Ampere Scientific

DOE SBIR Award DE-SC0020980

Reducing the Cost of Ingots Utilized in Large Steam Cycle Components by Heat Flux Manipulation during VAR Processing to Control Solidification

Phase I Industry Support

UNIVERSAL STAINLESS & ALLOY PRODUCTS, INC.

CONSARC

CARPENTER

+

Additional Phase II Industry Support

SPECIAL METALS A PCC Company

GE Energy

Energy Industries Of Ohio

GE Aviation

*SMC to host industrial trials

Outline

- Phase I Results
  - Modify Existing Furnace to be able to melt for up to 5 minutes
    - Run Experiments on Short Arc Gap Melting with *VARmetric*™
    - Validate Measurement System
    - Verify Arc Gap Measurement via Optical Methods
    - Develop Arc Gap Measurement Algorithm
    - Validate Arc Gap Measurements During Melting
  - Analyze Data to Identify Deleterious Conditions

  - Additionally
    - Completed the Energy I-Corps Program
    - Developed Additional Industry Support
    - Rebranded Ampere Scientific
    - Proved that *ARControl* ™ can be utilized to tailor heat flux distributions

Our Technology in Brief

Based upon DOE Patent 8,111,059 exclusively licensed to AmpSci

R&D 100 Award Winner – 2013

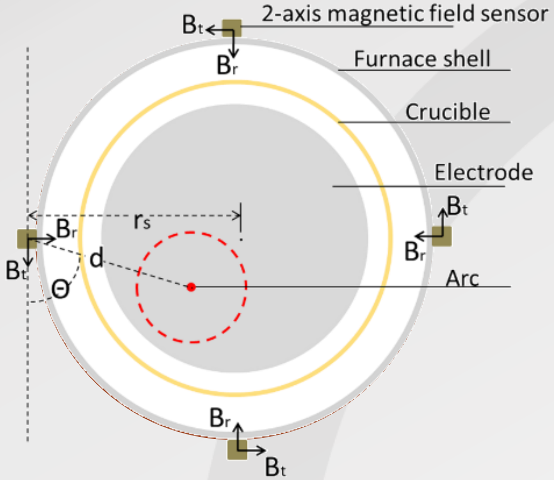
FCL Award Winner - 2013

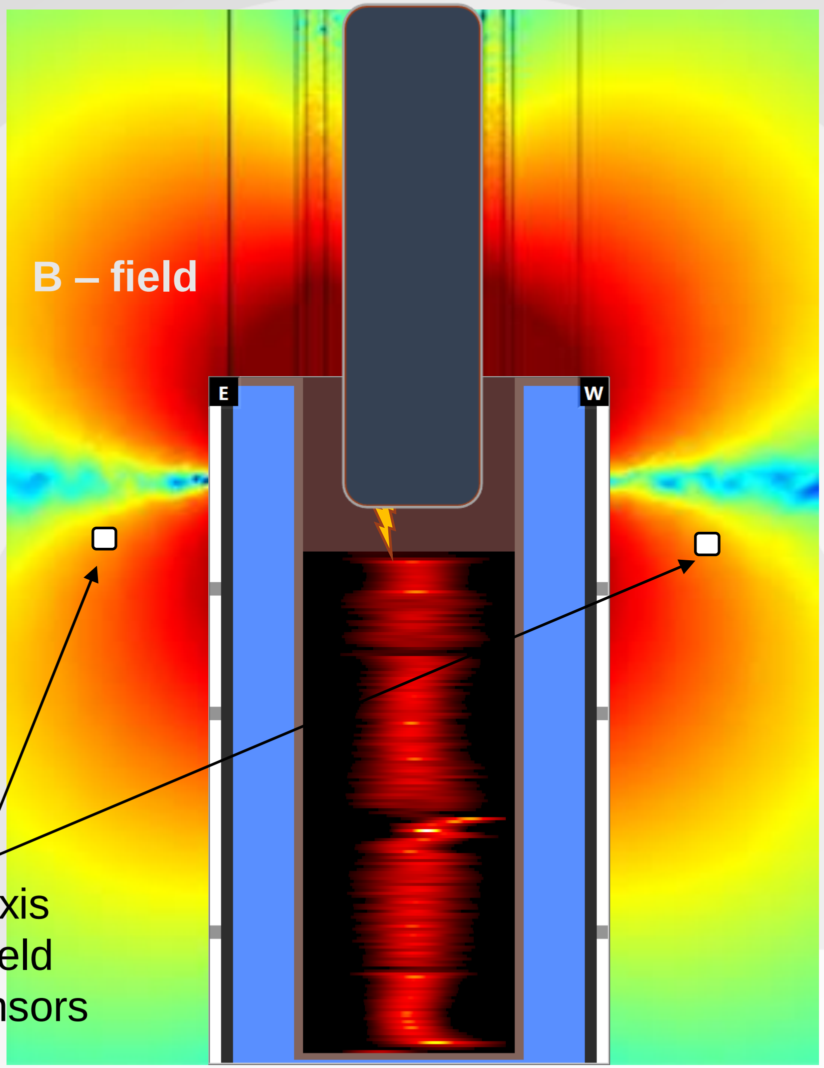
- APS capitalizes on the Maxwell-Ampere law to locate electric currents

$$\nabla \times \vec{B} = \mu \left[\vec{J} + \frac{\partial \vec{D}}{\partial t} \right]$$

- All electric current sources generate superimposed magnetic fields – including the arc!
- Arc movement induces changes in source current paths

- Provides vector direction to current source and geometry of the conductive pathway

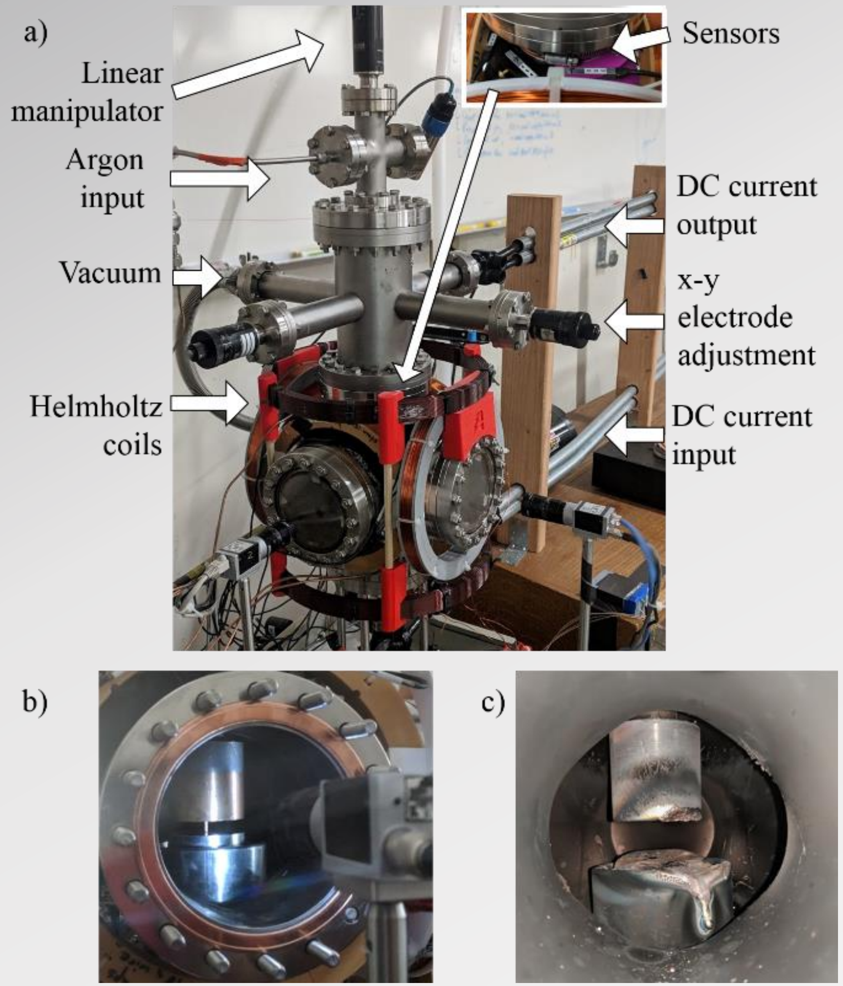




3-Axis B-field Sensors

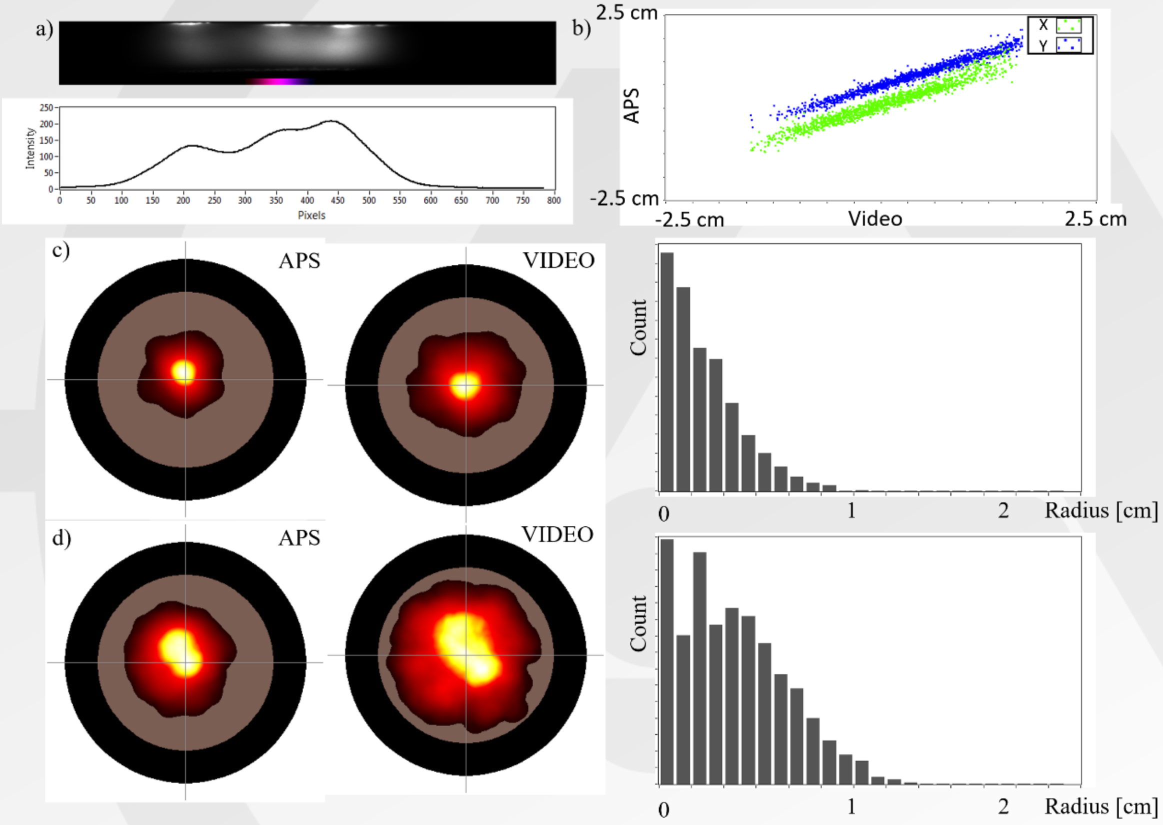
Experimental VAR Modifications

Out with the Old …



Successfully used for arc dynamics measurement, *VARmetric*™ validation and the development of *ARControl* ™ (NSF SBIR Phase I and II)

Could not melt, so differences in plasma physics during melting and non-melting weren't accounted for, including short arc gap, drip short controlled operations as in superalloy processing



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Modifications

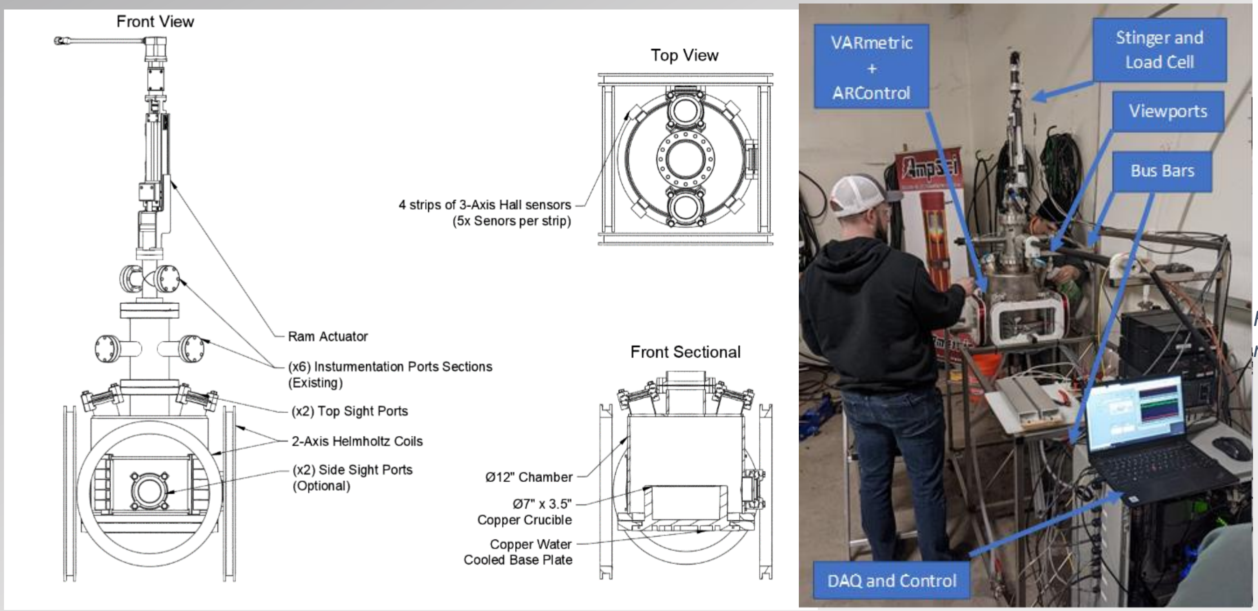

Figure 1 - As designed and as-built images of the modifications made to the AmpSci research VAR in support of this SBIR effort.

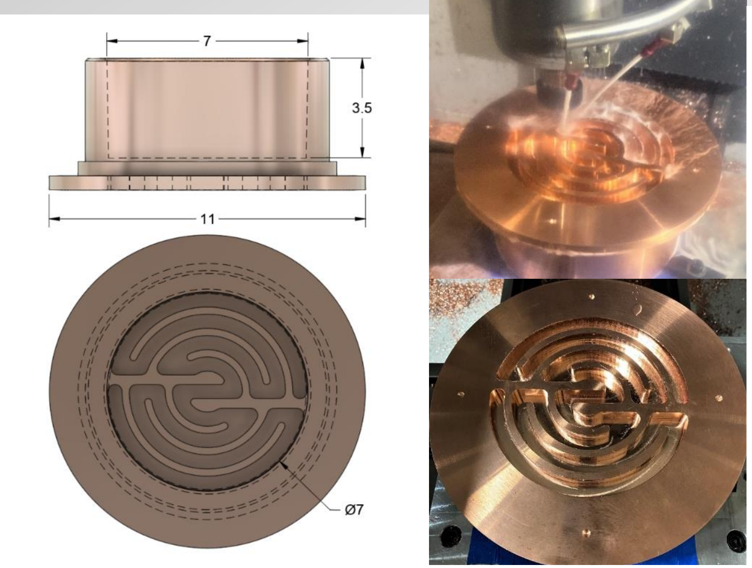

Figure 2 - As designed and as-machined copper crucible required to sustain melting of highly segregation prone alloys.

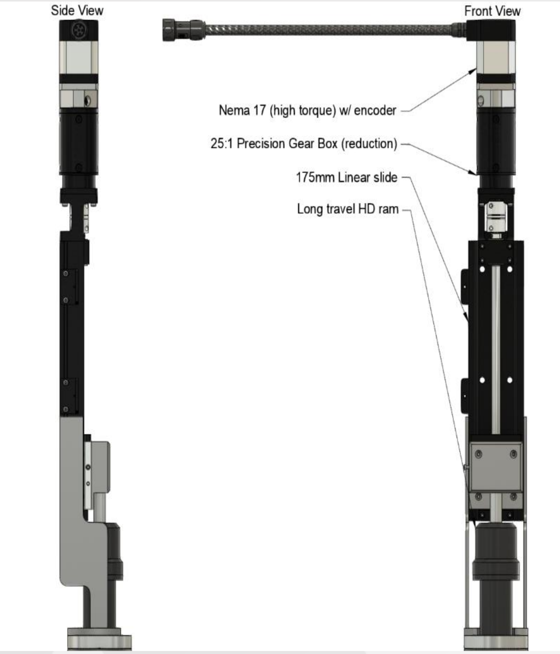

Figure 4 - Electrode linear actuator redesign for automatic control of electrode position.

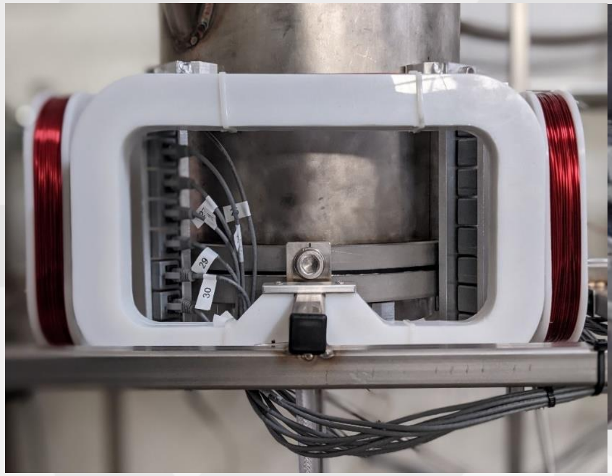

Figure 5 - Side view of the new furnace chamber with VARmetric and ARControl mounted.

Figure 6 – Post run melt pool inspection

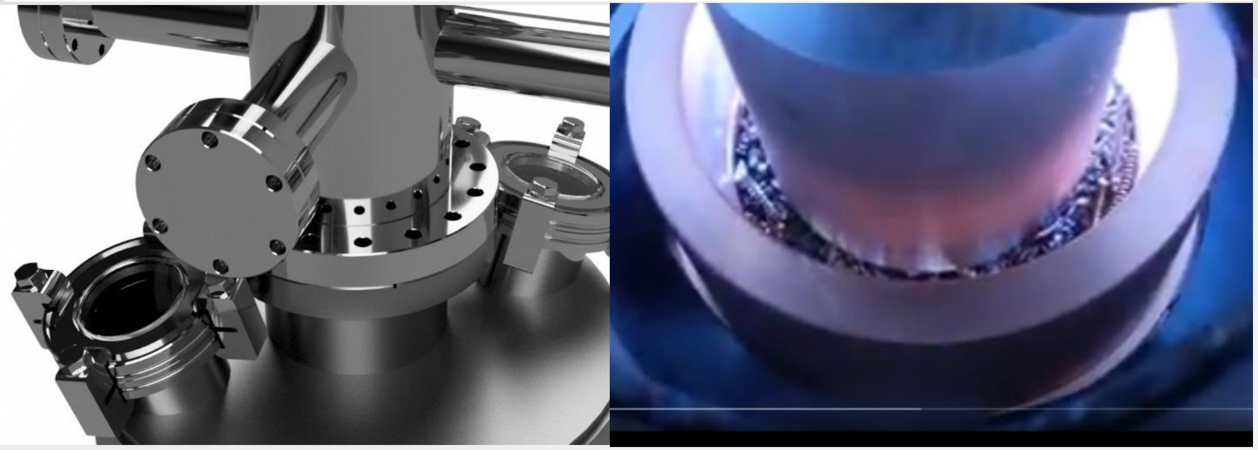

Figure 3 - Viewports (left) were designed to provide visual and video camera access of the melt pool and arc dynamics (right).

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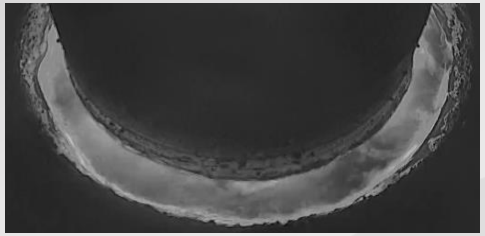
In with the New



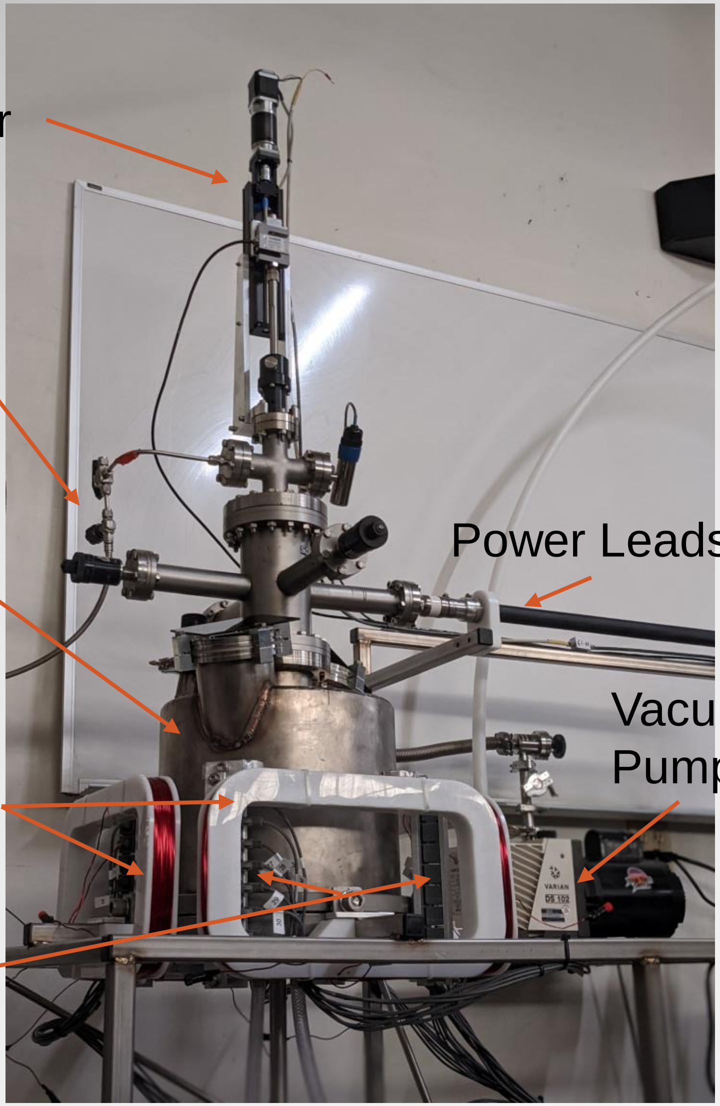
Digitally Controlled Linear Manipulator

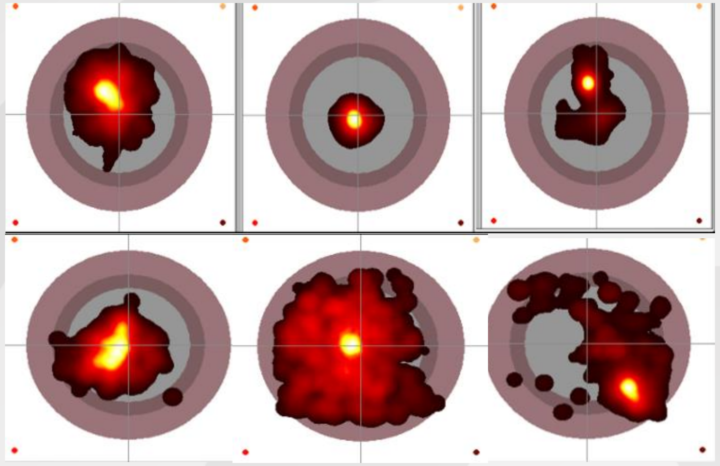
Argon Backfill

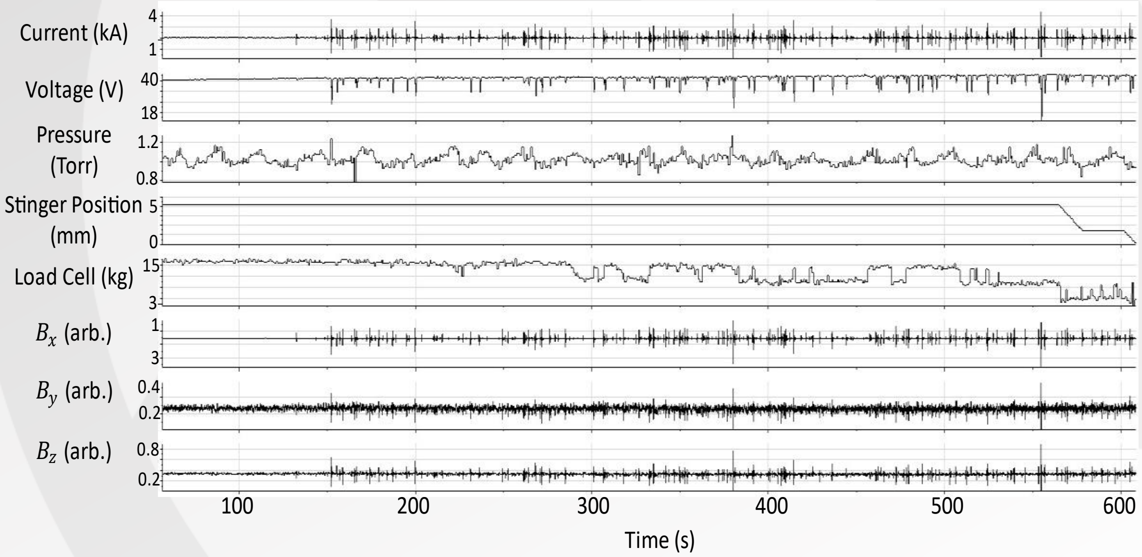
Created larger melt zone for full liquid pool containment

ARControl™ Helmholtz Coils

VARmetric™ Sensors







Why did we do these modifications?

Allowed us to develop melting conditions for durations in excess of 10 minutes (project target was for melting for at least 5 minutes)

This enabled investigations not available in the previous system:

- Short arc gap conditions (arc gaps in the range of 5-15 mm)
- Drip-short dominated melting (as in normal superalloy processing)
- Allows for direct comparison between lab and industrial VAR operations as they pertain to these two items
- Allows for ingots that can be analyzed for differences in solidification
- Allows for studies on the affects of applied transverse magnetic fields (*ARControl*™)
- With *ARControl*™, this allowed us to artificially set up ‘deleterious’ operating conditions and to analyze the results (eg, cause and affect between constricted arcs and solidification changes)
- Allowed us to develop the arc gap measurement theory

Experimental Validation for Short Arc Gap Melting

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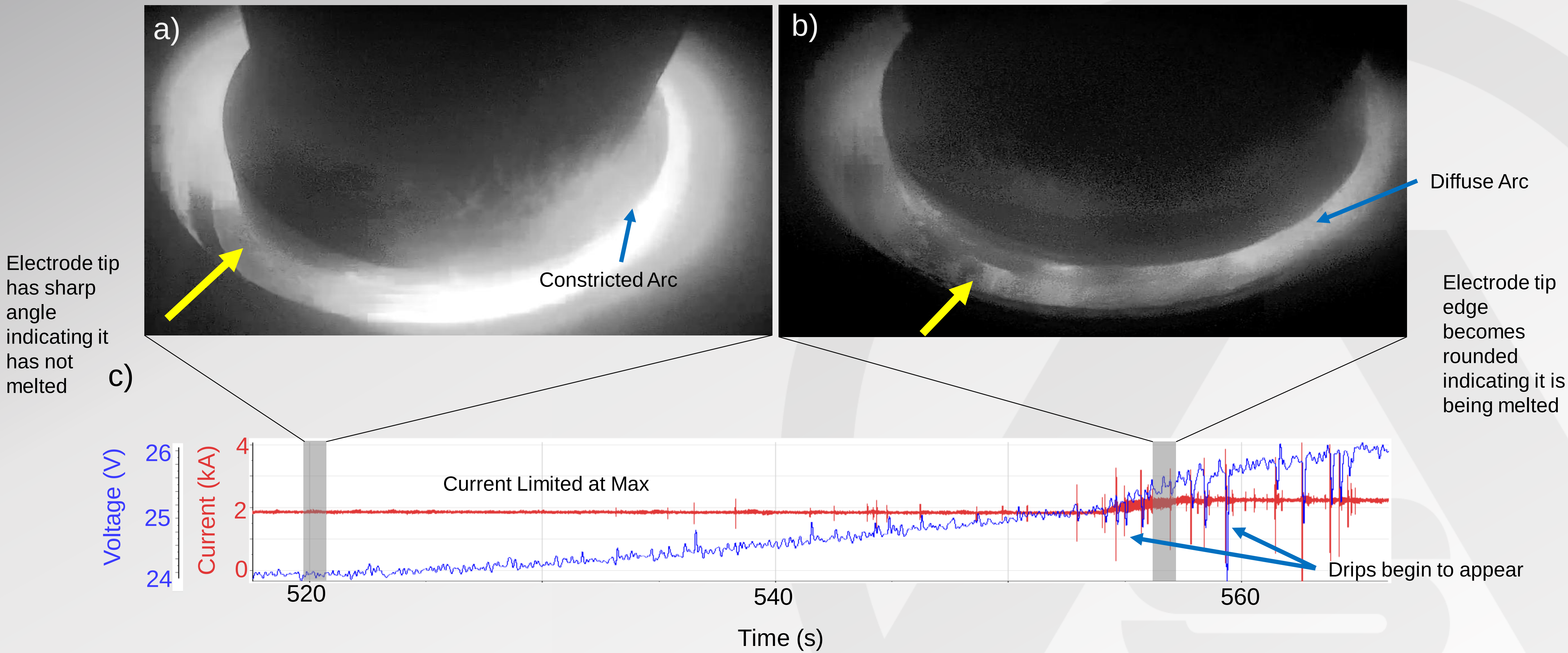
Verify Measurement System



Startup Operations – Melting has not begun

Transition to Melting

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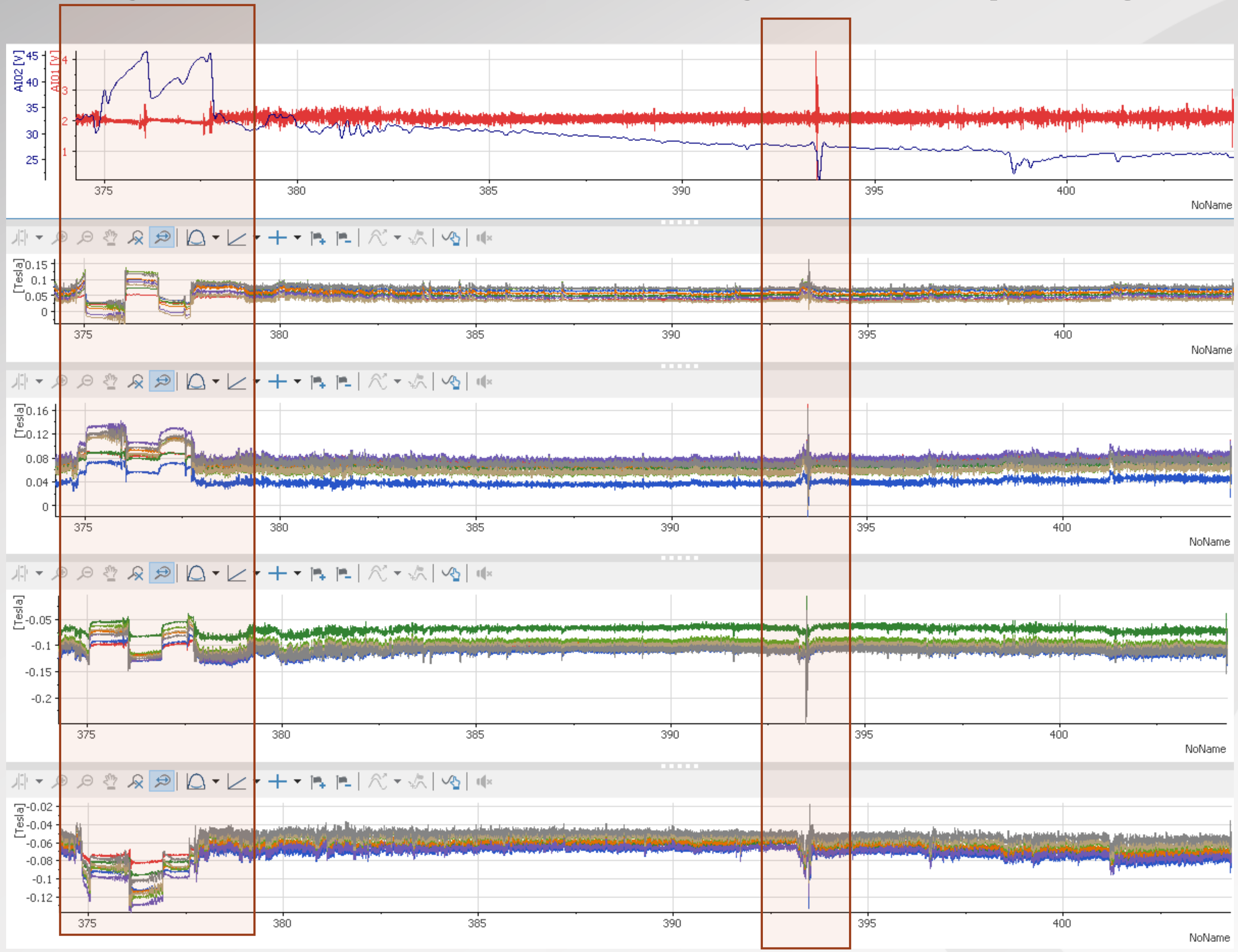
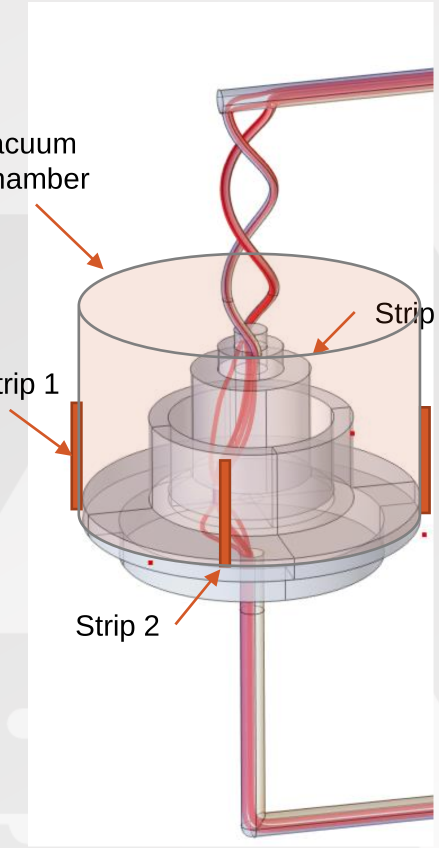
Verify Measurement System (Magnetic Fields)





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Validate Arc Measurements During Melting

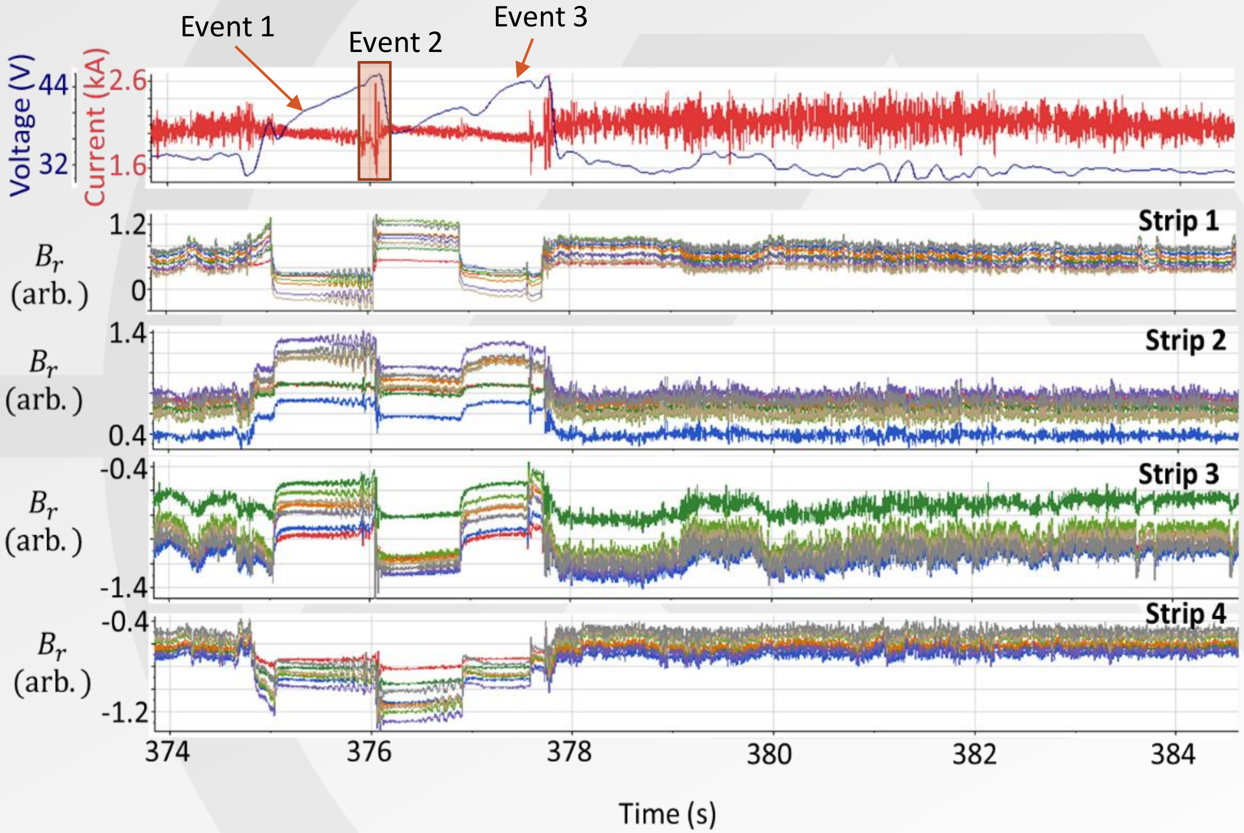
Identifiable events caught on camera are correlated with *V, I* and *Bx, By, Bz*

Example:

1. Here, side arc event (Event 1) was identified by magnetic fields.

2. This event was followed by a constricted arc underneath the electrode (Event 2)

3. And then by another side arc (Event 3)



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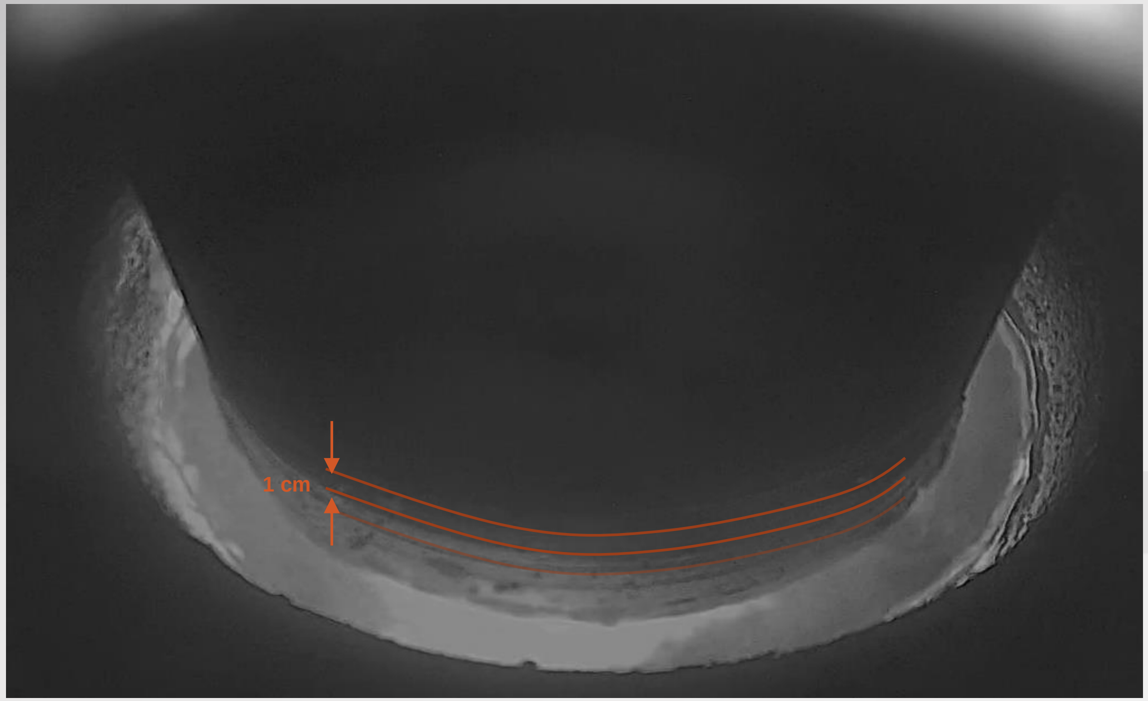
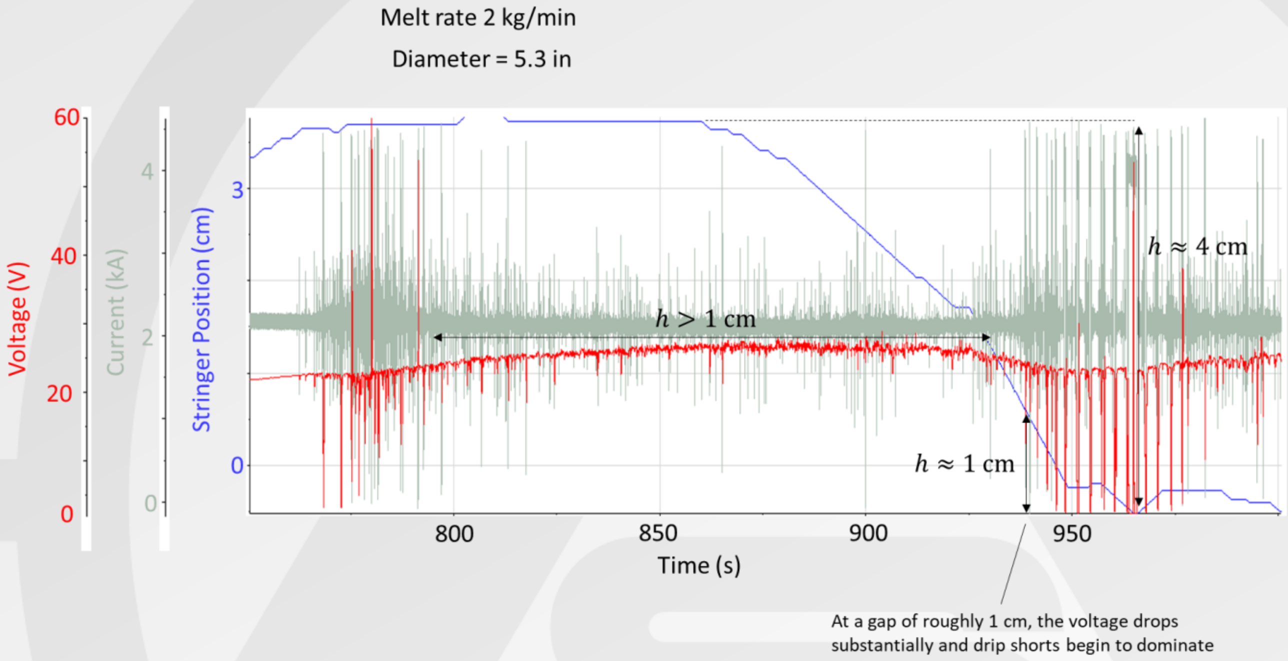
Verify Arc Gap Measurement System

Optical



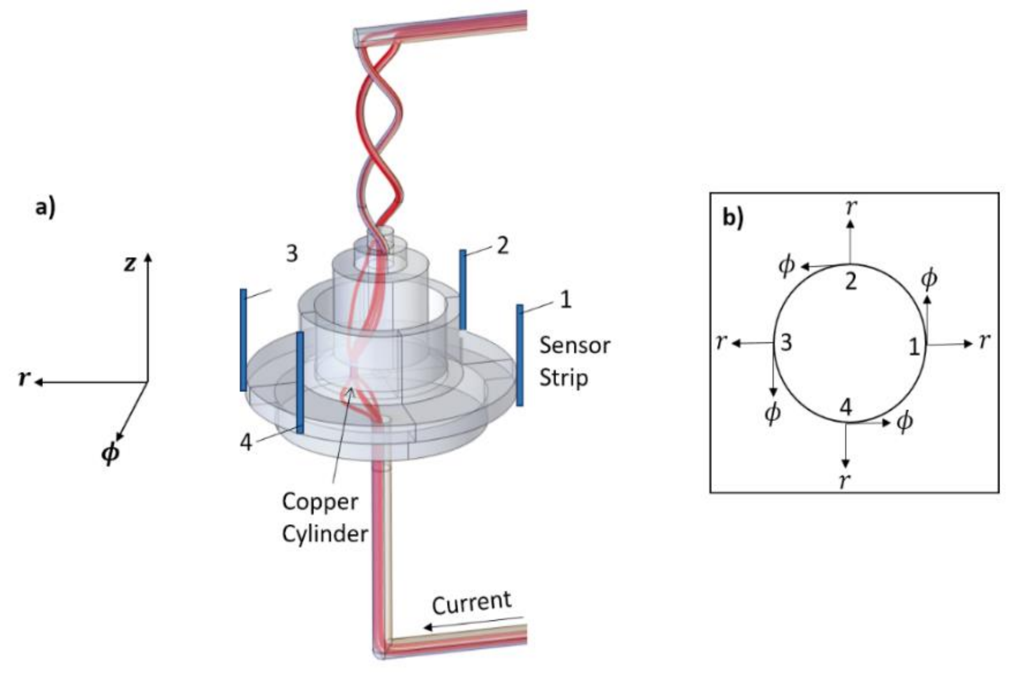
Lines were etched on the electrode to measure melt rate.
Melt rate + Ram Position were used to calculate arc gap

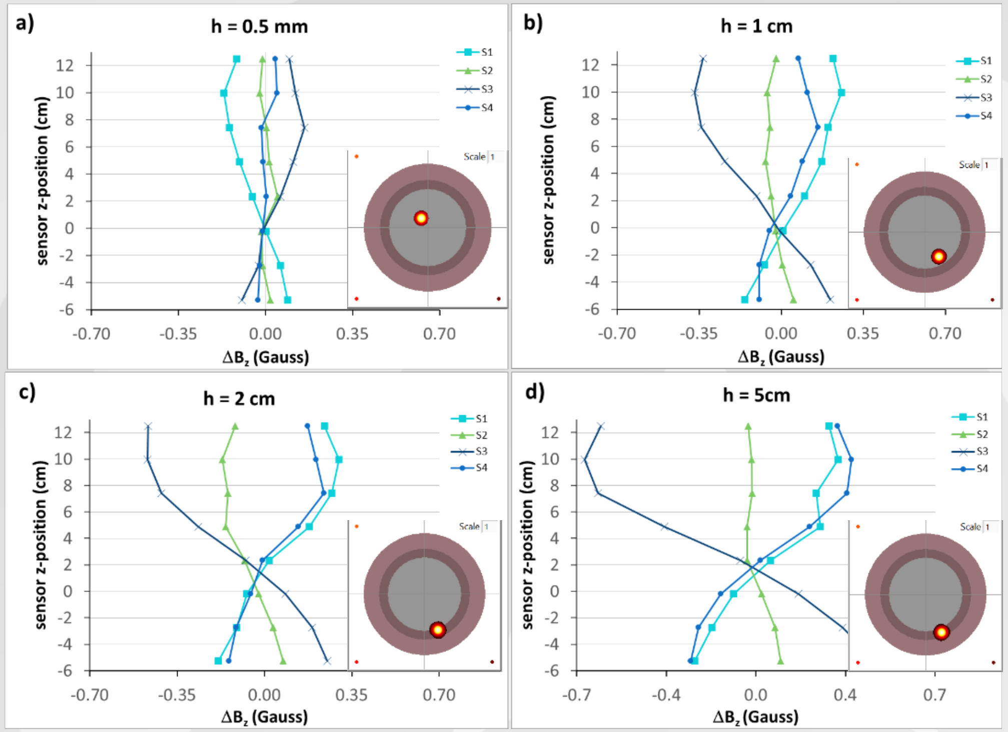
Experimental ('Dip' Test)



Electrode ram position was used to 'dip' the electrode tip.
Ram travel and current/voltage profile provides arc gap measurement

Arc Gap Measurement Algorithm





Placed copper cylinders of various sizes (0.5, 1, 3, and 5 cm) between electrode and ingot and passed current through the system.

- Bz (magnetic field in the z-direction) provides a unique signature when we analyze each column of sensors
- Arc gap measurement algorithm utilizes Bz field to localize the arc gap.
- Statistics of the field variations are used to estimate the arc gap length
- Dip tests are used to calibrate/verify

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Arc Gap Measurement and Arc Gap Tracking

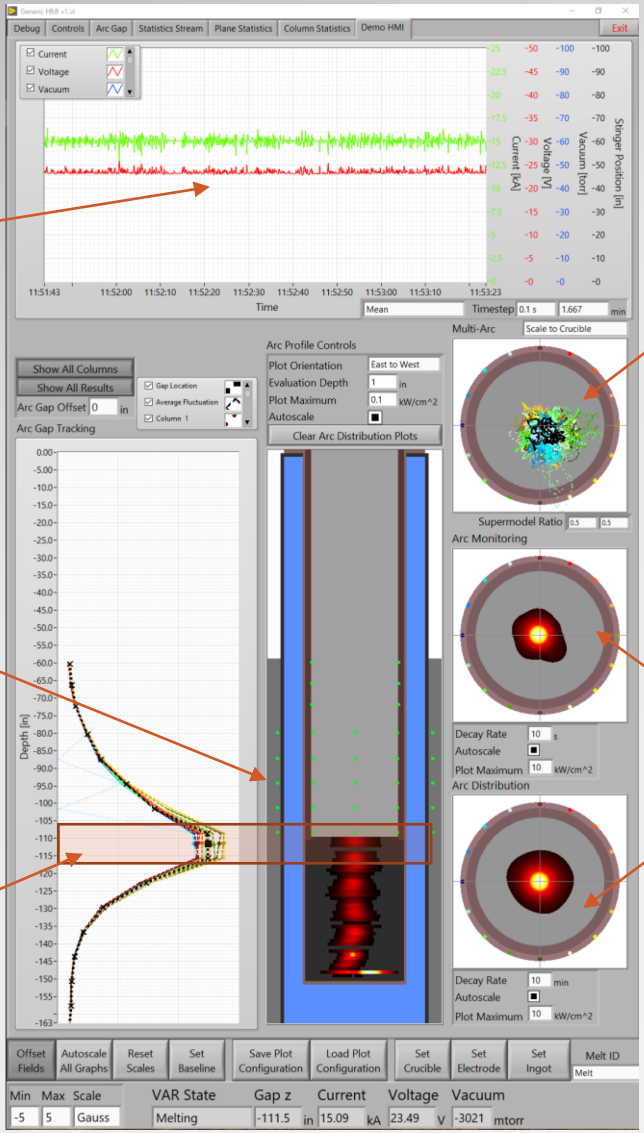
Process Data

Measured (Colored) and Mean (Black) Drip Locations

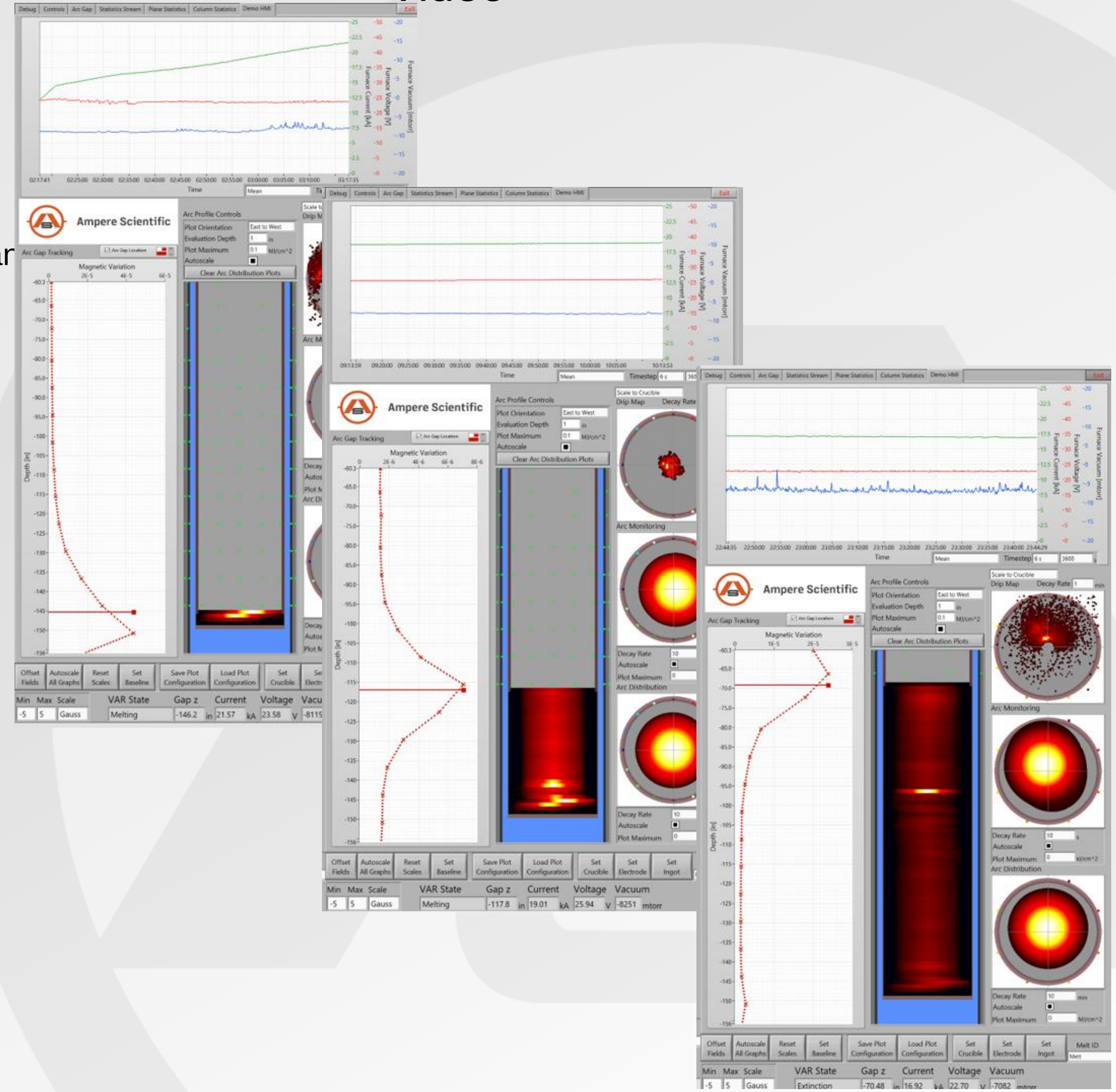
Sensor Locations

Arc Distributions
10 sec
10 min

Arc Gap Tracking



Video



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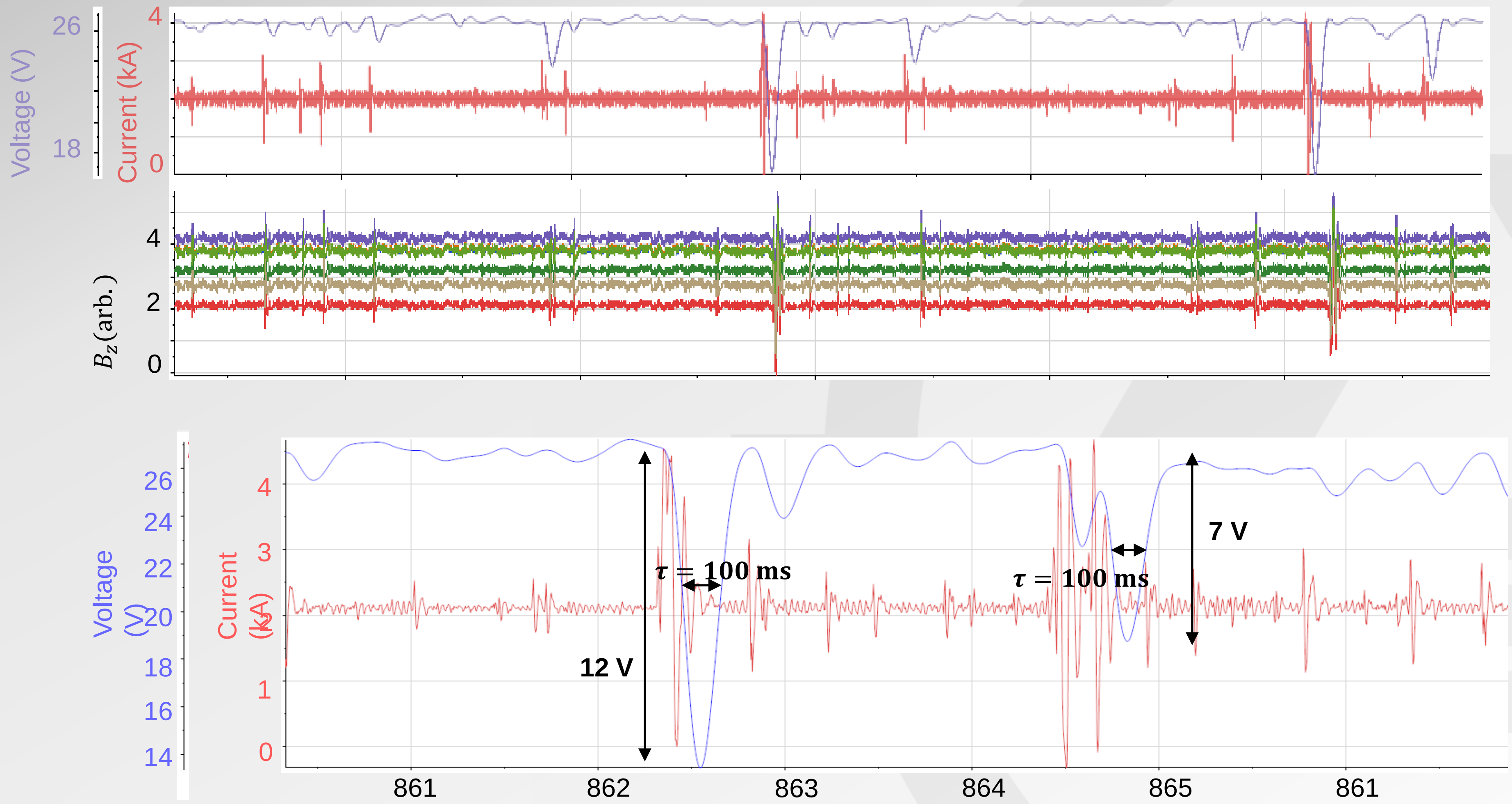
Analyze Data

Drip Shorts



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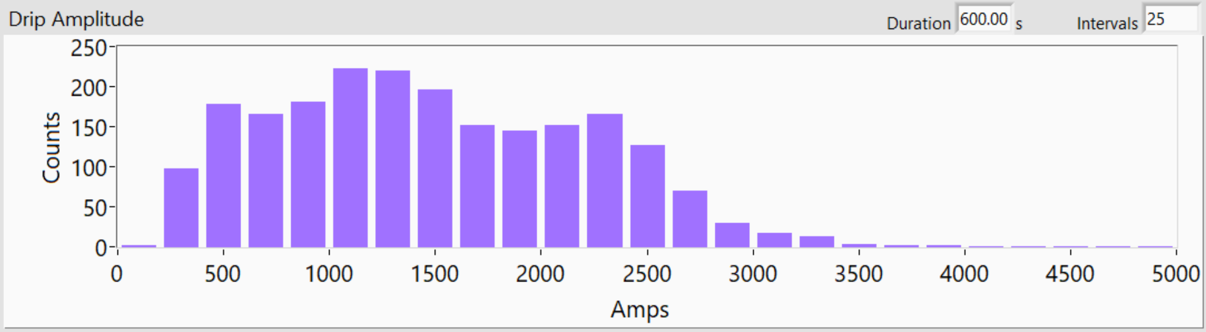
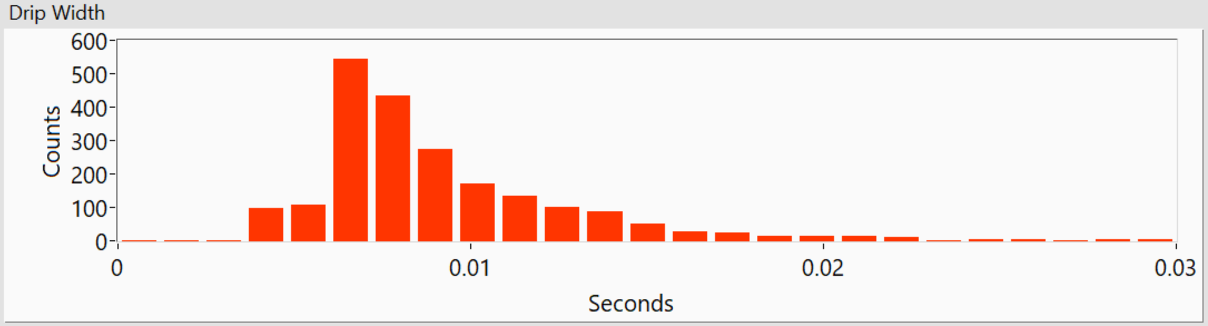
Drip Short Analysis

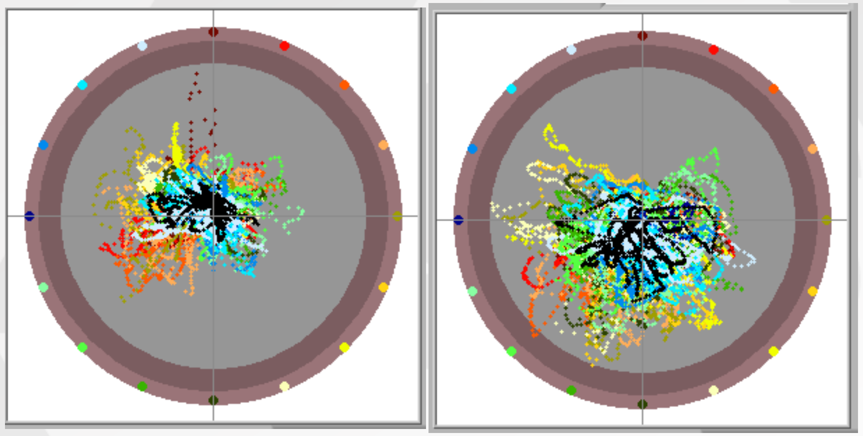
Drip short analysis tools applied on data from industrial installation

Drip statistics





Drip locations



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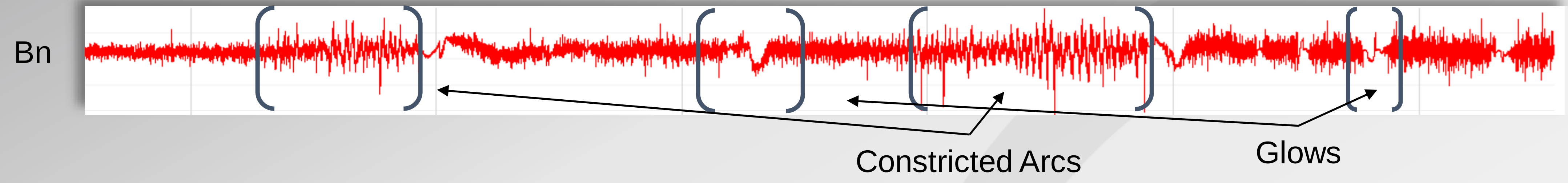
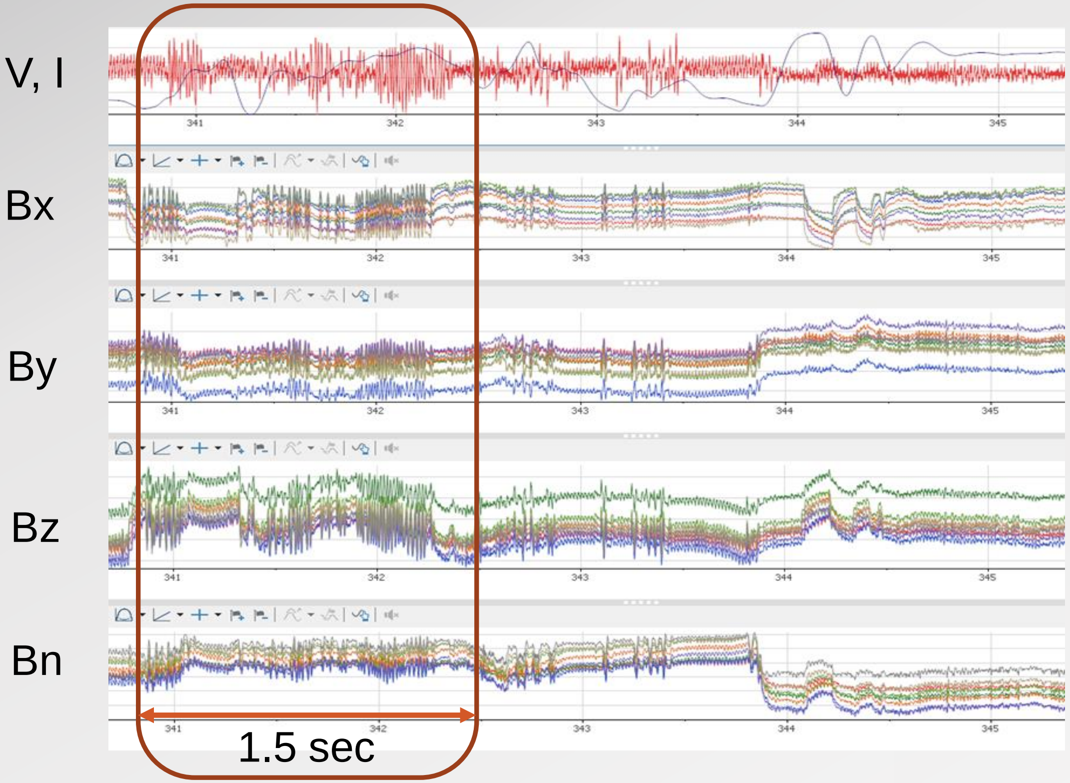
Constricted Arcs

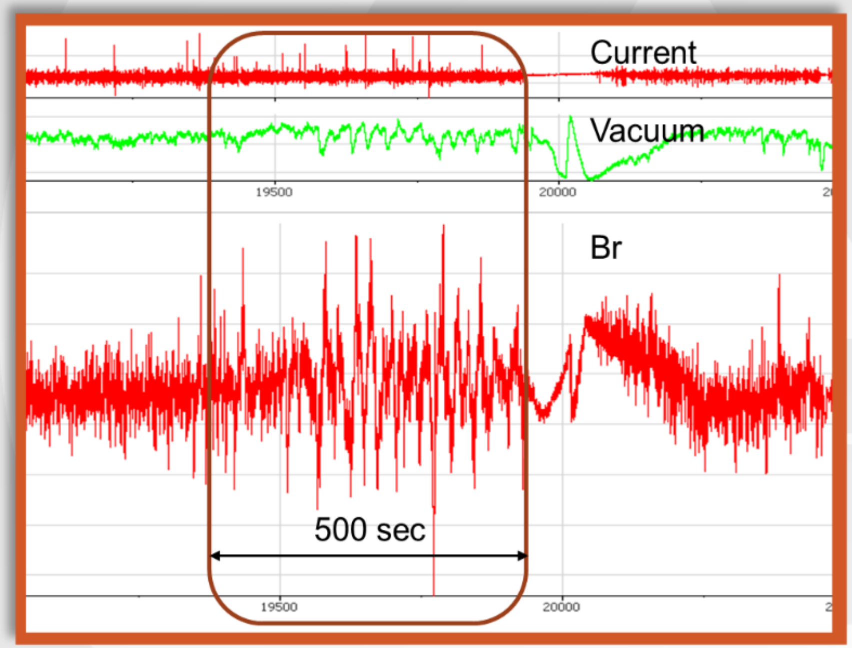
Analyze Data for Deleterious Conditions

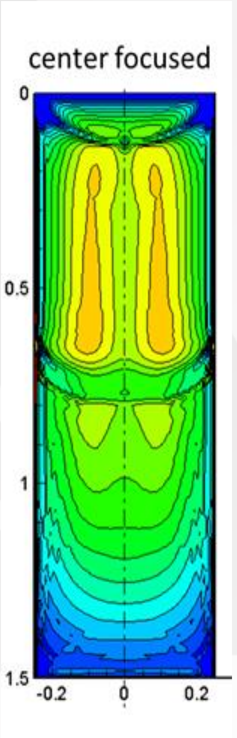


Constricted Arc in Lab Furnace



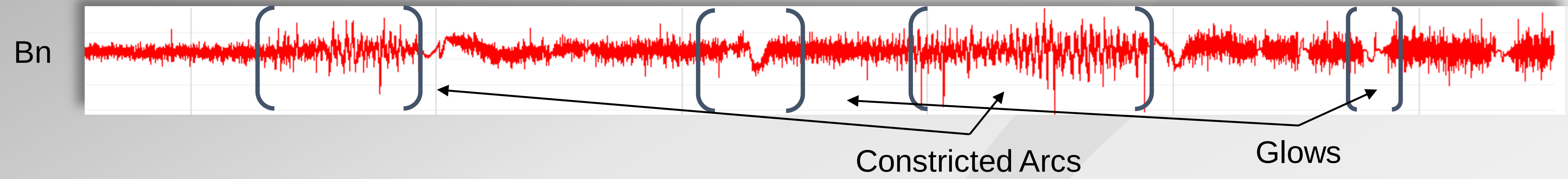
Constricted Arc in Industrial Furnace

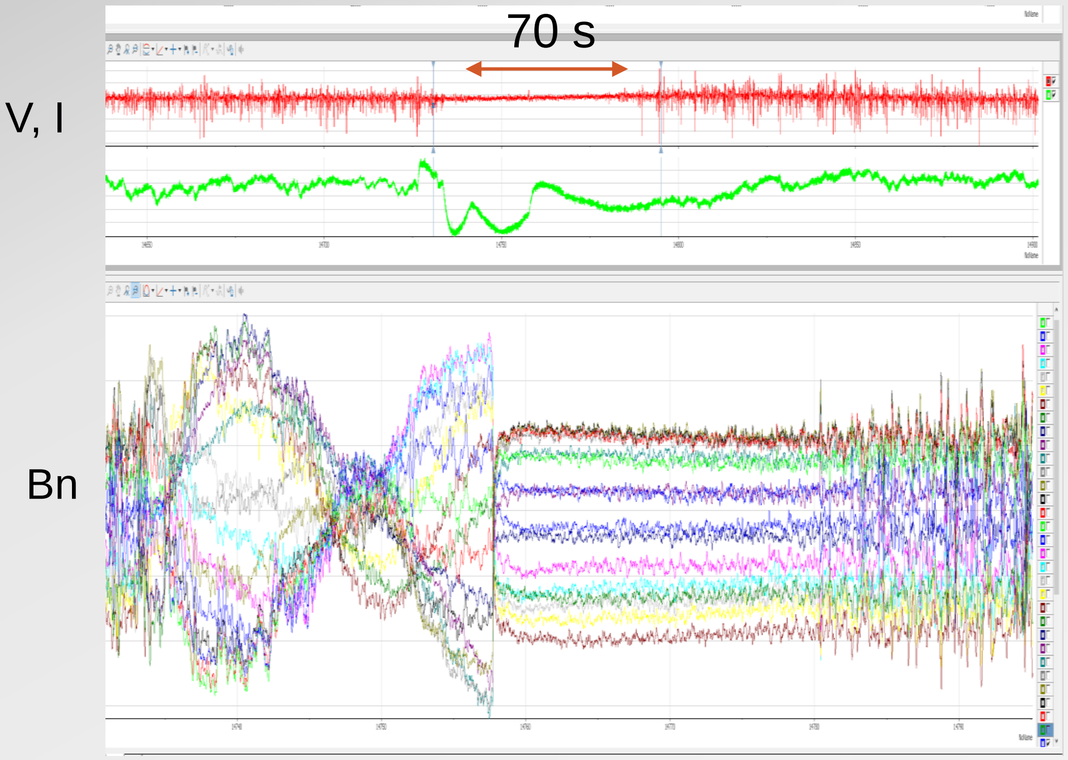


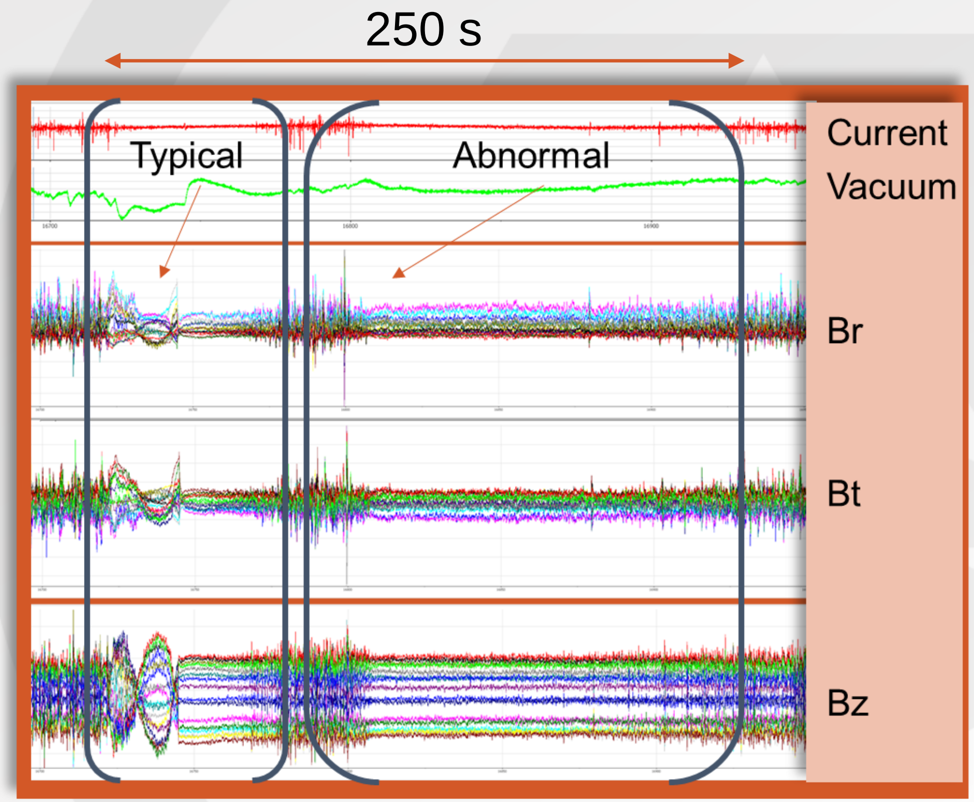


Glows

Analyze Data for Deleterious Conditions







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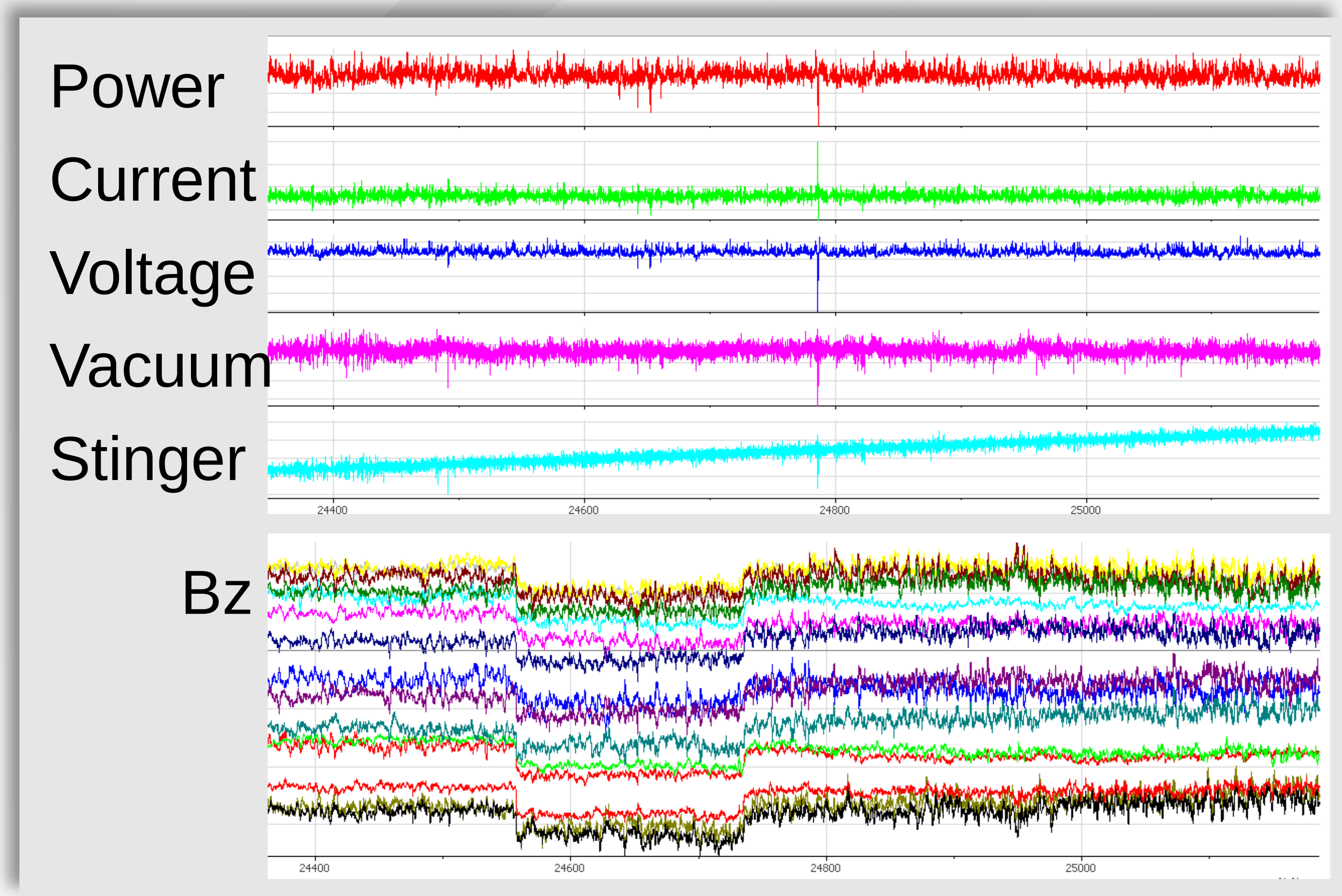
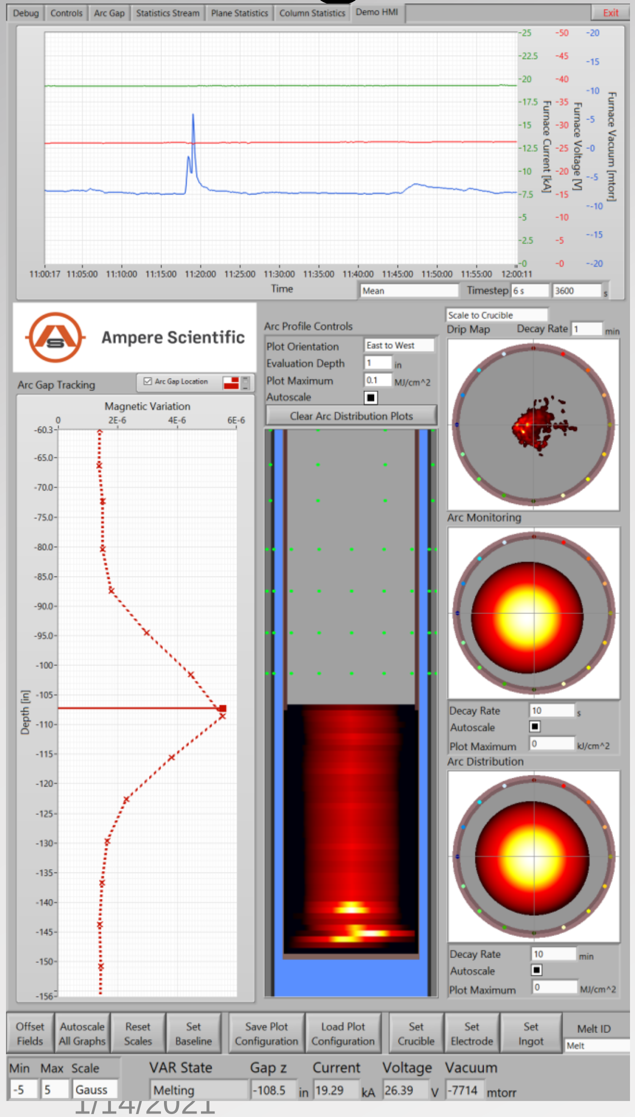
Analyze Data for Deleterious Conditions

Contact Resistance (Shelf Fall-in)

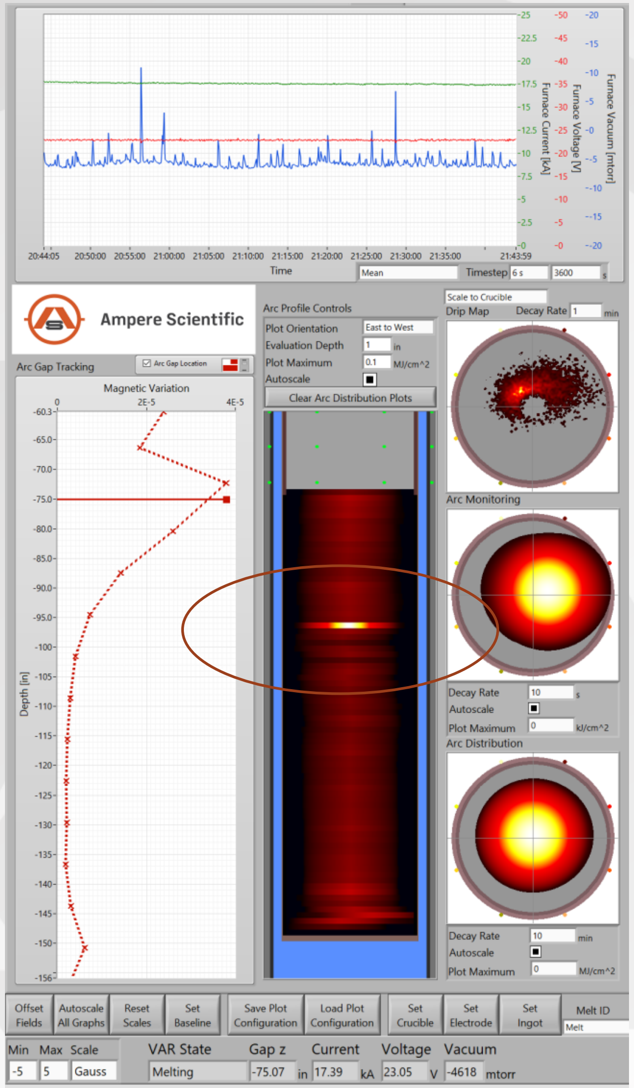
- Event late in steady state undetected in power, current, voltage, vacuum, and stinger position
- Lower planes detects a dip in Z-magnetic field (more field pointing down)
- Upper planes detects a rise in Z-magnetic field (more field pointing up)
- All sensors around the plane experience similar magnitude of change
- Event is detectable by all planes of sensors including in the radial/tangential fields
- Possible change in contact resistance between ingot and crucible?
- Event is temporary and appears to revert after ~200 seconds



"Long Arc"



- Left – *VARmetric*™ detects a "long-arc" condition where a diffuse arc was sustained while no drips were present
- Right – After a control change, dripping was re-established



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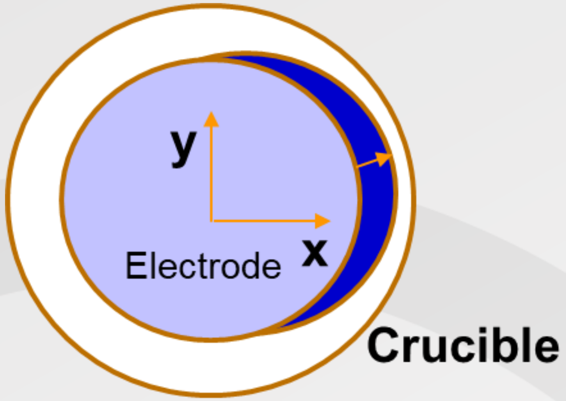
Electrode Movement/Centering



Slower movement of electrode toward crucible wall

Faster movement from the wall back to the center

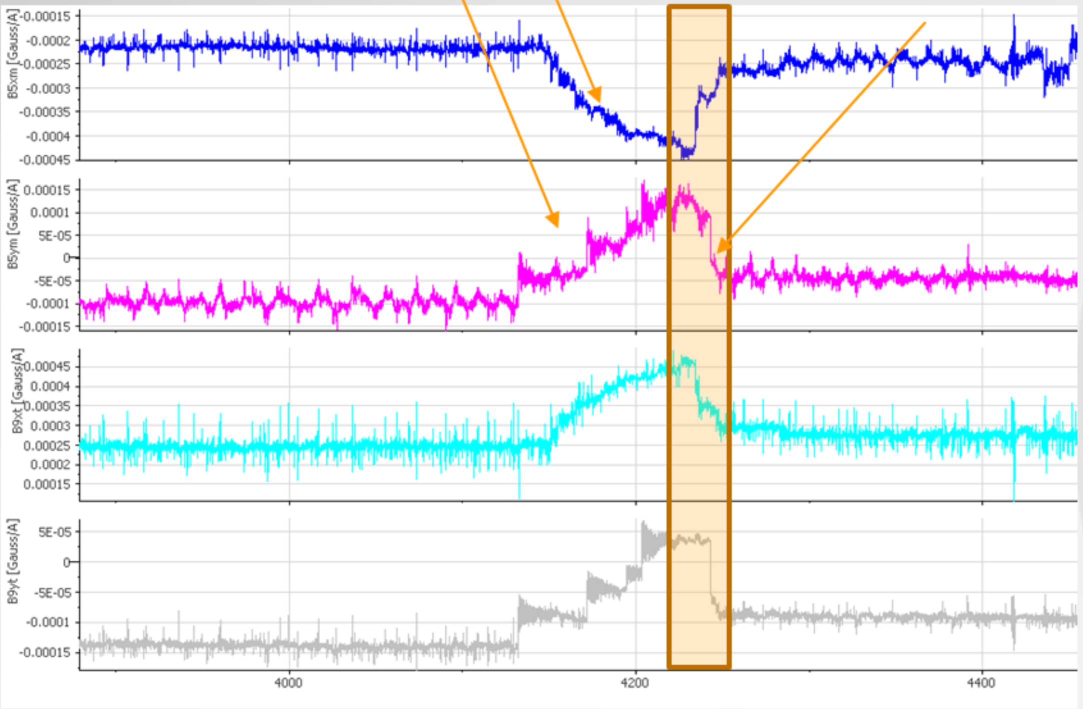
Movement back to center (detected in x-y plane)

Bx

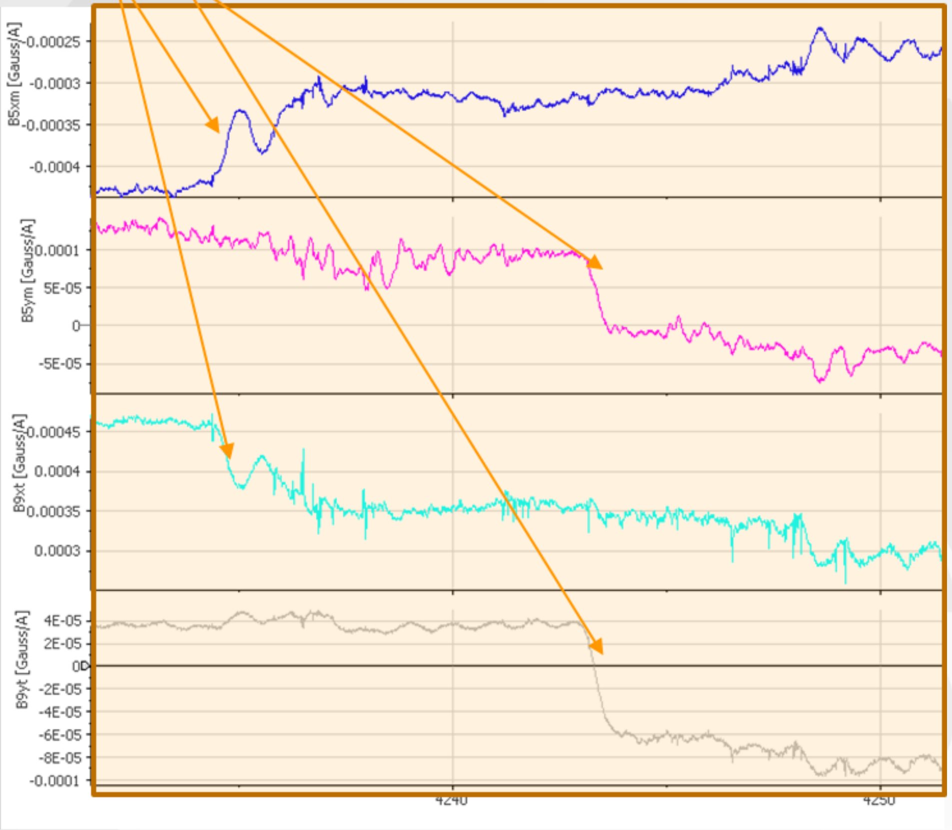
By

Bz

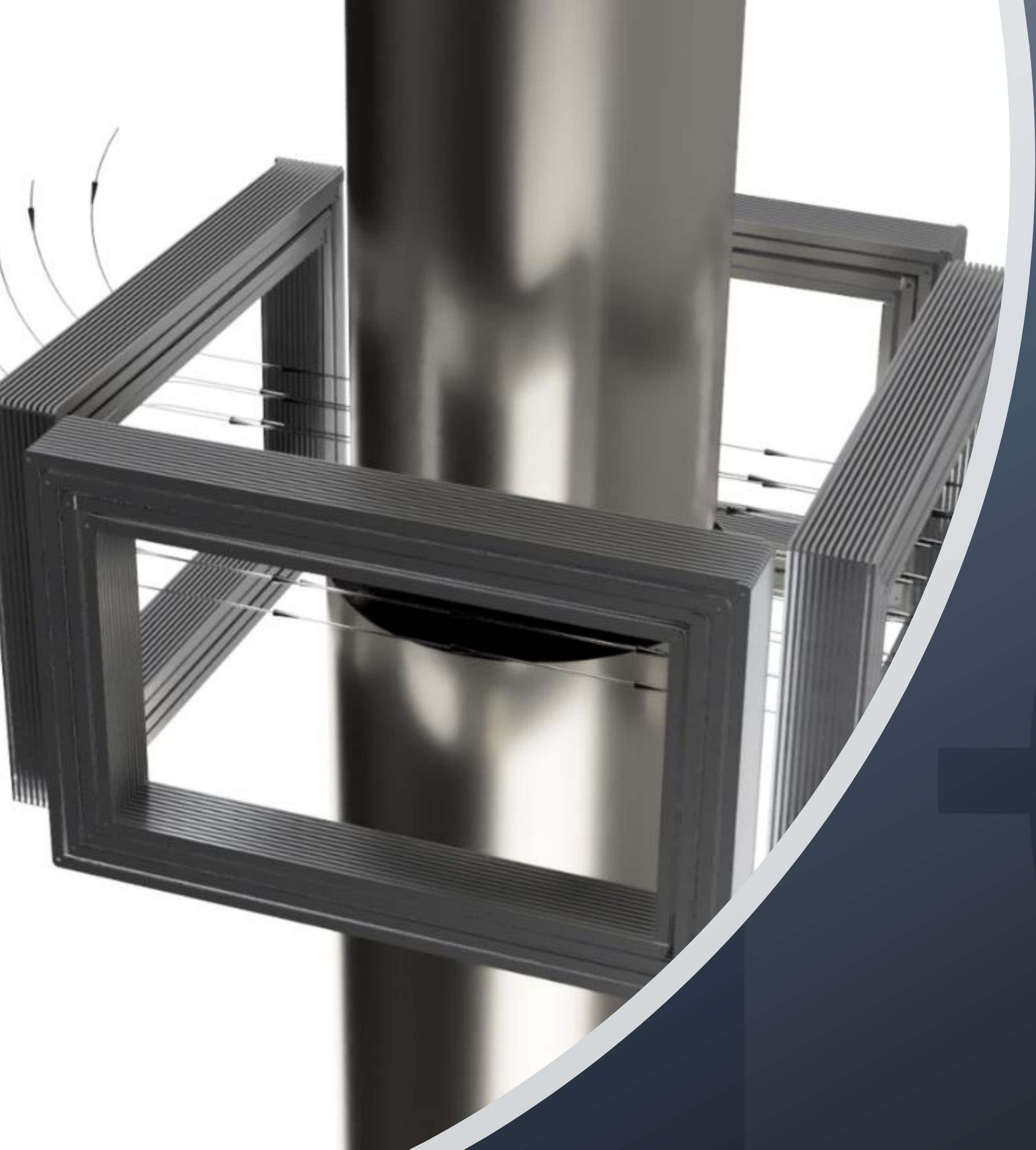
Bn



Time [s]



Time [s]



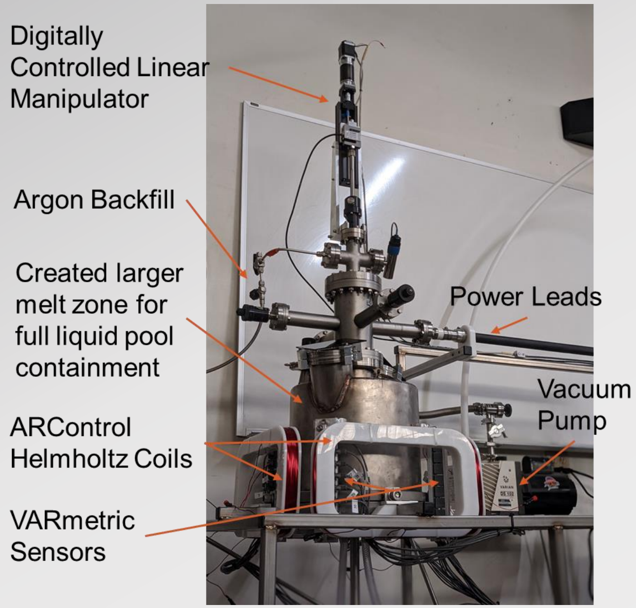
Other Advances

- *ARControl*™
- Energy I-Corp
- Rebranding

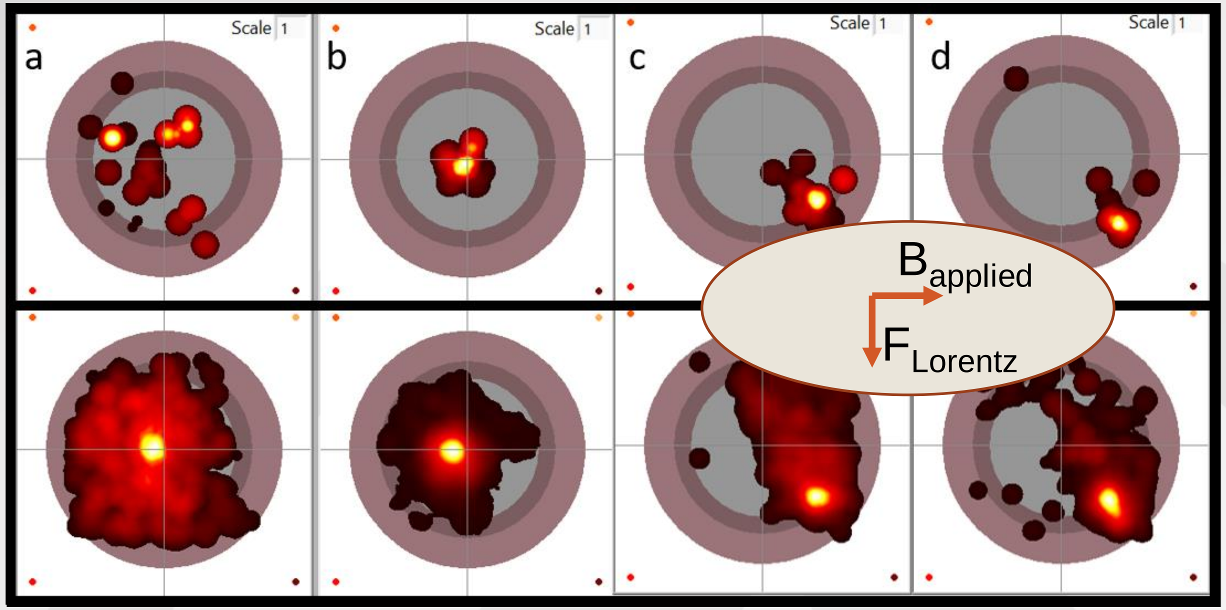
ARControl™

Can we tailor the heat flux such that we can influence solidification?

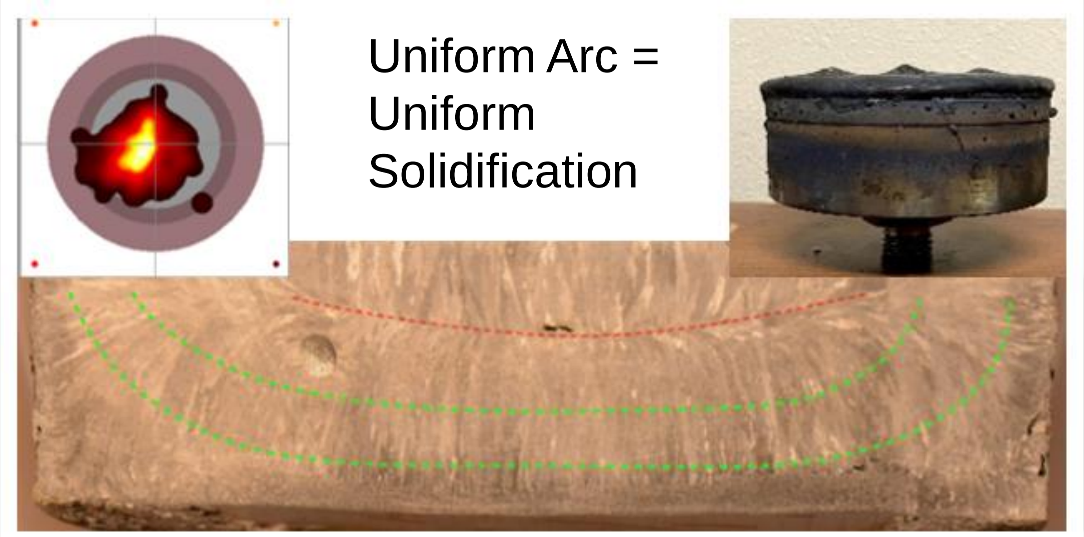
If yes, then we can dictate solidification to most any degree we want



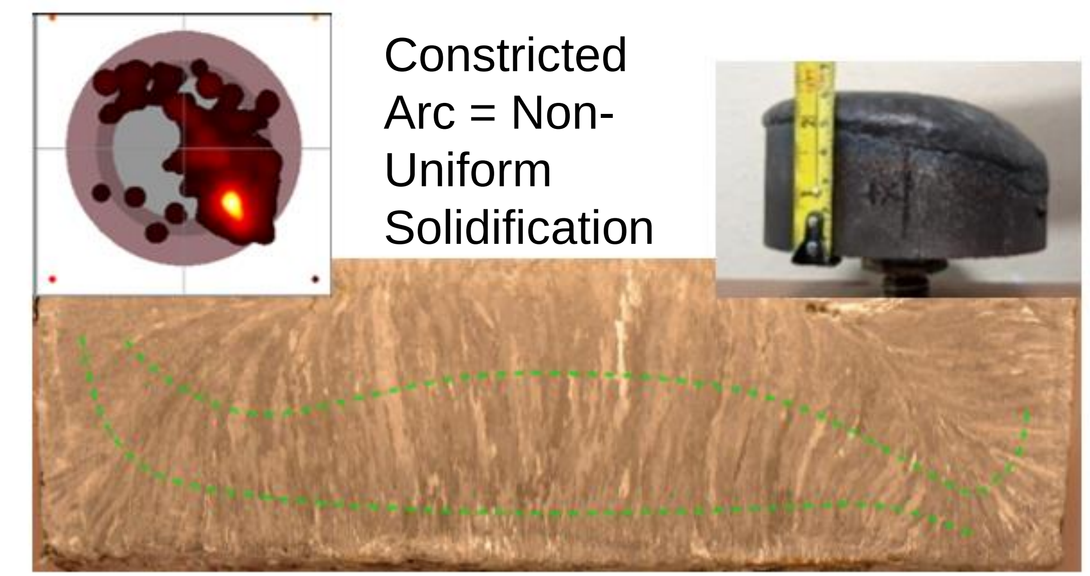
0.1 sec arc position decay rate



0.1 min arc position decay rate



Uniform Arc = Uniform Solidification



Constricted Arc = Non-Uniform Solidification

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Energy I-Corp Program

1. The Company/Team
   - Ampere Scientific / 024
   - Team Members
     - ➢ Dr. Paul E. King, CEO
     - ➢ Paul Turner, Sales Engineer
     - ➢ Nathan Pettinger, Project Engineer

2. Business Thesis
   a) Ampere Scientific offers a tool that makes base metal ingots clear of defects so that we can implement larger ingots while increasing production safety, increasing yield and decreasing the cost through better process control

3. We will enter the market through two avenues, direct sales and through an OEM partnership

4. Interviews Completed
   a) We completed 68 Interviews

Interviewees by category:
- •Gen. Mgr Melting Operations
- •Dr. R&D
- •Dir Process Dev.
- •Metallurgists
- •Commercial Equipment Vendors
- •Regulatory, Insurance, Airlines Maintenance and Operations

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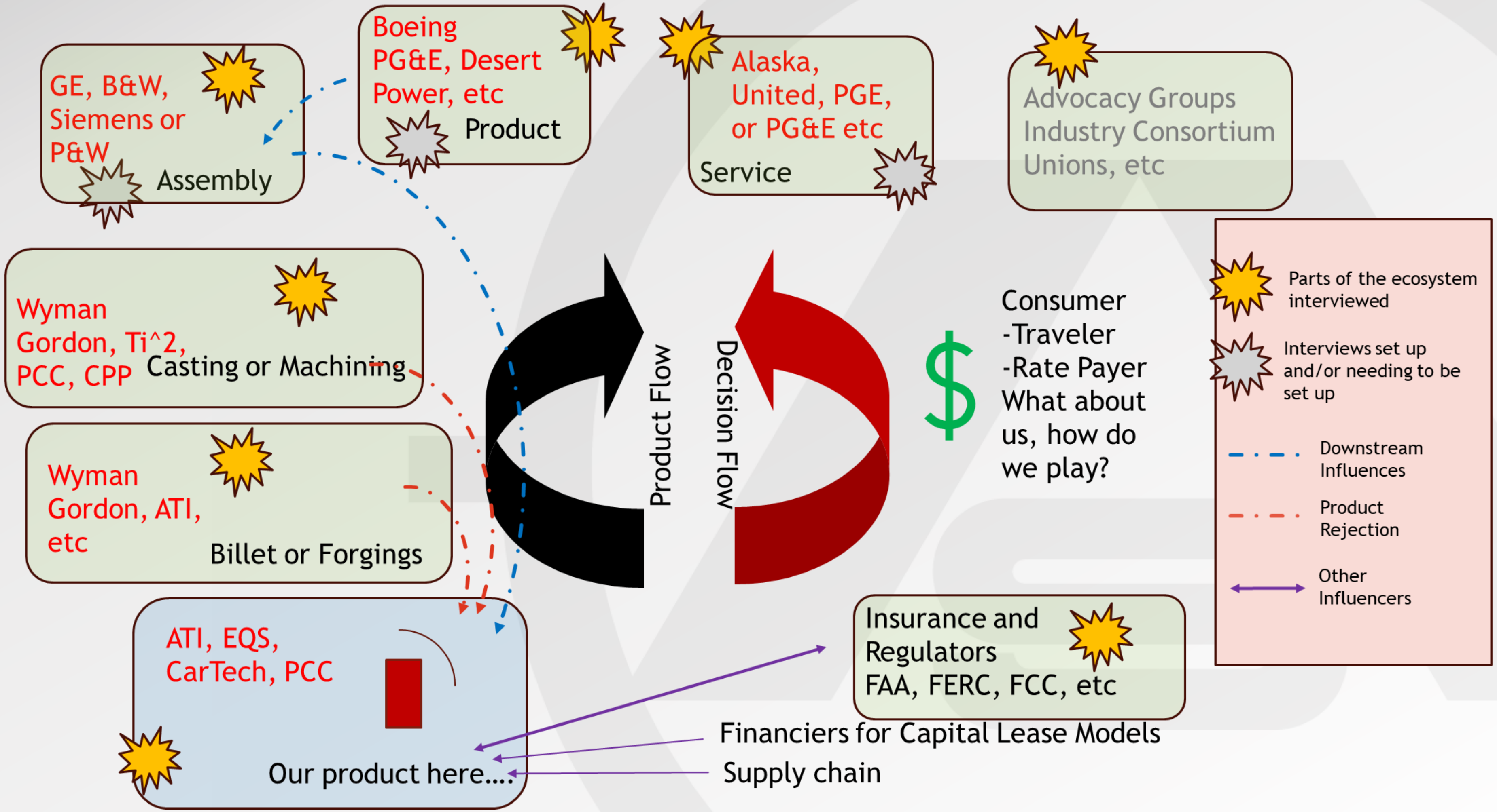
Path to Market – Value Chain Assessment (I-Corp Program Results)

Interviewed 68 people ranging from regulatory/insurance to product end users

Still engaging with other engine OEMs, OEM Trade Organizations (JETQC / JENQC), and their customers



Key Market Findings

1. **There is a need for larger ingots** than can be currently manufactured with existing technology
   - The need is being driven by the downstream customers and specifically by some of the very large end users.
   - Most of our customers have been clamoring for larger super alloy ingots for decades
2. In terms of savings, the following order of efficiency gains should dictate product development and validation:
   - Yield, especially side wall (shelf)
   - Overall product quality
   - Safety in operations
   - Decreased electrical usage

ROI Expectation:
1-3 years for large companies
3-5 years for small companies

3. Our customers are influenced by their customers for the adoption of new technologies
   - In power generation and aerospace, this is true especially from the turbine OEM standpoint

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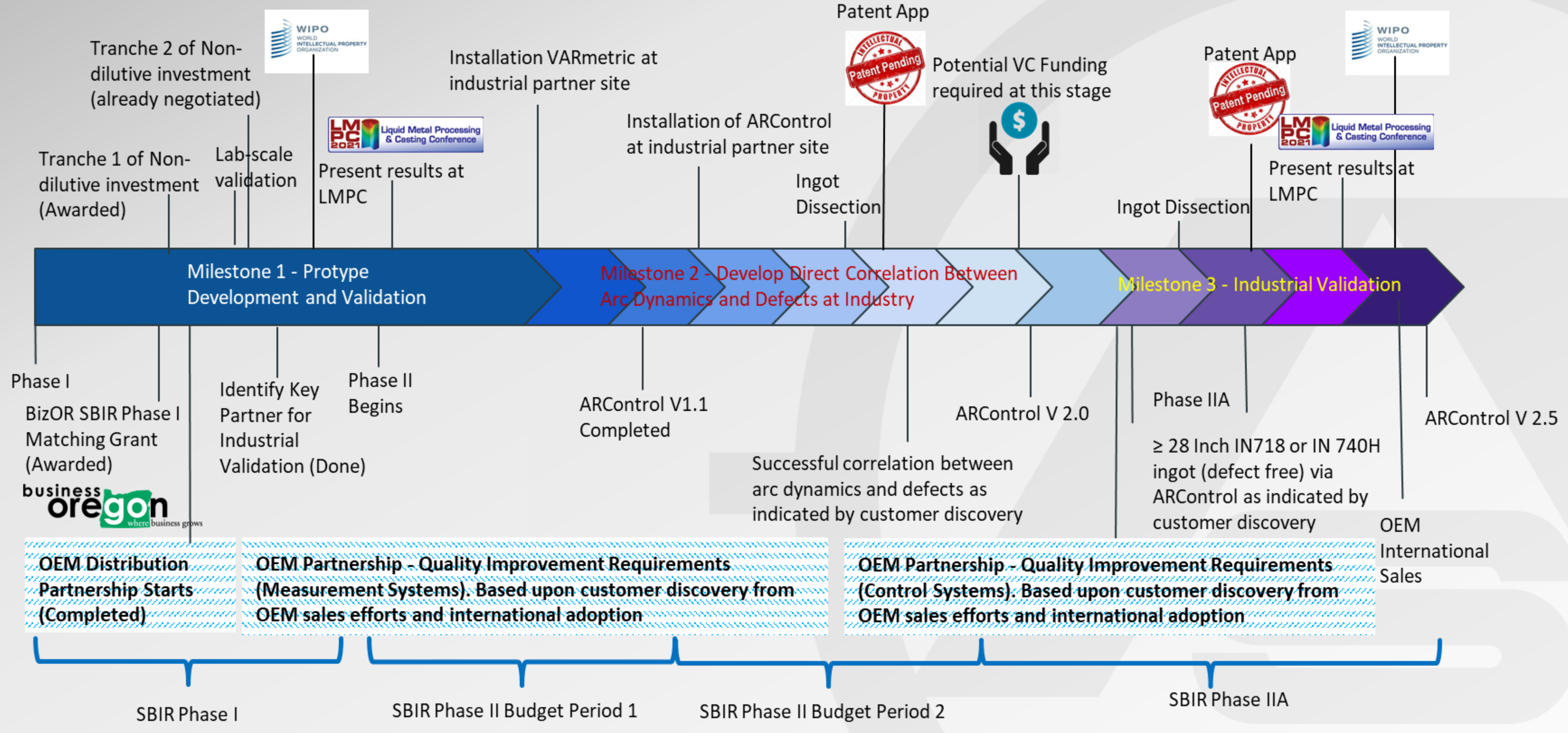
Roadmap to Technology Acceptance



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Work performed at DOE under Industrial Funding (CRADA), Validation done on Industrial VAR

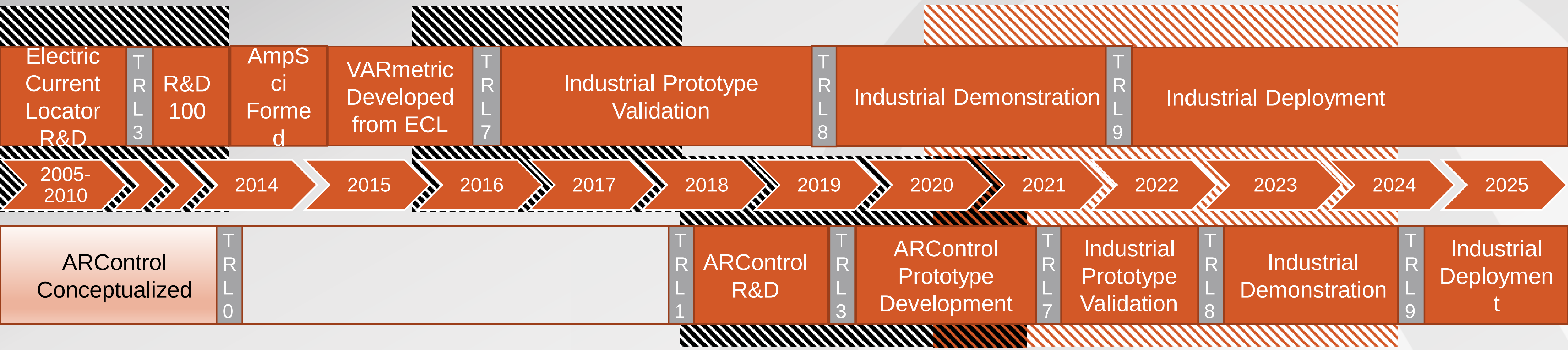
Work performed at Industrial site under Joint Development Agreement

Work performed under DOE, Business Oregon and Industry Funding

Phase I

Phase II

Phase IIA/B



Work performed under NSF, Business Oregon and Industry Funding, Validation done on Lab and Industrial VAR

R&D on Reactive Metals Processing

R&D on Non-Reactive Metals Processing

Industrial Engagement & Matching Funding

- Consarc
  - Consarc Corp., one of the worlds largest VAR, ESR and Vacuum Metallurgy equipment suppliers, and AmpSci have signed an agreement that provides Consarc World-Wide rights to resell *VARmetric*™
    - Consarc has 1000 engineering/sales employees in 40 countries
  - The agreement provides them exclusive rights from an OEM standpoint (eg, we can't sell to their competitors but can sell to customers of their competitors)
  - Provides for AmpSci performing direct sales to anyone we choose except the OEM direct competitors.
- Business Oregon
  - Funded by lottery funds, Business Oregon is the State of Oregon's official Economic Development Agency
  - AmpSci won an SBIR Phase I Matching Grant Award from Business Oregon
    - The grant was to be used to hire on an additional full-time employee to support the project

Rebranding

AmpSci throws out the old logo and develops a new, modern logo that reflects our products. The circle with the horizontal bars are recognized as the universal engineering sign for the Ammeter, while Ampere Scientific is represented by its initials inside the Amp-meter

Say Goodbye Old AmpSci

DOE SBIR Phase II Considerations

Phase II Primer

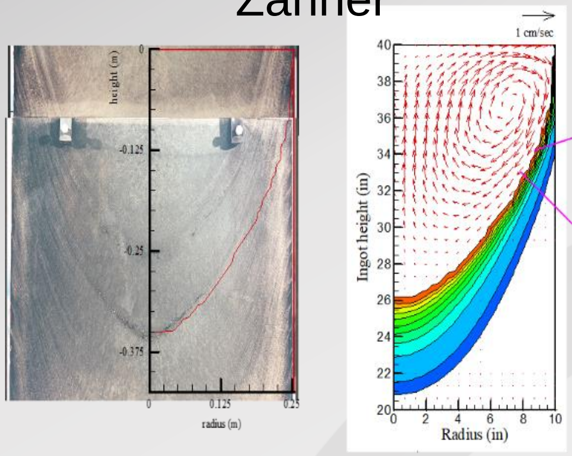
Zanner *et al* proved that arc distributions dictate solidification including dictating solidification angles

Poirier showed how solidification angles trap solute rich elements to form defects

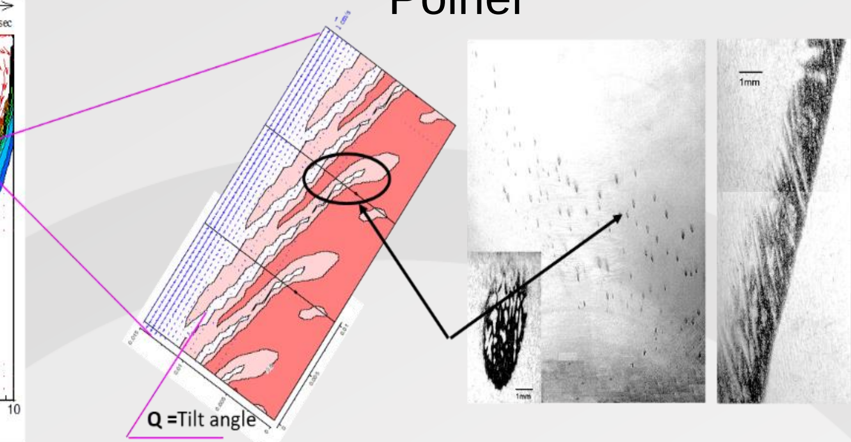
Motley showed (computationally) how short duration interrupts in arc distributions affect solidification within the ingot

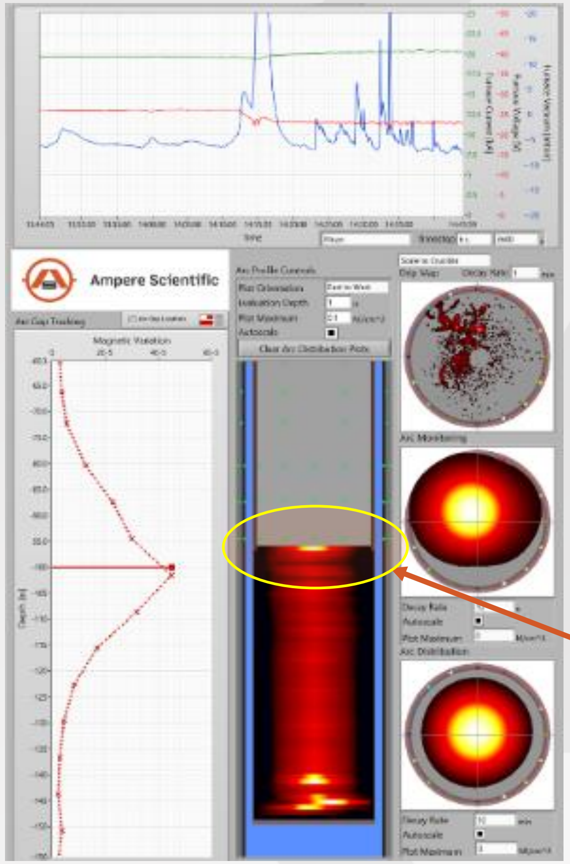
AmpSci developed *VARmetric*™ to measure arc distributions in real time during operations and subsequently developed active control over those distributions.

Zanner

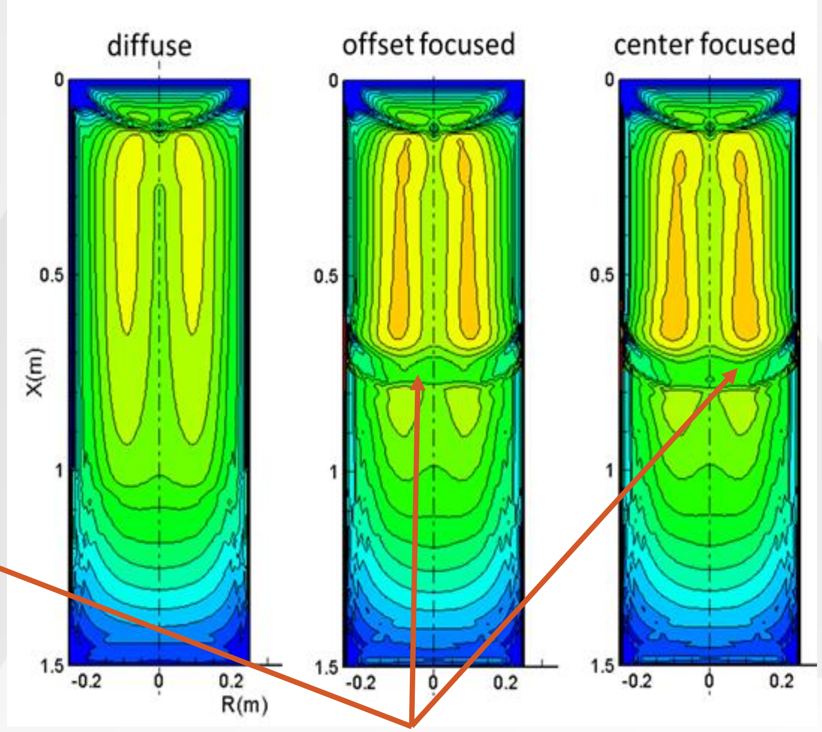


Poirier



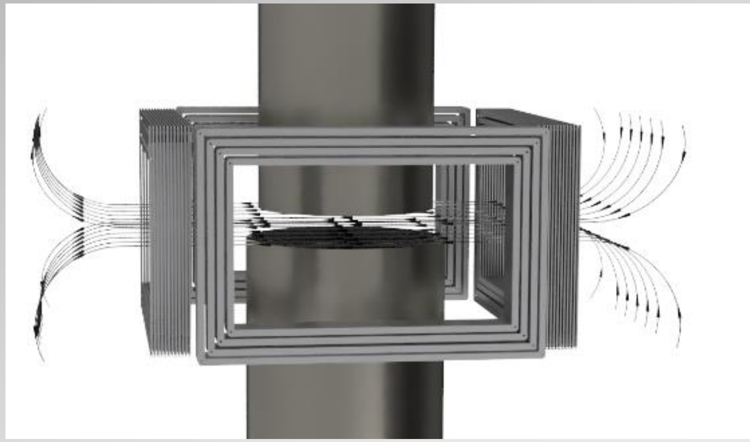


Motley

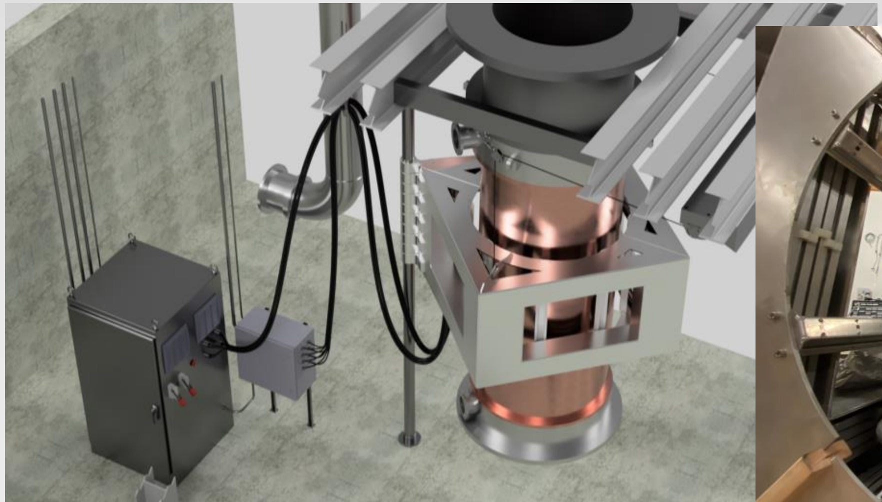


Constricted Arcs lead to solidification changes and defects

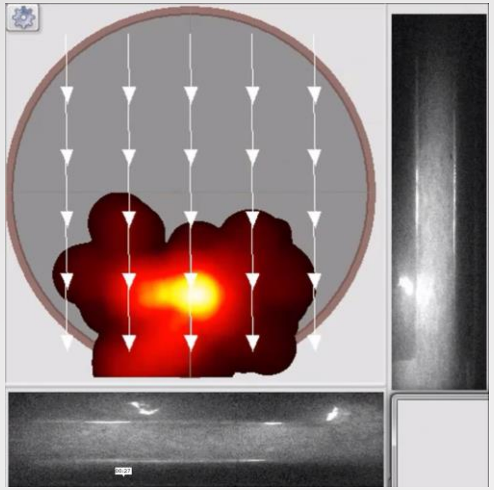
Application of *ARControl*™ for larger ingots



Application of transverse magnetic fields via Helmholtz coils to tailor the arc distribution during melting

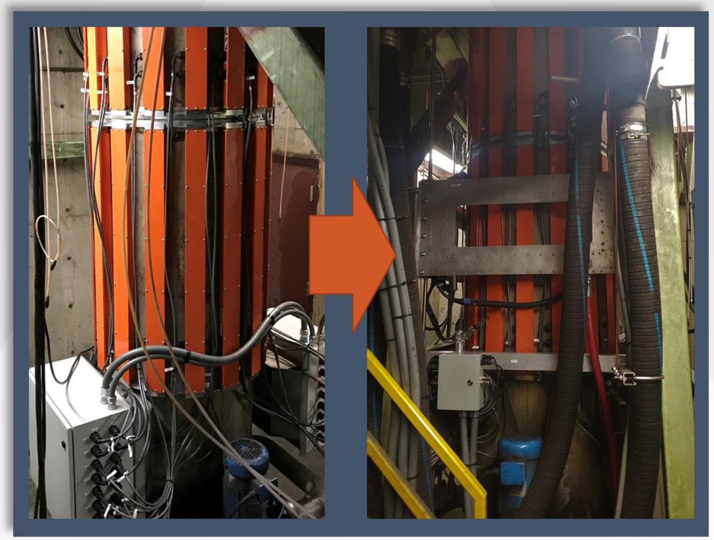


Prototype *ARControl*™ sent to Korea for reactive metals melting



Validation of *ARControl*™ in laboratory setting

Prototype *ARControl*™ at ATI for reactive metals melting



Phase II Plan

1. Install *VARmetric*™ on a VAR melting gamma prime strengthened alloys
2. Perform data analysis for baseline studies for up to 6 months
   a. Identify conditions that lead to off-normal quality
   b. Identify differentiators in heat flux between smaller and larger ingots
   c. Continue to develop database of events
3. Develop *ARControl*™ algorithm to tailor heat flux
   a. Utilize information from 2.b and simulation to predict heat flux required as a function of ingot diameter
   b. Develop control algorithm to implement the desired heat flux
4. Run *ARControl*™ experiments
   a. Drive the arc position to favor defects
   b. Destructively evaluate the ingot for defects to verify conditions
   c. Drive the arc position to favor larger ingots
   d. Destructively evaluate ingot for defects to verify control

Commitments from Industry

Host Site

Special Metals, A PCC Company

Backup Host Site

Universal Stainless & Alloy Products, Inc.

Industry Advisory Board Members

Consarc

Energy Industries Of Ohio

GE Energy

GE Aviation

Carpenter

Ampere Scientific

Thank You!

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Together with SMC, GE Power Generation, GE Aerospace, Carpenter Technologies, Universal Stainless and the Energy Industries of Ohio, we hope DOE will support our Phase II application!

Ampere Scientific

SBIR Acknowledgement and Disclaimer

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