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

RadiaBeam Overview

- 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

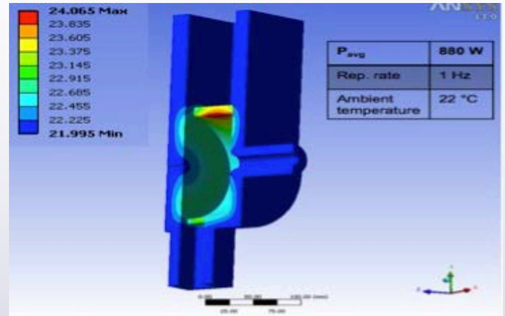
radiabeam TECHNOLOGIES

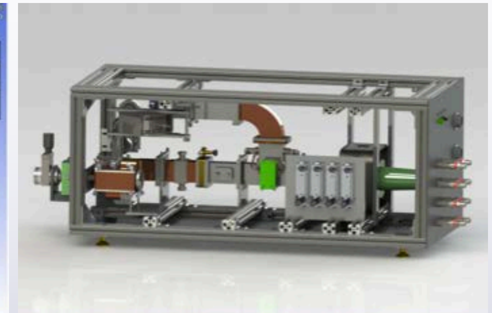
- Machine shop ("clean" and regular)
- Magnetic measurements
- RF (cold) test area
- Hot test cell (up to 2 MeV)
- Optics area
- Chemical cleaning and Clean rooms
- Total of 16,000 sq. ft. space

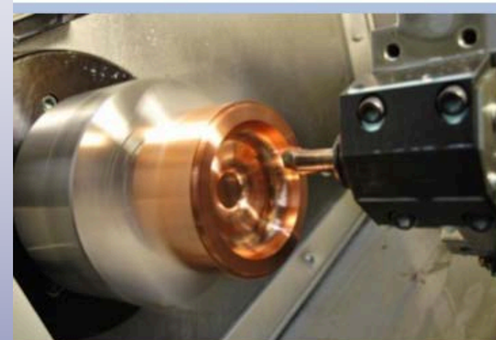
Capabilities

radiabeam TECHNOLOGIES

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

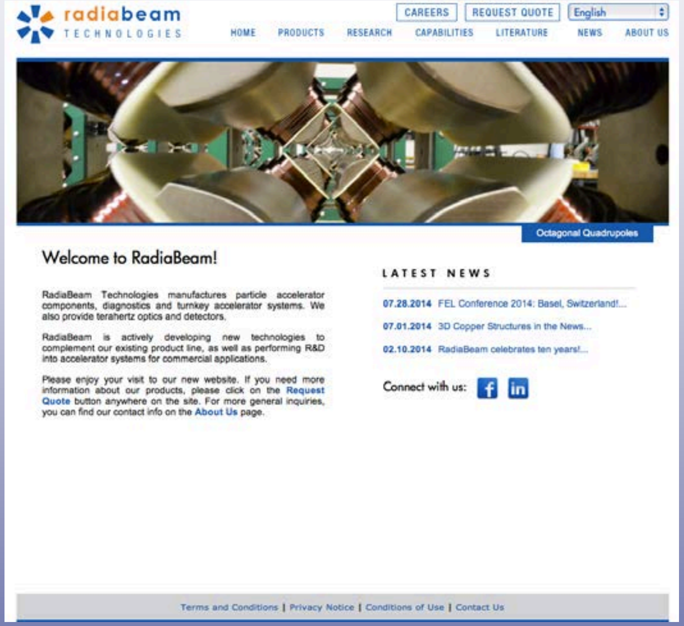






Products

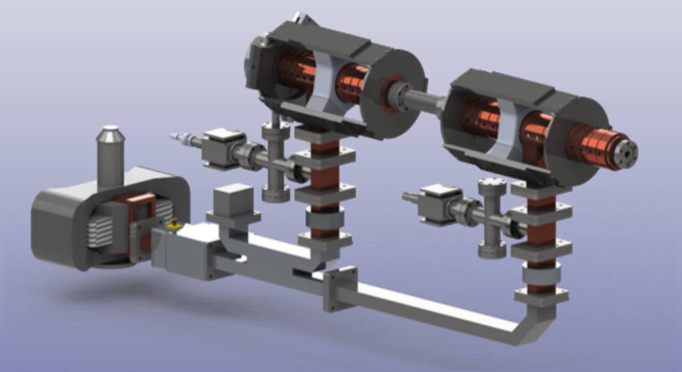
- Accelerator Systems
- RF structures
  - RF guns (particle sources)
  - Linear accelerators
  - Free Electron Laser (FEL) components
- Magnetic systems
  - Electromagnets
  - Permanent magnets
- Diagnostics
  - Beam profile monitors
  - Bunch length monitors
  - Charge, emittance, etc.



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!



Application	Energy	Average Power
Field-deployable high-energy radiography	1-4 MeV	10 – 100 W
Cargo Inspection/Fixed-installation Radiography	4-9 MeV	100 – 1000 W
Oncology	4-20 MeV	100 – 1000 W
E-beam Sterilization/Processing	10 Mev	10 – 50 kW
X-ray Sterilization/Processing	7.5 MeV	20 – 200 kW

radiabeam SYSTEMS

Growing List of Customers

radiabeam TECHNOLOGIES

Argonne NATIONAL LABORATORY
BROOKHAVEN NATIONAL LABORATORY
ENEA ENTE PER LE NUOVE TECNOLOGIE, L'ENERGIA E L'AMBIENTE
FERMI @elettra
SLAC NATIONAL ACCELERATOR LABORATORY
MAX-lab

PAL 포항가속기연구소 Pohang Accelerator Laboratory
TRIUMF
Lawrence Livermore National Laboratory
NIOWAVE
University of Colorado Boulder
INDIANA UNIVERSITY BLOOMINGTON

INFORMATION SYSTEMS LABORATORIES
eXcillum
Yale
CANDLE
Sandia National Laboratories
UCLA

Sterigenics
SPARKLE s.r.l.
PAUL SCHERRER INSTITUT PSI
Schlumberger
SIEMENS
Fermilab

WRIGHT STATE UNIVERSITY
OAK RIDGE National Laboratory
Idaho Accelerator Center
THE UNIVERSITY of WISCONSIN MADISON
Los Alamos NATIONAL LABORATORY
TRAD Tests & radiations

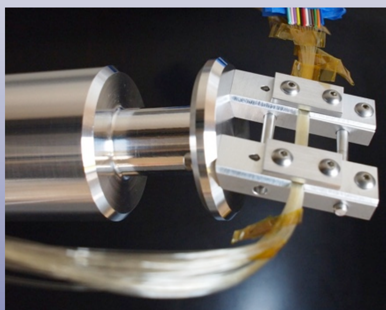
THE COLLEGE OF JUDEA & SAMARIA
BERKELEY LAB
TeamBest healthcare for everyone Your True Partner
iba
ACCURAY
MICHIGAN
KAERI
LNLS

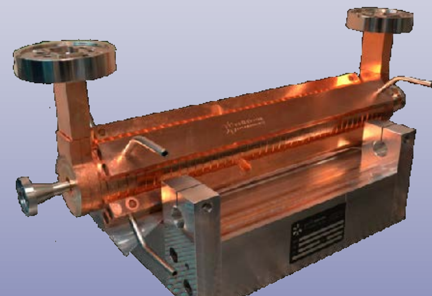
Canadian Light Source Centre canadien de rayonnement synchrotron
東京大学 THE UNIVERSITY OF TOKYO
NSRRC
VANDERBILT UNIVERSITY
UNIVERSITY OF HAWAII 1907
CINEL
INFN
KTH VETENSKAP OCH KONST

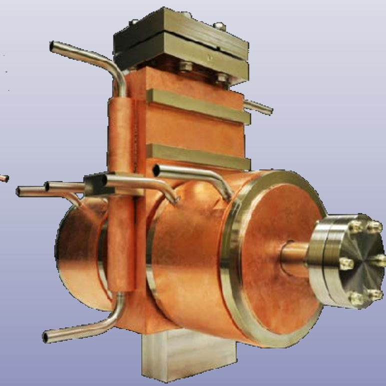
Funding Agencies

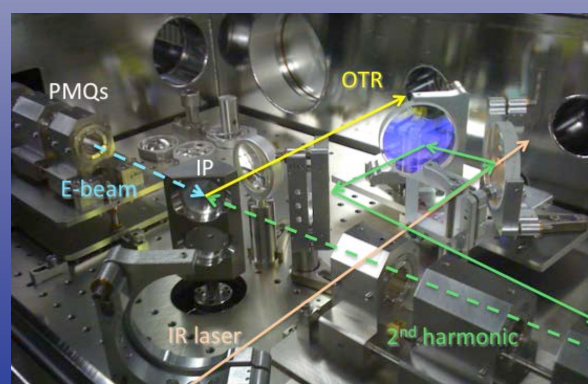
radiabeam TECHNOLOGIES

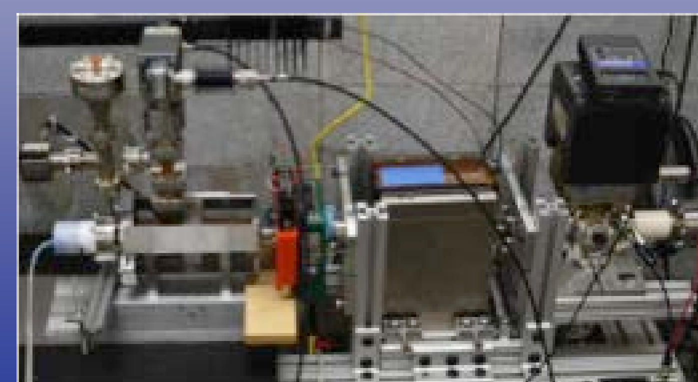
- Fund R&D to develop new products and technical solutions







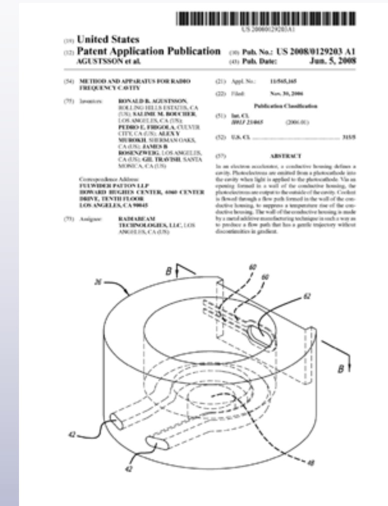




AM Research at RadiaBeam

radiabeam TECHNOLOGIES

- 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
  - *Fabricating Copper Components with Electron Beam Melting*, Advanced Materials & Processes, Vol. 172, Iss. 7, July 2014 (ASM International)
  - 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
  - C. Terrazas, *Characterization of High-Purity Niobium Structures Fabricated using the Electron Beam Melting Process* ,PhD Dissertation, UT El Paso, August, 2014


United States
Patent Application Publication
AGUSTSSON et al.
Pub. No.: US 2008/0129203 A1
Pub. Date: Jun. 5, 2008

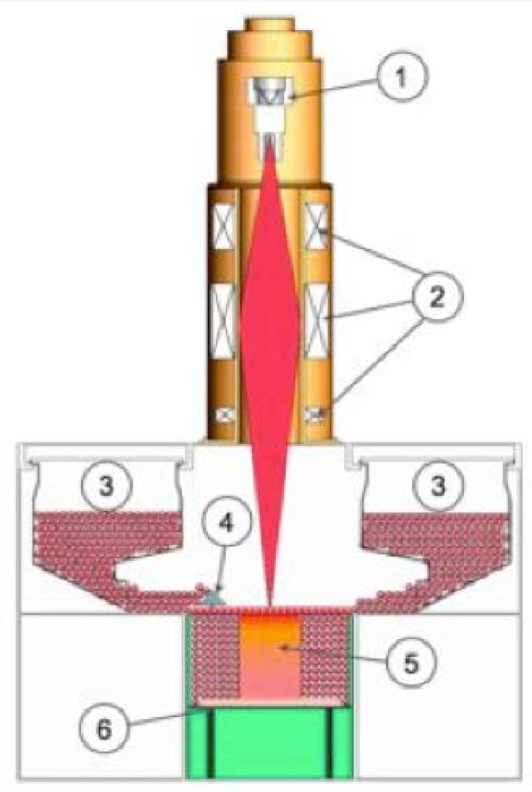

Fabricating Copper Components with Electron Beam Melting

ARCAM EBM® Additive Manufacturing

- Electron Beam Melting Additive Manufacturing (EBM AM) is a fabrication process were 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**


Acetabular cup and Turbine blade

ARCAM EBM Overview



ARCAM A2 TECHNICAL DATA

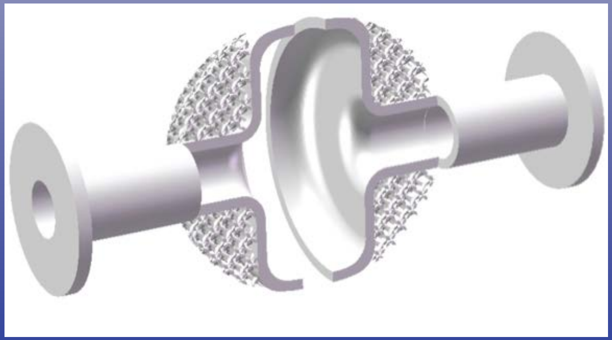
Build tank volume	250x250x400 mm and 350x350x250 mm (W x D x H)
Maximum build size	200x200x350 mm and Ø 300x200 mm (W x D x H)
Model-to-Part accuracy, long range [1]	+/- 0.20 mm (3σ)
Model-to-Part accuracy, short range [1]	+/- 0.13 mm (3σ)
Surface finish (vertical & horizontal) [2]	Ra25/Ra35
Beam power	50–3500 W (continuously variable)
Beam spot size (FWHM)	0.2 mm – 1.0 mm (continuously variable)
EB scan speed	up to 8000 m/s
Build rate [2]	55/80 cm^3/h (Ti6Al4V)
No. of Beam spots	1–100
Vacuum base pressure	$<1 \times 10^{-4}$ mBar
Power supply	3 x 400 V, 32 A, 7 kW
Size and weight	1850 x 900 x 2200 mm (W x D x H), 1420 kg
Process computer CAD interface	PC
CAD interface	Standard: STL
Network	Ethernet 10/100/1000
Certification	CE

[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

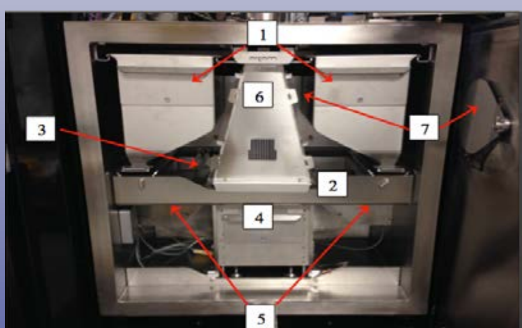
- **Project Goal:** Develop EBM AM for Nb, and experimentally validate SRF performance of prototype component(s)

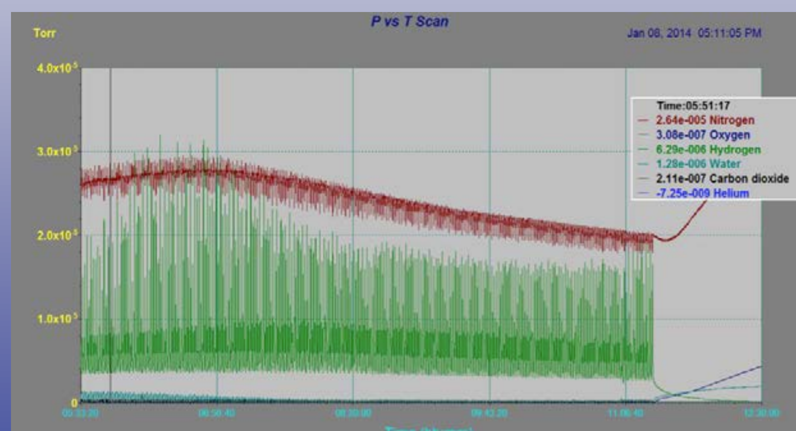
- **DOE NP Relevance:** SRF cavities and ancillary components are a key technology for DOE NP (and others)
  - Reduce or eliminate joints in current designs
  - Integrated stiffeners for mitigation of: Lorentz force detuning, microphonics, pressure fluctuations
  - Realize truly novel designs – more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



Phase II EBM Process Optimization

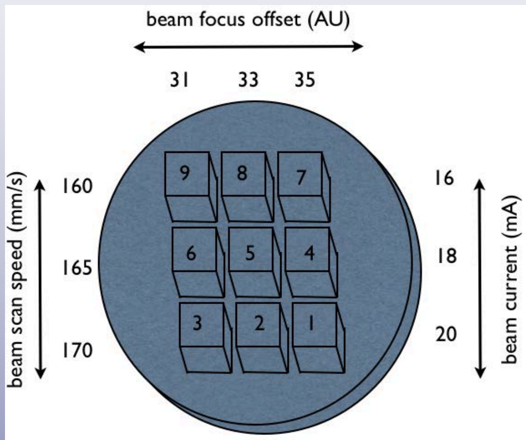
- Phase II (Year 1) concentrated on EBM process optimization
  - Feedstock powder
    - Still using reactor grade Nb (RRR~40)
  - Hardware and software improvements to EBM machine
    - New machine interior
    - Operating vacuum improved to low 10-5 Torr (from mid 10-4 Torr)
    - Process monitored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

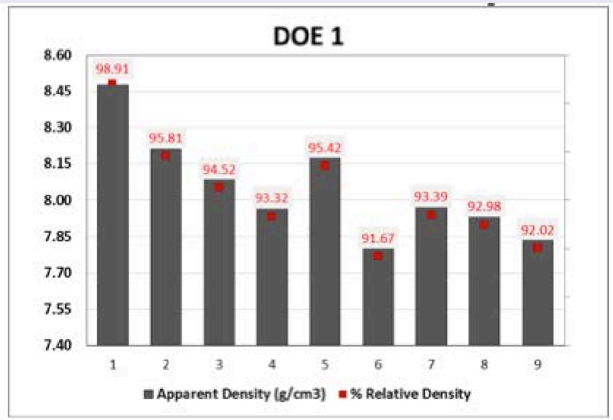


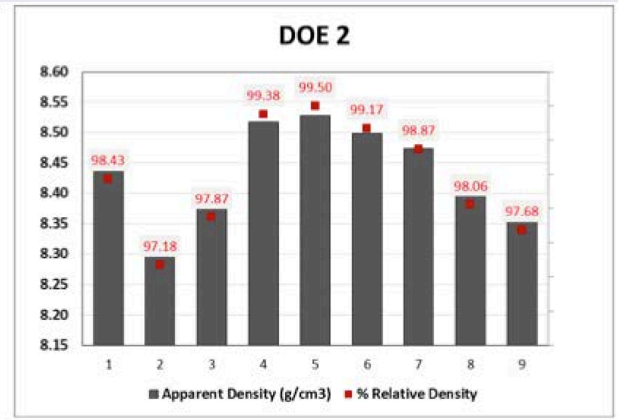


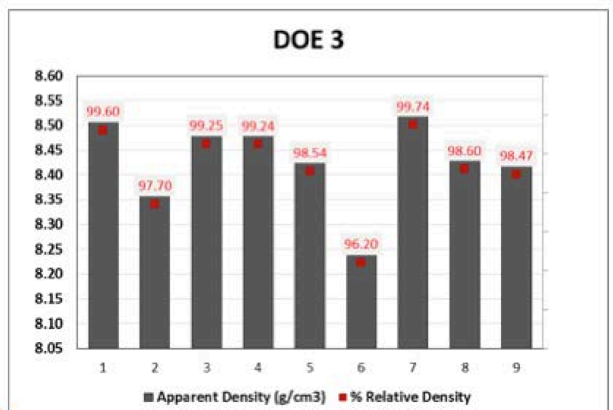
EBM Parameter Development

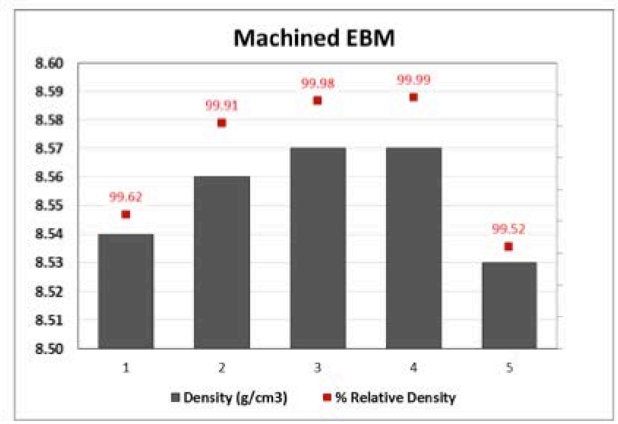
- Iterative Design of Experiment (DOE)
  - Improved as-EBM density > 8.55 g/cm3 (from a 8.51 g/cm3 in Phase I)





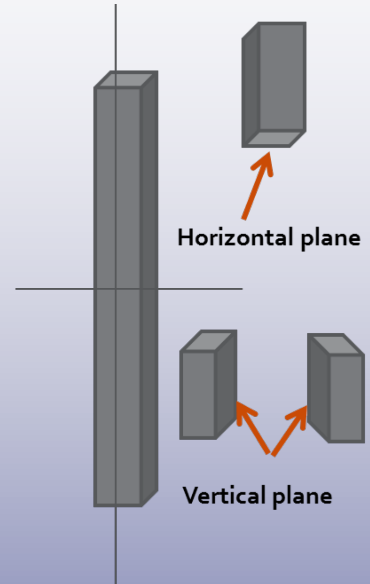


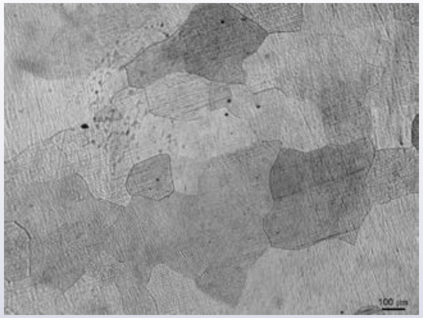


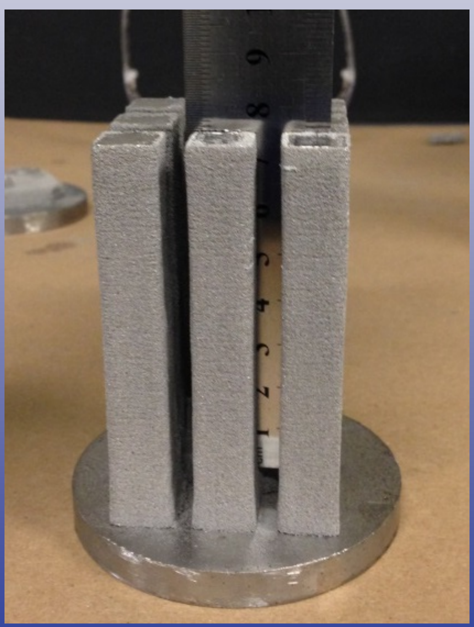


Microstructure

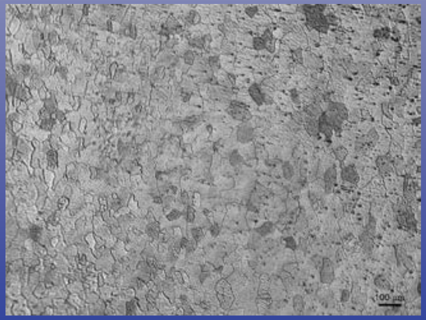
- EBM bar samples
  - Equiaxed grains in horizontal plane (~ 250 μm)
  - Elongated grains in vertical plane (~20 layers; ~1 mm)





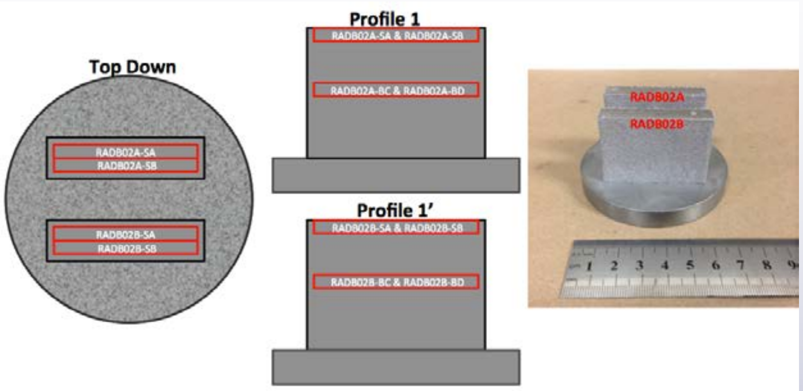


Wrought Nb; equiaxed grains in all directions



RRR Measurements

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



Sample ID	RRR	RRR T_{Low}	RRR T_{High}	T_c	ΔT_c
RADB02A-SA 1	17	10	300	9.06	0.11
RADB02A-SA 2	17	10	300	9.19	0.05
RADB02A-SB 1	18	10	300	9.06	0.06
RADB02A-SB 2	18	10	300	9.21	0.09
RADB02A-BC 1	18	10	300	9.10	0.08
RADB02A-BD 1	17	10	300	9.12	0.11
RADB02A-BD 2	17	10	300	9.18	0.08
RADB02B-SA 1	17	10	300	9.05	0.06
RADB02B-SA 2	18	10	300	9.14	0.17
RADB02B-SB 1	17	10	300	9.07	0.09
RADB02B-SB 2	16	10	300	9.16	0.05
RADB02B-BC 1	18	10	300	9.05	0.12
RADB02B-BC 2	18	10	300	9.19	0.06
RADB02B-BD 1	17	10	300	9.04	0.14
RADB02B-BD 2	17	10	300	9.18	0.08

Sample	RRR by R/R	RRR Low Temperature (K)	RRR High Temperature (K)	Tc (K)	Delta Tc (K)
RADB02A-SB PA	44	10.4	300.0	9.15	0.08

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

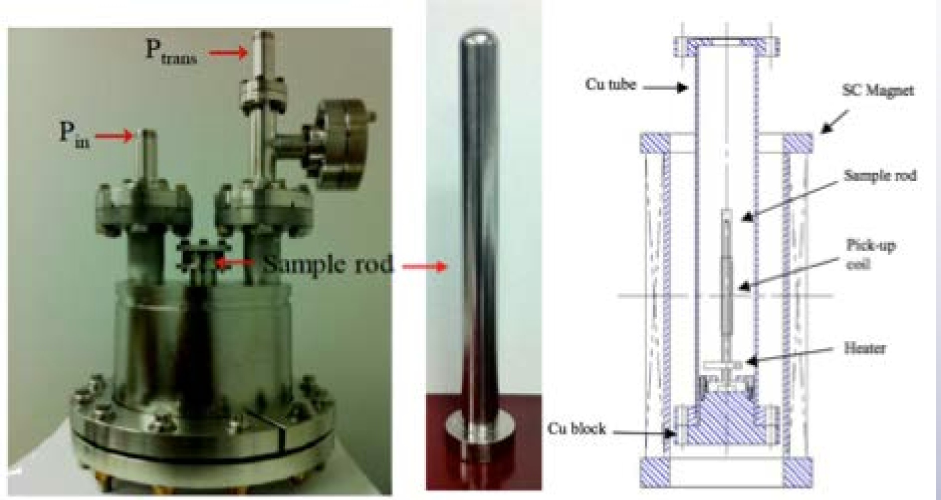
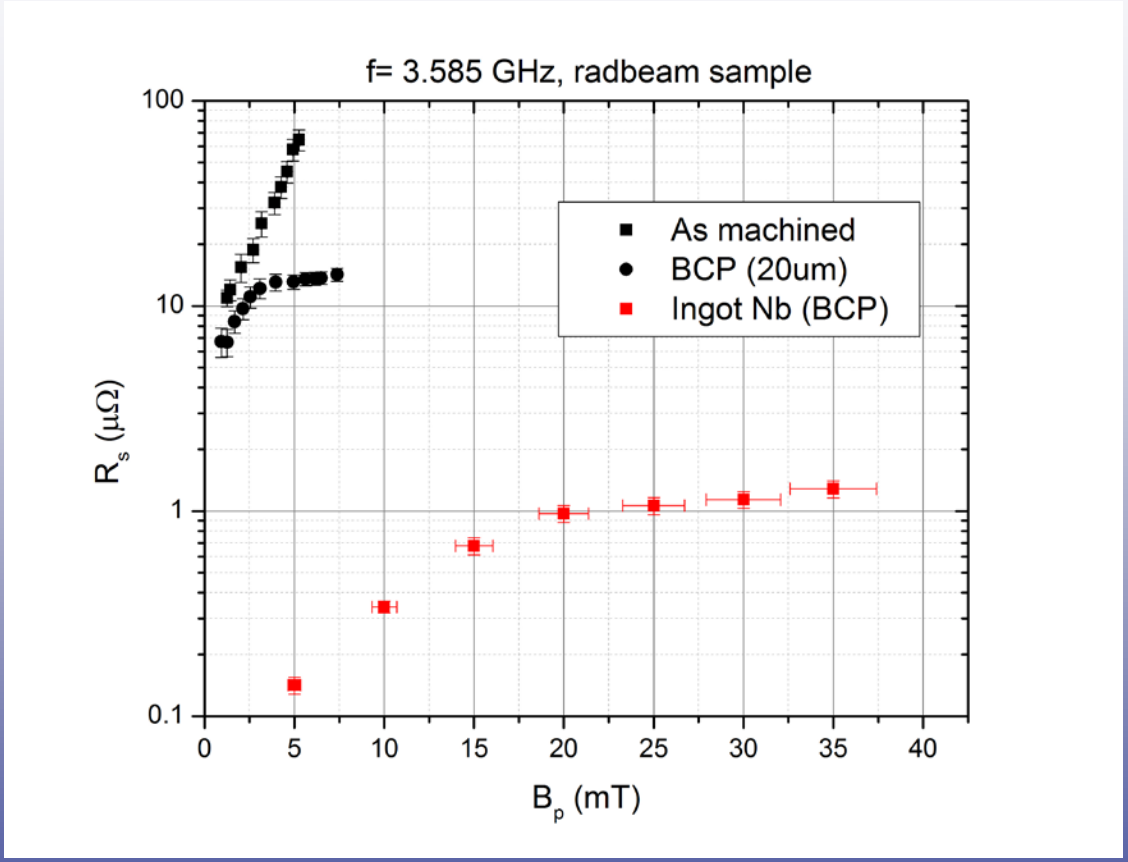


Figure 25: Photograph of the JLab TE011 cavity (Right), sample rod (Center), and system for measurement of superconducting properties (Left). [Courtesy of P. Dhakal, JLab.]

Preliminary results



EBM SRF Component Prototypes

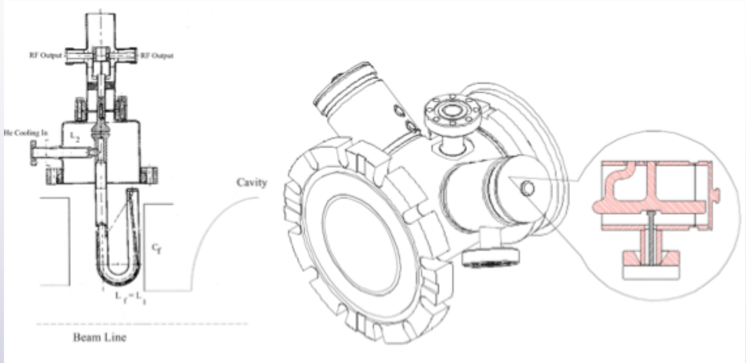
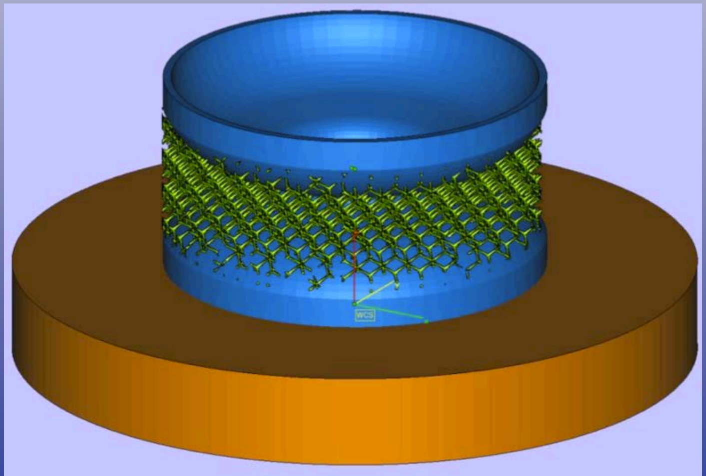
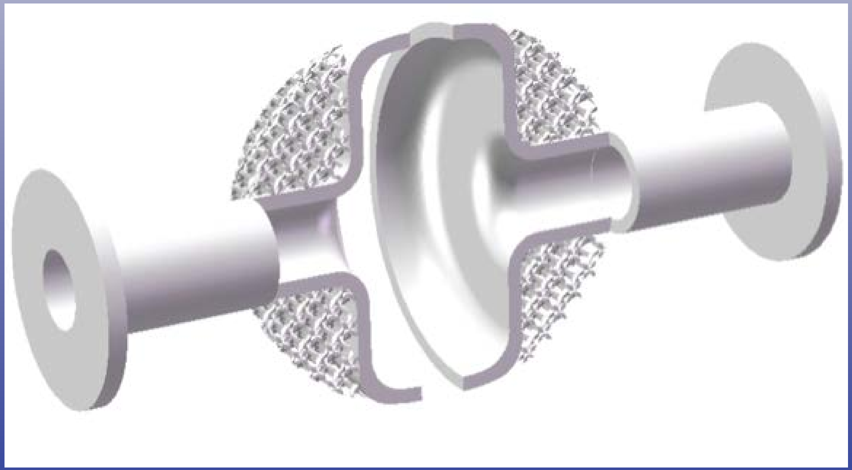


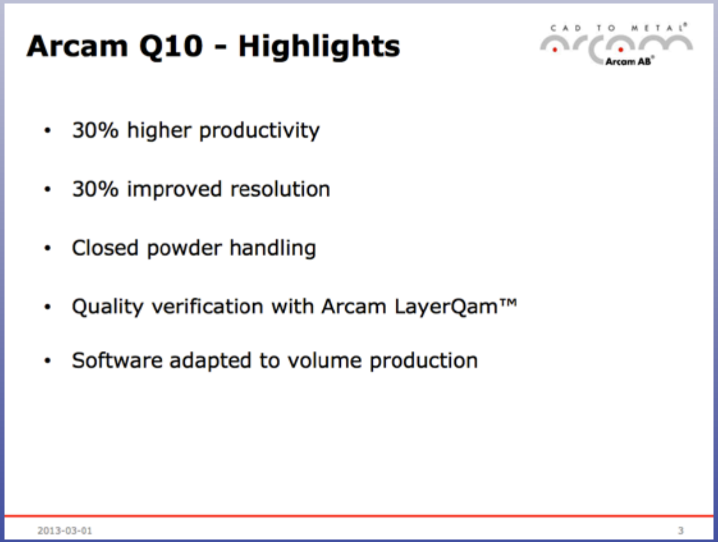
Figure 17: HOM coupler used for LEP-II at CERN (Left), TESLA-JLab type coupler (Courtesy of R. Rimmer) (Right).





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

2013-03-01 3

Thank you!

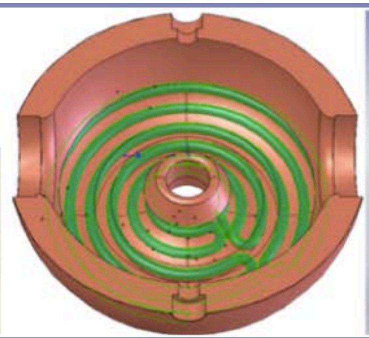
- Questions?

Extra slides

EBM material development summary

	EBM Ti6AL4V [i]	Wrought Ti6Al4V (ASTM F1472)	EBM Copper	Wrought C10100 Cu	EBM (reactor grade) Nb	Wrought Reactor Grade Nb
Density	>99.9%	–	8.84 g/cm^3	8.90 g/cm^3	8.55 g/cm^3	8.57 g/cm^3
Electrical Conductivity @ 20° C	–	–	97 % IACS	102 %IACS	–	–
RRR	–	–	–	–	19	40
Thermal Conductivity (@ 21° C)	–	–	390 W/m*K	391 W/m*K	50 W/m*K	53.7 W/m*k
YS (Rp 0.2)	950 MPa	860 MPa	76 MPa	69 MPa	135 MPa	110 MPa
UTS (Rm)	1020 MPa	930 MPa	172 MPa	220 MPa	225 MPa	226 MPa
Elongation	14 %	> 10%	–	–	35 %	50 %
Reduction Area	40%	> 25%	–	–	–	–
Fatigue strength @ 600 MPa	>10M cycles	–	–	–	–	–
Hardness	33 HRC	–	–	–	–	–
Modulus of Elasticity	120 GPa	–	–	–	–	–

i Arcam T64 Material Data Sheet, (http://www.arcam.com/CommonResources/Files/www.arcam.com/Documents/EBM%20Materials/Arcam-Ti6Al4V-Titanium-Alloy.pdf)

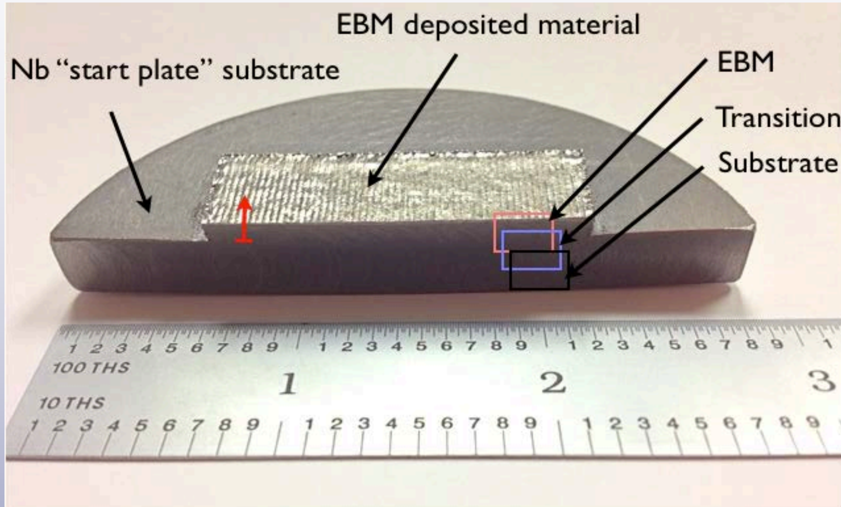



ARCAM EBM Overview

- 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



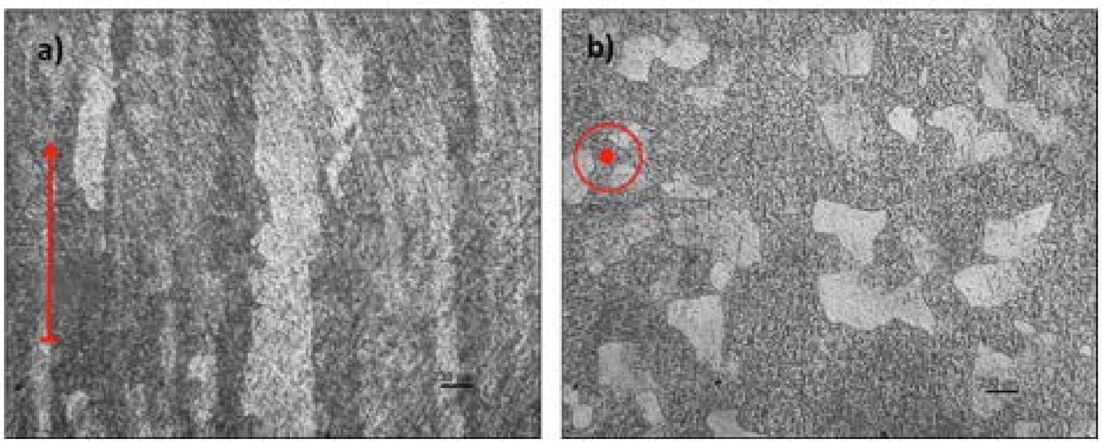
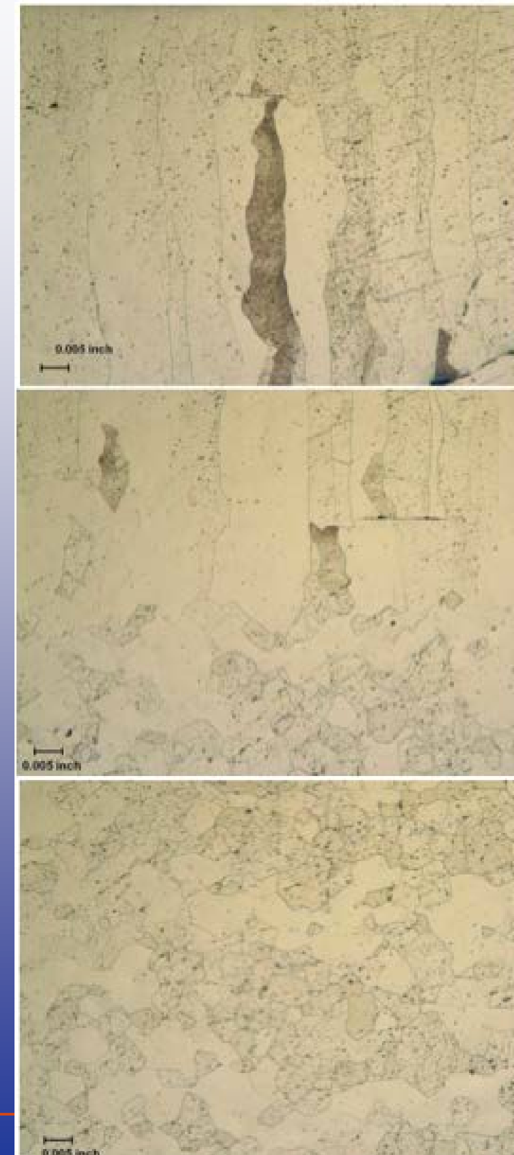
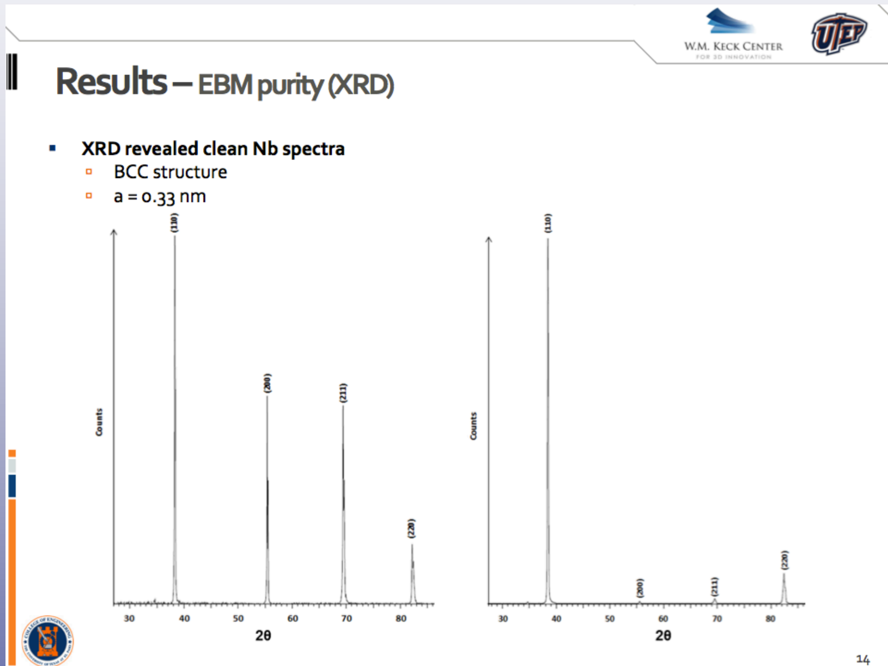


Figure 9: Vertical (a) and horizontal (b) micrographs of the EBM niobium showing elongated and irregular grains respectively, when etched with 1 part HF and 4 parts of HNO_3. The arrow depicts the build direction, and the scale shown is 230 µm.



Material testing



	Feedstock Niobium (Reactor Grade – Type 1)	Phase-I EBM Niobium	Phase-II EBM Niobium
Density (g/cm^3)	8.57	8.40 – 8.51	> 8.55
RRR	40 - 50	18-19	17-18
Thermal Conductivity (W/m*K)	53.7	–	50
YS (Rp 0.2) MPa	110	–	135
UTS (Rm) MPa	226	–	225
Elongation	50 %	–	35 %
Fatigue strength @ 600 MPa	–	–	In process
Vickers Hardness (GPa)	0.76 – 1.3	0.82 – 0.86	0.90 – 0.95

Project Schedule