Performance assessment of the new remote power supply controller for the Elettra Storage Ring magnets.

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Abstract – **Among the wide range of applications that power supplies are able to cover, the Particle Accelerator based Light Sources are one of the most demanding. In the specific case of the Elettra Storage Ring, a Synchrotron Radiation Facility operating since 1993, magnet power supplies with other critical devices are determining the quality of the photon beams and overall accelerator uptime. Because of that, they have to provide stable, reliable, precise and remotely controlled operation. From a strictly functional perspective, each magnet power supply can be seen as a power part, regulating the output current, and a control part to connect the unit to the remote control system. The original Elettra magnet power supplies are still reliably in operation but their control parts, based on VME boards and MIL 1553 interfaces, need an update to cope with ageing, components obsolescence and servicing. This paper presents the laboratory and on-field performance of the NewPSC (New Power Supply Controller), the board designed at Elettra to replace the VME-based power supplies control systems in the Storage Ring.**

Keywords—magnet power supply; remote control; particle accelerator; synchrotron light source; BeagleBone;

I. INTRODUCTION

The quality of the photon beams delivered to the beam lines in modern third generation (synchrotrons) and fourth generation (Free Electron Lasers - FEL) light sources is strictly related to the stability and controllability of the orbit/trajectory of the charged particles (usually electrons) running inside the accelerator. In both structures, either "closed" (i.e. Storage Rings, like Elettra – see, e.g. [1], [2]) or "open" (i.e. FEL, like FERMI, see e.g. [3], [4]), global feedback systems acquire the position of the particle bunches at specific points inside the particle accelerator. Then, accordingly to the theoretical model of the accelerator, the feedback system performs the correcting actions required to maintain stable the orbit/trajectory in the user dedicated photon emission regions. From the magnet power supplies (PS) point of view, the global feedback action applies new set points for the magnet currents in real time manner.

Moving from the general description to the specific case of the Elettra Storage Ring (SR), there are two power supplies sub-systems. The first one comprises the so-called "big" (in term of current, up to 2000 A) and "slow" (in term of correction repetition rate) magnet power supplies (42 units in total) [5]. The second sub-system is composed by the 164 "small" (up to 16 A) and relatively "fast" (up to 100 Hz) correcting magnet power supplies [6]. For the scope of this work, it is possible to consider the power supplies as follows (Fig. 1): a power part dedicated to the regulation of the output current with its low-level electronics and a control part, dedicated to supervision and remote control tasks. The power part energizes the associated magnet(s); the control part, consisting of low power mixed signal electronics, connects the PS to the remote control network. The reason for this modular scheme [7] is to separate the power and its low-level electronics from the controllers. It allows replacing or upgrading both parts of the PS independently (e.g. in case of servicing issues, component ageing or obsolescence). The VME-based PS controllers are in use since 1993, still providing "reasonably reliable" 24/7/run operations. Nevertheless, new technologies (in telecommunication and semiconductor) make the VME-based devices obsolete and too expensive to maintain. Consequently, an upgrade program focused on designing the new generation controllers for power supplies (NewPSC) has started, and the BeagleBone [8] is its core. Due to the smaller number of units (42 vs. 184) this upgrade program will modify the "Big" PS at first. A second phase will focus on the more numerous corrector PS.

II. THE REMOTE CONTROL OF SR PS

The Elettra Storage Ring is a complex plant, not only from the remote control perspective. The PS subsystem, in particular, is currently based on a hierarchical control system as described in paragraph B.

A. *Power supplies architecture*

The SR "Big" PS are custom design ones, following detailed technical specifications. The block diagram, shown in Fig. 1, refers to these PS. The interface to the Elettra Control System is the so-called EIU (Equipment Interface Unit): a VME crate installed inside the PS Cabinet (figures 2 and 3).

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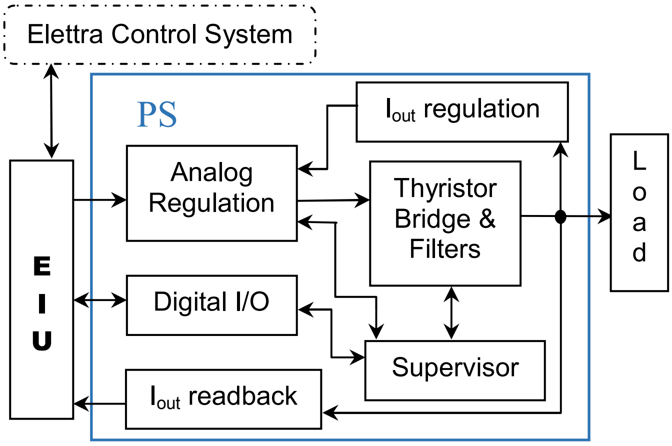

Fig.1 block diagram of the power supply

Fig.2 SR PS power supplies (3 units in a single cabinet)

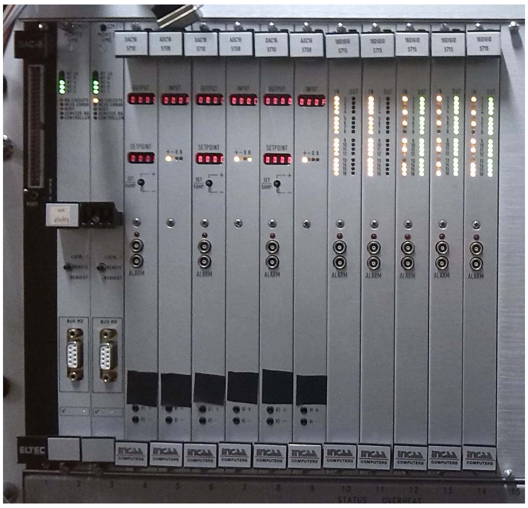

Fig.3 EIU (detail from Fig. 2).

With reference to Fig. 1, the following list reports the function of each block:

- Thyristor Bridge & Filter: The Thyristor Bridge converts the AC mains into regulated and filtered DC.
- I_{out} regulation: analog signal from a high precision dedicated DCCT (DC Current Transformer) for measuring the magnet current used in the regulation loop (Feedback).
- I_{out} read back: analog signal from a high precision dedicated DCCT – different from previous – for measuring the magnet current. It is forwarded to the control system (read back) via the EIU.
- Analog regulation: it implements the analog feedback loop that follows the analog reference input signal (from EIU) regulating the output current delivered to the magnet, by generating the thyristor trigger pulses.
- Digital I/O: 22 digital inputs indicating the status of the PS and 6 digital outputs controlling the PS.
- Supervisor: it's responsible for the whole operation of the system, both in normal and anomalous situations (i.e. interlock request).
- Load: magnets (e.g. dipoles, quadrupoles, or sextupoles) according to the specific function required by the accelerators electron beam optics.

The following signals are the interface between the PS and the EIU:

- analog input set point, also named as reference signal, a voltage in the 0 – 10 V range;
- analog output voltage, magnet current value, a voltage in the 0 – 10 V range;
- digital IO signals (pulses and levels);

B. *Control System architecture*

The connection of the EIU (and the associated PS) to the Elettra Control System is organized in layers (Figure 4.).

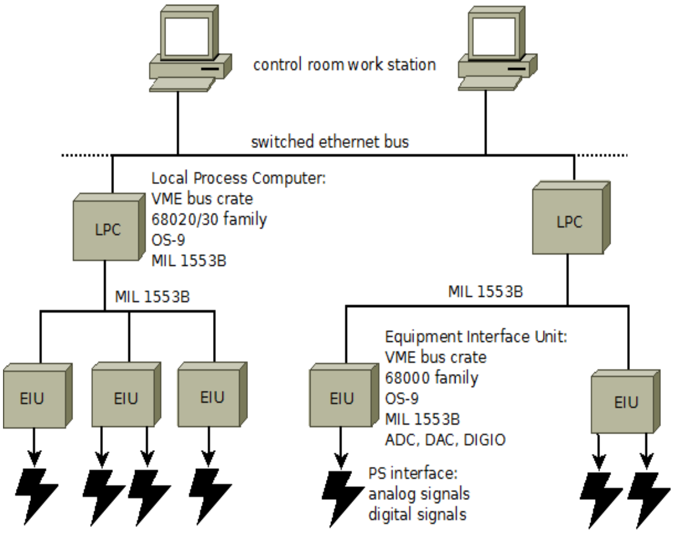

Fig.4 power supplies control system architecture.

With reference to Fig. 4, the levels are:

- Top level: the control room workstations. It is dedicated to the supervision of the whole machine's sub-systems, both by human and automatic operation.
- Middle level: a set of Local Process Computers (LPC). It performs both bridging functions between Ethernet and MIL networks and local supervision/control tasks.
- Bottom level: a set of Equipment Interface Units (EIU). It performs local supervision/control tasks.

In particular, the EIU are directly related to the operation and interfacing between PS and control system. As already mentioned, the EIU is the control system node directly connected to each PS through their dedicated interfaces.

The practical implementation of an EIU is a VME crate equipped with specialized VME boards. Figure 3 shows an example of VME crate connected to three PS in a single cabinet (figure 2). With reference to Figure 3, the boards are (left to right, the numbers refer to their position in the crate):

- 1: CPU board, the local controller.
- 2 and 3: MIL 1553B serial communication boards.
- 4, 6 and 8: DAC boards (16 bit).
- 5, 7 and 9: ADC boards (16 bit).
- 10 to 14: digital I/O boards.

Following the PS interface signals scheme (Fig. 1), each DAC board generates the reference voltage, and each ADC board reads the magnet current read back signal. Digital I/O VME boards provide commands and read status to/from the digital I/O of the PS interface.

III. NEWPSC

As already mentioned, the age and the obsolescence of the VME boards is an issue for guarantee high reliable operation of the Storage Ring. Our team started a program to design a new generation of local PS controller (NewPSC) to replace the EIU and part of the low-level electronic cards of the “Big” PS of the Storage Ring. The BeagleBone board has already been used at Elettra in other projects with excellent results [9], [10], and it has been considered as a promising choice for a first prototype of the NewPSC [11].

A. *BBC (BeagleBone Carrier) structure*

An in-house design allows replacing a full set of VME cards (CPU, communication, ADC, DAC, Digital I/O) with a single board, named BBC (BeagleBone Carrier). The VME CPU, the MIL 1553B serial communication and the digital I/O boards will be replaced by a BeagleBone, a single-board computer powered by an ARM CPU, open-source with native Ethernet interface. The VME DAC and ADC boards will be replaced with high precision components. More precisely the DAC is a 20-bit Analog Devices AD5791 [12], while the ADC is a 24-bit ΔΣ Texas Instruments ADS1271 converter.

Our team has developed two BBC prototypes (Fig. 5).

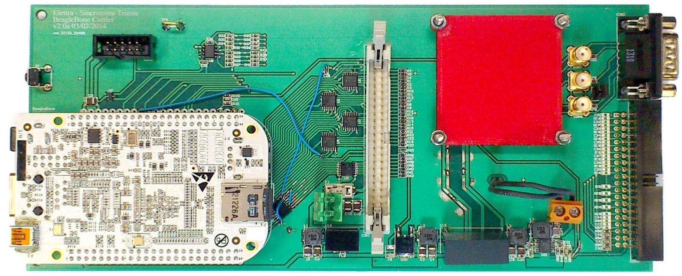

Fig.5 BBC hardware release 2 (the BeagleBone is visible at bottom-left).

The main components of the BBC are:

- BeagleBone board with Ethernet adapter,
- 20-bit DAC (set point),
- 24-bit ΔΣ ADC (read back),
- Digital I/O connectors,
- Touch screen for local control of the PS.

Both hardware releases share the same architecture, the main difference between them consists in the thermostatic system (under the red box in Fig. 5) for the analog subsystem to further improve its overall performances. The developed prototype allows easy replacement of the existing PS control part. It passed both the test in the laboratory (section IV) and the installation as a working machine inside Elettra Storage Ring (section V)

B. *NewPSC as “intelligent” node*

Being based on Texas Instruments AM3358 SOC (System on Chip), the BeagleBone board (rev. A6) can execute several complex tasks related to the power supplies, running both in remote and local control mode. In particular, the various functions (i.e. energy ramping, magnets cycling, remote control) that are currently distributed over different control system layers (Fig. 4) and implemented by VME crates (LPCs and EIUs), can be embedded in each NewPSC board by a dedicated software framework (Tango Device Server [13]). Thus the control system architecture can be reduced to a single layer by a direct network connection between the Ethernet switched bus (see Fig. 4) and each NewPSC board controlling its specific power supply interface. The current release of the Tango Device Server running inside the BeagleBone has been successfully tested. Adopting the necessary patches on the machine control system software (RPC calls based), the first NewPSC prototype has been fully integrated [14], [15].

IV. LABORATORY TEST OF THE NEWPSC

A series of laboratory tests were performed in order to measure the performance of the BBC. The most important ones are describing the DAC and ADC - their accuracy directly affects the performance of the PS. Laboratory test included noise performance, long-term stability, and temperature drift of the DAC and ADC.

A. *Noise performance of the ADC*

The modern delta-sigma (ΔΣ) ADC are providing high readout resolution (over 24 bits) keeping very high sampling rate (at least 100 kSPS). Unfortunately their output signal contains lot of noise and requires additional filtering.

In the NewPSC a Texas Instruments ADS1271, 24-bit ΔΣ ADC is used in high resolution mode. The ADC input range is extended to ±10 V using a differential amplifier with gain $G_{\mathrm{diff}} = 0.25$ V/V. The noise histograms were plotted (Fig. 6) while measuring 2.5 V reference. They present the number of occurrences of sample value over 400000 acquired samples. The zero on sample value axis equals to the mean value across all samples. The width of one bar equals to 3 LSB (9.54 µV at the input of differential amplifier or 2.38 µV at the input of the ADC). The noise of ADS1271 ADC is present on eight LSB. In practice this means that without digital filtering applied to the output data of ADC, its effective resolution is 16 bits.

The recorded noise performance of the NewPSC ADC circuit is better than those recorded on the Texas demo board ADS1271EVM under the same conditions.

B. *Long term stability*

The quality of the electron beam inside Elettra Storage Ring strongly depends on stability of the magnetic field inside the magnets and therefore on their excitation current. It is crucial to provide the PS with a stable set point (DAC) to the regulation circuitry of the PS and get good read back (ADC) values of the current in the magnets connected to the PS.

In order to measure long-term stability of the DAC and ADC, a laboratory setup was prepared. The NewPSC was tested in a Perani UC150/10 climatic chamber stabilizing the temperature of the inside environment at 21 °C (average temperature inside Elettra Storage Ring Service Area). The input of ADC circuit was connected to a 6.5 V reference Fluke 5440B. The output of the DAC was connected to an Agilent 34970A Data Acquisition Unit, then a 12-hour logging was started. The logs of DAC set point are presented on Fig. 7 and the logs of ADC readout on Fig 8. Each point on ADC readout plot equals to the mean value across consecutive 2048 samples.

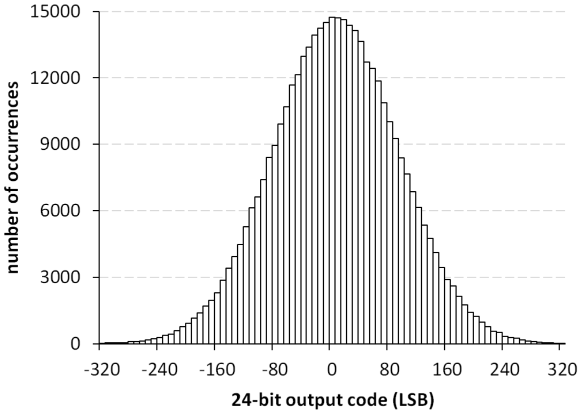

Fig.6 Noise histogram of ADC

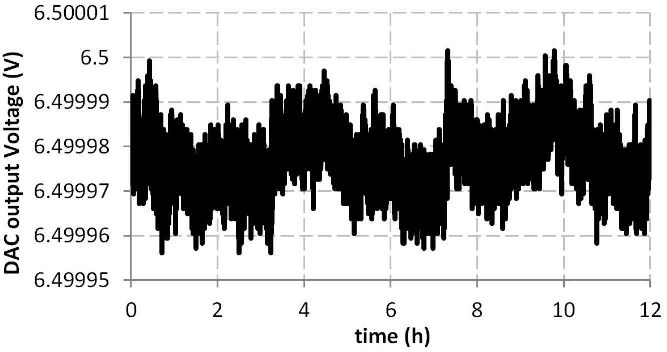

Fig.7 Log of the set point (DAC) over 12 hours

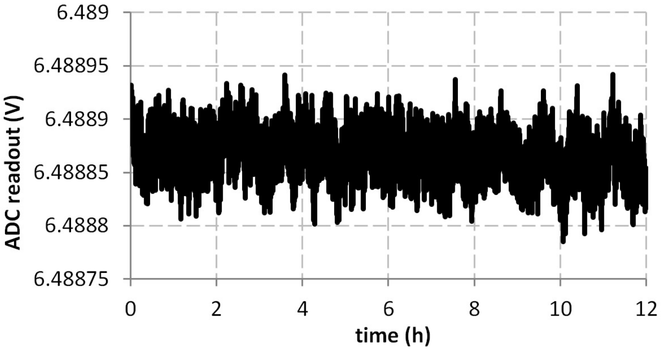

Fig.8 Log of the readout (ADC) over 12 hours

The data obtained from the 12-hour log shows that the NewPSC peak-to-peak variation of the DAC set point is 45 µV (±2.25 ppm over 10 V range). The peak-to-peak variation of the ADC read out is 150 µV (±7.5 ppm over 10 V range).

C. *Temperature drift*

Increasing the accuracy of the voltage and current measurements, the influence of the environment temperature has always to be taken into account. The average temperature inside Elettra Storage Ring Service Area is 21 °C but it can vary from 19 ºC to 23 ºC during the year.

The measured drift of the DAC output voltage over that temperature range is $\Delta U_{\mathrm{DAC}} = 130$ µV (13 ppm over 10 V range), for the 6.5 V set point (Fig. 9). The measured drift of the ADC circuit readout is $\Delta U_{\mathrm{ADC}} = 320$ µV (32 ppm over 10 V range), while measuring reference voltage 6.5 V (Fig. 10).

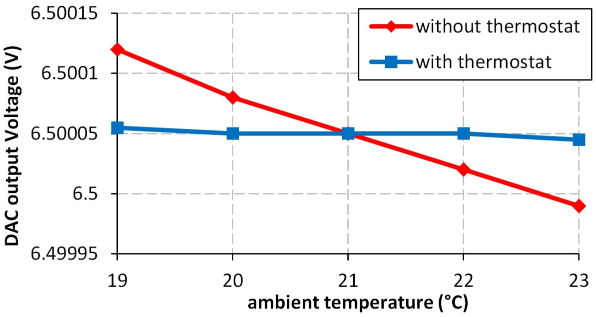

Fig.9 Drift of the DAC output vs. ambient temperature

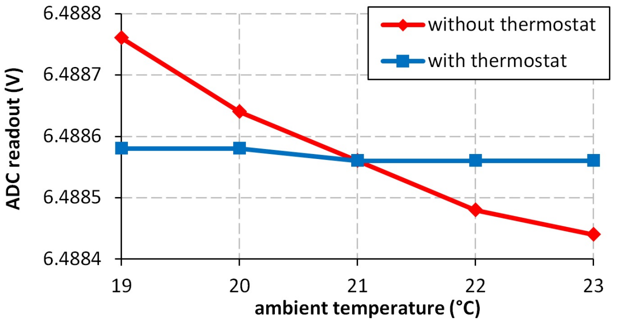

Fig.10 Drift of the ADC readout output vs. ambient temperature

The drift of the DAC output is mainly related to the drift of its voltage reference. Measured drift of the 10 V ADR01BRZ voltage reference is 90 µV (9 ppm) over the temperature range 19 °C to 23 °C. The drift of the ADC is related both to the drift of the reference and of the differential amplifier integrated circuits. Measured drift of the 2.5 V ADR431BRZ voltage reference is 20 µV (8 ppm) over the temperature range 19 °C to 23 °C.

To decrease the drift of the DAC output voltage and ADC readout a thermostat circuit was added. It is based on a small heater, glued to the bottom side of the PCB, under the DAC and ADC circuits, keeping the local temperature of the PCB at 35 °C. Then the heater as well as DAC and ADC circuits were closed in a small box (the red enclosure on top right in Fig. 4), to insulate them from the environment. With the thermostat, the drift of the DAC dropped to $\Delta U_{\mathrm{DAC}} = 10\ \mu\mathrm{V}$ (Fig. 9), and the drift of the ADC dropped to $\Delta U_{\mathrm{ADC}} = 10\ \mu\mathrm{V}$ (Fig. 10).

V. SR TEST OF THE NEWPSC

The testing of the NewPSC controller (HW release 1, without thermostat) in the Storage Ring service area has been structured in two phases, adopting the measurement setup shown in Fig. 11.

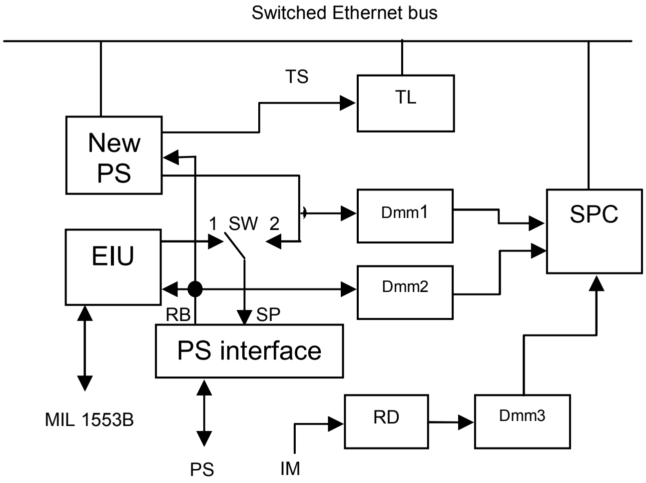

Fig.11 The measurement setup on a Storage Ring "Big" PS.

Three Keithley DMMs measure, respectively:

- NewPSC DAC output voltage (DMM1, PS interface analog input set point – SP);
- I_{out} read back from one of the PS internal Holec 500 SEP DCCT (DMM2, RB signal);
- magnet current (IM) read by a Danfysik 860MS Ultrastab DCCT (RD) used as external reference (DMM3).

Two temperature sensors (TSs) are respectively mounted on the ADC and DAC chips of the NewPSC board, and their readings are shared over the control network by a dedicated logger (TL). On the NewPSC side, the readings of its ADC and the digital word set to its DAC are collected and shared over the control network by the embedded Tango server running inside the BeagleBone. The supervising PC (SPC) collects data at 1-sample/second rate.

In the first phase (paragraph A), a NewPSC board was connected to the PS analog signals in parasitic mode (switch SW set to "1"). In the second phase (paragraph B), still in progress, the same NewPSC board is actively driving the PS interface by replacing the corresponding analog and digital signals generated or acquired by the EIU (switch SW set to "2").

A. Parasitic mode test

The goal of this phase was to evaluate the analog signal performances of the NewPSC board acting as passive observer of the analog and digital signals generated by the PS under normal operation.

During the real machine operation, the PS current is frequently adjusted by the EIU in order to keep the required characteristics of the electron beam in the Storage Ring, and therefore the stability of the ADC read back of the output current cannot be measured over a long period of time. On the other hand, being the PS current set value provided by the EIU, it is possible to fix the digital code sent to NewPSC DAC. The output voltage drift vs. temperature could then be logged, as shown in Fig.12 over more than 9 hours.

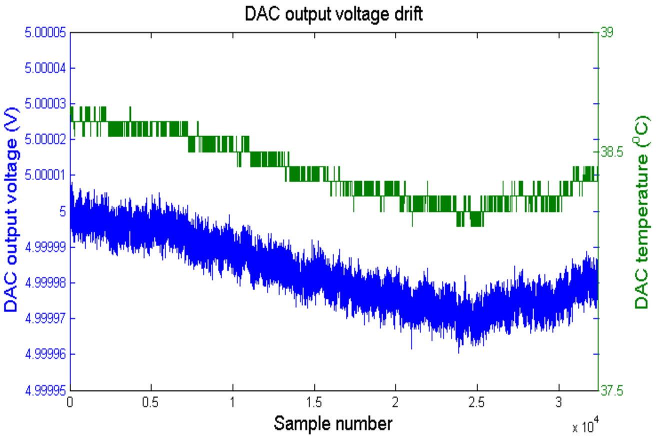

Fig.12 DAC output voltage (lower) drift vs temperature (upper) variations

The plot clearly shows how the PS reference voltage provided by the NewPSC is affected by temperature. The peak to peak logged variations are:

$\Delta V_{DAC\ peak\text{-}peak} = 47.6\ \mu V$, over a nominal set value of 5 V;

$\Delta T_{DAC\ peak\text{-}peak} = 0.5\ °C$;

B. Real mode test

The positive results gathered during the previous phase allowed the replacement of the signals managed by the EIU with those managed by the NewPSC board. In this way the analog reference signal is completely in charge of the NewPSC, as well as the digital signals related to the alarms and the PS start and stop procedures. Several logs have been carried out over the user dedicated machine shifts to capture as much data as possible to be related to the general behavior of the accelerator. A 45-hour log is reported in Fig. 13, the traces are (top to bottom):

- red - read back from ADC;
- blue – DMM2 connected to PS internal Holec DCCT;
- green - DMM3 connected to Danfysik 860MS Ultrastab DCCT, currently assumed as "reference".

The three plots are not overlapped due to the different calibration of the measuring devices.

VI. CONCLUSIONS

From the operations point of view the NewPSC seamlessly replaces the old EIU control unit, while improving analog signal processing and providing a more complete status and failure analysis.

The first prototype (hardware release 1) of the NewPSC is fully working and integrated in the current control system for normal operations of the accelerator. The second prototype (hardware release 2) keeps the same analog circuitry as the first one, featuring a thermostat circuit to stabilize the temperature of the analog signal processing parts. It is foreseen to proceed to a complete replacement of the EIUs using the hardware release 2, taking advantage of its excellent thermal stability.

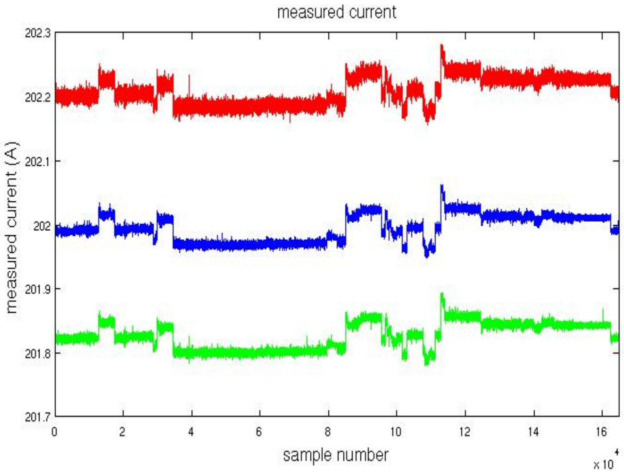

Fig.13 Log of output current (ADC, DMM2 and DMM3, top to bottom)

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