LEPP Accelerator Proposal to UCLC

LEPP Accelerator Group

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1 Superconducting radiofrequency systems

1.1 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. 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 ≈ 100 atmospheres) and dust-free surface preparation produce low field emission cavities with dark currents 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 LNS 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 LNS have shown that voltage breakdown in niobium cavities bears strong commonalties with DC voltage breakdown on room temperature 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]. 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 multi- TeV linear colliders where gradients above 100 MV/m are desired.

1.2 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 Q0 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 140C 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.

1.3 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 LNS 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 pules, 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].

1.4 Advances in high-gradient Nb cavity fabrication

Since electropolishing proves to be a superior surface preparation technique over chemical etching [7], we aim to install an electropolishing capability at LNS. 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 LNS has its own beam welder we have more flexibility to develop such a procedure.

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 methods 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.

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

At 2 K, the Q_0 value of 1300 MHz TESLA cavities is still within the temperature dependent BCS regime. Therefore 140C bake out increases Q0 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 Q0 by a factor of 10.

We plan to aim for this high Q0 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 Q0 for a pulsed superconducting linac. We will explore parameters that increase luminosity with a higher duty factor.

1.6 Studies of the application of Nb3Sn and MgB2 for superconducting rf cavities

Niobium has an rf critical field that limits the maximum accelerating gradient to 50 MV/m. Theoretically the rf critical field scales roughly linearly with the critical temperature. Nb3Sn has a theoretical field of 80 MV/m, whereas MgB2 may have a critical field over 150 MV/m. With our high power capability at 1300 MHz we are in a strong position to evaluate the rf critical field of these promising materials [10]. We have used this facility to verify agreement with theory for the rf critical field of lead and niobium.

Materials preparation will be carried out in collaboration with other labs. We aim to explore solid-state reaction, laser ablation and other fabrication techniques to explore the potential capabilities of both materials.

1.7 TESLA SRF cavity design studies to improve efficiency

With more efficient cavity designs, the ratio of accelerating field to peak field may be improved. 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.

1.8 Investigations of the use of 9-cell TESLA HOM coupler power signals to obtain beam position information

In warm rf structures developed for linear colliders, the power coupled out of the structure in the mode damping slots provides quite accurate information on the transverse position of the beam, which is a major asset in the beam-based alignment of the structures. Such information has not been available for the cold rf structures. However, recent work at the TTF has opened up the possibility of using the power extracted from the HOM couplers at the ends of the 9-cell cavities to provide beam position information. We would work to explore further this possibility, and attempt to develop this into a tool which could be used in the beam-based alignment of the cold rf structures.

1.9 Studies of TESLA cavity tuner design

In the baseline design, the TESLA cavity tuner motors must operate at liquid He temperature. This is a potential reliability issue. We would investigate the feasibility of tuner designs in which the motors are at room temperature.

1.10 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.

2 Linear Collider Damping Rings

2.1 Experiments at CESR-c to address issues in linear collider damping rings.

2.1.1 Experimental measurements of wiggler-related dynamic aperture limitations in CESR-c

Two classes of circular accelerators will generate their synchrotron radiation damping almost entirely in wiggler magnets: damping rings for linear colliders and some low-energy e+e factories1. Wigglers are unlike typical (dipole, quadrupole, etc.) accelerator magnets in that they have longitudinal magnetic fields which are comparable to their transverse fields. Also, the design orbit through a wiggler oscillates about its axis, so in general the design orbit has an angle and a displacement relative to the wiggler axis. The combination of the longitudinal field and the angle through the wiggler produces an effective field error, as does the combination of the field roll-off near the wiggler edge and the displacement from the wiggler axis. The effective field nonlinearity is quite strong and can influence the dynamic aperture. We intend to develop and test a design algorithm for wigglers and lattices which is capable of preserving the dynamic aperture in wiggler-dominated machines, and test this algorithm in CESR-c. This test will compare the expected performance of the CESR-c wigglers with actual measurements with beam. We will apply the same techniques to the various linear collider damping ring designs to demonstrate that they have adequate dynamic aperture (or optimize those designs until they have adequate dynamic aperture).

2.1.2 Experimental measurements of equilibrium beam emittances in a low-emittance configuration for CESR-c, to investigate the effects of intrabeam scattering

At the high particle densities of the linear collider damping rings, intrabeam scattering (IBS) will cause an increase of the emittance of the beams, which must not be too severe lest it degrade the collider luminosity. Several theoretical models [14],[15],[16] have been used to calculate IBS emittance growth rates. Calculations based on these models agree well with each other, but disagree with experiments done at the Accelerator Test Facility damping ring at KEK in which the emittance growth may have been higher than calculated by a factor of 1.5 to 2. We plan to use CESR-c, operated in a low-emittance mode, to make measurements of the IBS emittance growth rate to evaluate the accuracy of the theoretical models.

2.1.3 Experiments to investigate space charge effects in a low-emittance configuration for CESR-c

The space-charge tune shift in nearly every existing electron and positron storage ring is negligible, due to the near-cancellation of electric and magnetic space-charge forces at large γ. This is not the case for the damping rings for future linear colliders, in which the large density of particles creates a significant space charge tune shift. The tune shift is not the same for all particles in a Gaussian beam, and the area of the tune plane covered by the tune footprint of the beam is significant. If this tune footprint overlaps strong resonance lines, particles may be lost, or the emittance may grow. We want to determine if it is possible to operate a storage ring with the large space charge tune shift of the linear collider damping rings without excessive losses or emittance growth. To do this, we will operate CESR-c in a low emittance mode and scan the tune plane while monitoring beam lifetime, radiation, and beam size. These observations will be compared to particle-tracking simulations including space charge.

2.1.4 Investigations of collective effects (e.g., electron-cloud, fast-ion instabilities) in CESR-c

Several beam stability issues are of general concern for high energy physics and synchrotron radiation storage rings, and of particular importance for the damping rings of future linear colliders. Each of these will be investigated by machine studies in CESR-c:

- The instability threshold for the electron-cloud effect in a low emittance, wiggler dominated ring.
- The instability threshold for the fast-ion instability in a low-emittance ring.
- Impedance-driven instabilities at the short bunch lengths of the linear collider damping rings.
- Software feedback loops for the long-term control of emittance coupling and vertical dispersion.

High-quality beam diagnostics are required for the measurement of small beam sizes and short bunch lengths. We plan to improve the following existing CESR diagnostic systems:

- High-resolution beam size diagnostics (interferometric technique).
- Streak camera bunch length and shape monitoring.

We will also investigate strategies for electron emission suppression (e.g., by the use of coatings such as TiN).

2.2 Computational beam dynamics for damping rings

2.2.1 Particle tracking studies to determine the dynamic aperture in wiggler-dominated damping rings.

An object-oriented accelerator particle-tracking library, BMAD [18] is being used to simulate the effect of the CESR-c wigglers on single-particle beam dynamics. These simulations include second-order tracking routines through all CESR-c magnetic elements, including sextupoles and the measured nonlinearities in the arc quadrupoles. The wiggler field is modeled by integration through the 3-D field solution provided by a finite element magnetic modeling program, MERMAID [19]. We plan to extend this simulation program to the linear collider damping ring designs to determine the effect of the wiggler nonlinearities on the dynamic aperture in the presence of other nonlinearities and errors in the damping ring magnets. The simulation code will be benchmarked against observations of the CESR-c dynamic aperture after the damping wigglers have been installed.

2.2.2 Particle tracking studies of intrabeam scattering and space charge effects in damping rings.

We will support our experimental studies of intrabeam scattering (Section 2.1.2) and space charge tune shift (Section 2.1.3) in e+/e machines with particle tracking simulations. The goal of the IBS simulations is to benchmark the existing codes against observations in CESR-c. The space charge simulation studies will be done with BMAD, including a space charge element.

2.3 Review of TESLA damping ring design concepts and optics, and investigation of fast kicker options for the TESLA damping rings.

The large number of bunches (2820) and the relatively large inter-bunch spacing (337 ns) in the TESLA project gives a bunch train which is more than 200 km long. A damping ring of this size would be very costly, and so the bunch train is damped in a compressed form, with a bunch spacing of 20 ns, leading to a damping ring with a circumference of 17 km. This ring is still quite large, and, apart from the cost issue, has some technical disadvantages (such as large space charge effects) related to it large size. We would investigate other technical solutions (such as vertically stacked rings) for the damping rings, and compare the advantages and disadvantages relative to the baseline design. Many of the constraints on the ring design are determined by fast kicker technology. The rise and fall time of the TESLA damping ring injection and extraction kickers determine the circumference of the ring. There is considerable leverage in developing faster kickers, as this translates directly into a smaller circumference ring. The baseline system for 500 GeV (cm) parameters have a 20 ns specification for the kicker pulse width; this becomes about 12 ns for the 800 GeV (cm) parameters. Designs and prototype results exist [27] for conventional kickers with full widths of 7 ns, and design have been developed for more novel ultrafast schemes [28] using electron beams. We would explore these and other possibilities for fast kicker schemes, with specific application to linear collider damping rings, particularly TESLA.

2.4 Investigate superferric option for NLC and/or TESLA damping ring wigglers

The baseline design of wigglers for NLC and TESLA is based on permanent magnet technology. Superconducting wigglers were also considered in both cases but not chosen. At LEPP, we have experience both with permanent magnet systems, and, in connection with CESR-c, have developed expertise in the design and fabrication of superferric wigglers. We would re-examine the possibility of superferric wigglers for the linear collider damping rings. We would re-evaluate the technical and cost advantages and disadvantages of each technology choice.

3 Simulations

3.1 Simulations of beam halo from damping ring to IP

Understanding and control of beam halo is a crucial issue for linear colliders. The extent of the beam halo impacts the design of the collimation systems and muon spoilers, which in turn determine background conditions at the detector. Studies of the performance of collimation systems typically assume a certain level of beam halo. An effort will be made to simulate the sources of beam halo (e.g, due to scattering processes in the damping rings, dark current in the linac cavities, etc.) and track these particles from their source to the collimation systems, where they are removed from the beam. Comparisons will be made to the assumed halo used for the design of the baseline collimation systems for NLC and TESLA, and to the SLC beam halo experience.

3.2 Simulations of spin transport: source to damping rings, damping rings to IP.

Longitudinal polarization of the electron beam at the IP is a requirement for all linear colliders. The polarization is produced at the electron source and must be preserved through the damping and acceleration processes. To verify that the polarization can be preserved, spin transport simulations will be performed, tracking the spin of test electrons from the source to the IP. Potential sources of depolarization will be identified.

3.3 Simulations of main beam transport, source to DR, and DR to IP

One of the most important features of a linear collider is the need for the preservation of a very small vertical emittance during beam transport from the damping ring to the IP. The best estimate of whether this is possible or not comes from integrated simulations of beam transport from the damping ring to the IP. Elaborate simulation programs have been developed at SLAC, DESY and CERN for the linear collider projects, in which errors can be incorporated, and realistic tuning algorithms can be developed, based on the expected performance of diagnostic systems. The errors are both static and dynamic, and include initial alignment errors, instrumentation resolution, ground motion and mechanical noise. Dynamic stabilization schemes and linac-based and IP feedback can be incorporated.

These simulation efforts require considerable effort and care to include in a realistic way all the physics potentially responsible for emittance growth in the linacs and beam delivery systems. The worldwide effort in this area could benefit from additional manpower working in collaboration with the existing investigators to refine the simulation tools, develop improved tuning algorithms, and explore the tolerance of the baseline emittance preservation schemes to diagnostic faults. We would provide that additional manpower, as well as a fresh perspective on this important problem. We would also explore the utility of simulations of beam transport from the source to the damping ring. In addition, we would attempt to couple this main beam transport simulation work to the beam halo simulations mentioned above.

4 Global Accelerator Network

A strategy, the Global Accelerator Network [26], has been proposed to engage the largest possible intellectual resources in the design, construction and operation of the next large accelerator project. Because of its necessary size, complexity and cost, it must be international from the beginning. Through this concept, current accelerator laboratories could contribute major subsystems to the project and then commission, operate and maintain them from their home laboratory. To understand the benefits of this strategy, it is essential to begin with limited scale operation of existing accelerator facilities as soon as possible. We are collaborating with scientists at Fermilab to operate the A0 photoinjector system at Fermilab from Cornell and with scientists at DESY in Hamburg, Germany to carry out accelerator physics experiments with the TESLA Test Facility at DESY. The letters of invitation for these two collaborations are included in appendices A1 and A2. The level of effort to carry out these initial experiments would be a postdoctoral fellow and a graduate assistant under the supervision of one of our accelerator physics faculty members. The needed hardware would be two work stations and software that is compatible with the existing control systems at the two laboratories.

5 Polarized positron source R and D

A source of polarized positrons is extremely valuable for a variety of high-energy physics measurements at a future linear collider. Polarized positrons can be produced from a beam of circularly polarized high-energy photons striking a thin target [23],[24]. The circularly polarized photons are produced by a high-energy electron beam in a helical undulator. We intend to extend the present body of work on this concept to a full design study for a practical linear collider polarized positron source, including production and transport and an engineering model of a short undulator section.

6 Instrumentation development

Because of the extensive need for beam-based alignment in all types of linear colliders, beam diagnostic devices are key elements of the machine. At the same time, the very small beam emittance and the very high resolution requirements make the devices themselves extremely challenging.

The required beam instrumentation needed for a linear collider includes high resolution beam position monitors, beam size (emittance) monitors, luminosity monitors, and bunch length monitors. In addition, the beam polarization will need to be measured, at least in the main linac. All these devices will need to operate with unprecedented resolution and long-term stability.

There are a number of devices which are in the development stage. These include rf BPM's for the X-band main linac quadrupoles, laser wire beam size monitors, beam size monitors based on interferometry, and bunch length monitors based on rf deflection. We could help contribute to the further development of these devices by addressing some of the open issues, in collaboration with the existing efforts in these areas, either through calculations or by building prototype devices and/or associated electronics.

A number of new ideas are being considered for beam diagnostic techniques. These include the use of optical transition radiation and optical diffraction radiation to measure the beam size; synchrotron radiation from gradient undulators as a single-pass beam size monitor; electro-optic devices to measure beam wakes; and using spectral information from beam pickups to obtain bunch length information. We would like to investigate the feasibility of these schemes and develop prototypes which could be tested using beam from the CESR linac or synchrotron.

Finally, there are a number of diagnostic devices which address specific issues, but for which specific ideas have not yet been formulated. There is a need for beam size monitors capable of single-turn vertical size measurements in the damping rings; devices to measure the beam polarization in the damping ring and the linac; an ultra high resolution beam size monitor the beam at the IP; beam halo measurement devices; and instruments to measure the electron cloud density in the positron damping rings. We would work to develop ideas to solve these problems, evaluate the feasibility of these ideas, and build and test prototype devices where appropriate.

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