# Ultra-Low Cost Fabrication for $Nb_3Sn$ SRF Cavities Using Melt Casted Bronze Structures

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# Outline

- DOE Program Motivation & Goals
- Patent Pending Bronze Route (BR) & Internal Tin (IT) Fabrication Process (US 16/268,686)
- 3D Printing of Sand Molds & Melt Casting
- BR Heat Treat Cycle
  - Ex-situ
  - In-situ
- BR Test Results
- Summary

# Bronze Route (BR) Fabrication Process

| Materials Motivation: | Bronze (89/11) | Nb (99.99) | |
|---|---|---|---|
| • Cost ($/lb) | 3 | 300 |  |
| • UTS (MPa) @ 300 K | 255 | 180 |  |
| • Thermal Conductivity (k) @ 4 K (W-m/K) | 10 (brass) | 60-70 (RRR> 250) |  |

## Fabrication Motivation:

- Bronze Route (BR) is simplest/oldest/most reliable of $Nb_3Sn$ fabrication methods
- Single α-phase bronze ~ (Cu 90%/ Sn 10 %)

## Our Patent Pending (US 16/268,686) BR Fabrication Process (high level):

- Step 1: Indirect 3D Printing of Bronze Cavity *Sand*-Molds
- Step 2: Bronze Cast Cavity in Sand Molds
- Step 3: Mechanical/Electrical/Chemical Polishing Interior of Bronze Casted Cavity
- Step 4: Deposit Nb Films w/ ECR (eventually) HIPIMMS on Interior Bronze Casted Substrates/Scaffolds
- Step 5: Post Reaction Heat Treatment to optimize SRF properties
- Step 6: *(Optional)* Coat Exterior Walls with High Thermal Conductivity Copper (Cu)
- Step 7: Test & Evaluate
- Step 8: Repeat process for RF materials optimization

***DC wires optimized for small grains & Vortex Pinning vs. RF cavities optimized for large grains & Meissner State***

# Starting Bronze Ingot Materials

**What was the quality of the starting Bronze ingot material? … Not Ideal !!!**

- Commercial Grade: Centrifugally Cast Tin-Bronze:

| Trade name | Cu/Sn Content | Quality |
|---|---|---|
| ➢ 907 | 89/11 | |

- R&D Grade: Centrifugally Cast Tin-Bronze

| | | Old | New |
|---|---|---|---|
| ➢ 908 | 87/13 | | |
| ➢ 910 | 85/15 | | |
| ➢ 911 | 84/16 | | |
| ➢ 913 | 81/19 | | |

# 3D Printed Sand Molds & Melt Casting

**Cu and Bronze Melt Casting:**

- Dates back Milena (2500-800 B.C.)
- Little has changed
- No lower cost metal fabrication technique !!!
- Complex shapes with detail ~ 1 mm
- Large Objects … e.g. Liberty Bell
- Cheap & Fast < 1 day

**Sand Molds:**

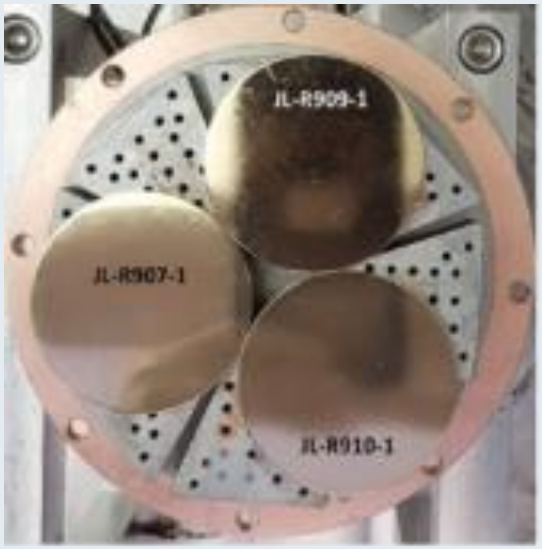
- One-time use→ Literally dirt cheap!!!
  - 9-cell SRF: one-off ~ $500
  - 9-cell SRF: > 100 ~ $30
- Modern twist for SBIR: 3D printing
  - Complex shapes: RF couplers etc.
  - Large Objects… 9-cell SRF
  - Rapid prototyping < 3 hours
  - 3D printer: capital investment ~ $100 k-$300 k

**Mold + Melt Cast 9-cell SRF Cavity (> 100)**

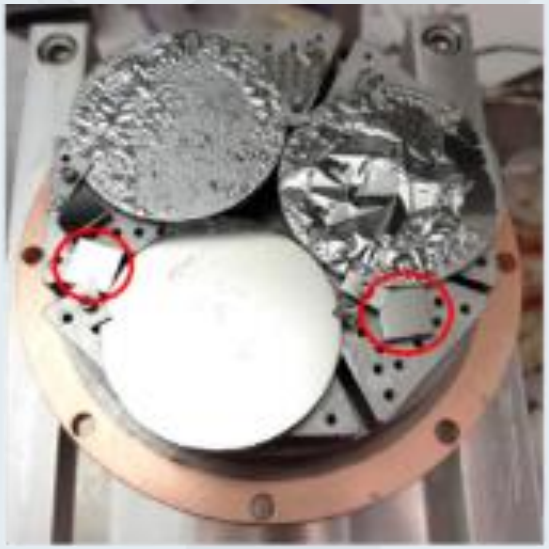
- ~ $100-$300/cavity
- < 1 day fab.
- UPS Ground Shipping @ 2 days

# ECR Deposition @ JLAB: -60/-120 V, Pre HT

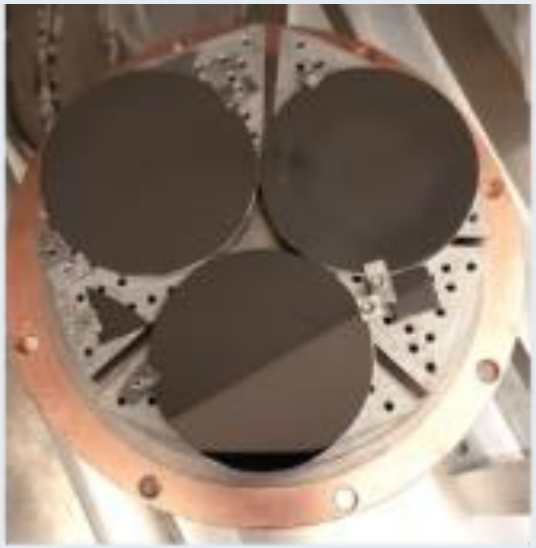
- Three (3) 10x10 & 2” samples deposited simultaneously (no substrate heating)
- 10x10 mm samples same as 2” @ - 60 V
- 10 x 10 mm samples different than 2” @ -120 V
- RRR ~ 189 pure Nb film (peeled from 2” sample)




Samples in chamber prior to Nb film deposition



Samples in chamber after Nb film deposition @ -120V



Alternate samples in chamber after Nb film deposition @ -60V

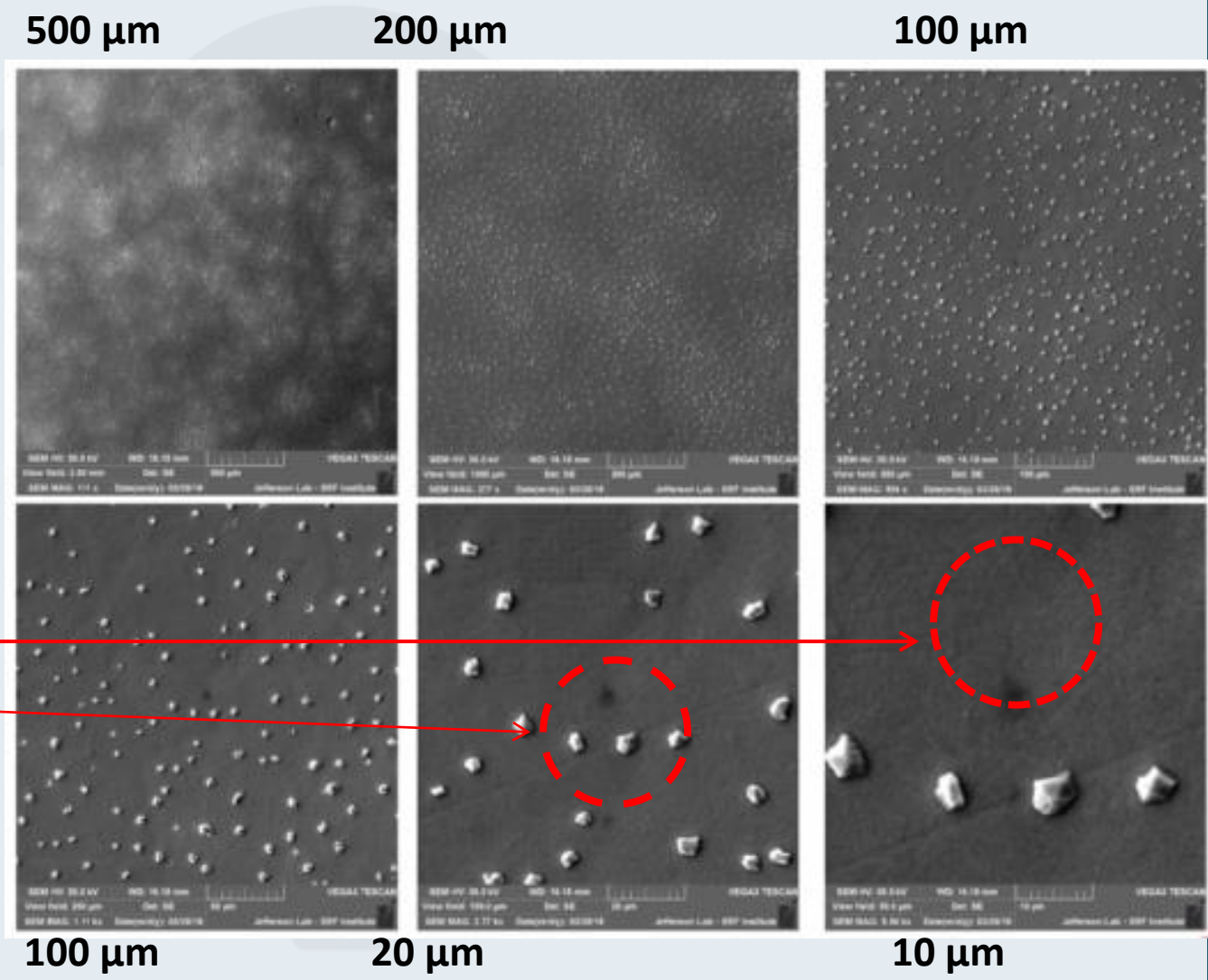
# SEM: 907 (89/11) Post 700° Vacuum Heat treat @ JLAB

**Parameters:**

- 2” round 907 (89/11)
- Mechanical polish
- BV: -60 V
- Vacuum HT: 700° C @ 24 hr

**Post HT Film Features:**

- Low Sn (~ 15 %)
- Cu rich precipitates

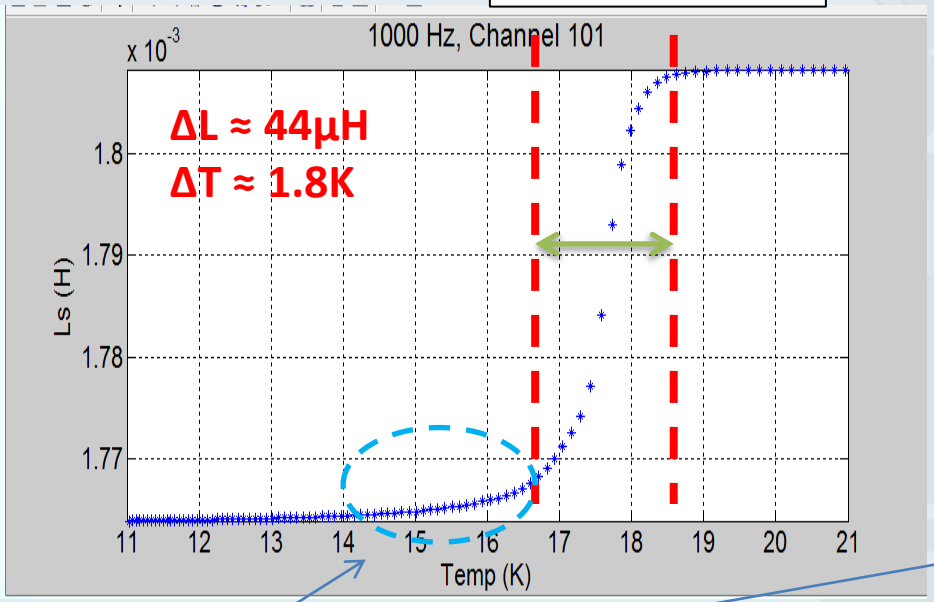


# AC Inductively Measured $T_c$

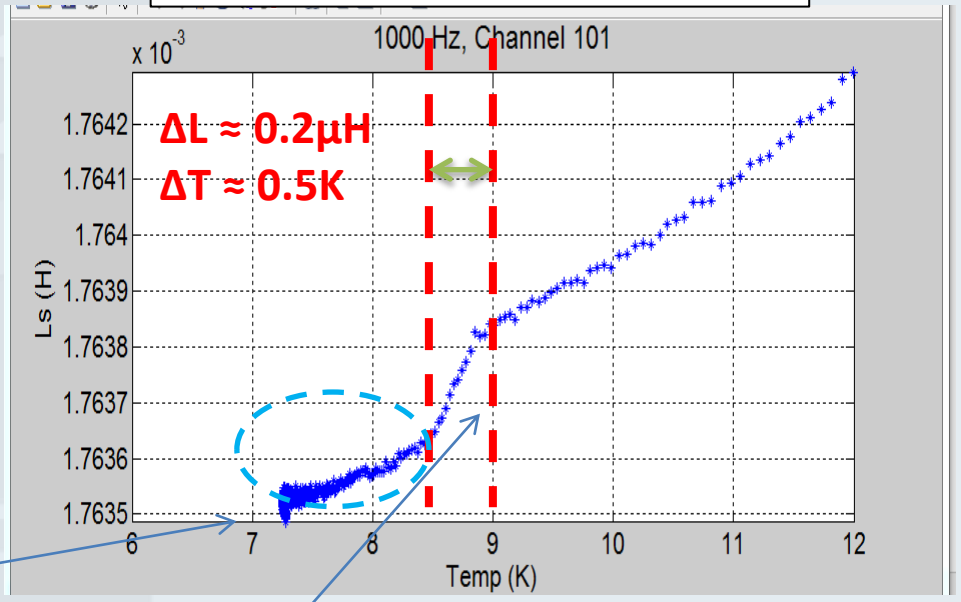
**Sample 911 (86 % Cu/ 14 % Sn)**

- **ΔL~ 44 µh → largest signal (surprisingly larger than pure Nb signal)**
- **$T_c$ onset right @ 17.3 K**
- **ΔT ~ 1.8 K**

**86/14**




**86/14 not converted Nb**




- **BTW: Tail measurement artifact: appears on all calibration samples e.g. : 1) Pb, 2) YBCO, and 3) Nb**

**Some pure Nb that did not convert:**

- **ΔL ~ 0.2 µH only 0.4 % of $Nb_3Sn$ signal**
- **Longer reaction time ??**
- **Nb too thick ?? → need longer reaction time**

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# General Film Quality Comparison of: $T_c$, ΔT, & ΔL

| Bronze | Sample Name | Nucleation Voltage (V) / Ion Energy (eV) | Heat Treatment | Soak Temperature (C) | Tc / Transition Width ΔT (K) | Inductive Signal Strength ΔL (μH) |
|---|---|---|---|---|---|---|
| C907 Cu/Sn: 89/11 | 907-1 | -120/184 | HT1 | 700 | NA | NA |
| | 907-2 | -60/124 | HT4 | 759 | 14.2/1.3 | 23 + 7 |
| | 907-3 | 0/64 | HT6 | 798 | 14.8/1 | 8 |
| | 907-4 | -240/304 | | | | |
| C909 Cu/Sn: 87/13 | 909-1 | -120/184 | HT1 | 700 | NA | NA |
| | 909-2 | -60/124 | HT4 | 759 | 16.3/1 | 30 + 7 |
| | 909-3 | 0/64 | HT6 | 798* | 16.6/1.3 | 33 + 10 |
| | 909-4 | -240/304 | | | | |
| C910 Cu/Sn: 85/15 | 910-1 | -120/184 | HT1 | 700 | 17.3/0.8 | 0.35 + 0.2 |
| | 910-2 | -60/124 | HT4 | 759 | 17.1/1.3 | 29 + 7 |
| | 910-3 | 0/64 | HT6 | 798* | 15.9/1.6 | 21 + 10 |
| | 910-4 | -240/304 | | | | |
| C911 Cu/Sn: 84/16 | 911-1 | -120/184 | HT2 | 700 | 16.5/1.4 | 35 + 8 |
| | 911-2 | -60/124 | HT5 | 700 | 15.2/1.2 | 32 + 3 |
| | 911-3 | 0/64 | HT7 | 759 | 14.8/0.9 | 17 + 10 |
| | 911-4 | -240/304 | | | | |
| C913 Cu/Sn: 81/19 | 913-1 | -120/184 | HT3 | 700 | 15.6/0.9 | 28 + 15 |
| | 913-2 | -60/124 | HT7 | 759 | 14.5/1.7 | 31 + 4 |
| | 913-3 | 0/64 | HT7 | 759 | 15.0/1.4 | 26 + 4 |
| | 913-4 | -240/304 | | | | |

*Soak temperature seemed to be too hot for these samples: they appeared slightly melted after heat treatment

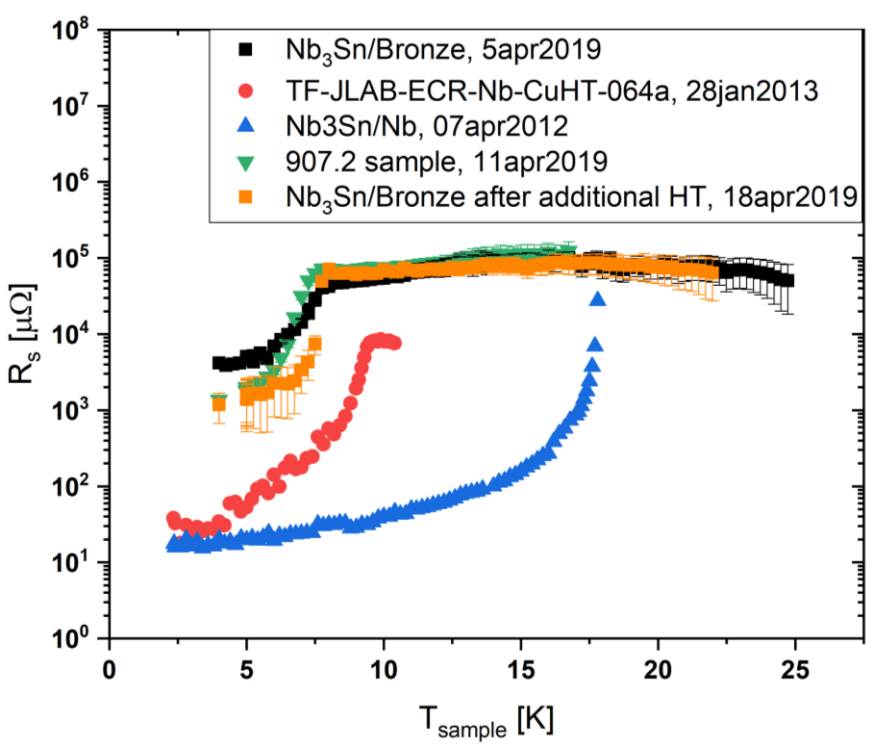
# $R_s$ & Q Measurements on 907 (89/11)

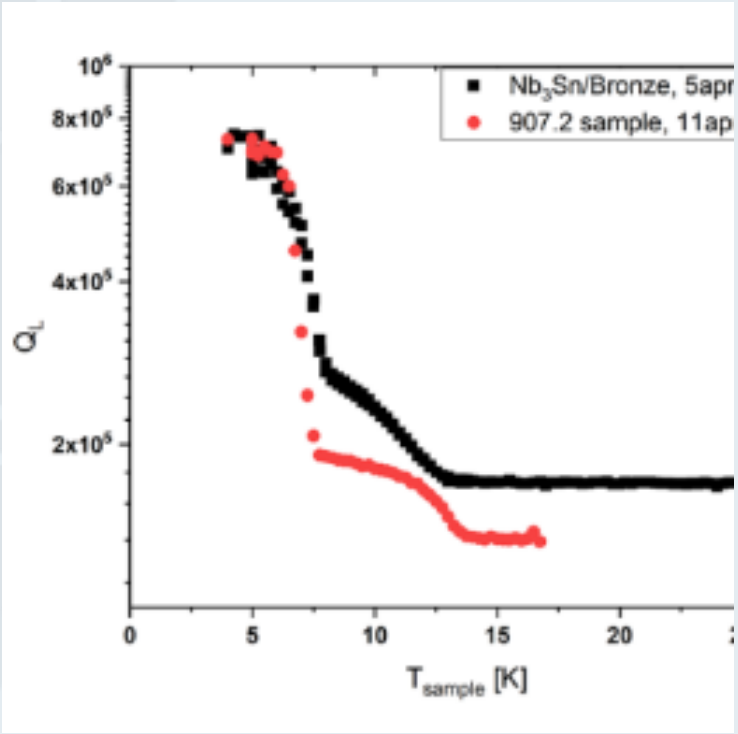
**Process conditions:**

- 907 (89/11)
- ECR: -60 V
- HT: 700° C for 24 hr
- HT: Vacuum furnace @ JLAB

**Test results:**

- $T_c$ ~ 14 K → off stoichiometric $Nb_3Sn$
- $R_s > 10^2$ $Nb_3Sn$ JLAB thin film



# Summary: High Points

- 3D printed sand molds by were quick, easy, low cost
- SRF cavity CAD design → 3D sand mold → Cu-Sn casting < 1 day (e.g. FedEx shipping ~ 2 days, BR Ex-Situ heat treat cycle ~ 10 days)
- 3D molds + Cu-Sn scaffold + casting <$1,000 (1) → < $300 (> 100)
- Easily adaptable to small & large other SRF components (e.g. couplers, crab cavities, etc.)
- Easily adaptable to IT process starting w/ Cu melt casted
- Easily adaptable to normal conducting Cu (possibly HPA??) cavities & components

# Summary: Low Points

- Key starting point: commercial grade, well mixed & work hardened bronze (>87/13)
- Melt casted surface very rough … better mechanical & electro-polishing
- $Nb_3Sn$ reaction diffusion of high quality Nb film deposition (e.g. ECR, HIPIMS) vs. low quality thermal vaporization or low energy sputtering
- "In-situ" heated (> 400°C) substrates vs. "Ex-situ" non-heated (< 200°C) substrates
- Bronze samples need its own DTA/TGA to avoid melting
- Optimize bronze substrate temp vs. deposition & incident ion energy
- Optimize heat treat for given bronze melt
- Need to address thermal strain (ε) of Cu-Sn on $Nb_3Sn$ degrading SC properties
- Bulk of technical literature useless … optimized RF properties ≠ DC properties: *Meissner (large grains)* ≠ *Vortex* state (small grains)
- Need to address low thermal conductivity issue in final product