

Development of Nuclear Quality Components using Metal Additive Manufacturing

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Advanced Methods for Manufacturing Workshop

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- RadiaBeam overview
- AM research at RadiaBeam
- Overview of EBM AM technology
- Goals and relevance of the Phase I/II project
- Phase I/II work

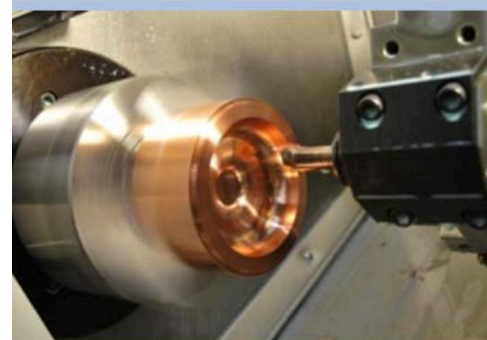
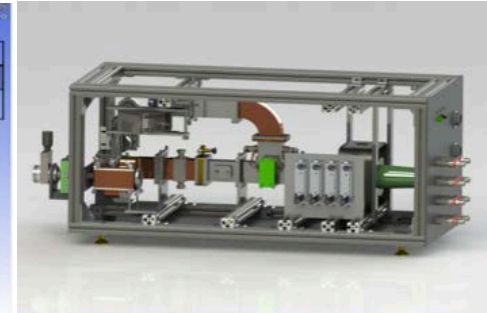
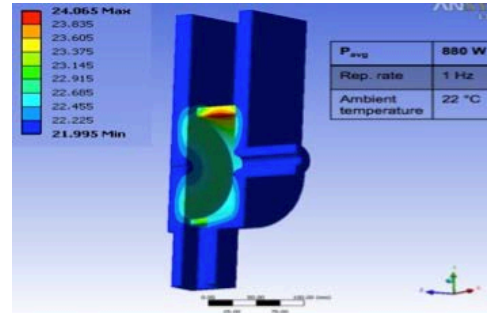
Who we are

- RadiaBeam has two core missions:
 - To manufacture high quality, cost-optimized accelerator systems and components
 - To develop novel accelerator technologies and applications
- Currently > 50 employees and growing
 - Consists of PhD Scientist (10), Engineers (18), Machinists (10), Technicians (8), and Administrative (4)



Capabilities

- Design (RF, magnetic, thermal-mechanical)
- Engineering
- Fabrication
- Assembly
- Testing
- Installation
- Service

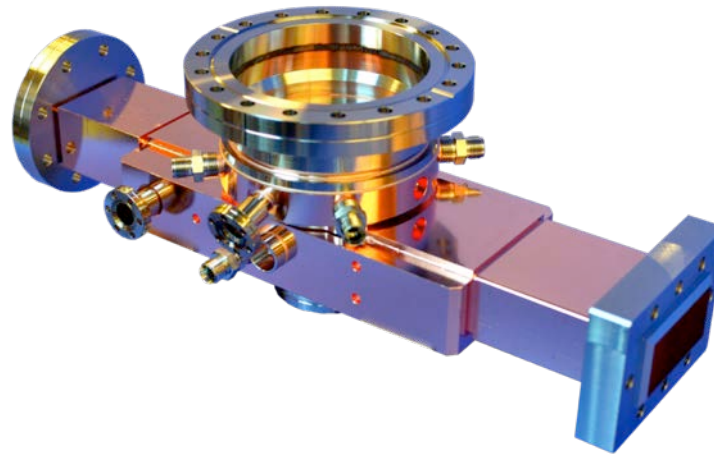


Facilities

- Machine shops (clean and regular)
- Assembly area
- Magnetic measurements lab
- Optics lab
- Hot test cell (up to 9 MeV)
- Clean room
- Chemical processing
- RF test lab
- Currently 16,000 sq. ft., and looking to expand to > 30k by mid 2016!



- Turnkey accelerators
 - Cargo inspection and Radiography
 - High-power Irradiation
 - Self-shielded irradiators
- E-beam diagnostics
 - Beam profile monitors
 - Bunch length monitors
 - Charge, emittance, etc.
- RF structures
 - RF photoinjectors
 - Bunchers
 - Linacs
 - Deflectors
- Magnetic systems
 - Electromagnets
 - Permanent magnets
 - Systems (chicanes, final focus, spectrometers)



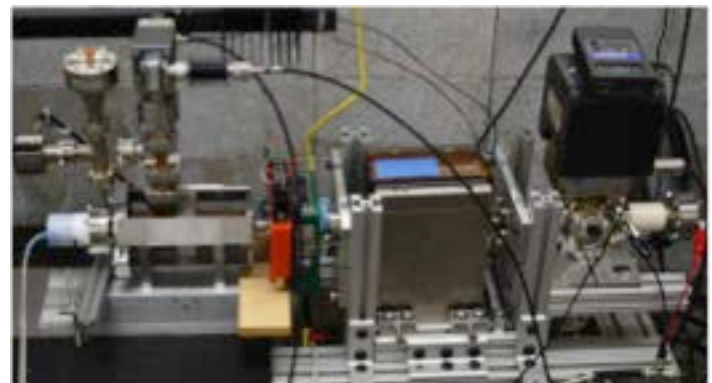
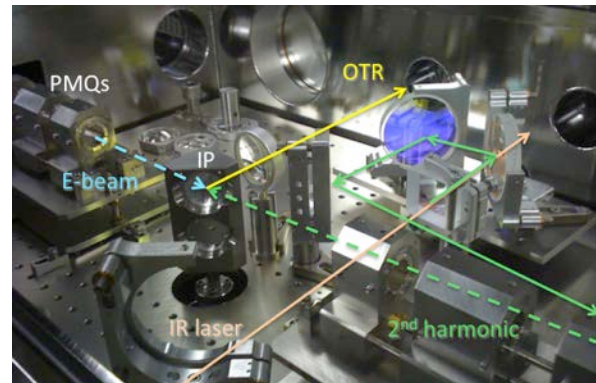
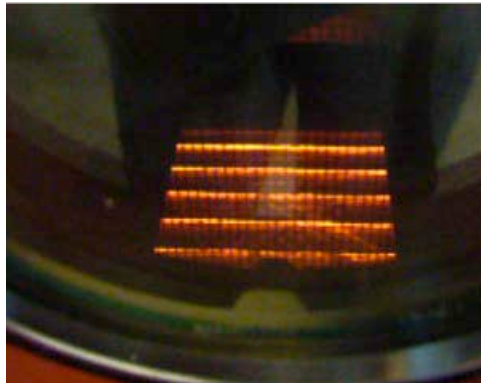
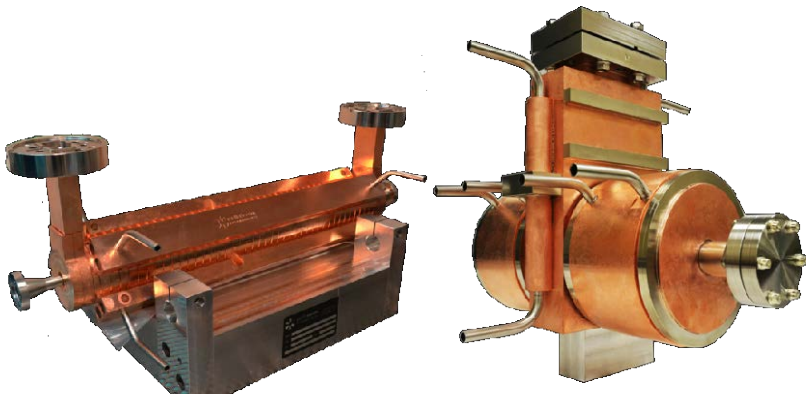
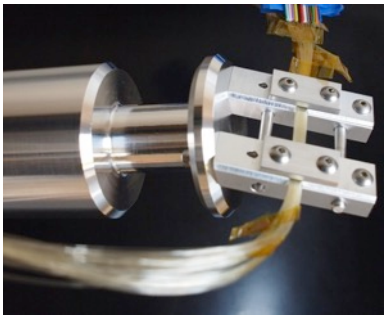
Growing list of customers...



Multiple Funding Agencies



- SBIR/STTR, BAA, commercial funded and self-funded R&D to develop new products and technical solutions



AM development at RadiaBeam



- 2006 to present: DOE and DHS SBIR/STTR, as well as Internal R&D funded
 - \$3.5M invested in copper, niobium, and multi-material EBM AM R&D
- Active collaboration with NC State, UTEP, JLab, UC Berkeley, LANL
- Developed accelerator designs and methods exploiting AM
 - NCRF accelerators (copper): US Patent 7,411,361 (2008): *Method and Apparatus for Radio Frequency Cavity*
 - SRF accelerators (niobium): US Patent 9,023,765 (2015); Joint patent with JLab - *Additive Manufacturing Method for SRF Components of Various Geometries*
- Dissimilar metal joining (Inconel 718 to 316 SS)
 - Applications in nuclear (fission and fusion) and concentrated solar power components (DOE Nuclear Energy Phase I/II (DE-SC0011826))
- RadiaBeam-led collaborations first to developed EBM AM process parameters for pure copper and niobium for NCRF and SRF components
 - T. Horn et. al., *Fabricating Copper Components with Electron Beam Melting*, Advanced Materials & Processes, Vol. 172, Iss. 7, July 2014 (ASM International)
 - C. Terrazas et. al., *Fabrication and characterization of high-purity niobium using electron beam melting additive manufacturing technology*, Int. J. Adv. Manuf. Technol., DOI 10.1007/s00170-015-7767-x
 - P. Frigola et. al., “Novel Fabrication Technique for the Production of RF Photoinjectors”, EPAC’08, Genoa, Italy, pp. 751-753 (2008).
 - P. Frigola et. al., “Advance Additive Manufacturing Method for SRF Cavities of Various Geometries”, SRF2015, Whistler, BC, Canada (2015)

United States Patent Application Publication
Pub. No.: US 2008/012983 A1
Pub. Date: Jan. 9, 2008

United States Patent
Patent No.: US 7,411,361 B1
Date of Patent: May 5, 2008

Method and Apparatus for Radio Frequency Cavity

Method and Apparatus for Radio Frequency Cavity

Fabricating Copper Components with Electron Beam Melting

Direct fabrication of fully dense metal structures using the electron beam melting (EBM) process developed by Annunzio, et al. has been successfully demonstrated for a wide range of materials including Ti-6Al-4V, Inconel 625, and Inconel 718. A growing interest in additive manufacturing (AM) for high performance components from copper and copper alloys is spurred by a variety of applications including novel radio frequency (RF) accelerating structures.

A critical issue for high average power, high brightness photoinjectors—the technology of choice for generating high brightness electron beams used in many of today's linear accelerators—is efficient cooling. RadiaBeam Technologies is exploring the use of AM to fabricate complex RF photoinjectors with geometries optimized for thermal management. Specially optimized internal cooling channels can be fabricated without the constraints typically associated with traditional manufacturing methods.

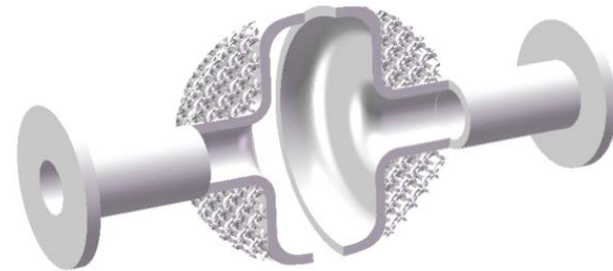
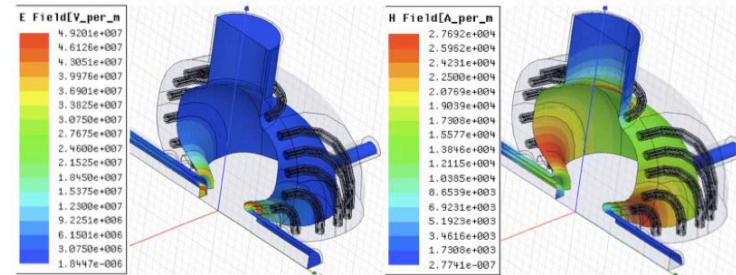
However, several properties of pure copper present significant processing challenges for the next AM. For one, pure copper has a relatively high thermal conductivity (401 W/m·K at 300K) which, while ideal for thermal management applications, rapidly conducts heat away from the melt area resulting in local thermal gradients. This can lead to layer curling, distortion, and ultimately build part failure. Additionally, copper's high ductility hinders post-build powder removal and recovery. Particles also tend to agglomerate, reducing overall flowability and resulting powder flow time. Because Cu is sensitive to oxidation, good care must be taken in handling and storage before, during, and after fabrication.

Fabrication methods. Initial experiments focused on developing viable parameters for processing copper using EBM. An Arcam model 112 at Los Alamos National University and an Arcam model A1 at the University of Texas El Paso fabricated the samples for these experiments. EBM parameters described elsewhere in detail. A circular start size made of oxygen free, high conductivity (OFHC) copper measuring approximately 10 x 10 mm (level) on a 10 mm thick bed of loose powder was the build substrate. Initially, the electron beam scans the start plate surface at high power and high speed, raising the powder temperature and causing it to lightly sinter together. This mechanical bond facilitates copper powder layer typical requires two separate parameter groups called shoves, which contain all of the required process parameters, such as beam speed and power, and focus offset. The first step, melting, which raises the powder temperature and causes it to lightly sinter together. This mechanical bond facilitates copper powder layer typical requires two separate parameter groups called shoves, which contain all of the required process parameters, such as beam speed and power, and focus offset. The first step, melting, which raises the powder temperature and causes it to lightly sinter together. This mechanical bond facilitates copper powder layer typical requires two separate parameter groups called shoves, which contain all of the required process parameters, such as beam speed and power, and focus offset.

ADVANCED MATERIALS & PROCESSES • JULY 2014

Why make accelerators using AM?

- Improve average power performance (thermal load)
 - Efficient cooling designs
- Improve peak power performance (RF breakdown)
 - Superior (engineered) material properties
- Revolutionize cavity design
 - Eliminate brazing/joining; monolithic design
 - Realize truly novel designs (and materials)
- Reduce time and cost of fabrication

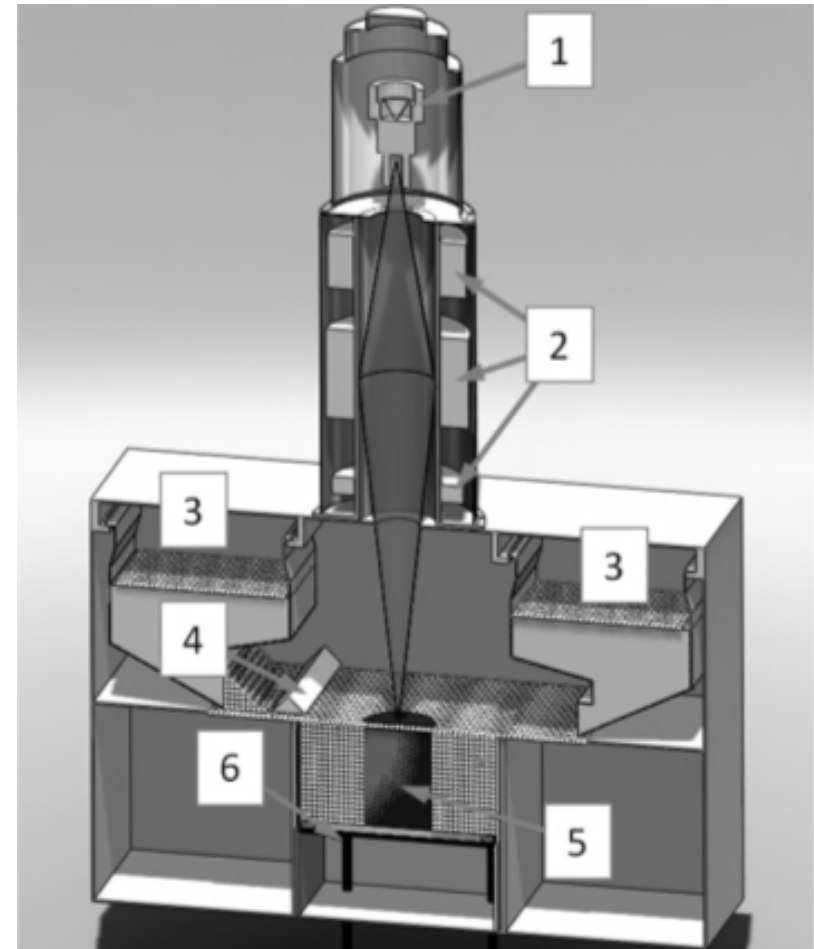


- Exploring AM for:
 - Alternative (non rare-earth) permanent magnets
 - Intermetallics compounds for SRF accelerator applications
 - Ceramics for Dielectric Wakefield Accelerator applications
 - Amorphous metals for induction accelerators
 - **Multi-material capability**
 - Repair (high value) damage components
 - Refractory metals for x-ray converters

EBM Background

- Arcam Electron Beam Melting (EBM)

1. Thermionic gun (60 kV)
2. Magnetic optics
3. Hoppers
4. Mechanical rake
5. Built part
6. Building platform



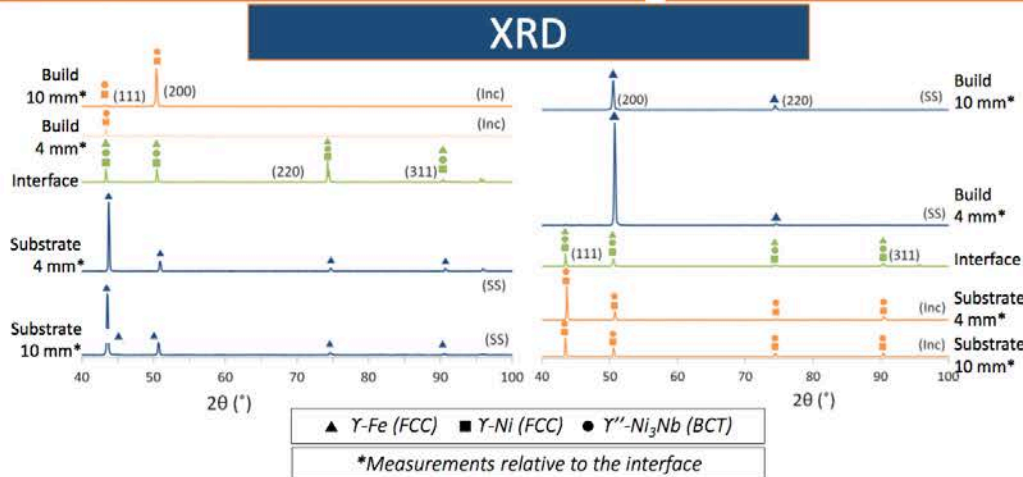
Project Goals and Relevance to DOE Nuclear Power

- Project Goal
 - Phase I – Experimentally demonstrate feasibility of joining dissimilar metals using EBM AM.
 - Phase II – Further the fundamental understanding of dissimilar metal joining using EBM AM
- DOE NE Relevance
 - Avoids use of filler materials
 - Vacuum ($\sim 10^{-4}$ Torr) limits contamination of oxides and nitrides
 - High quality joint while minimizing the thermal damage to surrounding material
 - Promise of realizing complex multi-material parts

- Research explored the feasibility of joining Inc718 and 316L SS using EBM AM.
- Simple geometries suitable for material testing were fabricated (Inc718 on 316L and 316L on Inc718) using Arcam EBM, and the joints characterized
- Material testing showed reduced presence of precipitates and narrower HAZ when compared to traditional welding processes
- Change in mechanical properties in the HAZ and the substrate were not greatly affected
- A. Hinojos et. al., *Joining of Inconel 718 and 316L Stainless Steel using powder bed fusion additive manufacturing technology*, Mater. Sci. Eng.: A, Pending review (Sept. 2015)

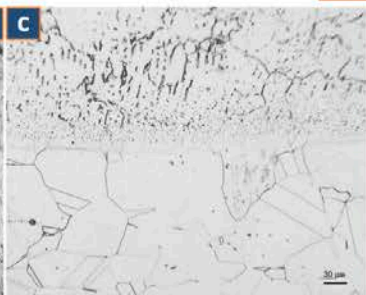
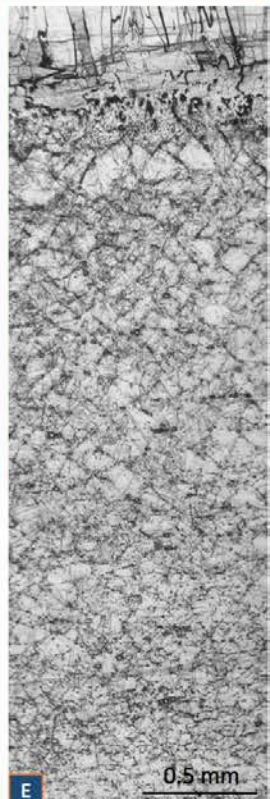
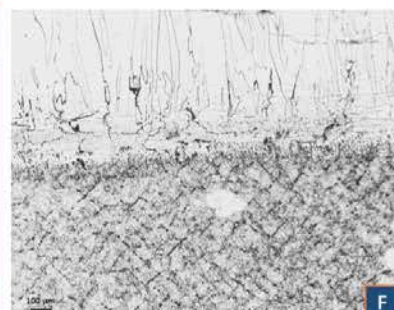
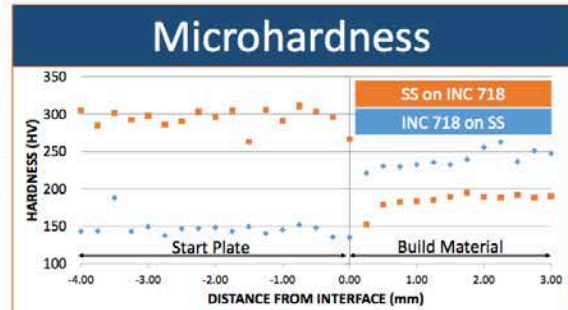
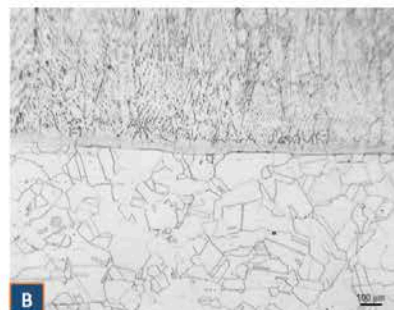
Inconel 718 (EBM) on 316L Stainless Steel

316L Stainless Steels (EBM) on Inconel 718



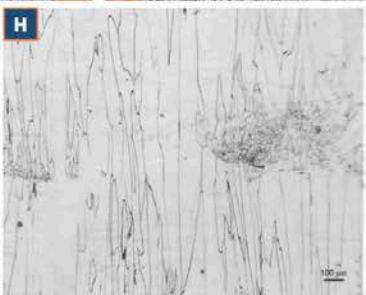
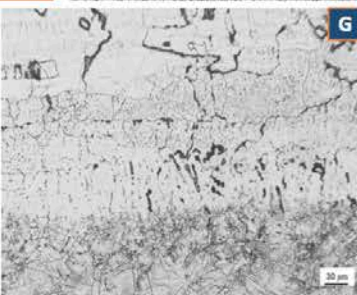
XRD scans were done 4mm from the interface and the edge in both the substrate and the build.

XRD showed characteristic peaks of γ -Fe (FCC $a=3.60 \text{ \AA}$), γ -Ni (FCC $a=3.59 \text{ \AA}$), γ'' -Ni₃Nb (BCT $a=3.60 \text{ \AA}$ $c=7.41 \text{ \AA}$).



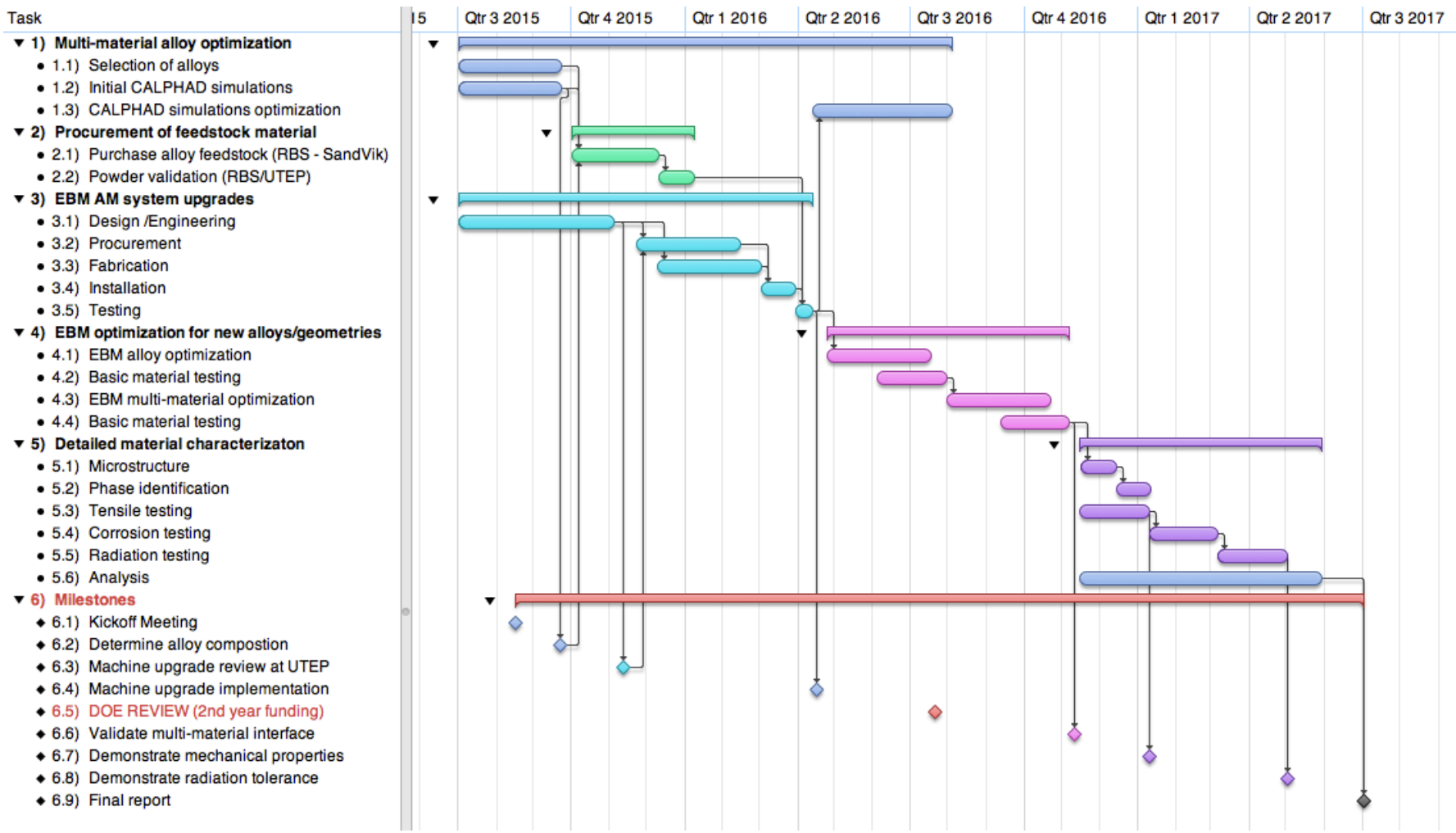
Metallography

- Figures A-D are EBM-fabricated Inc 718 on SS.
- Figures E-F are EBM-fabricated SS on Inc 718.
- Figures A & E represent areas beneath the start plate showcasing the HAZ.
- Figures B-C & F-G show the joined interface.
- D & H are the microstructures of the EBM-fabricated materials.



- Phase II goal: Further the fundamental understanding of dissimilar metal joining using EBM AM
 - Introduce simulations to guide material choice in joint design
 - Extend EBM processing to ferritic alloys
 - Extend material testing to nuclear reactor environmental conditions (high temperature, pressure, radiation)

Project schedule



Acknowledgements

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STTR Collaborators:

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- Ashley Reichardt, Peter Hosemann, Department of Nuclear Engineering at the University of California Berkeley
- Stuart Maloy, Ion Beam Materials Laboratory at Los Alamos National Laboratory