SPACEFLIGHT INSTRUMENTATION ENABLED BY ADDITIVE MANUFACTURING: A CASE STUDY ANALYSIS WITH THE JUICE/JOEE INSTRUMENT.
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Introduction: The Johns Hopkins University Applied Physics Laboratory (JHUAPL) is discovering unique applications for additive manufacturing (AM) for science instruments. One example is an electron collimator that will fly on the European Space Agency's JUpiter ICy moons Explorer (JUICE) mission. By fabricating this collimator using metal additive techniques, science requirements were achievable that otherwise couldn't be obtained with conventional manufacturing. Successful inspection and qualification of the collimators' complex geometry demonstrated the usefulness of AM in space instrument design.

Instrument Background. The goal of JUICE is to explore the Jovian system and three of its largest moons (Ganymede, Callisto and Europa) for habitable environments. JHUAPL is responsible for two instruments in the Particle Environmental Package (PEP); one of which is the Jovian Energetic Electrons (JoEE) instrument. JoEE's role is to probe acceleration mechanisms, magnetic field topology, and boundaries by the electron energy and angular distributions.

Science Requirements. The JoEE instrument is based on a circular design with nine individual sectors that create a ~100-600 Gauss closed magnetic field with minimal leakage (Figure 1). This requires an array of radial, highly directional, high aspect ratio holes for efficient collimation – each sector limited to an azimuthal field of view of 22.5 degrees.

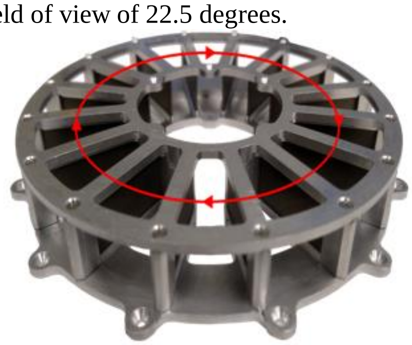

FIGURE 1: JOEE INSTRUMENT FRAME

A spherically-focused collimator arrangement maximizes field of view and measurement fidelity. Holes had to be small enough to confine particle trajectories within the face of detectors (Figure 2) but large enough to provide adequate foreground signal.

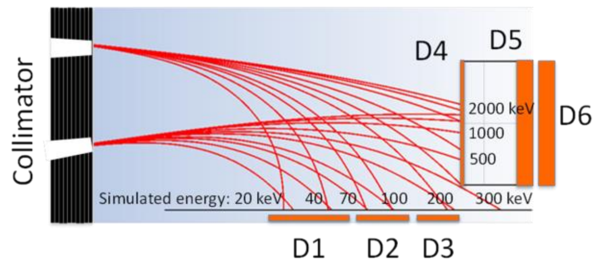

FIGURE 2: PARTICLE TRAJECTORIES

The material had to be of sufficient density to absorb off-vector energetic particles. Instrument size and mass limitations also had to be accounted for in the collimator design.

Collimator Design: Through ray tracing and simulation of particle trajectories, a required hole geometry for the collimator design was found that met the science requirements. Due to how the detectors were arranged in the instrument, each of the nine sectors was limited to fields of view of 22.5 degrees azimuth and 12 degrees polar. Based on these requirements, each sector required 518 tightly packed holes with an approximate diameter of 0.5mm. Hexagonal holes were preferred due to their greater packing density while maintaining a minimum wall thickness. Fabrication of such a precise hole geometry proved to be a manufacturing challenge. Conventional machining of the collimator holes was time-intensive and small drill bit sizes were prone to fracture. A layered approach involving the banded assembly of etched metal sheets would be challenging to assemble and ensure alignment of the many holes

Additive Approach. The hole geometry needed to meet requirements could not be manufactured conventionally. The JHUAPL team turned to additive manufacturing for its capability of producing complex geometries and lattice structures. Additive manufacturing is defined by ISO/ASTM as "a process of joining materials to make objects from 3D model data, usually layer upon layer" [1]. For this application, the metal powder bed fusion (PBF) process was investigated. This process involves a thermal source (in this case a laser) selectively fusing layers of material to form a solid part. 316L Stainless Steel was the material selected for the collimator for its nonmagnetic properties and density to absorb off-vector particles. AM industry experience and promising material data were also factors in material selection.

The final collimator design is depicted in Figure 3. It incorporates nine individual collimator segments that were assembled into a full collimator via interlocking tab features. Building each collimator individually allowed the holes to be oriented vertically during the additive process to achieve better hole resolution.

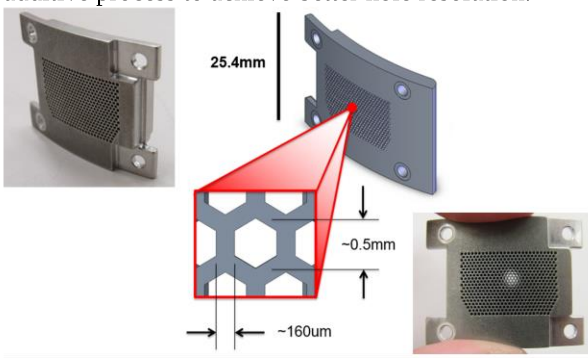

FIGURE 3: FINAL COLLIMATOR DESIGN

Through a series of design experiments, wall thicknesses of 160μm were achieved compared to the 300-400μm walls typical for commercial settings. However, AM remains a complimentary manufacturing method and requires post-processing to achieve the tight tolerances required for spaceflight. To ensure the collimator mating interfaces were within tolerance, a variety of subtractive methods were subsequently performed on the collimators including milling, electro discharge machining (EDM), and tumbling.

Calibration testing at NASA's Goddard Space Flight Center's high-energy beam facility revealed the AM fabricated collimators behaved as expected. Figure 4 shows the collimator's angular properties meet requirements.

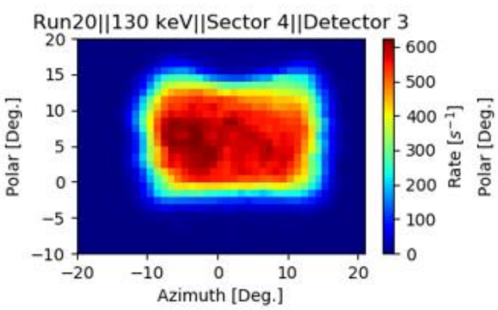

FIGURE 4: COLLIMATOR MAP EXAMPLE

Spaceflight Qualification: Because AM is a relatively new technology, it is not as repeatable a process as conventional manufacturing. To be qualified for spaceflight, additional testing and documentation is required to provide evidence that AM parts will pass requirements with margin. For the JoEE collimators, JHUAPL worked closely with NASA Marshall on utilizing their additive standards published in 2017 (MSFC-STD-3716 and -3717). These standards provided a defined system of foundational and part production controls to manage risk associated with the current state of PBF technology. Procedural requirements were clearly outlined for the metallurgical process, machine calibration and maintenance, material property data through tensile testing, and a formal production plan given part requirements.

A combination of proof testing and new inspection techniques were required to address the risks associated with metal AM. Proof testing of the collimators was performed prior to instrument integration. All testing (vibration, shock, thermal cycling) was performed at conditions well beyond expected launch and operation. In addition, an intensive ultrasonic cleaning process with particle count was performed on the collimators with deionized water and IPA. Inspection of the collimators involved a combination of coordinate measuring machine (CMM) inspection of exterior features and X-Ray Computed Tomography (XRCT) scanning of internal hole geometry. The density and depth of the holes made XRCT the most viable option for inspection. Novel methods were developed using advanced features of the XRCT software for the visualization and automation of complex volumetric and geometric analyses. These methods allowed for the characterization of wall thickness, focus location, porosity, and other defects critical to the structural integrity and function of the collimators.

Future Prospects of AM for Instruments: Additive manufacturing opens the instrument design space to more complex internal features, more compact and lightweight structures, and rapid design changes with greater process flexibility. The complex hole geometry in the JoEE collimator provided more efficient collimation and a greater field of view within a compact design. Thin-walled lattice structures generated via optimization will produce smaller, more lightweight instruments that can be more easily integrated on missions. Complex geometries can be used to build multi-functional parts with additive which will reduce instrument mass and simplify assembly. For example instrument support structures made of Tungsten could serve as electronics shielding. Other materials like Copper could be used for both shielding and thermal management. AM also allows for rapid redesign and iteration – multiple machine parameters and geometries for the JoEE collimator were tested in just a matter of months. Additive will shorten the overall production time and lower instrument cost. JHUAPL is continuing to investigate additive materials for these space instrument applications.

References: [1] ISO/ASTM52900. (2015). *Standard Terminology for Additive Manufacturing – General Principles – Terminology*. Retrieved December 15, 2019, from https://www.astm.org