Spaceflight Instrumentation Enabled by Additive Manufacturing

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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) is additively manufacturing space instruments to meet specific science objectives. One example is an electron collimator, built using additive manufacturing technology, that will fly on the European Space Agency's JUpiter ICy moons Explorer (JUICE) mission set to launch in 2022. The collimator is the first-ever additively manufactured mechanical component to be both fabricated and qualified for spaceflight at APL. By using metal additive techniques, the APL team achieved complex geometries that could not have been obtained with conventional manufacturing. The intricate collimators, each about the size of a quarter and peppered with hundreds of tiny holes, are assembled in a spherically focused arrangement. They confine particle trajectories within the face of the detectors in the instrument. Extensive collaboration between APL's Research and Exploratory Development Department and Space Exploration Sector led to the successful development and qualification of the flight collimator in just 2 years. The innovative capabilities of additive manufacturing will become an integral part of future space missions.

INTRODUCTION

APL is discovering unique applications for additive manufacturing (AM) for space science instruments. One example is an electron collimator that will fly on the European Space Agency's JUpiter ICy moons Explorer (JUICE) mission[1] set to launch in 2022. By fabricating this collimator using metal additive techniques, the team met science requirements that could not have been achieved with conventional manufacturing. Successful inspection and qualification of the collimator's complex geometry demonstrated the usefulness of AM in space instrument design.

Mission and 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. APL is responsible for two instruments in the Particle Environmental Package (PEP), one of which is the Jovian Energetic Electrons (JoEE) electron particle spectrometer. JoEE's role is to enable a better understanding of the processes that make Jupiter the solar system's largest particle accelerator by probing acceleration mechanisms, magnetic field topology, and boundaries.

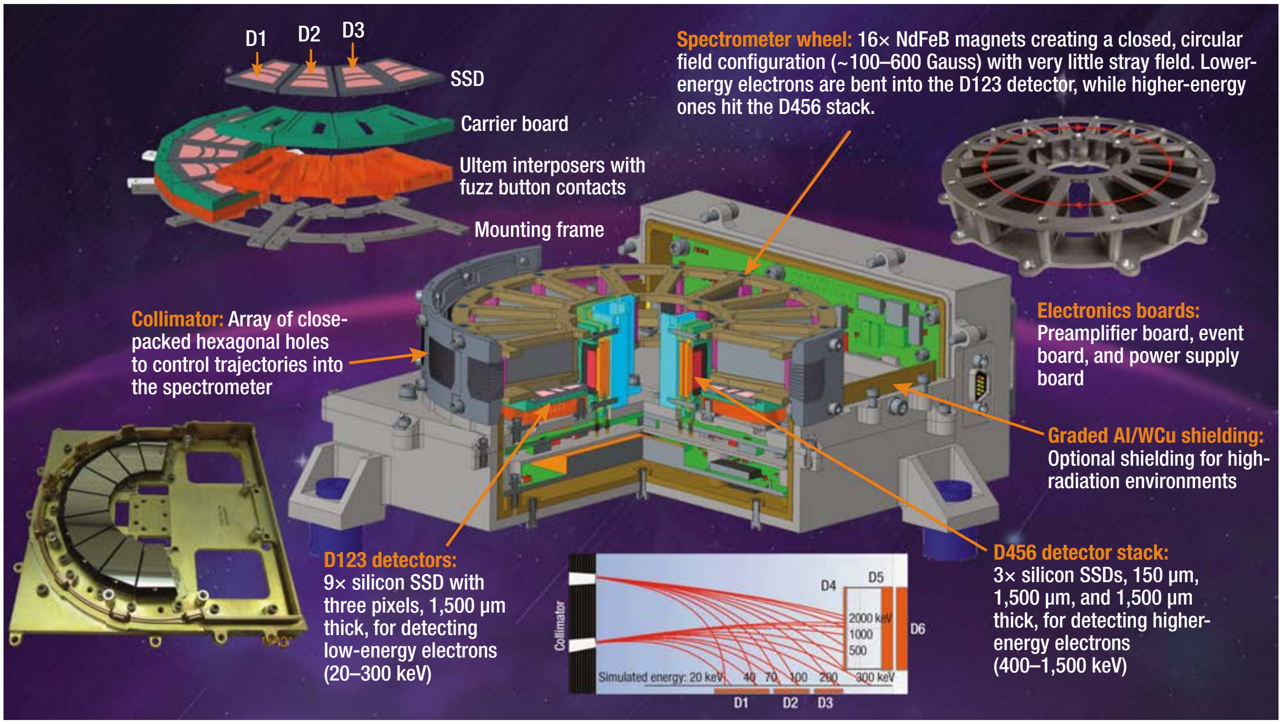

Figure 1. Cross-sectional view of JoEE instrument. Primary components include collimator segments, spectrometer wheel, electronics boards, silicon solid-state detectors (SSDs), and mechanical shielding made of aluminum and tungsten copper alloy.

Science Requirements

The JoEE instrument is a magnetic spectrometer with a solid-state detector stack that provides clean electron measurements between 20 and 1.5 MeV (Figure 1). The instrument is based on a circular design with nine individual sectors that create an ~100- to 600-Gauss closed magnetic field with minimal leakage. This design requires an array of highly directional, high-aspect-ratio holes for efficient collimation—each sector is limited to an azimuthal field of view of 22.5°.

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. Magnetic optics were used to properly focus particles onto the sensor's detector elements.

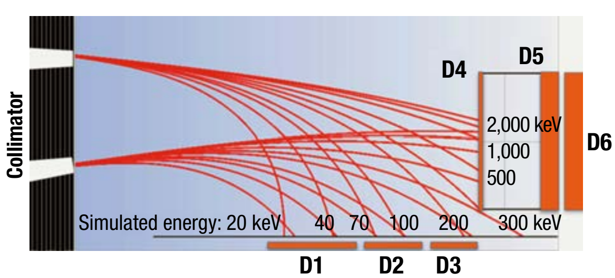

Figure 2. Simulated particle trajectories through the collimator for different energy levels. The collimator restricts the velocity vectors of particles entering the instrument to a set of well-defined trajectories onto the sensor's D1–D6 silicon solid-state detectors.

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

After many iterations of computer-aided design (CAD) and particle simulation, the team found a required hole geometry for the collimator that met the science requirements. Because of the detectors' arrangement in the instrument, each of the nine sectors was limited to fields of view of 22.5° azimuth and 12° polar. Sufficient geometrical factor was needed to provide adequate foreground signal. Based on these requirements, each sector required 518 tightly packed holes with an approximate diameter of 0.5 mm. Hexagonal holes were preferred for 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 bits were prone to fracture. The team considered a layered approach involving the banded assembly of etched metal sheets, but this approach would make it challenging to assemble the collimator and ensure alignment of the many holes.

Additive Approach

The hole geometry needed to meet requirements that could not be met with conventional manufacturing techniques. The APL team turned to AM for its ability to produce complex geometries and lattice structures. AM is defined by ISO/ASTM international standards as "a process of joining materials to make objects from 3D model data, usually layer upon layer."[2] For this application, the team investigated the metal powder bed fusion (PBF) process. This process involves a thermal source (in this case a laser) selectively fusing layers of material to form a solid part. The material selected for the collimator was 316L stainless steel 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 assembled into a full collimator, one segment for each sector of the instrument. Building each collimator individually allowed the holes to be oriented vertically during the additive build process to achieve better hole resolution. The collimator segments interface each other and the frame via interlocking tab features, which close gaps and prevent unwanted particles from passing through.

Through a series of design experiments, the team developed new additive machine parameters to meet the need for thin walls. Wall thicknesses of 160 µm were achieved compared with the 300- to 400-µm walls typical for commercial applications. However, AM remains a complementary manufacturing method and requires postprocessing to achieve the tight tolerances required for spaceflight. To ensure the collimator mating interfaces were within tolerance, the team subsequently performed a variety of subtractive methods on the collimators, including milling, electrical discharge machining (EDM), and tumbling.

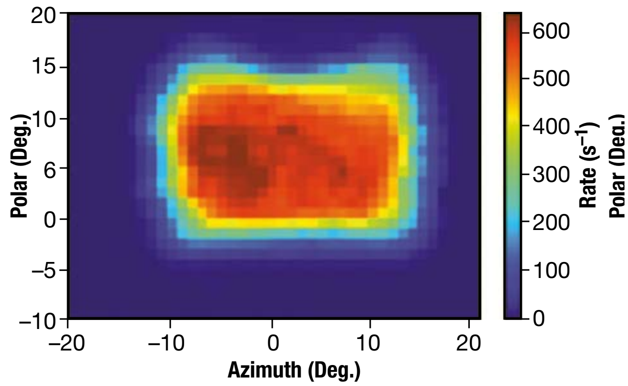

Figure 4. Angular characterization of JoEE using the AM collimator taken from calibration testing at the NASA Goddard high-energy beam facility. To characterize the instrument, the count rates were converted into electron differential intensities and phase space densities for the various defined ranges of energies and arrival angles.

Calibration testing was performed at the NASA Goddard Space Flight Center high-energy beam facility. Test results revealed that the AM-fabricated collimators were viable options to achieve the desired particle throughput and field of view. Figure 4 shows an example of the angular characteristics of the AM collimator for 130 keV energy in sector 4 for detector 3. Measurements were taken for various energy ranges and arrival angles across all sectors of the collimator. The angular properties measured during characterization and calibration activities met requirements for particle throughput and field of view.

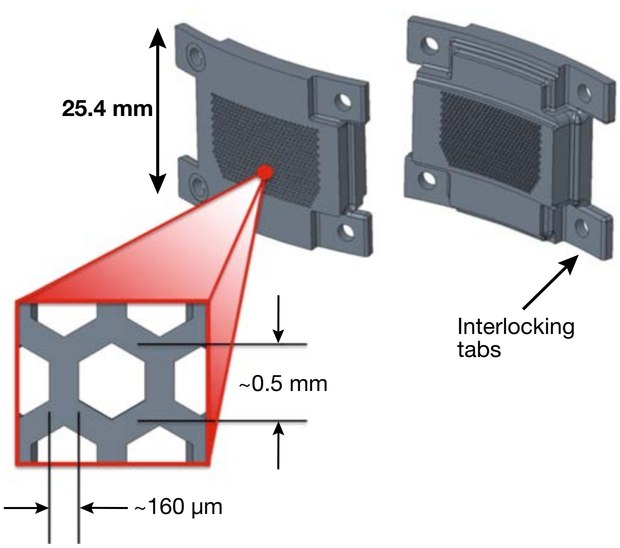

Figure 3. Final collimator design with dimensions shown for hole diameter, wall thickness, and overall height. Each segment shares mounting locations with adjacent segments via interlocking tabs.

SPACEFLIGHT QUALIFICATION

Because AM is a relatively new technology, it is not as repeatable a process as conventional manufacturing.

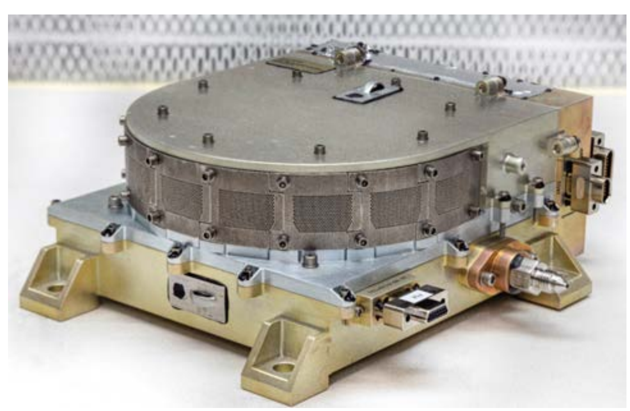

Figure 5. Flight JoEE instrument just before delivery. The dark gray components are the 316 stainless steel AM collimators.

For AM parts to be qualified for spaceflight, additional testing and documentation are required to provide evidence that the parts will pass requirements with margin. For the JoEE collimators, APL worked closely with NASA Marshall Space Flight Center to use its additive standards (MSFC-STD-3716[3] and MSFC-STD—3717[4]; see also the newly released NASA-STD-6030[5]). 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. Using additive metal parts on JoEE involved risks. For example, the collimators could fracture into pieces during launch and damage the fragile detectors or other instruments on the spacecraft. Thus, the collimators had to be validated through proof testing and inspection before instrument integration. The final flight JoEE instrument is pictured in Figure 5.

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 before instrument integration. All testing (vibration, shock, thermal cycling) was performed at conditions well beyond those expected at launch and during operation. In addition, the collimators were cleaned with deionized water and isopropyl alcohol in an intensive ultrasonic cleaning process that concluded with particle counts. Inspection of the collimators involved a combination of coordinate-measuring machine inspection of exterior features and x-ray computed tomography scanning of internal hole geometry (Figure 6). The density and depth of the holes made x-ray computed tomography the most viable option for inspection. The team developed novel methods using advanced features of the VGSTUDIO Max 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.

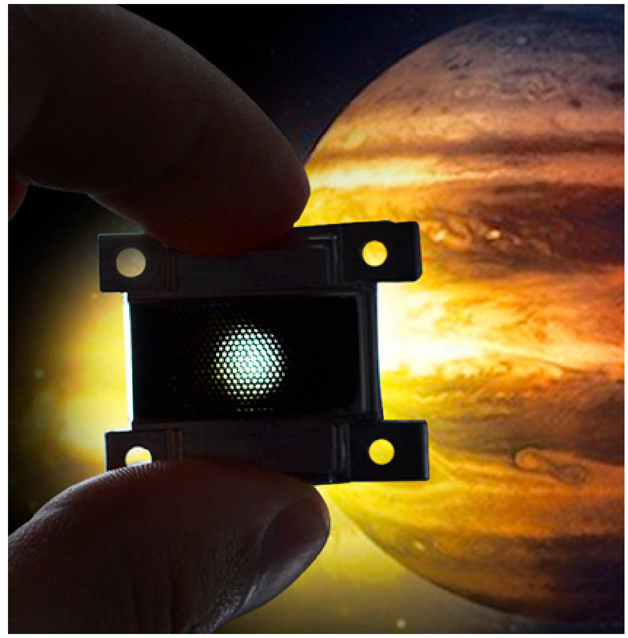

Figure 7. The JoEE collimator. The instrument will fly on the European Space Agency's juice mission to Jupiter, which is set to launch in 2022.

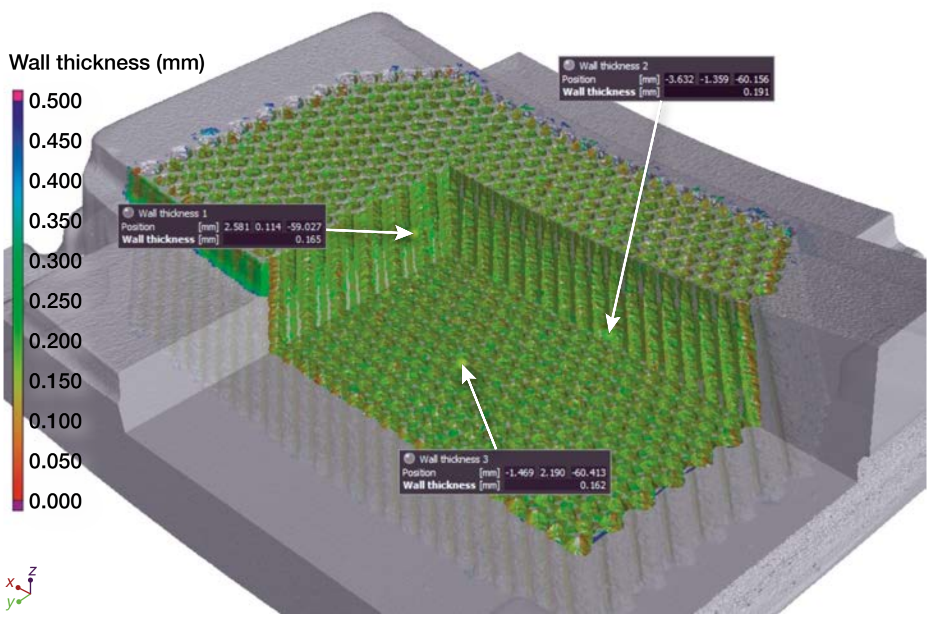

Figure 6. Wall thickness analysis of collimator using x-ray computed tomography software. This method allows for inspection of the part in cross-sectional slices useful for examining internal features.

FUTURE PROSPECTS

AM extends instrument design to include more complex internal features and compact, lightweight structures. The complex hole geometry in the JoEE collimator provided more efficient collimation and a greater field of view within a compact design. AM offers the advantage of rapid redesign and process flexibility.

The team tested multiple machine parameters and geometries for the JoEE collimator (Figure 7) in just a matter of months before settling on the flight process.

AM offers other advantages to space instruments. 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 multifunctional parts that 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.

Ongoing research efforts at APL are advancing capabilities in Tungsten AM for space applications. Tungsten was the initial preferred material for the JoEE collimator for its density, but it was not available at the time the collimator was being developed. APL recently developed a unique build process to fabricate a flight-like Tungsten collimator with ~300-μm walls. Postprocessing steps were tailored to maximize part quality despite some of the challenges of working with Tungsten: high thermal stresses, poor machinability, and susceptibility to cracking. The Tungsten collimator survived both vibration and shock testing, which suggests that the material is spaceflight worthy.

Space programs are increasingly looking to use dense materials in complex geometries for collimation, shielding, and support structure in instruments. APL's success on JoEE (and more recently with using Tungsten for space applications) has demonstrated that AM can meet this demand. AM's innovative capabilities for small-scale instruments will continue to be an integral part of space missions, and APL will remain on the forefront of advancing the state of the art.

REFERENCES

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Michael C. Becker is a mechanical engineer in APL's Space Exploration Sector. He has a BS in mechanical engineering from the University of Virginia and a master's in mechanical engineering from Johns Hopkins University. As a member of the Space Science Instrumentation Group, Michael has experience designing, building, testing, and integrating space instruments. He is currently the mechanical lead engineer for the Europa Imaging System (EIS) Narrow Angle Camera (NAC). Michael also supported the PEP-Hi (Particle Environment Package – Hi) instruments for the JUICE mission, notably overseeing the design, fabrication, and qualification of the additive collimator for the Jovian Energetic Electrons (JoEE) sensor. He has led APL independent research and development efforts to advance capabilities in Tungsten additive manufacturing to benefit space instruments such as CoPS (Compact Particle Sensor). His email address is michael.becker@jhuapl.edu.

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Michael Presley is a senior scientist studying materials and advanced manufacturing techniques with an emphasis on metallurgy. He earned a BS in welding engineering, an MS in materials engineering, and a PhD in materials science and engineering, all from The Ohio State University. He specializes in additive manufacturing (AM) and welding for space missions such as DART (Double Asteroid Redirection Test), JUICE (JUpiter ICy moons Explorer), Europa Clipper, CHAPS-D (Compact Hyperspectral Air Pollution Sensor-Demonstrator), and Parker Solar Probe. His recent work includes development of AM refractory alloys, rapid qualification of AM materials, application of machine learning to materials, and use of AM for spaceflight. He is currently leading a project to develop novel in-space welding techniques for orbital construction. He is a certified welding inspector and provides welding engineering support for operations across the Lab. Michael also guest lectures on additive manufacturing and design as part of the Johns Hopkins Engineering for Professionals program. His email address is michael.presley@jhuapl.edu.

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George B. Clark is a research scientist studying the physics of magnetospheric and auroral plasma phenomena in the magnetospheres of the outer solar system. He has a BS in physics from the University of New Hampshire and a PhD in physics from the University of Texas at San Antonio. George specializes in the analysis and interpretations of spacecraft data from missions such as Juno, Cassini, Galileo, and many more. One of his recent and more notable discoveries is the presence of mega-volt electric potentials over Jupiter's polar cap region—a phenomena that accelerates ions to very high energies into Jupiter's upper atmosphere. He is a member of the science teams for the Juno mission as well as the Jupiter Energetic particle Detector Instrument (JEDI). He is also the instrument scientist for JUpiter ICy moons Explorer's (JUICE's) Jovian Energetic Electrons (JoEE) sensor and deputy lead for the high-energy energetic neutral atom imager onboard the Interstellar Mapping and Acceleration Probe (IMAP)-Ultra. He was a guest investigator on JAXA's Hisaki mission and part of an International Space Science Institute (ISSI) team studying Jupiter's magnetosphere. George has also mentored several high school and undergraduate students as a part of APL's summer intern program. His email address is george.clark@jhuapl.edu.

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