

## BESS-Polar II : Fiber readout Time of Flight system

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**Abstract.** The Balloon-borne Experiment with a Superconducting Spectrometer (BESS-Polar II) [1] is exploring the scientific objectives of low energy antiparticle measurement and cosmic-ray flux modulation due to solar activity. BESS-Polar successfully conducted its second flight in December 2007 from McMurdo Station, Antarctica. A key detector element in BESS-Polar is a thin scintillator Time-of-Flight (TOF) hodoscope with fiber readout (Middle TOF) which enables the efficient detection of low energy ( $\sim 0.1$  GeV) cosmic-rays.

The Middle TOF consists of 48 scintillator strips with a thickness of 5.6 mm and is located inside the magnet bore just under the tracking detectors. The signal of each strip is delivered to a fine-mesh multi-anode photomultiplier tube (PMT) by a flexible bundle of 60 square plastic fibers (1×1 mm), which is serving as the light guide in a very confined space. We present the development of the Middle TOF and its performance during the BESS-Polar II scientific flight.

**Keywords:** BESS-Polar II, cosmic-ray antiproton, Time-of-Flight system

### I. INTRODUCTION

BESS-Polar [2,3] is a long-duration balloon-borne experiment flown over Antarctica investigating a possible low energy primary cosmic-ray antiproton component, the existence of anti-nuclei, and the fluctuation of the proton flux due to solar activity. The BESS-Polar experiment is based on the experience and the results of previous BESS experiments. Before describing the BESS-Polar experiment, we discuss the current cosmic-ray antiproton data.

The BESS program had 9 scientific flights since 1993 at northern latitude. The observation of cosmic-ray antiprotons by the BESS flights [4] is in generally in agreement with secondary production, created by the collisions of high energy cosmic-rays and the interstellar

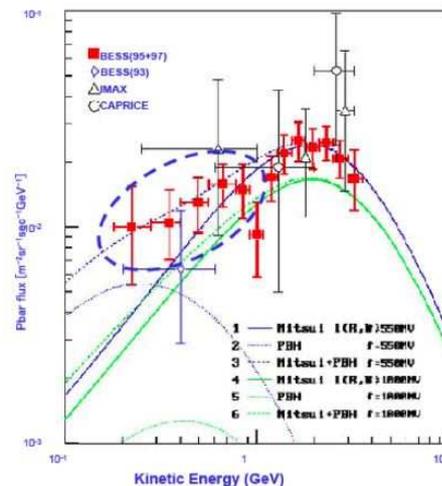


Fig. 1: The antiproton spectra of BESS 95+97

medium. One of the most interesting results is the antiproton spectra during previous solar minimum. The BESS 95+97 data show a flattening of antiproton flux at low energies compared to the secondary productions (Figure 1). The solid curves peaking around 2 GeV is a model prediction of the secondary production spectra. The dashed curve peaking around 0.2 GeV is a model prediction for a potential primary antiproton source.

However, the statistical errors of the low energy data from BESS (95+97) are large. Higher statistics particularly at low energy are needed to investigate the possible existence of a primary antiproton component, which is the scientific motivation for the BESS-Polar experiment. BESS-Polar is optimized for a high-statistics, low energy measurement realized in a long-duration ( $\geq 20$  days) observation in the low-geomagnetic region over Antarctica. Such a flight of BESS-Polar at solar minimum would provide statistics expected to be 20 times larger than of BESS 95+97.

TABLE I: The detectable lowest energy

	BESS	BESS-Polar (All detectors)	BESS-Polar (Middle TOF)
Thickness for trigger generation ( $\text{g}/\text{cm}^2$ )	18	10	4.5
Detectable lowest energy (GeV)	0.18	0.15	0.10

The BESS-Polar instrument is focused on reducing the material that particles traverse to enhance the sensitivity for low energy charged particles. The superconducting magnet has an ultra-thin coil and wall. A Middle TOF was added to detect low energy particles, which would not reach the lower TOF. Table I shows the comparison of the detectable lowest energy.

Figure 2 shows a schematic view of the BESS-Polar instrument, consisting of a superconducting magnet with an axial-positioned high-resolution jet-type central tracker (JET/IDC), the upper and lower TOF hodoscope (UTOF, LTOF) [5], the fiber readout TOF (Middle TOF) and the Silica Aerogel Cherenkov Counter (ACC) [6].

Most of the BESS-Polar II detectors were upgraded or refabricated to improve their performance. These upgrades were based on feedback from the BESS-Polar I science flight (2004).

In this paper, we will focus on the development Middle TOF and its in-flight performance.

## II. MIDDLE TOF

The Middle TOF has been added to the BESS-Polar spectrometer in order to improve the antiproton statistics in the lowest energy region and is placed just below JET/IDC, providing trigger for particles which cannot penetrate to the lower TOF. (Figure 2, 4)

### A. Basic structure of Middle TOF

The Middle TOF consists of several components, which are as follows:

1) *Scintillator and Fiber bundle*: The Middle TOF consists of 48 plastic scintillator strips with a dimension of  $5.6 \times 13.3 \times 950 \text{ mm}^3$ . A flexible bundle of 60 square plastic fibers ( $1 \times 1 \text{ mm}$ ) is used as a light guide connecting each end of the scintillator and a PMT. Square fibers were selected to ease their void-free arrangement into a bundle without any gaps as compared to the round fibers. In addition, the glued fiber bundle have good mechanical strength comparable solid acrylic light guide but are compiling to the complex routing inside the magnet.

2) *Photomultiplier*: The PMT for Middle TOF is a 2.5 inch fine-mesh 8 channel multi-anode PMT (R6504MODX-M8ASSY, HAMAMATSU PHOTONICS), which was selected for their magnetic field tolerance and small space requirement. To reduce the power consumption of Middle TOF electronics, the 8 anode channels of one PMT are used for the charge determination of the associated individual scintillator strips. The timing and trigger for these 8 strips is derived from the common dynode signal. The crosstalk between the anodes of the PMT is about 5-10 %.

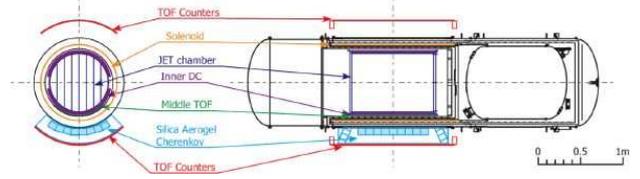


Fig. 2: The BESS-Polar II spectrometer

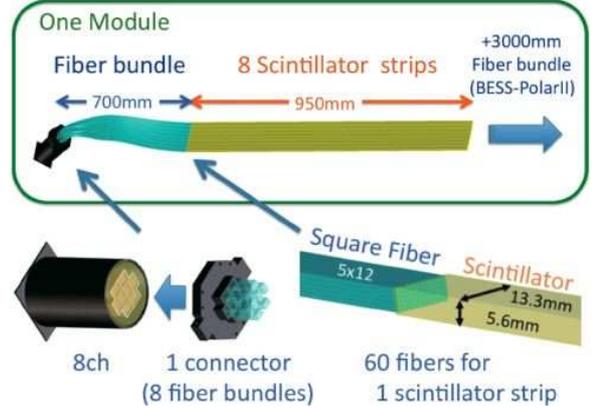


Fig. 3: The detailed structure of Middle TOF

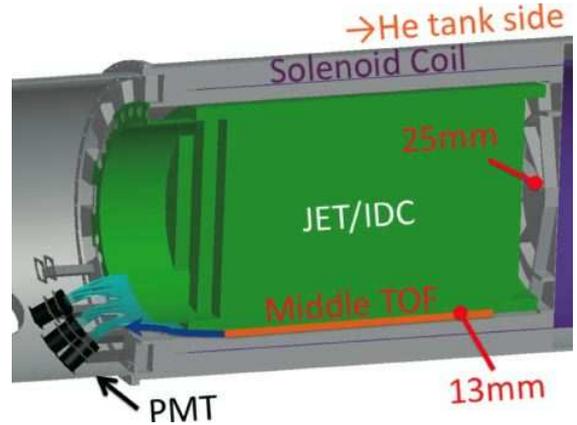


Fig. 4: The cross sectional view of the inside of the BESS Polar I superconducting solenoid magnet bore

3) *The structure of Middle TOF*: The structure of Middle TOF is illustrated in Figure 3. The 8 fiber bundles coming from the adjacent scintillator strips are joint in one connector which attaches to the PMT. We call the 8 strips of Middle TOF one module. In BESS-Polar I, the module could not be divided into individual strips, and an entire Middle TOF module needed to be installed as one unit.

4) *A cross sectional view*: A cross sectional view illustrating the location of the Middle TOF is inside the magnet bore under JET/IDC is shown in Figure 4.

The far end of the magnet bore near the liquid helium tank consists of an aluminum isogrid plate. The radial clearance between JET/IDC and the magnet bore is only 13 mm and axial space between the isogrid and JET/IDC is 25mm.

TABLE II: The parameters of Middle TOF

	BESS Polar I	BESS Polar II
Readout	single-end	double-sided
Scintillator	EJ204, Eljen	EJ200, Eljen
Attenuation length (m)	3.8	1.6
Pulse Width (ns)	2.2	2.5
Form (mm)	5.6×10×1000	5.6×13.3×950
Number of scintillators	64	48
Square Fiber	1×1 mm	1×1 mm
Number of fibers / scintillator	36 (4×9)	60 (5×12)
Length (mm)	500	700 / 3000

### B. BESS-Polar I Middle TOF

In BESS-Polar I, the scintillator signal was only read from one end because of the very limited space that was available. This single-end Middle TOF readout had the following problems:

- 1) The time resolution worsened from 320 ps to 530 ps when particles passed through the near to the far end of the scintillator due to the light attenuation in the strips. The non-uniformity of the time resolution reduced the performance of the particle identification with Upper TOF and Middle TOF configuration.
- 2) The single-end readout could not determine the axial position of a hit. The three dimensional track of the particle is determined by JET/IDC and the axial position information of the TOF counters. The single-end readout cannot check the track consistency between the axial information of JET/IDC and TOF reducing the rejection power for background / noise hits.

### C. BESS-Polar II Middle TOF

To overcome the problems of a single-ended MTOF, a new detector was developed for BESS-Polar II that read out both ends of the scintillator. However, there was no space to put PMT at the liquid helium tank side. Therefore, the PMT for both ends were placed on the accessible side of the magnet.

1) *Treatment of fiber handling:* The routing of fiber bundles from the liquid helium tank side have to avoid the fiducial region of the BESS-Polar II spectrometer because the interaction between cosmic-rays and the fiber bundle reduce the performance of detectable lowest energy. Under this restriction, we determined the structure of BESS-Polar Middle TOF (Figure 5). The Middle TOF of BESS-Polar I & II are compared in table II. The fiber bundles of liquid helium tank side are crossing at the isogrid and turned back to the other side to avoid the fiducial region and limit the amount of bending required.

2) *Fiber connector:* To install Middle TOF of BESS-Polar II strip by strip, we have to introduce an additional improvement. To avoid the difficulties of simultaneously installing and routing the 4.7m long fibers of 8 adjacent scintillator bars in a module, we developed a fiber connector to the PMT that could be assembled after the individual fiber bundles were routing inside the magnet bore. Figure 6 shows the structure of the fiber

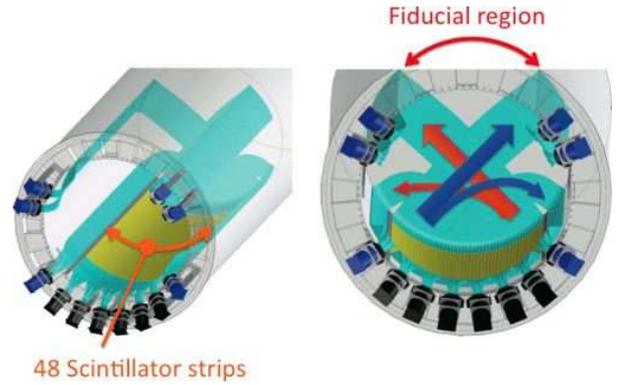


Fig. 5: The structure of double-sided readout BESS-Polar II Middle TOF

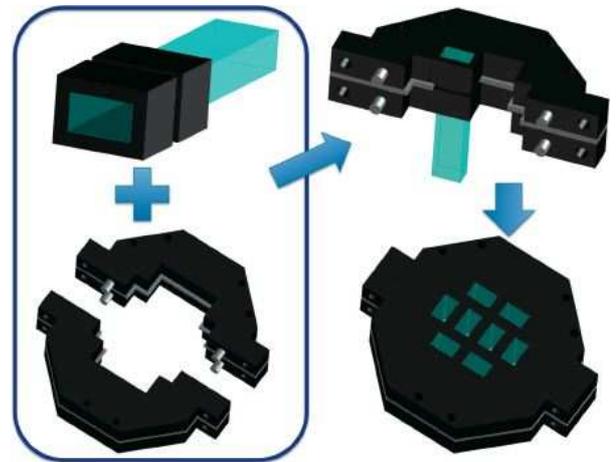


Fig. 6: The fiber connector of BESS-Polar II Middle TOF

connectors. The end pieces on each fiber bundle were joint in a fiber connector and were interconnected by a tongue-and-groove technique providing a perfectly flat surface which interfaced the PMT.

### III. THE PERFORMANCE OF MIDDLE TOF

The Middle TOF worked very well without any problems during 24.5 day long BESS-Polar II flight. For the following discussion, we evaluated the performance of each Middle TOF strip by selecting protons with  $E \geq 2 \sim \text{GeV}$ .

Before evaluating the performance, we show definitions of several parameters. Figure 7 shows the definitions for the evaluation of the performance. We define the  $Z$  axis as the axial in direction of the scintillator strip. The trigger timing of each counter is  $T_{UTOF}$  and  $T_{MTOF}$ , respectively. The position information of  $Z$  axis is acquired by the track of JET/IDC and the time difference between  $T_R$  and  $T_L$ .  $V_{eff}$  ( $\sim 150 \text{ mm/ns}$ ) is the actual velocity of photons in the scintillator.

$$Z_{TOF} = \frac{T_R - T_L}{2} \times V_{eff} \quad (1)$$

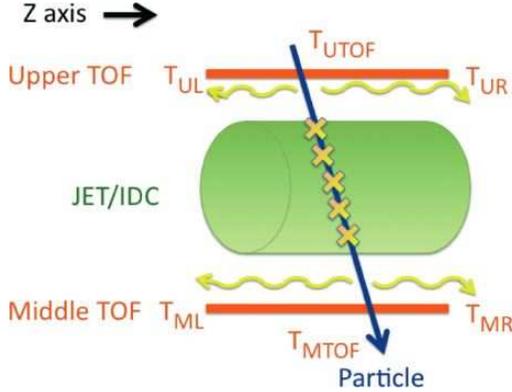


Fig. 7: The definitions for the calculation of the performance

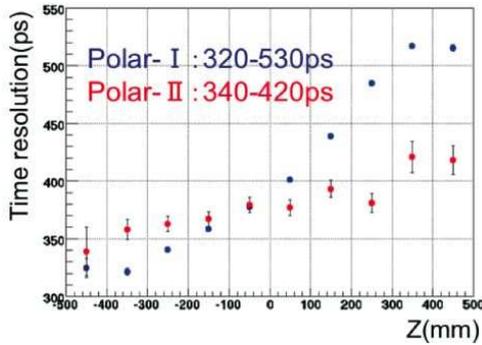


Fig. 8: The time resolution of BESS-Polar I and BESS-Polar II

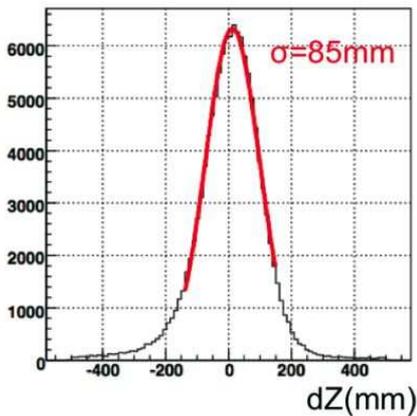


Fig. 9: The axial position resolution of Middle TOF

#### A. Time resolution

To evaluate the time resolution, we compared the time difference,  $\Delta T$ , of the expected time in the Middle TOF,  $T_{trk}$ , derived from the track reconstruction with the measured time,  $T_{tof}$  in the Middle TOF. The width of the  $\Delta T$  distribution is a measure of the time resolution.

$$\Delta T = T_{tof} - T_{trk} \quad (2)$$

$$T_{tof} = T_{MTOF} - T_{UTOF}, \quad T_{trk} = \frac{L_{path}}{c\beta_{trk}} \quad (3)$$

Figure 8 compares the time resolution of BESS-Polar I and BESS-Polar II Middle TOF as a function of the axial position. The position dependence of the time resolution is improved compare to BESS-Polar I Middle TOF.

#### B. Axial position resolution

To evaluate the axial position resolution of Middle TOF, we evaluated  $\Delta Z$  which is the axial position difference between Middle TOF ( $Z_{MTOF}$ ) and the tracking information ( $Z_{trk}$ ).

$$\Delta Z = Z_{MTOF} - Z_{trk} \quad (4)$$

Figure 9 shows the  $\Delta Z$  plot. The axial position resolution of the Middle TOF is 85 mm. On the other hand, the axial position resolution of lower TOF is about 30 mm. The energy loss of low energy particles ( $\sim 0.2\text{GeV}$ ) is about 8 times higher than high energy particles which were used for these evaluation. The expected axial resolution with low energy particles is  $1/\sqrt{8} \times 85(\text{mm}) = 30(\text{mm})$ . Therefore, the performance of the axial information of Middle TOF for low energy particles is almost same as that of lower TOF for high energy region.

#### IV. CONCLUSIONS

The BESS-Polar II flight successfully was carried out over the Antarctica from December 23, 2007 to January 21, 2008. We acquired  $4.5 \times 10^9$  events during 24.5 days data taking, and all detectors operated nominally without major problems during the flight. The BESS-Polar II Middle TOF demonstrated a significant improvement in the Z position uniformity of the time resolution and provided additional position information for the track reconstruction. These detector improvements enhanced particle identification and the background / noise rejection.

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#### REFERENCES

- [1] K. Yoshimura *et al.*, Adv. Space Res. 42 (2008) no.1664
- [2] A. Yamamoto *et al.*, 27th Intl. Cosmic Ray conf. (2001) pp.2135.
- [3] T. Yoshida *et al.*, Adv. Space Res. 33 (2004) 1755.
- [4] S. Orito *et al.*, Phys. Rev. Lett 84 (2000) 1078
- [5] N. Thakur for the BESS-Polar Collaboration (OG.1.5)
- [6] K. Sakai for the BESS-Polar Collaboration (OG.1.5)