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Book of Abstracts

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Superconducting materials such as niobium have been extremely useful for accelerator technology but require low temperature operation ~2 K. The development of high temperature superconductors (HTS) is promising due to their operating temperatures being closer to that of liquid nitrogen ~77 K. This work aims to determine the high-power RF performance of these materials at X-band (11.424 GHz). We have tested several types of rare earth barium copper oxide (REBCO) materials, such as films deposited by electron-beam physical vapor deposition, coated conductors soldered to a copper substrate, and solid pucks formed from powder. RF testing was done via a hemispherical TE mode cavity that maximizes the magnetic field and minimizes the electric field on a 2-inch sample region. We will report on surface resistance vs temperature measurements at low and high power,as well as RF testing of a pulse compression cavity lined with REBCO coated conductors.

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Development of a Plasma-Enhanced Chemical Vapor Deposition System for High-Performance SRF Cavities and Thin Film Studies

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Next-generation, thin-film surfaces employing Nb3Sn, NbN, NbTiN, or other compound superconductors are essential for reaching enhanced RF performance levels in SRF cavities. However, optimized, advanced deposition processes are required to enable high-quality films of such materials on large and complex-shaped cavities. For this purpose, Cornell University developed and commissioned a plasma-enhanced chemical vapor deposition (CVD) system that facilitates coating on complicated geometries with a high deposition rate. This system is based on a high-temperature tube furnace with a high-vacuum, gas, and precursor delivery system, and uses plasma to significantly reduce the required processing temperature and promote precursor decomposition. Here we present the commissioned system with all the control aspects and safety considerations addressed and the materials we are interested in growing.

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Molecular beam epitaxial growth of sodium antimonide photocathodes

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The Center for Bright Beams (CBB) at Cornell University has been developing techniques to grow single-crystal photocathodes for electron sources using molecular beam epitaxy (MBE). As a result, the first single-crystal Cs3Sb photocathode was produced, which has shown high quantum efficiency and is expected to have a low mean transverse energy (MTE). Now, other alkali materials are being explored. In this work, we report the epitaxial growth of Na-Sb photocathodes at the PHOtocathode Epitaxy Beam Experiments (PHOEBE) laboratory at Cornell University.The photocathodes were characterized through quantum efficiency (QE) measurements and reflection high-energy electron diffraction (RHEED) patterns collected during growth. The RHEED streaky pattern shows angle dependence, confirming their single-crystal structure. Notably, these Na-Sb photocathodes exhibited a QE exceeding 1% at 400 nm, which is much higher than previous reports on this compound. The possible reasons for this discrepancy are discussed.

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Measurements of Stability Diagrams in the IOTA Ring at Fermilab

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Nonlinear focusing elements enhance the stability of particle beams in high-energy colliders via Landau Damping, a phenomenon that acts through the tune spread these elements introduce. This experiment at Fermilab's Integrable Optics Test Accelerator (IOTA) aims to investigate the influence of nonlinear focusing elements on transverse beam stability by employing a novel method to directly measure the strength of Landau Damping. This method employs an active transverse feedback system as a controlled source of impedance to induce a coherent beam instability. The beam's resulting growth rate can then be used to directly measure the stability diagram, a threshold which maps the system's stability conditions. A proof-of-principle experiment of this measurement method was first explored at the LHC, where the experiment at IOTA aims to map out the entirety of the stability diagram and to obtain the beam distribution function from the stability diagram, a procedure never done before that would enable one to obtain the beam distribution tails. Here we present the experiment's methods and the initial results of stability diagram data analysis, simulations, and plans for further investigation.

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Synthesis of ordered Na-K-Sb photocathodes with oxygen-enhanced quantum efficiency

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Alkali antimonide photocathodes are recognized for their efficacy as photoemissive materials in electron sources. This study investigates the fabrication of ordered films of sodium potassium antimonide via Molecular-Beam Epitaxy (MBE) and the impact of oxygen on their performance at the PHOtocathode Epitaxy Beam Experiments (PHOEBE) laboratory within the Center for Bright Beams (CBB) at Cornell University. We utilized a co-deposition technique to reduce the Mean Transverse Energy (MTE) while maintaining high quantum efficiency (QE). The synthesized photocathodes were characterized in terms of their QE and crystal structure. QE measurements were taken across the 400- to 700-nm wavelength range to determine their utility in the visible light spectrum. Reflection high-energy electron diffraction (RHEED) patterns confirmed the successful growth of ordered crystal structures for the first time on both Si(111, 100) and STO. The oxygen background was also measured before sample growth and was found to correspond to an increase in photocathode QE in

samples using Si substrates. An excess of oxygen still proved to decrease photocathode photoemissivity. Conversely, STO substrates showed QE loss with increased oxygen background, likely due to the contributions of the oxygen within the substrate to the photocathode composition. Additionally, not all oxidations proved detrimental to the photocathodes' photoemissivity. A sample grown on STO, under the same conditions as the sample grown on Si, was able to recover the lost QE. The conditions that lead to this increased resistance are being further investigated.

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Status of the CYBORG beamline at UCLA: First Room Temperature Photoelectrons, soon available at 80 K!

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The intrinsic emittance obtained from radio-frequency (RF) photoinjectors is notably reduced by increasing the launch field at the cathode. Moreover, cryogenic RF guns offer the possibility of producing stronger fields, due to the higher bulk conductivity and lower breakdown rate, while reducing the mean transverse energy (MTE) of near-threshold photo electrons. Such devices thus constitute an ideal tool for driving low emittance electron applications like ultra fast electron diffraction (UED) and free electron lasers (FELs). The CYBORG beamline at UCLA is a stepping stone facility meant to investigate the production of very low MTE photoelectrons in cryogenic RF guns. Here we report on the status of the beamline operation. In particular, we recently produced the first photoelectrons from the C-band RF gun at room temperature and are currently working on the diagnostics that will allow a thorough characterization of such beams. We also discuss some of the technical challenges that we encountered in the process and the ones that we are still addressing.

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Identifying the connections between grain growth and flux expulsion in low RRR niobium SRF cavities

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The SRF community has shown that high temperature annealing can improve the flux expulsion of niobium cavities during cooldown. The required temperature will vary between cavities and different batches of material, typically around 800 C and up to 1000 C. However, for niobium with a low residual resistance ratio (RRR), even 1000 C is not enough to improve its poor flux expulsion. The purpose of this study is to observe the grain growth behavior of low RRR niobium coupons subjected to high temperature annealing to identify the mechanism for improving flux expulsion.

We observe that low RRR material experiences less grain growth than high RRR when annealed at the same temperature. We search for the limitations to grain growth in low RRR material and develop a diagnostic based on grain structure to determine the appropriate recipe for good flux expulsion. The results of this study have the potential to unlock a new understanding on SRF materials and enable the next generation of high Q/high gradient surface treatments.

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Investigating Dirac semimetal cadmium arsenide as a potential low-MTE photocathode

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We report on the quantum efficiency (QE) and mean transverse energy (MTE) of photoemitted electrons from cadmium arsenide ($\mathrm{Cd_3As_2}$), a three-dimensional Dirac semimetal (3D DSM) of interest for photocathode applications due to its unique electronic band structure, characterized by a 3D linear dispersion relation at the Fermi energy. Samples were synthesized at the National Renewable Energy Laboratory (NREL) and transferred under ultra-high vacuum to Arizona State University (ASU) for measurement using a photoemission electron microscope (PEEM). The maximum QE was measured to be $3.37 \cdot 10^{-4}$ at 230 nm, and the minimum MTE was 55.8 meV at 250 nm. These findings represent the first reported QE and MTE measurements of $\mathrm{Cd_3As_2}$ and are an important step in evaluating the viability of 3D DSMs as low-MTE photocathodes. Such photocathodes, constrained to lower MTEs by the electronic band structure, may prove effective in advancing beam brightness in next-generation instruments and techniques.

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Development of a Plasma-Enhanced Chemical Vapor Deposition System for High-Performance SRF Cavities and Thin Film Studies

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Next-generation, thin-film surfaces employing Nb3Sn, NbN, NbTiN, or other compound superconductors are essential for reaching enhanced RF performance levels in SRF cavities. However, optimized, advanced deposition processes are required to enable high-quality films of such materials on large and complex-shaped cavities. For this purpose, Cornell University developed and commissioned a plasma-enhanced chemical vapor deposition (CVD) system that facilitates coating on complicated geometries with a high deposition rate. This system is based on a high-temperature tube furnace with a high-vacuum, gas, and precursor delivery system, and uses plasma to significantly reduce the required processing temperature and promote precursor decomposition. Here we

present the commissioned system with all the control aspects and safety considerations addressed and the materials we are interested in growing

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MTE and QE Behavior of Cs_3Sb Photocathodes under Varying Wavelengths at Room and Cryogenic Temperatures

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The ASU cryogenically cooled DC electron gun offers an advanced platform for photocathode testing at room and cryogenic temperatures. Using a four-dimensional phase space reconstruction via the pinhole scan technique, we measure the Mean Transverse Energy (MTE) of alkali antimonide photocathodes, providing comprehensive experimental validation of the theory predicting reduced (MTE) near the photoemission threshold. Our results demonstrate this reduction across multiple wavelengths at both room and cryogenic temperatures, addressing a gap where such validation was previously lacking.
While reducing cathode temperature lowers MTE, it often compromises quantum efficiency (QE). In this work, we also demonstrate a cooling method that preserves QE for extended periods, achieving lower MTE alongside higher QE. We corroborate our measurement through simulation and cross-platform measurement validating this technique for detailed photocathode characterization and advancing electron source development.

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Improving 1-D TD-DFT Simulations of Optical Field Emission from Nanopatterned Cathodes

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Nanopatterned cathodes, operating under the strong optical field emission regime, are promising candidates for high brightness electron beam generation. Previous theoretical studies have indicated that brightness monotonically increases with the enhanced laser intensity, provoking the thermomechanical studies to determine the cathodes'limits. We present an in-progress ab initio calculation of the dominant heating process, vacuum heating, within a one-dimensional time-dependent density-functional theory framework. The Hartree potential embodies the mixed geometry of the chosen system, the nanoblade, where the vacuum region is treated with cylindrical symmetry and the bulk region with planar symmetry. Additionally, with the goal of improving backscatter current yields, we present progress in improving these rescattering simulations by developing an effective one-dimensional surface potential which adheres to reflection probabilities as calculated via density-functional theory. For all these efforts, numerical solution stability remains problematic.

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Tuning Niobium Oxides for Sn Nucleation

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With a critical temperature twice that of niobium, Nb_3Sn is the most promising alternative material for the future of Superconducting Radio-Frequency (SRF) technology, steadily advancing towards practical applications. In this collaborative study, we developed a framework to synthesize, characterize and compare substrate preparations based on oxide composition and surface roughness, aiming to understand tin nucleation mechanisms and design optimal substrate surfaces for high quality Nb_3Sn films. Our results show that anodized Nb substrates provide more nucleation sites and offer insight into the chemical composition of the oxide layer before and after heating to nucleation temperatures.

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Inelastic electron scattering in photoemission

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The emission of photo-excited electrons through inelastic scattering mechanisms is demonstrated to be prevalent in both semiconductor and metal photocathodes. This type of Franck-Condon process requires an intermediate 'particle'to simultaneously satisfy momentum and energy resonant electron emission into the vacuum states; optical phonons in polar semiconductors and the reciprocal lattice vector in metals. An analytical theory of (optical)phonon-mediated Franck-Condon photo-excited electron emission is shown to be very consistent with the measured emission properties (both QE and MTE) of (i) a Cesiated GaAs(001) photocathode at 808nm [J. Phys. D: Appl. Phys. 54, 205301 (2021)] and (ii) a GaN(0001) photocathode from just below its band gap energy to 5eV. Preliminary results will also be presented to illustrate that incorporating Umklapp electron scattering effects into our band-based photoemission theory [New J. Phys. 21, 033040 (2019)] provides for an improved understanding of near and below threshold electron emission from metal photocathodes.

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Picometer-scale emittance and space charge effects in nanostructured photocathodes

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Generation of ultralow-emittance electron beams with high brightness is critical for several applications such as ultrafast electron diffraction, microscopy, and advanced accelerator techniques. By leveraging the differences in work function and electronic structure between different materials, we enabled spatially localized photoemission, resulting in picometer-scale emittance from a flat photocathode. We also investigated space charge effects by measuring how the emission spot size, as measured in a photoemission electron microscope, changes with the number of electrons emitted per laser pulse. When more than one electron is emitted simultaneously, Coulomb repulsion causes a substantial broadening of the observed source size, enabling us to investigate the limitations imposed by vacuum space charge forces during pulsed photoemission. Our results highlight the potential of nanoscale photoemitters as high-brightness electron sources and offer new insights into electron correlations that emerge after ultrafast photoemission.

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Oxidation Studies of Au Capped Nb Surfaces

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Niobium surfaces readily form thick, non-superconducting oxide layers that can severely degrade radio frequency performance. These oxides create surface hot spots, which can lead to vortex nucleation and ultimately cause cavity quenching. We aim to prevent this deleterious Nb oxide formation by capping Nb surfaces with thin gold layers. We deposited gold layers ranging from ultra-thin (0.25 and 1 monolayer, ML) to thick (10 ML) on various Nb surfaces. Following annealing treatments, we employed scanning tunneling microscopy to characterize the surface morphology and electron spectroscopy to quantify the passivation efficacy under atmospheric exposure. Our findings indicate that, despite these treatments, both pre- and post-annealing surfaces still formed the niobium pentoxide phase.

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Co-sputtering of Nb3Sn into SRF cavity using composite target and optimizing surface homogeneity

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Nb_3Sn is a promising alternative to bulk Nb for superconducting radiofrequency (SRF) cavities due to its higher critical temperature (Tc ~18.3 K) and superheating field (Hsh ~400 mT), enabling improved cryogenic efficiency. Nb_3Sn coating method for superconducting radiofrequency (SRF) cavity has been developed following co-sputtering of Nb-Sn composite target using a DC cylindrical sputter coater. Deposition parameters and annealing strategies were optimized for uniform Nb_3Sn coating. 1.5 µm Nb-Sn film was deposited onto 2.6 GHz Nb SRF cavity and annealed at 600℃ for 6 h, followed by 950℃ for 1 h. Cryogenic RF testing confirmed Nb_3Sn formation with Tc = 17.8 K. A post-annealing light Sn recoating process improved the cavity's performance, achieving $Q_0 = 8.5 \times 10^8$ at 2.0 K.

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Correlating Atomic-Scale Structure with Superconducting Properties for Metallic, (3x1)-Oxidized, and Nitrogen-Dosed Nb(100)

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Superconducting radio frequency (SRF) cavities are the fundamental accelerating components of linear particle accelerators. Niobium is the material of choice for SRF cavities due to its high malleability, thermal conductivity, and superconducting critical temperature (T_C). Despite Nb having a T_C of ~9 K, the practical operating temperature of a Nb SRF cavity is ~2 K, below the boiling point of He and consequently quite expensive to operate. The improvement of Nb SRF cavities and the lowering of operating costs has been focused primarily on the development of new materials on the Nb surface. Due to the ~100 nm superconducting penetration depth of Nb, only ~1 micron of material need be deposited onto the Nb surface to completely change its superconducting properties. One of the primary limitations to both Nb SRF cavities and the new materials under study is the presence of a thermally stable and robust oxide. Understanding the formation, stability, and dynamics of the oxide and its effects on the operation of Nb SRF cavities requires study both of material superconducting properties and atomic-scale surface material chemistry. Helium atom scattering (HAS) is a surface diffraction technique that has the ability to probe surface structure, bonding, and dynamics. The chemically inert He and an ultra-high vacuum (UHV) environment make HAS an ideal probe for the chemically reactive and sensitive Nb surface. Furthermore, experts in the field have developed theory involving the He-electron interaction and the surface electron-phonon interaction to formulate an equation by which HAS data can be used to determine an electron-phonon coupling

(EPC) constant (lambda) for the surface (lambda_S). These data can then be used to find surface analogues for T_C along with other superconducting properties relevant to SRF cavity operation. We study the Nb(100) surface for its recognizable and stable (3x1)-O NbO oxide reconstruction. We find a lambda_S of 0.50 +/- 0.08 for the metallic Nb(100) versus a bulk lambda of ˜1, demonstrating that the superconducting state is significantly modified at the surface. We also find a lambda_S of 0.20 +/- 0.06 for the (3x1)-O reconstruction. Lower lambda_S corresponds to lower T_C and overall poorer superconducting performance. Therefore, our studies strongly corroborate a strong body of previous literature that has hypothesized that the oxide diminishes superconducting performance for both bare Nb and new materials built atop it. From this fundamental starting point, we look towards understanding better how and why nitrogen-dosed cavities improve superconducting performance. Currently, we know trace nitrogen is helpful for SRF cavity performance while thick NbN layers are not. Preliminary findings begin to show some information for how nitrogen diffuses into the surface and how nitrogen dosing affects EPC behavior.

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Zr-Nb Surface Alloys for Thermally Stable, Low-Loss SRF Cavities

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Superconducting radiofrequency (SRF) cavities are limited by losses that originate in the top ˜100 nm of the niobium surface. Zr–Nb alloys offer a promising route to reducing these losses by passivating the surface with ZrO_2 and suppressing lossy Nb_2O_5. In this project, we alloy Zr into Nb through evaporation and thermal diffusion, building on methods developed for Nb_3Sn films. Our goal is to produce smooth, thermally stable, Zr-rich surfaces and investigate their chemical and structural properties using in situ and ex situ tools. Ultimately, we aim to establish a pathway toward SRF cavity surfaces with improved performance and reduced oxide-related losses.

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Development of Sodium Potassium Antimonide Photocathodes for Electron Cooling at Brookhaven National Laboratory

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The success of electron cooling [1,2] for the Electron-Ion Collider (EIC) relies on the development of high-performance photocathodes (PCs) for photoinjectors. Ideal PCs are expected to exhibit high quantum efficiency (QE), low emittance, long operational lifetime, and minimal dark current. Alkali antimonide photocathodes are strong candidates to meet these demanding requirements. Among them, Na-K-Sb stands out due to its enhanced robustness, especially under high-temperature conditions caused by high-power laser illumination used to generate high-current electron beams [3].

It also offers long-term QE consistency compared to other alkali antimonides such as K2CsSb and Cs3Sb. This work presents the growth and characterization of Na-K-Sb photocathodes, including detailed QE measurements and spatially resolved QE mapping and decomposition behavior under elevated temperatures. These results demonstrate the potential of Na-K-Sb as a promising candidate for high-current, high-brightness electron sources that can significantly enhance the performance of electron cooling systems at the EIC.

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Studies of Nb in Preparation for Gold Capping Layers

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Bulk niobium is the standard material of choice for superconducting radio frequency (SRF) cavities for accelerator applications. However, the native niobium oxide that forms when niobium is exposed to atmosphere may inhibit cavity performance. Ongoing work at Cornell University proposes to chemically remove the niobium oxide and replace it before it can reform with a sub-nm layer of non-oxidizing gold deposited with electrochemical deposition. Here we report progress on cavity-scale and sample-scale testing of this work. We report RF results characterizing the baseline performance of the 2.6 GHz cavity to be used in the study, as well as sample imaging and surface characterization of comparable niobium samples.

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Progress on New Compound Superconductors for SRF Cavities

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Nb3Sn has led the way among higher-Tc alternatives to Nb for SRF applications, but it is still very far from its fundamental limits, especially in terms of quench field. While it is tempting to consider superconductors with even higher fundamental limits, we take an alternative approach, learning from the challenges encountered in Nb3Sn R&D and exploring materials that could more easily approach their fundamental limits and provide practical alternatives to Nb in the near future.

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