3D Printing & Scripted Design of Fusion Diagnostics

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Introduction

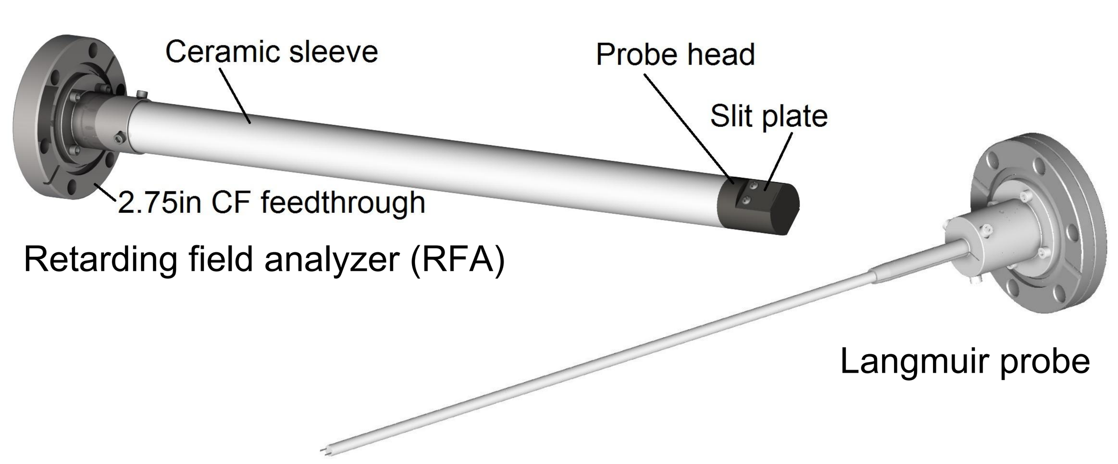
There is a well-established set of plasma diagnostics for fusion applications, but they can be expensive, difficult to fabricate, and require significant time to design. Woodruff Scientific, Inc. (**WSI**) has received a Phase II SBIR award from the DOE to investigate the potential of additive manufacturing (**AM**), or 3D printing, to impact this issue. AM relaxes or removes many of the constraints of conventional manufacture (**CM**), reducing the time and cost of both design and fabrication. Furthermore, AM allows for a significant increase in part complexity at little or no additional cost, potentially leading to improved diagnostic functionality.

WSI is currently:

- optimizing the design of several diagnostics for AM
- assessing the capability of state-of-the-art 3D printing processes for UHV-compatible, high-temperature metals and ceramics
- researching topology optimization and generative design algorithms
- developing scripted design processes that automatically generate semi-custom diagnostics from user input

Conventional Diagnostic Designs

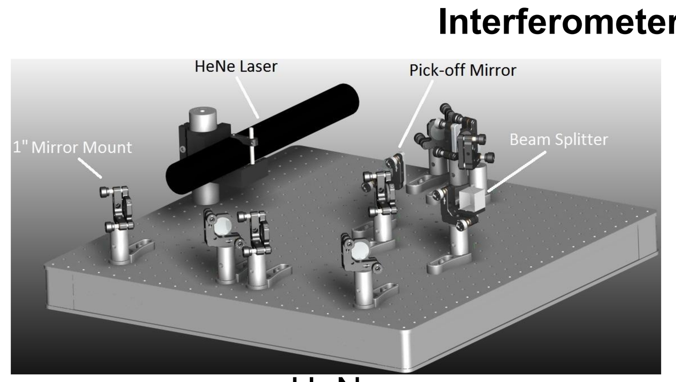
Electrostatic probes



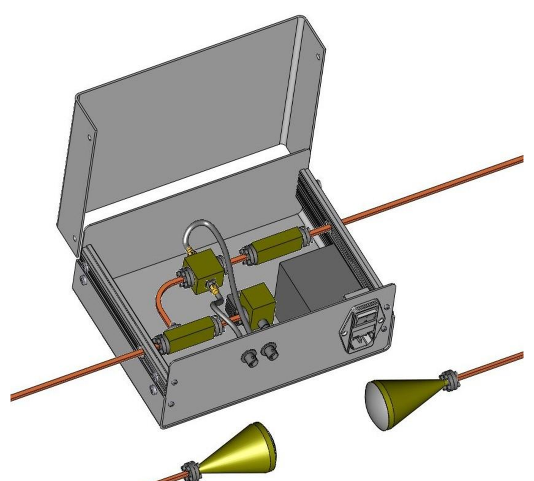
Retarding field analyzer (RFA)

Langmuir probe

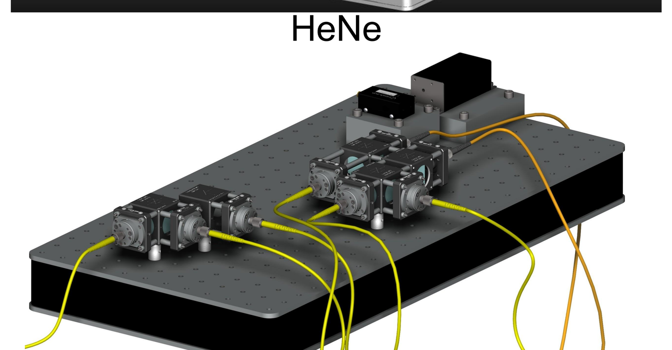
Interferometers



HeNe

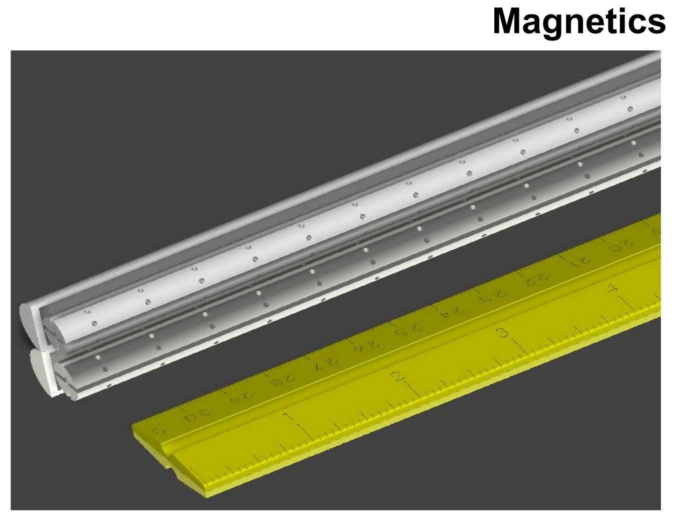


Microwave

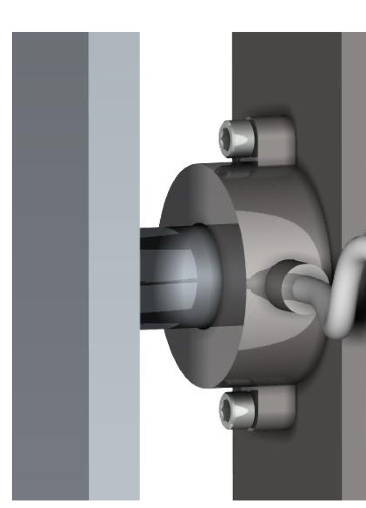


Fiber-coupled

Magnetics

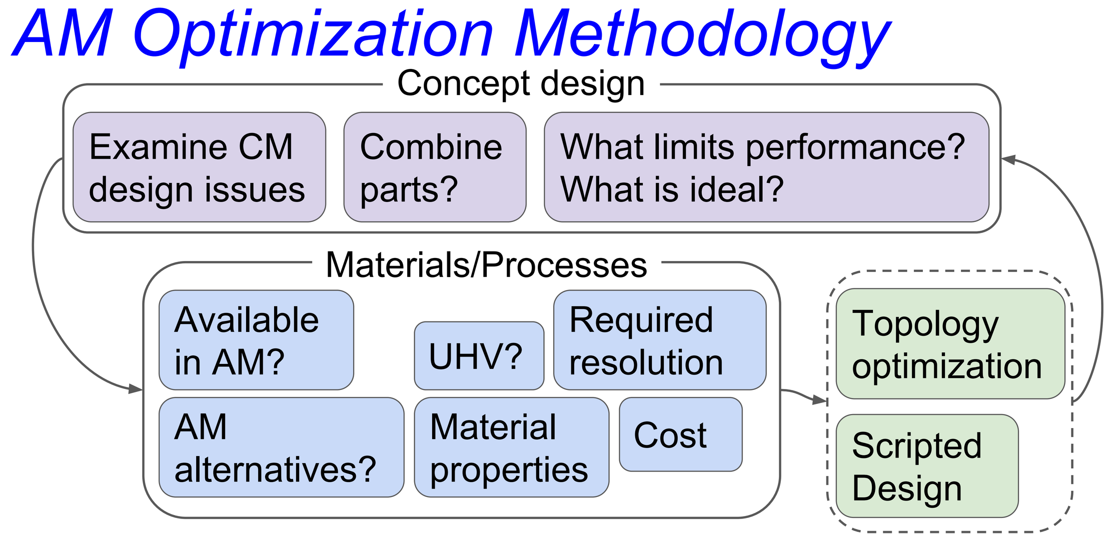


$\dot{B}$ coil array



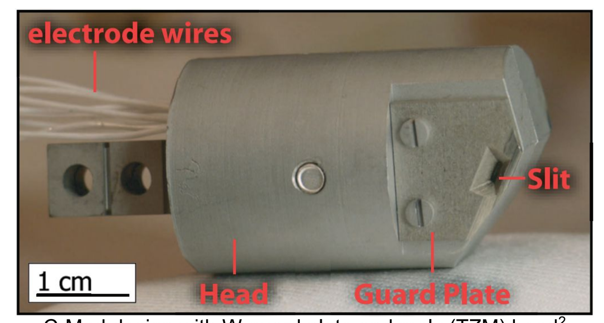
Mounted Rogowski coil

AM Optimization Methodology

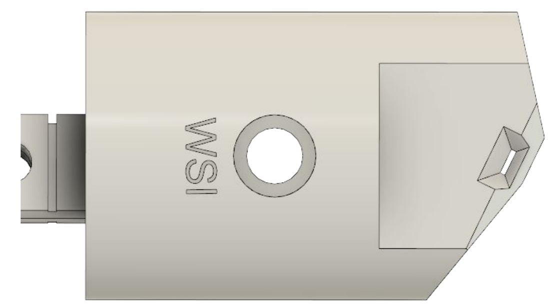


3D Printed RFAs for Alcator C-Mod

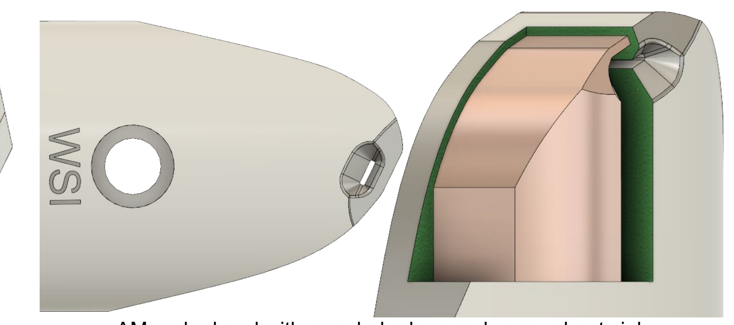
WSI is collaborating with Alcator C-Mod to test a set of AM tungsten (W) retarding field analyzer (RFA) probe heads, based on the state-of-the-art design by C-Mod researcher Dan Brunner and others[2]. The probe must reciprocate three times up to the LCFS during a shot, where it will encounter a heat flux of 0.4 GW/m^2. Pictured below are the C-Mod RFA and the three AM RFA probe heads that are currently being printed.



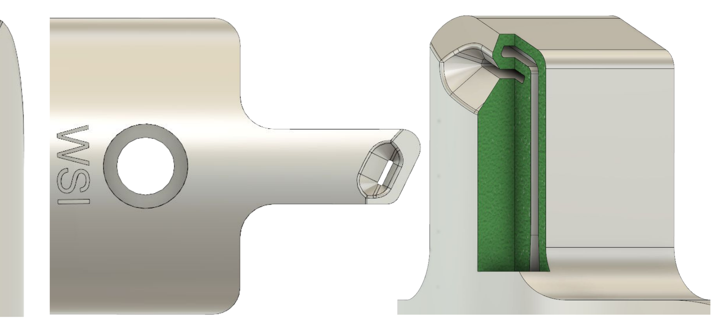
C-Mod design with W guard plate and moly (TZM) head[2]



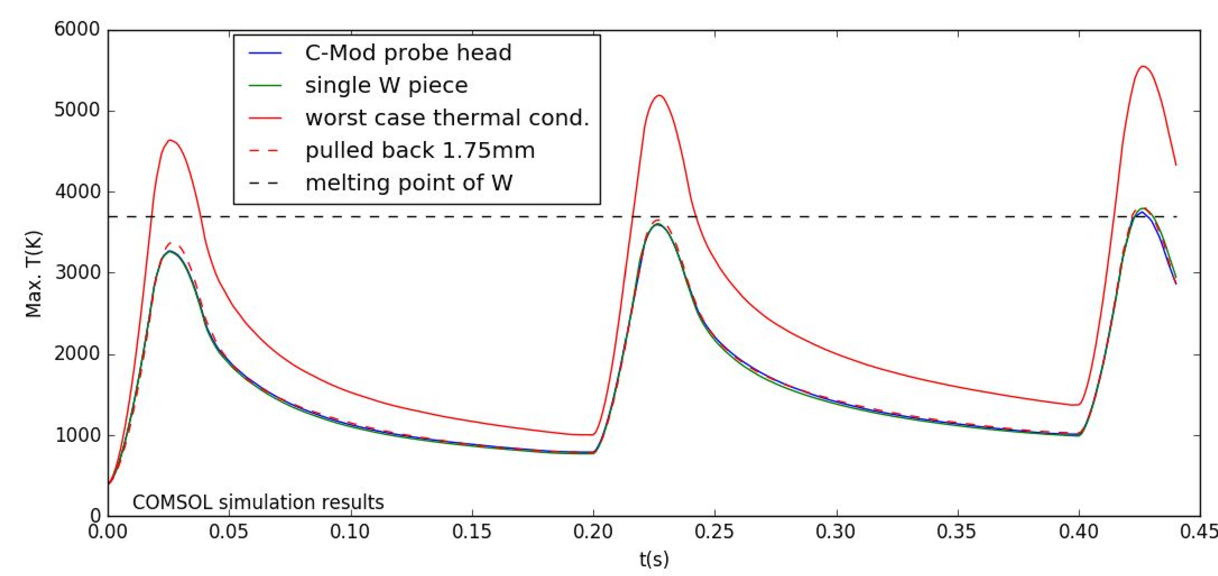
AM "single W piece" probe head



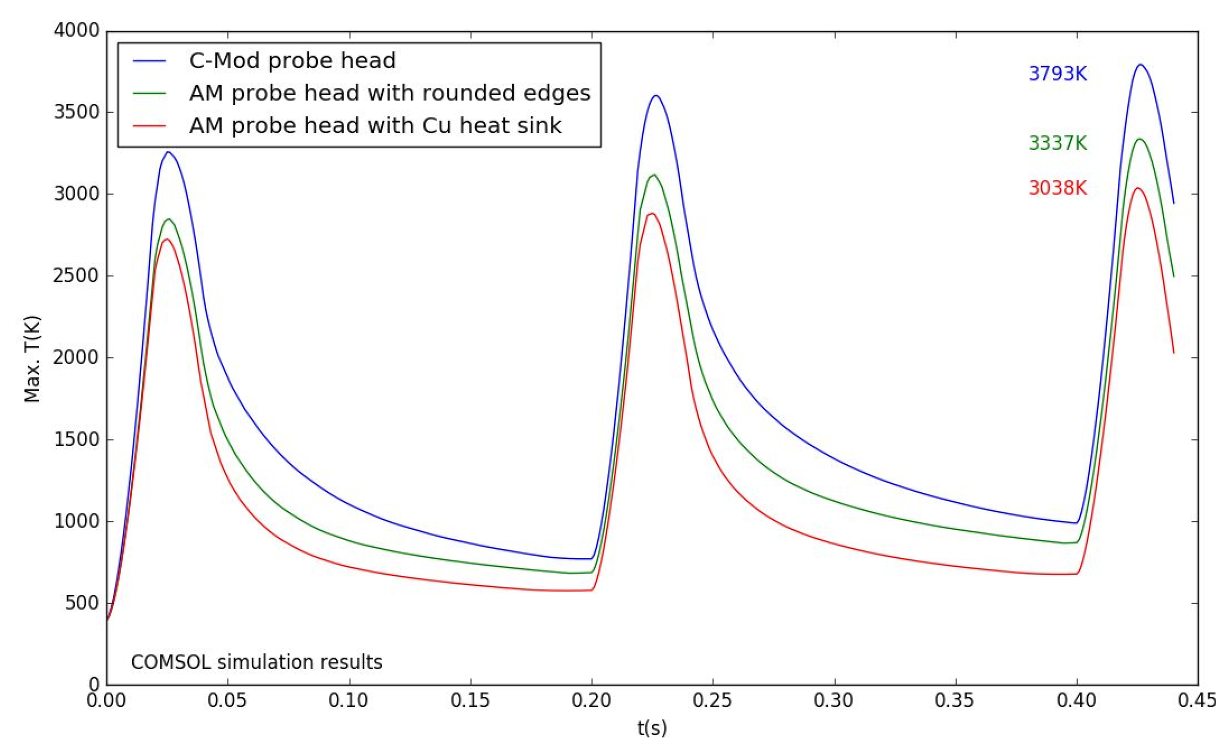
AM probe head with rounded edges and copper heat sink



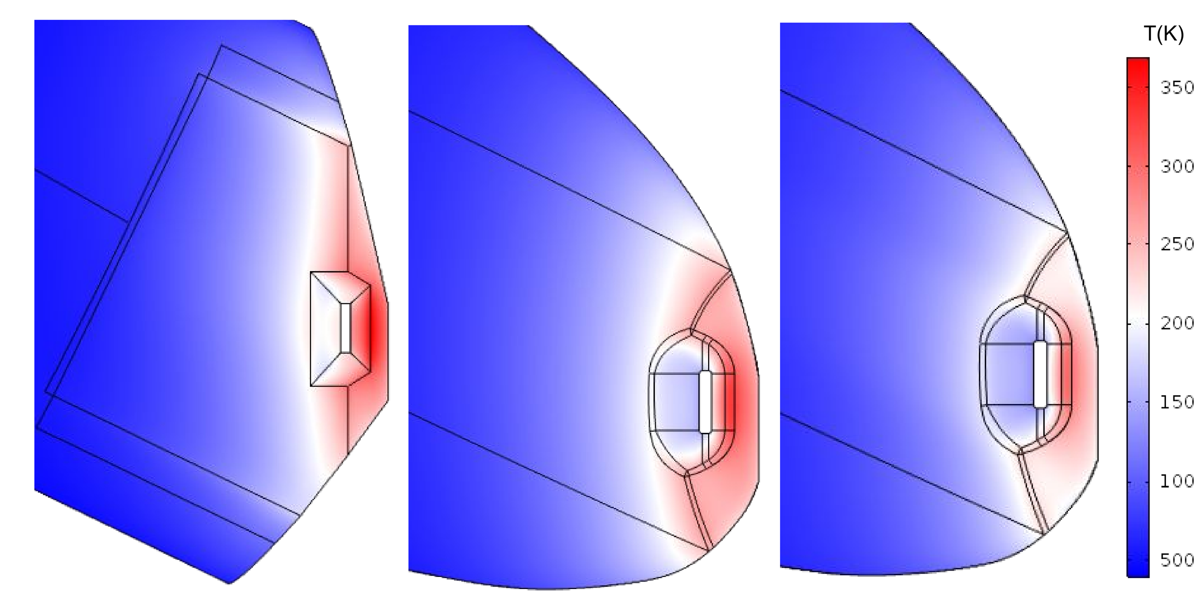
AM probe head with rounded edges and cooling channels



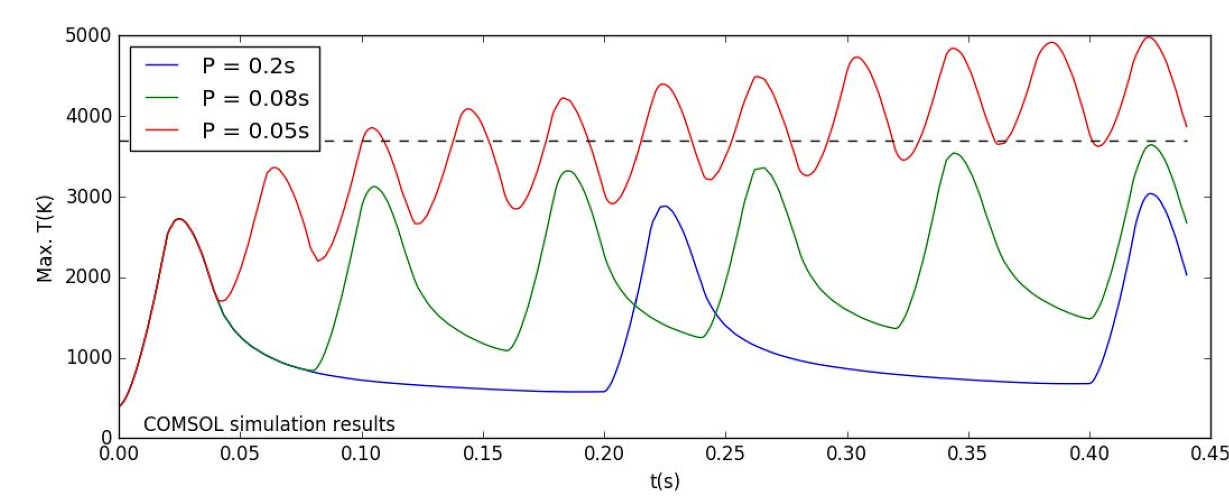
The thermal conductivity of AM tungsten may require the probe to be used a shallower depths.



Rounding the sharp corners may provide a 450K reduction in peak temperature, and the Cu heat sink may reduce that by another 300K. This improvement would increase the lifetime of the probe, allow it to be inserted up to 0.85mm further into the plasma, or allow the reciprocation period to be reduced to collect more data, as shown to the right.



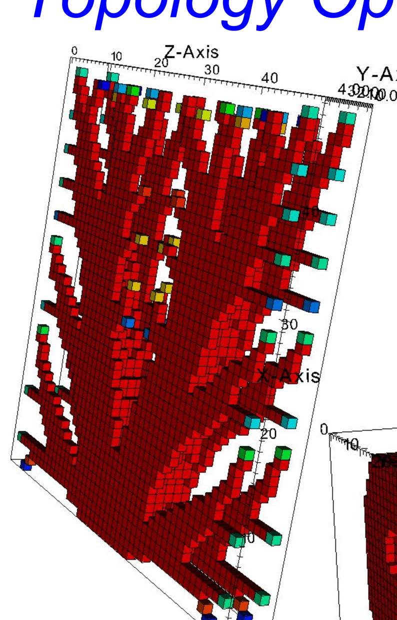
COMSOL simulation results showing the C-Mod RFA (left), RFA with rounded edges (center), and RFA with Cu heat sink (right) at peak temperature.

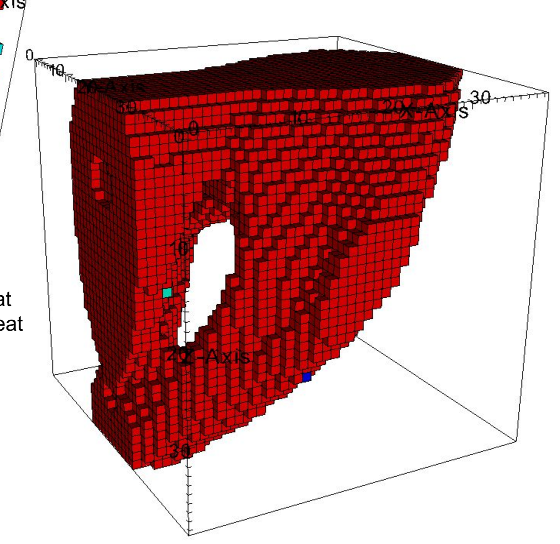


WSI and C-Mod intend to test the "single W piece" and heat sink probe heads before the planned shutdown of C-Mod in September. The probe head with cooling channels will not be tested on C-Mod, but will undergo helium flow testing to better assess its performance.

Topology Optimization

Topology optimization algorithms take inputs like heat flux or mechanical loads and produce an arbitrary shape that satisfies the requirements with the minimum material.





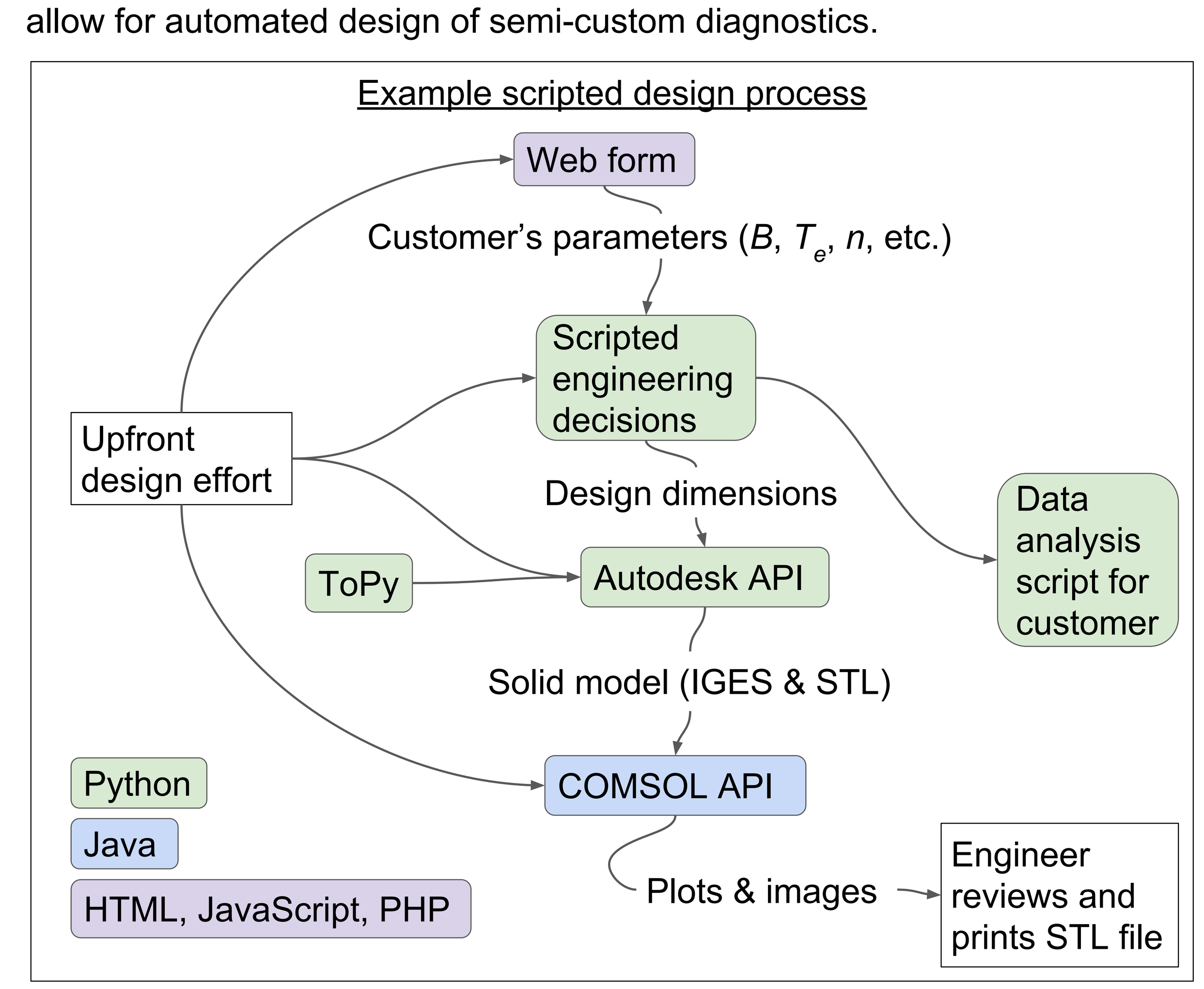
Shapes produced by ToPy that are optimized for maximum heat convection (above) and load support (right) with minimized material.

AM processes can print these arbitrary shapes at reduced weight and material cost.

Open source topology optimization packages like ToPy (written in Python) are readily available and improving rapidly.

Scripted Design

Solid modeling and FEA tools are now providing access to their underlying APIs, which can be used to perform design tasks from scripts. These can be combined with web pages, open source design tools, and other scripts to allow for automated design of semi-custom diagnostics.

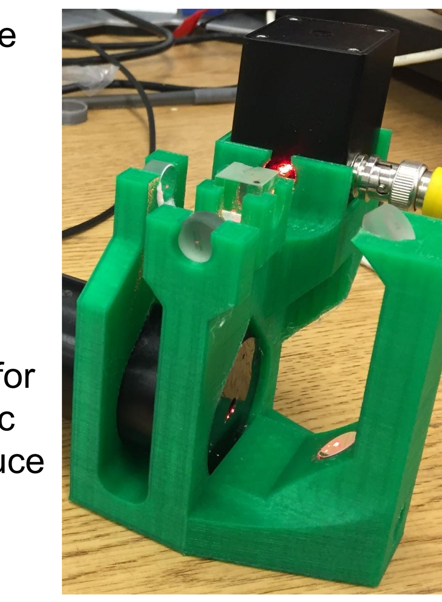


Pre-Aligned Monolithic Interferometer

Interferometers can take a long time and be very expensive to align.

WSI is exploring 3D printed, monolithic interferometers with the alignment built in. They just need to be aligned with the chamber.

Desktop printers are not accurate enough for this application, but laser sintering of plastic and metal is highly accurate and can produce parts with a wide range of stiffnesses.



Outgassing of AM Metals for UHV

Preliminary results of outgas testing of AM aluminum (ALSI10), stainless steel (PH1), and Inconel (IN718) are shown below. Further testing is required for a statistical assessment and to compare the AM metals to their conventional counterparts tested in the same chamber, but this data suggests the AM metals perform comparably. Additional AM materials, including alumina, will also be tested.

AM metal	Outgas rate (TorrL/cm^{2}s)	CM metal	Outgas rate (TorrL/cm^{2}s)[1]
AlSi10	2.19×10^{-8}	Al-6061	2.5×10^{-8} (10h)
PH1	1.29×10^{-8}	SS 304	8×10^{-11} (44h)
IN718	-6.30×10^{-9} **	IN625	2×10^{-9} (20h)

*reached lower final pressure than control

Impact on Cost

Scripted design significantly reduces the cost of Concept (CDR), Engineering (EDR) and Product Design Reviews (PDR) for a diagnostic by automating the engineering labor.

AM reduces the cost of fabrication, testing, and materials in many cases by reducing the number of components and using less material.

This table shows estimates of the costs of AM devices relative to CM devices for a given cost category.

Diagnostic	C_{Total}	C_{CDR}	C_{EDR}	C_{PDR}	C_{Fab}	C_{Test}	C_{Mat}
Magnetic field coil	0.06	0	0	0.1	0.1	0.1	0.1
Magnetic coil array	0.062	0	0	0.1	0.1	0.1	0.1
Rogowski coil	0.062	0	0	0.1	0.1	0.1	0.1
Calibration jig	0.14	0	0	0.1	0.5	0.1	0.1
Langmuir probe	0.35	0	0	0.1	0.5	1	0.9
RFEA	0.35	0	0	0.1	0.5	1	0.9
HeNe interferometer	0.71	0	0	0.1	0.9	0.2	0.9
CO2 interferometer	0.72	0	0.2	0.1	0.9	0.2	0.9
CO2 polarimeter	0.72	0	0.2	0.1	0.9	0.2	0.9
mm interferometer	0.73	0	0.2	0.1	0.9	0.2	0.9
Thomson Scattering	0.85	0.1	0.9	1	0.9	0.2	0.95
Inverse Compton	0.92	1	1	1	0.9	1	0.9
Spectrometer	0.49	0	0.1	0.1	1	1	0.95
Bolometer	0.59	0	0	1	0.7	1	0.95
Scintillator	0.33	0	0	0.1	0.1	1	0.9

Conclusion

- Fusion diagnostics are often difficult and expensive to manufacture
- Additive manufacturing has progressed rapidly in the last decade, allowing high-resolution printing in materials applied in fusion
- There remain many aspects to be assessed (primarily properties of AM materials), but AM may have the potential to significantly affect diagnostic cost and performance right now

Future Work

In the second year of Phase II, WSI plans to:

- Test additively-manufactured RFA probe heads on Alcator C-Mod
- Test a laser-sintered, monolithic interferometer
- Assess the mechanical strength, outgassing and thermal properties of AM tungsten and other materials
- Further explore multi-material printing, including with tungsten
- Further explore topology optimization and generative design
- Optimize several additional diagnostics for AM
- Deploy a scripted process that designs and simulates several diagnostics from user input via a web form

References

[1]E. A. Moshey, "A compilation of outgassing data in vacuum materials" PPPL Technical Report No. 82-001 Rev. A, 15 Feb. 1982
[2]Brunner, LaBombard, Ochoukov, & Whyte. (2013). Scanning retarding field analyzer for plasma profile measurements in the boundary of the Alcator C-Mod tokamak. *Review of Scientific Instruments, 84*(3), Review of Scientific Instruments, 2013, Vol.84 (3).