Advance Additive Manufacturing Method for SRF Cavities of Various Geometries

DOE Nuclear Physics STTR Grant: DE-SC0007666

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DOE Nuclear Physics SBIR/STTR Exchange Meeting Aug. 6-7, 2014
Acknowledgments

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**DOE NP STTR Phase I/II Grant DE-SC0007666**
Outline

- RadiaBeam Technologies Overview
- AM Research History at RadiaBeam
- Overview of EBM AM Technology
- Goals and Relevance of Project
- Phase II Work
Founded in 2004 as a spin-off from UCLA’s Particle Beam Physics Lab

Core Mission:
- Provide well-engineered, high quality, cost-optimized accelerator systems and components
- Develop novel accelerator technologies and applications

Today: 40 employees
- Consists of PhD Scientists (7), Engineers (19), Machinists (6), Technicians (5), and Administrative (3)
- Experience from working at National Labs (BNL, FNAL, LLNL, LANL) and Industry (SureBeam, L-3, Siemens, Varian, Accuray)
Facilities

- Machine shop (“clean” and regular)
- Magnetic measurements
- RF (cold) test area
- Hot test cell (up to 2 MeV)
- Optics area
- Chemical cleaning and Clean rooms
- Total of 16,000 sq. ft. space
Capabilities

- Design
- Engineering
- Fabrication
- Assembly
- Testing
- Installation
- Service
Products

- Accelerator Systems
- RF structures
  - RF guns (particle sources)
  - Linear accelerators
  - Free Electron Laser (FEL) components
- Magnetic systems
  - Electromagnets
  - Permanent magnets
- Diagnostics
  - Beam profile monitors
  - Bunch length monitors
  - Charge, emittance, etc.

www.radiabeam.com
Accelerator Systems

- Designed specifically for customer’s application
- Wide variety of specs and options available
- Designed, built, delivered, and commissioned complete turnkey systems in < 9 months!

<table>
<thead>
<tr>
<th>Application</th>
<th>Energy</th>
<th>Average Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field-deployable high-energy radiography</td>
<td>1-4 MeV</td>
<td>10 – 100 W</td>
</tr>
<tr>
<td>Cargo Inspection/Fixed-installation Radiography</td>
<td>4-9 MeV</td>
<td>100 – 1000 W</td>
</tr>
<tr>
<td>Oncology</td>
<td>4-20 MeV</td>
<td>100 – 1000 W</td>
</tr>
<tr>
<td>E-beam Sterilization/Processing</td>
<td>10 Mev</td>
<td>10 – 50 kW</td>
</tr>
<tr>
<td>X-ray Sterilization/Processing</td>
<td>7.5 Mev</td>
<td>20 – 200 kW</td>
</tr>
</tbody>
</table>
• Fund R&D to develop new products and technical solutions
AM Research at RadiaBeam

- 2006 to present: DOE and DHS SBIR/STTR, as well as Internal R&D funded
  - Total of 6 Phase Is, and 3 Phase IIs
- Active collaboration with NC State, UTEP, JLab
- Developed accelerator designs and methods exploiting AM
  - NCRF accelerators (copper): US Patent 7,411,361: *Method and apparatus for radio frequency cavity*
  - SRF accelerators (niobium): Joint patent with JLab - pending: *Additive Manufacturing Method for SRF Components of Various Geometries*
- First to developed EBM AM process parameters for copper and niobium
  - C. Terrazas et al., *EBM Fabrication and Characterization of Reactor-Grade Niobium for Superconductor Applications*, Proceeding of Solid Freeform Fabrication Symposium, UT Austin, August 4-5, 2014
Electron Beam Melting Additive Manufacturing (EBM AM) is a fabrication process where parts are built by melting thin layers of metal powder.

An electron beam melts each layer to a geometry defined by a CAD model.

EBM AM parts are fully-dense, functional parts.

EBM AM advantages:

- Cost/time savings
- Excellent material properties
- Freedom in design
ARCAM EBM Overview

ARCAM A2 TECHNICAL DATA

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build tank volume</td>
<td>250x250x400 mm and 350x350x250 mm (W x D x H)</td>
</tr>
<tr>
<td>Maximum build size</td>
<td>200x200x350 mm and 300x200 mm (W x D x H)</td>
</tr>
<tr>
<td>Model-to-Part accuracy, long range¹</td>
<td>+/- 0.20 mm (3σ)</td>
</tr>
<tr>
<td>Model-to-Part accuracy, short range¹</td>
<td>+/- 0.13 mm (3σ)</td>
</tr>
<tr>
<td>Surface finish (vertical &amp; horizontal)²</td>
<td>Ra25/Ra35</td>
</tr>
<tr>
<td>Beam power</td>
<td>50–3500 W (continuously variable)</td>
</tr>
<tr>
<td>Beam spot size (FWHM)</td>
<td>0.2 mm–1.0 mm (continuously variable)</td>
</tr>
<tr>
<td>EB scan speed</td>
<td>up to 8000 m/s</td>
</tr>
<tr>
<td>Build rate²</td>
<td>55/80 cm³/h (Ti6Al4V)</td>
</tr>
<tr>
<td>No. of Beam spots</td>
<td>1–100</td>
</tr>
<tr>
<td>Vacuum base pressure</td>
<td>&lt;1 x 10⁻⁴ mBar</td>
</tr>
<tr>
<td>Power supply</td>
<td>3 x 400 V, 32 A, 7 kW</td>
</tr>
<tr>
<td>Size and weight</td>
<td>1850 x 900 x 2200 mm (W x D x H), 1420 kg</td>
</tr>
<tr>
<td>Process computer/CAD interface</td>
<td>PC</td>
</tr>
<tr>
<td>CAD interface</td>
<td>Standard: STL</td>
</tr>
<tr>
<td>Network</td>
<td>Ethernet 10/100/1000</td>
</tr>
<tr>
<td>Certification</td>
<td>CE</td>
</tr>
</tbody>
</table>

¹ Long range: 100 mm, short range: 10 mm, measured on Arcam Standard Test Part (ASTP).
² Measured on Arcam Standard Test Part (ASTP).
³ Settings optimized for fine surface quality / settings optimized for high build speed.
Project Goals and Relevance

- **Project Goal:** Develop EBM AM for Nb, and experimentally validate SRF performance of prototype component(s)

- **DOE NP Relevance:** SRF cavities and ancillary components are a key technology for DOE NP (and others)
  - Reduce or eliminate joints in current designs
  - Integrated stiffeners for mitigation of: Lorentz force detuning, microphonics, pressure fluctuations
  - Realize truly novel designs – more physics driven, less manufacturing driven
    - Very thin walls (<1mm) with lattice supports
    - Integrate the helium vessel and cavity?
Phase II EBM Process Optimization

- Phase II (Year 1) concentrated on EBM process optimization
  - Feedstock powder
    - Still using reactor grade Nb (RRR~40)
  - Hardware and software improvements to EBM machine
    - New machine interior
    - Operating vacuum improved to low 10-5 Torr (from mid 10-4 Torr)
    - Process monitored real-time with RGA
  - Fabrication of samples for material testing
EBM Parameter Development

- Iterative Design of Experiment (DOE)
  - Improved as-EBM density > 8.55 g/cm³ (from a 8.51 g/cm³ in Phase I)
Microstructure

- EBM bar samples
  - Equiaxed grains in horizontal plane (~250 µm)
  - Elongated grains in vertical plane (~20 layers; ~1 mm)

Wrought Nb; equiaxed grains in all directions
• Performed at JLab SRF Institute using standard “4-probe method”
• Uniform SC properties
• \( T_c \approx 9.1 \) to 9.2 K, with sharp transitions
• As-EBM RRR \( \approx 17-18 \) (roughly half of feedstock material)
• RRR \( \approx 44 \) after BCP dip +800° C 3hr HV in Ti box
SRF Testing

- JLab TE011 cavity employs the removable probe as the center conductor in the coaxial resonator
  - Surface resistance
  - Quench field
  - Compare to wrought Nb
- Probe was EBMed and successfully leak checked
- Tested at JLab
Preliminary results

![Graph showing preliminary results for f = 3.585 GHz, radbeam sample]

- **As machined**
- **BCP (20um)**
- **Ingot Nb (BCP)**

**Legend:**
- Black square: As machined
- Black circle: BCP (20um)
- Red square: Ingot Nb (BCP)
EBM SRF Component Prototypes

Fermilab: 3.9 GHz, 3rd Harmonic SRF Cavity Drawings – Rev. B

Figure 17: HOM coupler used for LEP-II at CERN (Left), TESLA-JLab type coupler (Courtesy of R. Rimmer) (Right).
Challenges (Opportunities)

- Improving as-EBM material quality
  - More parameter optimization near SRF surface(s)
- As-EBM part is rough, “near-net-shape”
  - Improve as-EBM surface roughness; ~ Ra 10µm
  - Centripetal Barrel Polishing (CBP)
  - Laser polishing?
- Size
  - Relatively small (effective) build envelope (~200 mm dia. x 200mm)
- Dedicated Nb EBM machine?

Arcam Q10 - Highlights

- 30% higher productivity
- 30% improved resolution
- Closed powder handling
- Quality verification with Arcam LayerQam™
- Software adapted to volume production
Thank you!

- Questions?
## EBM material development summary

<table>
<thead>
<tr>
<th>Property</th>
<th>EBM Ti6Al4V [I]</th>
<th>Wrought Ti6Al4V (ASTM F1472)</th>
<th>EBM Copper</th>
<th>Wrought C10100 Cu</th>
<th>EBM (reactor grade) Nb</th>
<th>Wrought Reactor Grade Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>&gt;99.9%</td>
<td>8.84 g/cm³</td>
<td>8.90 g/cm³</td>
<td>8.55 g/cm³</td>
<td>8.57 g/cm³</td>
<td></td>
</tr>
<tr>
<td>Electrical Conductivity @ 20°C</td>
<td>-</td>
<td>-</td>
<td>97% IACS</td>
<td>102% IACS</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RRR</td>
<td>-</td>
<td>-</td>
<td>19</td>
<td>40</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity (@ 21°C)</td>
<td>-</td>
<td>-</td>
<td>390 W/m*K</td>
<td>391 W/m*K</td>
<td>50 W/m*K</td>
<td>53.7 W/m*K</td>
</tr>
<tr>
<td>YS (Rp 0.2)</td>
<td>950 MPa</td>
<td>860 MPa</td>
<td>76 MPa</td>
<td>69 MPa</td>
<td>135 MPa</td>
<td>110 MPa</td>
</tr>
<tr>
<td>UTS (Rm)</td>
<td>1020 MPa</td>
<td>930 MPa</td>
<td>172 MPa</td>
<td>220 MPa</td>
<td>225 MPa</td>
<td>226 MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>14 %</td>
<td>&gt; 10%</td>
<td>-</td>
<td>-</td>
<td>35 %</td>
<td>50 %</td>
</tr>
<tr>
<td>Reduction Area</td>
<td>40%</td>
<td>&gt; 25%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fatigue strength @ 600 MPa</td>
<td>&gt;10 M cycles</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hardness</td>
<td>33 HRC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>120 GPa</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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ARCAM EBM Overview

- Commercialized by ARCAM AB (Sweden) ~ 2000
- First machine sold in the US to NCSU in 2003
- Today ~ 100 machines in the US
- ~ 6 machines in academic institutions (2 at NCSU, 2 in UTEP)
- ORNL’s MDF partner with Arcam in 2012

https://www.youtube.com/watch?v=iegi6D5MKmk
Material testing

Figure 9: Vertical (a) and horizontal (b) micrographs of the EBM niobium showing elongated and irregular grains respectively, when etched with 1 part HF and 4 parts of HNO₃. The arrow depicts the build direction, and the scale shown is 230 μm.
Material testing

Results – EBM purity (XRD)

- XRD revealed clean Nb spectra
  - BCC structure
  - a = 0.33 nm

<table>
<thead>
<tr>
<th>Property</th>
<th>Feedstock Niobium (Reactor Grade – Type 1)</th>
<th>Phase-I EBM Niobium</th>
<th>Phase-II EBM Niobium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>8.57</td>
<td>8.40 – 8.51</td>
<td>&gt; 8.55</td>
</tr>
<tr>
<td>RRR</td>
<td>40 - 50</td>
<td>18-19</td>
<td>17-18</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m*K)</td>
<td>53.7</td>
<td>_</td>
<td>50</td>
</tr>
<tr>
<td>YS (Rp 0.2) MPa</td>
<td>110</td>
<td>_</td>
<td>135</td>
</tr>
<tr>
<td>UTS (Rm) MPa</td>
<td>226</td>
<td>_</td>
<td>225</td>
</tr>
<tr>
<td>Elongation</td>
<td>50 %</td>
<td>_</td>
<td>35 %</td>
</tr>
<tr>
<td>Fatigue strength @ 600 MPa</td>
<td>_</td>
<td>_</td>
<td>In process</td>
</tr>
<tr>
<td>Vickers Hardness (GPa)</td>
<td>0.76 – 1.3</td>
<td>0.82 – 0.86</td>
<td>0.90 – 0.95</td>
</tr>
</tbody>
</table>
**Project Schedule**

- **1.** Design prototype SRF Cavity
  - 1.1. Cavity design choice
  - 1.2. Engineering and CAD model

- **2.** Procurement of feedstock material
  - 2.1. Nb wire
  - 2.2. Nb powder atomization

- **3.** Upgrades to EBM machine
  - 3.1. Procurement Arcam interior
  - 3.2. Pass-through fabrication
  - 3.3. Cleaning and installation

- **4.** EBM optimization for RRR niobium
  - 4.1. EBM parameter optimization
  - 4.2. Material testing and validation
  - 4.3. EBM TE011 cavity probe
  - 4.4. Surface treatment
  - 4.5. DC and RF probe testing

- **5.** EBM Cavity fabrication and testing
  - 5.1. EBM Cavity fabrication
  - 5.2. Mounting and welding
  - 5.3. Mechanical testing
  - 5.4. Surface treatment
  - 5.5. Assembly, bake, and VTA testing

- **6.** Milestones
  - 6.1. Project-Cavity review at JLab
  - 6.2. Project-Machine review at UTEP
  - 6.3. Demonstrate DC and RF SC properties
  - 6.4. Demonstrate mechanical properties
  - 6.5. Single cell cavity high power testing
  - 6.6. End Phase II