Enhanced Second Generation (2G) High Temperature Superconducting (HTS) Wire for Electric Motor Applications

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American Superconductor Corporation
with: Brookhaven National Laboratory
Brookhaven Technology Group
University of Buffalo
Project Period: June 1, 2017 – May 31, 2020

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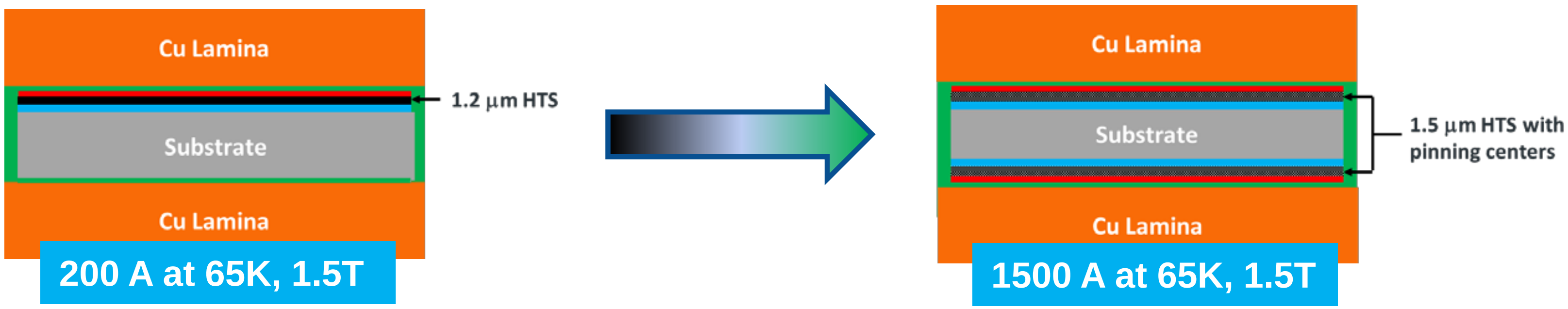
Project Objective

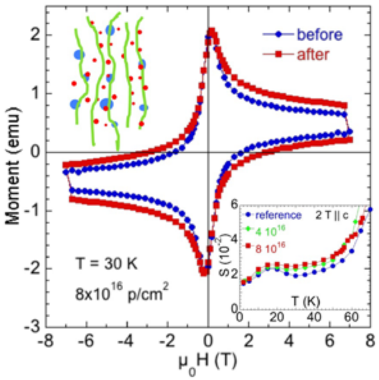
- Increase the critical current (I_c) by 7x and lower the cost by 50% of HTS wire designed for commercial electric machine applications operating at ~65K in magnetic fields of ~1.5T

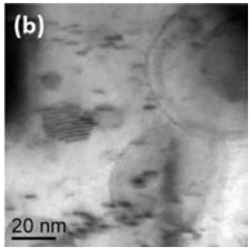


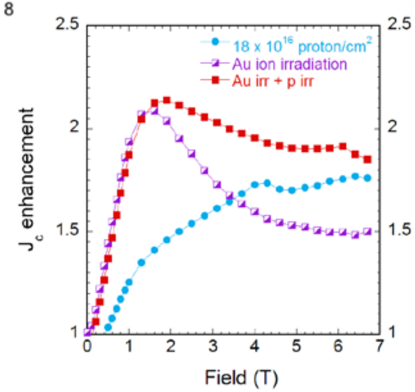
- Performance of today's "state-of-the-art" wire is suppressed in the presence of the magnetic field in rotating machines at the desired operation temperature of ~65K.
  - This requires large wire quantities for each machine to achieve the needed amp-turns, reducing the economic viability of commercial applications.
- Current solutions include
  - Lower operation temperatures (30-40K) – increased cooling cost and complexity
  - Thicker HTS layers – technical limits, increased wire cost and reduced yield
  - Enhanced pinning – increased wire cost, reduced yield and wire uniformity

Fundamental Knowledge to be Gained

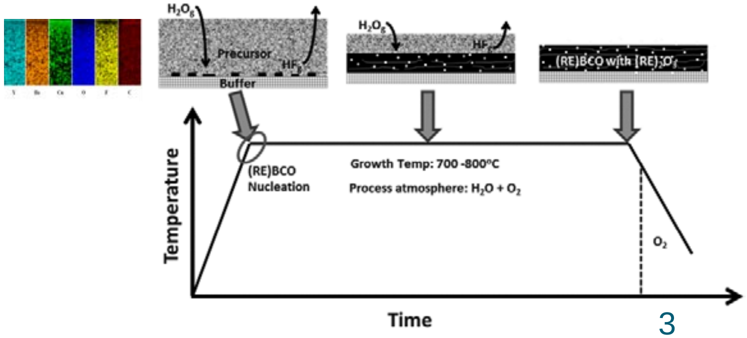
- **Pinning Science**
  - Structure and density of ion irradiation induced defects depend on the ion identity, ion energy and dosage. As structure and density of the defects vary, the pinning properties vary. Thus optimizing pinning at specific temperature and field regimes requires understanding nature of defect structure





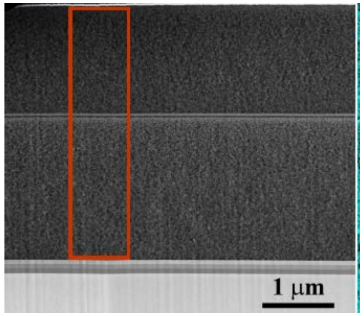


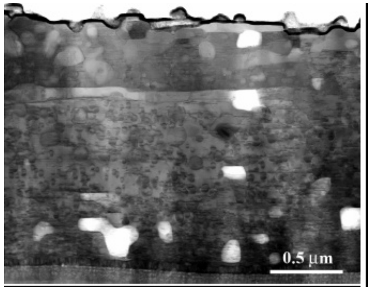
- **Epitaxial Growth of MOD-based Films**
  - Controlled growth of defect-free, thick MOD films requires control of multiple chemical reactions and kinetic and equilibria conditions. Gaining a better understanding of key parameters and controlling them in thick films is critical to pushing the thickness limitations of the technology



Technical Innovation

- Rotating machines are designed for operation at 30–40K; however, wire cost is still a dominate factor in commercial acceptance, limiting use to demonstration projects.
- AMSC's program is structured around three technical innovations
  - Increased HTS layer thickness (1.25X increase in I_c)
    - Solution-based process limited by single layer thickness uniformity or interface between multi-layers during pyrolysis process.
    - Advanced pyrolysis process designed to overcome both limitations should result in increased I_c with no corresponding increase in equipment or process time.

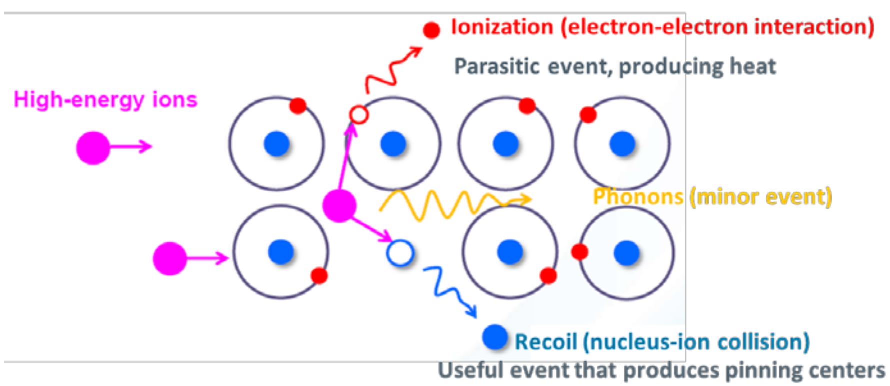


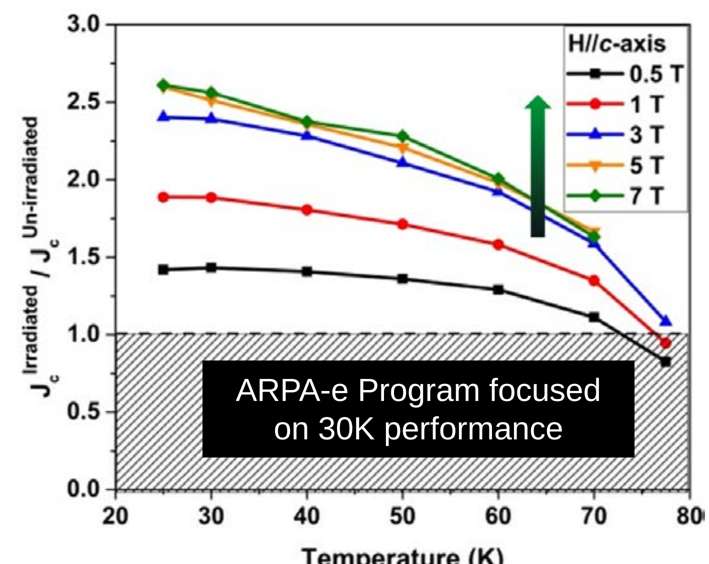


  - Two HTS layer architecture (2X increase in I_c)
    - Depositing HTS on both sides of substrate doubles I_c (and J_e) of wire and reduces material cost.
    - Innovative engineering approach designed for deposition and processing of HTS layers on both sides of substrate.
    - Process reduces cost of substrate, Ag, lamina and reduces wire fabrication (slitting, lamination) and testing time.

Technical Innovation

- Uniform distribution of nano-sized defects optimized for targeted operating conditions (3X increase in I_c at 65K, 1.5T)
  - Reel-to-reel ion irradiation of HTS produces uniform, controlled distribution of point defects throughout the HTS layer
  - Density and size of defects can be engineered to enhance pinning at specific temperatures and fields.
  - Irradiation process is extremely uniform and repeatable producing uniform wire properties with no yield or uniformity issues.
  - Depending on ion identity, ion energy and dosage, irradiation can reduce wire cost ($/kAm) at operating conditions by up to 50%



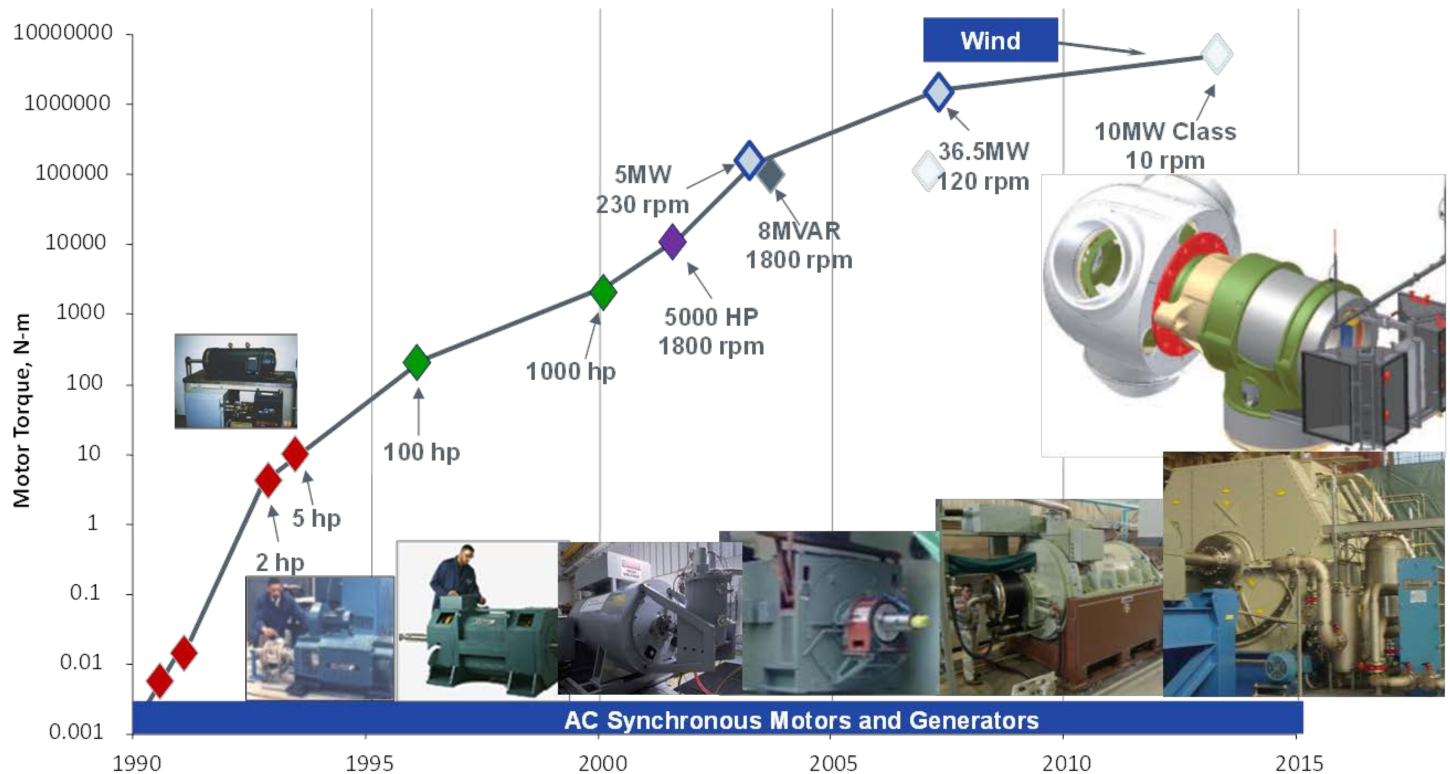


Technical Approach

- **Project Approach**
  - Year 1: Focus on development and verification of three individual technologies
  - Year 2: Integration of the individual technologies into a single wire
  - Year 3: Verify process in 200 m length wire and validate performance in a 500 hp motor test coil.
- **Participants and Roles**
  - AMSC – Program management, wire design, characterization, performance assessment, manufacturing engineering development, coil development and testing,
  - BNL – Optimization of pinning defect structure and roll-to-roll ion irradiation
  - BTG – Prototype process/equipment development for 2-sided HTS wire fabrication, slitting and rapid thermal annealing
  - UB – Microscopy and characterization
- **Program Risks**
  - Manufacturing issues related to 2-sided HTS architecture
    - POP for key manufacturing steps established; primary focus of year 1; gated by specific performance milestones
  - Ion Irradiation process feasibility and cost
    - Technical and commercial feasibility POP established in ARPA-e program and follow up effort; gated by specific milestones for program goals
  - Organizational / IP Risks
    - Close collaboration among participants, redundant resources if needed, IP agreements

Technical Approach

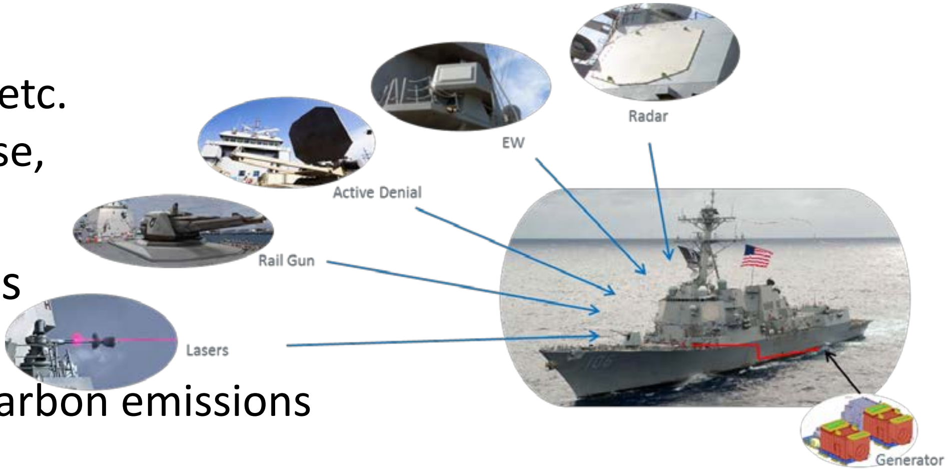
- AMSC is world-leader in 2G HTS wire manufacturing and commercialization with strong collaborations in the utility, industrial and military markets
  - History of commercial and military cable, coil and motor development; extensive knowledge of commercial applications and cost/performance requirements; experience with system design and integration



Transition (beyond DOE assistance)

- **Anticipated Markets for Enhanced HTS Wire**
  - Rotating electric machines market (field windings)
    - High torque applications (wind, hydroelectric, ship propulsion, etc.)
    - Airborne generators (field windings and stators)
  - Magnet market
    - High field applications (fusion, research, MRI, etc.)

- **Targeted End Users**
  - Military
    - Ship protection, generators, motors, etc.
    - Weight/volume benefit, reduced noise, new/improved capabilities
  - Electric Equipment OEM and Utilities
    - Generators, motors
    - Volume, power, efficiency, reduced carbon emissions
  - Other Users
    - Fusion, high-field magnets, MRI, aircraft/space propulsion
    - Higher fields, volume, weight, efficiency, reduced carbon emissions



Transition (beyond DOE assistance)

- **Commercialization Approach**
  - Provide system based solutions to end users
  - Collaboration with OEM’s to offer system based solutions
  - Direct wire sales to OEM’s and other customers
- **Technology Sustainment**
  - Identify applications and establish price sensitivity (wire and system)
  - Target applications based on market size and price sensitivity
  - Increased manufacturing capacity will reduce wire cost and open new markets
  - Target additional markets

Measure of Success

- Technical acceptance of HTS applications is growing in the utility, military and industrial markets
- Wire cost in terms of $/kA*m (at operating conditions) is a remaining barrier
- A successful program should lower wire cost to acceptable levels for establishing a commercially viable market for rotating machines – Success will ultimately be measured by acceptance of HTS machines for economic reasons and not only technical performance
- Broad introduction of cost-competitive HTS applications will reduce the cost of energy, reduce greenhouse gases, enhance energy efficiency, improve grid reliability and create new jobs

Project Management & Budget

Budget Year 1

Task 1 - Ion Irradiation Development

Key Milestone: I_c of 400 A/cm-w at 65K, 1.5T (short sample)

Task 2 - Two-layer HTS Wire Architecture

Key Milestone: Ic of 315 A/cm-w in each HTS layer (from 20 m length)

Task 3 - Thicker HTS Film

Key Milestone: I_c >405 A/cm-w at 77K, sf (short sample)

Task 4 – Characterization

Task 5 - Project Management

Budget Year 2

Task 6 - Ion Irradiation Development

Task 7 - Two-layer HTS Wire Architecture

Key Milestone: I_c >900 A/cm-w at 65K, 1.5T (from 50 m length)

Task 8 - Thicker HTS Film

Task 9 - Characterization

Task 10 - Project Management

Budget Year 3

Task 11 - Process Integration, Yield and Cost Analysist

Key Milestone: I_c >1400 A/cm-w at 65K, 1.5T (50 m length)

Task 12 - Motor Coil Testing

Task 13 - Characterization

Task 14 - Project Management

Technical Milestones throughout program to verify schedule and technical progress

Key samples provided for independent testing and verification throughout the program

Total Project Budget	
DOE Investment	**$4,499,998**
Cost Share	**$1,169,530**
Project Total	**$5,669,528**

Results and Accomplishments

- New project – Start date TBD
- Year 1 Focus
  - Develop and validate key technologies for producing 2-sided HTS wire architecture
  - Optimize ion irradiation process for targeted operating conditions of 65K, 1.5T
  - Verify new pyrolysis approach for increasing thickness of single layer HTS film

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