Project Description

1. Introduction

Accelerator science has emerged as an important scientific discipline. It is also the basis for colliders and x-rays sources and has applications for industry, medicine and perhaps in the long run, for nuclear power. The study of particle beams and the development of beam instrumentation invariably reveal new phenomena, and the frontier of accelerator science advances only when these are understood and overcome. As we push toward higher currents, higher energies and higher density beams, new phenomena come into view, ranging from non-linear collective effects governing the behavior of dense bunches, to new surface effects in superconductors and detailed physical processes involved in photoemission.

In spite of the importance of accelerator science, the number of accelerator physicists graduating from US doctoral programs is startlingly small – about 11 each year [1]. A few decades ago, particle or nuclear physicists occasionally migrated to accelerator science because they saw it as a way to advance their research; this pipeline is now drying up, both because the research has become more complex and because particle and nuclear physicists are now minority users of accelerators. Unfortunately, there is little educational infrastructure to take its place. Cornell is one of the few universities in the nation with a doctoral program in accelerator physics, and the largest within a university physics department.

This program, which would span three years beginning in April 2014, has two interlinked thrusts; frontier accelerator research, and expanding Cornell's record of training future leaders in accelerator physics. We will extend the opportunity for quality education beyond the Cornell community by inviting students at other universities to pursue thesis research at Cornell under the guidance of Cornell faculty. The program will investigate issues critical to the performance of low emittance storage rings, electron sources, high-power beams, and superconducting cavities for particle acceleration. These are the grand challenges facing accelerator science, and with this work, we hope to enable new paradigms for future accelerators.

1.1 Research Program

The research program builds on the technical expertise and depth of Cornell's accelerator team and has two overarching goals: 1) to understand the physics and reach the limits of high power, low emittance beams, and 2) to understand the phenomena at play in microwave superconductivity and the interaction between cavities and high intensity beams. Students are integral to both aspects of this program.

Emittance, a measure of the six-dimensional phase space volume occupied by a beam, is a key measure of accelerator performance. For a given beam current, the emittance determines a collider's luminosity or a light source's brightness. The ultimate limit to emittance in a storage ring arises from the quantum emission of synchrotron radiation. In a photoemission source, the limit is set by the thermal emittance and the accelerating gradient at the photocathode. Whether the limit is quantum or thermal, it can be achieved only by overcoming many other barriers, some of them familiar, and others that are yet to be discovered. We will study emittance in two contexts (a lead Cornell faculty member specified for each area):

- **Emittance limits in storage rings (led by Prof. David Rubin).** The CESR Test Accelerator (CesrTA) has developed an exceptional suite of instrumentation, which combined with the highly configurable optics capability of CESR and deep expertise in storage ring physics makes the facility uniquely suited to the study of phenomena that can limit the performance of light sources and damping rings. We plan to exploit this capability to study the collective as well as single particle limits to beam emittance in electron and positron rings.
- **Ultra-low emittance photoemission sources (led by Prof. Ivan Bazarov).** Cornell is at the forefront of bright-beam production with the world's highest average brightness operating source. We plan to revolutionize low emittance beam production by employing improved photocathodes

inside a cryogenically cooled electron gun, and to use this new type of source to achieve the theoretical emittance limit.

Superconducting RF (SRF) acceleration is the gold-standard for modern accelerators, and among current and proposed approaches, it is by far the most energy efficient. Our work will focus on the following areas:

- **Physics of microwave superconductivity (led by Prof. Matthias Liepe).** The sources underlying surface resistance, which currently limit the performance and efficiency of SRF cavities will be studied. This will benefit accelerators for research and could enable new, safer, accelerator-driven nuclear power reactors. We will also advance high-gradient and large aperture SRF cavities, needed for high-energy electron-positron colliders and muon colliders, respectively.
- **High-Power Energy-Recovery loops (led by Prof. Georg Hoffstaetter).** The use of SRF technology developed at Cornell along with the world's highest current photoinjector opens a unique and cost effective opportunity to advance the understanding and reach of high-power beams. Using a compact loop around a single superconducting cavity, we intend to dramatically increase the beam current employed in energy recovery, opening a path to beams of unprecedented quality and intensity for a large variety of scientific endeavors.

Accelerators that would benefit from this program include a luminosity-upgraded LHC at CERN, a Higgs Factory, Japan's super B-factory, the new Fermilab injector, FRIB at MSU, the SNS at ORNL and its upgrade, ultimate storage rings and Energy Recovery Linac light sources, LCLS-II, and the European XFEL, as well as compact (table-top) accelerators requiring very bright beams either for ultrafast electron diffraction or as drive beams for plasma-wakefield accelerators.

There are strong intellectual interconnections across this program and within the Cornell accelerator science group. The same SRF team serves CESR, the photoinjector and basic research in RF superconductivity, the same beam-instrumentation experts design sophisticated diagnostics for CESR and the photoinjector, and the same vacuum scientists contribute to RF cavities, CESR, the photoinjector and the proposed recirculation loop. This commonality of purpose and shared use of expertise and resources is cost effective and contributes to the quality of the research.

1.2 Student involvement

Cornell is a leader in doctoral education in accelerator science. The graduate student experience at Cornell may be unique: the students work with leaders in the field, on problems of great interest, and they work extensively with the accelerator and accelerator hardware. As a result of this training, they are in enormous demand when they graduate. Some go on to become professors at one of the few universities with a program in accelerator physics. Many others go on to leadership roles at accelerator labs in the US and around the world.

The principal investigators on this proposal are the primary mentors of graduate students in accelerator physics at Cornell. This year, five graduate students were awarded doctoral degrees in accelerator science; ten are currently in the program, and we plan to add three new accelerator students in the next two years. Of these, nine will be funded under this award, which is the backbone of our educational program and research. Smaller additional support, complementing this program, has been requested under pending proposals to DOE. A proposal is also pending for a Physics Frontier Center, the "Center for Bright Beams", which would bring scientists from a broad range of disciplines into accelerator science. The Center would extend the work proposed here by developing the theory underlying the science, and applying approaches from other fields. The Center would be value-added, and relies strongly on the core program described here. Areas of overlap are modest, consisting largely of graduate student support, and should the Center be funded, we will work with program officers to address them.

Students will be engaged in every aspect of this proposal: currently one (Kelvin Blaser) works on CesrTA; five (Siddharth Karkare, Jared Maxson, Steven Full, Hyeri Lee, and Hexuan Wang) work on the photocathodes or photoinjector; and four (Nick Valles, Sam Posen, Daniel Hall, and Daniel Gonnella) work in SRF. These students are first-rate, attracted by the richness of our accelerator program and the opportunity to work at the frontier of accelerator science. This program will further expand graduate student training by launching a new initiative, Graduate Education in Accelerator Research (GEAR), to encourage students from other universities to carry out their thesis research at Cornell. This initiative is described in Section 7.2.

Currently, between 40 and 50 high-school, community college, and undergraduate students participate in our accelerator research each year, with undergraduates coming from the Cornell student body, from regional community colleges, and from a Research Experience for Undergraduates (REU) program.

1.3 The structure of this proposal

Sections 2, 3, 4, and 5 describe this research program in more detail, including its goals (in italics) and milestones (bold). The goals describe the thrust of the program, while the milestones indicate specific targets and the date by which we hope to achieve them, denoted by the quarter of the calendar year (e.g. Q1-2015). Section 6 covers results from previous grants and section 7 discusses the broader impacts of the proposed research, including an exciting outreach program.

2. Emittance limits in storage rings

Emittance is perhaps the single most important performance figure of merit for electron/positron storage rings. The design luminosity of the next generation B-meson and tau-charm e^+e^- circular colliders demand spectacularly low vertical emittances. The luminosity of linear colliders similarly depends directly on the minimum emittance (vertical beam size) that can be achieved in the damping rings, as does the brilliance of synchrotron light sources. During the past decade, accelerator scientists have managed to reduce the emittance in electron rings to within an order of magnitude of the theoretical (quantum) limit by careful alignment and emittance tuning methods. But as we approach the theoretical minimum, multi-particle, collective effects become increasingly important, and many of them are incompletely understood. These effects include intra-beam scattering, space charge, the electron cloud effect for positron beams and ion trapping in electron beams. Each phenomenon has a characteristic dependence on beam energy, beam and bunch current, bunch spacing, bunch size, etc., and each effect may be relevant in a different operating regime. As we reduce the "zero"-current emittance, the equilibrium emittance will eventually be entirely dominated by collective effects, and new phenomena will likely emerge. Indeed some of the effects important in lepton storage rings can also limit intensity in proton accelerators (electron cloud) and linear accelerators (fast ion).

We propose to investigate the most important emittance limiting effects with beam measurements in the CESR test accelerator. The measurements will rely on the specialized instrumentation, with some refinements, that was developed for the CesrTA program. We will take advantage of the flexibility of the CESR optics and energy reach, the accelerator control system that interfaces sophisticated modeling and analysis software with beam based measurements, and the expert scientific staff that operates the accelerators and carries out the research. We plan to address the following questions and technical requirements:

(1) How does the growth and decay of the electron cloud depend on the magnetic field environment? We will use time resolving shielded pickups and microwave techniques to study cloud evolution in dipole, quadrupole, and wiggler fields.

(2) How do the thresholds for beam blowup and head-tail instability, due to an electron cloud, depend on the emittance and the charge of the bunch, as well as the density of the cloud itself? A stripline detector will be designed to measure head-tail motion.

(3) How does the density of ions evolve along a train of electrons? How does it depend on the quality of the vacuum? What is the threshold for coupled bunch instability in terms of ion density? What is the threshold for incoherent emittance growth of the electron beam due to interaction with the ion stream? How does the instability threshold depend on the bunch emittance and charge?

(4) How do intra-beam scattering growth rates and Touschek lifetime depend on beam energy, transverse coupling, RF voltage, and "zero" current emittances? Simultaneous measurement of horizontal and vertical beam size are essential to this study.

(5) How can we identify and mitigate the non-static sources of vertical emittance? These include power supply noise, stray magnetic fields, ground motion, and ground currents.

(6) Sensitivity to emittance growth of very low emittance beams requires an x-ray vertical beam size monitor with better resolution and reduced systematics, and a planned second generation device will meet these requirements. To complement and cross-check its performance, the capability of the visible light beam size monitor will be extended to measure vertical as well as horizontal size.

(7) Tests at CesrTA of vacuum chamber treatments that reduce the yield of secondary electrons have produced a catalog of mitigations [2]. Are there surface treatments that can significantly reduce the quantum efficiency that is the yield of primary electrons due to photo-emission?

(8) Diffraction radiation offers a nondestructive measure of beam size in a linear accelerator where no synchrotron radiation is available. We are collaborating with CERN on the development of a diffraction radiation beam size monitor and will test it in CESR.

2.1 Electron Cloud

Trains of closely spaced bunches of positrons or protons are typically accompanied by a cloud of low energy electrons, seeded by photo-electrons emitted from the walls of the vacuum chamber by synchrotron radiation. The electrons are accelerated in the potential well of the positively charged beam, strike the chamber walls and produce secondary electrons. The cloud grows exponentially until it saturates. Emittance growth and instabilities arising from the complex interactions between the bunch and cloud limit the intensity of the beam.

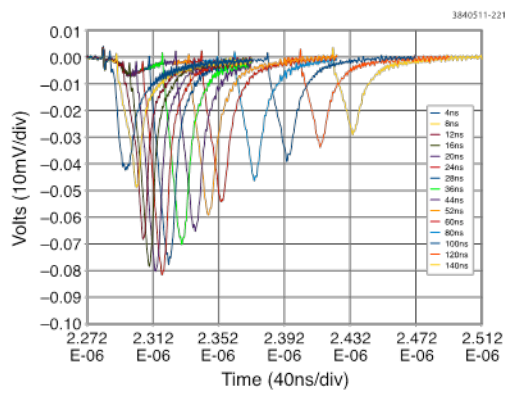

Figure 1. Overlay of two bunch data with spacings in multiples of 4 ns at 2.1 GeV with an aluminum chamber in a zero field region. The growth and decay of the cloud is mapped out by the second (witness) bunch.

Using specialized instrumentation in the CESR storage ring, we have characterized the growth and decay of the cloud and benchmarked codes that model it with direct measurements [3][4][5][6][7][8] with retarding field analyzers, an effort lead by graduate student Joe Calvey. We have tested more than a dozen vacuum chamber treatments that mitigate the growth of the cloud [9][10]. High bandwidth beam position and beam size monitors have allowed measurement of the effect of the cloud on the beam dynamics, including thresholds for emittance dilution and instability [11][12]. This work has led to the designs of vacuum chambers for SuperKEKB, the SPS upgrade planned for the LHC's second long shutdown, and the ILC damping ring. In spite of this progress, there are many outstanding questions regarding the effect of the electron cloud on the positron beam, which must be understood in order to design stable, ultra-high intensity light sources and damping rings. We propose to address these limitations as follows:

Electron cloud in dipole and quadrupole fields. While the electron cloud is well-characterized in field-free regions, our understanding of its behavior inside dipole and quadrupole magnets, which make up a large fraction of a storage ring guide field, is much more qualitative. We have developed specialized instrumentation for investigating the properties of the cloud and plan to adapt those instruments to dipoles and quadrupoles. Shielded pickups and time resolving analyzers measure the cloud formation and decay as shown in Figure 1 when used in conjunction with a witness bunch [13][14][15][16][17] that trails the primary bunch and kicks cloud electrons present at that moment into the detector. The pulse shapes yield information about relative contributions from photo-emission and secondary processes [18]. Our dipole chicane [19] will be equipped with newly designed time resolving electron cloud detectors and shielded pickups in order to study the cloud in a variable dipole field. We will install the instrumented chicane into a region of our storage ring with higher synchrotron radiation, as needed to seed a measurable cloud.

Using a shielded pickup in a large aperture quadrupole magnet [20], we have recently made the first ever observation of trapped cloud electrons in the field of a quadrupole in a storage ring [2][21]. The phenomenon of trapped electrons could have important implications for the performance of high intensity (and strong focusing) positron storage rings. To improve our sensitivity, we will build a compact detector that can be fitted into an arc quadrupole vacuum chamber, where there is a significantly higher flux of synchrotron radiation and correspondingly more cloud electrons.

Retarding field analyzers and shielded pickups measure the flux of electrons at the wall of the vacuum chamber. The absolute electron cloud density along the axis of the vacuum chamber is measured by coupling TE microwaves into and out of the beam-pipe and observing their response to the presence of the electron cloud [22][23][24][25][26][27][28], and we propose to develop it for use in dipole and quadrupole fields and high field wigglers. This effort will be facilitated by the use of the dipole chicane, as the standing wave modes in the chicane vacuum chamber have already been characterized by calculation and bead pull.

Goal: *Measurement of the absolute cloud density in dipole and quadrupole fields using microwaves.*

Goal: Characterization of growth, decay, and mitigation of the electron cloud in dipole and quadrupole fields using time resolving detectors (shielded pickups).

Milestone Q4-2015: Relocate chicane to the arc of the storage ring where there is intense synchrotron radiation, for characterization of growth and mitigation of the cloud in a dipole, and install a second-generation quadrupole shielded electron cloud pickup to characterize quadrupole trapping.

RF engineer John SIkora and Research Associate (RA) Jim Crittenden will supervise undergraduate and REU students in the analysis of the shielded pickup and TE wave measurements, adding to the seven undergraduates who have already contributed. Measurements will require about 10 shifts of machine studies time in each of the three years of the grant period.

Beam-cloud interaction. Ultimately, it is the interaction of the positron bunches with the electron cloud that limits the emittance and intensity of the circulating beam. We have measured the electron cloud induced tune shift of the bunches in a train, from which we extract the average cloud density traversed by each bunch (Figure 2) [6][29]. Two undergraduates contributed to the interpretation of the tune shift measurements. The measurement of vertical beam size of each bunch in the train allows identification of the cloud density at which beam size begins to blow up. This is shown in Figure 3. Finally, measurement of the position spectrum of each bunch in the train reveals the onset of instability [30][31][32]. California Polytechnic Institute Prof. R. Holtzapple and six students contributed to this study. Our simulations [33][34], spearheaded by post-doc K. Sonnad in collaboration with M. Pivi at SLAC, suggest that the threshold for the beam size blowup and single bunch head tail instability will increase when the bunch has very low vertical emittance and high charge because in this case the head of the positron bunch pinches the cloud electrons so that the tail experiences a higher effective density [11]. We propose to investigate this dependence experimentally, again exploiting the unique capability of CesrTA instrumentation, namely the 250 MHz beam position monitors and beam size monitor, with the ultimate aim of developing a simulation that reliably predicts the performance of future high-intensity positron (and proton) accelerators.

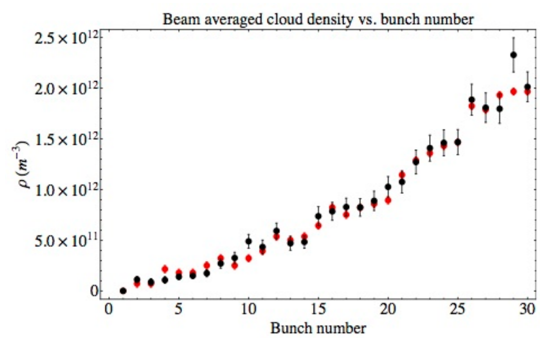

Figure 2. Average initial (before the "pinch") electron cloud density vs. bunch number, comparison between estimate from measured tune shifts (red) and, simulation (black) from POSINST.

Goal: Measurement of the dependence of electron cloud induced emittance growth and instability on the emittance of the bunch in a vanishing cloud, the charge of the bunch, and the density of the cloud.

A strip-line beam position monitor optimized for sensitivity to head-tail motion will be developed to study this effect [35].

Goal: Measure threshold for electron cloud induced head tail instability in terms of bunch charge, and emittance, and local cloud density.

Milestone Q2-2015: Design, assembly, installation and test of strip-line for measuring head-tail motion.

Electron cloud work, including the design of the strip-line beam position monitor, will be carried out by a new graduate students and REU summer students, Cornell undergrads, post-doc Kiran Sonnad, and accelerator engineer Mike Billing and RA J. Crittenden. The studies will require approximately two dozen machine studies shifts spread over the three years of the award.

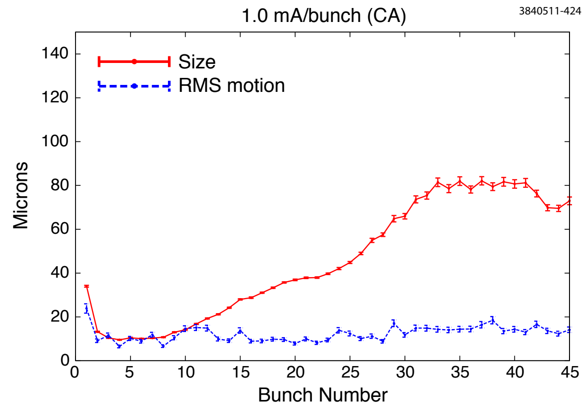

Figure 3. Bunch by bunch beam size and rms motion at 14ns spacing, 1mA/bunch, 45 bunches. The beam profile is measured with the xray beam size monitor. Blowup first appears in bunch 10. Blowup of the first bunch is not well understood.

Primary and secondary emission yields. The veracity of electron cloud simulations rely on detailed knowledge of primary and secondary emission yields (PEY and SEY). While the SEY yields are known, due to *in situ* studies that we have carried out [36][37], the primary yields (quantum efficiencies) are not. We will therefore plan to add a UV source to our SEY instrument in order to measure the quantum efficiencies. Two Cornell undergrads contributed to development of the instrument and analysis of the measurements.

Goal: In-situ determination of quantum efficiency of vacuum chamber materials.

Quantum efficiency measurements will be done by RA Walter Hartung and an undergraduate student. Several hours/week of access to the device in the storage ring are required to monitor SEY and PEY and their dependence on beam processing.

2.2 Fast Ion Instability

The fast Ion instability of an electron beam is the analog to the electron cloud instability for positrons, but because ions are much more massive than electrons, the phenomenology is very different. The positively charged ions are produced by scattering and photoionization of the residual gas, and are trapped and oscillate transversely in the potential well of the electron beam with a characteristic frequency that depends on the species. The ions dissipate rapidly after the passage of the bunch train. The motion of the ions couple the motion of leading and trailing bunches in the train that can result in instability [38][39]. The fast ion instability has been observed in storage rings, including ALS [40] and SPEAR [41]. Recent measurements at SPEAR correlate features of multi-bunch spectrum with pressure and ion concentration and are in qualitative agreement with theory. The fast ion instability will ultimately limit the performance of high intensity damping rings, light sources, and linear accelerators.

CesrTA instrumentation is capable of measuring the size of individual bunches and emittance growth (if any) due to the ions, as well as turn-by-turn position spectra to characterize instabilities. Simulation with CESR parameters indicates that the bunch-dependent emittance growth will be measureable with the x-ray beam size monitor. It also suggests that turn-by-turn position measurement of each bunch in the train will yield spectra that will reveal the ion oscillation frequency and ion species. We propose a series of measurements varying bunch spacing, bunch charge, train length, beam emittance, chromaticity, and gas pressure. Our goals are to measure the thresholds for instability and beam blowup and to qualify the model. Measurements with positron beams in similar conditions will help to distinguish the beam-ion interaction from other collective effects.

Goal: Characterization of fast ion effect with measurements of bunch-by-bunch and turn by turn vertical beam size and position spectra and development of the theory.

The growth and decay of the ion cloud is critical input to the modeling code. We propose to use witness bunch measurements, (similar to those that have been so effective for characterizing growth of the electron cloud) to measure those properties of the ion cloud.

Goal: Ion density measurements throughout the ring using witness bunches

Fast ion instability studies will be the thesis topic of a new graduate student, working with post-doc Avishek Chatterjee. The studies will require approximately two-dozen shifts of machine time concentrated in the first two years of the award.

2.3 Intra-beam and Touschek scattering

Recent graduate M. Ehrlichman's thesis was a definitive expose of measurements and analysis of intra-beam scattering in CesrTA. We have made the most complete measurements to date of intra-beam scattering (IBS), and developed the analytical tools for comparison with theory [42][43][44] (see Figure 4). Intra-beam scattering leads to current dependent growth of the beam size. The CesrTA capability for simultaneous measurement of bunch height, width and length is essential to a complete understanding of the physics. We have measured dependence on "zero" current emittances, RF accelerating voltage, and in various lattice configurations with both electrons and positrons. The determination of the dependence of beam size on RF voltage has already revealed an unexpected coupling of longitudinal and transverse motion [45]. We propose to explore beam energy dependence (anticipated to be ~$1/E^3$), and the effect of transverse coupling to complete the study.

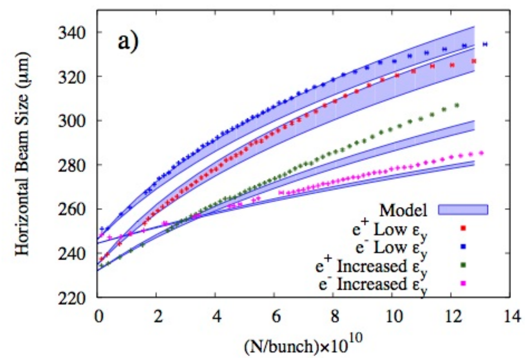

Figure 4. Horizontal beam size vs particles/bunch. Points are data. Band is the theory. The width of the band corresponds to the uncertainty in measurement of the "zero" current vertical beam size.

Touschek scattering is a regime of intra-beam scattering in which relatively large scatters kick particles outside of the energy aperture, limiting beam lifetime. Indeed, the dependence of beam lifetime on bunch current is an indirect measure of bunch density and emittance [46]. By combining beam size (height, width and length) data with the measured Touschek lifetime we can close the loop on intra-beam scattering theory. The ongoing investigation of intra-beam scattering and the extension to include the Tousheck effect will be the work of post-doc Jim Shanks and a new post-doc, RA W. Hartung, and a new graduate student. The studies will require about 8 shifts of dedicated CESR running time, primarily during the second year. Initial data are already on disk awaiting analysis.

2.3.1 Visible light beam size monitor

The measurement of the horizontal beam size provided by the visible synchrotron light interferometer [47] (Figure 5) has been essential to the study of IBS and the longitudinal-transverse coupling affected by dispersion in the RF cavities [45], and to our ability to monitor the 3-dimensional volume of the bunch as we vary bunch charge. We propose to upgrade the device by (a) extending its capability to measurements of vertical beam size, complementing the x-ray beam size monitor, by increasing vertical acceptance, and

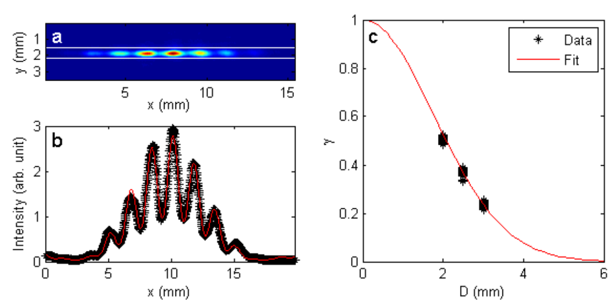

Figure 5. (a) A typical interference pattern of SR using a *D*=2.0 mm double slits. (b) The horizontal intensity profile integrated between two white lines in (a) and the best fit. (c) The visibility measured using three different sets of double slits (*D* = 2.0, 2.5, and 3.0 mm). The red line is the best fit.

(b) replacing the CCD camera (which gives time averaged measurements) with a high speed photo-diode array with single pass capability. The effectiveness of the beam size monitor is largely thanks to the effort of post-doc Suntao Wang in collaboration with undergrads from California Polytechnic Institute. Wang and electronics engineer Nate Rider are tasked with the upgrade.

Goal: Measurement of vertical beam size with visible light interferometry as cross check of x-ray beam size measurement.

Milestone Q1-2015: Increase vertical acceptance of visible light beam size monitor and configure optics to image two slit interference pattern with widely separated (20mm) slits, for measurement of vertical beam size.

Goal: Synchronized turn-by-turn measurement of horizontal (visible light monitor) and vertical (x-ray monitor) beam size, thus providing a unique capability to monitor height and width simultaneously in a single pass.

Milestone Q1- 2016: Commission visible light beam size monitor for bunch-by-bunch and turn-by-turn operation with photo-diode detectors and x-ray beam size monitor digitizers.

2.4 Equilibrium emittance in the “zero”-current limit

Vertical emittance is generated by magnet misalignments and field errors. With a combination of frequent survey and alignment and sophisticated beam-based techniques for diagnosing residual errors developed by then graduate student J. Shanks, we routinely achieve sub 10 pm-rad vertical emittance for both electrons and positrons [48][49][50]. As most of the effects described above (electron cloud head-tail threshold, intra-beam scattering growth rates, fast ion threshold, Touschek lifetime, etc.) depend strongly on vertical beam size, we have powerful incentive to further reduce the “zero” current emittance. There is evidence that the residual emittance is dominated by “noise” on the beam from the RF system, magnet power supplies, feedback system, or possibly stray fields from the synchrotron [48]. We are developing simulations to learn how different sources of noise might couple to the beam, and how to identify those sources in the turn-by-turn position spectra of circulating bunches. In addition we will reduce systematic position measurement errors that limit our ability to correct coupling and dispersion errors, with improved quadrupole centering algorithms and beam-based measurement of beam position monitor tilts.

Goal: Routinely achieve sub 5 pm-rad vertical emittance for both positrons and electrons by further reducing systematic measurement error (especially with respect to vertical dispersion) and identifying and eliminating sources of beam jitter.

Our sensitivity to all of the emittance diluting effects described above is significantly enhanced as the “zero” current emittance is reduced. We propose to revisit measurements of these collective effects as we progressively deliver ever smaller beam size.

Milestone: Repeat measurements of IBS, electron cloud induced emittance blowup and instability, fast ion instability with 5 pm-rad vertical emittance.

As a graduate student, J. Shanks developed the emittance tuning algorithm that is now in routine use for correcting optics and minimizing vertical beam size [48]. The effort to better understand measurement systematics and identify non-static sources of emittance blowup will be the project of new graduate student, Kelvin Blasér with RAs Robert Meller and David Sagan.

2.4.1 X-ray beam size monitor

The x-ray vertical beam size monitor [51][52][53][54][55][56][57] is capable of measuring the size of a each bunch in a train of bunches individually, and in a single turn. As such, it is invaluable for studies of the bunch dependent emittance growth characteristic of electron cloud and fast ion effects. The ability to identify the bunch in which blowup first appears is essential to our measurement of the threshold for emittance dilution for electron cloud and will be used for that purpose in our study of fast ion. The single pass capability is also an important tool in our search for sources of emittance blowup, as it allows discrimination between beam jitter and beam size. We propose to develop a second generation device with a dedicated x-ray beam line located where dispersion is near zero, eliminating a systematic uncertainty in relating measured size to normal mode emittance, and with a wiggler source of x-rays (the bend magnet source at present provides insufficient x-ray flux for low beam energies). In addition to improved performance and reduced systematics, the new device will remain operational for all of CESR running (and not exclusively for CesrTA studies) so that it can be used to diagnose beam behavior during CHESS operations and we can extend our emittance studies to high energy. The existing x-ray beam size monitor was built in collaboration with scientists from KEK and with contributions from Cornell grad students Nic Eggert, Walter Hopkins and Ben Kreis. The upgrade will be managed by Nate Rider working with a new graduate student, vacuum physicist Dr. Yulin Li, accelerator engineer M. Billing and RAs Daniel Peterson and Brian Heltsley. We estimate 24 shifts of dedicated CESR running time, spread over years 2 and 3 of the grant period will be required to commission the new device.

Goal: Vertical beam size monitor with micron resolution that is available for use in all experimental programs at CESR.

Milestone Q4-2016: Commission positron x-ray beam size monitor with dedicated beam line and tunable source

2.4.2 Diffraction radiation beam size monitor

Non-interceptive beam size monitors will be essential for many future accelerators. In the CLIC linac for example, both the Drive Beam and the very small emittance Main Beam will have charge densities that preclude the use of classical intercepting devices.

For relativistic beams, Diffraction Radiation (DR) appears when the particle moves in the vicinity of a medium (a target). The electric field of the particle polarizes the target atoms, which oscillate emitting radiation, known as DR, with a very broad spectrum. The spatial-spectral properties of the radiation are sensitive to a range of beam parameters. Coherent DR (when the wavelength of emitted light is comparable to or longer than the particle bunch length) has been used to characterize the longitudinal electron beam profile at FLASH at DESY, CTF3 at CERN and SUNSHINE at Stanford, and DR in the optical wavelength range (ODR) was applied for transverse beam parameter monitoring at ATF at KEK, FLASH at DESY and APS at Argonne.

The goal is to work toward shorter wavelengths in order to measure more compact beams [58][59]. An initial chamber operating in the optical range was tested in December 2012 and April 2013, but suffered from image saturation [60]. CERN has recently rebuilt the image acquisition system, and new tests at wavelengths of 440nm and 230nm are planned for December 2013. We propose to support the completion of the development of this instrument by carrying out tests at CESR.

Goal: Non-interceptive measurement of horizontal and vertical beam size with diffraction radiation

Milestone Q4-2016: Measurement of vertical beam size with diffraction radiation with micron resolution of sub 10 micron beam.

Accelerator engineer M. Billing will coordinate the installation of hardware in CESR and the experimental program. Approximately one dozen machine studies shifts over the next 3 years will be required to develop and commission the DR beam size monitor.

In addition we will collaborate with CERN to develop and test vacuum chambers designed to minimize photon reflectivity, quantum efficiency and mitigate secondary electron emission to suppress electron cloud. This work will be led by a graduate student with oversight from vacuum physicist Y. Li.

Goal: Vacuum chamber that absorbs 99.99% of photons emitted by the beam.

2.4.3 CESR accelerator complex

The CESR accelerator complex, (source injector, booster and storage ring), is readily adapted for this research program. For low emittance studies, it operates at 2.1 GeV with twelve 1.9 T superconducting damping wigglers that transform CESR to a uniquely wiggler dominated configuration. The maintenance and operation of this equipment, and the flexibility with which it can be transformed from dedicated x-ray source operating at 5.3 GeV to CESR test accelerator, depends on the expertise of electrical, RF and software engineers, specialists in accelerator hardware and operation, digital electronics, vacuum science, cryogenics, and with technical support and machine operators. Many of the individuals whose principle responsibility is to machine operation are also involved in CesrTA research (including RF engineer John Sikora, accelerator engineer Mike Billing, vacuum scientist Yulin Li, and RA David Sagan), and have contributed to the design of new instrumentation and data collection techniques, and serve as student mentors.

3. Ultra-low emittance photoemission sources

Intense electron beams are key to a large number of scientific endeavors, including electron cooling of hadron beams, sub-picosecond ultrafast electron diffraction, electron-positron colliders, secondary-particle beams such as photons and positrons, and new high gradient accelerators that use electron-driven plasmas. Photoemission is the method of choice for producing such beams: it provides the highest charge density, lowest emittance, shortest pulse length, and most flexible time structure. Photoemission additionally enables polarization at the source, creating beams that can serve as powerful spin-sensitive probes in electron colliders or as probes of magnetic materials in electron microscopes.

Spectacular progress in photoemission sources over the last two decades has brought new opportunities into view. For example, a 50 mA polarized electron source (about ×10 higher than available today) would enable an electron-ion collider with an unprecedented luminosity. A high bunch charge electron source with sufficiently low 4D transverse emittance (about ×10 smaller than today) could remove the need for an expensive damping ring of electrons in a future electron-positron collider. An ultra-low emittance, high current electron source coupled with an ERL could provide an accelerator with superior beam brightness and more flexible modes of operation than the conventional storage rings for internal fixed-target particle physics experiments and x-ray science. Similarly, a photoemission gun producing 100 fs electron bunches with 10^6 electrons per pulse and a transverse beam emittance of 2-3 nm (×10 improvement over the best transverse emittance numbers today) would transform ultrafast electron diffraction by allowing much larger coherence length and thus molecular movies of biologically significant large proteins in a small laboratory setting.

In the last two years, work at Cornell has in many ways cleared the path towards these novel projects by demonstrating the world's highest brightness and average current photoemission-based source of relativistic electrons. Our ambitious goals for the next three years are described in the following sections.

3.1 Cornell high-brightness photoinjector research

Over the last five years, we have established a world-leading effort in photoinjector source development, the underlying beam theory and simulations, and expertise in guns, photocathodes, and lasers. The strength of the group is in combining various cathode advances and innovations with the world's brightest photoinjector. This ability to both formulate the frontier questions for high brightness source development and to implement the solutions makes breakthroughs in accelerator science possible.

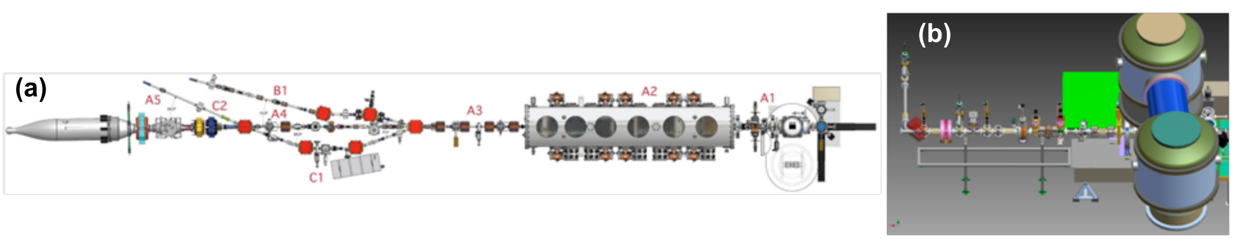

Figure 6: Photoemission sources at Cornell: (a) 5-10 MeV photoinjector (20 m long); (b) a dedicated 500 kV photoemission gun followed a diagnostics beamline (3 m long). The beam direction is right to left.

Currently we operate two photoemission sources, both at the frontier of the emittance limit: the 10 MeV photoinjector (Figure 6a) and a dedicated photoemission gun lab with 0.5 MeV energy and advanced diagnostics beamline (Figure 6b). In the 10 MeV photoinjector, the beam is produced in a laser-driven photoemission gun (A1), accelerated to as much as 10 MeV in superconducting RF cavities (A2), after which beam parameters are measured (A4, C1, B1, C2), and finally absorbed in a beam dump (A5). Among the achievements are the world-record current of 75 mA [61][62][63] and record low beam emittances for any CW photoinjector, a work led by a recent graduate Colwyn Gulliford [64]. This is very significant in terms of the equivalent brightness achieved from this source: it would already out-perform the best existing storage rings by a substantial factor if the beam were accelerated to a similar energy. The dedicated photoemission lab (Figure 6b) on the other hand, is well suited for advanced studies of space charge dynamics near the photocathode, laser shaping and its effect on the beam dynamics, and exploration of new photocathode materials and their characterization inside the high-voltage photoemission gun.

With the Phase 1B ERL grant (NSF DMR 0807731) coming to an end (expires mid-2014), we direct our efforts fully towards meeting the 100 mA average current goal in the 10 MeV photoinjector. Additionally, our proposal “Advanced concepts for measuring and improving high-brightness, high-power electron beams in photoinjectors for ERLs, linear colliders, beam coolers and FELs” to the DOE seeks operational support for the 10 MeV photoinjector over the course of 2 years with the goal of addressing the high average current regime of the beam operation, and the associated beam physics and diagnostics. The low emittance frontier, on the other hand, is addressed in this proposal by means of the dedicated photoemission gun laboratory (Figure 6b) by 1) pushing the beam emittance to a record small value from the newly constructed 500 kV gun, 2) by breaking new ground in ultra-low emittance beams via a cryogenically-cooled DC photoemission gun, and 3) use of ultra-low emittance photocathodes.

3.2 Research plan to improve beam emittance

Despite much progress already, further emittance improvements are both anticipated and required for many applications. The implications of brighter beams are many – e.g. a lower emittance x-ray source permits relaxed requirements on the beam energy therefore making the entire accelerator more affordable. As the beam emittance improves and reaches uncharted territory, a new set of questions for the physics of high brightness beams will need to be addressed. For example, as much colder photocathodes become available, what will set the lower limit to the emittance for a given bunch charge? Will the virtual cathode instability, in which the bunch tail experiences strong self-forces and breaks apart, preclude one from reaching the theoretical maximum charge density compatible with the electric field on the photocathode? Can cryogenically-cooled photocathodes be practically realized inside a photoemission gun delivering an improved emittance beam even with a high bunch charge? The Cornell group plans to address all of the above questions using the cutting-edge accelerator facilities and our broad expertise. Prof. Ivan Bazarov and Dr. Bruce Dunham will lead these research efforts.

3.2.1 A low emittance 500 kV photoemission gun

An improved DC gun has been recently constructed and will be commissioned with the beam at the time of the new funding cycle. The virtual cathode instability will be characterized as to its effect on the transverse phase space in addition to the longitudinal (energy–time) dynamics. Our fourth-year PhD student, Jared Maxson, has built the new gun with the help of senior colleagues, and he will lead in its commissioning to perform the beam studies for his thesis titled “Demonstration of beam brightness limit and characterization of virtual cathode instability in photoemission guns”.

Extensive multi-objective optimizations using space charge simulations indicate future improvements with beam emittance to below 0.2 mm-mrad for 80pC/bunch using the new gun. The program will involve adaptive 3D shaping of the laser pulse for lowest emittance beams.

Goal: Understand beam dynamics near photocathodes, including control of the virtual cathode instability for ultra-low emittance high density beams.

Milestone Q2-2016: Demonstrate emittance of <0.3 mm-mrad with 80 pC/bunch out of the improved photoemission gun.

3.2.2 Cryogenically-cooled photoemission gun

The beam dynamics in photoinjectors depends strongly on a number of factors such as the non-linear space charge, initial 3D laser shape, aberrations and optics, and beam alignment, and requires detailed beam dynamics modeling and extensive computer optimizations for obtaining optimal performance. The maximum achievable transverse (4D) brightness is proportional to the electric field at the photocathode and inversely proportional to the transverse temperature of photoemitted electrons [65]. While the electric field is determined by the photoemission gun technology, the electron temperature is set by the material properties of the particular photocathode. The highest electric fields are 10-100 MV/m depending on the gun technology. The photocathode's effective transverse temperature (including possible effects due to the surface roughness), or more conventionally, its mean transverse energy, varies typically between 1 eV and 0.1 eV.

Recently, graduate student Jared Maxson has shown that another effect will limit the emittance of intense beams. He formulated a fundamental photoemission brightness limit from disorder induced heating [66], which arises from unscreened potential of the nearby electrons and its subsequent relaxation immediately upon photoemission. For typical electron densities encountered in modern photoinjectors this disorder-induced heating is of the order of cryogenic temperatures (few meV).

This leads us to propose a photoemission gun of moderately high voltage (< 300kV), which will allow for cryogenic cooling of the photocathodes in addition to maintaining very high electric field during the photoemission. Detailed beam dynamics simulations support this idea. Third-year PhD student Hyeri Lee, and the mechanical engineering master's student Bradly Verdant will pursue construction of a cryogenic high voltage gun to realize "Cryogenically cooled electron source with ultra-low emittance photocathodes". Dr. Xianghong Liu, a vacuum and cryogenics expert, will provide the necessary guidance in critical areas of designing and commissioning of the device.

Goal: Approach the theoretical brightness limit imposed by disorder induced heating near the photocathode and the intrinsic temperature of the photoelectrons.

Milestone Q1-2017: Build (Q3-2016) and operate cryogenic DC photoemission gun with an ultra-low emittance photocathode (Q1-2017).

3.2.3 Photocathode research

The advances in low emittance and high current electron sources by our group over the last several years can be mainly attributed to the photocathode since all the basic limits to the beam parameters are defined at the cathode. The photocathode program at Cornell is among the premier groups in the world. Recent accomplishments include:

- First complete characterization of a number of practical photocathodes for accelerators such as GaAs [67], GaN [68], GaAsP [69], Cs_3Sb [70], CsK_2Sb [71], and NaK_2Sb [61] including generating coldest electron beams from high quantum efficiency (QE) materials with sub-picosecond response time [64];
- First demonstration of a robust photocathode operation at world record average current and lifetime [61][62];
- Extensive photoemission physics modeling and comparison with experimental data for GaAs [72][73] and layered semiconductor structures .

Unique facilities (Figure 7) and expertise make this work possible. Many families of photocathodes can be grown, analyzed, moved under vacuum, installed in the guns and tested in the photoinjector. This process has enabled an improvement in the transverse temperature of a photocathode grown by molecular beam epitaxy (MBE), and a doubling of the brightness of the relativistic electron beam. A number of DOE laboratories have contacted us for guidance on photocathode recipes and growth chamber designs. To further the sharing of photocathode results within the community, we have started a collaborative website and helped launch the Physics of Photocathodes for Photoinjectors Workshop series, which Cornell University hosted in October, 2012.

Ten undergraduate students per year typically participate in the photocathode lab, and currently there are two PhD students. A recent example of student work was done in collaboration with the Tech-X company, one of our graduate students, Siddharth Karkare, and two undergrad helpers, Eric Sawyer and Teresa Esposito. This project, a Monte-Carlo photoemission software simulator, was completed and data was collected to verify the code performance [72]. Dr. William Schaff, an MBE expert, will provide leadership

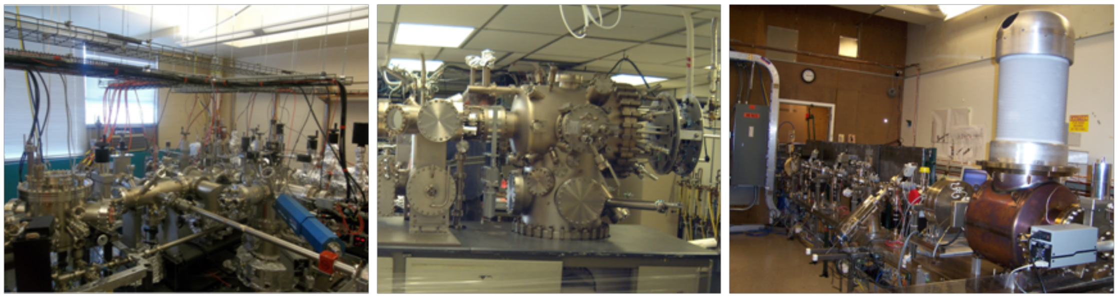

Figure 7: Cornell photocathode research facilities. Multipurpose cathode chamber (left), dedicated MBE growth reactor (center), photoemission gun with diagnostics (right). Photocathodes under UHV can be moved between these chambers.

in synthesizing novel structures, which are predicted by such simulations to have low emittance. He and Dr. Luca Cultrera, an expert in alkali photocathodes, will work with graduate and undergraduate students under Prof. Ivan Bazarov's supervision to realize new and superior photocathode materials and growth recipes.

Building on the success of our previous accomplishments we intend to pursue three directions in photocathode research: 1) ultra-low emittance photocathodes; 2) improved robustness and photocathode lifetime; and 3) photocathode theory and simulations. These are the topics of the PhD research presently pursued by two of our graduate students: a fourth-year PhD student Siddharth Karkare with his topic of “Narrow cone low emittance photocathodes for photoinjectors”; and the second-year PhD student Hexuan Wang (a Mount Holyoke College graduate who recently joined the photocathode research) with her future research area being “Ultra-low emittance photocathodes from advanced semiconductor structures grown by molecular beam epitaxy”. A new PhD student, Hyeri Lee, will pursue the topic of “Cryogenically-cooled photocathodes for next generation beams with sub-thermal transverse energy spreads”.

Goal: Understand lattice crystal momentum conservation and physics limits on electron temperature for cryogenically-cooled photocathodes.

Goal: Obtain quantitative agreement between the observed photocathode lifetime and multi-physics modeling for various materials.

Milestone Q3-2016: Realization of photocathode materials with sub-thermal transverse temperature and sub-picosecond response time.

Milestone Q3-2016: Realize Monte-Carlo simulation with the ability to model quantum layered structures of ultra-low emittance photocathodes with the goal of “engineering” materials for sub-thermal sub-picosecond photoelectron production.

4. RF Superconductivity

Over the last 20 years, superconducting radiofrequency (SRF) accelerating cavities have become an enabling technology for the accelerator-based sciences such as particle physics, nuclear physics and the materials sciences. The exceptional success of this technology comes from its outstanding performance: (1) SRF cavities can accelerate beams of ultra-low emittance with relative energy stabilities in the 10^{-4} to 10^{-5} range; (2) SRF cavities operate with exceptional efficiency, with cavities currently in operation having intrinsic quality factors around 10^{10} and achieving AC power to beam power efficiencies approaching 50%; (3) SRF cavities can operate continuously with accelerating fields in the tens of MV/m region, enabling a wealth of scientific studies requiring continuous beam operation. Other acceleration techniques – established and proposed – do not provide such a powerful combination of capabilities.

Furthermore, aggressive research over the next years can lead to a new generation of SRF cavities with even higher performance by optimizing the treatment of niobium cavities and by using alternative superconductors. The fundamental research on SRF cavities proposed here will result in deeper understanding of RF superconductivity and help to lay the foundation for this new generation of SRF cavities.

We propose to address the following questions:

(1) What sources contribute to the residual surface resistance of SRF cavities? How can these be controlled? Diminishing residual resistance would allow operating SRF cavities with quality factors in the 10^{11} range with ultra-high efficiency at high CW accelerating gradients, thus sharply reducing the cost of CW SRF systems.

(2) What limits the field strength in realistic SRF cavities? How does the limiting field depend on material properties and geometry? Can metastable fields above the lower critical field be reached? Can alternative superconductors with small coherence length be produced with sufficient quality to avoid flux penetration at small defects, allowing operation at metastable fields? Studying these questions will enable us to develop improved cavity fabrication and treatments for increasing the gradient yield in niobium cavities and for increasing the maximum field well above H_{c1} in Nb_3Sn cavities. Theory predicts that Nb_3Sn cavities have the potential of reaching accelerating gradients twice those of niobium cavities if the H_{c1} barrier can be overcome.

(3) Can low frequency cavities, e.g. the 325 MHz and 650 MHz cavities envisioned for the muon collider, be produced, and can lessons learned from fundamental SRF studies be applied to such cavities? Their size requires rather thick niobium walls for mechanical stability and the expense becomes excessive. We therefore pursue options for building large copper cavities, coated with a thin layer of niobium. This will not only reduce the cost of the cavities dramatically, but also the better heat capacity of the copper may significantly simplify the cooling system so that the cryostat becomes less costly.

In the following sections we describe our plans for addressing each of these.

4.1 Ultra-High Efficiency SRF Cavity Research

Significant scientific and technical challenges remain to be addressed in order to realize the full potential of SRF technology. One of the most important challenges is achieving the smallest surface resistances in superconducting cavities (or similarly the highest possible intrinsic quality factors Q_0). Achieving the highest Q_0 is especially important for the feasibility of future particle accelerators operated in CW mode, for which the dynamic cryogenic load from the RF fields in the SRF cavities can be significant, and determines the cost optimal operating field. Cost studies show that typical quality factors currently achieved in SRF cavities installed in cryomodules ($Q_0 \sim 2 \times 10^{10}$) limit the cost-optimal accelerating field to ~15 MV/m, well below the ~45 MV/m field limit of niobium SRF cavities. SRF cavities with quality factors in the 10^{11} range would allow increasing the cost-optimal CW operating field by about a factor of 2 – reduce the required SRF linac length by a factor of 2 – and thus would sharply reduce the cost of CW SRF systems.

According to the BCS theory, the surface resistance should fall exponentially with temperature as $e^{-\Delta/kT}$. However measurements at $T < 0.2T_c$ show that the surface resistance reaches a residual value (the residual surface resistance). The total surface resistance (which is proportional to $1/Q_0$) can therefore be written as: $R_{total} = R_{BCS}(T) + R_{residual.}$ The lowest residual surface resistance measured in a niobium superconducting cavity was achieved in a 1.3 GHz cavity fabricated, prepared, and tested at Cornell by our graduate student Dan Gonnella [74]. Supervised by Prof. Liepe, Dan will continue his PhD research program on ultra-high Q_0 cavities as discussed in this proposal. The residual surface resistance was less than 0.4 nΩ, and the cavity reached a record Q_0 of 3×10^{11} at 1.4 K. However, such results are currently the rare exception, and typically niobium cavities reach a maximum quality factor between 2 and 5×10^{10} at low temperatures, limited by residual resistances in the 5–15 nΩ range. New cavity treatments involving nitrogen doping of the RF surface layer and alternative SRF materials with higher critical temperatures T_c have been shown to strongly reduce the BCS part of the surface resistance, but cavities produced using such improved methods and materials currently show the same large variation in residual surface resistance with the resulting reduction in Q_0. These significant fluctuations in performance are a clear indication that we currently do not fully understand what the important parameters are during cavity fabrication, processing, and cool down, and how to control them to achieve lowest residual surface resistance and thus highest Q_0 reproducibly. We therefore propose to study the sources contributing to residual surface resistance in detail.

Single cell cavities will be used in the initial phase for the residual resistance studies. They allow rapid preparation and testing, thus efficient exploration of a large parameter space. We will use existing 1.3 GHz single cell cavities and plan to fabricate six additional single cell niobium cavities to allow for good statistics and for dissecting the cavities for further analysis of areas with high residual resistance. Half of the new cavities will be made out of fine grain niobium material, while the other half will be made out of large grain material. Each cavity will be prepared and performance tested with large scale, high sensitivity temperature mapping several times. Our existing high sensitivity thermometry system for single cell cavities allows measuring temperature increases below 1 mK, thus gives nΩ sensitivity in surface resistance. Surface resistance and the London penetration depth will be measured as functions of temperature to determine critical temperature, energy gap, mean free path, and residual resistance of the RF penetration layer. Surface treatment will be varied (centrifugal barrel polishing, buffered chemical polishing, vertical electro-polishing, hydrofluoric acid rinsing, medium to high temperature treatments, etc.) to systematically explore the impact of these treatments on residual resistance. Guided by location of areas of increased surface resistance by temperature mapping, the cavities will be dissected to extract samples for advanced surface studies with Auger/SIMS, XPS, EBSD, and FIB/TEM available on the Cornell campus. Comparing areas of high residual resistance with those of low resistance with these tools will give insight into the source of the increased residual surface resistance at certain locations.

In the second, equally important phase, the improved cavity process for lowest residual surface resistance will be transferred to multicell cavities. Existing multicell cavities will be used and tested with our existing, high-sensitivity multi-cell temperature mapping system, developed and heavily utilized by Postdoc Mingqi Ge. Graduate student Dan Gonnella, supported by our cavity test expert Dr. Andriy Ganshyn, will conduct the multicell low residual resistance work.

Goal: Make it possible to reliably achieve high quality factors in SRF cavities in the 10^{11} range by improving processing techniques, guided by improved understanding of the contributions to the RF residual surface resistance of niobium.

4.2 High Gradient SRF Cavity Research

A re-entrant shaped single cell cavity that was constructed by Cornell in collaboration with KEK in Japan has established world record accelerating fields in a single cell cavity: E_{acc} ~ 55 MV/m [75]. Advanced Energy Systems, Inc. has fabricated a nine-cell cavity with this same cell shape as the single cell cavity. One focus of our high gradient work is now to translate the very high gradients achieved in single cell cavities to the same performance in multi-cell cavities.

The critical field where vortices (that would cause massive losses) penetrate into a superconductor is ultimately limiting the maximum gradient of SRF cavities. At the lower critical field H_{c1} it is energetically favorable for vortices to be inside the bulk of a superconductor. However, metastable operation of SRF cavities is theoretically possible until a higher superheating field H_{sh} because a surface barrier prevents vortex entry above H_{c1} up to H_{sh}. It is therefore of highest importance to fully understand the dependence of the superheating field on temperature, material properties, and superconductor geometry (bulk superconductor; thin layer superconductor on top of bulk superconductor; multilayer superconductors) to be able to determine the most promising surface for highest gradient SRF cavities.

Small defects of the size of the coherence length of the superconductor can lower the energy barrier, resulting in vortex entry, strong dissipation, and likely quench of the cavity at fields well below the superheating field. Alternative superconductors for SRF application like Nb_3Sn [76] have superheating fields well above that of niobium (about twice as high, theoretically allowing accelerating fields up to 100

MV/m in SRF cavities), but are higher-κ superconductors, and thus have a low H_{c1} (typically < $0.25 \cdot H_{sh}$) and small coherence lengths (few nm). These promising alternatives are therefore especially vulnerable to defects, and it is currently unclear if metastable fields well above H_{c1} can be realized in SRF cavities. For the future of high gradient SRF it is therefore critical to study metastability in superconductors, and explore if metastable fields well above H_{c1} can be realized for higher-κ materials.

The proposed high gradient research program has the following three components:

1) High gradient in multi-cell cavities of optimized cell shaped

We propose to continue R&D on our existing re-entrant shape nine-cell cavity to further increase gradients by improving our multi-cell vertical electro-polishing setup and other steps used in preparing the surface of the cavity. Additionally, we will use new cavity shapes from a collaboration with KEK to move multi-cell voltages closer to the world-record gradient in single cells.

Goal: Move gradients in re-entrant nine-cell cavities toward the world record gradient observed in Cornell's single cell re-entrant cavity.

2) Superheating magnetic RF field limits for superconductor

As discussed above, the maximum field in a SRF cavity is ultimately limited by the superheating magnetic field. There has been a theoretical breakthrough (collaboration between Cornell's SRF group and Cornell theoretical condensed matter physicists) to calculate the theoretical limit for high κ material properly [77]. The graduate student Mark Transtrum did most of this theoretical work. Recently, he was also able to calculate the theoretical limit for a κ~1 material like niobium at low temperatures. We propose to continue the collaboration with the condensed matter theory group to fully calculate the dependence of the limiting field on the Ginzburg-Landau parameter κ at low temperatures. In addition, we propose to extend these theoretical studies towards thin superconducting layers and multi-layer superconductors. The theoretical work would be accompanied by experimental measurements of the RF critical magnetic field of different superconductors using our unique high RF pulsed-power setup, which was used successfully by our graduate student Nick Valles to measure the temperature dependence of the superheating field of bulk niobium; see Figure 8.

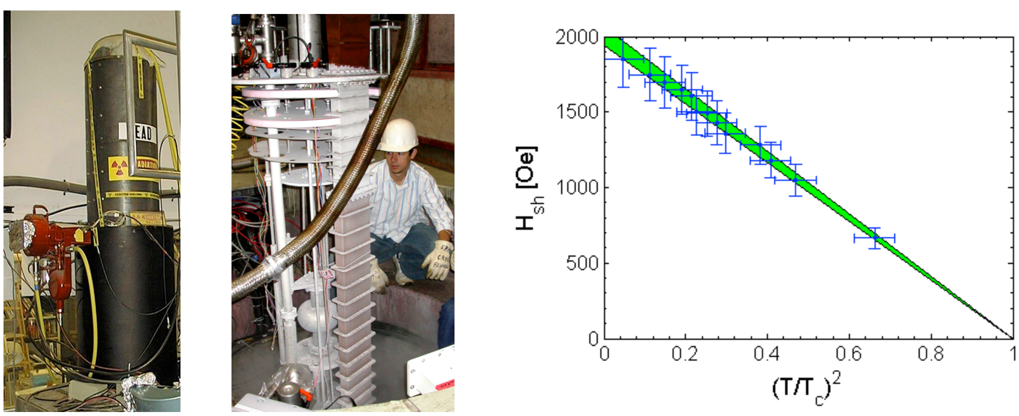

Figure 8. Left: 1.5 MW pulsed klystron. Middle: Graduate student Nick Valles with his waveguide insert for pulsed operation of single-cell SRF cavities at high power. Right: Measured temperature dependence of the superheating critical field of niobium.

Goal: Calculate the RF critical magnetic field at low temperatures as function of the Ginsburg-Landau parameter for bulk and thin multi-film superconductors.

3) Metastability and high gradients in alternative superconductors with low H_{c1}

Defects lowering the surface energy barrier to vortex penetration are likely an important cause of quench at fields well below the theoretical limit. This limiting mechanism, relevant type of defects, and metastability will be studied systematically. Niobium cavities will be doped with impurities (nitrogen, argon) by heat treatments in low-pressure atmospheres to vary κ of the surface layer and thus vary H_{c1}. In addition, high κ Nb_3Sn cavities will be coated in our existing Nb_3Sn diffusion furnace. These cavities will be cryogenically tested in our RF test infrastructure with full scale temperature mapping to determine the loss distribution over the surface of the cavities. These measurements allow for determining material properties, critical fields, and their spatial variation. Field limiting (defective) areas will be localized, and extracted from the cavities for advanced surface studies with Auger/SIMS, XPS, EBSD, and FIB/TEM. This approach allows for determining the nature of the field limiting defects. Based on this information, improved cavity fabrication and treatments will be developed for increasing the gradient yield in niobium cavities and for increasing the maximum field well above H_{c1} in Nb_3Sn cavities.

Goal: Demonstrate that metastable fields well above H_{c1} can be achieved in high κ SRF cavities.

Students and post-docs have been major players in this activity, and a new graduate student supervised by Prof. Liepe will do much of the proposed high gradient research.

4.3 Muon SRF Accelerating Cavity Research

Muons are fundamental particles like electrons, so muon colliders would have the same advantages as electron-positron colliders. In addition, synchrotron radiation by muons is less than that by electrons by $(m_e/m_\mu)^4 \approx 6 \times 10^{-10}$, which allows muon colliders to be much smaller than $e+$ $e-$ colliders of the same center-of-mass energy. The ultimate goal is a multi-TeV μ+ μ − collider. In addition, a storage-ring-based "neutrino factory" could produce intense beams of neutrinos from muon decays.

Because muon beams are secondary beams produced by the decay of pions, the beam sizes and energy spreads are initially large and ionization cooling is needed to reduce the beam sizes so that the beams can be accelerated to high energy. To accommodate the large beam sizes even after cooling, the SRF accelerating cavities for the initial stages of acceleration will have to operate at low frequencies of 325 MHz and 650 MHz. Because the lifetime of the muon is only 2.2 microseconds there is a large premium on achieving high accelerating gradients greater than 20 MV/m to accelerate the beams to relativistic energies as quickly as possible. Pulsed superconducting cavities can provide this acceleration in an economic way.

So far, the primary focus of the SRF R&D activities at Cornell appropriate for accelerating muon beams was the development of a single cell superconducting cavity operating at 200 MHz. Two cavities were manufactured by our collaborators at CERN by sputter coating electropolished copper cavities with several micrometers of pure Nb, and then tested at Cornell. The better of the two 200 MHz cavities achieved an accelerating gradient of 11.4 MV/m but had a significant Q slope at higher gradients indicating poor Nb surface quality [78]. Achieving a consistent high quality film of Nb has proved to be very difficult because of the large physical size of the cavity.

In parallel with the sputtering program, sheets of 1 mm thick Nb explosion bonded to a 3 mm thick sheet of Cu were manufactured. The explosion-bonded sheets were spun into single cell 500 MHz cavities by our collaborator, Enzo Palmieri, in Italy, producing two good cavities with high-quality Nb inner surfaces. The cavities were sent to Research Instruments in Germany and will have beam tubes and flanges electron beam welded onto them. Initial testing of these cavities will be carried out early in 2014, following our standard chemistry at Cornell. Together with a new graduate student supervised by Prof. Liepe, the young cavity expert RA Fumio Furuta, who has achieved very high gradients in ILC cavities, will work on these cavities, and on other techniques to produce Nb coated copper cavities, as discussed below. Prof. Hartill has led research on muon accelerators from many years, and will continue to support the muon SRF research proposed here with his expertise.

The goal of the muon cavity R&D program is to demonstrate the feasibility of producing high gradient, low frequency, and low cost SRF cavities for efficient and rapid acceleration of low-energy muons. The research would include the following parts:

1) Explosion bonded Nb-on-Cu cavities:

By using bonded materials with ~1 mm thick Nb for the inner cavity surface, established surface preparation techniques for solid Nb can be used. This work will be done with 500 MHz cavities instead of the needed 325 MHz to minimize cost. Still, 500 MHz is sufficiently low in frequency to require a cavity with surfaces of a similar scale as the 325 MHz cavities and will address all of the technical challenges in producing larger single-cell RF cavities. The plan is to finish the assembly of the two explosion-bonded cavities presently at Research Instruments, and to construct two more explosion-bonded 650 MHz cavities. These four cavities will then go through our standard cavity preparation, and will be performance tested. A vertical EP system similar to the successful development at Cornell for 1.3 GHz cavities will be constructed for 500 and 650 MHz cavities and a series of cavity tests will determine the optimal surface treatment.

Goal: Achieve $Q_0 > 10^9$ at 4.2K and 17 MV/m in a low frequency, explosion-bonded Nb-on-Cu cavity.

2) Alternative fabrication method of Nb-on-Cu cavities:

An alternative way of manufacturing Nb-on-Cu cavities would be by first making a niobium cavity from 1 mm wall thickness, then coating the outer surface with a thin layer of copper by plasma coating or electroplating to provide a starting surface, and finally electroforming 3 or 4 mm of Cu on the outside of the cavity to provide the necessary mechanical rigidity while maintaining excellent thermal conductivity. We plan to explore this technique by applying it first to one of our existing 1.3 GHz single cell cavities. After succeeding with the 1.3 GHz cavity, a 650 MHz prototype using 1 mm thick Nb would be constructed and tested using this construction technique.

While other proposed work of Cornell's SRF group focuses on coating cavities with innovative materials, e.g. Nb3Sn, or Niobium diffused with nitrogen, the technique we want to develop here uses niobium itself as superconducting surface, on a substrate of copper.

Goal: Achieve $Q_0 > 10^9$ at 4.2K and 20 MV/m in a 650 MHz Nb cavity with an electroplated copper mantel.

5. High-Power Energy Recovery in an SRF cavity

Building on the combined strengths of two Cornell accelerator groups, the photoemission source development and the SRF teams, we propose to demonstrate record current recirculation in a specially built for high current beams SRF cavity and the world-record average current and brightness Cornell photoinjector. This accelerator frontier will allow us to address a number of important outstanding beam physics questions and will enable future forefront accelerators based on recirculating SRF linacs.

To accomplish these goals, we plan to significantly increase the performance of the aforementioned world-record beams by boosting them to higher powers with a small energy recovery recirculation loop. In this program we will design and build a small recirculation loop with 20 MeV maximum energy capable of transporting up to 100 mA beam current (see Figure 9). The major components of the loop are already available (electron source, SRF booster cavity, SRF linac cavity and high power beam dump), thus, the total project cost will be minimal. This recirculation current will be significantly beyond anything previously demonstrated in an energy recovery linac (ERL) and will open a new regime for scientific studies of high-power beams, including halo formation due to collective effects or nonlinear dynamics, ion clearing and ion instabilities, RF control under extreme conditions and management of Higher-Order Mode (HOM) heating.

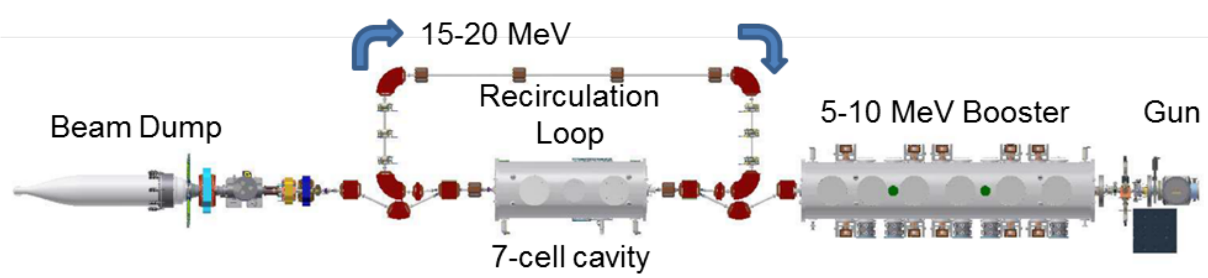

Figure 9. The compact energy recovery recirculation loop concept. The existing photoinjector, a cryomodule containing one 7-cell SRF cavity, and high power beam stop will be used to recirculate up to 100 mA beam current at 15-20 MeV beam energy.

Because of the many advantages of high-brightness beams, ERLs have been proposed as drivers for light sources, electron-hadron colliders, and electron coolers, e.g. for the Cornell ERL, the KEK ERL light sources, eRHIC, the MEIC, the LHeC hadron-electron colliders, and the BNL electron cooler for RHIC. The research outlined here represents the forefronts of accelerator science directly relevant to these and other new high-power accelerators.

Milestone Q1-2016: Complete installation of the return loop and demonstrate energy recovery for low currents.

Below we list a number of pressing accelerator physics challenges which we will be able to uniquely address with the compact ERL.

Instabilities: The Beam Break-Up (BBU) instability can limit the beam current in recirculating accelerators employing SRF. It occurs when Higher-Order Modes (HOMs) in a cavity excite the beam in such a way that it can add energy to the very same mode after its return for deceleration. When the beam current is above a threshold, this feedback leads to exponentially increasing HOM power.

BBU has been simulated and compared to measurements in the past in collaboration between Cornell and JLAB and the results were very encouraging [79]. However, much remains to be done. The cavities at JLAB FEL would have produced a threshold current of merely 3 mA if installed alone without the help of a special optics taking advantage of the FEL's short linac length. Cornell's cavities were designed with a corresponding threshold current exceeding 1000 mA [80]. PhD student Changsheng Song simulated the BBU instability to secure large enough currents. This was achieved by an intricate optimization of the SRF cavity shapes performed by PhD student Nicholas Valles. Because of the large advance by a factor of 300, a test is very much needed.

Goal: Determine the threshold current for the dominant BBU modes and test approaches to calculating and stabilizing BBU.

High beam-power effects in the loop, including ions: The particle motion in high-current beams has three distinct components that are exceedingly hard to simulate and to describe by an accurate theory: (a) self-consistent nonlinear particle dynamics for one particle in the field of the beam; (b) two-particle scattering events; and (c) coherent effects of the full beam interacting with its environment (E&M fields such as higher-order modes, ions, or electron clouds). Beam studies in the loop will allow a comparison between intricate theories and measurements.

Goal: Design a layout for a return loop that uses energy recovery to produce high-brilliance beams, and equip it with diagnostics sufficient for the studies of this section.

Ion phenomena are routinely observed in storage rings and will be studied in CESR as describe in section 2.2. In low-emittance ERLs, ions can be particularly damaging and have to be eliminated by clearing electrodes. In particular, the impact of the fast-ion instability is unknown. This instability starts from random noise in the centroids of bunches and grows quickly with time following a power law. The end of the bunch-train in a ring naturally limits the growth time, but it is not yet known how long the growth is sustained in a continuous beam operation with energy recovery. The extension of fast-ion theory to coupled electron/ion-beam dynamics in continuous beams will be compared to measurements in the loop. PhD student Steven Full is simulating the fast ion instability in ERLs with the support of undergraduate students. We will study the efficacy of the clearing electrodes for avoiding nonlinear focusing from ions, BBU from the ion-impedance, and the fast-ion instability.

Goal: Benchmark simulations of beam dynamics under ion accumulation against high-precision measurements in the loop, and show that clearing electrodes can eliminate ions successfully.

Halo control in the recirculation loop: The test loop also allows the study of beam loss due to inevitable causes such ghost pulses from the injector laser, occasional field break down, or dark current due to field emission. Such losses must be properly characterized and controlled. We intend to develop the techniques for continuous and reliable particle-loss monitoring with efficient and fast beam abort essential for any high-power beams.

Goal: Use radiation measurements to localize and understand sources of beam halo.

Milestone Q1-2017: Achieve up to 100 mA energy recovery with fractional beam loss below 10^{-6}.

Low-loss high-reliability operation CW SRF: Many applications of CW SRF require high beam quality with very rare interruptions. To provide such beam quality, the SRF fields have to be exceedingly well controlled by a Low-Level Radio Frequency (LLRF) system. We have developed such a system with state of the art parameters and are ready to demonstrate its effectiveness in the test loop. The postdoc Vivian Ho will contribute to this work. The long-term operation of the test loop will enable an analysis of the average number of field breakdowns.

Milestone Q1-2017: Amplitude and phase stability of SRF of 10^{-4} and 0.1 degrees for up to 100 mA beam recirculating beam current.

Profs. Georg Hoffstaetter and Ivan Bazarov will provide supervision to 2 PhD students (one beam dynamics and one SRF) involved in this project along with a post-doc Adam Bartnik, who has been instrumental in demonstrating low emittance and high beam current out of the Cornell photoinjector and will be optimizing performance of the injector with ERL loop. Bruce Dunham will direct the construction of the mini-loop and manage the overall resources as well as the daily beam operations. Post-doc Chris Mayes will design the beam optics and magnet layout for the loop. Dr. Ralf Eichhorn will supervise the SRF component of the operations.

6. Results from prior NSF support and past achievements

6.1 Lepton Collider (NSF PHY 1002467)

Dates: 5/1/11-4/30/14, Amount: $15,009,973, PI: David Rubin co-PIs: Donald Hartill, Georg Hoffstaetter

Intellectual Merit

The results of the prior support include detailed knowledge of electron cloud physics that is captured in computer models, measurement of thresholds for beam blowup in terms of electron cloud density and from intra-beam scattering, electron cloud model parameters for more than a dozen different mitigations that were tested in CESR, emittance tuning procedures and correction algorithms that routinely yield sub-10 pm-rad vertical emittance, and x-ray beam size monitors with micron resolution that can independently measure the height of bunches space as few as 4 ns apart.

With prior support we have established the CesrTA Collaboration, an international collaboration of scientists at accelerator laboratories and universities. Collaborators have contributed both equipment and intellectual capital to the program, motivated by requirements of new accelerators and machine upgrades (SuperKEKB, LHC, Project-X, synchrotron light sources, etc.) as well as scientific curiosity. The full list of participants is available as the author list to the “Cesr Test Electron Cloud Research Program: Phase I Report” [19]. Collaborating institutions include Argonne National Laboratory, Australian Synchrotron, Brookhaven, California Polytechnic Institute, CERN, Cockroft Institute, FNAL, INFN-LNF (Frascati), KEK, Lawrence Berkeley National Lab, and SLAC.

With this same support we have established that very high intrinsic quality factors in SRF cavities can be preserved when a cavity is installed into an accelerator cryomodule. An existing one-cavity cryomodule was modified to host a 7-cell SRF cavity. After installation of the cavity, a record high intrinsic quality factor in a cryomodule was measured, demonstrating that the cavity can be protected successfully from environmental factors, which have the risk of degrading cavity performance.

Broader impact

The findings of the CesrTA electron cloud research program formed the basis for the design of the damping rings for the International Linear Collider [81]. Mitigations developed and tested at CesrTA (Figure 10) are being incorporated into the SuperKEKB B-factory that is being built at KEK in Japan. Evaluation of mitigations has informed the design of LHC

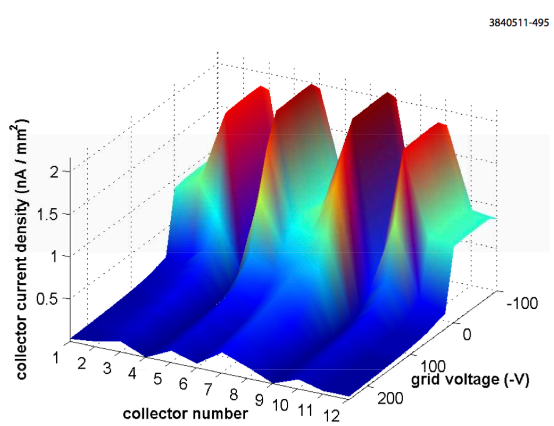

Figure 10. Grooved wiggler measurements with RFA: 1x45x1.25 mA e+, 2.1 GeV, 14 ns. Collector number corresponds to horizontal position and grid voltage to electron energy

upgrades where electron cloud effects are observed to limit the number of proton bunches that can be circulated in the collider. Our investigation of emittance tuning instrumentation and methods has contributed to the development of that science for synchrotron light sources and damping rings for linear colliders, and CesrTA scientists are regular contributors to the Low Emittance Rings Collaboration.

With prior NSF support we have produced nearly 150 publications and reports including 3 PhD thesis [2][47][43] and two dozen REU reports. All three of the PhD graduates are now employed as working accelerator physicists. The complete bibliography of CesrTA publications and reports is available at the following link [82]. The conversion of CESR from colliding beam machine to a laboratory for the study of the physics of beams in low emittance storage rings is documented in the 448 pages of the report [19].

6.2 Superconducting RF (SRF) Development for the Project X Neutrino Beam to DUSEL (NSF PHY-0969959)

Dates: 10/1/10-9/30/13, Amount $892,260, PI: Georg Hoffstaetter co-PIs: Matthias Liepe, Hasan Padamsee

Intellectual Merit

This work advances the frontier of design for high-duty-factor SRF cavities by minimizing dynamic refrigerator loads (by maximizing shunt impedance and by minimizing surface resistivity) at 1.8 K while respecting the need for eliminating trapped modes in the cavities. Furthermore, all important features of SRF cavity production are identified and clearly expressed in a published form that directly aids the mentoring process for industrial cavity production.

Broader Impact

Results have wide application in other fields with research based on accelerators such as neutron and x-ray based materials research. Additionally student training is accomplished at both the graduate and undergraduate levels through participation in each aspect of the work. American companies will be in a better position to compete for high technology business and more suppliers will be available for American projects that must now depend on European or Japanese companies for supply that will already be strained by projects in those regions.

Industrialization

Cornell's SRF group is highly successful in transferring SRF technology and production techniques to industry. Examples include: a) A 500MHz single-cell cavity cryomodule for high-current storage rings was prototyped at Cornell, and the technology transferred to Accel (now Research Instruments) and to Advanced Energy Systems (AES) / NY. These companies have equipped 7 international ring accelerators with these SRF accelerating modules. b) We have advised and trained AES / NY and Niowave / MI on reliable methods for the production of SRF cavities, and helped qualify these companies as vendors for US research laboratories. c) Cornell's Oscillating Super-leak Transducers (OSTs) were developed to find the quench spot of an SRF cavity by triangulating second-sound waves. This method turned out to be so successful that approximately 10 international laboratories requested these detectors. We therefore transferred this technology to AES / NY where these sensors can now be purchased.

6.3 IMR: Phase 1B Energy Recovery Linac (ERL) Technology R&D (NSF DMR 0807731)

Dates: 10/1/10-9/30/14, Amount: $30,948,000, PI: Georg Hoffstaetter co-PIs: Ivan Bazarov, Joel Brock, Matthias Liepe

Intellectual Merit

This award led to the development of the key accelerator science and technology necessary to build a successful full-scale ERL-based hard x-ray light source. We designed, built and tested an injector that achieved 75mA average current at 1300 MHz repetition rate, and a normalized emittance of 0.3 μm at a bunch charge of 77 pC. These parameters meet the needs of an ERL. In addition, the cathode lifetime is good enough to run for ~1 week uninterrupted. The current is far beyond the previous record from a photoemission electron injector of 32 mA. Extensive photocathode R&D was necessary for these achievements.

We also designed, built and tested SRF cavities suitable for an ERL main linac. They have high Q, low field emission, strongly damped higher-order modes and a high beam breakup threshold. Extensive computer modeling of 7-cell cavities led to the designs to meet these goals, as well as all of the requirements for industrial production of the cavities. Seven cavities have been constructed and all meet the requirements for Q and gradient. One cavity was tested in a horizontal cryostat, and achieved a world-record Q of 1×10^{11} at 1.6 K. These cavities will be built into a cavity string and mounted in a prototype cryomodule for the ERL main linac.

Unlike the flat beams typically produced in a synchrotron light source, ERL beams are round. To take advantage of this, a new type of permanent magnet undulator was developed. The 'Delta' undulator has a new configuration, with a 5 mm round aperture to match the beam. A prototype has been built and tested with beam, matching all of the simulation results. This design is now being copied by other labs, due to its simplicity and low cost.

The beam dynamics issues in a high power ERL are critical to understand in order to maintain the low emittance from the injector, reduce or eliminate halo and background radiation, and to minimize the effects of non-linearities. Extensive simulations have been carried out to study all of these effects, and have been incorporated into the design of the optics for the full-scale ERL.

Finally, the results from these studies demonstrate that all of the requirements for an ERL-based hard x-ray light source can be met. In addition, the results are useful not only for us at Cornell, but for many other proposed machines that need high-brightness, high-power electron beams, such as LCLS-II, RHIC, and LeHC.

The ERL Phase 1b project has led to over a 100 journal and conference papers and 3 PhD theses. A complete list is available at the following links [83][84].

Broader Impact

Community engagement

Graduate student Jared Maxson helped co-led workshop on the Science of Sound at the 2011 Expanding Your Horizons Program, an annual one-day conference held at Cornell University to encourage middle school girls to pursue careers in STEM. Jared also participated in a skit encouraging women to continue their undergraduate careers in physics at the 2012 Northeast Conference for Undergraduate Women in Physics conference hosted at Cornell University.

Graduate student Sam Posen staffed a science booth at the New York State Fair, which offered over 2000 visitors the opportunity to explore concepts related to electron excitation through hands-on activities, such as building radio speakers from cups, magnets and ceramic magnets.

Figure 11. Grad student Sam Posen at the NY State Fair.

In October 2011, Sam networked with Ithaca City School District (ICSD) science teachers as part of the ICSD-Cornell University Resource Fair, sharing CLASSE resources, materials and ideas that educators can use in their classrooms [85]. He has also traveled to New York City (Figure 11), helping to facilitate a session on magnetism to a group of 40 middle school science teachers as part of the biannual Cornell Science Sampler Series hosted at Weill Medical College in Manhattan. All of our graduate students regularly provide tours of the Newman SRF area and CESR tunnel and Wilson Lab experimental facilities. Approximately 200 visitors, ages 8-80, tour the ERL prototype and control room each year, led by RA's and graduate students.

Post-doc Kiran Sonnad gave a seminar in September 2013 at California Polytechnic University at San Luis Obispo on the basics of accelerators and the CESRTA program. Senior Research Associates Bill Schaff and Bob Meller spoke to a group of secondary school teachers as part of a professional development module about solar cells, lectured to the AP physics classes at Ithaca High School on conceptual and intuitive special relativity and gravity, coached them on exam preparation and project design, and developed and repaired apparatus for the AP course laboratories.

Summer Research for Community College Students

Sixteen students from local community colleges joined us in research through Summer Research for Community College Students, a program initiated by Professor Matthias Liepe. This program, which started in 2010 under Professor Liepe's NSF CAREER award, has attracted about 10 applications for every open slot. The effect has been extremely positive, and nearly all of the participating students have gone onto 4-year colleges studying topics in science, math and engineering.

7. Broader Impact

7.1 Impact on Accelerators and Industry

Accelerators deliver x-rays, produce high-energy particles and create the conditions found in the center of stars and the early stages of our Universe. By one estimate, between 1939 and 2009, a Nobel Prize was awarded every 2.9 years for research made possible or carried out at least partially on an accelerator [86]. By improving the performance of accelerators, this proposal will benefit all of these. It will also make them more cost effective to build and operate.

Today's accelerators are also a critical tool for industry, medicine, national defense, and research, and may offer a path to safe nuclear energy. Annual sales of industrial accelerators, for example, exceed $2B, and are growing at an estimated 10% per year [87]. For example, our research has direct impact on semiconductor companies, which are desperate for high power light sources at 13.5 nm in order to provide the high-throughput lithography required to produce their next generation chips. They are exploring the use of high power FELs driven by an energy recovery linac, and our high-power injector meets the required specifications for emittance, current and reliability. In addition, the cavities we have designed for high threshold currents and high Q are an ideal match for the high average power FEL. We expect that much of this technology can be transferred to industry to enable next generation semiconductor manufacturing. Our past research has led to several current SBIR's, and we anticipate that the research proposed here will have similar impact on industry.

The PI's will continue to serve on advisory and executive committees to accelerators around the world. Professor Don Hartill is currently the Chair of the APS Division of the Physics of Beams.

7.2 Graduate education and GEAR

One goal of this program is to increase the number of graduate students pursuing doctoral degrees in accelerator physics. To address this, we propose to launch a new program, Graduate Education in Accelerator Research, or GEAR, that would invite doctoral students from all universities to carry out their thesis research at Cornell. The student would spend two years at Cornell doing research under the supervision of one of our accelerator faculty members, working on a topic of interest to that faculty member. The student's home faculty advisor would also have the opportunity to participate. In advance of starting research at Cornell, the student would be expected to take prerequisite courses at the home institution and attend the particle accelerator school.

This approach differs from opportunities offered to students by the national labs, in that they will be supervised by faculty, and will interact extensively, and deeply, with the accelerator or device targeted by their research in a way that is possible only at a university-based accelerator. During the program period, we anticipate sustaining the number of Cornell doctoral students in our program and adding two GEAR students. These students will be involved in every aspect of the program described above.

Goal: Launch the Graduate Education in Accelerator Research Program (GEAR) to enable 2 graduate students from other universities to carry out their thesis research at Cornell.

7.3 Outreach

This proposal has a two-pronged outreach program, both of which focus on accelerators. One program brings community college students into the lab to work with us in accelerator research. The other is directed at the 25 school classes who come to visit the lab on field trips each year.

7.3.1 Summer Research for Community College Students (SRCCS)

We propose to bring four community college students to join us each summer for an 8-week internship. The main focus of the internship will be research in accelerator physics, on the projects described elsewhere in this proposal, but it would also include formal seminars, lectures, tours of research facilities, social and recreational events, and building an interactive exhibit for the lab's outreach program. Some of these activities piggyback on programming already in place for the lab's Research Experience for Undergraduates (REU) program. The community college students will be assigned a faculty mentor who defines the research project, guides the student's project, and provides one-on-one training. This continues a highly successful program that was begun by Prof. Matthias Liepe under his now expired CAREER award.

7.3.2 Tour squad

Each year, approximately 1000 visitors tour the Cornell accelerator facility, many of them school classes who come on field trips. We plan to form a new graduate student Tour Squad charged with both leading tours and preparing material to make the tours more engaging. Three teams will focus on three areas of research (CESR, injector/loop and SRF) and develop 15-20 minutes of material for visitors. This work will be done under the guidance of Lora Hine, a professional science educator.

One target audience is early learners, since many of our visitors are children. For them we envision material such as the "Wilson Lab Scavenger Hunt" handout that we sometimes provide to young students touring the tunnel. We will also create posters and/or hands-on developmentally appropriate exhibits for display and use in the tunnel.

For older children and adults, we will explore the possibility of producing media tools for use online and/or display on monitors inside of CESR tunnel. This could include simulations, videos, animations, interviews and interactive tutorials describing certain aspects/equipment at the lab. For example, animations could depict electron/positron pair production, acceleration in SRF cavities, or the path of charged particles from the linac to synchrotron to CESR.

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