The Conversion and Operation of the Cornell Electron Storage Ring as an International Linear Collider Damping Ring Test Accelerator

In 2008 the Cornell Electron Storage Ring (CESR) will end nearly three decades of providing electron-positron collisions for the CLEO experiment. At that time it will be possible to reconfigure CESR as a damping ring test accelerator, CesrTA, for the International Linear Collider (ILC) project. As the world's only operating wiggler-dominated storage ring, CESR offers a unique opportunity with which to investigate beam physics and instrumentation critical to the design and operation of the ILC damping rings that are perhaps the most challenging accelerator system in the ILC. The CESR-c damping wigglers are the technology choice for the ILC baseline design [1]. CesrTA will operate with horizontal emittances in the nanometer range and a vertical emittance and bunch spacing approaching those specified for the ILC damping rings. A core component of the CesrTA research program will be to study the electron cloud effect (ECE) in the damping wigglers as well as in other machine components, and techniques to suppress it – a critical ILC design issue. An instrumented vacuum section with wiggler, bend, quadrupole and drift regions will be used for these studies. The measurements from these studies will be used to test the simulations of ECE. The changes required to make CESR available as a test accelerator are modest so that research results will be available in time for use by the ILC program.

Ultra low vertical emittance operation will be achieved using the sophisticated tools developed by the CESR operations group to correct orbit, focusing, coupling, and dispersion errors from beam based measurements. Improved algorithms based on these techniques will be developed as part of this project, as will new instrumentation designed to measure the very small vertical beam size. Needed improvements in magnet alignment will be accomplished using survey techniques developed by our British collaborators. ECE suppression techniques in the wigglers, crucial for finalizing the ILC design will be investigated. The CESR injector can deliver electron as well as positron beams so that effects peculiar to electrons as well as positrons, e.g., the fast ion instability, will be studied to distinguish species dependent effects.

We have actively supported the ILC Reference Design Report of 2007 and this proposal is focused heavily on supporting the ILC Engineering Design Report of 2010.

The broader impacts of this work are significant. The use of real time measurements for the optimization of beam performance via interactive algorithms has applications in several other areas of research of high complexity. The fast x-ray profile monitors being developed here and the other instrumentation developed for CesrTA will be very useful for synchrotron radiation research and other accelerator applications. Ultra low emittance continuous tuning to be developed will be essential for new synchrotron sources as will mitigation of ECE for electron beams, a now established effect. Of primary importance for the broader impact of this work is the hands-on training of accelerator and x-ray beam line scientists that serve around the world as principals and staff of laboratories for nuclear and particle physics and x-ray science.

Faculty, staff and students participate in a broad gauged program of outreach and education involving graduate and undergraduate students and the general public with special emphasis on K-12. The laboratory’s intellectual and physical resources are used to promote the adventure of science directly to young people as well as to provide workshops and direct support for teachers of science in their own classrooms and in group settings on campus. In addition, we have been collaborating with underrepresented populations in both urban settings of New York City and rural areas here on the edge of Appalachia. Creation of materials for the classroom is also an important part of our work in helping teachers in New York State deal with changing science curricula.

PROJECT DESCRIPTION

The Conversion and Operation of the Cornell Electron Storage Ring as an International Linear Collider Damping Ring Test Accelerator

1. Introduction

In early 2008 the Cornell Electron Storage Ring (CESR) will conclude nearly three decades of providing electron-positron collisions for the CLEO experiment. At that time it will be possible to reconfigure CESR as a damping ring test accelerator, CesrTA, for the International Linear Collider (ILC) project [2]. With its twelve damping wigglers, CesrTA will offer horizontal emittances in the nanometer range and vertical emittances in the several picometer range approaching ILC damping ring emittances. An important feature of the CesrTA concept is the ability to operate with positrons or electrons. Positron operation will allow detailed testing of electron cloud issues critical for the operation of the ILC positron damping rings. Electron operation will allow us to explore the impact of the fast ion instability and to follow up on potential electron cloud effects for electrons that have appeared in early studies with CESR and at KEK [3]. By alternating operation between electron and positron beams, we will be able to carefully characterize and distinguish various species dependent and independent effects, in particular the electron cloud effect, in a single ring. Other key features of the CesrTA plan include operation with wigglers that meet or exceed all ILC damping ring requirements, the ability to operate from 1.5 to 5.5 GeV beam energies, a test bed for developing low emittance tuning algorithms and instrumentation, and the availability of a large insertion region for testing damping ring hardware. The evolutionary approach to developing low emittance tuning algorithms along with the development of state of the art survey techniques to correct the positions of the storage ring magnetic elements and the fast x-ray imaging techniques required for measuring these very small vertical beams sizes are essential to the success of the project.

2. Schedule and Budget

This project is designed to match the schedule for the ILC Engineering Design Report (EDR). The budget for FY 08 is for capital equipment only. It is assumed that the budget for operating the storage ring during this period will come from the current Cooperative Agreement (NSF PHY-0202078). This CesrTA proposal will support a proportionate fraction of the operating cost of the storage ring beginning October 1, 2008.

3. Damping Ring Physics and Technical Issues

A number of critical R&D items have been identified by the ILC Damping Rings Group as important research priorities for the next few years. Among the highest priorities on the list are the demonstration of machine correction and tuning techniques to achieve the specified ultra low emittance performance, characterizing the electron cloud build-up in the machine and validating methods to suppress it, and characterizing the fast ion instability and developing methods to suppress it. By converting CESR to the CesrTA configuration, we expect to provide important data on each of these issues in time for the ILC EDR. In particular, CesrTA offers a unique opportunity for studying emittance dilution due to electron cloud effects (ECE) and fast ion instability (FII) at emittances characteristic of the ILC damping rings. In addition, damping ring hardware and instrumentation can be developed and tested with beam in the CesrTA prior to the start of ILC construction.

3.1 Electron Cloud Effects

Clouds of low energy (few eV) electrons are generated in the environment of a circulating charged particle beam primarily by photo-emission from the walls due to synchrotron radiation. In an electron storage ring, the low energy electrons are driven away from the beam while in a positron ring, the electrons are drawn into the path of the beam. The resulting electron cloud can introduce nonlinear focusing and amplitude dependent tuneshifts that contribute to emittance blowup. The electron cloud can also couple transverse motion from one bunch to the next along a train leading to a dipole instability. Passage of the beam through the electron cloud focuses the positron beam and defocuses the electron beam and the electron cloud lifetimes are such that the cloud density typically increases with the passage of the train with a bunch-dependent tune shift appearing as its signature. Emittance dilution begins well before the appearance of the instability [3].

Electron cloud phenomena severely constrain the parameters of the damping ring, including the ring circumference, beam current, bunch spacing, bunch length, vacuum chamber aperture, and ring energy. The maximum beam current in the ring (and therefore the minimum circumference) is limited by the build-up of the electron cloud. Evolution of the cloud and cloud-induced instabilities leading to emittance dilution depend on the bunch spacing. Simulations indicate that the electron cloud effects are more severe as the bunch length increases, whereas, single bunch collective effects tend to be less severe with longer bunches. Sensitivity to the destabilizing effects of the electron cloud scales inversely with ring energy. The growth of the electron cloud depends on the aperture of the vacuum chamber [4]. Multipacting is enhanced by a smaller cross section vacuum chamber. The density of the cloud depends on the chamber geometry and surface chemistry (secondary emission coefficient), local magnetic fields, the characteristics of the positron and electron beams, and generally increase with beam density [5]. Thus, the understanding of the electron cloud effect is essential for choosing the right combination of parameters.

To limit electron cloud effects, the addition of an antechamber on the vacuum chamber limits the number of primary photo-electrons that can reach the surfaces in the vicinity of the beam. Grooves or fins that are machined into the chamber can also interfere with the trajectories of secondary electrons that can lead to multipacting, and coatings like TiN can significantly reduce the number of secondary electrons. It is anticipated that methods to control electron cloud growth in the bend, quadrupole and wiggler vacuum chambers will all be necessary to achieve the operating specifications for the damping rings. We plan to test the effectiveness of grooved chambers and surface coatings to suppress the secondary emission yield, along with clearing electrodes that sweep the electrons from the vacuum chamber [6].

There have been measurements of the accumulation of an electron cloud, and the impact of the cloud on the circulating beam in many storage rings [4], but there have been no measurements in a wiggler dominated machine with the high beam current and ultra low emittance characteristic of the ILC positron damping ring. There are currently twelve superconducting high field wigglers in CESR with parameters very similar to those specified for the ILC damping ring. The CESR lattice can be reconfigured for ultra low emittance operation approaching that of the ILC damping ring. In CesrTA we will measure the characteristics of the electron cloud in a damping wiggler vacuum chamber along with the buildup in a bending magnet, quadrupole magnet, and straight vacuum chambers. We will instrument the vacuum chambers in these magnets to measure the dependence of the cloud density, growth rate, and decay time on beam current and bunch configuration and spacing, beam emittance and energy. We will determine thresholds for head tail (emittance blowup) and coupled bunch instabilities as well as emittance dilution below these instability thresholds. The experimental measurements will be accompanied by numerical simulations so that the modeling codes can be benchmarked in a wiggler dominated machine operating in the ILC ultra low emittance regime.

Understanding electron cloud physics in the regime relevant to the ILC positron damping ring is critical if we are to have confidence that the ring design will deliver the requisite low emittance bunches at the lowest possible cost. This project offers the opportunity to measure the properties of the electron cloud in that regime.

3.2 Fast Ion Instability

An electron beam is subject to the effect of the fast ion instability (FII). Ions are created by interaction of the beam with the residual gas molecules. The ions may dilute the emittance of the electron bunch in an electron beam by a mechanism similar to the effect of the electron cloud on the positron bunch in a positron beam [7]. Similarly, ions may couple bunches within a train. The instability threshold depends on the beam configuration, bunch charge density, and residual gas pressure. The FII can dilute the emittance of the electron beam and ultimately limit the bunch and current density of the electron damping ring if not controlled. We will use the CesrTA to explore the fast ion instability in the emittance, charge density, and beam current regime that is characteristic of the ILC electron damping ring.

Ions will oscillate transversely in the field of the electron beam with a frequency that depends on the mass of the ion species and the charge of the electron bunch. The appearance of that frequency in the spectrum of the stored electron beam is a signature of the beam ion interaction. It is anticipated that the ion density will increase along the length of the train of bunches, and we will measure individual bunch size, frequency, and tune shift to further characterize the effect.

Just as the electron cloud physics impacts the design of the positron ring, ion effects have a significant leverage on the specifications of the electron ring, including ring circumference, train length, bunch charge, vacuum chamber aperture and pumping speed. In order to allow the ions to clear it will be necessary that there are gaps between the trains of bunches. Larger circumference permits longer gaps and implies lower current. The bunch train length and the bunch charge may be limited by ion effects. If the total current is fixed, but the number of bunches is increased, then the length of the train increases and the space available for the ion clearing gap shrinks. Finally, the accumulation of ions depends on the residual gas pressure, thereby determining chamber aperture and vacuum system requirements. It is clear that a cost effective design of the electron ring depends on a thorough understanding of ion effects, and that depends on good measurements in the relevant parameter regime [8].

3.3 Ultra Low Emittance Operation

The baseline design for the ILC damping ring beam calls for an extracted geometric horizontal emittance of about 800 pm and vertical emittance of 2 pm. The horizontal emittance is a property of the lattice and depends on near zero residual dispersion in the damping wigglers. The vertical emittance is due to the transverse coupling in tilted quadrupoles, offset sextupoles, and the vertical dispersion generated by tilted bends or offset quadrupoles. The damping ring design requires that the coupling of horizontal to vertical emittance be less than 0.25%. Accelerator physicists at the ATF at KEK have measured a vertical emittance of 4.5 pm at very low bunch intensity $< 2 \times 10^9$ electrons/bunch, or about 10% of the design intensity. The measured horizontal emittance in the ATF experiment was about 1.1 nm. The corresponding x-y emittance coupling was about 0.3% [9].

The vertical emittance of a damping ring, provided that the vertical dispersion is negligible, scales as $\varepsilon_y \sim C_{xy}\varepsilon_x$, where C_{xy} is the coupling and ε_x the horizontal emittance. Minimizing the vertical emittance depends on a careful survey of the magnetic elements, and on beam based correction of the orbit, the vertical dispersion, and the coupling. To maintain operation at the lowest vertical emittance, it will be necessary to continuously tune the storage ring. For the operation of CESR for high energy physics and as a light source we use beam based measurements and have developed fitting algorithms to correct the machine orbits, and to minimize betatron phase and coupling errors and the residual vertical dispersion. We routinely correct phase errors to less than a degree and coupling errors to a fraction of a percent [10]. In CESR, closed orbits are displaced electrostatically to accommodate counter-rotating bunch trains, and sextupole feed down is an inevitable consequence. We have developed techniques to measure and correct errors in the sextupole distribution to minimize the dependence of optical parameters on particle species. The beam based measurement and correction machinery that is used routinely in CESR today is based on our 25 year experience of operating the storage ring. We will use the same machinery with further refinement to minimize vertical emittance of the beams via continuous tuning of the test accelerator to the needed level.

We will exploit low emittance to enhance our sensitivity for the exploration of electron cloud effects and fast ion instability. Confidence in the design of the damping ring depends critically on an understanding of the sources of emittance coupling and the development of robust beam based alignment algorithms so that it can be systematically minimized. CesrTA offers a unique opportunity to demonstrate this.

3.4 Ultra Low Emittance Diagnostics

In order to achieve ultra low vertical emittance and characterize the beam properties in that regime, it is important to provide suitable machine diagnostics. We plan to continue to develop these techniques so that they are an integral part of CesrTA operation. Particular areas of R&D include development of a fast x-ray beam profile monitor that will be capable of bunch-by-bunch and turn-by-turn transverse beam profile measurements. The high speed detector technology being pursued also offers the potential for longitudinal bunch-slicing in order to provide beam information in three dimensions. This method offers much faster response and similar resolution to laser-wire techniques that are being pursued elsewhere. A second area of development is the methodology for real-time vertical dispersion measurements. The excellent resolution and fast processing time of the new digital BPM system makes it possible to rapidly measure the vertical dispersion to high precision by introducing a continuous small energy oscillation in the beam. Controlling the vertical dispersion in the machine and correcting for slow drifts will be crucial to maintaining the required emittance in the ILC damping ring. We are presently exploring techniques to achieve this goal and intend to apply them to CesrTA operations.

Associated with the development of the above techniques is the development of continuous tuning techniques capable of taking advantage of the transverse emittance and dispersion information. One of the key goals of the CesrTA experimental plan is to develop real-time operations techniques to monitor and maintain the ultra low emittance performance of the damping rings. We intend to devote significant operating periods to the task of learning how to maintain the damping ring parameters reliably.

4. CesrTA Design

4.1 Machine Requirements

In order to obtain the smallest possible beam emittance, the CESR-c wigglers need to be located in regions with zero dispersion. CESR has two 18 m long interaction regions (IR) that meet this criterion. Figure 1 shows the present location of the CESR-c wigglers and the straight sections in the ring that occur in each of L0-L5. L0 is the South IR with the CLEO detector while L3 is the North IR the location of the former CUSB detector. The CesrTA conversion will move six of the twelve wigglers, which are presently located in the arcs of the machine, to the South IR (L0). The wigglers located in the L1 and L5 straights will remain in place and zero dispersion regions will be created in the local optics at those places. The move of the six superconducting wigglers to L0 will use the cryogenics support in that region currently feeding the superconducting IR quadrupole magnets. Two spare wigglers will be used as test vehicles for testing possible solutions for the vacuum chamber design to the limit the buildup of the electron cloud. These modified wigglers will then be substituted for one or more of the wigglers in the South IR. This configuration of the wigglers will leave the North IR (L3) available for insertion devices such as specialized beam instrumentation and potential prototype damping ring hardware testing.

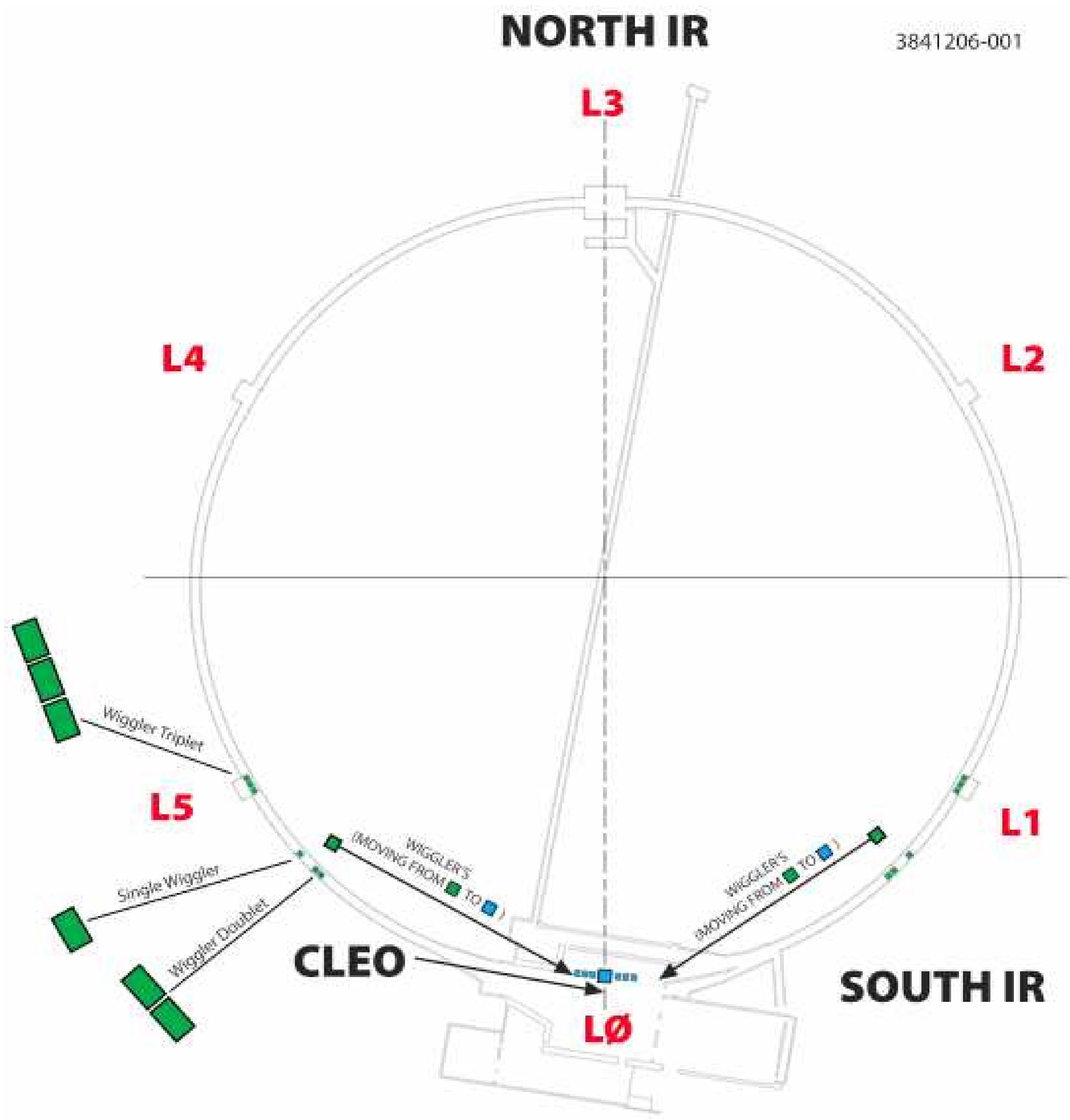

Figure 1. Schematic of the CESR tunnel showing the straight sections located at each of L0-L5 and the present and future locations of the CESR-c superconducting damping wigglers.

4.2 Operating Parameters

We have designed optics for CesrTA using the TAO program and other tools based on the BMAD accelerator simulation library [11]. Figure 2 shows the optics functions for our baseline lattice design.

We have used the flexibility of the individually controlled quadrupoles in CESR to arrive at the key machine parameters that are given in Table 1. The integer horizontal tune in this design has been chosen in order to minimize the emittance. Our goal is a vertical emittance in the 5-10 pm range for use in our beam dynamics studies. Touschek lifetime estimates for the 5 pm case and 2 x 10^{10} particles per bunch (the ILC design specification) yield a value of order 10 minutes when IBS effects are included.

Table 1: CesrTA Parameters.

Parameter	Value*
No. of Wigglers	12
Wiggler Field	2.1 T
Beam Energy	2.0 GeV**
Energy Spread ($\Delta E/E$)	8.6 x 10^{-4}
Vertical Emittance	5 – 10 pm
Horizontal Emittance	2.25 nm
Transverse Damping Time	47 ms
Q_x	14.57
Q_y	9.62
Q_z	0.075
Total RF Voltage	8.5 MV
Bunch Length	9 mm
Momentum Compaction	6.4 x 10^{-3}

* Numbers in the table are zero current values.
** CESR can operate from 1.5 GeV to 5.5 GeV.

The equilibrium horizontal emittance obtained for this configuration is 2.25 nm. It is dominated by intrinsic emittance generated by the wigglers themselves. Emittance generated in the wigglers scales in proportion to the value of the horizontal beta function in the wiggler and inversely with the cube of the wiggler bending radius. Further optimization of the lattice and wiggler fields offers the possibility of further reduction of the horizontal emittance to values below those obtained so far.

The dynamic aperture of this optics has been evaluated for fractional energy offsets of 0.5% and 1% and is shown in Figure 3. The tracking code employs the same wiggler map as is used for CESR-c calculations [12]. Particles are considered lost when their amplitude exceeds the real physical aperture. The projected horizontal emittance of the injected beam is ~ 1000 nm. The beam is assumed to be fully coupled so that the vertical emittance is half the horizontal (~ 500 nm). These calculations indicate an acceptable dynamic aperture.

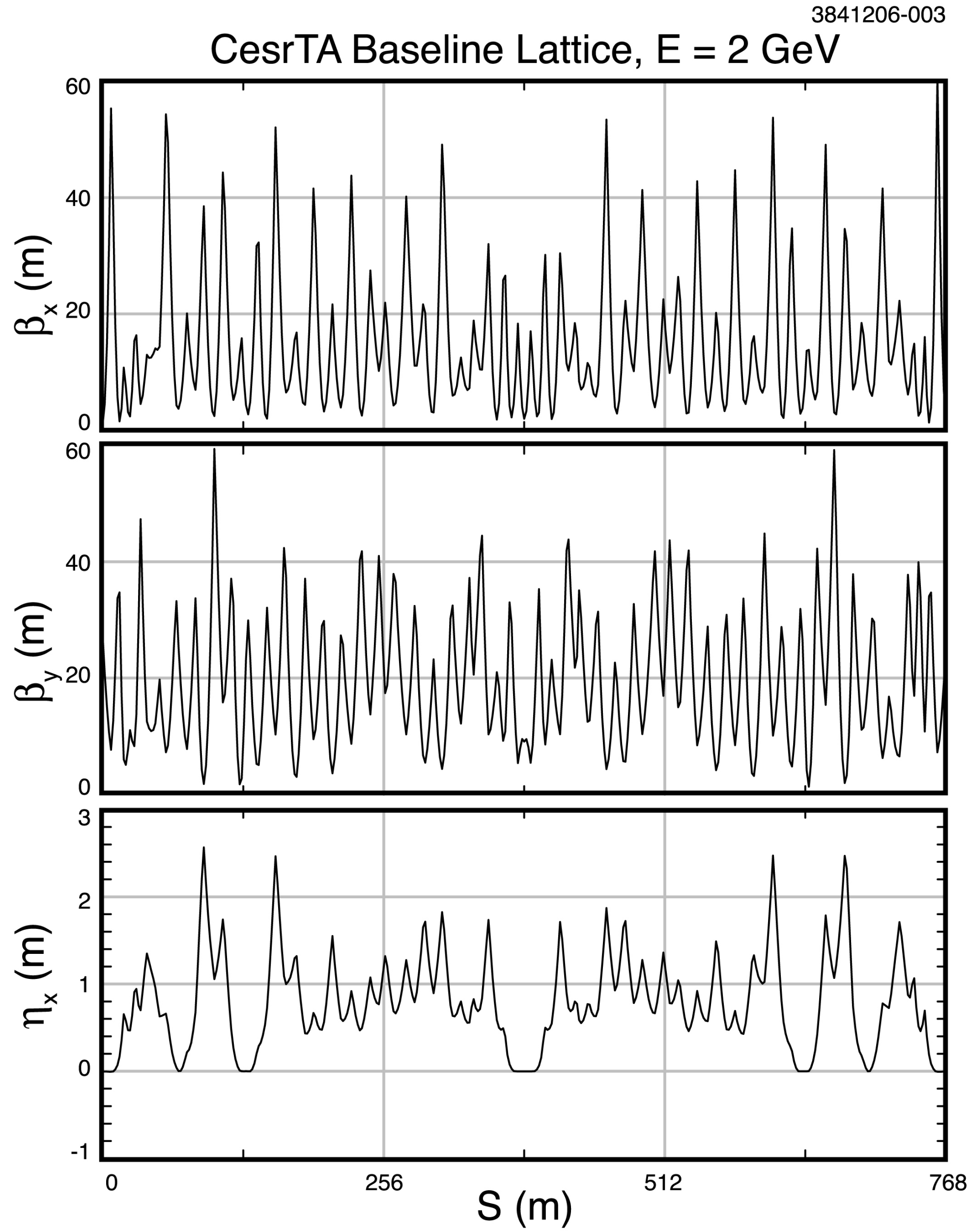

Figure 2. CesrTA Lattice Parameters for 2.0 GeV Operation

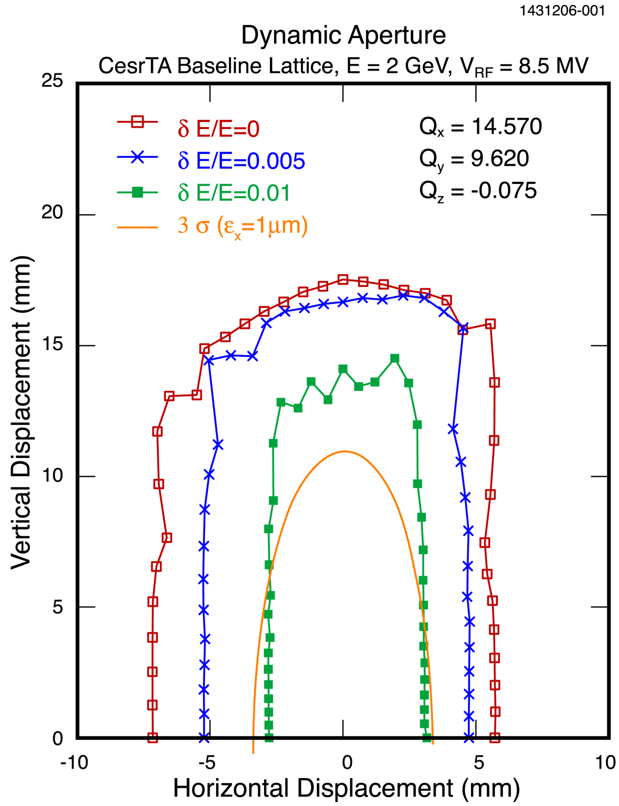

Figure 3. CesrTA dynamic aperture for 0.5% and 1.0% energy offsets for 8.5 MV accelerating RF voltage. The elliptical curve corresponds to 3σ of the rms size of the injected beam.

4.3 Magnet Misalignment Tolerances

Our ability to operate CesrTA in the ultra low emittance mode proposed here is strongly dependent on our ability to correct for magnet misalignments. Magnet misalignments in CESR create vertical dispersion and couple horizontal and vertical emittance. In order to achieve the target vertical emittance, the sensitivity to misalignments has been characterized and algorithms for correcting misalignments have been evaluated. Table 2 shows the nominal alignment resolution that we can achieve with existing survey techniques.

Table 2: Nominal magnet alignment resolution in CESR

Element	Alignment
quad, bend, and wiggler offset	150 μm
sextupole offset	300 μm
quad, bend, wiggler, and sextupole roll	100 μrad

Simulations have been performed incorporating the random misalignment of elements using multiple seeds. These simulations assume that, with sufficient effort, we can achieve alignment accuracies around the ring which are consistent with our alignment resolution. Figure 4 shows that, with alignment errors at the nominal level of our alignment resolution, the resulting uncorrected vertical emittance in CesrTA would be approximately 140 pm. The dominant sensitivity is to vertical offsets of the CESR quadrupoles.

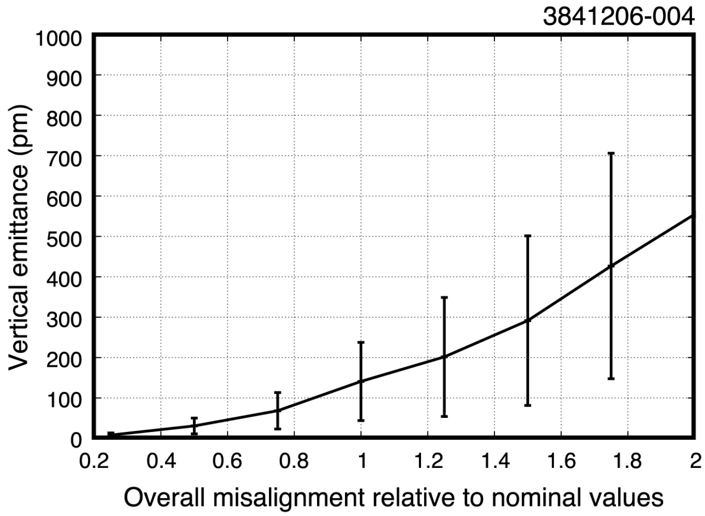

Figure 4. Impact of magnet misalignment normalized to the nominal alignment resolution on uncorrected vertical emittance.

We are pursuing a two-pronged approach to ameliorate the effects of magnet misalignments. The first seeks to improve our alignment capability by employing improved survey techniques along with more precise positioning mechanisms on our magnet stands. If the overall alignment resolution can be improved by a factor of four, using state of the art survey methods developed by our British collaborators from the John Adams Institute [13], then the uncorrected vertical emittance would drop to ~ 8 pm. The second path is to compensate for the effects of residual magnet misalignments using steering magnets and skew quadrupoles to correct the measured orbit distortion and dispersion. This technique has been evaluated using simulations that take BPM resolution into account. When the distributions of magnet misalignments are set to the nominal values, as given in Table 2, we obtain the corrected vertical emittances that are shown in Table 3. The results of our simulations for 200 random seeds are summarized in Fig. 5. These values are consistent with reaching our target values of 5-10 pm for the vertical emittance.

Table 3: Corrected vertical emittances for magnet misalignments at the level of our nominal alignment resolution

Corrction Type	Average Value	95% Limit
Orbit Only	10.2 pm	21.4 pm
Orbit + Dispersion	3.9 pm	8.2 pm

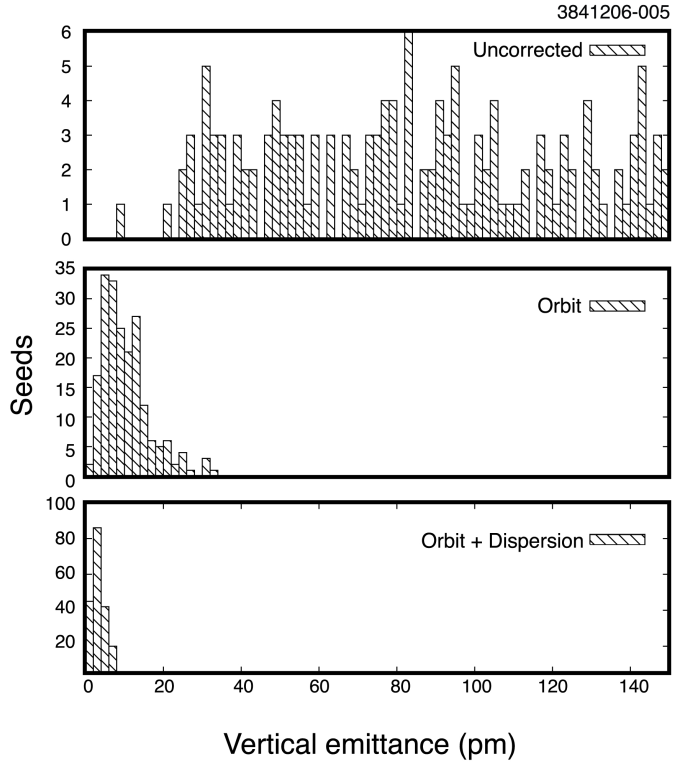

Figure 5. Distribution of vertical emittance for 200 seeds when (top) no correction of orbit or dispersion (middle) orbit but no dispersion correction, and (bottom) orbit and dispersion correction.

4.4 The Effect of Intrabeam Scattering

Intrabeam scattering (IBS) [14] will play a significant role in the emittance that can be attained in CesrTA with a bunch charge corresponding to the ILC bunch charge. For our baseline 2.0 GeV lattice with ε_x = 2.25 nm, a 9 mm bunch length, and assuming that the machine has been corrected to achieve a 5 pm vertical emittance in the zero current limit, we find that the horizontal emittance grows by a factor of ~ 2 as we move from the zero current limit to a bunch with 1 x 10^{10} particles. For an ILC bunch with 2 x 10^{10} particles, the horizontal emittance is 2.7 times larger than the zero current value. In the limit that the vertical emittance is dominated by coupling, these same growth factors will apply. Since the IBS growth rates scale as γ^{-4}, the emittance blowup can be reduced further by lengthening the bunch, or, at the expense of a slightly larger zero current emittance, moving to a higher energy. We have explored a 2.5 GeV lattice with a horizontal emittance that varies from ε_x = 2.85 nm at zero current to ε_x ~ 4.5 nm at 2 x 10^{10} particles per bunch. This flexibility to control the operating conditions in CESR gives us confidence that low emittance operation for the beam dynamics tests can be achieved.

5. Primary CESR Conversion Activities

In order to operate the CESR ring as a test accelerator to study the properties of an ultra low emittance damping ring, several ring modifications are required. The core modifications to CESR are:

- Relocation of the CESR-c damping wigglers to regions with zero dispersion.

- Removal of the CLEO solenoid compensation elements and the final focus quadrupoles in the South IR.
- Installation of local diagnostics for measuring electron cloud densities, particularly in and around the dipole, quadrupole and wiggler magnets.
- Installation of the necessary instrumentation to obtain and measure ultra low emittance beams.
- Improvements to CESR alignment and survey capabilities to provide the precision alignment required for ultra low emittance operation.

5.1 Damping Wiggler Relocation to the L0 Straight

As has already been described, six of the current twelve CESR-c damping wigglers can remain in their present locations in the L1 and L5 straight sections of the CESR ring. The remaining six wigglers must move to a region that can be configured for zero dispersion in order to achieve ultra low emittance operation while still preserving the damping time of the ring. For CesrTA, these wigglers will be moved to the L0 straight, the present location of the CLEO detector and the associated IR focusing and compensation magnetic elements. The CLEO detector will remain in place. The following is a list of changes that will be needed in the L0 region:

- Remove the interaction region focusing and solenoid compensation elements. This includes the superconducting quadrupole focusing packages, the permanent magnet quadrupoles located inside of CLEO, and the superconducting anti-solenoids
- Remove the CLEO beryllium beam pipe and drift chambers
- Install all magnets needed for the CesrTA optics
- Install a vacuum chamber that transits the empty bore of the CLEO detector
- Remove the six wigglers that are presently located to the south of the L1 and L5 straights in CESR and move them along with their power supplies to L0 and provide a suitable support and alignment system
- Adapt the existing cryogenics support for the L0 superconducting magnetic elements to provide cyrogenic support to the six wigglers.
- Upgrade the vacuum chambers through the L0 straight section with diagnostics to monitor for the presence of the electron cloud throughout the region
- Provide a synchrotron radiation beam dump downstream of the wigglers in the direction of the positron beam by upgrading the present fast luminosity monitor window

As part of the vacuum system upgrade L0, we expect to install solenoid coils on all of the straight vacuum chambers that are not inside a magnet. We may carry this out for all the additional straight sections of vacuum chamber in CESR if further tests show this to be needed. We intend to install vacuum chambers in this region to explore various ECE suppression methods including NEG coatings, grooved surfaces, and clearing electrodes. This will make this region a flexible electron cloud laboratory for studying ECE suppression techniques intended for use in the ILC damping rings. This will be carried out by laboratory staff under the supervision of Project Director Mark Palmer with some of the materials being supplied by our collaborators from SLAC and LBNL.

5.2 Modifications to the L3 Straight

There will be minimal modifications to the equipment in the L3 straight section during the first two years of the CesrTA program. Depending on the availability of prototype ILC damping ring components, this region can be adapted for tests in realistic ILC damping ring conditions during the third and fourth years of the program.

This conversion plan will ensure that we start our studies with the fully reconfigured CesrTA optics by early Fall 2008. Because we do not expect that significant numbers of damping ring prototype elements by future collaborators will be ready for testing before the end of 2009 modifications to the L3 straight region will be delayed until there is need for tests.

5.3 Instrumentation

Two key instrumentation upgrades are required as part of the CesrTA conversion. The turn-by-turn beam position monitor (BPM) system currently in use in one sector of the ring must be extended to the full ring. To achieve the needed fast feedback for fast vertical dispersion tuning as early a possible, only the beam detectors at the vertically focusing quadrupoles will be equipped with the new system. The remaining beam detectors at the horizontally focusing quadrupoles outside the fully converted region will continue to use the present relay-based readout system that requires of order thirty seconds to carry out a standard orbit measurement for optics correction. This will provide the needed speed and resolution given the short Touschek lifetimes that will occur as an integral part of ultra low emittance operation. It has been observed at the KEK-ATF that high resolution single-pass beam position measurements offer the best machine correction capability because of lost particles striking the BPM buttons and contaminating the signal if integration over multiple turns is used [15]. Project Director Dr. Mark Palmer will oversee this project.

The second instrumentation upgrade is to provide high resolution beam profile measurements for characterizing the emittance of the beam. For 2 pm vertical emittance and a typical vertical beta functions on the order of 25 m, the typical vertical beam size is approximately 7 μm. Beams this small can be characterized using laser-wire techniques and with synchrotron light beam profile monitors utilizing x-ray wavelengths. This x-ray technique has been used successfully at the KEK-ATF using a relatively slow detector and imaging by means of Fresnel optics [16]. At Cornell, a fast x-ray camera, capable of bunch-by-bunch imaging is presently under development. We propose, with the support of our CHESS colleagues, to complete two camera units and install two x-ray optics lines, employing Fresnel optics, to image the vertical and horizontal beam size for each beam. The initial cameras will be one dimensional measuring only the vertical beam size. The second stage of this project is to develop a two dimensional camera with 256 pixels suitably scaled in size to maximize the vertical resolution. This camera would have sufficient resolution for use in the ILC damping rings. The project will be carried out under the supervision of Prof. Jim Alexander.

The streak camera setup for longitudinal beam measurements [17] located in the L3 region will remain in its present location. Prof. Don Hartill and collaborator Prof. Robert Holtzapple from Alfred University will continue to maintain and use this important diagnostic tool.

5.4 Feedback System

In order to understand the ECE with bunch spacing comparable to the 3.08 ns bunch spacing specified for the ILC damping rings, we will operate CESR with 4 ns bunch spacing. In order to evaluate the damping requirements of the feedback system, a review of observed instabilities in the ring has been conducted. The impedance of the CESR has been studied with measurements and simulations over the course of its operations. A review of these measurements indicates that transverse dipole feedback systems for horizontal and vertical motion with damping rates larger than 40 $m^{-1}s^{-1}ma^{-1}$ will stabilize a beam with 4 ns bunch spacing and required beam current. A system based on an extension of our current system can achieve this requirement. The system will include the capability of damping either electron or positron trains of bunches in both horizontal and the vertical planes. It will employ analog processing of beam position monitors with variable gain low level amplifiers driving the power amplifiers connected to the present CESR feedback kickers. The system is specified to operate with exponential damping for a maximum of 1.5 x 10^{11} particles per bunch with oscillation amplitude < 5 mm. In order to keep the bunch-to-bunch coupling sufficiently low, wider bandwidth power amplifiers may be required. This is currently under study. Dr. Robert Meller will supervise this upgrade.

Longitudinal bunch lengthening of order of 10% for 9 mm bunch lengths in the neighborhood of 2 x 10^{10} per bunch has been observed. Although this is not a large effect, by adjustment of the momentum compaction and the RF accelerating voltage, a constant bunch length can be maintained for typical experiments. The existing longitudinal feedback will be upgraded to suppress any potential longitudinal dipole or quadrupole instabilities.

5.5 RF System

With the present four CESR superconducting radio frequency (SRF) cavities in the ring, the total available RF voltage is approximately 10MV. These cavities will allow us to achieve a bunch length of 9 mm, the current ILC damping ring design bunch length.

5.6 Alignment and Survey Systems

As has already been described, maintenance of the CesrTA magnet alignment at the limit of our present alignment resolution is critical for ultra low emittance operations. In order to insure our ability to maintain such tolerances as well as to develop the actual techniques to be employed for the ILC damping rings, we have entered into collaboration with the Linear Collider Alignment and Survey Group (LiCAS) [13] for this purpose. There are four specific alignment and survey tasks that form the core of this collaboration:

- Extend the capabilities of the LiCAS-II survey system to the curved sections of the ILC, such as the damping rings, and validate the concept in CesrTA. This will extend the fraction of the ILC beamlines with a realistic survey concept to the 95% level.
- Develop fixed installations, such as hydrostatic leveling systems, in regions where the LiCAS-II survey train will be unable to operate. In the case of CesrTA, this will include, but may not be limited to, the injection regions of the machine where the injection transport line into CESR will block the access of the survey train. The train will be moved across to the north region to complete the survey.
- Develop installations capable of continuous monitoring of magnet positions. These installations, applied to critical magnets, will allow evaluation of the position stability through various running conditions and the measurement of the reproducibility of the magnet alignment over many operational cycles.
- Develop a better understanding of the interaction between beam based alignment and the survey process in the various ILC accelerators.

Ultimately, this effort will be important in helping CesrTA attain its target emittances as well as helping to specify the alignment and survey systems required for the ILC damping rings. The focus of the LiCAS collaborators will be to provide the survey unit, install it and develop its operations capabilities. Cornell's contribution to the effort will focus on the areas of fixed infrastructure to support the system, operational support for the alignment and survey work, and survey data analysis. Prof. Tigner and Prof. Hartill will oversee this effort.

In addition to the implementation of the new survey techniques, a general program of refurbishing magnet supports to insure magnet stability and upgrading the alignment mechanisms, particularly for the quadrupole magnet supports, will be undertaken.

5.7 Magnets and Power Supplies

Simulation studies of low emittance tuning indicate that our present complement of corrector magnets should be satisfactory for CesrTA operations. Magnets required for the reconfiguration of the L0 and L3 regions are all available in our present inventory. We will upgrade the alignment mechanism on all of our quadrupole tables by early 2009 to improve the resolution with which we can position these magnets.

We are presently evaluating the impact of power supply stability and corrector zero-crossover issues on ultra low emittance operations. We determine the need for any modifications to the CESR magnet power and control system during 2007. The bulk power supplies for the quadrupoles and correctors will be upgraded to reduce the ripple that has caused tune fluctuations in the past. Prof. Hartill will be responsible for the magnet power supplies.

6. Research and Development Program

6.1 CesrTA Research Program

Our proposed research program will address several key ILC damping rings R&D issues in time for the EDR in 2010. ILC Damping Rings R&D objectives have been evaluated by the S3 task force, appointed by the ILC Global Design Effort (GDE) R&D board, and rated as low, moderate, high, or very high priority [18]. A list of objectives identified as very high or high priority, to which our research program directly contributes, includes:

- Characterization of the electron cloud build-up (including its impact on emittance performance) and methods to suppress it, particularly in the wiggler sections (very high)
- Characterization of the fast ion instability and methods to suppress it (very high)
- Demonstration of the specified damping ring vertical emittance (very high)
- Develop strategies for low emittance tuning (high)
- Specify requirements for survey, alignment and stabilization (high)
- Specify orbit and coupling correction scheme (high)
- Specify vacuum chamber material and geometry (high)
- Develop engineering designs for damping wigglers (high)
- Develop instrumentation for monitoring emittance damping (high)
- Specify overall requirements for instrumentation and diagnostics (high)

The following sections describe how the CesrTA project will contribute to this critical R&D effort required in order to develop a robust design for the ILC Damping Rings.

Prof. Dave Rubin and Dr. Mark Palmer will organize the CesrTA research program and will be assisted in carrying out the measurements by our collaborators from Alfred, ANL, KEK, LBNL, SLAC, John Adams Institute, the Cockroft Institute, and Cornell Faculty and staff.

6.1.1 Electron Cloud Studies

The CesrTA program offers unique opportunities for ECE research in preparation for the ILC EDR. In particular we can:

- Study the growth and suppression of the electron cloud in damping wigglers meeting ILC specifications, and compare the simulations for electron cloud growth with experimental observations.
- Study the impact of the electron cloud on the dynamics of ultra low emittance beams and compare with simulations to predict the performance of the ILC damping rings.

The R&D program for the damping wiggler vacuum chambers will begin with the replacement of the vacuum chambers in two spare CESR-c 8-pole wigglers with instrumented chambers that will be built as part of the collaboration between SLAC, LBNL and Cornell. The two new chambers will have segmented retarding field analyzer (RFA) detectors on their top surfaces and will use their lower surfaces for electron cloud suppression. In one case the suppression method will be a clearing electrode, while in the second case a grooved surface will be employed. These wigglers will be installed at the start of April 2008 with the first dedicated measurement to take place in late spring. After the major ring upgrade in the middle of 2008, the L0 "electron cloud laboratory" will provide a dedicated region with wiggler, bend, quadrupole, and drift regions instrumented with RFAs for studying local electron cloud growth. We will instrument the vacuum chambers in each of these elements to measure electron cloud growth using retarding field analyzers. We, along with our collaborators from ANL, LBNL, LLNL, and SLAC will then carry out detailed comparisons between simulation and experiment to validate our understanding of the electron cloud growth issues during the EDR period. A special focus of the program will be to measure the EC growth in damping wigglers meeting the ILC specifications and evaluate the performance of the proposed suppression techniques (vacuum chambers with grooved surfaces and clearing electrodes). We will work closely with our collaborators at SLAC and LBNL to finalize the necessary technical designs in time for the ILC EDR. In the final years of the program, we and our LBNL colleagues plan to construct an ILC damping wiggler prototype and its associated vacuum chamber. This will be the subject of a separate proposal. The prototypes could then be tested with beam in CesrTA.

In order to understand the impact of the electron cloud on ultra low emittance beams we will study the beam dynamics of a witness bunch trailing a train of positrons that serves as a generator of the electron cloud [19]. By varying the intensity of the leading train, the distance of the witness bunch from the train, the properties of the witness bunch (e.g., its charge and emittance) and the beam energy, we will be able to study, in detail, the impact of the electron cloud on the witness bunch dynamics and measure the emittance-diluting impact of the cloud. We have implemented a range of bunch-by-bunch instrumentation (e.g., tune measurements, beam position and profile monitors) that is presently in use for ECE studies at CESR [20]. We will continue to develop these techniques and extend them to the low emittance bunches and 4 ns bunch spacings of CesrTA. We, along with our collaborators, expect to deliver initial results from our beam dynamics studies by the end of 2009, in time for the ILC EDR, and the results of more thorough studies in 2010-11 as part of an ongoing effort to obtain the lowest possible vertical emittance in CesrTA.

6.1.2 Fast Ion Instability

The ability to operate CesrTA with either electrons or positrons will allow us to probe the impact of ions on ultra low emittance beams. We will explore this with trains of electrons having 4 ns spacing and a variable gap between trains so that ions are cleared once the train passes by. In order to characterize the impact we will measure bunch-by-bunch tune and beam size. We will calculate the characteristic frequencies for ions likely to occur in the residual gas and measure the amplitude of these frequencies in the beam spectrum and correlate these with RGA measurements. We will measure the response of the beam spectrum to changes in pressure, for instance by turning off pumps or deliberately increasing the partial pressure of a particular gas (ALS added He to see the effect) [21]. We will also explore the dependence on bunch current, bunch spacing and emittance. The data we obtain will be compared with the theoretical expectations and simulations being used in the design of the ILC damping rings.

We, along with collaborators will perform initial experiments in this area during 2008 and 2009 so that their evaluation can be incorporated into the ILC EDR. As with the electron cloud measurements, we expect increased sensitivity to the impact of the FII on ultra low emittance beams as we proceed with the program of gaining operational experience with these extreme beams in later operation.

6.1.3 Ultra Low Emittance Operation and Associated Beam Diagnostics

As was described above, the simulations of our ability to correct the optics in CesrTA indicate that we can attain vertical emittances that approach the specifications of the ILC damping rings. Our collaborators at the Cockroft Institute and SLAC will participate directly in helping us achieve this goal. Although our expectation is that experiments at the KEK-ATF with its electron beam will continue to play the lead role in initially demonstrating the specified damping ring vertical emittance, the ability to achieve similar emittance goals at CesrTA is complementary in the overall damping ring R&D program. Because CesrTA has beams of both positrons and electrons, exploring the emittance-diluting effects of the electron cloud is a unique aspect of the proposed program. Work at CesrTA will also support the development of additional correction and tuning techniques along with hardware as the KEK-ATF moves into a period of supporting beam delivery system research as part of ATF-II.

Our collaborators at FNAL will provide beam dynamics simulation support (both manpower and computing) to help model the electron cloud, ion effects, intrabeam scattering, and other beam dynamics effects on ultra low emittance beams. Implementation of real-time techniques and algorithms for dispersion and emittance measurement and the development of suitable methods to use this information for continuous tuning and correction of the machine will take place primarily during 2009 and 2010 with continuing development beyond as required.

6.1.4 ILC Damping Ring Component Prototyping and Testing

From 2010 through 2011 we expect the CesrTA program to consist of completing the electron cloud and fast ion studies and begin the testing of prototype systems for the ILC damping rings. In order to properly characterize these systems, the ability to operate at ultra low emittance will be a prerequisite. ILC-specific systems that we envision testing include vacuum chambers for suppressing electron cloud growth, a prototype of the damping wiggler, and damping ring instrumentation. SRF cavities and fast kickers supplied by others could be tested as well. No support for a 650 MHz cavity system or fast kicker tests is being requested here.

7. ILC Collaborators

Table 4: Present plans for CesrTA collaboration for ILC damping ring research.

Collaborators	Institution	Topic
M. Pivi and L. Wang	SLAC	Electron cloud studies, wiggler chambers for electron cloud suppression
Y. Cai and PEP-II Beam Physics Group	SLAC	Machine correction and ultra low emittance tuning
A. Reichold and D. Urner	Oxford	Alignment and survey requirements and upgrades
S. Marks, R. Schlueter and M. Zisman	LBNL	Wiggler chambers for electron cloud suppression
C. Celata, M. Furman and M. Venturini	LBNL	Simulation of electron cloud in wigglers
A. Molvik	LLNL	Electron cloud measurements
J. Byrd, S. de Santis, M. Venturini, and M. Zisman	LBNL	Wiggler and electron cloud and FII studies
K. Harkay	ANL	Electron cloud measurements
K. Ohmi, J. Flannagan, N. Ohuchi, M. Tobiyama, Y. Suetsugu and K. Shibata	KEK	Electron cloud measurements and simulation
P. Spentzouris, J. Amundsen and L. Michelotti	FNAL	Beam dynamics simulations and measurements
A. Reichold	John Adams Inst.	Automated Survey Techniques
A. Wolski	Cockcroft Inst.	Machine correction and ultra low emittance tuning
R. Holtzapple	Alfred Univ.	Instrumentation and beam measurements
J. Urakawa	KEK	R&D program coordination
L. Schächter	Technion-Haifa	Electron cloud measurements and analysis

8. ILC Schedule and Milestones

The CLASSE ILC research program is specifically designed to answer key questions in time for the ILC EDR and subsequently to support validation of key ILC accelerator and detector technologies. Figure 9 shows the schedule for operating CesrTA for damping ring physics studies.

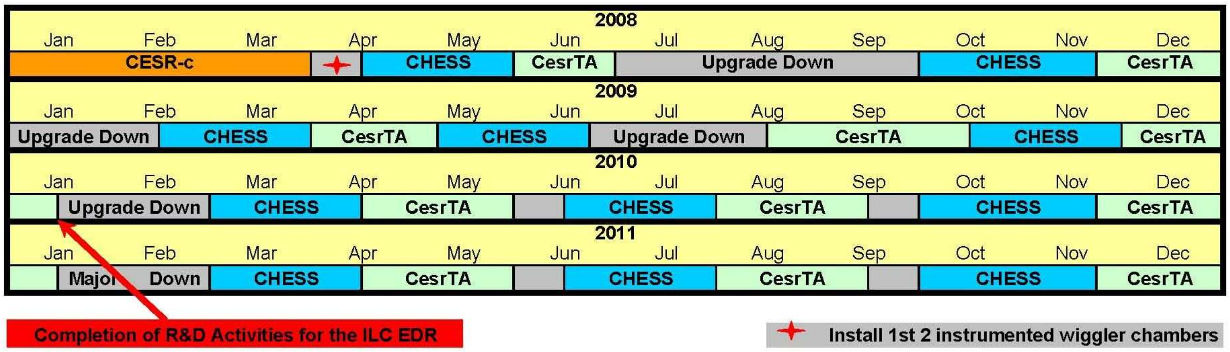

Figure 9. Proposed CesrTA Operating Schedule for 2008-2011: CesrTA runs are shown in light green, Cornell High Energy Synchrotron Source (CHESS) runs are shown in blue, and machine downs are shown in gray. The end of CESR-c/CLEO-c operations is March 31, 2008. During the CesrTA period, CHESS will be providing an average of 120 running days for their users per year.

The following is a list of key R&D milestones for the ILC research program at CLASSE.

2008:

- Install the first 2 instrumented wiggler chambers with electron cloud suppression hardware during April down period. Conduct first physics experiments in June to measure the electron cloud growth and determine the efficacy of the suppression techniques in the modified wiggler vacuum chambers (*see Sect. 6.1.1*). Initial tests will take place before any other ring modifications occur. Expectations are that we will be operating with a horizontal geometric emittance of ~ 10 nm and vertical emittances of several hundred picometers. The beam current for 4 ns spacing bunch train operation will likely be limited by the longitudinal multi-bunch instability.
- Move the damping wigglers and reconfigure the CESR ring for compatibility with the ultra low emittance lattice during July-September down (*see Sect. 5*). The theoretical horizontal emittance in this configuration is ~2.25nm.
- Begin the beam-based and instrumental alignment program to reduce transverse coupling and vertical dispersion. The program to reduce vertical emittance will depend on (and be limited by) the existing BPMs and our traditional survey and alignment instrumentation. (*see Sect. 6.1.3*).
- Prepare the optics line for the x-ray beam size monitor for the positron beam.
- Begin experiments at low emittance to explore emittance dilution and instability thresholds due to electron cloud and fast ion effects.

2009:

- Complete the upgrade of the BPMs at vertically focusing quadrupoles and the longitudinal feedback upgrade for 4ns capability.
- Install a substantial fraction of the alignment and survey (LiCAS) upgrade.
- Commission the x-ray beam size monitor for the positron beam and install the optics line for the electron beam size monitor (*see Sect 5*).
- Measure emittance dependent and emittance diluting effects associated with the ECE, FII, and IBS. Compare observations with current models and evaluate the expected ILC Damping

Ring performance for the ILC EDR (*see Sect.6.1-6.3*). The new BPMs and survey equipment, and the experience gained with beam based alignment techniques during the previous year, will enable us to further reduce the vertical emittance. The x-ray beam size monitor will provide the capability to measure the very small beam size and provide tuning feedback.
- Install new vacuum chambers for monitoring the electron cloud and ions in wigglers, dipoles, quadrupoles and drift regions.
- Carry out further measurements of electron cloud growth and tests of electron cloud suppression techniques with bunch trains consistent with the ILC design specifications. Prepare evaluations for the ILC EDR (*see Sect. 6.1*).

2010:

- Begin full operation of LiCAS survey techniques and evaluation for the ILC EDR (*see Sect. 5.6*).
- Complete the upgrade of BPM system for ultra low emittance tuning.
- Commission x-ray beam size monitor for electron beam.
- Establish optimal emittance tuning algorithms and limits and evaluate the beam species dependence of the emittance performance (*see Sect. 6.1, 6.2, and 6.3*).
- Circulate beams of both electrons and positrons with emittance, bunch and charge configuration comparable to the ILC damping ring specifications and measure thresholds for instability and emittance growth.
- Test prototype ILC wiggler vacuum chamber in CESR wiggler at 5 GeV (*see Sect. 6.4*).
- Provide ILC EDR contributions.

2011:

- Conduct beam tests of ILC damping ring prototypes (*see Sect. 6.4*).
- Continue ultra low emittance beam dynamics and tuning studies (*see Sect. 6.1-6.3*).

Figure 10. below is a GANTT chart of these activities to illustrate in a graphical way the sequence of steps that the evolving research program for the CesrTA will follow. This combined with the proposed operating schedule given above in Figure 9 gives the complete picture of the laboratory operations during the CesrTA project.

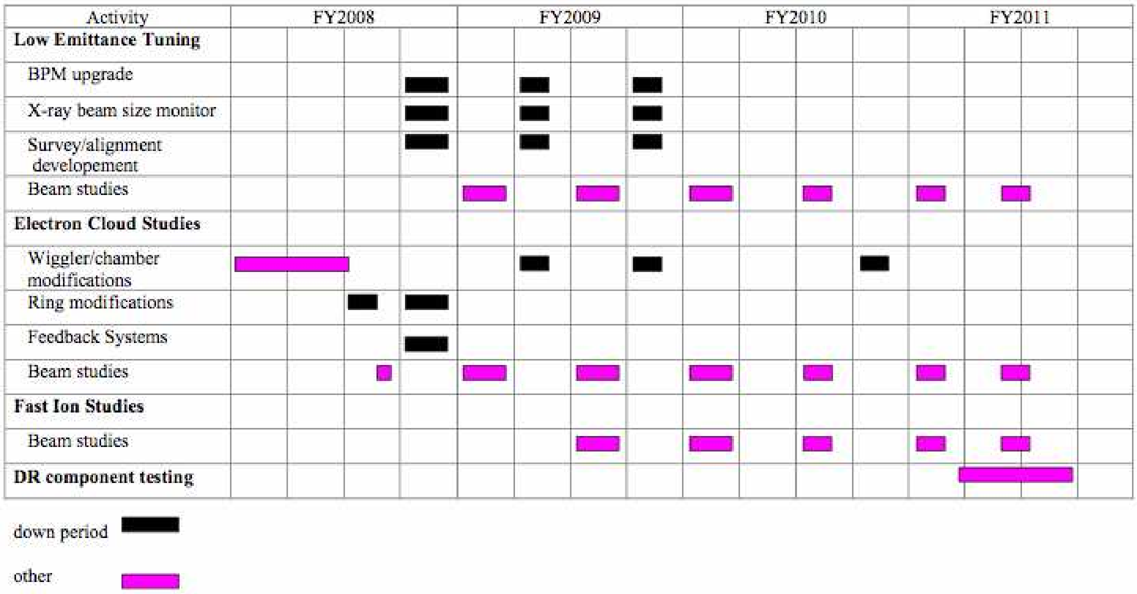

Figure 10. GANTT Chart for CesrTA Research Program.

9. CesrTA Project Management

The Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE) provides an infrastructure for the management of parallel but interrelated projects based on accelerators. The structure is shown below in Figure 10. Besides the evident connection to the university administration, other essential connections are made through the fact that many of the principals are Cornell faculty: the Chair of the Directorate, the two Scientific Directors and, in the present instance, the PI for this proposal who is the senior faculty person for accelerator physics, David Rubin. These connections make possible the all important student (undergraduate, graduate and post doctoral) involvement for education, training and research opportunity. In addition, they give access to the intellectual resources in the wider university community – engineering, IT, chemistry, condensed matter physics as well as important administrative units within the university such as Personnel, Office of Sponsored Programs and the Dean's and Provost's offices. Other accelerator faculty are also involved as co-PI's: Gerald Dugan, Don Hartill, and Maury Tigner. Connection to the organization's technical infrastructure and operating capability is provided through the Technical Director, David Rice, who manages the engineering, technical services and operations personnel. The Project Director is Mark Palmer, also an accelerator physicist with expertise in instrumentation. He is concerned with planning as well as operational matters concerned with doing the measurements and system investigations proposed herein. He is responsible for creating and maintaining the relevant project WBS and using Microsoft Project for schedule projection and tracking.

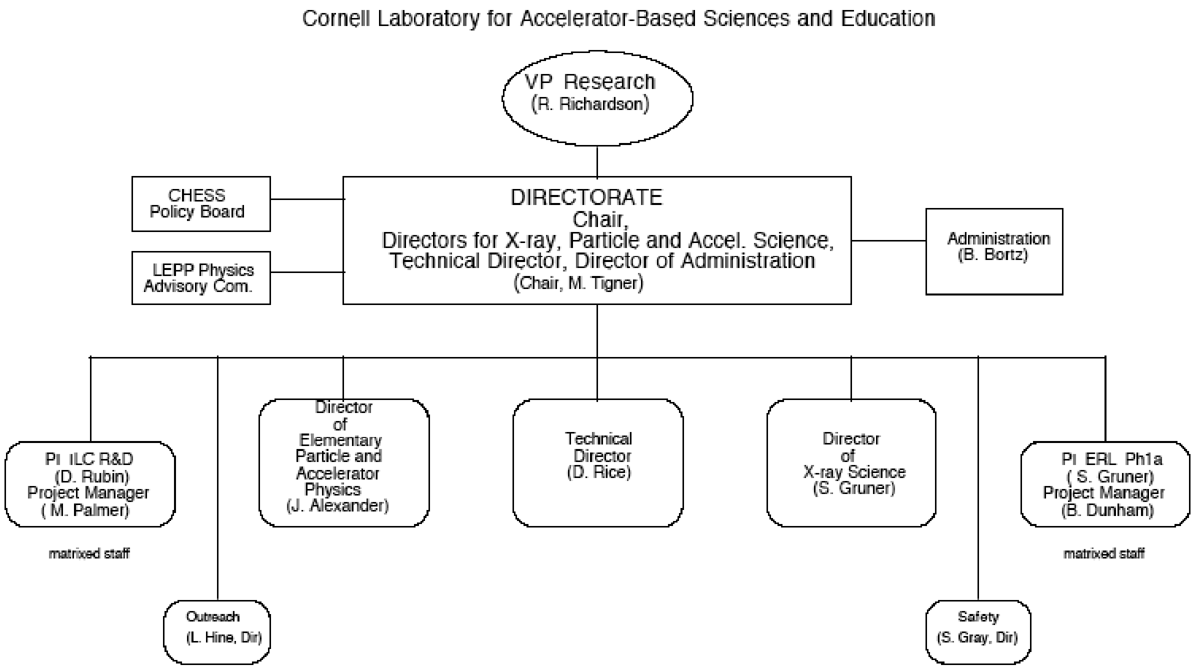

Fig. 10. CLASSE Organization Chart showing Faculty and Senior Administrators

10. Project Summary

Use of the CESR physical and intellectual infrastructure for R&D in support of the ILC Engineering Design Report and preparation for developments beyond, offers a unique opportunity to capitalize on existing EPP community resources. Local experience with elements of the positron source through the damping rings and the ring to main linac transport with its complex optics and superconducting accelerator sections is an almost perfect match to ILC R&D needs. The centerpiece of these activities is the application of the CESR ring to study of the Electron Cloud Effect and Fast Ion Instability and potential methods for their amelioration in long-period dedicated runs of the accelerator. Ancillary to this is the program to implement ultra low emittance operation through significant improvements in alignment, instrumentation, and tuning procedures. The natural suitability of CESR as a laboratory for these studies has attracted collaborators from the three regions participating in the ILC, adding to the strength of what is being proposed. The layout of the accelerator is also such that various prototypes of subsystem hardware can be inserted and tested as the ILC design develops. The intermingling of the several activities proposed gives advantage of a wider circle of scientific and technical experience that can be shared among them to the benefit of all.

11. Broader Impact

11.1 ILC Global and Regional Management Collaboration Activities

ILC activities are globally coordinated by the GDE with its central and regional management units, accountable to the supporting agencies in the three regions. Cornell faculty and staff are heavily involved in the management and coordination of these international activities. Currently G. Dugan serves as the Regional Director for the Americas (through April 2007), M. Tigner is past chair of the International Linear Collider Steering Committee (ILCSC) and currently serves as chair of the Linear Collider Steering Group of the Americas (LCSGA), M. Palmer serves as a member of the Americas Regional Team as

Deputy Manager for the Damping Rings as well as being a member of the Global R&D Task Force S3 (damping rings). D. Hartill serves as a member of the ILC Machine Advisory Committee. H. Padamsee is a member of the Global Design Effort (GDE), a member of the GDE R&D Board and Co-leader of the combined Cavity and String Test Task Forces S0/S1, co-leader of the S2 Task Force, and co-leader of the WBS X.9 collaboration for ART. R. Meller serves as Cornell Representative to the International Collaboration Board for the ATF at KEK (see letters of support).

11.2 Scientific and Technical Impacts

The accelerator physics and technology of ultra low emittance tuning, electron cloud effects for both positron and electron beams and ion effects have significant impact well beyond the damping rings for the ILC.

The current generation of light source storage rings under construction and in design depend on achieving low emittances without precedent, similar to that required for the ILC damping rings. Thus all methods being developed for achieving and maintaining low emittance in the ILC damping rings are relevant to current developments in light source design and operation. The beam currents being planned for the most recent storage ring based light sources are also comparable with that of the ILC damping rings. Thus, mitigating the electron cloud phenomenon and its impact on diluting emittances of both electron and positron beams is particularly germane to these light sources as well. Likewise, mitigating ion effects on the emittance of ultra high brightness electron beams, important for the ILC damping rings will also be important for light sources based on storage rings. The instrumentation being developed for the emittance tuning and electron cloud studies will also be useful for next generation light sources. In particular one notes the fast bunch by bunch x-ray beam size camera being developed in collaboration with x-ray scientists and the high resolution beam position monitor electronics and software.

The understanding of electron cloud effects associated with positive ion beams is also important for heavy ion fusion studies [22] and storage rings for neutron sources.

Not only will the CesrTA studies alluded to above produce substantial knowledge relevant to the broader fields mentioned, the diverse participation of the CesrTA program attested to by the attached letters will assure that this information is widely available at the potential points of use.

Of primary importance in broader impacts of this work is the hands-on training of accelerator and x-ray beam line scientists that serve around the world as principals and staff of laboratories for nuclear and particle physics and x-ray science.

11.3 Outreach

As part of this proposal we plan to continue our past level of commitment to outreach, an important aspect of scientific research. Faculty, students and staff in Laboratory for Elementary-Particle Physics (LEPP) have demonstrated a firm commitment to outreach and are pleased to be part of a global movement to advance efforts that promote science literacy. We are committed to providing graduate students with access to frontier research facilities and to provide the training necessary to meet the growing demand for experts in accelerator-based technologies. We have developed undergraduate programs that offer students the opportunity to contribute to projects involving cutting-edge research and technology. We have devoted significant resources and staff-time connecting with K-12 students, educators, and the public to share with them the technological and scientific advancements made possible through research conducted at particle accelerator facilities.

11.3.1 Graduate Programs

The average population of PhD students in experimental elementary particle and accelerator physics is 22 with 9 currently in accelerator physics and 13 in EPP. Roughly one PhD per year is granted in each of particle and accelerator physics. As noted, our students are in great demand in accelerator and particle physics laboratories. The growing use of accelerators and the size of accelerator projects has resulted in demand outstripping supply. We will continue out efforts to recruit exceptional talent into graduate work in the accelerator based sciences.

11.3.2 Undergraduate Programs

The Laboratory has been able to involve both undergraduates and high school students in research activities. Since 2003, ten high school students have participated in voluntary internship programs at the Lab where they have worked with mentors on a variety of accelerator-based research projects. The Lab employs between 30-35 undergraduate students each year, in part-time and full-time summer positions. Ten members of Cornell's Society for Physics Students have actively participated in after school enrichment programs for middle and elementary school students sponsored by the Lab during the past three years. The SPS Chapter at Cornell received the Blake Lilly Award for their outstanding efforts to positively influence the attitudes of school children.

The Laboratory has hosted 153 REU students and 17 RET participants since the summer of 1998 in collaboration with Wayne State University. Wayne State is located in inner-city Detroit, providing us with a pool of accessible minority candidates to participate in the program. During the summer of 2006, three students participating in the Cornell REU program were involved in investigating important aspects of damping ring physics, an integral part of the proposed International Linear Collider (http://www.lepp.cornell.edu/Research/AP/ILC/WebHome.html). Mentors for the 2007 REU program at the Lab are already planning research projects for the incoming students that include further investigation of damping ring dynamics using the CESR ring. See the ILC news line article at: *http://www.linearcollider.org/newsline/readmore_20061005_feature1.html*

11.3.3 Outreach to the Community

In addition to sharing our sense of wonder over the elegant beauty of the universe, future outreach efforts at the Lab will convey the excitement surrounding upcoming discoveries in particle physics. New particle accelerators with their ingenious designs and high energies will play an important role in unraveling the mysteries of the universe. By describing these and the anticipated physics discoveries, we will attempt to convey to our outreach audience the knowledge and understanding made available through the collaborative research efforts using the LHC and ILC.

Over 1000 people visit and tour the Lab each year, representing an audience interested in learning about the behavior of the subatomic world and the machines that allow us to observe these fundamental particles. In 2006, approximately 525 middle/high school students received guided tours and 85 middle/high school teachers toured the Lab. These numbers, higher than those in 2005, indicate that the staff at the Lab is doing an excellent job meeting the educational needs of local K-12 students and teachers. During this same time period, there were nearly 110,000 hits on the Lab's Education and Outreach web pages available at: *http://www.lepp.cornell.edu/Education/WebHome.html*

Visits to area schools provide children with the opportunity to learn about science topics beyond those addressed in the adopted classroom curriculum and allow laboratory staff to share their knowledge and unique perspectives with an audience that might not ever walk onto a university campus. Our connections with New York City's public school children have increased our contacts with under-represented students during the last few years. This coming July, we will be collaborating with the

Center for Radiophysics and Space Research to host the *Cornell Physical and Space Sciences Summer Institute*. This institute will provide New York City middle school teachers with the opportunity to gain content knowledge aligned with the NY City Science Standards and the NY State Learning Standards. Participants will interact with scientists conducting cutting-edge research in accelerator science and learn about state-of-the-art technology in the setting of a world-class research university.

11.3.4 Outreach to Science Educators

In 2006, thirty-five physics educators from throughout the country assembled at Cornell to discuss the crisis in physics education as part of the Lab-sponsored "Preparing Future Physics Teachers" conference. Physics faculty from university, state and community colleges shared their concerns and strategies for recruiting, training and retaining future high school physics teachers. As a result of the conference, the Lab produced a recruitment brochure encouraging high school seniors and undergraduates to consider a career as a high-school physics teacher. The Physics Department at Cornell has become part of the Physics Teacher Education Coalition (PTEC), an association of institutions of higher education dedicated to the improvement of physics and physical science teacher education.

As state-wide physics test scores come under continued scrutiny and as the number of high school students taking physics is at the 30% level nationally, we have hosted two conferences devoted to exploring the advantages of changing the current high school science curriculum to determine if teaching conceptual physics in ninth grade to all students is beneficial to young learners. We continue to be a resource to school administrators and teachers who are interested in implementing Physics First in their own high schools.

The NY State Education Department with the National Science Resources Center is implementing a science education initiative that will build leadership within NY State school districts. The initiative will provide research-based products and services to assist NYS school districts in initiating, implementing, and sustaining effective inquiry-centered pre-K-12 science programs for all students. The Lab's Director of Educational Programs is serving on one of the Enhancing Collaborative Leadership for Improved Performance in Science Education (ECLIPSE) leadership teams committed to developing a model that provides a comprehensive approach to district-wide systemic change in science education.

The Lab is an active participant in the international collaboration InterActions, whose members are representative of the world's particle physics laboratories. The main purpose of the collaboration is to communicate important information to policy makers, serve as a resource for communicators of particle physics, and to link the public to particle physics education and outreach material. Information about the ILC is an important component of these activities.

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