BEST

Beamline Enhanced Stabilization Technology

CAENels
Gear For Science

User's Manual

Rev. 2 –August 2024

BEAMLINE ELECTRONIC INSTRUMENTATION

This product is CE & UKCA compliant.

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User Manual – Models – Options – Custom Models

This manual covers the following standard BEST models:

Model	Ordering code
BEST Central Unit	COMP-BEI0004

which includes:

- 3 Optical Cables - OM2-50/125µm, Multimode Duplex DK-2533-10, length = 10 m;
- 6 SFP Fiber Optic Transceivers - 4.25Gbps 850nm 3 V ~ 3.6 V LC Duplex Pluggable - FTLF8524P2BNV

The BEST can be equipped with up to two TetrAMM devices and one PreDAC device. See their correspondent User's Manuals for all the ordering codes available.

Table Of Contents

Document Revision	Date	Comment
0.1.0	April 16th 2014	Document created and edited
1.0.0	July 24th 2014	Main information and features added
1.0.1	August 18th 2014	Password font corrected
1.1	October 29th 2014	Manual graphics changed
1.2	September 25th 2018	Manual Updated
1.3	October 10th 2019	Added EPICS documentation
1.4	June 3rd 2020	Review of the text
1.5	December 16th 2021	
1.6	March 22th 2021	Major text revision and Update. BEST Local GUI screenshots taken from version 1.3-6
1.7	November 22nd 2022	Added UKCA compliance logo
2	August 8th 2024	Updated address and revision numbering

Safety information - Warnings

CAEN ELS will repair or replace any product within the guarantee period if the Guarantor declares that the product is defective due to workmanship or materials and has not been caused by mishandling, negligence on behalf of the User, accident or any abnormal conditions or operations.

Please read carefully the manual before operating any part of the instrument

⚠WARNING⚠

Do NOT open the boxes

CAEN ELS s.r.l. declines all responsibility for damages or injuries caused by an improper use of the Modules due to negligence on behalf of the User. It is strongly recommended to read thoroughly this User's Manual before any kind of operation.

CAEN ELS s.r.l. reserves the right to change partially or entirely the contents of this Manual at any time and without giving any notice.

Disposal of the Product

The product must never be dumped in the Municipal Waste. Please check your local regulations for disposal of electronics products.

Read over the instruction manual carefully before using the instrument.
The following precautions should be strictly observed before using the BEST system:

WARNING

- Do not use this product in any manner not specified by the manufacturer. The protective features of this product may be impaired if it is used in a manner not specified in this manual.
- Do not use the device if it is damaged. Before you use the device, inspect the instrument for possible cracks or breaks before each use.
- Do not operate the device around explosives gas, vapor or dust.
- Always use the device with the cables provided.
- Turn off the device before establishing any connection.
- Do not operate the device with the cover removed or loosened.
- Do not install substitute parts or perform any unauthorized modification to the product.
- Return the product to the manufacturer for service and repair to ensure that safety features are maintained

CAUTION

- This instrument is designed for indoor use and in area with low condensation.

The following table shows the general environmental requirements for a correct operation of the instrument:

Environmental Conditions	Requirements
Operating Temperature	0°C to 45°C
Operating Humidity	30% to 85% RH (non-condensing)
Storage Temperature	-10°C to 60°C
Storage Humidity	5% to 90% RH (non-condensing)

1. Introduction

The BEST (Beamline Enhanced Stabilization Technology) is a software and instrumentation suite, which was especially designed to control and stabilize the intensity (I_0) and position (horizontal and vertical) of the photon beam in synchrotron radiation X-ray beamlines.

The BEST instrumentation building blocks are:

- the **readout** block – i.e. TetrAMM device;
- the **control and interface** block – i.e. BEST Central Unit;
- the **actuator** block – i.e. PreDAC device.

A simplified block diagram of the BEST architecture is shown in the following figure:

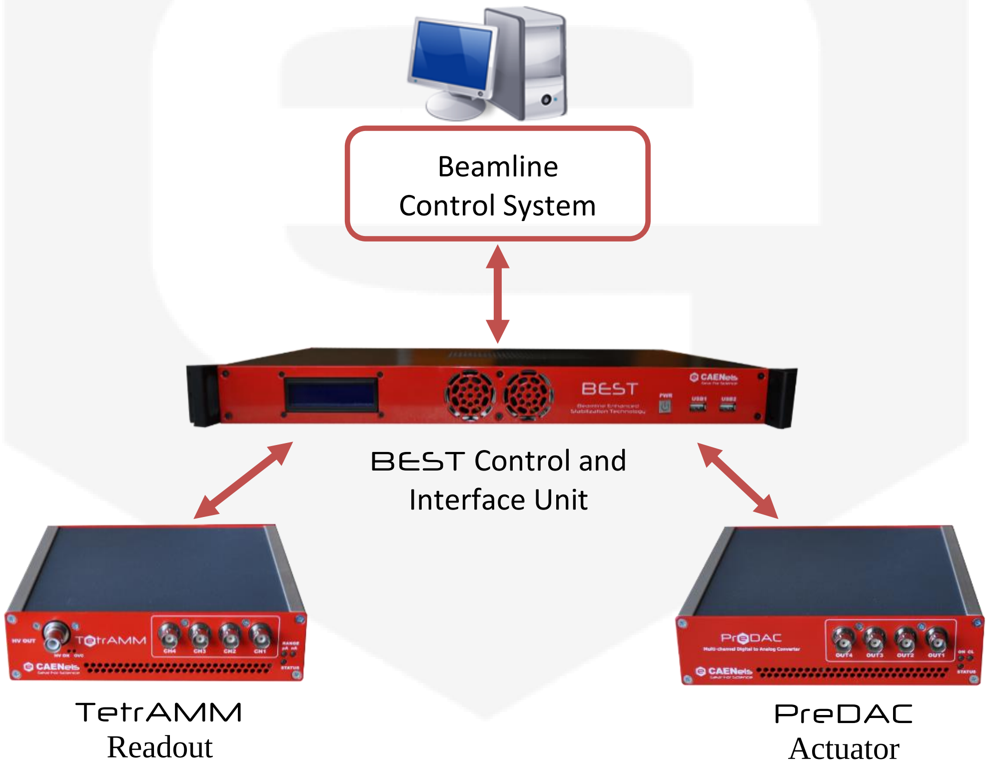


Figure 1: Simplified architecture of the BEST instrumentation suite.

In order to control and stabilize the X-ray it is necessary to determine the position and intensity of the beam. For this reason the first building block of the BEST system is a readout device called TetrAMM, which is a picoammeter instrument with high sampling speed connected to a phBPM (photon Beam Position Monitor).

The current from the phBPM are acquired by the TetrAMM and sent to the BEST Central Unit using a very low latency SFP connection.

The BEST Central Unit takes care of all the calculations to obtain the beam position and intensity information. The BEST Central Unit calculates the correction necessary to stabilize the intensity and position of the beam at the desired setpoint, using a fast PID algorithm. The correction setpoints are then sent to the actuator block using a low-latency SFP interface. The critical tasks are performed in hardware using a FPGA device in order to have a deterministic computing time, maximum calculation speed and high reliability. The X-ray beam intensity is constantly monitored and can be used to automatically enable or disable the PID controller, by determining if the beam is ON (intensity higher than a specific threshold) or if the beam is OFF (intensity lower than a specific threshold). The control and interface unit offers a local graphical interface (Local GUI), which allows to fully monitor, manage and control the beam position and intensity. A standard 10/100/1000 TCP-IP Ethernet link allows remote control and configuration of this system, hence it is possible to connect the control unit directly to the beamline control system.

The actuator device, called PreDAC, receives the correction/compensation data calculated by the BEST Central Unit and drives the beamline optics, using its internal high precision digital-to-analog converters to generate an output voltage signal capable of driving piezoelectric actuators acting on the optical elements. In this way it is possible to close the control loop and to stabilize the X-ray beam.

The FPGA-based hardware architecture allows performing the control algorithms at a maximized speed and with very low latency in order to guarantee full effectiveness of the BEST correction performance over a frequency spectrum up to several kHz. The slower and non-critical tasks (i.e. configuration commands) are separately performed on an embedded industrial PC running a Linux OS with dedicated software.

The distributed architecture was selected in order to maximize the performance, both in terms of speed as well as of sensitivity and accuracy, of the whole system. The TetrAMM readout system should be placed as close as possible to the phBPM and the PreDAC system as close as possible to the actuator driving the beamline optics in order to reduce the noise pickup on the analog part of the feedback system. The internal BEST computation and communication between the three system blocks are all performed in a fully digital way, therefore excluding all additional noise sources that can strongly affect the controller and stabilization loop performances at high speed. All three building blocks are interconnected via low-delay fast communication SFP links running a proprietary protocol. The SFP links on the back of the BEST Central Unit are directly interfaced to a powerful FPGA board that performs the position and control algorithms and sends correction values to the DACs embedded in the PreDAC device.

The BEST system was designed with one of its main focuses on configurability expandability and flexibility, being able to control and monitor up to two readouts - TetrAMM devices (i.e. up to 8 picoammeter channels) and one multichannel actuator - PreDAC device (i.e. up to 4 DAC channels) from one single BEST central unit.

1.1 TetrAMM overview

The CAENels TetrAMM picoammeter is a 4-channel, 24-bit resolution, wide-bandwidth, wide input dynamic range picoammeter with an integrated optional bias voltage with bias ratings covering the ±30V up to ±4 kV range. It is composed of a specially designed transimpedance input stage for current sensing combined with analog signal conditioning and filtering stages making use of state-of-the-art electronics. This device can perform bipolar current measurements, which makes it well suited for extremely low input signals. Low temperature drifts, good linearity and very low noise levels enable users to perform very high-precision current measurements.

The TetrAMM is housed in a light, robust and extremely compact metallic box that can be placed as close as possible to the current source (BPM detector), in order to reduce cable lengths and minimize possible noise pick-up on the weak signals coming from the BPM. It is specially suited for applications where multi-channel simultaneous acquisitions are required, a typical application being the currents readout from 4-quadrant photodiodes or diamond-based detectors routinely used to monitor X-ray beam displacements.

The TetrAMM communication to a host PC when used as a standalone unit relies on a standard 10/100/1000 Mbps Ethernet TCP/IP protocol while its integration with the BEST (Beamline Enhanced Stabilization Technology) system is performed via the SFP link placed on the rear panel.

The TetrAMM unit and its I/O connections can be easily seen in **Figure 2** (front) and in **Figure 3** (rear).

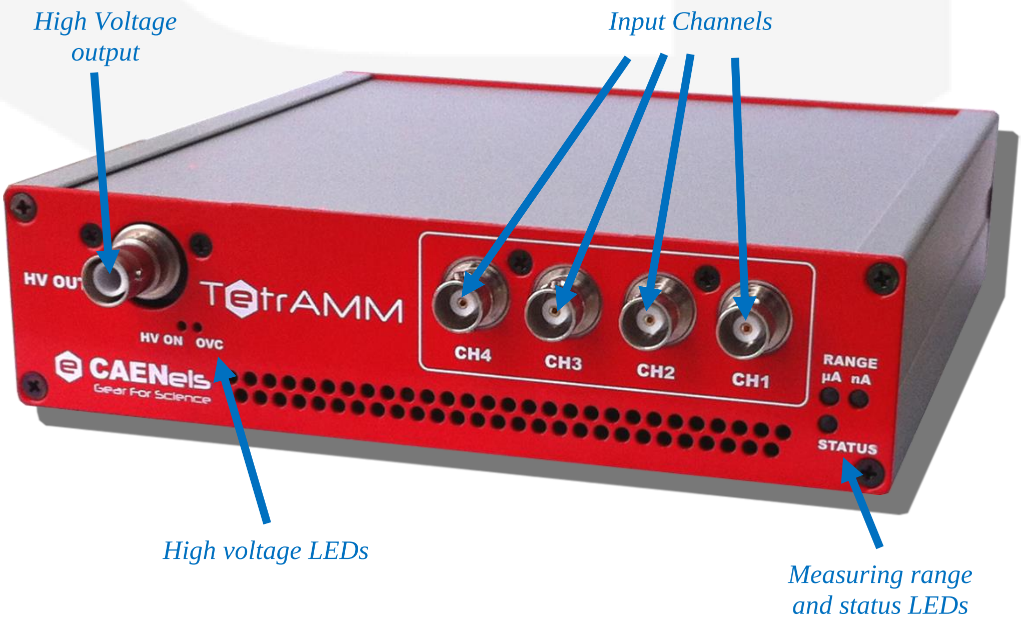


Figure 2: front view of a TetrAMM unit

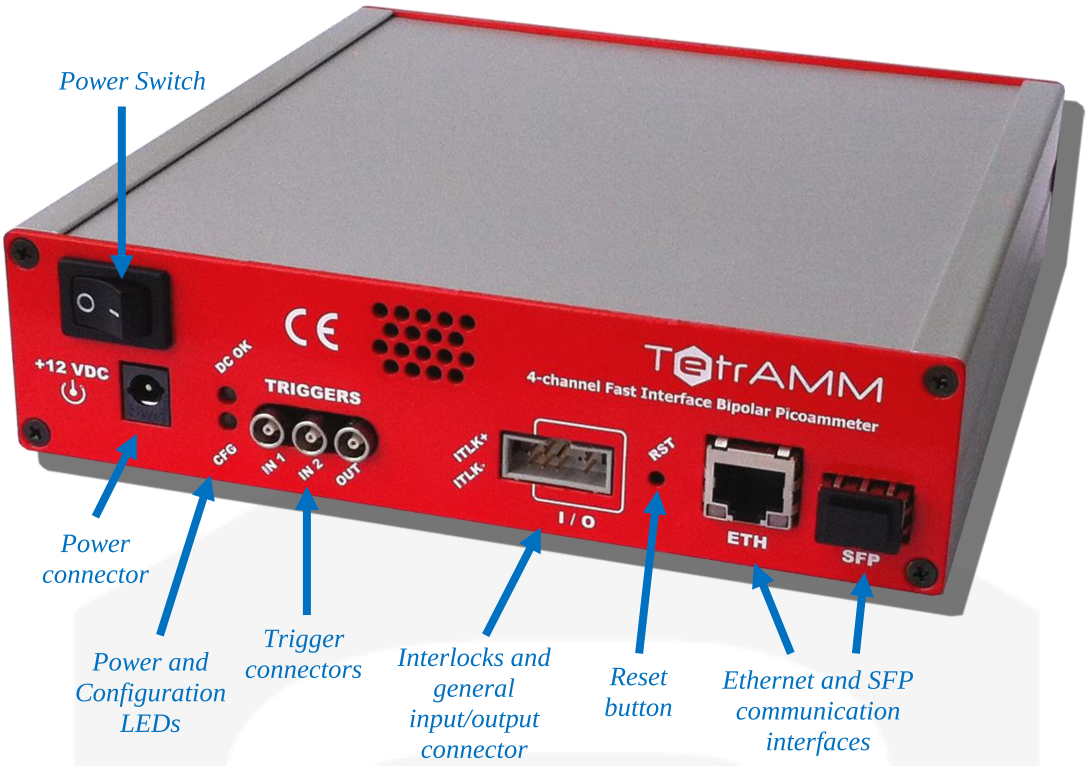


Figure 3: rear view of a TetrAMM unit

1.2 BEST Central Unit overview

The BEST Central Unit is a 1U rack-mount system, which houses:

- a dedicated hardware with next generation FPGA to perform all the critical tasks as the system computation and correction calculations and
- an industrial PC running Linux OS, which allows overall control and tuning of the system using a GUI (Graphical User Interface) software.

A dedicated high speed hardware (integrated in the next generation FPGA logic) takes care of all the critical tasks controlled by the PID algorithm, such as: stabilization, intensity monitoring and positioning of the photon beam. The FPGA logic receives the acquired X-ray data from all TetrAMM devices via a high speed SFP link. The received data (i.e. current outputs from the phBPM) is elaborated to obtain beam position and intensity information. The FPGA performs also the control PID algorithms in an optimized way, adding a very low delay to the feedback loop in order to guarantee the BEST correction performances over the highest possible frequency spectrum. The computed corrections are sent to the actuator block (the PreDAC unit) using the SFP interface.

The non-critical tasks are, as mentioned earlier, performed in the embedded industrial PC running a Linux OS. The communication between the PC and the FPGA is performed trough a PCI Express protocol, therefore all elaborated data and configurations of the high speed hardware are accessible from the dedicated Linux graphic software. The BEST Central Unit comes with a user-friendly GUI interface, which allows to:

- configure the BEST system;
- configure the system feedback actuation (i.e. PID parameters, detector configuration);
- monitor main physical quantities data (i.e raw TetrAMM currents, beam position and intensity, FFT, CSP);
- control the beam position with a simple "*point and click positioning*" feature or by entering a setpoint manually.

Remote control of the Central Unit is also possible using a dedicated EPICS driver using a standard 10/100/1000 Ethernet link. This provides the possibility to connect the BEST Central Unit directly to the beamline control system.

The BEST Central Unit and its I/O connections can be easily seen in **Figure 4** (front) and in **Figure 5** (rear).

Figure 4: Front view of a BEST Control and Interface Unit

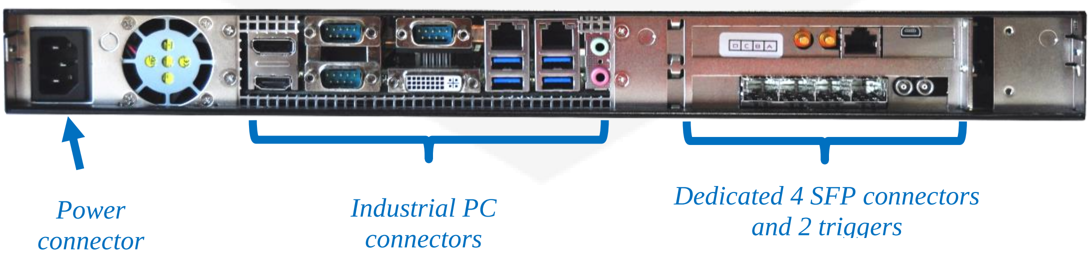


Figure 5: Rear view of a BEST Central Unit

1.3 PreDAC Overview

The PreDAC is a (up to) 4-channel, 21-bit resolution, wide-bandwidth Digital to Analog Converter (DAC) which is especially designed for seamless operation within the BEST system. At the core of the PreDAC system there is a high-speed 16-bit digital to analog converter that uses dithering technique and active low-pass filtering to obtain a stable high accuracy (21-bit) output signal.

This device is capable of outputing up to ±12 V bipolar voltage with an ultimate resolution of 12 µV – i.e. 21 bits on the bipolar full output range. Output voltage noise is suppressed using a 4th order active low-pass filter with cut-off frequency (-3 dB) of 10 kHz. Its minimized temperature-induced drifts, good linearity and very low noise levels enable users to perform high-precision voltage signal generation.

The standard PreDAC has two voltage output channels but can be optionally upgraded to have three or even four output channels on a single unit. It is housed in a light, robust and extremely compact metallic box that can be placed as close as possible to the actuator power driver/amplifier in order to reduce cable lengths and consequently minimize possible noise pick-up on the analog signal path. It is specially suited for applications where multi-channel simultaneous actuations are required, a typical application being control of position (X, Y) and intensity (I_0) of the photon beam in synchrotron radiation or XFEL X-ray beamlines.

The PreDAC communication to a host PC when used as a standalone unit is guaranteed by a standard 10/100/1000 Mbps Ethernet TCP/IP protocol while its integration in the BEST (Beamline Enhanced Stabilization Technology) system is performed via the SFP link available on the rear panel.

The PreDAC unit and its I/O connections can be easily seen in **Figure 6** (front) and in **Figure 7** (rear).

Figure 6: front view of a PreDAC unit

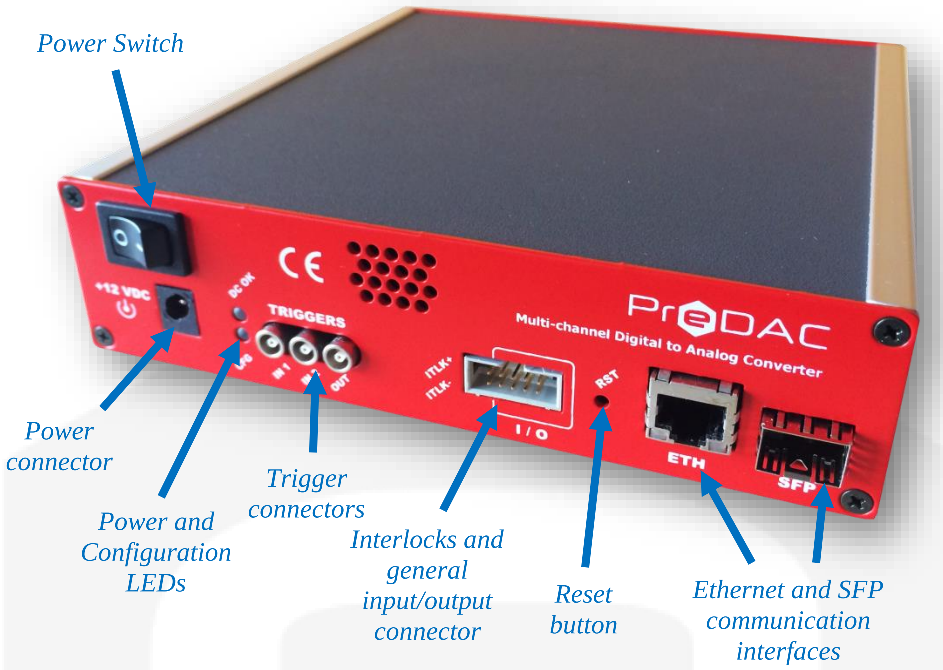


Figure 7: rear view of a PreDAC unit

<u>It is very important to limit, when required, the PreDAC voltage outputs in order to prevent any possible damage to the connected units (for example the piezoelectric actuators).</u> To perform this task, please refer to the "MIN" and "MAX" Commands of the PreDAC User's manual.

2. BEST System Installation

The following sections describe the various steps to interconnect the BEST instrumentation.

2.1 Connect the TetrAMM to the phBPM

The first building block of the BEST instrumentation suite is the TetrAMM picoammeter. This unit is designed to read and convert to digital format the analog currents from the phBPM (photon Beam Position Monitor). This data is essential to determinate position and the intensity of the X-ray beam.

The TetrAMM must be connected with the phBPM using the four analog input connectors placed on the front side of the unit. The BNC connectors are miniature quick connect/disconnect RF connectors mainly used for coaxial cables. Channel incremental numbering, as can be seen in **Figure 8**, is right-to-left (CH1 is to the right while CH4 is to the left). Please note that the order of the BNC connections with the phBPM is not important, as the BEST Control and Interface Unit software allows to freely select the input channel configuration.

Figure 8: BNC input connectors

The TetrAMM unit must be placed as close as possible to the analog current source (e.g. phBPM detector), in order to reduce cable lengths – i.e. cable capacitance – and to minimize consequent noise pick-up. It is also highly recommended to use high quality BNC cables to connect the TetrAMM inputs with the current sources.

Depending on the TetrAMM custom model selected, the TetrAMM can be equipped with a High Voltage bias module (up to +/- 4kV, monopolar) or with a Low Voltage bias module (up to +/- 30 V, bipolar). These bias voltage modules can be used as bias/polarization source for the position-sensing system (e.g.: split ion chamber, diamond QBPM…). The Low Voltage bias module has a standard BNC output connector, while the High Voltage bias module has a SHV output connector. The SHV connector is similar to the BNC but uses a very thick and protruding insulator (**Figure 9**). The insulation geometry makes the SHV connector safe for handling high voltage sources, by preventing accidental contact with the live conductor in an unmated connector or plug.

Figure 9: High Voltage SHV connector

2.2 Connect the PreDAC to the Beamline optics

The BEST suite is usually driving several beamline optics units in order to control and stabilize the X-ray beam at the desired position and with the desired intensity. This task is performed by the PreDAC device. This unit is designed to control the piezo/amplifier of the piezoelectric actuators that drive the position of the beamline optical elements and therefore the position of the X-ray beam. The PreDAC device is designed to provide maximum flexibility in order to tailor its output to a wide variety of piezoelectric actuators. The number of PreDAC outputs depends upon specific beamline characteristics and can be optionally increased from the default value of two up to four.

The output voltage BNC connectors that must be connected with the driver/amplifier of the piezoelectric actuators are located on the PreDAC front panel. Channel incremental numbering, as can be seen in **Figure 10**, is right-to-left (OUT1 is on the right while OUT4 is on the left). Please note that the order of the BNC connections with the piezoelectric units is not important, as the BEST Central Unit software allows to freely select the output channel configuration.

Figure 10: PreDAC BNC output connectors

The PreDAC unit must be placed as close as possible to the piezoelectric actuator driver/amplifier, in order to reduce cable lengths – i.e. cable capacitance – and to minimize consequent noise pick-up. It is also highly recommended to use high quality BNC cables to connect the PreDAC outputs.

2.3 BEST Central Unit PC connections

The BEST Central Unit allows to monitor and configure the dedicated high speed hardware using the local GUI, or remotely using EPICS. The software controls the dedicated hardware through the PCIe interface.

In order to use the Linux OS it is necessary to connect the industrial PC to a mouse, keyboard and a monitor. There are two additional USB slots on the front side of the BEST Central Unit. The rear side of the BEST Central Unit (**Figure 5**) is equipped with standard PC connections, such as[1]:

- 1 Display Port
- 1 HDMI
- 1 DVI
- 2 Ethernet
- 4 x USB 3.0 compliant

[1] The PC connections can slightly vary in time since the industrial PC of the Central Unit is kept up-to-date when newer technologies are widely adopted worldwide.

2.4 BEST system interconnection

The TetrAMM and PreDAC units have to be connected with the BEST Central Unit, which controls the whole system. The communication between the units is obtained with a dedicated fast speed SFP optic interface.

On the rear panel of the PreDAC and TetrAMM units there is a dedicated SFP slot providing the communication between the devices and the BEST Central Unit. Firstly it is necessary to insert the SFP optics transceiver module into the SFP slot positioned on the rear panel, as shown in **Figure 11**.

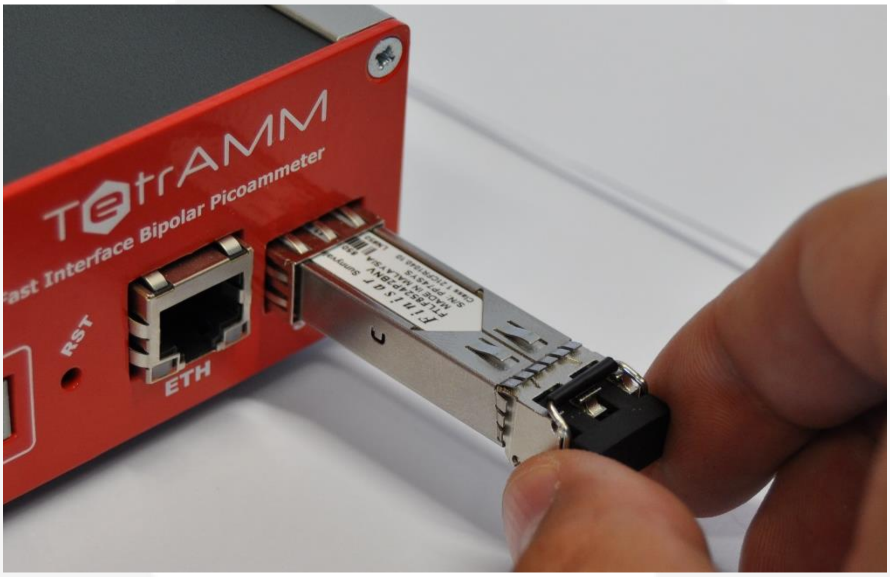


Figure 11: Connection of the SFP optic transceiver into its slot

Remove the caps from the SPF transceiver module from the cable connector and simply plug the cable connector into the transceiver module as shown in the following picture:

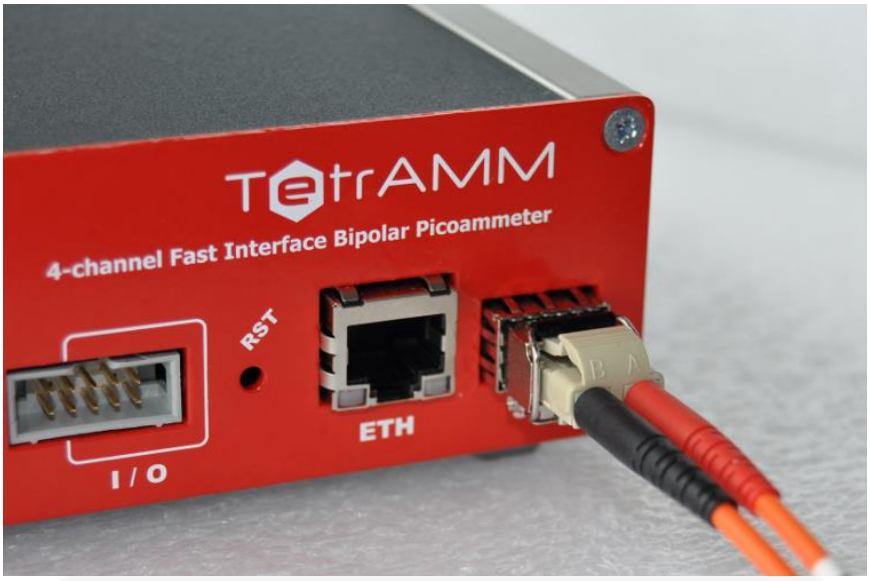


Figure 12: SFP connection

Note that it is not necessary to connect the Ethernet cable, because the TetrAMM and PreDAC devices operate as slaves of the BEST Control and Interface unit. The Ethernet communication is still available, but it operates in read-only mode.

The fiber optic cables from the peripheral devices must then be connected to the BEST Central Unit. Similar as for the TetrAMM and PreDAC devices the SFP optic transceivers should be plugged into the dedicated slots on the rear side of the BEST Central Unit, but in this case **<u>the correct orientation of the SFP transceiver is upside-down.</u>**

On the rear side of the BEST Central Unit there are 4 SFP slots. Channel incremental numbering, as can be seen in **Figure 13**, is right-to-left (SFP A is the one the right while SFP D is the one on the left).

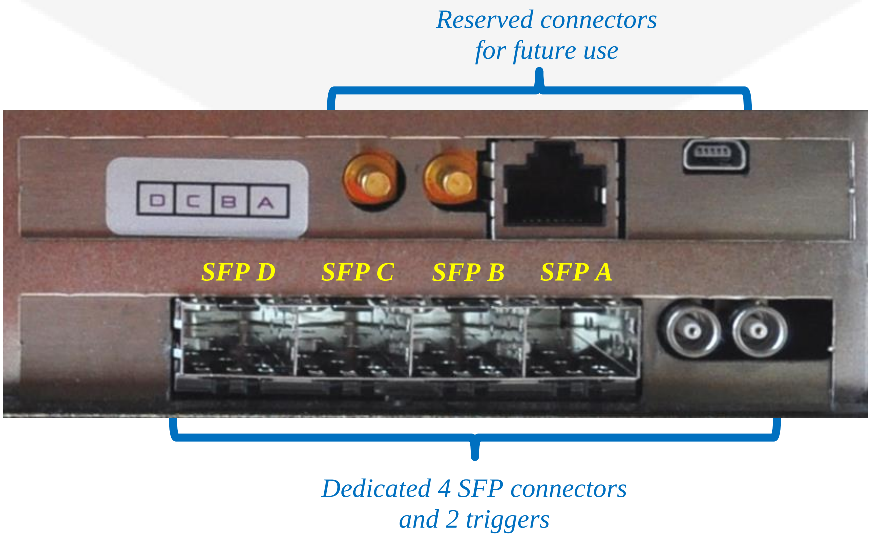


Figure 13: BEST Control unit SFP connection

The order of the SFP connection is indeed very important for the BEST Control unit to communicate with the right device. The correct connections have to be as indicated hereafter:

- **SFP A <-> 1st TetrAMM – MASTER UNIT**
- **SFP B <-> 2nd TetrAMM (optional) – SLAVE UNIT**
- **SFP C <-> PreDAC**
- **SFP D <-> Reserved**

2.5 BEST system power-up

The BEST instruments can be now connected to the mains power. The TetrAMM and PreDAC units use the CAENels PS1112 power supply. The PS1112 linear power supply can be used either with a 115V – 60Hz AC power line (e.g. United States) or with a 230 V – 50 Hz AC Line (e.g. Europe); be sure to select the correct input voltage rating by switching the AC Line Voltage Select switch placed on one side of the box. Possible switch positions, one for each input voltage rating, are shown in the following **Figure 14** (230V and 115V respectively):

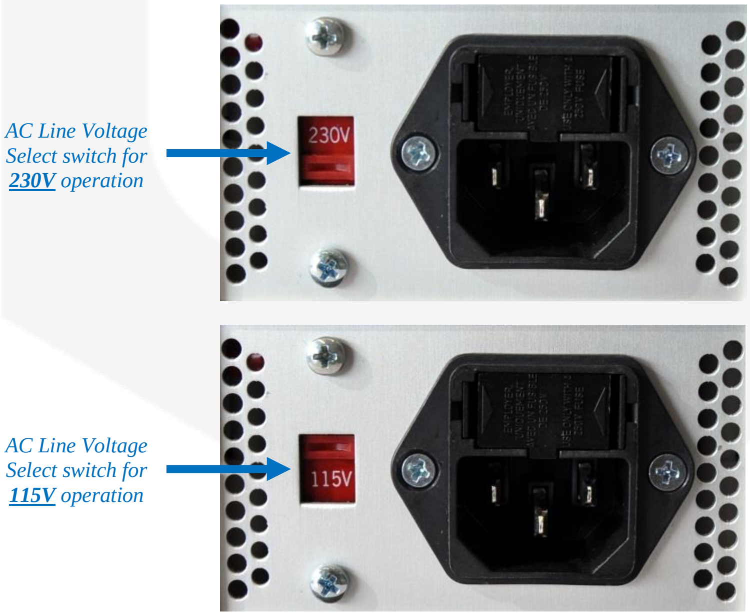


Figure 14: PS1112 AC line voltage select switch

The BEST Central Unit is powered using an internal power supply unit with extended input voltage range (100 - 240V).

After connection to the main power, the BEST units are now ready to be used. To switch on the units use the power buttons located on the rear side of the TetrAMM and PreDAC and on the front side of the BEST Central Unit.

3. BEST Central Unit Overview

3.1 Controller Schematic

Figure 15 provides a schematic representation of all the functional blocks implemented in the Central Unit.

The first operation carried out by the Central Unit is to convert the currents readouts provided by the TetrAMMs in position (X, Y) and intensity (I_0).

Before entering the PIDs, the position (X, Y) and intensity (I0) are sent to the *BPM selector* block. This block allows the user to select which BPM should be assigned to which PID controller.

An averaging module is placed in between the *BPM selector* and the PID. This module, configurable by the user, defines the update frequency (sampling frequency) of the PID controller. The PID controller can work up to 100 kHz, which correspond to no average (or average of 1 sample) on the positions samples. Typical update frequencies are 10-100Hz or even lower for slow mechanics.

Finally, the PIDs outputs go in the *output selector* block which can be configured by the user to assign each PID output to the desired PreDAC channel.

More detailed information regarding the configuration of each block can be found in chapter 4.

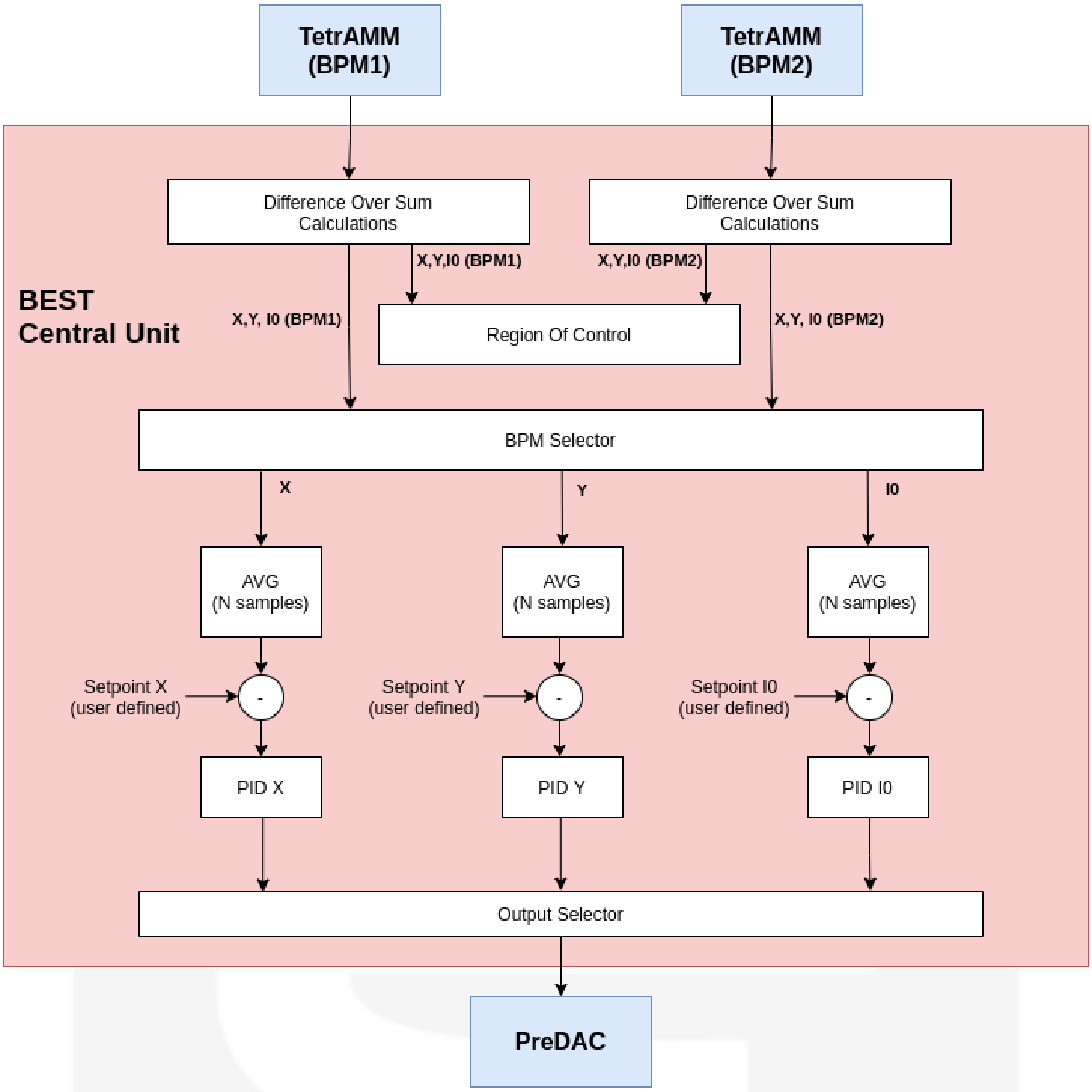


Figure 15: BEST controller functional overview

4. BEST Local GUI

This chapter describes the main features of the BEST Local GUI (Graphical User Interface). To execute the program it is necessary to power on the BEST Central Unit. The BEST Local GUI is already installed on the Linux OS. To run the program simply click on the "BEST Local GUI" icon present on the Linux desktop.

The default Linux OS user and password are (case-sensitive):

- User: *best*
- Password: *WeAreTheBest*

4.1 Main Window

The main screen of the BEST Local GUI is shown in **Figure 16**.

The main graph is located in the upper section and shows the current beam position in the XY (horizontal & vertical) plane. This is a 2D representation of the positions derived from the currents first read by the TetrAMMs and then transformed in positions using the usual difference-over-the-sum equations and the BPM scaling parameters (see 4.3 for more info).

Various possible plots can be selected in the bottom section of the GUI in order to better monitor and/or analyze X-ray beam properties or perform sanity checks on the feedback system (see **Errore. L'origine riferimento non è stata trovata.**). The quantities are real-time plots and the time window can be adjusted by the user.

A *feedback control* panel located in the top-right part of the GUI allows users to activate, pause or reset the feedback controller, change the controller input/output configuration and set the desired setpoints (see 4.1.2).

The *PID configuration* panel is located in the bottom-right part of the GUI and gives to users the possibility to change and tune all PID parameters according to the required system dynamics.

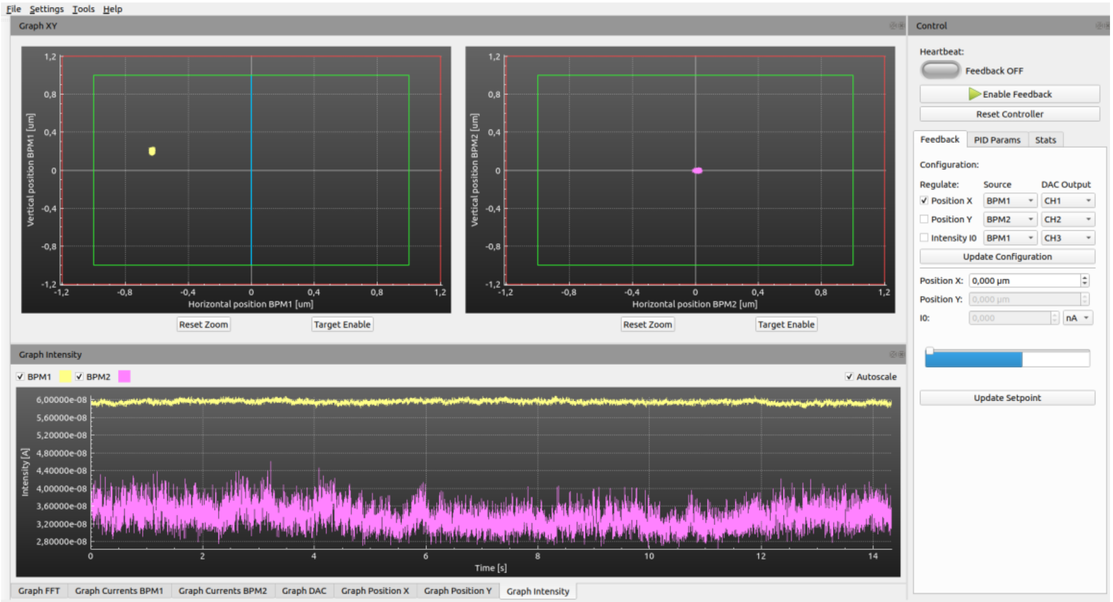


Figure 16: BEST Local GUI main window

Some specific settings should be changed and properly initialized according to the beamline configuration prior to starting the feedback system. What these setting are and where to find them will be clarified in the following sections.

4.1.1 Graph XY

The Graph XY window in the upper section of the GUI shows the X-ray beam position in XY plane (**Figure 17**). The graph is updated in real-time with a fixed time window of one second, thus the user can get a precise view of the beam position distribution in the last second.

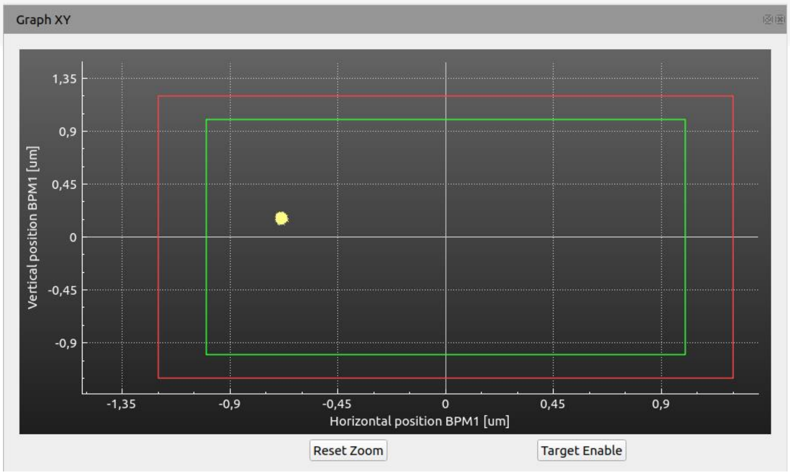


Figure 17: Graph XY

As described before, the PID control of beam position can be performed in different configurations. For example it is possible to control the beam in a single dimension (i.e. Y - dimension is regulated by the system and X is free) or in both dimensions (i.e. X and Y dimensions are regulated by the system). When the PID controller acts only in one dimension, the setpoint is a line pointer, otherwise when it acts in two dimensions the setpoint is represented by as a blue cross pointer (as it can be seen in **Figure 16**).

The green rectangle within the Graph XY window represents the Region Of Interest (ROI), i.e. the area where the user is allowed to position the setpoint. The red rectangle (always larger than the green one) shows the Region Of Convergence (ROC), i.e. the area where the PID controller acts on the beam position. If in any case the beam position leaves the ROC, the feedback regulation is stopped. The dimension of these two regions can be set by the user in the corresponding configuration window (see section 4.4).

In the Graph XY window it is also possible to perform "Point and Click Positioning". This feature allows the user to move the beam to the desired setpoint position by simply clicking on the XY graph area. To enable this feature it is necessary to select the "Target Enable" button. An example of this feature is shown in **Figure 18**.

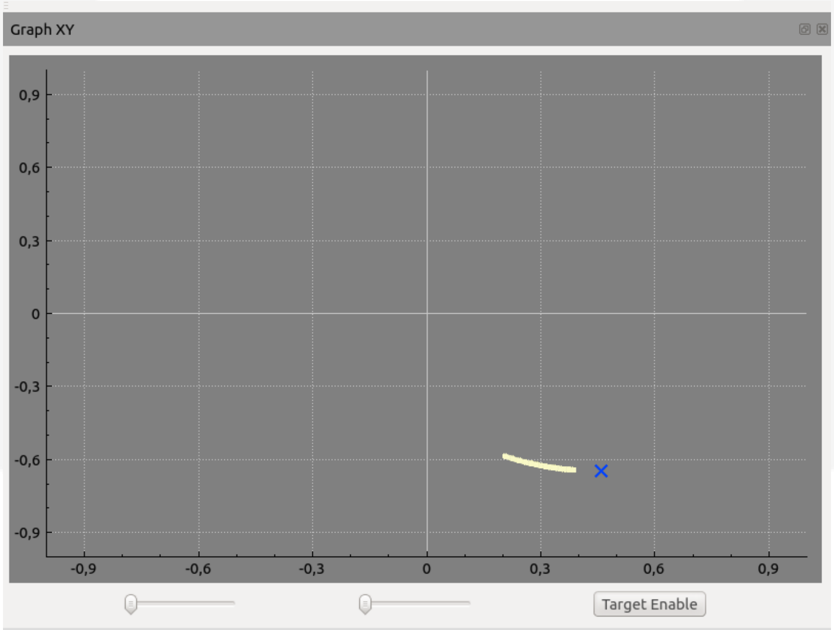


Figure 18: Point and Click Positioning

4.1.2 Feedback Control Panel

The main settings of the PID feedback control are placed in the *feedback control* panel on the top-right part of the GUI main window.

The *feedback control* panel can show two tabs:

- The *statistics* section tab (**Figure 19**), where the real-time mean value of the beam position (X-Y) and of the beam intensity (I_0) and its related standard deviation are visualized;
- The *control* section tab (**Figure 21**), which groups all the main feedback control input/output parameters.

The *statistics* section tab reports mean values and standard deviations of X, Y and intensity (I0) of the BPM data at the maximum sampling frequency (100 kHz). The standard deviation of X, Y and I0 at 100 Hz (average of 1000 samples) is also reported.

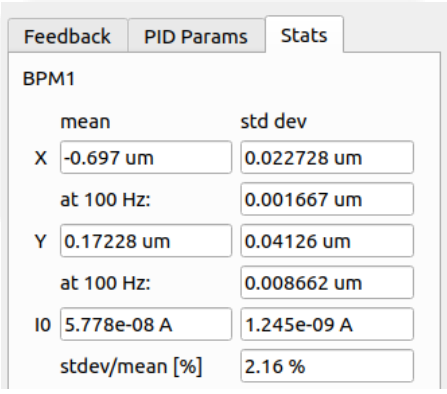


Figure 19: Feedback statistics section.
In this example one TetrAMM (BPM1) is connected to the Central Unit.

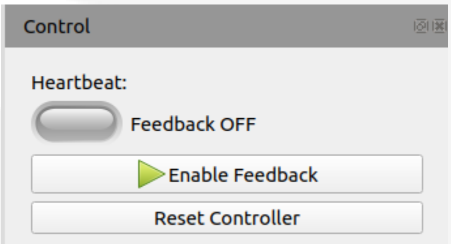


Figure 20: Heartbeat, Enable/Disable Feedback and Reset controller

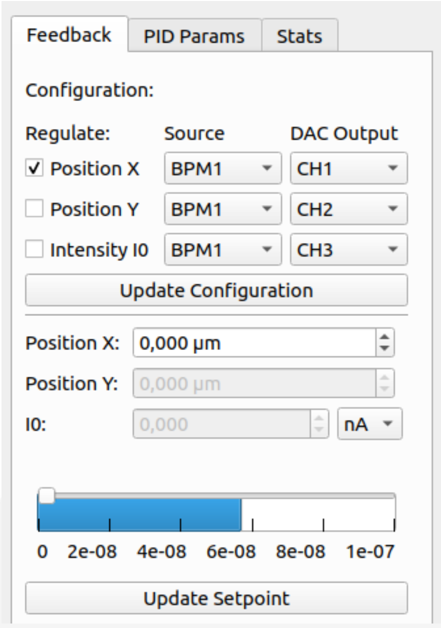


Figure 21: Feedback control section

The *control* section is composed by a "Heartbeat" indicator (Figure 20), which shows the feedback status. There are four possible statuses:

- *Feedback OFF* – the feedback loop is disabled and on output there are only user defined offsets (user defined offset is the *PID offset* field in the PID configuration panel, see section 4.1.3). This mode can be used to manually position the beam in a desired location by changing the *PID offset* field.
- *Feedback ON* – the feedback is enabled and the output is calculated by the PID algorithm (see **Figure 23** for a visual representation of the PID structure).
- *Fault: Out of ROC* – this is an error message which means that the beam position has moved outside the user defined ROC; as a consequence the feedback is automatically stopped. Before starting again the feedback with the "Enable feedback" button it's necessary to set back the PID status and its output to the initial values; this can be done with the "Reset Controller" button.
- *Beam OFF* – this condition indicates that the beam intensity went below the user defined "Beam Off Threshold" value (without going out of the ROC region, see section 4.4 for more information) which indicates that beam was shut down. In this condition the feedback is *paused* since it makes no sense to stabilize a non-existing beam. If the beam intensity comes back again, the feedback will be automatically moved from *pause* to *Feedback ON* state.

The "Enable/Disable Feedback" button allows to start or to stop the feedback regulation of beam position to the selected setpoint.

The "Reset Controller" button resets all internal states (e.g. the integrated value of error) of the PID controller.

The feedback configuration options are placed below the "Enable/Disable Feedback" and "Reset Controller" buttons:

- *Regulate* – select which PID to enable,
- *Source* – select which BPM to use as source for the PID ("BPM Selector" block in **Figure 15**),
- *DAC output* – assign the PID output to the desired PreDAC output ("Output Selector" block in **Figure 15**).

The feedback configuration options come into force after pressing the "Update Config" button.

Lastly, the beam position setpoint can be changed manually by specifying the beam position ("Position X" and Position Y") in µm. New values come into effect after pressing the "Update Setpoint" button.

4.1.3 PID Configuration Panel

The PID parameters of the four independent PID loops available in the BEST hardware are all accessible from the GUI main window. To modify a parameter simply change its value and click the "Update" button to make the changes effective.

The PID parameters (**Figure 22**) are used in the FPGA logic for the BEST fast feedback computation algorithms. The BEST system can control and stabilize up to three variables:

1. **X**: horizontal position;
2. **Y**: vertical position;
3. $\mathbf{I_0}$: intensity.

A digital filter (simple average) is applied to the input data received from the TetrAMMs before entering the PID (see "AVG" block in **Figure 15**). This filtering is performed to maximize the signal-to-noise ratio and to reduce the feedback actuation frequency that can be set using the field "Freq" in the PID Configuration menu. This parameter is of paramount importance and is correlated to the dynamical performances of the positioning mechanics driven by the PID. Certain positioners are stiff, lightweight and fully backlash-free, therefore they can be actuated to track the setpoints generated by the PID at relatively high frequencies of 100 Hz and above. Other positioners may be intrinsically slower, therefore they can be actuated at frequencies of only a very few tens of Hz. Slow thermal drifts are easily compensated by running the PID at just around 1 Hz.

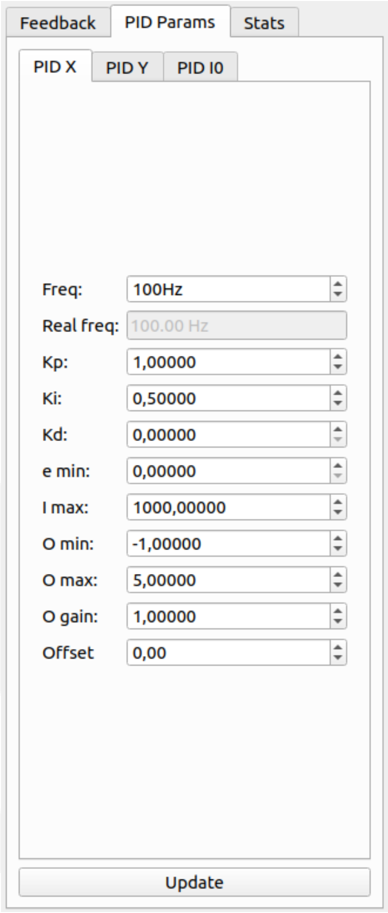


Figure 22: PID Parameters window

The feedback actuation frequency ("Freq" in the PID configuration menu) is obtained by averaging the phBPM source signal (always sampled at 100 kHz) by an integer number of samples. For this reason, only a discrete range of frequencies ("Real freq" in the PID configuration menu) corresponding to integer multiple of samples in the averaging algorithm can be obtained. If, for example, the user selects Freq = 100 Hz the averaging is performed on 1000 samples and "Real freq" will exactly be 100 Hz, while if the user selects 90 Hz the average is performed on the closest possible integer number of samples (1112) and "Real freq" of the PID will be 89.928 Hz, slightly different from the one required by the user. In other words, the "Real freq" field shows the nearest, real and applicable actuation frequency value based on the required "Freq" setting.

The usual K_p, K_i and K_d parameters are needed to calculate the well-known PID algorithm (**Figure 23**). There are also several other parameters available to the user; they can further optimize and fine tune the PID controller and therefore improve system performances.

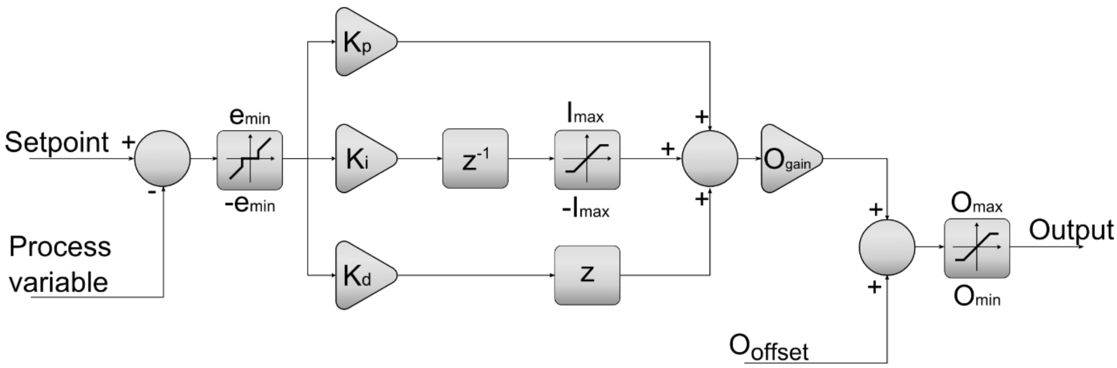


Figure 23: PID Regulator architecture

The “e_{min}” value set the smallest error value which is taken into account for the PID calculation. All smaller values are trimmed to zero. In most cases this parameter should be set at zero, although it can be used to stop the controller if a predefined error from the loop target is reached and the user wants to freeze the system and avoid continuous very small corrections. It sets the minimum tuning bandwidth of the closed-loop feedback.

The “I_{max}” parameter sets the saturation limit of the integral part of the PID controller.

The PID output (in Volts) is limited between the set “O_{min}” and “O_{max}” values. It is recommended to set these values carefully in order to prevent any potential damage to the input stage of piezoelectric actuator driver/amplifier or even to the actuator itself. For example, piezoelectric actuators often have asymmetric input voltage ranges, much wider in a given polarity than in the opposite. N.B.: we point out that it is possible to set further limits for the minimum and maximum value of the PreDAC output, which are set in a lower level firmware and therefore provide an additional protection layer. Please refer to the PreDAC User's Manual, “MIN” and “MAX” Commands.

The output of the PID controller is multiplied by the “O_{gain}” value to change the gain of the closed loop and, mainly, to invert the PID response. Normally this parameter is only set either to 1 or -1.

“O_{offset}” can be used to steer the beam to a selected working point. Furthermore, In order to benefit from the maximum excursion in both direction of the piezoelectric actuator, it is suggested to set O_{offset} at the center of the piezo driver/amplifier input range.

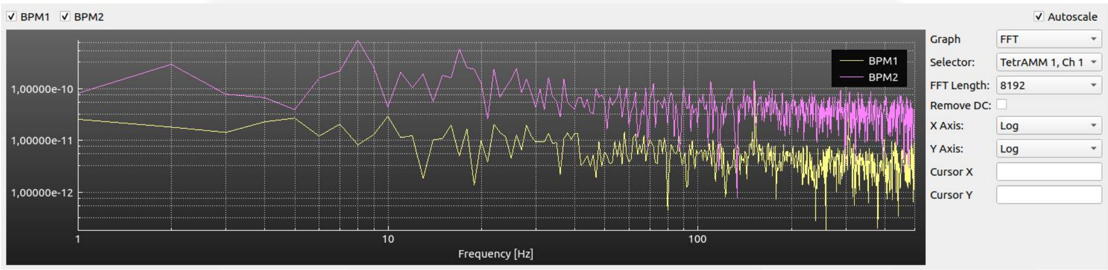
By pressing the “Update” button, all new parameters are downloaded to the controller on the FPGA and they take effect immediately.

4.1.4 Additional Graphs

On the bottom part of the main window, further additional graphs of the main physical quantities are grouped into tabs. When two TetrAMMs are connected to the BEST Central Unit, the graph of the second BPM (usually in pink) is added to the same graph tab of the first BPM (usually in yellow), with except for the "Currents Graph Tab", where and additional graph tab is created for the second BPM.

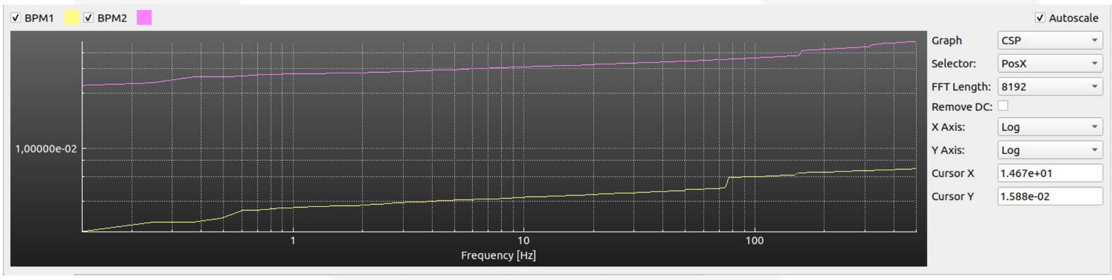
4.1.4.1 FFT Graph Tab

The FFT Graph Tab shows the real-time FFT of the main physical quantities. The User can dynamically select the physical quantity on which the FFT is performed on. Available quantities are currents, position and intensity.

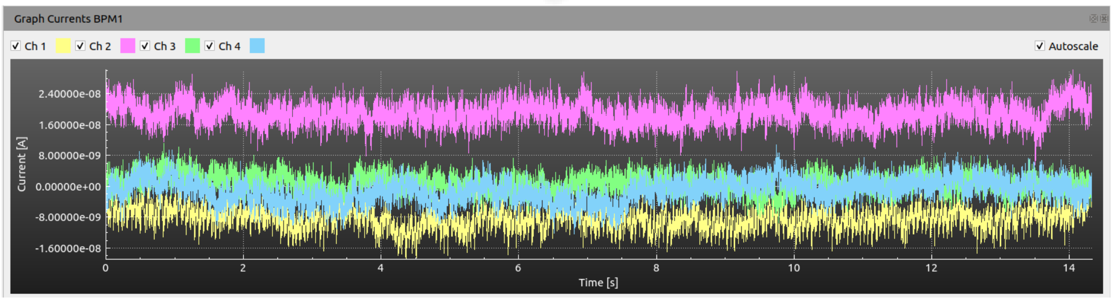


Additionally, instead of the FFT graph, it is possible to plot the real-time CSP (Cumulative Spectral Power) which is calculated as:

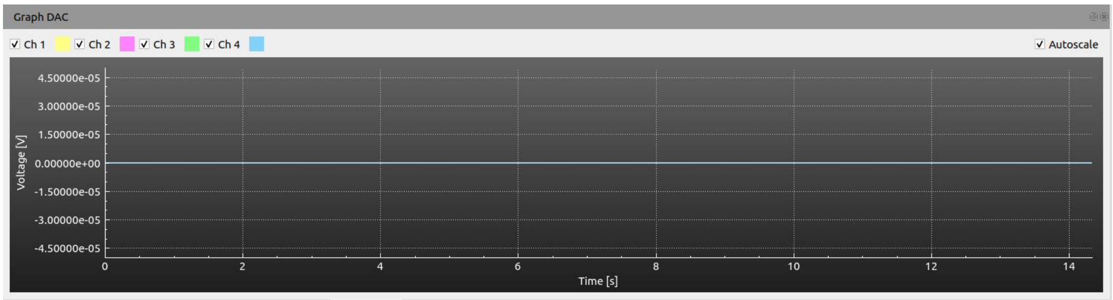
$$CSP(y) = cumsum\left(\frac{FFT(y)^2}{2}\right)^{1/2}$$



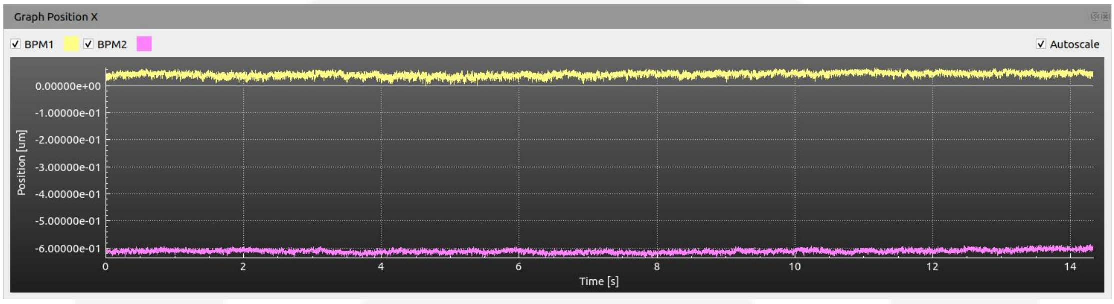
4.1.4.2 Currents Graph Tab



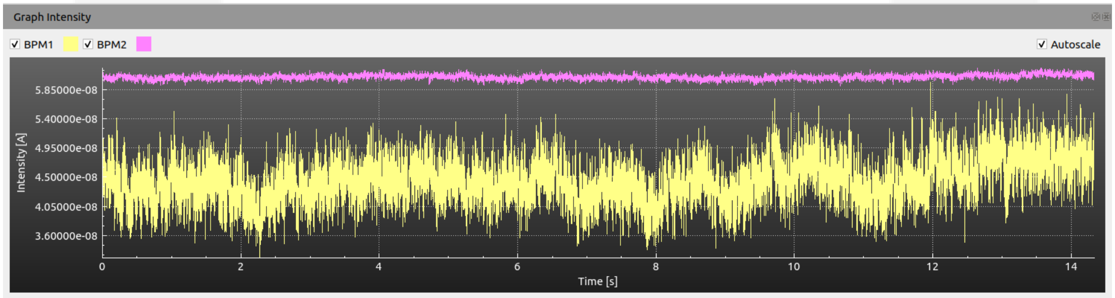
4.1.4.3 DAC Graph Tab



4.1.4.4 Position Graph Tab



4.1.4.5 Intensity Graph Tab



4.2 Login

This dialog allows access at different levels to the BEST Local User Interface. Having different access levels prevents inexperienced users from changing accidentally system critical settings.

The user interface has three different access levels:

- **Administrator mode:** provides authorization to set and modify freely all the beamline related settings, as well as to change setpoints and feedback parameters and configuration. Username for this mode is: *admin*, and the password is: *WeAreTheBest*.
- **User mode:** does not allow changing the beamline related settings, but provides authorization to change setpoints and feedback parameters and configuration. Username for this mode is: *user*, and the password is: *BeamlineUser*.
- **Cruise mode:** it is a mere visualization access, does not allow to change any configuration of the BEST system. It is only possible to visualize the acquired data. Username for this mode is: *cruise*, and it has no password.

An example of a login dialog is shown in **Figure 24**. User can access to this window by clicking on *Settings->Login*. "Current level" field shows current access level and is changed whenever a new correct combination of username and password is entered.

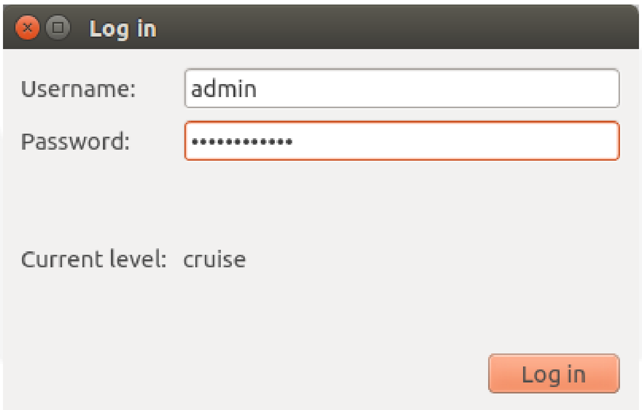


Figure 24: Login window

4.3 Beamline Configuration

This window allows calibrating and setting the BEST system to exactly match the actual beamline configuration. Its proper configuration is of paramount importance in order to insure a correct functionality of the system and a meaningful calibration of the units used to display data. Users can access this window by clicking on *Settings->Beamline*.

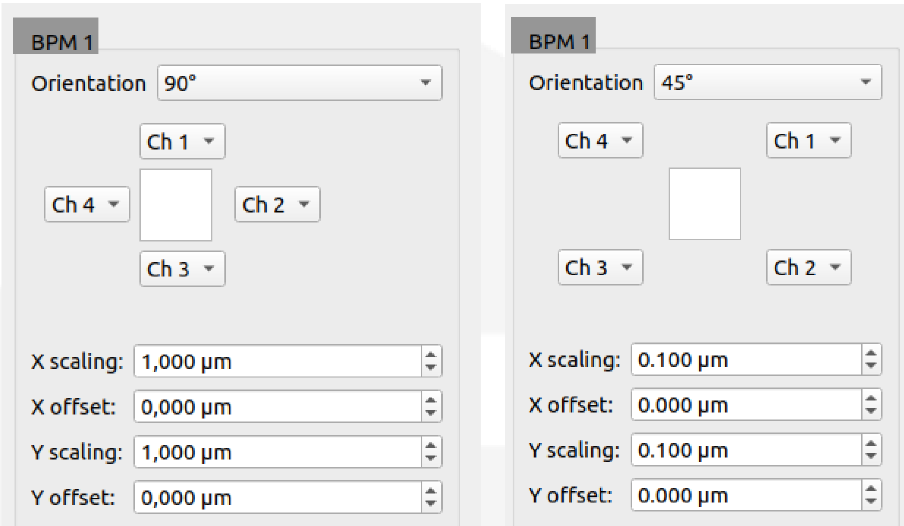


Figure 25: Beamline Configuration window for a 90° phBPM system (on the left) and for a 45° phBPM system (on the right).

A quick overview of the available beamline configuration options are represented in the following sections.

4.3.1 Beam Position Monitor

The BPM (Beam Position Monitor) section allows the input of the correct phBPM geometry, by selecting how the readout channels of the TetrAMM are matched to the phBPM. It also provides the capability to properly calibrate the position-sensitive detector by inserting the experimentally determined scaling factors in the beam position calculations.

In a standard 90° phBPM system (e.g. systems based on photodiodes located top/bottom & left/right of a scattering foil), the X-Y and Intensity (I_0) of the Beam are calculated with the following formulas:

$$X = K_X \frac{I_{RIGHT} - I_{LEFT}}{I_{RIGHT} + I_{LEFT}} + Offset_X$$

$$Y = K_Y \frac{I_{TOP} - I_{BOTTOM}}{I_{TOP} + I_{BOTTOM}} + Offset_Y$$

$$I_0 = I_{TOP} + I_{BOTTOM} + I_{LEFT} + I_{RIGHT}$$

where I_{TOP}, I_{RIGHT}, I_{BOTTOM} and I_{LEFT} are the acquired input channels currents values. Referring to **Figure 25**, I_{TOP}, I_{RIGHT}, I_{BOTTOM} and I_{LEFT} are assigned to Ch1, Ch2, Ch3 and Ch4 respectively, K_X and K_Y are respectively "X scaling" and "Y scaling" parameters and $Offset_X$ and $Offset_Y$ are respectively "X offset" and "Y offset" parameters.

It is recommended to either scan the detector in the beam or move the beam in a controlled way over the detector in order to correctly match the TetrAMM channels to the detector.

K_x, K_y are the scaling factor for X and Y dimension, respectively. They should be determined experimentally by moving the beam over the detector (or vice-versa) by a known amount and comparing this given amount with the un-calibrated response of the phBPM. Then, they must be store in the X scaling and Y scaling input windows shown in **Figure 25**.

In some cases, a second phBPM is installed on the same beamline, either intrinsically with a different geometry (e.g.: diamond-based phBPM) or with the phBPM system rotated CW by 45° in order not to get shadowed by the first unit upstream. Then, the computation needs to be modified. The equations used in a 45° rotated phBPM system are the following:

$$X = K_X \frac{(I_{TOP-RIGHT} + I_{BOTTOM-RIGHT}) - (I_{TOP-LEFT} + I_{BOTTOM-LEFT})}{I_{TOP-RIGHT} + I_{BOTTOM-RIGHT} + I_{TOP-LEFT} + I_{BOTTOM-LEFT}} + Offset_X$$

$$Y = K_Y \frac{(I_{TOP-RIGHT} + I_{TOP-LEFT}) - (I_{BOTTOM-RIGHT} + I_{BOTTOM-LEFT})}{I_{TOP-RIGHT} + I_{BOTTOM-RIGHT} + I_{TOP-LEFT} + I_{BOTTOM-LEFT}} + Offset_Y$$

$$I_0 = I_{TOP-RIGHT} + I_{BOTTOM-RIGHT} + I_{TOP-LEFT} + I_{BOTTOM-LEFT}$$

Referring to **Figure 25**, $I_{TOP-RIGHT}$, $I_{BOTTOM-RIGHT}$, $I_{BOTTOM-LEFT}$ and $I_{TOP-LEFT}$ are assigned to Ch1, Ch2, Ch3 and Ch4 respectively, K_X and K_Y are respectively "X scaling" and "Y scaling" parameters and $Offset_X$ and $Offset_Y$ are respectively "X offset" and "Y offset" parameters.

4.3.2 Bias Voltage - optional

The Bias Voltage settings allow to set the bias voltage possibly required by the detecting system. The field "HV Status" shows whether the optional embedded bias voltage module in the TetrAMM is switched ON or OFF. The bias voltage module can be switched on by clicking the "Enable HV" button. Then the desired bias output voltage value can be set by entering its value in "Bias voltage" field and by pressing the "Set HV" button.

The fields "Voltage readout" and "Current readout" report the real, measured voltage and current values at the output of the bias voltage module.

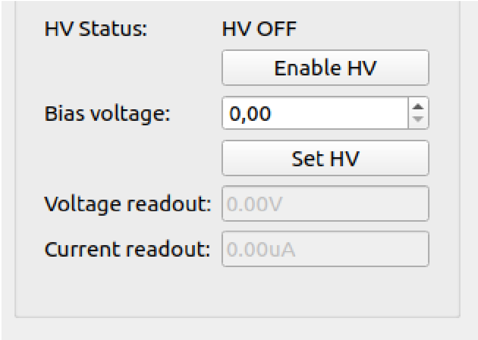


Figure 26: Beamline Configuration window: bias voltage module settings.

4.4 Region of Convergence and Region of Interest

Before enabling the PID controller, the user should set precisely the region of convergence and the region of interest areas. By clicking on *Settings->ROC/ROI* a new window shows up which enables user to set the desired values (see **Figure 27**).

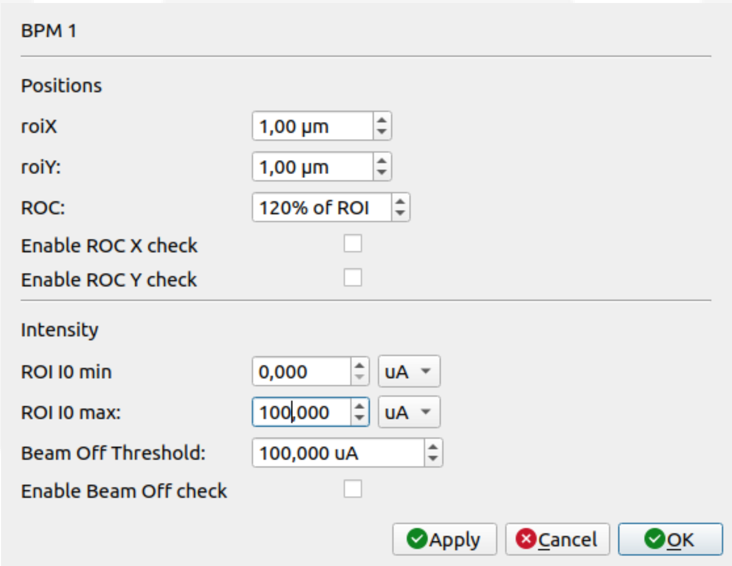


Figure 27: ROC/ROI Settings window

The Region of Convergence (ROC) is the maximum area where the PID controller stabilizes the beam to a certain setpoint. If for any reason the beam position goes outside of this area, the controller stops and shows the error: Beam out of ROC.

The Region of Interest (ROI) defines the area where the target beam position can be set by the user, either by pointing and clicking (**Figure 18**) on the XY graph or by entering the desired values. The ROI can be, at most, as large as the ROC, whilst typically the ROC includes a larger area than the ROI in the X-Y space.

Finally, the user can set a Beam-Off threshold value for the intensity readout of the phBPM (Beam Off Threshold). When the "Enable Beam Off check" input field is checked, the Central Unit will pause the feedback loop if the beam intensity goes below the defined threshold and it will automatically reactivate the feedback loop when the intensity goes back to values above the set threshold.

Please note the difference between the *stop* condition (if the ROC input fields are checked) that fully freezes the feedback loop when the beam position goes out of the ROC, and the *pause* condition, that temporarily pauses the feedback loop when the beam intensity goes below the Beam Off Threshold.

4.1 DAC Manual Output Control

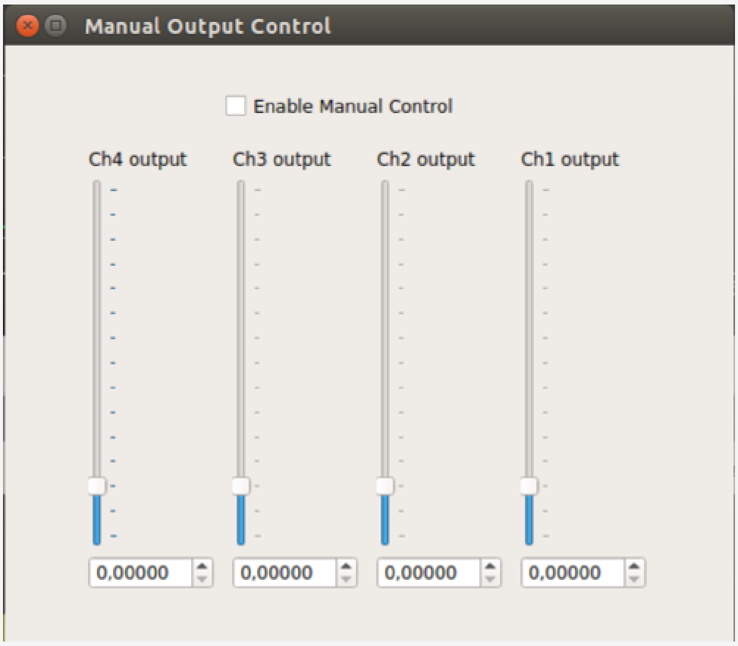


Figure 28: Manual Output Control configuration window.

From *Tools->Manual Output Control* the user can drive each of the PreDAC outputs manually by checking the "Enable Manual Control" checkbox.

4.2 Picoammeter Configuration

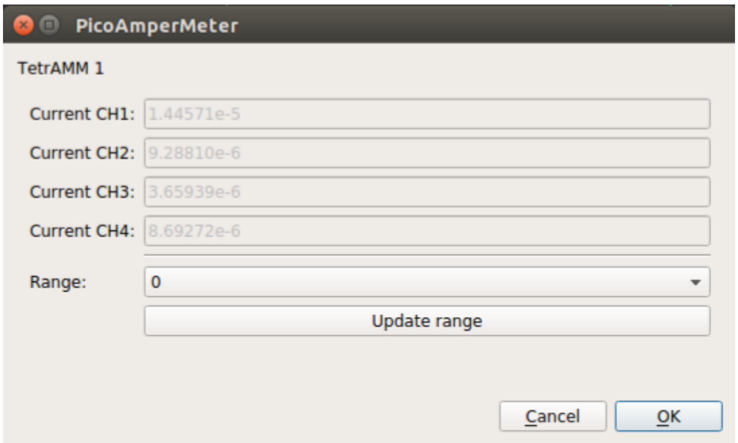


Figure 29: Picoammeter configuration window.

From *Settings->Picoammeter Configuration* the user can change the TetrAMM reading range (gain). Available options are "0" (higher current range) and "1" (lower current range).

4.3 SFP Info

The "SFP Info" window, which is accessible from *Settings->SFP Info,* shows the devices connected to the SFP Connectors placed on the rear side of the BEST Control Unit.

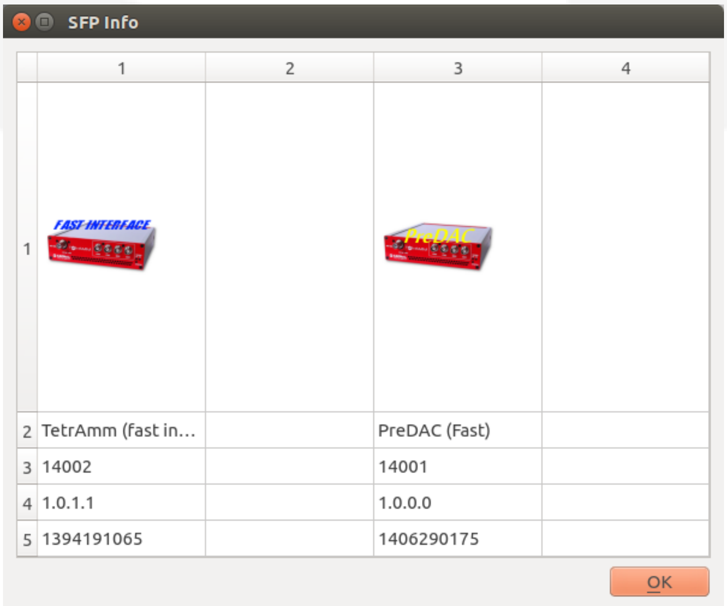


Figure 30: SFP Info window

4.4 Frequency Analysis Tool

The "Frequency Analysis Tool" window, which is accessible from *Tools->Frequency Analysis Tool,* allows the user to perform a dynamical frequency analysis of the system by determining its Bode plots (phase and amplitude). The Bode plot is a graph of the frequency response of a system. It is usually a combination of a Bode magnitude plot, expressing the magnitude of the transfer function (in [m]/[V]), and a Bode phase plot, expressing the phase shift (in degrees). Both axis in the Bode magnitude plot are in logarithmic scale, while only the x-axis in the Bode phase plot is in logarithmic scale.

We follow the established, classic approach: a sinusoidal stimulus of constant amplitude generated by the PreDAC is swept through a pre-defined frequency range and, in parallel, the system response is read by the TetrAMM and analyzed by the Central Unit. The Frequency Analysis Tool uses the I/Q modulation/demodulation principle to extract magnitude and phase of the system response.

We provide a very simple graphical interface allowing the user to:

- Set the start and stop frequency of the test;
- Set the spacing and the number of points for the frequency analysis;
- Set the PreDAC output channel to use as frequency signal stimulus;
- Set the TetrAMM input channel for the I/Q demodulation; this allows studying both direct correlation (i.e.: stimulus and response applied and read on the same variable, either X or Y) and cross-correlations (e.g.: stimulus on X Vs. response on Y);
- Set the fixed amplitude of the sinusoidal stimulus in Volts p-p.

The acquired data can be exported in .csv format for further analysis.

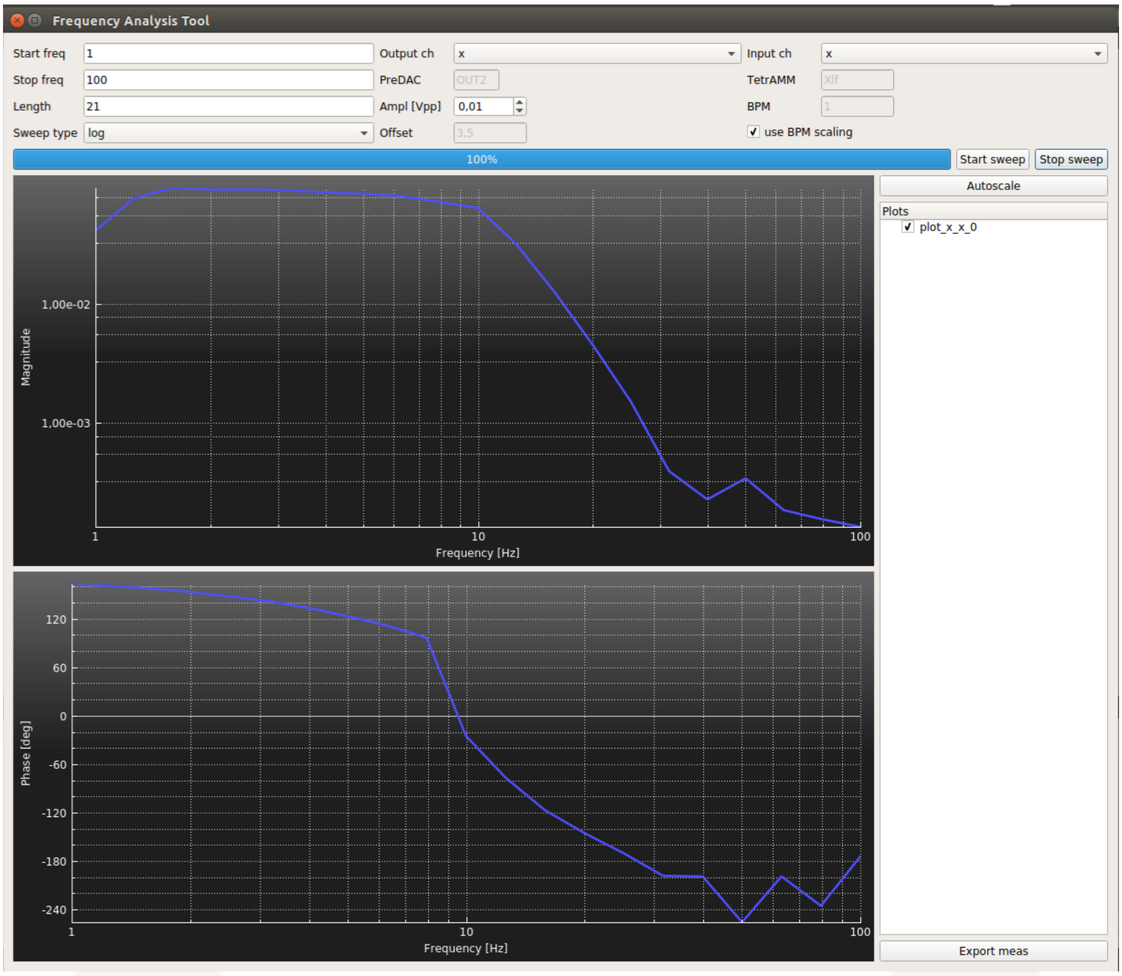


Figure 31: Frequency analysis tool window

5. EPICS

EPICS is a software environment widely used in accelerators facilities to remotely operate and monitor a given set of instruments/modules.

Using a client/server technique, where servers (and ioc controllers) collect data from the instrumentation in real-time and clients access those data via the channel access network protocol, EPICS allows integration of instruments with a given set of commands.

In order to do so, **BEST-EPICS-IOC** is an open-source software available on the **github** platform. It is based on the functionalities offered by the BEST library that is part of the BEST software suite and constantly updated with new features. An API reference manual of the BEST library is available at CAEN ELS website.

BEST-EPICS-IOC offers a wide set of instructions to query and configure the BEST Central Unit. A specific command's reference manual with a full list and description of EPICS commands is available at CAEN ELS website.

The BEST system is compatible with EPICS-7 (base-7.0.6.1). To show the basic EPICS functionalities we will monitor the EPICS commands from the BEST Local User Interface. The **BEST-EPICS-IOC** source code is available at https://github.com/CAENels/best-epics-ioc.

5.1 EPICS IOC Integration

Start the BEST Local User Interface

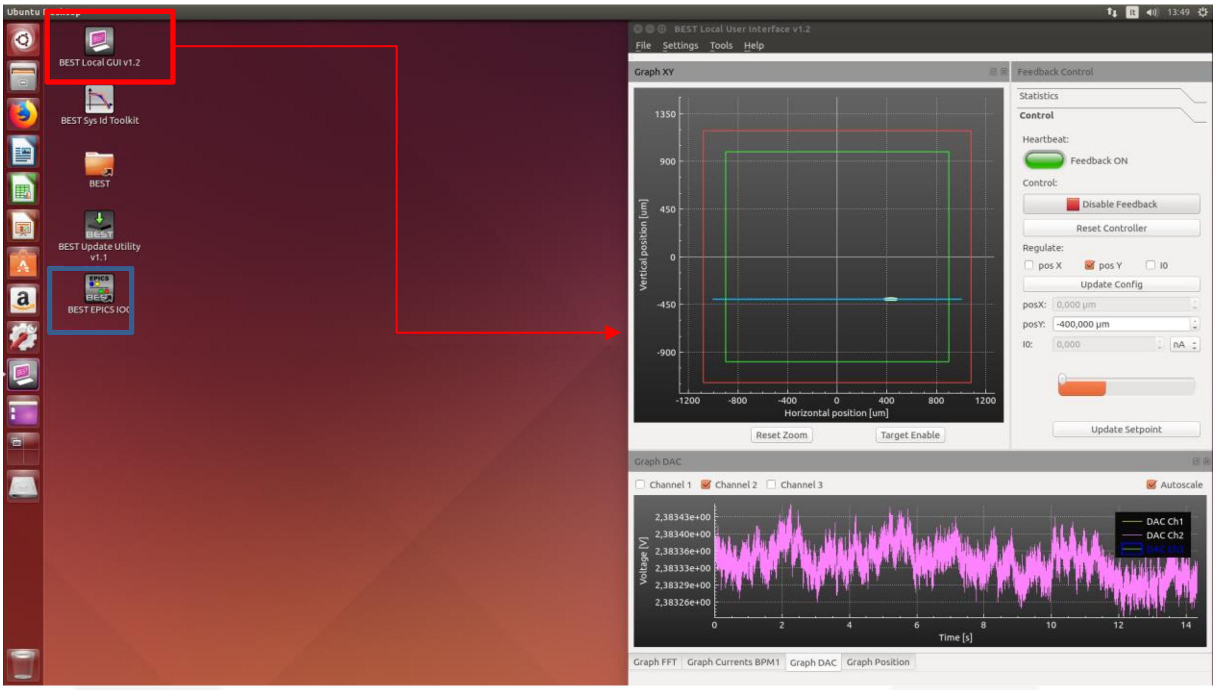


Figure 32: Run the BEST Local User Interface.

In order to start the EPICS server, double-click the BEST EPICS IOC application (framed in blue in the picture above).

After launching the application, a terminal appears and the EPICS server will return the EPICS server shell:

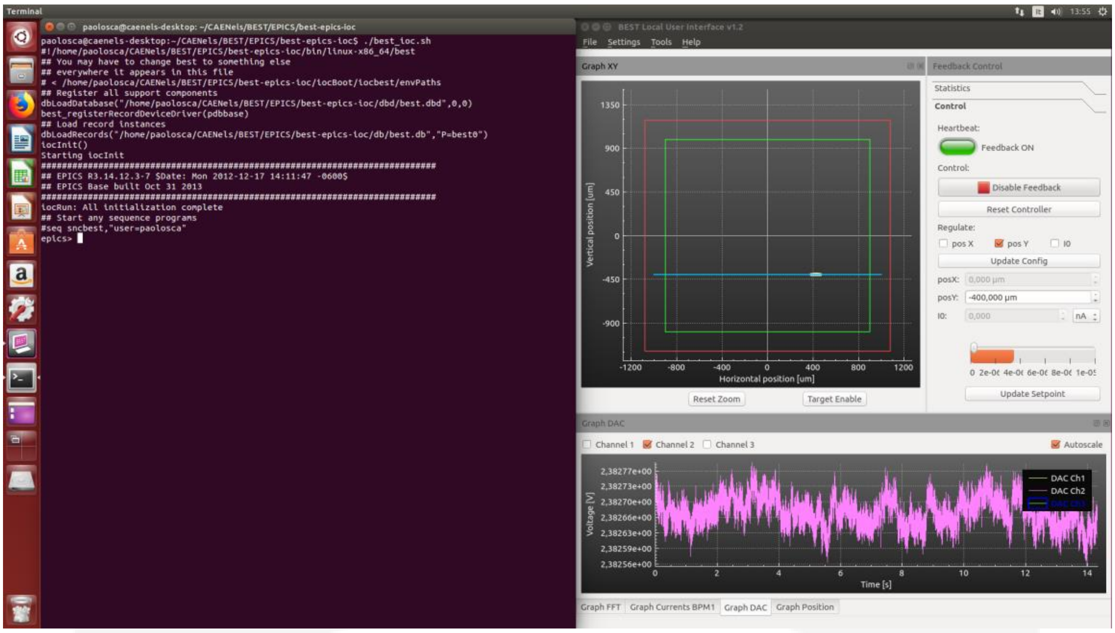


Figure 33: Run the BEST EPICS server.

The system shows that the procedure is completed, therefore EPICS control is allowed:

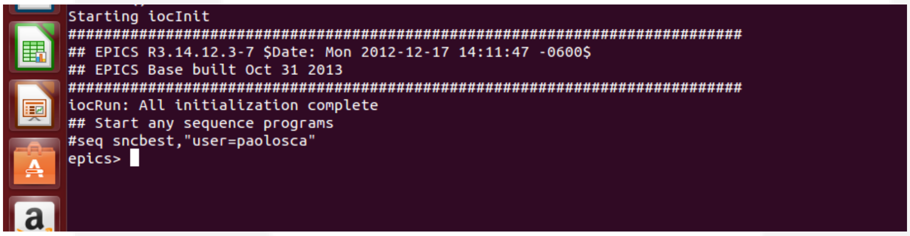


Figure 34: BEST EPICS server initialization.

By typing “dbl” it is possible to see the complete list of the BEST EPICS commands.

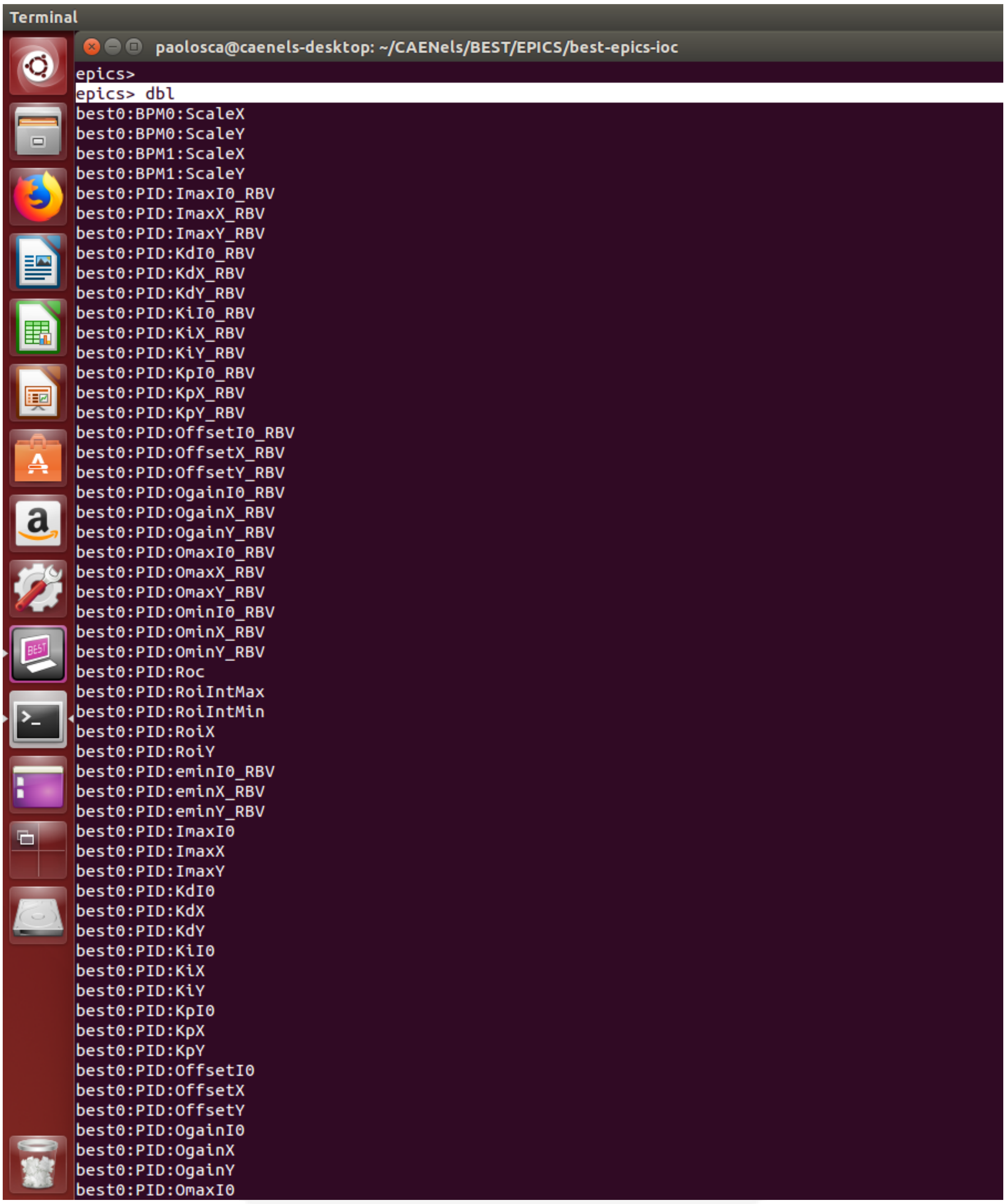


Figure 35: BEST EPICS commands.

From the client side, assuming EPICS is correctly installed, the user has access to all the commands available (e.g. caput, caget, camonitor, etc.).

5.2 BEST login using EPICS

As for the BEST Local User Interface, also EPICS respects the login credentials reported in section 0. To Login do as follows:

```
$ caput best0:Login:UserPass admin:WeAreTheBest
Old : best0:Login:UserPass
New : best0:Login:UserPass          admin:WeAreTheBest
```

5.3 Controlling the PreDAC output in Open Loop

In order to control the PreDAC in open loop, the first operation is to ensure that the feedback controller is disabled:

```
$ caput best0:PID:Enable 0
Old : best0:PID:Enable                    OFF
New : best0:PID:Enable                    OFF
```

The PreDAC output MUX has to be set to 0. This means that the PreDAC is controlled by software (i.e. from the Linux driver through PCIe).

```
$ caput best0:PreDAC0:OutMux 0
Old : best0:PreDAC0:OutMux                SW via PCIe
New : best0:PreDAC0:OutMux                SW via PCIe
```

Lastly, the user can set the PreDAC output voltage:

```
$ caput best0:PreDAC0:OutCh2 3.25
Old : best0:PreDAC0:OutCh2                0
New : best0:PreDAC0:OutCh2                3.25
```

The PreDAC output voltage can be monitored from the BEST Local User Interface:

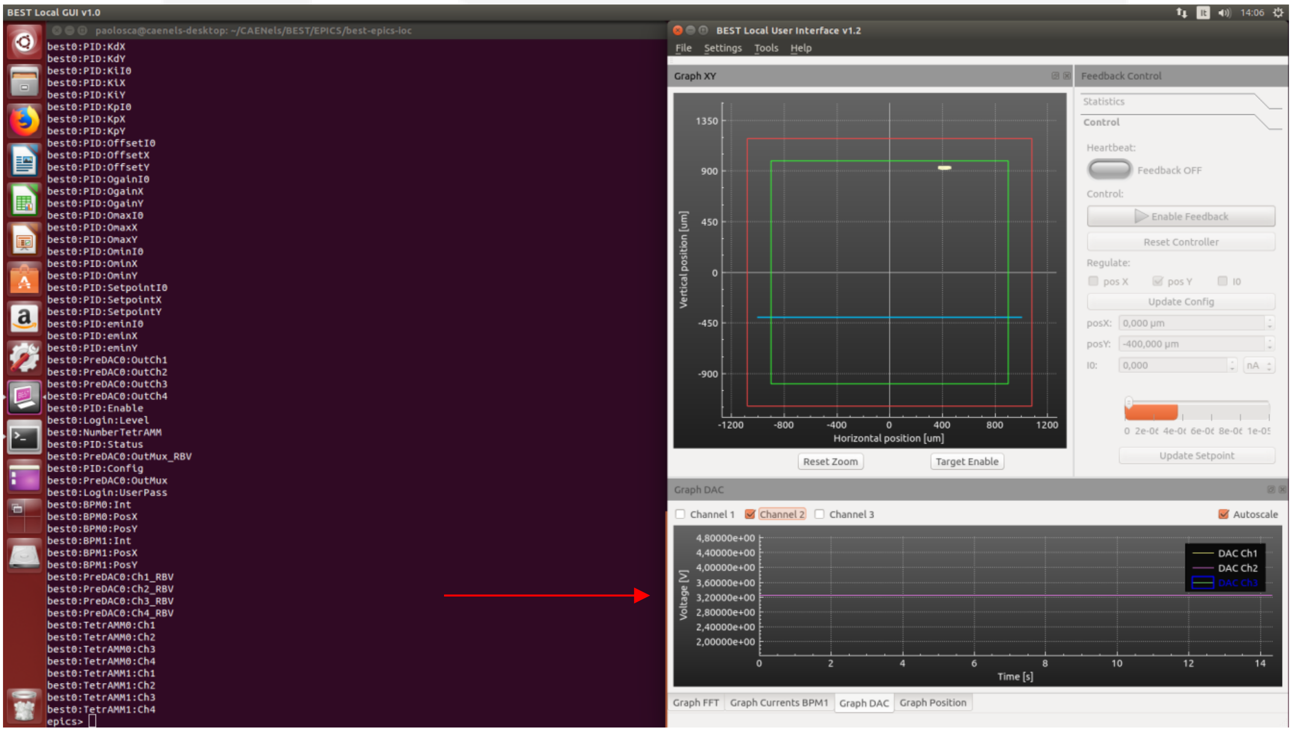


Figure 36: BEST EPICS controlling PreDAC output.

5.4 Controlling the PreDAC output in Closed Loop:

The closed loop configuration is the default configuration where the feedback controller implemented in FPGA logic performs all the calculations in order to get the X/Y positions or intensity to the user defined setpoint.
The user must firstly ensure that the PreDAC output is driven by hardware (i.e. FPGA) and not by software (i.e. through the PCIe):

```
$ caput best0:PreDAC0:OutMux 1
Old : best0:PreDAC0:OutMux            SW via PCIe
New : best0:PreDAC0:OutMux            FPGA
```

Now the feedback controller can be enabled:

```
$ caput best0:PID:Enable 1
Old : best0:PID:Enable                OFF
New : best0:PID:Enable                ON
```

And finally it is possible to control the position in closed loop:

```
$ caput best0:PID:SetpointY -600
Old : best0:PID:SetpointY             0
New : best0:PID:SetpointY             -600
```