Em# ELECTROMETER COMES TO LIGHT

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Abstract

Em# project is a collaboration project between MAX IV Laboratory and ALBA Synchrotron to obtain a high performant four-channel electrometer. Besides the objective of accurate current measurements down to the pico-ampere range, the project pursues to establish a reusable instrumentation platform with time stamped data collection able to perform real time calculations for flexible feedback implementations.

The platform is based on a FPGA responsible of acquisition and synchronization where a real-time protocol between the modules has been implemented (Harmony) [1]. The data acquired is transmitted via PCIe to a Single Board Computer with an embedded Linux distribution where high level processing and synchronization with upper levels of Control System is executed.

In this proceeding, the reasons that lead to start a complex instrument development instead of using a Commercial On the Shelf (COTS) solution will be discussed. The results of the produced units will be analysed in terms of accuracy and processing capabilities. Finally, different Em# applications in particle accelerators will be described, further widening the functionality of the current state-of-the-art instrumentation.

INTRODUCTION

Instrumentation development for low current measurements is one of the key activities in the Computing Division of ALBA Synchrotron. Em# project is the evolution of previous project ALBA Em, which established a knowledge background important to fulfil new equipment requirements.

Background – ALBA Em

In 2011 ALBA Em was developed, a four channel electrometer that allowed low current measurements for X-Ray beam diagnostics or experiment applications since the first day of operation at ALBA Synchrotron [2]. More than 40 units have been used with good acceptance from scientific users.

ALBA Em was composed of four units of in-house developed ALBA Current Amplifier and one commercial Rabbit RCM4200 micro-controller core. This microcontroller core has a custom interface connector that, when connected to a custom designed board is able to control the four current amplifiers. The firmware code running in the microcontroller core was developed using proprietary IDE.

The good performance in current measurement led to continued use of ALBA Em as a standard electrometer for new beamlines in the following construction phases of ALBA Synchrotron. Unfortunately the production of new units was not possible since the microcontroller core was declared obsolete on 2013. This impediment together with the new functionality needs in experimental end stations forced an equipment redesign in 2013.

New requirements for upcoming development project were stated following scientific user needs. The most important requirement was to increase the ADC resolution, as the embedded ADS7870 ADC in the microcontroller core was just 11 bits in single-ended configuration. Another limiting parameter to be improved was the sampling rate of the same ADC which was limited to 1 kS/s. The possibility to isolate the detector ground of equipment from the facility ground in order to avoid ground loops and reduce induced current due to electromagnetic noise was another must for the new development. Yet another new requirement, also related to the ground loop break, was the possibility to make current measurements with detector's ground voltage-biased respect to equipment and facility ground, in order to avoid the loss of generated charges in the detector by applying an electric field to it.

The Em# (Fig. 1) development has been framed in a collaboration agreement between MAX IV Laboratory and ALBA Synchrotron. The collaboration is not closed to other institutes and facilities, although the project is already at the production phase and the pending development tasks are related to gateware and software.
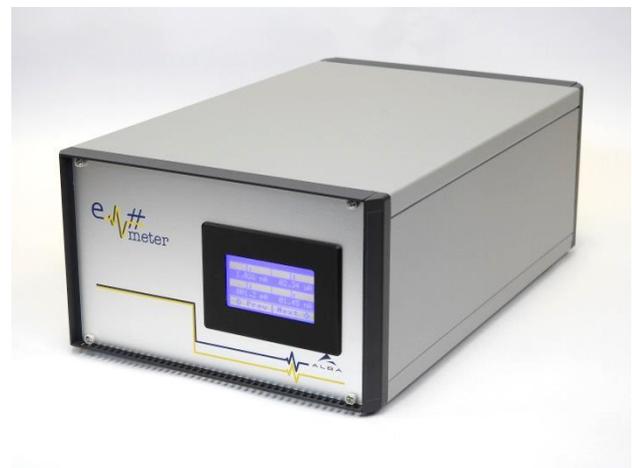
Figure 1: Em# first production unit.
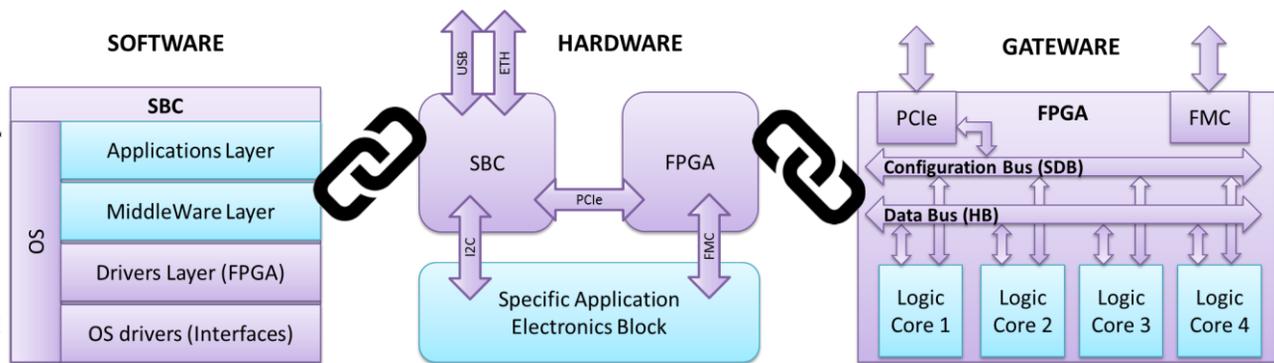
Figure 2: Instrumentation platform block diagram.

INSTRUMENT DEVELOPMENT VS COMMERCIAL SOLUTION

When the ALBA Em microcontroller core was found obsolete and new requirements from the users emerged, the discussion about how to cover current measurement instrumentation needs was open. In this chapter the reasons that lead to start an instrumentation development project instead of acquiring COTS instrumentation will be exposed.

The first important reason to develop a new electrometer was the possibility to reuse the in-house developed ALBA Current Amplifier, which has a performance comparable to other well-known commercial current amplifiers [3]. Moreover, there is also an advantage to have knowledge of the equipment core as the current measurement elements: it is an added value in case of instrumentation support to the users. This knowledge advantage is not only limited to the sensing element as it concerns the whole equipment.

The ALBA Current Amplifier was foreseen to be the only element reused from previous electrometer. The control part of the equipment had to be designed from scratch, but it was also a good opportunity to design an instrumentation platform (involving hardware, gateware and software) that could be reused for future instrument developments. The decision to develop this instrumentation platform (onto the Em# is built on) allows a complete knowledge of acquisition system configuration and control, which is an important aspect in this kind of instrumentation.

The last, but not least, advantage of the instrument development is the unit cost. Based on ALBA Em experience, the unit cost of a commercial electrometer with the same characteristics is four times higher.

All these reasons, together with the spirit of learning, led ALBA to start the Em# project.

INSTRUMENTATION PLATFORM

One of the reasons to develop Em# was to take advantage of this new design to establish an instrumentation platform that will be reusable for future equipment developments. This platform is composed by hardware, software and gateware (Fig. 2), where all the parts that would be reused for future developments correspond to violet blocks.

From the hardware point of view the platform is composed by a Single Board Computer (SBC), a FPGA module and a Specific Application Electronics Block (SAEB). The SBC is a tiny cost-effective but powerful enough computer to allocate a layer-based control system, where high-level control of the equipment is performed. The FPGA module performs the low-level control of the SAEB and allocates time-resolved functionalities like data acquisition and processing. The SAEB is the hardware that provides the equipment with its specific application, being the current sensing in the Em#. Selected interfaces used to communicate between modules are standard ones.

The control system of the platform embedded in the SBC is based on a custom light Linux distribution where only necessary parts of the Operating System are compiled. Generic control system layers are the Linux driver layer (related to selected communication interfaces) and the driver layer (related to communication and configuration of FPGA logic cores). Higher software layers (Middleware and Applications) define the specific application of the equipment.

The instrumentation platform gateware is based in a dual bus strategy. A configuration bus is used to setup FPGA logic cores from the SBC while a data bus is used for fast transfer between cores. The usage of logic cores is related to the specific application of the equipment, like those used to control the SAEB, the acquisition engine or a determined data processing.

In the case of developing new instrumentation equipment, only blue blocks from Figure 2 will be changed, summarized in: hardware SAEB, software middleware and application layers and FPGA logic cores. This reusable design strategy is intended to reduce the development stage for future projects, at the expense of extending the Em# design period. The design of this instrumentation platform has been done during the Em# design, as explained in the following chapters.

Em# HARDWARE ARCHITECTURE

The selection of industry standard interfaces to be used between the different modules composing the new equipment was the first step in the hardware design, while

the selection of components to fulfil these interfaces requirements was done in a later stage [3]. The main advantage of this philosophy is that an obsolete unit could be easier to be replaced in the future as standard interfaces division produce independent blocks identification and, ideally, only one of them should be redesigned.

The hardware architecture diagram (Fig. 3) is composed by 3 blocks connected between them by the following standard communication interfaces:

1. Ethernet
2. Universal Serial Bus (USB)
3. Peripheral Component Interconnect Express (PCIe)
4. FPGA Mezzanine Card (FMC)
5. Inter-Integrated Circuit (I^{2}C)
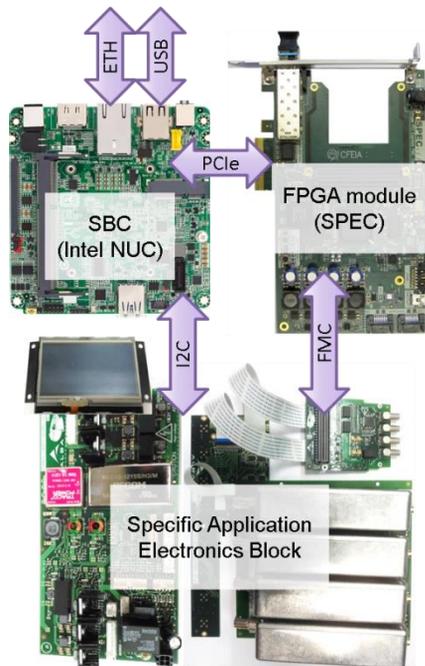
Figure 3: Em# hardware architecture.

Single Board Computer (SBC)

The selected SBC is an Intel NUC DE3815TYBE with a 100 mm x 100 mm small form factor. This commercial module includes an Intel Atom with x86-64 architecture, with a 4GB DDR3L memory and a 4GB eMMC, where the software and firmware are stored. Standard interfaces included in this module are PCIe, I^{2}C, Ethernet and USB. The PCIe interface is used to communicate with the FPGA module while the I^{2}C standard is interfacing the SAEB. The Ethernet interface is used for external communication with the facility Control System enabling the remote control of the equipment. The USB interface is used for Software, Firmware and BIOS update using an USB pen drive.

FPGA Core

Simple PCIe FMC Carrier (SPEC) is the selected FPGA module for Em#. This board was developed by CERN and is available under Open Hardware License [4]. SPEC includes a Xilinix Spartan 6 XC6SLX100T FPGA which is used for the low level control of the Custom

Electronics block via FMC interface. SPEC board also includes PCIe interface used to communicate with SBC.

Specific Application Electronics Block

This block is composed by a series of custom or commercial electronics boards that make up the specific functionalities of the equipment.

Human-Machine Interface   Commercial module EA DIP128-6 touch-panel display is located on the front of the Em#. This HMI allows a user to both obtain information about the equipment state, the measured currents and configure basic parameters of the equipment. This HMI is controlled by the SBC via I^{2}C interface.

Current Amplifier   The first stage for the Em# current sensing is the current amplification, which is carried out by inherited ALBA Current Amplifier from ALBA Em. Basic features like transimpedance amplification (8 current measurement ranges from 100 pA to 1 mA) and filtering (second order low-pass filter with cutoff frequencies from 0.5 Hz to 3200 Hz) remain unchanged from previous project. New features are available in the ALBA Current Amplifier like a better thermal management and temperature sensing that allows the implementation of gain compensation vs the temperature.

Digitalization   The digitalization is performed by a FPGA Mezzanine Card (FMC) developed at ALBA under OHL license [5]. It is based on a four channel 400 kS/s 18 bits ADC capable to work with ground voltage bias. The ADC is placed in an isolated part sharing ground only with the current amplifiers and thus detectors. The analog signals are then digitalized in the isolated area and transferred to the FPGA via digital isolators. This strategy supposes an innovation as historically the isolation was done in the analog signal part with an isolation amplifier and digitalized at normal ground potential by a second stage. The isolation between analog and digital ground allows breaking ground loops during measurement decreasing the noise level, and minimizing the non-linearity errors as isolation amplifier stage is no longer needed.

Current Measurement with Voltage Bias   Thanks to the FMC ground isolation and a careful design of the whole equipment, there is the possibility to bias the analog ground of connected detector, current amplifier and ADC up to ±1 kV respect to the facility ground. The isolated ground bias is controlled by a specific FPGA core that controls its connection to the Em# High Voltage input depending on user configuration and allows implementing configurable safety limits for each application. As this feature is not mandatory for a big part of applications but has a considerable effect in the total cost of the equipment, there are two production versions of Em#, one with voltage bias capability (Em#_HV) (Fig 4) and one without it (Em#_LV), which has direct analog outputs from current amplifier.

Connectivity   The presence of the FPGA and the usage of the fast data bus allow real-time processing applications by adding specific logic cores. Application related FPGA cores will be developed as long as needs continues to rise from the scientific users. Feedback applications are

expected to be important in Em# project and for this reason a wide variety of I/O capabilities are present in this hardware architecture. In addition to the standard trigger input channel, the Em# offer four configurable I/O 100 MHz single-ended digital channels (that could also be used for independent channel triggers), nine configurable I/O channels with 20 MHz differential and single-ended signals, four switchable 5V and 500 mA power outputs and four analog DAC outputs of ±10 V 100 kS/s with 16 bits (Fig. 4).

Figure 4: Rear panel of Em#_HV.

Power Management   Em# Hardware architecture includes a power management strategy that senses the current consumption of the different equipment modules. A control script running in the SBC is in charge of evaluating those diagnostics and disabling power supply parts in case of excessive power consumption detection.

Em# CONTROL SYSTEM

The Em# software development [6] has been divided into three software projects, distributed in a single software package: Operating System, gateware and control software.

Operating System

The Em# features a complex embedded control software based on Linux OS. A light Embedded Linux has been customized specially for this equipment using Yocto [7], with only the necessary drivers to control the available hardware and with enough functionality to run the required applications. It also includes all functionalities to allow an easy equipment update using Ethernet network or USB.

Gateware

The gateware software runs in the SPEC FPGA. Written in VHDL, it has been designed focusing on fast acquisition and data sharing between the different modules inside the FPGA, as well as with the main software running in the SBC. The FPGA uses the Self Describing Bus (SDB) [8] framework that helps to self-detect and manage the FPGA contents. It describes a series of structures used to provide metadata of the FPGA logic blocks. That allows the main software to automatically discover and configure them at runtime via PCIe bus. The acquisition

is carried out using a fast data acquisition bus oriented to ease data sharing among the different FPGA cores. That fast data bus name is Harmony Bus (HB) [9]. FPGA cores are connected using Bridges that act as bus arbiters, broadcasting the data to other bridges to share it with the rest of FPGA cores. The data size sent in the HB is 64-bits, where 32-bits are data, 24-bits are used for timestamp (TS) and 8 for the data source identification (ID). The ID's can be assigned dynamically which allows a flexible configuration of the FPGA functionality. Developed Logic Cores in the FPGA are related to specific control of elements of the Custom Electronics block like the ADC, DAC, I/O interface, HV bias or SPI. Many others cores have been developed to implement the low-level functionalities of Data Acquisition, Trigger Management and Feedback.

Control Software

The SBC contains the main software. It has been designed to have high versatility in the application design and easy user control of the equipment. Versatility means that the software is easily adaptable to new functionalities or hardware changes with the only modification of high level software parameters. The layer-based architecture of the control software contains the physical device drivers of the hardware connected to the SBC (FPGA core, HMI, Custom Electronics), the algorithms, operations and applications to control the whole equipment by using a custom light Linux distribution. In conclusion it is a multi-purpose software customized to work as an electrometer. It offers easy user control, both from remote or local control interfaces. Remote control is available via telnet (using the SCPI protocol [10]), via ssh using the advanced control tools or via web using a webserver. The Em# runs a Tornado Web server [11] that establishes a channel of exclusive communication for each client which serves all web pages to monitor or diagnose the status of the electrometer, as well as configure the different parameters available (Fig. 5). Local control is available using navigation menus in the touch-screen display. The main software is written in Python to take profit from the clean and straightforward syntax, while still performing well, helping the easy integration of new functionalities.
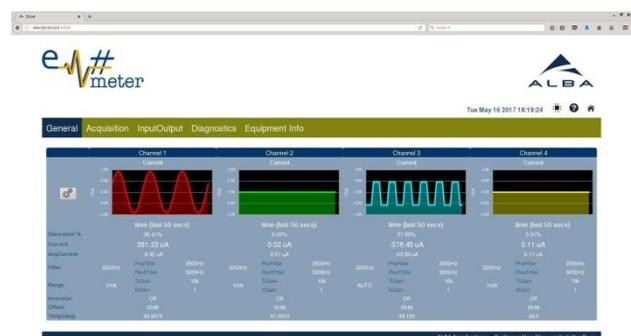
Figure 5: Em# web page.

Em# CALIBRATION

Together with the development of the electrometer different laboratory test benches for test and calibration have been designed.
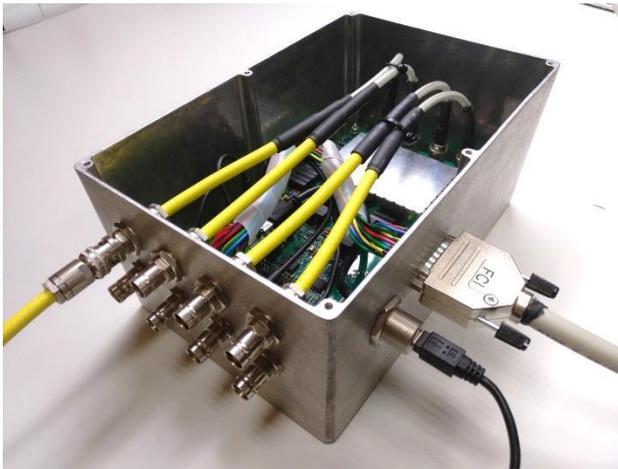
Figure 6: Em# calibrator.

The Calibrator (Fig. 6) is used to calibrate the gain of different ranges due to the high dependence on the gain resistors impedance. The high-value resistors used in transimpedance amplifier have tolerances around 10%, which affects directly the current amplification gain. The Calibrator allows to automatically correct each ALBA Current Amplifier gain and offset at software level increasing the instrument's precision. In addition the Calibrator allows a complete Em# functionality test to ease production testing.

The Calibrator generates a current for each range by the usage of a very precise voltage source and an array of resistors. The voltage source can be either the same Em# DAC output or a calibrated internal voltage reference based on Linear LTZ1000, which thermal drift is only 0.05 ppm/ºC. This setup allows calibrating the gain and offset of the four CA channels, the DAC, and checks low-pass filters of the CA channels using a sinusoidal signal generated by the same Em# DAC.

The calibration and test is performed by the Em# unit controlling the Calibrator via the USB port of the SBC. Doing in this way the tests and calibration can be done automatically without the need of any extra equipment.

The results of the calibration related to each module are stored in their embedded EEPROMs. This distributed calibration result storage makes possible to change components of the electrometer in case of damage without the need of a complete new calibration execution. Finally the calibration is sent to a centralized Data Base that permits to follow the aging of components.

A FLEXIBLE PLATFORM

The analog output and digital input/output connections of the electrometer allow the interaction with external equipment. An example of such equipment is a rack mounted multiplexer [12] with eight inputs and one output, which is connected to one of the four electrometer current inputs (Fig. 7). In this way, up to thirty-two channels can be connected to the same Em# without the need of any extra power source. The intended use of this equipment is to be used when currents readings does not need the full performance of the electrometer nor being constantly monitored. Firsts measurements shows that signals in the order of 10 pA can be measured with long term stability better than 1 pA.

Figure 7: An 8 channel multiplexer. Up to 4 multiplexers can be interfaced by the same electrometer.

Em# PRODUCTION

Hardware and mechanical design phase finished on September 2016. ALBA produced 12 Em# units in late 2016 and 12 more are foreseen to be produced at the end of 2017. MAX IV has produced 50 Em# units at the beginning of 2017 and 25 more are currently under production during this conference. Those 75 units are already booked by the accelerators and beamlines under commissioning phase. As MAX IV has more beamlines funded soon, a third batch is foreseen within two years.

MEASUREMENTS AND EXPERIMENTAL RESULTS

Em# first units at ALBA have been used for laboratory applications, as new beamlines where this equipment will be installed are still under construction. Figure 8 shows the Em# good performance when measuring 25 fA steps in a ramp current signal with 4.8 s integration time and configured in the 1nA range, meaning a dynamic range of 92 dB.
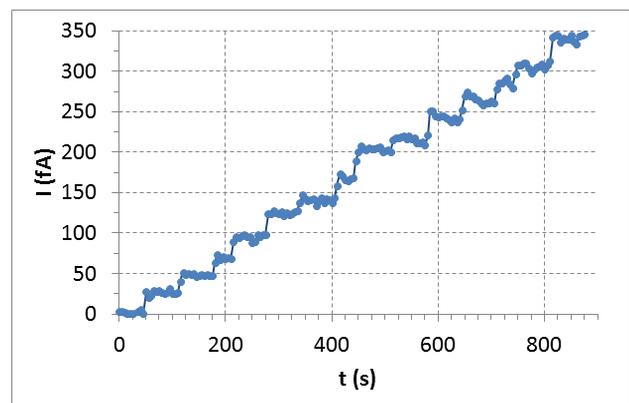
Figure 8: 25 fA steps ramp current signal measured with Em# in 1nA range, 0.5 Hz filter and 4.8 s integration time.

At MAX IV Em# has been used in the first beamline experiments. One of those examples is the absorption spectrum of N2 taken at the Veritas beamline to investigate its resolution of mechanics and optics (Fig. 9). The measurement shows that the resolution ratio of the beamline exceeds 50.000 at those energies and that the electrometer performance allows using it as a detector in this beamline end station. This measurement was taken with the Em# integrated into the Tango/Sardana control system showing that the project now reached a new level of maturity.
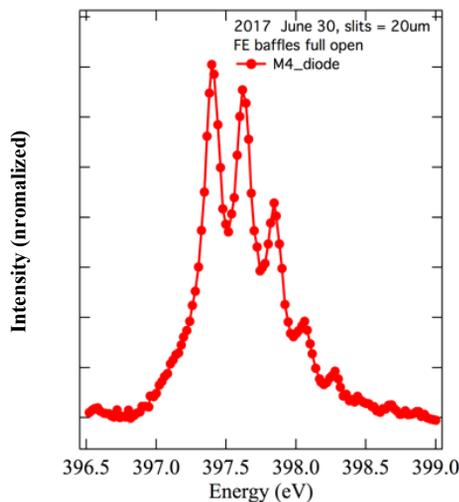
Figure 9: Absorption spectrum of N2 from Veritas beamline acquired with the EM# electrometer.

Another practical example of Em# use is the evaluation of a beam positioning detector consisting of a diamond substrate with four separate plates and a common back plane at the NanoMAX beamline. Figure 10 shows the two plates current measurements of a single direction beam scan onto the surface of the detector allowing a beam position calculation with a nanometer resolution. Using this calculus a feedback loop can be implemented via a PID core inside the FPGA using a piezo stage in the optics as the actuator to correct slow drifts in position due to temperature changes.
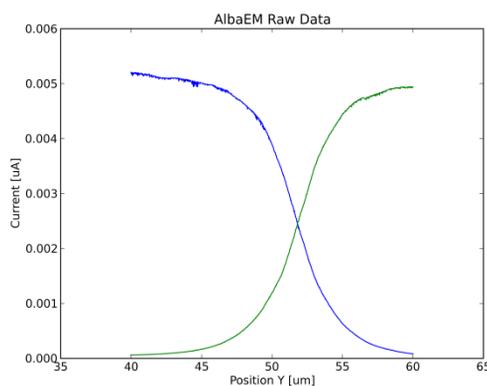
Figure 10: Two plates, single direction beam positioning with a diamond substrate measured with Em#.

CONCLUSION

Em# electrometer design phase is finished. The results have met the expected high performance meeting the user requirements for which it was designed.

The designed instrumentation platform developed in the Em# will be reused for future redesigns or new equipment developments. This reuse of the instrumentation platform applies to the three components of the platform: hardware, gateware and software. The included FPGA offers the possibility to Em# to implement high-value applications used in experimental end stations like data-stamping or feedback. Those advanced applications are under gateware and software development, while the hardware design is finished.

Currently there are 62 Em# produced working units at ALBA Synchrotron and MAX IV Laboratory and 37 more are in production process.

ACKNOWLEDGEMENT

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