Development of Nuclear Quality Components using Metal Additive Manufacturing

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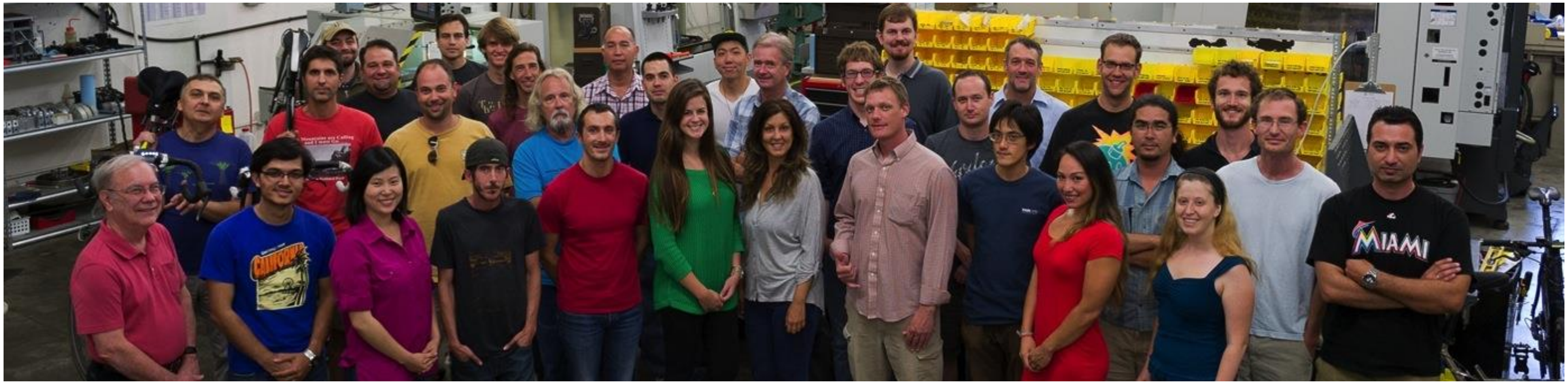
Advanced Methods for Manufacturing Workshop
Lockheed Martin, September 29, 2015

Outline

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

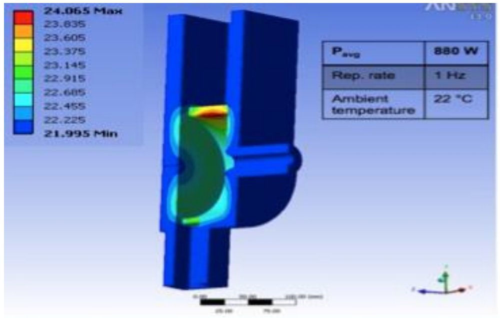
Who we are

- 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)

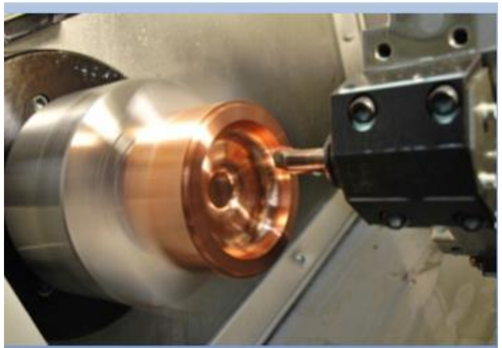


Capabilities

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



P_{avg}	880 W
Rep. rate	1 Hz
Ambient temperature	22 °C

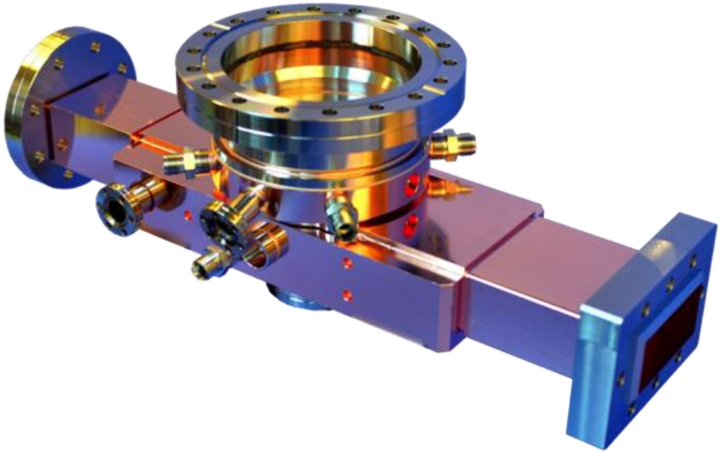


Facilities

- 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!

Products

- 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)



radiabeam SYSTEMS

Growing list of customers…

Argonne NATIONAL LABORATORY
ISL
iba
SPARKLE RADIOPHARMACEUTICALS
CERN
NSRRC

CINEL
KAERI
healthcare for everyone TeamBest® Your True Partner
University of Colorado
UNIVERSITY of HAWAI'I® MĀNOA
UNIVERSITY OF Nebraska Lincoln

東京大学 THE UNIVERSITY OF TOKYO
NIOWAVE Accelerating Your Particles
Schlumberger
ACCURAY®
Sterigenics.
Fermilab
SIEMENS
Yale University
Lawrence Livermore National Laboratory
EUROTEK
Mizzou University of Missouri - Columbia
TRIUMF
excillum
BROOKHAVEN NATIONAL LABORATORY

UCLA
VETENSKAP OCH KONST KUNGL TEKNISKA HÖGSKOLAN
TRAD Tests & radiations
BERKELEY LAB
ess EUROPEAN SPALLATION SOURCE
LNLS Laboratório Nacional de Luz Síncrotron sirius
INFN Istituto Nazionale di Fisica Nucleare

OAK RIDGE National Laboratory
WRIGHT STATE UNIVERSITY
Idaho Accelerator Center
प्रगत प्रौद्योगिकी केन्द्र, इंदौर CENTRE FOR ADVANCED TECHNOLOGY, INDORE
PAL
Canadian Light Source Centre canadien de rayonnement synchrotron

ARIEL UNIVERSITY
ENEA ENTE PER LE NUOVE TECNOLOGIE, L'ENERGIA E L'AMBIENTE
INDIANA UNIVERSITY BLOOMINGTON
Sandia National Laboratories
CANDLE
Los Alamos NATIONAL LABORATORY
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

MICHIGAN®
KIT Karlsruher Institut für Technologie
FERMI @elettra
SLAC NATIONAL ACCELERATOR LABORATORY
MAX IV
SOLEIL SYNCHROTRON
VANDERBILT UNIVERSITY
PAUL SCHERRER INSTITUT PSI

Multiple Funding Agencies

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

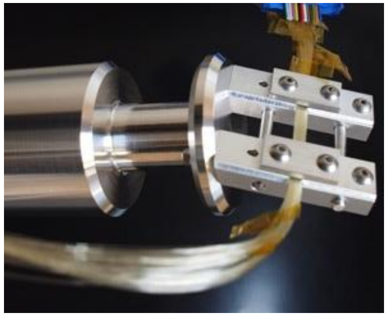
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

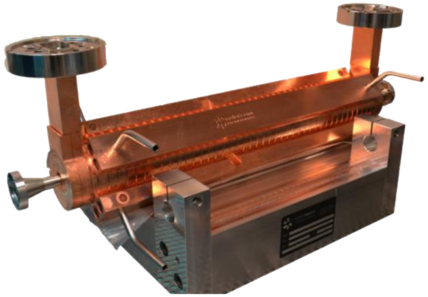
U.S. DEPARTMENT OF HOMELAND SECURITY

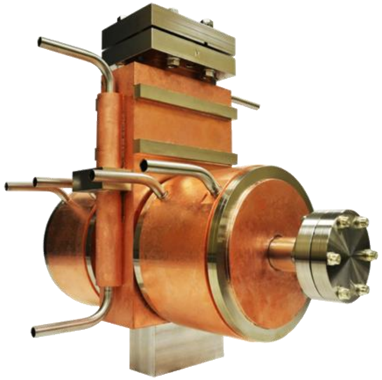
DEFENSE THREAT REDUCTION AGENCY UNITED STATES OF AMERICA

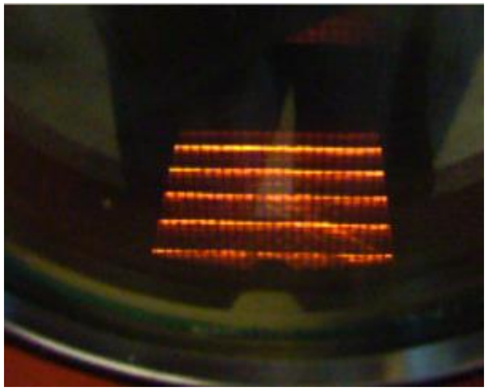
NSF

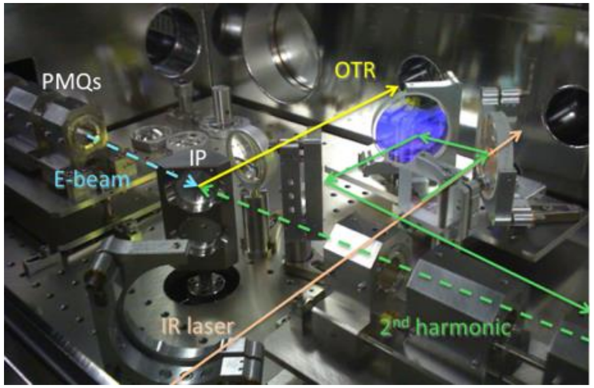
DARPA

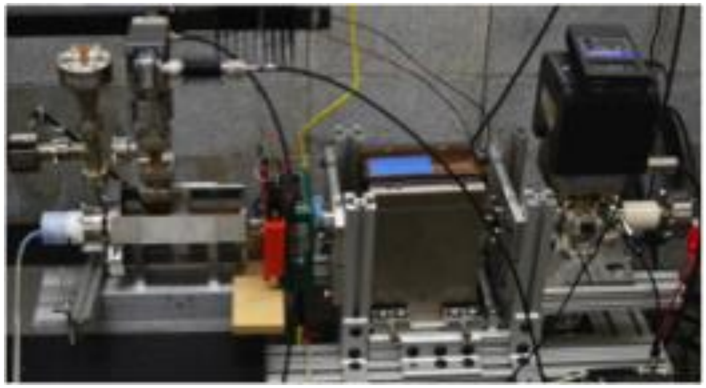






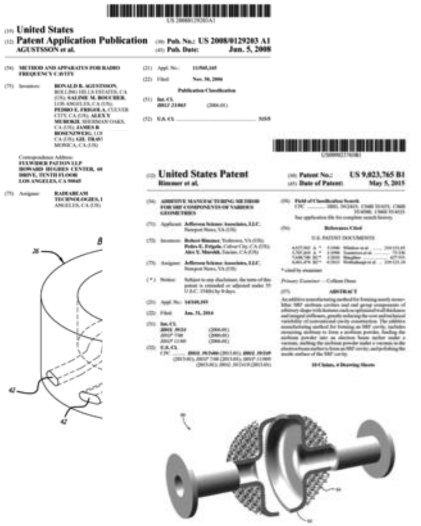






AM development at RadiaBeam

- 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)



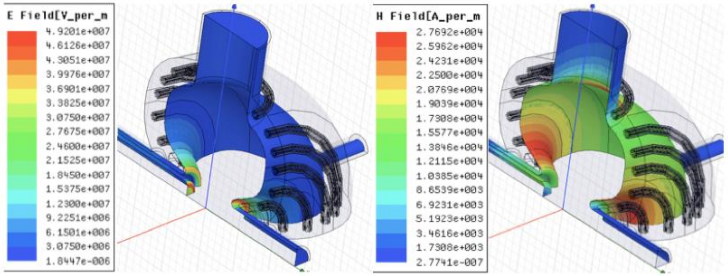
United States
Patent Application Publication
AGUSTSSON et al.
Pub. No.: US 2008/0129203 A1
Pub. Date: Jun. 5, 2008
METHOD AND APPARATUS FOR RADIO FREQUENCY CAVITY

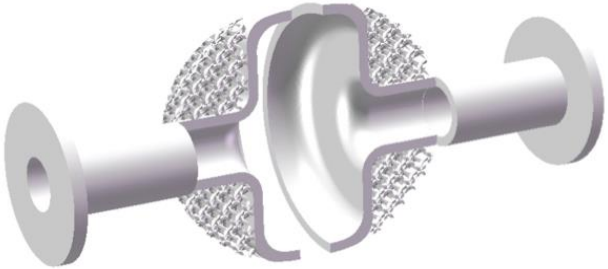
United States Patent
Rimmer et al.
Patent No.: US 9,023,765 B1
Date of Patent: May 5, 2015
ADDITIVE MANUFACTURING METHOD FOR SRF COMPONENTS OF VARIOUS GEOMETRIES

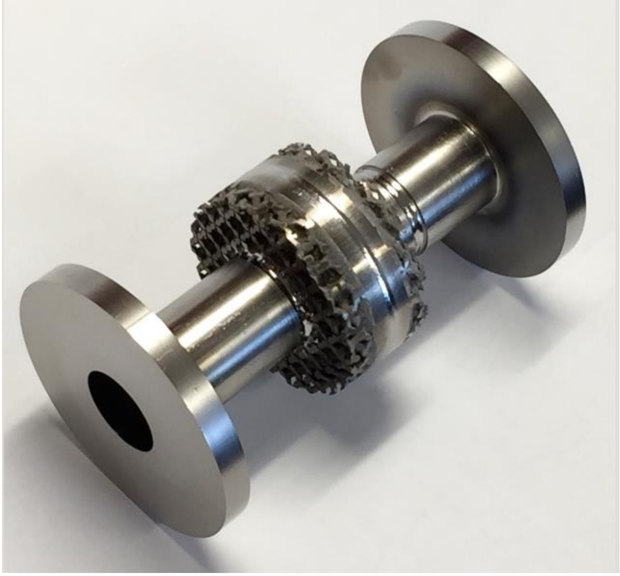
Fabricating Copper Components with Electron Beam Melting

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







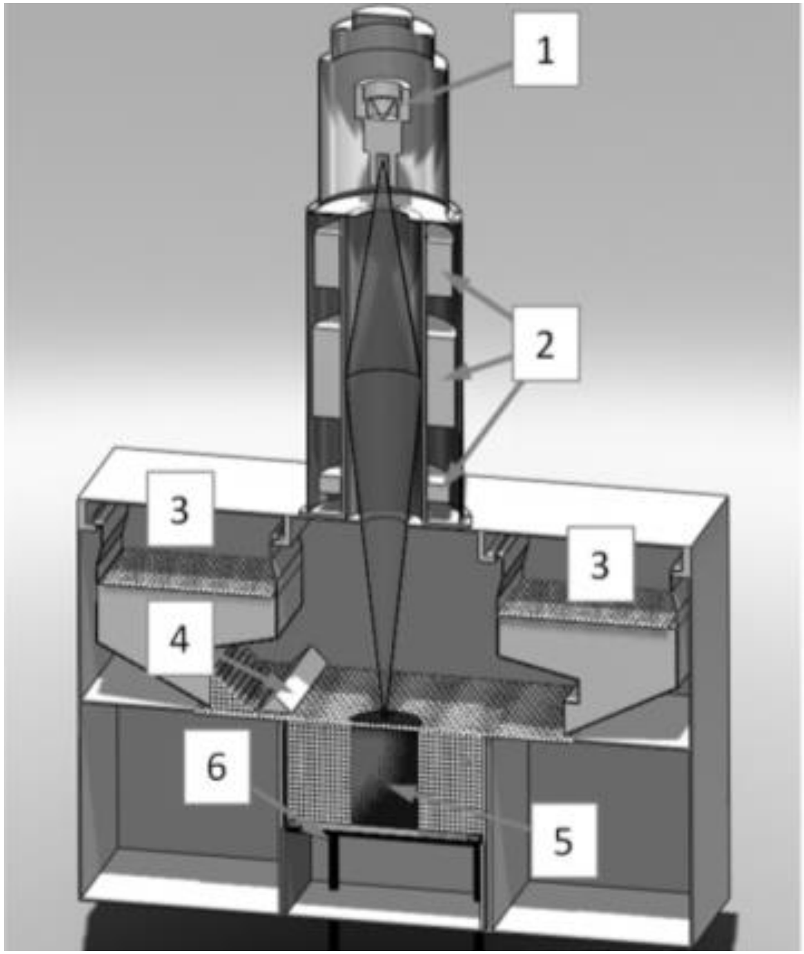
Active areas of interest

- 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 (~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

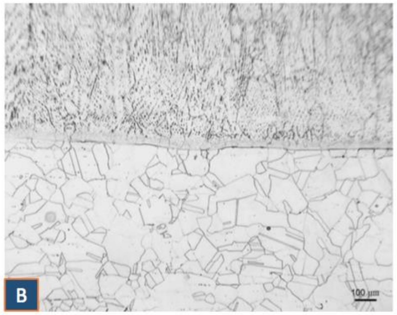
Phase I Summary

- 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)

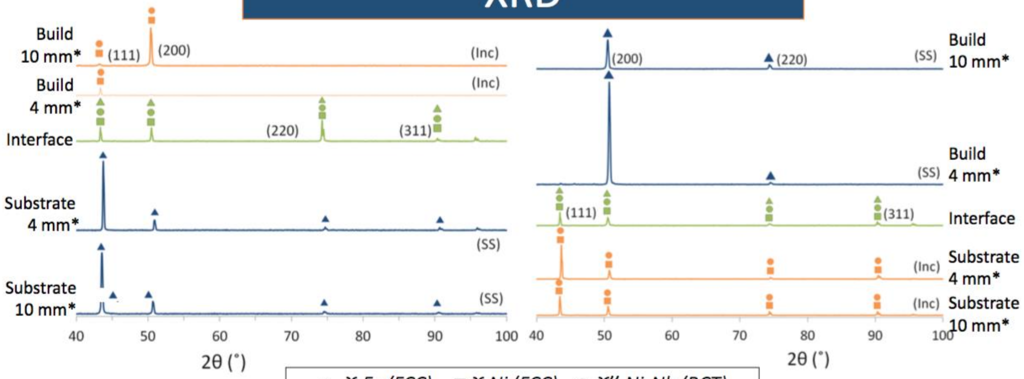
Joint Characterization

Inconel 718 (EBM) on 316L Stainless Steel

316L Stainless Steels (EBM) on Inconel 718



XRD

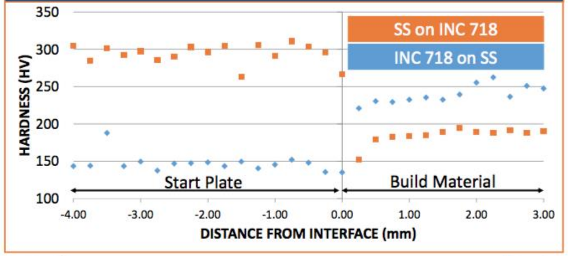


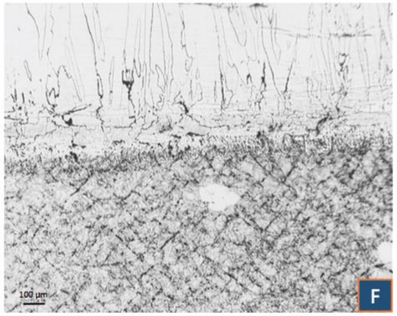
▲ Υ-Fe (FCC) ■ Υ-Ni (FCC) ● Υ''-Ni$_3$Nb (BCT)

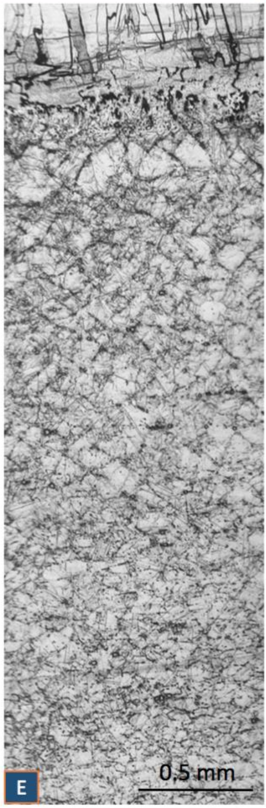
**Measurements relative to the interface*

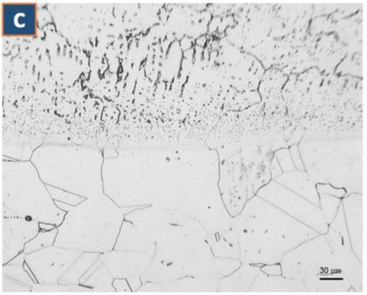
- ☐ XRD scans were done 4mm from the interface and the edge in both the substrate and the build.
- ☐ XRD showed characteristic peaks of Υ-Fe (FCC a=3.60 Å), Υ-Ni (FCC a=3.59 Å), Υ''-Ni$_3$Nb (BCT a=3.60 Å c=7.41 Å).

Microhardness



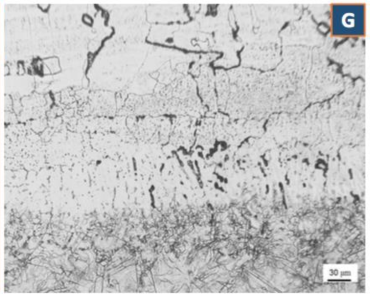


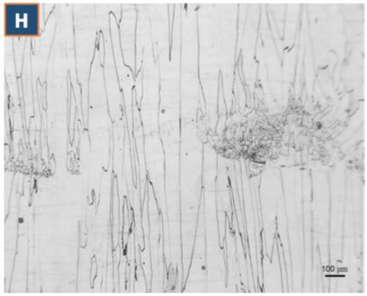




Metallography

- ☐ 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.

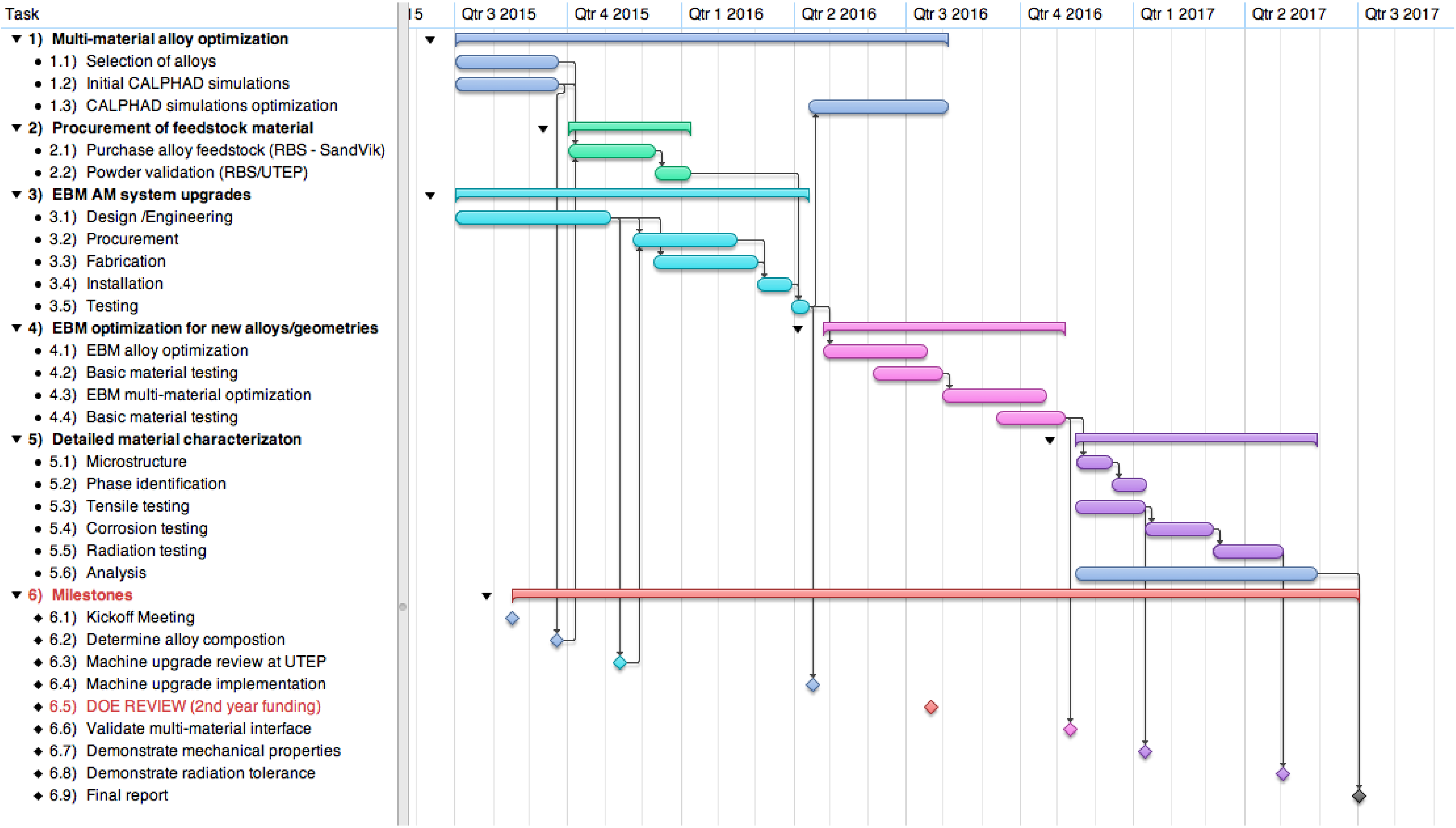




Phase II

- 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



Task

- 1) **Multi-material alloy optimization**
  - 1.1) Selection of alloys
  - 1.2) Initial CALPHAD simulations
  - 1.3) CALPHAD simulations optimization
- 2) **Procurement of feedstock material**
  - 2.1) Purchase alloy feedstock (RBS - SandVik)
  - 2.2) Powder validation (RBS/UTEP)
- 3) **EBM AM system upgrades**
  - 3.1) Design /Engineering
  - 3.2) Procurement
  - 3.3) Fabrication
  - 3.4) Installation
  - 3.5) Testing
- 4) **EBM optimization for new alloys/geometries**
  - 4.1) EBM alloy optimization
  - 4.2) Basic material testing
  - 4.3) EBM multi-material optimization
  - 4.4) Basic material testing
- 5) **Detailed material characterizaton**
  - 5.1) Microstructure
  - 5.2) Phase identification
  - 5.3) Tensile testing
  - 5.4) Corrosion testing
  - 5.5) Radiation testing
  - 5.6) Analysis
- 6) **Milestones**
  - 6.1) Kickoff Meeting
  - 6.2) Determine alloy compostion
  - 6.3) Machine upgrade review at UTEP
  - 6.4) Machine upgrade implementation
  - 6.5) DOE REVIEW (2nd year funding)
  - 6.6) Validate multi-material interface
  - 6.7) Demonstrate mechanical properties
  - 6.8) Demonstrate radiation tolerance
  - 6.9) Final report

Acknowledgements

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STTR Collaborators:

- Alejandro Hinojos, Jorge Mireles, Sara M. Gaytan, Lawrence E. Murr, Ryan B. Wicker, W.M. Keck Center for 3D Innovations at the University of Texas at El Paso
- 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