A BETA-PARTICLE HODOSCOPE CONSTRUCTED USING SCINTILLATING OPTICAL FIBERS AND POSITION SENSITIVE PHOTOMULTILPLIER TUBES

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ABSTRACT

A hodoscopic detector was constructed using scintillating optical fibers and position sensitive photomultiplier tubes to determine the location of beta-active micron-sized particulates on air filters. The ability to locate beta active particulates on air-sample filters is a tool for environmental monitoring of anthropogenic production of radioactive material. A robust, field-deployable instrument can provide localization of radioactive particulate with position resolution of a few millimeters. The detector employs two crossed layers of scintillating optical fiber on which a filter is placed for assay. The detector is intended to be sensitive to activity greater than 1 Bq. To reduce power and the number of electronic read-out channels, position sensitive photomultiplier tubes are used to determine those fibers transmitting scintillation light. The physical design, position reconstruction method, and expected detector sensitivity are reported.

OBJECTIVE

The filter activity survey technique (FAST) is intended to provide a method of detection for beta active particulates collected on air filters used in treaty monitoring programs. The FAST system is intended to extend the filter triage efficacy by identifying filters with beta-active particulates with greater than approximately 0.75 Bq events (1 Bq = one disintegration per second). The identification of these lower-activity laden filers can then be given higher high-purity germanium (HPGe) counting priority and used for planning of follow-on sampling activities.

The FAST system provides additional sensitivity by taking advantage of the particulate nature of the beta-active particles of interest to treaty monitoring programs. A filter is expected to have a predominately uniform background of activity 2 Bq/cm^2 coming from radon daughters or other radioisotopes naturally present in the atmosphere. The detection goal is to identify a particle having an activity of 0.75 Bq that is essentially a point source of beta radiation. Using two crossed arrays of scintillating optical fibers, it is possible to create radiation detection elements of approximately 10 mm^2, depending on the exact width of the optical fibers used and the resolution of the instrument. These 10 mm^2 detection elements would see an effective signal-to-noise ratio equal to 3.75 from the 0.75 Bq signal and a background of 0.2 Bq per 10 mm^2. Counting a typical 16-in. diameter filter without position sensitivity that has ten of these 0.75 Bq activity particles gives a signal-to-noise ratio of 0.0029, approximately a factor of 1300 worse than expected for the FAST system.

The active element of the FAST apparatus is constructed using two single-fiber think arrays of scintillating optical fibers crossed at right angles. The fibers in the top layer, closest to the filter, have a 0.5 mm by 0.5 mm square cross-section. The bottom layer is composed of 1.0 mm by 1.0 mm square cross-section fibers. Each of the two crossed arrays of fibers defines one coordinate axis on the filter plane. The scintillating optical fibers are connected to a position sensitive photomultiplier tube (PMT), with one PMT per layer. Thus each PMT provides information along a single axis of the filter plane. Combining coincident information from each of the two PMTs allows for the two-dimensional reconstruction of the location of activity on the filter. The critical components (plastic optical fibers and PMTs) of the system are robust in transport allowing for field deployment of the system in a large luggage-sized case. To make the FAST system as effective and sensitive as possible, a number of issues were investigated in the construction of the detection components and the integration of the software reconstruction. Design schematics are shown in Figure 1.

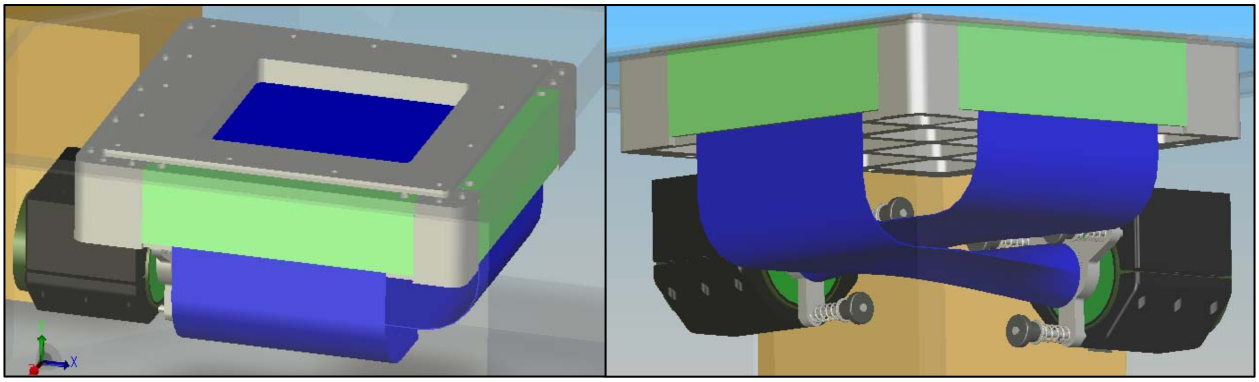

Figure 1. Design schematics of the internal components of the FAST apparatus. The fiber layers are blue. Position sensitive photomultiplier tubes (PS-PMTs) are held by black support blocks. Grey and green parts are plastic superstructure.

RESEARCH ACCOMPLISHED

The work done to make a field ready FAST system focuses on studying the light collection properties of the underlying detection mechanism and implementing a design approach in response to the component-by-component requirements.

Introduction: Position Sensitive Photomultiplier Tubes

The use of position sensitive photomultiplier tubes (PS-PMTs) dramatically reduces the number of electrical components and electrical read-out channels needed for the FAST system. The information from hundreds of optical fibers are collected by two PS-PMTs and reduced two four electrical read-outs per PS-PMT. The position of light on the face of the PS-PMT is determined from ratios of these electrical signals. The "energy" measured on each of the four PS-PMT channels (A, B, C, and D) are used to reconstruct the location of the light on the PMT's front window. The equations used to calculate the x and y coordinates are:

$$x = \frac{(A-B)}{(A+B)} \qquad y = \frac{(C-D)}{(C+D)}$$

A two-dimensional histogram is then filled using the calculated x and y coordinates. The entries in the histogram are given a weight equal to the sum of the four channels, E = A + B + C + D, which properly represents the total energy of the event seen by the PS-PMT.

Fiber Resolution

The response of the PS-PMT to light traveling down a single 1 mm by 1 mm cross-sectional optical fiber determines the ability of the PS-PMT to resolve the physical location of the fiber on the face of the tube. Greater ability to identify light from individual fibers in the fiber array is directly related to the ability of the FAST system to resolve locations of activity on the air filter. Conversely, restated as a design requirement, the reconstruction resolution of a single optical fiber on the face of the PS-PMT defines the proximity beyond which fibers are individually identifiable. In simple terms, the size of the reconstructed spot generated by a fiber on the face of the PS-PMT defines how far apart fibers should be spaced. Figure 2 shows two scintillating optical fibers having a physical separation (denoted by the subscript "mm") of Δ_{mm} = 14.19 mm center-to-center on the face of the PS-PMT. This value sets the scale to convert between the PS-PMT's coordinate (dented by the subscript "PMT") and physical coordinates measured in millimeters. A two-dimensional fit was applied to the histogram of two irradiated fibers shown in Figure 2 to extract the *x* and *y* coordinates of the centers of the peaks and to determine a (Gaussian based) measure of the peak widths. This fit has the form

$$\begin{aligned} z \;=\; & a_0 + a_1 e^{-\frac{1}{2}\left[\left(\frac{x-x_1}{\sigma_{x_1}}\right)^2+\left(\frac{y-y_1}{\sigma_{y_1}}\right)^2\right]} \\ & + a_2 e^{-\frac{1}{2}\left[\left(\frac{x-x_2}{\sigma_{x_2}}\right)^2+\left(\frac{y-y_2}{\sigma_{y_2}}\right)^2\right]} \\ & + a_3 e^{-\frac{1}{2}\left[\left(\frac{m_{xy}x+b-y}{\sigma_{xy}}\right)^2+\left(\frac{m_{yx}x+b-y}{\sigma_{yx}}\right)^2\right]} \end{aligned} \qquad [1]$$

where *z* is the color-height of the histogram, a_n are height-magnitudes, and the exponential functions define two, 2-dimensional Gaussian peaks and a saddle region bridging between the two peaks. The fit variables are constrained such that specific peaks and the saddle region are selected by each portion of the formula. The fit determined the following tabulated values; only variables relevant to determining the fiber resolution are shown.

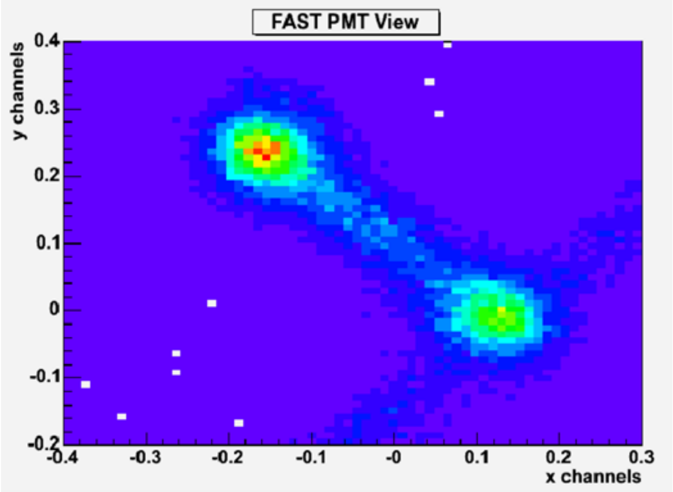

Figure 2. Reconstruction of a single position sensitive photomultiplier tube (PS-PMT) having two scintillating optical fibers attached to the face of the tube. Red indicates greater intensity.

Table 1. Resulting parameters from a two Gaussian fit to the histogram in Figure 2

Parameter		**Value (PMT)**
Large, Upper Left Peak	Center (x_1 , y_1)	(-0.1560 , 0.2330)
Large, Upper Left Peak	Widths (σ_{x1} , σ_{y1})	(0.0398 , 0.0406)
Smaller, Lower Right Peak	Center (x_2 , y_2)	(0.1310 , -0.0050)
Smaller, Lower Right Peak	Widths (σ_{x2} , σ_{y2})	(0.0443 , 0.0409)

From these we determine an average resolution, $\langle\sigma_{PMT}\rangle = 0.0414$, and the separation between the centers of the two peaks, $\Delta_{PMT} = 0.373$, both measured in the PMT's coordinate system. Using a ratio, we can now determine the absolute physical resolution of the peaks:

$$\frac{\langle\sigma_{mm}\rangle}{\langle\sigma_{PMT}\rangle} = \frac{\Delta_{mm}}{\Delta_{PMT}} \quad \rightarrow \quad \frac{\langle\sigma_{mm}\rangle}{0.0414} = \frac{14.19}{0.373} \quad \Rightarrow \quad \langle\sigma_{mm}\rangle = 1.58\text{mm} \qquad [2]$$

Light Sharing

In Figure 2 from the previous section, it is noted there is a raised saddle region of events spanning between the two fibers shown. This is the blue-ridge generally following a y = x–0.1 formula through the green peak in the lower right corner. This saddle region is a ridge created due to light sharing between fibers that are physically adjacent to one another *at the location of the radiation interaction*. The reason the ridge appears is because the PS-PMT is an analog instrument: if there is light coming out of two fibers, the PS-PMT responds with a set of four output signals that is a light intensity weighted average. That is, if two fibers have the same intensity of light, then the PS-PMT will give an output signal that is exactly between the two fibers on the face of the tube. In general, this is a hindrance to being able to distinguish single fiber illumination. To address this issue it is important to understand the source of the light sharing.

When radiation interacts in the scintillating optical fibers, the end result is the production of light. The light produced is isotropic. In fact only 3% to 4% of the scintillation light is captured and transmitted by the optical fibers Saint-Gobain (2005). The remaining greater than 95% of the scintillation light leaves the fiber in which is was generated. Secondary fibers, physically adjacent to the primary fiber, have the possibility to capture and transmit some fraction of the isotropic scintillation light leaving the primary fiber. This is the process by which light sharing among fibers is created. To combat light sharing between fibers, a series of tests were conducted looking for fiber coatings that could both serve to first reduce or eliminate light sharing and second act as an adhesive to bond the together into arrays. The secondary adhesion requirement for the coating was a design consideration to minimize the amount of material between the source of the beta particles and the active scintillating core of the optical fibers. That is, the coating should not attenuate a large fraction of the beta particles the FAST system is intended to detect. The two best coating are shown in Figure 3. The best coating scheme was to aluminize the optical fibers and then coating then in a white, urethane based extramural absorber. However, this process was time consuming and only moderately better than only using the white extramural absorber. Since the extramural absorber coating acts as a bonding agent it was the chosen coating scheme.

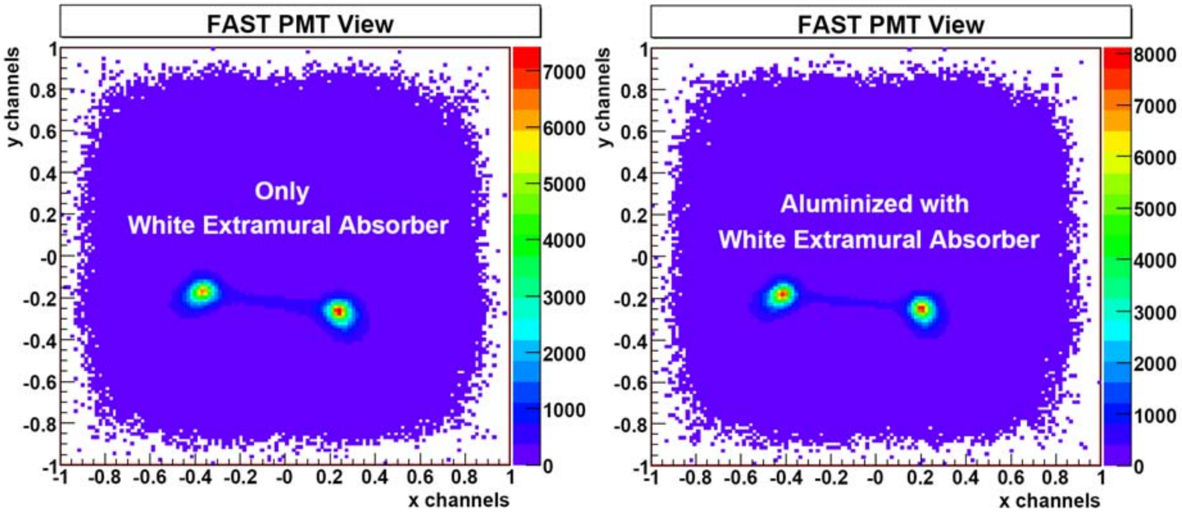

Figure 3. Light sharing between adjacent fibers and the reduction thereof by coatings.

Fiber Puck Design

From the requirements of the preceding sections, several hundred fibers from one layer are attached to a single PS-PMT. The design takes into account several features of the components. The analog nature of the PS-PMTs and the residual light sharing among fibers calls for placement of fibers adjacent to another on the face of the tube. In this way, if there is light sharing or incorrect reconstruction of the PS-PMT, the induced error will only contribute to a small shift in the estimation of the location of the beta activity on the assayed filter, on the order of a few millimeters. Likewise, fibers that are physically distant from one another on the filter measure surface, should be physically distant from one another on the face of the PS-PMT. These considerations lead to a fiber layout on the face of the PS-PMT having a snaking pattern across to the tube face, placing adjacent fibers closer together and columns of the pattern further apart. This is diagrammed in Figure 4.

Beta Attenuation Simulation

To determine the location of beta activity on an air filter, an emitted beta particle must interact and produce scintillation light in *both* of the crossed layers of optical fibers. For this to take place the beta particle must not be stopped by the top layer of fibers before reaching the bottom layer of fibers. To understand the effect of beta attenuation in the FAST detection elements a FLUKA (http://www.fluka.org/) simulation was performed. The simulation determined when more than 10 keV of energy is deposited in both fiber layers for a series of mono-energetic electrons incident perpendicular to the crossed-array. The effect of variable thickness aluminum entrance windows was also studied. The result of the simulation, shown in Figure 5, clearly demonstrates there is approximately a 200 keV energy threshold reduction (from ~500 keV to ~300 keV) availed by using 0.5 mm by 0.5 mm cross-sectional fibers. Over the range of expected thicknesses of the aluminum entrance windows, the change in apparatus is comparatively small.

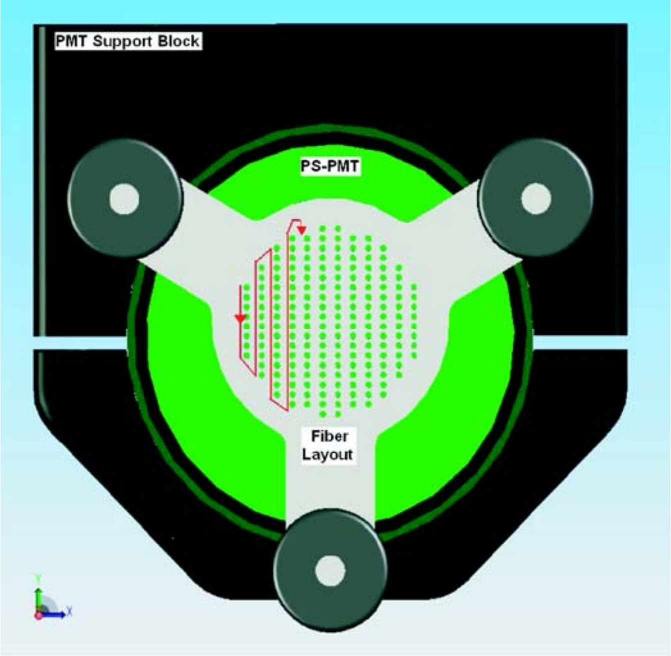

Figure 4. Fiber puck design schematic. Individual fibers are positioned in the holes. The “snaking” red path shows the fiber layout relative to the flat filter assay surface.

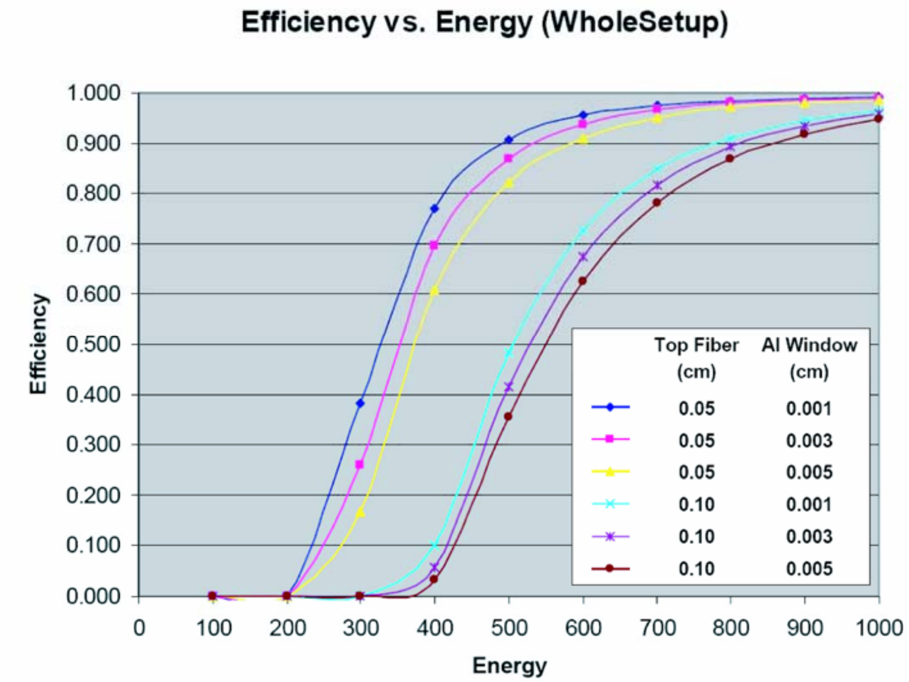

Figure 5. Total beta detection efficiency as a function of the initial beta particle energy for various thicknesses of the FAST detection components.

First Filter Map Reconstruction

The hardware assembly complete, the developing calibration tools necessary for the full reconstruction of the filter activity map provide a glimpse of the operational capability of the FAST system. Figure 6 is a screen image of the analysis program showing the FAST system's response to a beta source collimated to 1 mm diameter. The mirror/ghost images appearing in the filter activity map of the known *single* collimated source are due to both the yet to be optimized hardware configuration and the scaling symmetry present in the reconstruction algorithm. Once the already demonstrated resolution (see Figures 2 and 3) is obtained, it is clear from this initial filter activity map that 4 mm full width at half maximum resolution will be achieved.

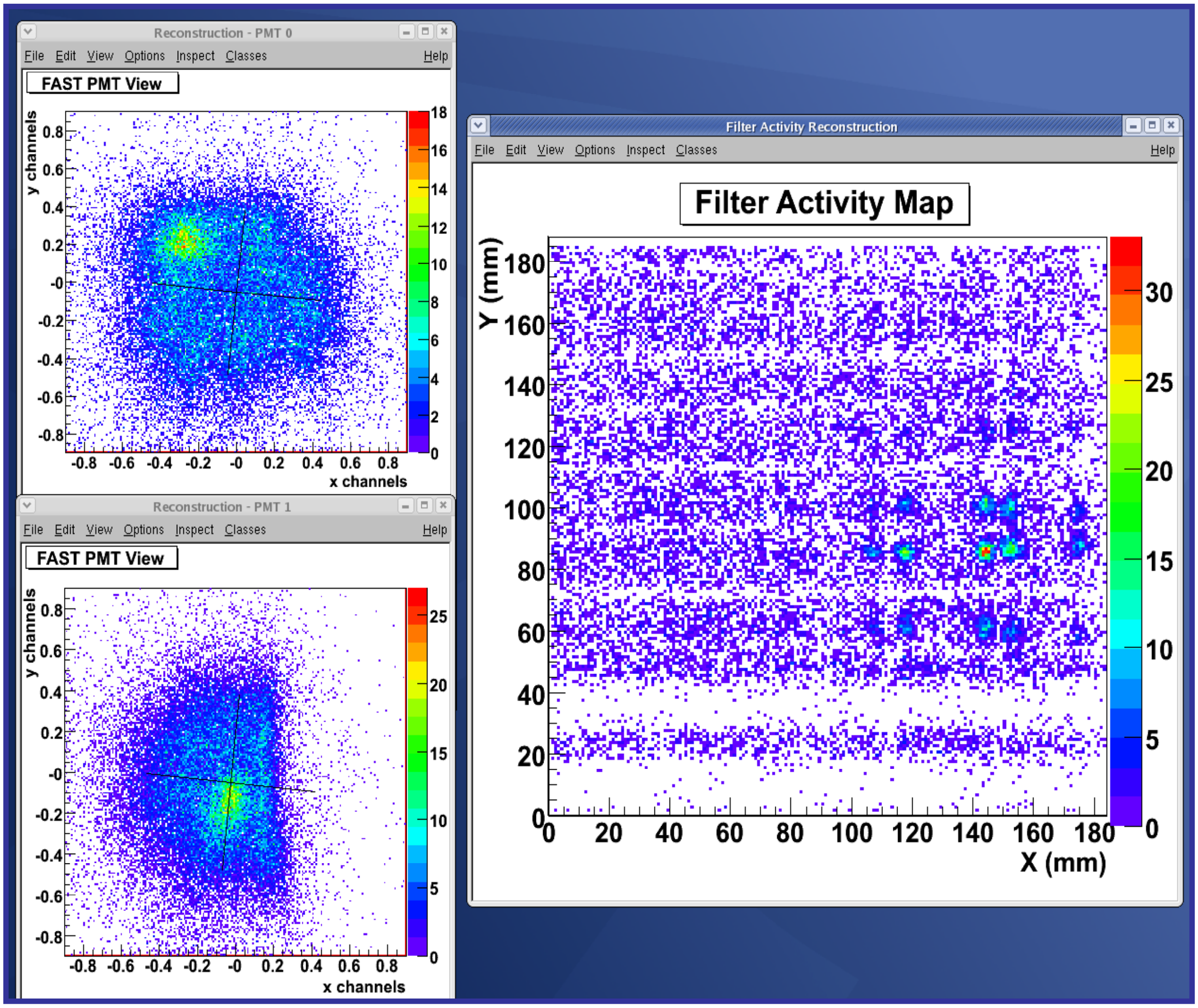

Figure 6. Screen capture of an early full two-dimensional reconstruction of the filter assay area. A 1 mm diameter Sr-90 source is located on the detection surface. Mirror images seen in the filter activity map are due to less than optimal single PS-PMT resolution and scale symmetries in the calibration program.

CONCLUSIONS AND RECOMMENDATIONS

The FAST system has demonstrated the ability to identify beta activity and is expected to provide particulate location information on the few millimeter scale. The technology employed is similar to that applied to particle detectors located at high-energy physics accelerator facilities (Baehr et al., 1994 and Kuroda, 1989). The technical challenge was optimizing these components to operate effectively at particle energies six orders of magnitude lower. The detection portion of the apparatus is composed solely of plastic optical fibers, two position sensitive photomultiplier tubes, and one small electronics crate with an on-board central processing unit (CPU). These components are expected to be robust in field deployment.

Work continues on the optimization of the automated diagnostics and calibration routines to streamline the user interface. Analysis software is progressing past the most simplistic reconstruction algorithms to provide greater fidelity and result reliability. Figure 7 shows the FAST apparatus on a test bench where this work is being conducted. The coming year will transition this instrument to the end users for true field deployment.

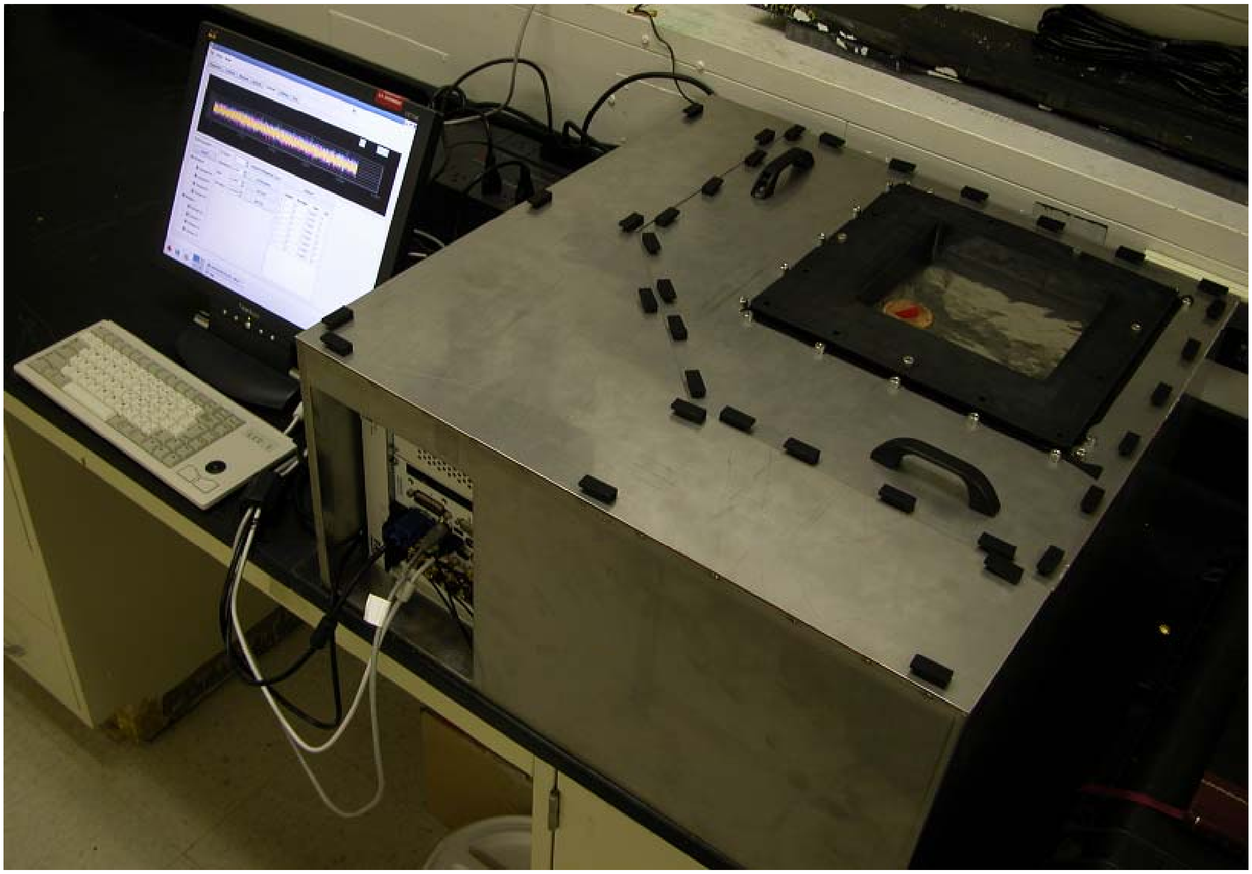

Figure 7. All components of FAST are self-contained except for the keyboard and monitor. The filter assay surface, redesigned for quarter folded filters, is inside the black rectangle at the upper right.

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