

Radiation-Hardness of PIN/VCSEL Arrays for the ATLAS Pixel Detector

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Overview and Introduction

ATLAS is a very large experiment now in the final stages of construction at CERN's Large Hadron Collider (LHC) facility in Geneva, Switzerland. The goal of ATLAS is to measure and analyze the radiation emitted by 14 TeV proton-proton collisions produced by the LHC. Analysis of these very-high-energy collisions is expected to provide experimental verification of some as-yet-unsubstantiated predictions of the Standard Model, such as the existence of the Higgs-Boson and the unity of fundamental forces at high energies, and also to provide insight into physics beyond the Standard Model, such as supersymmetry. The name ATLAS is ostensibly an acronym for "A Toroidal LHC ApparatuS."

In order to more quickly achieve statistical significance in measurements of low-probability events, and to maximize the precision of higher-probability measurements, the LHC has been designed to reach a luminosity of $10^{34}/(\text{s}\cdot\text{cm}^2)$. The enormous fluence of charged particles and high-energy photons through semiconductor electronics within the detectors results in a gradual degradation of these systems' electronic response. Unfortunately, the cheapest, simplest, and most effective method of protecting electronics from radiation damage, i.e., shielding, destroys valuable data by capturing, deflecting, annihilating, or otherwise ruining interesting particles mid-flight, and is therefore unsuitable for use in particle detectors. In order to maximize the useful lifetime of detector systems, they can be "radiation-hardened" by designing systems to function adequately for as long as possible in spite of inevitable deterioration.

The ATLAS Pixel Detector is a cylindrical array of very small silicon ionization detectors enclosing the region in which the LHC's counter-rotating proton beams

intersect. By tracking particles emitted from the collision region as they pass through 3 concentric cylinders of pixels, the trajectories and momenta can be determined. Since trajectory and momentum are the first measurements made of particles emitted from the interaction region, the Pixel Detector's inner surface lies closer to the interaction region than any other ATLAS component, exposing it to the highest fluence of radiation. As a result, radiation-hardness is an essential design parameter for Pixel Detector systems.

The Pixel Detector will communicate with other ATLAS systems and the "outside world" via an array of rad-hard "opto-boards." These opto-boards convert electrical pulses from "hits" on silicon pixels into laser light, by using the pulses to trigger arrays of Vertical-Cavity Surface-Emission Lasers (VCSELs). VCSELs are very small solid-state lasers which emit coherent light when powered by an electrical current. The optical data is transmitted out of the detector area via rad-hard optical fibers. Opto-boards also receive control signals for Front-End electronics (discussed later) via similar fiber-optics, and convert them into electrical signals with an onboard PIN diode. A PIN diode performs essentially the inverse function of a VCSEL, generating an electrical current when illuminated with light. Over the planned lifetime of the SLHC Pixel Detector, the Gallium-Arsenide (GaAs) VCSELs and PIN diodes used on second-generation opto-boards will absorb enough radiation to have considerable detrimental effects on their light output and current response.

For the past several years, the ATLAS team within Ohio State's High Energy Experiment group has performed irradiation studies of VCSELs and PIN diodes. These studies have several goals:

- 1) Better anticipate the pattern and pace of deterioration in these components during the ATLAS experiment
- 2) Determine our ability to slow and/or repair radiation damage through annealing
- 3) Determine which commercial vendors manufacture the longest-lived PIN/VCSEL arrays
- 4) Possibly gain some general insight into the physical mechanisms of radiation damage to semiconductor electronics

These studies are performed by exposing opto-boards populated with various makes of PIN diode and VCSEL to the 24 GeV proton beam at CERN's Proton Synchrotron (PS) facility, also called the "Test Beam." Mounting the VCSELs and PIN diodes directly in the path of the test beam allows the electronics to accumulate in a matter of weeks (and in some cases days) an absorbed radiation dose equivalent to what they would receive in several years at the periphery of the SLHC interaction region. During these intense test beam irradiations, we monitor the performance of the VCSELs and PIN diodes by transmitting pseudo-random electrical pulses to the opto-boards, simulating pixel "hits." We then read out the fiber-optic signal from the VCSELs and compare it to the dummy data. The number of errors (disagreements between dummy data and opto-board output) and the intensity of light emitted by the VCSELs is tracked as a function of time, and indirectly of absorbed radiation dose. Several other factors related to the control and optimization of the opto-boards are measured as well, but errors and optical power are the quantities of primary interest.

In the 2006 and 2007 beam tests, we identified several makes and models of PIN and VCSEL which appear to operate satisfactorily well beyond the anticipated SLHC

dosage. Our data shows that annealing VCSELs can, contingent on total dose and the recent rate of dose accumulation, restore a substantial percentage of optical power lost to radiation damage. Optical power never returns to its original value, however, and there is a threshold of absorbed radiation beyond which no amount of annealing has been shown to improve the response significantly. This supports the notion that there are multiple mechanisms of radiation damage which occur in semiconductors, all having similar effects on the electronic properties of the device in the short term, but varying in their permanence and ameliorability.

OSU's beam tests are ongoing, on an annual basis, as the group continues to test the rad-hardness of new PIN and VCSEL candidates for the SLHC Pixel Detector upgrade. Other subjects of research and unresolved curiosity in the past two years have been an irregularly reproducible problem with certain VCSELs taking too long to reach full optical power after receiving the first pulse of a signal, and the effects of higher TEM modes on data rate and accuracy in newer multimode VCSEL arrays.

The LHC, ATLAS, and the SLHC

The Large Hadron Collider is being built at CERN to extend our experimental knowledge of fundamental physics into new energy regimes. Fermilab's Tevatron, currently the highest-energy accelerator facility in the world, can reach energies of 2 TeV in proton-antiproton collisions. At full power, the LHC will collide protons at 14 TeV. Many heretofore unobserved events are predicted to occur at intervening energies, including, perhaps most importantly, production of the Higgs-Boson, a theoretical cornerstone of the Standard Model.

ATLAS is one of two LHC detector systems (the other being CMS) designed to "catch" the Higgs, by recognizing the characteristic radiation produced when this short-lived particle decays inside the detector. In order to accurately measure and characterize radiation emerging from the interaction region, ATLAS employs several layers of cylindrical detectors, each designed for different measurements (fig. 1).

ATLAS and the LHC are physically gigantic. The LHC accelerator ring is 27 km in diameter. The ATLAS detector is roughly seven stories tall, and 46 meters long. Knowlton Hall on Woody Hayes Drive is a good comparison.

In order to keep pace with the enormous flux of particles through the many detector elements, ATLAS generates about 1 Petabyte (10^{15} bytes) of raw data per second. This unmanageable data rate is reduced by several layers of filtering and complex read-out triggers to about 100 megabytes per second of stored data.

After 3-4 years of operation, the LHC and associated experiments are expected to reach a point of rapidly diminishing returns on data collection at the commissioned luminosity ($10^{34}/(\text{s}\cdot\text{cm}^2)$). At that time, the LHC is scheduled for a luminosity upgrade in

order to gain a new statistical edge. The Super-LHC (SLHC) upgrade, scheduled to be completed in 2016, will increase the LHC's luminosity by a factor of ten to roughly $10^{35}/(\text{s}\cdot\text{cm}^2)$. In the course of this upgrade, many detector systems will also be upgraded or replaced, including the Pixel Detector.

The Inner Detector and the Pixel Detector

The Pixel Detector is part of a larger ATLAS system called the Inner Detector (fig. 2), which also includes the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT). All three systems are designed to measure the 3-dimensional position of particles as they move outward from the interaction region. The Inner Detector is contained inside a large solenoidal magnet which generates a powerful (2 Tesla) magnetic field parallel to the proton beam. This field bends the trajectories of charged particles emerging from the interaction region. Their momenta can then be calculated from the curvature of their tracks in the Inner Detector.

The Pixel Detector (fig. 3) is the smallest and innermost instrument of the Inner Detector, and therefore of all ATLAS, as well. The Pixel Detector itself, not including mechanical and electronic support structures, is about a half-meter in diameter and 1.5 meters long. The detector is composed of three concentric cylindrical (or "barrel") layers, and six disk layers, three at either end of the barrels. Barrel Layer-0 (or "b-Layer") is only 5cm in radius. Layer-1's radius is roughly 10 cm, and Layer-2 is 13 cm from the central axis.

The surface of each disk and barrel layer is tiled with $2\times 6\text{ cm}^2$ silicon sensor modules (fig. 4), each containing 47,232 individual pixels. The surface of all three barrels

and six disks is about 1.7 m^2 , which requires 1,744 sensor modules to cover, or slightly over 80 million pixels.

A “pixel” is a $50 \times 400 \text{ }\mu\text{m}^2$ rectangle of doped silicon, with one face connected to Front-End (FE) electronics that register particle hits on the pixel. When a charged particle traverses the pixel volume, it ionizes electrons from atoms near its path. The sensor volume is held at a high electrical potential relative to the FE electronics, so the liberated electrons (and associated holes) travel “downhill” and produce a small, brief, current in the FE chips. Each pixel has a unique data channel in the FE electronics which is associated with the pixel’s three-dimensional location in the detector. By reporting the channel over which the initial pixel current was received, the FE electronics identify where in space the “hit” occurred.

The Optical Data Link

When the FE electronics detect current on a pixel channel, it triggers a signal to the Pixel Detector’s Optical Data Link (“Opto-Link”). Information about the pixel hit, such as time, current, and the channel over which it was received, are transmitted electronically via Low-Voltage Differential Signaling (LVDS) to the Opto-Link. The LVDS information is there converted into pulses of laser light which are carried to the “outside world” via rad-hard fiber-optic cables (fig. 5).

The Opto-Link is implemented as an array of 288 “Opto-Boards” mounted inside the pixel support tube, a short distance from the detector (at Patch Panel 0). Each opto-board is printed on a $2 \times 6.5 \text{ cm}^2$ Beryllium Oxide circuit board (fig. 6). BeO was chosen instead of conventional fiberglass circuit boards for its excellent heat conduction.

The combination of electronic and optical technologies in the Pixel Detector data link is referred to as “hybrid opto-electronics.” There are several advantages to this design approach for the Pixel Detector. The first is radiation-hardness. OSU’s irradiation studies have demonstrated that SLHC-generation opto-boards can withstand punishing doses of ionizing radiation, with some boards in 2007 maintaining acceptable light output (with annealing) above 55 and 70 MRad for GaAs and Si components, respectively.

Optical signals can be generated and transmitted reliably at much lower power compared to electrical signals. The most power-hungry Opto-Boards will operate at 2.4 Watts in a worst-case scenario. Optical transmission also minimizes the need for amplification of the FE electrical signal, since it only needs to get as far as Patch Panel 0. This reduces power consumption and material (such as amplification electronics and dense metallic wire). Power is a limited resource inside the detector, and minimizing material reduces multiple scattering, which is one of the major limitations on momentum resolution in the Inner Detector. Additional benefits of optical transmission include high bandwidth, and electrical decoupling, which prevents unwanted ground loops between the data link and read-out systems.

VCSELs AND PIN DIODES

Conversion on the Opto-Boards from electronic to optical data is accomplished by small solid-state components called Vertical-Cavity Surface-Emission Lasers (VCSELs). A VCSEL is a type of laser diode, which produces coherent light when powered by an electrical current. VCSELs are power-efficient compared to previous laser-diode technologies. The various VCSEL candidates studied by OSU in 2006-2007 produce up

to 3.5 mW of optical power when driven by currents no more than 5 mA. VCSELs' structure allows them to be fabricated with a relatively efficient single-wafer process, making the sort of production yields required for the Pixel Detector and SCT (which employs a similar opto-link) possible. Optical properties, such as wavelength and available modes, can also be customized in the fabrication process. This allows the ATLAS project to purchase VCSELs with the telecommunications-standard wavelength of 850 nm and couple their output into "off-the-shelf" parts and cables where feasible. VCSELs can also operate at very high frequency, removing a possible bottleneck for data readout. The VCSELs studied in 2006 and 2007 operate at frequencies of 2.5, 5, or 10 GHz. VCSELs are controlled by the Opto-Board's VCSEL Driver Chip (VDC), which translates the FE signal into current to drive the VCSEL.

The on-detector Front-End electronics are controlled via optical signals received through the Opto-Link. The control signals are converted from light to electrical current by an array of PIN diodes on each opto-board (P-I-N refers to the three types of semiconductor used in the device). PIN output is interpreted by the Opto-Board's Digital Optical Receiver Integrated Circuit (DORIC). Commands are then decoded and relayed electronically to the on-detector components.

The VCSELs and PIN diodes being tested for the SLHC Pixel Detector are manufactured in arrays of twelve called "Opto-Packs" (fig. 7). The very small lasers or PIN diodes are mounted in a ceramic housing that provides mechanical and electrical connections. Each Opto-Board has one PIN array, on the bottom, and on top it has either one or two VCSEL packs, depending on which pixel layer it connects to. The innermost barrel layer (b-layer) experiences a much higher hit rate than the outer barrels, requiring

greater bandwidth for data readout. In the Opto-Link, that additional bandwidth is supplied by an additional VCSEL pack and VDC on each b-layer board.

RADIATION DAMAGE IN SEMICONDUCTORS

High doses of ionizing and non-ionizing radiation can have detrimental effects on the electronic properties of semiconductors such as VCSELs and PIN diodes. There are several mechanisms by which such damage occurs. This list is not exhaustive, but includes the examples most relevant to OSU's beam tests.

Ionization of electrons in semiconductor crystals by charged particles is called "ionization damage." Just as in a pixel hit, charged particles passing through a semiconductor can wrench electrons from atoms inside the crystal. The freed electrons then drift away subject to electrical potentials inside the device. In sufficient quantity ionization damage degrades electronic performance by altering the distribution, availability, and energy states of charge carriers within the device.

"Bulk damage" refers to the displacement of nuclei from their proper location within the semiconductor's crystal structure. This occurs primarily due to hard-scattering interactions (think "collisions") with massive particles such as protons and neutrons. Almost every important property of a semiconductor is determined in part by its regular, crystal structure. Enough disruptions of that structure will result in observable disruptions to the device's electronic properties.

Transient effects called "soft errors" can also occur, wherein a high fluence of charged particles briefly creates or suppresses a current or voltage in the device, producing unintended output.

In OSU's 2006-2007 beam tests, ionization and bulk-displacement effects combined to degrade the efficiency of both VCSELs and PIN diodes, at a rate roughly proportional to the test beam fluence. As the absorbed radiation dose increased, the light output of VCSELs dwindled, as did the current output of PIN diodes. High error rates measured while the boards were in the beam are likely attributable to soft errors caused by enormous in-beam particle fluences.

It is possible to ameliorate radiation damage somewhat through a process called "annealing." Annealing involves either running a high current through the device or raising its temperature for a sustained period of time. High current encourages electrons to diffuse into the holes created by ionizations, effectively replacing electrons that were lost and restoring something like a pre-irradiation distribution of charge carriers.

High-temperature annealing can be accomplished by "cooking" irradiated devices in specialized ovens, or as a result of current annealing; all semiconductors have internal resistance, which dissipates some power as heat when under current. Temperature annealing may correct some bulk displacements by adding thermal energy to the semiconductor crystal, allowing atoms near a displacement to overcome local potential-energy minima, and to collectively seek a lower-energy state – presumably the original lattice structure. This is roughly analogous to agitating a box so that its contents settle more efficiently.

BEAM TESTS

OSU's ATLAS group is currently responsible for irradiation-testing PIN diode and VCSEL candidates for use in the Opto-Link upgrade which will be installed with the new SLHC Pixel Detector. To maximize the useful lifetime of the SLHC Opto-Link, it is crucial to construct second-generation Opto-Boards with the most rad-hard PIN and VCSEL arrays available. In order to determine experimentally which devices fit that bill, it is necessary to measure the performance of PIN and VCSEL arrays from each potential manufacturer *in situ*, as working components of a functioning opto-board, while they are irradiated up to and beyond their anticipated lifetime dose in ATLAS.

OSU's irradiation experiments are performed at CERN's Test Beam facility, in a building called the East Hall. The East Hall contains several fixed-target locations which are bombarded by particles diverted from the Proton Synchrotron (PS) ring (fig. 8). During Beam Tests, our Opto-Boards occupy a target location called Irrad-1 (fig. 9). As a result of decades of exposure to scattering and activation in Test Beam targets, the area around Irrad-1 is dangerously radioactive. To protect workers and researchers, irradiation experiments are set up and run from inside a room called "T7," separated from the target area by several meters of solid concrete. Inside T7, irradiation targets are mounted to a motorized shuttle which carries them into the path of the proton beam at Irrad-1 (fig. 10). Once there, the shuttle can raise and lower the target out of or into the direct path of the beam, as users desire. Because the shuttle has spent as much time near the beam as every target since its installation combined, it, too, is very radioactive, and persons working in T7 and utilizing the shuttle must observe radiation-safety precautions such as wearing personal dosimeters and disposing of irradiated refuse inside a shielded locker.

The Test Beam itself is composed of 24 GeV protons, delivered to the target in "spills" lasting 2.4 seconds. Spills are directed to different experiments located around the PS ring on a 7- to 9-spill supercycle. For higher average dose rates, several spills to a target can be scheduled per supercycle.

The number of protons delivered in a single spill varies with the tuning and condition of the PS, but is typically within $5E10$ and $15E10$ protons/spill. At the Irrad1 target, the beam is focused on an area approximately 2cm by 2cm. Proton fluence within this area is roughly gaussian, though the center and width of the peak vary with tuning of the beam.

For OSU's Beam Tests, four Opto-Boards are mounted in the Irrad-1 target shuttle, connected to two motherboards (fig. 10), which mimic connections between opto-boards and the Pixel Detector's FE electronics. From the shuttle, Opto-Boards and motherboards communicate with a control and data acquisition (DAQ) system in T7 via very long cables fed from a motorized spool. The DAQ system is four identical boxes of specialized electronics, one connected to each Opto-Board (fig. 11). The boxes continuously monitor VCSEL optical powers and other quantities related to optimization and control of the Opto-Boards, transmit pseudo-random input to the Opto-Boards through the motherboards, and count errors when the opto-boards try to read the input back. Data is written to text files on a laptop computer connected to all four boxes through an ethernet connection. Parameters determined by human input, such as board numbers, whether to set the boards in an anneal or irradiation cycle, and notes to attach to the current data set, are entered on the laptop, through an interface created in LabView.

Before the irradiation begins, we choose a target proton fluence by converting the expected SLHC doses in MRad to equivalent 24 GeV proton fluence. We divide the target fluence by the length of our beam time to set a rough pace for the irradiation. This will help to guide decisions about when and how long to keep the boards in the beam. If we are ahead of schedule, we can better afford to spend time annealing, which helps the VCSELs to continue operating longer, giving us more data. If we are behind, there is incentive to keep boards in the beam even when VCSEL powers become uncomfortably low, so that our results will show performance up to the boards' full anticipated lifetime dose.

All these decisions while taking data depend on reasonable estimates of doses and dose rates, so the various methods of dosimetry employed in the Beam Tests are extremely important. All values of absorbed radiation doses in this experiment are derived from measurements of proton fluence through the target. There are several methods of measuring proton fluence employed at the Test Beam facility, each with its different uses.

Proton fluence is most accurately measured by irradiating thin foils of Aluminum along with the targets. The preponderance of unstable isotopes (eg., $(11)\text{C}$, $(18)\text{F}$, $(13)\text{N}$, $(24)\text{Na}$) in homogeneous Aluminum is a known function of particle fluence and energy, so the induced activity in Aluminum foils can be used to calculate the cumulative proton flux. When the shuttle is returned and the target is disassembled, a high-resolution activity map of the activated Aluminum foils is created and analyzed to determine the proton fluence precisely.

Three Al foils are included in our target apparatus – before, between, and behind the two motherboards. For the 2006-2007 Beam Tests, total proton fluences ranged from $2E15/cm^2$ to $4E15/cm^2$, with errors between 4% and 8%, after measurements were combined in weighted averages.

In order to retrieve foils for spectroscopy, the entire shuttle and target apparatus has to be recalled from Irrad-1 and "parked" for some time in an intermediate location while its radioactivity declines to a safe level. The length of time the shuttle has to cool is dependent on how radioactive it is when removed from the beam. Once the shuttle is recalled to T7 and foils are collected, spectroscopic analysis can take several hours. Time spent in cool-down and waiting on spectroscopy results disrupts data acquisition and can be a waste of valuable beam-time. For this reason, Al spectroscopy is typically only used after an irradiation is complete, to calculate an authoritative final dose. The only time spectroscopy measurements were taken during an irradiation while I worked on the beam tests was during the 2007 irradiation. In that instance, the shuttle had to be recalled for separate reasons (replacing a twitchy PIN diode dosimeter), so retrieving and analyzing the front foil caused no additional inconvenience, and posed no additional radiation hazard.

Post-irradiation spectroscopy provides an authoritative value for the total proton fluence once the irradiation is concluded. However, it provides no basis for important decisions about dose rates and exposure times while an irradiation is ongoing. In order to obtain reasonably accurate dose values during the irradiation, we rely on measurements made using a Secondary Emission Chamber (SEC) located at Irrad-1. The SEC is an evacuated chamber containing several layers of thin aluminum foils placed perpendicular

to the path of the beam. Proton flux through the chamber ionizes electrons from the surface of the foils. Alternate foils are held at high electrical potential, which attracts the freed electrons and conducts them out of the chamber as an electrical current. Outside the chamber, the current is measured and integrated over the duration of a spill to obtain the charge, and thereby the number of ionized electrons. This number, times some proportionality factor, is reported to the T7 as a dimensionless “SEC count.”

There is no general conversion of secondary emission measurements to proton fluence. However, under stable beam conditions, the relationship is linear. An independent measurement of fluence for a known change in SEC count allows us to calculate the protons/cm²/SEC factor (for specific beam and target conditions) experimentally.

To determine the SEC factor, the target is placed in the beam with a temporary foil for a very brief exposure, typically ten spills. After ten spills, the shuttle is recalled and the foil is removed. The increase in SEC count over the ten spills is then compared to a quick spectroscopic analysis of the activated Al foil, to determine the SEC factor. The SEC factor is then used to convert SEC counts to proton fluence, until the end of the irradiation or the factor has to be measured again.

The SEC factor is sensitive to many variable beam parameters, and has to be measured every time adjustments or repairs are made to the beam. When these parameters are not well controlled, SEC-based dosimetry is unreliable. During the 2007 beam test, the PS beam profile was unstable. Fluence and focus varied substantially from spill to spill. In order that we might not have to rely solely on SEC calculations for

dosimetry, the beam manager installed an experimental PIN diode dosimeter in the shuttle with our target.

The idea behind the PIN dosimeter is that the operating voltage of a Silicon PIN diode (similar to those used in the Opto-Link) creeps upward as it is irradiated, due to effects similar to those which degrade the electronic response of our VCSELs and PIN diodes. If the voltage rise in a PIN diode has been carefully characterized, the voltage of a similar PIN can then be used to infer its accumulated dose. For a variety of reasons, the PIN dosimeter proved less than reliable for our purposes. As the radiation dose increases, the rate of voltage increase declines. This reduces the precision of dose measurements, as a greater range of doses fall within the PIN voltage margin-of-error. Once a point of diminishing returns was reached, the PIN dosimeter had to be replaced, a time-consuming and very radioactive procedure. Variations in temperature at the target location had observable effects on the PIN voltage, but how to account for these variations in our dose calculations was not well understood. Other unknowns, such as manufacturing variations between PIN diodes, also cast suspicion on PIN doses. It is important to note that our 2007 beam test was an early, experimental use of the PIN dosimeter. It is likely that the system was pressed into service before all the bugs were worked out, since we badly needed a "second opinion" to complement the twitchy SEC measurements.

When the shuttle was recalled in order to replace the PIN dosimeter, we took the opportunity to retrieve the front foil and get a reliable fluence measurement. We discovered that both the PIN and SEC were drastically underestimating the fluence, and that we had very nearly achieved our target dose, with a substantial portion of our beam

time remaining. This allowed us to swap out the four boards in the shuttle for four spares, and to take a whole new set of data.

Once our beam time ends and we dismount the irradiated Opto-Boards and decamp from T7, the analysis of our data is fairly straightforward. The VCSELs that retain the highest optical powers and develop the fewest “dead” channels are the strongest candidates for the SLHC Opto-Link. There are some subtleties, such as which boards respond more and faster to annealing, but even that comes out in the final optical powers, given time to anneal post-irradiation (fig. 12).

My Work with the OSU ATLAS Group, 2006-2008

When I began working for OSU’s ATLAS group in June 2006, we were preparing to fly to CERN with the irradiation experiment. The DAQ control boxes were a new innovation that year, and my first responsibilities were related to their assembly. I designed and printed labels for the front and back panels and assembled the electrical and optical connections on the control box chassis. I also built a very simple power supply for the control boxes from parts and designs provided to me. Before it was ever plugged in to the control boxes, my power supply was retired in favor of commercial supplies, as it was not designed to specification, and had problems operating on European electricity. During this period I also used the tools in the Smith Lab machine shop to cut the fiberglass mounting brackets that hold our opto-boards in the Irrad-1 shuttle.

I spent some time in the run-up to the 2006 Beam Test characterizing VCSELs, a job I would do much more of in 2007/2008. For purposes of quality control and to help

select specific VCSEL packs for installation on Beam Test Opto-Boards, each VCSEL needs to have its optical and electronic properties characterized. The light output of each VCSEL in a 12-channel opto-pack is measured as a function of driving current. This is done by plugging the VCSEL pack into a fiber-optic cable which fans out to 12 separate optical fiber connections. The VCSELs are placed under a microscope, and driven one-at-a-time by touching electrical probes mounted on 3-axis micrometer arms to the gold contacts (see fig.7). The fanout connection corresponding to the channel under current is plugged into an optical power meter, and light output is measured over the VCSEL pack's operational range of current. In order to control power measurements for losses in the fanout cable, attenuation in each fiber channel is measured. The established power output of a control VCSEL (set to 1 mW when coupled to the meter by a much shorter fiber-optic connection) is compared to measurements of the same VCSEL taken at the opposite end of each fanout channel. One interesting result of the fiber characterizations is that power loss in these cables is sensitive to curvature and winding of the cable. Because light is guided through these cables by a radial refraction-index gradient, bending the fibers increases the angle of incidence along the length, and off-axis transmission (power loss) increases.

During the two weeks we spent waiting for the beam at CERN in 2006, there was plenty of time to optimize code in the reprogrammable microprocessors which control the DAQ boxes. My programming knowledge at the time was very limited, but I expanded it somewhat by kibitzing while Shane fine-tuned the boxes' measurements and sample rates.

Beam-time at CERN is a limited and valuable resource, so once the beam is up and running, we take data around-the-clock. This requires us to monitor the experiment in shifts, of which I took a share during both the 2006 and 2007 Beam Tests. The individual on-duty is responsible for visiting the T7 periodically. If the shuttle is in the beam, this ensures that someone is available to remove the boards should the VCSEL optical powers fall to dangerously low levels. During anneal cycles, we monitor optical power to make sure that we do not waste beam time by annealing more than is necessary or useful. During a visit to the T7, the individual on-duty notes the optical powers, SEC count, and beam status in the logbook, then calculates doses, dose rates, and times-to-target-dose. If conditions such as optical power, beam status, and cumulative dose are right to begin a new irradiation or anneal cycle, she or he resets the DAQ system, moves the shuttle into or out of the beam, and emails up-to-date data to everyone in the group.

In 2006, The DAQ boxes took measurements of 49 separate quantities on four opto-boards, and calculated several more, each at a sample rate of once every two to four minutes, for nearly a month. Visualizing these large data sets in common plotting programs like Microsoft Excel could be very tedious. For the greater convenience of myself and others, I created a spreadsheet and plotting template in Excel which could easily import new data and which would automatically update the plots of each measurement. The template worked, but it was excessively large (~200 MB for all four Irrad '06 data sets), making it difficult to share data and transfer charts from one format to another.

Concurrent with the 2006 Beam Test, several OSU graduate and post-doctorate students were working at CERN to test and assemble parts of the first-generation Pixel

Detector Opto-Link. The biggest part of this work was Quality Assurance testing of the opto-boards. A smaller, but still time-consuming, task was testing and labeling the hundreds of rad-hard fiber cables that would be connected between the Pixel Detector's Patch Panels. Fiber testing was done with a piece of custom electronics designed by an OSU undergraduate. The fibers being tested were used to complete an open optical connection in the test rig. The optical power received at the end of each fiber channel, as a percentage of input power, was read out to a laptop computer. If the loss was small enough on every channel, the cable passed. It was then labeled in nonmagnetic permanent ink with a unique serial number, using a simple binary bar code. The serial number could be used to look up the cable's test results at any time in the future. During my time at CERN in 2006 I tested and labeled around two hundred of these rad-hard fibers, out of more than 550.

Both summers I helped mount our target apparatus in the Irrad-1 shuttle, and in 2006 I assisted the dismount after our beam time was over. In 2007 our beam time was extended, and I left CERN before the dismount. I was on-hand, however, for the swapping of the Opto-Boards midway through that irradiation campaign.

Mounting, dismounting, and exchanging Opto-Boards in the shuttle is one of the most difficult parts of the Beam Tests. Many electronic and optical cables between the shuttle and trailing patch panel have to be connected, bundled, and routed in such a way that they will not be overextended or bent too sharply while the shuttle is in transit from the T7 to Irrad-1. For reasons of radiation safety, all of this has to be accomplished in a challenging workspace, stooping to see the shuttle through a side opening in a low metal box, and reaching around leaded glass windows to work with the Opto-Boards. Often a

radiation alarm is flashing and sounding above your head. Despite the ergonomic impediments, radiation-safety demands that the mount, swap, and dismount be performed in as deliberate and efficient a manner as possible, to minimize exposure to radiation from the shuttle and target.

Once the 2006 irradiation was complete, plotting the data for evaluation and presentation became primarily my responsibility. A useful feature on plots of our data is a graph of radiation dose on the same time-scale as other measurements (fig. 12). This allows us to easily compare trends in dose-rate and total dose to trends in quantities like VCSEL optical power. This was first done by simple linear interpolation between SEC measurements, and conversion to MRad using the historical SEC factors recorded in the log book. After we received spectroscopy results from CERN, we recalculated our “best guess” for intermediate doses by renormalizing the SEC-based dose curve so that the final dose matched the best value extracted from spectroscopy measurements.

Before the Beam Test in 2007, I spent many days’ worth of work characterizing new VCSELs. I also expanded my repertoire into PIN diode characterizations. In order to establish a pre-irradiation baseline for the loose GaAs PIN samples which were included in the 2007 target, the current output of each PIN channel was measured with an incident optical power of 1 mW. This was done in very much the same way as VCSEL characterizations, but the probes were connected to a digital multimeter instead of a voltage source, and the fanout channels were plugged into a powered VCSEL calibrated for 1 mW output, instead of an optical power meter. I took more measurements on the GaAs PIN diodes after they were returned to Columbus from CERN, and again after they were temperature-annealed.

Prior to the 2007 Beam Test, The DAQ boxes were upgraded. Their measurement sample rates increased from once every two to four minutes, to two to four per minute. This produced data files which outgrew Excel's plotting limitations (32,000 data points per series), but not the spreadsheet capacity. To overcome this problem, and to reduce the unwieldy size of the 2006 plot templates, I programmed a script in Visual Basic to pseudo-randomly select and plot 32,000 points from chosen data series. The script could be executed on-demand at any time, so that the graphical plot data did not have to be saved and moved with the files. This reduced the size of the chart files, and it did plot the Beam Test's entire time range in spite of Excel's plot series limitations. It ran very slowly, however, requiring several minutes to create some plots, and even though it makes almost no difference to the appearance of the graphs, plotting random samples of data sets is just bad form.

When it was decided to replace the first four opto-boards and take a completely new data set during the 2007 beam Test, I was assigned to write a detailed description of a proposed replacement procedure. Several revisions of this document were circulated within the group for comments and suggestions, in order to help anticipate problems and challenges which might arise in the swap-out.

After the 2007 spectroscopy results were posted to the web late in October 2007, I was given the job of extracting the best values for the final doses, based on the four spectroscopy measurements taken with each sample set. Given multiple measurements of a single quantity, the best value is determined by a Chi-Squared average, with weights determined by the absolute error of each measurement. By combining redundant

spectroscopy measurements in a simple weighted average, we were able to reduce the error of our cumulative-dose figures substantially.

Early in 2008, I started working on an Opto-Link project which had been begun by others in Winter 2007, but then orphaned. Some Opto-Board VCSELs take too long to reach full optical power after they receive the first pulses in a data stream from the VCSEL Driver Chip. This can cause the first bits of data in a particular stream to be transmitted at low power, and possibly lost to attenuation, noise, or power thresholds “upstream.” The practical consequences of the problem can be minimized by making sure to connect the offending VCSELs to a very particular kind of optical cable, but the physical reasons behind the slow turn-on effect remain unclear.

One possibility being considered by OSU’s ATLAS group is that slow turn-on could be due to the presence of higher TEM modes in modern “multi-mode” VCSELs. Light produced in higher modes will have different transmission properties at the optical fiber connection. If when the VCSEL is first switched on, the number, variety, or dominance of active modes fluctuates before reaching a steady state, the measured optical power is likely to fluctuate as well. From the first student to work on this question, I inherited a prototype of an apparatus designed to map the shape and intensity of light emitted by VCSELs. I have made several important improvements to the device, but when last put to the test, it was still not equal to the difficult measurement for which it is designed. The slow turn-on measurement is an open project, with further improvements on the drawing board.

After we got the Opto-Boards from the 2007 irradiation back from CERN, the DAQ system was set up in Columbus and we continued to take annealing data on those

boards which maintained the best optical power after irradiation. As of late May 2008, we were still taking anneal data on four of the most resilient boards. This has more than doubled the size of several of the 2007 data sets, finally overflowing Excel's maximum spreadsheet dimensions and rendering my plotting and data-shaping scripts almost useless. For a time, we made due by reducing the data sets to "Excel size" with a command-line script, but this method deleted as much as three-quarters of our data to fit the whole time range into Excel plots. In June 2008, I developed a Python script which can read and plot unabridged beam-test datasets quickly, regardless of size. Barring drastic changes to data formats, this should prove a durable solution to the chore of visualizing beam-test data.

As of summer 2008, I am still working for OSU's ATLAS group. As we begin to prepare for the 2008 Beam Test, I am continuing to revise and refine the slow-turn-on test apparatus, and I am also involved in research projects within the group unrelated to ATLAS.

CONCLUSION

Now that I am approaching graduation and the end of my work with OSU's ATLAS group, I hope that my contributions have been valuable, and that my advisors will be encouraged to give other undergraduates some of the same opportunities I've enjoyed through this work.

Becoming a very small part of a collaboration as enormous as ATLAS was in some ways a disorienting experience, and it seemed like a long time before I came to a functional understanding of how OSU's work, and my own, fit into the "big picture."

There is no ATLAS textbook or newcomers' manual. It can take a long time for someone with no experience in research to discover what questions they need to ask in order to orient themselves, both amongst the minute technical details of OSU Beam Tests, and within the truly grand scheme of the (S)LHC/ATLAS collaboration. My hope is that this report will help future undergraduates who join this project to more quickly begin asking those questions.

Alexander Law

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Figures 1-5 are from "ATLAS Note." Figure 8 is from CERN's website,

<http://cern.ch>. Figure 9 is from the Irrad-1 website.

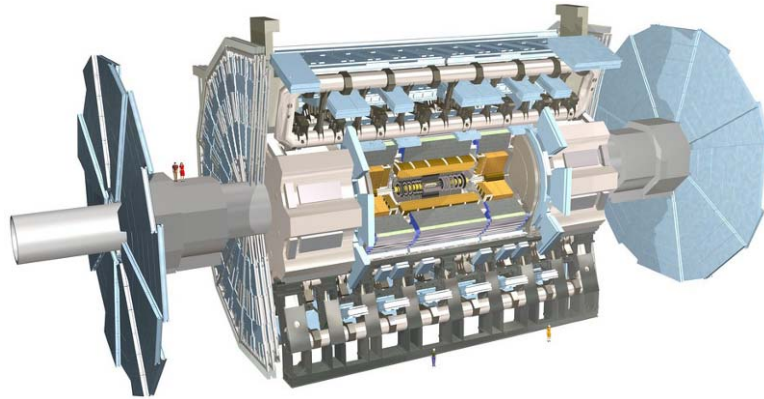


Fig. 1 – Cut-away diagram of the ATLAS detector, showing layered, cylindrical design. Central orange region contains the Inner Detector.

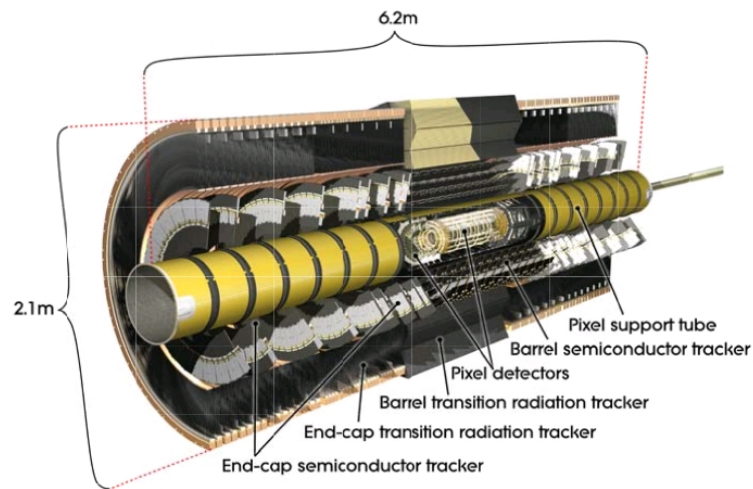


Fig. 2 – Cut-away diagram of the Inner Detector

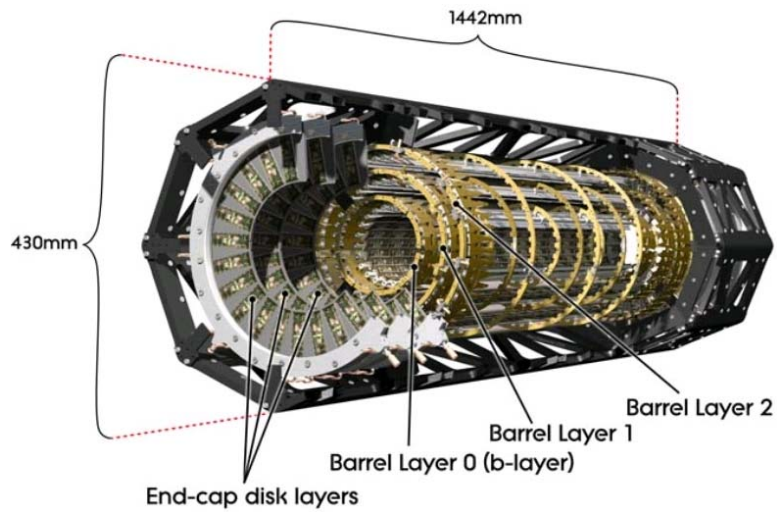


fig. 3 – Cut-away diagram of the Pixel Detector

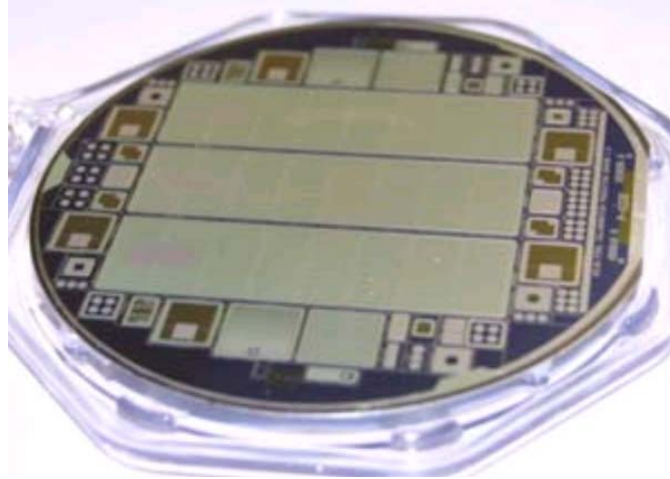


fig. 4 – Sensor tiles printed on a 4-inch diameter Silicon wafer. The 3 large rectangles in the center are sensor modules.

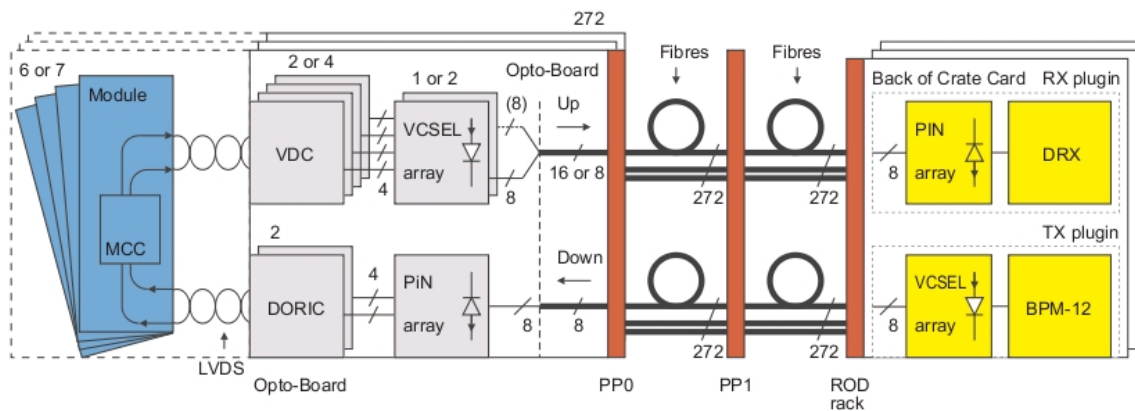


fig. 5 – Functional diagram of the Pixel Detector Optical Data-Link (Image from “ATLAS Note”)

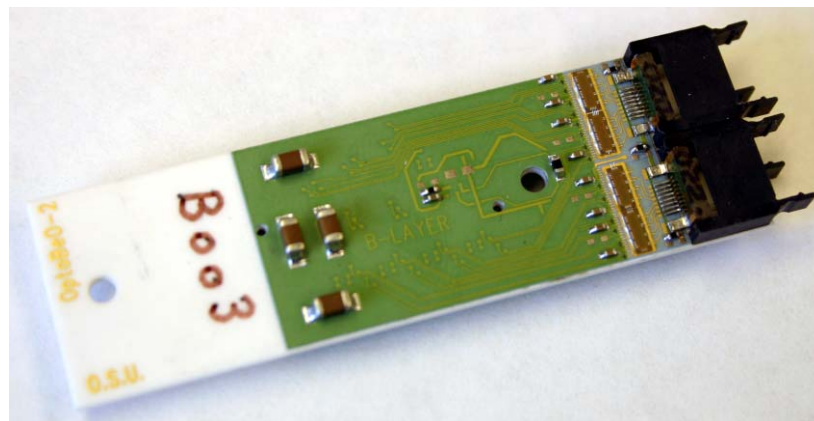


fig. 6 – b-Layer Opto-Board, 4x6.5cm². Note 2 VCSEL packs (labeled 020 and 022)

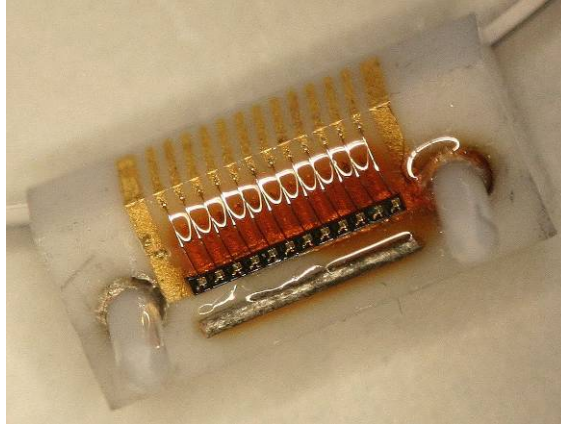


fig. 7 – Front view of an SHLC Opto-Pack. See fig. 6 for scale.

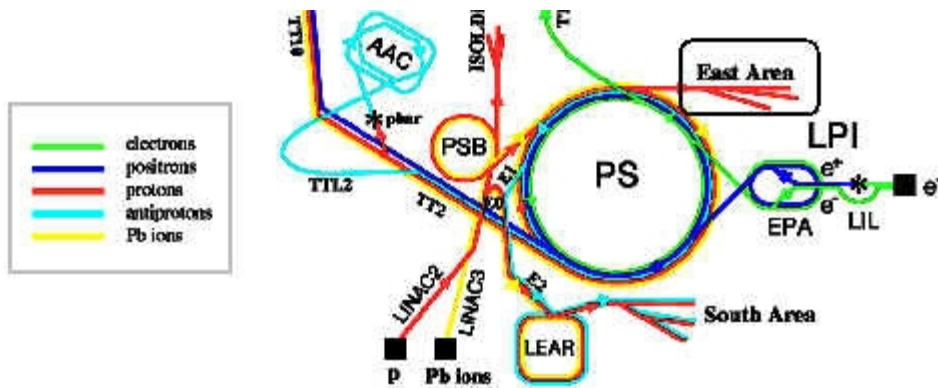


fig. 8 – Diagram of lower-energy CERN accelerators. Note East Hall in upper right.

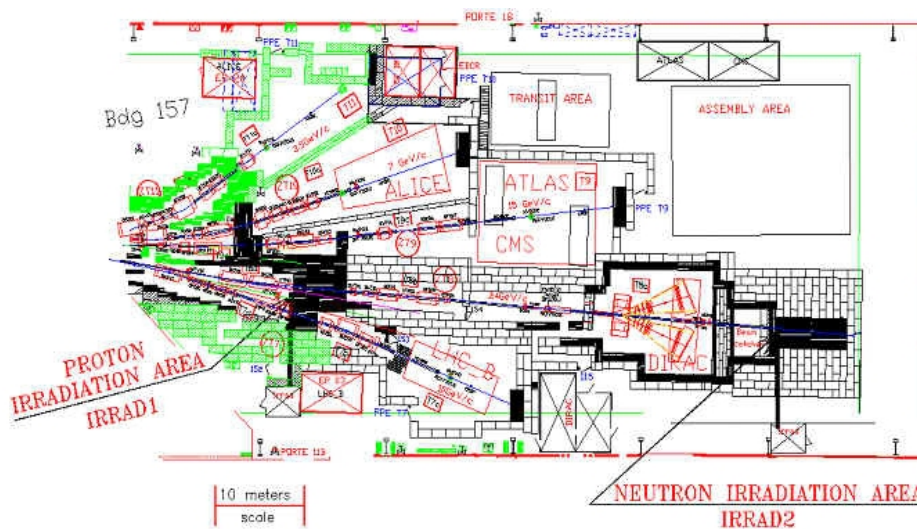


fig. 9 – Floor plan of East Hall showing beam lines (blue) and target areas. To locate T7, follow the vertical black line from Irrad-1.

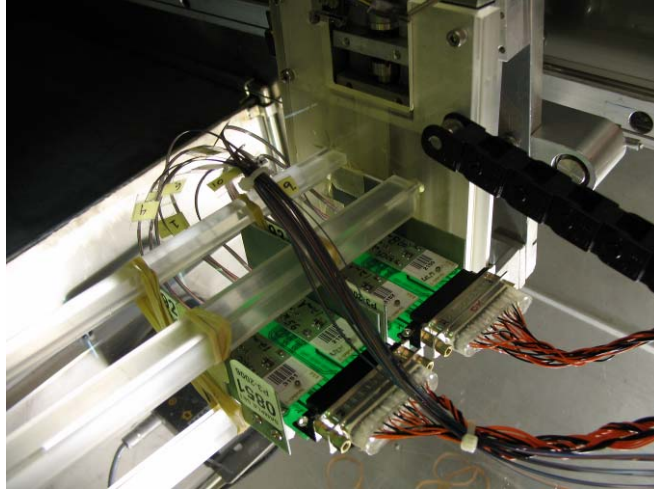


fig. 10 – Opto-Boards mounted in the shuttle to Irrad-1

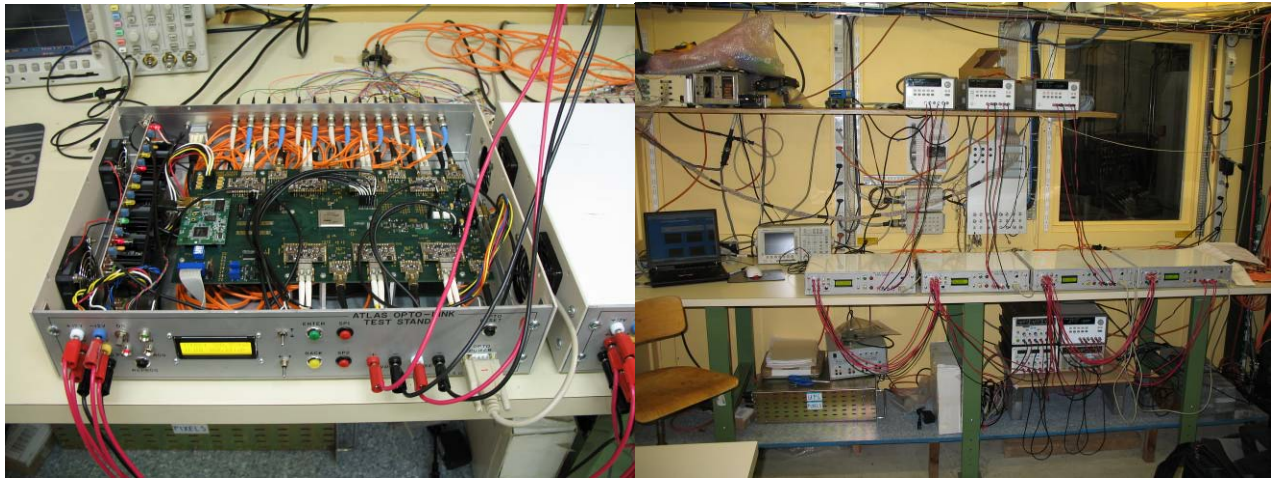


fig. 11 – Left, one of four DAQ control boxes. Right, the complete DAQ system assembled at CERN

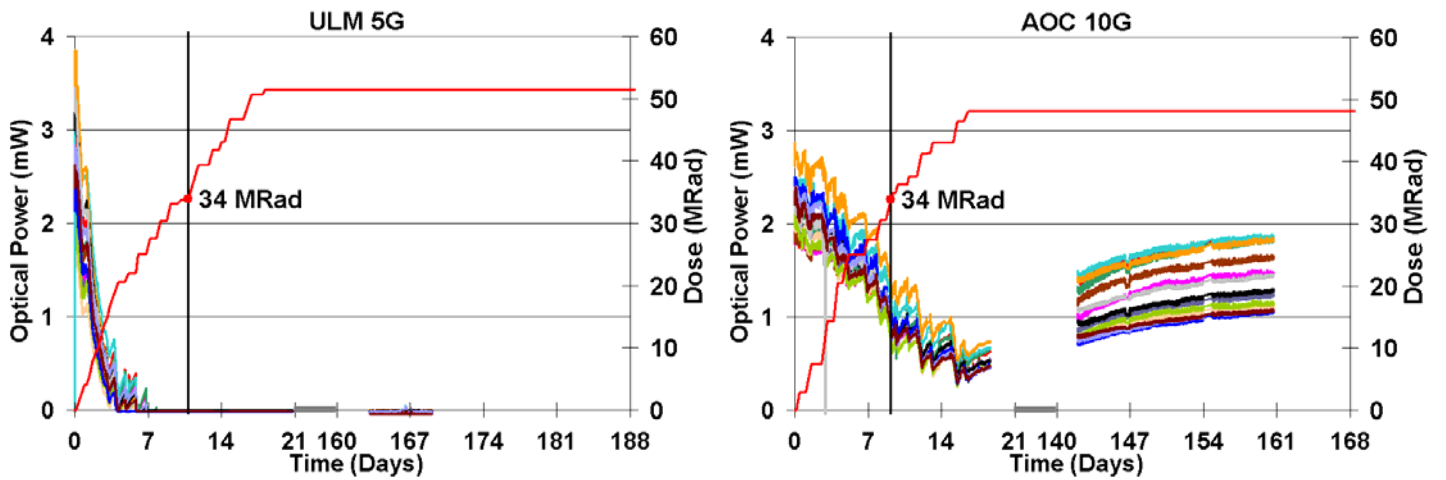


fig. 12 – VCSEL optical powers of the best and worst boards from the 2007 Beam Test