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1. The Muon g-2 experiment

The new Muon g-2 experiment at Fermilab (E989) plans to measure the muon anomaly $a_\mu = (g-2)/2$ to an uncertainty of 16 x 10^{-11} (0.14 ppm), derived from a 0.1 ppm statistical error and roughly equal 0.07 ppm systematic uncertainties on ω_a and ω_p. The proposal efficiently uses the unique properties of the Fermilab beam complex to produce the necessary flux of muons, which will be injected and stored in the (relocated) muon storage ring. To achieve a statistical uncertainty of 0.1 ppm, the total data set must contain more than 1.8 x 10^{11} detected positrons with energy greater than 1.8 GeV, and arrival time greater than 30 μs after injection into the storage ring.

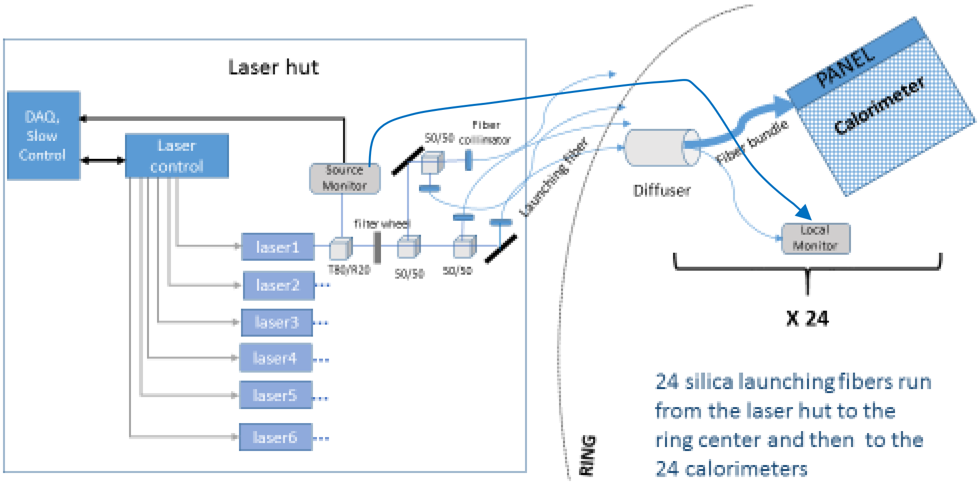
With a higher expected beam rate, more rapid filling of the ring, and even more demanding goals in systematic uncertainties, the collaboration has had to devise improved instrumentation. The ring kicker-system will be entirely new, optimized to give a precise kick on the first turn only, to increase the storage fraction. The magnetic field will be even more carefully prepared and monitored. The detectors and electronics are entirely new, and a state-of-the-art calibration system will ensure critical performance stability throughout the long data taking periods. New in situ trackers will provide unprecedented information on the stored beam. The first physics data-taking is expected in mid 2017.

2. The Muon g-2 Laser Calibration system: introduction and requirements

The Muon g-2 experiment will require a continuous monitoring and re-calibration of the detectors, whose response may vary on both a short timescale of a single beam fill, and a long one of accumulated data over a period of more than one year. It is estimated that the detector response must be calibrated with relative accuracy at sub-per mil level to achieve the goal of the E989 experiment of keeping systematics contributions due to gain fluctuations at the sub-per mil level on the beam fill scale (0-700 μs) and at the sub per cent level over the longer data collection period. The calibration system must be stable to the 10^{-4} level in 2 hours in order to fulfill these requirements. This is a challenge for the design of the calibration system because the desired accuracy is at least one order of magnitude higher than that of all other existing, or adopted in the past, calibration systems for calorimetry in particle physics.

As almost 1300 channels must be kept calibrated during data taking, the proposed solution is based on the method of sending simultaneous light calibration pulses onto the readout photo-detectors through the crystals of the calorimeter. Light pulses should be stable in intensity and timing in order to correct for systematic effects due to drifts in the response of the crystal readout devices. A suitable photo-detector system must be included in the calibration architecture to monitor any fluctuation of the light. The guidelines given by the experiment to define in the correct way the architecture of the entire system could be found in [G. Venanzoni, "The New Muon g-2 experiment at Fermilab (E989)", European Physical Society Conference on High Energy Physics (HEP-EPS 2015), Vienna, Austria, 24 July 2015.]. The crucial points for the realization of this system are: i) the light source; 2) the distribution system that shares the light to the calorimeters with sufficient intensity and sufficient homogeneity among them.

The light source should be in the same spectral range accepted by the photodetectors and has to be powerful enough to ensure a sufficient amount of light for each calorimeter station when considering losses due to the distribution chain.



24 silica launching fibers run from the laser hut to the ring center and then to the 24 calorimeters

Figure 1: Schematic view of the Laser Calibration System design.

On the basis of several tests with different light distribution schemes [A. Anastasi et al., "The calibration system of the new g-2 experiment at Fermilab", *Nuclear Instruments and Methods in Physics Research A* **824**, 716-717 (2016)], the design of the laser calibration system has been frozen in the scheme reported in Fig. 1. In a laser hut placed just outside the ring, there are six independent laser heads (pulsed diode lasers Picoquant), whose lights are each divided into four beams and then sent to 24 calorimeter using 25 m-long quartz optical fibers. For each calorimeter the laser beam is uniformly expanded and coupled into a bundle of 60 PMMA optical fibers by means of an engineered diffuser. The light pulses are delivered into the 54 SiPMs through 54 PMMA fibers, kept in place on a thin Delrin plate (10 mm thick) placed between the ring vacuum chamber and the calorimeter. On the plate the pulses are deflected by 54 right-angle prisms into the crystals in order to reach the photosensors (SiPMs) at the end of the PbF_2 crystals. The energy level of each laser beam is monitored by a source monitor system (SM) that evaluates the average laser power using PIN diode photodetectors and a pulsed absolute light source (^{241}Americium+NaI). The Picoquant lasers heads are very stable (1% RMS over 12 hours and 3% peak-to-peak for $\Delta T(amb) < 3$ K), the SM is able to monitor laser power changes at the per-mil level. A second monitoring system (local monitor or LM) is provided by bringing one of the optical fibers of the bundle back to the laser hut by means of 24, 25 m-long PMMA fibers that illuminate calibrated PMTs. The LM monitors fluctuation occurring between the laser head and the end tip of the bundle. LM PMT gains are calibrated with a second light pulse extracted from the SM, the two pulses being time delayed by 250 ns.

3. The Laser Calibration system: Technical description of the components

The following list summarizes the Muon g-2 laser calibration system that consists of:
1) the Laser heads;
2) optical components and collimators;
3) 24 x 25 m-long quartz fibers for light distribution (one per calorimeter);
4) a beam expander incorporating an engineered diffuser, close to each calorimeter, to distribute uniformly the laser light to the 54 transport fibers;
5) 24 bundles of 54 fibers (+ spare + monitor) to transport the light from the diffusers to the calorimeters;
6) 24 light distribution plates made with Delrin in front of the calorimeter crystals. Each one hosts 54 right-angle prisms to deflect by 90° the output of the optical fibers into the PbF_2 crystals;
7) 6 source monitors to measure the laser intensity stability and furnish the fast pulse to the local monitor PMTs;
8) 6 local monitors to measure the stability of the light distribution system.

In the following, we technically describe each component of the calibration system.

3.1 Laser heads

We have chosen a diode laser by Picoquant, for its characteristics of power, reliability (at least 5000 hours of operation), stable intensity (1% pulse to pulse), multi-head driver (Mod. PDL 828 'Sepia II' drives up to 8 laser heads), and flexibility of modulation of the output frequency, required to test the effects of pile-up in the calorimeters. We chose the laser head with the highest available average power: a multimode head (LDH-P-C-405M) with average power 20 mW @ 40 MHz, pulse FWHM: < 600 ps, energy/pulse > 625 pJ, which has been tested extensively for about two years, giving excellent results. Nevertheless the laser head's output power is insufficient to activate the high number of SiPM photosensors to be calibrated (1296) in the experiment and this forced us to use multiple laser heads. A conservative estimate led us to choose a configuration with 6 laser heads for the calibration system.

3.2 Optical components, collimators and fibers

Each of the six laser beams is split into 4 beams by three 50:50 cubic splitters and sent to a total of 24 adjustable collimators placed in front of 24 optical fibers (launching fibers). The light losses in these steps are of the order of 7% for each cube and 20% for the collimator. We chose optical fibers made of quartz, which does not degrade with the short wavelength of the laser light (405 nm) so as to minimize the beam attenuation (5 dB/km). To limit the costs (about 600 m of fiber length), 0.4 mm-diameter fibers were chosen. A 12-position filter wheel will be placed at the output of each laser head, to be able to vary the amount of light sent to the calorimeters and make linearity checks.

3.3 Diffusers and bundles

To expand the beam output from the optical fibers and create a beam profile as uniform as possible, an engineered diffuser by Thorlabs was chosen (Mod. ED1-S20). The optical fibers bundle in front of the diffuser, located 50 mm away, collects about 10% of the light exiting the launching fiber.The tests showed an excellent uniformity between the fibers of the bundle and its dependence on the distance of the bundle from the launching fiber. The solution we chose is a light-tight tube, with the quartz launching fiber as input and the fiber bundle as output. Inside the tube we placed both a lens for collimating the beam exiting the launching fiber and a diffuser in front of the fiber bundle. For the bundle, we chose a large 1 mm-diameter PMMA fiber, with improved mechanical characteristics (Mitsubishi Eska GK-40). The large diameter is required to be insensitive to the spatial non-uniformity of the flat top beam created by the diffuser placed in front of the bundle. PMMA was chosen because its Minimum Bend Radius is lower than for quartz: the GK-40 model tolerates bending radii down to 20 mm. This small curvature radius is necessary for the next point.

3.4 Light distribution plates

For reasons of reduced space between the ring wall and the calorimeters, the optical fibers carrying the optical calibration signal to the crystals and SiPMs, cannot make a 90° angle with the crystals' front face, but are instead parallel to it. To make the 90° deflection into the crystals, we use right-angle optical prisms (8 mm X 8 mm). The prisms and the fibers are fixed together by means of a Delrin plate (10 mm thick) placed in front of the crystals. The plate is quite stiff but has a low interaction cross section for the positrons originating from the decay of muons. Each fiber is routed to an individual prism (accommodated in a through square hole) via a groove which has a curved end part, with a bending radius of about 40 mm (see Fig. 3).

3.5 Source and local monitors

The monitoring system consists of 6 Source Monitors (SM) and 24 Local Monitors (LM).

The SM monitors the fluctuations of the laser light source and provides corrections for these fluctuations. The laser light is mixed in the SM and viewed by a redundant system of 2 large-area (10 mm x 10 mm) PIN diodes (Hamamatsu S3590-18) and a PMT (Hamamatsu H5783). The PMT is also illuminated by an absolute reference signal provided by a low-activity (about 6 Hz) Americium radioactive source coupled to a NaI crystal. The SM uses 30% of the laser light to reach the required statistical precision rapidly, and monitors the average fluctuations over a longer period by the absolute reference. The prototype is characterized by a large thermal inertia so as to minimize the effect of temperature fluctuations and effective electrical shielding. In order to ensure uniform distribution of light on the detectors and insensitivity to "beam pointing" fluctuations, a commercial diffusing sphere was used (Thorlabs, mod. IS200).

The local monitor consists of a PMT (Photonics XP2982) that receives two optical signals. The first signal is the reference from the source monitor, collected from a port of the integrating sphere, and is used to calibrate the gain of the PMT. The second signal comes from the fiber bundle in the vicinity of the calorimeter and is representative of the calibration signal sent to the SiPM. The two optical signals are separated in time by 250 ns, since the first signal travels a distance of approximately 2 meters, while the second of about 50 m (25 m one way in the quartz fiber, 25 m return in the PMMA fiber). In order to study and compensate for any fluctuations due to temperature of the transmission coefficient of the local monitor optical fibers, we will use two types of fibers: quartz and PMMA. The system is redundant, and allows to monitor any solarizing effect of the PMMA fibers.

4. Tests of the prototype Laser calibration system with beams (Frascati and SLAC)

A test of the laser calibration system and the full light distribution chain using a 5-element calorimeter prototype was performed (February 2016) at the Beam Test Facility, Laboratori Nazionali di Frascati, with a 450 MeV electron beam. All components of the laser calibration system (except for the source monitor and local monitor frontend electronics) were those which will be used for the Muon g-2 experiment at FNAL.

Details are given in [A. Anastasi et al., “Electron beam test of the calibration system for the muon g −2 experiment” *Nuclear Instruments and Methods in Physics Research A*, submitted (2016)].

Figure 2 shows the main results of the Frascati test beam: the SiPM signals from electrons (black) and laser (purple). The red crosses represent the SiPM signals corrected for the two monitors.

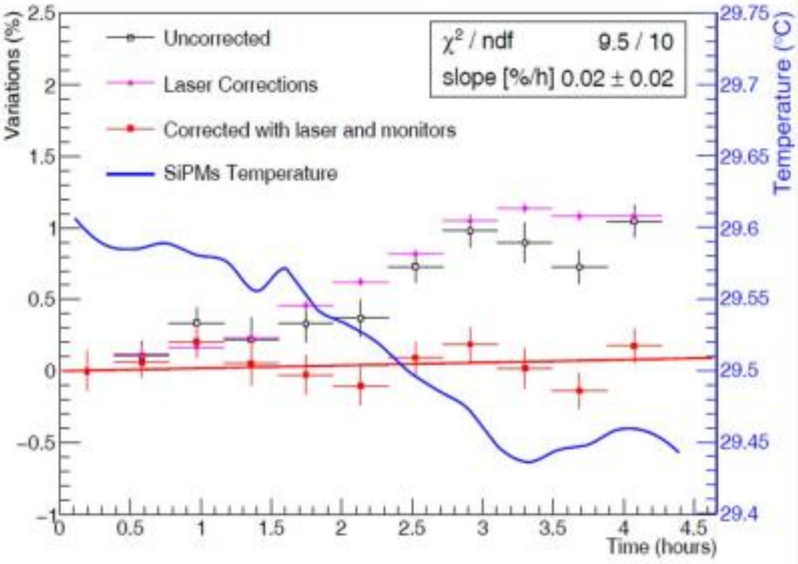


Figure 2. SiPM response to electrons (black) and laser (purple). Red crosses are the electrons signal corrected for bias drift, laser intensity fluctuations and transmission efficiency. The linear fit to corrected data shows no residual slope within statistical uncertainty.

A test of the laser calibration system and the full light distribution chain using a complete 54-crystal calorimeter was performed at ESTB facility in SLAC (June 2017). Both the final version of the in-house electronics developed by the Italian collaboration and the waveform digitizers developed for the experiment were used for the monitor detectors (PiDs and PMTs), while waveform digitizers were used for the calorimeter SiPMs. The laser control system, designed to study how the SiPM gain changes with luminosity was also tested. The beam particles were 3 GeV electrons, for most of the time, but 2.5, 3.5, 4.0, 4.5, and 5.0 GeV electrons were also used. Analysis of the collected data is ongoing. Results confirm those of the LNF test beam: correction with the monitor appears to be effective, see Fig. 3. The gain drift is corrected completely within statistical uncertainty (the linear fit gives a slope of 0.02 ±0.02 %/h).

Details are given in [A.T. Fienberg et al., “Performance of the instrumentation for measuring the anomalous precession frequency in the Fermilab Muon g-2 experiment” JINST, to be submitted (2016)].

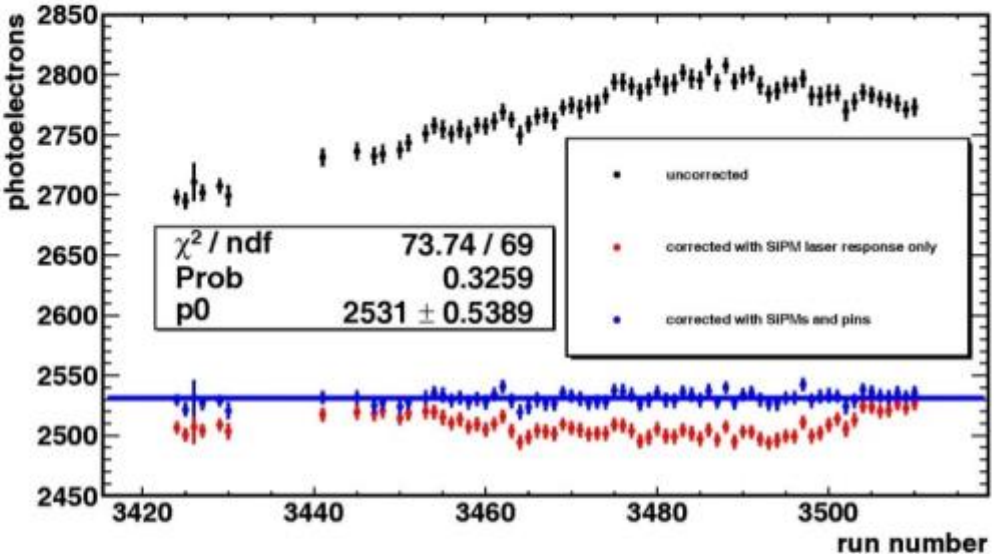


Figure 3. SiPM response to electrons (black). Red points are the electron signals corrected for SiPM bias drift. Blue points are further corrected for laser intensity variability.

5. Assembly status of the Laser calibration system

In July 2016, the assembling of the laser calibration system has started at Fermilab. Figure 4 shows the material delivered in June to the assembling room in Dzero hall at Fermilab.

Figure 4. Material delivered to the assembling room at Dzero at Fermilab.

5.1 Light distribution plates

The mechanical workshop at LNF milled the 25 plates made of Delrin, according to the drawing shown in Figure 5.

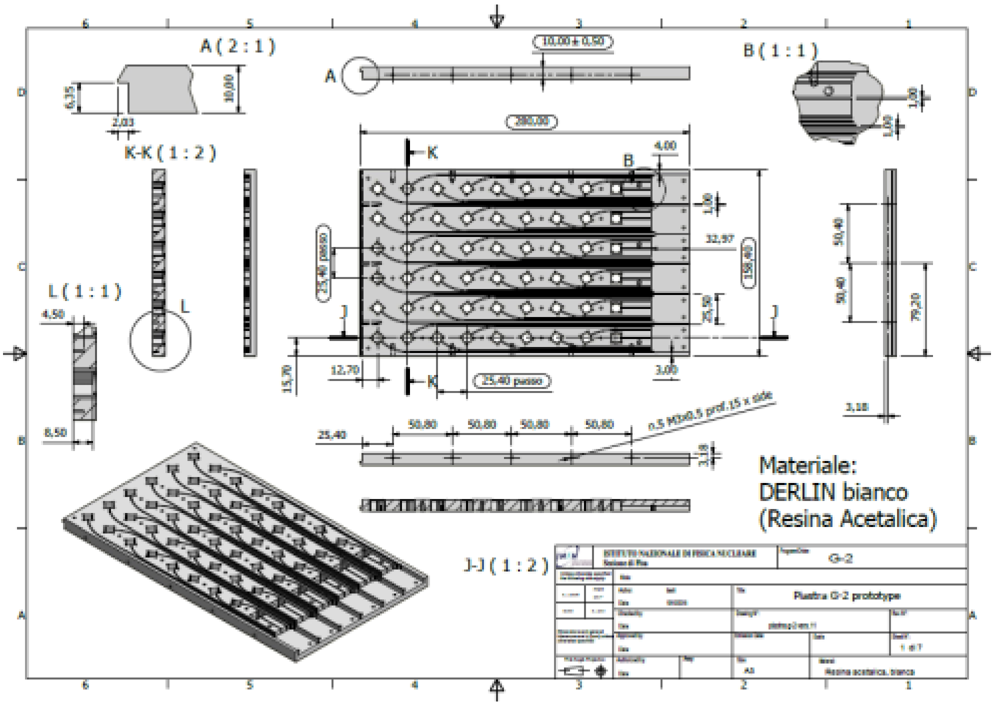


Figure 5. Technical drawing of the light distribution plate.

Figure 6 shows the plates before and after right-angle prisms were glued to the plates.

Figure 6. Light distribution plates before and after gluing of right-angle prism.

5.2 Diffuser and light distribution box

In order to hold in position plates and diffusers, a light distribution box was designed, as reported in Fig. 7a. The light distribution box is connected to the calorimeter box. The light distribution box also houses the fiber bundle that connects the diffuser to the light distribution plate. As a first step, diffusers were assembled and installed inside the bundle boxes, see Fig. 8. Then, the light distribution plate was connected to the box and the fibers of the bundle (see Fig. 9) glued to the plate, see Fig. 10a. To complete the light distribution box, the cover caps are added to make the box light-proof (Fig. 7b). The box is now ready to be connected to the calorimeter whose assembly at Dzero has not yet started. The output of the plate, which illuminates the crystals, is shown in Fig. 10b. We performed a quality check by measuring the output of each channel using an optical power meter (Newport mod. 1918-R) with flat photodiode sensor (Newport mod. 918D-ST-UV); the graph of a typical output signal is shown in Fig. 10c; typical uniformity better than 20% was achieved.

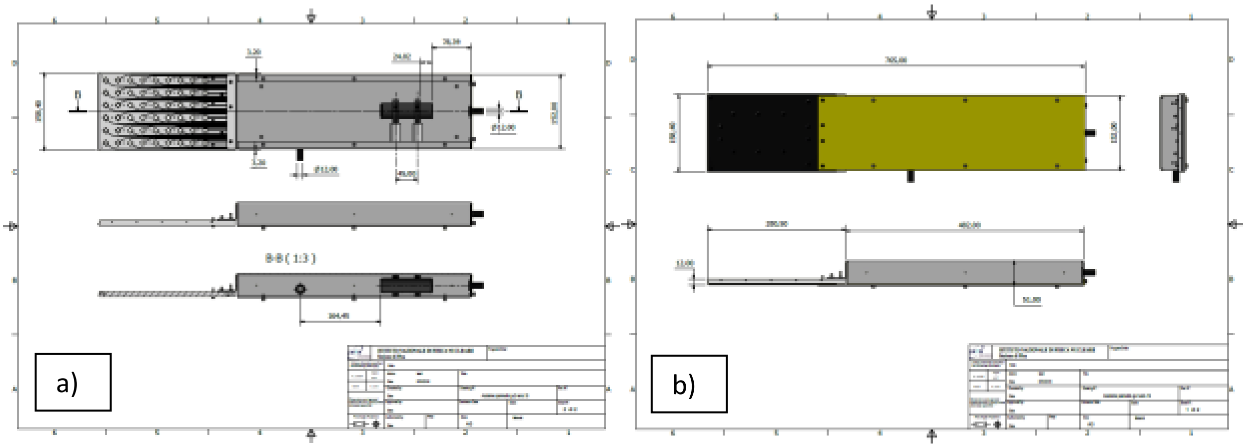


Figure 7. Technical drawing of box housing the diffuser.

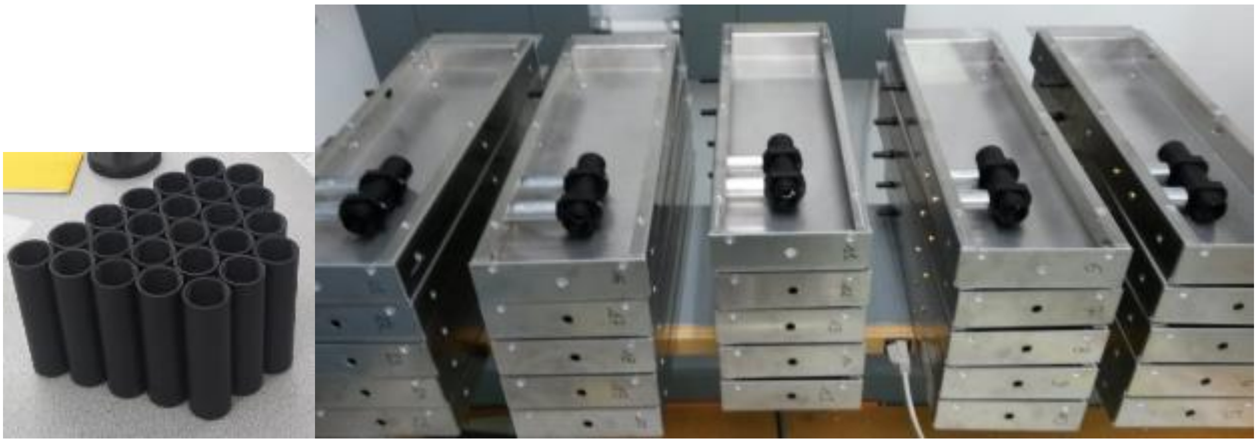


Figure 8. Diffusers assembled and installed in the boxes.

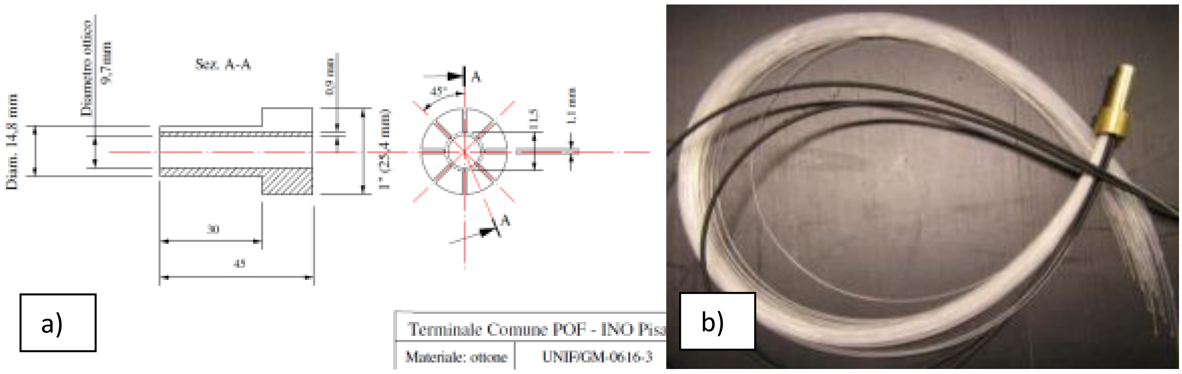


Figure 9. Optical fiber bundle: a) ferrule with housing for removable local monitor optical fibers; b) the bundle.

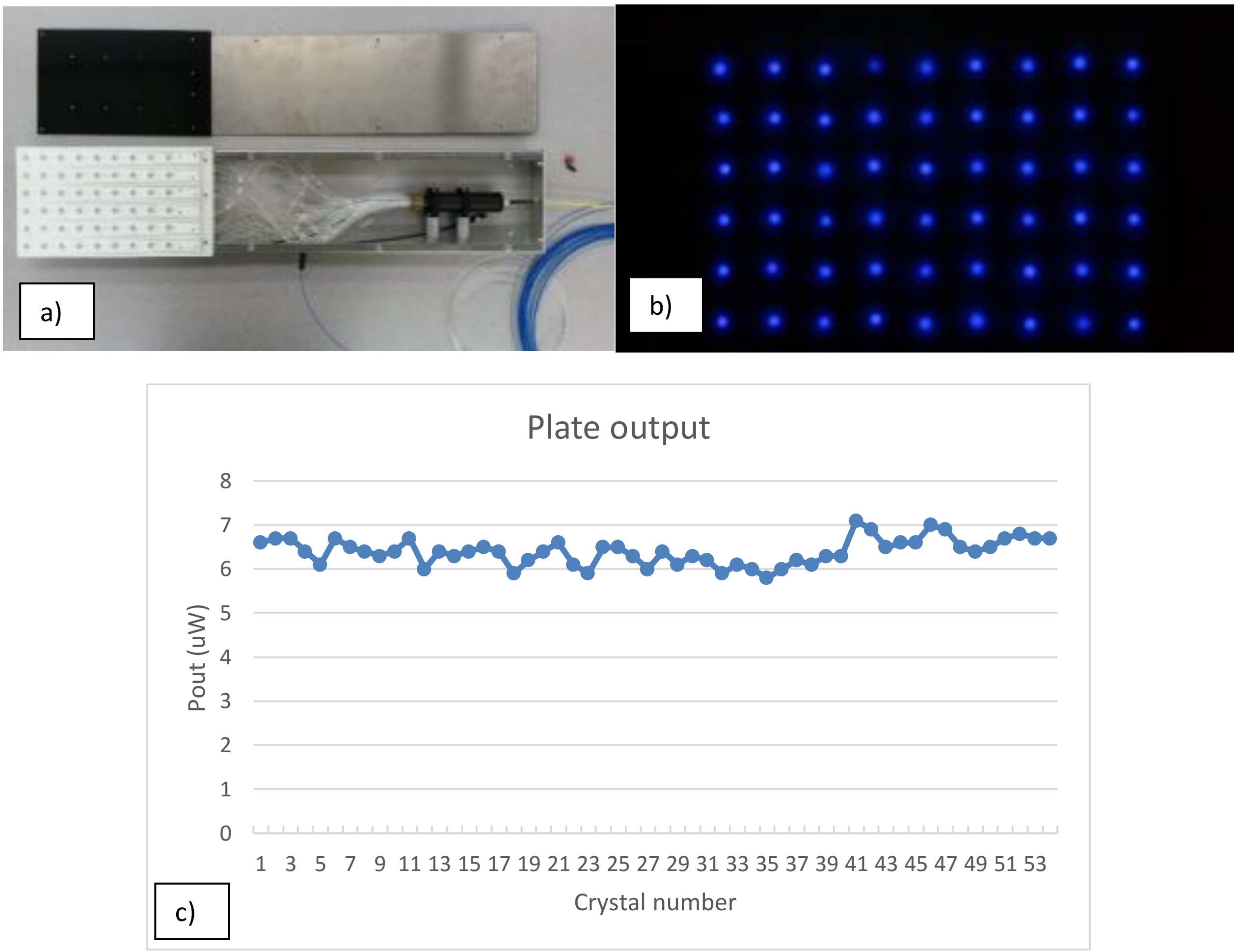


Figure 10. a) Light distribution plate connected to the box and fibers of the bundle glued to the plate; b) output of the plate number 5 (scattered by white paper); c) output of the plate number 5 measured using light power meter.

In Fig. 11 the assembly procedure of the crystals in the calorimeter is shown. Fig. 11a shows the rear view of the disassembled calorimeter. First, the light distribution box is connected to the calorimeter (panel b, back view of the light distribution plate made with Delrin). Then a bracket to prevent the Delrin plate from bending is added (the crystals are pushed by a spring). In step three the PbF_2 crystals are mounted (blue parts in panel d). Finally, the side panels of the calorimeter box are added, the bracket is removed (panel e) and the calorimeter is completed with the top cover.

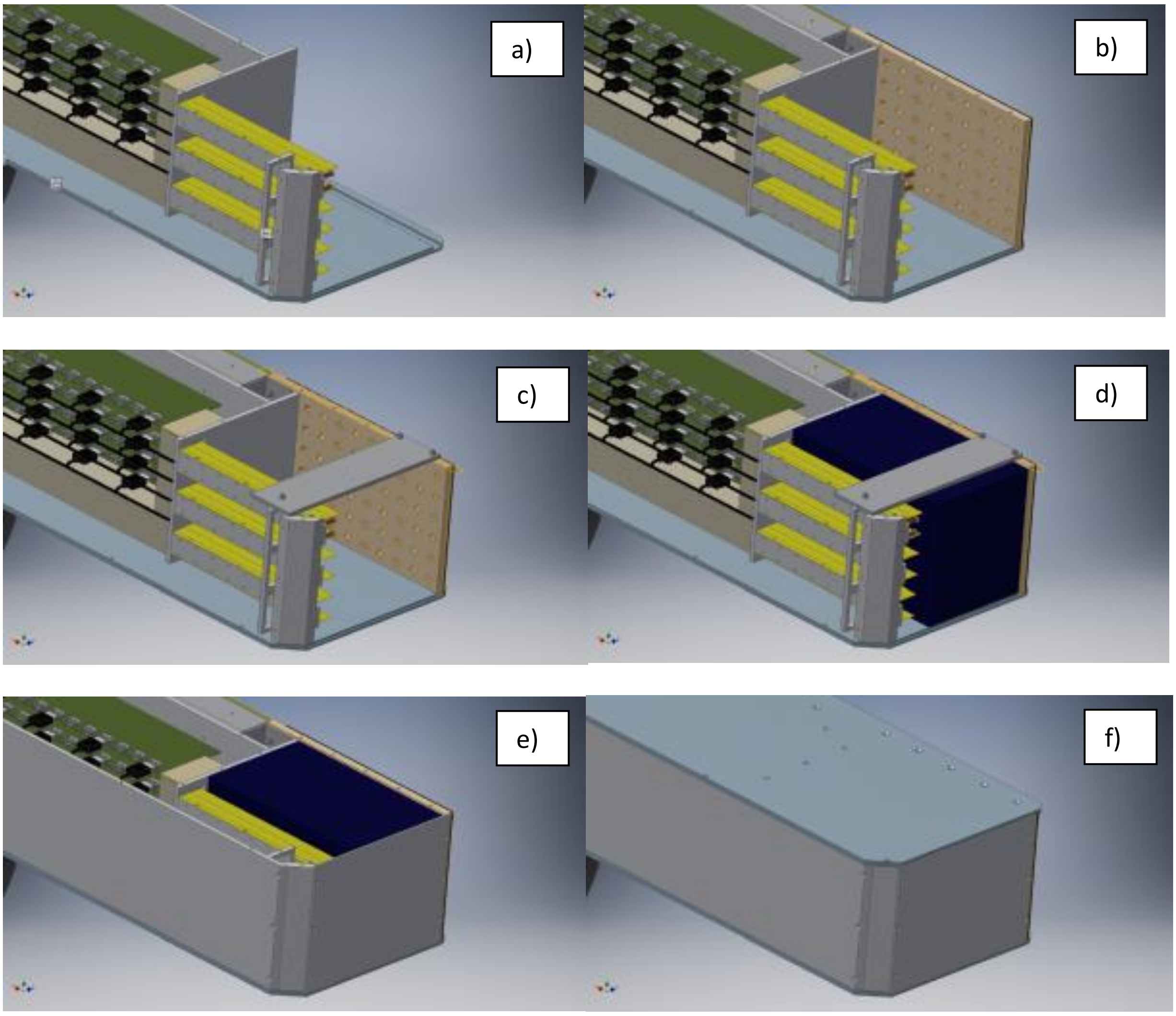


Figure 11. Assembling procedure for the calorimeters.

5.3 *Optical components*

All optical components (mirrors, beam splitters, filter wheels, collimators, optical fibers) and the lasers (Sepia II, driver boards, 6 laser heads) required for the assembly of the laser calibration system were purchased and assembled. Unfortunately, at this moment (31 October 2016) the laser hut is not yet completed (missing the optical table cover and the interlock system for the lasers). We expect to complete the assembly by the end of this year.

5.4 *Source and local monitors*

The source monitor parts are under construction in Italy and will be sent to Fermilab in November. We expect to complete the assembly at Fermilab by the end of this year.

The local monitor is under assembling. We expect to complete the assembly later this year. Figure 12 shows the drawings of the box containing 5 PMT; 5 boxes will be used to monitor the 24 calorimeters (1 spare PMT).

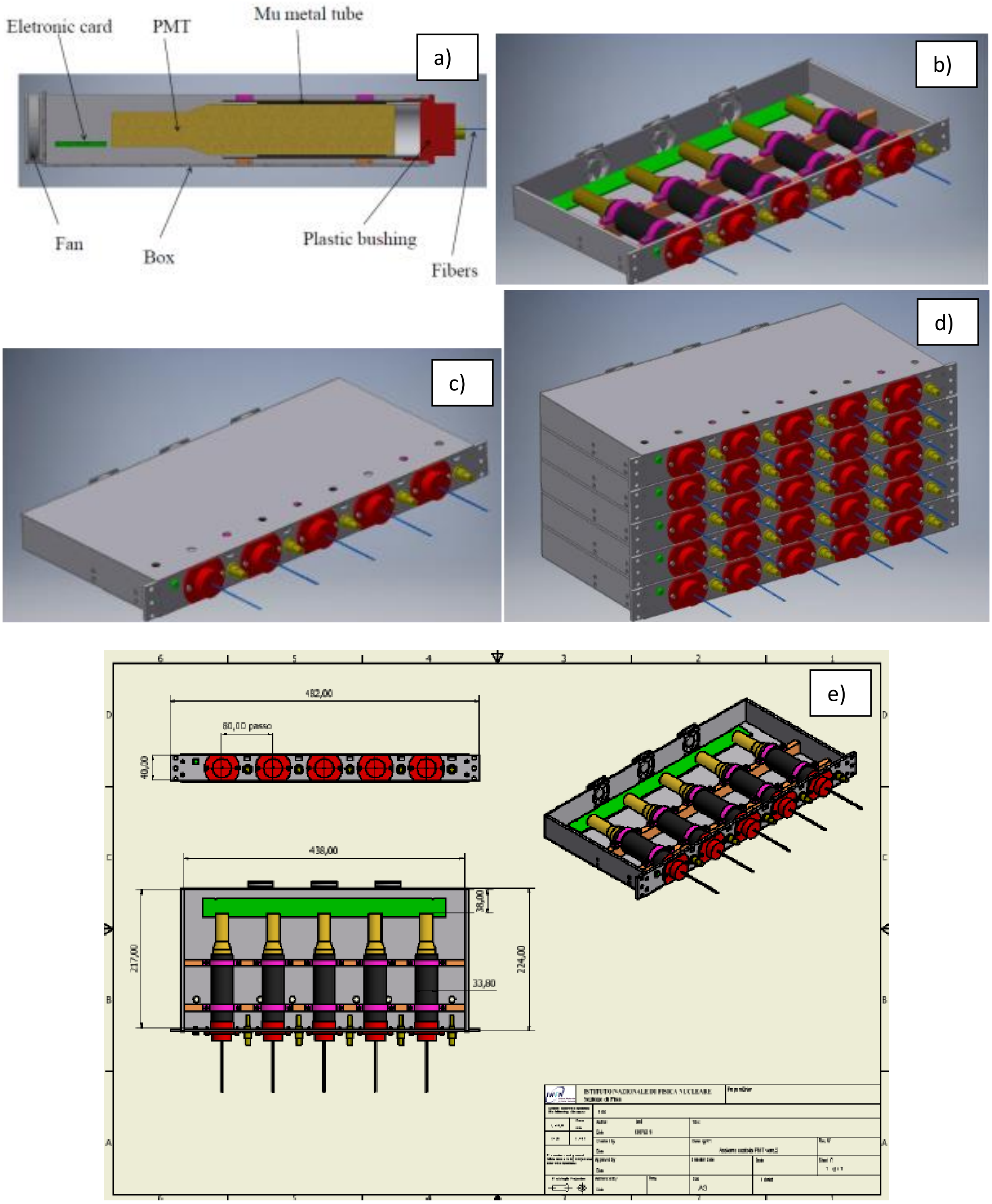


Figure 12. Assembling of the local monitor.

The green part in panels b and e of Fig. 12 is an electronic board, which interfaces with the waveform digitizer of the data acquisition. The board is under construction, and its scheme is shown in Fig. 13.

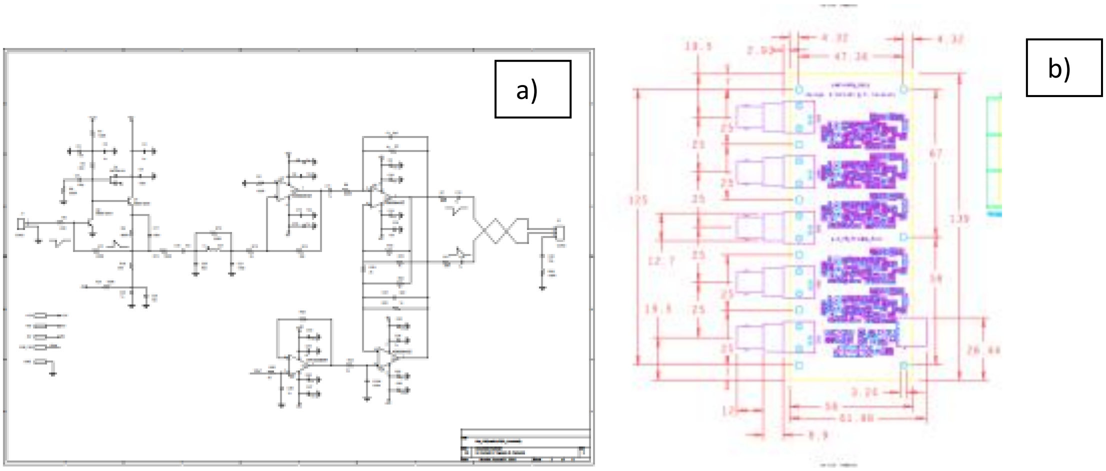


Figure 13. The electronic board: a) single channel scheme; b) 5 channels layout.

The 6 (+1 spare) optical fiber mini-bundles which bring the source monitor calibration signal to the PMTs of the local monitor are already at Fermilab, see Fig. 14.

Figure 14. The optical fiber mini-bundle.

6. Conclusion

The laser calibration system installation is on schedule. Much of the equipment has already been purchased and shipped to Fermilab. The light distribution box, with diffuser, bundle and Delrin plates have been assembled and are ready to be integrated in the calorimeters. The optical components and lasers to be housed in the laser hut are ready to be installed. The optical fibers (launching and local monitor fibers) were purchased, cut to size, polished and inserted into PVC corrugated conduit, and are ready to be installed inside the Muon g-2 ring. Only the two monitor systems are still being assembled, as envisaged in the schedule.