF systems integration, installation in the ESS and evaluation,
- Chosen firmware components preparation.

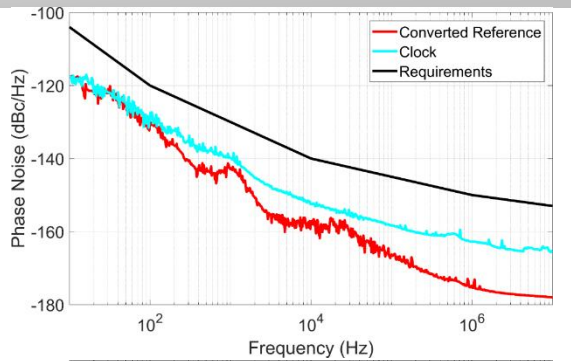
The MTCA modules: RTM Carrier

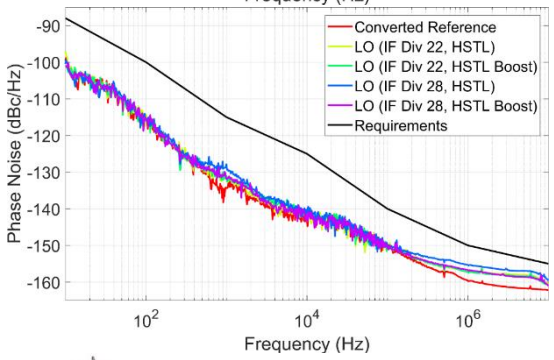
- **Designed, developed, produced** and delivered by National Center for Nuclear Research (**NCNR**)
  - Universal MTCA AMC module with:
    - Artix-7 FPGA chip,
    - DDR3 memory,
    - Interfaces (PCIE, LLL, CLKs, Mgmt. Signals),
    - others,
  - Front board for RTM Piezo Driver,
  - Front board for Local Oscillator board,
- **Two prototype versions** prepared and **successfully tested** with dedicated modules in the local test-stands,
- The RTM carrier delivery:
  - Quantities to cover all LO-RTM and Piezo-RTM modules for elliptical resonators systems,
  - **All required boards produced**, tested and delivered to ESS,
  - Modules integrated in LLRF systems (or delivered for temporary storage before next LLRF systems integration)



The MTCA modules: LO RTM

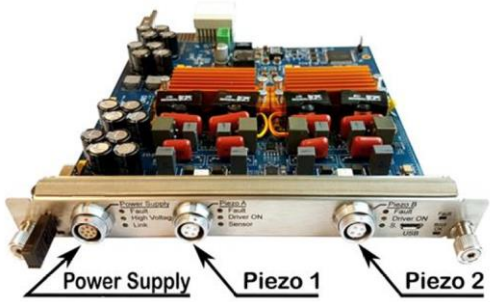
- **Local Oscillator (LO) - designed, developed, produced** and delivered **by ISE-WUT**
  - Produces the Local Oscillator frequency signal from 704,42 MHz reference:
    - Two different intermediate frequnecy available (1/22 and 1/28 ref. freq.),
    - Four outputs for 4 different LLRF system operation,
    - Signals power diagnostics included,
  - Produces clock signals for the LLRF digitizers:
    - Clock frequency 1/6 ref. freq. ~117 MHz,
    - Four outputs for 4 different resonators operation.
- **Two prototype versions** prepared and **successfully tested** with dedicated modules in the local test-stands,
- The LO modules delivery:
  - Covid-19 pandemic situation driven design adjustments required due to components obsolescence and/or long delivery time,
  - **All required boards produced**, tested and delivered to ESS,
  - Modules integrated in LLRF systems (or delivered for temporary storage before next LLRF systems integration)





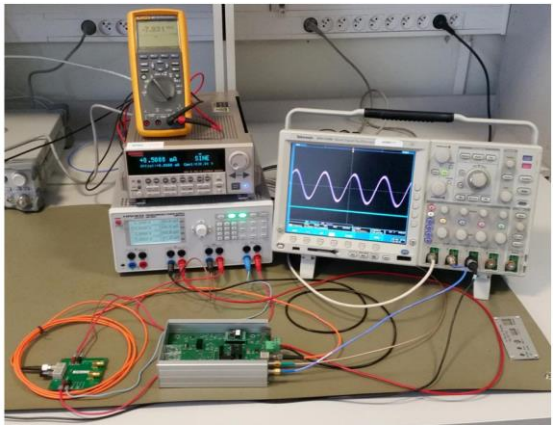
The MTCA modules: Piezo Driver RTM

- **Piezo Driver RTM and external Power Supply Module- designed, developed, produced** and delivered **by DMCS-TUL**
  - Provides two independent piezo supply channels:
    - Output voltage (0- 200V, -40 to 160V),
    - Can work in actuator and sensor mode,
    - Output signal BW up to 3 kHz,
    - External power supply module for high voltage delivery,
    - Integrated acquisition capability of voltage and currents of ouput and input signals,
    - Integrated diagnostics and over-voltage and over current protection,
    - Flexibility of configuration for operation with spoke and elliptical cavities.
- **Four prototype versions** prepared and **successfully tested** with dedicated modules in the local test-stands and in the ESS test stand 2 and Freia (spoke and H-Beta) ,
- The Piezo Driver modules delivery:
  - **Specification change** as well as **Covid-19 pandemic** situation driven design adjustments required due to components obsolescence and/or long delivery time,
  - **All required boards produced**, tested and delivered to ESS,
  - **Modules integrated in LLRF systems** (or delivered for temporary storage before next LLRF systems integration).

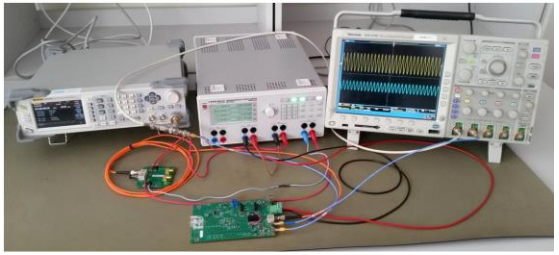


Other hardware modules

- **Electron-pickup modules production, testing and delivery**
  - Part of the protection system,
  - Design by ESS, Produced and tested by NCNR,
  - Full production and delivery of 118 pieces (plus spares) - finished



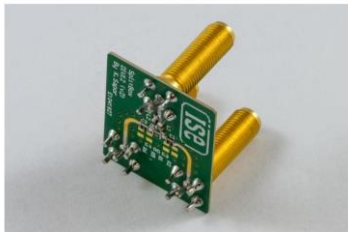
- **PIN-Diode modules production, testing and delivery**
  - Part of the protection system,
  - Design by ESS, Produced and tested by NCNR,
  - Full production and delivery of 125 pieces (and spares) - finished

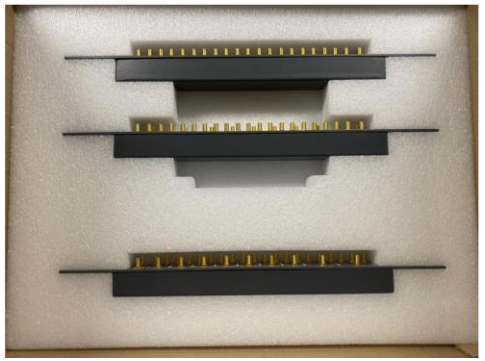


Other hardware modules

- **PSS switch modules production, testing and delivery**
  - One of the actuators in the protection system,
  - Design by ESS, Produced and tested by WUT-ISE,
  - Full production and delivery of 126 pieces (plus spares) - finished

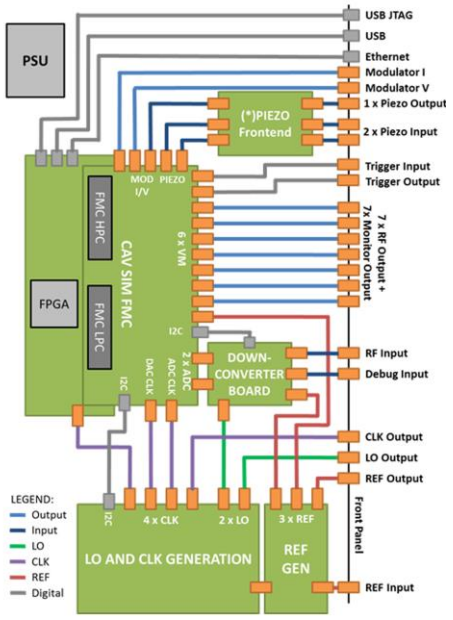
- **RF split-box modules**
  - Cavities and reference RF signals splitting modules
  - Design, Produced and tested by WUT-ISE,
  - Full production and delivery of all required modules - finished



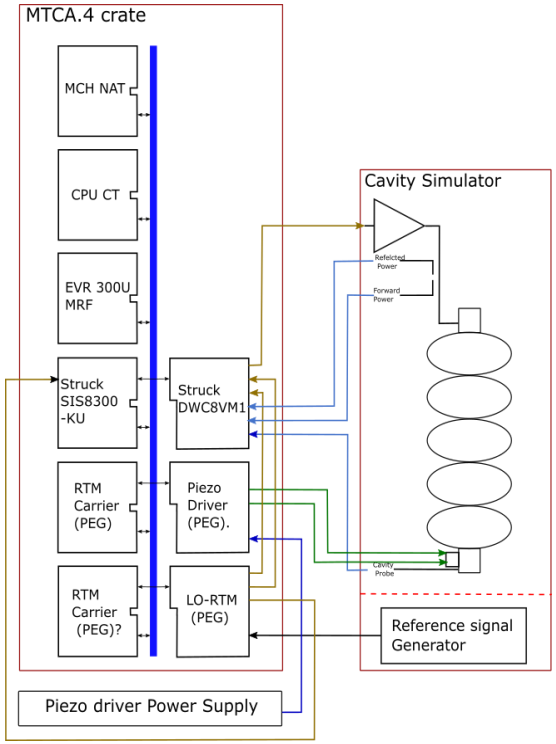


Cavity Simulator

- **Hardware based superconducting cavity resonator for 704 MHz M-Beta and H-Beta structures**
  - Configurable/programable cavity simulator with RF front-end,
  - Provides (among the others):
    - Cavity and RF chain signals (forward, reflected and transmitted power, amplifier input and output signals),
    - Configurable RF model (for 5 and 6 Pi-modes configuration)
    - Integration of the piezo tuner frontend (programable cavity sensitivity to the piezo excitation voltage) ,
  - Design, Produced and delivered (4 pcs.) by WUT-ISE,
  - Simulator (as initially predicted) has been used for the HW/FW/SW development work on the PEG and ESS side. Additionally, it has been used during the LLRF system post-installation acceptance tests.



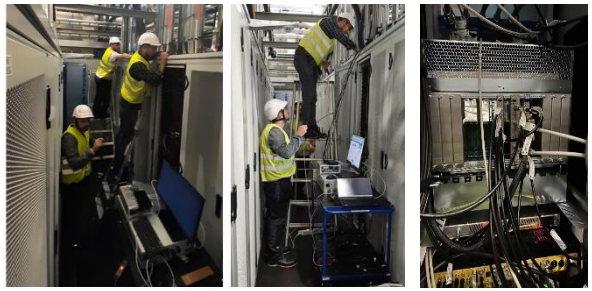
The LLRF reference system integration and evaluation



- **The first fully integrated LLRF system for elliptical cavities**
- Set-up included COTS and PEG modules
- Established and maintained by TUL-DMCS,
- Used for:
  - Hardware evaluation,
  - Firmware and software development and evaluation,
  - Integration and verification test preparationand evaluation.
- Allowed for infrastructure weakness and faults determination and diagnosis,
- Still maintained in operation for the FW improvements testing and potential main systems servicing purposes.

The LLRF system integration and installation

- LLRF systems MTCA.4 crates initial integration done by ESS (ICS)
- NCNR provided further integration and installation services in the klystron gallery,
- TUL-DMCS equipped installed systems with delivered piezo driver,
- All systems verified at the LLRF in/out patch panels with cavity simulator connected and completed predefined testing routine.
- LLRF systems with piezo driver installation in the gallery:
  - M-Beta section – DONE,
  - H-Beta section – DONE up to HBL-020,

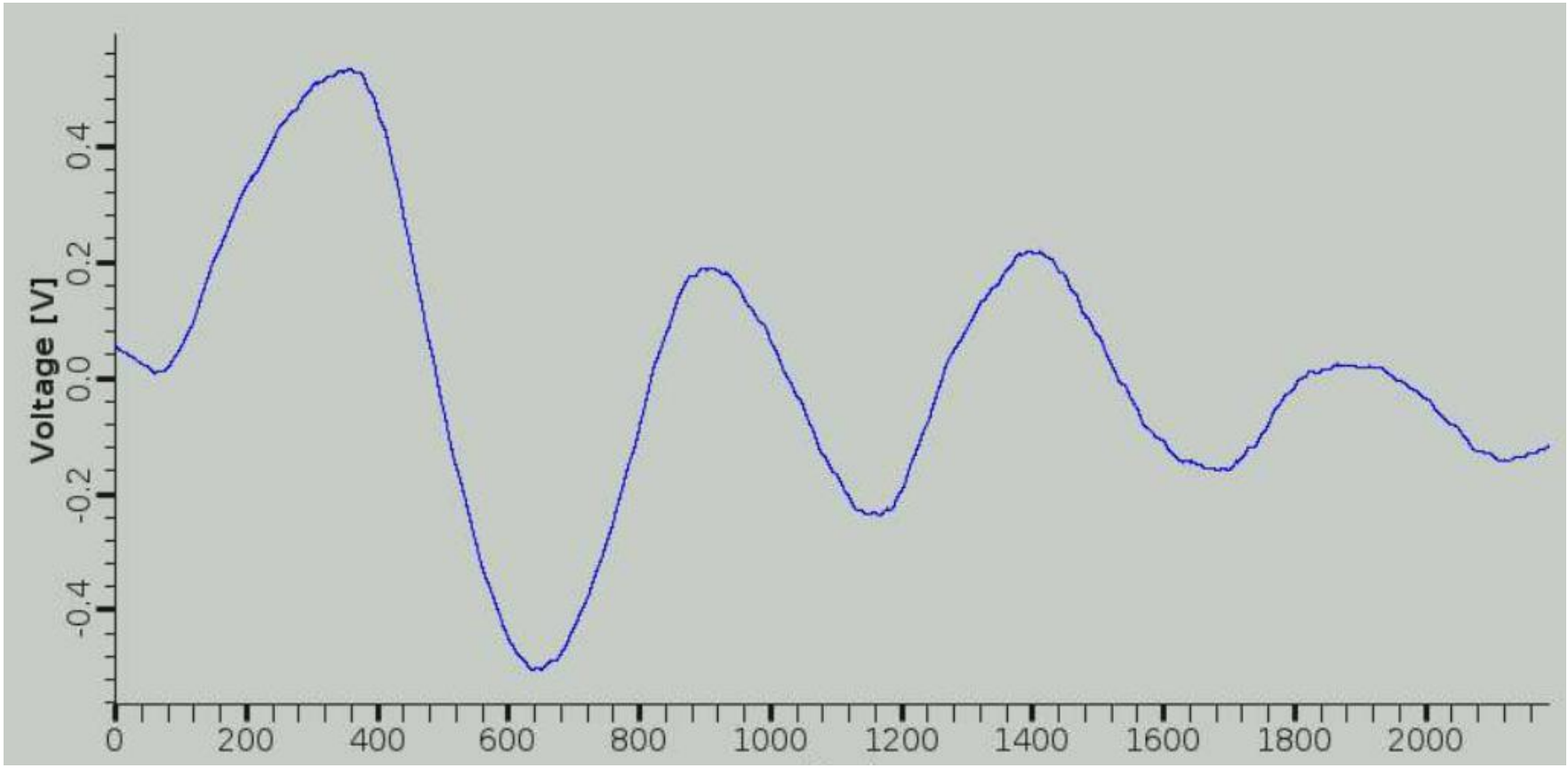


	Aisle	System	HPD ID	RTM Carrier ID	PPSM ID	Tested		Visual inspection	Comments
2	MBL-010	E01	H011	478	v1.57	A007	Err, repeated and OK	OK	Ok, piezo cabl. not con.	no piezo cable
3		E02	H013	498	v1.57	A003	OK	OK	Ok	
4		E03	H014	477	v1.58	A001	OK	OK	Ok	
5		E04	H015	474	v1.57	A004	OK		Ok	
6	MBL-020	E01	H016	494	v1.57	A014	OK	OK	Ok	no labels
7		E02	H017	471	v1.57	A013	OK	OK	Ok	no labels
8		E03	H018	499	v1.57	A015	OK	OK	Ok	no labels
9		E04	H019	495	v1.57	A012	OK	OK	Ok	no labels
10	MBL-030	E01	H020	483	v1.57	A009	OK	ERR, no RF	Ok	no labels
11		E02	H022	496	v1.57	A010	OK	OK	Ok	no labels
12		E03	H023	492	v1.57	A011	OK	OK	Ok	no labels
13		E04	H024	484	v1.57	A008	OK	OK	Ok	no labels
14	MBL-040	E01	H025	485	v1.58	A018	OK	REF	Ok	
15		E02	H026	472	v1.57	A016	OK	OK	Ok	
16		E03	H027	493	v1.57	A112		In operation	Ok	In operation
17		E04	H028	497	v1.57	A017	OK	OK	Ok	
18	MBL-050	E01	H029	479	v1.57	A019	OK	REF	Ok, piezo cabl. not con.	
19		E02	H030	491	v1.57	A020	OK	In operation	OK	
20		E03	H031	473	v1.57	A023	OK	OK	Ok	
21		E04	H032	501	v1.57	A024	OK	OK	Ok	
22	MBL-060	E01	H033	481	v1.57	A025	OK		Ok, piezo cabl. not con.	
23		E02	H034	489	v1.57	A026	OK		Ok	
24		E03	H035	475	v1.57	A027	OK		Ok	
25		E04	H036	488	v1.57	A028	OK		Ok	
26	MBL-070	E01	H037	480	v1.58	A029	OK		Ok, piezo cabl. not con.	
27		E02	H038			A030	OK		Ok	
28		E03	H039			A031	OK		Ok	
29		E04	H040			A032	OK		Ok	
30	MBL-080	E01	H041			A033	OK		Ok, piezo cabl. not con.	
31		E02	H042			A034	OK		Ok	
32		E03	H043			A035	OK		Ok	
33		E04	H044			A036	OK		Ok	RTM Carrier dis

Scope summary

- **Hardware components design, evaluation and production for M-Beta and H-Beta cavities control systems:**
  - **RTM Carrier board,**
  - **RTM Piezo Driver,**
  - **Local Oscillator board,**
  - **PSS switch,**
  - **Pin diode,**
  - **Electron pick-up,**
  - **RF splitbox**
- **Hardware cavity simulator design and evaluation,**
- **Reference LLRF system integration and evaluation,**
- **LLRF systems integration, installation in the ESS and evaluation,**
- **Chosen firmware components preparation.**

Scope summary



Conclusions

- **Full scope** of the LLRF systems for elliptical superconducting cavities **has been delivered**,
- In **cooperation with ESS the PEG** partners were able to design and produce **dedicated MTCA.4 modules** (RTM carriers, LO RTMs and Piezo Drivers) and other hardware sub-systems,
- Tight cooperation allowed for better interfaces specification which facilitated integration in the latter stage of system delivery,
- **Fruitful cooperation** between **ESS and PEG** (three Polish institutions) **allowed for completion of co-design, prototyping, production and installation work** on complex LLRF control system,
- Successful delivery of integrated and ready for deployment system was possible due to the partnership relations in the group and with ESS (against main showstoppers – pandemic, inflation, semiconductor market crisis etc.),
- Some aspects of the work is being continued to the next level under separate projects and agreements.

Thank You