Research Statement

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I. INTRODUCTION

Here I will present my plan for research towards SRF cavity cost reduction for the ILC project as an assistant professor at KEK. I will explain my past research and experience in the field of SRF and accelerator science. This includes research into electropolishing using advanced electrochemical techniques such as electrochemical impedance spectroscopy, and research into new methods of polishing Nb_3Sn SRF cavities using centrifugal barrel polishing. This experience makes me well qualified for performing research at KEK.

Using my experience in electrochemistry, I plan to study new methods of electropolishing SRF cavities such as bipolar electropolishing that do not require the use of toxic HF acid. This research goal is well aligned with KEK's initiative to reduce the manufacturing costs of SRF cavities by eliminiating the costly safety and environmental hazards of using HF acid.

Additionally, my research plan includes a study of the mechanical properties of niobium which will help improve the press forming method used to fabricate large grain niobium cavities. Large grain cavities are a major milestone for reducing the raw material cost of SRF cavities, which represents a large portion of their overall cost.

These research goals make good use of the unique capabilities of KEK and are well aligned with the lab's mission to improve SRF cavity production capabilities for the ILC project.

II. RESEARCH EXPERIENCE

My research as a PhD student in the Northwestern University Materials Science and Engineering department was funded by a collaboration between Fermi National Accelerator Laboratory (FNAL), organized by Sam Posen, and my advisor professor David Seidman. Through this collaboration I have gained an extensive knowledge of materials science and metallurgy in addition to experience with accelerator science and superconducting radiofrequency (SRF) cavity technology.

My work at FNAL has led to several developments in manufacturing capabilities for Nb_3Sn SRF cavities. These capabilities include the development of a new mechanical polishing technique for Nb_3Sn cavities, which produces smooth Nb_3Sn films that were previously unobtainable using chemical polishing methods.[3] Nb_3Sn films treated with mechanical polishing have a mirror-like finish which cannot be obtained using other polishing methods. This improvement in surface roughness led to a significant increase in the maximum accelerating gradient of a Nb_3Sn cavity.

In addition to mechanical polishing, I have also worked on a new Sn coating procedure, which has been used to heal Nb_3Sn cavities that have suffered degradation due to excess stresses applied to the cavity. Due to the thin and brittle nature of the Nb_3Sn films used in Nb_3Sn cavities, they are susceptible to developing cracks during handling and tuning. Using a short, low-temperature Sn coating, a large percentage of the performance of a stress degraded cavity was recovered.

In addition to my work on Nb_3Sn, I have also dedicated a lot of time to understand electropolishing (EP). This process, which is applied to Nb SRF cavities has been a large driver in cavity performance improvements over the past several decades. However, our fundamental understanding of the physical mechanisms of this process are still lacking. By systematically polishing Nb samples at different voltages and temperatures I was able to show that etching is caused by insufficient voltage applied to the sample, and is not significantly affected by the electrolyte temperature or the presence of nitrogen doping in the Nb.[2]

Through my research, I have become an expert in various measurement techniques for surface characterization. Electron microscopy, both transmission and scanning, has been an important tool for my research since the beginning. Mulitple imaging techniques, such as electron dispersive x-ray spectroscopy and electron backscatter diffraction, were

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utilized to analyze my samples. I am also an expert in using dual beam FIB/SEM instruments to prepare samples such as microtips for atom probe tomography or lamella for TEM. Additionally, I have used a dual beam FIB/SEM to perform three-dimensional EDS measurements, which involves the automated serial sectioning of a sample utilizing a focussed ion beam followed by imaging using EDS to obtain a 3D view of the sample composition. I used this method to image Sn-deficient regions in Nb_3Sn thin films which are a major source of performance degradation in Nb_3Sn cavities. [1] Apart from electron microscopy, I also have experience with many other analysis techniques such as laser confocal microscopy, secondary ion mass spectroscopy (SIMS), atomic force microscopy (AFM), and x-ray photoelectron spectroscopy (XPS).

I have presented my research at many conferences such as the International Conference on Radio-Frequency Superconductivity (SRF), the International Particle Accelerator Conference (IPAC), the Applied Superconductivity Conference (ASC), and the Cryogenic Engineering Conference and International Cryogenic Materials Conference (CEC/ICMC). I was a recipient for the IPAC'23 Student Grant, and I am a part of the Fermilab Accelerator PhD Program, which provides me with a grant for my tuition and stipend.

III. RESEARCH PLAN

Thanks to my research experience in SRF cavities, I am a well suited candidate to continue the world-leading SRF technology research for the International Linear Collider at KEK. Thanks to the unique capabilities available at KEK there are several research topics that I plan to explore: low cost HF-free bipolar electropolishing, and the fabrication of medium and large grain Nb SRF cavities. With my expertice in material science and electrochemistry, I can make a significant contribution to these topics.

A. Low Cost HF-free Bipolar Electropolishing

Thanks to my first-hand experience of working with electropolishing, I am well aware of the costs, both monetary and environmental, of performing EP on Nb SRF cavities using HF containing electrolyte. HF presents a significant danger to the environment and to the people who work with it on an industrial scale, which complicates the Nb cavity EP process and increases the cost of the cavities. In order to meet the production target of around 900 cryo-modules required for the ILC, the EP process must be improved to allow for greater scalability.

One way to achieve this is to eliminate the use of HF or any other hazardous chemical from the EP process. There are several technologies available to achieve this such as plasma electropolishing (PEP), centrifugal barrel polishing (CBP), and bipolar electropolishing (BPEP). Of these, BPEP is the most mature for replacing traditional chemical polishing methods. KEK is well suited to conduct research on BPEP thanks to its extensive record of studying and using EP for SRF cavity production. Additionally, KEK has the ability to perform vertical EP, which is necessary for BPEP due to the low viscosity of the electrolyte.

Bipolar electropolishing has been shown to be effective for polishing Nb SRF cavities. The main drawback of BPEP which has prevented mass adoption of the process is the slow material removal rate. To be competitive with traditional EP, the removal rate must be at least as fast as cold EP, which is used to achieve the final, high quality surface finish. Currently, the BPEP method takes too long to polish a cavity, which is not scalable to large volume cavity production.

To improve the polishing rate of BPEP, a better understanding of the process is necessary. The polishing rate is determined by the electrolyte and the voltage pulse waveform. The optimum electrolyte for BPEP is one that is close to neutral due to the safety and easy handling of such an electrolyte. The electrolyte should also be highly conductive to carry the large polishing currents of cavity polishing with minimal ohmic losses. Finally, any catalytic properties of the electrolyte that improves the reaction rate of the dissolution process are desirable, but extremely hard to predict without detailed knowledge of the niobium oxide film chemistry. The magnitude and duration of the voltage pulse must also be optimized to maximize the polishing current and create a smooth surface. Temperature, acidity, cathode design, and electrolyte mixing also play an important part in determining the outcome of the polishing. All of these parameters cannot simply be optimized using trial and error methods as the number of combinations is too large.

To optimize these parameters it is more reliable and reproducible to first obtain a deeper understanding of the process. This can be accomplished using electrochemical measurements such as electrochemical impedance spectroscopy (EIS), which provides information about the underlying chemical reactions that drive the process. Once these processes are well understood, the polishing parameters can be more easily optimized to provide faster polishing and better surface quality.

B. Deformation and Annealing Study on Large Grain Niobium

I am very excited about the research efforts at KEK on the development of medium and large grain cavities. KEK is well equipped for this type of research with the ability to perform almost every step of the manufacturing process in-house including cavity forming, welding, polishing, and heat treatment. To accomplish this research effort it is essential that we understand the mechanical properties of large grain niobium. Due to the anisotropic mechanical properties of large grain niobium, cavities manufactured using press forming methods frequently show defects such as cracks, dimensional deviations, and overall lower material strength. These issues complicate the manufacturing process and make it difficult to comply with high pressure gas safety (HPGS) regulations. To make large grain cavities viable for the ILC project, these issues will need to be resolved. Here, I propose a modification to the commonly used press forming method for fabricating large grain cavities.

Instead of forming the cavity in a single, large deformation step, the forming process can be split into multiple, progressive deformations. After each deformation the niobium is annealed at a high temperature. The annealing step removes statistical and geometrically necessary dislocations created during the deformation via recovery, annihilation of dislocation of opposite sign, and recrystallization, the creation of new grain boundaries by dislocation rearrangement. Annealing reduces the residual stresses in the material from the deformation and improves the ductility of the material for further deformation. This reduces the effects of the work hardening characteristics of different grain orientations resulting in a more isotropic deformation and lower spring-back. By incorporating one or more annealing steps in the press forming process, the mechanical properties of the large grain niobium can be improved to eliminate dimensional deviations and comply with HPGS regulations.

The goal of my research will be to evaluate the press forming and annealing processes for large grain niobium by manufacturing half-cells using a progressive press forming method. I will utilize the press forming equipment at available at KEK's cavity fabrication facility to create several large grain niobium half-cells with different levels of deformation. These half-cells will be annealed in a heat treating furnace at 900 °C or higher to activate the recrystallization process. I plan to investigate the grain texture and lattice distortion of the half cells after pressing and annealing using electron backscatter diffraction (EBSD), a technique that I have used many times before to analyze the grain structure of Nb_3Sn thin films. The dimensional accuracy and spring-back will be measured using a coordinate measuring machine (CMM).

Development of the intermediate press forming dies will be labor-intensive, so an initial experiment using smaller single crystal or bi-crystal niobium mechanical testing samples will be used to investigate the effects of different grain orientations and accumulated strain on the recrystallization process. These samples can also provide more data on the mechanical properties of large grain niobium.

This study will provide insight into the deformation mechanisms of large grain niobium and the recrystallization process leading to better large grain cavity dimensional accuracy and fewer manufacturing defects.

IV. CONCLUSION

The importance of developing new fabrication techniques for low cost, large scale production of SRF cavities is an essential part of ensuring the success of the ILC project. Towards this effort, I have detailed two research projects that are particularly suited to my skills and the capabilities of KEK.

The first project is the study of bipolar electropolishing. This method can reduce the cost of cavity polishing by eliminating the need for toxic HF acid. This is necessary to ensure safety and environmental integrity as the production of SRF cavities is ramped up. My plan is to apply my knowledge of electrochemistry and advanced electrochemical analysis techniques to optimize the removal rate and surface finish produced by BPEP. This will allow for a wider adoption of the technique in the SRF community reducing our reliance on HF acid. Using the vertical EP capabilities at KEK will be essential for my research, since BPEP has been shown to be more reliable using this method of EP.

The second proposed topic is the study of large grain niobium mechanical properties and annealing properties. This research is important for the fabrication of large grain cavities, which are expected to reduce the raw material costs of niobium SRF cavities. My research will help eliminate manufacturing defects for large grain cavity fabrication and ensure that the large grain cavities comply with the relevant safety regulations. This research project will require a deep understanding of metallurgy and material science, which have been at the center of my studies as a PhD student. Additionally, KEK is well equipped for this type of research with access to press forming equipment and many years of experience with cavity fabrication among the talented scientists working there.

[1] E Viklund, J Lee, DN Seidman, and S Posen. Three-dimensional reconstruction of nb 3 sn films by focused ion beam cross sectional microscopy. *IEEE Transactions on Applied Superconductivity*, 33(5):1–4, 2023.
[2] E.A.S. Viklund, L. Grassellino, S. Posen, T.J. Ring, and D.N. Seidman. Studies on the Fundamental Mechanisms of Niobium Electropolishing. In *Proc. SRF'21*, number 20 in International Conference on RF Superconductivity, pages 50–52. JACoW Publishing, Geneva, Switzerland, 10 2022.
[3] Eric Viklund, David N Seidman, David Burk, and Sam Posen. Improving nb3sn cavity performance using centrifugal barrel polishing. *Superconductor Science and Technology*, 2023.