LIBERA

LIBERA BOOK

Solutions for Particle Accelerators

2019

INSTRUMENTATION TECHNOLOGIES

Libera

SOLUTIONS FOR **PARTICLE ACCELERATORS**

The accelerator community knows us as the Libera folks. It looks like we've left an impression since our story began back in 2003. Since then, nine out of ten 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. 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

Founder of Instrumentation Technologies

LIBERA REFERENCES

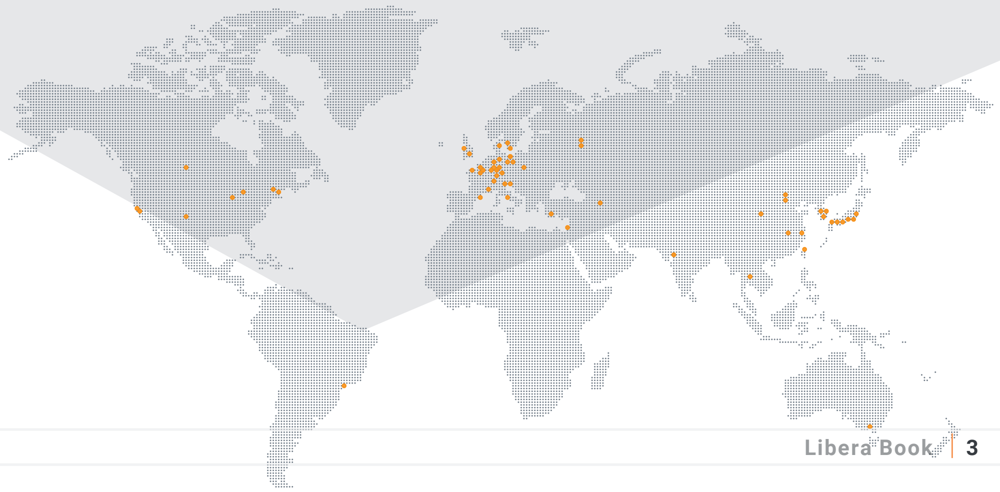
Asia
Chinan Biomedical Technology
HiSOR
HUST
IBS—RISP
IHEP—BEPC II, ADS, CSNS
IMP-CAS—C-ADS, LEAF, SSC- LINAC, CSR, HIRFL
IMS—UVSOR
ISSP
KEK—PF, PF-AR, LINAC, SUPER B, J-PARC, cERL
Nagoya University—Aichi Synchrotron
NewRT Medical Systems
NSRRC—TLS, TPS
PAL—PLS II, XFEL ITF
Peking University
RRCAT—INDUS, INDUS II
SACLA—SPring-8
SINAP—SSRF
SJTU
SLRI
Tsinghua University
USTC, NSRL—HLS, HLSII

Australia
Australian Synchrotron

Europe
AVO-ADAM—LIGHT
CANDLE
CELLS—ALBA
CERN
DELTA
DESY—PETRA III, FLASH, DESY XFEL, DORIS III
Diamond Light Source
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
Physics Institute of the University of Bonn
PSI—SLS, SwissFEL
RRC Kurchatov Institute—SIBERIA II
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
LANL—LANSCE
LBNL—ALS
Michigan State University—FRIB
Northwestern University
SLAC—LCLS, SPEAR

South America
ABTLuS—LNLS



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BPM ELECTRONICS

Libera Beam Position Monitor (BPM) electronics feature a 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 Brilliance+	Libera Photon
Libera Single Pass H	Libera Single Pass E	
Libera Spark	Libera Spark	
	Libera CavityBPM	

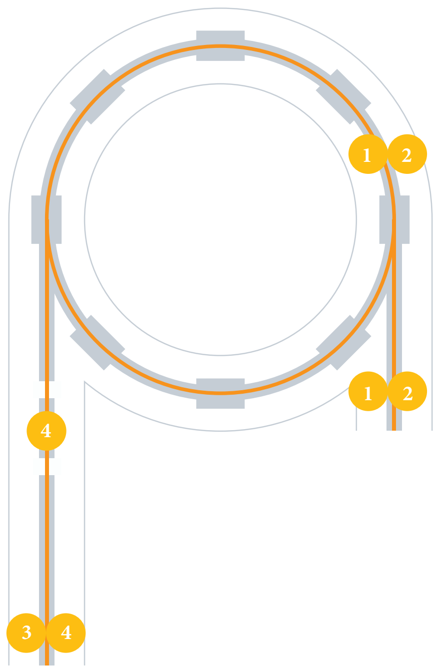
For circular machines, the closed loop operation can be further expanded with dedicated modules that extend the instrument capabilities enabling global orbit feedback. These modules fit inside the instruments and provide fast serial communication links that can be used with optical or copper cables,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

Hadron

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 various levels of measurement performance and functionalities. The BPM pickup types 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 proton/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
- Extensions: Fast data streaming, feedback application, serial I/O interface

2 Libera **Spark HR**

- Used in proton/hadron synchrotrons and ring-to-target beam transfers
- Bunch-by-bunch data processing
- Extensions: Interlock output, real-time data streaming, analog output, digital (serial) I/O

3 Libera **Single Pass H**

- Used in proton/hadron linear accelerators
- Beam position and phase measurements calculated for two signal harmonics
- Extensions: Fast data streaming, feedback application, serial I/O interface

4 Libera **Spark HL**

- Used in proton/hadron linear accelerators and transfer lines
- Extensions: Interlock output, real-time data streaming, analog output, digital (serial) I/O

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

Hadron BPMs capabilities and performance	for CIRCULAR machines		for LINEAR machines	
	Libera Spark HR	Libera Hadron	Libera Spark HL	Libera Single Pass H
General Product code	LSHR	LHAD	LSHL	LSPH
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
Cooling	Passive	Active (fans)	Passive	Active (fans)
Power supply	PoE	110/220 V, 250 W	PoE	110/220 V, 250 W
Timing signals	Electrical (up to 3)*	Electrical (4)/Optical	Electrical (up to 3)*	Electrical (4)/Optical
Fast data links	RJ-45	RJ-45 & SFP	RJ-45	RJ-45 & SFP
Maximum input signal *	< 1.2 V peak pulse voltage*	< 2 V peak pulse voltage*	< +10 dBm*	+10 dBm
Input gain/attenuation	Fixed	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 cextended/customised depending on user requirements // ** measured with K=10mm

Table 1: Hardware capabilities and performance 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	Optional*	Optional*	Optional*	Optional*
Slow data	No	Yes	No	No
Gain control	No	External amplifier module***	Yes	No
Selectable processing window	Yes	Yes	Yes	Yes
Processing delay	Yes	Yes	Yes	Yes
Multi-chassis synchronization	Trigger-based	Reference clock with PLL	Trigger-based	Trigger-based
Data time stamping	Trigger-counter	Based on external RF clock	Trigger-counter	Trigger-counter
Interlock detection and output	Optional**	No	Optional**	Yes
Postmortem capability	No	Yes	No	No
FFT/FFT peak	No	Yes	No	No
Single-pass measurement	Yes	Yes	Yes	Yes
*Requires additional module	ETH interface	GDX module	ETH interface	GDX module
** Requires additional module	DAI module		DAI module	
*** External variable gain amplifier		Amplifier 110		

Table 2: List of functionalities of hadron beam position monitors

Electron

Electron & Photon BPM Electronics

Instruments intended for use in linear and circular electron machines 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 supported are button, stripline, and cavity-type pickups.

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

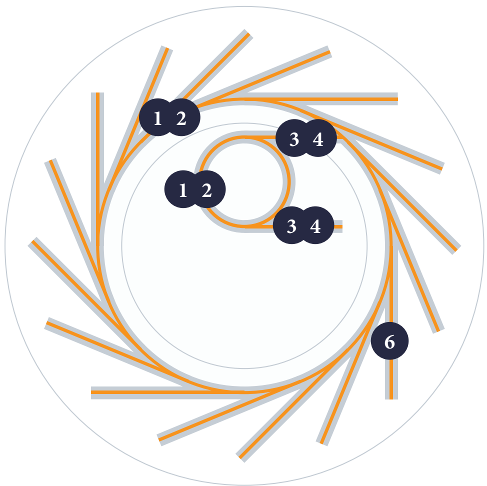
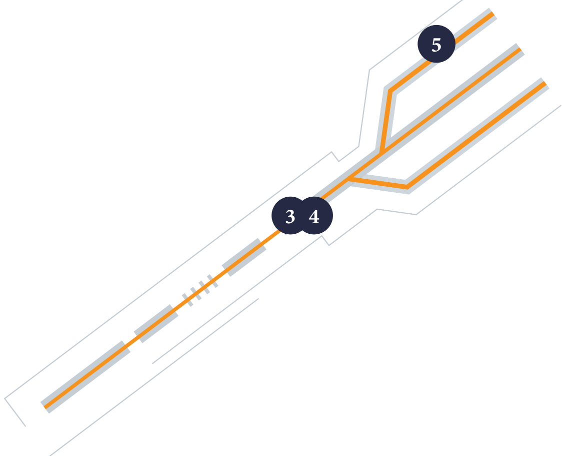


Figure 3: Example of a 4th generation light source (FEL / ERL)



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
- Extensions: Fast Orbit Feedback application,serial I/O interface

2 Libera Spark ERXR

- Used in electron synchrotrons
- Data bandwidth from 15 MHz to 5 Hz
- Fast data link towards orbit feedback
- Extensions: Interlock output, real-time data streaming, analog output, digital (serial) I/O

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: DWC module
- Extensions: Fast data streaming, feedback application, serial I/O interface

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
- Extensions: Interlock output, real-time data streaming, analog output, digital (serial) I/O

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 16 ns bunch spacing
- 3 GHz and 6 GHz versions
- Extensions: Interlock output, real-time data streaming, analog output, digital (serial) I/O

6 Libera Photon

- Used in synchrotron and FEL beamlines
- Data bandwidth from 80 kHz to just a few Hz
- Compatible with diamond and blade detectors
- Extensions: Interlock output, real-time data streaming, analog output, digital (serial) I/O

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.

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
General product code	LSXR	LBRP	LSEL	LSPE	LCAV
BPM slots	1	1 - 4	1	1 - 4	1
Supported input frequency range	< 750 MHz	< 700 MHz	< 750 MHz	< 700 MHz	< 6 GHz
A/D conversion	125 MHz/14 bit	130 MHz/16 bit	125 MHz/14 bit	160 MHz/16 bit	500 MHz/14 bit
Cooling	Passive	Active (fans)	Passive	Active (fans)	Passive
Power supply	PoE	110/220 V	PoE	110/220 V	110/220 V
Timing signals	Electrical (3)*	Electrical (4)/	Electrical (up to 3)*	Electrical (4)/Optical	Electrical (up to 3)*
Calibration	Manual / Pilot tone	Crossbar switch DSC	Manual/Static	Manual/Static	Manual/Static
Fast data link	RJ-45	RJ-45 & SFP	RJ-45	RJ-45 & SFP	/
Maximum input signal*	< -10 dBm continous	< +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 10 kHz data rate	0.04 µm**	0.07 µm**	/	/	/
Position RMS at slow 10 Hz data rate	0.02 µm**	0.02 µm**	/	/	/
Position RMS at single bunch	< 10 µm**	/	4 µm**	1 µm**	< 1 µm
Position RMS at macro pulse/ continuous wave	/	/	< 4 µm	< 1 µm	< 1 µm

* Can be customized // ** Measured with K=10 mm

Table 3: Hardware capabilities and performance 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	Optional *	Yes	Optional *	Optional *	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	Optional**	Yes	Optional**	Yes	Optional**
Postmortem capability	No	Yes	No	No	No
Single-pass measurement	No	Yes	Yes	Yes	Yes

* Requires additional modules	additional ETH interface		Additional ETH interface	GDX module	
** Requires additional module	DAI module		DAI module		DAI module

Table 4: List of functionalities of electron beam position monitors

Photon

Photon BPM Electronics

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

Photon BPM capabilities & performance	 Libera Photon
General product code	LPHO
Input channels	4
Input frequency range	< 80 kHz
A/D conversion	2.5 MHz/18 bit
Cooling	Passive
Power supply	PoE
Timing signals	Electrical (3)
Calibration	Manual
Fast data link	RJ-45
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 (10 kHz data rate)	< 0.02 µm
RMS uncertainty @ 180 µA (10 Hz data rate)	< 0.01 µm

Table 5: Hardware capabilities and performance 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). Pulse repetition up to 10 Hz is supported.
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. Users can change filtering blocks' coefficients to adjust filters' response.
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, 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. DAI1 extension module is required.

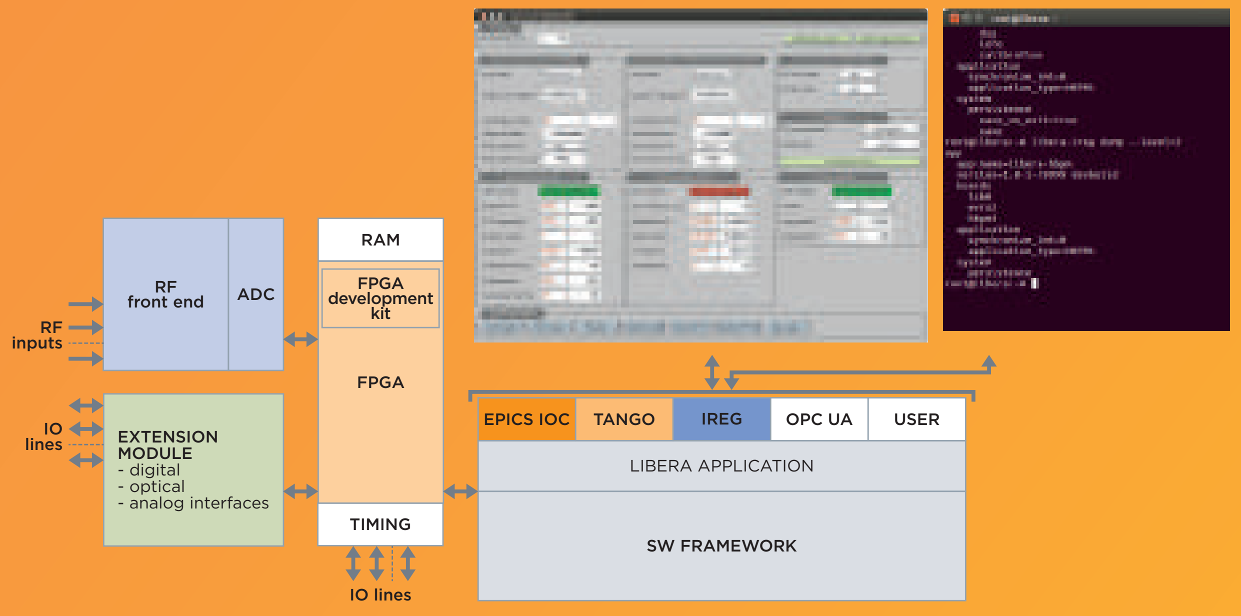
Table 6: List of functionalities of the Photon beam position monitor

Architecture & Platforms

The general architecture of 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 of the real-time DSP algorithms and filling data into 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 calculated information such as position, phase, intensity, and so on, is stored in the memory. All the information is available to the user through the instrument software interfaces and control system adapters.

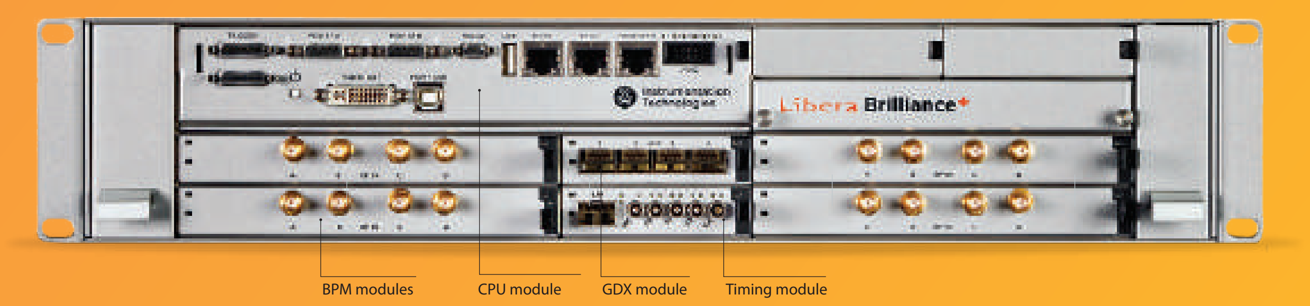
The default instrument configuration already provides all I/O lines required for normal operation, however the instrument functionalities can be further expanded with extensions requiring different HW modules, depending on the instrument platform—see the section on Extensions (page 36).

Figure 4: Generalized block diagram of Libera BPM electronics



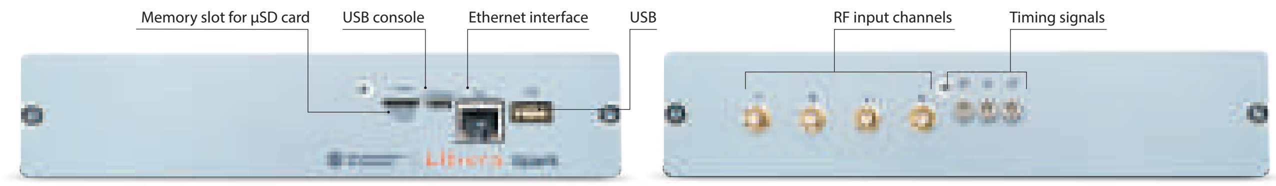
BPM electronics are available in different technology platforms that have different form factors. Platform B is based on the MTCA.0 modular technology and hosts up to four BPM modules in a 2U 19" chassis. Several extensions are available for the orbit feedback and timing system—see the section on Extensions.

Figure 5: BPM electronics based on Platform B



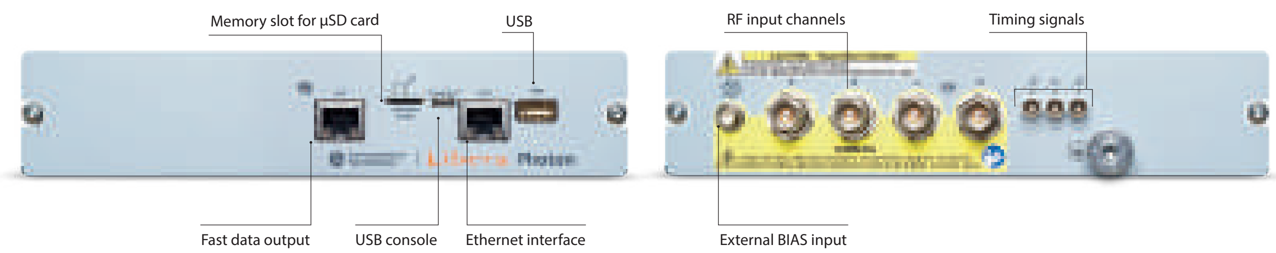
Platform C is based on system-on-chip technology. Due to its low power consumption, the instrument is powered over Ethernet with PoE standard, and is passively cooled. Given the small dimension (BPM electronics is contained in a 1U 9.5" chassis), it can be installed in the tunnel close to the BPM pickup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

Figure 6: BPM electronics based on Platform C



Photon BPM electronics is still based on 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 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

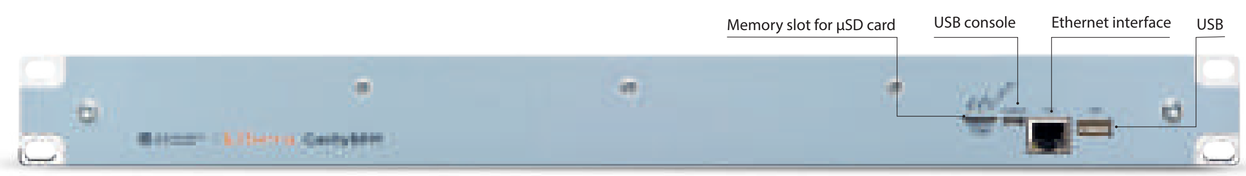
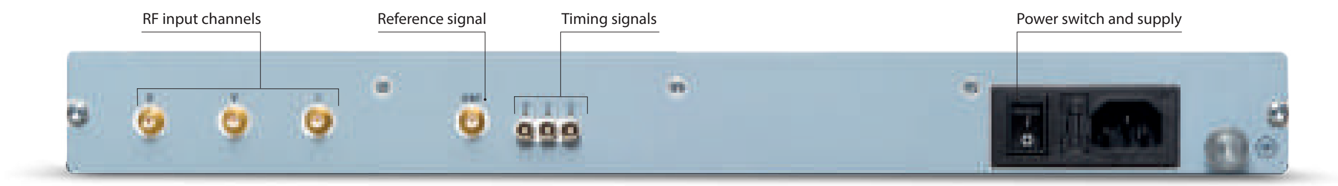


Figure 9: CavityBPM electronics based on Platform C, back panel



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 and intra-pulse losses. This effectively makes it possible to detect and select only those losses that 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

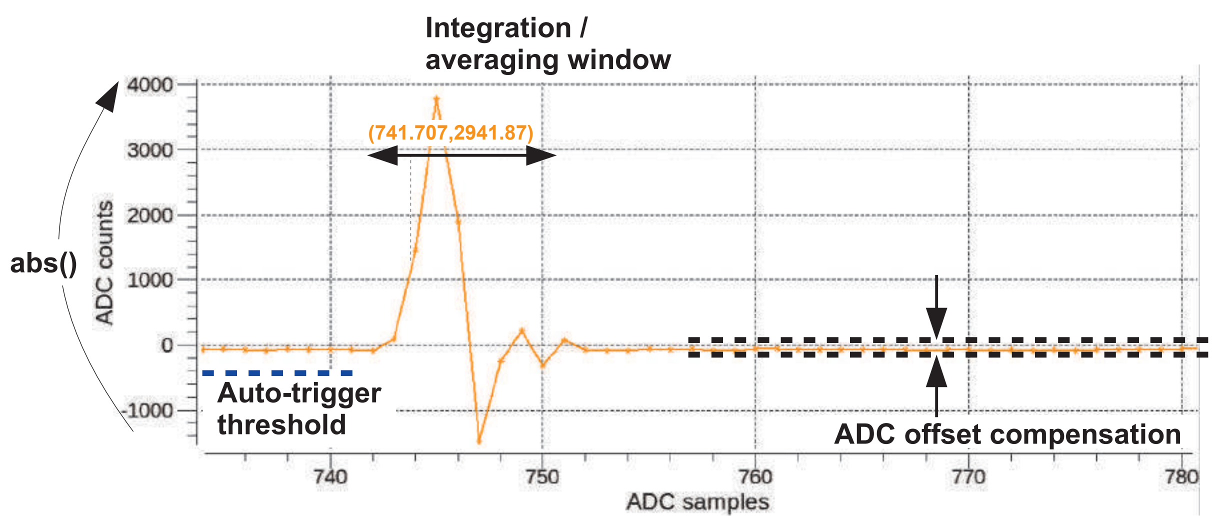
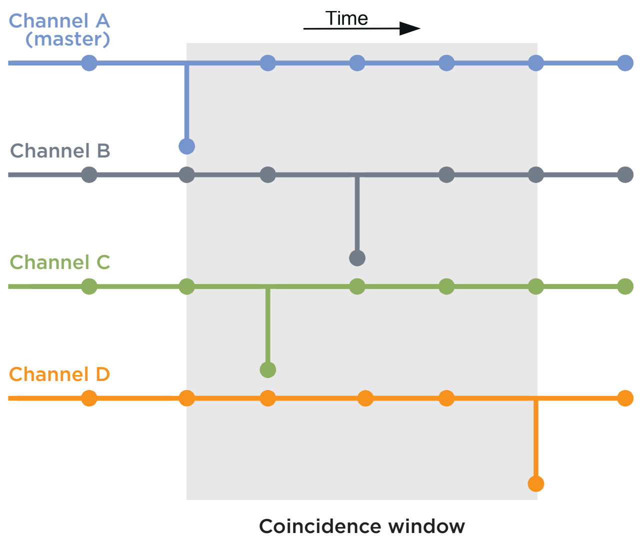


Figure 11: Coincidence loss monitoring

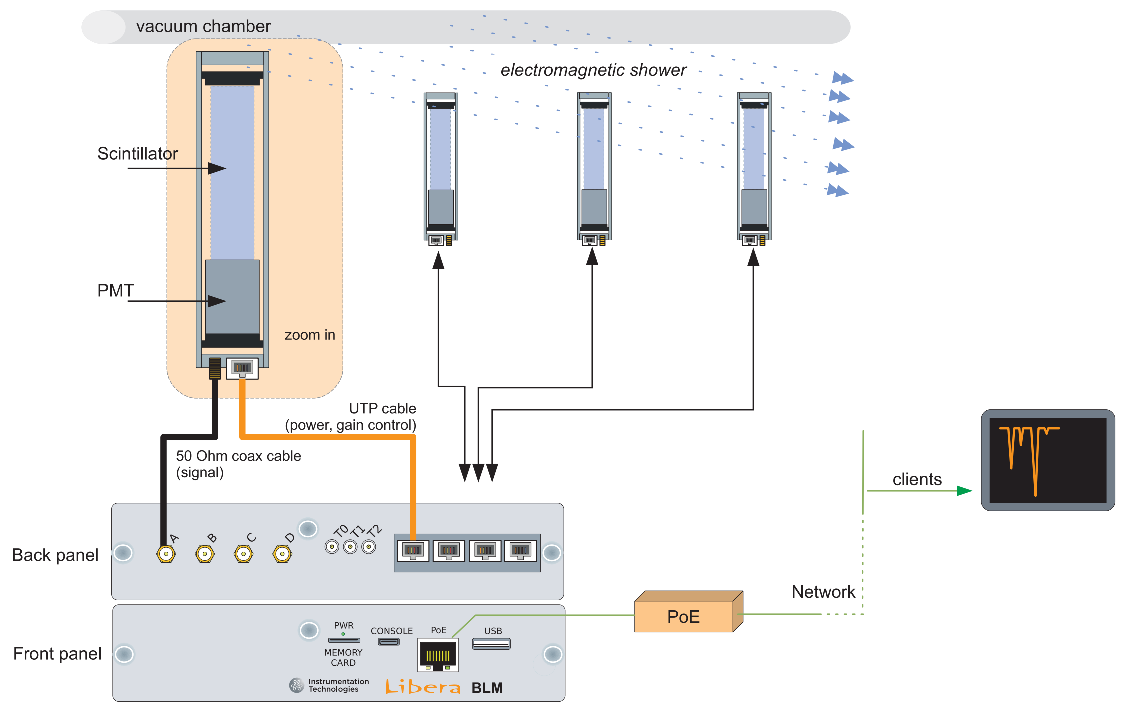


In parallel, losses are continuously monitored and counted at a rate of 8 ns. Counting modes are fully configurable for static and dynamic loss thresholds. Being locked to a sampling clock and an external clock, it is possible to adjust up to two configurable detection windows that monitor only a selected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

With up to four 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.

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 Libera Beam Loss Monitors are summarized in Table 7.

	Libera BLM	Beam Loss Detector (BLD)
		
General product code	LBLM	LBLD
Input channels	4	Scintillator Rod for γ-ray detection EJ-200 from Scionix) Typical dimensions: • Length: 100 mm • Diameter: ~22 mm Aluminum housing, ~2 mm Lead shielding
Input frequency range	~35 MHz large signal bandwidth ~50 MHz small signal bandwidth	
Matching impedance	50 Ω/1MΩ, selectable	
A/D conversion	125 MHz/14 bit	
Cooling	Passive	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
Power supply	PoE	
Timing signals	Electrical (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
Maximum input signal	±1.25 V @ 1 MΩ ±5 V @ 50 Ω	
Output channels	4x power supply (up to ±15 V) 4x gain control (up to +12 V)	

Table 7: Hardware capabilities of Libera Beam Loss Monitor and the photo-multiplier tube

Functionalities

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

	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.

Table 8: Hardware functonalities of Libera Beam Loss Monitor and the photo-multiplier tube

DIGITIZERS

Besides the general purpose digitizer, the idea is to provide the user with a base from which to develop its own application. The instruments provide all the building blocks which are used for the other applications: from the gain-controlled RF input signals to the ADC data storage, from the offset removal to the exposure of processing parameters through the control system interface.

The available software and firmware infrastructures provide an already working template, with the possibility to extend its functionalities in a time-efficient manner, focusing only on its core part: the signal processing algorithms. The instruments are network-attached devices, offering several standard interfaces that facilitate integration into the control system (EPICS, Tango, TCP-IP socket, etc.). The Standard Graphical User interface is provided with the instruments.

Libera Digit 125

The Libera Digit 125 is a 4-channel digitizer with dual 14-bit ADCs and a sampling frequency of 125 MHz. The data is stored in a configurable buffer with a maximum of 8 M data samples stored per channel.

Figure 13: Libera Digit 125

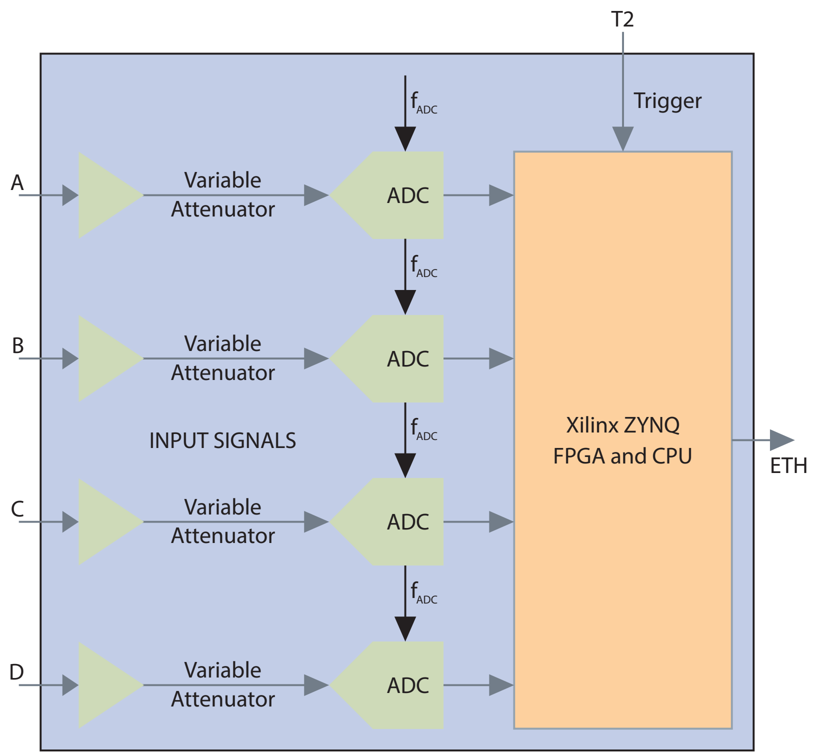
AC and DC coupled versions

The DC-coupled version has a front end with a 40 MHz bandwidth, suitable for time-domain processing of signals coming from different types of sensors. The AC-coupled front end has a bandwidth ranging from 10 MHz to 700 MHz and is suitable for narrow-band signals and digital down-conversion applications.

Flexible data buffering

A single trigger input is used to trigger the data acquisition in a large ADC buffer with total size of 8 MS per channel. The data buffer size can be reduced in order to support higher acquisition trigger frequencies.

Figure 14: Block diagram of Libera Digit 125



Technical Specifications of Libera Digit 125	
General product code	L125
Input channels and connector	4, SMA connector
ADC conversion	125 MSps, 14 bit
Input signal bandwidth	AC-coupled: 10 MHz – 700 MHz DC-coupled: 40 MHz
Input impendance	AC-coupled: 50 Ω DC-coupled: selectable 50 Ω / 1 MΩ
Maximum input signal level	AC-coupled: ± 1 V @ 50 Ω DC-coupled: ± 5 V @ 50 Ω 1.25 V @ 1 MΩ
Input gain / attenuation	SW programmable 0-31 dB channel independent
Trigger signal level and connector	3.3 V TTL, LEMO connector
FPGA / CPU	Zynq-7020 / ARM Cortex-A9
Booting	Micro-SD, TFTP server
Power	PoE
Cooling	Passive

Table 9: Technical specifications of Libera Digit 125

Libera Digit 500

The Libera Digit 500 is a 4-channel digitizer with dual 14-bit ADCs and a sampling frequency of 500 MHz, phase locked to an external reference signal. The data is stored in a 4 GB configurable, segmented buffer, with different acquisition modes and trigger rates up to 1 kHz.

Figure 15: Libera Digit 500

Digitizer with Phase-locked sampling frequency

Each of the four inputs is adjusted in amplitude with a 31 dB software-controlled variable attenuator and later sampled by the ADC converter with sampling controlled by an external reference signal locked through a phase locked-loop (PLL). The dynamic range of the system is over 90 dB.

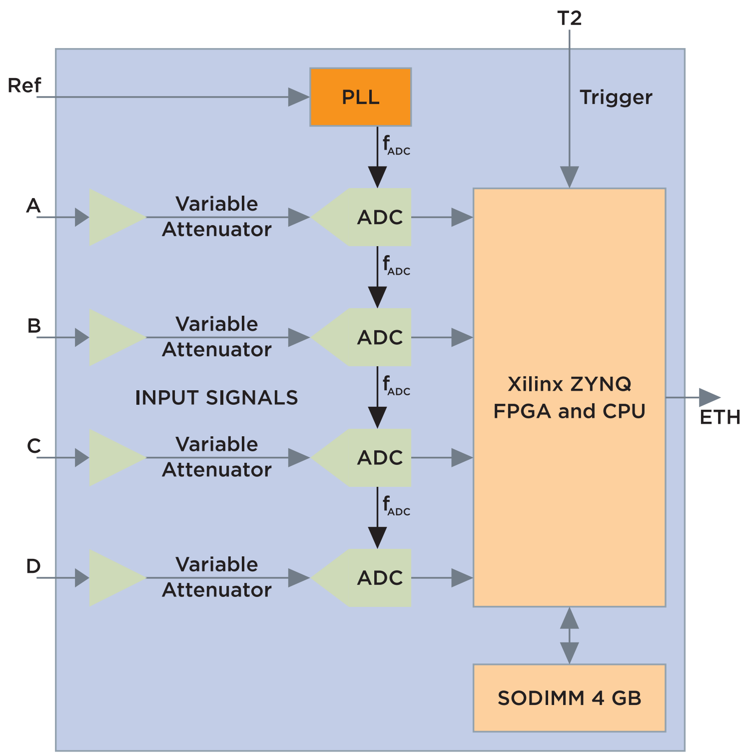
AC and DC coupled versions

The DC-coupled version has a front end with 250 MHz bandwidth, suitable for time-domain processing of signals coming from different types of sensors. The AC-coupled front end has a bandwidth ranging from 1 MHz to 2 GHz and is suitable for narrow-band signals and digital down-conversion applications. The front end can also be customized to include different types of analog filtering.

Digital offset removal and flexible data buffering

The ADC data offset can be removed in the FPGA before the data is stored. One trigger input is used to trigger the data acquisition in a large ADC buffer with a total size of 4 GB. The buffer can be segmented in chunks of a minimum of 32,768 samples and can be acquired in different modes.trigger frequencies.

Figure 16: Block diagram of Libera Digit 500



TECHNICAL SPECIFICATIONS OF LIBERA DIGIT 500	
General product code	L500
Input channels and connector	4, SMA connector
ADC conversion	500 MSps, 14 bit
Input signal bandwidth	AC-coupled: 1 MHz – 2 GHz
Input impendance	50 Ω
Maximum input signal level	DC-coupled / AC-coupled: ± 1 V / 10 dBm
Input gain / attenuation	SW programmable 0-31 dB channel independent
Dynamic range	90 dB
Reference signal level and connector	- 2 dBm – 4 dBm, SMA
Trigger signal level and connector	3.3 V TTL, LEMO connector
Sampling clock	Locked to external reference via PLL (300 MHz – 500 MHz)
Memory	4 GB RAM / 1.07 seconds of data per input chanel
Memory organization	Segmented buffer / min. chunk size 32768 samples per channel
FPGA / CPU	Zynq-7035 / ARM Cortex-A9
Booting	Micro-SD, TFTP server
Power	Normal power supply, PoE++
Cooling	Passive

Table 10: Technical specifications of Libera Digit 500

CURRENT METER

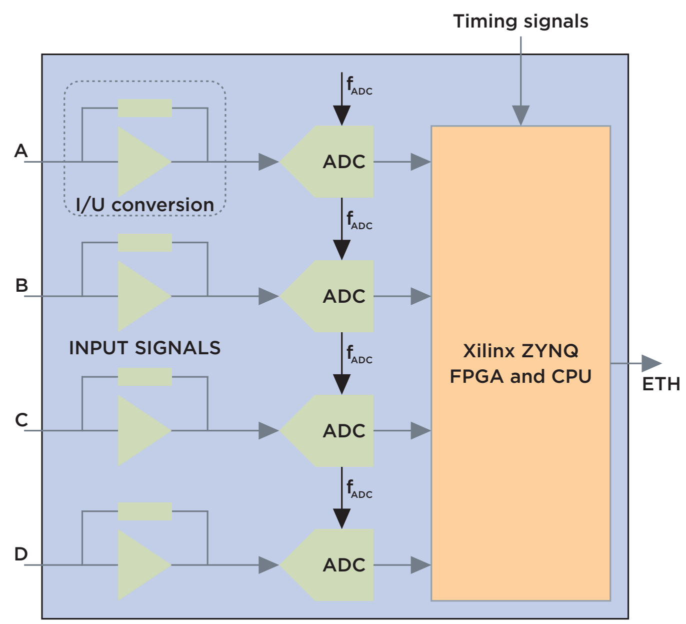
The Libera Current Meter is a general purpose current measuring device with 4 input channels, compatible with all current sources and capable of measurements from ± 60 nA to ± 2 mA. The instrument features six current ranges that can be switched manually or automatically, and each channel is factory-calibrated against a known current source.

The Libera Current Meter is typically used to measure currents from Faraday cups, wire scanners and grids, and loss detectors with current outputs.

Interfaces & Signal Processing

Figure 17: Libera Current Meter

Figure 18: Block diagram of Libera Current Meter



Input currents are converted into voltage via a trans-impedance amplifier, with six different gains depending on the current range selected via software. The signals are then digitized using 18-bit and 2.5 MSPS A/D converters. Offsets and gain errors can be calibrated for each channel using a nominal current source.

A trigger input is used to trigger fast data acquisition in a large buffer with a total size of 1 million samples per channel. The data buffer size can be reduced in order to support higher acquisition trigger frequencies. The fast data is averaged and filtered down to a slow data stream. The slow data is available continuously and is intended for monitoring DC currents.

Libera Current Meter capabilities	 Libera Current Meter
General product code	LCME
Input channels	4
Input frequency range	< 80 kHz
A/D conversion	2.5 MHz / 18 bit
Cooling	Passive
Power supply	PoE
Timing signals	Electrical (3)
Calibration	Manual (factory calibrated)
Maximum input signal	< 2 mA
Current ranges	±60 nA, ±0.2μA, ±2μA, ±20μA, ±200μA, ±2mA
Temperature drift, typical	< 1% / °C
8-hour stability (1 °C) (23°C, 1 μA)	30 nA peak-to-peak
RMS uncertainty @ 1 μA (slow 10 Hz data)	< 50 pA

Table 11: Current Meter capabilities

Libera Current Meter functionalities	 Libera Current Meter
Short pulse detection	Used for pulsed currents with signal dynamics within the measurement bandwidth (< 80 kHz).
DC current monitoring	Typically used for monitoring the DC currents from various current-type sensors.
Automatic range control	Measurement range can be adjusted to input current automatically to provide most optimum performance.
User recalibration	Recalibration is possible through software interface to maintain best accuracy.

Table 12: Current Meter functionalities

DIGITAL LLRF

The Libera LLRF is a digital processing and feedback system that 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

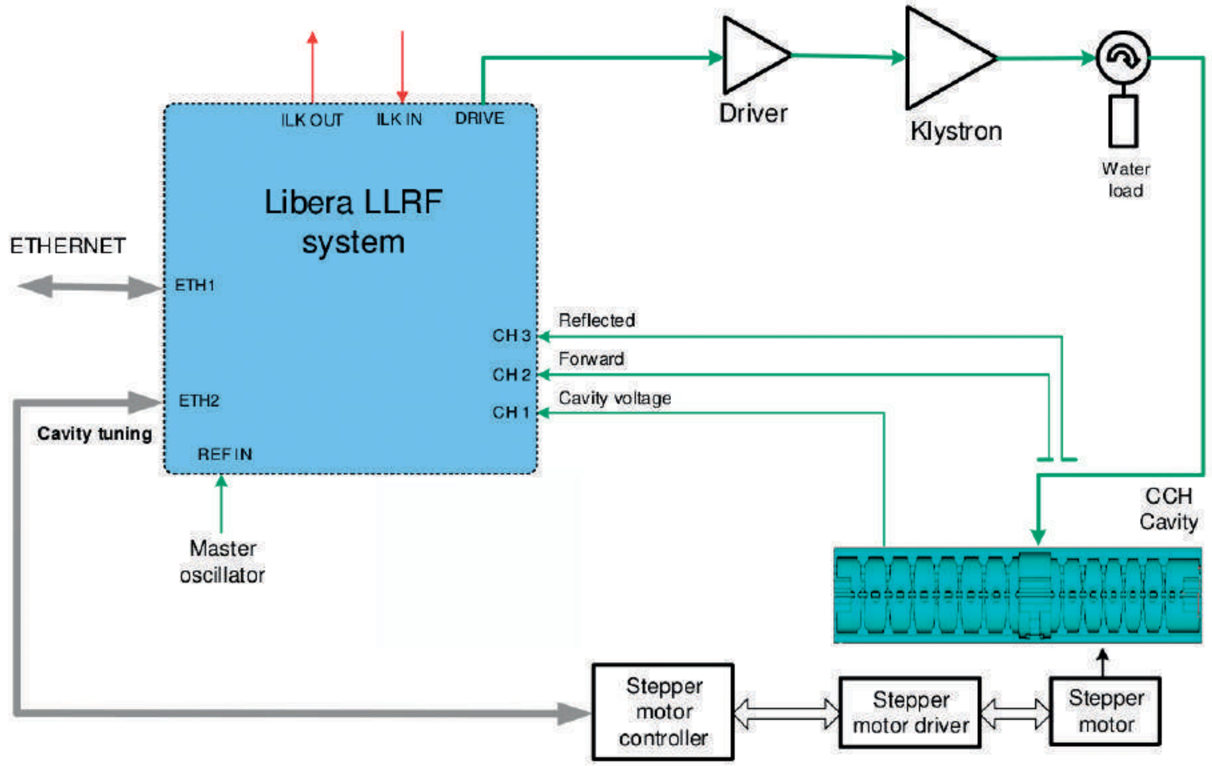
By monitoring the forward and reflected signals from the RF cavities, the system can be interfaced to control slow and fast tuners (e.g., stepper motors and piezo controllers) which modify the cavity mechanical properties.

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 19 presents a possible configuration of Libera LLRF in the accelerator environment:

Figure 19: Possible configuration of Libera LLRF in the accelerator environment



Interfaces & Signal Processing

The Libera LLRF system is based on the MCTA.0 standard with several AMC boards connected to the chassis front panel (Figure 20).

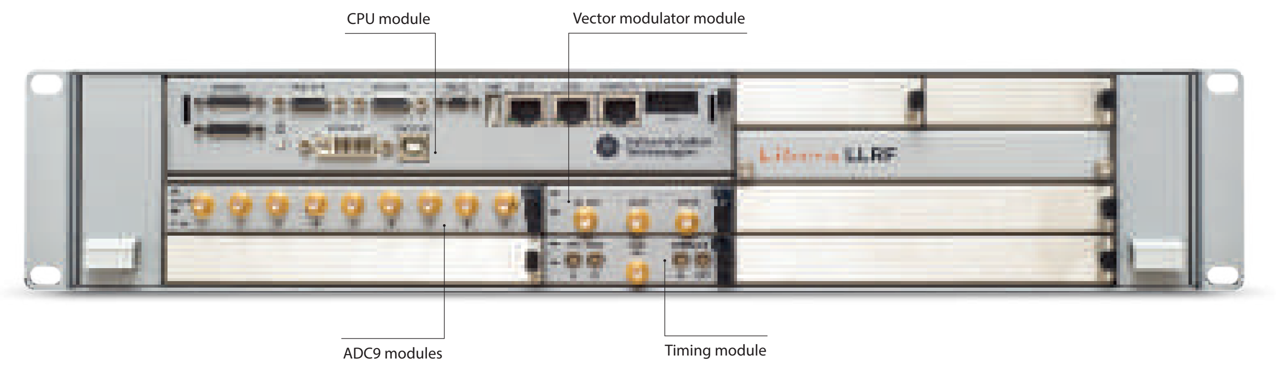
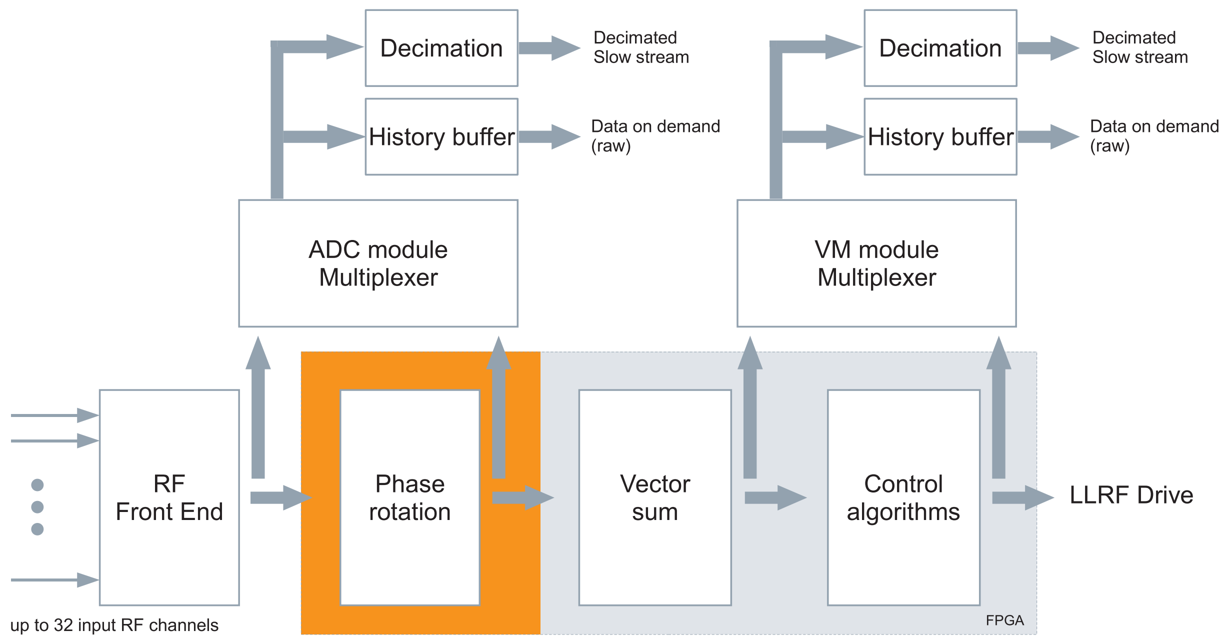


Figure 20: Libera LLRF

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 less 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 130 MS/16 bit A/D converters: this data is stored in the device memory and is available to the user. The digitized signals are later transferred to the Vector Modulator board, where the feedback logic is actually implemented (Figure 21).

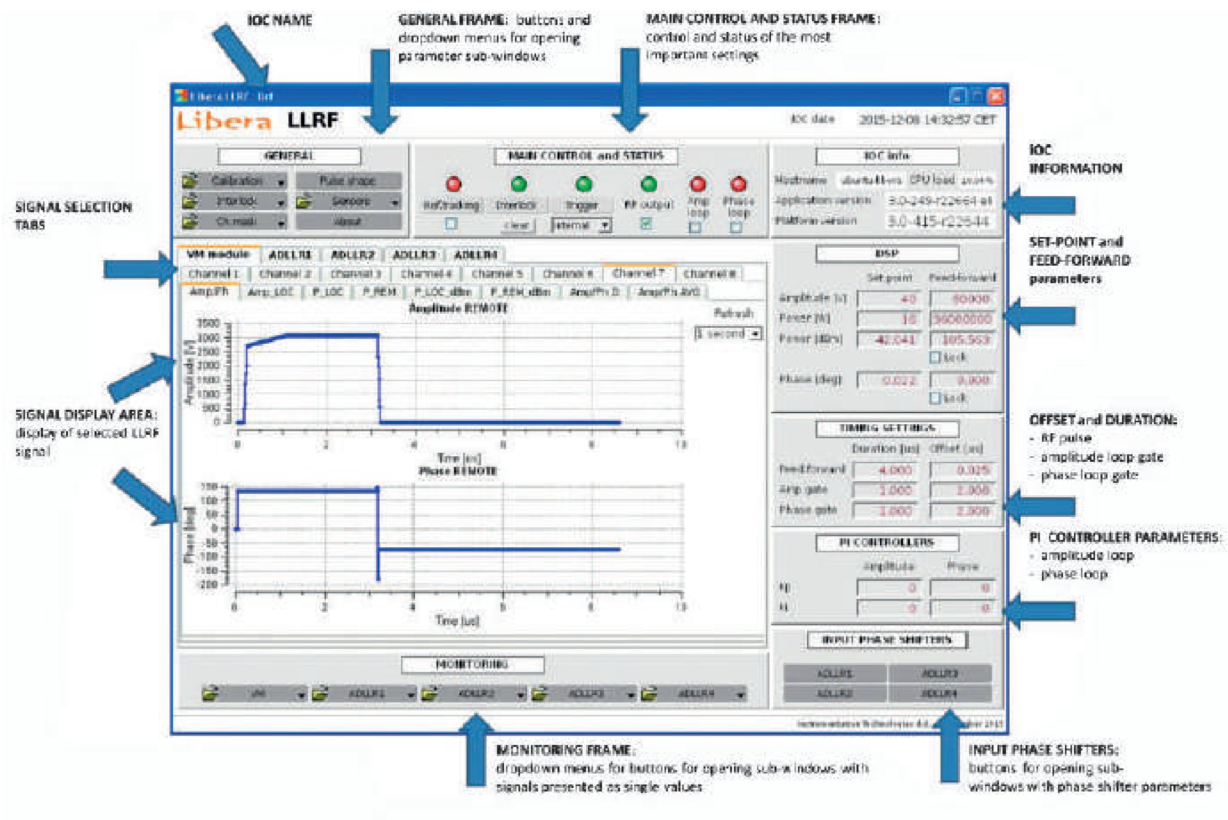
Figure 21: Signal processing in the Libera LLRF system



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 don't 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 22.

Figure 22: Graphical User Interface (GUI) for the Libera LLRF



Capabilities & Functionalities

The capabilities of the Libera LLRF system are summarized in Table 13.

	Libera LLRF
General product code	LLRF
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
RF output channels	2 (1 RF drive, 1 calibration output)
Maximum RF output power	> 10 dBm
Cooling	Active
Power supply	110/220 V

Table 13: Capabilities of the Libera LLRF system

The functionalities of the Libera LLRF system are summarized in Table 14.

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 23) • Calibration output usable for RF cables and RF front-end electronics calibration

Table 14: Functionalities of the Libera LLRF system

Performance Specifications

The main performance specifications of the Libera LLRF system are summarized in Table 15. The results were obtained at the DESY FLASH and Daresbury Laboratory EMMA at a 1 MHz BW pulsed mode of operation.

	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

Table 15: Performance specifications of the Libera LLRF system

Figure 23: Libera LLRF temperature stabilized RF front-end

Interface Extension

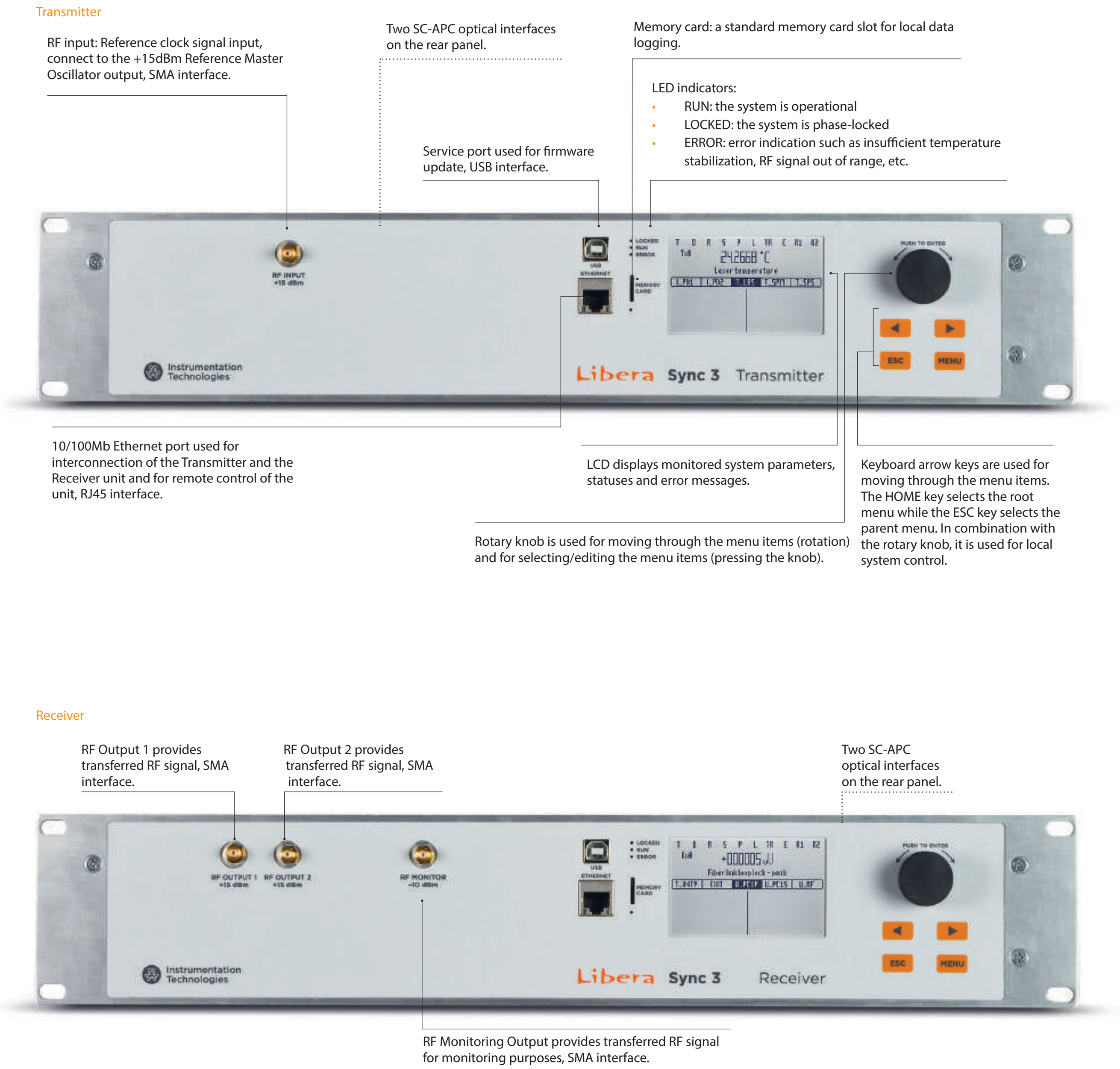
Libera LLRF interfaces can be upgraded through software modules or physical interface upgrade modules:

- A secondary Ethernet port can be used for data streaming through protocols like UDP or similar in order to transfer LLRF data to remote servers.
- A USB port can be used to interface LLRF to cavity tuning systems.

CLOCK TRANSFER SYSTEM

Libera Sync 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 24).

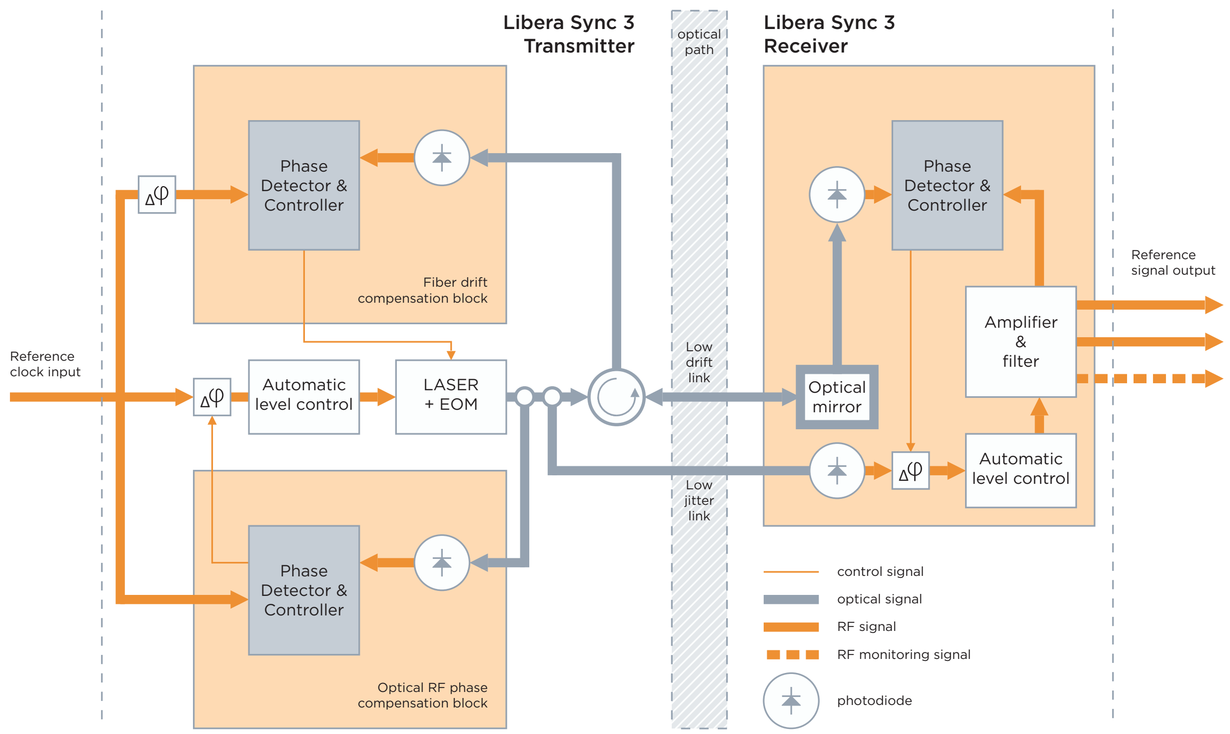
Figure 24: Clock transfer system (Libera Sync 3)



The transmitter input signal is a continuous wave RF reference signal that 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 is 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 25: 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 16.

	Libera Sync 3
General product code	LSYN
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 %

Table 16: Performance specifications of the Libera LLRF system

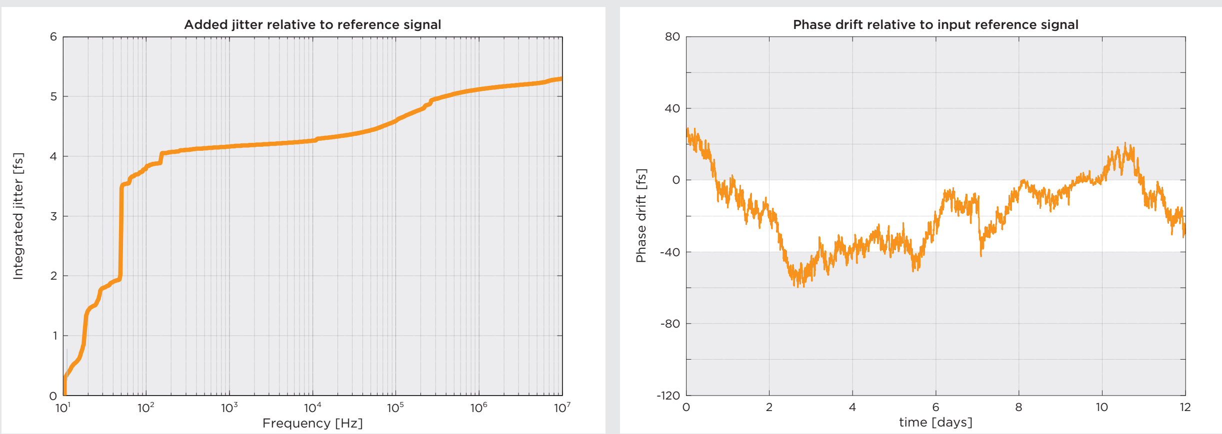
Performance Specifications

The performance specifications of the clock transfer system are summarized in Table 17, while Figure 26 presents the added jitter measurement and long-term stability for the Libera Sync 3.

	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.

Table 17: Performance specifications of the clock transfer system

Figure 26: Added jitter and long-term phase stability measured with Libera Sync 3

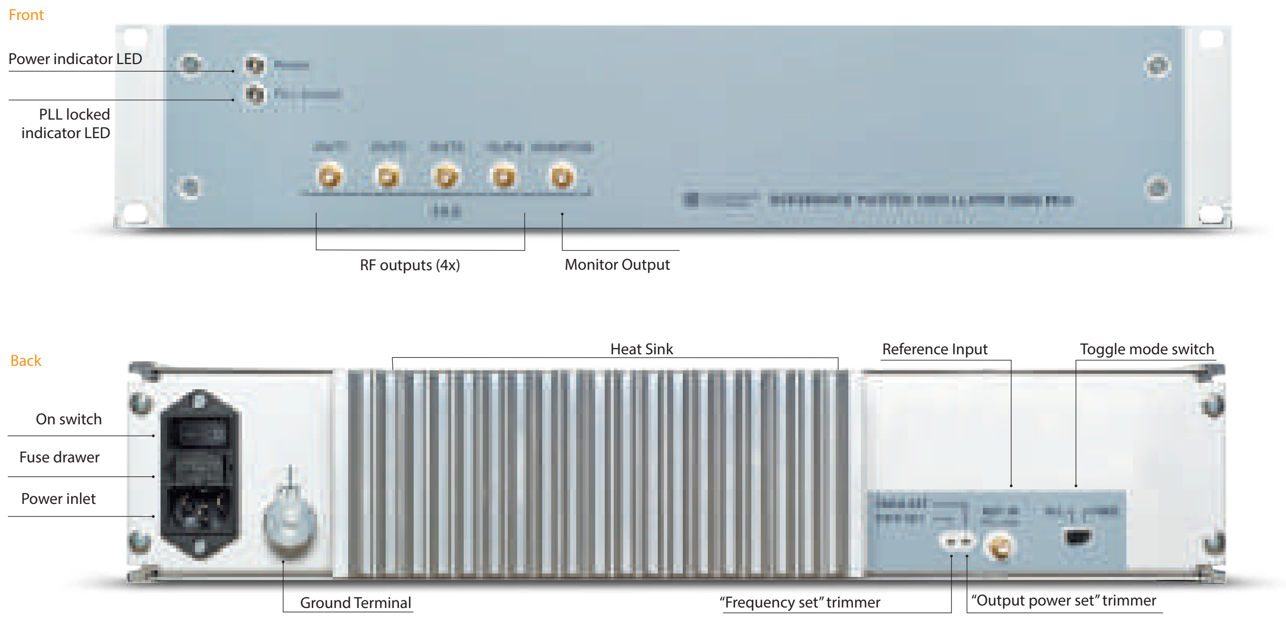


REFERENCE MASTER OSCILLATOR

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 to 40 °C) combined with extremely low phase noise, below 30 fs in a range between 10 Hz and 10 MHz. The front and back panels of the instrument are shown in Figure 27.

Figure 27: Reference Master Oscillator, front & back panel

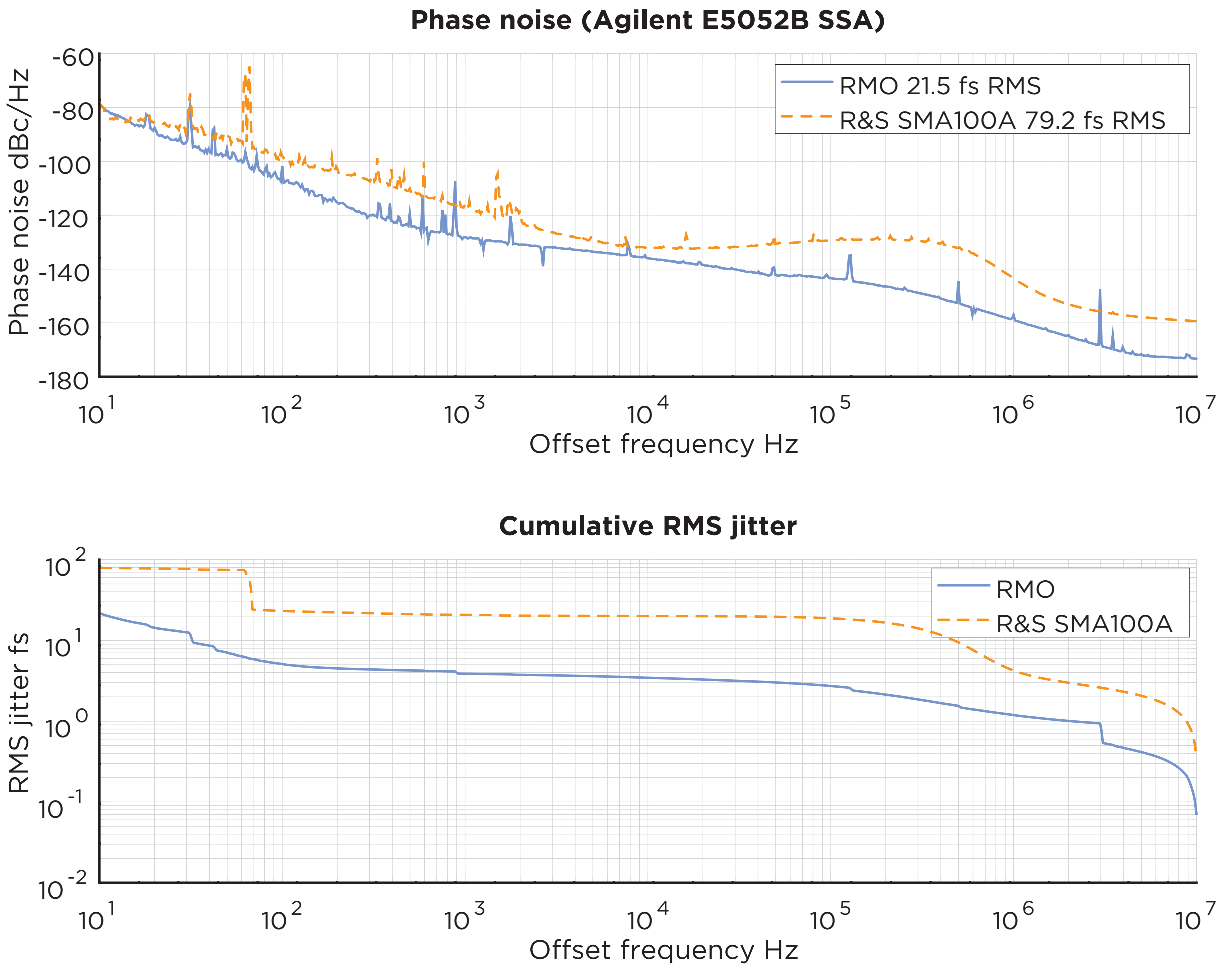


The RF specifications of the Reference Master Oscillator are presented in Table 18.

	Reference Master Oscillator - RMO
General product code	LRMO
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)	< 0.1 deg/°C
Harmonic suppression	< 55 dBc up to 5th harmonic
PLL lock time	< 60 s

Table 18: RF specifications

Figure 28: 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 29).

Figure 29: RMO distribution amplifier, front panel

The RMO distribution amplifier can be customized in terms of number of RF outputs. The frequency of the outputs can be divided from the provided input frequency for applications where coherent subharmonics are required.

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, for example, the Libera Hadron.

Figure 30: Amplifier 110

The main features of the Amplifier 110 are shown in Table 19.

	Amplifier 110
General product code	LAMP
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

Table 19: Amplifier 110 specifications

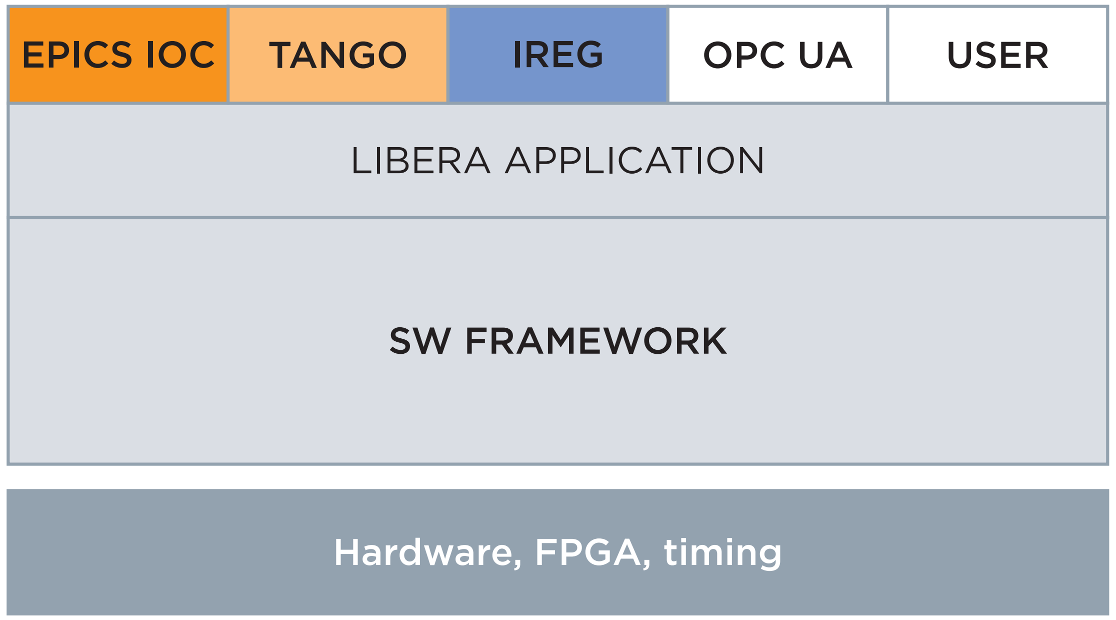
CONTROL SYSTEM INTEGRATION

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 31 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 31: Software and Firmware layers within Libera instruments

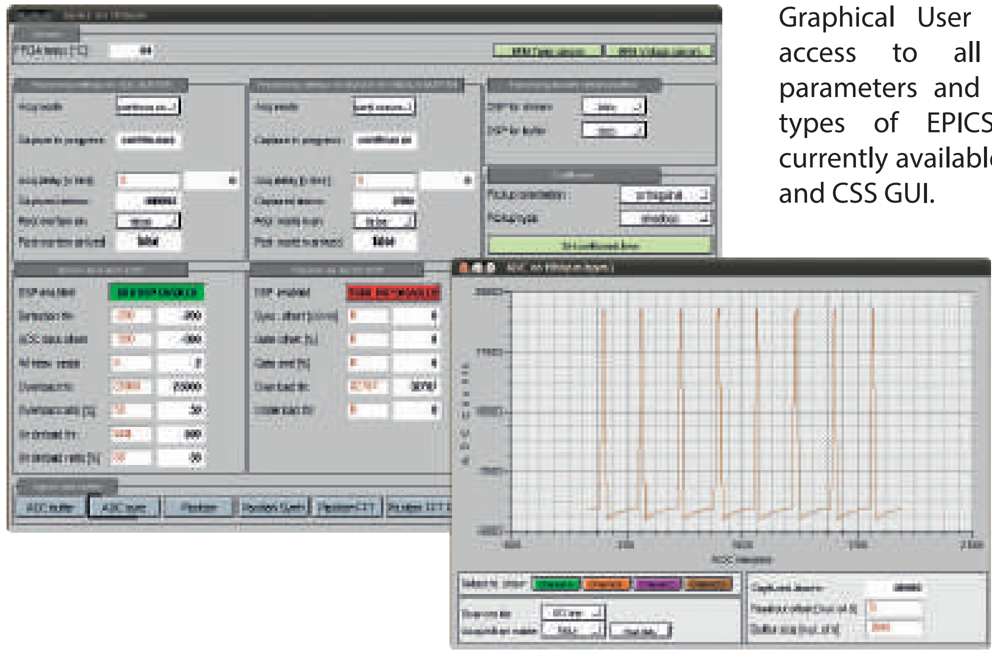


All the common control system interfaces are supported!

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.

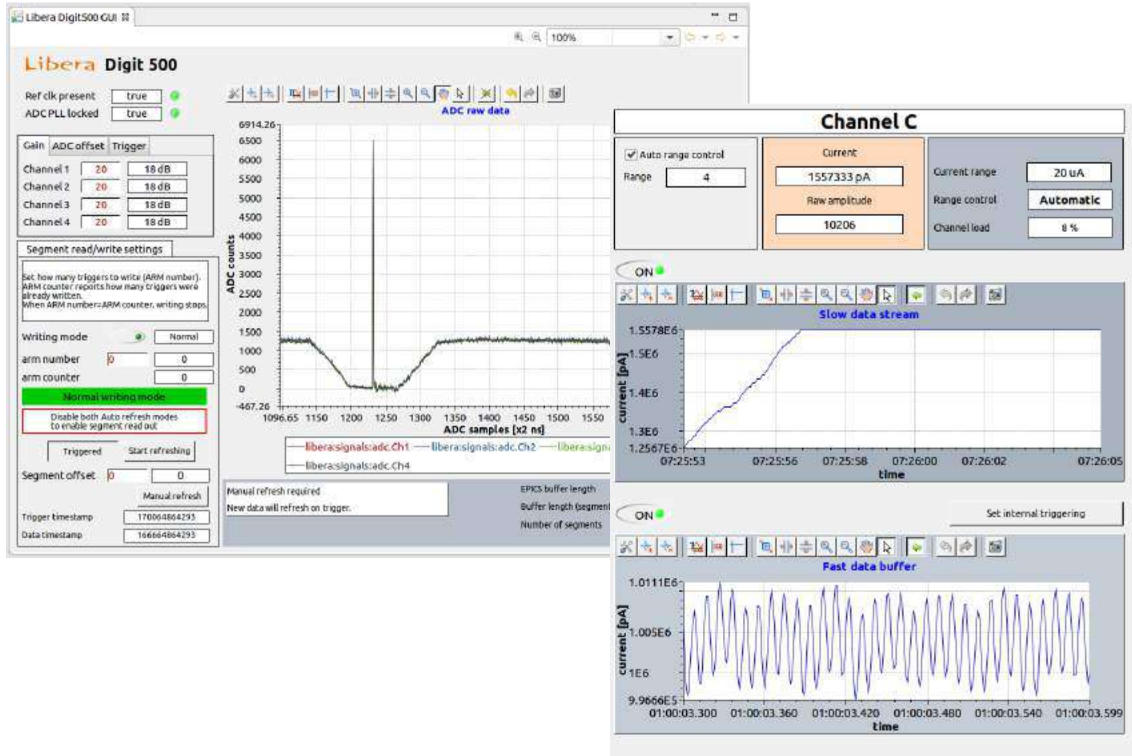
GUI - GRAPHICAL USER INTERFACE

Figure 32: Example of EDM-based GUI



Graphical User Interfaces provide access to all the instrument parameters and signal data. Three types of EPICS-based GUIs are currently available: EDM GUI, Qt GUI, and CSS GUI.

Figure 33: Example of CSS-based GUI



EXTENSIONS

Libera instruments can be integrated with other accelerators' subsystems by extending their functionalities using specific modules and custom-developed applications (Table 20).

Extension	Description / example	Works with
Fast Orbit feedback solution	• Complete solution for electron machines that use Libera Brilliance+ instruments (Figure 35).	• 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 35).	• 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 36).	• 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.

Table 20: Extension options for Libera instruments

DAI Module

The DAI module extends the inter connection capabilities of Libera Platform C instruments as shown in Table 21 (Libera Spark, Libera Photon, Libera Digit).

Figure 34: 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)	up to 20 Mbps, half-duplex

Table 21: Technical specifications of the 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 35.

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 the 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 36.

Figure 35: Complete orbit feedback solution for electron/hadron machines

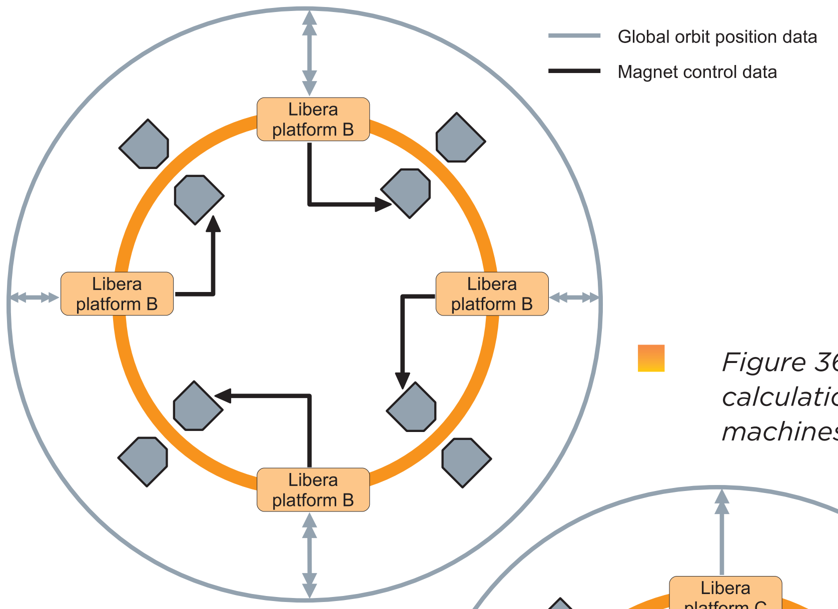
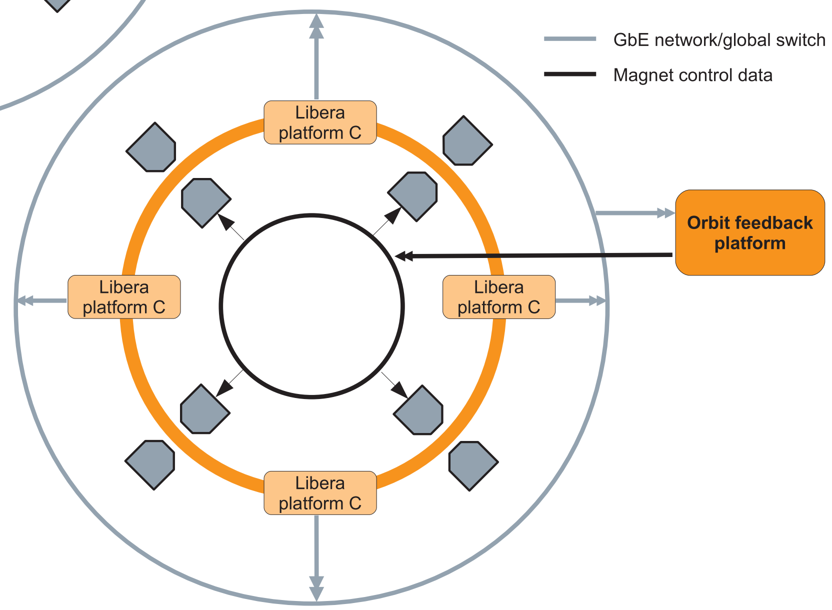


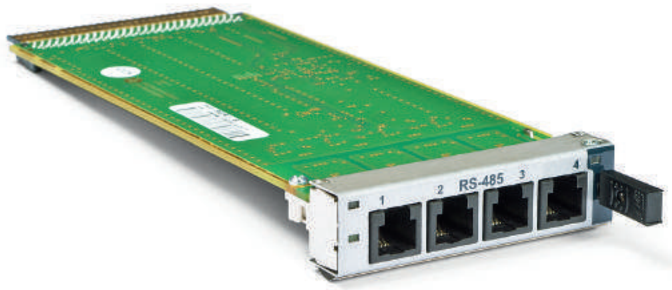
Figure 36: Standalone orbit feedback calculation engine for electron/hadron machines



SER Module

The SER module features four RS-485 interfaces directly controlled from the GDX module. The protocol and the baud rate are specified by the application in the GDX module (Table 22).

Figure 37: 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

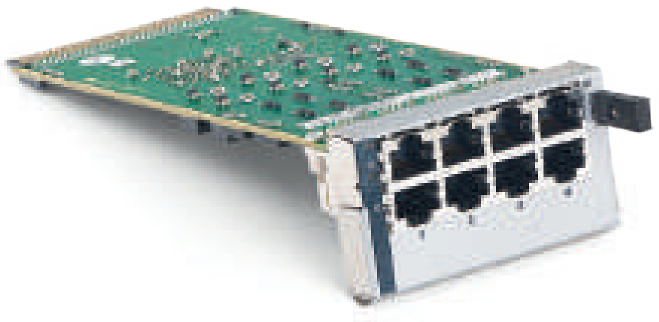
* Specified by application in the GDX module

Table 22: Capabilities of SER module

SER II Module

The SER II module features eight RS-485 interfaces directly controlled via the PCI express links (Table 23).

Figure 38: SER Module II



	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

Table 23: Capabilities of SER II module

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 24).

	GDX module
FPGA chip	XC6VLX24OT-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	

Table 24: Capabilities of GDX module

Figure 39: GDX module

DWC Module

The DWC-SP circuit is a four-port RF downconverter that can be used to down-convert the RF input signals from S-band to an intermediate frequency (Table 25).

Figure 40: 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	Max 15 dBm	Max 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

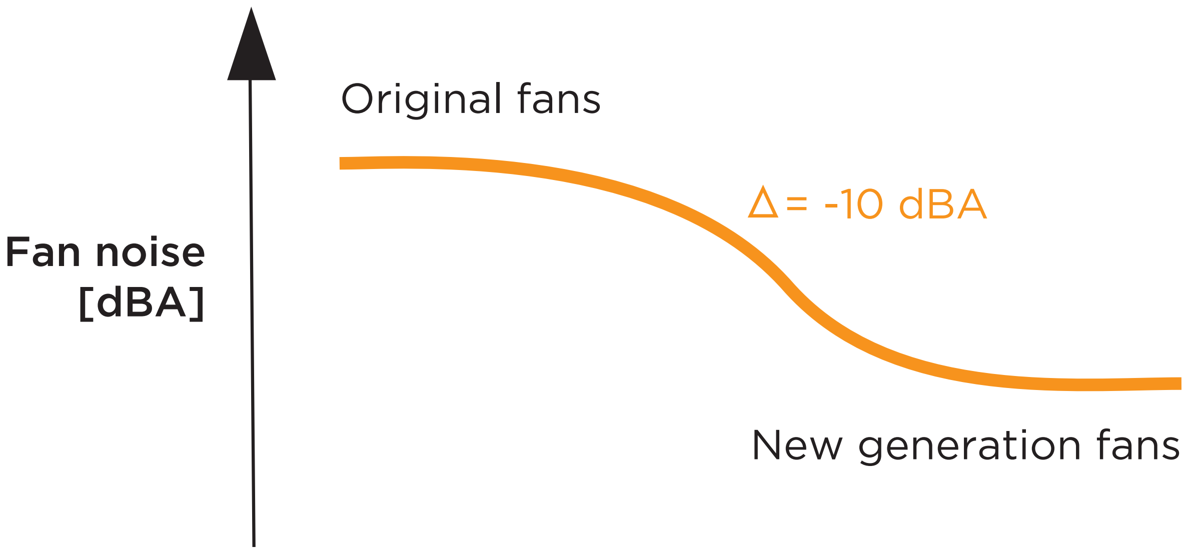
Table 25: Technical specifications of the DWC module

LIBERA UPGRADES

Fans

The initially delivered instruments (Libera Platform B) have been in use for over seven 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 41: Acoustic noise reduction with new generation fans



Inter Connection Board (ICB)

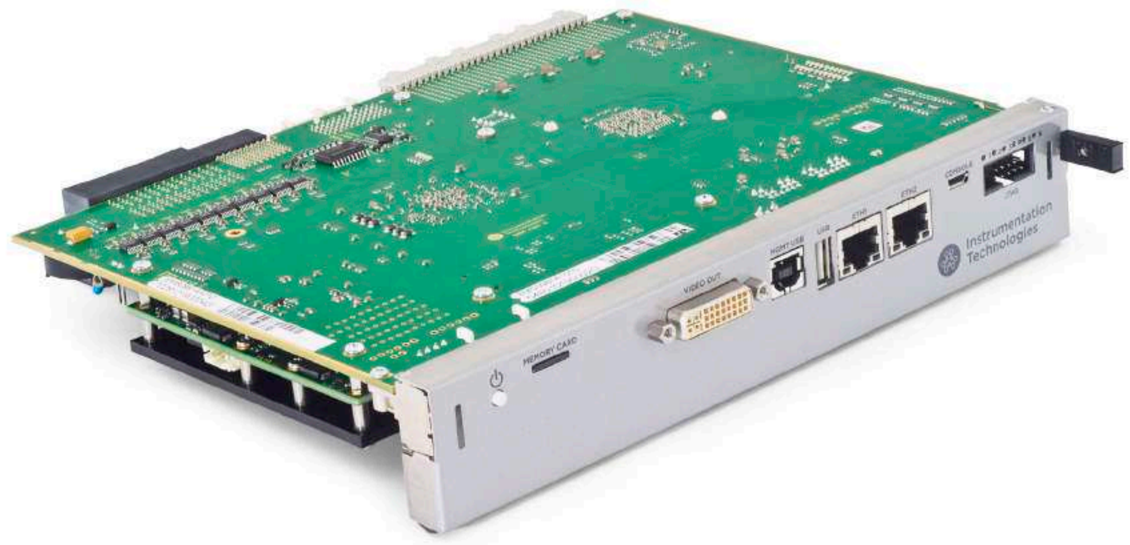
In line with user requirements, the processing capability of the Platform B instruments can be upgraded with a new Inter Connection Board (ICB).

Compared to the existing version, it features a newer generation Intel CPU, and support for a newer Operating System. Hardware interfaces were refreshed and adapted to user needs.

Item	Specification 2019-	Specification 2016-2019
CPU	Intel Core i5-3230M 2.6/3.2 GHz Dual Core	Intel Core i5-3230M 2.6/3.2 GHz Dual Core
	Kaby Lake H chipset	
	PCI Express revision 3.0	PCI Express revision 3.0
	Max memory 64 GB, DDR4-2400	Max memory 32 GB, DDR3-1333/1600
Interfaces	2x Gigabit Ethernet	2x Gigabit Ethernet
	USB console	Mini RS-232 console
	VGA/DVI	VGA/DVI
	USB	USB
		2x PCIe, 2x LXI, MGMT ETH
Storage	MicroSD for operating system and software	USB FLASH for operating system and software
Operating system	Ubuntu 18.04 or Centos	Ubuntu 14.04

Table 26: CPU module specification.

Figure 42: Inter Connection Board version 2019



SERVICES & SUPPORT

Libera

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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