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FERMI NATIONAL ACCELERATOR LABORATORY

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PIP-II SRF Couplers: Fabrication Status and Addressing Ceramic Yield Challenges

Tommaso Aiazzi

U.S. DEPARTMENT of ENERGY
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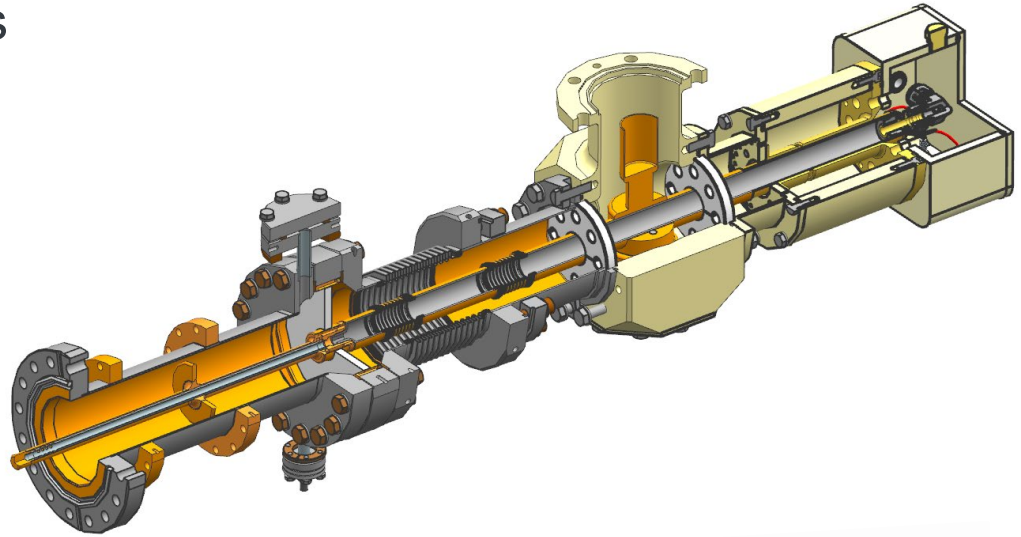
SSR & 650 Couplers

325 & 650 MHz Fundamental Power Couplers

325 MHz Fundamental Power Couplers

- SSR1 — 4.5 kW (CW, <15% reflection)
- SSR2 — 11 kW (CW, <20% reflection)

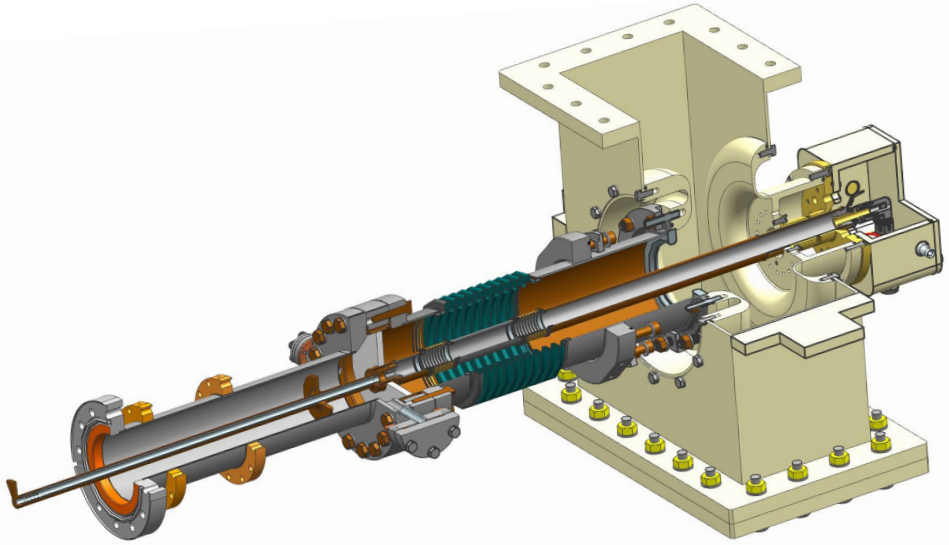
Tested at: 12 kW CW 100 % reflection



650 MHz Fundamental Power Couplers

- LB 650 — 26.6 kW (CW, <25% reflection)
- HB 650 — 43 kW (CW, <25% reflection)

Tested at: 50 kW CW 100 % reflection



Coupler Production & Testing Status

78/117

Couplers Fabricated

66/66 — 650 MHz

12/51 — 325 MHz

23

Units Fully Inspected

20 — 650 MHz

3 — 325 MHz

2

Rejections

1 — 650 MHz

1 — 325 MHz

Testing Pipeline

- **Incoming inspection**
  - Leak check, visual, particulate count
- **Warm high-power test**
- **Post-test inspection**
  - Leak check, visual inspection

Minor Delays / Reworks

- Cleanliness, esp. copper coating
- HB / LB configuration mix-ups
- CF flange damage

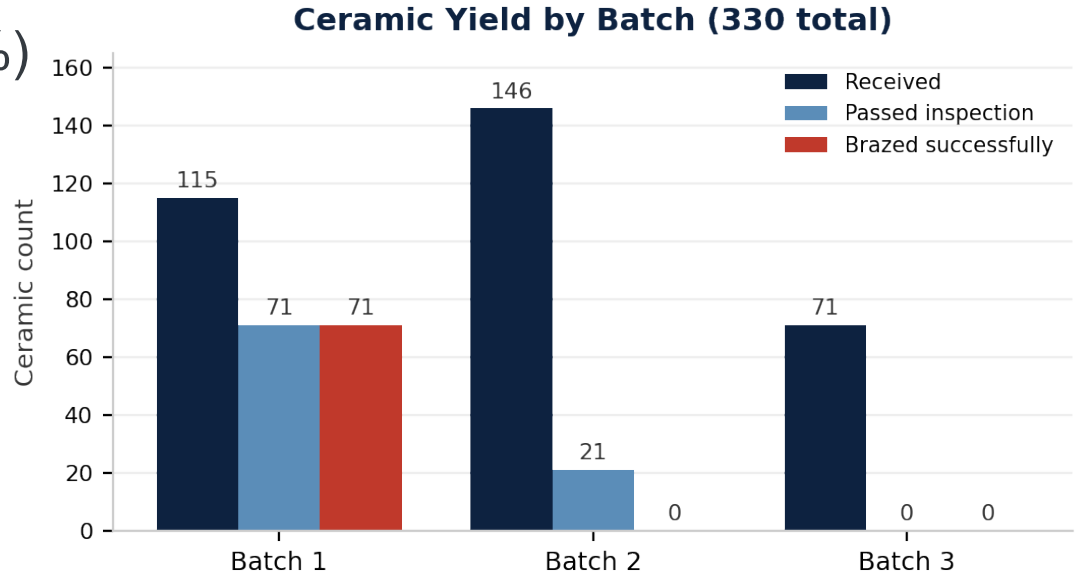
Rejection Reasons

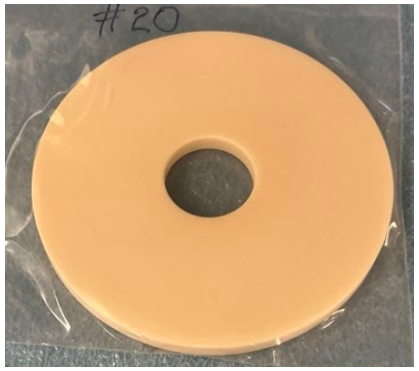
- Performed high-power test without air cooling the antenna
- Chip in ceramic caught at incoming

Ceramic Window Failures – Vendor 1

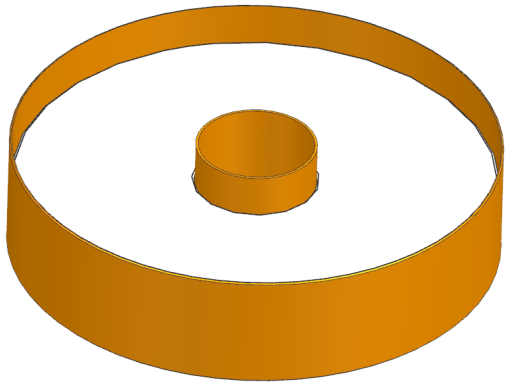
Leaks at the ceramic-to-metal braze interface

- Received 330 ceramic (alumina content > 99.6%) divided in 3 batches, only 92 passed the inspection
  1. 115 received, 71 passed inspection, 100% yield in brazing
  2. 146 received, 21 passed inspection, 0% yield in brazing
  3. 71 received, 0 passed inspection

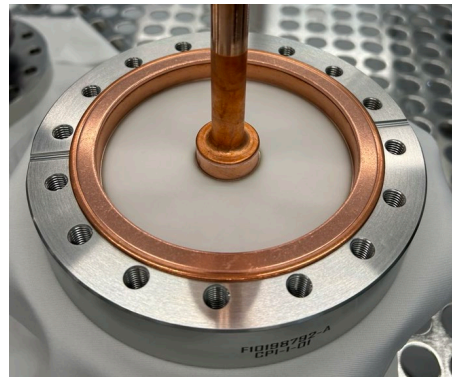




Base ceramic disk



Intermediate copper sleeve assembly

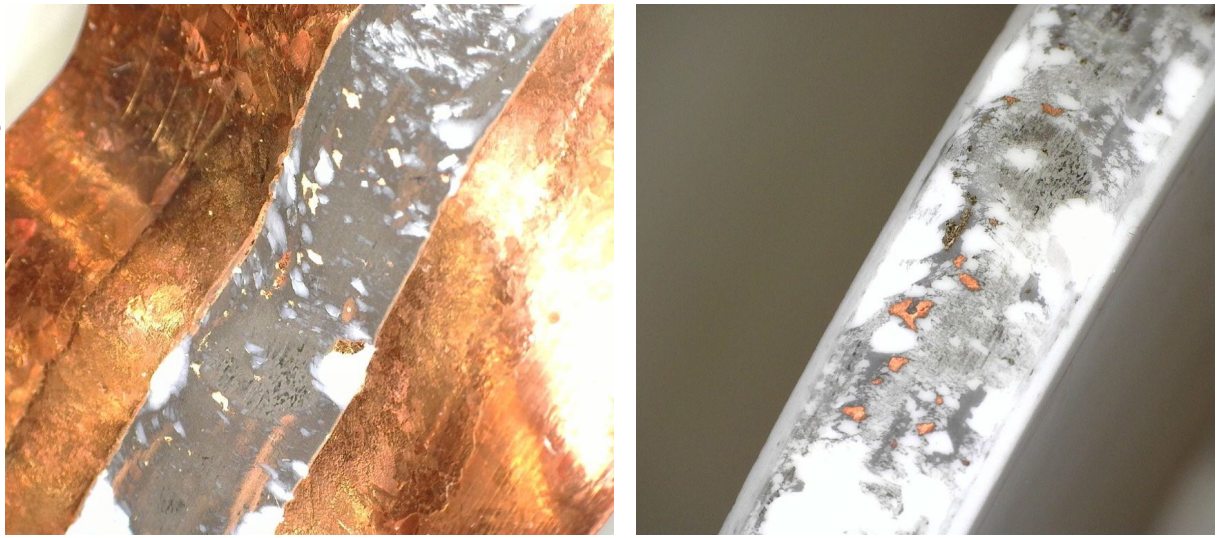


Final window assembly

Ceramic Window Failures – Vendor 2

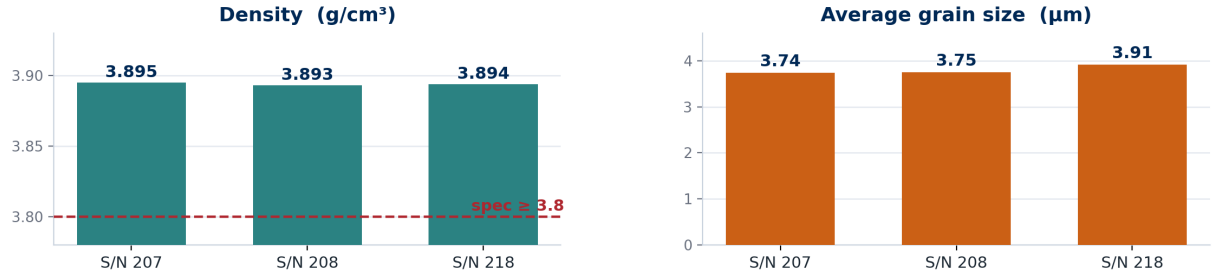
Leaks at the ceramic-to-metal braze interface

- Changed vendor due to high rejection rate
- Same specification used to order and all the ceramics went through the same inspection process
- 24 out of 60 received passed inspection
- 0% yield on brazing
- A peel test was done to assess the brazing, showed that the adhesion and strength was very good on a global basis, but the uniformity was very nonuniform across the sealing surface
- Test on density and grain size were also done and didn't show any non-conformities



Peel tests

Bare-ceramic inspection — 3 units (Kyocera)



All dimensions, density and grain size within spec — **the ceramic conforms; the failure is in the braze.**

Ceramic inspection process

1 Visual

- Cracks, chips, unusual markings, discoloration

2 Dimensional

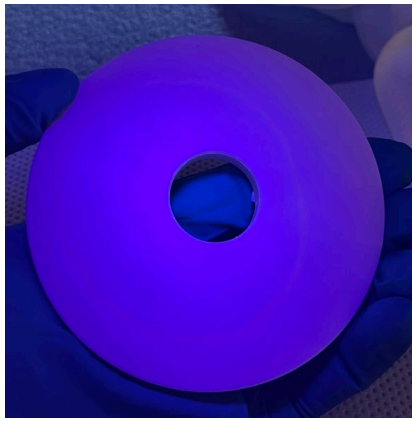
- Calibrated caliper / CMM
- OD Ø100.98 (+0/−0.05) mm
- ID Ø25.4 (+0.05/−0) mm
- Thickness 7 ± 0.1 mm

3 Dielectric loss (RF)

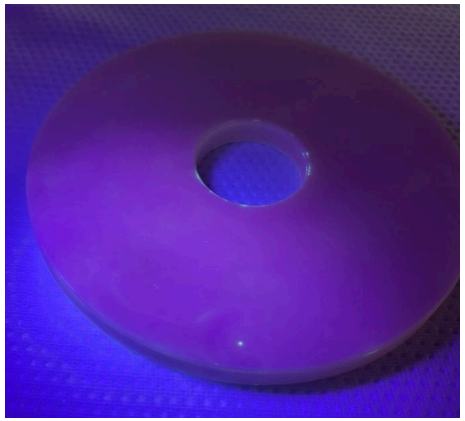
- Performed before metallization
- Disc in a Cu cavity
- Loss tangent derived from the result
- Reject if $\tan \delta > 1 \times 10^{-4}$

4 Dye penetrant

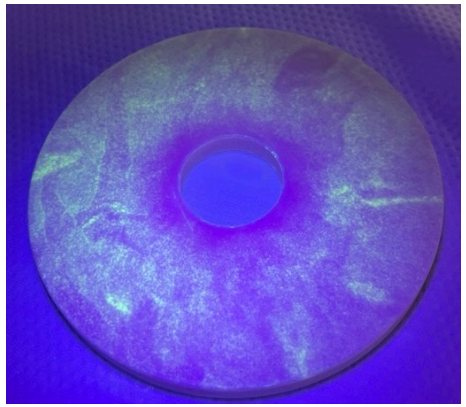
- ZL-4C penetrant, 10 min dwell
- Rinse, then ZP-4D developer, 10 min
- UV inspection of all surfaces for cracks
- Any indication → reject



pass

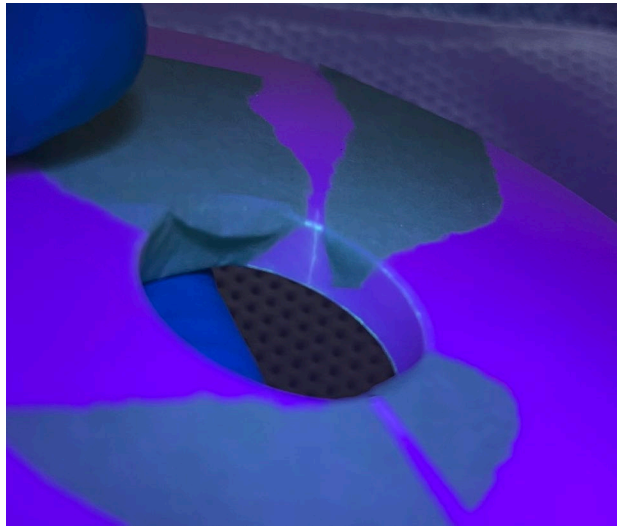


spare

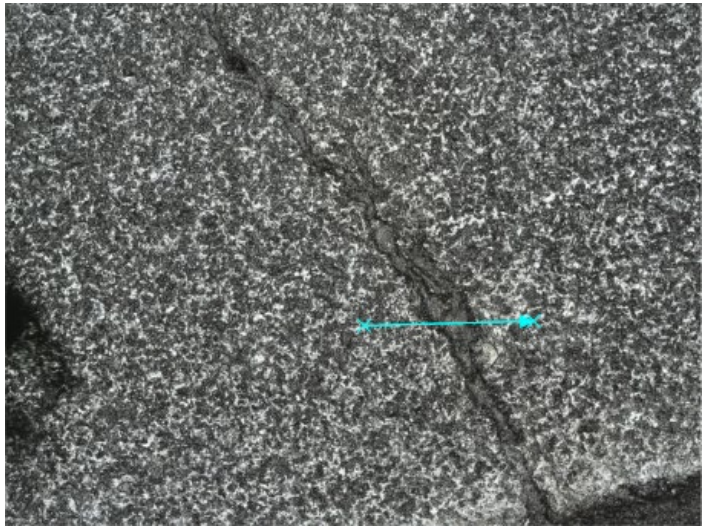


fail

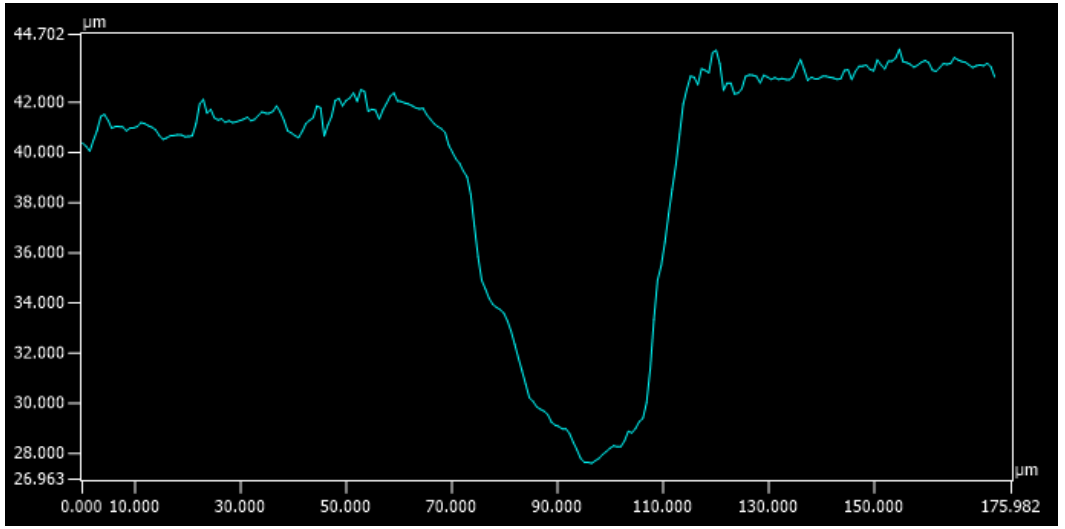
Crack inspection



Dye penetrant under UV



SEM
crack along the surface



SEM
profile graph

Suspect cracks are confirmed by dye penetrant under UV, then mapped optically and at the surface by SEM.

Toughness check: we tried to fail a good disc on purpose. Deep diamond-point scribes followed by wrench blows produced no cracking or chipping. The bulk alumina is far tougher than the failures suggest, pointing to the braze joint, not the ceramic, as the crack origin.

Possible Failure Mechanisms

Root cause not confirmed - candidates under active evaluation

Residual braze stress

CTE mismatch between Cu/SS and Al_2O_3 (7–8×) locks tensile stress into the joint on cooling.

Pre-existing ceramic flaws

Micro-cracks or porosity that pass incoming visual and dimensional inspection but act as crack initiation sites.

Braze process variability

Furnace temperature, dwell time and fillet geometry all change the final stress state from unit to unit.

Metallization quality

Edge definition and adhesion of the metallization. Human error in reproducing the process

Base powder material

The base powder material variation can impact the brazing.

Ruled out: handling

Impact and drop tests caused no damage. Transportation and handling are effectively eliminated as crack drivers.

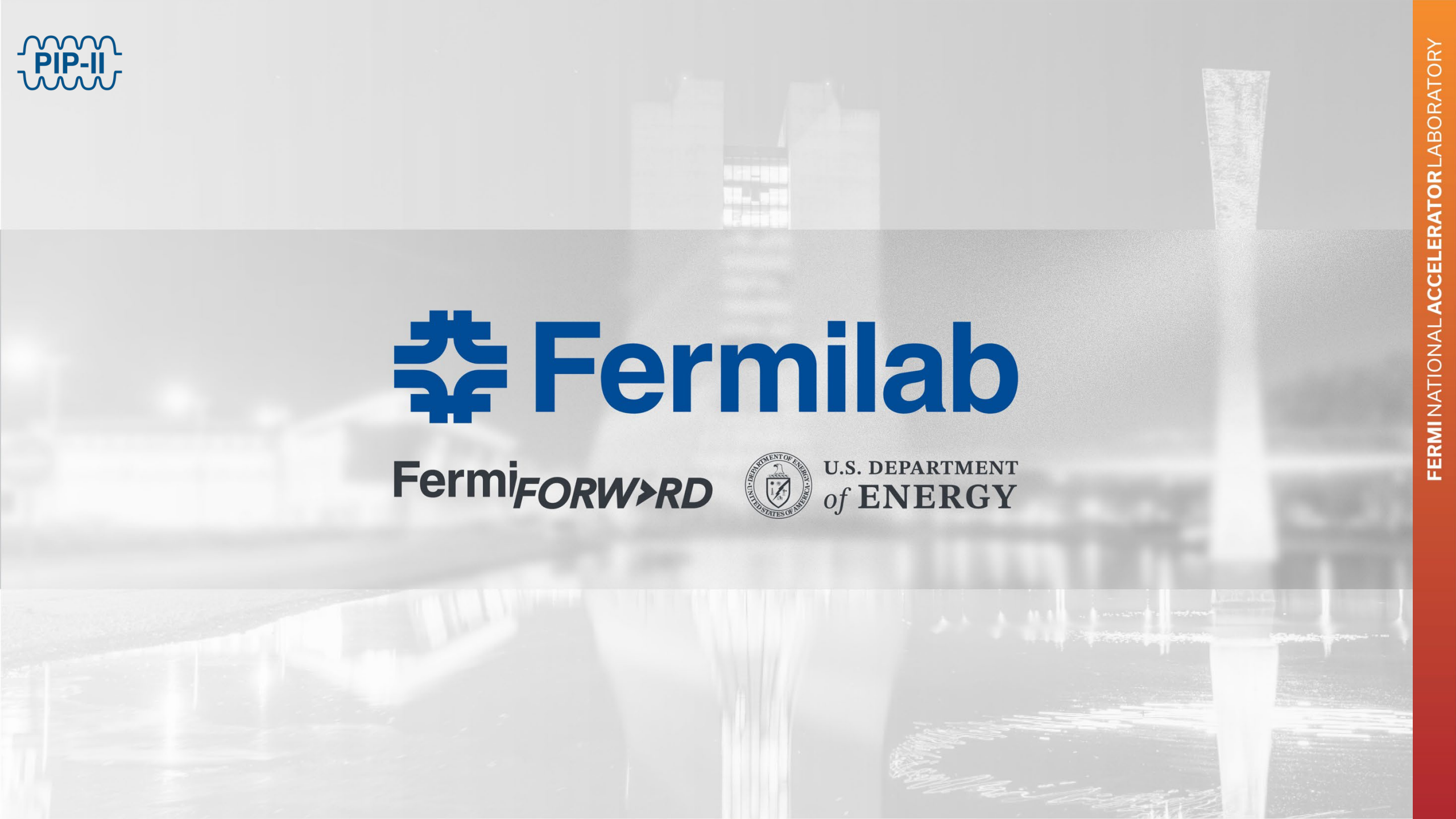
Conclusions

Recommendations for future projects

- **Procure the full ceramic powder lot during prototyping**
  - Develop and lock the fabrication and braze process on that powder, then reproduce it in production. Powder changes, even from the same vendor, can break a qualified process.
- **Braze-qualify every new batch on arrival**
  - With multiple lots or vendors, test the new ceramic immediately; don't wait until the known-good batch runs out.
- **Define an objective, repeatable acceptance criterion, agreed with the vendor**
  - Makes rejection consistent and defensible, and reduces unnecessary scrap.

Open Questions

- Inspection currently relies on inspector experience, there is no objective, scientific acceptance criterion
- Is our rejection rate stricter than it needs to be? Are we scrapping serviceable parts?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