Advanced Additive Manufacturing Method for SRF Cavities of Various Geometries

DOE Nuclear Physics STTR Grant: DE-SC0007666

Presented by Marcos Ruelas

on behalf of Pedro Frigola, PI

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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
Who We Are

- Founded in 2004 as a spin-off from the UCLA Particle Beam Physics Laboratory
- Core mission is to provide well-engineered, high quality, cost-optimized accelerator systems and components, & develop novel accelerator technologies and applications
- ~50 employees, including 9 PhD scientists and 22 engineers
- Experience from US Labs, International Labs, Universities, and Industry
- Worldwide sales, service, and consulting
Facilities

- Two Machine shops
- 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
  - Turnkey injectors
  - Transport lines
  - Industrial linacs

- Diagnostics
  - Beam profile monitors
  - Bunch length monitors
  - Charge, emittance, et cetera

- RF structures
  - RF photoinjectors
  - Bunchers
  - Linacs
  - Deflectors

- Magnet systems
  - Electromagnets
  - Permanent magnets
  - Systems (chicanes, final focus, spectrometers)
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>
Multiple Funding Agencies

SBIR, BAA, & commercial funded and self-funded R&D to develop new products and technical solutions
Additive Manufacturing Development at RadiaBeam
AM Development at RadiaBeam

- 2006 to present: DOE and DHS SBIR/STTR, as well as Internal R&D funded
  - Total of 7 Phase Is, and 4 Phase IIs
- 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: Method and apparatus for radio frequency cavity
  - 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)
  - First to developed EBM AM process parameters for copper and niobium
  - C. Terrazas t. 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 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 Ø 300x200 mm (W x D x H)</td>
</tr>
<tr>
<td>Model-to-Part accuracy, long range(^1)</td>
<td>+/- 0.20 mm (3σ)</td>
</tr>
<tr>
<td>Model-to-Part accuracy, short range(^1)</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>FB scan speed</td>
<td>up to 8000 m/s</td>
</tr>
<tr>
<td>Build rate(^3)</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). 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

• Year 1 concentrated on EBM process optimization
  • Feedstock powder
  • Hardware and software improvements to EBM machine
  • Fabrication of samples for material testing

• Year 2 focus on geometry optimization and SRF 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
  - Equiaxied grains in horizontal plane (~ 250 µm)
  - Elongated grains in vertical plane (~20 layers; ~1 mm)

Wrought Nb; equiaxed grains in all directions
## Material Properties

<table>
<thead>
<tr>
<th></th>
<th>EBM Ti6Al4V [16]</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>-</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>
</tr>
<tr>
<td>Electrical</td>
<td>-</td>
<td>-</td>
<td>97 % IACS</td>
<td>102 % IACS</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Conductivity @ 20°C</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RRR</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>Thermal</td>
<td>-</td>
<td>-</td>
<td>390 W/m*K</td>
<td>391 W/m*K</td>
<td>50</td>
<td>53.7</td>
</tr>
<tr>
<td>Conductivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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>
</tbody>
</table>

RRR Measurements

- Performed at JLab SRF Institute using standard “4-probe method”
- Uniform SC properties
- $T_c \sim 9.1$ to $9.2$ K, with sharp transitions
- As-EBM RRR $\sim 17-18$ (roughly half of feedstock material)
- RRR $\sim 44$ after BCP dip +800°C 3hr HV in Ti box
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
TE011 Test Results

TE011 Samples \((f=3.585 \text{ GHz})\)

- **Short pin as-machined**
- **Short pin + BCP (20\(\mu\text{m}\))**
- **Long pin + BCP (50\(\mu\text{m}\))**
- **Ingot Nb + BCP**

**Graph Details:**
- **y-axis:** \(R_s (\mu\Omega)\)
- **x-axis:** \(R_p (\text{mT})\)

**Legend:**
- Green circle: Short pin as-machined
- Purple circle: Short pin + BCP (20\(\mu\text{m}\))
- Red square: Long pin + BCP (50\(\mu\text{m}\))
- Blue diamond: Ingot Nb + BCP
EBM SRF Cavity Prototype Design

Fermilab: 3.9 GHz, 3rd Harmonic SRF Cavity Drawings – Rev. B
2/3/2006
Single cell cavity fabrication

- 3.8 GHz half-cells were AM using EBM technology
- RF surfaces were machined (turned), and half-cells were e-beam welded into two single-cell cavities
- 100µmBCP + annealing at 800° C/3h + 20µm BCP
SRF Test Results

- Qo, Eacc, and Hpeak low compare to wrought reactor grade cavity
- Encouraging results: Quench field corresponding to \( \sim 10 \text{ mT} \)
Phase II +

- Develop commercial end-group components
- Improving as-EBM material quality
  - Focus on AM process parameters near SRF surface(s)
- Improve “near-net-shape” capability
  - Improve as-EBM surface roughness; ~ Ra 10µm
  - Centripetal Barrel Polishing (CBP) + Electro polishing (EP)
- Partner with EBM platform manufacture to develop custom machine
Thank you!

Questions?
Extra slides
• 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
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
  - \( a = 0.33 \text{ nm} \)

<table>
<thead>
<tr>
<th></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>