Libera Book

2018 Edition

Solutions for Particle Accelerators

Instrumentation Technologies

20 YEARS

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The accelerator community knows us as Libera folks. Apparently has the story that started back in 2003 left some marks. Nevertheless, 9 out of 10 synchrotron light sources around the world have been equipped with our Libera beam position stabilization systems. But Libera is much more than just the sum of its products. It means the best possible performance for the price. It means innovation, quality and reliability. It means long-term support. However it is the relationships we have nurtured over the years with our customers that we cherish most.

Libera products seamlessly combine hardware and software into powerful instruments that measure a variety of beam parameters. Those measurements are then used in feedback loops to optimize the performance of a particle accelerator. Different accelerators have different needs. However, through the re-configurability and modularity of Libera instruments we can accommodate a variety of end-user requirements.

Libera instruments are developed and manufactured by the Instrumentation Technologies company. Established in 1998, the business has grown from a garage-based start-up to an established company known for its Libera and Red Pitaya products and for launching the Center of Excellence for Biosensors, Instrumentation and Process Control (COBIK).

Rok Uršič
Chairman of the Board of Directors

Table of Contents

BPM Electronics

Libera Beam Postion Monitor (BPM) electronics feature high resolution position measurement of the beam (electrons, protons, ions, photons, etc.). Their flexible digital signal processing calculates the beam position with different bandwidths and techniques, enabling measurements in different beam modes and regimes:

- pulsed, single bunch
- pulsed, micro/macro pulse
- bunch-by-bunch
- turn-by-turn
- first-turn measurement
- closed loop (fast, slow)

Different BPM electronics are optimized depending on the accelerated particles and the type of machine. They can be categorized as follows:

Hadron	Electron & Photon
Libera Hadron **Libera Single Pass H** **Libera Spark**	**Libera Brilliance+** **Libera Single Pass E** **Libera Spark** **Libera CavityBPM** **Libera Photon**

For circular machines, the closed loop operation can be further expanded with dedicated modules that extend the instrument capabilities enabling global orbit feedback. These modules fit inside the instruments and provide fast serial communication links which can be used with optical or copper cables, GbE and RS-485 interfaces. These interfaces can be used to control the corrector magnets and/or pre-amplifiers.

Hadron BPM electronics

Instruments intended for use in Hadron machines are shown in Figure 1. Several versions are available, based on different technology and form-factors. They provide different levels of measurement performance and functionalities. The BPM pickup types which are supported are button and shoebox pickups.

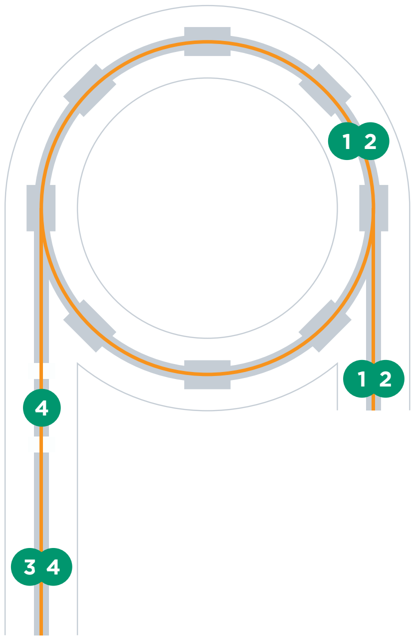


Figure 1: *Example of hadron machine: LINAC injector, transfer line, synchrotron and extraction line*

1 Libera Hadron

- Used in hadron synchrotrons
- Bunch-by-bunch position calculation
- Large buffers for ADC and position data storage
- Tune measurement, fft processing, slow monitoring, closed orbit feedback functionality etc.
- Accessories: Amplifier 110, SER II module, GDX module

2 Libera Spark HR

- Used in hadron synchrotrons and ring-to-target beam transfers
- Bunch-by-bunch data processing
- Accessories: DWC module, DAI module

3 Libera Single Pass H

- Used in Hadron linear accelerators
- Beam position and phase measurements calculated for two signal harmonics
- Accessories: GDX module

4 Libera Spark HL

- Used in hadron linear accelerators and transfer lines
- Accessories: DAI module

The capabilities, performance and functionalities of the hadron BPM electronics depend on the specific instrument and are presented in Tables 1 and 2.

Table 1: *Hardware capabilities and performance of hadron beam position monitors*

Hadron BPMs capabilities and performance	for CIRCULAR machines		for LINEAR machines	
				
	Libera Spark HR	**Libera Hadron**	**Libera Spark HL**	**Libera Single Pass H**
BPM slots	1	1 - 4	1	1 - 4
Supported input frequency range	< 35 MHz	< 55 MHz	< 750 MHz	< 700 MHz
A/D conversion	125 MHz/14 bit	250 MHz/16 bit	125 MHz/14 bit	130 MHz/16 bit
FPGA/CPU	Zynq-7020, ARM Cortex-A9	Virtex 6, COMe module	Zynq-7020, ARM Cortex-A9	Virtex 5 & 6, COMe module
Operating System	Linux	Linux Ubuntu 14.04	Linux	Linux Ubuntu 14.04
Cooling	Passive	Active (fans)	Passive	Active (fans)
Power supply	PoE	110/220 V	PoE	110/220 V
Timing signals	Electrical (up to 3)	Electrical (4)/Optical	Electrical (up to 3)	Electrical (4)/Optical
Fast data links	Copper	Copper/Optical	Copper	Copper/Optical
Maximum input signal *	< 1.2 V peak pulse voltage	< 2 V peak pulse voltage	< +10 dBm continuous	< +10 dBm continuous
Input gain/attenuation	Programmable, 31 dB	Fixed	Programmable, 31 dB	Fixed
Temperature drift, typical	2 μm/°C	2 μm/°C	0.3 μm/°C	0.5 μm/°C
Position RMS at bunch-by-bunch data rate	10 μm **	6 μm **	/	/
Position RMS at fast 10 kHz data rate	/	< 1 μm **	/	/
Position RMS at slow 10 Hz data rate	/	< 1 μm **	/	/
Position RMS at 1 MHz data rate	/	/	< 1 μm	< 2 μm, < 0.01°

* Can be customized, ** K=100 mm

Table 2: *List of functionalities of hadron beam position monitors*

Hadron BPMs functionalities	for CIRCULAR machines		for LINEAR machines	
				
	Libera Spark HR	**Libera Hadron**	**Libera Spark HL**	**Libera Single Pass H**
Bunch-by-bunch processing	Yes	Yes	No	No
Fast data	Yes*	Yes	Yes*	Yes
Slow data	No	Yes	No	No
Gain control	No	External amplifier module	Yes	No
Multi-chassis synchronization	Trigger-based	Reference clock with PLL	Trigger-based	Trigger-based
Data time stamping	Trigger-counter	Yes, external RF clock	Trigger-counter	Trigger-counter
Interlock detection and output	No	No	No	Yes
Postmortem capability	No	Yes	No	No
FFT/FFT peak	No	Yes	No	No
Single-pass measurement	Yes	Yes	Yes	Yes

* Optional

Electron and Photon BPM electronics

Instruments intended for use in 3rd and 4th generation light sources are shown in Figure 2 and Figure 3. Several versions are available, based on different technology and form-factors. They provide different levels of measurement performance and functionalities. The BPM pickup types which are supported are button, stripline and cavity-type pickups.

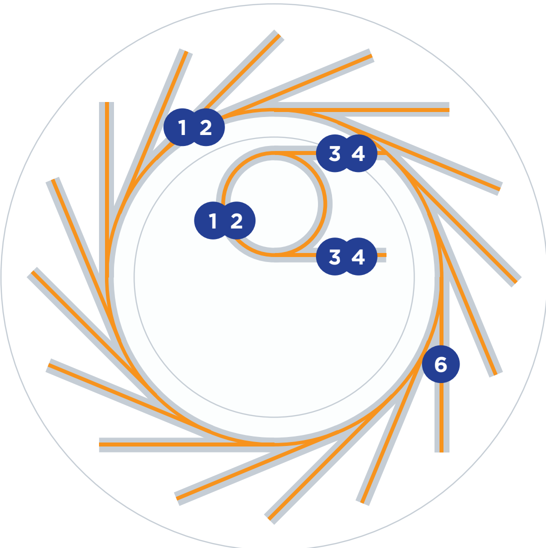


Figure 2: *Example of 3rd generation light source (synchrotron)*

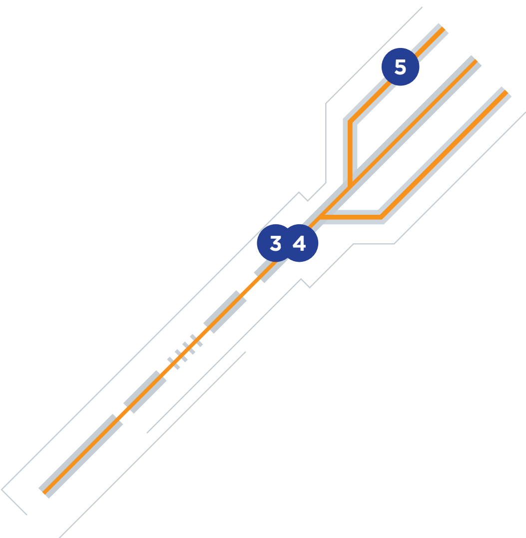


Figure 3: *Example of 4th generation light source (FEL / ERL)*

1 Libera Brilliance+

- Used in electron synchrotrons
- Data bandwidth from 15 MHz to 5 Hz
- Sub-micron long-term stability
- Built-in orbit feedback and timing system interfaces
- Accessories: GDX module, SER module, orbit feedback application

2 Libera Spark ERXR

- Used in electron synchrotrons
- Data bandwidth from 15 MHz to 5 Hz
- Fast data link towards orbit feedback
- Multiple analog and digital I/O interfaces
- Accessories: DAI module

3 Libera Single Pass E

- Used in electron LINACs
- Event announcing of beam patterns
- Flexible DSP can process various filling patterns from single bunch to CW
- Accessories: GDX module, DWC module

4 Libera Spark EL

- Used in electron LINACs and transfer lines
- Flexible DSP can process various filling patterns from single bunch to CW
- Accessories: DWC module, DAI module

5 Libera CavityBPM

- Used in FEL undulator sections and interaction points
- Supporting S-band and C-band cavities, High-Q and Low-Q
- Bunch-by-Bunch data processing down to 16ns bunch spacing
- 3 GHz and 6 GHz versions
- Accessories: DAI module

6 Libera Photon

- Used in synchrotron and FEL beamlines
- Data bandwidth from 80 kHz to few Hz
- Compatible with diamond and blade detectors
- Multiple analog and digital I/O interfaces
- Accessories: DAI module

The hardware capabilities, performance and functionalities of the electron beam position monitors are summarized in Tables 3 and 4. The instruments are generally built on three platforms, each of them offering specific advantages.

Table 3: *Hardware capabilities and performance of electron beam position monitors*

Electron BPMs capabilities and performance	**for CIRCULAR machines**		**for LINEAR machines**		
					
	Libera Spark ERXR	**Libera Brilliance+**	**Libera Spark EL**	**Libera Single Pass E**	**Libera CavityBPM**
BPM slots	1	1 - 4	1	1 - 4	1
Supported input frequency range	< 750 MHz	< 700 MHz	< 750 MHz	< 700 MHz	< 6.5 GHz
A/D conversion	125 MHz/14 bit	130 MHz/16 bit	125 MHz/14 bit	160 MHz/16 bit	500 MHz/14 bit
FPGA/CPU	Zynq-7020, ARM Cortex-A9	Virtex 5 & 6, COMe module	Zynq-7020, ARM Cortex-A9	Virtex 5 & 6, COMe module	Zynq-7035, ARM Cortex-A9
Operating System	Linux	Linux Ubuntu 14.04	Linux	Linux Ubuntu 14.04	Linux
Cooling	Passive	Active (fans)	Passive	Active (fans)	Passive
Power supply	PoE	110/220 V	PoE	110/220 V	110/220 V or PoE++
Timing signals	Electrical (up to 3)	Electrical (4)/Optical	Electrical (up to 3)	Electrical (4)/Optical	Electrical (up to 3)
Calibration	Manual/Automatic	Crossbar switch, DSC	Manual/Static	Manual/Static	Manual/Static
Fast data link	Copper	Copper/Optical	Copper	Copper/Optical	Copper
Maximum input signal*	< -10 dBm continuous	< +4 dBm continuous	< 5 V peak pulse voltage	< 7 V peak pulse voltage	< +16 dBm
Input gain/attenuation	Programmable, 31 dB	Programmable, 31 dB, automatic mode	Programmable, 31 dB	Programmable, 31 dB	Programmable, 31 dB
Temperature drift, typical	2 μm/°C	0.2 μm/°C	0.3 μm/°C	0.3 μm/°C	0.3 μm/°C
Position RMS at turn-by-turn data rate	0.3 μm	0.5 μm	/	/	/
Position RMS at fast data rate (0-2 kHz bandwidth)	0.04 μm	0.07 μm	/	/	/
Position RMS at slow data rate (0-4 Hz bandwidth)	0.02 μm	0.02 μm	/	/	/
Position RMS at single bunch	/	/	4 μm	1 μm	< 1 μm
Position RMS at macro pulse/ continuous wave	/	/	< 4 μm	< 1 μm	< 1 μm

* Can be customized

Table 4: *List of functionalities of electron beam position monitors*

Electron BPMs functionalities	**for CIRCULAR machines**		**for LINEAR machines**		
					
	Libera Spark ERXR	**Libera Brilliance+**	**Libera Spark EL**	**Libera Single Pass E**	**Libera CavityBPM**
Bunch-by-bunch processing	No (only single bunch/single turn)		Yes	Yes	Yes
Turn-by-turn processing	Yes	Yes	No	No	No
Fast data	Yes*	Yes	Yes *	Yes	No
Slow data	Yes	Yes	No	No	No
Gain control	Yes	Yes (automatic)	Yes	Yes	Yes
Multi-chassis synchronization	Reference clock with PLL		Trigger-based	Trigger-based	Trigger-based
Data time stamping	Yes	Yes	Trigger-counter	Trigger-counter	Trigger-counter
Interlock detection and output	Yes*	Yes	Yes *	Yes	No
Postmortem capability	No	Yes	No	No	No
Statistics and FFT	No	Yes	No	No	No
Single-pass measurement	No	Yes	Yes	Yes	Yes

* Optional

The hardware capabilities, performance and functionalities of the photon beam position monitor are presented in Tables 5 and 6.

Table 5: *Hardware capabilities and performance of the Photon beam position monitor*

Photon BPM capabilities & performance	 **Libera Photon**
Input channels	4
Input frequency range	< 80 kHz
A/D conversion	2.5 MHz/18 bit
FPGA / CPU	Zynq-7020, ARM Cortex-A9
Operating System	Linux
Cooling	Passive
Power supply	PoE
Timing signals	Electrical (3)
Calibration	Manual
Fast data link	Copper
Maximum input signal	< 2 mA
Current ranges	±60 nA, ±0.2µA, ±2µA, ±20µA, ±200µA, ±2mA
Temperature drift, typical	0.01 µm/°C
8-hour stability (23°C, 200 µA)	0.02 µm
RMS uncertainty @ 180 µA 2 kHz bandwidth	< 0.02 µm
RMS uncertainty @ 180 µA 5 Hz bandwidth	< 0.01 µm

Table 6: *List of functionalities of the Photon beam position monitor*

Photon BPM functionalities	 **Libera Photon**
Short pulse detection	Used for pulsed currents with signal dynamics within the measurement bandwidth (< 80 kHz). Supports pulse repetition up to 10 Hz.
DC signal monitoring	Typically used for monitoring the currents from blade detectors or other current-type detectors in the beamlines.
Configurable processing bandwidth	Parallel processing provides data buffers at configurable data rates and bandwidths. Filter response can be adjusted by adjusting filtering block coefficients.
Current measurement	Amplitude in each channel can be transformed into current with a simple calculation equation. Current value requires manual calibration and has limited accuracy.
Postmortem data storage	Dedicated memory buffer is intended for storing the data just before a postmortem trigger event. Complete functionality provides configurable buffer size and write offset, and reports important information about the absolute time of the postmortem trigger event.
External BIAS support	External BIAS source can be connected directly to the instrument to apply a BIAS to all 4 channels.
Analog and digital outputs	Analog and/or digital outputs can be used to control auxiliary components or convert current values to analog voltage. DAI extension module is required.

Architecture and Platforms

A general architecture of the Libera BPM electronics is presented in the block diagram in Figure 4. At the heart of every instrument is a digitizer consisting of ADCs and an FPGA processor running all the real-time DSP algorithms and filling data in the memory. RF signals from the BPM pickups are processed by the analog RF front-end which filters, amplifies, attenuates and down-converts them, if necessary. The signals are later digitized by the ADCs. The ADC data is processed inside of the FPGA and the calculated information such as position, phase, intensity etc. is stored in the memory. All the information is available to the user to through the instrument software interfaces and control system adapters.

The default instrument configuration already provides all I/O lines required for normal operation, however the hardware interfaces can be further expanded with various estension modules, depending on the instrument platform - see the section on Extensions (page 29).

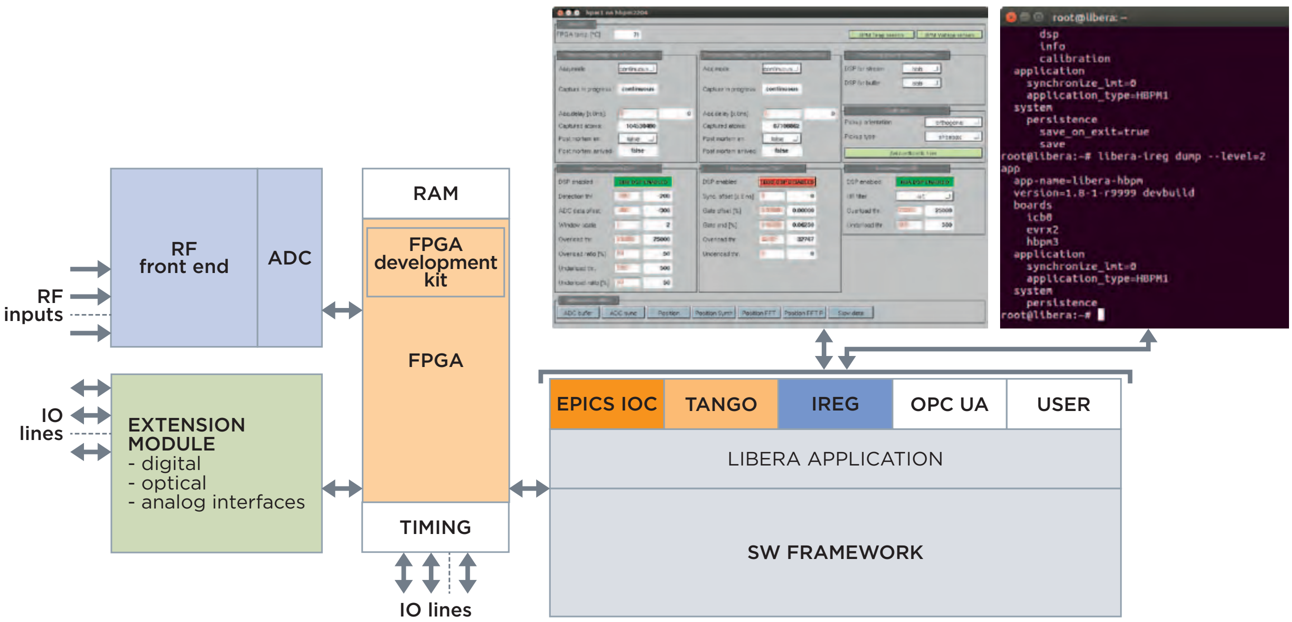


Figure 4: *Generalized block diagram of Libera BPM electronics*

BPM electronics are available in different technology platform which have different form factors. The Platform B is based on the MTCA.0 modular technology and in a 2U - 19" chassis hosts up to four BPM modules. Several extensions are availble for the orbit feedback and timing system - - see the section on Extensions.

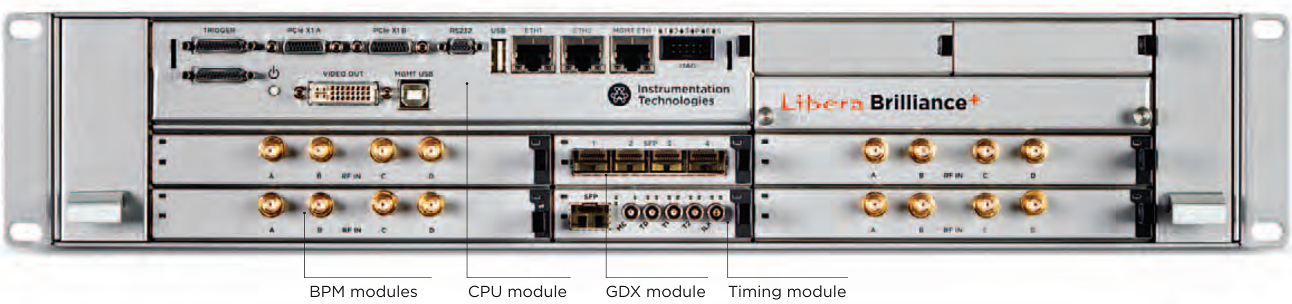


Figure 5: *BPM electronics based on Platform B*

Platform C is based on system-on-chip technology. Due to its low power consumption, the instrument is powered over Ethernet with PoE standard, and is passively cooled. Given the small dimension (BPM electronics is contained in a 1U - 9.5″ chassis), it can be installed in the tunnel close to the BPM pickup in an appropriate radiation protected location - see Figure 6.

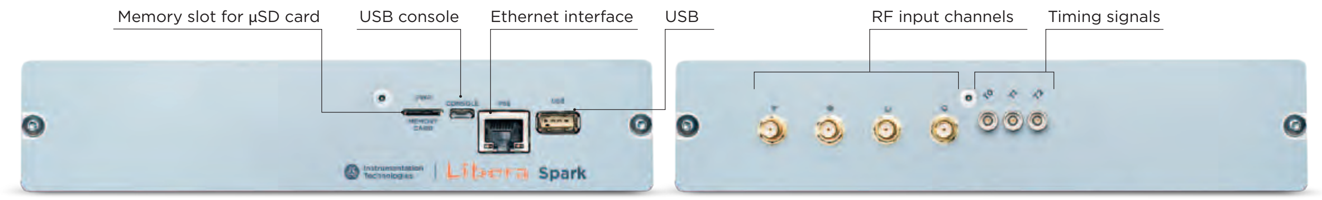


Figure 6: *BPM electronics based on Platform C*

The Photon BPM electronics is still based on the Platform C and provides a second RJ-45 interface that is used to output the Fast data stream and a USB port. TRIAX connectors are used for input channels (Figure 7).

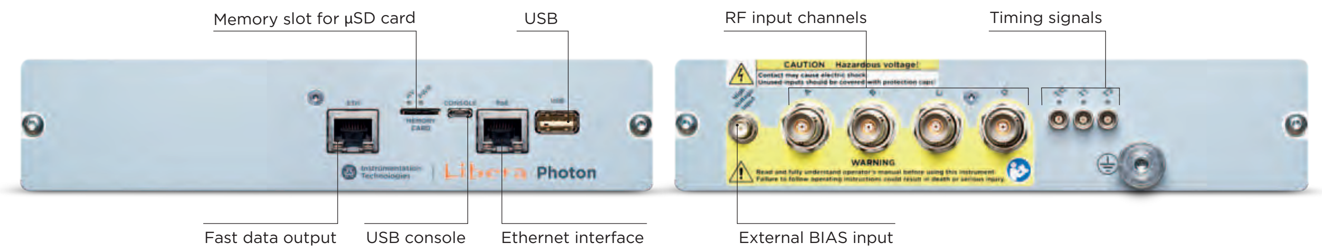


Figure 7: *Photon BPM electronics based on Platform C*

The BPM electronics for the cavity-type of BPM pickups are also based on Platform C, which in this case is enlarged to a 1U, 19″ chassis due to the higher amount of heat that needs to be passively dissipated. The instrument can be expanded to four RF inputs and SFP connectors for fast data exchange.

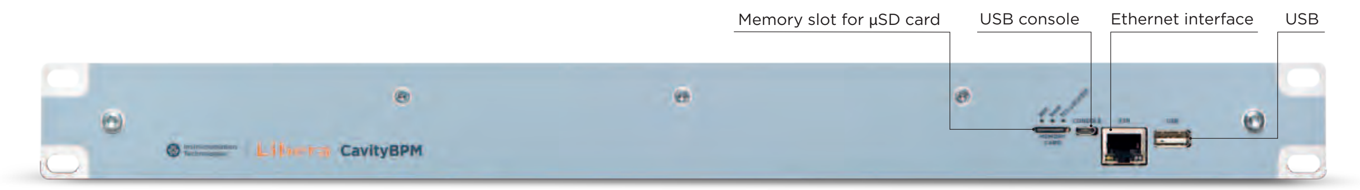


Figure 8: *CavityBPM electronics based on Platform C, front panel*

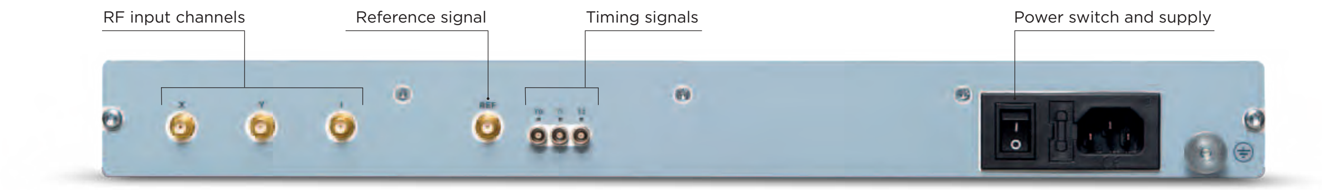


Figure 9: *CavityBPM electronics based on Platform C, back panel*

Beam Loss Monitor

The Libera BLM handles all types of losses, and measures them with a high level of detectability and high time resolution. In contrast to other BLM systems, the beam loss monitor from the Libera family detects the losses ranging from a single electron to the huge losses that usually occur during injection. Thanks to its high time resolution (8 ns), it provides detailed insight into sub-turn losses. This effectively makes it possible to detect and select only those losses which come from a part of the beam-fill pattern.

The beam loss monitor is available in two configurations:
- Beam loss monitor electronics
- Beam loss monitor system (electronics + detector)

Signal Processing

The signal from the beam loss detector (usually a photo-multiplier tube) is typically a unipolar pulse or train of pulses with negative polarity. It is possible to detect huge losses and very small losses thanks to the switchable front-end input impedance. The input signal is sampled by a PLL-controlled sampling clock.

The raw sampled data is stored in a buffer upon a trigger event. Further down the processing chain, the data is processed in order to remove the static offset and apply averaging and integration factors (Figure 10). The buffered data provides a quantitative view of the loss shape.

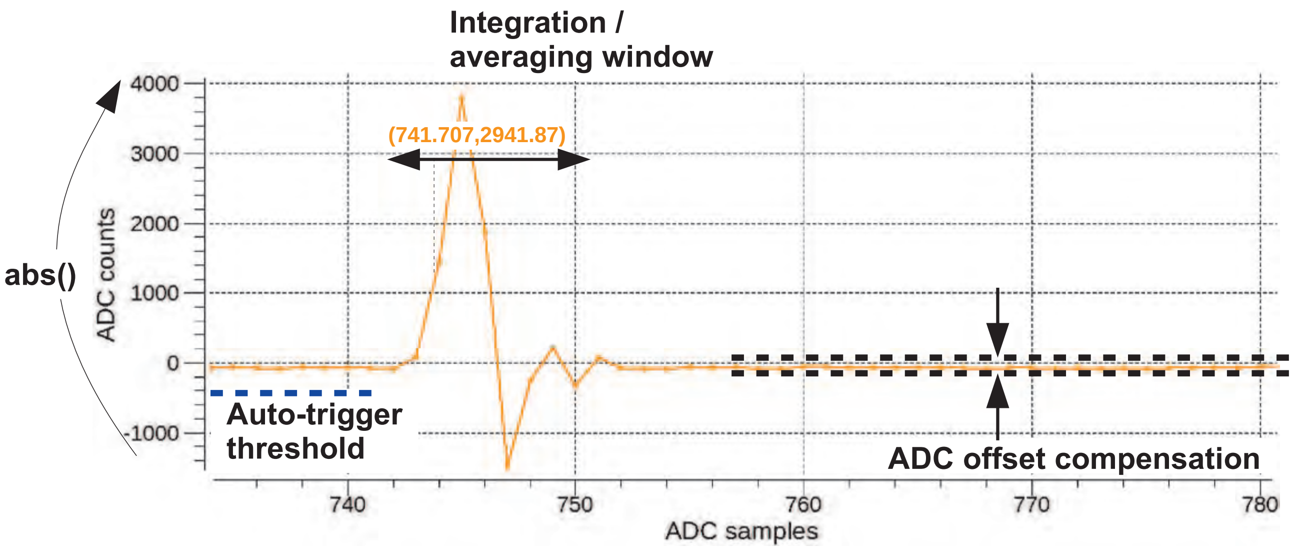


Figure 10: *Beam loss signal processing parameters*

In parallel, losses are continuously monitored and counted at a rate of 8 ns. Counting modes are fully configurable for static and dynamic loss thresholds. Being locked to a sampling clock and an external clock, it is possible to adjust up to 2 configurable detection windows that monitor only a selected part of the fill pattern.

With up to 4 beam loss detectors connected to the same instrument, an algorithm can automatically detect if the loss was detected in all detectors at the same time (coincidence counting mode). Coincidence is monitored in a configurable time window as shown in Figure 11.

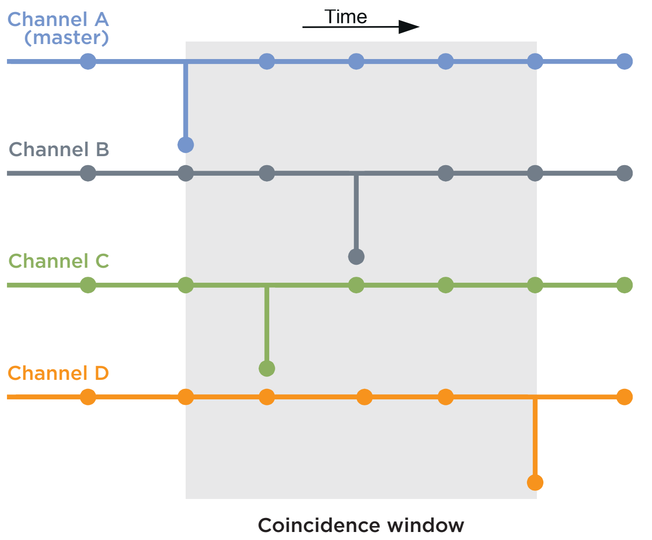


Figure 11: *Coincidence loss monitoring*

The beam loss monitor system consists of the beam loss detector and readout electronics. The electronics are provided in a standard 1U, 9.5" housing and are powered through a PoE compliant Ethernet interface. For each of the four possible beam loss detectors, the electronics provide PMTs with power supply and gain control (Figure 12).

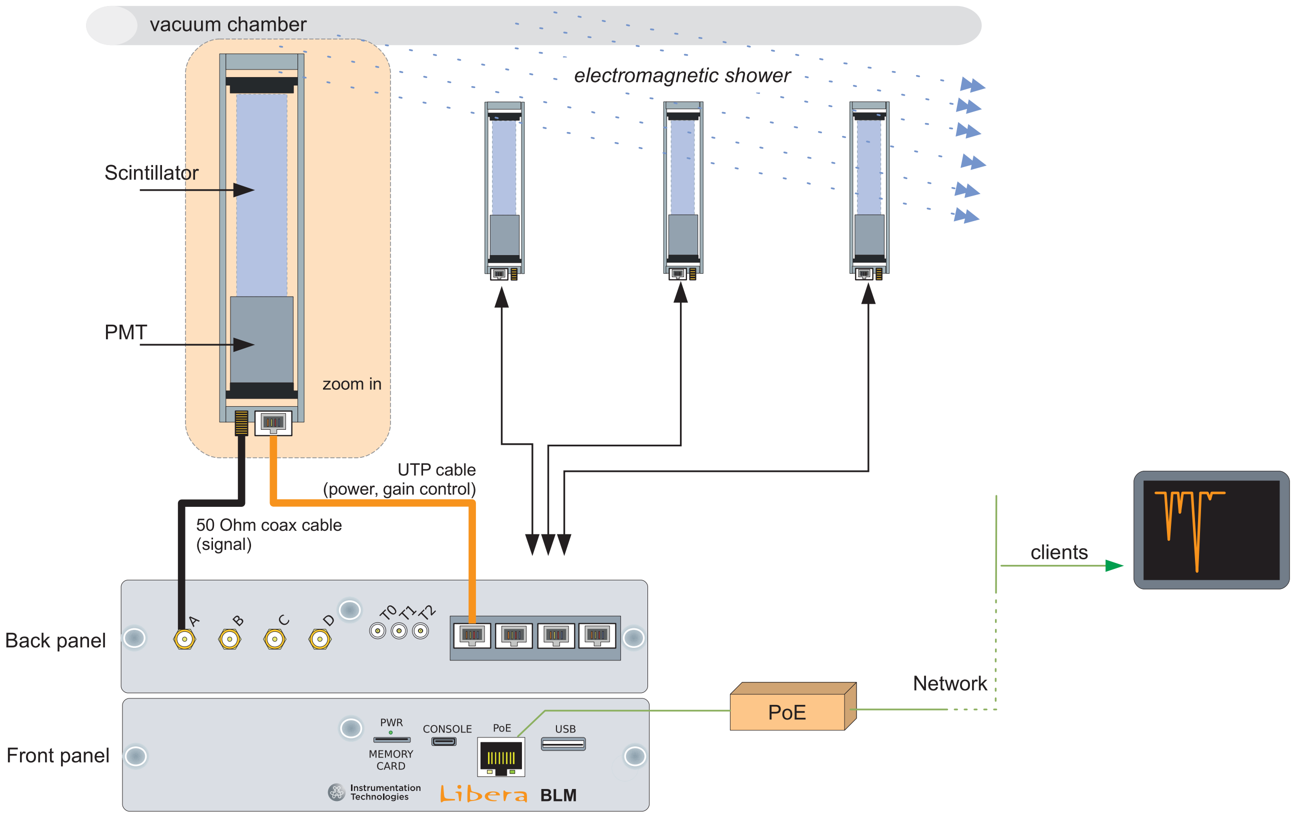


Figure 12: *Beam loss monitor system configuration*

Capabilities

The hardware capabilities of beam loss monitors are summarized in Table 7.

Table 7: *Hardware capabilities of the beam loss monitor and the photo-multiplier tube*

<table>
<tr><th></th><th>Libera BLM</th><th>Beam Loss Detector (BLD)</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Input channels</td><td>4</td><td rowspan="4">Scintillator Rod for γ-ray detection (Scionix EJ-200)
Typical dimensions:
• Length: 100 mm
• Diameter: ~22 mm
Aluminum housing, ~2 mm Lead shielding</td></tr>
<tr><td>Input frequency range</td><td>~35 MHz large signal bandwidth
~50 MHz small signal bandwidth</td></tr>
<tr><td>Matching impedance</td><td>50 Ω/1MΩ, selectable</td></tr>
<tr><td>A/D conversion</td><td>125 MHz/14 bit</td></tr>
<tr><td>FPGA / CPU</td><td>Zynq-7020,
ARM Cortex-A9</td><td rowspan="4">Photosensor (Hamamatsu 10721-110)
• Input voltage: (5±0.5) V
• Input current: 2.7 mA maximum
• Gain control voltage: 1.1 V maximum (at 1 MΩ)
• Rise time: 0.57 ns
• Dark current: 1 nA (typical)
• Peak sensitivity wavelength: 400 nm
• Dimensions (H × W × D) mm: approximately 50 × 22 × 22</td></tr>
<tr><td>Operating System</td><td>Linux</td></tr>
<tr><td>Cooling</td><td>Passive</td></tr>
<tr><td>Power supply</td><td>PoE</td></tr>
<tr><td>Timing signals</td><td>Electrical (3)</td><td rowspan="3">Beam loss detector
• Dimensions (H × W × D) mm:
approximately 220 × 25 × 25 (without the fitting holder)
• Weight: approximately 150 g (without the lead cover)
• Operating temperature: +10°C to +40°C</td></tr>
<tr><td>Maximum input signal</td><td>±1.25 V @ 1 MΩ
±5 V @ 50 Ω</td></tr>
<tr><td>Output channels</td><td>4x power supply (up to ±15 V)
4x gain control (up to +12 V)</td></tr>
</table>

Functionalities

The functionalities of the beam loss monitor are summarized in Table 8.

Table 8: *Hardware capabilities of the beam loss monitor and the photo-multiplier tube*

	Libera BLM
Low loss detection	Detecting volumes as low as a single electron loss using high input impedance and high gain.
Strong and fast loss detection	Detecting strong losses during injection (typically).
Automatic loss detection	Adjustable threshold for automatic buffer storage
Configurable processing parameters	ADC offset compensation, integration and averaging window lengths, loss detection windows and individual channel delays.
Counting modes	Select between static and dynamic thresholds for loss counts. Apply a custom recovery time and threshold.
Coincidence loss detection	Compare up to 4 channels for simultaneous loss events.
Loss value calibration	Compensate the raw loss value with current gain settings (attenuation, photosensor dynamic gain and photosensor static gain).
Postmortem data storage	Dedicated memory buffer is intended for storing the data just before a postmortem trigger event.
Photosensor control	Provide power supply and adjust gain control voltage to up to 4 independent channels.

Digitizers

The idea behind the general purpose digitizers is to provide the user with a base from which to develop its own application, or a powerful tool to prototype future applications. As described in Table 9, the instruments provide all the building blocks which are used for the other applications, from the RF input signals to the control system interface.

Table 9: *Capabilities of the multipurpose digitizers*

	Libera Digit	**Libera Digit 500**
		
Dimensions (H x W x D) mm	44 x 210 x 210	44 x 482 x 236
FPGA / CPU	Zynq-7020, ARM Cortex-A9	Zynq-7035, Dual Core ARM Cortex-A9
RAM	1 GB	SODIMM 4 GB
Max number of acquired data atoms	8 MS	500 MS
Platform management	Passive cooling, Power over Ethernet, network boot, SD card boot	Passive cooling, Power over Ethernet, network boot, SD card boot
Input channels	4	4
A/D conversion	125 MHz/14 bit	500 MHz/14 bit
Sampling clock	Manual set, free running*	Manual set, HW PLL
Timing signals	3	3
Maximum input signal	+/- 1 V*	+/- 2 V*
Input gain/attenuation	Variable	Variable
Bandwidth	DC to 50 MHz	DC to 2 GHz
Input impedance	Selectable 1 MΩ / 50 Ω	50 Ω

* Configuration can be modified to order

The available software and firmware infrastructures provide an already working template, with the possibility of extending its functionalities in a time-efficient manner, focusing only on its core part: the signal processing algorithms.

Digital LLRF

The Libera LLRF is a digital processing and feedback system which monitors and stabilizes the quality of the beam acceleration by controlling the phase and amplitude of the RF field injected into the machine accelerating structures.

Being designed to be modular and reconfigurable, the system can fit the exact requirements of any kind of accelerator, providing three core functions:

- **Stabilization of the cavities' RF fields:** depending on the RF signals acquired from the accelerating structures and the set-point specified by the user, the fast feedback loop controls the properties of the RF signal, which is later used to drive the Klystrons.
- **Cavity tuning:** by monitoring the forward and reflected signals from the RF cavities, the system can be interfaced to control slow and fast tuners (e.g. stepper motors and piezo controllers) which modify the cavity mechanical properties.
- **Machine Diagnostics:** the user is able to analyze all the signals digitized by the system, as well as the status of the feedback loop. Several signals can also be monitored by the system in order to generate Interlock events if something unexpected happens.

The block diagram presented in Figure 13 presents a possible configuration of Libera LLRF in the accelerator environment:

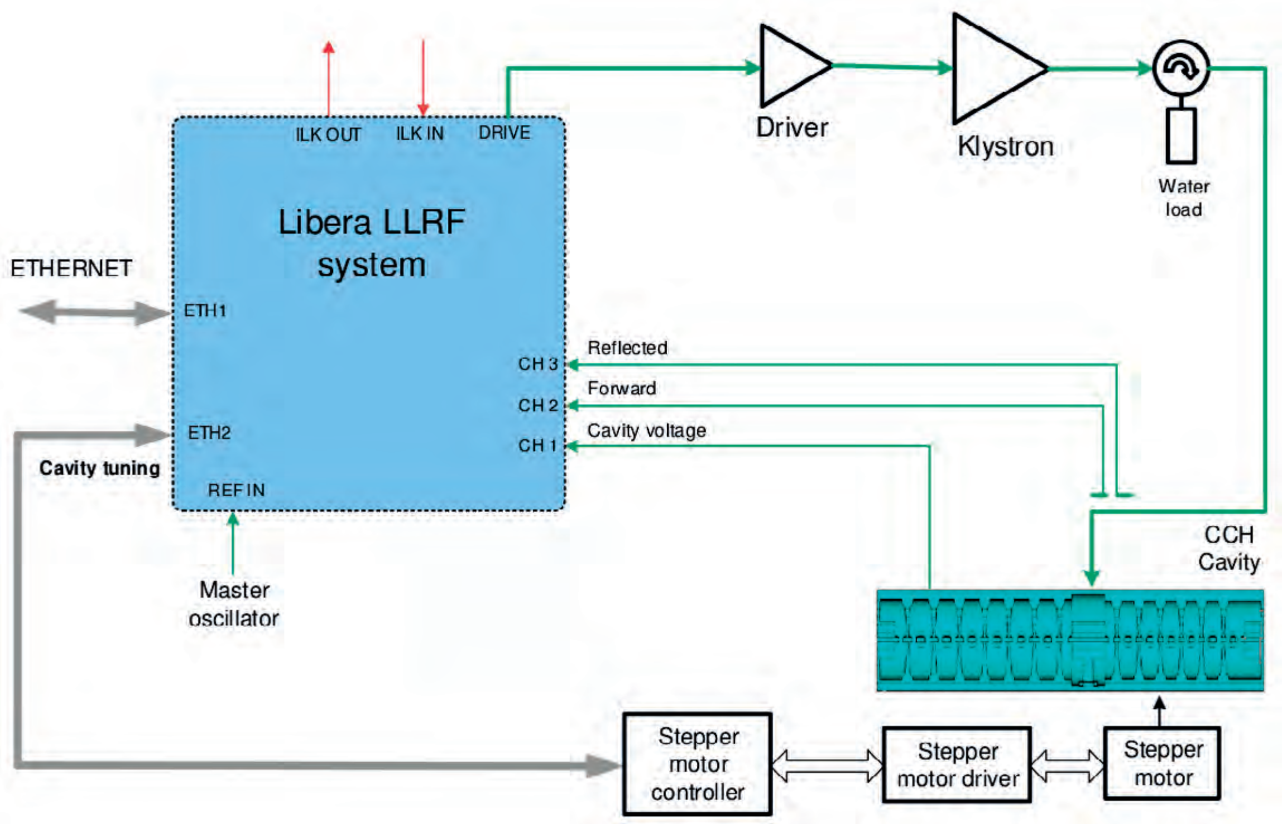


Figure 13: Possible configuration of Libera LLRF in the accelerator environment

Interfaces and Signal Processing

The Libera LLRF system is based on the MCTA.0 standard with several AMC boards connected to the chassis front panel (Figure 14).

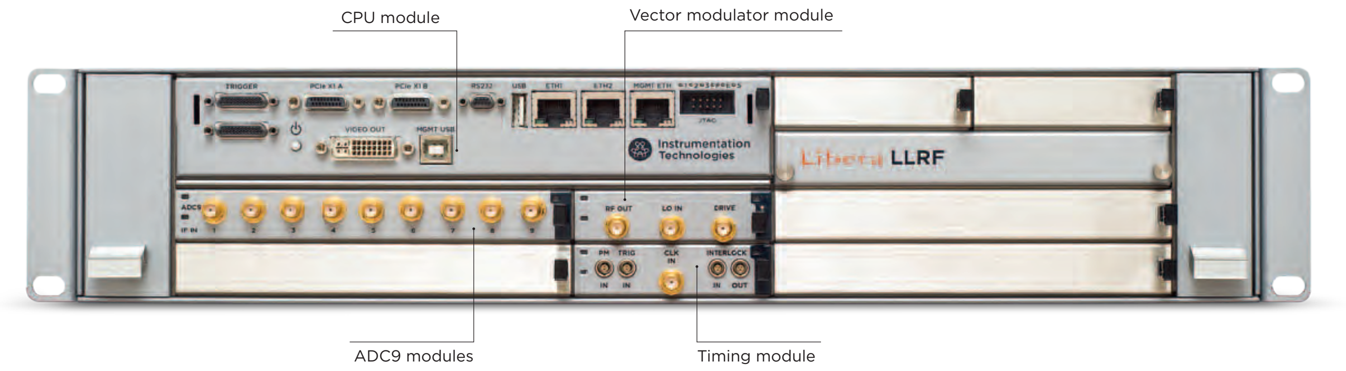


Figure 14: *Digital Libera LLRF*

Up to four processing modules (ADC9) can be connected to the system in order to acquire up to 32 RF signals from the cavities; if fewer signals need to be acquired, the number of ADC9 modules can be reduced.

The ADC9 modules are responsible for the analog signal processing of the input signals and their digitization with 130MS/16 bit A/D converters: this data is stored in the device memory and available to the user. The digitized signals are later transferred to the Vector Modulator board, where the feedback logic is actually implemented (Figure 15).

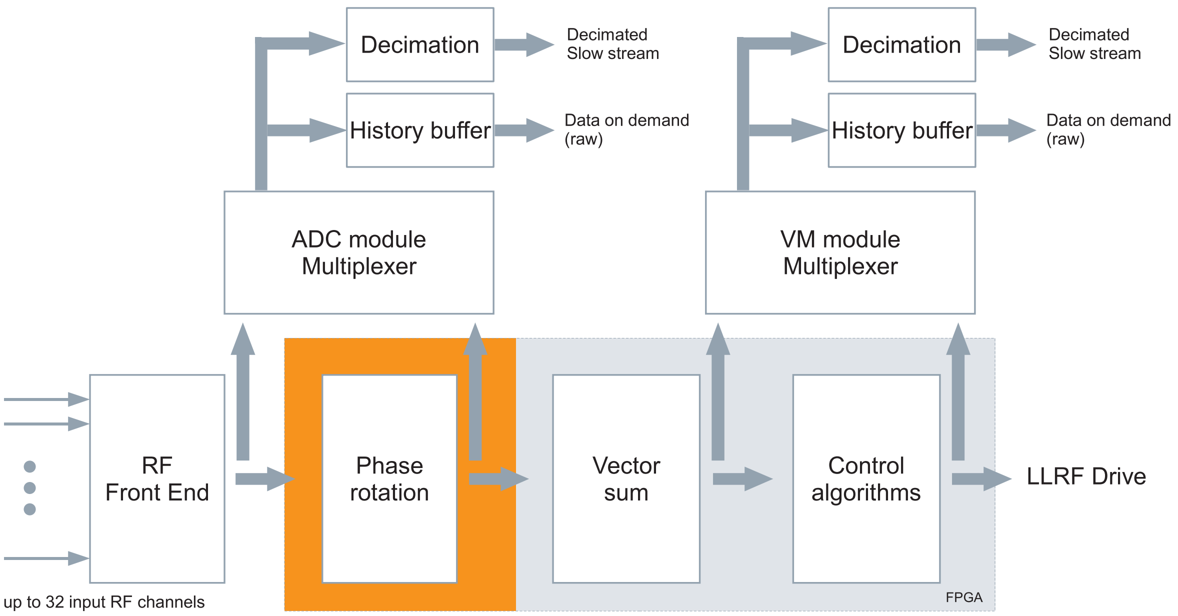


Figure 15: *Signal processing in the Libera LLRF system*

The phase rotation block is used to calibrate each different input signal in phase and amplitude; this is so that differences in RF cabling and delays resulting from the beam time of flight do not influence the calculation. The vector sum then combines all the acquired signals into one equivalent signal, which is used as the input for the control algorithm.

In addition to the data digitized through the A/D converters, the user can also analyze the signals inside the feedback loop, either at the original rate or at decimated rate. One of the possible ways to monitor all this information is through the system Graphical User interface (GUI), as presented in Figure 16.

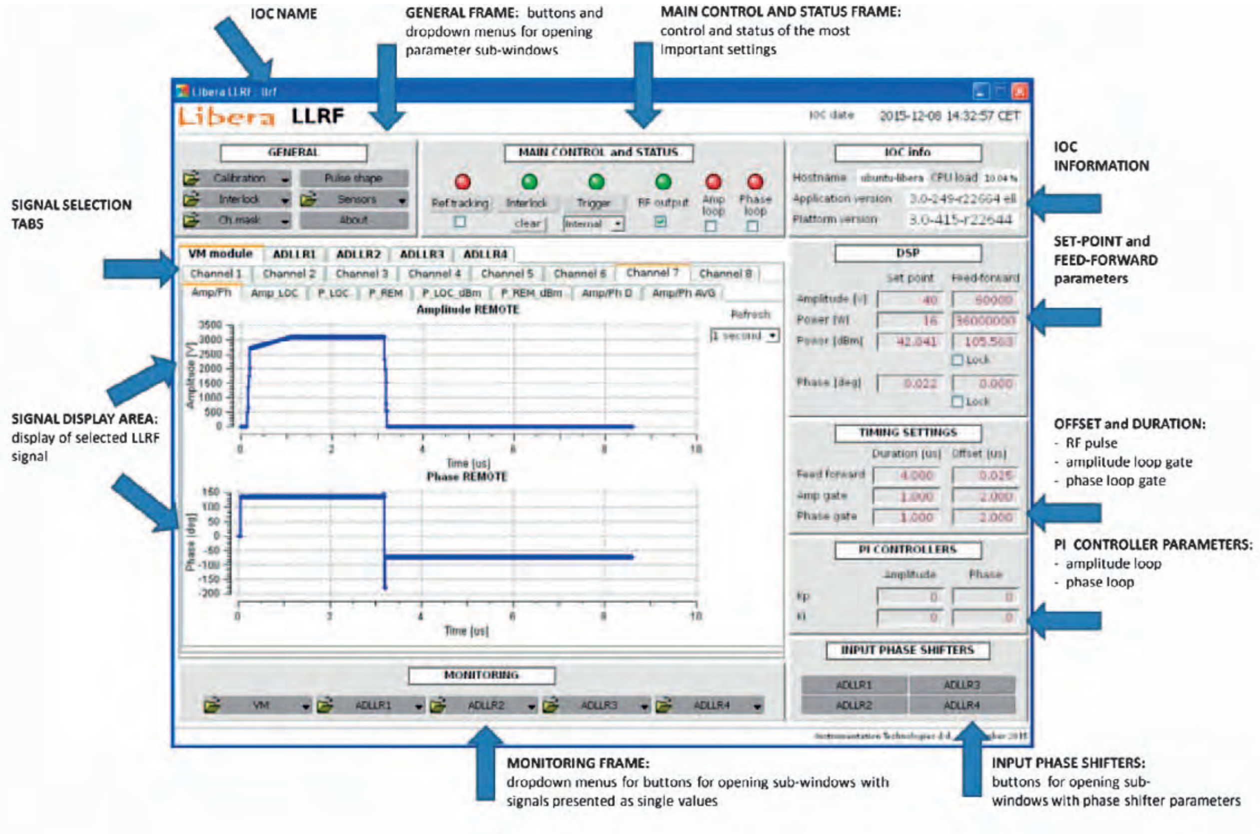


Figure 16: Graphical User Interface (GUI) for the Libera LLRF

Capabilities

The capabilities of the Libera LLRF system are summarized in Table 10.

	Libera LLRF
Dimensions (H × W × D) mm	88 × 448 (483) × 310
RF input channels	Up to 32 (8 per ADC9 module)
RF input frequency	Up to 12 GHz
Maximum RF input power	20 dBm
A/D conversion	130 MHz/16 bits
Operating system	Linux Ubuntu 14.04
RF output channels	2 (1 RF drive, 1 calibration output)
Maximum RF output power	> 10 dBm
Cooling	Active
Power supply	110/220 V

Table 10: Capabilities of the Libera LLRF system

Functionalities

The functionalities of the Libera LLRF system are summarized in Table 11.

***Table 11:** Functionalities of the Libera LLRF system*

Functionality	Description
Machine Operation mode	• Continuous wave (CW) • Pulsed • Combined
Fast-feedback loop	• Gain Driven Resonator (GDR) and Self-Excited Loop (SEL) • Intra-Pulse and Pulse-to-Pulse feedback • Separate or combined loop (Amplitude and Phase, I & Q) • Beam Loading compensation • Compensation for Klystron non-idealities • Compatible with variable RF frequency machines • Extensible to multiple inputs from cavities driven by the same klystron
Cavity tuning	• Based on the cavity detune measurement algorithms: based on forward and reflected signals for CW machines, based on cavity voltage decay on pulsed machines. • Slow tuning with PID controller and stepper motor driver interface. • Fast tuning loop with piezo controller
Signal monitoring and Diagnostics	• Input signals and internal feedback signals • Visualize raw or demodulated signals on the graphical user interface • Direct measurement of amplitude and phase • Derived measurement of signal power and cavity resonant frequency
Machine Protection	• Fast interlock interface (Input and Output) with active low logic
Temperature Compensation	• Temperature stabilized RF front-end within separated chassis (Figure 12) • Calibration output usable for RF cables and RF front-end electronics calibration

Performance Specifications

The main performance specifications of the Libera LLRF system are summarized in Table 12. The results were obtained at the DESY FLASH and Daresbury Laboratory EMMA at a 1 MHz BW pulsed mode of operation.

***Table 12:** Performance specifications of the Libera LLRF system*

	Libera LLRF
Amplitude stability	< 0.01% RMS
Phase stability	< 0.01° RMS
Latency (Input → Drive output)	Down to 250ns
Long-term temperature stability with temperature stabilized RF front-end	< 100fs RMS / 72 hours

***Figure 17:** Libera LLRF temperature stabilized RF front-end*

Clock Transfer System

The Libera Sync system is used to transmit high-quality clock signals from a source, usually a Reference Master Oscillator, to numerous systems that need to be synchronized along the machine (e.g. LLRF stations). It consists of a transmitter and a receiver connected to a pair of single-mode optical fibers (Figure 18).

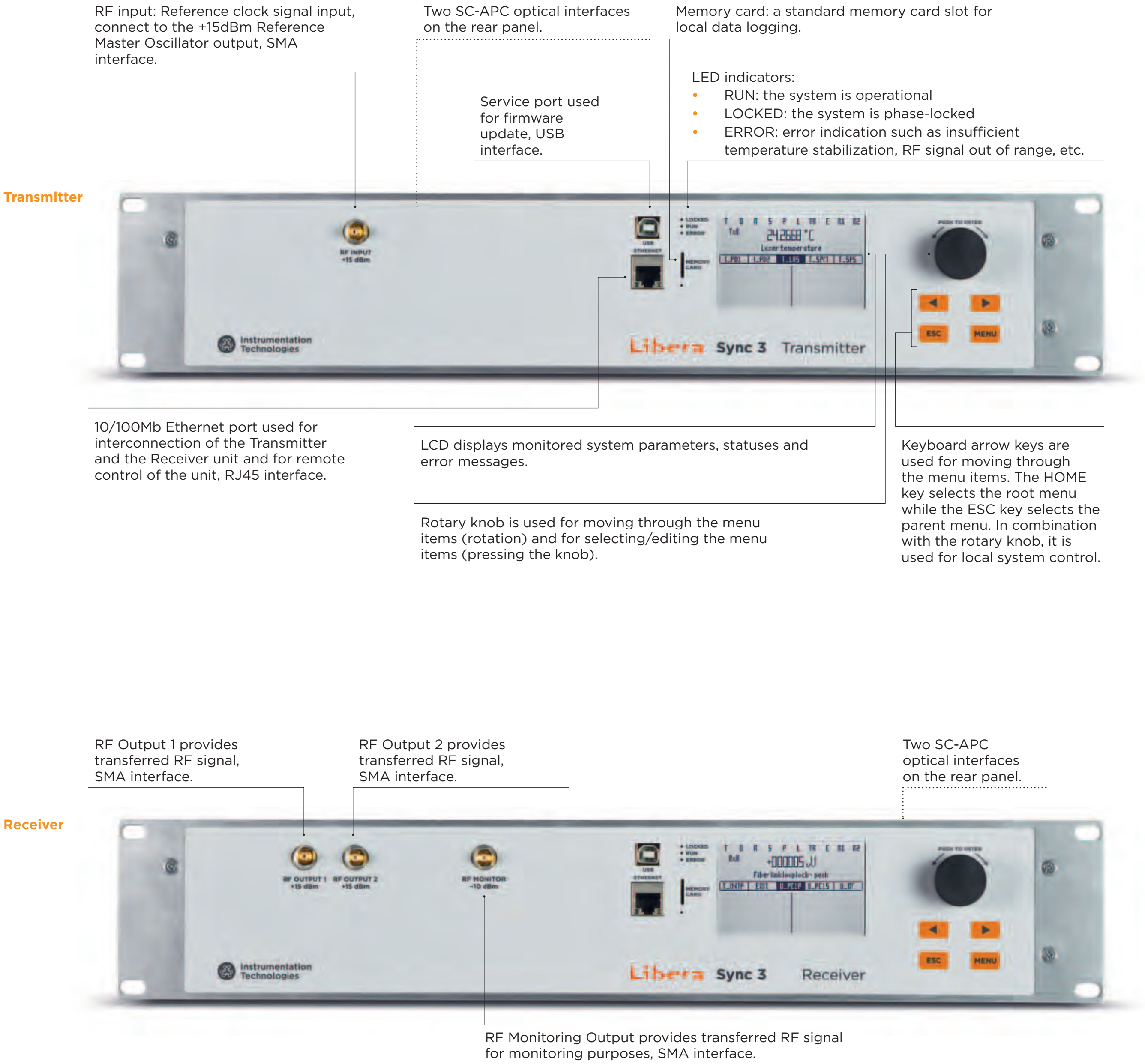


Figure 18: *Clock transfer system (Libera Sync 3)*

The transmitter input signal is a continuous wave RF reference signal which modulates an optical carrier through an electro-optical modulator. The modulated signal is split into two parts and fed into the two optical links: a low-drift link and a low-jitter link (see the block scheme in Figure 19). The low-drift signal is partially reflected at the receiver and used to perform phase drift compensations in the transmitter.

At the receiver, the optical signals from both links are demodulated into the RF domain. The low-jitter signal is amplified, filtered and stabilized in amplitude and phase., filtered and stabilized in amplitude and phase using the low-jitter signal. This signal is used to provide two RF outputs and one monitoring output.

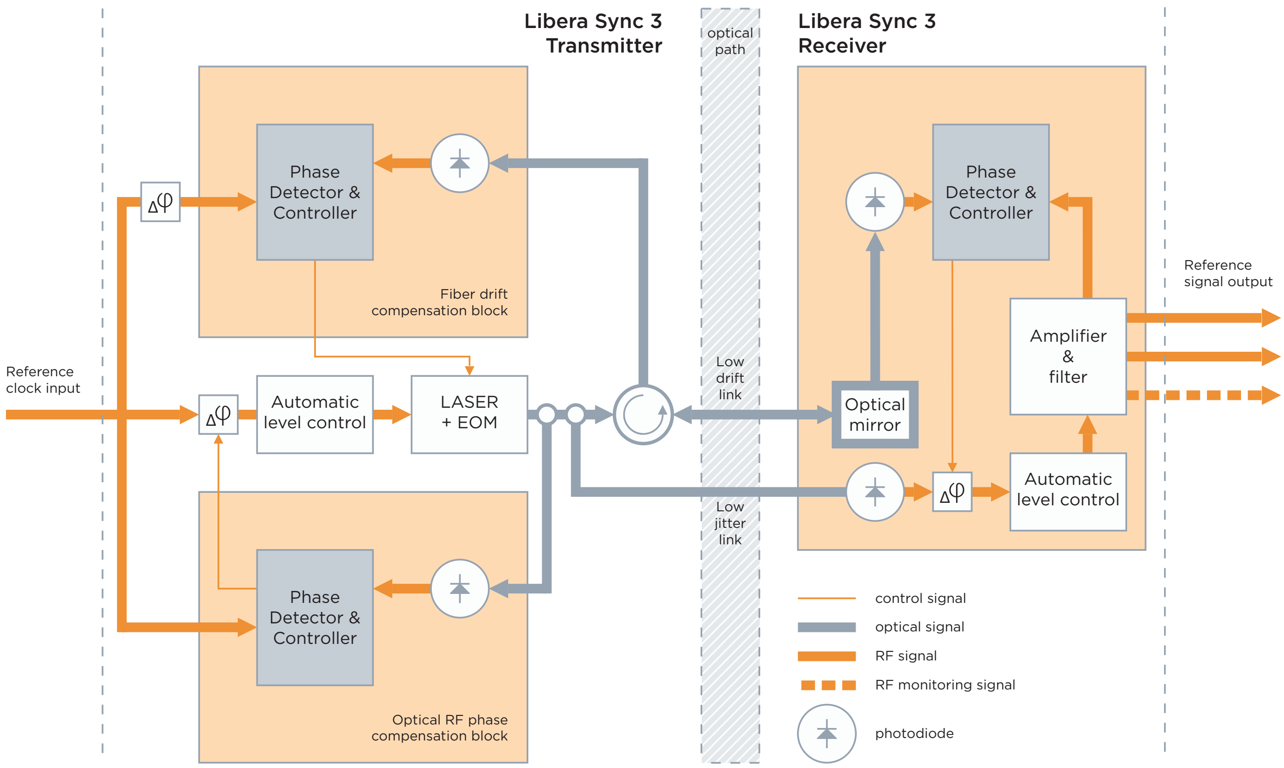


Figure 19: Libera Sync 3 block scheme

To achieve the required performance and stability over the long term, both transmitter and receiver units must be installed in an environment controlled for both temperature and humidity. Once tuned, the system requires very low maintenance.

Capabilities

The Libera Sync 3 covers S-band frequencies; its capabilities are summarized in Table 13.

Table 13: *Capabilities of the clock transfer system*

	Libera Sync 3
Carrier frequency	2.856 GHz or 2.9988 GHz
RF inputs	1
RF input level	(15 ± 1) dBm
RF outputs	2
RF output level	(15 ± 0.5) dBm
Optical link length (maximum)	1500 m
Optical fiber drift compensation range	500 ps
Dimensions	2U 19" standard
Calibration and tuning mode	Automatic
Operating temperature range	20 – 30 °C
Operating relative humidity range	0 – 80 %

Performance Specifications

The performance specifications of the clock transfer system are summarized in Table 14, while Figure 20 presents the added jitter measurement and long-term stability for the Libera Sync 3.

Table 14: *Performance specifications of the clock transfer system*

	Libera Sync 3
Added jitter RMS @ 10 Hz to 10 MHz	< 10 fs
24-hour drift	< 40 fs peak-to-peak typ. < 100 fs peak-to-peak max.

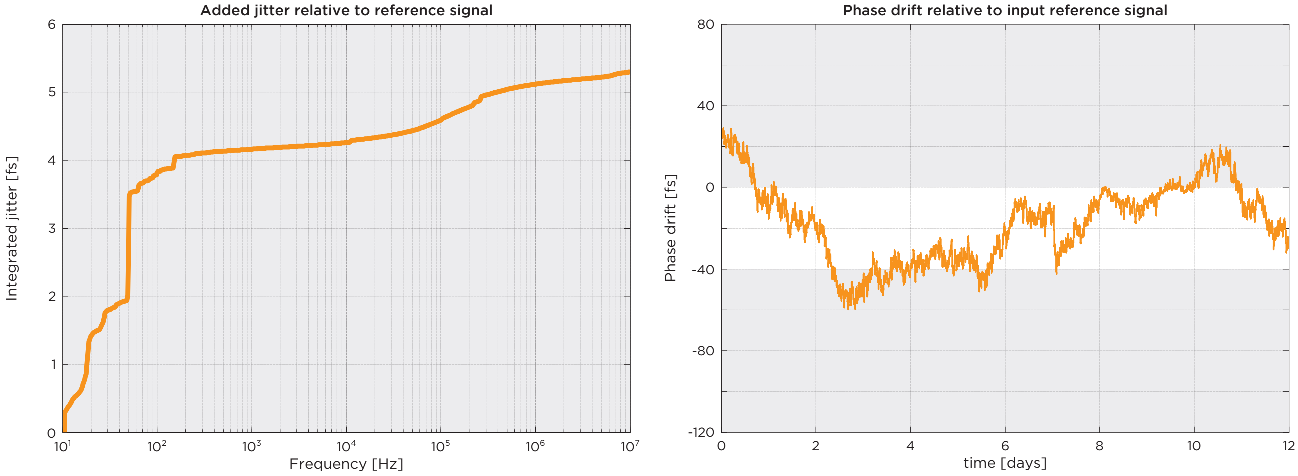


Figure 20: *Added jitter and long-term phase stability measured with Libera Sync 3*

Reference Master Oscillator

The Reference Master Oscillator (RMO) provides a sine wave signal with low phase noise to four outputs with a maximum power of + 18 dBm per output. The device free-runs on an internal OCXO which can additionally be locked to an external 10 MHz reference signal.

The oscillator has very good frequency stability when free-running on OCXO (+/- 0.3 ppm in range of temperature from 20 °C to 40 °C) combined with extremely low phase noise, below 30 fs in the range between 10 Hz and 10 MHz. The front and back panels of the instrument are shown in Figure 21.

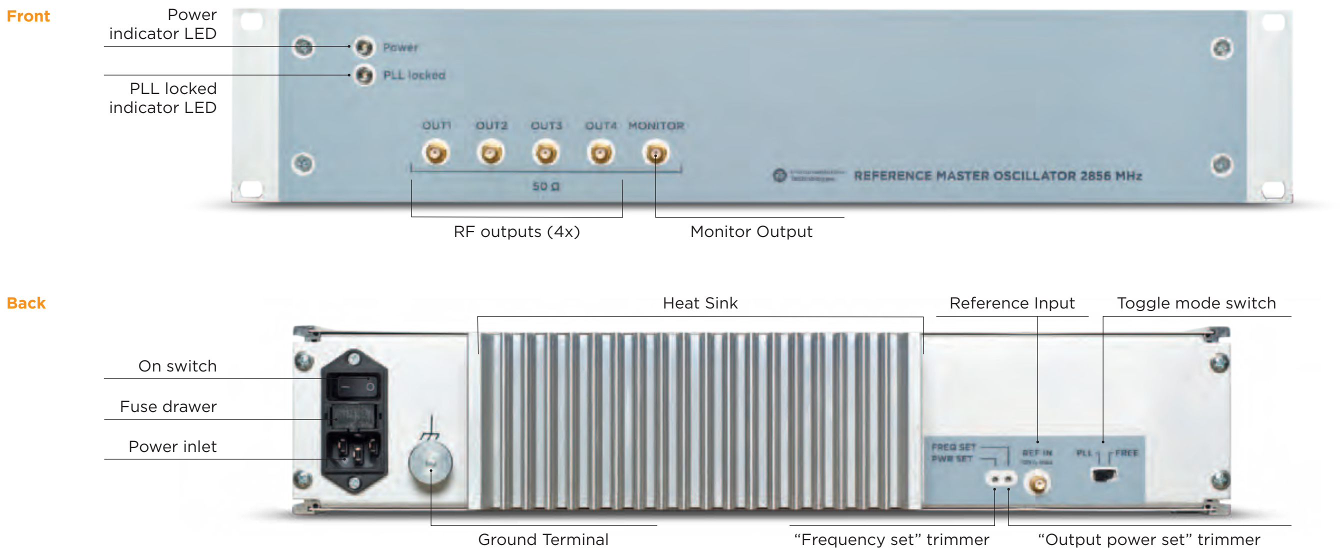
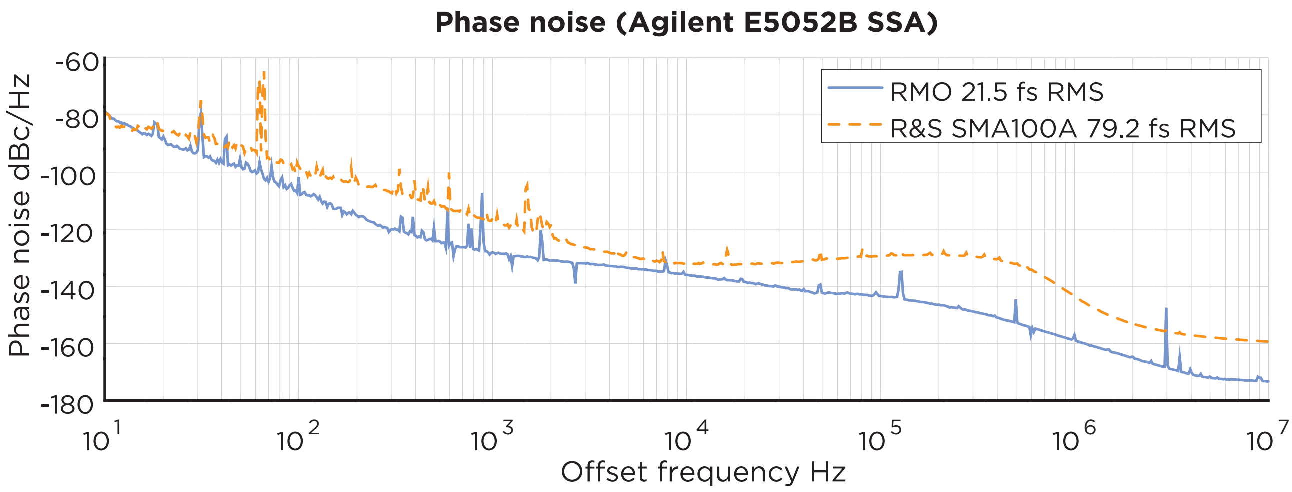


Figure 21: *Reference Master Oscillator, front & back panel*

The RF specifications of the Reference Master Oscillator are presented in Table 15.

Table 15: *RF specifications*

	RMO
Minimum settable power per output	+13 dBm
Maximum settable power per output	+18 dBm
Monitor output power (referenced to outputs)	-20 dB
Output power stability	0.08 dB/°C
Amplitude balance between any two outputs	< 0.3 dB
Return loss	-20 dB
Frequency stability (free-running mode)	+/- 0.3 ppm
Integrated phase noise (max)	< 30 fs (10 Hz – 10 MHz)
Phase drift between any two outputs (typical)	0.01 deg/°C
Harmonic suppression	< 55 dBc up to 5th harmonic
PLL lock time	< 60 s



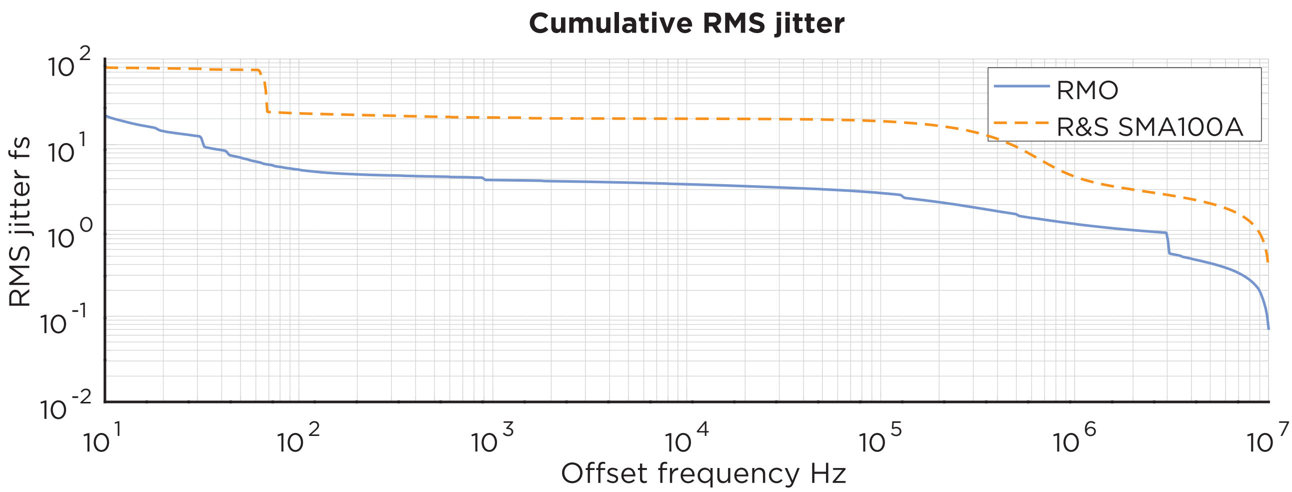


Figure 22: *Typical reference master oscillator phase noise performance compared with a Rohde & Schwarz SMA100A RF generator*

The number of RF outputs can be further increased by means of an optional temperature-stabilized distribution amplifier unit connected to the Reference Master Oscillator unit. The distribution amplifier supports up to 12 RF outputs (Figure 23).

Figure 23: *RMO distribution amplifier, front panel*

Wide Dynamic Range Low Noise Amplifier

The Amplifier 110 is a four-channel, low noise, non-inverting measurement amplifier. Its gain can be set in increments of 10 dB from -50 dB to 60 dB via an SPI control interface.

The Amplifier 110 is intended to reduce wide dynamic ranges in order to enable further signal processing and acquisition. An example of application is pickup signals in beam position monitoring in accelerators, where the Amplifier 110 can be used in combination with e.g. the Libera Hadron.

Figure 24: *Amplifier 110*

The main features of the Amplifier 110 are shown in Table 16.

Table 16: *Amplifier 110 specifications*

	Amplifier 110
Dynamic range	from -50 dB to 60 dB
Input voltage	max. 230 V peak (max. average input power 1.5 W per channel)
Output voltage	±2 V peak
Bandwidth	from 40 kHz to 55 MHz
Gain error between channels	max. ±0.1 dB
Output referred added noise	< 15 mVrms, for gain 60 dB < 5 mVrms, for gains <60 dB
Input and output impedance	50 Ω

Control System Integration

The software modules are implemented using the Libera BASE framework, which provides hardware abstraction and simplifies development and integration. Libera BASE also takes care of all general tasks such as platform management and health monitoring. Besides this, the Libera BASE is an extensible application layer with configuration parameters (registry tree) and signal acquisition, processing and dispatching functionality. On the top layer, it provides the Measurement and Control Interface (MCI) with a development package and an example CLI utility for open interaction in different control systems (see Figure 25 for details). All the software runs on a standard Linux Ubuntu distribution.

The FPGAs reside in several modules and are smoothly integrated into the Libera BASE framework. Using the FPGA development kit, it is also possible to change the functionality and implement different processing algorithms in the extension module.

The TCP/IP socket enables connection via telnet/minicom/nc to the instrument. The IREG interface provides a generalized way to communicate to the instrument, establishing a TCP-IP connection (e.g. via Telnet). Using the same libera-ireg command-line syntax, the user can read the data and control every parameter.

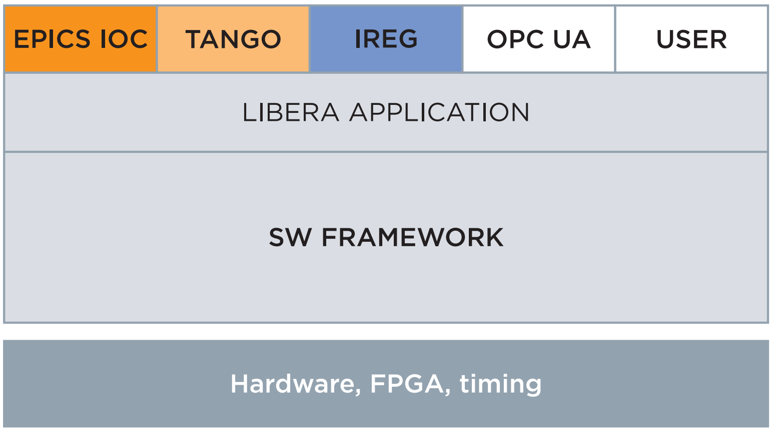


Figure 25: *Software structure*

All the common control system interfaces are supported. The EPICS IOC, for example, runs inside the instrument and provides out-of-the-box access to process variables. Parameters and signals are accessible using a simple command-line utility, and access from Matlab is also supported.

GUI

Graphical user interfaces provide access to all the instrument parameters and signal data. Two types of EPICS-based GUIs are currently available: EDM GUI and QT GUI. The graphical user interface is part of the standard software package.

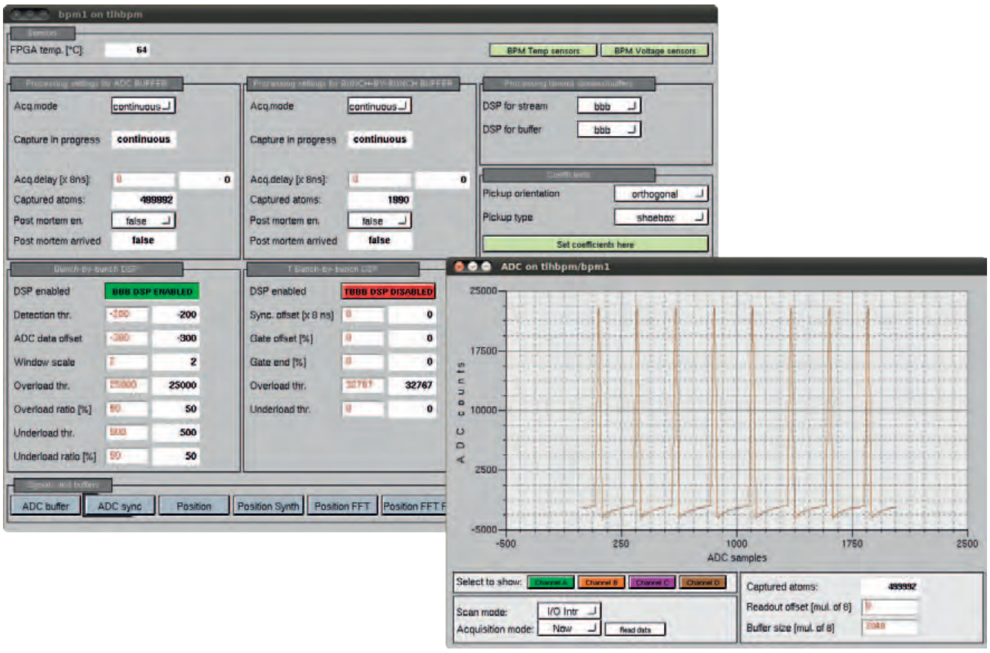


Figure 26: *Example of EDM-based GUI*

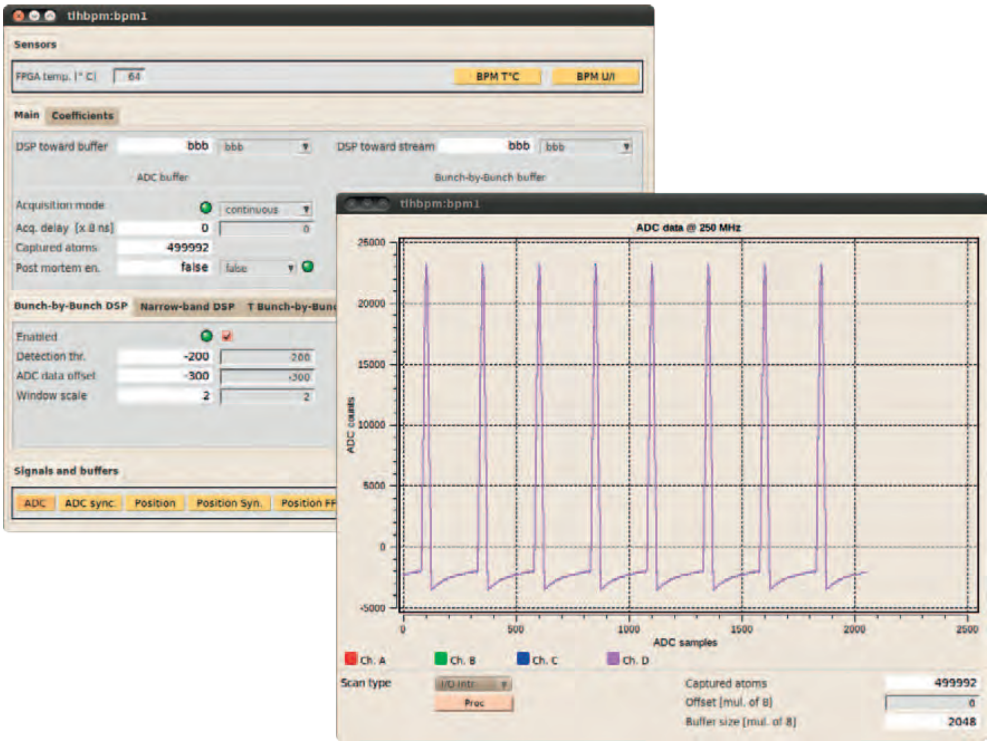


Figure 27: *Example of QT-based GUI*

Extensions

Libera instruments can be integrated with other accelerators' subsystems using extension modules and custom-developed applications (Table 17).

Table 17: *Extension options for Libera instruments*

Extension	Description / example	Works with
Fast Orbit feedback solution	• Complete solution for electron machines that use Libera Brilliance+ instruments (Figure 29).	• Libera Brilliance+ • GDX module • SER module • Orbit feedback application software • Dedicated optical network • Magnet data receiver*
	• Complete solution for hadron machines that use Libera Hadron intruments (Figure 29).	• Libera Hadron • GDX module • SER II module • COFB application software • Dedicated optical network • Magnet data receiver*
	• Standalone calculation engine with input/output interfaces for synchrotrons with other-than-Libera BPM electronics (Figure 30).	• Global orbit data source • Libera Platform B instrument • GDX module • Orbit feedback application software • Magnet data receiver*
Interlock module	• Interlock detection and hardware interface towards Machine Protection System. • Compatible with Libera Platform C instruments.	• Libera Platform C instrument • DAI module • Interlock detection software
Digital I/O channels	• Add 2 extra digital I/O interfaces (LEMO) for communication and/or control of auxiliary components. • Compatible with Libera Platform C instruments.	• I/O control software** • DAC control software**
Analog outputs	• Add an analog output to control an auxiliary component or transform a selected digital value (e.g. SUM, position, etc.) into a 16-bit analog value.	• DAC control software**
Serial interface	• Add a RS-485 interface for half-duplex communication with auxiliary components. • Compatible with Libera Platform C instruments. • Add multiple RS-485 interfaces for real-time data streaming towards magnet receivers.	• Libera Platform B instrument • SER / SER II module • RS-485 control software**
Frequency down conversion	• Convert a higher-frequency signal to match the input capabilities of a Libera instrument.	• DWC module

* Not provided by Instrumentation Technologies
** Basic control included only. Can be customized by users using source code.

DAI module

The DAI module extends the interconnection capabilities of Libera platform C instruments (Libera Spark, Libera Photon, Libera Digit) (Table 18).

Table 18: *Technical specifications of the DAI module*

Interface	Description
LEMO single (2x)	Single-ended LEMO, Input/Output configurable
LEMO differential (1x)	Differential LEMO, Interlock output (requires external circuit)
SMA (1x)	16-bit 100 kSps DAC output, 1 V at 50 Ohm
RJ-14 (1x)	6p6, up to 20 Mbps, half-duplex

Figure 28: *DAI module*

Orbit Feedback Solutions

A complete orbit feedback solution consists of several Libera instruments based on Platform B, all equipped with the GDX module which enables them to exchange the orbit beam position data via an optical network.

Inside of every GDX module, specific data processing calculates the corrections to apply to the magnet controllers (via the optional SER or SER II modules). The correction can be made locally or globally. A general schematic is shown in Figure 29.

A standalone orbit feedback solution is another possible topology, consisting of one or two Libera Platform B instruments equipped with the GDX module (optionally also with the SER/SER II module). Global orbit data is exchanged between the BPM electronics via dedicated broadband network or concentrated in the data server. Global orbit data packets must be provided to the GDX module over a copper or optical link. The orbit feedback application inside the module applies custom-written algorithms and data processing before being sent to the magnet controllers (locally or globally). A general scheme is shown in Figure 30.

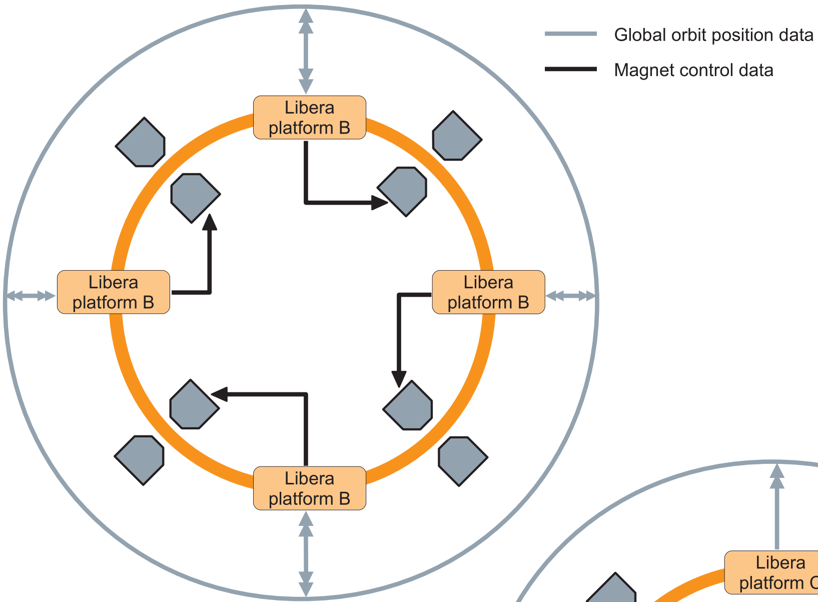


Figure 29: *Complete orbit feedback solution for electron/hadron machines*

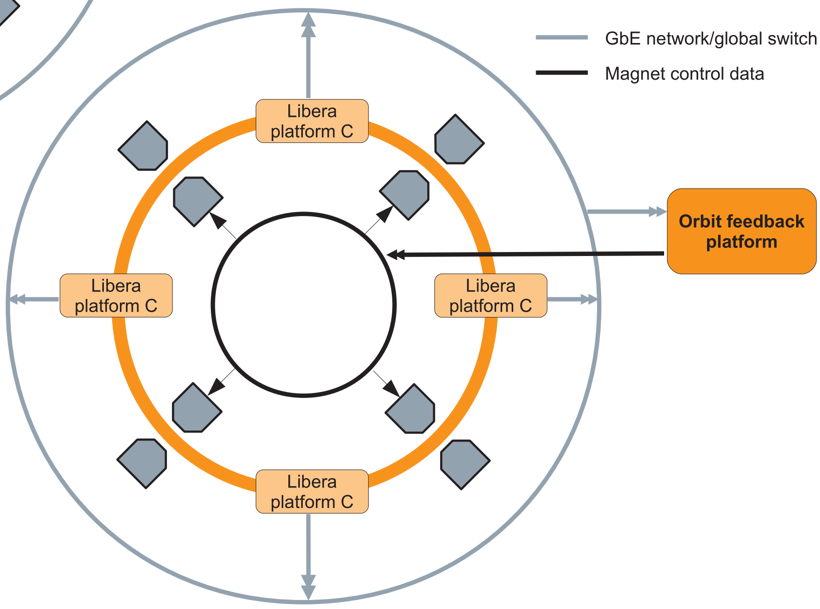


Figure 30: *Standalone orbit feedback calculation engine for electron/hadron machines*

SER module

The SER module features four RS-485 interfaces which are directly controlled from the GDX module. The protocol and the baud rate are specified by the application in the GDX module (Table 19).

Figure 31: *SER module*

Table 19: *Capabilities of SER module*

	SER module
I/O interfaces	RJ-25, LVDS links to GDX module
Baud rate*	Up to 2.5 Mbit/s
Protocol*	Asynchronous protocol EIA 485, byte per byte

* Specified by application in the GDX module

SER II module

The SER II module features eight RS-485 interfaces which are directly controlled via the PCI express links (Table 20)

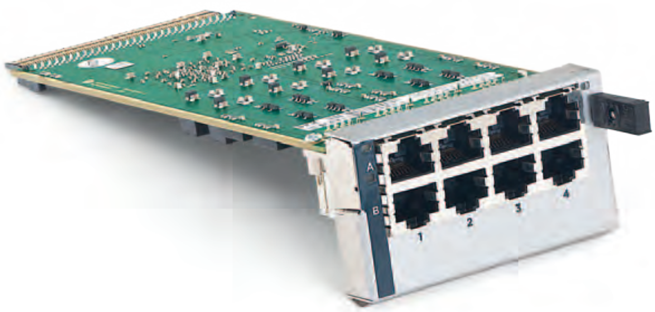


Figure 32: *SER II module*

Table 20: *Capabilities of SER II module*

	SER II module
I/O interfaces	RJ-45, PCI express links
Electrical protocol	Asynchronous protocol EIA 485, byte per byte
Protocol	High speed USI protocol

GDX module

The GDX module extends the interconnection capabilities of the BPM electronics. Four protocol independent small form pluggable (SFP) slots can be used to build a closed loop of all the instruments in the accelerator. It features a Virtex6 FPGA which is completely open to user-developed applications. It can process the internal (within the chassis) and external position data at various data rates (Table 21).

Figure 33: *GDX module*

Table 21: *Capabilities of GDX module*

	GDX module
FPGA chip	XC6VLX240T-2FF784C
Memory	2 GB DDR3
I/O interfaces	4x SFP+ compliant, compliant multiprotocol operations, LVDS links to AMC connectors
SFP protocol	AURORA, GbE, others on request; independent to each SFP
PCIexpress x4 bus interface to instrument's backplane	
On-board **clock synthesizer** and **programmable VCXO** for clock generation	
Board management is already established	

DWC module

The DWC-SP circuit is a four port RF down-converter which can be used to down-convert the RF input signals from S-band to an intermediate frequency (Table 22).

Table 22: *Technical specifications of the DWC module*

	1.3 GHz	3 GHz
Supply voltage	6 V DC	6 V DC
RF Input connector	SMA	SMA
RF Input frequency	1300 MHz	2856 MHz
RF Input power	< 15 dBm	< 15 dBm
LO Input connector	SMA	SMA
LO Input frequency	800 MHz	2356 MHz
LO Input power	5 dBm	5 dBm
RF Output connector	SMA	SMA
RF Output frequency	500 MHz	500 MHz

Figure 34: *DWC module*

Libera Upgrades

Libera instruments are a lively symbiosis of hardware components, software code and user experience.

Fans

The firstly delivered instruments (Libera Platform B) have been in use for over 7 years and their fans have rotated over 20 billion revolutions. Now might be a good time to consider replacement with our new generation of fans. They look the same but you can hear the difference. The new fans are much quieter, which brings your Libera Platform B instrument below the noise floor of your laboratory.

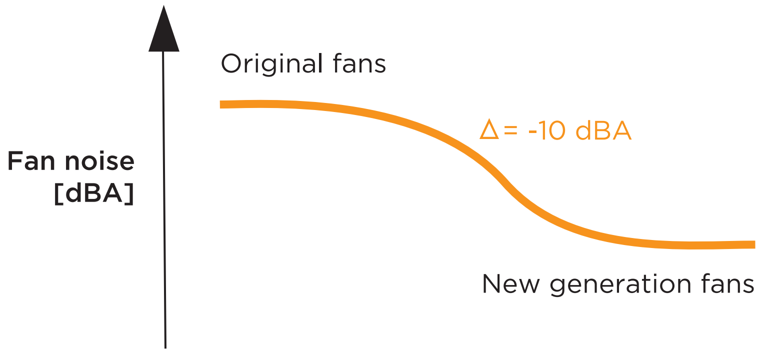


Figure 35: *Acoustic noise reduction with new generation fans*

Central Processing Unit (CPU)

The original software functionalities installed in the Libera Platform B instruments allowed users to explore beam movement and do countless hours of machine studies. Through the years, demands have increased and users are requesting more data in shorter times.

To meet user requirements, the CPU in Libera Platform B instruments can be upgraded from the reliable workhorse Intel Atom N270 1.6 GHz to the newer generation Intel i5-3610ME 2.7 GHz (Table 23). The upgrade includes more memory (2 GB), newer Linux Ubuntu operating system and support for the latest Libera software releases.

Table 23: *CPU benchmark comparison*

	Intel Atom N270	Intel Core i5-3610ME
Clockspeed	1.6 GHz	2.7 GHz (3.3 GHz turbo)
# of physical cores	1 (2 logical cores per physical)	2 (2 logical cores per physical)
CPU mark	270	3786

Services and support

Commissioning assistance
Assistance in installation, commissioning and integration into the control system.

On-site and remote support
Get in touch with our skilled engineers, who have a full knowledge of the system. We will help you with hardware, software or system integration issues throughout the product's lifecycle.

On-site demonstration and testing
Try the instruments on your machine. One of our experts can visit you and assist you with testing.

Training
Hands-on training sessions on the use of Libera instruments are organized either on-site or at Instrumentation Technologies premises.

Instrument customization
Our flexible hardware and software architecture provides different options for extending functionalities.

Warranty extension
Extend the standard warranty period for the instruments and fix the cost of potential malfunctions in advance.

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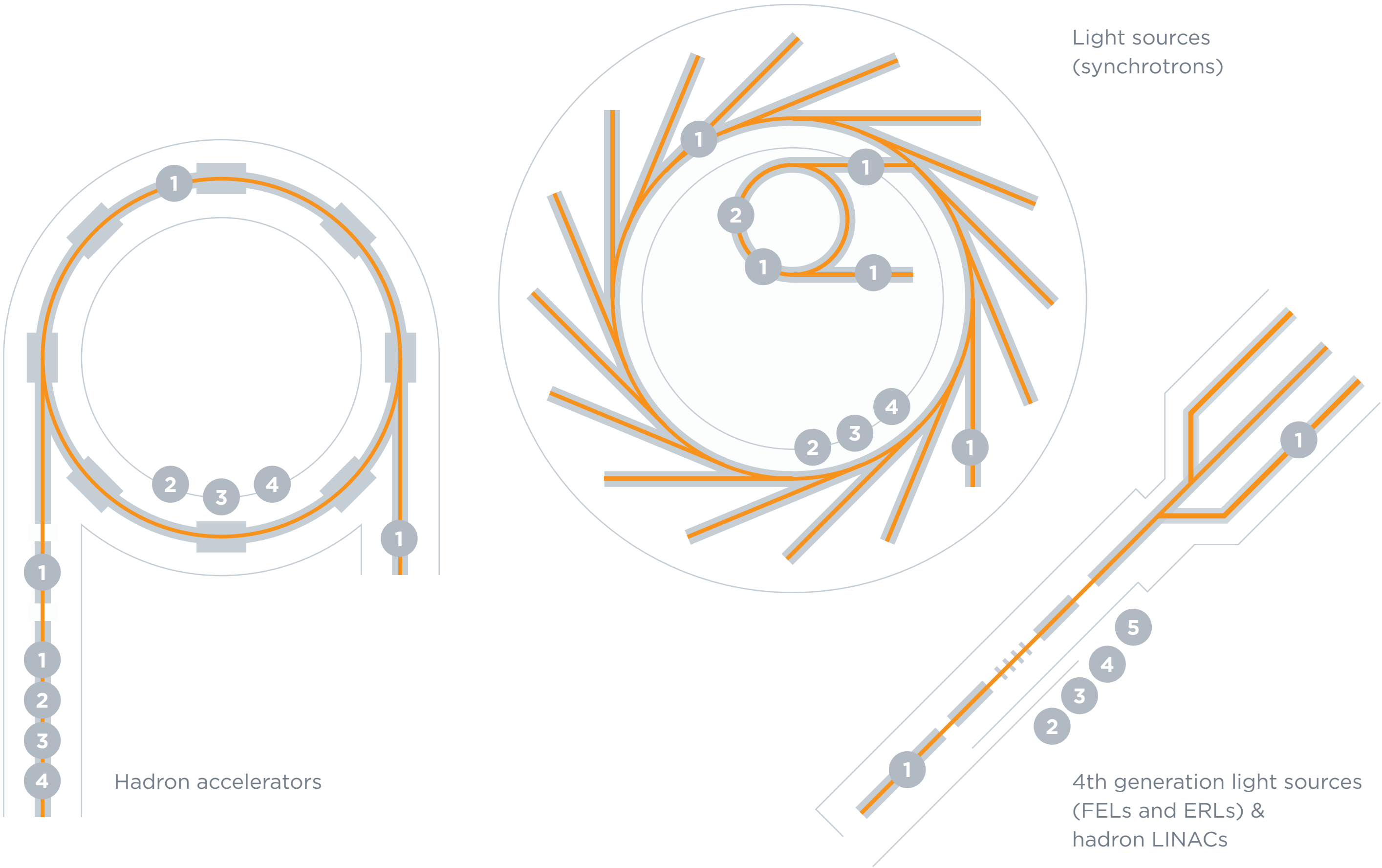
Libera

1. BPM ELECTRONICS
2. BEAM LOSS MONITOR
3. DIGITIZERS
4. DIGITAL LLRF
5. CLOCK TRANSFER SYSTEM

YOUR IDEA



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