INSTRUMENTATION
TECHNOLOGIES

LIBERA

The evolution of Libera LLRF technology for Linear Accelerators

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WWW.I-TECH.SI

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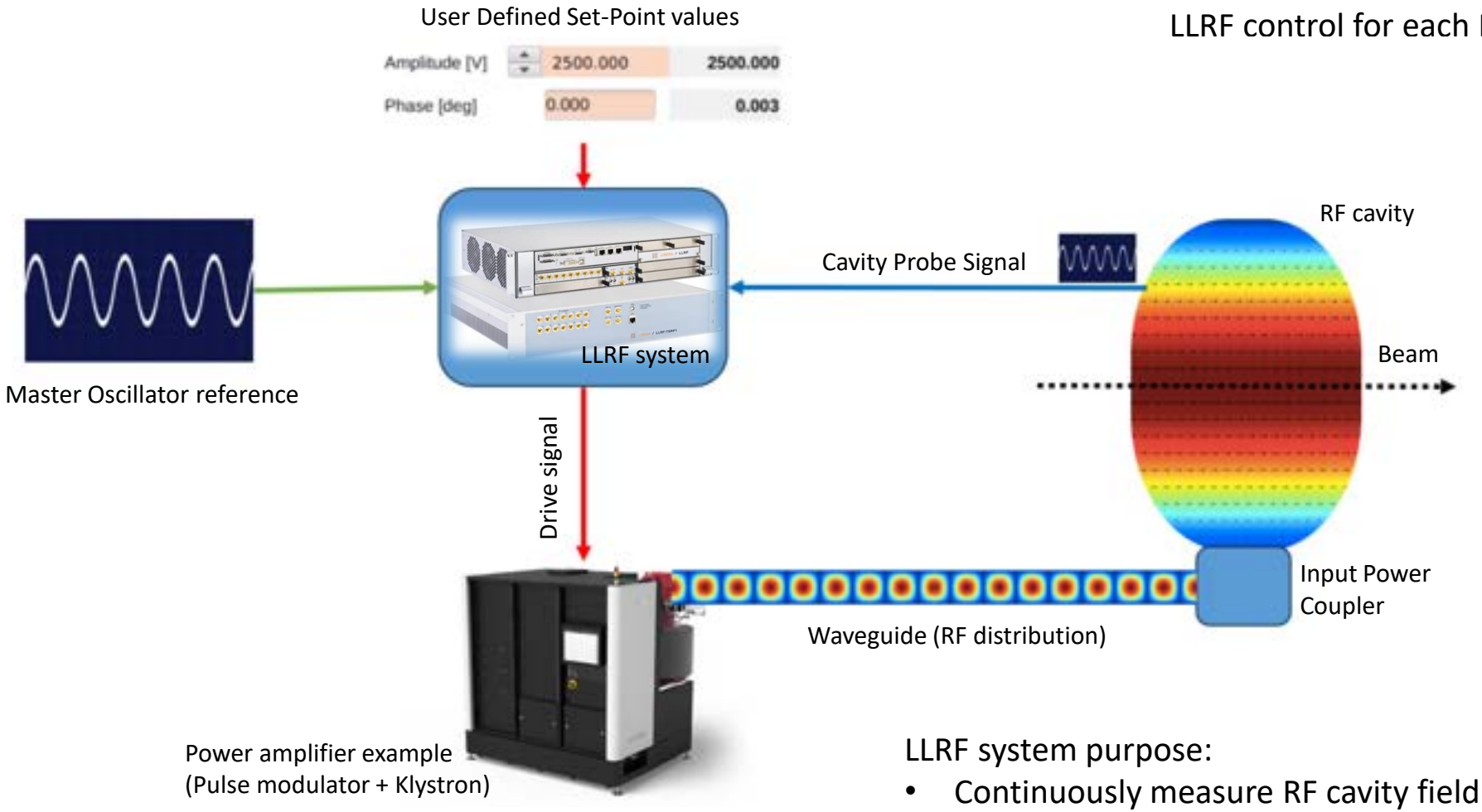
Digital LLRF control introduction



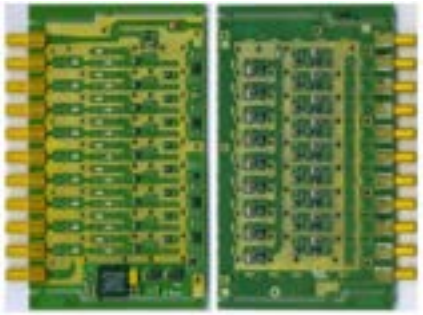
LLRF system purpose:

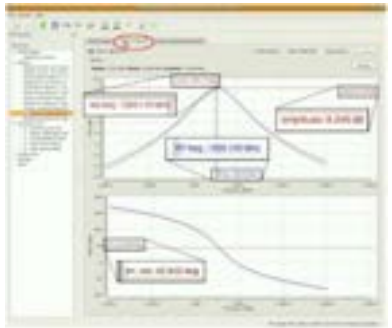
- Continuously measure RF cavity field amplitude and phase
- Control high power RF to keep cavity field stable

First Steps of Libera LLRF: LINAC 2008

Following the success of the Libera Electron and Brilliance BPMs in 2006, Instrumentation Technologies began addressing LLRF applications by the end of 2007. This required a modular approach, which marked the birthplace of Platform B.

Libera LLRF was unveiled and demonstrated live at LINAC 2008 in Victoria, British Columbia.



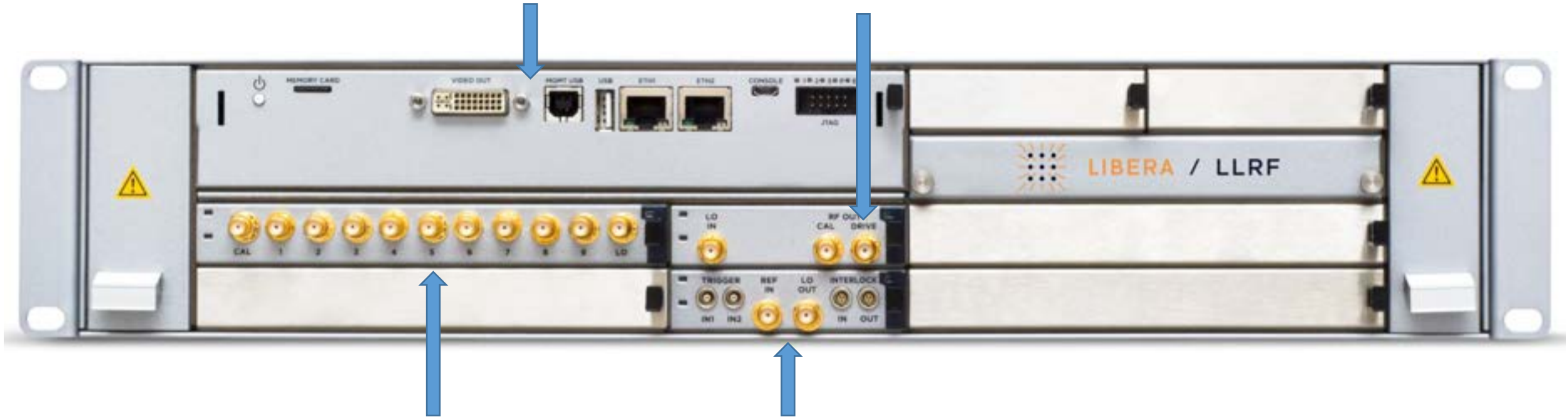


This was the result of extensive development work focused on a new MTCA-based platform, integrating advanced hardware, FPGA, and software technologies.

Libera LLRF platform

The **ICB module** provides Ethernet connectivity, PCIe backplane communication, and CPU processing.

The **VM module** runs the LLRF control algorithm and outputs the RF drive.



The **ADC module** performs frequency conversion, digitization, and basic FPGA processing; up to 4 are supported.

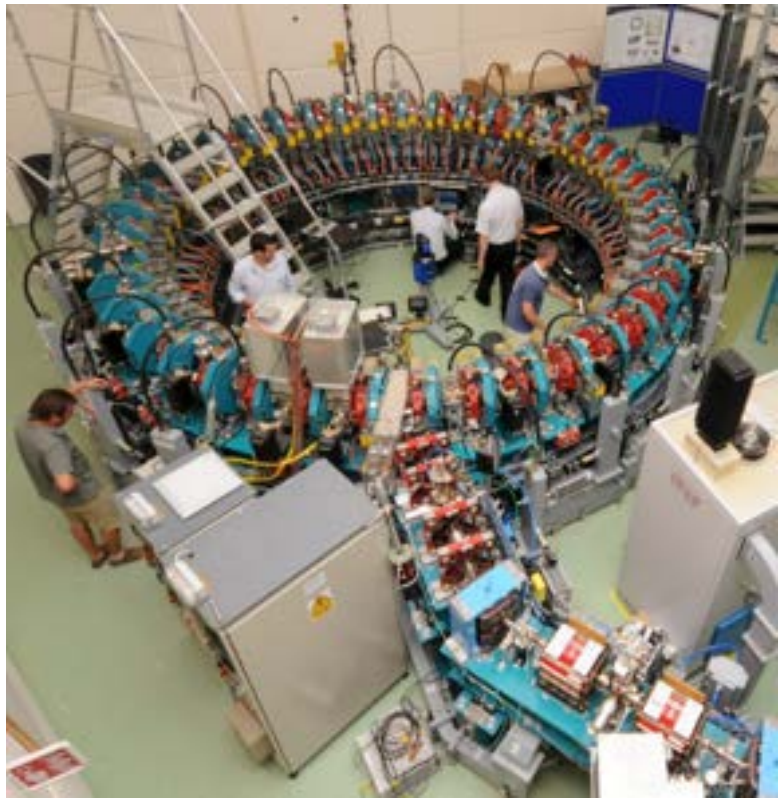
The **TCM module** supplies the sampling clock, distributes triggers, handles interlocks, and generates the LO signal.

First Libera LLRF application: EMMA FFAG

Science & Technology Facilities Council

EMMA, the first **non-scaling FFAG** accelerator, supports high-energy electron acceleration with variable RF frequency for diverse applications.

- 19 RF cavities, 1.3 GHz, variable frequency
- Serpentine acceleration with Libera LLRF
- Mechanical plunger cavity tuning

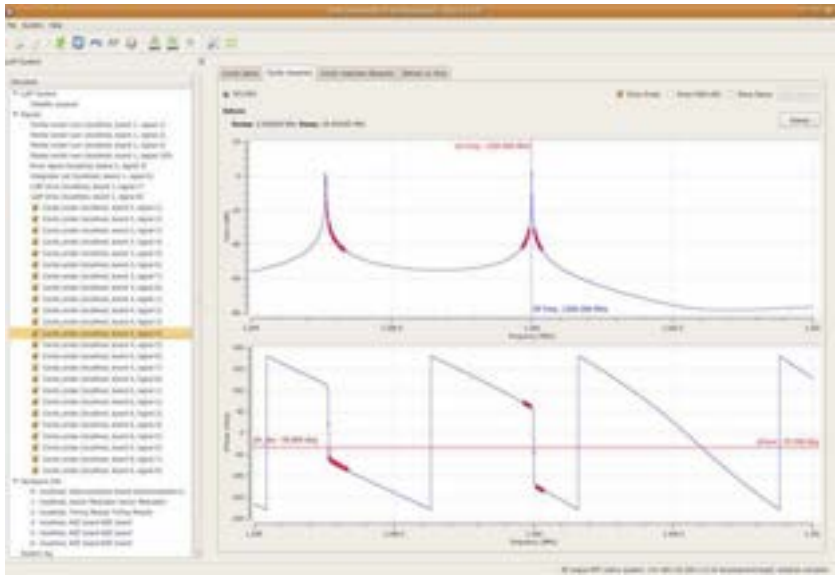


Libera LLRF high-power bench testing

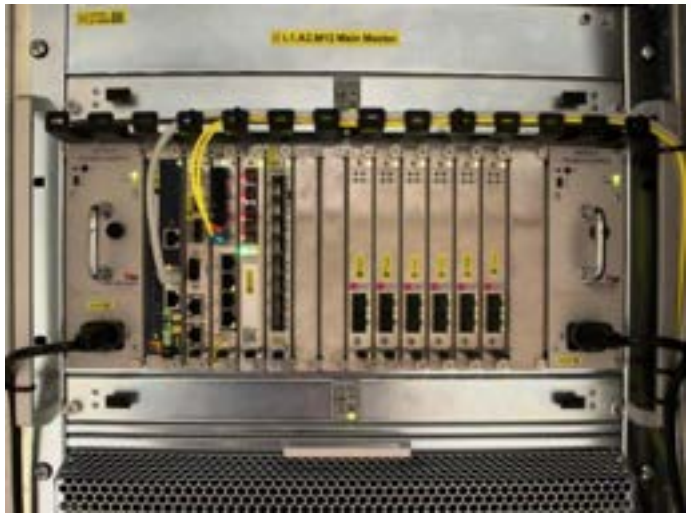
EMMA FFAG Libera LLRF installation (2010): 19 cavity vector sum control

Libera LLRF demonstration at FLASH (DESY)

Libera LLRF demonstration installation at FLASH (DESY)



Libera LLRF FLASH ACC456 cavity response analysis

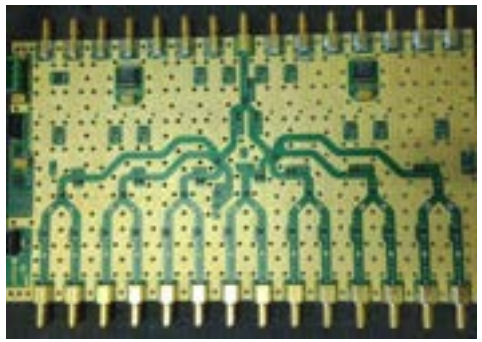


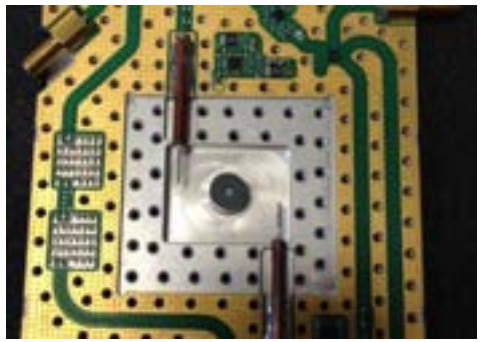
DESY's in-house developed MTCA.4-based LLRF system.

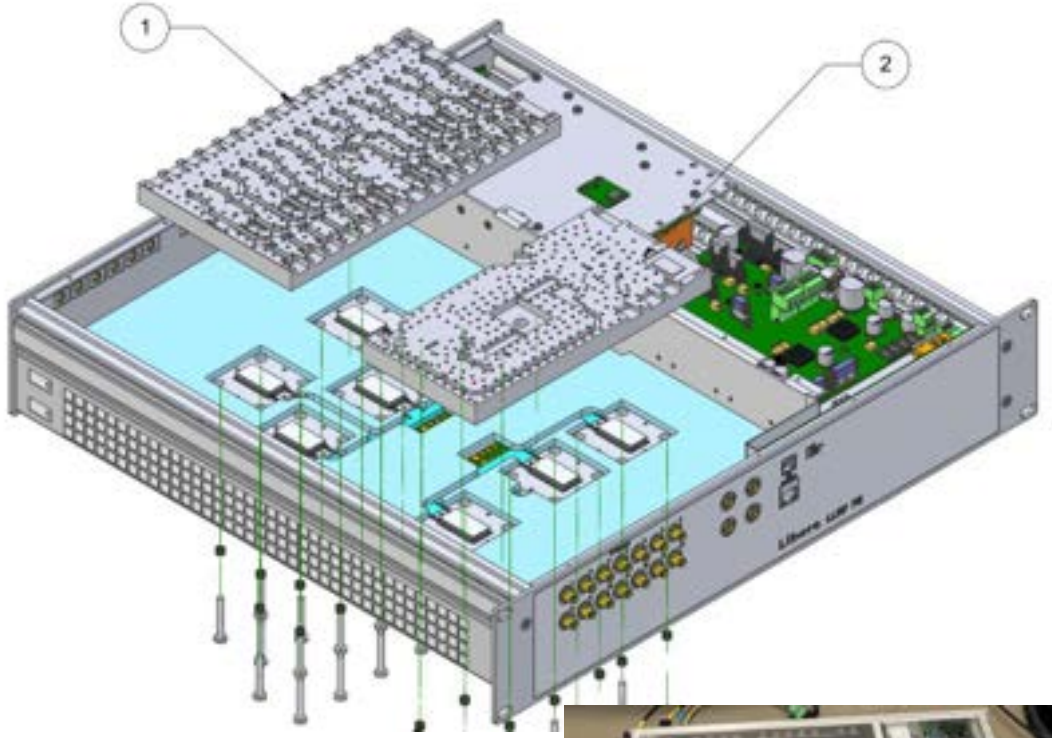
- In 2009, the **European XFEL** at DESY was identified as a key target project for LLRF development.
- During this time, the Libera LLRF system was demonstrated at DESY as a potential solution.
- Later DESY opted for internal development and created the MTCA.4-based LLRF system.

- **High-power closed-loop tests** on 24 SC 1.3 GHz cavities (ACC456), achieving 10 MV/m average gradient and up to 30 MV/m operation (July 2009).
- **Three Libera LLRF units** installed in the FLASH rack, enabling advanced diagnostics and control.
- **Field stabilization**: 0.009% amplitude and 0.0095° phase (vector sum of 24 cavities); loop gain of 71.
- **Vector sum calibration** with beam, passband mode suppression, feedforward flexibility, beam loading operation, and SASE mode demonstrated.

New technologies, temperature stabilized front-end unit

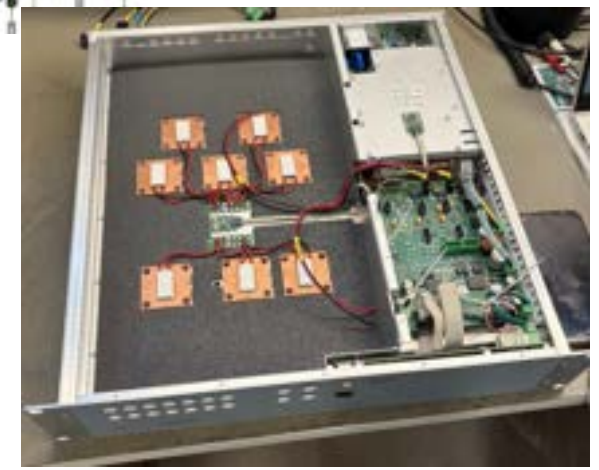




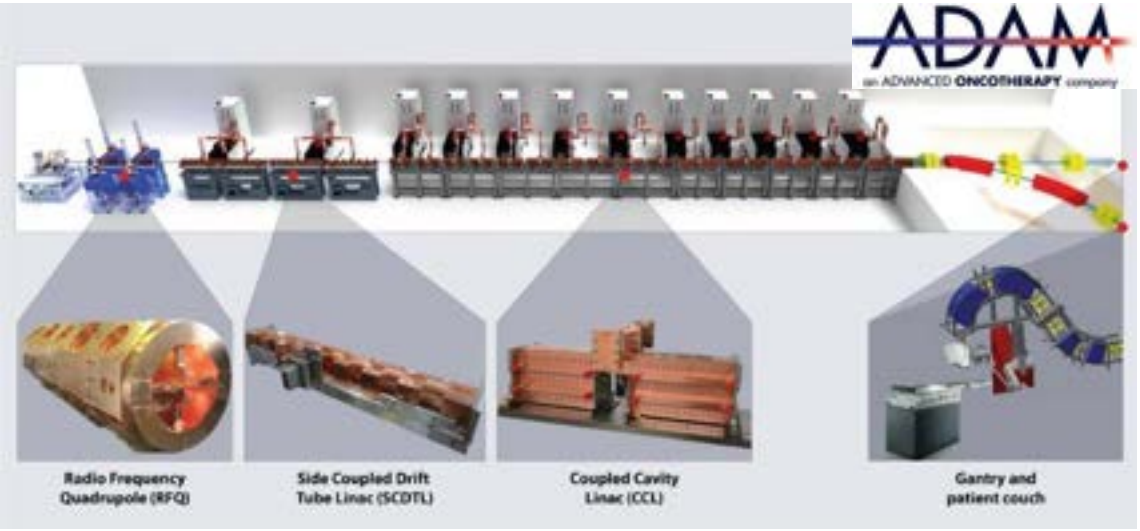


INFN
LNF
Istituto Nazionale di Fisica Nucleare

- Libera LLRF upgrade with a **high-performance RF design** to support **S- and C-band applications.**
- **Temperature-stabilized Libera LLRF front-end** housed in a dedicated chassis for long-term stability.
- This design was introduced for the **demanding ELI-NP Gamma Beam Project**, led by **INFN Frascati**, to meet stringent stability and performance requirements (2014-2016).



Further extension of Libera LLRF functionality

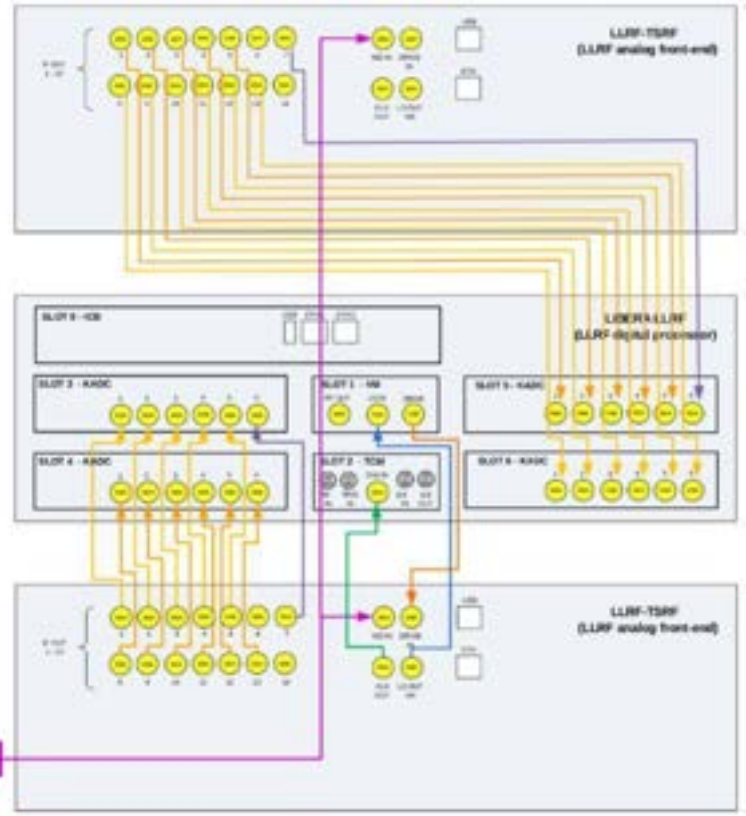


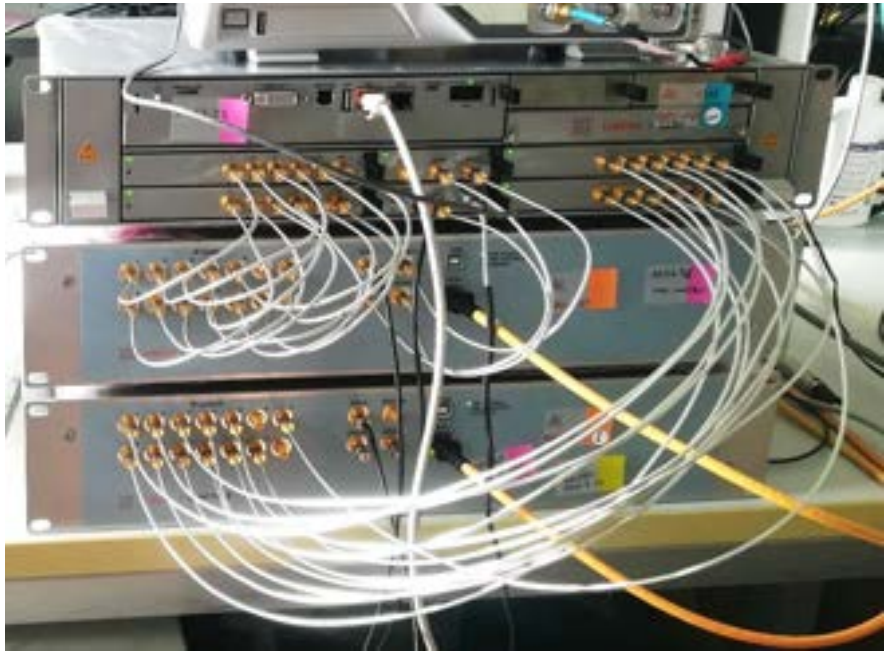
First KUPVM delivered in 2019

- **First KUPVM delivered in 2019**
- Real time control system interface and pulse shape control at 200 Hz
- Continuous data archiving interface
- 13 Libera LLRFs delivered for the AVO/ADAM proton therapy LINAC Libera LLRF application

Libera LLRF FPGA upgrade: Xilinx KUP technologies

New generation 6 channel KADC module based on Xilinx KUP technology.





- FPGA upgrade to **Kintex Ultrascale+** (KUP) technology.
- Introduction of new **6-channel KADC** module and **KUPVM** processing module.
- Support for **22 input channels** via two temperature-stabilized front-end units.
- Software upgrade: new operating system and a **CSS Phoebus**-based **GUI** with enhanced features.
- First upgraded Libera LLRF units **delivered to ANL** LINAC in 2020 with SLED RF pulse compression functionality.
- The LINAC upgrade began alongside the **APS-U** storage ring project, which included the upgrade of **560 Libera Brilliance+ BPMs**.

Argonne NATIONAL LABORATORY

Libera LLRF evolution

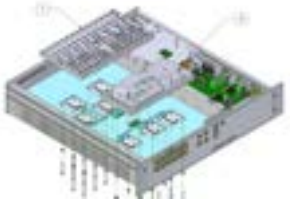
Libera LLRF development LINAC 2008 Demo

2008

First Libera LLRF delivery (EMMA STFC commissioning 2010)

2009

2010



Starting Libera LLRF TSRF development (2014)

2014

2016

KADC (6 ch)

2019

First Libera LLRF double TSRF delivery

2020

Starting X-Band LLRF development

2023

KADC8 (8ch 250 MSps)

TCMA (250 Msps)

ICB2

2024

New generation modules development KADC8, ICB2, TCMA

2009 Demonstration at FLASH DESY 2009

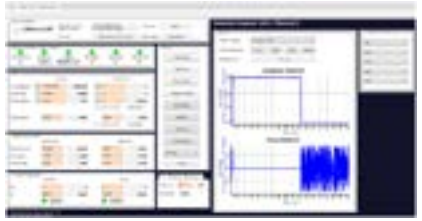
2016 First delivery of Libera LLRF with TSRF front-end

2019 First KUPVM based Libera LLRF delivery

Qt GUI

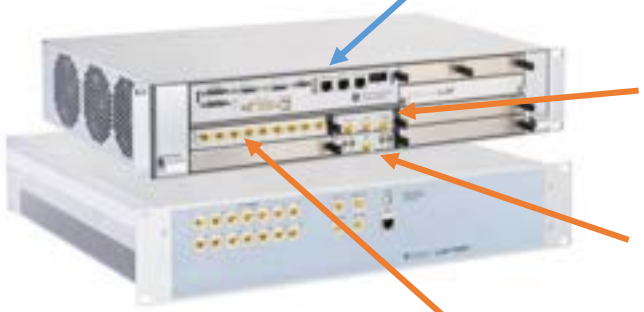
caQtDM GUI

PyQt GUI



Phoebus CSS GUI

Recent platform upgrades



New ICB module (version 2)

- A new ICB module with state of the art CPU:
  - Intel I5 or I7
  - 2.5 & 10 GbE
  - HDMI output
  - IPMI over LAN support

New KUPVM board

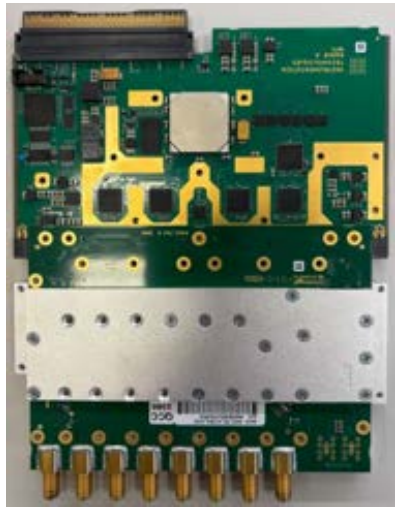
- A new VM module based on Kintex Ultrascale FPGA

New TCMA board

- Latest components
- Up to 250 MHz ADC clock

New KADC8 board

A new ADC input module based on new 250 MSps capable ADCs and Kintex Ultrascale FPGA and larger memory capabilities.

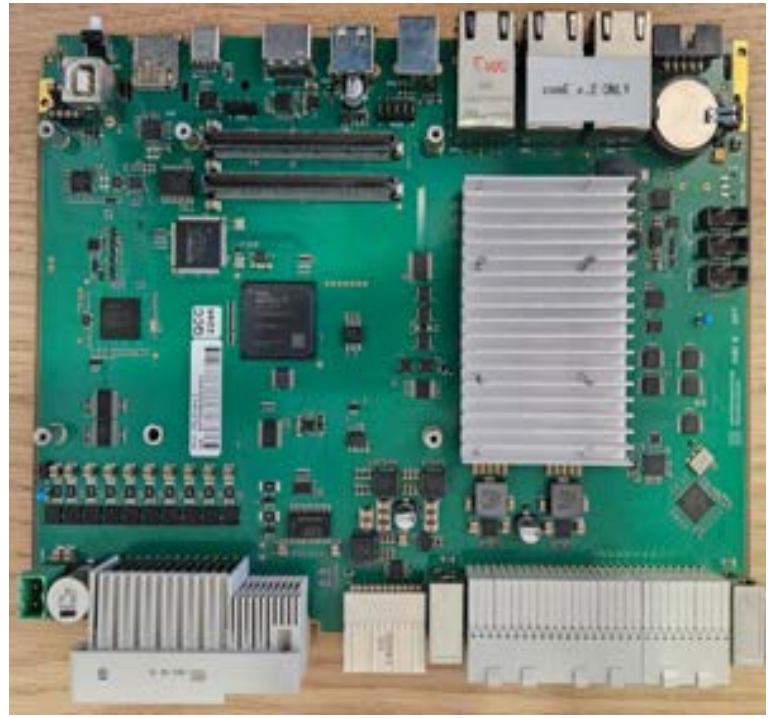


ICB module upgrade – comparison

ICB Version 1

SD card	**Boot/storage media**	SD card (Optional NVME up to 1TB on COMe)
DVI	**Video**	HDMI
MicroUSB	**COMe console**	USB-C
2x 1 GbE	**Ethernet**	**1 x 2.5GbE** **1 x 10 GbE** 1 x 100MbE -mng
Gen1/2	**PCIe**	Gen 1/2/3
USB 2.0 480Mbps	**USB-A**	USB3.1 5Gbps
Lattice LFE2M	**FPGA Glue logic**	Xilinx Artix-7
NXP LPC2378	**MCU**	NXP LPC54608
Intel Core i5-7440EQ	**CPU type**	Intel Core i5-13600HE
5711	**CPU mark**	**26540**
4 (Threads 4)	**# of Physical Cores**	**12 (Threads 16)**

ICB Version 2



Software upgrades

- Libera LLRF **software** evolves with hardware to meet new requirements
- Runs on Ubuntu LTS; upgraded to 18.04 in 2020, **24.04** now available
- Key OS-related features:
  - **NTP** time synchronization
  - **Network boot** support
- Each OS upgrade includes full **regression testing** and **validation** across all components

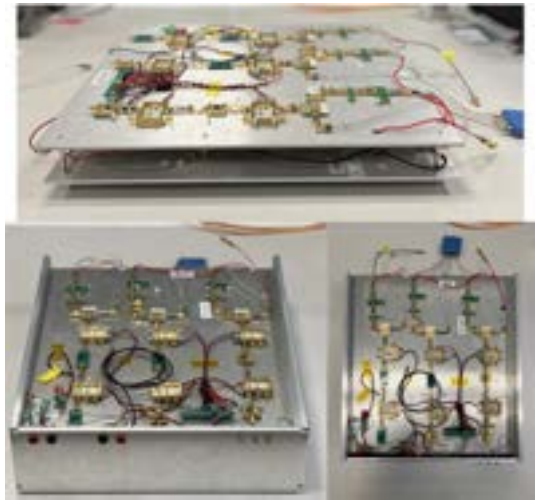
Summary and New Areas of Development

- Libera LLRF has undergone continuous **evolution**, with major hardware and software upgrades, **platform modernization**, and successful deployment across a range of accelerator projects. We are **renewing the subsystems** to address component obsolescence and to introduce **state-of-the-art technologies**, ensuring long-term reliability and performance.

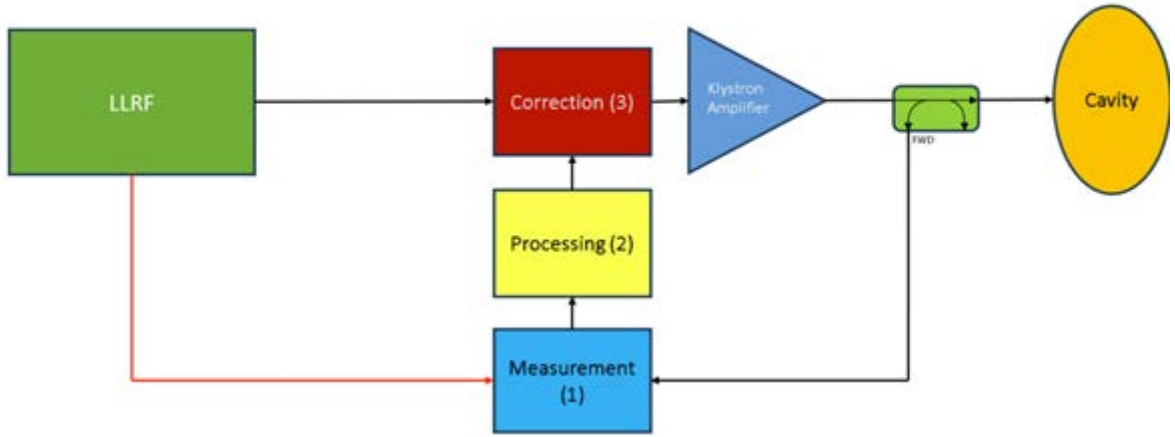
- Ongoing activities are focused on developing an **X-band Libera LLRF prototype** as part of the EuPRAXIA Doctoral Network (DN) project.

- Following validation, the prototype will enter an industrialization phase, leading to the creation of **a new Libera LLRF** version addressing X-band applications.

- Additional activities target the development of an **intra-pulse analog feedback system**, aiming to suppress RF system jitter contributions and enhance overall stability.



X-band LLRF prototype



Intrapulse feedback concept

Thank you!
Questions?

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Libera LLRF