# ADVANCING ACCELERATOR COMPONENTS DESIGN THROUGH ADDITIVE MANUFACTURING

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## *Abstract*

Additive manufacturing (AM) enables new design approaches for accelerator components by allowing internal features, such as conformal cooling channels, to be integrated directly into parts. At the ISIS Neutron and Muon Source, development began with a polycarbonate cooling jacket for an RF plasma chamber, later replaced with glass-filled nylon due to sealing limitations. The work was extended to metal AM, including a stainless-steel beam dump produced by direct metal laser sintering (DMLS), demonstrating the need for selective post-machining of sealing surfaces. These lessons informed the design of an ion source main flange with internal cooling channels, successfully prototyped, machined, and validated using neutron imaging at the IMAT instrument. Current research focuses on ceramic AM for plasma chambers, integrating cooling channels within the ceramic wall to allow closer RF coil placement. A digital-light-processing (DLP) printed alumina green-body chamber has been produced as a proof of concept, supporting future development in aluminium nitride (AlN) and multi-material ceramic–copper systems for improved thermal management.

## INTRODUCTION

Mechanical engineering for particle accelerators frequently demands components with complex internal features - conformal cooling channels, lightweight structures and integrated assemblies - that are difficult or impossible to produce by subtractive methods. AM offers a route to such geometries across polymer, metal and ceramic feedstocks [1]. This paper summarises three streams of development at ISIS that progressively extend AM into vacuum- and thermally-critical accelerator hardware: (i) a polymer cooling jacket for an RF plasma chamber, (ii) a DMLS stainless-steel beam dump and a main flange with internal cooling channels validated by neutron imaging, and (iii) a DLP-printed alumina plasma chamber as a stepping stone towards AlN ceramics.

## POLYMER AM

A 3D-printed (selective laser sintering, SLS), epoxy-impregnated polycarbonate cooling jacket was developed and tested as a first iteration to cool an RF plasma chamber under realistic pressure and thermal loads. Experimental testing up to ~2.7 kW demonstrated cooling performance consistent with simulation, validating the overall concept; however, after thermal cycling, leaks developed at the O-ring interface, driven primarily by the limited print resolution and surface finish on the sealing face (Fig. 1). The test campaign also revealed thermal expansion mismatch in the rig, polymer degradation, and galvanic corrosion within the cooling loop. While the cooling principle was proven, these limitations made clear that the polycarbonate route could not deliver the sealing reliability required.

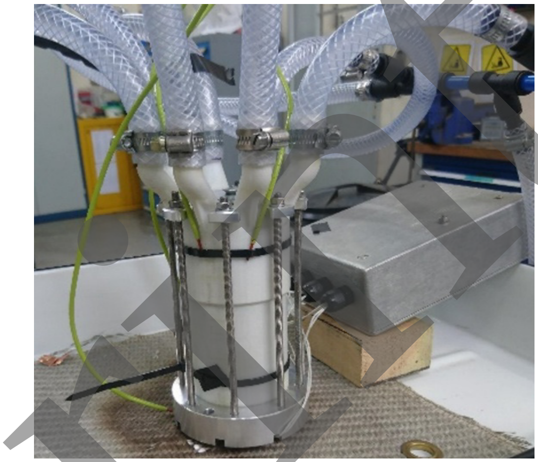

Figure 1: Epoxy-impregnated polycarbonate cooling jacket on the test rig.

The design was therefore transitioned to glass-filled nylon (SLS), which offers higher temperature resistance, improved mechanical robustness, greater dimensional stability under thermal cycling, and a superior as-printed surface finish for reliable O-ring sealing (Fig. 2). Compared with the epoxy-impregnated polycarbonate prototype, the glass-filled nylon material is less susceptible to thermal deformation and degradation, making it better suited for sustained operation under realistic pressure and thermal loads.

Figure 2: Glass-filled nylon cooling jacket assembled over the plasma chamber.

The outer housing used in ion source insertion was manufactured from Stainless Steel primarily to accommodate and support internal components. However, because of its proximity to the RF coil, the metallic housing was

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susceptible to parasitic inductive heating during operation. To mitigate this effect, the housing was redesigned and manufactured in nylon PA12 using SLS printing, followed by post-machining of critical interfaces and mounting features. The polymer housing significantly reduced RF-induced heating while also simplifying fabrication, reducing weight, and enabling rapid design iteration.

In this work, most prototype components were initially produced using fused deposition modelling (FDM), as the process enables rapid, low-cost fabrication and iterative design changes during early-stage development. FDM was particularly useful for assessing geometric fit, assembly integration, routing of cooling channels, and general mechanical compatibility before committing to higher-quality manufacturing routes.

Once designs were sufficiently mature, components were transitioned to selective laser sintering (SLS) or multi jet fusion (MJF) manufacturing. Compared with FDM, powder-bed fusion processes offer improved dimensional accuracy, more uniform mechanical properties, and superior structural integrity. Although similar base polymers may be used across these processes, SLS and MJF parts are generally stronger and less anisotropic, as they are formed through layer-wise sintering or fusing of powder particles rather than deposition of discrete extruded filaments. This reduces inter-layer weaknesses and results in improved stiffness, sealing performance, and durability under thermal and mechanical loading.

## METAL AM

A stainless-steel beam dump was produced by powder-bed metal AM and evaluated in its as-built condition. Initial inspection revealed significant surface roughness and dimensional inaccuracies, with up to 0.77 mm variation on sealing faces and out-of-tolerance features that prevented direct fitting of standard connections (Fig. 3). Vacuum performance testing (pump-down and helium leak detection) showed that, despite the poor finish, acceptable sealing could be achieved using compliant Viton O-rings. Post-machining was still required to bring critical features into tolerance, confirming that metal AM unlocks complex geometries, but secondary machining remains essential for precision sealing surfaces and other critical interfaces.

Building on these learnings and on early design-for-AM (DfAM) engagement with the manufacturer, a main flange with a complex internal cooling channel was designed. An initial prototype was first printed to check powder removal, print success, and surface condition (Fig. 4). Based on the observations, the internal channel bend radii were increased at locations identified as potential powder-clog points, and the need for post-machining of vacuum-critical surfaces was confirmed.

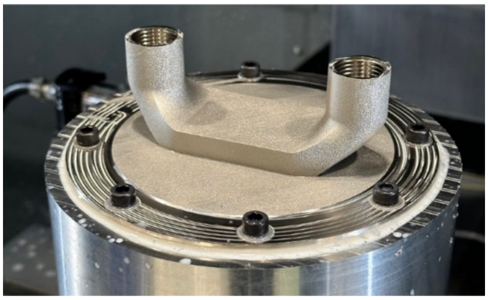

Figure 3: 3D-printed SS 316L beam dump after post-machining.

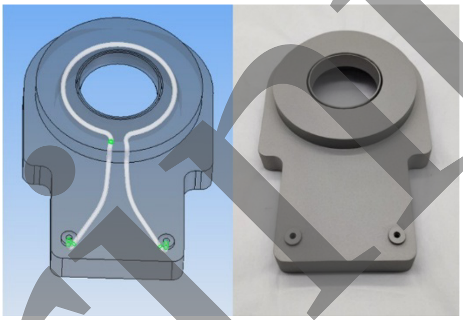

Figure 4: Initial prototype flange with cooling channel diameter of 1.2 mm.

The flange measures ⌀260 mm × 15 mm, with internal cooling channels down to 1.2 mm diameter running close to the O-ring groove. To verify the as-printed geometry, channel position, internal pores and voids were inspected by neutron imaging on the IMAT instrument at ISIS [2] (Fig. 5). Once the channel position was confirmed, post-machining and vacuum seal welding with leak checking were completed. The final flange was produced in 316L by DMLS with selective post-machining of sealing and interface features (Fig. 6).

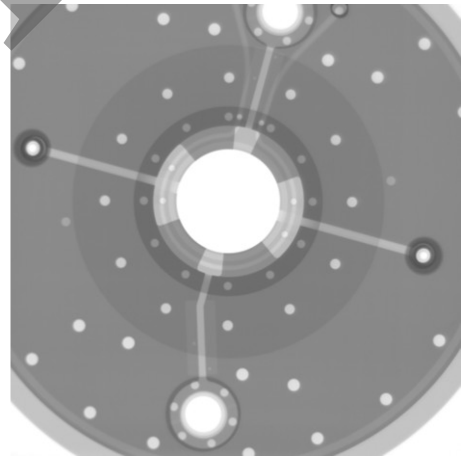

Figure 5: IMAT neutron image of the printed flange confirming channel position.

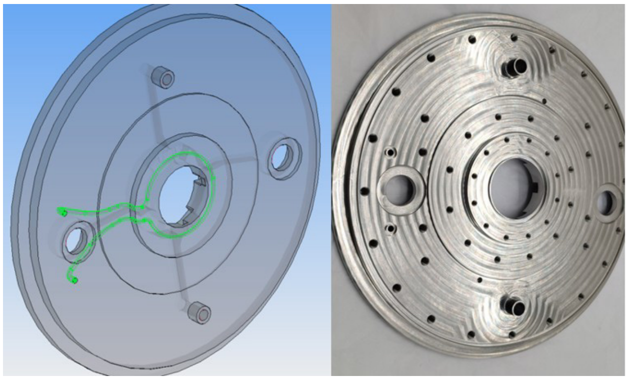

Figure 6: Final post-machined flange with internal channel.

## CERAMIC AM

A ceramic plasma chamber (⌀120 mm × 80 mm) with integrated internal cooling channels was successfully produced using DLP-based ceramic AM. Initial challenges related to part weight and peeling forces during the print were overcome using a bottom-up printing approach combined with optimised process parameters. A full-scale prototype was first fabricated in alumina to demonstrate printability, structural integrity and green-body stability, requiring approximately 2 kg of tailored ceramic suspension (Fig. 7). The dense alumina route is now well established for lithography-based ceramic manufacturing [3].

Based on this proof of concept, the process can now be extended to AlN, which offers substantially better thermal performance than alumina but requires a controlled-atmosphere print and sintering process due to its non-oxide nature. A future multi-material ceramic–copper architecture is also being explored to combine the electrical isolation of the ceramic with the high thermal conductivity of copper at the cooling interface.

Figure 7: Green-body alumina plasma chamber after DLP printing, showing inlet and outlet ports.

## LESSONS LEARNED

AM enables engineers to produce complex geometries that are difficult to achieve using conventional methods - particularly internal cooling channels, lightweight structures, and integrated assemblies. However, successful AM depends on selecting the appropriate material, printing technology, and post-processing route for the intended operating environment and functional requirements. The key lessons drawn from this work are:

- Confirm manufacturer print-bed size, post-processing capability, and supplier-specific DfAM guidelines at the concept design stage.
- Verify hot isostatic pressing (HIP) and heat-treatment certification with suppliers; use CT scanning and DfAM practice to reduce porosity and ensure proper powder removal and accurate machining.
- Polymer 3D printing is best suited to external supports, fixtures, and non-vacuum applications.
- Metal 3D printing is suitable for vacuum and internal cooling-channel applications due to its strength, leak tightness, and thermal performance.
- Hybrid manufacturing approaches (additive + CNC post-machining) are often essential to achieve functional sealing surfaces, tight tolerances, and reliable interface integration in vacuum applications.
- Ceramic printing requires shrinkage consideration and early supplier consultation; oxide ceramics are increasingly commercialised, while non-oxide ceramics remain limited due to controlled-atmosphere processing requirements.

## CONCLUSION

AM has been used to incorporate conformal cooling into accelerator components made from polymers, metals, and ceramics at ISIS. A DMLS-printed 316L main flange has been validated by IMAT neutron imaging, and an alumina plasma chamber green body has been produced using DLP-based ceramic AM. Future work focuses on the transition to non-oxide ceramics, in particular AlN, and on multi-material ceramic-copper additive manufacturing for high-heat-load plasma chamber cooling.

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