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HYBRID METALIZED POLYMER CORE HARDWARE DESIGN AND INITIAL RESULTS FOR PROTOTYPE MASS OPTIMIZED PULSED POWER HARDWARE

Presented by Charles Rose

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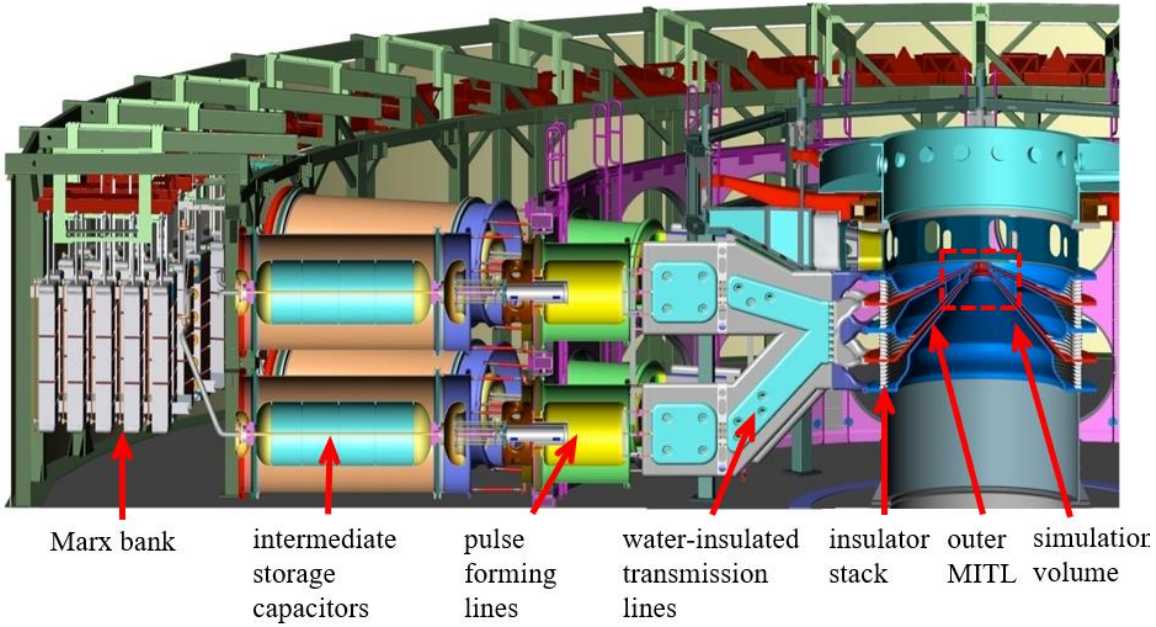
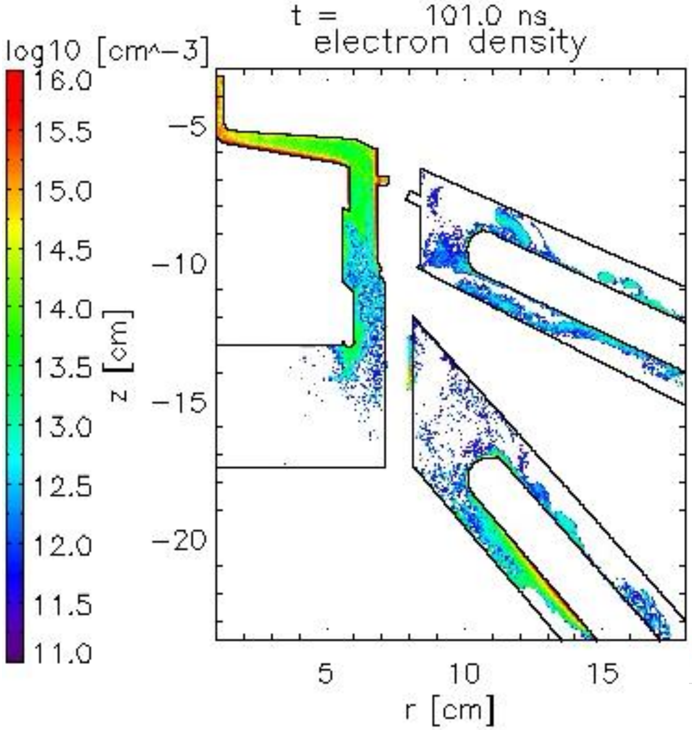
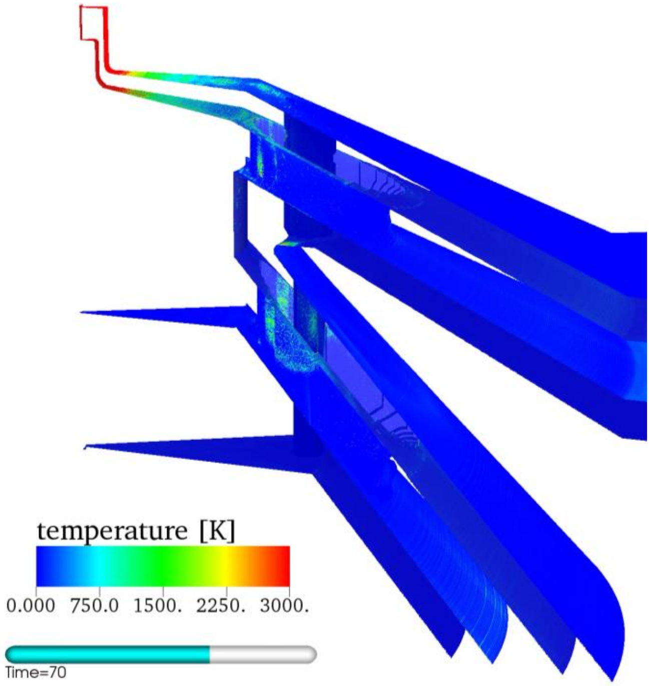
MOTIVATION

Traditional power flow hardware design/manufacture does not meet requirements for next generation pulsed power (**NGPP**). To meet mission requirements we must design for operation at considerably harsher conditions than Z-today (>2X capability) which delivers on the order of ~ 20 MA over ~ 100 ns, at ~ 80 TW of electrical power.

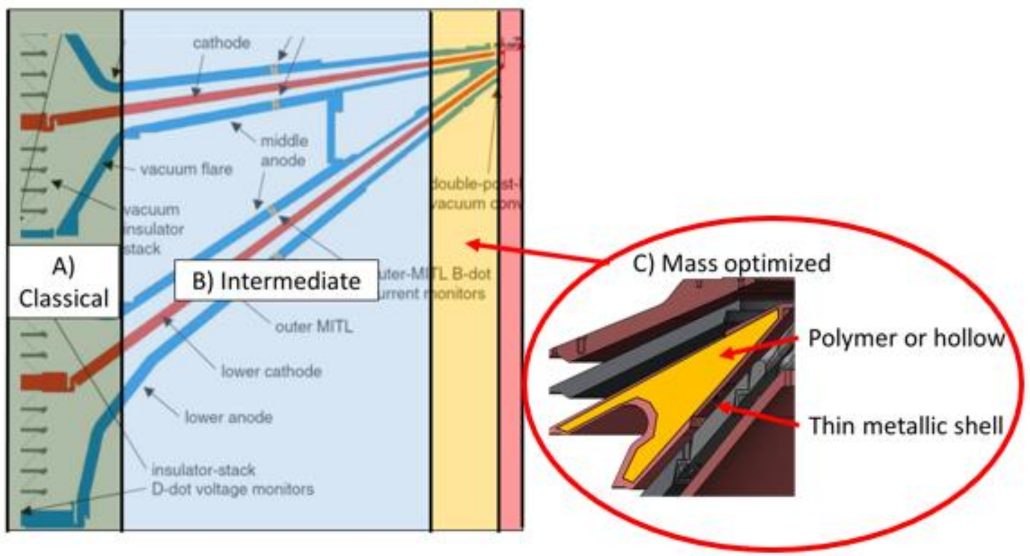






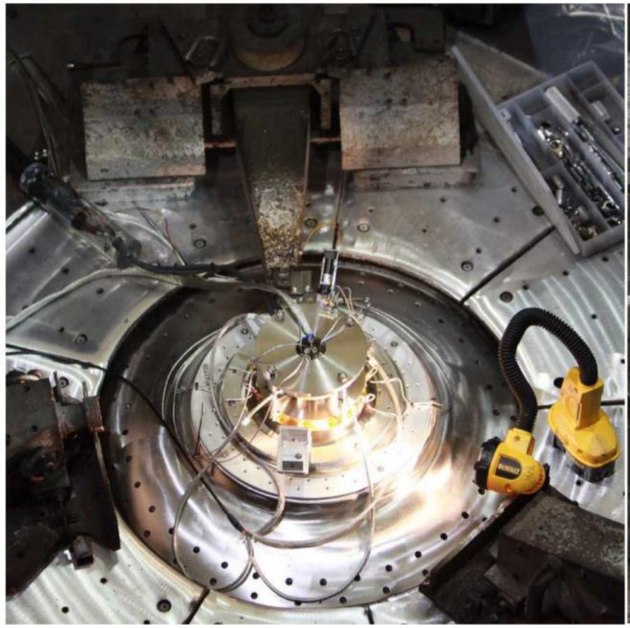
Images/simulation credit: Nichelle Bennett

DEBRIS MITIGATION IS A MAJOR LIMITATION FOR NGPP



Large amounts of debris are generated every shot. Given NGPP will be greater than 2X current delivery the anticipated “explosion” radius is expected to double generating potentially untenable volumes of debris.

Pre-shot photo of MagLIF load hardware

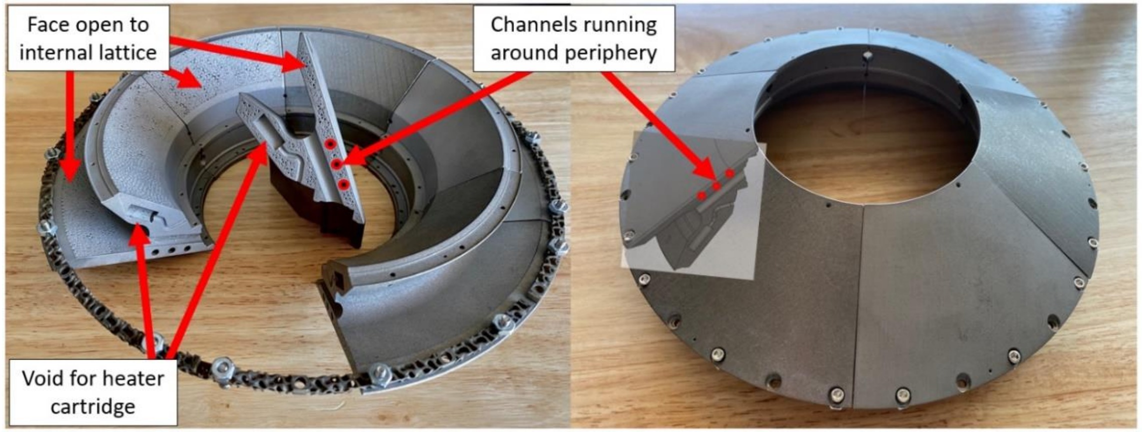


Post-shot photo of damage

Images credit: SAND2016-9145PE

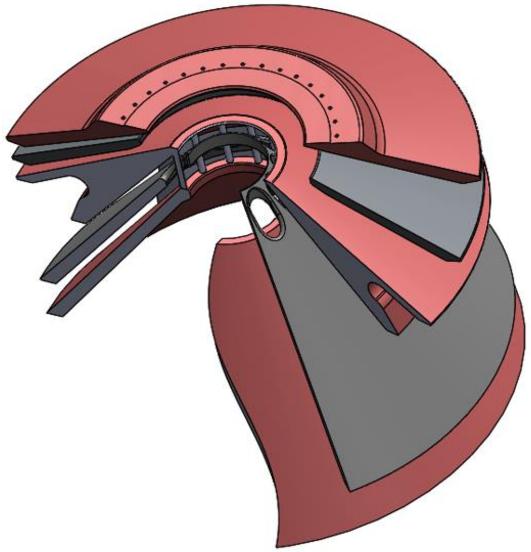
➔ Solution direction is to dramatically mass optimize hardware

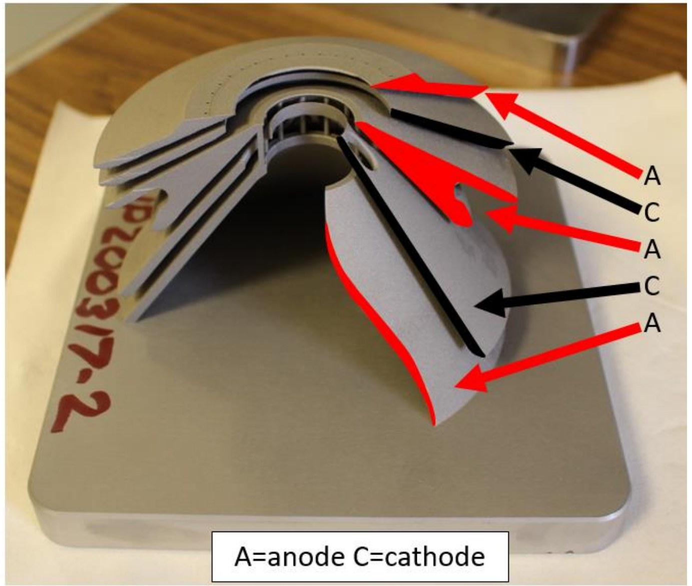
INITIAL SWEEP OF AM FOR POWER FLOW HARDWARE

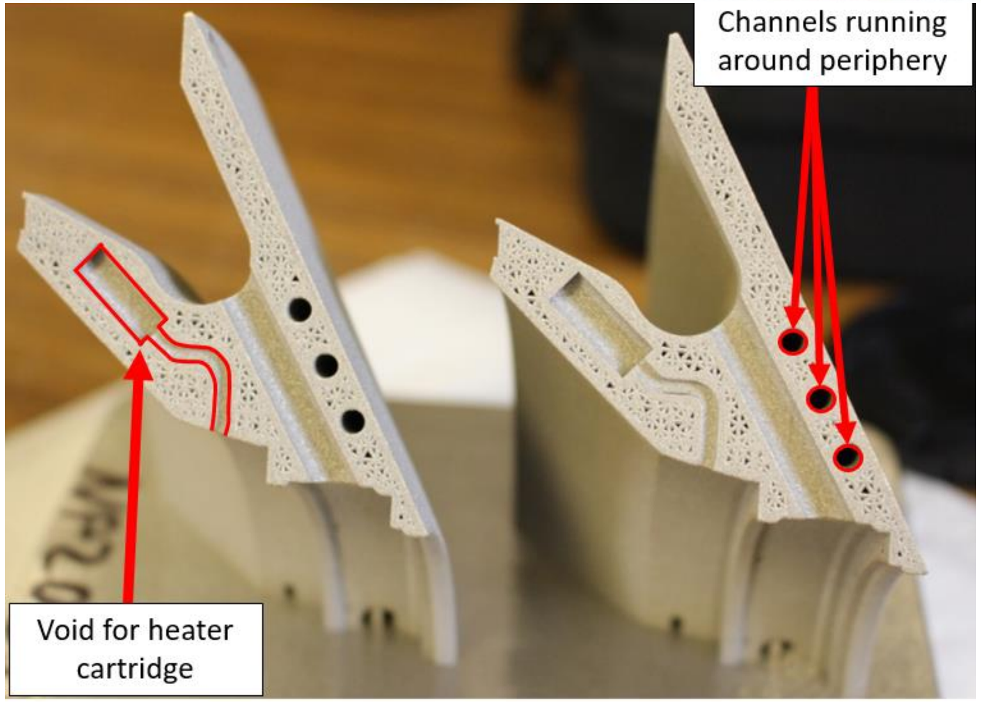


Laser Powder Bed Fusion (LPBF)

Exceptionally good at small scales, integration of internal features etc. Severely volume limited and residual stress limits dramatic expansion, surface finish for pulsed power best out of all AM, but not suited as printed







INITIAL SWEEP OF AM FOR POWER FLOW HARDWARE

Directed Energy Deposition (DED)

Well suited for larger components, scalability is large ➔ Robot arm and turn table etc. Surface finish is very poor and requires extensive post processing.

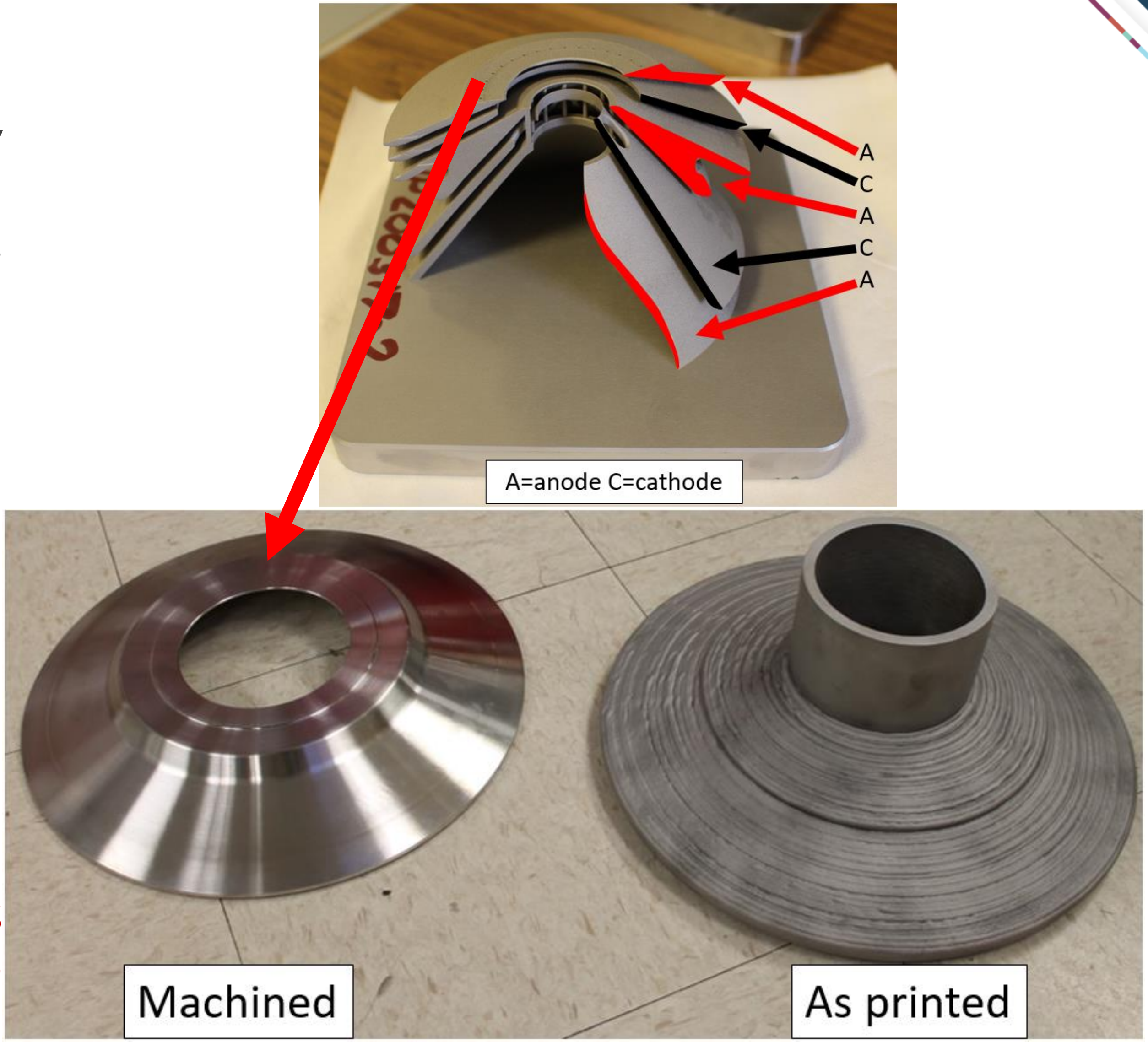
Laser Engineered Net Shaping (LENS)

Great for small scale, but difficult to scale

Fused Deposition Modeling (FDM)

Does not print fully metallic

Key take away: No single process provides flexibility necessary for NGPP. Impetus to explore alternatives ➔ HMPC



ESSENTIAL CONCEPT

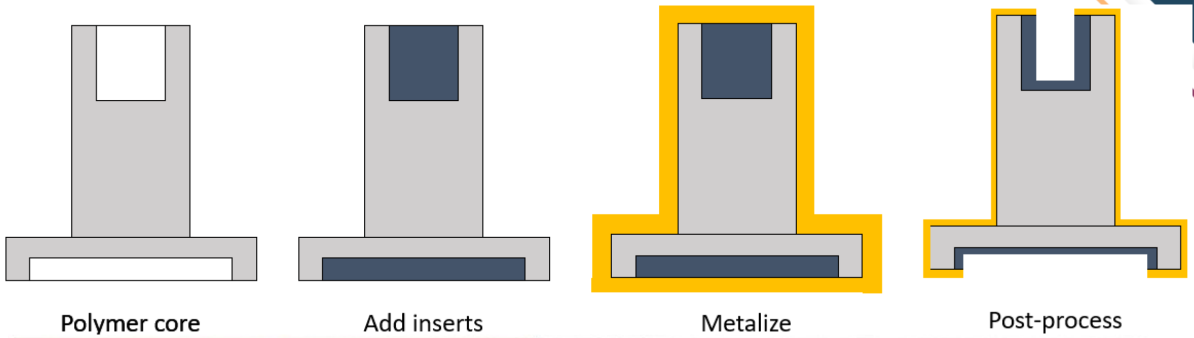
Hybrid Metalized Polymer Core (HMPC)

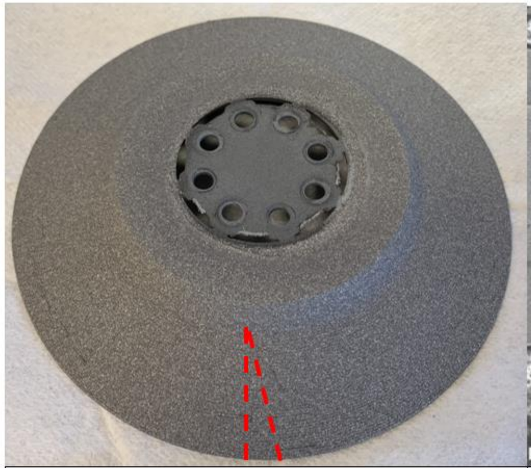
Essentially a polymer core with necessary inserts that has been metalized.

Scalability is very high, surface finish requires post processing but much less than DED. Poor ability to coat high aspect ratio holes and spray is direction dependent ➔ Poor corner quality. **AM by design equates to high ability to light weight and internal features become possible**.

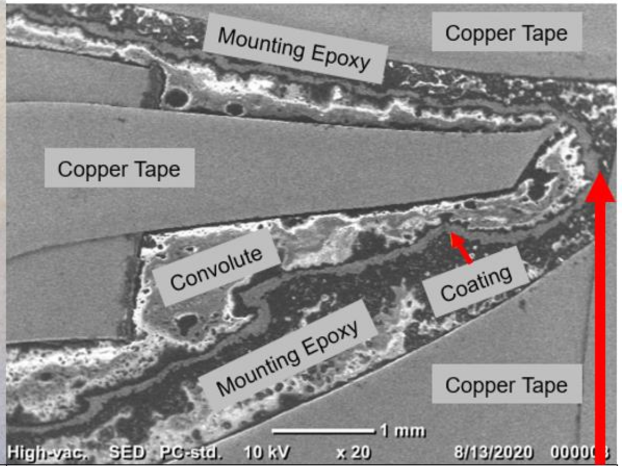
Metallization accomplished by multiple means including: electroplating, Twin Wire Arc (TWA) and Cold-Spray (CS).

➔HMPC may be the best chance for debris mitigation on NGPP

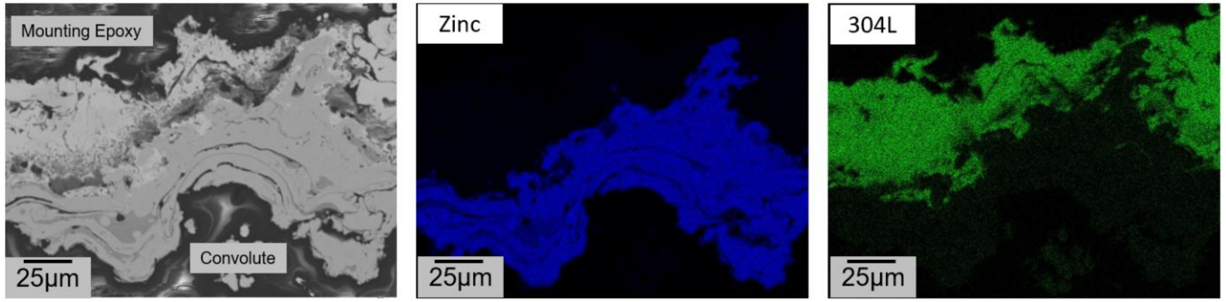




Cut Directions

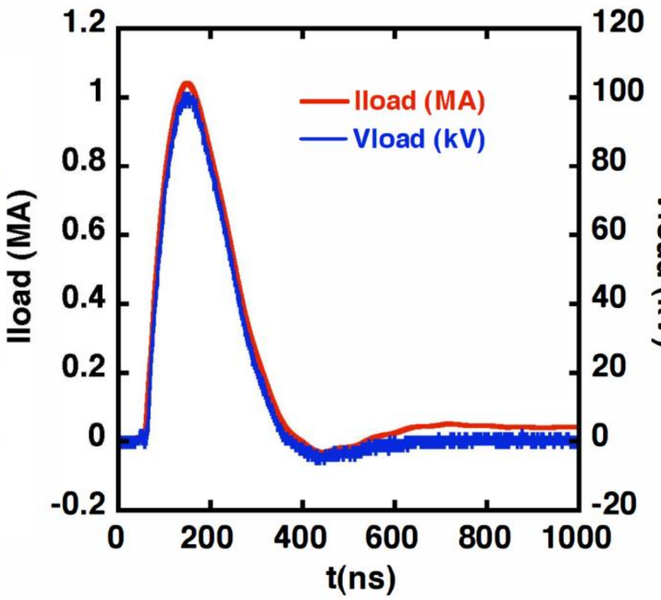


Great edge coverage despite high spray angle



TEST-BED: MYKONOS LTD

Mykonos is a Linear Transformer Driver (LTD) at Sandia National Laboratories in Albuquerque New Mexico capable of delivering ~ 1 MA into a matched load. Practically, load inductance is always higher and delivered currents are on the order of 0.5 - 0.9 MA



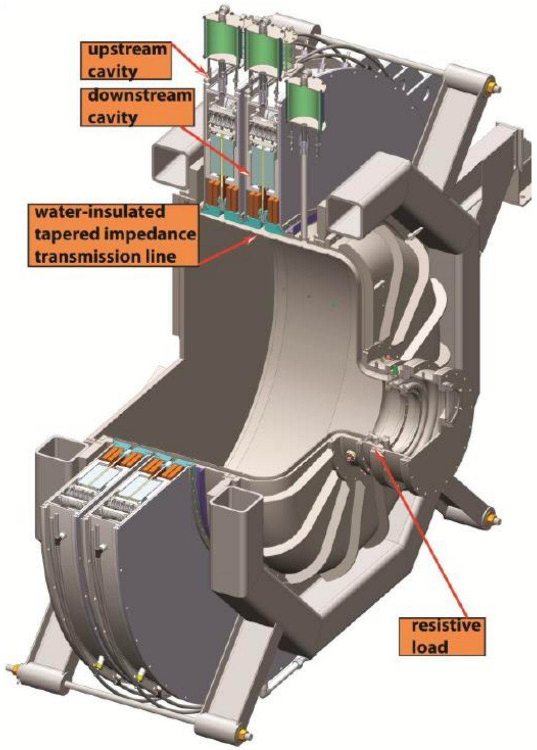
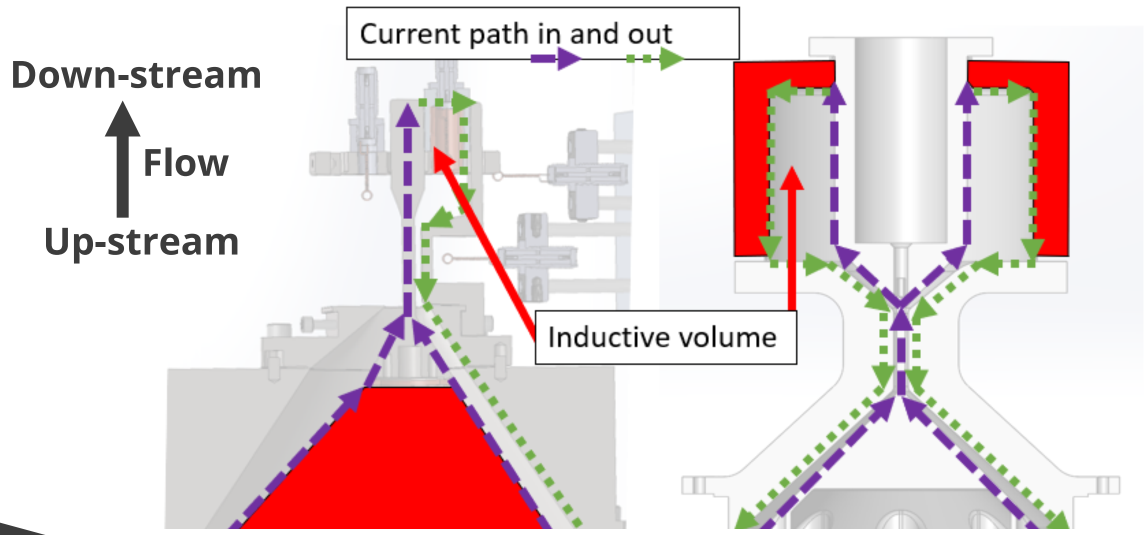


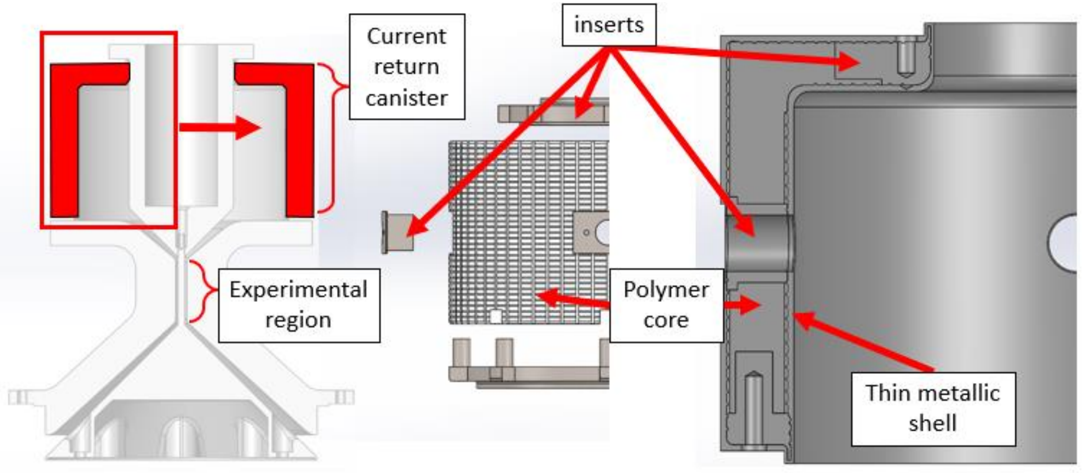
Image and waveform credit:
M. G. Mazarakis *et al*., "Experimental validation of the first 1-MA water-insulated MYKONOS LTD voltage adder," *2011 IEEE Pulsed Power Conference*, Chicago, IL, USA, 2011, pp. 625-628, doi: 10.1109/PPC.2011.6191552.

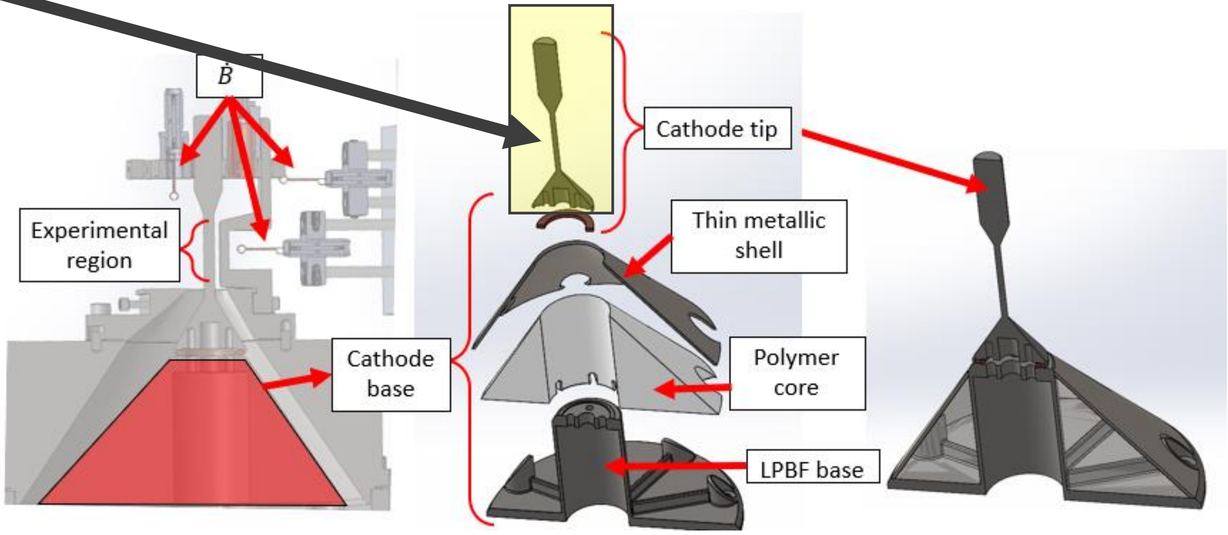
Image Credit:
M. E. Savage *et al*., "Temporally shaped current pulses on a two-cavity linear transformer driver system," *2011 IEEE Pulsed Power Conference*, Chicago, IL, USA, 2011, pp. 844-849, doi: 10.1109/PPC.2011.6191525.

INVESTIGATE HMPC OVER 3 SHOT SERIES

- Utilize two different hardware topologies
- Field up and down stream components
- Field experimental region (cathode tip)

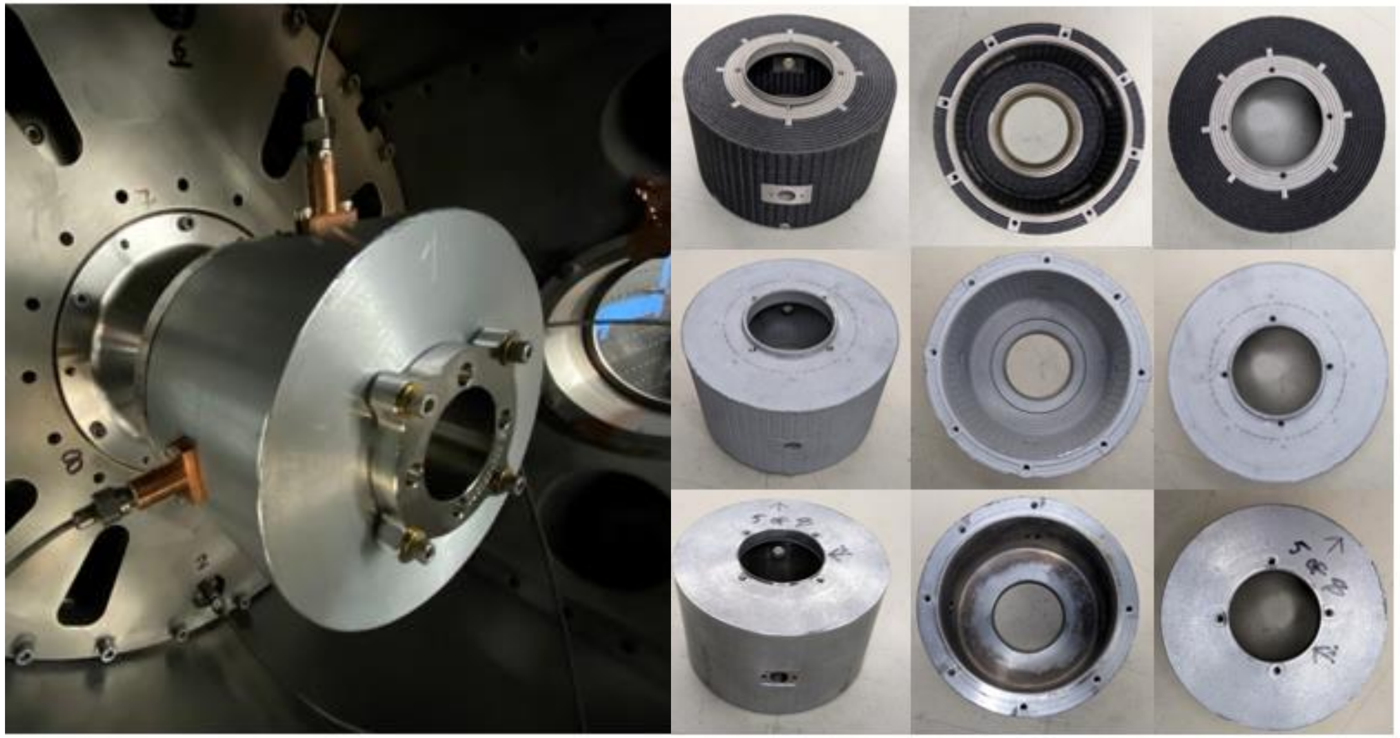






1ST SERIES: DOWNSTREAM CURRENT RETURN CANISTER

- Redesign current return canister based off of Brian Hutsel's previous work*
- HMPC polymer core requires low-melt bond coat (often zinc) before stainless can be sprayed via TWA.
- Intent was for external shell to be TWA 304L (~ 1 mm), but machine failed during run forcing us to run with a zinc power flow surface!



* B. T. Hutsel *et al.*, "Millimeter-gap magnetically insulated transmission line power flow experiments," *2015 IEEE Pulsed Power Conference (PPC)*, Austin, TX, USA, 2015, pp. 1-5, doi: 10.1109/PPC.2015.7296902.

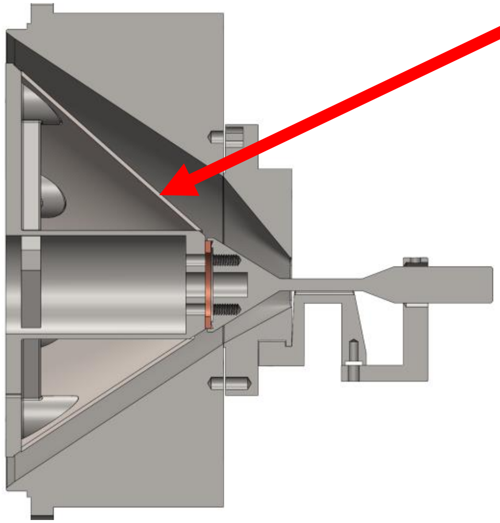
2ND SERIES: UPSTREAM CATHODE BASE

- Redesign cathode base based off of Derek Lamppa's previous work.

- Hybridize FDM + LPBF + TWA and CS.

  ➔ intermediate machine step between TWA CS

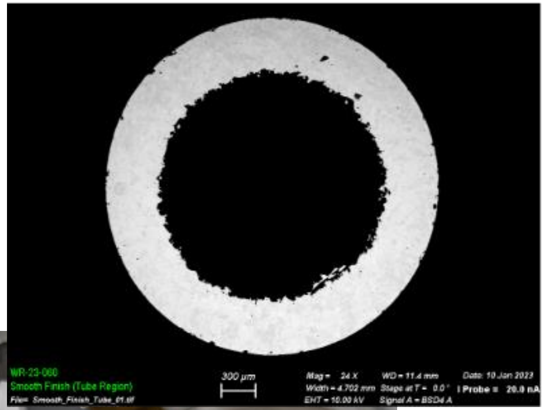
- Also produce fully LPBF "thick" (~1 mm) and "thin" (200 um) versions to test hollow core complications

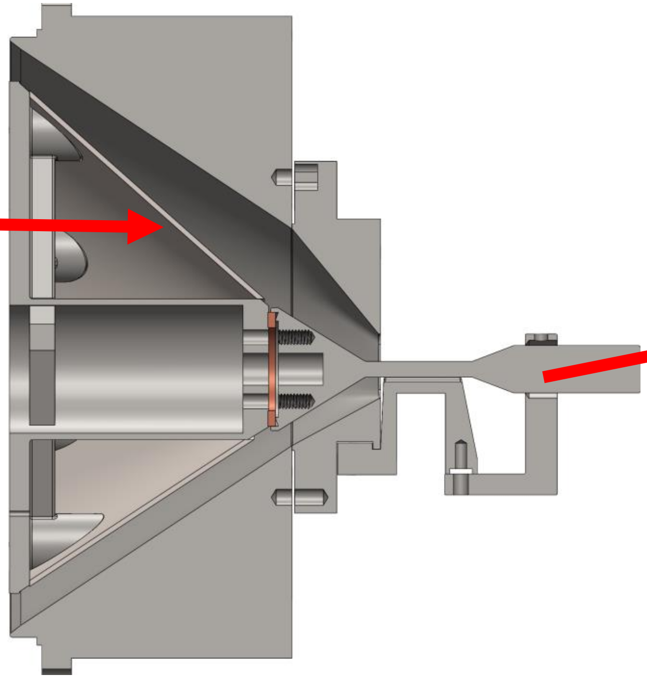


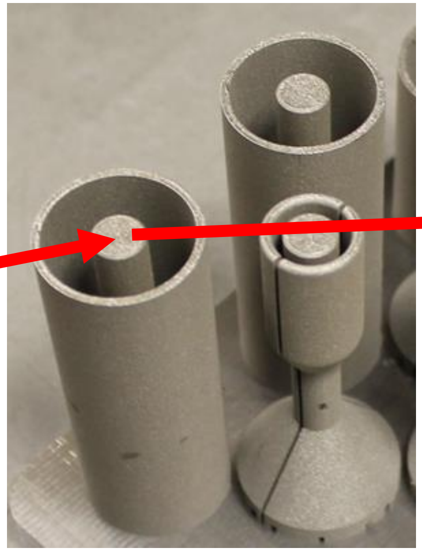
3RD SERIES: EXPERIMENTAL HIGH FIELD REGION

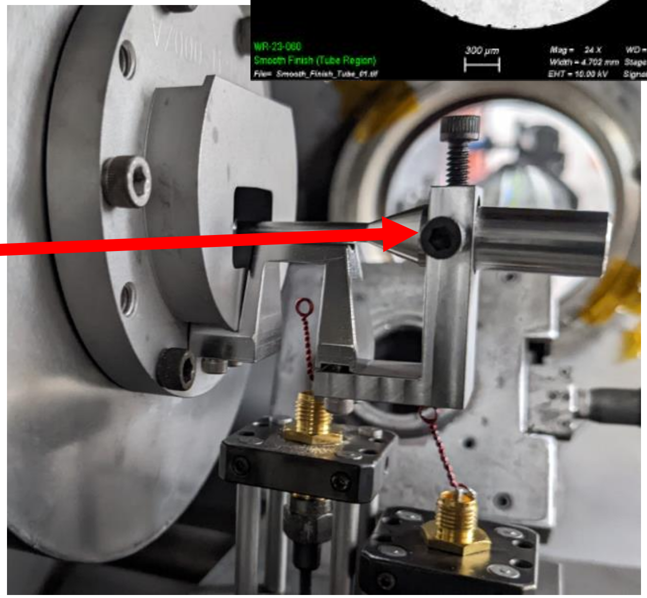
- 3D print both cathode base and tip (experimental region) with LPBF
- Cathode tip printed both solid and hollow
  - Hollow cathode simulates HMPC where core is etched out

We believe this is the first fully additive powerflow cathode with Z-like current densities







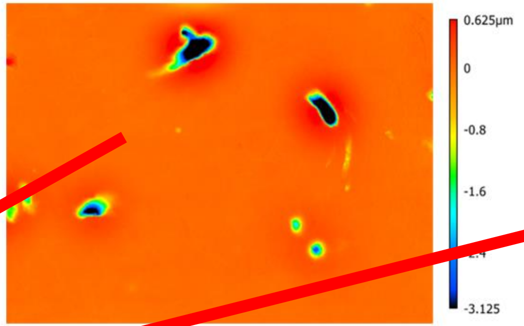


QUICK ASIDE: HIGH SURFACE FINISH ON LPBF HARDWARE

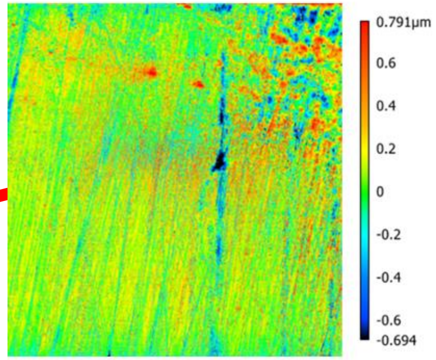
Roughness, N	Roughness values, Ra	
ISO grade numbers	micrometers (μm)	microinches (μin.)
N12	50	2000
N11	25 — As printed	1000
N10	12.5	500
N9	6.3	250
N8	3.2	125
N7	1.6	63
N6	Powerflow upper limit	32
N5	0.4	16
N4	0.2	8
N3	0.1	4
N2	0.05	2
N1	0.025	1

Image Credit:
https://en.wikipedia.org/wiki/Surface_roughness

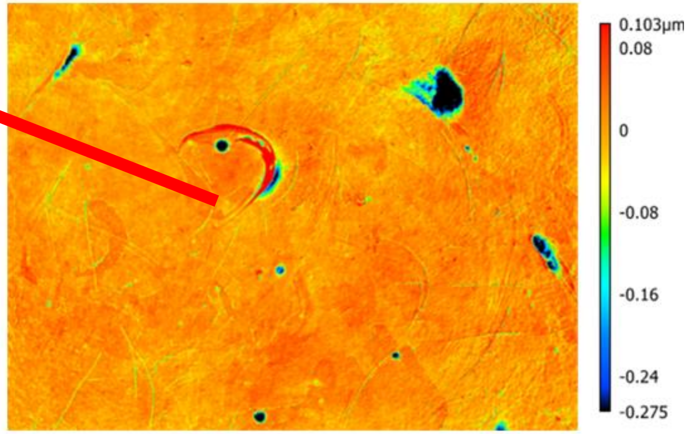
As-printed + electropolish
~ 1.8 μm Ra

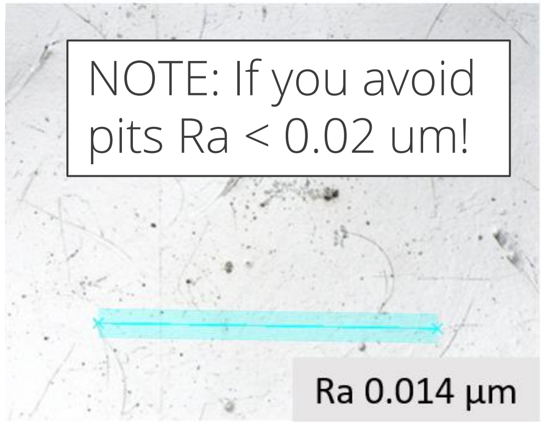


Print + mechanical polish
~ 0.75 μm Ra



Print + mechanical polish + electropolish
~ 0.2 μm Ra



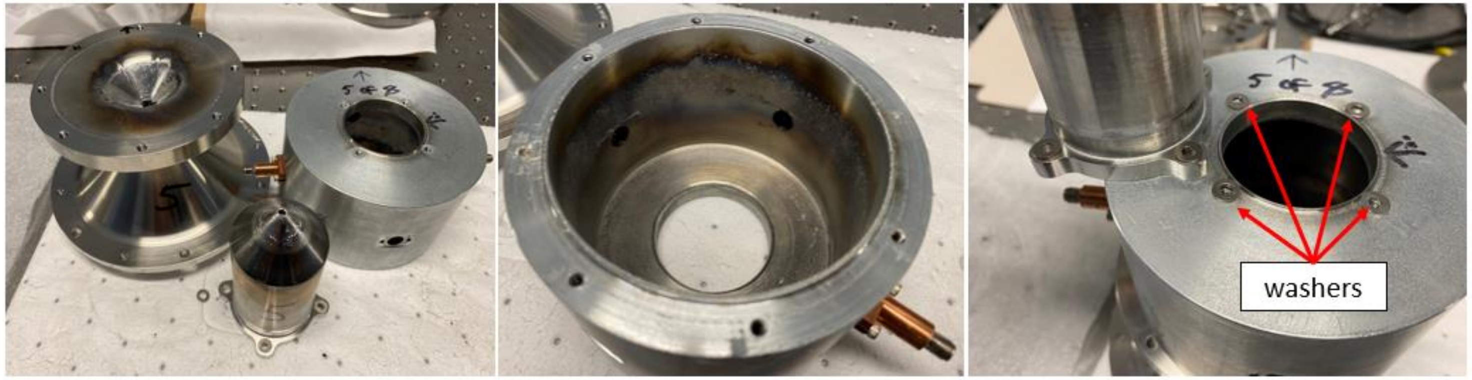


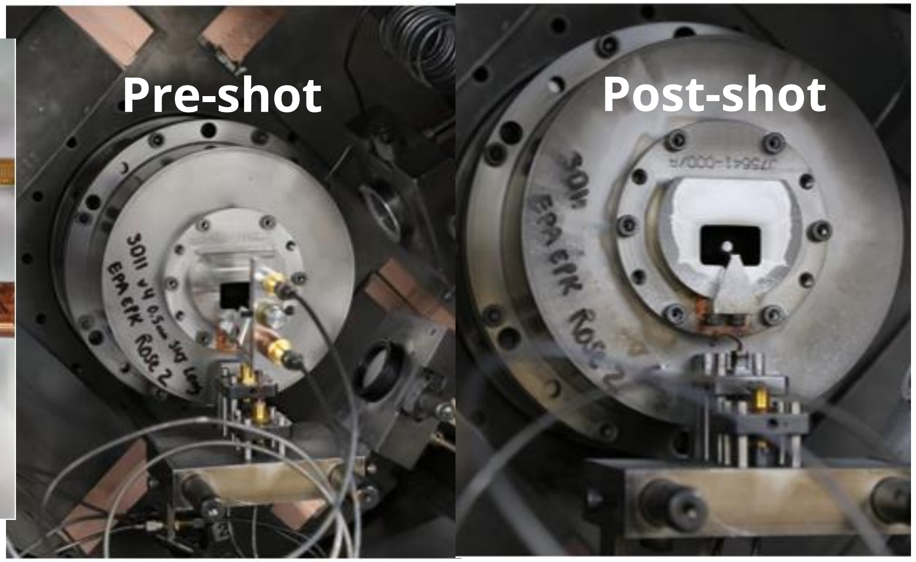
RESULTS: POST SHOT HARDWARE

Return canister survived ~ 600 kA shots at ~ 1 mm of zinc. Part was/is reusable.

Cathode base survived ~ 700 kA shots with ~ 1 mm zinc on surface and part is/was reusable.

Cathode tip transmit ~ 800 kA essentially <u>non perturbative</u> for both solid and hollow core with 500 μm of 316L SS

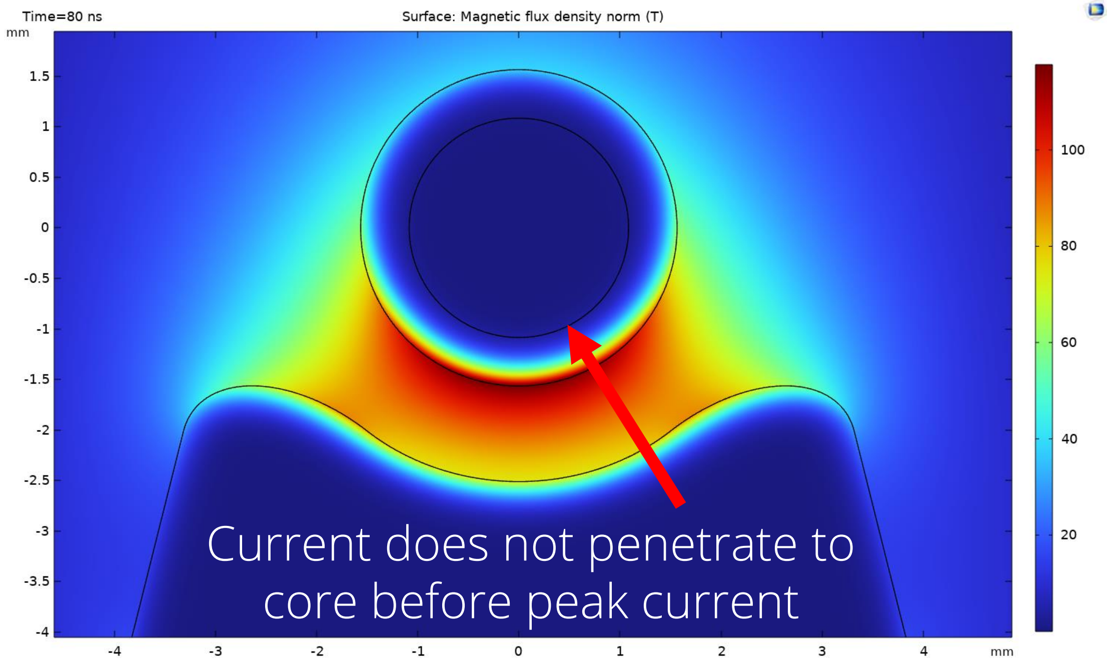


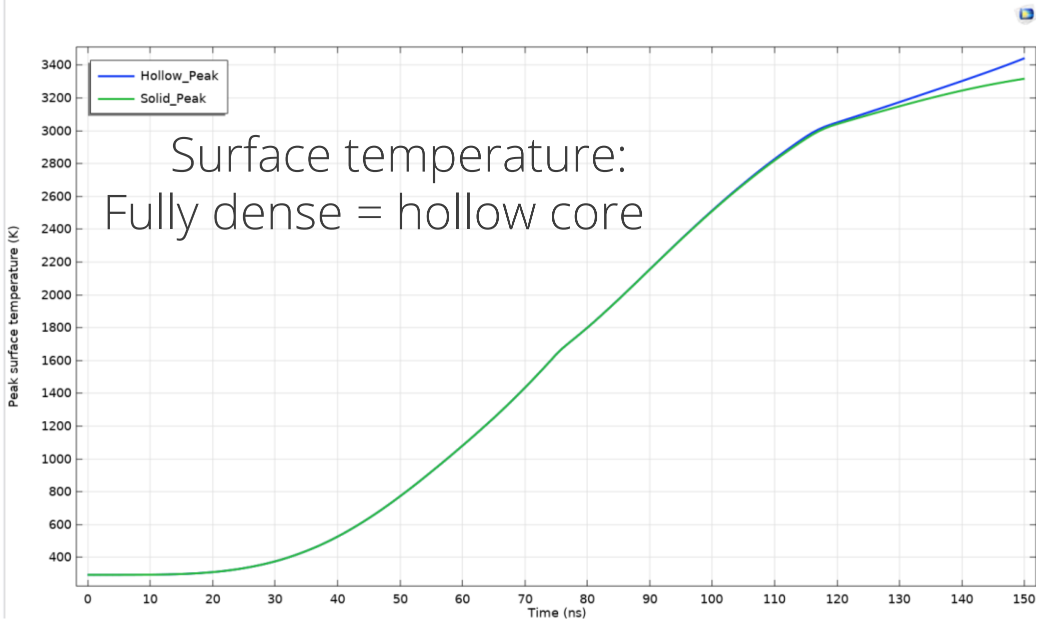


WHY DID HOLLOW CORE BEHAVE THE SAME AS SOLID?

Current does not diffuse deep enough to reach the central hollow region before peak current

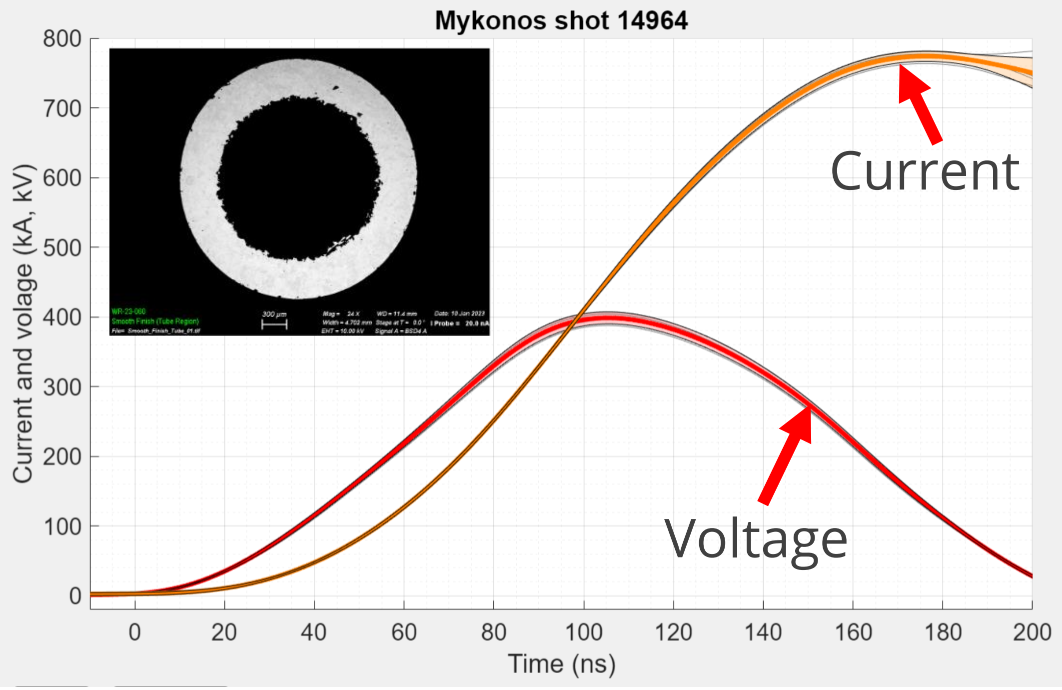
➔ solid will behave same as hollow ➔ This is how we mass optimize

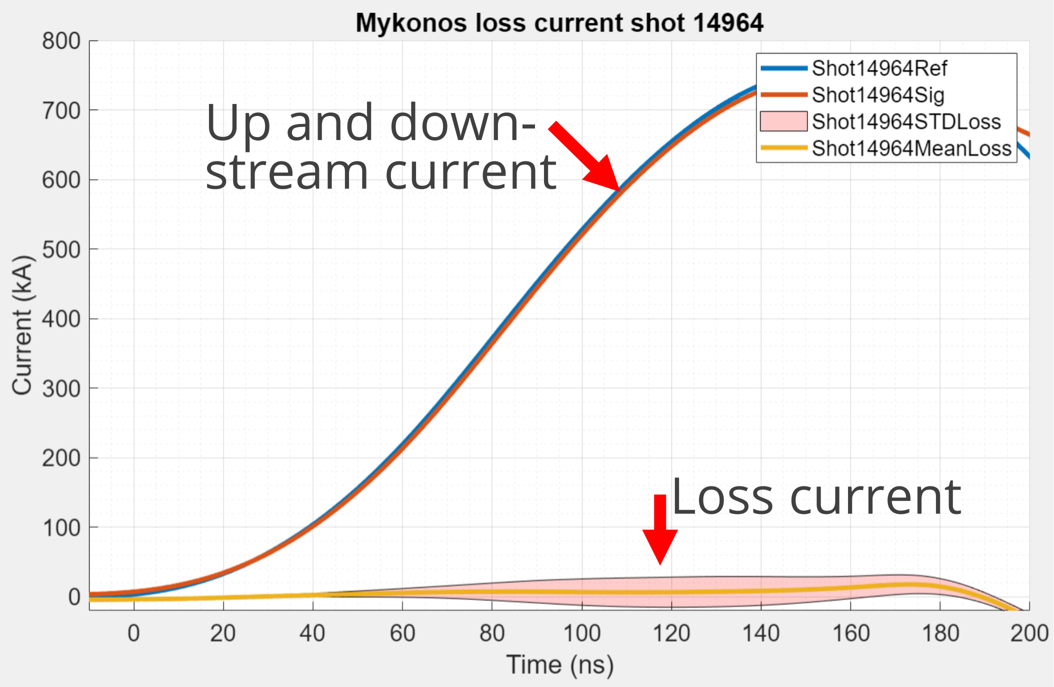




RESULTS: DELIVERED VOLTAGE AND CURRENT

- Capacitive storage always charged to ~ 70kV equates to ~ 400- 450 kV at load
- Load hardware inductance limits peak current to ~ 750 - 800 kA (this shot ~ 775 kA)
- Waveforms for apples:apples hardware essentially the same e.g., hollow vs. solid



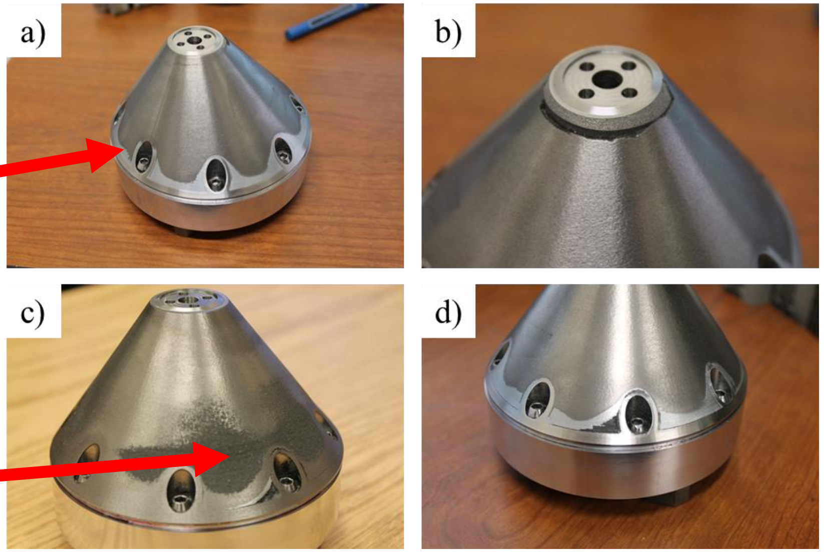


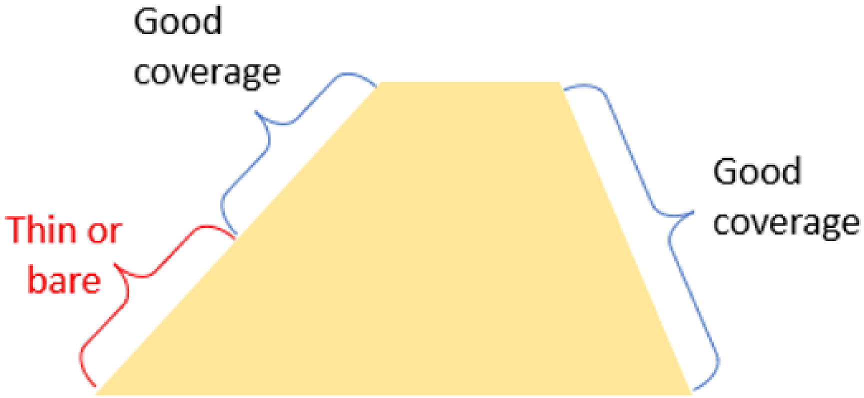
PITFALLS AND LIMITATIONS OF HMPC

HMPC hardware for powerflow is currently difficult to manufacture. Given this, a re-design with this process at the heart should greatly reduce complexity and costs

Bond coat limiting progress (zinc or aluminum intermediate etc.), need to find high-temp polymer to directly coat higher temp metallics (304L)

A-symmetry and high aspect ratio holes are very difficult, but mitigated with clever use of inserts



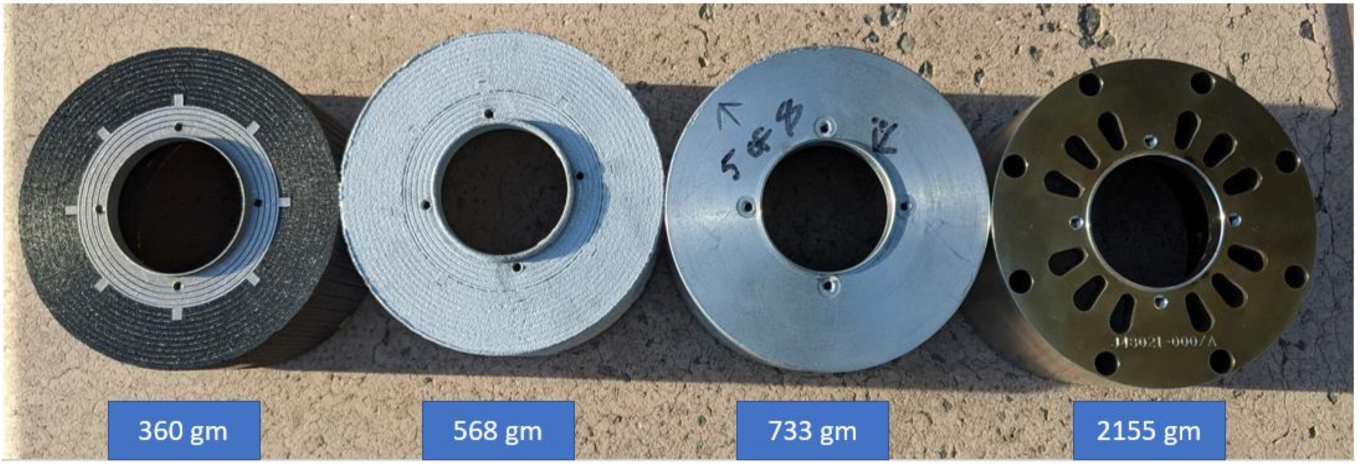


KEY TAKE AWAY: HMPC MASS SAVINGS ARE EXCELLENT

HMPC ~ 3X mass savings accomplished. Further mass optimization could be done.

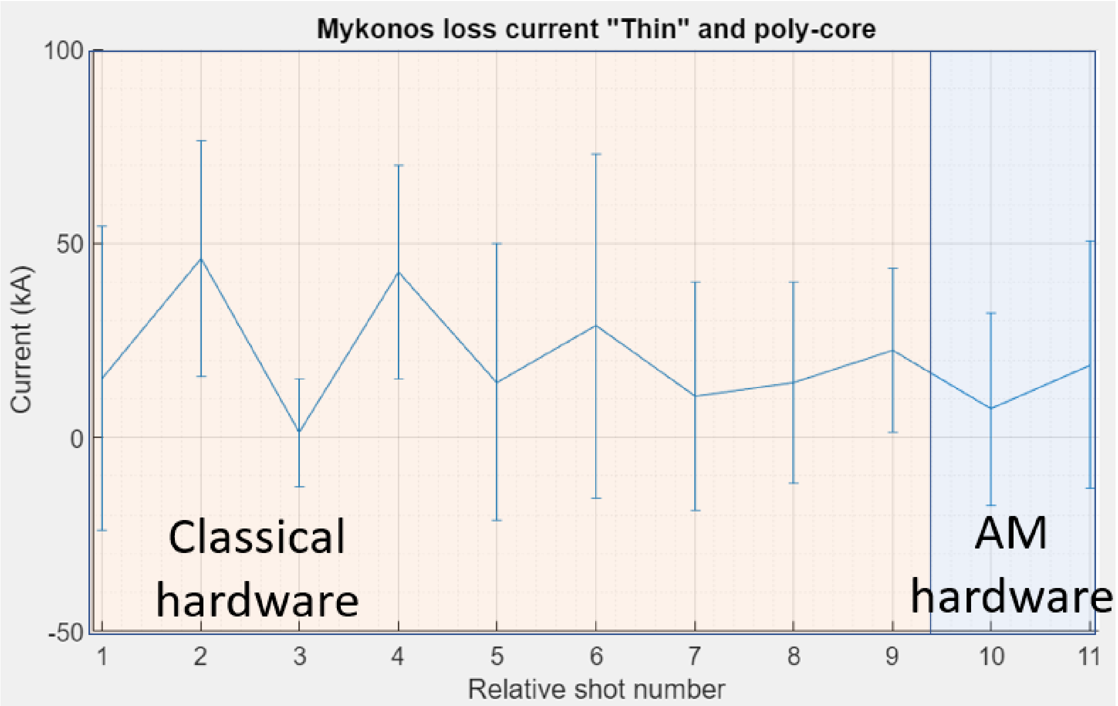
Components were noticeably easier to work with and install

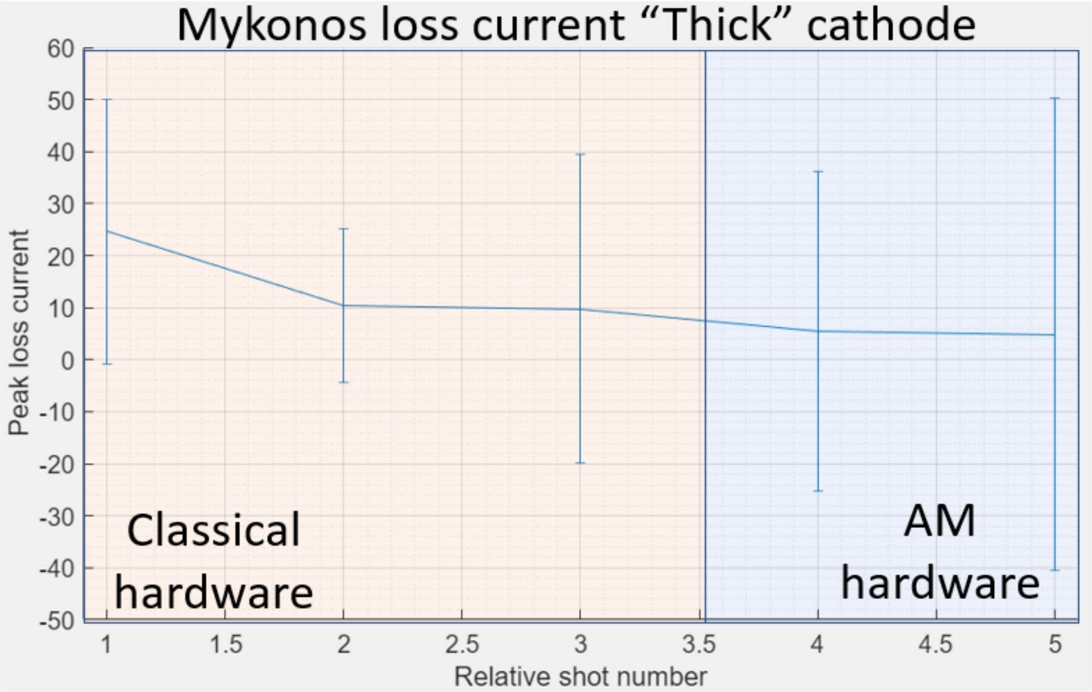
Machine was essentially none-the-wiser for any case. Polymer core, hollow core, zinc vs stainless etc.



KEY TAKE AWAY: HMPC IS NON-PERTURBATIVE TO POWER FLOW

- HMPC survived all up/down-stream shots with essentially no observable differences.
- Process appears viable for debris mitigation on NGPP



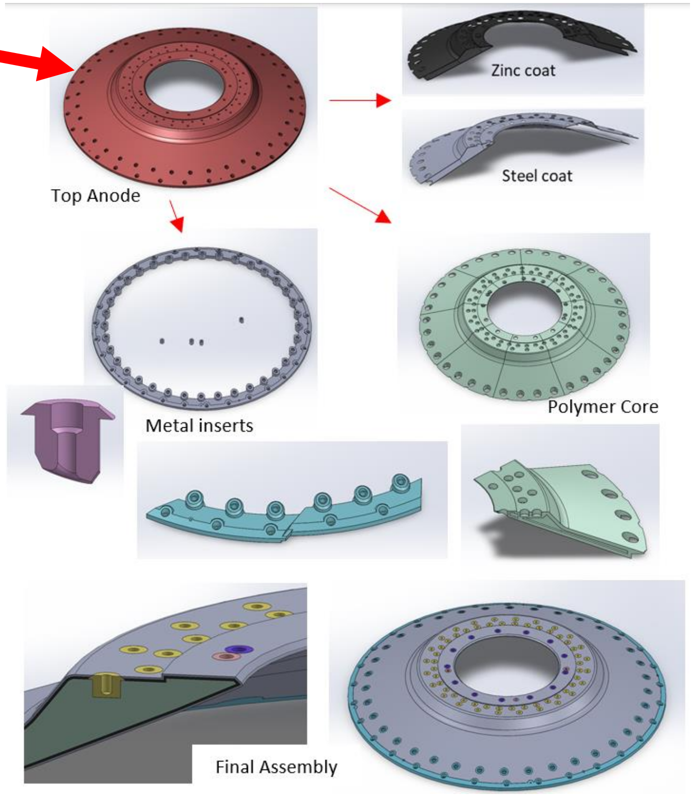


NEXT STEPS FOR HMPC

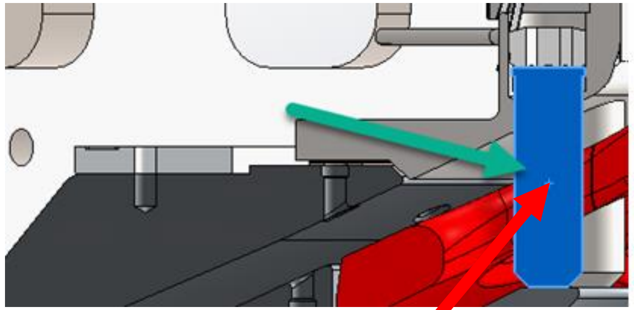
Flesh out scalability by developing and fielding full-scale Z convolute.

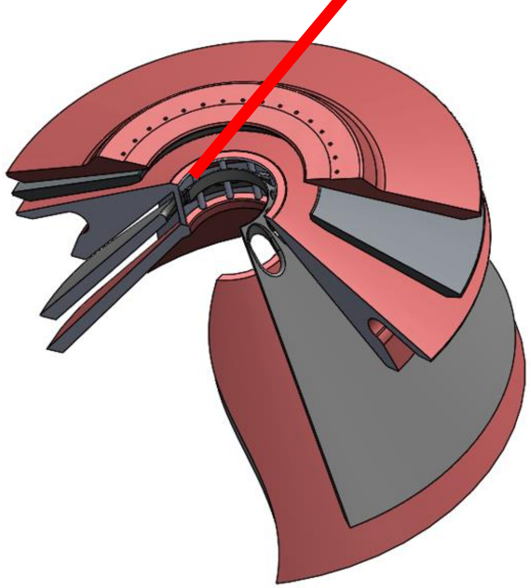
Flesh out Z-like conditions by building upper/lower Z anode post(s) ➔ Ideally garnering a ride along shot

Collaborate with external partner to define early goals/gaps etc. necessary to pivot into industrial fabrication space, ideally capitalizing on economy of scale and recent advancements in additive manufacturing.



Upper anode post





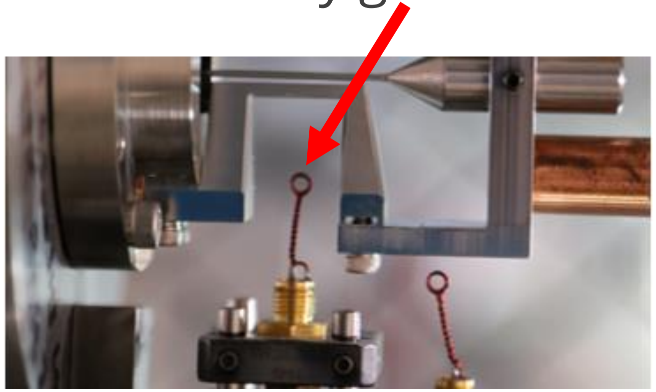
QUESTIONS?

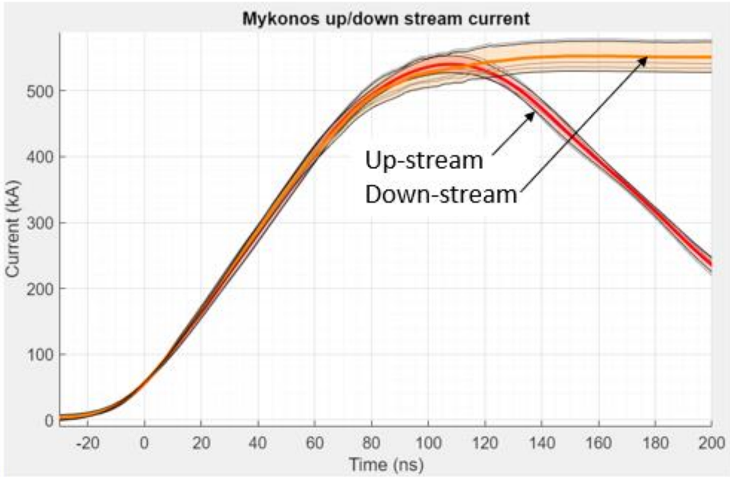
BACKUP SLIDES: DEFINE LOSS CURRENT

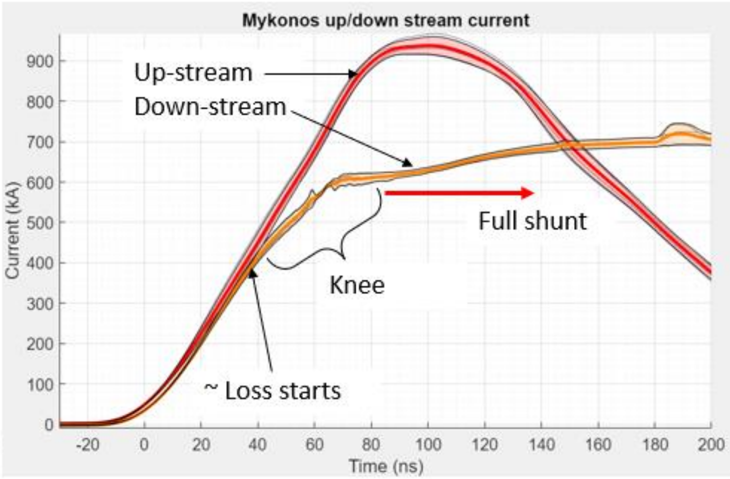
Loss current is primary metric for hardware performance comparison at this time

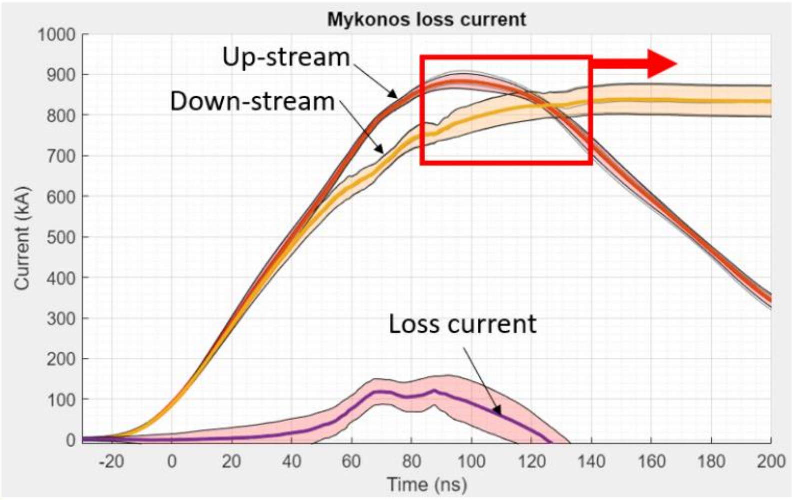
Essentially difference between up and down-stream current measurements

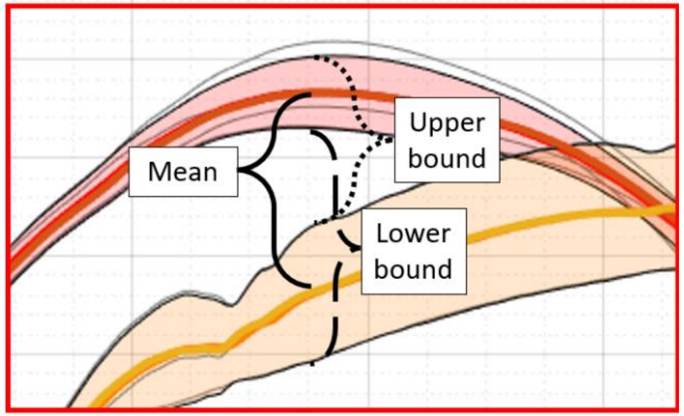
Measurement is difficult with large error currently given free-field B-dots











Loss and associated error computed as:

Loss = mean loss ± (maximum loss – mean loss)

➔ Need to rethink/redesign down-stream current measurement