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Study of the hybrid controller electronics for the nano-stabilization of mechanical vibrations of CLIC quadrupoles

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ABSTRACT: In order to achieve the required levels of luminosity in the CLIC linear collider, mechanical stabilization of quadrupoles to the nanometre level is required. The paper describes a design of hybrid electronics combining an analogue controller and digital communication with the main machine controller. The choice of local analogue control ensures the required low latency while still keeping sufficiently low noise level. Furthermore, it reduces the power consumption, rack space and cost. Sensitivity to radiation single events upsets is reduced compared to a digital controller. The digital part is required for fine tuning and real time monitoring via digitization of critical parameters.

KEYWORDS: Analogue electronic circuits; Hardware and accelerator control systems; Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases); Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons)

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Contents

1 Introduction

In new linear accelerators, like the future Compact LInear Collider (CLIC) [1], sigma beam sizes are as small as 1 nm vertical and 40 nm horizontal. This requires extremely precise and stable quadrupole magnets. It has been calculated that for CLIC's main beam quadrupoles (MBQ) the integrated root mean square (r.m.s.) vibration of the power spectral density (PSD) down to 1 Hz needs to be 1.5 nm vertically and 5 nm horizontally [2]. A stiff active stabilization system has been developed to isolate the MBQs from ground movements, water-cooling induced vibrations and other technical noise sources, see figure 1a. There are about 4000 magnets in four different sizes to be stabilized: from type 1, with a length of 420 mm and 100 kg up to type 4 with a length of 1925 mm and 400 kg. Figure 1b shows a type 1 magnet used as a testbench for the CLIC's stabilization electronic controller, which is the subject of the present paper. The following sections explain the design constraints, describe the electronics and present experimental stabilization results.

2 Electronics design constraints

The task of the electronic controller is to acquire data from velocity sensors, process it and generate the required signals that drive the actuators of the stabilization system. Typical vertical ground vibration levels recorded at different locations around CERN can be seen in figure 2. The sensors used are Guralp seismometers, which measure absolute velocity with a sensitivity of 2000 V/(m/s).

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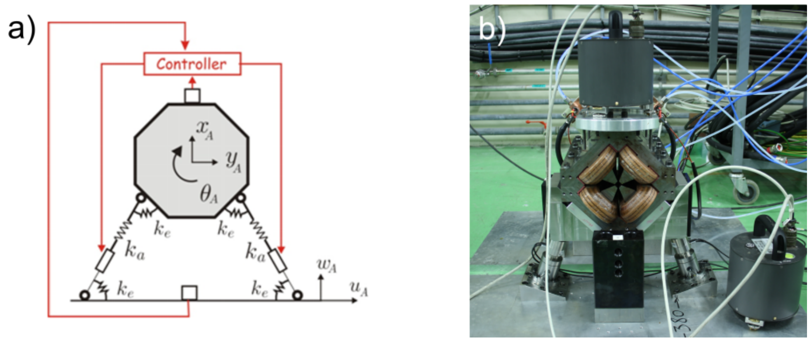

Figure 1. a) Stabilization control strategy b) Type 1 magnet on prototype stabilization system.

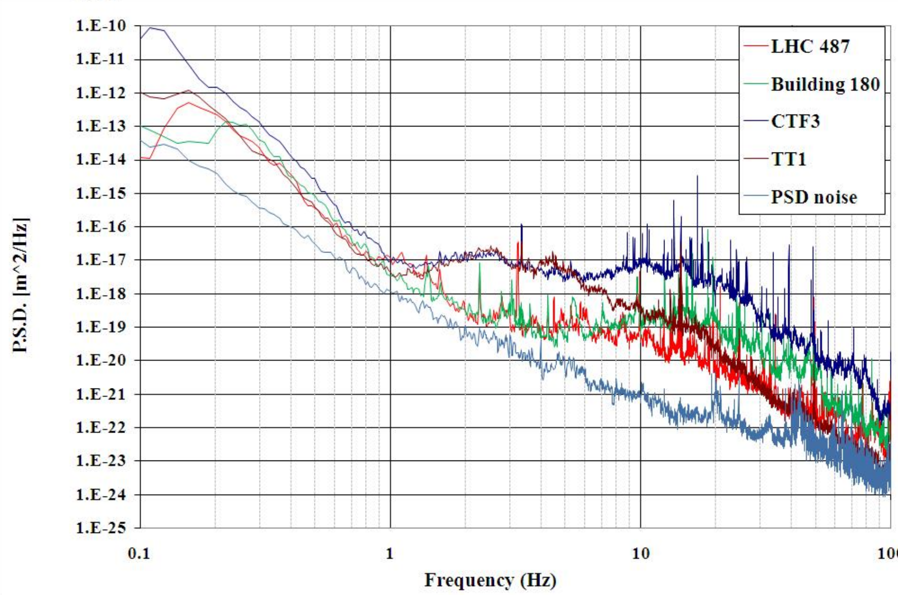

Figure 2. PSD of absolute displacement measured in different locations at CERN.

The relevant bandwidth for the stabilization control is 100 mHz to 100 Hz, resulting in a typical input signal dynamic range of $20 * \log 10\left(\frac{\text{highest signal level}}{\text{smallest signal level}}\right) = 60\,\text{dB}$. The resulting required input resolution is $2\,\mu$V. In addition to stabilization, the controller needs to be able to reposition the magnets every 20 ms if required, with steps up to 50 nm in a range of $\pm 5\,\mu$m in lateral and vertical direction with a precision of 2 nm. The output dynamic range can be obtained then by the ratio $20 * \log\left(\frac{\text{full positioning scale}}{\text{smallest stabilisation output}}\right) = 140\,\text{dB}$.

Due to the low frequency of the involved signals, 1/f noise sources will be dominant over white noise. In addition to internal noise sources, the system will be located in an electromagnetically noisy environment in the tunnel. Special attention is needed for cabling, shielding and housing. Especially high is the 50 Hz peak, but it conveniently coincides with the beam repetition rate.

It has been demonstrated in [3] that latency above 80 μs in the control loop negatively affects performance. For this reason a local control strategy was chosen over remote central control, leading to a local controller situated next to each stabilized magnet in the tunnel.

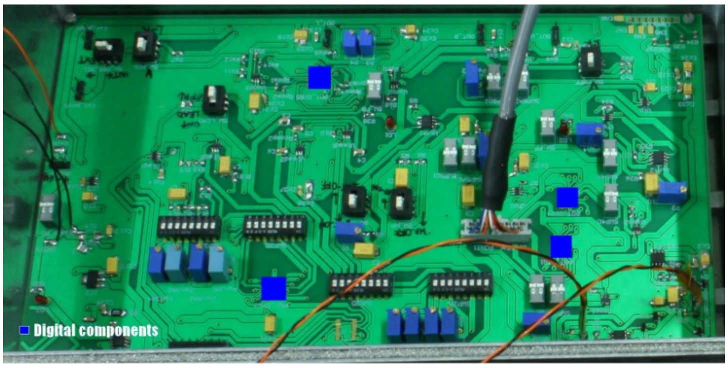

Figure 3. Hybrid controller prototype PCB.

Preliminary calculations have been done for the radiation levels that electronics close to the magnets will receive in a worst-case scenario [4]. Absorbed doses of 1 Gy, 1 MeV Neutron Equivalent Fluence of 1e10 cm^{-2} and <20 MeV Hadron Fluence of 1e8 cm^{-2} can be expected, normalised to 180 days with a main beam of 9 GeV. These levels are to be taken into account in the design of the electronics, its location in the tunnel and necessary shielding.

Other important constraints are space, which is scarce in the tunnel and must include the volume added by the required radiation shielding, and cost, since there will be around 4000 local stabilization controllers. The next section describes an implementation of the stabilization and positioning controller for CLIC.

3 Hybrid controller

An electronic circuit was designed and built to implement the control algorithm, based in feedforward and a feedback of the movement of the magnet with respect to the ground [5].

Figure 3 shows the printed circuit board (PCB) of the fourth generation prototype controller which is described in this section. It is made of an analogue circuit built with discrete low noise commercial components, and variable resistor chips controlled digitally through a communications port which needs to be driven from outside the board. Digital resistors are marked in blue, to highlight the majority of analogue components in the design.

For reference, the first generation of the controller prototype was made of a *National Instruments PXI* crate using 18 bit analogue to digital converters (ADC) and 16 bit digital to analogue converters (DAC), running *Real-Time Labview*. The second and third generation consisted of fully analogue circuits, with parameters configurable with the help of resistor trimmers.

3.1 From mostly digital to mostly analogue

There is a general trend in electronics to perform digital data processing whenever it is possible. It has the advantages of flexibility, cost reduction through the use of standard components, reuse of intellectual properties, and the fact that noise is only added to signals during digitization, among others. The first prototype of the controller was, as mentioned before, digital with only ADCs and DACs to interface sensors and actuators.

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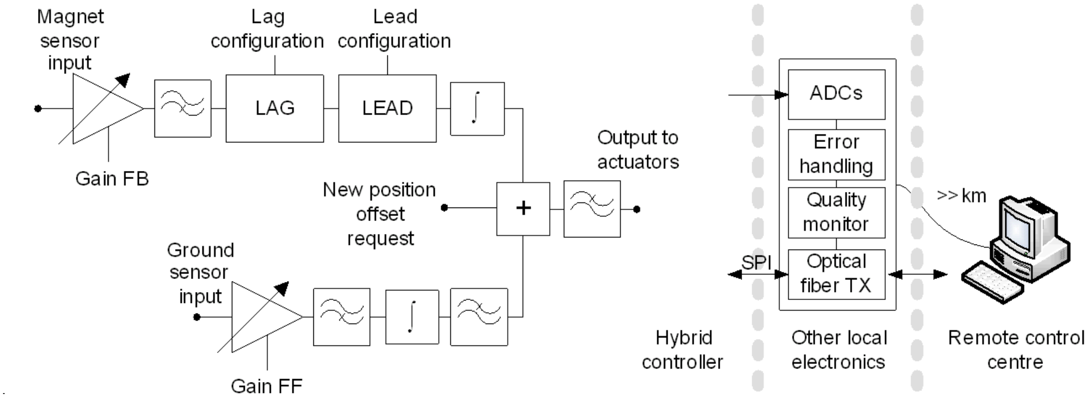

Figure 4. Schematic architecture of stabilization and positioning system.

However, in the CLIC stabilization control strategy all necessary signal processing can be performed with a low number of first and second order filters, gains and inverters, all equivalent to simple analogue building blocks. Feasibility of a full analogue controller was successfully tested, achieving low enough noise levels. A drawback is the fixed configuration of parameters once the circuit is installed. Therefore the last iteration was the creation of a hybrid circuit which benefits from the low latency and simplicity of analogue in the signal control loop, while keeping remote configurability capabilities thanks to digitally controlled components.

This configuration poses many advantages: by minimising the amount of digital electronics, sensitivity to single events caused by radiation is reduced, although effects caused by accumulated dose cannot be neglected and a plan to compensate for them will be needed in the final design. The whole controller was implemented in an electronic card of 4e-2 m^2 consuming less than 2 watts, using only commercial components. Latency was kept to a minimum with the analogue control loop, saving the ADC, DAC and computing time that a digital control would require. Although delay constraints can be met with a digital controller, high clock and sampling rate are necessary, increasing the bandwidth at which the system is susceptible to interferences, compared to an analogue circuit with less than 1 kHz bandwidth.

3.2 Architecture

The hybrid controller has three independent analogue signal chains that are added to create the output that will drive the actuators in the legs. Figure 4 illustrates the architecture of the controller with a block diagram. The first chain is for feedback control; it takes the velocity of the magnet as an input, filters it, amplifies and inverts its sign, integrates it to obtain displacement and applies second order lag and lead operators. Those are filters with one pole and one zero, commonly used in control that locally alter the gain and the phase to increase overall stability. The lead component can be switched off depending on the specific velocity sensor being used. The feedforward chain has as input the velocity of the ground, applies a negative unity gain to it, and integrates it to obtain displacement. Both feedback and feedforward have parameters that can be configured, like the gain and the corner frequencies of both lead and lag. This is implemented using 10 bit digital potentiometers controlled via a serial peripheral interface (SPI) bus. All inputs for sensor signals use differential instrumentation amplifiers with 110 dB common mode rejection to optimize signal

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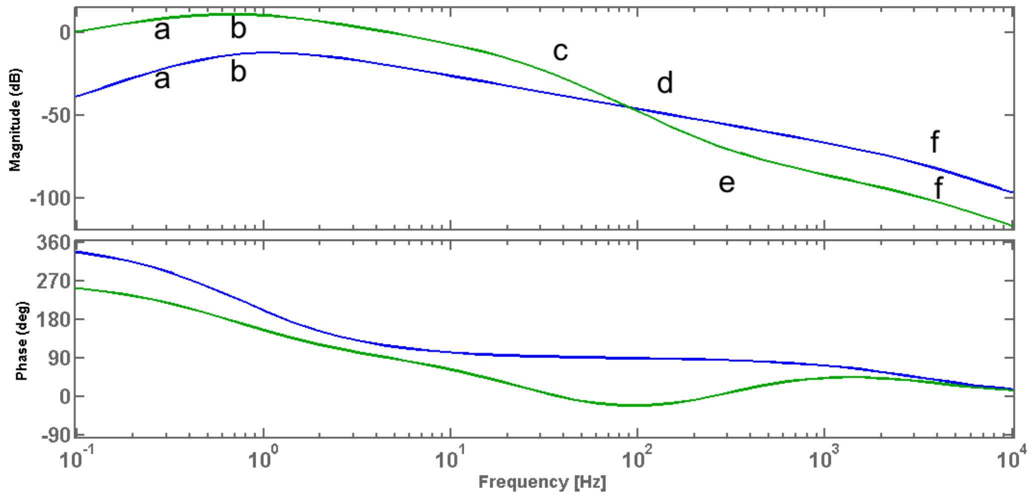

Figure 5. Open loop frequency response of hybrid controller.

to noise ratio. The last chain is the positioning control, which adds an offset to the output signal, and therefore to the actuators. Currently the positioning is performed in open loop, but a proportional integral closed loop controller has been designed [6] and is being implemented. Finally a low pass filter is applied to limit the bandwidth.

A prototype of the electronics for stabilization has been produced and tested for vertical vibrations. The simultaneous use of two identical controllers for vertical and horizontal is possible by just combining the separate outputs using the Jacobian matrix that defines the legs, as the movements are orthogonal.

There is also a power amplifier, not represented in the schema, to drive the piezoelectric ceramics that act as the leg actuators. The calibrated gain of this amplifier is however taken into account in the whole system's gain, altogether with the sensitivity of the vibration sensors.

Finally, in order to control the hybrid circuit, there is a need for some extra local digital electronics. The functions to be performed are transducing light from the optical fibre links into electrical signals, driving the SPI protocol to configure parameters, digitization of analogue sensor outputs for remote monitoring, computing simple merit figures of the system's performance, and error handling. This part can be located together with the hybrid controller, or at a distance of several meters, provided that the outputs of the sensors are locally pre-amplified to compensate for the extra noise before digitization. A higher distance from the magnet could be beneficial for the digital electronics, as it is in principle more sensitive to single event effects. Due to the low noise requirements, the distance from the sensors to the hybrid controller needs to be short, since the sensor cables are the most sensitive to electromagnetic interference. This results in a trade off between sensor noise and radiation exposure. For the current prototype, the digital electronics has been implemented using a *National Instruments PXI*.

3.3 Frequency response

Figure 5 shows the open loop frequency response of the feedback (green) and feedforward (blue) chains of the hybrid controller. We can see the high pass filters **a**, start of integrator **b**, lag's zero

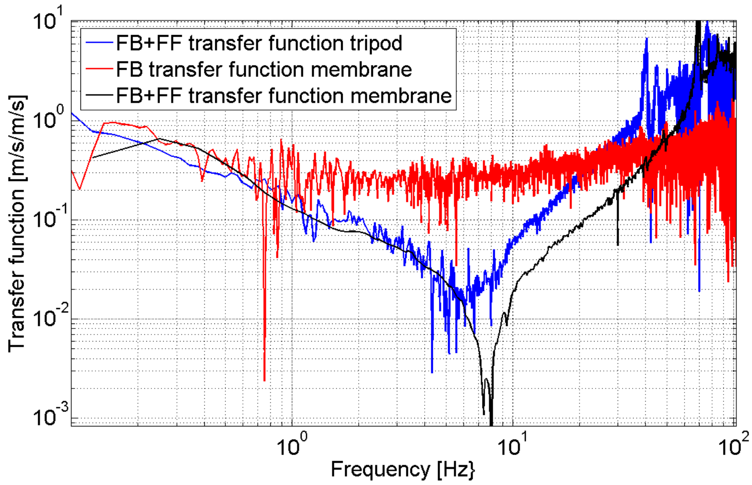

Figure 6. Module of transfer function between the ground vibration and the stabilized mass.

c and pole **e**, the feedforward low pass filter **d**, and the bandwidth limiter low pass filter **f**. The frequency response can be easily matched with the architecture structure in figure 4.

4 Experimental results

Three different setups have been used to test the controller. At first, a vertical single degree of freedom (d.o.f.) system with a small weight guided by a metallic membrane was built, later a 2 d.o.f. with a 100 kg mass on two legs with actuators and a fixed point in a tripod configuration, and finally a type1 magnet with water cooling on two legs. All setups have an equivalent ratio of the mass and stiffness of the actuators.

4.1 Stabilization and position achievements

The transmissibility between the ground and the stabilized mass is shown in figure 6 for the tripod and membrane testbenches. Vibration attenuation is achieved in a bandwidth that depends on the configuration of some parameters as well as on the mechanics of the system.

For illustration, the shape of the transfer function on the membrane curves has been optimized for a wide bandwidth (red curve up to 85 Hz) or for high attenuation on a narrower band (black curve only 55 Hz but attenuation up to 1000). An optimized transfer function can be obtained for specific needs and conditions by configuring the circuit parameters. In [5] it is discussed the influence of stabilization's ratio and shape of CLIC's MBQ into luminosity, which is a measure of collisions performance. The integrated vibration levels against the frequency are represented in figure 7 for the membrane and tripod testbenches, under different vibrations levels. Objective MBQ is the vibration level required for CLIC's main beam quadrupoles, and Objective FF is the level for the final doublets in CLIC's final focus. This figure shows that stabilization to a level below BMQ requirements has been achieved from both high and low ground vibration levels for both the membrane (0.3 nm @ 1 Hz) and tripod (0.5 nm @ 1 Hz) testbenches.

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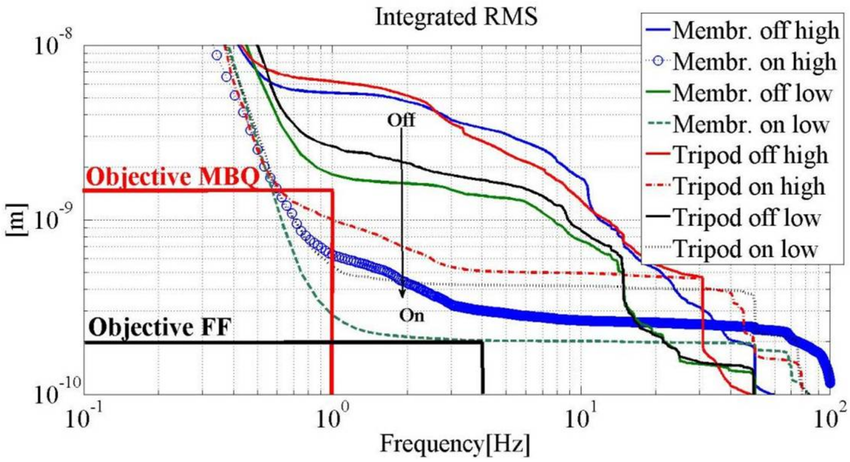

Figure 7. Integrated r.m.s. results of stabilization on different testbenches.

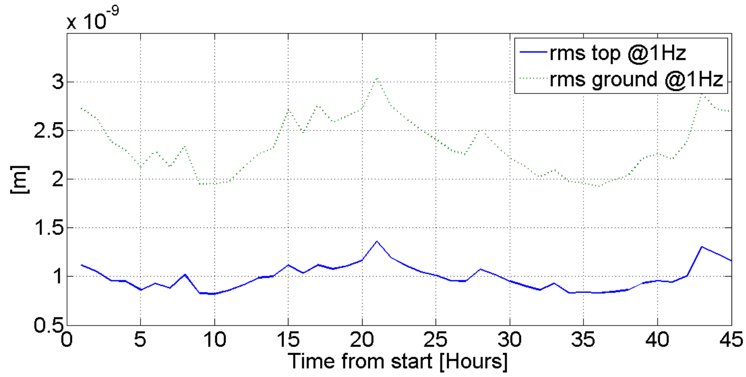

Figure 8. Evolution during 45 hours of the stabilization system, in meters R.M.S. @ 1 Hz.

4.2 Long term measurements

Feasibility of the stabilization system over long time has been proven with a test run over 45 hours in the 2 d.o.f. testbench. Figure 8 shows the recorded r.m.s. values of mass and ground, and it can be seen that the stabilization stays within the requirements during a long period. During the test, performed in the ISR tunnel at CERN, temperature was kept within 1 degree.

4.3 Effect of digital operation

A main disadvantage of a hybrid circuit is that the digital components can inject noise in the analogue part. In order to quantify the effect of the perturbations produced by changing a parameter during stabilization, an experiment was carried out with the gain factor of the feedforward chain. This value was changed using different clock speeds for the SPI protocol. Figure 9 shows the transient induced vibration effect in the magnet due to crosstalk and settling time of the potentiometer. In principle this does not pose a problem as the circuit parameters do not need to be changed while there is beam. However a switch will be introduced to isolate the output during parameter changes, temporarily disabling stabilization. After comparing different clock speeds, it was decided to use a 100 ns period to minimize the time the stabilization needs to be disabled.

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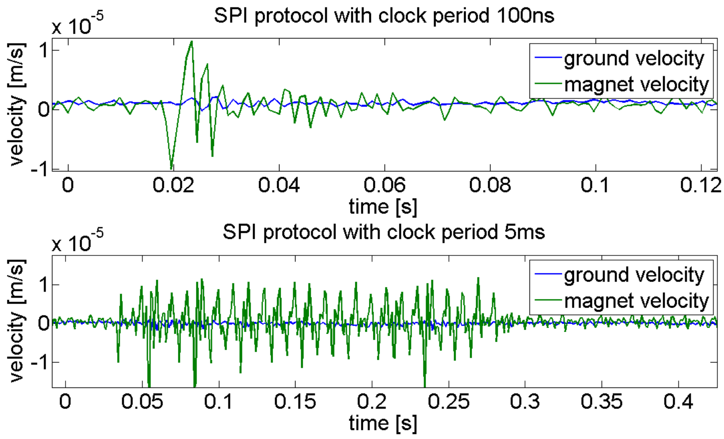

Figure 9. Effect of remotely changing a parameter during stabilization.

5 Future work

Digitization of signals for remote monitoring will be added to the controller. Also a remote adaptative automatic control will be designed to find an optimal configuration of the stabilization controller, with parameters evolving as the vibration levels and spectrum might change. Radiation tests and optimization for hardness is to be programmed. Mechanical encasing and radiation shielding are to be studied. The controller will be tested on the type1 prototype magnet with water cooling on, and with simultaneous vertical and horizontal stabilization. Finally the positioning range needs to be enlarged, as currently the full ±5 μm is not yet attainable with the controller electronics.

6 Conclusions

In this paper the main constraints faced by the stabilization controller electronics were presented. It was explained how latency penalization forces the stabilization controller to be local, and the reasons to opt for a hybrid solution: latency, remote configurability, simplicity, cost, space and tolerance to radiation. The created electronic prototype was described functionally, structurally and characterized in the frequency domain. Vibration levels of 0.3 nm r.m.s. at 1 Hz were achieved, five times lower than the requirements, demonstrating feasibility of the stabilization system and controller. Measurements of the transient distortion introduced by parameter changes were given and showed harmless, as long as changes are done without beam. The future work will focus on adding remote signal monitoring, test resistance to radiation, stabilization on type 1 with water cooling and improvement of the positioning dynamic range.

Acknowledgments

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