Design of Electronics for a High Energy Photon Tagger

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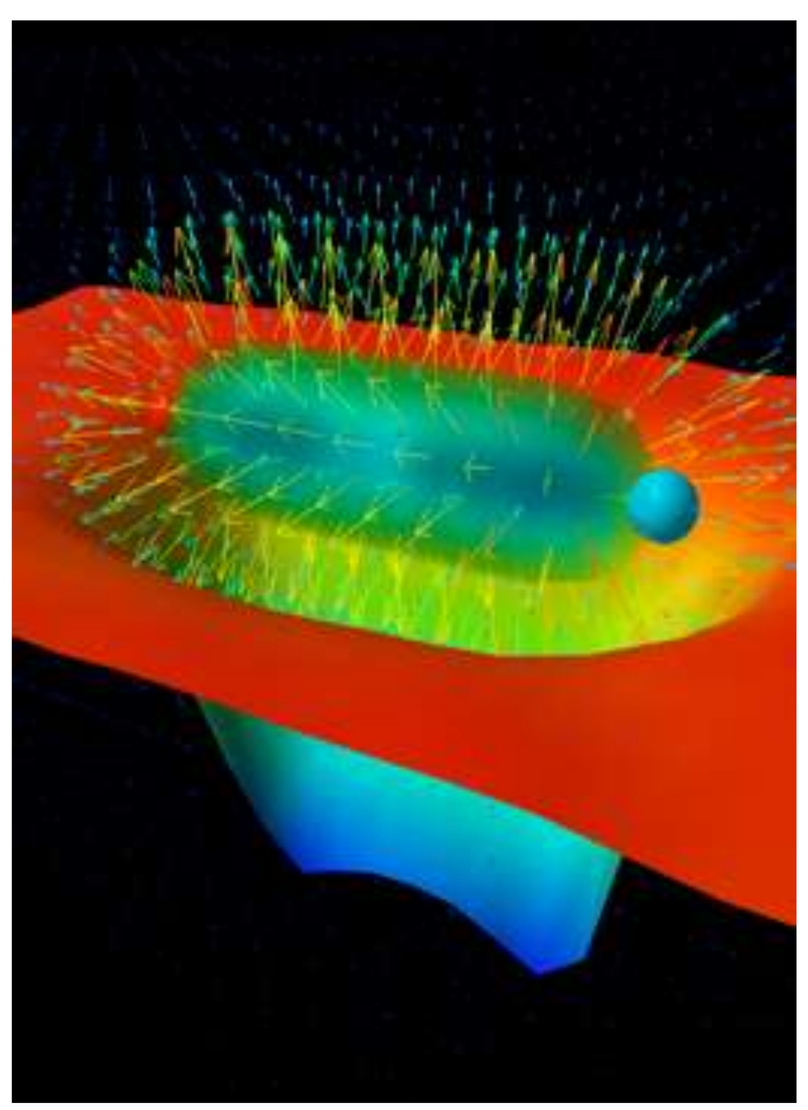
Abstract

GlueX is a nuclear physics experiment which aims to discover how quarks and gluons are confined within hadrons. Quarks and gluons are elementary particles that are the building blocks of heavier particles like protons and neutrons. Protons and neutrons are the lightest members of a large family of composite particles called hadrons that make up the atomic nucleus. The physical theory that governs hadrons, quantum chromodynamics (QCD), tells us that hadrons can be grouped in a hierarchical table that is analogous to the periodic table of the elements. The hadron that plays the role of hydrogen in this table is known as a meson, which consists of a quark and an anti-quark bound by an elastic string of gluons. According to QCD, this string should be able to vibrate, giving rise to more energetic particles in the same family of the table. Mesons with vibrating glue are referred to as exotic mesons. Experimental evidence is now mounting for the physical existence of exotic mesons. The goal of the GlueX experiment is to produce exotic mesons in large numbers in order to unambiguously identify them, map their spectrum and measure their properties.

The GlueX experiment will produce mesons by colliding high-energy particles of light (photons) with a liquid hydrogen target. At the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility, high-energy electrons from the accelerator are directed onto a piece of diamond crystal. As these electrons pass through the diamond, they lose some energy by radiating high-energy photons in a process known as bremsstrahlung. If the diamond is oriented such that the electrons travel nearly parallel to the planes of atoms in the crystal, then the photons produced are polarized in the direction perpendicular to the planes, and the process is called coherent bremsstrahlung. Among the myriad particles produced by the collisions of polarized photons with protons in the liquid hydrogen target are the mesons of interest to the experiment. To separate these from all of the other radiation produced in the target, it is essential to measure the energy and time of each photon in the beam. The "photon tagger" accomplishes this by measuring the energy of the electrons as they exit the diamond. Electrons coming out of the back of the diamond radiator are deflected by a magnetic field into an array of optical fibers that glow (scintillate) when high-energy electrons pass through them. The scintillation produced by these electrons is then carried by waveguides to solid state light detectors called silicon photomultipliers (SiPMs).

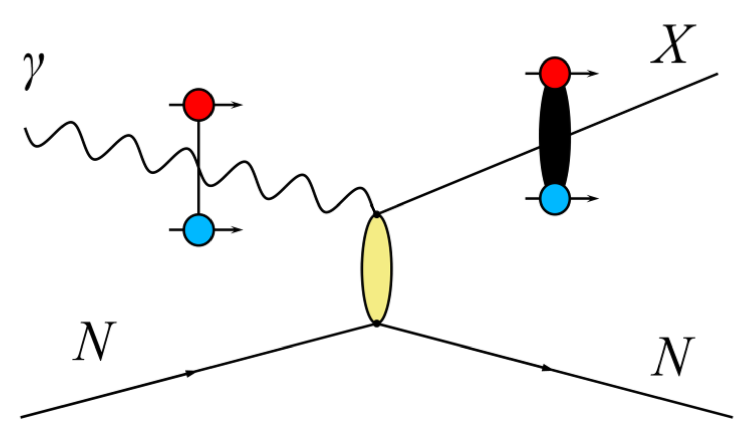
The goal of this research project is to design and prototype electronics for the readout of signals from the SiPMs. The primary function of the readout electronics is to amplify the signals for subsequent digitization. Their second function is to provide the bias voltage that is necessary for each SiPM's operation and to monitor critical environmental parameters. The project entails the design and layout of circuit boards to accomplish the above functions, and the production and testing of prototypes.

Mesons, Quarks, and Gluons



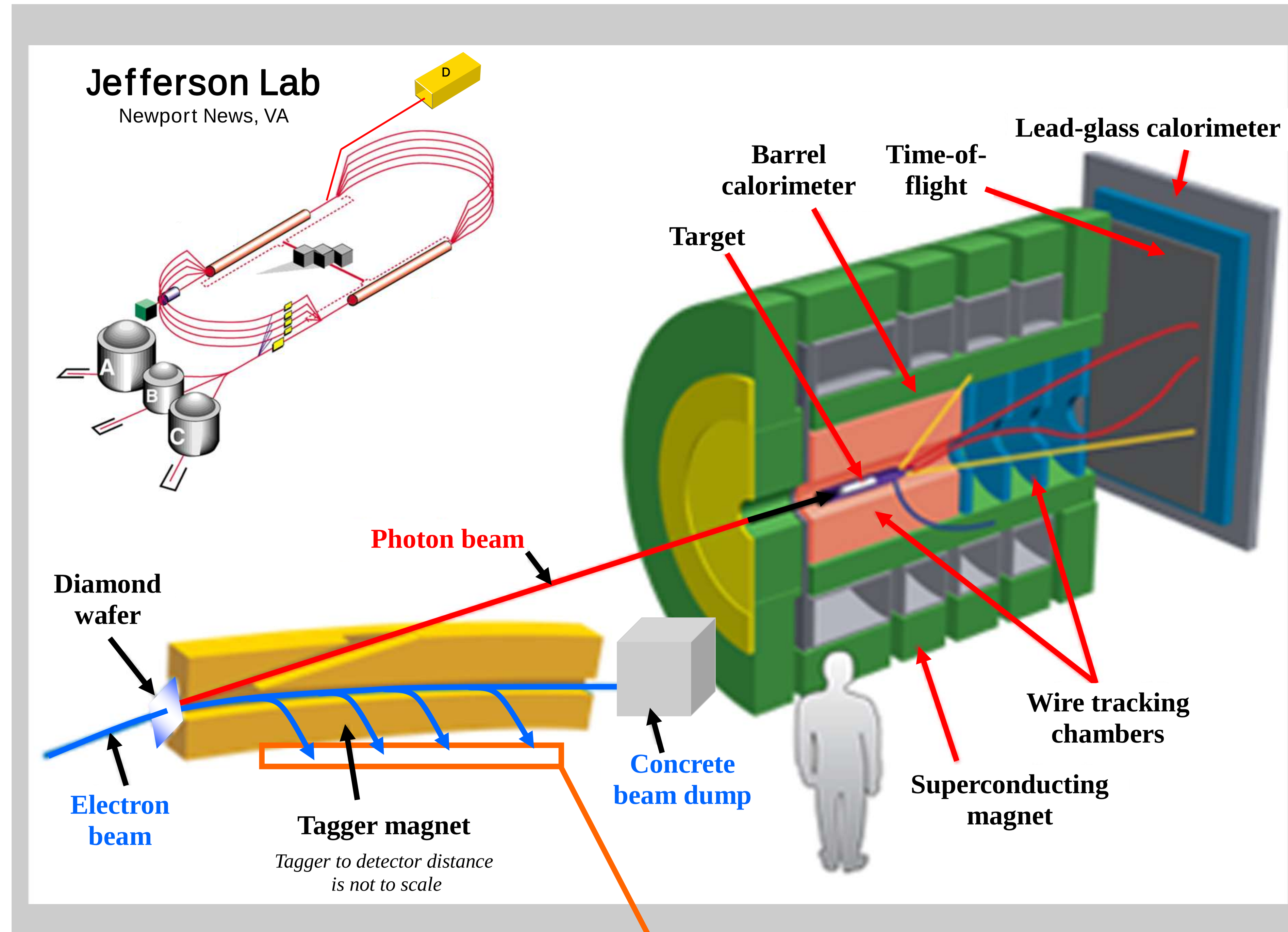
The computerized rendering to the left shows a typical meson, consisting of a quark and an antiquark held together by a gluonic flux tube. Quantum chromodynamics predicts that the gluonic flux tube connecting the quark and antiquark can become excited and start to vibrate. Mesons with vibrating glue are known as exotic mesons.

One way to produce exotic mesons is to try to excite the gluons in ordinary mesons using high energy photons, as shown in the Feynman diagram below.



GlueX

The diagram below shows the basic setup of the GlueX experiment [1-3]. High energy bremsstrahlung photons are generated by passing electrons from the accelerator through a diamond crystal wafer. The electrons are deflected by a magnet, and the photons continue on to the liquid hydrogen target. Effects of the photon-proton collision in the target are observed and recorded if the photon is in the energy range of interest.



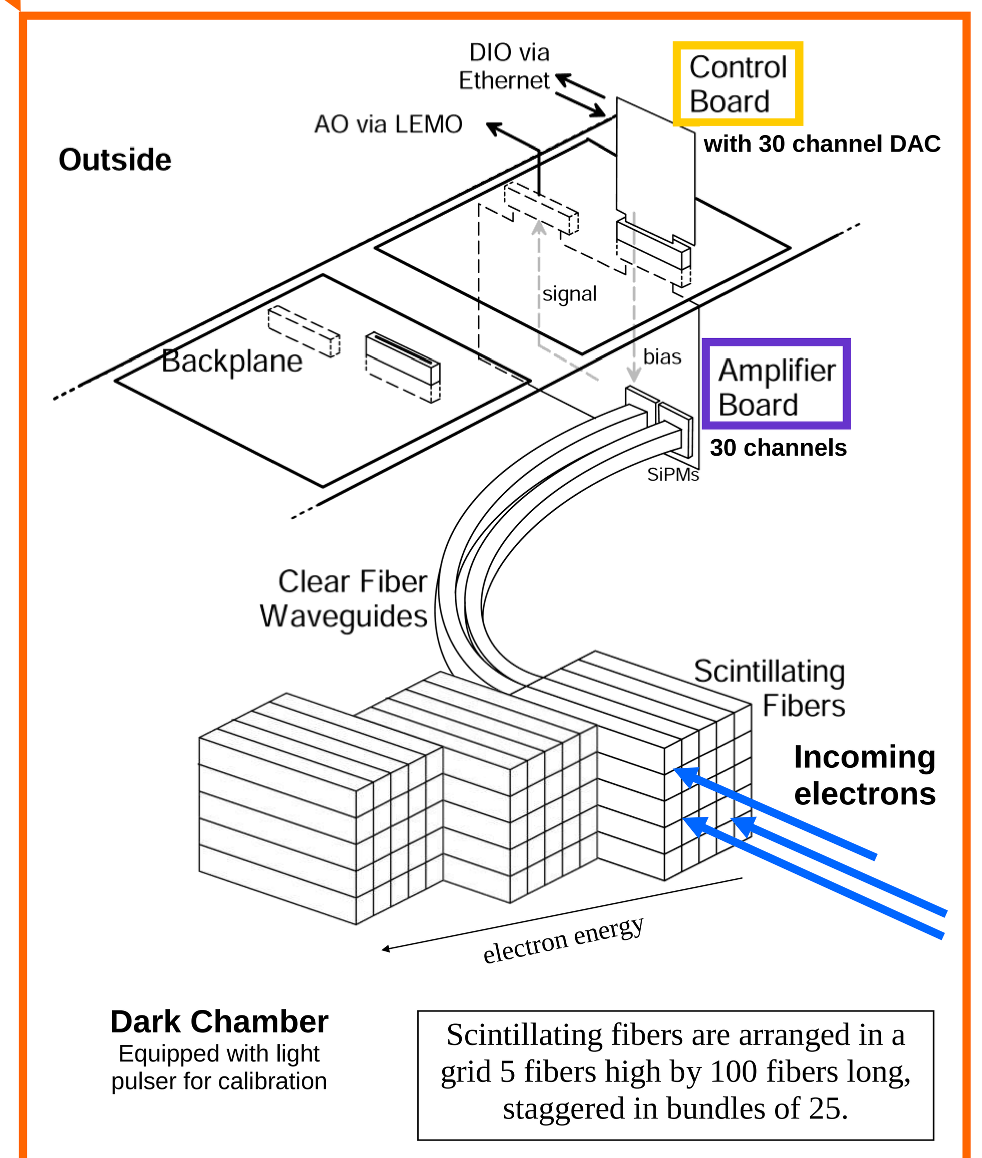
The Photon Tagger

Analysis of the reactions in the detector requires knowledge of the bremsstrahlung photon energy. A device called the photon tagger is responsible for measuring the energy of these photons. The photon tagger consists of a light-sealed "dark chamber" which contains the SiPMs and amplifier circuit boards, and also a series of control circuit boards exposed to the outside. Each amplifier circuit board is connected to its own control board by means of a backplane.

Measuring Photon Energy

$$E^{initial}_{electron} - E^{final}_{electron} = E_{photon}$$

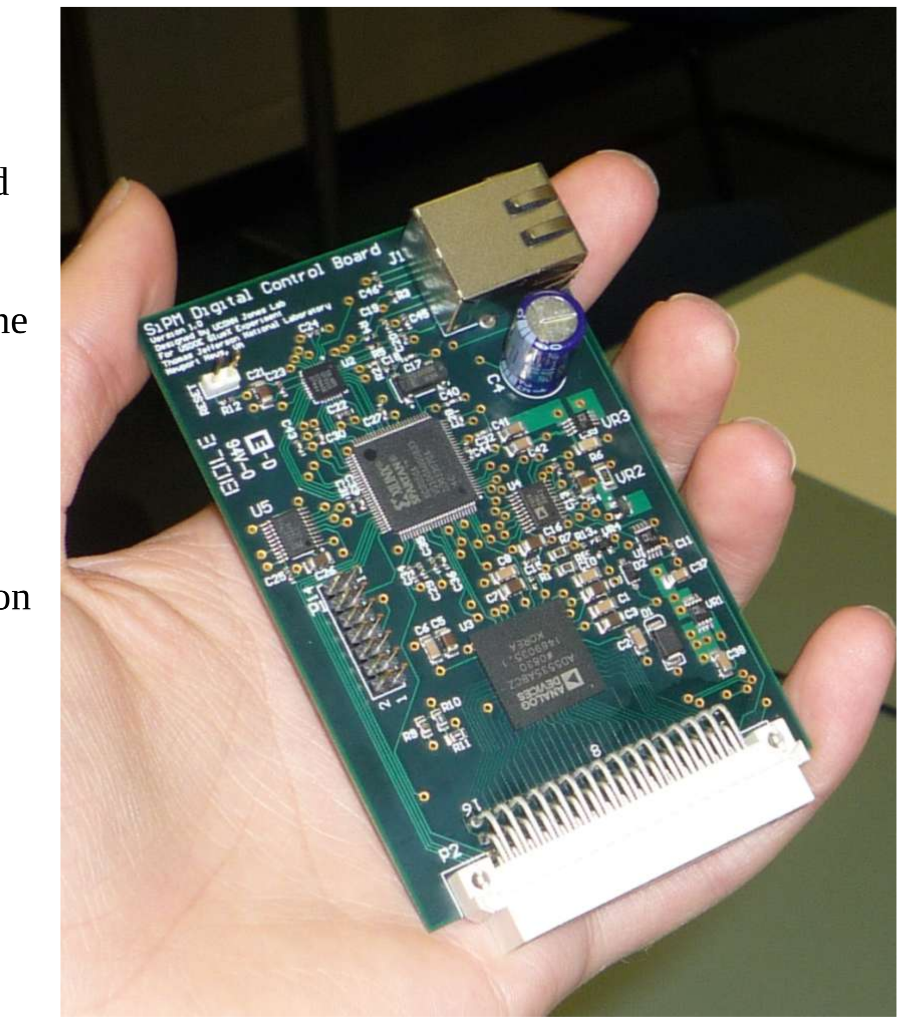
The tagger magnet separates the electrons from the photons, and also spreads out the electrons depending on their energy. The SiPMs detect the final energy of the electrons after they leave the tagger magnet. Since the initial energy of the electrons is set by the accelerator and the final energy is measured by the SiPMs, the energy lost in the diamond crystal can be calculated. This is the energy of the bremsstrahlung photon.

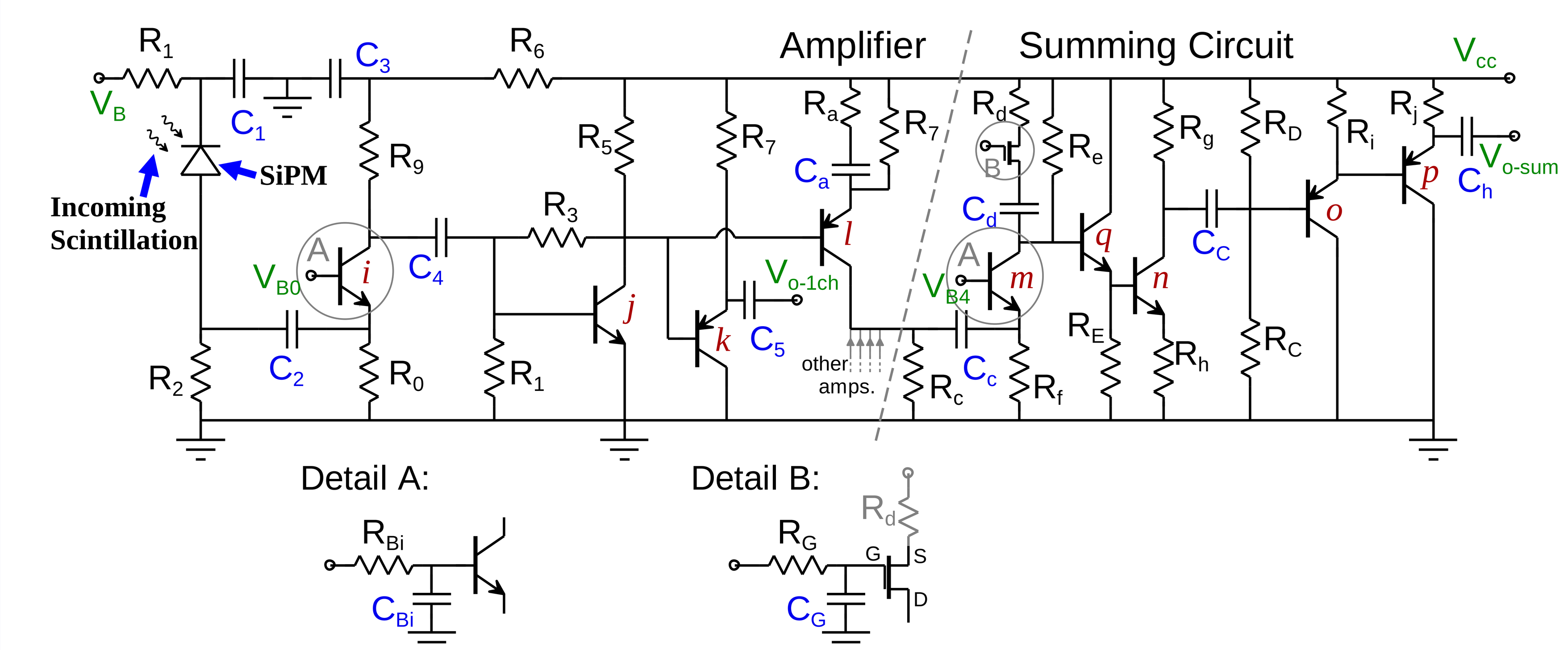


The Control Board

The SiPM Digital Control Board, also known as the "digital board" or "control board," was the first circuit board designed for the photon tagger. The control board has several main components.

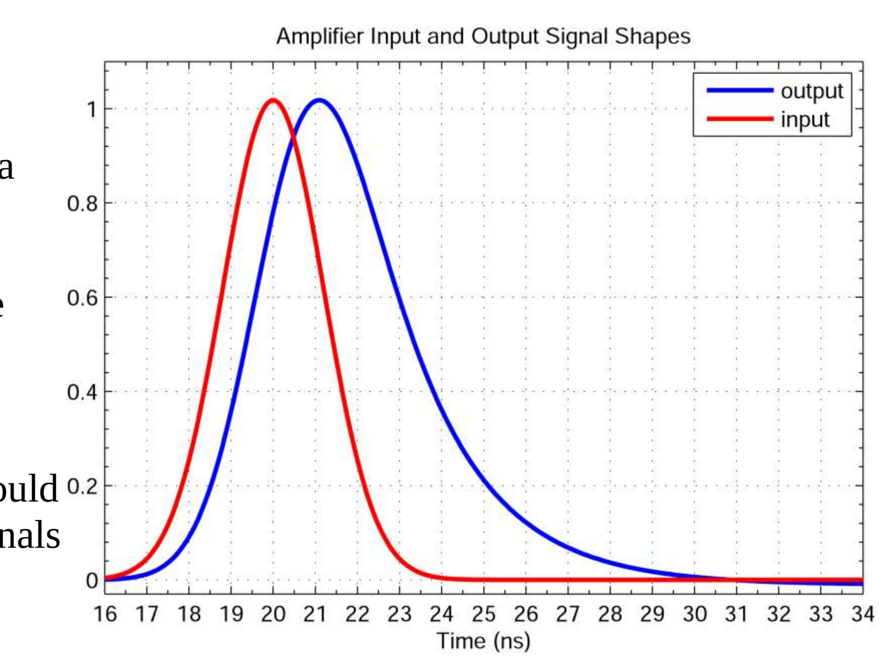
- Field programmable gate array (FPGA)—This is the "brain" of the control board. It accepts commands from master computer, and also controls and monitors all other components on the board.
- Digital-to-analog converter (DAC)—This component takes commands from the FPGA and outputs bias voltages which are sent to the SiPMs on the amplifier board.
- Analog-to-digital converter (ADC)—The ADC measures critical voltage levels in the tagger circuitry, and reports them back to the FPGA.
- Ethernet controller—The Ethernet controller converts signals from the FPGA into standard computer networking signals, allowing for easy connection with the master computer.





The Amplifier Board

When scintillation reaches a SiPM, the SiPM produces a very small current pulse. To be useful to the GlueX experiment, these small pulses of current must be converted into larger pulses of voltage. Transimpedance amplifier circuitry on the amplifier board handles this conversion. A summing circuit on the amplifier board combines signals from each column of 5 scintillating fibers, since all electrons hitting a particular column should have the same energy, and then outputs the summed signals to the backplane and out of the tagger.



To the right is a plot comparing the input signal from a SiPM to the output signal from the amplifier. The signal amplitudes have been normalized for easier comparison of the signal shape. The plot shows that the amplifier responds within 1 ns, and creates a pulse that rises with a shape very similar to shape of the SiPM signal.

References

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2. http://cerncourier.com/cws/article/cern/38296
3. http://gluex.org/