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CESR STATUS AND PLANS

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Abstract The CLEOII detector was installed and the CUSB detector upgraded during a year long shutdown. Within the next few years the machine will be reconfigured for collisions at a single IP, and to accomodate 14 bunches per beam. With the CESR Plus upgrade the peak luminosity will be increased to $5 \times 10^{32} cm^{-2}s^{-1}$ from the present value of $10^{32} cm^{-2}s^{-1}$. An R&D effort is underway with a goal of a design for a B Factory that can attain a peak luminosity of $10^{34} cm^{-2}s^{-1}$.

INTRODUCTION

Recommissioning of the Cornell Electron Storage Ring follows a year long shut down to install a new experimental detector in the south IR and upgrade the photon spatial resolution of the north area detector. Upgrades to the linac and injection system that have been completed during the shutdown are anticipated to yield a substantial increase in the injection rate into the storage ring. A pair of electrostatic separators has been removed from the storage ring, and the remaining electrostatic elements reconfigured to permit separation of the beams at each of the fourteen crossing points during injection, and collisions exclusively in the two low beta interaction regions once injection is complete. The peak luminosity of $1.02X10^{32} cm^{-2}s^{-1}$ that was achieved prior to the shutdown with seven bunches per beam is expected to be recovered as operation resumes.

The beam-beam limited luminosity will be upgraded (CESR Plus) during the next two years by a rebuild of the horizontal separators, replacement of the RF cavities with four new 5-cell structures, a doubling of the number of bunches from seven to fourteen, the elimination of one of the two interaction points, and the enhancement of the beam width at the remaining IP. Currents of about 300ma/beam will be required to operate the reconfigured machine at the beam-beam limit. The scheme of upgrades is anticipated to yield a five fold increase in peak luminosity.

The study of CP violation in the B-meson system requires at least an order of magnitude increase in peak luminosity beyond CESR Plus. Insofar as luminosity scales with circulating charge, a factor of ten increase in luminosity implies currents of about 3A

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per beam and in the CESR tunnel that translates to nearly 3MW/beam of synchrotron radiation power. An R&D effort is underway to address the technical challenges of storing and colliding the high currents of multiple bunch beams intrinsic to a B-factory, including the development of RF accelerating structures and beam separators, the design of the vacuum system, and the study of beam-beam dynamics.

CESR STATUS

The Cornell Electron Storage Ring operates with seven bunches per beam to attain a peak luminosity of $10^{34} cm^{-2} s^{-1}$ at a center of mass energy of $10.6 GeV$. The total current is about $70 ma$ per beam. The vertical β^* at the two interaction points is $1.5 cm$ and the final focus quadrupoles are somarium-cobalt permanent magnets. The closed orbits of the electrons and positrons are distorted by horizontal electrostatic deflections such that the beams are separated at the twelve parasitic crossing points in the arcs. The peak luminosity is limited by the performance of the DC separators which break down at the high voltages required of high current beams.

DETECTORS

During the past year a new detector was installed in the south interaction region. The charged particle tracking of the CLEOII detector is provided by a 50000 wire cylindrical drift chamber, a ten layer inner drift chamber and a three layer straw chamber with innermost radius of $3.5 cm$ immersed in a $1.5 T$ solenoidal field. Neutrals are detected by a system of some 8000 cesium iodide crystals instrumented with photo-diodes, all of which are inside of the coil of the superconducting solenoid. The north area detector was upgraded to improve photon spatial resoultion.

INJECTOR

In an effort to improve the injection efficiency and reduce the time required to fill the storage ring, the year long down period was exploited to upgrade the linac and synchrotron injector. The scenario to fill with seven bunches per beam is to accelerate a train of bunches in each linac pulse and synchrotron cycle. The number of positron bunches that can be transferred from synchrotron to storage ring is limited to six by the rise time of the extraction kicker. The number of electron bunches that can be accelerated in each linac pulse was limited to three by the transverse wakes generated at the low energy end of the linac. The offending impedances are significantly reduced with the installation of a redesigned prebuncher cavity. In addition all of the accelerating sections and focusing elements in the linear accelerator were realigned, new beam position monitors installed, optics analyzed and modified, and diagnostic software developed. We anticipate simpler tuning and improved reproducibilty of injector conditions. Finally, the pulsed elements were upgraded to permit a doubling of the injector repetition rate from 30Hz to 60Hz.

CESR

In anticipation of future upgrades to single IP operation with fourteen bunches per beam, a pair of vertical electrostatic separators was removed from the storage ring. The electrostatic elements were used to separate the beams vertically at the interaction point during injection. The horizontal separators are reconfigured to yield the required separation at the south interaction point and at the parasitic crossing points in the arcs during injection. An adjustment of the separator voltage brings the beams into collision at the south IP while preserving separation elsewhere. The horizontal separators (the current limiting component) are in the process of being refurbished with the installation of new ceramic feedthroughs and electronics to permit more effective high voltage processing.

The synchrotron light facility was upgraded with the addition of a 24-pole wiggler and three new x-ray lines. A biological hazards facility was installed in conjuction with the beam lines

CESR PLUS

During the next few years the CESR peak luminosity will be enhanced with an increase in the beam-beam current limit and the required upgrade of the single beam current carrying capability. We raise the beam-beam limit by eliminating one of the two interaction regions, doubling the number of bunches per beam from seven to fourteen, and increasing the horizontal dispersion (beam width) at the interaction point. The increase in total current is by a factor of four to nearly 300 ma/beam. We anticipate a five-fold increase in peak luminosity.

ONE IR

In CESR the bunches collide twice per revolution. If we eliminate one of the collisions we expect to attain a higher critical charge density at the remaining interaction point.[1][2] A measure of saturated tune shift in a configuration with one versus two collisions per turn with the CESR indicates a minimum 20% increase in critical current density.[3] Recent experience at PEP suggests that optimization of the colliding beam conditions is somewhat simpler in a machine with a single interaction point.[4]

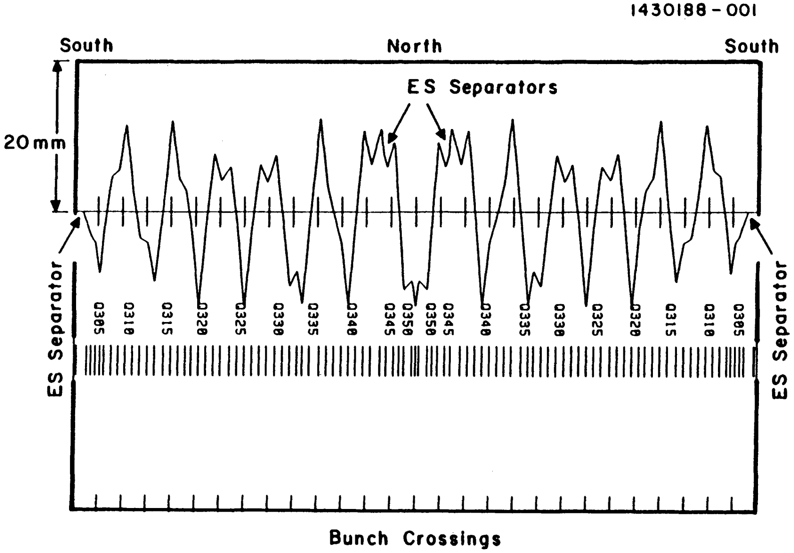
We rely on the two pairs of horizontal separators associated with multibunch operation to eliminate the collision in the north interaction region. The vertical separators that surround the interaction region, and that have been used to separate beams during injection are removed from the machine. The horizontal separators are powered symmetrically in the east and west arcs to attain an antinode in the differential orbit at the symmetry point, the north IP. The optical elements within the pretzel region are constrained to yield separation at the thirteen parasitic crossing points that occur with seven bunches per beam, (and the 27 that occur with 14 bunches per beam), and to insure isochrony of electron and positron orbits.[5] The phase advance from the south interaction point to the southernmost separator is close to $\frac{1}{4}\lambda$ so that with that pair of elements at zero voltage the beams are separated at all of the crossing points as is required during injection. We are thus able to eliminate all of the vertical separators from the machine. With only the pair of horizontal separators in the north powered, beams are separated at all crossing points for injection. Powering of the pair located in the south brings the beams into collision at the south IP.

14 BUNCHES PER BEAM

The number of bunches per beam is constrained by the distance of the separators from the interaction point, and in a machine with a single vacuum chamber and separation in only the horizontal plane, by the number of horizontal betatron wavelengths around the ring. A parasitic crossing of the 14 e^+ and e^- bunches occurs at a distance equal to one-half of the bunch spacing s from the interaction point. The beams must be separated before they have traveled the length $s/2$ and the horizontal separator is necessarily located something less than $s/2$ from the interaction point. For CESR this implies moving the separator nearer the IP. With the removal of the vertical separator, space is made available for the horizontal separator $\sim \frac{1}{4}\lambda$ from the IP.

High Tune The separation of electron and positron beams at s is given by $\Delta x(s) = 2k\sqrt{\beta_k \beta(s)}\sin(\phi(s) - \phi_k)$, where β_k and ϕ_k are the β-function and phase at the location of the electrostatic kick, k. The bunches are most efficiently displaced if the crossing points are an odd integer number of quarter wavelengths from the separator. If there are n_b bunches in the beam then there are $p = 2n_b - n_{IP}$ parasitic crossing points and necessarily of order p half wavelengths. In a lattice consistent with 14 bunches per beam the integer part of the horizontal tune is 13. The closed orbit for a 14 bunch lattice is shown in Fig. 1.

CESR presently operates with an integer tune of 9 in both horizontal and vertical dimensions. An increase of the horizontal tune to 13.4 dramatically reduces the average dispersion around the ring and strong sextupoles are required to compensate the chromaticity. But the elimination of an interaction region significantly reduces the chromaticity and the demands on the sextupoles. We find that the horizontal chromaticity suffers a net increase of 10% while the vertical chromaticity actually decreases by 30% in the high tune single IR machine as compared to the tune of 9, two IR configuration. The sextupoles are nevertheless stronger than in the tune of 9 lattice due to the reduced dispersion in the arcs, but not as strong as in an experimental tune of 11 lattice that yielded good luminosity and tune shift.[6] We will further exploit the normalization of IR optics to introduce additional sextupole magnets and thereby effect a reduction in all sextupole strengths.



1. The closed orbit for electrons is indicated. The positron orbit is the reflection about the undisplaced trajectory. The beams are separated at 27 of the 28 crossing points that occur with 14 bunches per beam and a single collision point.

Parasitic Crossings and Differential Orbits As noted above, large numbers of bunches per beam imply many parasitic crossings and a long range beam-beam effect. We observe that with increasing beam currents, higher separator voltages are required to preserve tune shift and beam lifetime. Doubling the number of bunches doubles the number of parasitic crossings and the horizontal aperture may limit bunch charge.

Magnet errors and nonlinear elements effect the separated beams differentially.[7] We observe a 10 – 20% degradation in luminosity in collisions of single bunches if the electrostatic closed orbit distortion is applied. In the low current limit no further degradation is observed as more bunches are added to each beam.[8] The effects of the parasitic crossings appear near the beam-beam limit.

With 14 bunch per beam operation the pretzeled region extends to within 5 meters of the interaction point. A new scheme for compensating the solenoid compensation' relies exclusively on rotations of the three pairs of IR quadrupoles.[9]

SINGLE BEAM LIMITS

To maximize the single beam threshold it is necessary to attain the required RF power with a minimum impedance. The power available to the beam is limited at present by the RF window that isolates cavity vacuum from atmospheric waveguide. The impedance simply scales with the number of cells. We plan to replace the two existing 14 cell cavities with four 5-cell structures. The impedance is reduced by 30% and the power available to the beam is doubled. Delivery of the new cavities is expected to begin in January of 1990 with installation in CESR about six months later. The cell shape, fundamental coupling and higher order mode loading of the existing structure is preserved in the replacement cavities.

In the existing machine configuration with $11ma$/bunch in 7 bunches the radiated power is $90kW$ and higher order mode power $39kW$/beam. If the upgraded machine is operated at its beam-beam limit the synchrotron radiation will be $342kW$/beam. The power radiated into higher order modes is given by $P_{hom} = k_{eff}I^2_{bunch}/fN$, where k_{eff} is the effective loss parameter, I_{bunch} the current per bunch, N the number of bunches and f the revolution frequency. The bunch current and number of bunches will be increased but the effective loss parameter decreased. Two-thirds of the loss parameter is associated with the 28RF cells and the remaining third with the electrostatic separators. Then we write very approximately that $k_{eff} \sim 42$ RF cells equivalent, where k_{eff} is given in units of CESR RF cells. In the upgraded machine there will be 20 RF cells and two pairs of separators so that $k_{eff} \sim 27$ in the same units. Then simple scaling yields $P^{cesrplus}_{hom} \sim 183kW$/beam.

Including about $30kW$ per 5-cell cavity to sustain the accelerating voltage the total power transmitted at each of the four windows is $293kW$. Experience with high power operation of the CESR cavities indicates that transmission of nearly $400kW$ is practical. For example, an RF cavity was operated for several weeks in CESR with $360kW$ fundamental power transmitted through the window. There was no indication of any degradation of the performance of the ceramic window and inspection showed no deterioration. CESR parameters already attained and those anticipated for the CESR Plus upgrade are indicated in Table I.

Similar scaling arguments can be used to estimate the stability of single beams in the CESR Plus. The single bunch stability limit is observed in the existing configuration to be about $28ma$. If we suppose that the limit scales with the the number of RF cell equivalents, then the single bunch threshold will increase to over $43ma$/bunch.

The bunch lengthening threshold scales according to[10]

$$I_{thresh} \propto \frac{\sigma_z \alpha}{(Z_n/n)}, \tag{1}$$

where σ_z is the bunch length, α the momentum compaction factor and Z_n/n the broadband impedance. The bunch length is not typically measured in CESR. There is a single measurement of bunch length versus current that permits a qualitative determination of

TABLE I. CESR and CESR Plus Parameters

Parameter	CESR	CESR Plus
Interaction Regions	2	1
β_v^*	1.5cm	1.5cm
η^*	0.55m	0.66m
σ_x	0.52mm	0.57mm
ν_h	9.38	13.38
ν_v	9.36	9.36
Bunches	7	14
Bunch Spacing	110m	55m
Current/bunch	11ma	21ma
Total current/beam	77ma	294ma
Synch Power/beam (5.3GeV)	90kW	342kW
HOM power/beam	39kW	183kW
k_{eff}(RF cell equiv.)	42	28

a threshold. At the time of the measurement the effective impedance corresponded to 21 RF cell equivalents and $\alpha = 0.015$. The zero current bunch length was $\sigma_z = 2.2cm$ and no lengthening was observed for a current of $24ma$/bunch.[11] There was no measurement at higher currents. We conclude that the threshold was greater than $24ma$. In CESR Plus the momentum compaction is reduced to 0.008, the bunch length to $\sigma_z = 1.4cm$, and the impedance increased to 27 RF cell equivalents. Then the lower limit for the bunch lengthening threshold is according to (1), $I_{thresh} > 8.1ma$. Single bunches with currents in excess of $28ma$ and zero current length of $1.7cm$ have been stored. There was no evidence of bunch lengthening but neither was there a direct measurement of bunch length. It is therefore uncertain whether bunch lengthening will appear with our attempt to store $21ma$/bunch in the upgraded machine.

Multibunch and multiturn instabilities can arise if the beam couples to high Q parasitic modes in the vacuum system. Single beams of 14 bunches with currents in excess of 12ma/bunch have been stored without active feedback. The current was limited by overheating of a ceramic section of vacuum chamber. The source of the narrow band impedance is the RF cavities. The number of RF cells in CESR Plus will be 20. The number of cells at the time of the 14 bunch measurement was 28. The associated change in the narrowband impedance suggests that the lower limit on the multibunch threshold $I_{thresh}^{multi} > 17ma$/bunch. The broadband feedback system is being upgraded to accomodate 14 bunches/beam.

In summary, the essential changes of the CESR Plus upgrade are the elimination of one interaction region, reconfiguration of horizontal separators, and installation of new RF cavities. The cavity installation and removal of north area low beta optics will proceed with the conclusion of the CUSB experimental program in late 1990. The single beam limit will subsequently increase with the design and installation of new electrostatic separators, multibunch feedback system, and the upgrade of the vacuum system. By late 1992 we expect to achieve a peak luminosity of $5 \times 10^{32} cm^{-2} s^{-1}$ on the $\Upsilon(4s)$ resonance and an integrated luminosity of 25 pb^{-1}/day.

B-FACTORY R&D

In order to measure rare processes such as decays of B mesons, mixing of B_s and $\bar{B}_s$, and CP violation in the B system, a sample of at least $10^8 B\bar{B}$ pairs is required.[12] CESR is now capable of producing $10^6 B\bar{B}$ pairs on the $\Upsilon(4s)$ resonance in a year. We need a 100 fold increase in integrated luminosity or $L_{peak} = 10^{34} cm^{-2} s^{-1}$. There are other requirements we would like to impose on a B-factory to be built at Cornell including:

1. $L_{peak} = 10^{34} cm^{-2} s^{-1}$, at $Ecm = 10.6 GeV$.
2. $E_{cm-max} = 15 GeV$, above the threshold for B_c perhaps at less than full luminosity.
3. Capability for symmetric (5.3+5.3) or asymmetric (3.4+7.5) operation on the $\Upsilon(4s)$.
4. Use of the existing CESR tunnel, injector and detector appropriately upgraded.

The luminosity (units of $10^{34} cm^{-2} s^{-1}$) of a symmetric machine is given by

$$\mathrm{L} = 11.5 \frac{I \xi_y (1 + \sigma_y / \sigma_x)}{\beta_y^*}, \qquad (2)$$

where I(A) is the average current, ξ_y the tune shift parameter, σ_y and σ_x the vertical and horizontal beam sizes at the IP, and $\beta_y^*(cm)$ the vertical (or minimum) value of the amplitude function. We find that for flat beams ($\sigma_x \gg \sigma_y$) and reasonable choices of $\beta^* \sim 1cm$, and $\xi_y \sim 0.03$, that a current of nearly $3A$ is required to achieve a luminosity of $10^{34} cm^{-2} s^{-1}$. The tune shift is degraded if the bunch length is greater than the minimum β. Therefore $\sigma_z < 1cm$. Since we suppose the machine to be constrained to fit inside the CESR tunnel the average bending radius is fixed. We find that:

1. Synchrotron radiation power is $3MW$/beam.
2. If the focusing lattice is similar to CESR's so the momentum compaction $\alpha \sim 0.015$, then the peak accelerating voltage is $V \sim 30MV$.

An effort is underway at Cornell to design such a machine and to develop the required technology. We describe some of the related hardware development, machine physics issues, and plans for experimental investigation of these issues with CESR.

SUPERCONDUCTING RF

Evidently a B Factory must store high current beams of multiple short bunches. The strong longitudinal focusing for short bunches implies high accelerating voltages. It is essential to design RF structures that can provide a maximum of voltage while offering a minimum of impedance. Superconducting cavities are so characterized. Due to their very high shunt impedance the voltage per RF cell (and therefore per unit of impedance) can be an order of magnitude higher than in a copper structure.

Because of the high power that must be coupled to the beam it is likely that the number of cavities will be determined by the power handling capability of the RF window. If we suppose that windows are limited at about $P_{window} < \frac{1}{2}MW$ (400kW in CESR) then we need about 10 windows per beam. Ten 500Mhz cells can provide 30MV if each can sustain a gradient of 9MV/m. We are thus lead to consider single cell, superconducting cavities, each coupling nearly $\frac{1}{2}MW$ into the beam.

In order to minimize the impedance associated with the coupling ports we are investigating the use of a waveguide coupling through a narrow slot located on the beam tube and parallel to its axis. We have in bench measurements identified a configuration that yields the required external Q of 2×10^5. Wakefield calculations using the 3d MAFIA code[13] indicate that the HOM losses due to the slot are at a level of 1% of the losses due to the accelerating cell as a whole.

In addition heavy damping of higher order modes is essential to the stability of the beam. The loaded Q for the highest impedance longitudinal mode (TM011) in a single cell has been measured. A waveguide coupler is located on an enlarged diameter beam tube. HOM losses from the beam due to the presence of the slot have not yet been evaluated. We find that $Q_{ext} = 80$ for the TM011 and $Q_{ext} = 120$ for the TM020.[14]

BEAM SEPARATION

Radiation of beam power into higher order modes scales as the square of the bunch charge. In this context it is advantageous to space the bunches as close together as possible so as to minimize the charge in each bunch. The proximity is limited by the separation of the beams at the first parasitic crossing point. To obtain a maximum charge density at the IP it is necessary that there be no significant long range beam-beam interaction due to near misses. We are investigating the use of electrostatic separators, low frequency strip line kickers, high frequency RF separators, magnetic separation depending on a very slight energy asymmetry, and the possibility of a crossing angle. To date a clear favorite has not emerged.

Crossing the beams at a small angle is an attractive alternative in so far as it requires no special (and potentially unreliable) hardware. There are no separators or cavities that present significant impedance to the beam and dissipate large amounts (typically

$\sim 100kW$) of HOM power. If the beams are flat and the crossing angle is in the horizontal plane then it is plausible that there will be negligible deterioration of the tune shift if the crossing angle is small compared to the characteristic spreading angle of the bunch.

An experiment to measure the effect of just such a crossing angle has been designed for CESR. It relies on a lattice in which the phase advance from the IP to the horizontal separator is one-half wavelength. Then powering the separators on each side of the IP asymmetrically yields the crossing angle.

ROUND BEAM EXPERIMENT

Referring back to (2) it is clear that more luminosity is attained for less current if the tune shift parameter is increased. Simulations[15] of the beam-beam interaction suggest that the tune shift limit for round beams ($\beta_x = \beta_y, \epsilon_x = \epsilon_y$) is significantly higher than it is for flat beams. In addition if $\sigma_x = \sigma_y$ then we get twice the luminosity for a given tune shift than for flat beams. We have developed a CESR lattice that will permit an experimental investigation of the collisions of nearly round beams.[16] We expect to perform the experiment some time during the next few months.

Significant R&D is essential to a design of a very high luminosity B-factory. An effort to address the technical issues is underway at Cornell. A proposal to build such a machine depends on the outcome of our research program.

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