Additive Manufacturing of Plasma Diagnostics: Opportunities and Challenges of a New Paradigm in Experimental Plasma Science

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Outline of This Talk

- A brief description of additive manufacturing.
- Examples of 3D-printed equipment and diagnostics, inside and outside vacuum.
- Electroforming of printed parts to improve vacuum compatibility.
- Facility to test equipment under vacuum conditions: heat loads, plasma-facing.
- Work in progress.

Additive Manufacturing – 3D printing

- Plastics most common, but able to print in elastomers (with/ without overmolding on hard plastics), ceramics, and metals.
- Already in many universities for student projects, research labs are taking interest.
  - NASA, ESA (AM Aimed at Zero Waste and Efficiency, AMAZE) project), funding research on AM.

- Reduction of costs:
  - Reduce manufacturing time.
  - Complex shapes.
  - Monolithic designs.
- Requires shift in design paradigm

Hinges for the Airbus A320. Conventional (background), 3D-printed (foreground).

Common types of AM plastic/resin printers

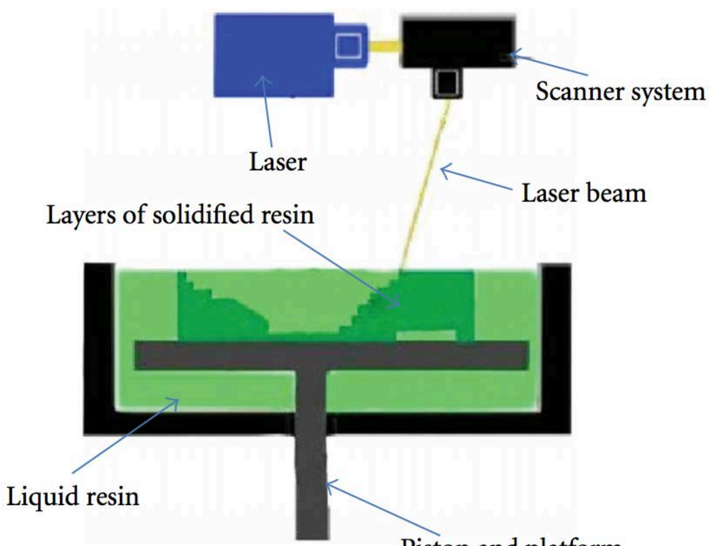


FIGURE 5: Stereolithography.

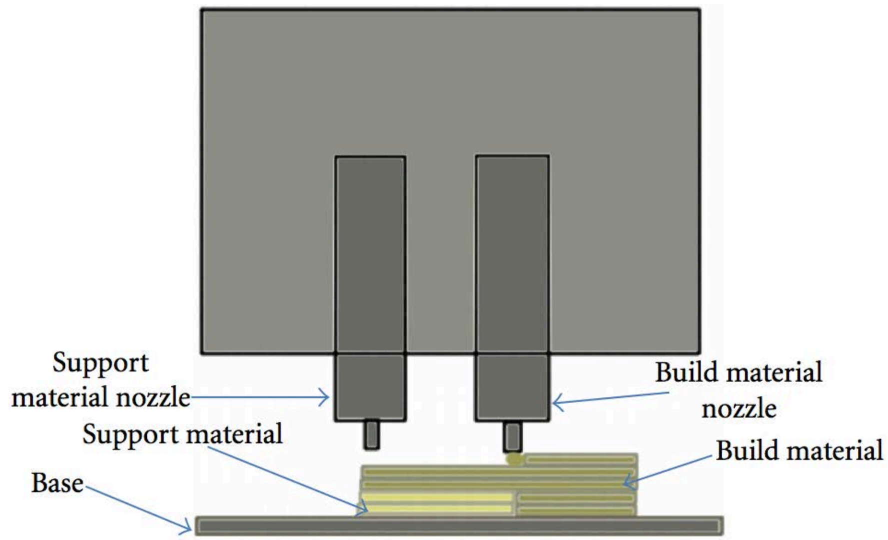


FIGURE 8: Fused deposition modeling.

- Fused deposition of plastics is perhaps the most common type of 3D printer, as printers and materials can be cheap.

K. V. Wong and A. Hernandez, ISRN Mech. Eng. **2012**, 208760 (2012).

Common types of metal AM printers

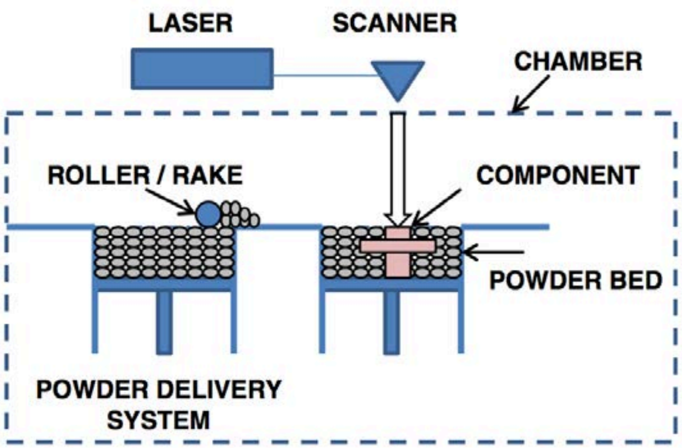


Fig. 1 Generic illustration of an AM powder bed system

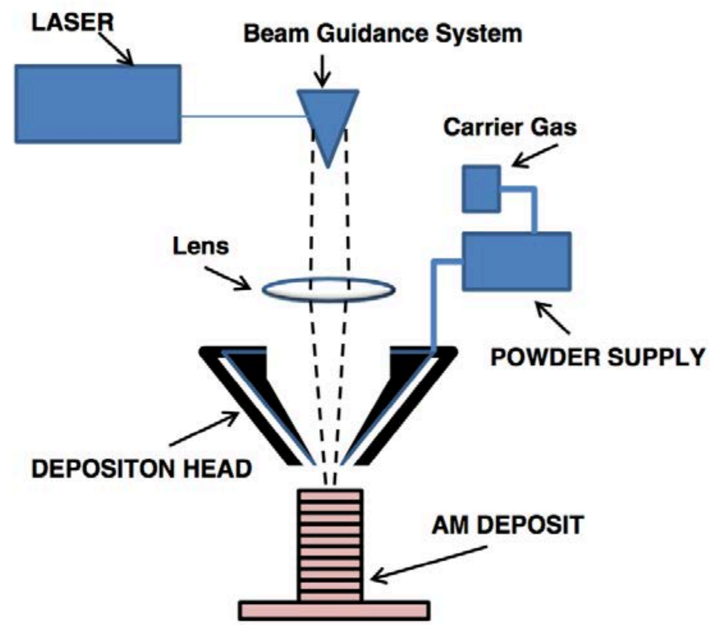


Fig. 2 Generic illustration of an AM powder feed system

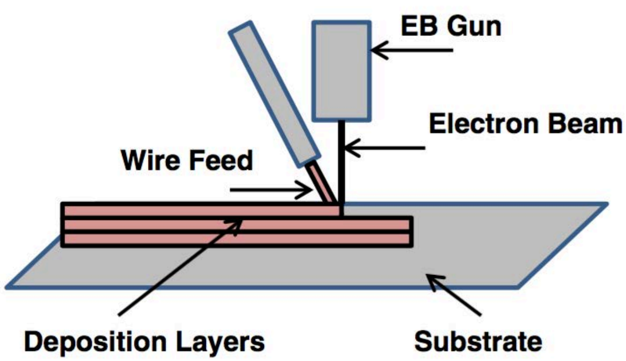


Fig. 3 Generic illustration of an AM wire feed system

W. E. Frazier, J. Mat. Eng. Perform. **23**, 1917 (2014).

AM Metals/Ceramics better suited for plasma-facing

- Possible to AM with ceramics, but also challenging, and metals and ceramics limited.

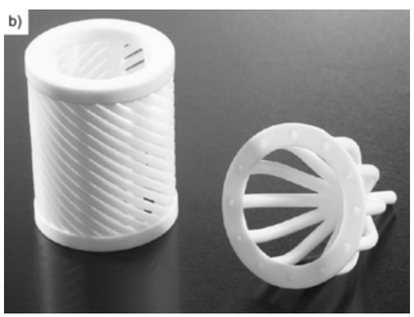


Image from Ref. 1.

Overview of AM processes to shape ceramics.[2]

classified by ISO/ASTM								not (yet) classified by ISO/ASTM	
Single step		Multi-step							
Directed energy deposition	Powder bed fusion	Vat photo-polymerization	Material jetting	Material extrusion	Sheet lamination	Binder jetting	Electro-phoretic deposition	Electro-photographic printing	

	Powder bed fusion														
multi-step / single step	single step												multi-step		
binding mechanism	full melting			partial melting					solid state sintering	chemically induced binding			partial melting		gelling
powder deposition mechanism	conven-tional	slurry coater	aerosol assisted spray deposition	conven-tional	slurry coater	slurry sprayer	ring blade	electro-phoretic deposition	conven-tional	conven-tional	slurry coater	ring blade	conven-tional	slurry coater	slurry coater

Selected alloys used in commercial AM processing[2]

Titanium	Aluminum	Tool steels	Super alloys	Stainless steel	Refractory
Ti-6Al-4V	Al-Si-Mg	H13	IN625	316 and 316L	MoRe
ELI Ti	6061	Cermets	IN718	420	Ta-W
CP Ti			Stellite	347	CoCr
γ-TiAl				PH 17-4	Alumina

[1]J. Deckers, J. Vleugels, and J. –P. Kruth, J. Ceram. Sci. Tech. **05**, 245 (2014).

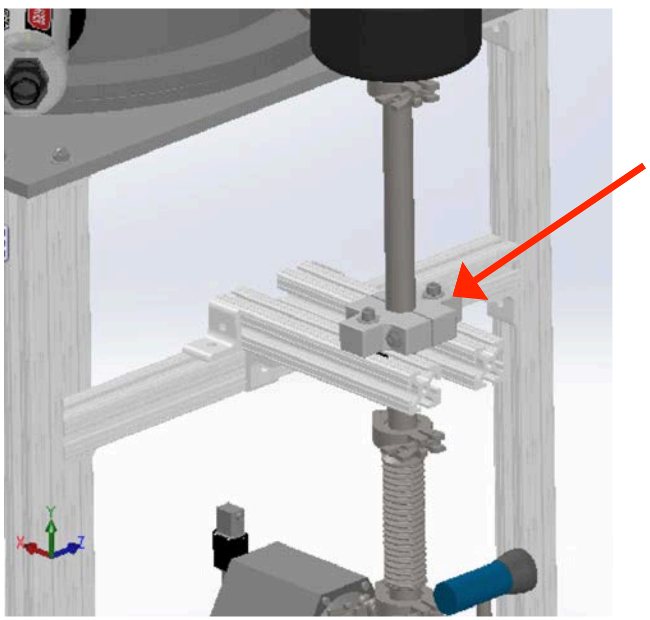
[2]W. E. Frazier, J. Mat. Eng. Perform. **23**, 1917 (2014).

Additive Manufacturing of Plasma Diagnostics

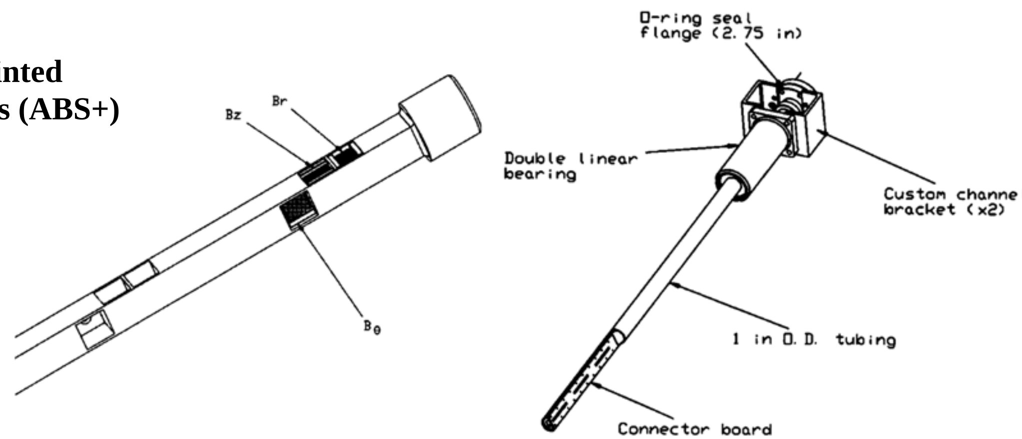
- Many plasma diagnostics well developed: physical principles well understood.
- But still expensive and time-consuming to build:
  - Large budget portion of plasma experiments is in diagnostics.
  - Usually have to fit particular experiment, and even particular location (port) within a vessel.
- Two main categories of components for plasma diagnostics: *in vacuum, external to vacuum chamber*.
  - AM can help reduce costs and innovate in both categories.

External to vacuum: AM can replace many parts in plasma diagnostics

- Parts that are not subject to high heat loads or high stresses, are easy to implement with AM.
- Provided printer has high enough resolution, can save in cost and time from design to realization.
- Electroforming can add stiffness at reduced weight for plastics



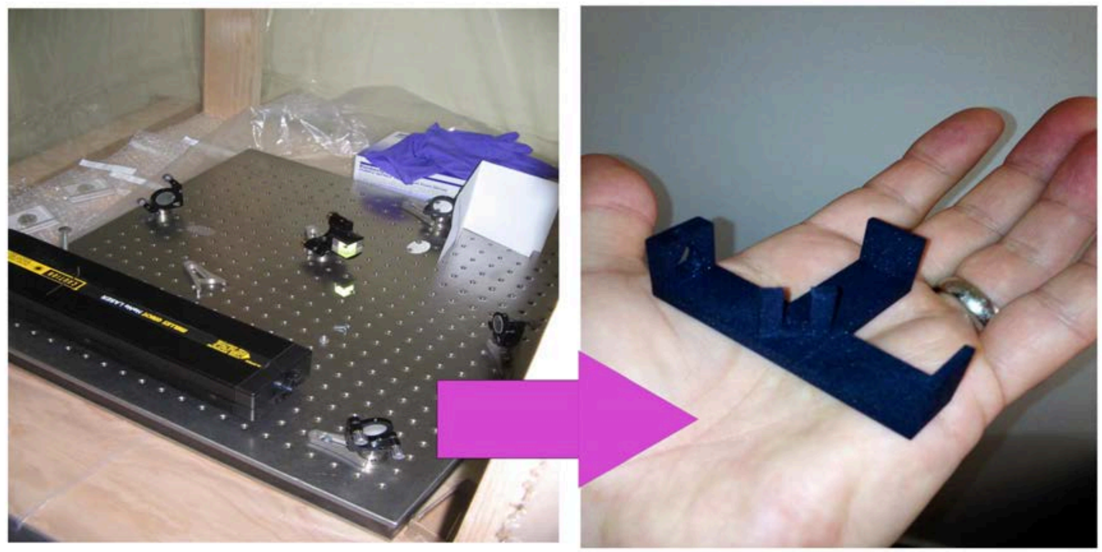
3D printed clamps (ABS+)



C. A. Romero-Talamás, P. M. Bellan, and S. C. Hsu, Rev. Sci. Inst. 75, 2664 (2004)

External: allow a change in design/build paradigm

- Replacing traditional diagnostics (or at least parts external to vacuum) with ones enabled by AM methods opens new paradigms.
- Compactness, cost.

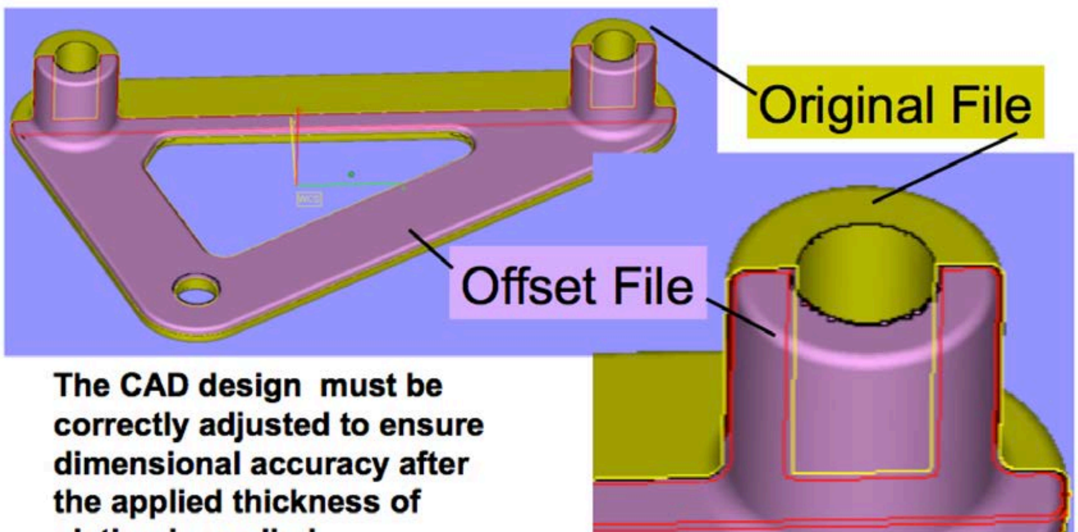


HeNe Interferometer built on a 23” optical board (left). Equivalent interferometer built using AM. Courtesy of Simon Woodruff, Woodruff Scientific.

- Still an issue: Print precision, surface quality, stiffness, vibration.
- Post-print processing? Surface treatment.

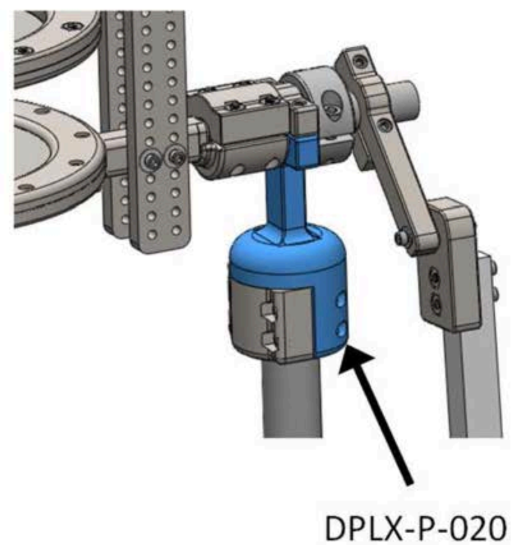
Electroforming of plastics for vacuum compatibility

- In collaboration with RepliForm, learning to design components for electroplating of ABS plastic.



The CAD design must be correctly adjusted to ensure dimensional accuracy after the applied thickness of plating is applied

Image courtesy of RepliForm



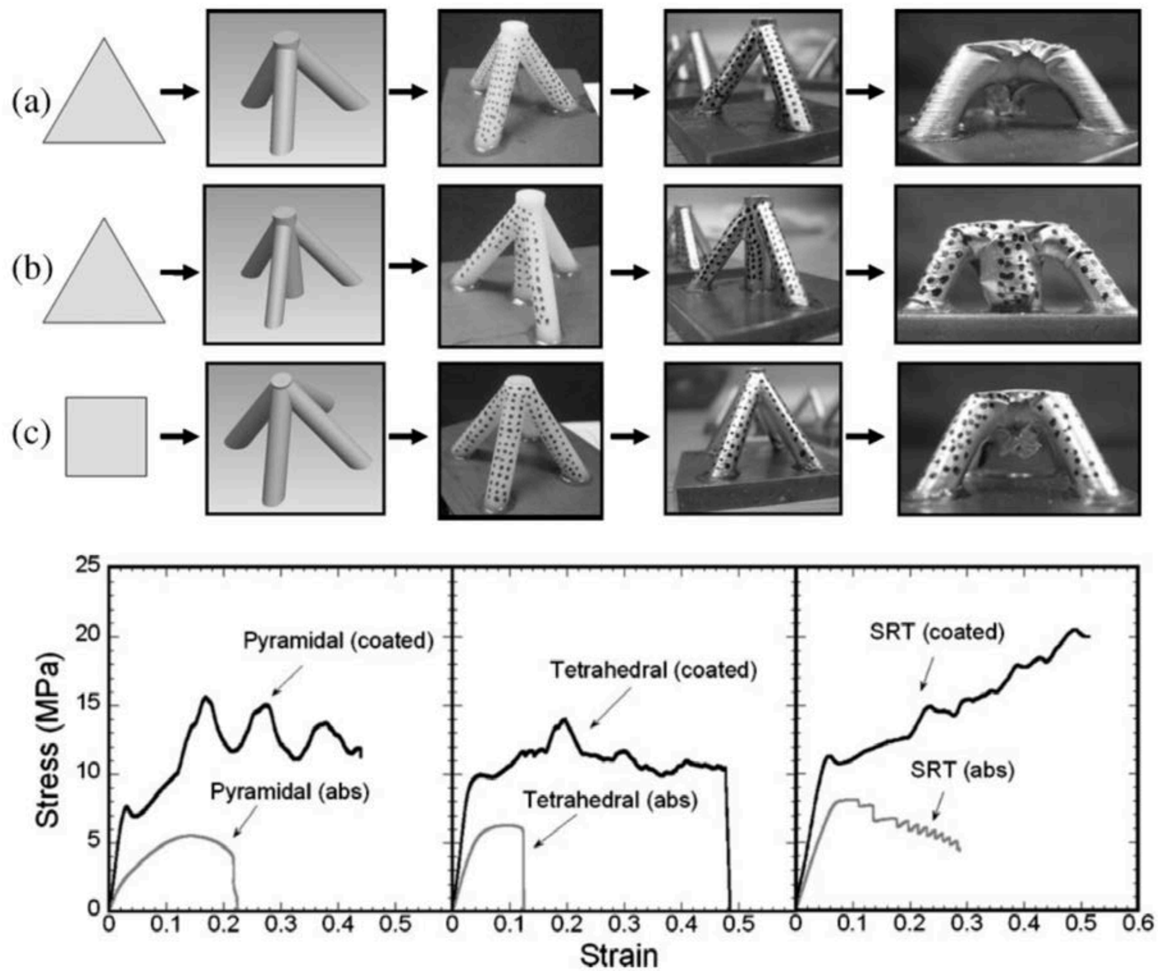
Coating thickness vs Application

- Purpose of coating*
  - EMI 0.002" (50 μm) (nominal)
  - Cosmetic 0.005-0.008" (125-200 μm)
  - Environmental Barrier 0.002-0.004" (50-100 μm)
  - Structural 0.001-0.016" (25-400 μm)
  - Heat conduction 0.001-0.012" (25-300 μm)
  - Abrasion 0.002" (50 μm)
  - Electric Conduction
- The purpose needs to be clearly defined BEFORE parts are 3D printed.

* Data from RepliForm

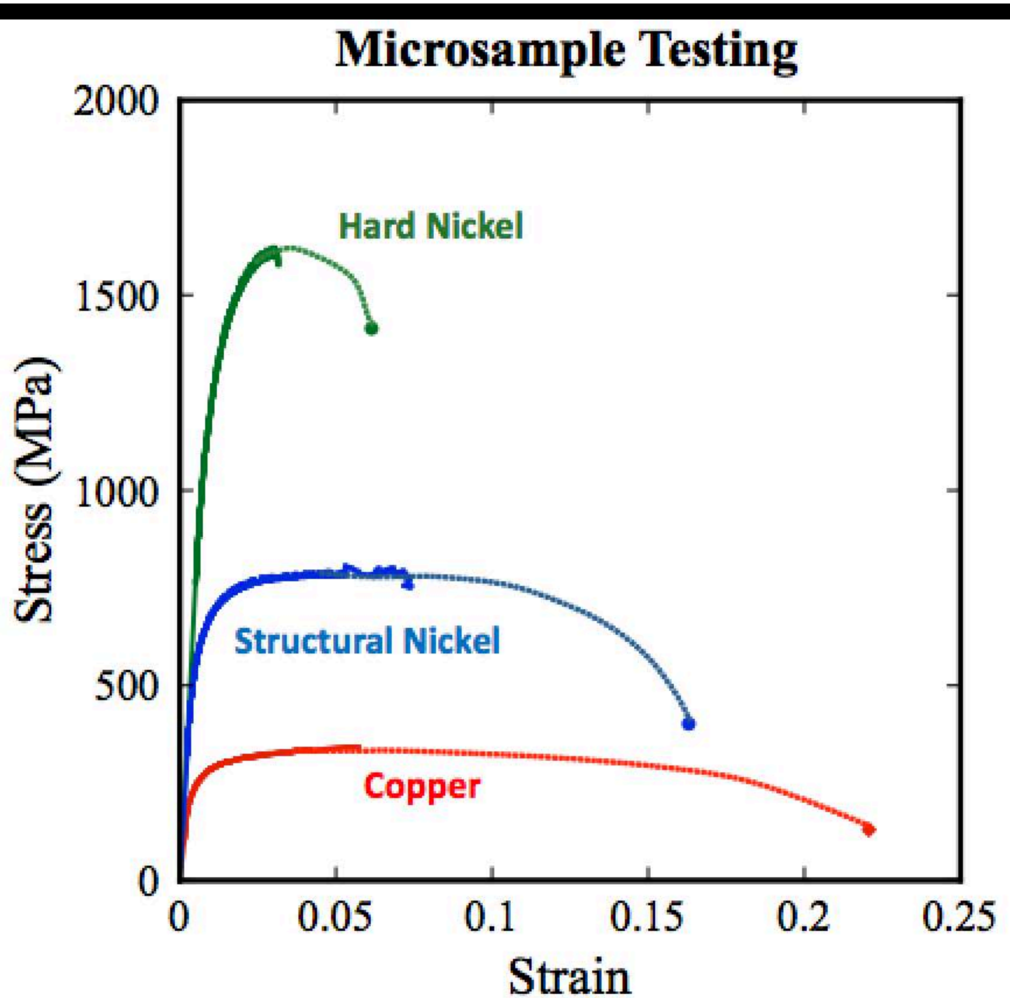
Mechanical properties of electroforming on ABS+

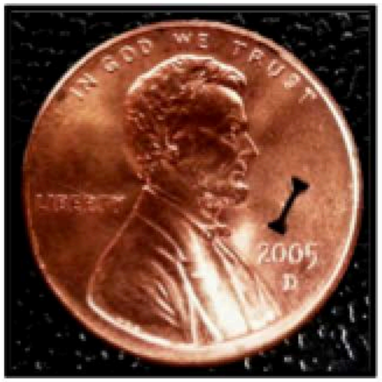
- Coating of Cu-Ni investigated in core topologies.
- Strength and stiffness dramatically increased with coatings.
- Toughness (amount of energy absorbed before failure) also improved



S. Markula, S. Storck, D. Burns, and M. Zupan, Adv. Eng. Mater. **11**, 56 (2009)

Mechanical properties of coating material only

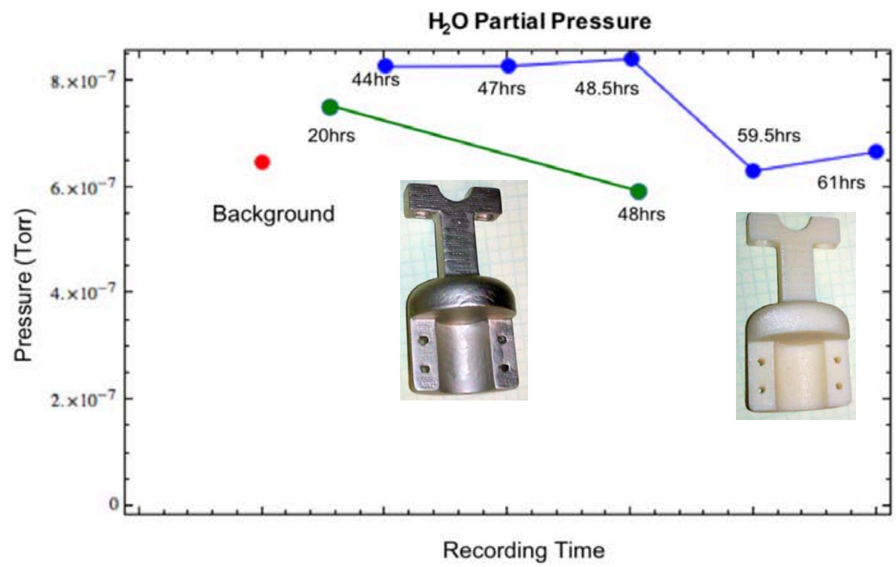




S. Storck, and M. Zupan (UMBC), Investigation into Copper and Nickel Electrodeposition using Microtension Samples and Microstructure Characterization, Manuscript in Preparation.

What about electroformed AM plastics for vacuum?

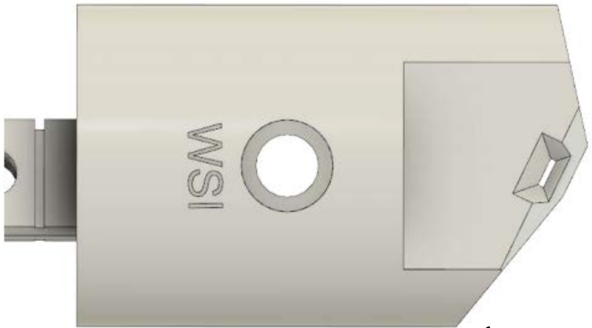
- AM parts made of plastic and metal-coated have improved vacuum compatibility (w.r.t. plastic alone), but not much better heat resistance.
- However, over many vacuum-air cycles metal coating detached from plastic.
  - Created a virtual leak the following cycle from the air trapped between the metal coating and plastic.



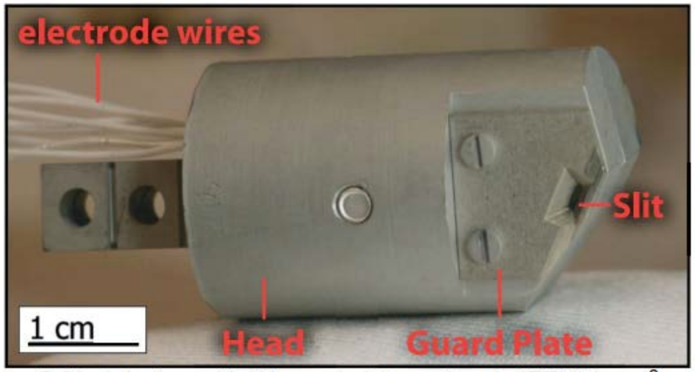
- Electroformed part (green line) never reached below 10^{-7} Torr and eventually increased outgassing from detaching.

Metal for vacuum and plasma facing AM parts

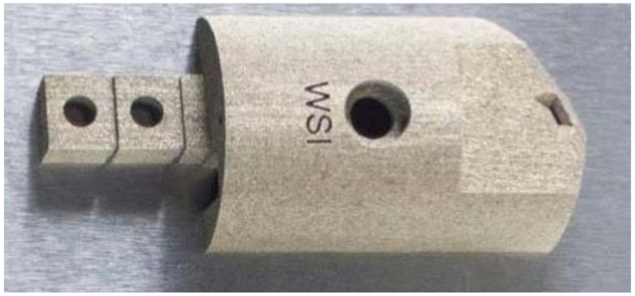
- Case study: collaboration between Woodruff Scientific and Alcator C-Mod to install an AM Retarding Field Analyzer (RFA) probe.



AM "single W piece" probe head[1]



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



- AM probe similar to CM probe for comparison.

[1]M. Quinley, D. Brunner, A. Card, et al., APS-DPP 2016, Abstract BAPS.2016.DPP.NP10.173

[2]D. Brunner, B. LaBombard, R. Ochoukov, and D. Whyte, Rev. Sci. Instr. **84**, 033502 (2013).

AM probe eventually failed

- AM Probe outgassed for longer; after baking ok.
- After about 10 discharges, probe melted and sprayed tungsten into plasma (causing disruption).
- Lower thermal conductivity, surface roughness (E-field concentration and high heat) may be to blame.

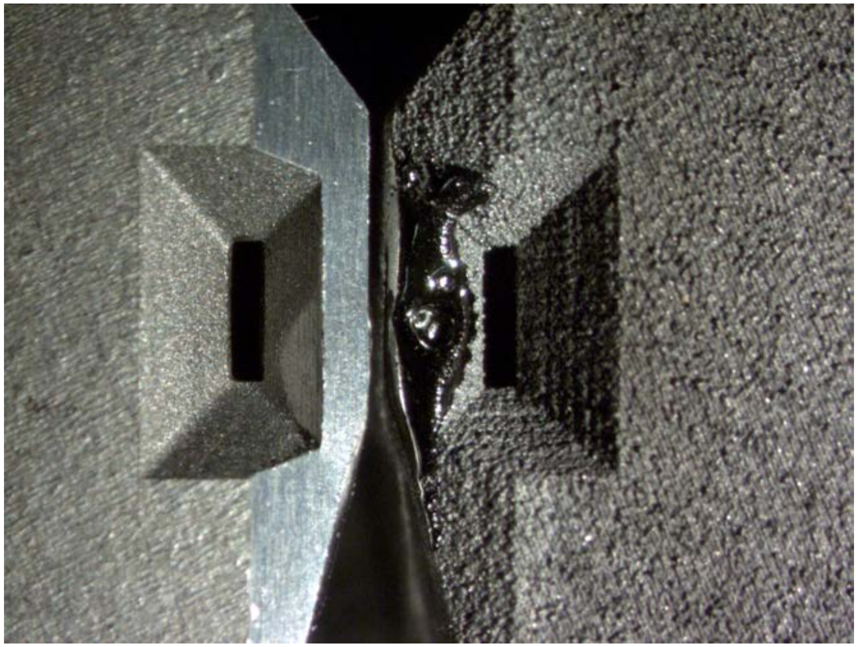


Image by D. Brunner (MIT)

RFA Probes: CM (left), AM (right).

Most pressing: Outgassing of metal AM parts

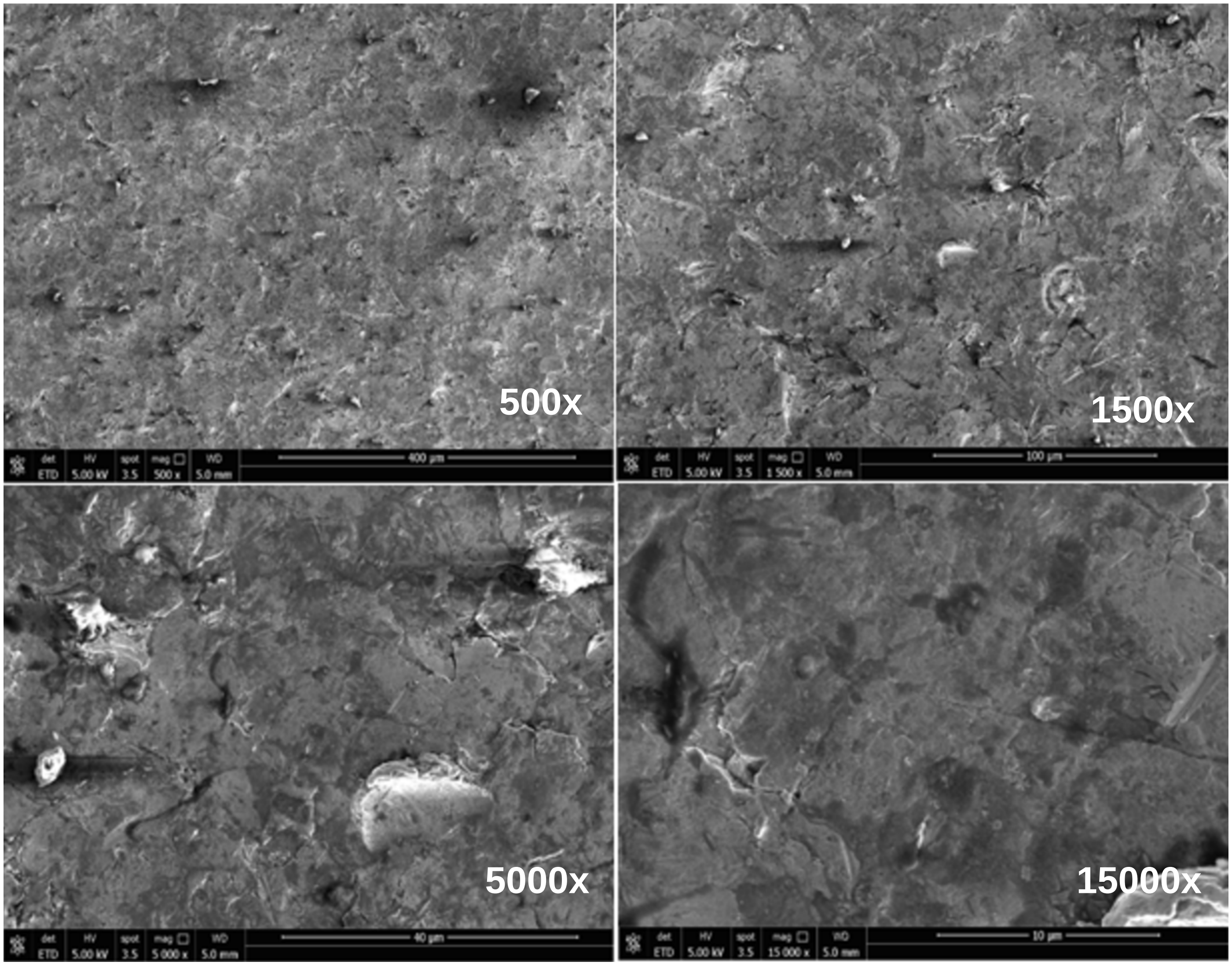
- The AM metal printing inherently lowers density by leaving voids in material, where gas can be trapped, absorbed.
- Surface roughness leads to adsorbed (water, etc.).
- We've investigated outgassing for other materials, and compared them to similar CM materials, with mixed results (see below).

AM metal	Outgas rate (TorrL/cm^2s)	CM metal	Outgas rate (TorrL/cm^2s)[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)

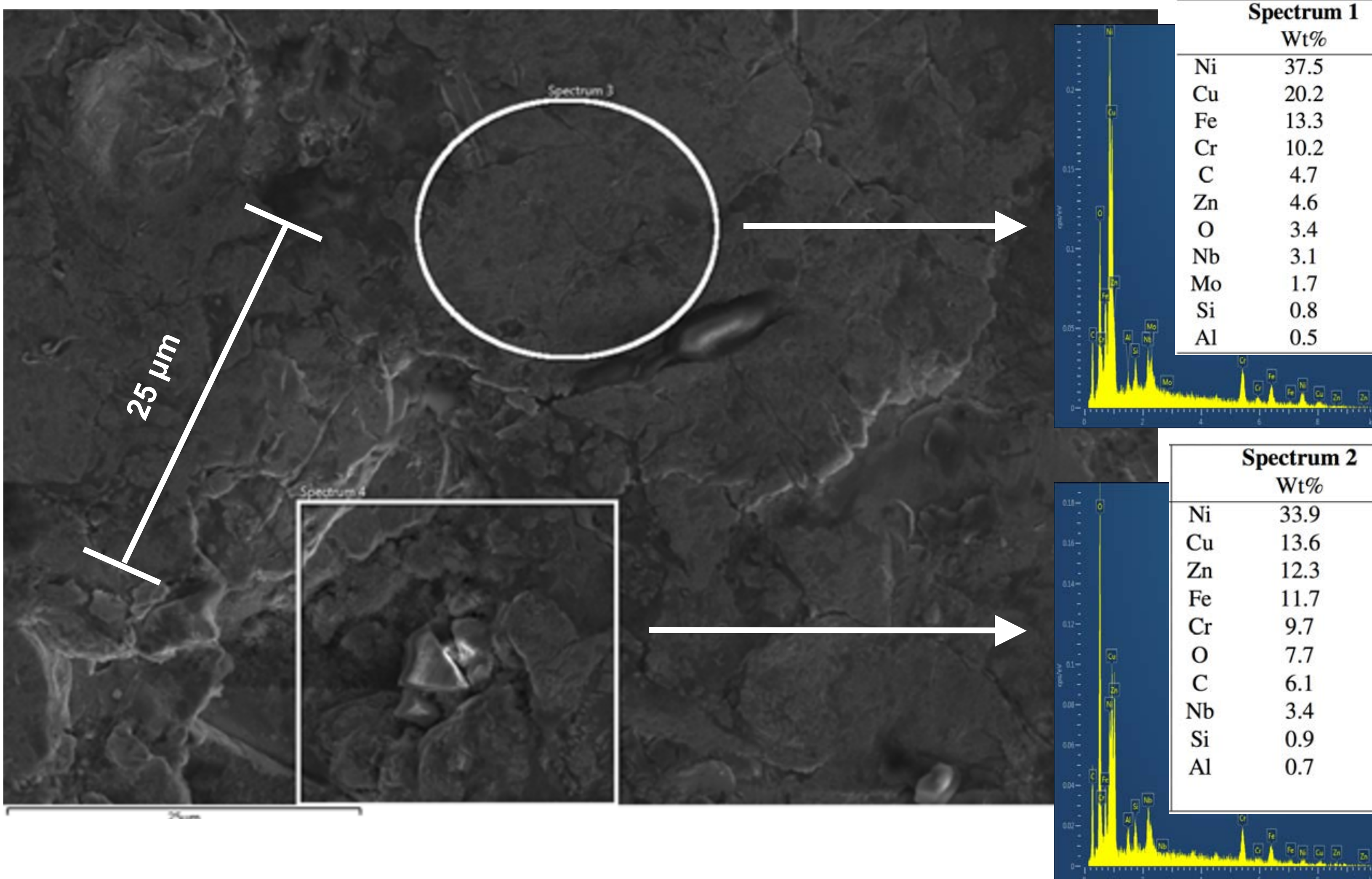
*reached lower final pressure than control

[1]E. A. Moshey. Technical Report No. 82-001 Rev. A, PPPL, 15 Feb. 1982.

IN718 Micrograph using SEM



X-ray spectra of IN718: surface anisotropy



Spectrum 1	Wt%	σ
Ni	37.5	2.6
Cu	20.2	1.4
Fe	13.3	1.3
Cr	10.2	0.8
C	4.7	0.4
Zn	4.6	0.7
O	3.4	0.3
Nb	3.1	0.5
Mo	1.7	0.5
Si	0.8	0.1
Al	0.5	0.1

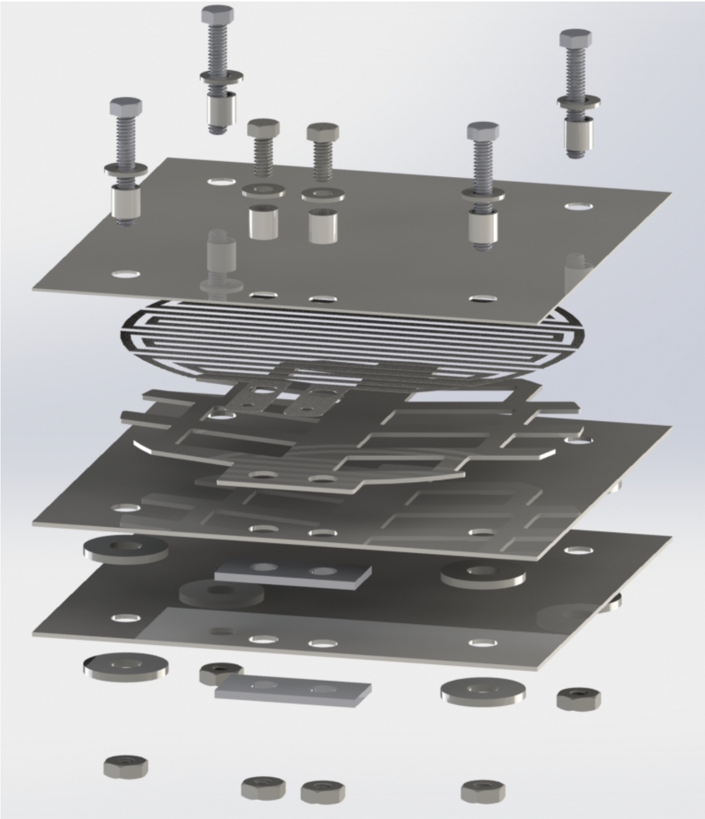
Spectrum 2	Wt%	σ
Ni	33.9	2.1
Cu	13.6	1.2
Zn	12.3	0.8
Fe	11.7	1.3
Cr	9.7	0.8
O	7.7	0.4
C	6.1	0.5
Nb	3.4	0.5
Si	0.9	0.1
Al	0.7	0.1

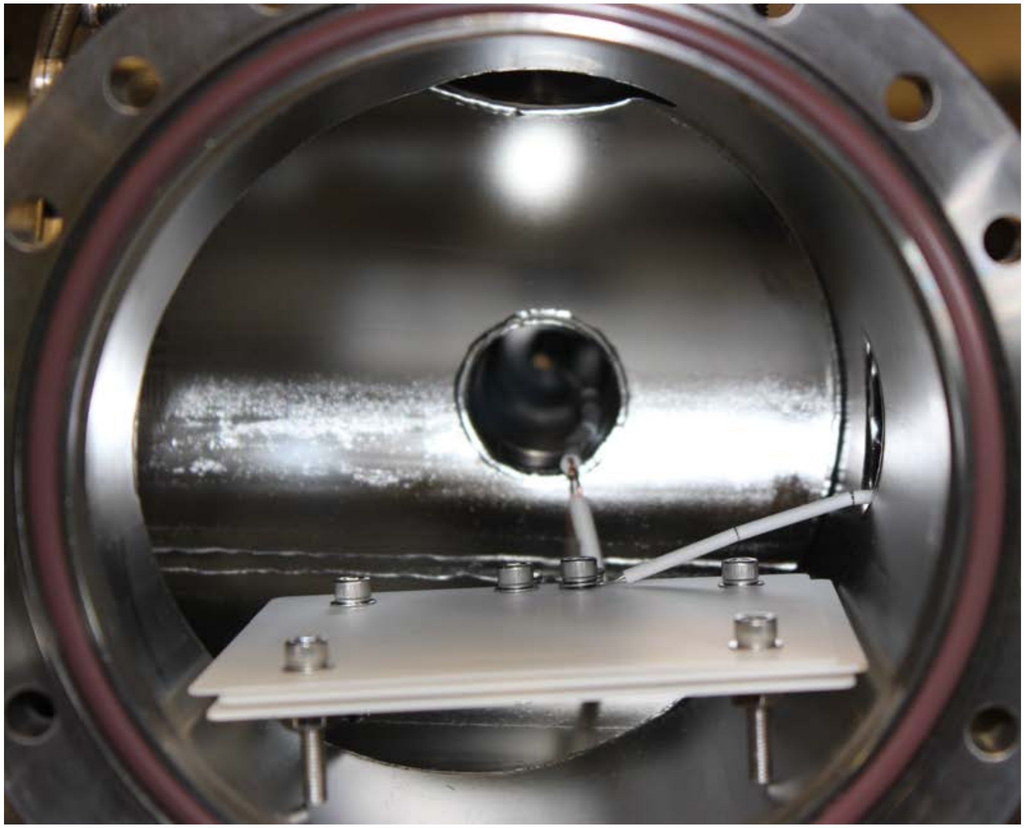
IN718 Surface elements lead to water adsorption

- IN718 surface surface smoother than RFA probe above.
- High heat during laser sintering leads to non-uniform component concentrations at the surface (and probably throughout the volume).
- Porosity/cracks also an issue for outgassing.
- Plan on testing IN718 (and other AM parts) with heater element inside vacuum to observe outgassing history.
  - Unheated decreases pressure, but heated should increase first and eventually decrease.

Heater plate to accelerate outgassing

- Heater plate had to be designed so the setup itself wouldn't outgass or trap air during venting cycles.





Needs: standards and testing for AM parts/ materials for plasma diagnostics

- Outgassing database of AM parts not helpful unless process standardized (printer type, beam energy, scan speed, material, etc.).
- Need better control of printing process: plasma community needs access to metal/ceramic printers for research.
- Explore post processing: surface finishing, coatings.
- Design optimization based on physics/engineering requirements[1].
- Plasma facing testing at relevant ion, neutron energies and fluxes.
  - Need neutronics calculations/experiments to reduce activation in AM materials and coatings.

[1]J. Stuber, K. Chung, et al.,APS-DPP 2016, Abstract BAPS.DPP.2016.NP10.172

End of Presentation