Proposal to the
University Consortium for a Linear Collider

August 29, 2002

Proposal Name

Research in Superconducting Radiofrequency Systems

Classification (accelerator/detector: subsystem)

Accelerator: rf system

Personnel and Institution(s) requesting funding

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Project Overview

Below we describe the on-going R&D under our regular NSF contract. We assume that this research will continue to be funded at the levels we have requested in our five-year NSF proposal, 020278, also referred to as the Blue Book, CESRP 01-1. *In the following text, we have noted in italics where funding is requested for specific items from UCLC.*

Rapid advances in superconducting cavity performance have made RF superconductivity an important technology for a variety of accelerators, fulfilling the needs for high energy physics, nuclear physics, radioactive beams for nuclear astrophysics, intense proton accelerators for neutron spallation sources, muon acceleration for future neutrino factories and muon colliders, storage ring light sources, free electron lasers, fourth generation x-ray free electron lasers, and energy recovery linacs.

Improved understanding of gradient-limiting mechanisms, together with technology advances, are responsible for the steady increases in performance [5]. Gradients of 25 MV/m at Q values of 10^{10} are now regularly achieved in one-meter long superconducting structures suitable for TESLA (TeV Energy Superconducting Linear Accelerator). To reach such gradients, high-purity, high thermal-conductivity niobium is used to prevent thermal breakdown of superconductivity, while high pressure rinsing and clean room assembly techniques are used to reduce field emission and voltage breakdown. LEPP research has played a major role in pushing cavity performance to these levels.

The goal of our future R&D program will be to push gradients towards the theoretical limit (50 MV/m), which is another factor of two higher than achieved levels. Advances in understanding gradient and quality factor (Q) limitations, together with progress in gradients will benefit the goals of TESLA and its upgrades to higher energies and luminosities.

1. Studies of field emission and dc, rf breakdown in Nb and Cu cathodes

   One phenomenon that limits cavity performance is field emission [5]. Field emitted electrons gain energy from cavity fields and deposit power on the cavity wall, lowering the quality factor and increasing the heat load. Through bremsstrahlung, field emission also generates high x-radiation levels that limit accelerator operation. Dark current is also harmful to accelerator beam quality.

   During the course of advances to present gradient levels, microparticle contamination has been determined to be the main cause of field emission in superconducting cavities [6]. At LEPP, emitters have been individually located using temperature mapping techniques. This is a powerful diagnostic technique in which a dense array of sensitive thermometers rapidly samples the temperature at the outer wall of a cavity. After cavity dissection, and surface analysis with a scanning electron microscope (SEM), the emitters are identified and analyzed for the presence of foreign elements using an attached EDX (energy-dispersive x-ray analysis). More sensitive surface analyses are carried out by sending cavity sections to outside analytic facilites, such as scanning Auger electron microscopes (SAM), and secondary ion mas spectrometry (SIMS). *Funds requested under UCLC will be used to pay for these outside contracts.* DC field emission studies on cm^2 room temperature niobium cathodes also reveal micro-particles to be the main source of field emission.

   Following up on these discoveries (and similar findings at other labs), techniques such as high pressure rinsing (at $\approx$ 100 atmospheres) and dust-free surface preparation produce low field emission cavities with dark currents well below the microampere range [7]. Megasonic cleaning techniques will be explored to compare their effectiveness for cleaning surfaces. However, experience with operating cavity systems show the need for an in-situ technique to limit field emission from dirt that may accidentally get into accelerator cavities during final assembly, or accelerator installation, or long-term operation.

   Field emission eventually leads to momentary voltage breakdown of the cavity vacuum. This has mostly a beneficial effect, known as conditioning. After a voltage breakdown event, it is usually possible to raise the electric field until field emission grows intense once again at another emitter on the cavity surface [6].

   We have learned much about the nature of field emission. Studies at LEPP have shown that high power conditioning eliminates field emission by triggering voltage breakdown at field emission sites. Gradient gains of factors of 3 are common [3]. Further studies at LEPP have shown that voltage breakdown in niobium cavities bears strong commonalties with DC voltage breakdown on room temperature niobium and copper cathodes [6].

   Both CEBAF and LEP made 20 % gains in gradient and substantial reduction in radiation levels by another procedure called helium processing [5]. Here helium gas is introduced at a pressure below discharge, and the cavity is operated at high fields. After time periods of a half-hour to many hours, emission decreases.

   We have developed special vehicles to study breakdown in both RF and DC fields [6]. Simulation programs have been developed to trace the evolution of voltage breakdown starting from field emission. Through these devices we have advanced our basic understanding of voltage breakdown. Important questions remain open about field emission and voltage breakdown, such as the role of gases and the oxide layer, and the mechanism by which helium processing works. We aim to continue our studies of field emission and breakdown using both rf cavities and dc breakdown on Nb cathodes. Extending these studies to copper cathodes will benefit NLC and multi- TeV linear colliders where gradients above 100 MV/m are desired.

2. Studies of the sources of high field Q-slope and quench field in Nb cavities

   Another field limitation is a less understood phenomenon called the high field Q-slope [7]. In very clean cavities that show little or no field emission, there persists a steady decline in Q_0

above 20 MV/m, followed by a quench between 20 and 30 MV/m. Absence of x-rays corroborates absence of field emission. Temperature maps reveal that power dissipation occurs over large sections in high magnetic field regions of the cavity. Yet the losses are not uniform. Collaborative work at several laboratories shows that electropolishing, instead of the standard chemical etching procedure, substantially reduces the Q-slope and increases the quench field. Another cavity treatment (baking at 140^{o}C for 48 hours) further improves the high field Q-slope of electropolished cavities, and raises the quench field substantially. Baking also has a slight beneficial effect on the Q-slope of chemically etched cavities, but no significant effect on the quench field.

There is little understanding of what causes high field Q-slope, nor is there any understanding of why electropolishing and baking help to reduce it. Also, the connection between quench field and Q-slope is poorly understood.

We plan to use our state-of-the-art thermometry system to identify hot regions responsible for the Q-slope, and premature quenches [8]. These studies will be carried out on single cell cavities with surfaces prepared a variety of methods, such as chemical etching, electropolishing, heating, and anodizing. After identifying lossy regions we will dissect the cavity and study the spots with surface sensitive techniques such as Auger, SIMS (secondary ion mass spectrometry), and XPS (x-ray photoelectron spectroscopy). Auger and SIMS will give surface sensitive elemental information, while XPS will help sort out differences in surface oxides. Use of other surface techniques may be warranted. *Funds requested under UCLC will be used to help pay for some of these outside contracts.*

This work will be carried out in collaboration with the Applied Superconductivity Center (ASC) at the University of Wisconsin, who will carry out surface analysis funded through outside contracts.

3. Studies of pulsed operation of Nb cavities at high gradients

   At DESY, several 9-cell structures that were limited to gradients of 25 MV/m in CW operation were able to reach 30 to 35 MV/m during pulsed operation for a millisecond TESLA pulse length [2]. During LEPP exploration of high peak power processing of field emission, we were able to reach accelerating gradients of 45 MV/m for shorter time periods of a few microseconds with 5-cell, 1300 MHz TESLA type cavities. Higher gradients are possible for short pulses because there is not enough time for defects to heat up and trigger a quench.

   Operating a superconducting linear collider at 45 MV/m gradient with short pulses of a few microseconds (or perhaps even to few tens of microseconds) opens the possibility to increase TESLA energy to one TeV. This may provide an expeditious energy upgrade path. But the luminosity would be lower than the baseline TESLA parameter set due to the shorter bunch train that can fit inside the reduced pulse width. Nevertheless, a quick exploration at one TeV would be valuable if there are any new particles in this regime.

   In conjunction with our efforts to reach higher gradient throughout short pulses, we aim to explore the one TeV/lower luminosity parameter space allowed by the inherent flexibility of the TESLA approach to the linear collider. We plan to use a TESLA parameter optimization program developed during our TESLA concept development phase [1].

4. Advances in high-gradient Nb cavity fabrication

   Electropolishing

   Since electropolishing proves to be a superior surface preparation technique over chemical etching [7], we aim to install an electropolishing capability at LEPP. If the need for 9-cell arises, we plan to install a complete facility. However, electropolishing a complete 9-cell TESLA cavity is cumbersome because of the small opening, and the danger of hydrogen contamination during electropolishing. One attractive alternative is to electropolish open half-cells before welding them together. DESY has tried this procedure through their cavity vendor, but failed because the welding contaminated the cavity. We aim to explore ways to better shield the cavity surface during welding. Since LEPP has its own beam welder we have more flexibility to develop such a procedure.

   This project will be carried out in collaboration with Fermilab.

   Cavity Spinning

Main linac modules carrying superconducting cavities are the largest cost item for TESLA. Several cost reduction efforts are underway for cavity fabrication. Two of these, originating at INFN, Italy, involve spinning multicell cavities from a single sheet, and from a single pipe [9]. This method promises 9-cell cavity fabrication times of a few hours as compared to several days by the standard stamping and welding method. It also eliminates welds, potential sources of gradient limitations in the future. Single cell 1300 MHz spun cavities have been tested to reach gradients of 40 MV/m. However, INFN is the only institute that is capable of this technique, which also remains a manual operation involving substantial operator judgment. Given the method‘s promise, we propose to develop a US-based supplier equipped with automatic spinning tools. Single cell cavities will be fabricated first both from sheet and tube. After successful results we will produce multicell cavities. *Funds requested under UCLC will be used to pay for outside contract work involving fabrication of niobium cavities.*

This work will be done in collaboration with Fermilab.

5. Studies of methods to improve Q and the consequences for linear collider operations (implications for pulse length, bunch charge, etc. re-optimzation).

   There are many ways to benefit from higher Q's. Preliminary explorations of TESLA parameters show that it's possible to double the luminosity by doubling the repetition rate from 5 to 10 Hz. Usually such a step calls for doubling the AC power installation. But if the Q_0 of cavities can be improved to 5×10^{10}, then the refrigerator associated AC power is much less, making it possible to double the luminosity with only a 60% increase in AC power. Another potential benefit from higher Q is to halve the number of klystrons by increasing the filling time and doubling the pulse length. Fewer klystrons increases the reliability of accelerator operation. As TESLA upgrades energy with higher gradients, higher Q's will lower thetotal AC power demand.

   At 2 K, the Q_0 value of 1300 MHz TESLA cavities is still within the temperature dependent BCS regime. Therefore 140^oC bake out increases Q_0 by 50%, due to a lowering of the mean free path, as predicted by the BCS theory. Lowering the operating temperature to 1.5 K should raise Q_0 by a factor of 10, to yield Q values over 10^{11}.

   We plan to aim for this high Q_0 and determine what other loss mechanisms may crop up. One of the important mechanisms is rf losses due to residual DC magnetic field. This would have to be shielded to a few tenths of a milligauss.

   In conjunction with Q-raising efforts, we plan to study how to take advantage of higher Q_0 for a pulsed superconducting linac. We will continue to explore parameters that increase luminosity with a higher duty factor.

   This work will be done in collaboration with visitors from Fermilab who wish to train in SRF technology.

6. TESLA SRF cavity design studies to improve efficiency

   With more efficient cavity designs, the ratio of accelerating field to peak field may be improved with innovative shapes. Although such improvements are potentially small (10%), they translate directly into an increase in the collider's top energy, for the same wall plug power, and are thus worth pursuing.

   This work will be carried out in collaboration with Fermilab.

7. Development of US vendors for TESLA 9-cell cavities

   Currently, all industrial vendors of TESLA superconducting cavities are in Europe. The development of US vendors for these cavities would be a significant benefit. We would work with potential vendors in this country to interest them in this work.

SRF Infrastructure. Newman Laboratory at Cornell has extensive infrastructure for research and development in RF superconductivity as well as for production, preparation, and testing of superconducting cavities. These facilities have been used to build the prototype SRF cavities for CEBAF and TESLA, as well as all the cavities that power the present storage ring at Wilson Laboratory (CESR). Cavity production facilities include a 100 ton press for deep drawing niobium caviyty cells, digital control milling machines for precise die machining, an electron beam welder large enough for TESLA scale cavities, and a large UHV furnace to purify cavity half cells at 1300 C. Cleaning facilities include open and closed cavity etching systems that can handle TESLA type cavities, high purity water rinsing systems, and high pressure (100 atmospheres) water rinsing. There is a new 1100 sq ft class 100 clean room for cavity assembly and a smaller class 100 area for preparing smaller test cavities. There are several portable clean room set ups for critical assembly. Test setups include three radiation shielded pits, two of which can accomodate 1300 MHz cavities. We have several cryostats, and cryostat inserts to test cavities from 200 MHz to 3000 MHz, several 200 Watt cw power sources and a 1.5 MW pulsed klystron for high pulsed power processing. High power testing capabilities exist for windows at 500 MHz and HOM loads at 2450 MHz. Research facilities include a rapid thermometry system for studying single cell 1500 MHz cavities, field emission apparatus, and a dedicated scanning electron microscope with energy dispersive analysis for element identification installed in a class 1000 clean room.

FY2003 Project Activities and Deliverables

(assuming the support requested in our regular five-year NSF proposal 0202078)

1. Studies of field emission and dc, rf breakdown in Nb and Cu cathodes

   In order to have a timely impact on structure preparation and gradient realization, this work will be carried out in the first two years. Possible collaborators will be SLAC and ASC. SLAC will provide copper samples prepared by the same techniques as copper NLC rf structures. ASC will assist with microscopic surface analysis such as field emission scanning Auger and secondary-ion mass spectroscopy. ASC work will be paid for through funds requested for outside contracts.

   The first year's deliverables will be progress reports and papers to conferences and journals.

2. Studies of the sources of high field Q-slope and quench field in Nb cavities

   This work will span the entire three year proposal period. As gradients in superconducting cavities continue to rise toward the theoretical upper limit of 50 MV/m, we expect new loss mechanisms to arise that will need investigation.

   The first year's deliverables will be progress reports and papers to conferences and journals.

3. Studies of pulsed operation of Nb cavities at high gradients

   This work will not start until the second year.

4. Advances in high-gradient Nb cavity fabrication

   Electropolishing

   Preliminary work, such as half cell electropolishing, half cell puriifcation, and clean electron beam welding, will start in the first year.

   The first year's deliverables will be single cell Nb cavities with electropolished surfaces and test results published.

   Cavity Spinning

   This work will not start until the second year.

5. Studies of methods to improve Q and the consequences for linear collider operations (implications for pulse length, bunch charge, etc. re-optimization).

   Preliminary work on TESLA parameter exploration and magnetic shielding calculations can already continue in year one, with the help of undergraduate students as independent study course-projects.

   The first year's deliverables will be TESLA parameter lists with high Q.

6. TESLA SRF cavity shape studies to improve efficiency

   Using powerful field calculation codes we have already developed a candidate shape that can lower peak surface magnetic fields by 10%. In the first year, we aim to fabricate single cell cavities.

   The first year's deliverable will be a single cell cavity with new shape.

7. Development of US vendors for TESLA 9-cell cavities

   During the first year, we will develop contacts with industrial firms. Possible candidate firms are Advanced Energy Systems (AES) and Advanced Design Consulting (ADC), General Dynamics (GD) and Babcock and Wilcox (B&W). These firms have been involved in Nb cavity fabrication for projects such as CEBAF and APT.

FY2004 Project Activities and Deliverables

(assuming the support requested in our regular five-year NSF proposal 0202078)

1. Studies of field emission and dc, rf breakdown in Nb and Cu cathodes

   This work will continue in the second year.

   The second year's deliverables will be progress reports and paper published.
2. Studies of the sources of high field Q-slope and quench field in Nb cavities

   This work will continue in the second year.

   The second year's deliverables will be progress reports and papers.
3. Studies of pulsed operation of Nb cavities at high gradients

   This activity will start in year 2, when our klystron will be operating through collaboration with Fermilab.

   The second year's deliverables will be test results on pulsed operation.
4. Advances in high-gradient Nb cavity fabrication

   Electropolishing

   In the second year, we aim to fabricate and test single cell cavities.

   The second year's deliverables will be single cell NB cavities with electropolished surfaces and test results.

   Cavity Spinning

   Contacts with potential US vendors will be established in this year to spin single cell cavities.
5. Studies of methods to improve Q and the consequences for linear collider operations (implications for pulse length, bunch charge, etc. re-optimzation).

   In the second year, the test dewar will be shielded and single cell cavity tests started.

   The second year's deliverables will be test results on single cell cavities with high Q to be published.
6. TESLA SRF cavity design studies to improve efficiency

   In the second year, we aim to test the single cell cavities fabricated in the first year.

   The second year's deliverables will be test results on single cell cavities with improved shape.
7. Development of US vendors for TESLA 9-cell cavities

   During the second year, we will continue to develop contacts with industrial firms.

FY2005 Project Activities and Deliverables

(assuming the support requested in our regular five-year NSF proposal 0202078)

1. Studies of field emission and dc, rf breakdown in Nb and Cu cathodes

   This work will be completed in the second year.
2. Studies of the sources of high field Q-slope and quench field in Nb cavities

   This work will continue in the third year.

   The third year's deliverables will be progress reports and papers.
3. Studies of pulsed operation of Nb cavities at high gradients

   This work will continue in the third year.

   The third year's deliverables will be progress reports and papers.

4. Advances in high-gradient Nb cavity fabrication

   Electropolishing

   In the third year, we aim to fabricate and test 9-cell TESLA style cavities.

   The third year's deliverables will be 9-cell cavities with electropolished surfaces.

   Cavity Spinning

   After establishing appropriate industrial contacts in the US, spinning contracts for multicell cavities will be awarded in the third year. If cavity tests are successful, we propose to continue the work by asking the firm to spin a 9-cell cavity.

   The third year's deliverables will be contracts with a US firm to fabricate cavities by spinning.

5. Studies of methods to improve Q and the consequences for linear collider operations (implications for pulse length, bunch charge, etc. re-optimzation).

   In the third year, we aim to extend the Q benefits to multicell structures.

   The third year's deliverables will be progress reports and papers.

6. TESLA SRF cavity design studies to improve efficiency

   If the results of the tests in year 2 are successful, we will fabricate and test multicell cavities in the third year.

   The third year's deliverables will be multicell cavities with improved shape and test results.

7. Development of US vendors for TESLA 9-cell cavities

   After developing contacts with industrial firms in the first two years, we aim to select one firm and work together with the firm to teach them how to fabricate multicell cavities. By year three, we anticipate that the US and world funding situation for the next linear collier will be sufficiently bright to attract real interest from these firms.

   The third year's deliverables will be contracts with vendors.

Budget justification and three-year budget, in then-year K$

We ask for the following support levels under UCLC to pay for outside contracts for analysis work to accompany field emission, Q-slope, and other related studies using the sophisticated equipment and facilities described above. We do not possess these instruments at LEPP. In later years, UCLC funds will also be used to pay US companies to learn how to fabricate niobium cavities.

Outside analysis work includes sample studies using the following surface analytic instruments:
SAM: Scanning Auger Microscope
FESAM: Field Emission Scanning Auger Microscope
SIMS: Secondary Ion Mass Spectrometry
XPS: X-ray Photo Electron Spectroscopy.

Year 1: Surface analysis: $30 K
Year 2: Surface analysis: $30 K
Year 3: Surface analysis: $30 K.

Spinning outfits: for niobium cavities. These funds are for US firms to learn niobium cavity fabrication technology.

Year 2: Outside firm to spin single cell cavities: $35 K
Year 3: Outside firm to spin multicell cavities: $60 K

Institution: Cornell University

Item	FY2003	FY2004	FY2005	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	0	0	0
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	0	0	0	0
Equipment	0	0	0	0
Travel	0	0	0	0
Materials and Supplies	0	0	0	0
Other direct costs: Surface Analysis Contracts	30	30	30	90
Other direct costs: Spinning Contracts	0	35	60	95
Total direct costs	30	65	90	185
Indirect costs	0	0	0	0
Total direct and indirect costs	30	65	90	185

References

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