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Novel fabrication techniques for low-mass composite structures in silicon particle detectors

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ABSTRACT

The structural design of silicon-based particle detectors is governed by competing demands of reducing mass while maximizing stability and accuracy. These demands can only be met by fiber reinforced composite laminates (CFRP). As detecting sensors and electronics become lower mass, the motivation to reduce structure as a proportion of overall mass pushes modern detector structures to the lower limits of composite ply thickness, while demanding maximum stiffness. However, classical approaches to composite laminate design require symmetric laminates and flat structures, in order to minimize warping during fabrication. This constraint of symmetry in laminate design, and a "flat plate" approach to fabrication, results in more massive structures. This study presents an approach to fabricating stable and accurate, geometrically complex composite structures by bonding warped, asymmetric, but ultra-thin component laminates together in an accurate tool, achieving final overall precision normally associated with planar structures. This technique has been used to fabricate a prototype "I-beam" that supports two layers of detecting elements, while being up to 20 times stiffer and up to 30% lower mass than comparable, independent planar structures (typically known as "staves").

1. Design

1.1. Overall concept

The I-beam is a low-mass silicon support structure proposed for the first two barrel layers in the baseline layout of the Pixel Detector for the ATLAS Phase II Upgrade [1] at the LHC at CERN. The layout of the I-beam structure is shown in Fig. 1. It integrates mechanical support, cooling, power, and data for two concentric layers of silicon in a circular pattern of identical monolithic beams. These are end-supported structures which require no additional support in the active sensing region. Assembly is by clam-shelling of two halves, as a surface assembly step or in-situ in the experimental cavern.

At top and bottom, thin carbon fiber laminates (100–150 μm) provide stiffness and a bonding platform for pixel modules. Beneath these surfaces a high-conductivity carbon foam transmits heat to embedded coolant tubes. A thin web section of carbon fiber mechanically couples the two layers, increasing the total sectional inertia 3 orders of magnitude greater than would be achieved with individual thin beams. Space under the flanges and inside the web provide ample packaging room for power and data.

1.2. Comparison of layout designs

In most existing detector layouts, individual sensing layers are maintained in distinctly separate structures. The rationale behind this design choice is to retain individual accessibility and/or reparability. In reality, however, two or more layers are typically coupled inadvertently through assembly or access constraints, rendering the independence of individual layers questionable, and in fact making much of the structure and mass either partly or entirely redundant.

In Table 1 and Fig. 2, four different approaches to supporting two adjacent detector layers are shown. The I-beam design embraces the implicitly coupled nature of detector layout, and explicitly integrates two layers into one, thereby reducing the mass of structural supports while increasing stiffness and overall performance.

The traditional approach to monolithic beam structures in detector applications – a closed, box-type beam – is shown in comparison with the I-beam in Fig. 3. Both concepts possess virtually equal merit, at the level of mass and stiffness. However, in the layout context, it is evident that the box beam occupies almost all of the free space between the layers, even while not

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fully supporting the detector modules. The I-beam, on the other hand, occupies approximately 75% less space, fully supports the detector modules, and leaves ample room for service routing, which is critical in the overall layout.

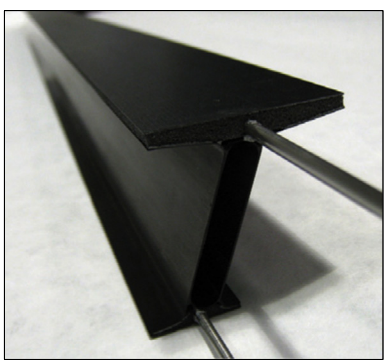
1.3. Novel laminate and assembly approach

In most composite laminates, ply orientations are chosen following multiple needs. Longitudinal plies (i.e. 0°) are used to enhance bending stiffness, angled plies (i.e. 45°) give torsional resistance, and transverse plies (i.e. 90°) impart robustness and transverse stability. Generally, a combination of these plies, in what is known as a "symmetric" arrangement, are used in any given part to create a robust and warp-free design. However, in the case of ultralight detector structures, the use of many plies and many orientations makes for heavier than necessary designs. The I-beam avoids symmetric laminates and the full collection of ply orientations in each constituent part, as shown in Fig. 4, instead relying on the collection of plies in the final bonded assembly in order to arrive at the necessary strength, straightness, and stiffness.

The I-beam also simplifies construction by avoiding the complex fabrication issues of box-section components. While closed sections exhibit reduced warping and have better handling characteristics than open ones, bonding operations (both foam and pipe), mandrel (mold) removal, and final dimensions are difficult to control in closed-section designs, due to the fact that the entire part accuracy is embedded at elevated cure temperature during the lamination process. Conversely, for the I-beam, final assembly accuracy is achieved by room-temperature bonding of previously cured subparts, which allows for a more deterministic approach to arriving at a final precision structure. Since all I-beam subsections are open, mandrel (mold) removal and reassembly for bonding are also greatly facilitated.

1.4. Mass and X_0

Radiation length and mass are calculated for the materials used in constructing a 1 m I-beam prototype built in 2011. The measured mass of 1.58 g/cm exceeded the design estimate by only 3.8%, showing that mass could be very accurately predicted. The calculated radiation length averaged over the I-beam cross-section



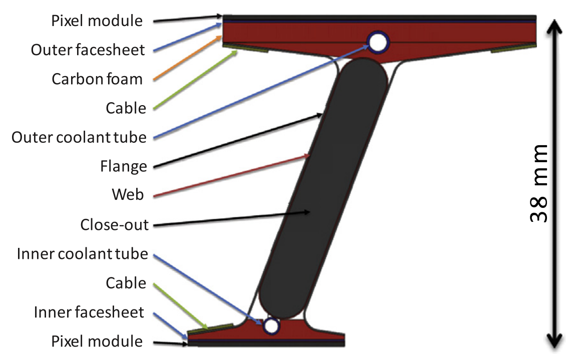


Fig. 1. 1 m long I-beam mechanical prototype (left) and cross-sectional structural layout (right).

Table 1
Comparison of different structural approaches (shown in Fig. 2) with the I-beam as reference.

	Relative mass	Relative stiffness	Stiffness/ mass
I-beam	1.00	1.00	1.00
Box beam	1.11	1.10	0.99
Single sided bi-stave	1.05	0.87	0.84
Double sided bi-stave	1.47	1.20	0.81
Single double sided stave	0.87	0.01	0.01

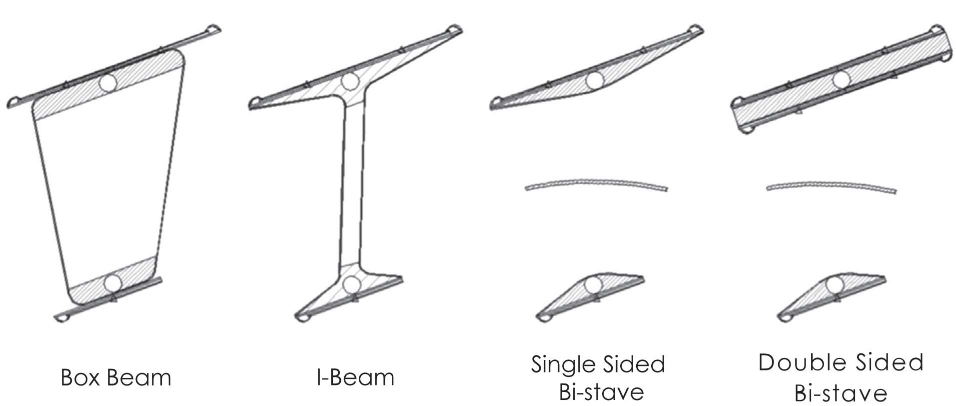


Fig. 2. Comparison of four different approaches to supporting two detecting layers.