# Cherenkov Counter Development for the Super-TIGER Balloon Payload

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**Abstract:** The Super-TIGER balloon payload aims to precisely measure the abundance of elements heavier than iron in the galactic cosmic radiation with high statistics and single charge resolution in the range $10 \leq Z \leq 42$. In addition, it will provide exploratory charge measurements up to $Z < 56$. The first Antarctic flight for the Super-TIGER instrument is scheduled for the 2012 Austral Summer. Super-TIGER has an effective geometrical acceptance that is 6.4 times larger than its predecessor the Trans-Iron Galactic Element Recorder (TIGER). The instrument employs two Scintillating Fiber Hodoscope planes providing position information and three layers of plastic scintillator to detect interacting events in the stack. Charge identification is derived from the scintillator and two light-diffusion Cherenkov counters, one with an acrylic radiator ($n = 1.49$) and the other with a silica-aerogel radiator ($n = 1.043$ and $1.025$). Each Cherenkov counter has an aperture of $118\ \mathrm{cm} \times 240\ \mathrm{cm}$ and is $20\ \mathrm{cm}$ tall. The inside of each counter is lined with highly reflective Gore-Tex and viewed by 42 Hamamatsu R877-100 ($5\ \mathrm{inch}$ diameter) high quantum-efficiency photomultiplier tubes (PMT). In this paper, we will discuss the design of the two Cherenkov counters for Super-TIGER. In particular, we will describe the use of a Geant4 Monte-Carlo simulation to optimize the detector geometry for light output uniformity as well as for determining the dynamic range required per PMT. A general overview of the Super-TIGER program, the Scintillating Fiber Hodoscope, and the Scintillator will be given elsewhere at this conference.

**Keywords:** Super-TIGER, aerogel, Cherenkov, Cerenkov, Ultra-heavy GCR, galactic cosmic rays, PMT, Charge identification, Composition, PMT linearity.

## 1 Introduction

Super-TIGER is a long-duration balloon-borne instrument currently being constructed and is scheduled for its first Antarctic flight in late 2012. The objective of Super-TIGER is to test and clarify an emerging model of cosmic-ray origins and models for atomic processes by which nuclei are selected for acceleration. The precise measurement of ultra-heavy elemental abundance ($Z \geq 30$) with good charge resolution is a sensitive probe of the origin of cosmic rays.

Super-TIGER builds on the heritage of the successful Trans-Iron Galactic Element Recorder (TIGER) experiment, employing plastic scintillators together with acrylic and silica-aerogel Cherenkov counters to determine particle charge. With reduced material to minimize nuclear interactions, Super-TIGER has $\sim$6.4 times larger effective acceptance than its predecessor and will measure the elemental abundance of $30 \leq Z \leq 42$ with single charge resolution and high statistics. In addition, it will provide exploratory charge measurements up to $Z \leq 56$. It will also measure with high statistical accuracy the energy spectra of the more abundant elements in the interval $10 \leq Z \leq 42$ at energies $0.8 \leq E \leq 10$ GeV/nucleon.

Super-TIGER is comprised of two independened and identical detector moduls situated side-by-side on the balloon gondola. Each detector modul has an active aera of $118\ \mathrm{cm} \times 240\ \mathrm{cm}$, is 82 cm tall, and weighs $\sim$620 kg. A module consists of two scintillating-fiber hodoscopes for trajectory reconstruction, three plastic scintillator charge detectors to flag nuclear interaction within the stack and charge identification, and a two light-diffusion integrating Cherenkov counter with an acrylic (C1: $n = 1.49$) and silica-aerogel (C0: $n = 1.043$ and $1.025$), respectively, for the charge and energy determination. A detailed discussion on the Super-TIGER instrument and scientific goals

[1], the scintillator charge detector [2] and the scintillating fiber hodoscope [3] will be presented elsewhere at this conference. Here we will focus on the development of the Cherenkov counter, including the discussion on a Geant4 Monte-Carlo computer simulation used to optimize the detector geometry, estimate the dynamic range requirement per photomultiplier tubes (PMT) as well as mechanical consideration to reduce weight, nuclear interaction probability as well as ease of assembly allowing to install the delicate silica-aerogel radiator in the field before and simple disassembly on recovery after the flight.

### 1.1 Charge and Energy Determination

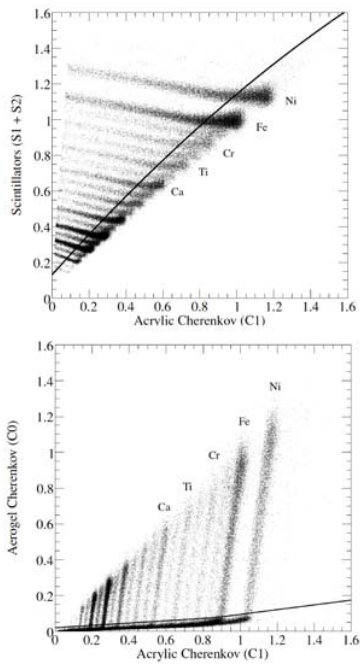


Figure 1: Charge identification technique exemplified with TIGER-2003 data [4]. Top panel shows the scintillation signal versus acrylic Cherenkov response. The lower panel show a cross plot of the aerogel versus acrylic Cherenkov response for particle above the aerogel threshold. The detector responses are shown up to nickel.

The charge determination in Super-TIGER is illustrated in Fig. 1: (1) For particles above the acrylic (C1) but below the silica-aerogel (C0) Cherenkov threshold, a combination of scintillator and acrylic Cherenkov signal sorts the elements into distinct charge bands, shown in the top panel of the figure. In this range the acrylic Cherenkov response also provides an energy measurement. (2) For particles above the C0 threshold, a combination of the aerogel versus acrylic Cherenkov response provides the charge identification. In the later case, where the C1 response only slow increases with increasing particle velocity, elements of a given charge, $Z$, follow a linear relation in a cross-plot of the two Cherenkov signals, as shown in the lower panel of Fig. 1. Here the kinetic energy can be derived by the aerogel Cherenkov response.

## 2 Description of the Cherenkov Counters

Fig. 2 shows an exploded view of a Super-TIGER acrylic Cherenkov module. The construction of the aerogel Cherenkov is the same except for the radiator. Each module has an aperture of $118\ \mathrm{cm} \times 240\ \mathrm{cm}$ and is $20\ \mathrm{cm}$ tall, which is twice the active area of the TIGER counter. The mechanical structure of the detector is formed by 5 cm wide and 20 cm tall rectangular extruded aluminum tubes, which are joined by machined Al corner and center blocks. For ease of handling during integration and recovery, the Cherenkov module splits into two half modules. A composite detector support (see section 2.1) forms the bottom lid for each Cherenkov half-module, on which the Cherenkov radiator rests. The top lid of the counter is a Tedlar membrane stretched to Al frame. The PMT mount from the outside into circular cutouts in the side walls. The aerogel Cherenkov counter (C0) is placed above the acrylic Cherenkov counter (C1). All inside surfaces of the counter are covered with highly reflective Gore-Tex (0.25 mm). All joints are designed to not only provide mechanical support but also serve as ambient light barriers. The two Cherenkov counters provide significant mechanical stiffness to the instrument module and have a total weight of 120 kg and 100 kg for the acrylic and aerogel Cherenkov counter, respectively.

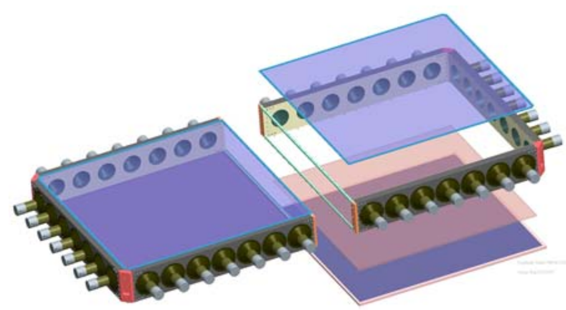

Figure 2: Exploded view of an acrylic Cherenkov module: Two half-modules are joined to form one light-integration volume viewed by 42 PMT.

The radiator for both the acrylic and aerogel Cherenkov counter is mounted on the lower support lid. For the acrylic counter a single $1.11$ cm thick radiator $(n = 1.49)$ rests directly on the bottom support lid of a half-module held in place by retainer clips. In the aerogel Cherenkov counter 4 aerogel blocks each with nominal dimensions of $55$ cm $\times$ $55$ cm and $3$ cm tall are placed in a $2 \times 2$ array to form the radiator. To protect the fragile aerogel from potential stress due to deformation of the counter during landing and recovery, each aerogel block placed on a thin composite pallet and secured by a UV-transparent low density PE film ($\sim 0.025$ mm) to the palette. This aerogel mounting technique has already been successfully used in the BESS experiment [5]. To provide uniform support and cushioning for the slightly concave aerogel blocks, a piece of soft foam is placed underneath Gore-Tex covered composite pallet before securing the aerogel block PE film to the pallet. This aerogel pallet is held to the lower support lid with Velcro. The silica-aerogel used in Super-TIGER is provided by the California Institute of Technology. These are the last remaining large-area aerogel block from Airglass in Sweden that were produced in the early 1990's. There are not enough of $n = 1.043$ aerogel blocks on hand to fill both aerogel Cherenkov modules. Instead 3 of the 4 aerogel Cherenkov half-module will have the $n = 1.043$ aerogel and the last half-module will be augmented by $n = 1.025$ aerogel.

There are a total of 42 5-inch Hamamatsu R877-100 high quantum-efficiency PMT per counter. Great care is taken to reduce the weight of the PMT assembly. However, the PMT account for ~40% of the counter weight. We designed a thin $(0.50$ mm) $\mu$-metal shield adding only $50\%$ to the weight of the bare PMT and also serves as mechanical housing and ambient light shield. Magnetic shielding of the PMT is required to reduce the effects of the earth magnetic field orientation on the PMT performance. Bench tests have shown that PMT gain varies by $\sim 5\%$ without magnetic shielding and that $0.15$ mm $\mu$-metal provide sufficient shielding. Additional weight saving is achieved by reducing the amount of HV encapsulation with a compact HV divider design.

The signal of each PMT is pulse-high analyzed (PHA) and the gain of each PMT can be adjusted by trimming the respective PMT HV via command. The PHA board and HV supplies for a set of 7 PMT are consolidated into a single electronics box. An LED calibration system allows PMT gain correction in flight. We will discuss the PMT bleeder design further in Section 3.1.

### 2.1 Detector Support Substrate

To increase collection power, Super-TIGER has less material in the particle's path and thus fewer nuclear interaction losses than its predecessor. TIGER used ~3.2 g cm$^{-2}$ of GATORFOAM, a foam-core composite with cardboard card-stock face sheets, as detector support and close-out [6]. For Super-TIGER, the number of support panels was reduced and we developed a custom, rigid, uniform ultra-low density detector support composite. The composite consists of a low-density, closed-cell Polymethacrylimide foam core (Rohacell 31 IG) with 0.143 mm hardend aluminium face sheets, which are bonded with a ~0.040 mm thick Hysol EA 9396 epoxy adhesive. Deflection tests have demonstrated that the Rohacell-Al composite is twice as stiff as a GATORFOAM panel of the same thickness, yet the Rohacell-Al has a lower column-density. We contracted Triangle Labs in Carson City, NV to fabricate the full scale composite panels of 125 cm $\times$ 250 cm. The core thickness for the hodoscope support is $1.58$ cm and for the plastic scintillator and Cherenkov counters the core is $1.27$ cm thick. The silica-aerogel pallets have a 0.47 cm core with $0.076$ mm Al faces. The total grammage of the Super-TIGER support planes is reduced to $0.87$ cm$^{-2}$, of which 50% are in the Al face sheets. As aluminium (Al) has more than double the nuclear interaction length of the C-H composition of the foam core [7] for the same grammage this increases the transparency of the substrates for high-Z particles.

## 3 Geant4 Model

We employed a Geant4 Monte-Carlo computer simulation of the Super-TIGER Cherenkov counter to address questions of detector performance and dynamic range requirements for the PMT. Since the Cherenkov light yield follows $Z^2$, the study has been be conducted for single-charged particles. The expected results for higher charges can be scaled, this also keeps the number of tracked optical photons low and thus significantly reduce the runtime of the simulation.

To obtain meaningful results from the simulation, all relevant optical properties were measured prior and implemented into the simulation code. For example, using a spectrophotometer, the reflectivity of Tyvek and Gore-Tex were measured as a function of the wavelength. Also the transmittance of the aerogel (Rayleigh scattering parameter) was measured. The absorption length of aerogel was a free parameter in the simulation, since it is hard to measure with the small sample sizes that can be accommodated in the spectrophotometer.

A computer model of the TIGER Cherenkov counter, which had 16 Burle S83006 PMT and Tyvek reflector, was used to determine the aerogel absorption length. The absorption parameter was adjusted in the simulation to match the light yield as a function of position seen in the TIGER-2003 flight data, which changed by $\sim 50\%$ along the diagonal from the center to the corner. Similarly, the model was verified for the acrylic Cherenkov detector, where the TIGER-2003 flight showed a $\sim 15\%$ light yield variation center-to-corner. TIGER had a nominal light yield of 6 and 29 photoelectrons (NPE) for single-charged, relativistic particles, with normal incidence for the aerogel and acrylic Cherenkov counter, respectively.

With known optical properties for the simulation, possible configurations of the Super-TIGER Cherenkov counter were explored, which used Hamamatsu R877-100 high quantum-efficiency PMT and high-reflectance Gore-Tex reflector. The optimum performance fulfilling all requirements imposed by integration and recovery was found and is described above. Fig. 3 shows the acrylic Cherenkov response map for one quadrant. Although the Super-TIGER Cherenkov counter has a larger acceptance and a smaller aera ratio of photosensor to reflector, the use of the high performance Gore-Tex reflector maintained a similar re-

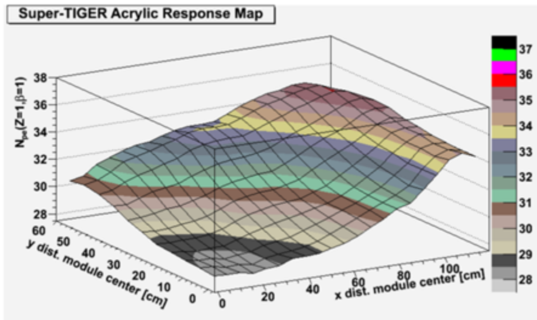


Figure 3: Simulated response map for one quadrant of the Super-TIGER acrylic Cherenkov counter.

sponse map gradient to TIGER as well as equivalent NPE statistics for the aerogel and acrylic counters.

### 3.1 PMT Dynamic Range

The dynamic range required for the Cherenkov PMT is bound at the upper end by the maximum fraction of the total light yield detected in a single PMT and at the lower end by the ability to measure single NPE at threshold. The total light yield in the Cherenkov counter scales with $Z^2$ and we require single charge resolution in the charge range $10 \leq Z \leq 60$, which corresponds to a factor of 36 in the light yield. The higher light yield on the acrylic Cherenkov counter will set a more stringent requirement for the upper limit of NPE seen in a PMT.

The Geant4 simulation was used to determine the probable upper fraction of the total light yield seen by a single PMT. An ensemble of events was generated in the Cherenkov counter with an isotropic flux entering the Super-TIGER aperture. For each event the PMT with the largest NPE was found and normalized to the total light yield seen in all PMT. For 99.7% of all events the PMT with the largest signal was less than 40% of the total light yield. Such a large fraction of the total light was seen, when the particle passed through the radiator close to that PMT. The simulation has also shown that the total light yield varies by a factor of 4 due to particle position and incidence angle.

Using a nominal light yield of 30 NPE in the acrylic Cherenkov counter for single charged, normal incidence particles, the ability to measure up to $Z = 60$ and a factor $\times 4$ for position-depended yield, a maximum total light yield of $4.32 \times 10^5$ is expected. Of this yield, up to $40\%$ might be seen in a single PMT, which would require a PMT linearity up to 86,400 NPE.

However, linearity tests with the R877-100 PMT and standard base (linear) have shown that at nominal HV above 4000 NPE the anode signal deviates from a linear response. An extensive study was done to use a combination of anode and dynode signal to maintain a linear response over the required range. Also tapered PMT bleeder were considered. The result of this study was that not only the last dynodes were affected by space-charge effects at higher light levels, but even the lower dynodes show space-charge effects, which doesn't allow coverage of the full dynamic range with realistic system noise assumptions.

The solution to producing a linear PMT response over the dynamic range was a strongly tapered base reducing the gain in the first dynodes and thus reducing the overall gain of the PMT. To maintain linearity in the anode signal up to 86,400 NPE a nominal gain of $2.0 \times 10^4$ was needed. A charge-sensitive amplifier was incorporated into the PMT base to reduce effects of system noise on the measurement.

## 4 Conclusion

Large-area acrylic and aerogel Cherenkov counters have been designed and are currently being constructed for the Super-TIGER experiment. The first flight for Super-TIGER is scheduled for late 2012 from Antarctica. Super-TIGER will achieve single charge resolution in the range $10 \leq Z \leq 60$.

## Acknowledgements

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