The Calibration of the Flight Radiation Environment Detector (FRED)

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\textbf{Abstract:} The mixed radiation field in the Earth’s atmosphere is caused by the interaction of cosmic and trapped radiation with the atmosphere. A plethora of secondary particles is created which, together with the primary radiation, creates this complex natural mixed radiation field. Apart from charged particles (predominantly protons, electrons, muons, pions, and alpha particles), it also contains neutral particles, i.e., neutrons and gamma rays, which are generally difficult to measure. The Flight Radiation Environment Detector (FRED) was designed to measure quantitatively the contributions of the charged and neutral components. It consists of four segmented silicon solid-state detectors which form a particle telescope and also form an efficient anti-coincidence to separate the neutral radiation. Thus FRED is also designed to measure the respective dose rate from charged and neutral particles. Here we present the general design of FRED and the results of a calibration campaign at the Heavy Ion Medical Accelerator in Chiba (HIMAC) facility at the National Institute of Radiological Sciences (NIRS), Japan.

\textbf{Keywords:} FRED, silicon detector, cosmic rays.

1 The Flight Radiation Environment Detector (FRED)

The Flight Radiation Environment Detector (FRED) is a small and light-weight particle detector telescope. The height of the housing is 99.5 mm, with a footprint on the plate of 112 mm x 100 mm. Due to the housing being made of magnesium the total mass is 371 g. Figure 1 shows a CAD drawing of FRED which illustrates the overall design. The detector stack (telescope) is located above the electronics box (EB). Printed-circuit boards (PCBs) are shown in green, a filter board (vertical) connects the detectors to the analog board, digital board and low-voltage power supply board (from top to bottom). The electronics concept is shown in Figure 3. The particle telescope is formed by four identical quadratic silicon solid-state detectors with two segments each. They are all 300 micron thick, the outer 30 x 30 mm segment surrounds the inner 22 x 22 mm segment. Figure 2 shows the telescope geometry. The inner detector segments span an opening angle of 60 degrees, the outer ones 120 degrees. Using coincidences between different detectors this known geometry allows FRED to determine the Linear Energy Transfer (LET) because the path length variations are kept within reasonable limits. LET is a crucial quantity in radiation protection, it is required to determine the equivalent dose of radiation and the average quality factor of a given radiation field using the ICRP 60 functions \textsuperscript{1}. Detectors B and C are glued together and placed very close together with detector D. This allows the B and D, as well as the outer segment of C to form a highly efficient anti-coincidence for the inner segment of detector C. Thus the inner segment of detector C (shown in red in Figure 2) allows us to measure the neutral component of a radiation field (but not to discriminate between neutrons and gammas). The electronics concept is shown in Figure 3. The 8 individual detector segments are connected by a filter board to the analog board with its 8 dual-gain charge-sensitive analyzers (CSAs). These are continuously read out by fast ADCs whose signals are fed to a Field Programmable Gate Array (FPGA) on the digital board.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{detector_stack.png}
\caption{Schematic of the detector stack.}
\end{figure}
which performs all the required logics as well as the pulse-height analysis and can store the data on a Secure Digital Card (SD card). All voltages including detector bias voltage are created in the low-voltage power supply on the power board which also serves as the interface for power (24 V nominal ± 12 V) and data via Universal Serial BuS (USB) and User Datagram Protocol (UDP).

2 Calibration measurements

For the performance determination of FRED it is necessary to perform calibration measurements as the output scale of FRED is in mV and has to be converted to a keV scale for the calculation of the energy loss in silicon. For the determination of this relation we have done several measurements with different charged particles. Because of the two amplification steps (low and high) we need a wide range of charged particle species and energies. For the determination of the calibration function for the two gain channels and the different detector segments we used a $^{207}$Bi source and a set of different heavy ion species. The heavy ion measurements were conducted at the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan. We used 100 MeV/nuc helium, 400 MeV/nuc carbon, 400 MeV/nuc oxygen, 600 MeV/nuc silicon and 500 MeV/nuc iron.

The measured heavy ion peaks in the high gain are shown in figure 4 and for the low gain in figure 5. An additional measurement was conducted with a $^{207}$Bi radioactive source for the high gain channel in order to generate more calibration points for low energy losses. Figure 6 shows the latter measurement in the high gain channel of the inner segment of detector A. For the calibration we used only the two designated peaks which originate from two electron emission lines with energies of 481.7 keV and 975.8 keV. The other two peaks in figure 6 are double lines which can not be clearly distinguished from each other with FRED. The calibration process will be explained more in detail in the following section.

**Fig. 4**: The measured heavy ions peaks in the high gain channel of the inner segment of the A-detector. The helium peak in red, the carbon peak in blue and the oxygen peak in black.

**Fig. 5**: The measured heavy ions peaks in the low gain channel of the inner segment of the A-detector. The carbon peak in blue, the oxygen peak in black, silicon peak in light blue and the iron peak in green. Due to fragmentation of the iron ions (green) in the beamline and detector housing.

**Fig. 6**: The measured signal in high gain of the inner segment of detector A with a $^{207}$Bi radioactive source.
3 Results

For the determination of the mean energy loss of the ion measurements, we used a Landau-Vavilov fit function. Figure 7 shows the carbon 400 MeV/nuc measurement in the inner segment of the A-detector (blue curve). The red curve displays the Landau-Vavilov fit function. This process was repeated for all detector segments and all heavy ions measurements. The mean energy loss in silicon of the heavy ions was calculated for the calibration with the software Stopping and Range of Ions in Matter (SRIM) [6]. Figure 7 shows the calibration values for the inner segment of the A-Detector which were determined with the heavy ion measurements. The points on the red curve are the result for the high gain and on the blue curve for the low gain. The red (high gain) and blue (low gain) curves show the calibration functions that were determined with a linear function fit \( f(x) = S \cdot x \) with the slope \( S \) as calibration factor. The results of the calibration factors for all detector segments and the two gain levels are shown in Table 1. The slope of the calibration function describes the bin width of the mV-channels because of the linearity relation between energy loss and mV-channels. The relation of the high gain and the low gain slope are described by the gain factor \( V \) between these two gains. The gain factor is \( \sim \)14 which means a channel bin in the low gain has a \( \sim \)14-times higher value than in the high gain.

The trigger threshold in the typical mode is at 15 mV for high and low gain for all detector segments excluding the C1-detector which has a trigger threshold of 12 mV. With the calibration values one can calculate the energy loss range for the different detector segments. The whole energy loss range for FRED is from 60 keV up to 270 MeV. This is equivalent to a Linear Energy Transfer (LET) range in water from 0.1 up to 429.8 keV/µm. The energy loss ranges for the different detector segments are summarized in Table 2.

As mentioned above, we conducted a measurement with a \(^{207}\)Bi radioactive source. The reference values were calculated with the software SRIM.

![Fig. 7](image-url)  
Fig. 7: The blue line shows the carbon 400 MeV/nuc measurement of the inner segment of the A-detector and the red line the Landau-Vavilov fit.

![Fig. 8](image-url)  
Fig. 8: The calibration function for the high (red curve) and low (blue curve) of the inner segment of the A-detector. The calibration points were calculated from the heavy ion measurements and from the measurement with a \(^{207}\)Bi radioactive source. The reference values were calculated with the software SRIM.

<table>
<thead>
<tr>
<th>Detector seg.</th>
<th>high gain / MeV</th>
<th>low gain / MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A inner</td>
<td>5.19 ± 0.02</td>
<td>72.32 ± 0.02</td>
</tr>
<tr>
<td>A outer</td>
<td>5.26 ± 0.01</td>
<td>73.23 ± 0.02</td>
</tr>
<tr>
<td>B inner</td>
<td>5.25 ± 0.02</td>
<td>73.84 ± 0.02</td>
</tr>
<tr>
<td>B outer</td>
<td>5.24 ± 0.02</td>
<td>77.46 ± 0.02</td>
</tr>
<tr>
<td>C inner</td>
<td>5.00 ± 0.02</td>
<td>70.50 ± 0.02</td>
</tr>
<tr>
<td>C outer</td>
<td>4.90 ± 0.01</td>
<td>71.11 ± 0.02</td>
</tr>
<tr>
<td>D inner</td>
<td>5.08 ± 0.03</td>
<td>70.01 ± 0.02</td>
</tr>
<tr>
<td>D outer</td>
<td>5.03 ± 0.01</td>
<td>66.86 ± 0.02</td>
</tr>
</tbody>
</table>

Table 1: Calibration values for the different detector segments

<table>
<thead>
<tr>
<th>Detector seg.</th>
<th>Energy loss range / MeV</th>
<th>Energy loss range / MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A inner</td>
<td>0.07785 - 18.165</td>
<td>1.084 - 253.038</td>
</tr>
<tr>
<td>A outer</td>
<td>0.07890 - 18.410</td>
<td>1.098 - 256.267</td>
</tr>
<tr>
<td>B inner</td>
<td>0.07875 - 18.375</td>
<td>1.107 - 258.352</td>
</tr>
<tr>
<td>B outer</td>
<td>0.07860 - 18.340</td>
<td>1.161 - 271.065</td>
</tr>
<tr>
<td>C inner</td>
<td>0.06000 - 17.500</td>
<td>1.057 - 246.750</td>
</tr>
<tr>
<td>C outer</td>
<td>0.07350 - 17.150</td>
<td>1.066 - 248.846</td>
</tr>
<tr>
<td>D inner</td>
<td>0.07620 - 17.780</td>
<td>1.050 - 245.008</td>
</tr>
<tr>
<td>D outer</td>
<td>0.07545 - 17.605</td>
<td>1.002 - 233.970</td>
</tr>
</tbody>
</table>

Table 2: Energy loss ranges for the different detector segments

As mentioned above, we conducted a measurement with a \(^{207}\)Bi source for more calibration points in the high gain channel. The calibration points are also shown in Fig. 8 as the first two points on the high gain slope. To determine these calibration points from the electron measurements, we used an intercalibration method between the different detector segments.

Figure 9 shows a 2-dimensional histogram of the inner segments of the A- and B-detector (high gain). The x-axis displays the signals in the A-detector and the y-axis in the B-detector. The electrons (black line) lose their total energy of 481.7 keV in both detector segments. The electrons on the red line also loose their total energy (975.8 keV) in the two segments. The extrapolation of these two lines to the x- and y-axis are the calibration points for the respective detector segment. For the intercalibration of the inner segment of detector C we need the summed signal of the inner segments of detector A and B. For the calculation of the summed signal it is necessary to convert the mV scale into the energy loss scale. For these conversions we used the calculated calibration values for the inner segment of the detectors A
The Design of the FRED

Fig. 9: The intercalibration of inner segment of the A- and B-detector (high gain) with a $^{207}$Bi radioactive source. The 481.7 keV (black line) and the 975.8 keV (red line) electrons of the source were used for the calibration.

Fig. 10: The intercalibration of inner segment of the C-detector (high gain) with a $^{207}$Bi radioactive source. The x-axis shows the summed signals (total energy loss) of the A- and B-detector in keV and the y-axis displays the signals in the inner segment of the C-detector in mV. The 481.7 keV (black line) and the 975.8 keV (red line) electrons of the source were used for the calibration.

and B (see Table I). Then it is possible to calculate a 2-dimensional histogram with the summed signal of the inner segment of detector A and B versus the inner segment of detector C. The result is shown in figure 10. Since some of the electrons stop in the C-detector it is possible to perform the same calibration process for the C-detector as for the A- and B-detector. This intercalibration process must be done for all detector segments to get additional calibration points for the high gains of all detector segments.

4 Conclusion

Here we show the design and the calibration of the Flight Radiation Environment Detector (FRED). It is a small (112 mm x 100 mm x 99.5 mm) and light-weight (371 g) particle detector telescope developed for mixed radiation fields, e.g. the radiation field in Earth’s Atmosphere. Due to the alignment of the detectors it is possible to distinguish between charged and neutral particles. For the demonstration of the performance of FRED we showed the calibration measurements with heavy ions and a $^{207}$Bi radioactive source. Due to these measurements we determined the operational energy loss range in silicon to 60 keV up to 270 MeV which is equivalent to a LET range in water of 0.1 up to 429.8 keV/µm.

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References