INSTRUMENTATION TECHNOLOGIES

LIBERA

Doctoral Network

School on Plasma Accelerators

LIBERA

Introduction to Digital Low-Level RF Systems

Manuel Cargnelutti

Instrumentation Technologies, Slovenia

Rome, April 26th, 2024

Agenda

- Instrumentation Technologies - company introduction
- RF system and Digital Low-Level RF (LLRF)
- Low-Level RF operation
- Libera LLRF implementation
- Towards a first commercial X-band LLRF

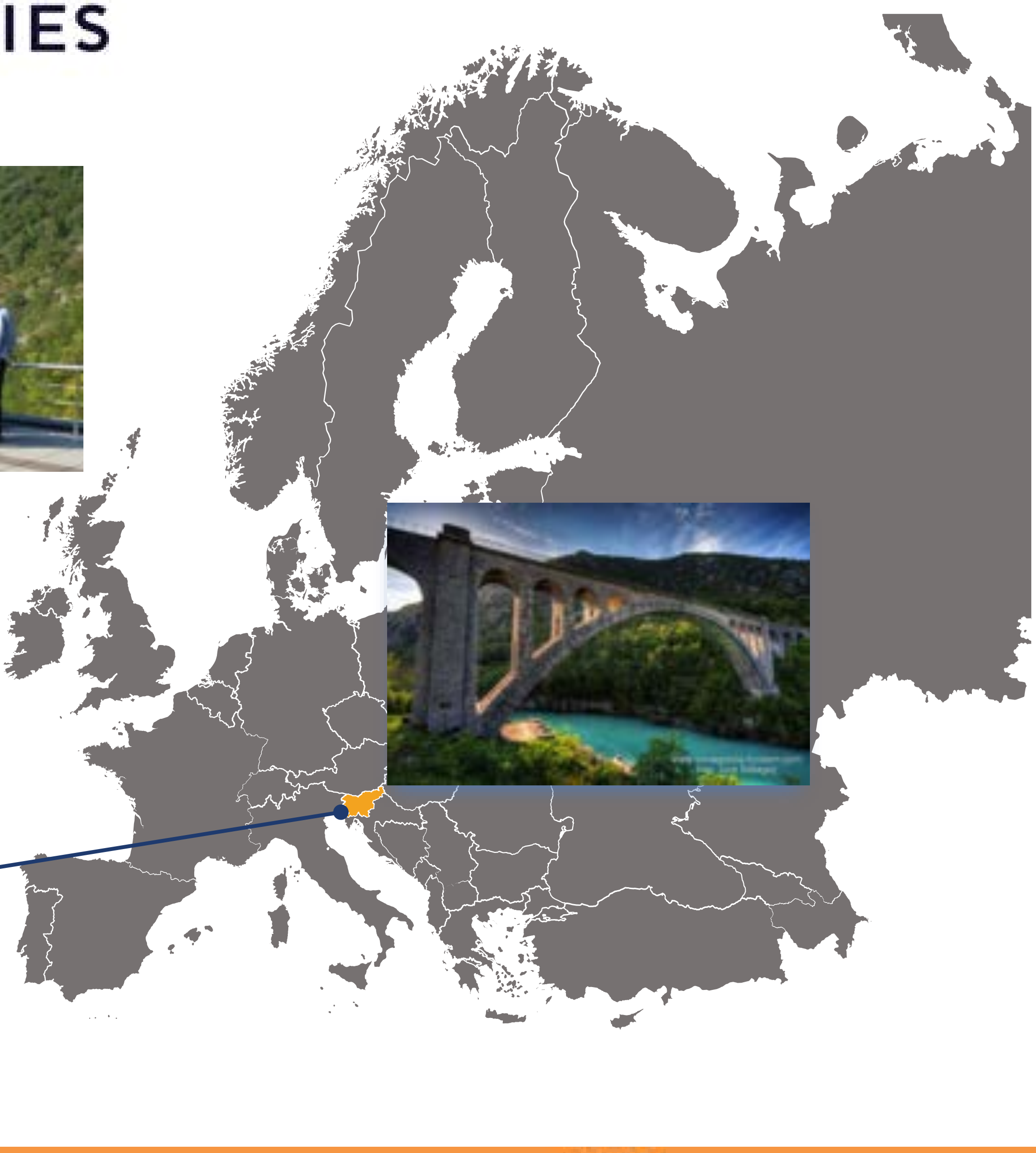
INSTRUMENTATION TECHNOLOGIES

Est. 1998

~50 employees

ISO 9001:2015 certified ISO

Headquartered in Solkan, Slovenia



Company Business Units

INSTRUMENTATION TECHNOLOGIES

LIBERA

SOLUTIONS
FOR INDUSTRIES

redpitaya

Beam-diagnostics-and-control instrumentation

- Particle Accelerators
- Nuclear Research Reactors
- Nuclear Fusion

Custom data-acquisition products

- Transportation Industry
- Energy Industry
- Test and Measurement

Open-source general-purpose lab devices

- Universities
- Research
- Industry

LIBERA was the result of collaborations

Libera Electron

Back in **1998**, all diagnostic systems were based on **analog electronics,** providing **limited information** about the beam.
Analog electronics were **not stable** against temperature and component aging.

Together with the synchrotrons in EU, Instrumentation Technologies developed the **1st Libera instrument**, consisting of an analog front end, fast A/D converters and a digital processor (FPGA).

The real-time processing power offered by the FPGAs, made **fast communication** between the instruments possible, enabling **fast-feedback** applications which are today a must in the new machines.

…and was quickly adopted worldwide!

LIBERA

> 6,000 instruments sold

to **> 80 laboratories** worldwide

Asia
Bhabha Atomic Research Center
Chinan Biomedical Technology
HiSOR
HUST
IBS—RISP
IHEP—BEPC II, ADS, CSNS
IMP-CAS—C-ADS, LEAF, SSC-LINAC, CSR, HIRFL
IMS—UVSOR
Inter University Accelerator Centre
ISSP
KEK—PF, PF-AR, LINAC, SUPER B, J-PARC, cERL
Nagoya University—Aichi Synchrotron
NewRT Medical Systems
NSRRC—TLS, TPS
PAL—PLS II, XFEL ITF
Peking University
RRCAT—INDUS, INDUS II
SACLA—SPring-8
SINAP—SSRF
SJTU
SLRI
Tokamak Energy
Tsinghua University
USTC, NSRL—HLS, HLSII
Australia
Australian Synchrotron
Europe
AVO-ADAM—LIGHT
CANDLE
CEA
CELLS—ALBA
CERN
DELTA
DESY—PETRA III, FLASH, DESY XFEL, DORIS III
Diamond Light Source
ELI - Extreme Light Infrastructure
ESRF—ESRF-EBS
Forschungszentrum Jülich—COSY
Fritz Haber Institute of the MPS
GANIL
GSI—FAIR
Helmholtz-Zentrum Berlin BESSY II
Helmholtz-Zentrum Dresden-Rossendorf —ELBE
IBPT—KARA
IJS
INFN—Daphne, ELI-NP, SPARC
IPNO
ISA—ASTRID II
Jagiellonian University—SOLARIS
JINR—NICA
LAL—THOM-X
Lund University—MAX III, MAX IV
MedAustron
Physics Institute of the University of Bonn
PSI—SLS, SwissFEL
Research Instruments
RRC Kurchatov Institute—SIBERIA II
ScandiNova
SCK-CEN
SDU—TARLA
SESAME
Sincrotrone Trieste—Elettra, FERMI
SOLEIL Synchrotron
STFC ASTeC—EMMA, CLARA
University of Twente
North America
ANL—APS, APS-U
Best Medical International
BNL—ERL, NSLS II, X-RAY ring
Canadian Light Source, CLS
Cornell University—CHESS, CESR
Idaho National Laboratory
LANL—LANSCE
LBNL—ALS
Michigan State University—FRIB
Northwestern University
NUSANO
Oak Ridge National Laboratory
RadiaBeam
SLAC—LCLS, SPEAR
South America
ABTLuS—LNLS

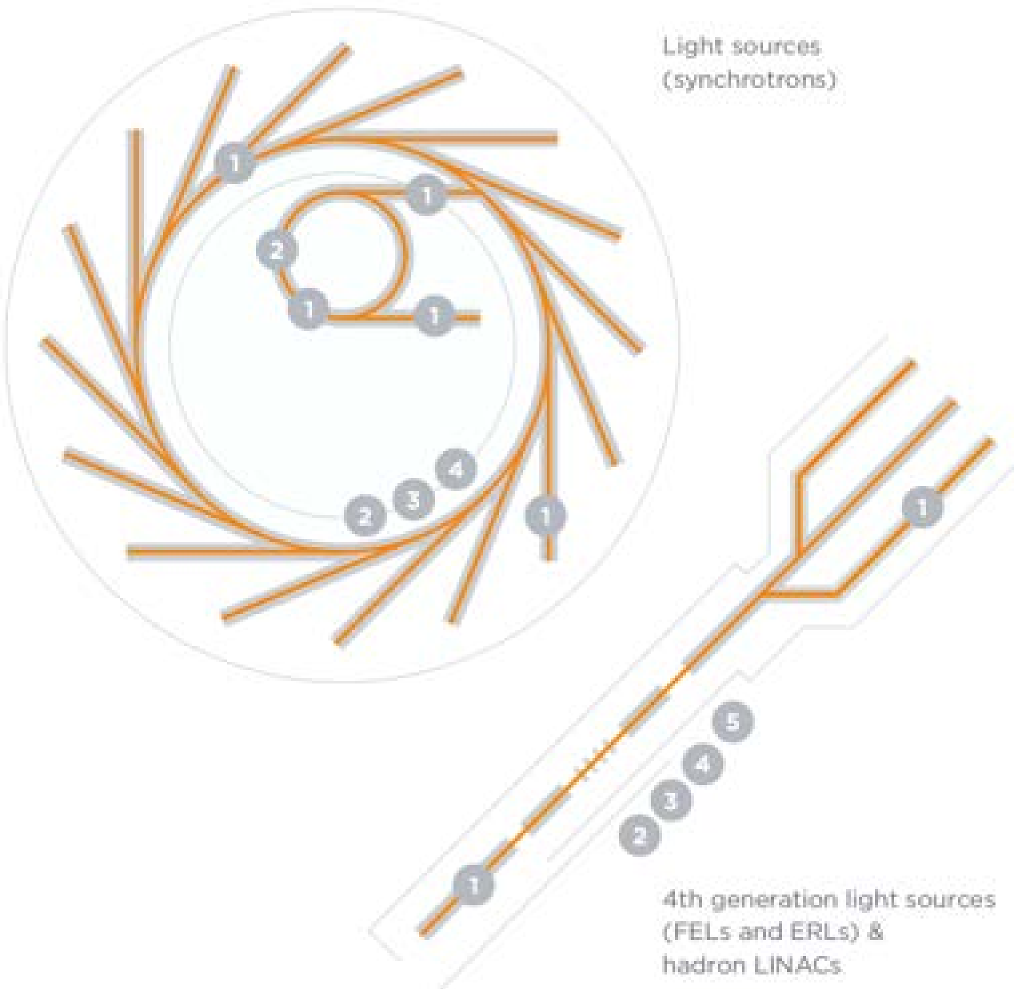
And today addresses many applications and machines

Beam Diagnostics
- Beam Position Monitoring
- Beam Loss monitoring
- Beam current / Beam phase

LLRF controls
- LINACs
- Proton synchrotrons

RF generation and transfer
- Reference Master Oscillators
- RF distribution systems

General Purpose
- RF Digitizers
- Current Meters



Typical instrument architecture

Input Signals

Actuators

Analog front-end and ADC

DAC and analog back-end

FPGA
Real-Time signal processing

CPU
Access to Signals and Parameters

Control System

LIBERA LLRF

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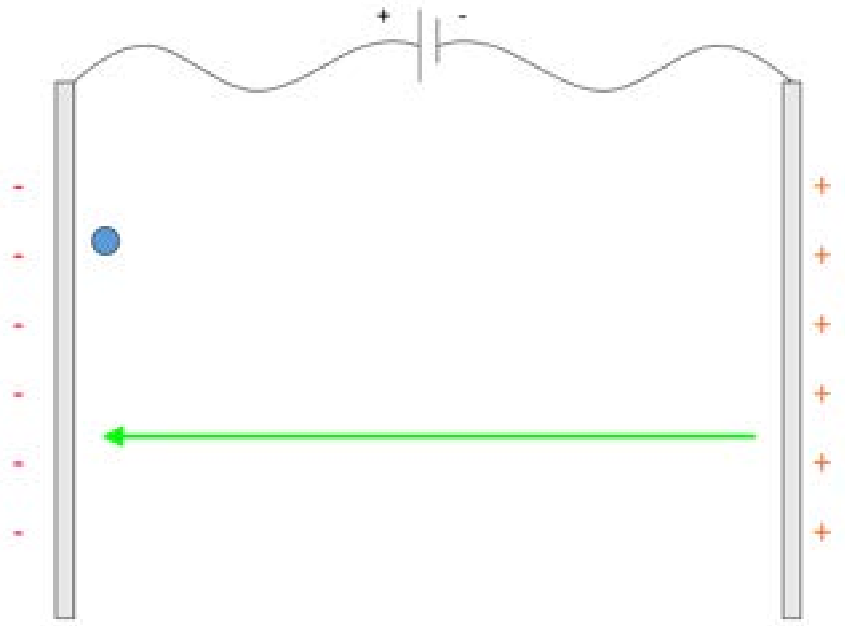
DC accelerators



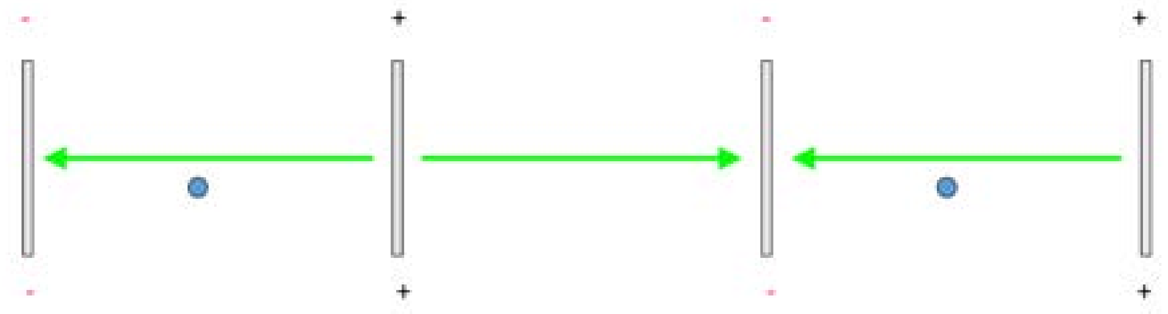
Courtesy of Dr. G.Burt

In DC or electrostatic accelerators, the particles travel through a constant **Electrostatic field**.
The energy they reach depends on the voltage gap between the two sides of the accelerator.

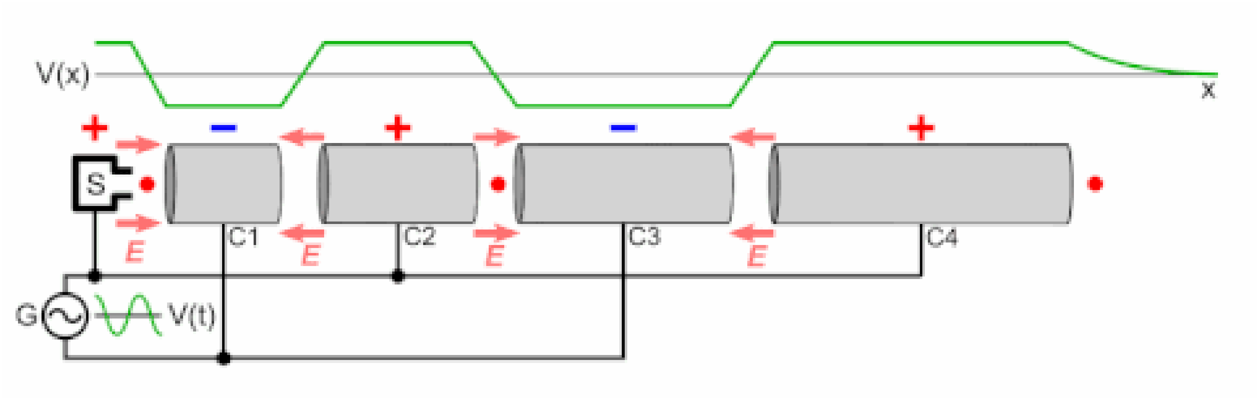
As an example, the **Cockroft-Walton** that used a smart voltage multiplier in order to achieve few 10s of MV.

The fundamental **limitation is the voltage breakdown** in the structures which limits the achievable voltage gradients to **3MV/m**

RF accelerators



Courtesy of Dr. G.Burt



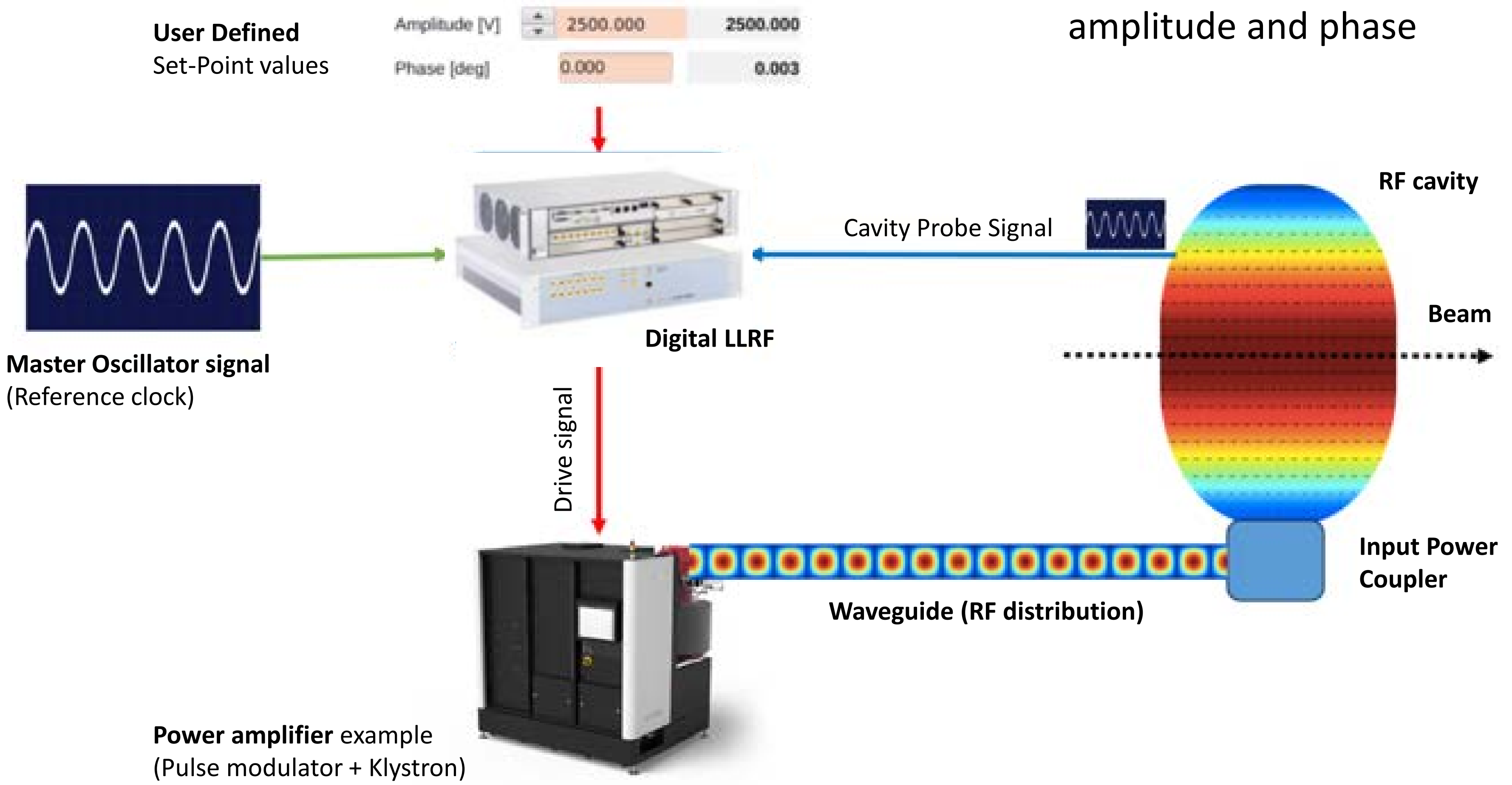
Principle: alternating the Electrical field across multiple plates along the particle accelerator.

The **RF field** within the RF structures should be **properly controlled** in order to be in a certain phase relation with the accelerated particles.

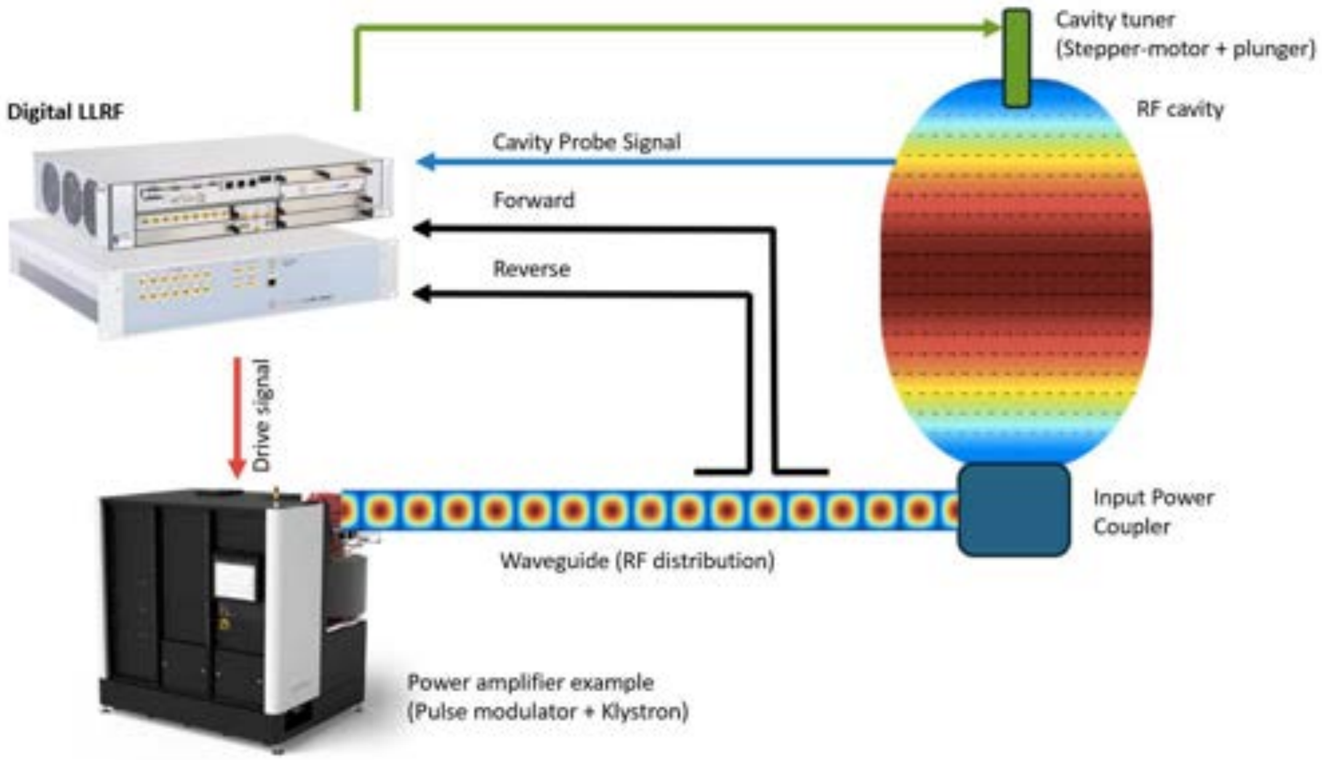
Achievable gradients: up to 100 MV/m

Digital LLRF purpose (I)

LLRF system purpose:
- Continuously measure RF cavity field amplitude and phase
- Control high power RF to stabilize cavity amplitude and phase

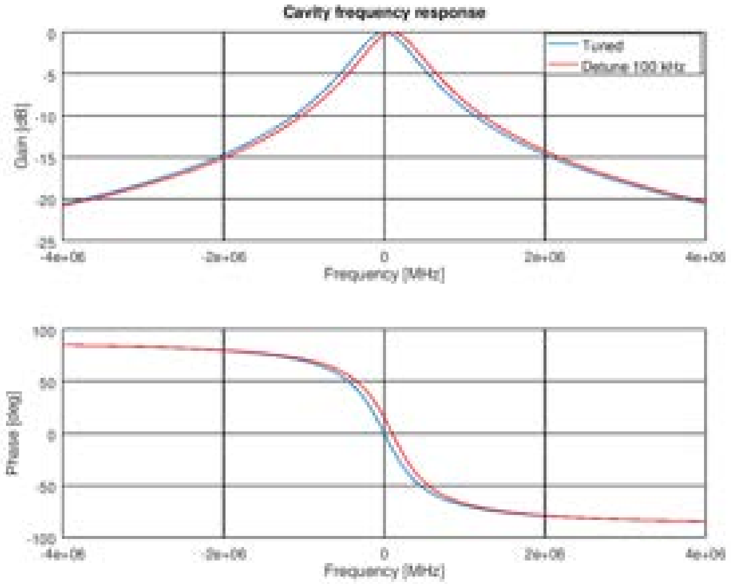


Digital LLRF purpose (II)



LLRF system purpose (continued):

- Measure the cavity resonant frequency and control the cavity tuning
- Trigger the machine protection system in case of unexpected signals in the cavity or in the RF distribution



Cavity material and parameters

Normal conductive
"warm" Copper cavities

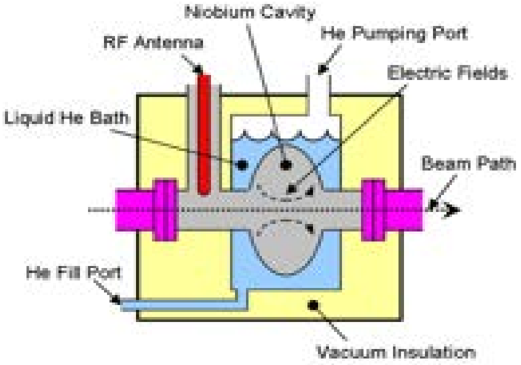
Normal conductive cavities

- Room temperature and water cooling
- Easier to manufacture and operate
- Pulsed beams
- RF frequencies from few 100 MHz to X-band
- Frequency tuning done with water temperature control and mechanical tuners

Cavity material and parameters

Normal conductive
“warm” Copper cavities

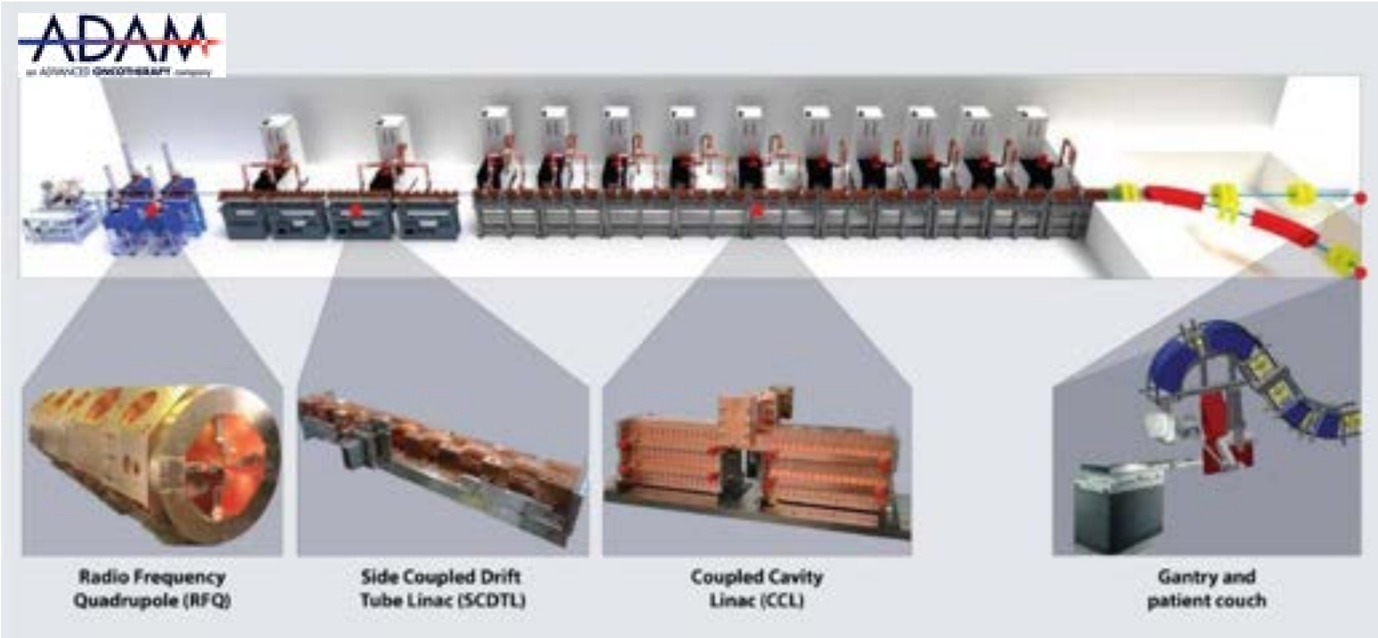
Super conductive “cold”
Niobium cavities



Normal conductive cavities
- Room temperature and water cooling
- Easier to manufacture and operate
- Pulsed beams
- RF frequencies from few 100 MHz to X-band
- Frequency tuning done with water temperature control and mechanical tuners

Super conductive cavities
- Cooling to 1.6K - 4.5K with liquid helium
- Challenging to manufacture and operate ($$$)
- Suitable for high duty cycle and CW operation
- Much higher efficiency compared to copper
- RF frequencies from few 100 MHz to few GHz
- More complicated frequency tuning done with piezo tuners

Example of normal conductive proton LINAC



750MHz RFQ
1 RF station

S-Band (3GHz)
SCDTL and CCL
12 RF stations

To achieve the desired beam energies, **several RF cavities are necessary**. Depending on the particle beam, the cavity frequencies might change as well as the cavity type.

Every RF station including a power amplifier needs to be controlled and synchronized with each other -> **each RF station needs a LLRF system**.

In order to have a common clock distributed for all the LLRF stations, an **RF distribution system** is also required!

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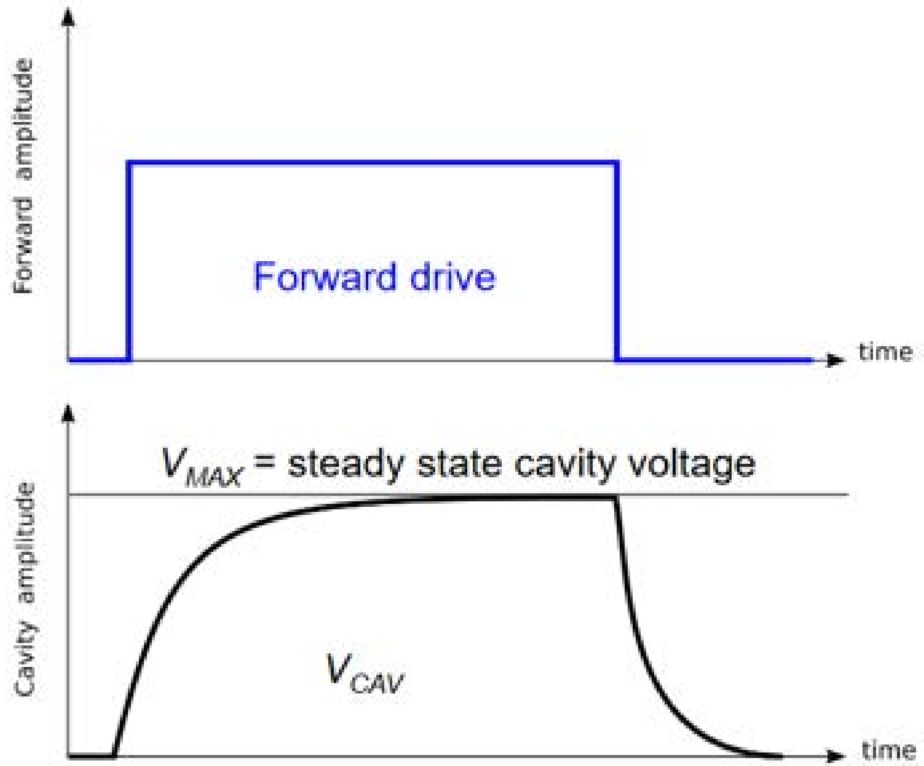
Feed Forward operation (I)



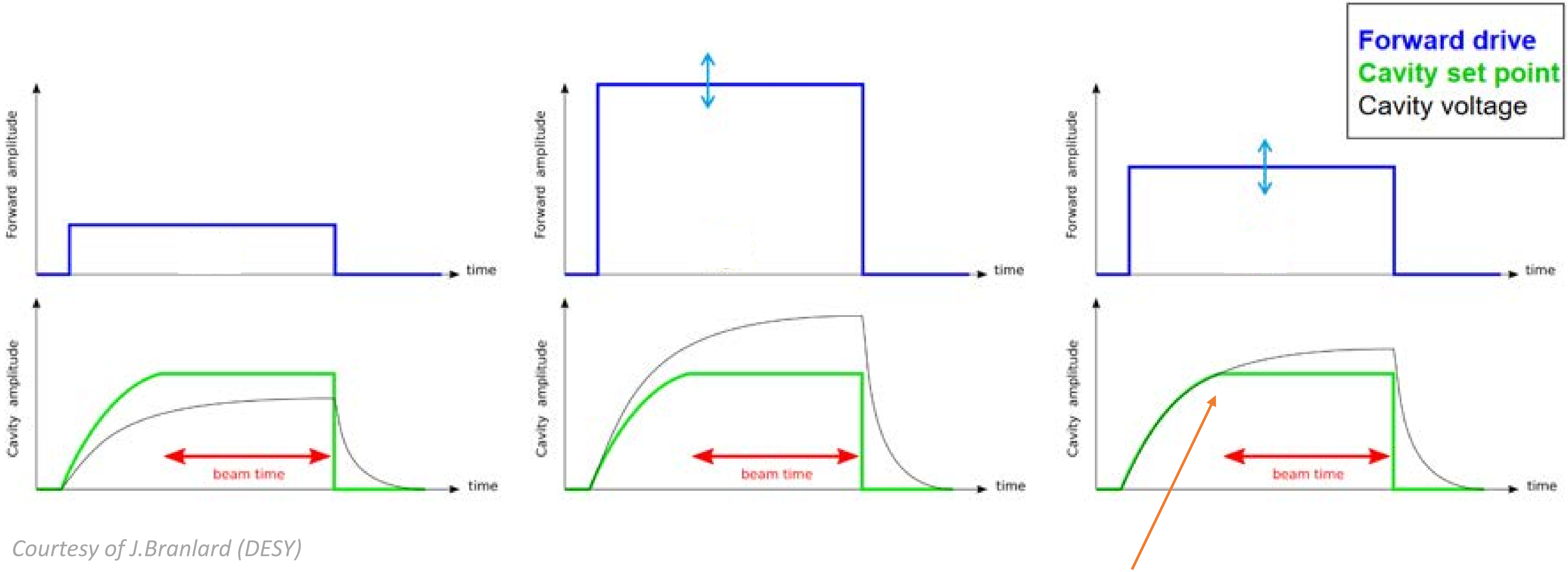
Courtesy of J.Branlard (DESY)

In **Feed-Forward operation**, we use the LLRF to generate a drive signal (Forward drive) that produces in the cavity (Vcav) a voltage that is as close as possible to our desired voltage.

In this process, we should consider the following aspects:

- The cavity has a filling time that depends on its quality factor. The same when the power goes off. It acts as a low-pass filter to the step response.
- This implies that the beam should arrive after the RF pulse
- Each cavity has a maximum voltage that can be filled in

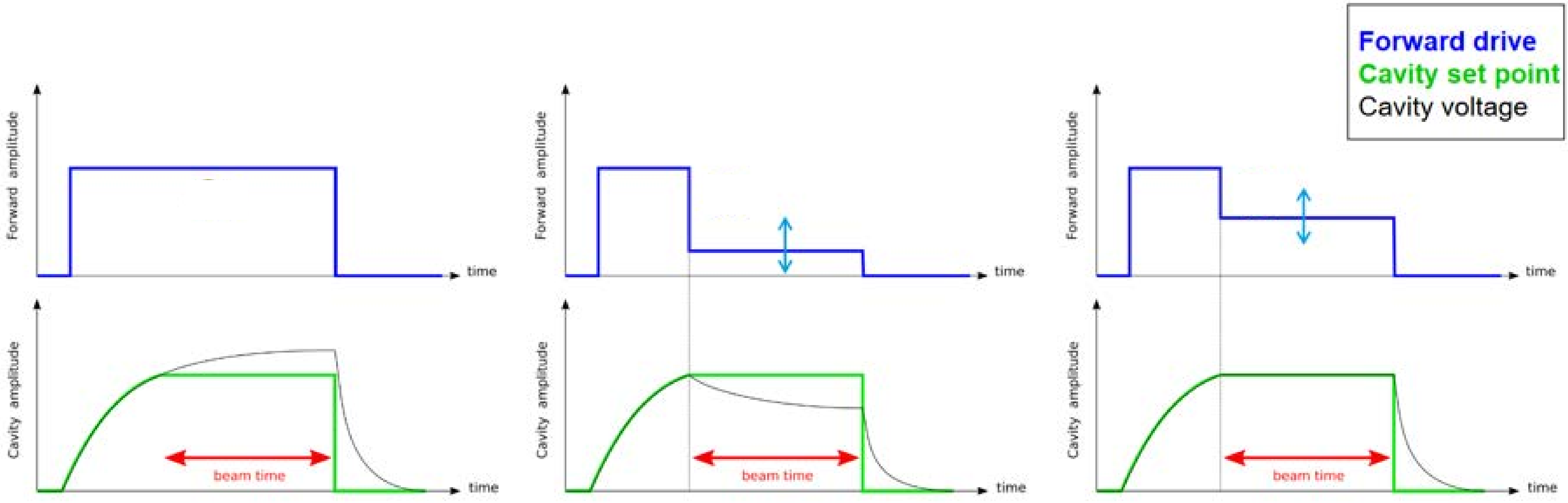
Feed Forward operation (II)



Courtesy of J.Branlard (DESY)

First step: defining the forward drive amplitude to match the cavity amplitude at the beginning of the beam time

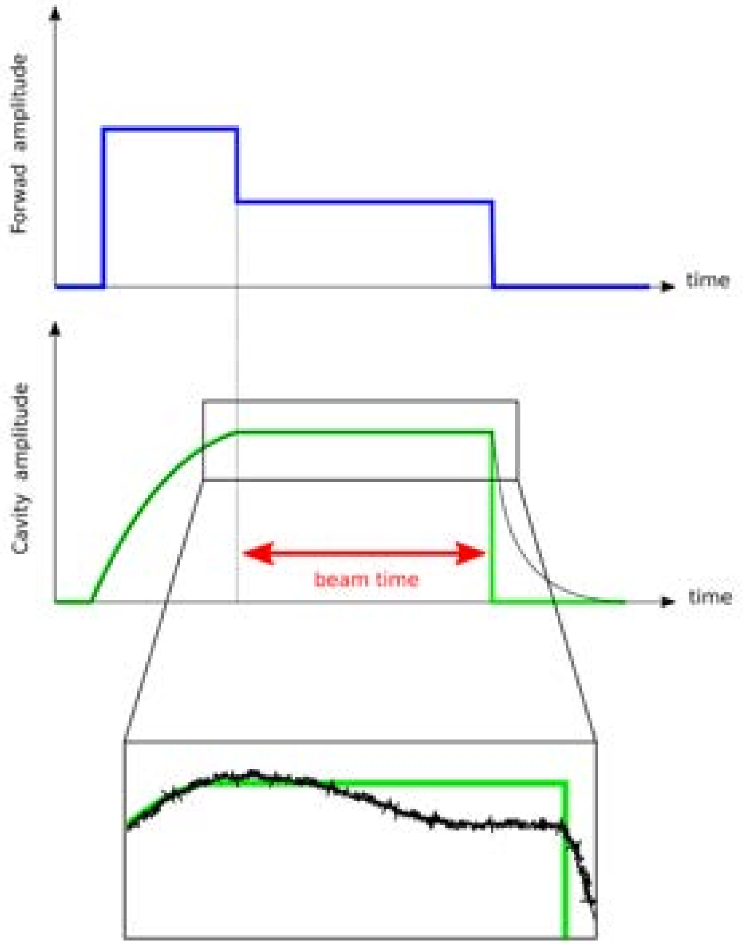
Feed Forward operation (III)



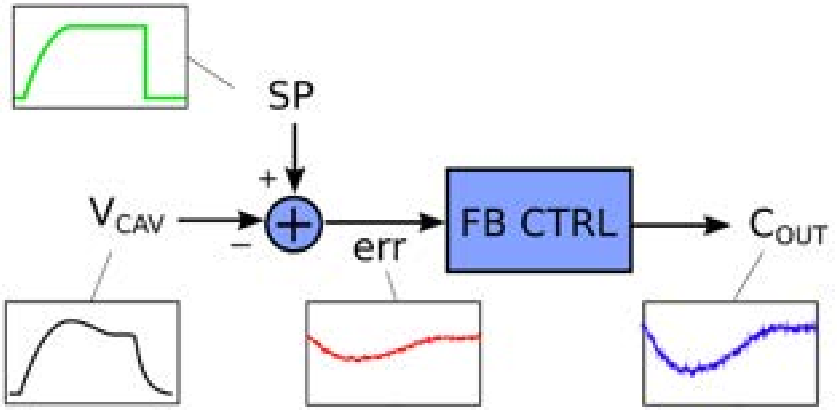
Courtesy of J.Branlard (DESY)

Second step: modulate the drive amplitude during the beam time to maintain the desired gradient

LLRF Feedback



No matter how precise we are setting the pulse shape, the system variations over time and temperature will require us to use a **feedback loop** to improve the regulation



We are very interested to maintain a certain **amplitude and phase stability (RMS)** within the pulse and from pulse to pulse. Both in short term (seconds) and on long-term (hours)

Courtesy of J.Branlard (DESY)

Important LLRF specifications

Physical interfaces:

- Number of RF inputs (8 or 16 or more) and expected signal levels
- Number of RF outputs (1 or 2) and signal levels
- Specific trigger signals (RF pulse, Beam pulse, Modulator signals)
- Machine Protection System interfaces (Interlock)

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Machine specifications:
- RF frequency
- Type of cavity (NC, SC)
- Pulsed (pulse duration, injection frequency) vs CW
- Cavity tuning requirements
- Control system interface

RF Frequency band	Frequency range
L-band	1-2 GHz
S-band	2-4 GHz
C-band	4-8 GHz
X-band	8-12 GHz

The higher the frequency, the smaller is the size of the RF components and RF structures **-> more compact machines**!

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- RF frequency
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Performance specifications:
- Front-end and Back-end: Bandwidth, sampling rate, added noise
- Short term amplitude and phase stability
- Long term amplitude and phase stability

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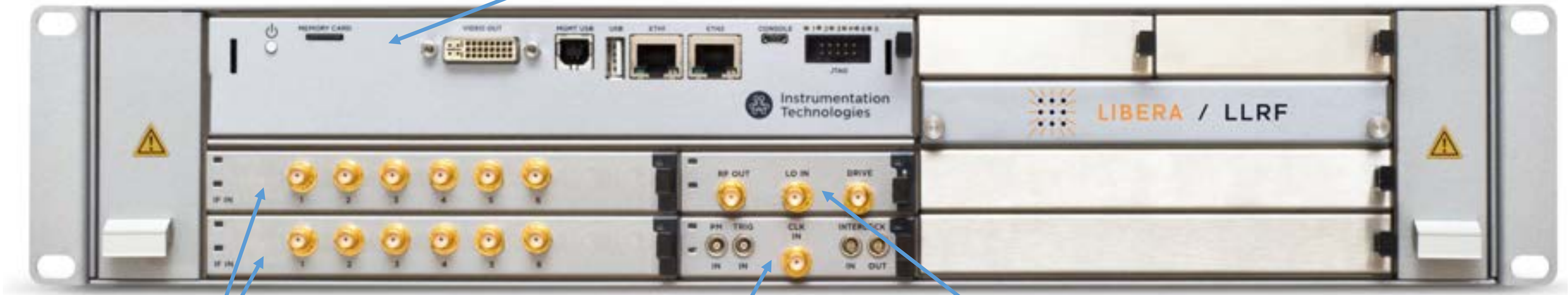
Libera LLRF – overview and modules

Modular platform based on MTCA technology

- Several modules are frequency dependent and require HW changes -> more customization flexibility
- The number of input channels can be scaled with more RF input modules
- Empty slots can be used for additional custom interfaces
- The platform is also used for other company applications (e.g. BPM electronics)

Libera LLRF – overview and modules

Inter Connection
Computer module



RF input modules with
RF front-end and ADCs

Timing and Clock
management module

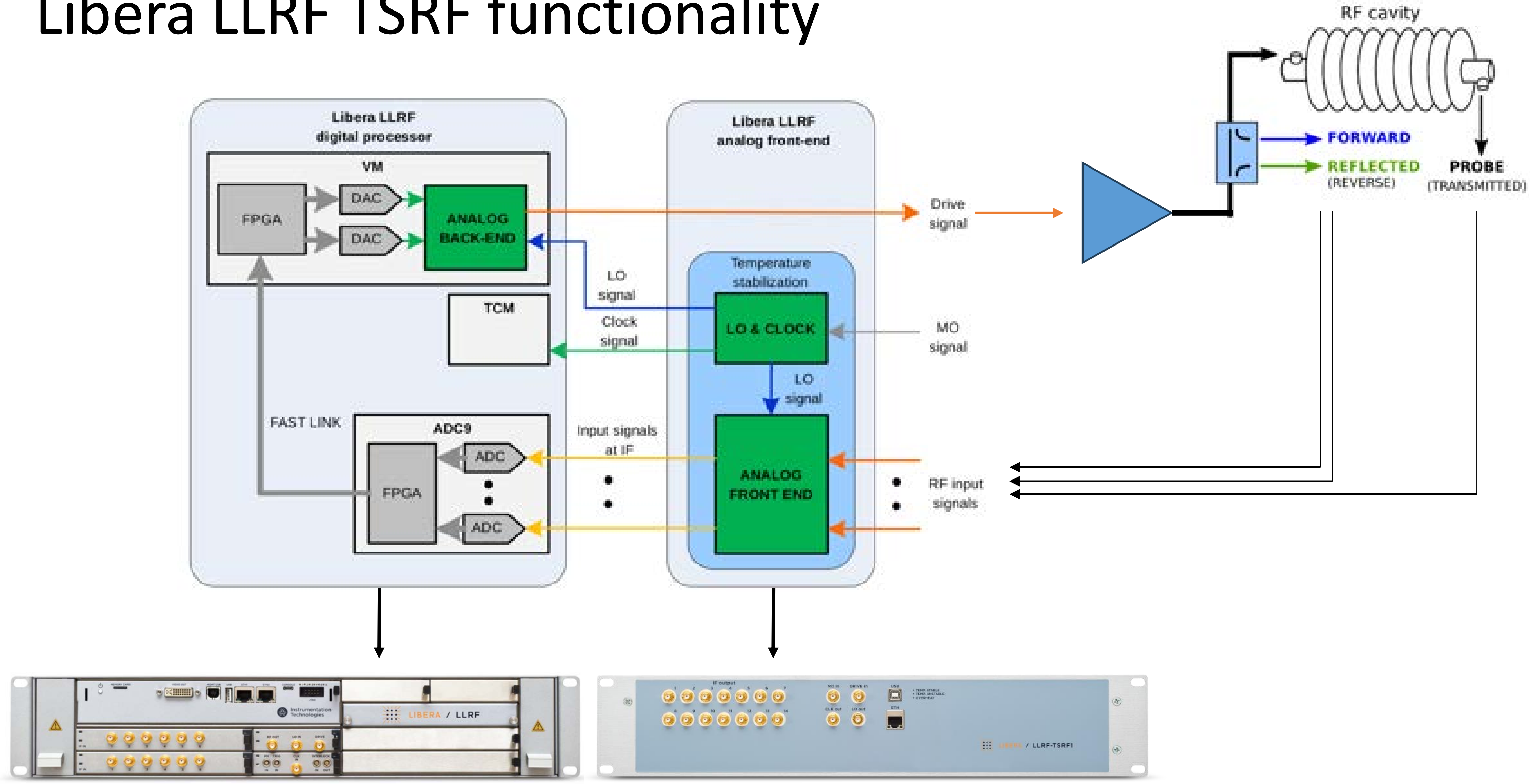
Vector modulator module
with DACs and RF back end

Libera LLRF with Temperature Stabilized Front End

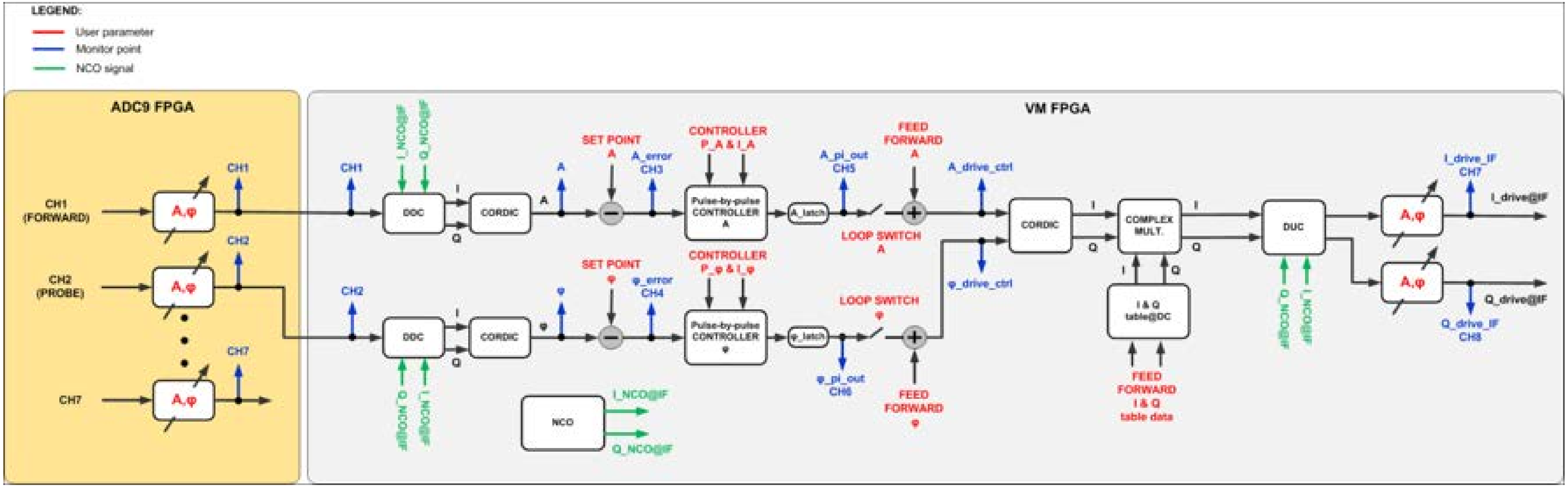
For the machines with higher stability requirements (FELs for example), even the small environment conditions deviations (T, RH%) affect their performance.

For this case, a temperature-stabilized RF front-end was developed assuring internal temperature **variations of < 0.01K**

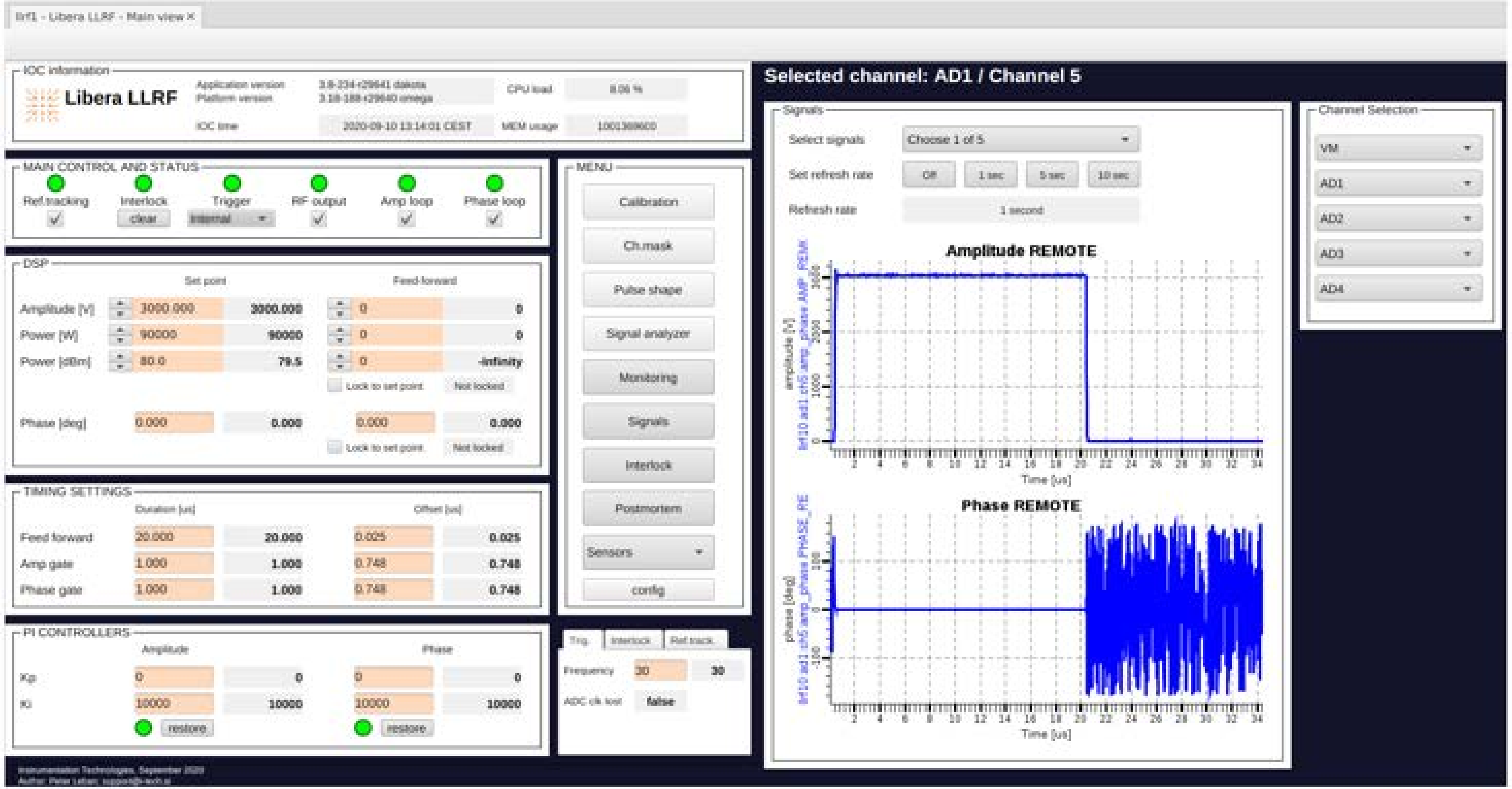
Libera LLRF TSRF functionality



Libera LLRF DSP block diagram



Graphical User Interface (Expert GUI)



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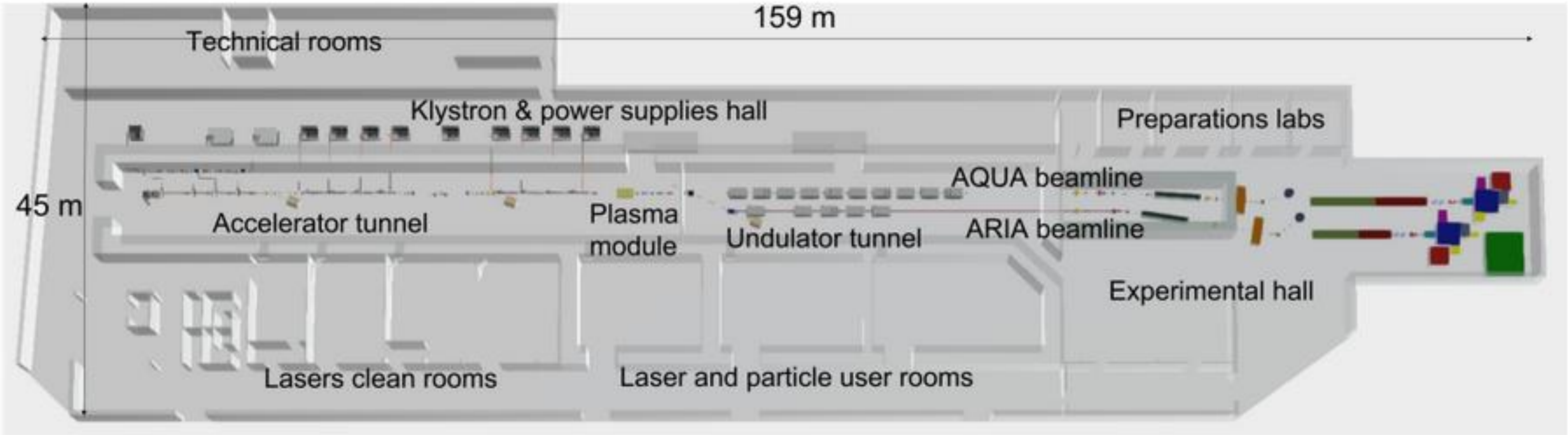
The EuPRAXIA@SPARC_LAB project

INFN LNF
Istituto Nazionale di Fisica Nucleare



The **EuPRAXIA@SPARC_LAB** electron LINAC will include

- An S-band injector providing electrons at 150MeV
- A series of X-band accelerating structures to boost the electron energy to 0.5-1GeV
- A plasma accelerator (1m) to boost the electron energy to 5GeV

Source: CDR and website

X-band Digital LLRF

A **few challenges** were identified when discussing the **LLRF requirements** with the RF group at INFN-LNF:

- Controlling the RF pulse properties at 12GHz for very short pulses (100ns) is a challenge.
- **Temperature drifts** influence the LLRF system stability even more at higher RF frequencies: need for **temperature stabilized down-conversion** implemented for X-band signals.
- At the moment there is **no commercial LLRF system** working in X-band that meets the performance requirements of the EuPRAXIA@SPARC-LAB LINAC

X-band Digital LLRF

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EuPRAXIA
Doctoral Network

A PhD project was proposed for the realization of a 2-channel LLRF prototype as part of the EuPRAXIA Doctoral Network

Phani Deep Meruga joined us in November 2023!

EuPRAXIA Doctoral Network

Thanks for your attention!

INFN LNF Istituto Nazionale di Fisica Nucleare

www.i-tech.si

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