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V CCSR-c – CCSR from 1.5 to 5.6 GeV per Beam

1 The CCSR-c Design Concept

1.1 Accelerator Goals

The objective of this conversion project is to operate the Cornell Electron Storage Ring, CCSR, effectively over the entire range of beam energies from 1.5 to 5.6 GeV, covering the ψ and Υ resonances with center-of-mass energies from 3.1 to 11.2 GeV/ c . “Effectively” in this context means operating at luminosities sufficient to increase the world data sample by at least an order of magnitude on several important resonances in this energy range.

1.2 Accelerator Physics Issues

Electron-positron colliding beam storage rings conventionally operate effectively over a modest energy range, often less than 2:1, limited by total synchrotron radiation power on the high end and lack of damping (low synchrotron radiation power) on the low end. Since the total synchrotron radiation power for a fixed bending radius ring varies as E^4 , these limits tend to be difficult to overcome. The damping times at 1.9 GeV are increased 25 times compared to 5.3 GeV. A second effect of the lower radiation is a decrease in horizontal emittance, or beam size, increasing the space charge density at the beams’ interaction point (IP), severely limiting the sustainable charge per bunch. Both these effects severely limit performance at low energy. Historically the luminosity of a given storage ring has been proportional to E^N where $4 < N < 7$. To operate CCSR at low energies we will enhance radiation effects by adding strong local bend magnets or wigglers.

The lower energy electrons are also more susceptible to disturbances from electro-magnetic fields, whether from the beam-beam interaction or “wake” fields induced by the beams themselves. The latter, combined with the reduced radiation damping, causes lower thresholds for single beam instabilities. The scaling of these phenomena with energy is well known and the extensive experience with CCSR at 5.3 GeV will be used as a reference point.

Beam loss phenomena such as Coulomb scattering from residual gas, and Touschek (intra-beam) scattering increase rapidly as the energy is lowered and will dictate limits to acceptable gas pressure and beam dimensions.

1.3 Accelerator Technology Issues

Several technological issues related to operating CCSR from 1.5 to 5.6 GeV are addressed in detail in the following sections. These include the magnet field quality, vacuum gas load and pumping, injector performance, wiggler magnet design and construction, RF, cryogenic systems, feedback and instrumentation, and accelerator control systems.

An additional consideration for accelerator components will be the need to efficiently switch between operation in the Charm region and operation at 5 GeV for CHES running and to condition the arc vacuum chambers as described below.

2 Facility Description

2.1 Accelerator Description

2.1.1 Overall Layout

CESR is a 768 m circumference electron-positron storage ring located on the Cornell University Campus in Ithaca, NY and is placed in a tunnel approximately 45 ft. beneath athletic playing fields. An artist's cutaway drawing of the facility is displayed in Figure 1. There is one interaction region (IR) in a $100 \times 80 \text{ ft}^2$ hall housing the CLEO detector. A linear accelerator and synchrotron, which is in the same tunnel as CESR, provides full energy, multibunch injection into the storage ring at rates as high as 350 mA/min.



FIGURE 1. Cutaway view of Wilson Laboratory and the accelerator tunnel.

Most of the CESR arc consists of 6.3 m long dipole bends with an 88 m bend radius. Quadrupoles and sextupoles with (usually) alternating polarities are located between each bend magnet. Each quadrupole and sextupole is powered independently from the others, giving full flexibility in optics. Figure 2 is a photograph of the storage ring and its injector synchrotron inside the tunnel.

To provide adequate separation between the synchrotron and the storage ring for the CLEO detector, a 26 m long straight section on each side of the interaction region allows the storage ring beam to drift away from the synchrotron, which has a smaller average radius than the storage ring. A series of “hard bend” magnets with 33 m bending radius close the orbit at the CLEO detector. The straight sections are used for RF cavities, horizontal electrostatic separators, and CHESS wiggler magnets.

Since N bunches per beam result in $2N$ crossings with counter rotating beams present, 4 electrostatic horizontal separators give the two beams anti-symmetric orbit perturbations, providing separation at 88 unwanted crossing points. A pair of vertical electrostatic deflectors is used to separate the beams at the crossing point diametrically opposite the IP.



FIGURE 2. Photograph taken in the accelerator tunnel, with the synchrotron on the left and CESR on the right.

2.1.2 Interaction Region

The CESR final focus quadrupoles are a hybrid of permanent magnet and superconducting magnets. The quadrupole nearest the IP is a 20cm long NdFeB vertically focusing permanent magnet lens. It is followed by a pair of 65cm superconducting quadrupoles that share a single cryostat. 45 degree skew quads and vertical steering magnets are incorporated in the same cryostat as the main s.c. quads. The design allows vertical β^* values as low as 0.7 cm. The quadrupoles are rotated by 4.5° about the beam axis to provide compensation for the 1.5T field of the solenoid of the CLEO detector (Figure 3). The skew quadrupoles provide for fine tuning of the solenoid compensation. The energy range of the IR optics extends from below 1.5GeV to at least 5.6GeV.

Round beam optics may be implemented with the addition of one of the iron/copper quads in the present IR, allowing equal β^* 's of 2-3 cm.

Beam position monitors close to the interaction point allow careful measurement and correction of the solenoid compensation.

The regions adjacent to the CLEO detector are effective particle background sources. Pumping is done by large high capacity titanium sublimation pumps, supplemented by several sputter ion pumps in both IR designs.

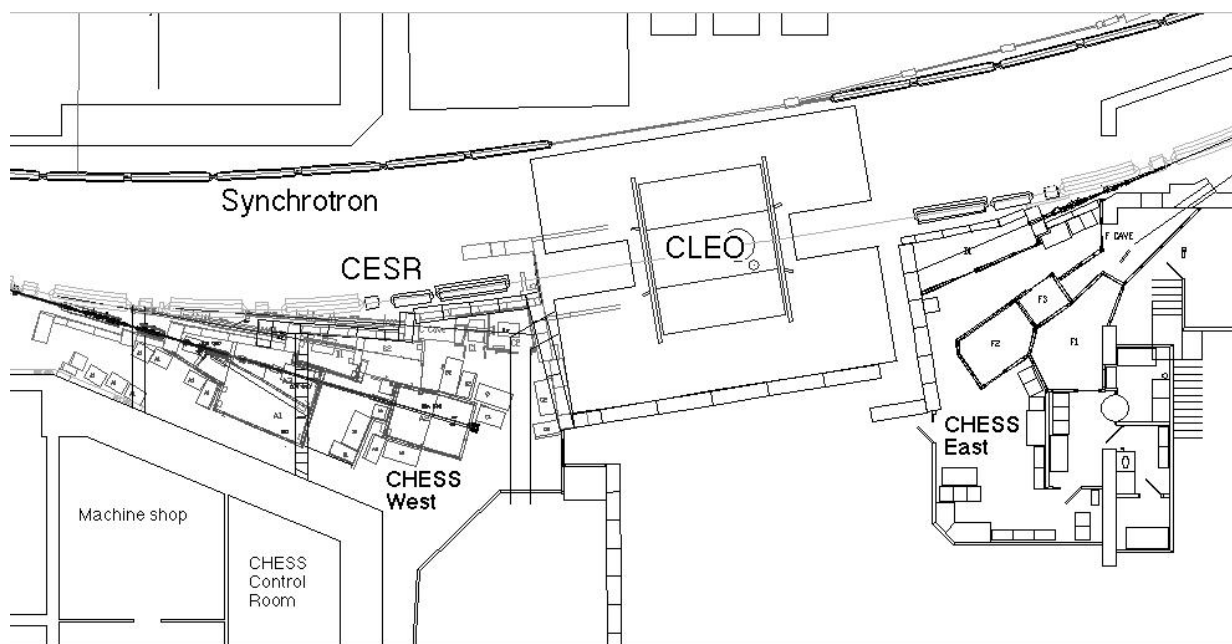


FIGURE 3. South Interaction Region of CESR with CLEO detector and CHESS East and West areas.

2.2 Synchrotron Radiation Facilities

The Cornell High Energy Synchrotron Source is a high-intensity high-energy X-ray source supported by the National Science Foundation. As a user facility, CHESS provides state-of-the-art synchrotron radiation facilities for research in Physics, Chemistry, Biology, and Environmental and Materials Sciences. A special NIH Research Resource, MacCHESS, supports special facilities for protein crystallographic studies.

The new Cornell University faculty beam lines and research area known as the “G-Line” was completed in Summer, 2001. Here faculty, postdocs, and students will work in interdisciplinary teams to build and operate these beam lines.

All together, the CHESS, MacCHESS, and G-Line staff members number 45 persons.

CHESS serves a wide spectrum of experimental groups from Universities, National Laboratories and Industry. Each year, 700-800 scientists and training scientists visit CHESS to collect data. In addition, a significant effort from the staff is aimed at developing synchrotron radiation experimental facilities and methods that utilize the high intensity photon flux provided by the Cornell Electron Storage Ring (CESR).

2.2.1 Layout

CHESS West is located West of the CLEO detector (see Figure 3). The area contains five user stations from three beam lines. The beam lines are oriented to make use of the radiation emitted from the electrons as they pass through wiggler and hard-bend dipole magnets (see Section 2.2.2 for station characteristics).

CHESS East is located East of the CLEO detector as shown in Figure 3. The area consists

of 4 experimental stations from two beam lines. The beam lines are oriented to make use of the radiation emitted from the positrons as they pass through wiggler and hard-bend dipole magnets.

The CHESS G-Line is located West of the CLEO detector and West of the CHESS West area. The beam lines are oriented to accept the radiation emitted from the positrons as they pass through the wiggler that also produces the radiation from the electrons for the CHESS A-line (see Table 1 below for station characteristics).

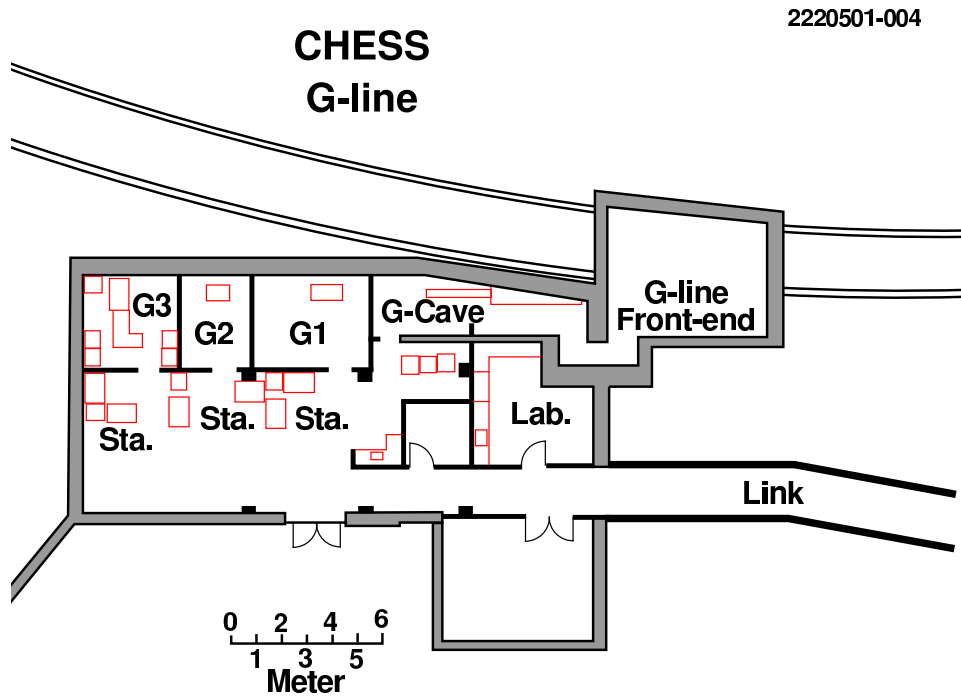


FIGURE 4. CHESS G-Line layout.

2.2.2 CHESS X-ray Beam Characteristics

Lines A,B, and C derive their radiation from the electron beam in CESR, and lines D, F, and G receive radiation from the positron beam.

3 Accelerator Physics Considerations

3.1 CESR Performance at 5.3 Gev

The integrated luminosity per unit time is the product of the peak luminosity and the overall luminosity duty cycle, which includes factors of luminosity lifetime during a run, filling time, tuning stability, breakdowns, and scheduling.

TABLE 1. CHESS beam line x-ray characteristics at 5.3 GeV with typical optics and experiments.

Station	Magnet Source	E_{critical}	Optics	Experiments
A1	1.0 horiz. mrad from 49 pole permanent magnet wiggler	15 keV	Vertical (Rh coated mirror) and Horiz. focusing (Si(111))	Macromolecular Crystallography
A2	1.0 horiz. mrad from 49 pole permanent magnet wiggler	15 keV	Vertical (Rh coated mirror) and Horiz. focusing (Si(111))	Crystal Growth Studies and Material Science
B1	0.4 horiz. mrad from 31.8 m radius electromagnet	10 KeV	White Beam	Angle Dispersive High Pressure Diamond Anvil Cell
B2	0.75 horiz. mrad from 31.8 m radius electromagnet	10 keV	Double crystal Ge(111) mono	Energy Dispersive High Pressure Diamond Anvil Cell
C1	Up to 6 horiz. mrad from 31.8 m radius electromagnet	10 keV	Double crystal Si(111) mono	High Temperature Powder Diffraction
D1	4.5 horiz. mrad from 31.8 m radius electromagnet	10 keV	Double crystal multi-layer mono	Small Angle Scattering
F1	1.0 horiz. mrad from 24 pole 1.2 T permanent magnet wiggler	22 keV	Vertical (Rh coated mirror) and Horiz. focusing (Si(111))	Macromolecular Crystallography
F2	1.7 horiz. mrad from 24 pole 1.2 T permanent magnet wiggler	22 keV	Vertical (Rh coated mirror) and Horiz. focusing (Si(111)) double bounce mono)	Multi-wavelength Anomalous Dispersion Macromolecular Crystallography
F3	6.0 horiz. mrad from 31.8 m radius electromagnet	10 keV	Double crystal Si(111) mono	High Temperature Powder Diffraction
G1	1.0 horiz. mrad from 49 pole permanent magnet wiggler	15 keV	Vertical (Rh coated mirror) Double crystal multilayer mono	Small Angle Scattering
G2	1.0 horiz. mrad from 49 pole permanent magnet wiggler split with G3	15 keV	Vertical (Rh coated mirror) Double crystal multilayer mono	Thin Films and Subpicosecond Time Resolved
G3	1.0 horiz. mrad from 49 pole permanent magnet wiggler split with G3	15 keV	Vertical (Rh coated mirror) Double crystal multilayer mono	Crystal Growth Studies and Material Science

3.1.1 Peak Luminosity

CESR has routinely started runs with peak luminosities of $1.1 - 1.2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ at beam energies in the 5.3 GeV region. Table 2 below gives the beam parameters related to peak luminosity.

TABLE 2. CESR operating parameters at 5.3 GeV.

Parameter		Value	Units
Peak Luminosity	$\hat{\mathcal{L}}$	1.3×10^{33}	$\text{cm}^{-2}\text{s}^{-1}$
Beam-beam parameters	$\xi_{y,x}$	0.065, 0.03	-
Focussing Function at IP	$\beta_{y,x}^*$	2.1, 100	cm
Bunch length	σ_L	1.9	cm
Number of bunches		45	
Current per beam		0.33	A
Betatron tunes	$Q_{y,x}$	9.58, 10.52	
Synchrotron tune	Q_S	0.052	

3.1.2 Luminosity Duty Cycle

Integrated luminosity is related to the peak luminosity ($\hat{\mathcal{L}}$) by the luminosity duty cycle:

$$\mathcal{L}_{Int} = \mathcal{L}_{Peak} \times D_{Lum} \times \Delta t \quad (1)$$

If we are interested in the luminosity over one fill-run cycle, the filling time and luminosity lifetime are the primary factors determining the luminosity duty cycle, D_{Lum} . Over one day, unplanned breakdowns and beam losses enter the picture. Over months, scheduled shutdowns and variability in machine performance are added. CESR fills in a “top up” mode where the beams remaining at the end of a run are preserved and additional electrons and positrons are added, saving considerable filling time and maintaining a more constant heat load on the vacuum system. Turn around times (run stop to run start) of 6 minutes have been repeatedly achieved. The luminosity duty cycle averaged over a day can exceed 70%.

3.1.3 Integrated Luminosity

High peak luminosity, combined with good luminosity duty cycle, has enabled CESR to deliver an average of 1.4 fb^{-1} per month to CLEO during the period from November, 2000 through June, 2001. The monthly performance is shown in Figure 5 below.

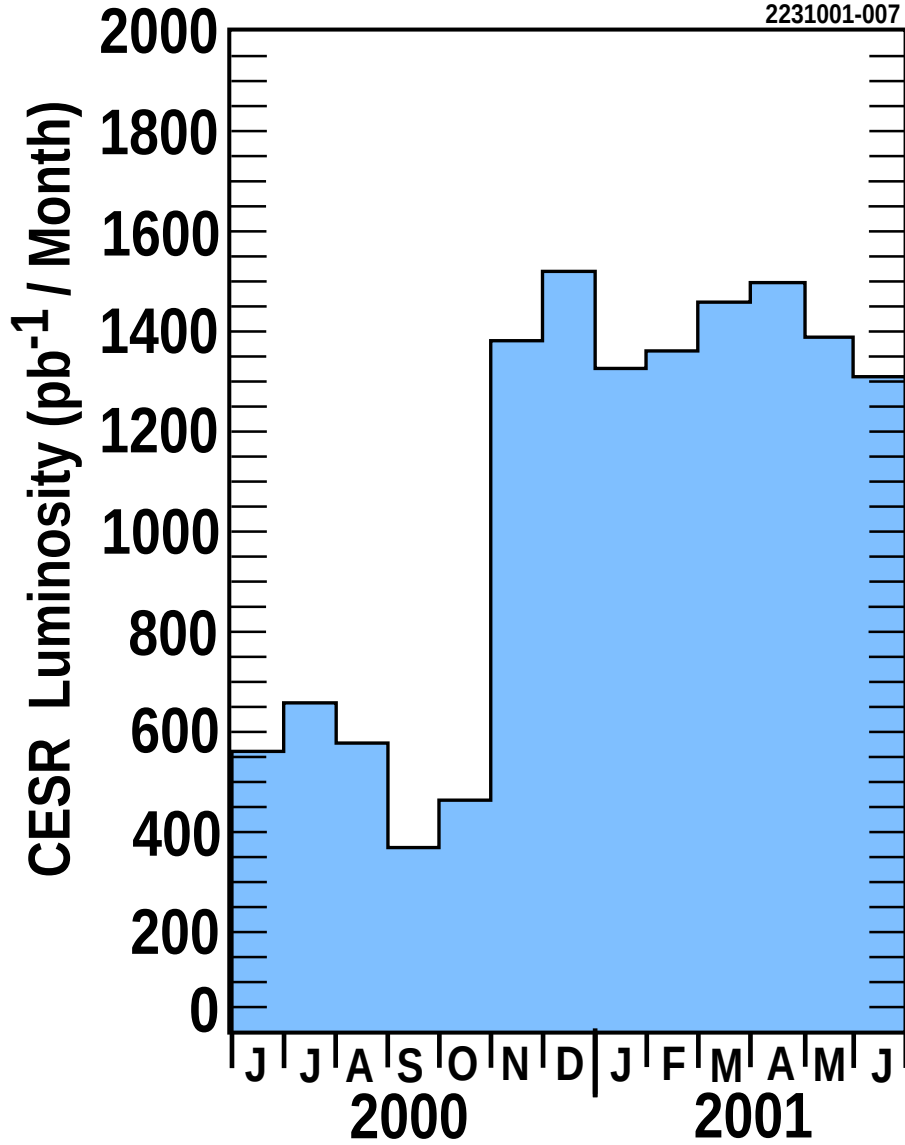


FIGURE 5. Monthly luminosity recently delivered by CESR.

3.2 Expected Performance vs. Beam Energy

3.2.1 Luminosity

Several energy dependent parameters determine the scaling of luminosity with energy. The instantaneous luminosity ($\mathcal{L}$) of a collider may usefully be expressed as:

$$\mathcal{L} = 2.17 \times 10^{32} (1 + r) \frac{I E_0 \xi_y}{\beta_y^*} \quad (2)$$

where:

- r is the vertical to horizontal beam size ratio at the interaction point,
- I is the total beam current,

- E_0 is the beam energy,
- ξ_y is the vertical beam-beam parameter, and
- β_y^* is the vertical focusing function at the interaction point.

One factor of energy is explicit in this expression. When luminosity is optimized I and ξ_y are as large as possible and β_y^* is as small as possible. If limits to any of these values are energy dependent, additional factors of E_0 will appear in the variation of luminosity with energy.

A simplified picture of the beam-beam interaction shows the particles of each beam being incoherently “heated” in all 3 dimensions, but predominantly the vertical plane, by passage through the other beam. This heating is dependent on the beam-beam parameters, ξ_y or ξ_x (represented collectively by ξ). Heating the beam results in an increase in emittance and cross section, there lowering ξ . The equilibrium value of ξ (and thus luminosity) is therefore related to the cooling rate (damping), which is produced by synchrotron radiation effects. The damping rate, α , is proportional to E_0^3 in a conventional collider. Experience at many colliders is consistent with $\xi_y \propto \alpha^{\frac{1}{3}}$, *i.e.*, $\xi_y \propto E_0$. Another factor of E_0 is implicit in the computation of ξ .

A second radiation related effect comes about through the natural horizontal emittance, ε_x , (phase space area) of the beam. Normally $\varepsilon_x \propto E_0^2$. This decrease in emittance may limit the current per bunch as can be seen in the expression for the horizontal beam-beam parameter, ξ_x , with a flat beam cross section and no dispersion at the interaction point:

$$\xi_x \approx \frac{Nr_e}{2\pi\gamma\varepsilon_x} \quad (3)$$

where:

- N is the number of electrons per bunch,
- r_e is the electron radius (2.8177×10^{-15} m), and
- γ is the relativistic factor.

As ε_x decreases, N may also need to decrease to keep ξ_x below its dynamically limited value. If this is the case, another factor of beam energy will enter in the luminosity scaling with energy.

In summary, in addition to the explicit dependence of luminosity on beam energy, most colliders find a factor of E_0 in the beam (bunch) current limits and two in the beam-beam parameter, ξ_y . The result is that without enhancement of radiation effects, $L \propto E_0^4$, as has been observed in many colliders.

Enhancement of the radiation from the beam may be accomplished by using “wiggler” magnets which bend the beam back and forth (or in a helical path) via alternating magnetic fields. Properly designed, the effects on the electrons’ orbits are minimal. The added radiation can be very strong, resulting in modification of the energy scaling laws described above. This will be described further in Section 3.2.3.

3.2.2 Beam Lifetime

The principal determinants of the single beam lifetime in CESR-c are expected to be the Touschek effect and beam-gas scattering from the residual gas in the vacuum chamber.

3.2.2.1 Touschek effect

“Intrabeam scattering” is the elastic Coulomb scattering of a single particle by other particles in the bunch. Multiple Coulomb scattering is an incoherent process that can lead to energy exchange between transverse and longitudinal oscillations, and a growth of transverse and longitudinal emittance. In an electron machine, the emittance growth rates are typically much smaller than the radiation damping rates, and usually have no impact on the equilibrium emittances.

However, the energy transfer in a single Coulomb scattering event will occasionally be sufficiently large that the scattered beam particles have final energies outside the energy acceptance of the machine. This loss mechanism is called the “Touschek effect”. The time dependence of the number of particles in a bunch is given by [1]

$$N(t) = \frac{N(0)}{1 + \frac{t}{T}} \quad (4)$$

in which T is the Touschek lifetime. This lifetime is a function of the machine lattice, the beam energy, intensity, emittances and momentum spread, and the momentum acceptance of the machine. The formula given in Equation (2) of Reference [1] has been used to evaluate the lifetime. The formula has been averaged over the current design lattice for 1.88 GeV operation. The results for the Touschek lifetime, for three different energies, and three different energy apertures, are shown in Figure 6. The beam parameters used at each energy are given in Table 3. The vertical emittances indicated in Table 3 and used in the calculation are approximately 1/2 actual colliding beam values (see Table 8).

TABLE 3. Beam parameters used for Touschek lifetime calculation.

Parameter	$E = 1.55$ GeV	$E = 1.88$ GeV	$E = 2.5$ GeV
Particles per bunch	4.5×10^{10}	6.5×10^{10}	8.2×10^{10}
Bunch length (rms)	9.9 mm	10.2 mm	10.2 mm
Relative momentum spread (rms)	0.075%	0.081%	0.077%
Horizontal emittance (rms)	214 nm	214 nm	214 nm
Vertical emittance (rms)	0.92 nm	0.83 nm	0.83 nm

The momentum acceptance of CESR-c is typically determined by the available transverse aperture at the points of maximum dispersion. For the current working lattice, including the pretzel, but excluding beam size effects, the physical relative momentum aperture is 0.87% , which corresponds to about 11 times the rms relative momentum spread (σ). However, care must be used to prevent nonlinear effects from reducing the transverse aperture to less than the physical aperture, which would cause the momentum aperture to be reduced below 11σ , decreasing the lifetime.

3.2.2.2 Beam-gas scattering

Loss of beam particles due to collisions with residual gas in the vacuum chamber is dominated by two processes: elastic Coulomb scattering and beam-gas bremsstrahlung.

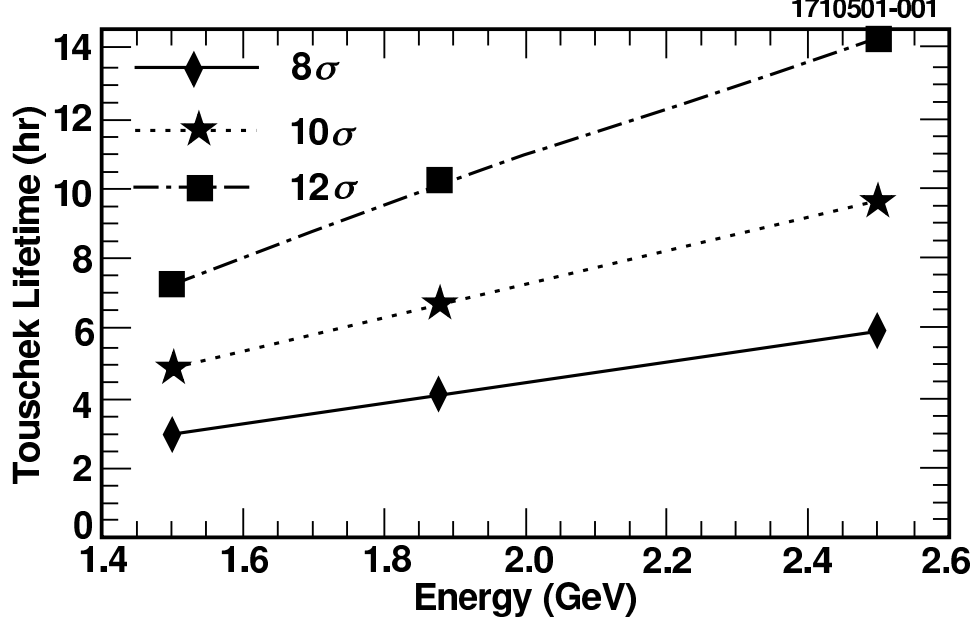


FIGURE 6. Touschek lifetime vs. energy; curves labeled by momentum aperture.

In the former case, electrons are lost when they Coulomb scatter at sufficiently large angles so as to leave the aperture. The cross section for scattering out of the aperture is [2]

$$\sigma_C = \frac{\pi r_0^2 Z^2}{\gamma^2} \left(\frac{\langle \beta_x \rangle}{A_x} + \frac{\langle \beta_y \rangle}{A_y} \right) \quad (5)$$

in which the average is taken around the ring, and A is the transverse acceptance, given by

$$A_{x,y} = \min \left(\frac{a_{x,y}^2}{\beta_{x,y}} \right) \quad (6)$$

Here a is the physical aperture (including the pretzel). For beam-gas bremsstrahlung, electrons are lost when they loose sufficient energy that they fall outside the momentum aperture. The cross section is [2]

$$\sigma_\gamma = \frac{4}{3} \frac{A}{N_A X_0} \left(\ln \left(\frac{1}{A_{\Delta p/p}} \right) - \frac{5}{8} \right) \quad (7)$$

in which $A_{\Delta p/p}$ is the relative momentum acceptance. Here A is the atomic mass, N_A Avagadro's number, and X_0 the radiation length.

The lifetime is related to the cross section by

$$\tau = \frac{0.474 T (^{\circ}\text{K})}{\sigma(b) P(\text{nTorr})} \text{ hr} \quad (8)$$

in which T is the absolute temperature, and P is the absolute pressure, of the residual gas. The partial and total lifetimes are shown in Figure 7, for N_2 gas, for which $Z=7$, $A=14$, $X_0=38 \text{ g/cm}^2$. The acceptances and average betas (obtained from the current 1.88 GeV design lattice) used are given in Table 4.

TABLE 4. Acceptances and betas used for beam-gas lifetime calculations.

$\langle\beta_x\rangle$	16.1 m
$\langle\beta_y\rangle$	18.6 m
A_x	14.7 μm
A_y	15.4 μm
$A_{\Delta p/p}$	0.87%

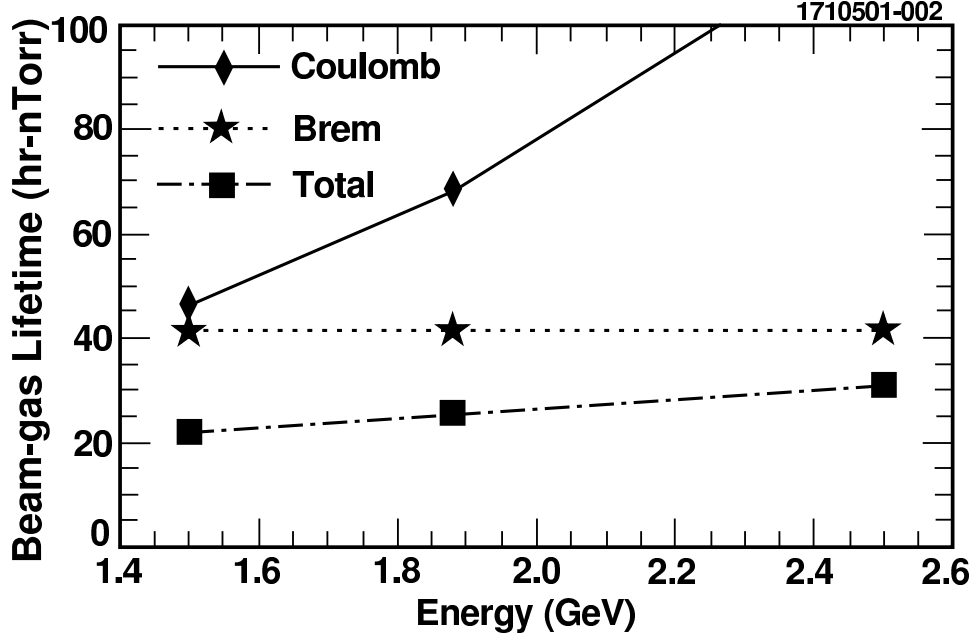


FIGURE 7. Beam-gas lifetime (at room temperature) vs. energy; curves labeled by scattering process. This is for a N_2 -equivalent pressure of 1 nTorr.

As for the Touschek lifetime, nonlinear effects may reduce the transverse aperture to less than the physical aperture, and this would decrease the gas scattering lifetimes.

3.2.3 Energy Scaling with Wigglers

In an electron storage ring without wigglers, the equilibrium horizontal emittance, energy spread, and horizontal amplitude damping rate, are determined by the synchrotron radiation from the bend dipoles in the ring, as described in Section 3.2.1. For a separated function machine such as CESR, the dependence of these quantities on the ring energy is given by the following equations:

$$\tau_{xr}^{-1} = \tau_{xr0}^{-1} \left(\frac{E}{E_0} \right)^3 \quad \sigma_{\delta r} = \sigma_{\delta r0} \left(\frac{E}{E_0} \right) \quad \varepsilon_{xr} = \varepsilon_{xr0} \left(\frac{E}{E_0} \right)^2. \quad (9)$$

If one inserts wigglers into the ring, with a wiggler field B_w , then there are additional contributions to the equilibrium horizontal emittance, energy spread, and horizontal amplitude damping rate, from the synchrotron radiation in the wigglers. If the dispersion at the

wigglers is zero, the dependence of these contributions on the beam energy and the wiggler field is given by

$$\begin{aligned}
\tau_{xw}^{-1} &= \tau_{xw0}^{-1} \left(\frac{E}{E_0} \right) \left(\frac{B_w}{B_{w0}} \right)^2 \\
\sigma_{\delta w} &= \sigma_{\delta w0} \sqrt{\left(\frac{E}{E_0} \right) \left(\frac{B_w}{B_{w0}} \right)} \\
\varepsilon_{xw} &= \varepsilon_{xw0} \left(\frac{E}{E_0} \right) \left(\frac{B_w}{B_{w0}} \right)
\end{aligned} \tag{10}$$

The total damping rate, emittance, and energy spread are then

$$\begin{aligned}
\tau_x^{-1} &= \tau_{xr0}^{-1} \left(\frac{E}{E_0} \right)^3 + \tau_{xw0}^{-1} \left(\frac{E}{E_0} \right) \left(\frac{B_w}{B_{w0}} \right)^2 \\
\sigma_\delta^2 &= \sigma_{\delta r0}^2 \left(\frac{E}{E_0} \right)^2 + \sigma_{\delta w0}^2 \left(\frac{E}{E_0} \right) \left(\frac{B_w}{B_{w0}} \right) \\
\varepsilon_x &= \varepsilon_{xr0} \left(\frac{E}{E_0} \right)^2 + \varepsilon_{xw0} \left(\frac{E}{E_0} \right) \left(\frac{B_w}{B_{w0}} \right)
\end{aligned} \tag{11}$$

Table 5 shows the values of the constants in these equations, assuming the normal 5.3 GeV CESR lattice, and 20 m of wiggler length, located as in the current 1.88 GeV design lattice.

TABLE 5. Constants in the damping rate, emittance, and energy spread relations. Bend magnet wiggler parameters (20 m of 2.1 T) are added according to Equation (11) for final storage ring parameters.

	E_0	1.88 GeV
	τ_{xr0}^{-1}	1.89 s^{-1}
Bend Magnet Parameters	$\sigma_{\delta r0}$	2.48×10^{-4}
	ε_{xr0}	26.7 nm
	B_{w0}	2.1 T
	τ_{xw0}^{-1}	18.0 s^{-1}
Wiggler Parameters	$\sigma_{\delta w0}$	7.72×10^{-4}
	ε_{xw0}	260 nm

Inspection of Table 5 shows that the coefficients of the terms coming from the ring bending magnets are anywhere from 4 to 20 times smaller than the wiggler terms. Thus, for $E=E_0$ and $B_w = B_{w0}$, the effects of the wigglers dominate those of the ring bending magnets.

Figures 8, 9, and 10 show, respectively, the horizontal damping time, rms relative energy spread, and rms horizontal emittance, vs. energy, for a fixed wiggler field of 2.1 T.

Because of aperture and lifetime restrictions, the increase in the relative energy spread and horizontal emittance above 1.88 GeV shown in Figures 8 and 9 are not desirable. The

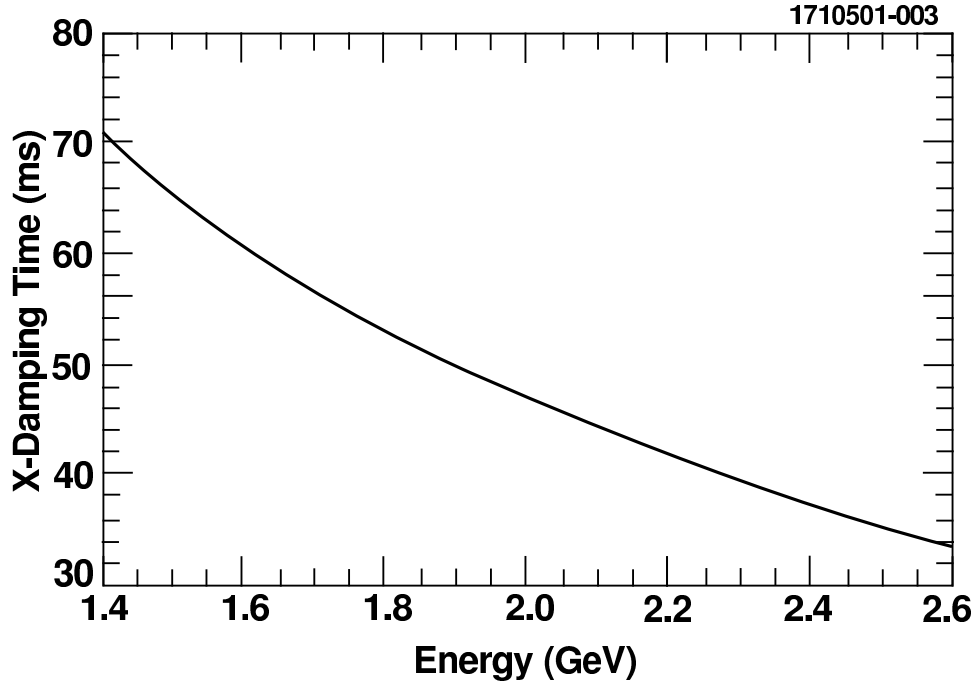


FIGURE 8. Horizontal damping time, vs. energy; wiggler field fixed at 2.1 T.

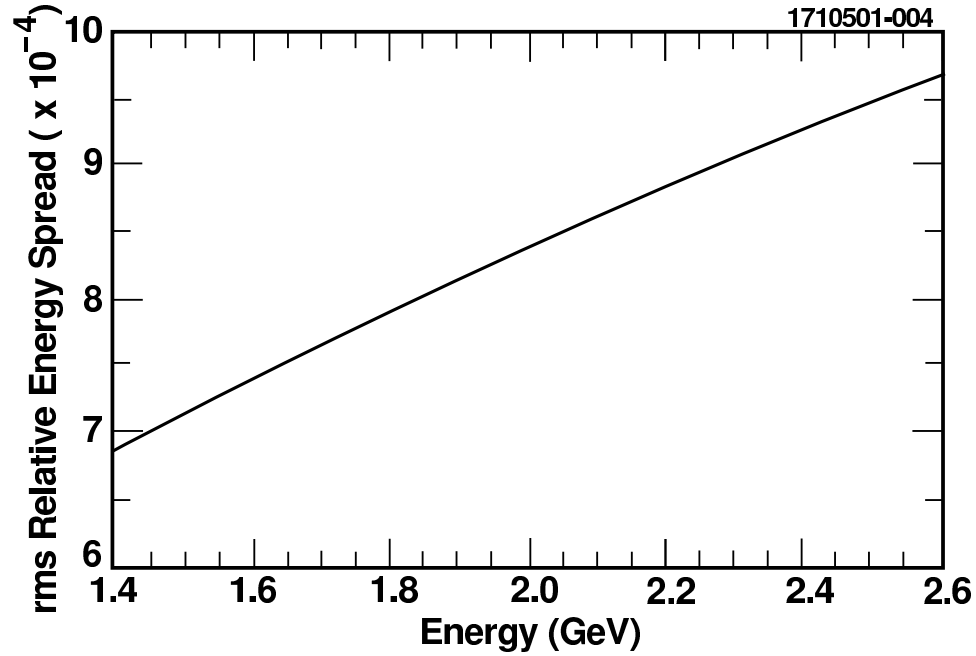


FIGURE 9. RMS relative energy spread, vs. energy; wiggler field fixed at 2.1 T.

emittance is able to be decreased by lattice manipulation, but the energy spread increase is inevitable. To prevent this from occurring, the wiggler field can be reduced as the energy increases. From Equation (11), the wiggler field must decrease with energy according to

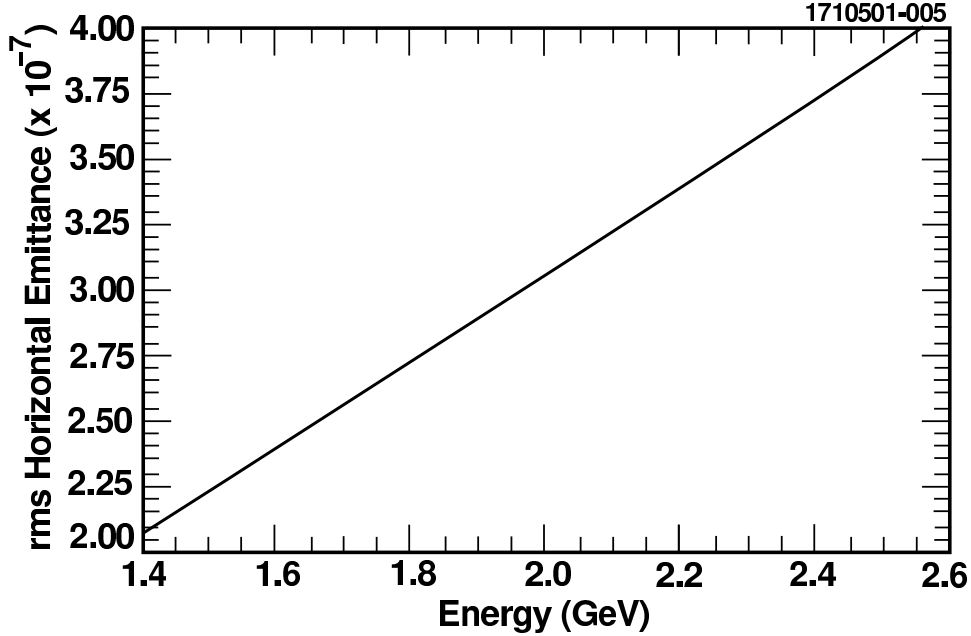


FIGURE 10. RMS horizontal emittance, vs. energy; wiggler field fixed at 2.1 T.

$$B_w(E) = B_{w0} \left(\frac{\sigma_\delta^2(1.89 \text{ GeV}) - \sigma_{\delta r0}^2 \left(\frac{E}{E_0}\right)^2}{\sigma_{\delta w0}^2 \left(\frac{E}{E_0}\right)} \right) \text{ for } E > 1.89 \text{ GeV} \quad (12)$$

The wiggler field, as a function of energy, is shown in Figure 11. This requires that the wiggler have a dynamic range from 1.5 T to 2.1 T.

Figures 12, 13, and 14 show, respectively, the horizontal damping time, rms relative energy spread, and rms horizontal emittance, vs. energy, for wiggler field which varies with energy as given in Figure 11.

3.2.4 Detector Backgrounds

Beam-generated detector backgrounds at CESR are well-described [3,4,5] in terms of scattered synchrotron radiation and collisions of beam particles with residual gas. In addition, there is a contribution to the radiation dose due to particle losses during the CESR injection process. We describe the energy-dependence of these background sources, present an estimate of backgrounds arising from Touschek scattering, and estimate the impact on backgrounds from the operation of superconducting cavities in the IR straight sections.

3.2.4.1 Synchrotron Radiation Backgrounds

Due to the crossing-angle collision geometry required for bunch-train operation, the beams are displaced horizontally in the strong interaction-region (IR) quadrupoles, and thus generate synchrotron radiation (SR). The dominant sources of SR in the IR are the final dipole before the IR straight (the “soft-bend”), and Q2, the horizontally focusing IR quadrupole. The near-IR vacuum chamber profile is designed to shield the central detector

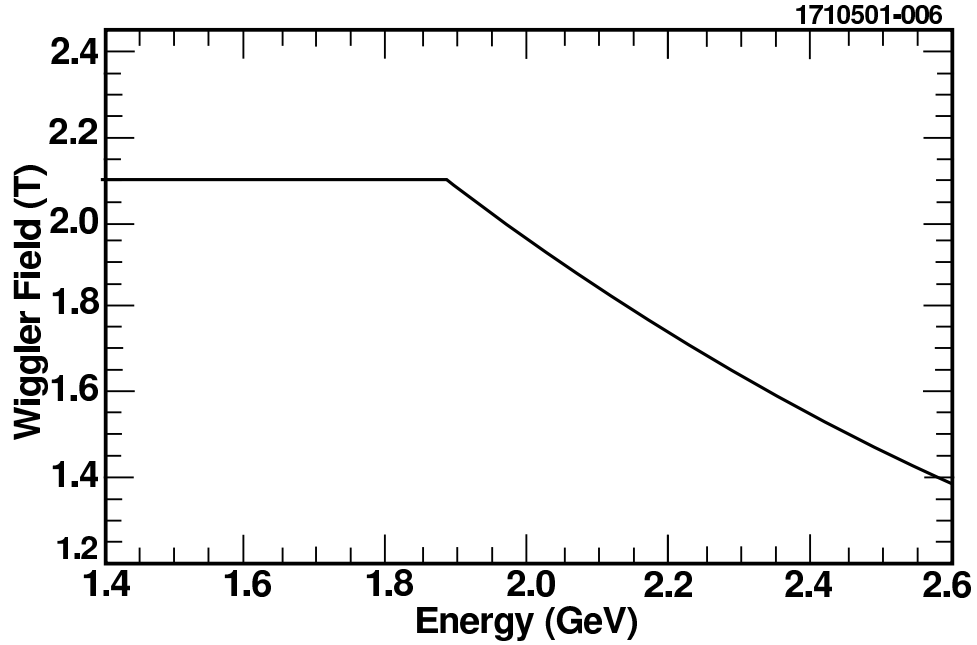


FIGURE 11. Wiggler field vs. energy.

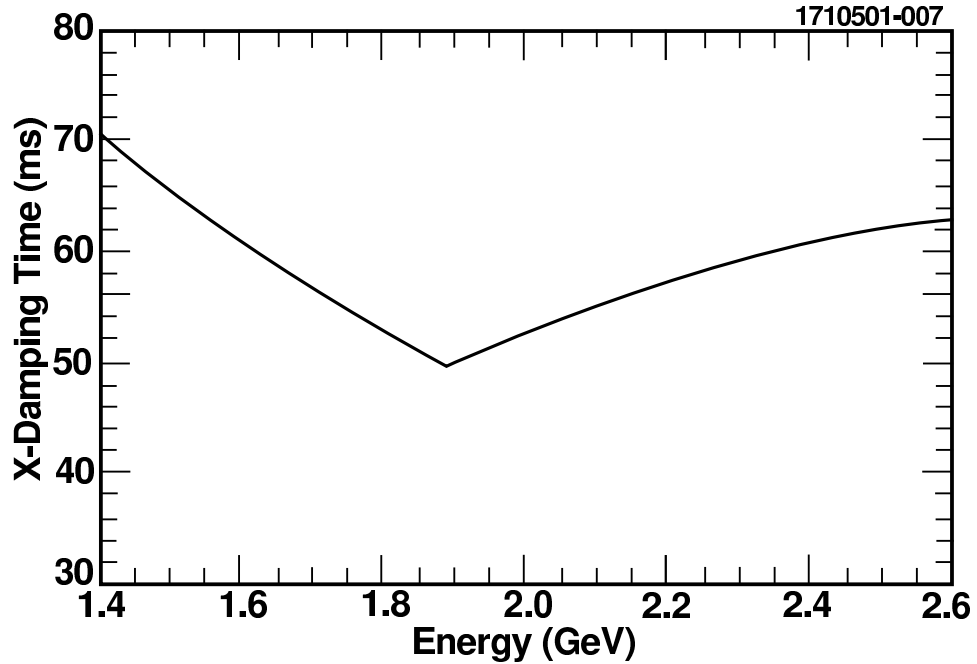


FIGURE 12. Horizontal damping time, vs. energy; wiggler field given by Figure 11.

beampipe from direct synchrotron radiation emitted by the incoming beams. As a result, synchrotron radiation contributes to detector backgrounds only through scattering mechanisms which propagate x-rays through the detector beampipe. X-rays which strike the upstream IR mask may forward scatter into the beampipe, whereas radiation which strikes the downstream mask surface may backscatter into the beampipe.

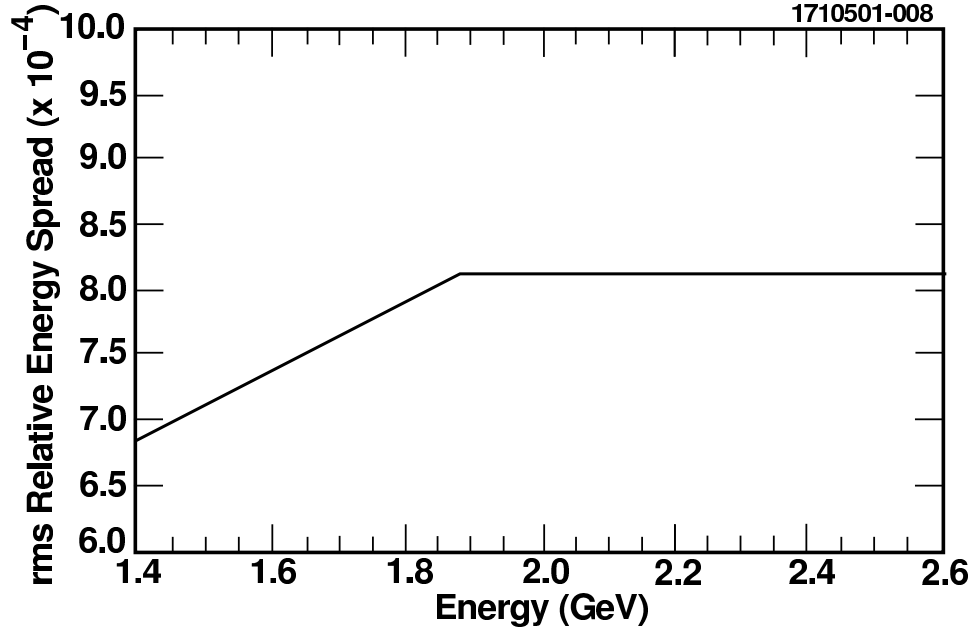


FIGURE 13. RMS relative energy spread, vs. energy; wiggler field given by Figure 11.

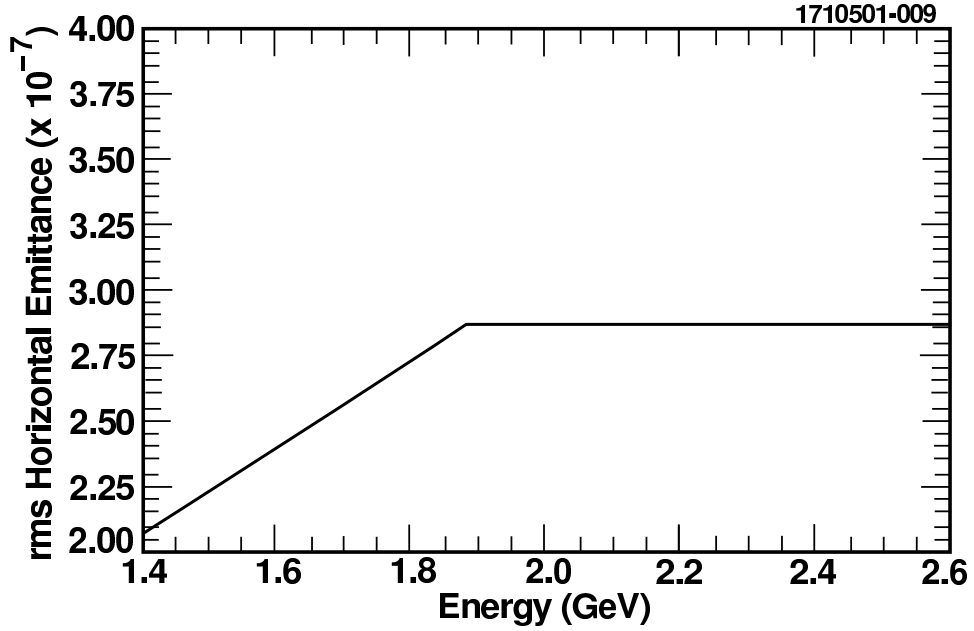


FIGURE 14. RMS horizontal emittance, vs. energy; wiggler field given by Figure 11.

The IR layout for CESR operation at low-energy is identical to that at 5.3 GeV. Additionally, the beam optics and trajectories through the IR are similar. Therefore, consideration of SR backgrounds at low-energy involves solely the strong dependence of the SR emission rate and spectrum on the beam energy. The critical energy of the synchrotron radiation emission at 5.3 GeV for the two sources mentioned above are 2.3 keV (soft-bend) and 3.2 keV (Q2), whereas at 1.88 GeV they become 0.10 keV and 0.15 keV respectively. Simulations of the

SR generation and scattering for the 1.88 GeV optics show that the SR emission is contained below ~ 5 keV and that the x-ray flux which strikes the beampipe is completely absorbed by the $5\text{ }\mu\text{m}$ gold coating. As a result, SR backgrounds are completely negligible for low-energy CESR operation.

3.2.4.2 Beam-Gas Backgrounds

Detector backgrounds arise from the interaction of beam particles with residual gas in the vacuum chamber. Coulomb scattering and Bremsstrahlung dominate these beam-gas interactions. A Coulomb scattering interaction produces a beam particle with potentially large betatron amplitude which, depending on the scattering angle and the location of the scattering event, may strike the vacuum chamber near the IR, generating electromagnetic shower debris which reaches the detector. A Bremsstrahlung interaction results in a beam particle of lower energy, and a γ -ray emitted along the direction of motion. The off-momentum particle may be transported to the IR where it is over-focused in strong quadrupoles and may strike the vacuum chamber. In CESR at 5.3 GeV, Bremsstrahlung dominates Coulomb scattering as a source of detector backgrounds by an order of magnitude.

Beam particles which strike nearest to the IP are more effective in generating background hits in the inner detector layers. The vacuum chamber nearest the IP onto which beam particles may be lost is referred to as the “IR mask.” Neglecting the finite beam size, the flux of scattered particles, N , striking the IR mask from a region of azimuth between s and $s + ds$ is

$$N \propto \left[\int_{mask} \frac{d\sigma_{coul}(E)}{d\Omega} d\Omega + \int_{mask} \frac{d\sigma_{brem}(E)}{dE} dE \right] \times I_{beam} \times \left(P_0 + \frac{dP}{dI}(E) I_{beam} \right) ds \quad (13)$$

For Coulomb scattering the integration is performed over all scattering angles which yield trajectories which strike the IR mask. Likewise, for bremsstrahlung the integration is performed over all energies which yield off-momentum trajectories which strike the IR mask. The pressure has both static (P_0) and dynamic (dP/dI) components.

The energy dependence of the integrated cross-sections is as follows. For Coulomb scattering the energy dependence, $d\sigma/d\Omega \propto 1/E^2$, is unrelated to the angular dependence so we expect the Coulomb component to scale as $1/E^2$ *in lattices with similar optical functions but different energies*. The bremsstrahlung differential cross-section depends only on the *fractional energy loss*. The energy dependence then arises solely through differences in the off-momentum transport properties of lattices of different nominal energy. For lattices with identical magnet layout and similar optical functions, the energy dependence should be small. The residual gas pressure depends on energy through the dynamic pressure rise, dP/dI , which is proportional to the *number* of SR photons emitted which in turn varies linearly with beam energy.

Inasmuch as the pressure is dominated by the dynamic rather than static component, we expect the Coulomb contribution to the *mask strike rate* to vary as I^2/E , and the bremsstrahlung as I^2E . Likewise, the energy deposition for coulomb and bremsstrahlung are expected to vary as I^2 and I^2E^2 , respectively. Of course, there is further energy dependence in the shower development which must be simulated with an electromagnetic shower code.

A calculation of the IR mask strike rates has been performed for three CESR configurations:

- CESR operation at 5.3 GeV with permanent magnet IR quadrupole optics,
- 5.3 GeV operation with the superconducting IR quadrupole optics (CESR Phase III), and
- CESR-c operation at 1.88 GeV with the superconducting IR quadrupole optics.

Figure 15 shows the integrated cross-sections for coulomb scattering and bremsstrahlung as functions of distance from the interaction point for the CESR-c case. These quantities (known as “source-effectiveness”), when folded with the residual gas pressure profile, yield the contribution to detector backgrounds from beam-gas interactions at a given source location s . It is seen that only beam-gas interactions within about 45 m from the IP lead to detector backgrounds. The bremsstrahlung component, beginning at about 13 m from the IP dominates the coulomb component in the source-effectiveness.

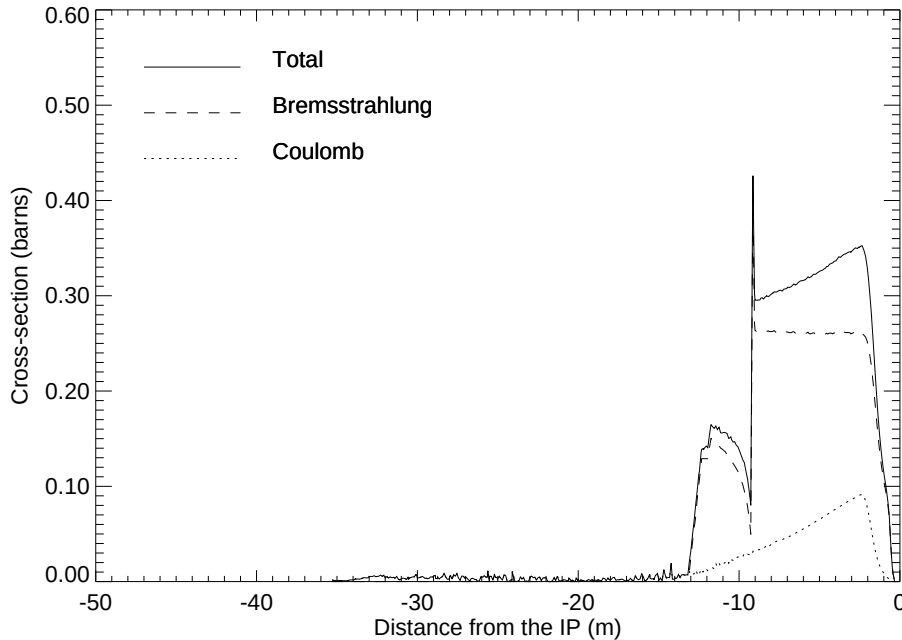


FIGURE 15. Integrated cross-sections for coulomb scattering and bremsstrahlung as functions of distance from the interaction point for 1.88 GeV CESR-c operation.

Table 6 shows a comparison of IR mask strike rates and energy deposition for the three CESR configurations described above. In each case, a realistic pressure profile based on the known vacuum pump locations, pumping speeds, chamber conductance and gas load has been used. The reduction in strike rates in going from the present CESR configuration to the Phase III configuration is due to a change in the IR vacuum chamber profile. In the former IR layout the limiting aperture was the IR mask itself (located 0.25 m from the IP), whereas in the Phase III configuration the limiting aperture is ~ 3 m from the IP. The resulting strike rates and energy deposition rates for CESR-c are consistent with the simple scaling arguments described above. We see that the energy deposition in CESR-c is reduced

TABLE 6. IR mask strike rates and energy deposition from beam-gas interactions for three CESR configurations.

	Present	Phase III	CESR-c
Energy [GeV]	5.3	5.3	1.88
Total Current [A]	0.70	1.0	0.36
Coulomb Strike Rate [kHz]	9.0	3.4	0.8
Bremsstrahlung Strike Rate [kHz]	101	41.7	2.3
Total Strike Rate [kHz]	110	45.1	3.1
Coulomb Energy Deposition [MeV/ μ s]	49	18	1.5
Bremsstrahlung Energy Deposition [MeV/ μ s]	330	77	1.5
Total Energy Deposition [MeV/ μ s]	379	94	3.0

by two orders of magnitude relative to present operation. As a result, we expect the detector background and radiation dose from beam-gas interactions in CESR-c to be negligible.

We have described the results of a generator-level analysis of beam-gas interactions in CESR-c. A full Monte-Carlo simulation of lost particle shower development in the CLEO detector is planned.

3.2.4.3 Touschek Scattering

Touschek scattering [1,6], the collision of particles within a bunch, results in two off-momentum particles, one with energy deviation $+\delta = \Delta E/E$ and the other with $-\delta$. These off-momentum particles follow trajectories similar to those for bremsstrahlung interactions. The Touschek scattering rate is a strong function of the beam energy and the beam dimensions. The rate increases rapidly with decreasing energy, decreasing bunch length and decreasing vertical emittance.

An estimate of the IR mask strike rate and energy deposition due to Touschek scattered beam particles has been obtained as follows. At each azimuthal location, s , the full range of energy losses ($-1 < \delta < 0$) and energy gains ($0 < \delta < 1$) is explored to determine the range of energy deviations which produce trajectories which strike the IR mask. Let $R(s, \delta)$ denote the Touschek scattering rate at s for a given momentum acceptance δ . If at s it is determined that trajectories in the range $\delta_{min} < \delta < \delta_{max}$ strike the IR mask, then the rate of IR mask strikes is $N = [R(s, \delta_{min}) - R(s, \delta_{max})]/2$ where the factor of two takes into account that the standard Touschek rate calculations assume two lost particles for each interaction, whereas here both the positive and negative energy error components are treated independently.

The IR mask strike rate from Touschek scattering is shown in Figure 16 for the 1.88 GeV CESR-c lattice (with $\varepsilon_y/\varepsilon_x=0.004$, $\sigma_s = 1\text{cm}$). It is seen that only a small region of the machine upstream of the IP contributes to the Touschek rate. The IR mask strike rate is completely dominated by the positive energy error scattered particles. The IR mask strike rates and energy deposition are tabulated in Table 7 for a few combinations of bunch length and vertical emittance. We see that for CESR-c design parameters the strike rate and energy deposition are similar to those from beam-gas interactions. The effects of Touschek scattering

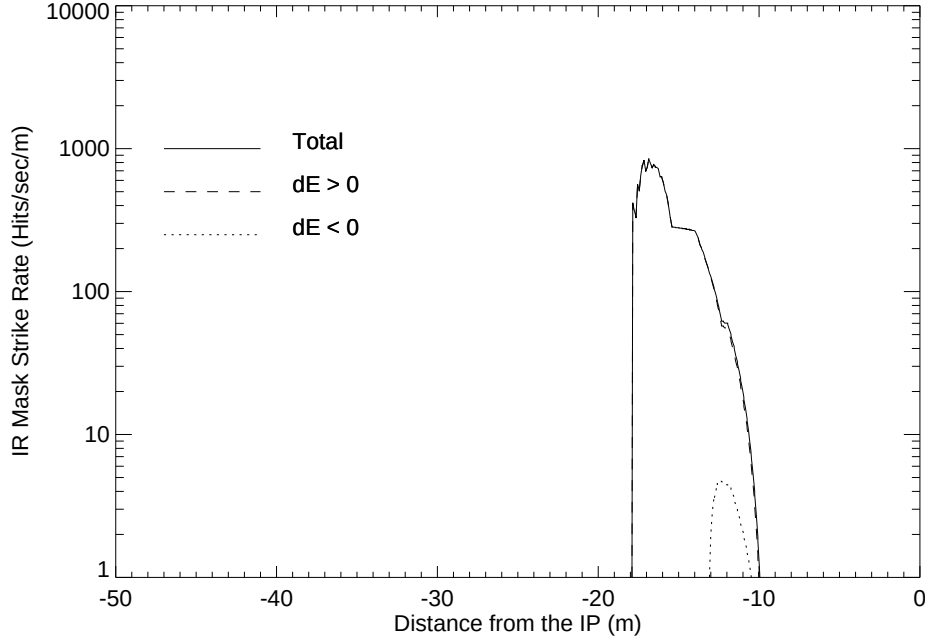


FIGURE 16. IR mask strike rate from Touschek scattering background.

may be visible, but the impact on detector backgrounds is expected to be negligible.

TABLE 7. Touschek scattering particle background for several operating conditions.

$\varepsilon_y/\varepsilon_x$	Bunch length	Strike Rate	Energy Deposition
	[cm]	[kHz]	[Mev/ μ s]
0.01	2	0.65	1.3
0.004	2	1.0	2.1
0.01	1	1.4	2.9
0.004	1	2.2	4.5

3.2.4.4 Radiation from SRF Cavities in the Interaction Region Straights

The installation of two additional superconducting RF cavities may be required to reduce the bunch length in CESR. Cavities will be installed in the IR straight adjacent to the CLEO detector, ~ 7 m from the interaction point. The cavities are a source of hard x-rays and low energy electrons and due to their proximity to the CLEO detector are a potential source of background radiation.

X-rays result from electrons which are liberated at field emission sites, accelerated in the RF fields, strike the cavity walls and generate photons by bremsstrahlung. Likewise, low energy electrons may be accelerated and ejected down the beam tube. It should be emphasized that x-rays outside of the vacuum chamber will be absorbed in a shielding wall

constructed between the cavity and the detector. Only those x-rays which propagate inside the vacuum pipe are a concern for detector backgrounds.

The x-ray flux emitted from a superconducting cavity and transported in a beam-tube geometry was measured under various cavity conditions. In most cases a spectrum with exponential energy dependence was observed to extend nearly to the full cavity field. The measured fluxes were strongly dependent on the cavity field and processing history. For example, one hour of high pulsed power processing at higher gradient was observed to reduce the x-ray emission by an order of magnitude at the operating gradient. As a result, we expect to operate at gradients below those achieved in processing by a safety margin of $\sim 10\%$. With this guideline, we expect hard x-ray count rates on the IR mask in the range of a few MHz, with a spectrum extending to the accelerating voltage of the cavity (~ 2 MeV). This gives total energy deposition rates of a few MeV/ μ s. This must be compared to the energy deposition from beam-gas interactions which deposits a few 10^2 MeV/ μ s at 5.3 GeV, or a few MeV/ μ s at CESR-c energies. We therefore expect the impact on detector backgrounds to be minimal, provided cavity operating gradients are kept safely below processing levels.

3.2.4.5 Injection Losses

In the last several years, injection losses in CESR have accounted for about 20% of the total integrated radiation dose delivered to the detector. The radiation conditions during CESR injection are strongly dependent on the operating conditions. For example, the tunes, pretzel amplitude, separation at parasitic crossings, trajectory through the IR, and injected beam conditions can all play a role in particle loss during injection.

At lower energy we expect to inject at similar tunes and with similar separation at the parasitic beam-beam crossing points, so we expect the dynamics which influence particle loss to be similar, with the important exceptions of effects due to the longer damping time and to the nonlinearities introduced by the wigglers. This opens up the possibility for greater particle loss at low energy. On the other hand, the total charge requirements are smaller since the beam currents are reduced. As a result, we expect the total radiation dose to remain approximately constant as the machine energy is reduced.

3.2.4.6 Summary

All the detector background sources considered, apart from injection losses, are expected to be greatly reduced for CESR operation at 1.88 GeV relative to that at 5.3 GeV. We therefore expect these traditional sources of background to be negligible. It is expected that the total accumulated radiation dose will be dominated by injection losses, which we expect to remain approximately constant as the machine energy is lowered. The detector backgrounds during HEP running are expected to be dominated by sources of particle loss associated with the beam-beam interaction itself, that is, the growth of vertical beam tails and subsequent loss of particles near the IR. This source of particle loss, present at all energies, should be similar in lattices with different nominal energies, but similar dynamic aperture properties and damping times.

3.2.5 CESR-c Parameter List

A detailed parameter list for CESR-c is presented in Table 8. Common to all configurations is a circumference of 768.4 m, arc bending magnet radius of 87.9 m, “hard bend” magnet radius of 31.65 m, and 45 bunches arranged in 9 trains of 5 bunches in each beam.

3.3 Lattice and Layout

The CESR ring layout will be modified to make space to accommodate wigglers for increased radiation damping and emittance control. Approximately 20 m of high field wigglers will be installed in the storage ring arcs.

3.3.1 Present Ring Layout

At present, dipole guide field magnets are uniformly distributed throughout the machine arcs leaving no contiguous drift space in which to install the 20 m of wigglers required for 1.5-2.5 GeV operation. Two pairs of antisymmetrically powered horizontal electrostatic deflectors support the differential closed orbits (pretzel) that permit bunch train operation. A single pair of vertical deflectors separate the beams at the crossing point diametrically opposite the single interaction point. A pair of permanent magnet wigglers generate x-ray beams for CHSS users.

3.3.1.1 Interaction Region

The final focus quadrupoles are placed symmetrically about the interaction point. The magnet nearest the IP is a 20 cm long vertically focusing permanent magnet(Nd). It is followed by a pair of vertically(Q1) and horizontally(Q2) focusing superconducting lenses. (See Figure 17). The configuration is designed to yield β_y^* as low as 7 mm at 5.3 GeV beam energy and to restore the vertical β function to a modest level at the parasitic crossing point nearest the IP. With the bunches in each train spaced 14 ns apart, that crossing point is 2.1 m from the collision point and the strong compact quadrupoles provide the requisite focusing.

The focusing functions with $\beta_y^* = 12$ mm, and 5.175 GeV beam energy, are shown in Figure 17. The chromaticity introduced by the IR quadrupoles is $dQ_y/d\delta \sim -13.0$, $dQ_x/d\delta \sim -2.6$.

At 1.88 GeV, the contribution of the short permanent magnet front end becomes much more significant. The focusing functions are shown in Figure 18, in the case of $\beta_y^* = 10$ mm. The beam-beam interaction at the first parasitic crossing point is further reduced, (as compared to 5.3GeV) as is the chromaticity that is generated by the IR.

With $\beta_y^* = 10$ mm and $\beta_x^* = 95$ cm, and 1.88 GeV beam energy, the chromaticity introduced by the IR quadrupoles is $dQ_y/d\delta \sim -4.0$, $dQ_x/d\delta \sim -1.7$.

The hybrid final focus allows for the possibility of round beam optics, in which $\beta_x^* = \beta_y^*$ and $\epsilon_x = \epsilon_y$. The permanent magnet and two superconducting quads are arranged as a triplet. The permanent magnet focuses vertically and the superconducting magnets horizontally and vertically respectively. A fourth resistive quad, located outside of the CLEO solenoid

TABLE 8. CESR-c parameters.

	HEP 11/00	Charm	J/ψ	2.5 GeV
Beam Energy [GeV]	5.30	1.88	1.55	2.50
Luminosity [$\div 10^{33}$ cm $^{-2}$ s $^{-1}$]	1.23	0.30	0.15	0.50
n_b (number of bunches)	45	45	45	45
r (v/h aspect ratio at the IP)	0.009	0.010	0.009	0.010
N [$\div 10^{11}$ e/bunch]	1.28	0.65	0.45	0.81
I [mA/bunch]	8.04	4.06	2.82	5.10
I_{tot} [A] (current / beam)	0.36	0.18	0.13	0.23
ξ_V (vert. tune shift parameter)	0.053	0.040	0.035	0.040
ξ_x (horiz. tune shift parameter)	0.0261	0.0355	0.0284	0.0343
Hor. rms Beam size at the IP [mm]	0.45	0.44	0.45	0.43
Ver. rms Beam size at the IP [μ m]	4.15	4.45	4.19	4.26
β_x^* [m]	0.96	0.87	0.87	0.87
β_V^* [cm]	1.80	1.00	1.00	1.00
$\theta_{C1/2}$ [mr] (crossing half-angle)	2.30	3.50	3.50	3.50
σ_L [cm] (bunch length)	1.80	1.00	0.97	1.05
ε_x [$\div 10^{-7}$ m](emittance)	2.10	2.19	2.31	2.15
emittance coupling (κ)	0.0045	0.0091	0.0076	0.0084
α_P (momentum compaction)	0.0115	0.011	0.011	0.011
Q_S (synchrotron tune)	0.054	0.110	0.105	0.104
Q_x (betatron tune)	10.53	10.52	10.52	10.52
σ_E/E_0 [$\div 10^{-4}$] (energy spread)	6.96	8.11	7.46	7.94
$\tau_{X,Y}$ [ms] (transv. damping time)	22.82	55.25	69.38	52.19
U_0 [MeV] (s.r. loss/turn)	1.19	0.18	0.11	0.25
V_C [MV] (accel. cavity voltage)	6.7	10.0	7.5	12.0
k [V/pc] (HOM loss parameter)	8.0	8.0	8.0	8.0
P_{HOM} [kW] (per beam)	59.2	15.0	7.3	23.8
P_{TOTAL} [MW] (both beams)	0.98	0.09	0.04	0.16
n_c (number of cells/ring)	4	5	4	5
Wiggler peak field [T]	1.2	2.10	2.10	1.75
Wiggler length total [m]	4.7	18.20	18.20	18.20

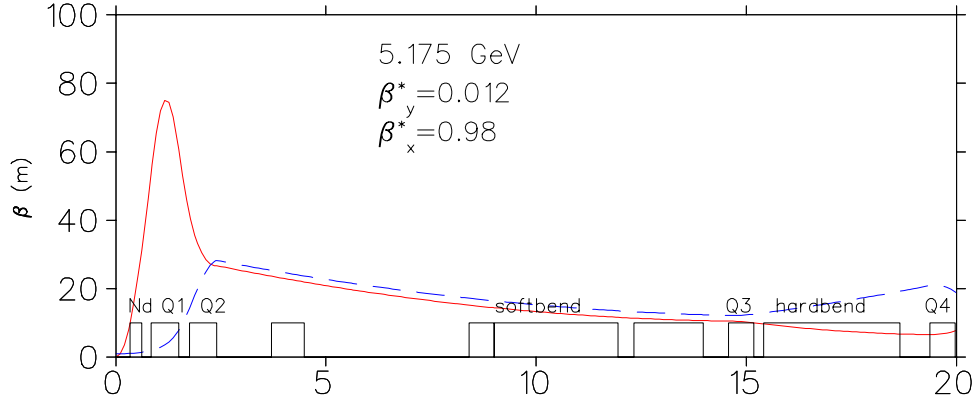


FIGURE 17. Interaction region. The β -functions in the interaction region at 5.3GeV

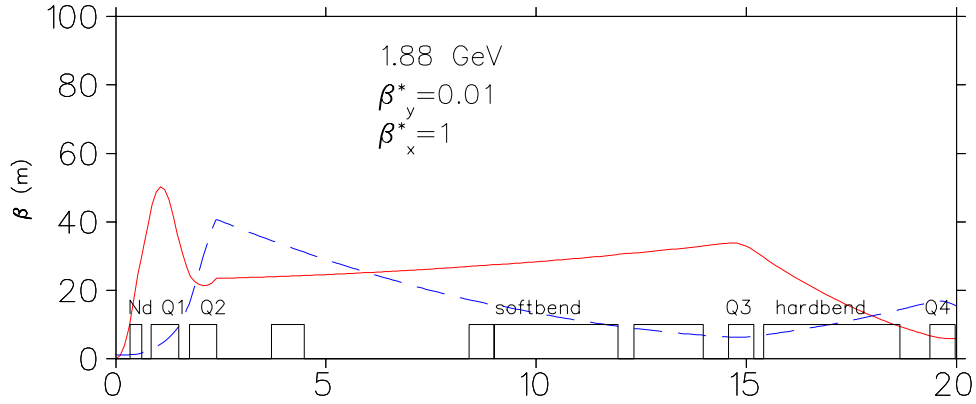


FIGURE 18. Interaction region. The β -functions in the interaction region at 1.88GeV, $\beta_y^*=10\text{mm}$, $\beta_x^*=94\text{cm}$

accomplish the match of IR to arc optics. Interaction region optics with $\beta_y^* = \beta_x^* = 30\text{mm}$ at 1.88GeV are shown in Figure 19

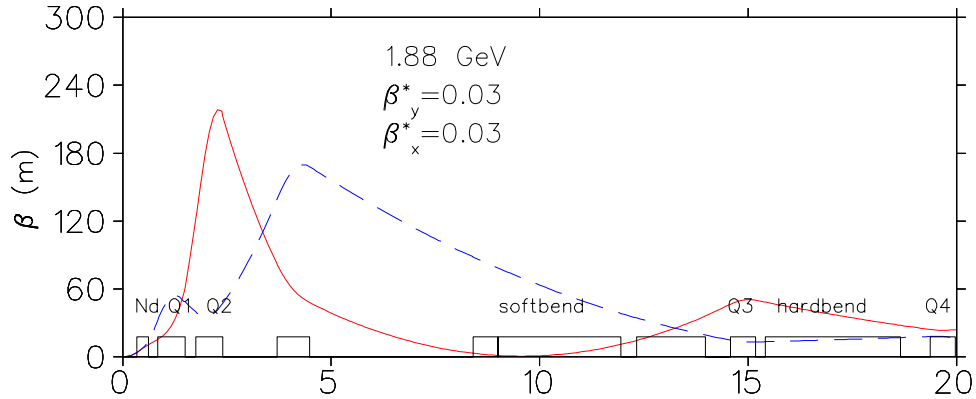


FIGURE 19. Interaction region. The β -functions in the interaction region at 1.88GeV for round beams $\beta_x^* = \beta_y^* = 30\text{mm}$.

3.3.1.2 Solenoid Compensation

In order to compensate the transverse coupling introduced by the CLEO solenoid the entire set of IR quadrupoles – permanent magnet, Q1 and Q2 – are rotated 4.5° about the beam axis. Consistent with the symmetry of the solenoid, the rotations are antisymmetric about the collision point. Superimposed on the final focus quadrupoles, and within the same cryostat, are skew quadrupole windings that are powered to fine tune the compensation. The third degree of freedom in the 3 pair decoupling configuration is provided by a resistive skew quad located adjacent to the first bend magnet (soft bend).

The effect of the solenoid field is compensated when the 4×4 transfer matrix through the IR insertion is block diagonal and there is no coupling of horizontal motion outside of the insertion to vertical displacement at the interaction point. Or in terms of the coupling matrix elements at the IP [7]

$$\begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ \sim & 0 \end{pmatrix}. \quad (14)$$

The compensation is tuned, first on the basis of beam based coupling measurements and then for luminosity, by adjustment of the interaction region skew quadrupole currents. The details of the compensation will in general depend on beam energy. Solutions have been identified for 5.3 GeV beam with 1.5 T solenoid and 1.88 GeV beam with 1.0 T solenoid field, both well within the range of the skew quadrupole correctors.

If we assume that the limiting beam-beam tune shift is the same in both vertical and horizontal planes, then that limit occurs when the emittances are related as $\varepsilon_y = (\beta_y^*/\beta_x^*)\varepsilon_x$, corresponding to a residual coupling of $\sim 1\%$, a level that is readily achieved with available diagnostics.

3.3.1.3 Lattice

The CESR lattice is designed to provide separation of the bunches in the counter-rotating beams at the parasitic crossings that occur with nine 5-bunch trains in each beam. The trains are nearly evenly spaced about the ring, and the bunches within each train spaced 14 ns apart. The beams are made to collide with a horizontal angle so that the trajectories are separated at the parasitic crossing points nearest the IP. The horizontal and vertical betatron tunes are 10.52 and 9.58 respectively and the horizontal emittance, including the contribution of the permanent magnet x-ray source wigglers is about 200 nm-rad. Dispersion at the interaction point is zero. The closed orbits of the electron and positron beams are shown in Figure 20. An important feature of the pretzeled orbits is that electrons(positrons) are displaced toward the electron(positron) injection septum, and beams approach the IR from the outside of the ring.

All of the CESR lattice quadrupoles are independently powered and the optimization of the optics depends critically on this flexibility. There is an approximate mirror symmetry, but no periodicity. The storage ring sextupoles are similarly independent and the strengths are chosen to minimize energy, amplitude, and pretzel dependence of betatron functions and coupling parameters, as well as to correct chromaticity. Typical lattice parameters are summarized in Table 9.

TABLE 9. CESR lattice parameters.

Parameter	Value
β_y^* (mm)	18
β_x^* (m)	1.0
η^* (m)	0.0
ε_x (nm-rad)	220
σ_E / E	6.8×10^{-4}
Energy loss / turn (MeV)	1.14
Beam energy (GeV)	5.175
Bunches/beam(trains $\times$ bunches/train)	9×5
Crossing angle (mrad)	± 2.6

3.3.2 Ring Modifications

The ring layout will be modified to provide semi-contiguous drift space for the installation of superconducting wiggler magnets. One of the 6.6 m long arc dipoles, with bend radius 87m will be removed, and the number of turns on the adjacent dipoles increased by 50%. (A similar redistribution of bend field was exploited to make space for the electrostatic deflectors that are now the basis of the pretzel separation scheme.) The proposed deployment of wigglers is shown in Figure 21.

3.3.2.1 1.88 GeV Lattice

The 1.88 GeV optics are designed to look as much as possible like the 5.3 GeV lattice with which we have considerable experience. The strong vertical focusing introduced by the damping wigglers is compensated by suitable adjustment of the arc quadrupoles. The dispersion function is tailored so that the horizontal emittance, which is dominated by the effect of the wigglers, is near 200 nm. Finally, the optical functions are chosen to optimize the efficiency of the pretzel separation and to minimize the long range beam-beam interactions at the multiple parasitic crossing points. The CESR-c lattice parameters are summarized in Table 10 and the optics and orbits shown in Figure 22. They are qualitatively very similar to 5.3 GeV optics[8].

The sextupole distribution that compensates chromatic functions is designed to minimize amplitude dependence of β -functions and tunes. Tracking studies indicate that the dynamic aperture is more than 20σ in both horizontal and vertical, excluding the wiggler nonlinearities, as shown in Figure 23. If we assume that the wiggler period is 40 cm, and that the horizontal field roll off is limited to 0.25% at 5.5 cm displacement from the wiggler axis, then the effect of the wiggler nonlinearities is to reduce dynamic aperture to $\sim 10\sigma$, for an on energy particle.

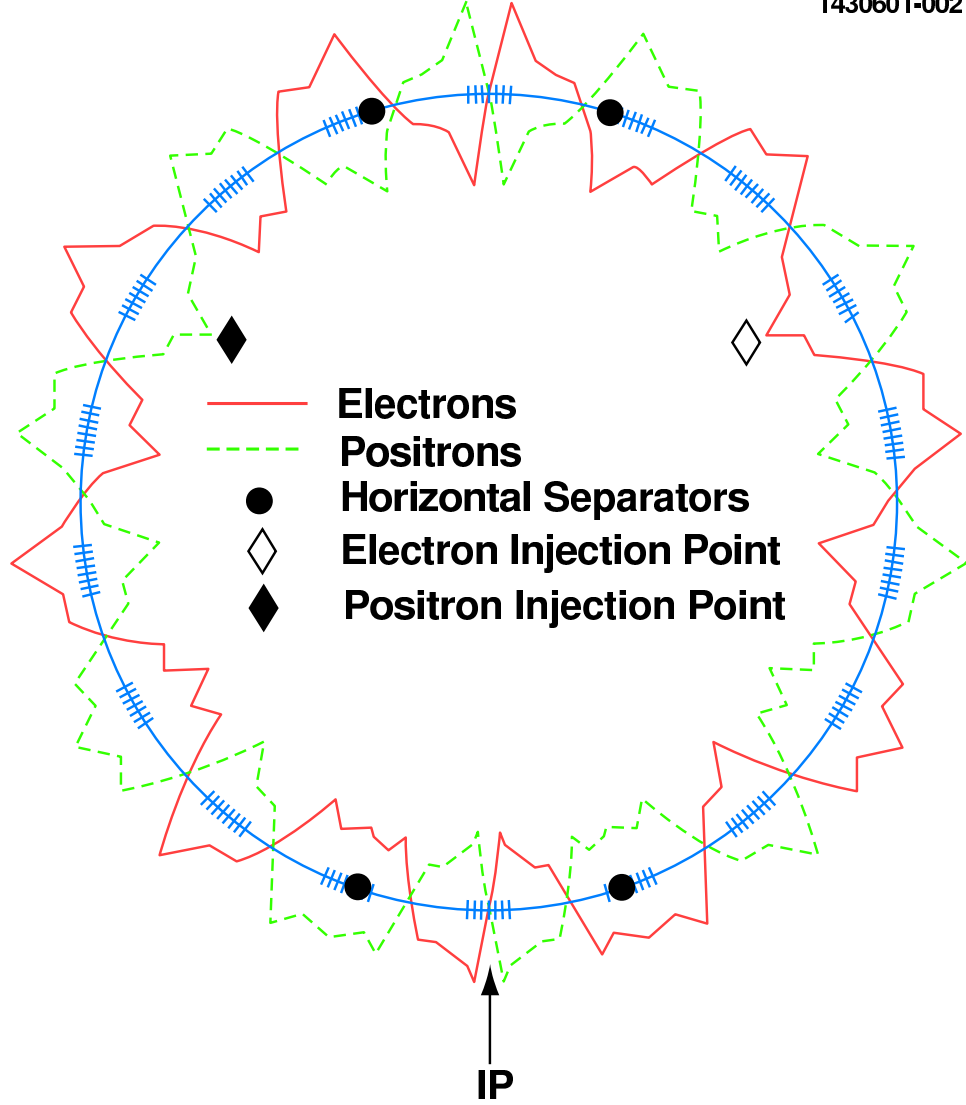


FIGURE 20. Pretzeled orbits. The maximum horizontal displacement of the beams from the center of the vacuum chamber is about 20 mm. The tic marks indicate the parasitic crossing points of electron and positron bunches corresponding to 9 trains with 5 bunches/train. The bunches within each train are 14 ns apart.

3.4 Beam Stability Considerations

3.4.1 Introduction

Several single bunch and multi-bunch effects are observed in CESR at 5.3 GeV, including the head-tail instability, bunch lengthening, a transverse multi-bunch photoelectron-induced instability, and a longitudinal multi-bunch instability. The single-bunch effects are inconsequential at 5.3 GeV for normal operating parameters. The multi-bunch instabilities are controlled by feedback systems. In this Section we scale the behavior of these effects, and the feedback damping, to lower operating energies. We also consider additional effects that are not observed at 5.3 GeV in CESR, including the transverse mode-coupling instability,

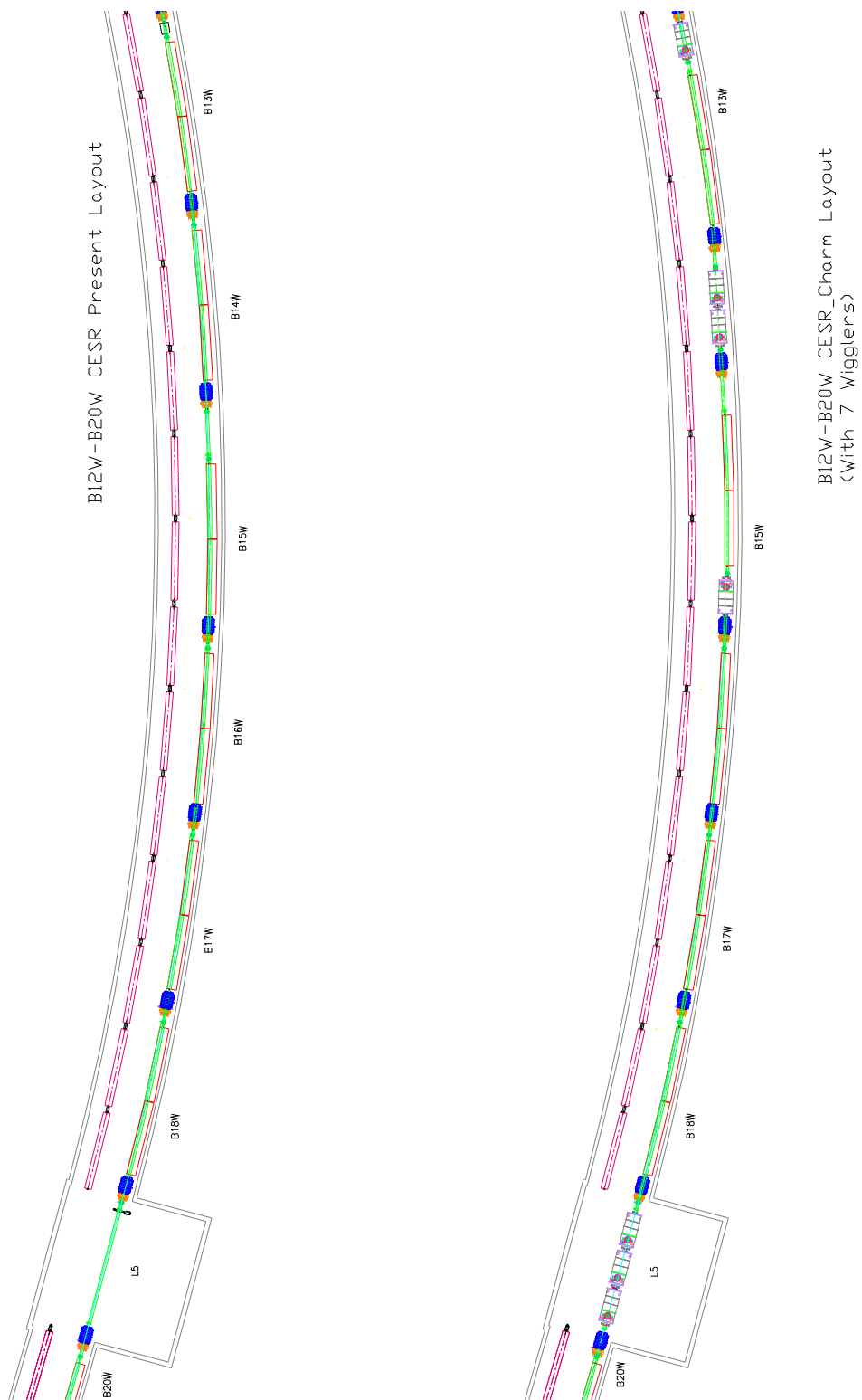


FIGURE 21. West arc of CESR indicating missing dipole and seven 1.3 m superconducting wigglers. Another seven wigglers are located similarly in the East arc.

TABLE 10. CESR-c lattice parameters.

Parameter	Value
β_y^* (mm)	18
β_x^* (m)	1.0
η^* (m)	0.0
ε_x (nm-rad)	220
σ_E / E	6.8×10^{-4}
Energy loss / turn (MeV)	1.14
Beam energy (GeV)	5.3
Bunches/beam(trains $\times$ bunches/train)	9×5
Crossing angle (mrad)	± 2.6

the longitudinal microwave instability, the electron cloud instability, and the fast ion instability. Each of these is found to be unimportant for the proposed machine. The beam-beam performance for our parameter set is simulated and found to be acceptable.

3.4.2 Single Bunch Stability Limits at 5.3 GeV

3.4.2.1 Transverse Single Bunch Stability at 5.3 GeV

Single bunch currents of more than 50 mA have been circulated in CESR at 5.3 GeV in high-energy physics conditions with no apparent transverse or longitudinal instability. For very large positive values of vertical chromaticity, an $m = -1$ vertical head-tail instability is observed. The threshold for this instability occurs at $I_b = 19.6$ mA for $dQ_y/d\delta = 9.7$ (vertical chromaticity) and at $I_b = 25.1$ mA for $dQ_y/d\delta = 7.3$. CESR is typically operated with much lower chromaticity and bunch currents of 10 mA or less, so this instability is not present during normal operations. No other transverse single bunch instabilities have been observed in CESR.

3.4.2.2 Longitudinal Single Bunch Stability at 5.3 GeV

No longitudinal single bunch instabilities have been observed in CESR. Minimal bunch lengthening has been observed. Under typical operating conditions, in which the zero-current bunch length $\sigma_z(0) = 18$ mm, the fractional bunch lengthening is $\sigma_z(10 \text{ mA})/\sigma_z(0) = 1.04$.

3.4.3 Projection of Single Bunch Stability Limits at Lower Energies

3.4.3.1 Transverse single bunch stability at lower energies

The growth rate of the m th head-tail mode is

$$\frac{1}{\tau_m} = \frac{N_B r_0 c}{2 \pi^2 \gamma} \frac{(dQ/d\delta) \omega_\beta \hat{z}}{c \eta \nu_\beta^2} \int_0^\infty d\omega \Re Z_\perp(\omega) J_m\left(\frac{\omega \hat{z}}{c}\right) J'_m\left(\frac{\omega \hat{z}}{c}\right), \quad (15)$$

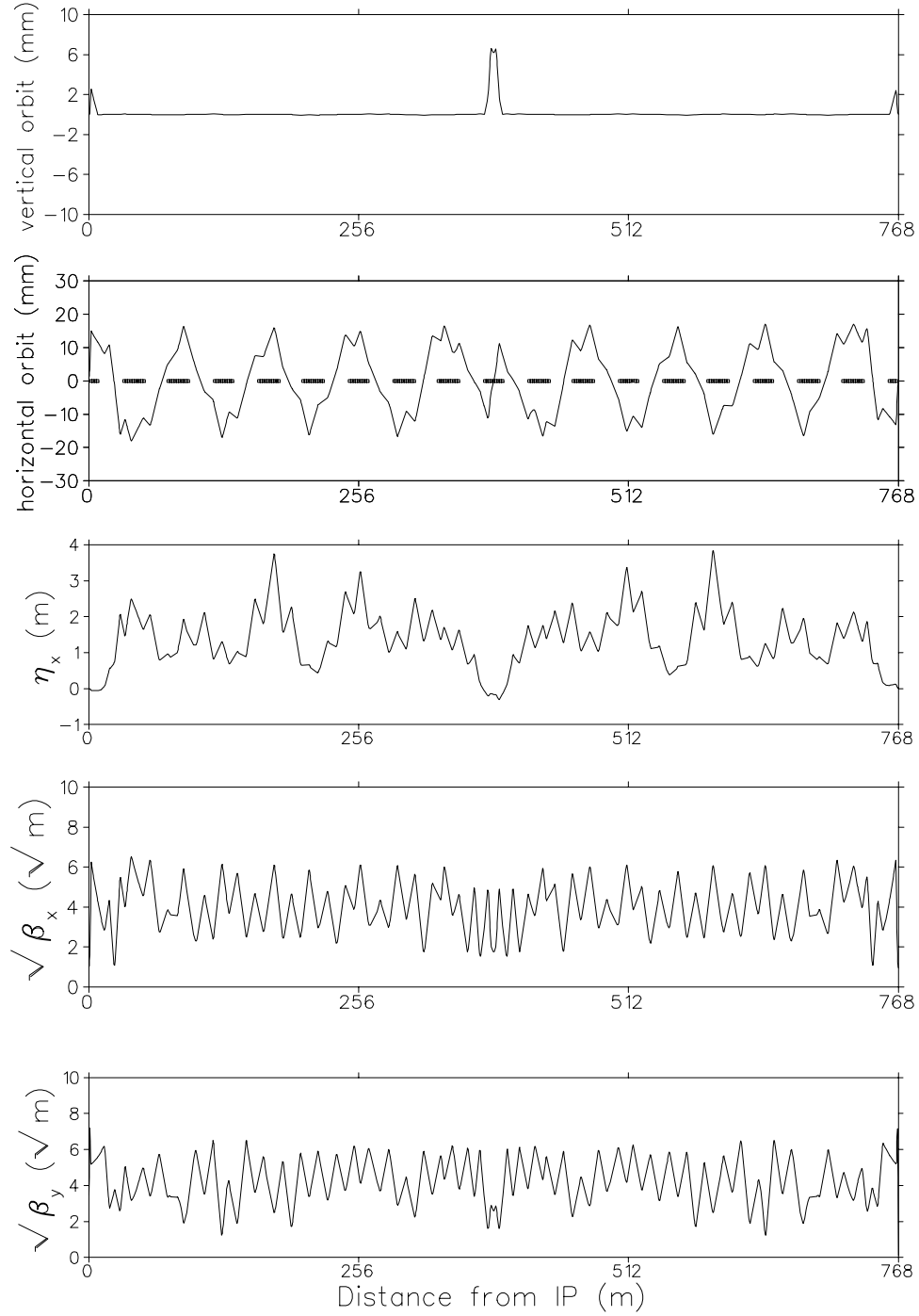


FIGURE 22. Lattice functions and closed orbits at 1.88 GeV with hybrid IR quadrupoles and damping wigglers. Wigglers are located in the arcs between quadrupoles between 75 m and 133 m from the IP and again 636 m and 692 m from the IP.

where N_B is the number of particles per bunch, r_0 is the classical electron radius, $\hat{z}$ is the z -amplitude of the synchrotron oscillation (airbag model), ω_β is the betatron frequency, and ν_β is the betatron tune. The mode will become unstable when the head-tail growth rate

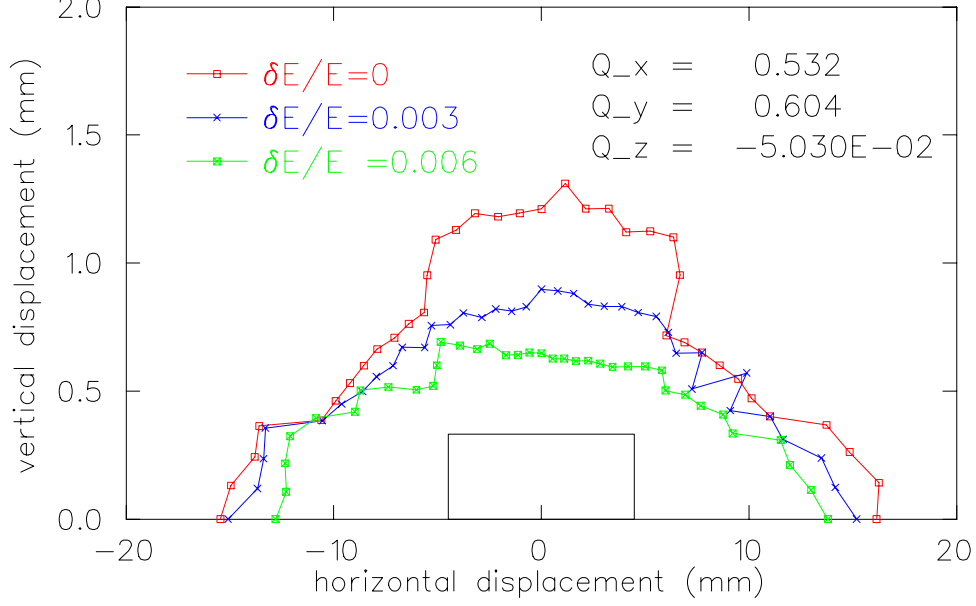


FIGURE 23. Dynamic aperture, including chromaticity correcting sextupoles and energy oscillations. Wiggler linear focusing is included but nonlinearities are not. The box indicates $x = 10\sigma_x$, $y = 10\sigma_y$.

exceeds the synchrotron radiation damping rate. We start by neglecting any change in the impedance integral in the above expression in going from the present 18 mm bunch length to the 10 mm bunch length of the proposed machine, and assume a vertical chromaticity $dQ_y/d\delta = +1$. Scaling from the observed $m = -1$ vertical head-tail instability threshold at 5.3 GeV we find that at 1.88 GeV the synchrotron radiation damping rate will be 12 times the head-tail growth rate. The detailed form of $Z_{\perp}(\omega)$ is not known, so the integral in the expression cannot be evaluated, but for any reasonable impedance model the integral must be at most be a few times larger at a bunch length of 10 mm than at the present CESR bunch length of 18 mm. We therefore expect that the $m = -1$ vertical head-tail mode will be stable.

The vertical single bunch coherent tune shift has been measured at 5.3 GeV in CESR with a bunch length of 10.5 mm. The measured tune shift is $\Delta Q_y/I_b = 4.1 \times 10^{-4}/\text{mA}$, which scales to an expected tune shift of $1.2 \times 10^{-3}/\text{mA}$ at 1.88 GeV. An estimate of the transverse mode-coupling instability threshold at 1.88 GeV is $I_{\text{thresh}} \approx Q_s/(\Delta Q_y/I_b) = 92$ mA, far above the design value $I_b = 4.06$ mA.

3.4.3.2 Longitudinal single bunch stability at lower energies

Bunch lengthening (in the regime of small fractional bunch lengthening) scales, for fixed σ_0 , as

$$(\sigma - \sigma_0) \propto \frac{\alpha_p I_b}{Q_s^2 E}. \quad (16)$$

Streak camera measurements in CESR at 5.3 GeV with low α_p optics and a bunch length of 10.5 mm show $\sigma = 10.46\text{mm} + (0.193\text{mm}/\text{mA})I_b$. Scaling to the proposed machine parameters at 1.88 GeV, the bunch lengthening will be a modest 0.125 mm/mA (5.1% at

the design current).

The threshold for the longitudinal microwave instability is

$$\hat{I} \leq F' \frac{E_0}{e} \frac{\eta \gamma \sigma}{|Z_{\parallel}/n|} \left(\frac{\Delta p_{FWHM}}{p_{\parallel}} \right)^2 \quad (17)$$

where $\hat{I}$ is the maximum instantaneous beam current, F' is a form factor which depends on the bunch charge distribution and impedance, and η is the slip factor. Holding the bunch length and $|Z_{\parallel}/n|$ constant (which implies the same F') and using the ultra-relativistic limit, one finds

$$I_b \propto \alpha_p E^2 \left(\frac{\Delta E}{E} \right)^2. \quad (18)$$

For CESR at 5.3 GeV, no longitudinal microwave instability was observed with a 10.5 mm bunch with bunch currents large as 14.6 mA. Using the scaling above, no instability will be observed at 1.88 GeV with currents as large as 1.8 times the design current. Similar margins of safety are present at 1.55 and 2.5 GeV.

3.4.4 Multi-Bunch Stability Limits at 5.3 GeV

3.4.4.1 Transverse Multi-Bunch Stability at 5.3 GeV

The dominant transverse multi-bunch instability in CESR is due to the interaction of the positron beam with photoelectrons. In CESR the photoelectrons are trapped in the beam chamber by the electrostatic field produced by the distributed ion pumps. The instability is horizontal. The maximum growth rate, 300 s^{-1} (with reduced voltages on pumps), occurs at a positron train current near 9 mA (4 or 5 bunches/train). This instability is damped by a bunch-by-bunch transverse feedback system, which has a damping rate of 400 s^{-1} per mA bunch current (horizontal) and 220 s^{-1} per mA bunch current (vertical). With the distributed ion pumps turned off, no electron cloud instability is observed for bunch spacing $\geq 8 \text{ ns}$. No transverse multi-bunch instability due to narrowband impedances is evident.

3.4.4.2 Longitudinal Multi-Bunch Stability at 5.3 GeV

A longitudinal multi-bunch instability, believed to be due to narrowband impedances in the RF cavities or other structures, is present in CESR at 5.3 GeV. This instability is damped primarily by a bunch-by-bunch longitudinal feedback system and by Landau damping due to the non-linearity of the RF waveform. The measured Landau damping rate is 430 s^{-1} . The growth rate, inferred from the measured Landau damping, is approximately 1.7 s^{-1} per mA total beam current, but varies with conditions. The feedback damping rate is 4.6 s^{-1} per mA total beam current.

3.4.5 Projection of Multi-Bunch Stability at Lower Energies

3.4.5.1 Transverse Multi-Bunch Stability at Lower Energies

In low energy operation we plan to turn off the distributed ion pumps, so photoelectron trapping, which causes the transverse multi-bunch instability, will be absent. Observations at 5.3 GeV, and particle-in-cell simulations, show that the electron cloud instability is absent

for bunch spacing ≥ 8 ns. Thus we do not expect any electron cloud effects for the design parameters. Instability growth rates due to narrowband impedances are too small to measure at 5.3 GeV. All multi-bunch growth rates will scale as E^{-1} , but the transverse feedback damping rate scales as E^{-1} as well. The lower maximum bunch current at lower energy allows the gain of the feedback system to be increased, so the machine is expected to be stable against transverse multi-bunch instability.

3.4.5.2 Longitudinal Multi-Bunch Stability at Lower Energies

At the shorter bunch length used in the proposed machine, Landau damping of the longitudinal multi-bunch instability will likely be reduced. However, both the instability growth rate and the feedback damping rate will scale as E^{-1} . Because the feedback system damping rate is larger than the instability growth rate at 5.3 GeV, and because lower maximum bunch current allows the gain of the feedback system to be increased at lower energy, the machine is expected to be stable against the longitudinal multi-bunch instability.

3.4.6 Ion Trapping at 5.3 GeV Operation

Ion and dust trapping is rarely observed in CESR, because the vacuum chamber has been well processed by the beam and the pressure is low. Events of reduced beam lifetime that appear to be due to ion or dust trapping are sometimes observed after portions of the vacuum chamber have been exposed to air. The frequency of these events diminishes after a few days of beam processing. The fast ion instability is not observed in CESR.

3.4.7 Projection of Ion Trapping at Lower Energy Operation

Because the vertical and horizontal beam size at low energies will be approximately the same as that at 5.3 GeV, but the bunch charge will be smaller, fewer ion species will be trapped in the beam at low energy than during present operations. Ion trapping is therefore not expected to be a problem at lower energies.

The characteristic rate for the fast ion instability, for constant bunch pattern, beam size, and gas background, is proportional to $I_b^{3/2}/\gamma$. The characteristic rate at 1.88 GeV is 0.90 times the rate at 5.3 GeV, so the fast ion instability is not expected to be present at the lower energy.

3.4.8 Beam-Beam Effects

The beam-beam performance was evaluated using the 6-D particle-in-cell strong-strong simulation code ODYSSEUS [9]. Simulation parameters included: the soft-Gaussian approximation, 15 longitudinal layers, and 5,000 macroparticles per beam. Linear transport through the accelerator arcs is assumed, and the crossing angle is not included. Coupling and vertical radiation excitation are excluded so that the beam-beam parameter reaches its saturated value when the beams come to equilibrium.

Figures 24 – 27 show tune plane scans of calculated luminosity at 5.30, 2.50, 1.88, and 1.55 GeV. The maximum luminosity values and corresponding tune shift parameter values are summarized in Table 11. The observed luminosity in CESR at 5.3 GeV with the same

TABLE 11. Luminosity predicted by beam-beam simulation.

E (GeV)	Q_s	I_b (mA)	Calculated $\mathcal{L}$ ($\text{cm}^{-2} \text{s}^{-1}$)	Calculated ξ_y
5.30	0.056	7.68	1.33×10^{33}	0.060
2.50	0.104	5.10	4.45×10^{32}	0.036
1.88	0.110	4.06	4.13×10^{32}	0.055
1.55	0.105	2.82	1.46×10^{32}	0.034

parameters used in the simulation is $1.3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, and is consistent with the value predicted by the simulation. The lower values of ξ_y at 2.50 and 1.55 GeV may reflect a disadvantageous choice of synchrotron tune.

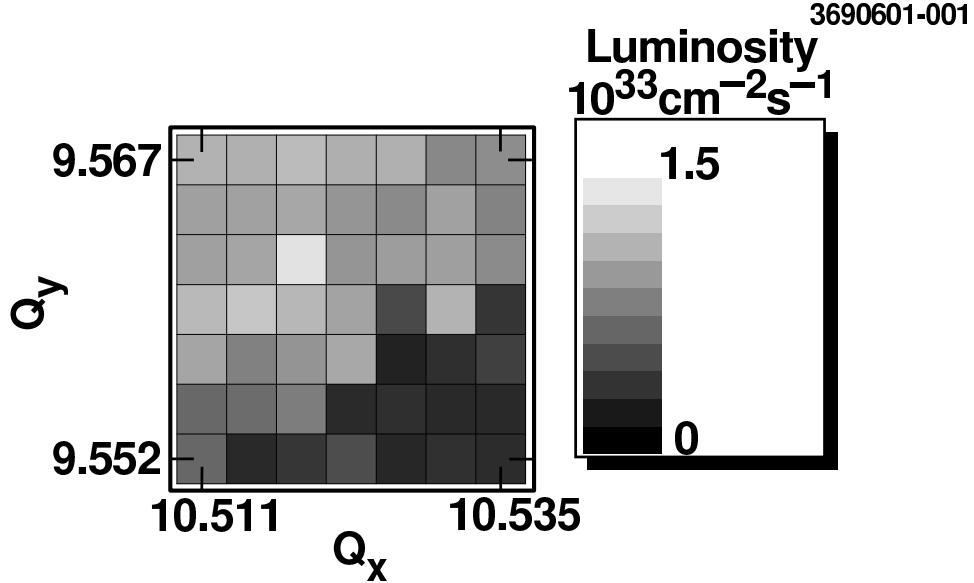


FIGURE 24. Calculated luminosity at 5.3 GeV from the beam-beam simulation.

4 Technical Systems

4.1 Magnets

4.1.1 Field Quality of Ring Magnets at Energy from 1.5 to 5.6 GeV

The CESR ring and transition region contains dipole bending magnets, quadrupole magnets, sextupoles and other small magnets used for chromaticity, coupling and orbit correction. The basic parameters for these magnets and principal details of their construction are given in Reference [10].

Below we discuss the field quality of the bending and quadrupole magnets, which can be critical for operation at energy from 1.5 to 5.6 GeV.

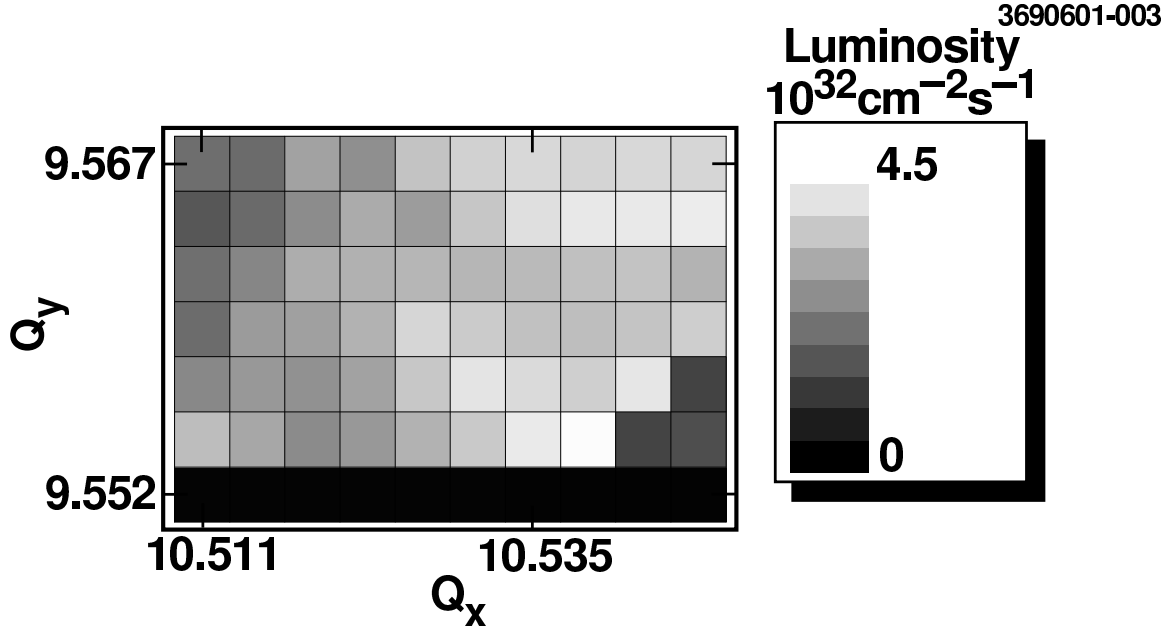


FIGURE 25. Calculated luminosity at 2.5 GeV from the beam-beam simulation.

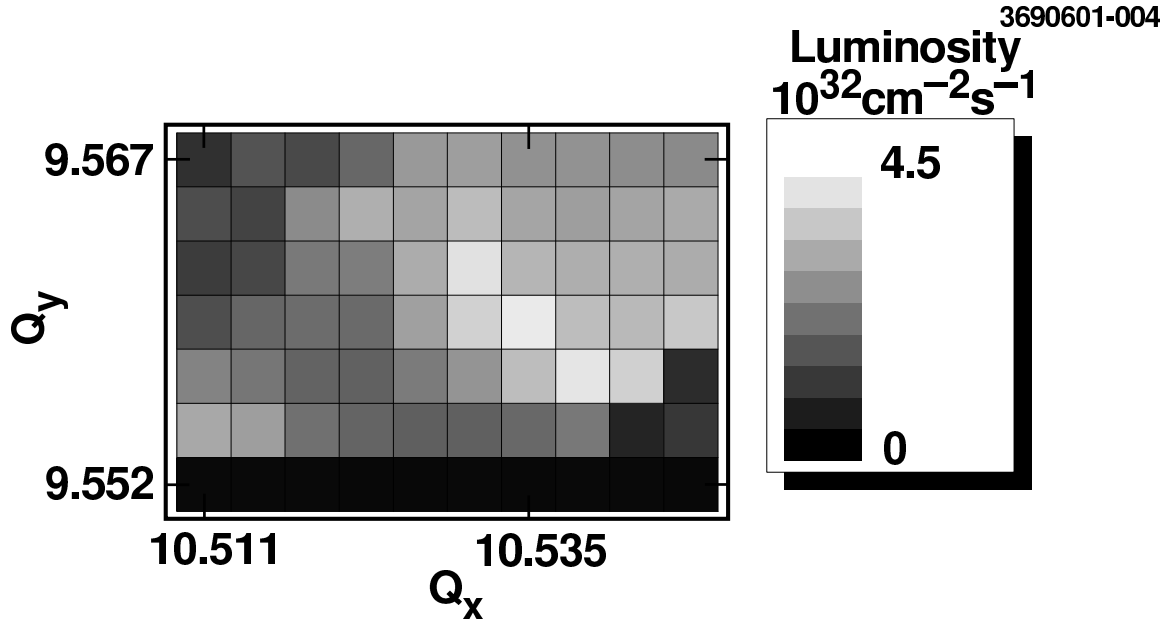


FIGURE 26. Calculated luminosity at 1.88 GeV from the beam-beam simulation.

4.1.1.1 Dipole Magnets.

Several types of bending magnets are used in the CESR ring and transition region. Models 201, 203, 204, 205, 206 have identical profile and differ only in the length and/or number of turns in the coils. Model 202 has the same gap and the pole shape as the others, but has wider return yoke. All of them have standard shaped endplates to provide proper magnetic field at the pole ends. All magnets are designated to operate at 8 GeV

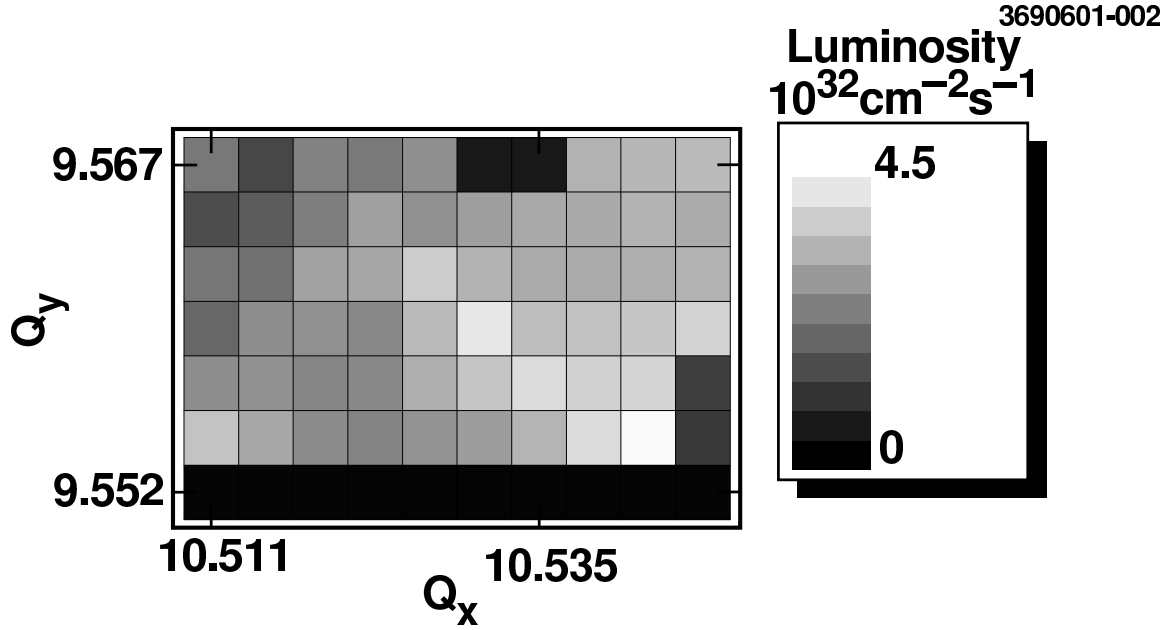


FIGURE 27. Calculated luminosity at 1.55 GeV from the beam-beam simulation.

energy with 991 A. To verify their ability to operate at energy in range 1.5 to 5.6 GeV we measured magnetic field characteristic of a prototype magnet built at the time of the magnets' construction. The prototype is 95 cm long with a profile identical to the model 201 and standard shaped endplates. The field characteristics of the prototype should be identical to the field characteristics of the CESR bending magnets.

Figure 28 shows the dependence of variation of the vertical field integrated over the magnet length on horizontal coordinate. Shown are results of measurement at ~ 600 A and 200 A of current which correspond to 4.8 GeV and 1.6 GeV operation.

There is no noticeable change in field quality between 600 A and 200 A. In both cases the nonlinear part of field variation, dB/B , is less than 5×10^{-4} in the beam occupied region. The measurement agreed well with data reported in [10].

From this we can conclude that magnetic field quality of CESR bending magnets at all energies between 1.5 and 5.6 GeV will be very similar to the present and will not create any problems for beam dynamics

4.1.1.2 Quadrupole Magnets

The CESR ring lattice consists of 90 Mark II and 2 Mark I quadrupole magnets. All of them have the same basic dimensions – bore radius 40 mm and effective length 60 cm. Note that because both types have very similar construction and magnetic field characteristics, the conclusion about Mark II can be applied to the Mark I type also.

The strength of most of the quadrupole magnets in CESR lattice is in a range between 0.18 m^{-2} and 0.32 m^{-2} . These values correspond to currents from 7A to 12 A at 1.5 GeV and from 25 A to 42 A current at 5.6 GeV operation. Analysis of the magnetic field measurements of the Mark II magnets has shown existence of systematic b5 and b9 multipole errors which depend on current as is shown on Figure 29.

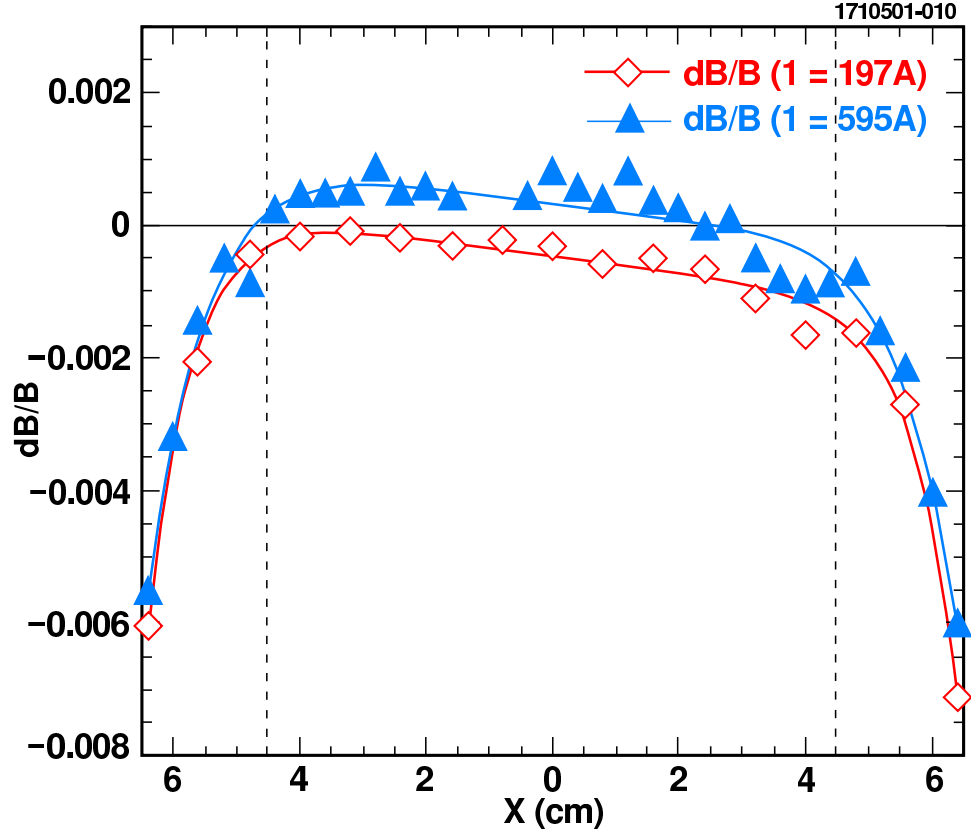


FIGURE 28. CESR bending magnet prototype. Variation of the vertical field integrated over the magnet length. Dashed lines indicate aperture available for beam.

There is no noticeable change in b_9 between 5.0 and 1.5 GeV operation and there is approximately 30% increase of b_5 for 1.5 GeV operation relative to operation at 5 GeV. Simulation of particle motion through CESR optics containing these multipole errors at 1.5 and 5.0 GeV have shown that the increase of b_5 does not affect the beam dynamics significantly. The conclusion can be made that magnetic field quality of Mark II and Mark I quadrupole magnets is satisfactory for operation in the energy range between 1.5 and 5.6 GeV.

4.1.2 IR Magnet System from 1.5 to 5.6 GeV

4.1.2.1 Superconducting Quadrupoles

The superconducting magnet system designed for the CESR Phase III upgrade [11] will be used for low energy operation. The main superconducting quadrupoles will be operated at a reduced current, considerably below the design current, commensurate with the reduced beam energy. The skew quadrupole winding on the main quadrupoles will be used to help compensate the coupling introduced by the 1 T CLEO solenoidal field. As this coupling is quite strong at low energies, the skew quadrupole windings will be operated at close to their design current. Additional coupling compensation will be provided by a small rotation of the permanent magnet quadrupoles (see Section 4.1.2.1.3).

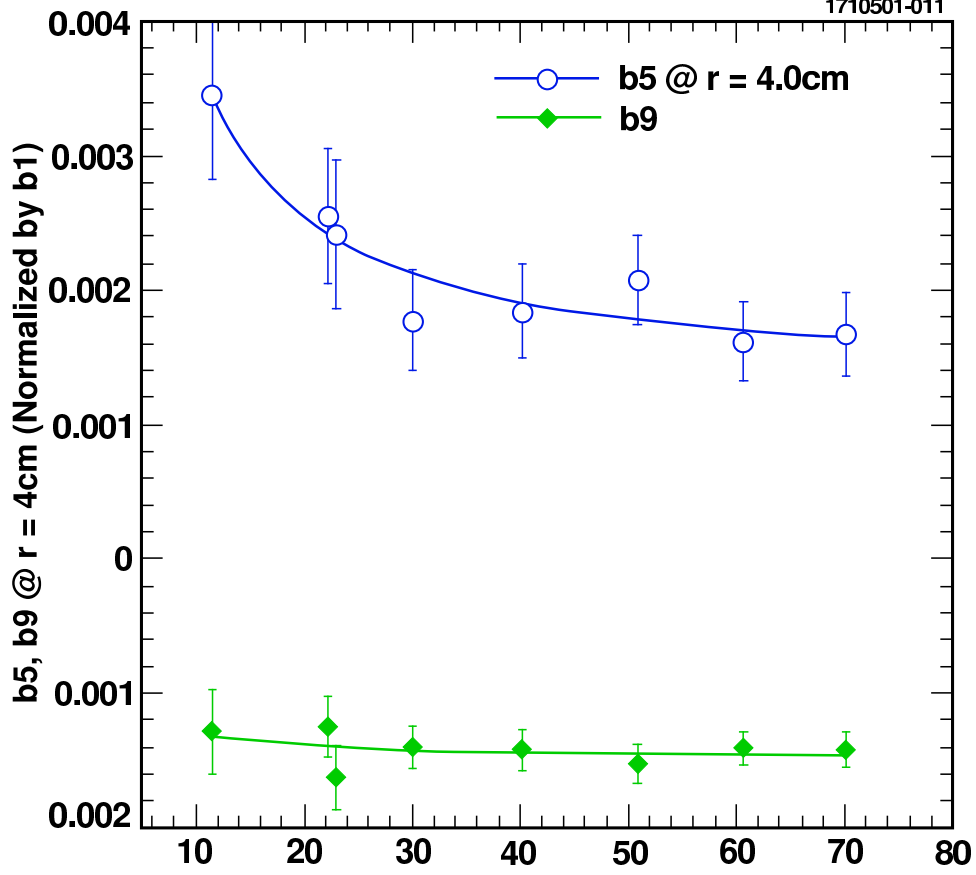


FIGURE 29. b5 and b9 multipoles errors as a function of current. Here are b5 and b9 normalized by b1 (gradient term) at 4 cm radius.

4.1.2.1.1 Main Quadrupoles

The standard expression for the two-dimensional average field (*i.e.*, field integral divided by effective length) in terms of error harmonics is

$$B_r(r, \phi) + iB_\phi(r, \phi) = B_0 \sum_{n=1}^{\infty} c_n \left(\frac{r}{r_{ref}} \right)^{n-1} \exp(in\phi) \quad (19)$$

in which B_0 is the average field at the reference radius. For an ideal quadrupole of average gradient G , $B_0 = Gr_{ref}$ and $c_n = 0$ for all n except $n = 2$, for which $c_2 = 1$.

The measured transfer functions and geometric harmonic errors of the main quadrupoles are presented in Table 12. In this table, the harmonic errors $c_n = b_n + ia_n$ are given in units (parts in 10^4), at a reference radius of 50 mm.

The design gradient for the main superconducting quadrupoles is 48 T/m, achieved at a current of 1225 A. For operation at 1.88 GeV, the required gradients in the pair of magnets in a cryostat are expected to be about 10.2 T/m and 7.3 T/m, corresponding to currents of 254 A and 183 A.

TABLE 12. Measured transfer function and harmonic errors for the superconducting IR main quadrupoles. Harmonic errors are in units (parts in 10^4), at 50 mm reference radius.

	SCM2 – Q1	SCM1 – Q1	SCM1 – Q2	SCM2 – Q2
	unit 1	unit 2	unit 3	unit 4
Integrated transfer function [T/kA]	26.141	25.929	26.157	25.931
b_3	-3	-25	-7	6
b_4	-1	-3	-3	-5
b_5	1	-1	-1	1
b_6	-8	-7	-7	-6
b_7	0	-1	0	0
b_8	0	0	0	0
b_9	0	0	0	0
b_{10}	0	0	-1	-1
b_{11}	0	0	0	0
b_{12}	0	0	0	0
b_{13}	0	0	0	0
b_{14}	0	1	0	0
a_3	4	-7	2	-21
a_4	0	-1	0	2
a_5	0	0	0	1
a_6	0	0	2	1
a_7	0	0	0	1
a_8	0	0	0	1
a_9	0	0	0	0

4.1.2.1.2 Skew Quadrupoles

The skew sextupole error in unit 4 will be compensated using an adjacent normal-conducting skew sextupole corrector, located outside the magnet cryostat. The normal sextupole error in unit 2 may be compensated using a system of iron shims placed in the warm bore tube. The necessity of this compensation is still under evaluation.

The calculated transfer function, and measured geometric harmonic errors of the skew quadrupoles in units 2 and 3 are presented in Table 13.

The design gradient for the superconducting skew quadrupoles is 4.8 T/m , achieved at a current of 325 A. For operation at 1.88 GeV, the required gradients in the pair of magnets in a cryostat are expected to be about 3.9 T/m and 4.8 T/m, corresponding to currents of

TABLE 13. Calculated transfer function and measured harmonic errors for superconducting IR skew quadrupoles. Harmonic errors are in units (parts in 10^4), at 50 mm reference radius.

	SCM1 – Q1	SCM1 – Q2
	unit 2	unit 3
Integrated transfer function [T/kA]	9.6	9.6
b ₃	0	8
b ₄	4	1
b ₅	0	3
b ₆	2	3
b ₇	0	0
b ₈	0	0
b ₉	0	0
b ₁₀	-1	0
b ₁₁	1	0
b ₁₂	-1	0
b ₁₃	1	0
a ₃	-5	6
a ₄	-1	4
a ₅	0	-1
a ₆	1	1
a ₇	0	0
a ₈	0	0
a ₉	0	0

264 A and 327 A.

4.1.2.1.3 Persistent Currents in the Superconducting Quadrupoles

The geometric errors presented above are expected to be independent of the magnet's excitation current; this was confirmed during the measurements by the agreement between warm and cold measurements. However, persistent currents in the filaments of the superconducting wire produce an effective magnetization that exhibits hysteresis and can produce field errors. These errors increase as the magnet current is reduced, and can potentially be a problem for low current operation.

In the critical-state model, the magnetization generated in a superconducting wire, con-

taining filaments of radius a , has a magnitude of

$$M = \frac{4}{3\pi} \varepsilon a J_c(B) \quad (20)$$

in which ε is the fraction of the wire which is superconducting, $J_c(B)$ is the critical current density in the wire, and B is the field at the wire. The harmonic error generated by a magnetic moment of magnitude m and direction ϕ_m , located at radius r_0 and azimuth ϕ_0 , is given by

$$c_n = i \frac{\mu_0 m}{2\pi \tilde{B}_0 r_0^2} n \left(\frac{r_{ref}}{r_0} \right)^{n-1} \exp(-i(n+1)\phi_0 - i\phi_m) \quad (21)$$

If m is due to persistent current magnetization, then the resulting perturbations to the magnetic field are given by

$$c_n = i \frac{\mu_0}{2\pi B_0} \frac{4n\varepsilon a}{3\pi} r_{ref}^{n-1} \int_{coil} d\phi_0 \frac{dr_0}{r_0^n} J_c(B(r_0, \phi_0)) \exp(-i(n+1)\phi_0 - i\phi_m(\phi_0)) \quad (22)$$

in which the integral is taken over the azimuthal and radial extent of the coil. The persistent current errors only appear at allowed harmonics, because of the symmetry of the coil: for a quadrupole, the first non-vanishing harmonic after $n = 2$ will be the duodecapole at $n = 6$. The errors will be larger at small currents, because B_0 in the denominator is smaller, and the critical current density $J_c(B)$ increases for small B . Figure 30 shows the measured duodecapole in the quadrupole, as a function of the current.

At high currents, one sees only the geometric duodecapole; at currents below about 400 A, the persistent current duodecapole is seen. At the expected low-energy operating point of 150-180 A, the persistent current effect can be seen from Figure 30 to be about 3 units. By arranging for operation on the upper leg of the hysteresis curve (*i.e.*, turning the current up to > 800 A, then back down), one can arrange for the persistent current duodecapole to cancel the geometric duodecapole, leaving duodecapole errors of about 5 units.

In Figure 31, the result from Equation (22) above is plotted, together with some of the data from Figure 30. The dependence of $J_c(B)$ on B has been modeled as

$$J_c(B) = J_{co} \exp\left(-\frac{B}{\bar{B}}\right) \quad (23)$$

with $J_{co} = 15,000$ A/mm², and $\bar{B} = 2.6$ T. The fit to the data is reasonable. A prediction is shown in Figure 32, based on Equations (22) and (23), for the persistent current skew duodecapole expected in the skew quadrupole. Since the skew quadrupoles will be operated with currents well in excess of 100 A, there should be no problem with persistent current harmonics in this case.

4.1.2.2 Normal Quadrupoles

The arcs will contain Mark II type quadrupole magnets. Their magnetic field quality has been discussed in Section 4.1.1.

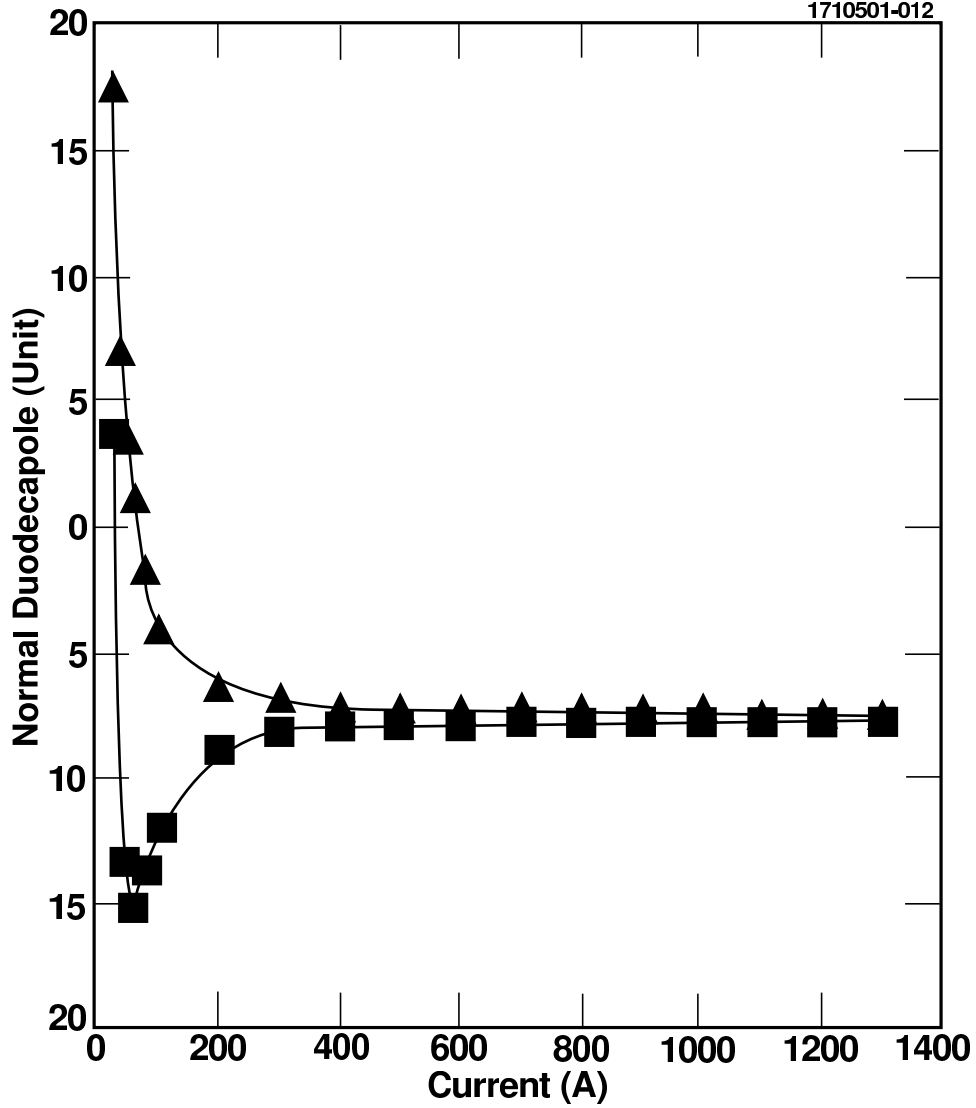


FIGURE 30. Measured duodecapole moment in prototype IR quadrupole.

4.1.2.3 Permanent Magnet Quads

The permanent magnet quadrupoles [12] will also be used for low energy operation. The quadrupoles are made of two 9.2 cm long sections. Also, as noted above, additional coupling compensation is provided by a small rotation of the quadrupoles. The measured multipole errors in the permanent magnet quadrupoles, as reported in Reference [12], are better than 10 units at a 28 mm reference radius.

Since the magnetic field in the permanent magnets is fixed, their focusing strength will increase inversely with the beam energy. In Reference [12], the temperature stability requirement is estimated to be 0.2°C , based on limiting the vertical tune shift to less than 0.0005. At 1.88 GeV, the requirement will be more severe, roughly 0.1°C .

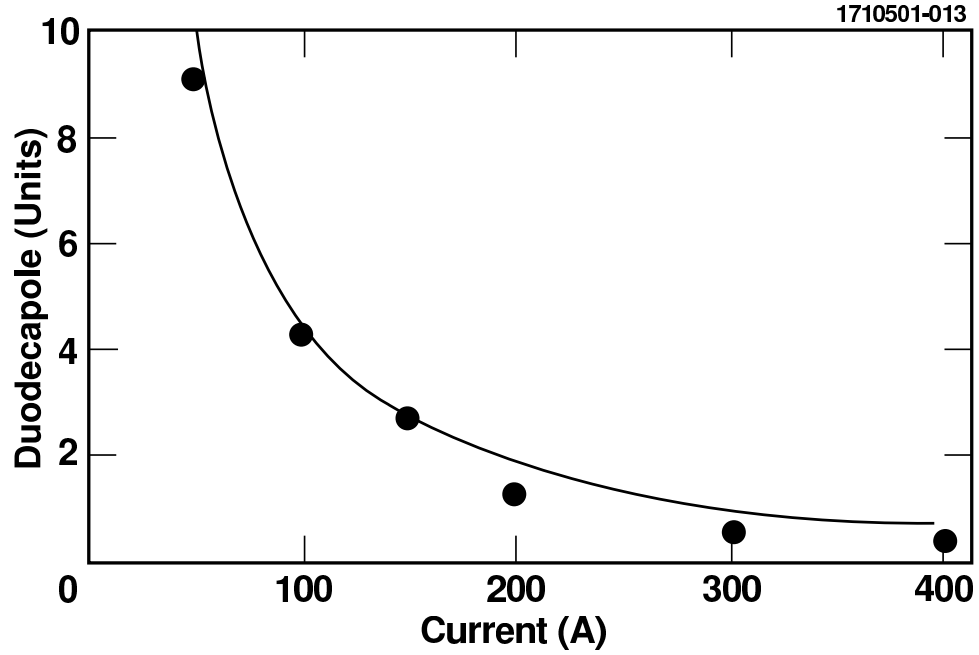


FIGURE 31. Prediction of the duodecapole in the main quadrupole, and comparison with data.

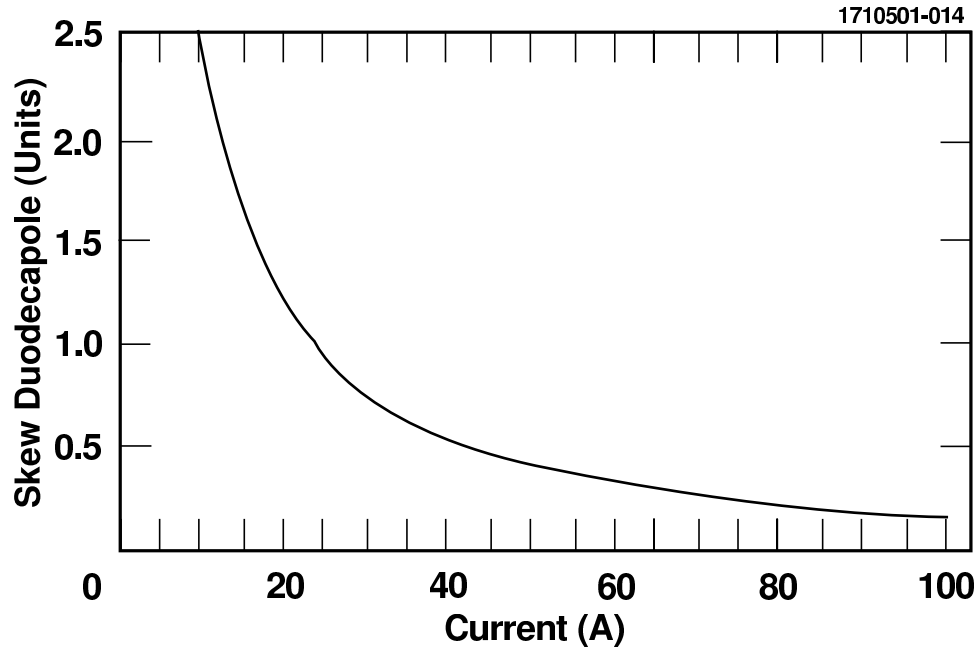


FIGURE 32. Prediction of the skew duodecapole expected in the skew quadrupole.

4.1.3 Wiggler Magnets

4.1.3.1 Performance Goals

The specifications of the wiggler units (period, peak field, etc.) are chosen to achieve the damping decrement, horizontal emittance, and energy spread required for optimum opera-

tion and for attaining maximum luminosity for CESR-c operation at low energies. In a ring where the majority of the synchrotron radiation comes from wigglers, the peak field (B_W) and total length (L_W) of the wigglers determine the damping time, horizontal emittance and energy spread of the beam as follows:

$$\text{Damping time:} \quad \tau \propto \frac{1}{L_W B_W^2}$$

$$\text{Horizontal emittance:} \quad \epsilon_x \propto B_W H_W$$

$$\text{Energy spread:} \quad \frac{\sigma_E}{E} \propto \sqrt{B_W}$$

where H_W is the normalized dispersion squared, which determines the effectiveness of local synchrotron radiation to generate emittance in the plane of the dispersion. The peak wiggler field is limited by energy spread in the beam, which is independent of the total length of wigglers (Section 3.2.3). Aperture requirements restrict fractional energy spread to $\leq 0.8 \times 10^{-3}$, corresponding to a wiggler field of approximately 2.1 T at 1.88 GeV. The damping time then determines the total length of wigglers needed. The wigglers will dominate radiation effects in CESR at 1.88 GeV. The nonlinear aspects of the wiggler insertions must be carefully crafted to avoid limiting the machine dynamic aperture. Clearly they must operate conservatively to assure good reliability. Finally, they will be built in standard modules to simplify construction, installation, and maintenance.

4.1.3.2 Design Concept & Prototype Module

The wiggler units are designed to be modular, all modules identical in cryostats of fixed length flange-to-flange so that they can be inserted in the CESR beam line at any appropriate location. The basic magnet design is of the super-ferric type, with superconducting coils producing the magnetic field which is shaped mainly by iron poles. The magnets will be optimized for a field strength of 2.1 T for operation of CESR-c at a beam energy of 1.88 GeV. The field quality will be tuned at a field of 2.1 T. This field will be maintained for HEP operation at and below 1.9 GeV beam energy (Figure 11), which includes most low energy running. Trim coils will be included for the end poles of each wiggler module to obtain the proper field integrals and to compensate for any irregularities. The pole profiles are optimized to minimize multipole errors.

The superferric concept was chosen for its simplicity of construction tolerances compared to air core superconducting magnets, for its cost and weight compared to an equivalent set of permanent magnet wigglers and for operating cost compared to conventional electromagnets. Further, permanent magnet wigglers would have to be removed from the beam line (or opened up) during running at the Υ or higher energies, which would require the fabrication of complex mechanical devices for each wiggler unit.

The requirements of accelerator parameters dictate the total length of 2.1 T wiggler field to be between 16 m and 26 m. The wiggler modules will be installed in the CESR ring as close to the IR region as possible to minimize the length of cryogenic and other utilities to be installed in the tunnel. These locations dictate a modular length of 1.3 m of magnet, with a corresponding insertion length 1.7 m of cryostat flange-to-flange, including an integral pump port.

The warm-bore ultra-high vacuum (UHV) copper beam-tube for CESR, although an integral part of the cryostat, is completely hermetic and does not share any vacuum welds or connections with the cryostat vacuum. The beam-tube will be completely fabricated,

leak-checked and baked out for UHV before assembly into the cryostat module. Copper is chosen as the beam-tube material in order to provide good electrical and thermal conduction as well as for efficient absorption of x-rays, as the cold mass must be well-protected from synchrotron radiation.

For ease of assembly around the beam-tube, the wiggler magnet cold-mass is designed in two halves, top and bottom, each in its own integral helium vessel. The cryogenic system is designed to operate at 4.5°K with a minimum amount of liquid helium in the vessels, in intimate contact with the coils and the iron.

The top and bottom magnet halves are independently assembled and each helium vessel is welded around it. Each pole and coil are independently assembled as a unit. These units are then assembled on to a long steel plate forming the return yoke over the full length of the magnet, with stainless steel support plates and a thin vacuum skin making up the rest of the assembly. One half of a cold mass magnet assembly without vacuum skin is shown in Figure 33.

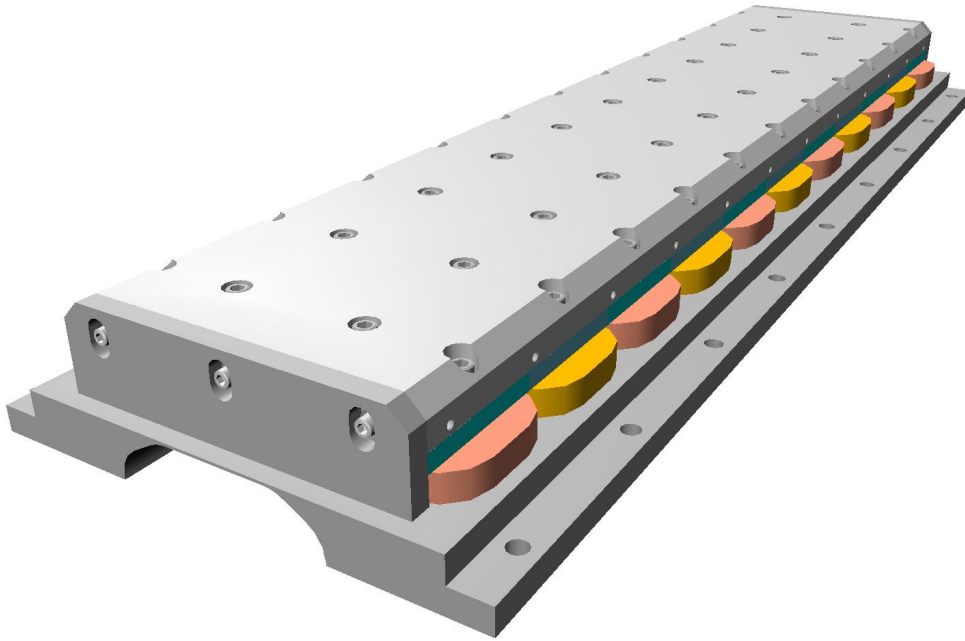


FIGURE 33. One half of a wiggler magnet assembly (cold mass) without vacuum skin.

The main coils are designed to operate at approximately 200 A. The superconducting wire is chosen to operate at $\sim 50\%$ of its short-sample field limit. The end-poles of each wiggler module include trim-coils that can be individually tuned to maintain the correct field integral and field quality.

To minimize heat loads, high temperature superconducting (HTSC) leads for the main current leads and either HTSC or thin copper conductors for each of the independent trim coil leads will be used.

Shunt resistors are incorporated for each coil to protect the coil in case of a quench in

that coil. The full quench-protection system is described in Section 4.1.3.6.

A full-scale prototype wiggler module including magnet and cryostat will be constructed and tested prior to production of the complete set of wiggler modules. The production will include spare modules so that in case of need, a module can be easily swapped out and replaced with a fully tested module.

4.1.3.3 Magnetic Design

The wiggler must produce the required synchrotron radiation by transverse acceleration of the beam without introducing excessive beam dynamics effects. Even a wiggler with an ideal field distribution (no variation across the width in the x dimension) will introduce both linear and nonlinear focusing in the vertical plane. (In the following discussion the s axis coincides with the design orbit (no closed orbit distortion) through the wiggler in the absence of magnetic field, y is vertical, and x horizontal).

In an ideal wiggler the vertical component of the magnetic field, $B_y(s, x, y)$, along the s axis (at $x = 0$, $y = 0$) is sinusoidal

$$B_y(s, 0, 0) = B_0 \sin(k_s s) \quad (24)$$

where $k_s = 2\pi/\lambda_w$ and λ_w is the period of the wiggler. Since the beam region is free of currents, Maxwell's equations also produce a longitudinal field (B_s) and variation with y ,

$$\begin{aligned} B_y &= B_0 \cosh(k_s y) \cos(k_s s) , \\ B_s &= -B_0 \sinh(k_s y) \sin(k_s s) . \end{aligned} \quad (25)$$

It is readily apparent that the B_s field is maximum between poles at the same place where the beam has a maximum horizontal angle, x' , producing a transverse field component from the beam's point of view. The effective B_x integrated through the wiggler is [13]

$$\int_0^{N\lambda} B_x ds = -\frac{N \lambda_w B_0^2}{2 B \rho} \left(y + \frac{2}{3} k_s^2 y^3 + \frac{2}{15} k_s^4 y^5 + \dots \right) \quad (26)$$

where B_x is the transverse field in the horizontal plane with respect to the beam path through the wiggler, N is the number of periods and $B\rho$ is the magnetic rigidity or momentum of the beam. From this equation it is clear that while the linear vertical focusing (first term in parenthesis) is independent of k_s , the remaining, nonlinear, terms will be minimized by increasing the wiggler period (decreasing k_s).

The previous discussion has assumed a "perfect" wiggler. If there is any variation of B_y across the magnet ($B_y(x)$) then additional focusing terms will be introduced. These will not be apparent in a straight-line integration through the wiggler, but will be brought forth by the interaction of the wiggling orbit with the field variations. These effects get worse as the period is lengthened since the amplitude of the beam's sinusoidal motion increases. The amplitude of the sinusoidal beam trajectory through a wiggler is

$$x_{amp} = \frac{B_y(x)}{k_s^2 B \rho} . \quad (27)$$

Nonlinear terms appear in both vertical and horizontal beam motion and must be included in beam dynamics computations.

The field of a wiggler with finite pole width may be improved by shimming the poles at the horizontal edges. Since the iron is operating in the saturation region, the effect of this shimming is reduced compared to that in a conventional iron magnet. The field quality also varies more with magnet excitation, potentially limiting the range of useful operating fields.

We have decided on a wiggler period of approximately 40 cm as a compromise between the large intrinsic nonlinearities on the short side, and reduced transverse field quality and departure from a sinusoidal field distribution on the long side. Tracking studies have shown that the nonlinearities from these wigglers (including a reasonable allowance for non-uniform ($B_y(x)$) yield an improved dynamic aperture compared to a shorter wiggler. Development and analysis is continuing.

When running at beam energies above 1.9 GeV the energy spread with 2.1 T wigglers will likely limit dynamic aperture, making it desirable to operate the wigglers at reduced field. We will be evaluating the wiggler design for field quality in the range of 1.7 to 2.1 T.

4.1.3.4 Cryostat

We plan that each wiggler magnet will be housed in an identical cryostat, so that availability of spare wiggler modules allows straightforward replacement of any unit. The cryostat design emphasizes simplicity of fabrication and assembly consistent with minimum heat leakage. Liquid helium and nitrogen cryogens will be supplied from the CESR central refrigeration plant through east and west transfer lines extended into the tunnels from the superconducting RF stations. The supply and return valves will be housed in cold-boxes adjacent to the cryostats in the tunnel. A liquid nitrogen shielded transfer line will carry cryogens from the cold box to the cryostat and the connection to the cryostat will be made through a custom feed through designed for low heat leakage with a liquid nitrogen intercept.

The cold mass is secured to the cryostat vacuum vessel using a low heat leak, eight-strap mounting scheme that prevents any significant motion during cool down. Adjustments need only to be made initially in the warm state to align the magnet axes relative to the beam-tube flanges. The suspension straps will have thermal intercepts at the 80°K radiation shield.

Initial cool-down to 80°K will be done using an independent liquid nitrogen line connected to a copper plate in the cold mass. Cool-down from 80°K to 4.5°K will use a warm helium recovery line. Cold helium gas will be returned during 4.5°K operation to the refrigerator through the main transfer line. The top and bottom halves of the helium vessel will be linked by circulation tubes designed for proper convective flow. Liquid helium level gauges will monitor and control the input flow of cryogen to the magnets. Spent nitrogen gas will be exhausted from the tunnel through a separate vent line. The cryostat includes a helium stack housing the current and instrumentation leads and a helium relief port to this vent line. The vacuum vessel will also include an emergency burst disk with a connection to this vent line. Figure 34 illustrates some details of the cryostat and cold mass.

A cryostat for the full length prototype wiggler module has been designed and parts are being fabricated as of September 2001. We are first building a short cryostat (0.7 m), which represents a flanged part of the final cryostat body and contains all the complex parts, e.g., cryogen feeds, a stack containing all SC leads, instrumentation leads and helium safety vent,

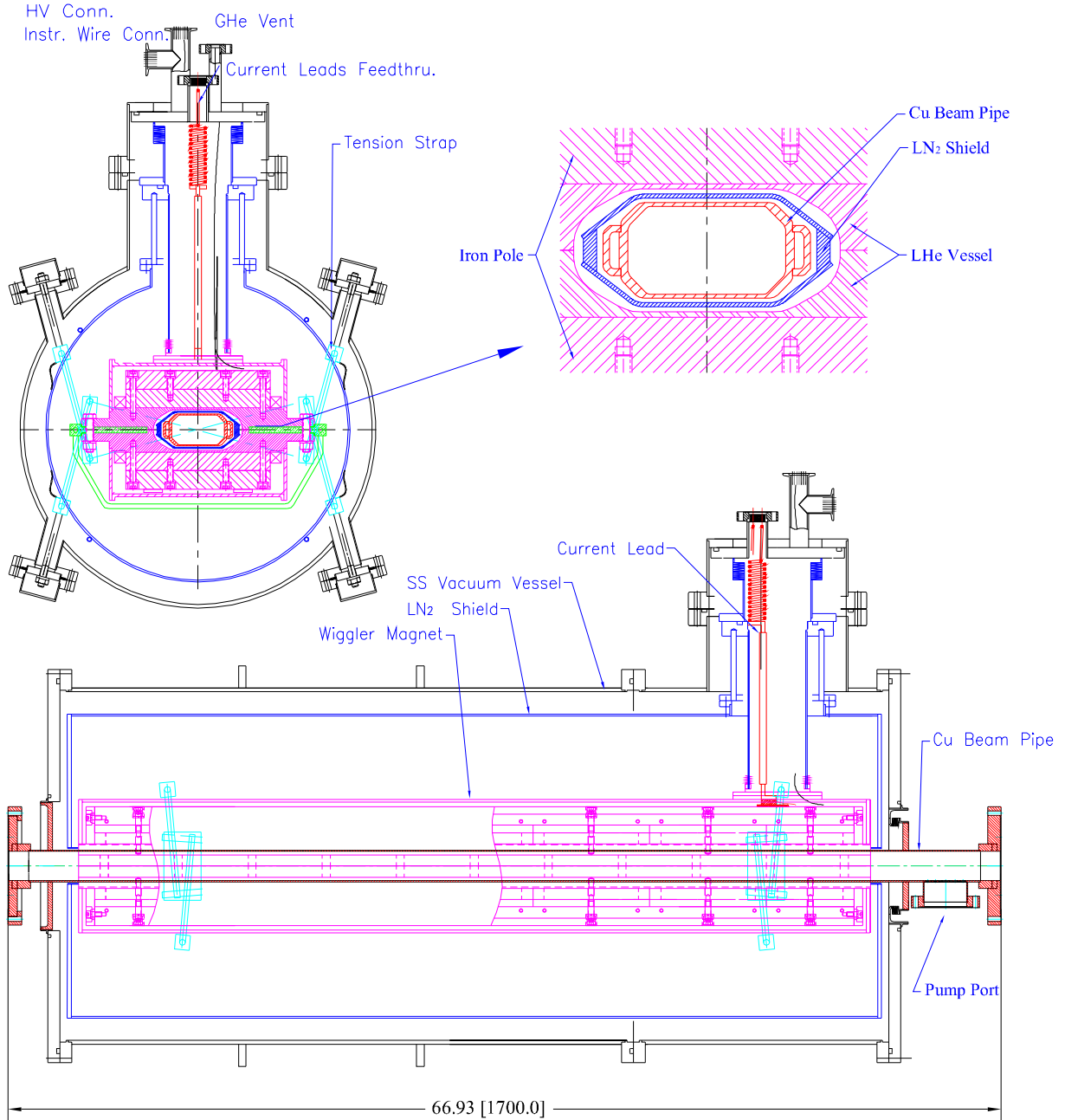


FIGURE 34. Cross sections of cryostat with suspended cold mass.

and the final suspension system. It will include a short version of the radiation shields and will be used to test the 3-pole wiggler magnet described above. This test will include the fabrication of separate helium vessels for top and bottom halves of the magnet as in the final design. This cryostat is long enough to test a 3-pole model of the 40 cm period magnet if necessary and will include provision to measure the field profiles in detail.

We have tested a model of the stack containing the final SC leads and associated cooling, showing that the SC leads work successfully at up to 340 Amps (the operating current is 200 Amps) with the chosen method of cooling with LN₂. Tests of the suspension and of the radiation shields and cryogen feeds are under way.

4.1.3.5 *Cryogen Production and Distribution System for the Wigglers*

4.1.3.5.1 Existing Refrigeration Plant and Cryogenic Loads

For the last several years, the Laboratory has been using two machines manufactured by CCI cryogenics, each of which can provide 600 W of refrigeration at 4.6°K with the aid of LN₂ pre-cooling. These have reliably supplied CESR's four superconducting RF cavities. With the associated valve boxes and transfer lines, the RF consumes about 700 W out of the available 1200 W. Recently we purchased another (used) 600 W machine, which we are presently refurbishing, and added the ~ 200 W load of the two superconducting quadrupole assemblies and their plumbing. CLEO's 1.5 T solenoid uses an independent plant, running on either of two 100 W machines. These have been used for both CLEO and CLEOII since 1979.

The three CCI machines with a total capacity of 1800 W will have an excess capacity of some 900 W to service the needs of the two future SRF cavities and the wigglers. Since the wigglers will need less than 100 W, we can expect to have adequate excess to meet the needs of the future RF, as much as 800 W for two cavities. Hence, we propose to use this existing plant, extending the distribution system to deliver cryogens to the wigglers in a relatively simple, low-cost way.

4.1.3.5.2 Description of Cryogen Delivery System

The SRF cavities are fed two-phase He at $\sim 4.6^\circ\text{K}$ (6 PSIG) through long (~ 50 m) multi-element transfer lines. The boil-off gas also returns through these lines at about 4 PSIG. The helium lines are vacuum insulated within a 6" O.D. tube and shielded from thermal radiation by a copper shield traced with LN₂ tubes. (The LN₂ delivery capacity is limited by the tube diameter to a flow which we calculate insufficient to create an oxygen deficiency hazard in the tunnel, even in the event of a break, with normal tunnel ventilation.) The cavities serve as phase separators; liquid level and cryostat pressure are proportionally controlled via inlet and outlet valves. The 6" transfer lines terminate in "satellite valve boxes" (SVB's), one in the East flare and one in the West, at about 45 m from the IP. The wiggler cryostats are located in two groups, further away from the IP. The first group of four (B14 group) begins about 47 m from the SVB's and the second group of three (L1/L5 group) starts about 27 m after the first group. There are thus seven cryostats in the East tunnel and seven in the West.

We propose to "tee in" to the existing lines just before they reach the SVB's, creating new branches to serve the wigglers. The first section is isolated from the SRF lines by shutoff valves for helium supply, return, and LN₂. It has an independent insulation vacuum (defined by a vacuum break, VB) so that it may be warmed up, leak-checked; etc, without interacting with the SRF line. This section of transfer line ends in a vacuum break at the B14 group. A special 7 m long insert transfers cryogens to and from the four wiggler cryostats through control and shutoff valves. The main transfer line continues on (with a vacuum break-defined insulation vacuum) until it reaches the L1/L5 group of cryostats, where another insert occurs for the final three wigglers.

Figure 35 shows a schematic of the distribution system (14 wigglers). Note that vacuum breaks separate

- the wiggler cryostats from the short, cross-tunnel lines,

- the cross-tunnel lines from the main line, and
- that the main line is likewise segmented for ease in leak checking.

To provide flexibility in cool-down of any wiggler, we provide a bypass valve between the cold helium return and a line to compressor suction (warm return). At the extreme ends of the line, a valve allows bypass between supply and return for cool down and test purposes.

The design is driven by what we have learned in building and using the lines to the SVB's. These are quite similar, but shorter, and have operated quite successfully for three years, with only occasional pumping of the insulation space. The long straight segments will be assembled in approximately 5 m long units and joined with conflat vacuum flanges and automatic tube welds for the inner lines. Access to the joints is made adequate by retracting a bellows in the vacuum jacket, while thermal stresses are absorbed by smaller bellows attached to the helium tubes in each 5 m long unit.

Because the number of cryostats, vacuum breaks, and control valves is large, we will minimize the associated heat leaks by careful design using fully shielded lines, LN₂ intercepts on valves and supports, and special thin walled materials. The equilibrium mass flows are small, typically 1.5 g/s at the SVB and diminishing at each succeeding wiggler. The line size is determined by convenience in cooldown conditions. Both supply and return are 3/4" O.D. tubing, contained within in a 4" I.D. copper shield. The "cross-tunnel" lines need carry only very small flows, the corresponding tubes and valves will be much smaller. The vacuum jacket size will be expanded as needed to accommodate the valve mounting requirements in that region. Figure 36 shows the transfer line in the neighborhood of a cryostat.

4.1.3.6 Quench Protection

The performance envelope described in Table 14 has been established for the CESR Superconducting (SC) wigglers.

4.1.3.6.1 Quench Behavior of Coupled Coils

An isolated superconducting coil exhibits different behavior from a coil that is part of an assembly of other coils. The isolated coil initially has zero voltage drop and this remains true until the quench reaches the voltage monitoring points. Two identical coils that are connected in series electrically behave quite differently from an isolated coil. Other coupling such as mechanical, magnetic or thermal coupling can also affect behavior.

TABLE 14. Performance criteria for wiggler quench protection.

Parameter	Minimum Value	Maximum Value	Concerns
stored energy per wiggler	70.8 kJ	70.8 kJ	thermal
inductance per wiggler	1 H	26 H	current ramp rate
current	80 A	330 A	current leads, quench switch
internal voltage	N/A	800 V	solid and film insulation
allowable external voltage	N/A	1000 V	He vapor breakdown

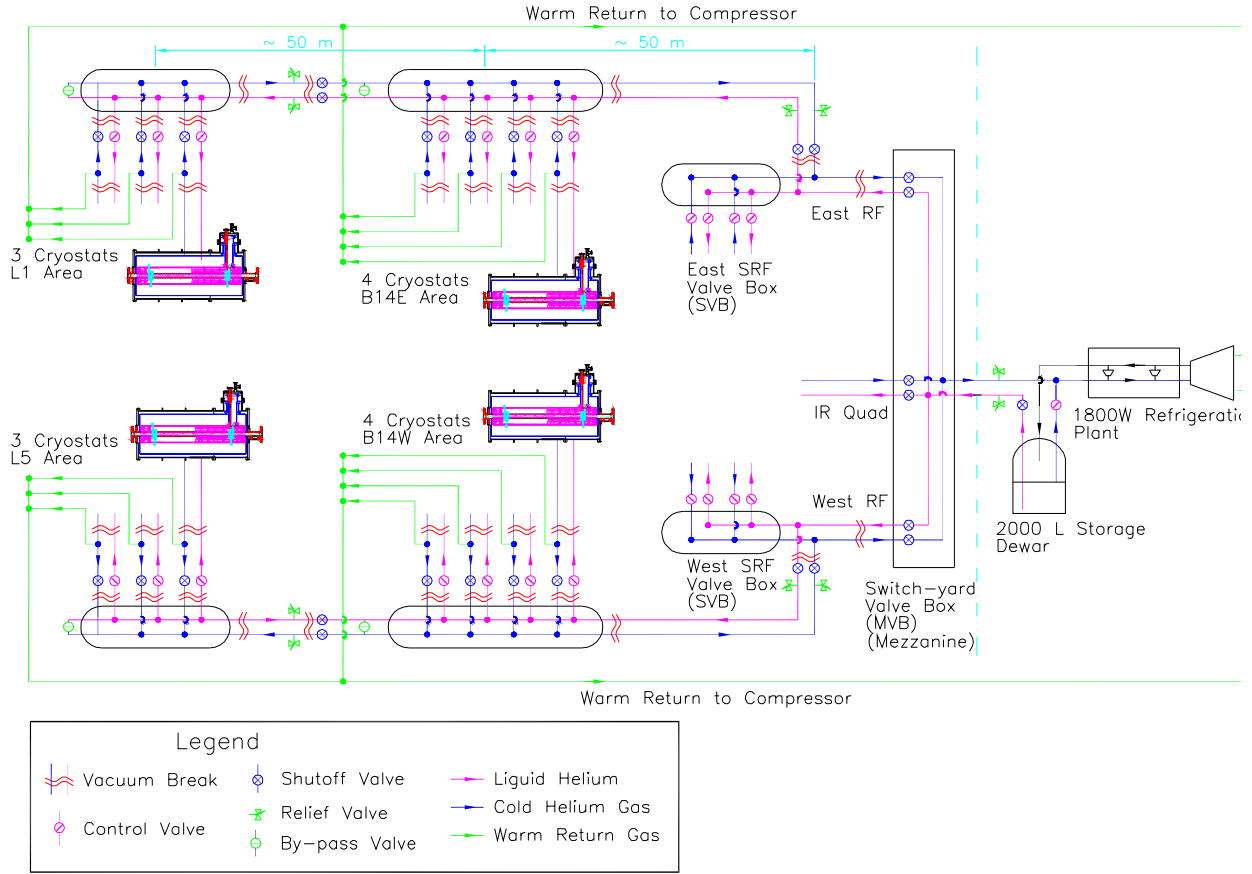


FIGURE 35. Liquid He distribution system in tunnel.

In the simplest two-coil system, where the coils are in series and have no other coupling, even if the quenching coil had zero volts across it, the current would begin to ramp down. The changing current would induce a voltage across the non-quenching coil, LdI/dt . In fact, since the total voltage across the circuit is zero, the quenching coil voltage will not be zero, rather it will be forced to have the same voltage magnitude across it as the non-quenching coil, but with the opposite polarity.

For the CESR SC wiggler, only three voltage taps need be brought out of the cryostat. Additional taps will be brought out for redundancy.

If the two coils are coupled magnetically, as in a dipole magnet or in one section of a charm wiggler, the mutual inductance of the coils provides for another difference between the pair of coils and the isolated coil. A voltage is induced across the non-quenching coil by the dB/dt from the quenching coil. If they are in separate circuits, then the voltage across the non-quenching coil is MdI/dt where M is the mutual inductance. Coupling between opposing wiggler poles will be about 0.3 so the mutual inductance will be $1/3$ the self-inductance of each coil. Coupling between adjacent coils will be approximately 0.95. Figure 37 is the equivalent circuit of one wiggler magnet.

Shunt resistors will be used across each coil inside the cryostat so that the quenching coil will be isolated from the other coils. These resistors will dissipate significant heat when ramping or during a quench. To avoid undesirable heating of the superconducting coils the

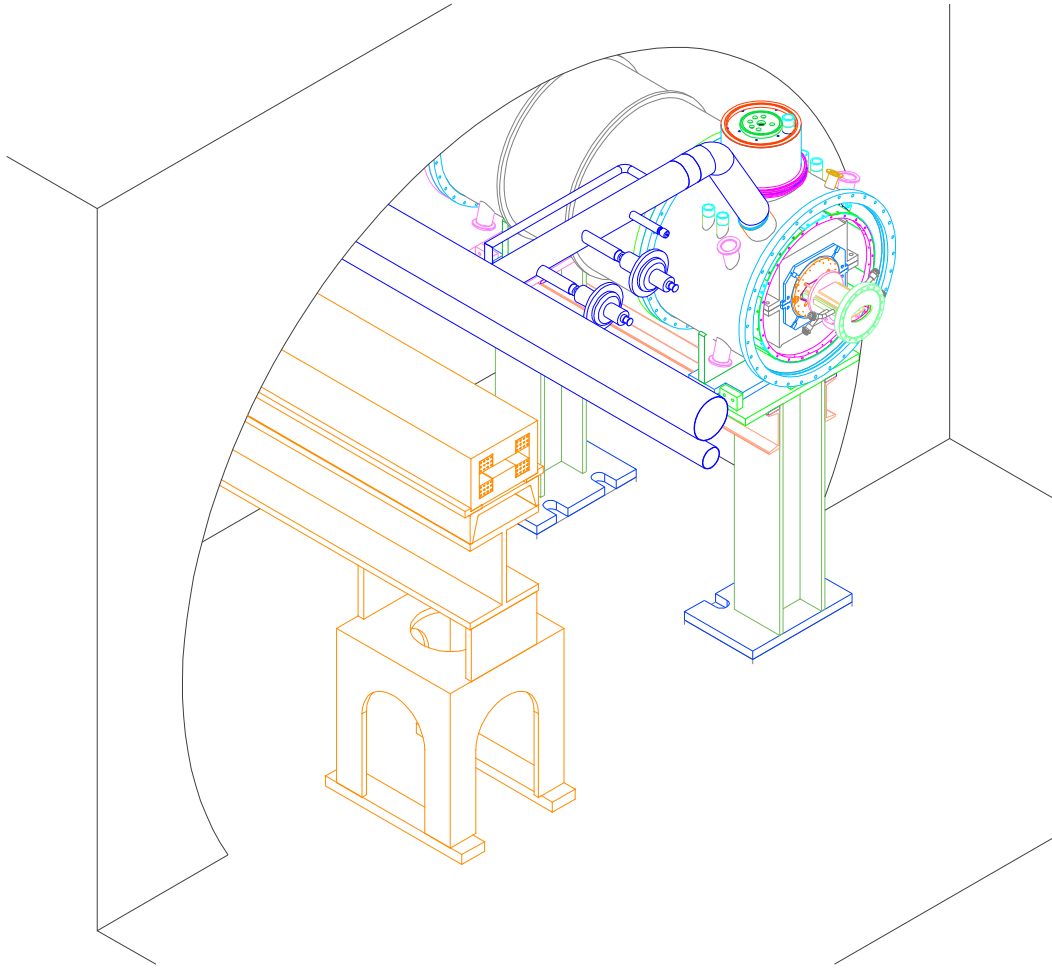


FIGURE 36. Cryostat and LHe transfer line in tunnel.

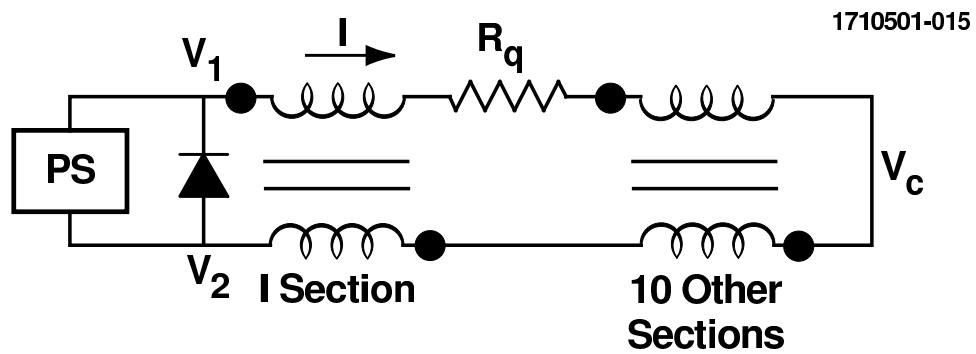


FIGURE 37. Equivalent circuit of a quenching wiggler.

resistors will be mounted to minimize thermal contact with the coils. An external power dissipation resistor will be connected as described in Section 4.1.3.6.3. We are exploring the option to use diodes in place of the individual coil resistors to further reduce energy dissipation in the liquid helium.

4.1.3.6.2 Quench Detection

Comparing the voltages between a quenching and non-quenching coil provides a very sensitive quench detector, particularly if the two coils are part of the same magnet and are well-matched. A detector that senses differences in the coil voltages is twice as sensitive as a dI/dt detector using one coil, and also provides partial cancellation of external voltages (*e.g.*, power supply voltages during ramping). Variability in the permeability of pole pieces may introduce a small asymmetry between coils, reducing slightly the effectiveness of this cancellation.

To implement this detection scheme, taps will be brought out from the magnet lead connections and from the connection between the top and bottom halves of the wiggler. With a differential voltage threshold of 0.5 V, the ramp rate threshold for change in difference current between halves, is 75 mA/s for an inductance of 3.3 H per coil.

The energy extracted by the external dump resistor is determined mainly by the value of that resistor with respect to the magnet quench resistance, not the quench protection delay time or threshold. For example, a typical calculation showed that reducing the detection threshold from 0.5 V to 0.5 μ V reduced the coil's absorbed energy from 2.9 kJ to 2.8 kJ, which does not justify the difficulty of using such a low threshold voltage. Thus the quench detection circuit parameters can be conservatively set to minimize noise susceptibility and occurrence of false trips.

An electronics system designed and tested for the CESR IR superconducting quadrupole magnets will be used for quench detection and magnet testing.

4.1.3.6.3 Quench Protection Circuit

Quench detection is relatively straightforward. Shunt resistors inside the cryostats provide primary quench protection with an external dump resistor for each wiggler to extract much of the energy from the cryostat in order to reduce thermal stresses and mitigate LHe loss.

The purpose of quench protection is to prevent energy transfer from other coils to the quenching coil. This is accomplished by using shunt resistors across each coil. Calculations for each possible configuration based on a simplified model after Wilson[14] show that the maximum internal temperature will be less than 180°K, even without an external dump resistor. Essentially, each coil must be capable of absorbing the energy associated with itself, unaided by heaters.

External protection for each wiggler will consist of a high current, high voltage switch and a metal resistor capable of absorbing all of the wiggler energy. High current switches under consideration are a 1200 V, 670 A IGBT and electro-mechanical contactors. The final decision will be based on reliability considerations. Although a solid-state switch may seem more attractive, the 1.5 volt drop across 11 switches in series will produce significant loss and will necessitate water cooling of these devices.

4.1.3.7 Modification of Arc Magnets

One 6.6 m long arc “chevron” magnet will be removed to create 3 long drift spaces on each side of CESR. The space chosen for this modification (bend magnet B14) is near an

instrumentation straight section on each side so a total of 4 wigglers can be placed in the spaces created by this modification.

A similar change was made in CESR in 1983 to create space for horizontal electrostatic separators for multi-bunch operation. Thus the details of the procedure and effort required are well known.

A “chevron” bend is removed and 3/8” square copper coils are added to the adjacent bends to increase their fields by 50%. These bends are moved toward the removed magnet, and slightly radially outward, to preserve geometry – both path length and matching transverse coordinates. (We chose to change path length slightly to optimize space for wigglers.) Finally, vacuum chambers must be modified to accommodate the new position of components.

4.1.3.8 Wiggler Magnet Tests

We have evaluated the technology of fabricating wigglers by making a short model of the full-length wiggler. A 3-pole wiggler magnet model with a pair of central “main poles” and two pairs of end-poles with trim windings has been tested several times and field measurements have been compared with the calculated field profiles. This test magnet has a period of 20 cm, and is shown in Figure 38.



FIGURE 38. 3-pole test magnet

The magnet was immersed in a vertical dewar, and run several times under different conditions of prestress with shims between coils. Field profile measurements were made during these tests using Hall-probes. Figure 39 shows a plot of peak field measured in the main pole vs. current.

Figure 40 shows a plot of the longitudinal field profile along an axis displaced 1.53 cm transversely from the central (beam) axis of the magnet. This was measured at a current of 170 A and a trim-coil current of 2.1 A (not optimized for zero integral).

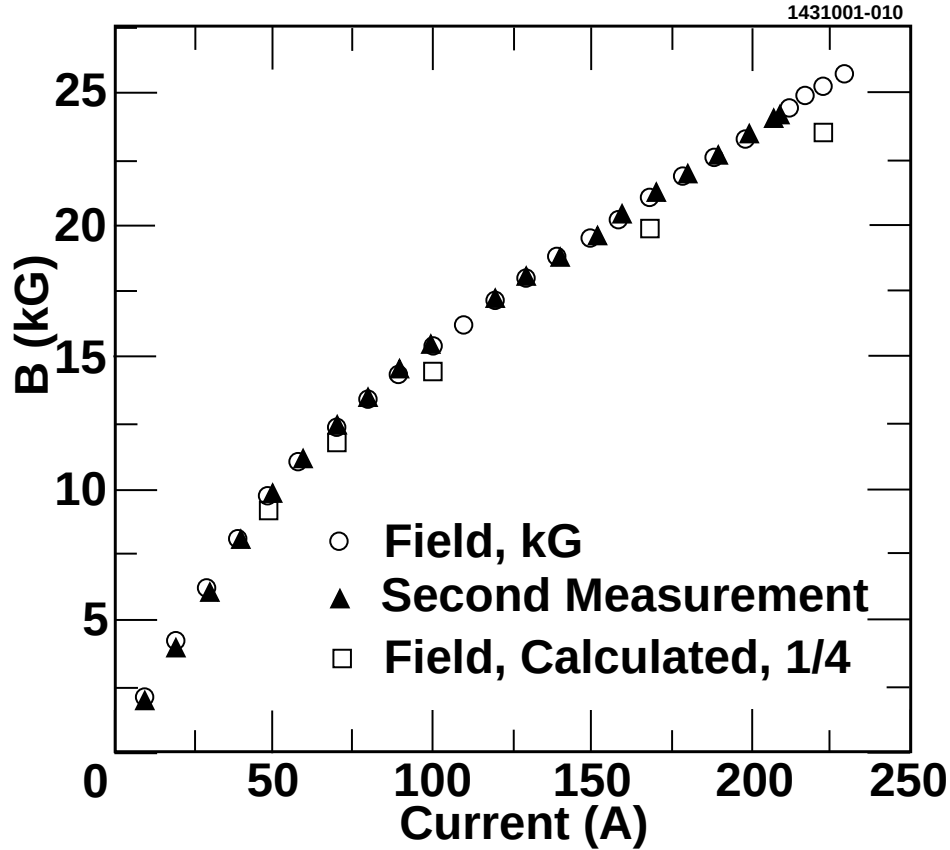


FIGURE 39. Peak magnetic field in main pole of 3-pole wiggler model vs. current

We have measured the transverse field distributions and longitudinal field integrals under different conditions and are using the results to trim the poles and trim currents for optimum field profiles.

The magnet coils operated successfully at maximum currents of ~ 245 A, very close to the expected short-sample limit load line for the wire. The required peak central field of 2.1 T is reached at ~ 170 A, so this represents a safe operating margin of 44%. The quench history of the magnet indicates that there is an initial quench at 110 A - 140 A in the various tests, followed by rapid training to above 170 A. However, successive tests were always performed after dismantling and reassembly, so this may not represent a lack of training memory. We believe that this initial quench (at a central field of 1.5 T to 1.7 T) may be due to “stick-slip” motion of coils wound tightly on the poles. We will evaluate the winding of coils free from the iron poles to remove the “stick”.

Two coils have been cut, polished and examined to determine the structure of the windings. The cross sections show very few voids and engineers at FNAL feel the coil package is quite robust.

An external committee of superconducting magnet experts reviewed the design of the full length prototype wiggler and cryostat, and the results of the 3-pole tests in September, 2001. The reviewers stated that the CESRc wiggler parameters were well within conventional superconducting magnet experience. The overall consensus was that the design was robust,

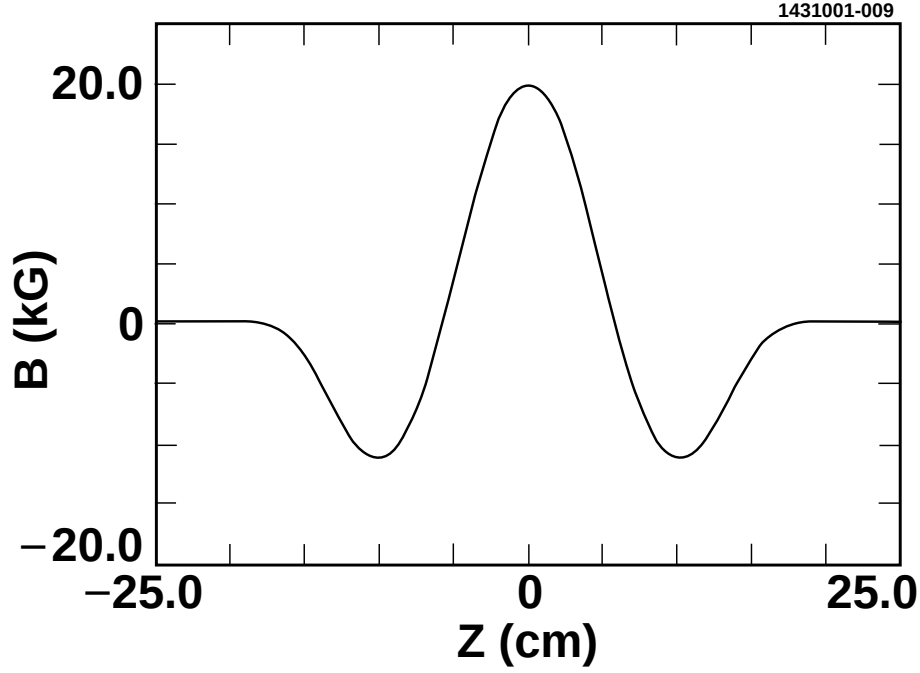


FIGURE 40. Vertical magnetic field vs longitudinal position in the 3-pole wiggler model measured along an axis displaced 1.53cm from the magnet center.

the team was experienced and that prototype wiggler fabrication could proceed with a few suggested improvements.

We are proceeding with the winding and testing of 40 cm period magnet poles, using a superconductor of larger diameter which is expected to operate with an even larger safety margin below its short-sample limit.

4.1.4 Magnet Power Supplies

In terms of both initial cost and maintenance costs, a single power supply is the obvious choice. Two considerations argue for independent power supplies: 1) a quench in one wiggler would then cause all of the series-connected wigglers to ramp down; and 2) small differences in physical dimensions or iron properties may require slightly different currents in each wiggler to maintain field quality.

Since the wigglers must be very reliable in order to sustain smooth operation, we must assume that quenches will be infrequent and that the first consideration does not demand independent power supplies. If one wiggler quenches the beam will be immediately lost in any case. Thus the extra time to isolate a wiggler and resume operation will be minimal.

If measurements determine that there is a need for small differences in current through each wiggler, small uni-polar trim supplies may be placed across each wiggler. These are relatively inexpensive and regulation requirements are modest.

A single power supply with output capability of approximately 100 volts and 500 amps will operate conservatively and can be controlled with a standard CESR high precision transducer regulated circuit. The main current will be stable at the 10^{-4} level. Individual trim supplies would supply ~ 10 amps at less than 1 volt with a 0.25% stability requirement.

4.2 RF System

4.2.1 Present RF Accelerating System

The present CESR RF system [15] consists of four superconducting cavity cryomodules operating with an average accelerating gradient of 6.2 MV/m providing total voltage of 7.4 MV and supplying RF power in excess of 270 kW per cavity to high current 5.3 GeV beams. Cryomodules are installed in pairs in the East (cavities E1 and E2) and West (cavities W1 and W2) RF straight sections in the CESR tunnel. Cryogen liquids are supplied to cryomodules via satellite distribution boxes located next to cavities in the CESR tunnel. A fifth, spare cryomodule is available in addition to the four installed in CESR.

Four transmitters are available to provide RF power to the cavities in the tunnel and to the RF processing area to perform various high power tests. Three transmitters use 600 kW CW YK1300 klystrons and one is equipped an 800 kW CPI klystron. The system can be configured to provide RF power from one klystron to one or two cavities depending on RF power demand. Its present configuration is shown in Figure 41: three transmitters are used to power the cavities while the fourth one is available for high power tests. The RF power distribution system consists of WR1800 waveguide straight sections, bends, and magic T's and ferrite circulators.

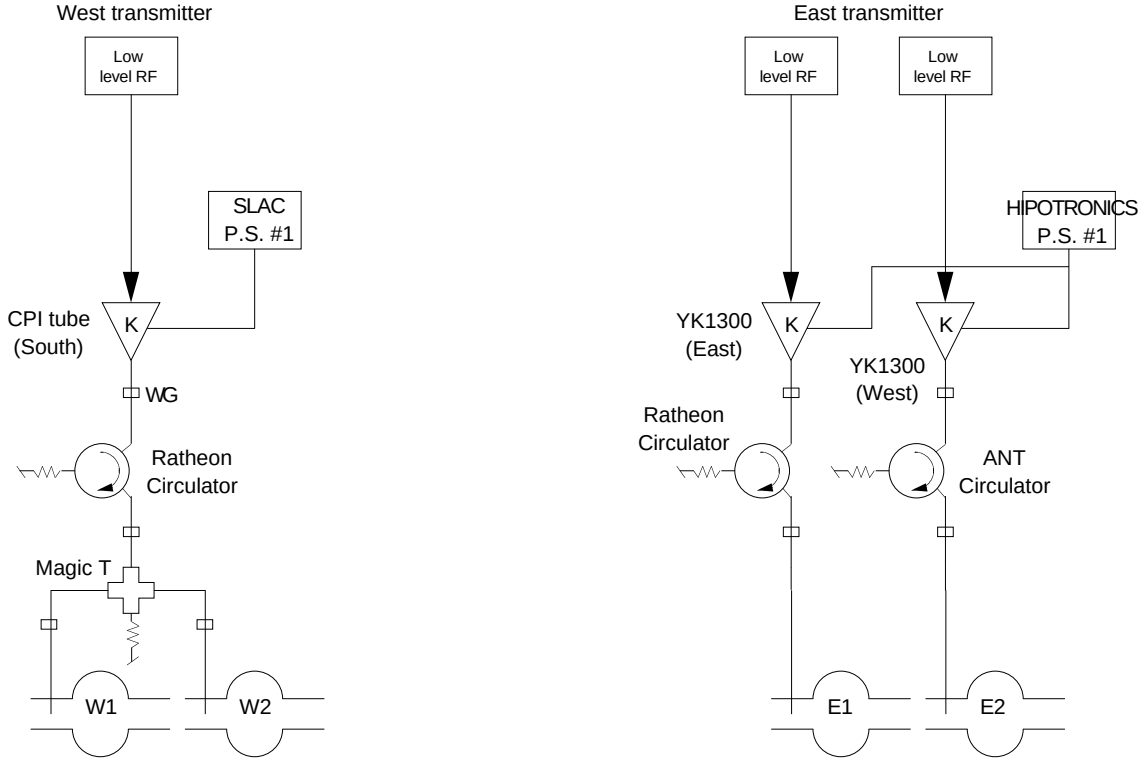


FIGURE 41. Present configuration of CESR RF system.

4.2.2 Planned Addition for Lower Energy Operation

4.2.2.1 Increasing Number of Cavities for Shorter Bunches

The CESR-c design calls for a short bunch length of 1 cm. As a result the total RF voltage will have to be increased to 7.5 MV at the beam energy of 1.55 GeV, 10 MV at 1.88 GeV, and 12 MV at 2.5 GeV. Though 7.5 MV voltage is available with existing 4 cavities, 12 MV may not be reachable and changes in the CESR-c lattice design may require even higher RF voltage.

Some of the additional voltage is available by increasing the capability of existing cavities. Three of our cavities can stably operate at accelerating gradient of 8 MV/m (producing 2.4 MV per cavity). One of the others will be modified to achieve the same gradient, providing CESR with a maximum RF voltage of 9.6 MV. Operating at even higher gradients may be possible and will be explored. As part of a previously planned upgrade for 5.3 GeV operation, two additional cryomodules were ordered and one or both of them can be added to the four existing modules as necessary. These additional cavities will be installed in the interaction region (IR) next to CLEO.

While RF voltage required by CESR-c is high, its power demand is very moderate: 160 kW at the energy of 2.5 GeV, 90 kW at 1.88 GeV, and 40 kW at 1.5 GeV. These power levels are quite modest compared to recent operation - one transmitter is more than adequate to supply necessary power. On the other hand such a low power demand at very high voltage will present a challenge for RF regulation loops. Beam synchronous phase at this conditions (six accelerating cavities) will be 88.9° at 2.5 GeV, 89.0° at 1.88 GeV, and 89.2° at 1.5 GeV, meaning that bunches will pass the cavity gap very close to the null of RF wave. Even the slightest RF phase error will cause a large cavity mismatch and an unacceptable change of cavity voltage and power delivered to beam. To ease this problem we propose to operate two out of six cavities in active mode and other four in passive mode. The synchronous phase for two active cavities then will become equal to 86.6° at 2.5 GeV, 87.1° at 1.88 GeV, and 87.5° at 1.5 GeV, which is still rather close to the RF voltage null, but should be manageable.

The four passive cavities will provide the extra voltage needed to shorten bunches. This voltage is induced by the beam and therefore its phase follows the beam automatically. A complication of this mode of operation is that the beam induced voltage will be changing during injection until the beam current reaches a level (say 100 mA) where the cavity tuner feedback loops begin to operate. The synchrotron tune and bunch length will be changing during this time as well (Figure 42). Special arrangements will be needed to assure proper operation of the longitudinal feedback system. A test has been performed in CESR demonstrating the viability of this technique by idling one of the 4 SRF cavities in CESR and adjusting the tuning angle accordingly.

4.2.2.2 RF Transmitter Modification

The high power circuits of the RF transmitters will not require significant modifications. New waveguide feeders will be added to IR cavities for high power processing and supplying RF power in active mode of operation. Three transmitters will be configured to two cavities per klystron (Figure 43). Depending on the energy of experiment we will choose the number of cavities operating in active and passive modes for most efficient operation of the RF system. Three stub waveguide transformers [16] will be installed to adjust individually each

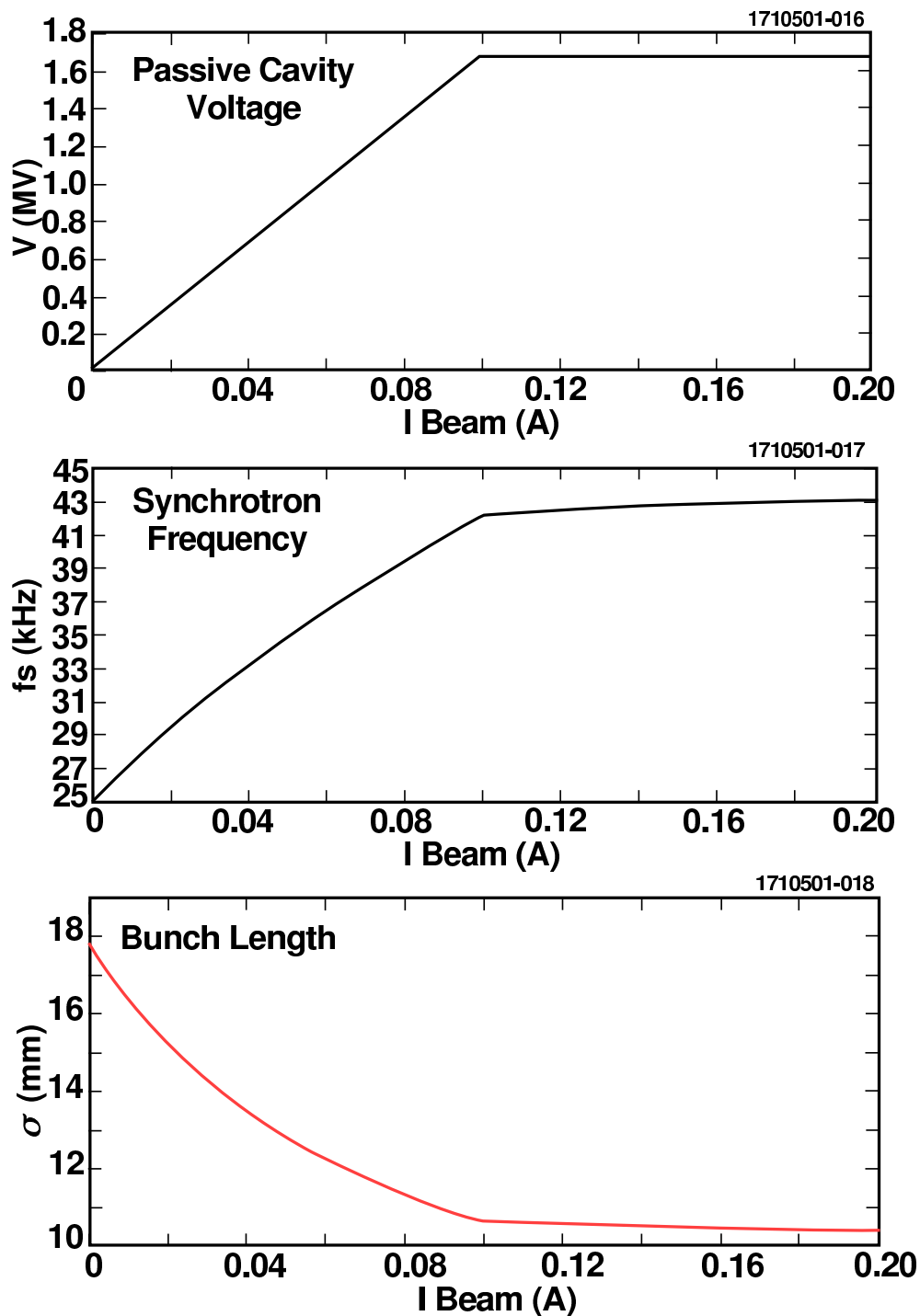


FIGURE 42. RF Voltage and longitudinal beam parameters at 1.88 GeV with 2 active and 4 idling RF cavities.

cavity coupling to its optimal value. The fourth transmitter will be available for processing area tests.

Two new sets of low level RF electronics and controls will be built for the new IR cavities. We will make extensive use of digital signal processing in the low level RF circuits. RF tuner

control of the existing cavities will be modified to be compatible with operation in the passive mode. RF regulation loops will require some improvements as well. At a later stage the RF electronics of the existing cavities will be replaced with the new design.

4.2.2.3 RF Cryogenic Modification

Two new satellite valve boxes will be installed in the IR region to provide cryogenics to the new cavities. Their design will be similar to the valve boxes used for the existing cryomodules but each will feed one cavity instead of two. We foresee operating the IR cavities at a lower temperature (~ 3 K) than the present cavities. Two new sets of cryogenic controls, data acquisition electronics, and interlocks will be designed and built for IR cavities. The new design will provide a basis for future upgrade of cryogenic electronics for other cavities.

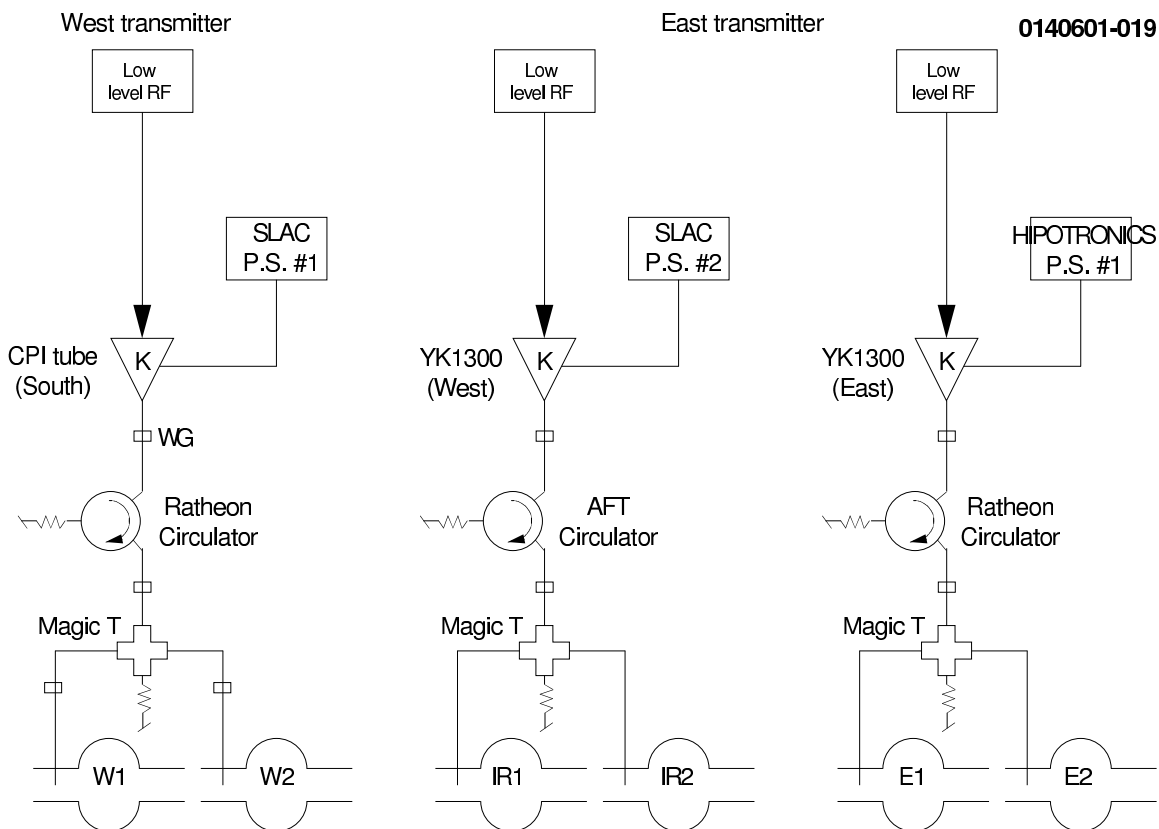


FIGURE 43. RF system configuration for CESR-c.

4.3 Vacuum System

4.3.1 The Present CESR Vacuum System

4.3.1.1 Vacuum Pumping and Pressure

The CESR vacuum system near the IR (± 15 m from the IP) is pumped by Titanium Sublimation Pumps (TiSPs), with distributed TiSPs situated between ± 6 and ± 15 from the IP, and lumped TiSPs located ± 2.6 m from the IP. The CESR IR vacuum performance is

monitored by 10 cold cathode ion gauges (CCGs), and an average pressure of less than 10^{-9} torr are routinely maintained at full stored beam current. Only 3 to 4 TiSP re-generations per year are necessary, and these re-generations can be easily fitted into the scheduled accelerator inspection accesses. A beam dose of ~ 100 A-hr is sufficient to condition the IR vacuum chambers to reach an acceptable average pressure of $< 2 \times 10^{-9}$ torr for HEP operations after a controlled dry-N₂ venting in the IR. Further improvement in IR vacuum is expected after the full installation of the CESR Phase III IR vacuum system, which includes vacuum chambers with higher gas conductance and an increased number of TiSPs close to the IR.

The vacuum system in the CESR arcs is pumped by over 100 lumped sputter-ion pumps (LIPs) and 78 distributed ion pumps (DIPs). Studies also show that a well-conditioned aluminum chamber wall provides significant dynamic pumping, or so-called “wall-pumping”, via re-adsorption of gas molecules. In fact, measurements and modeling showed a distributed wall-pumping speed of ~ 100 l/s-m, as compared to the DIP pumping speed of $40 \sim 60$ l/s-m in the UHV condition. With the combination of LIPs, DIPs and wall pumping, an average dynamic pressure of $1 \sim 2 \times 10^{-9}$ torr, measured by 50 CCGs, is routinely achieved throughout the CESR arc region with full beam currents. The gas-scattering beam lifetime at this pressure is about 10 hr. During the past years, many sections of CESR arc were vented for upgrades. Full re-conditioning of the vented sections is normally achieved with a beam dose < 100 A hr at 5GeV beam energy.

4.3.1.2 Vacuum Component Heating and Safety

Most CESR vacuum chambers and components are water cooled. There are over 800 thermocouples attached to various CESR vacuum chambers and components to monitor temperatures and to ensure proper functioning of cooling system.

Synchrotron radiation is the major source of heating of CESR vacuum chambers and components. Temperature data from HEP operations and dedicated machine studies all indicated that the installed cooling of the vacuum chambers and components is adequate to handle SR power with total beam current up to 1 A at 5.3 GeV.

Recent studies identified two kinds of vacuum components that needed additional cooling: ceramic chambers (in fast pulsed magnets) with thin resistive metallic coating; and the sliding joints (SLDJs). Forced air convection cooling has been added to all ceramic chambers to ensure the safe operation of these chambers at full design beam current. The studies revealed a coherent HOM heating in CESR sliding joints (SLDJs) only when the gap of a SLDJT falls within narrow well separated ranges. These resonant SLDJT gaps have been determined experimentally, and measures have been taken to set the openings of all CESR SLDJs away from the resonant gaps.

4.3.2 Projected Vacuum System Operation at Lower Energies

4.3.2.1 Vacuum Pumping and Pressure

When CESR operates at lower energies with reduced beam currents, the synchrotron radiation flux will be much lower than that for present 5.3 GeV operation. The reduced SR flux leads to a smaller beam-induced gas load in the CESR vacuum system.

The pumping system performance in the TiSP-pumped IR will not be affected at lower

energy operation, due to the chemical gettering nature of the TiSPs. However, the pumping performance of the CESR DIPs strongly depends on the dipole field, hence will be affected by the decreased dipole field when operating at lower beam energies. In the hardbend region near the IR ($\pm 15 \sim 35$ m from the IP), the dipole field will be above 1500 G and the DIPs in the HBs will maintain their full pumping speed at the lower energy. With the reduced beam-induced gas load, an average pressure of less than 10^{-9} torr is expected in the IR and near-IR at lower energy and thus gas induced particle backgrounds in the detector will not be an issue.

However the dipole field in the normal bend arc magnet is lowered to ~ 700 Gauss at 1.9 GeV and the DIPs in these dipole magnets will switch off. Based on a series of measurements and modeling of pressure profiles without DIP pumping in the arc region, an average pressure of 9×10^{-10} torr can be achieved with only lumped ion pumps and wall-pumping while running with 400 mA total beam current at 1.9 GeV. Beam lifetimes due to beam-gas scattering at this pressure will be above 10 hr at 1.9 GeV. Studies also showed no degradation in wall pumping for beam doses of $\gg 500$ A-hr. In addition, any long term degradation in wall pumping will be restored during periodic running for CHESS at 5.3 GeV. However, we must plan on running at over 5 GeV after any vacuum intervention to scrub the vacuum chamber walls. A beam dose of ~ 50 A-hr at 5 GeV is sufficient for the conditioning.

4.3.2.2 Vacuum Component Heating and Safety

The SR power (P_{SR}) will be greatly reduced at lower beam energy (E) at the lower design beam current (I), since $P_{SR} \propto E^4 I$. Therefore, SR heating to the vacuum system will not be an issue. HOM heating of the vacuum components, such as SLDJTs and ceramic chambers, will not pose an operational issue either as the bunch current is much less than that at the present 5.3 GeV operation.

4.3.3 Accommodation of the Wigglers

The wiggler assemblies will be installed in straight sections in CESR, either existing or created by re-arrangement of dipole magnets, as described in Sections 3.3.2 and 4.1.3.7.

The installation of the wiggler assemblies is straightforward in the straight sections with flanged vacuum chambers. In other sections, the existing extruded aluminum vacuum chambers have to be modified to accommodate the wiggler assemblies. The removal of these chambers and re-installation of modified chambers can be facilitated by cutting and later re-welding at stainless disk welding joints at SLDJTs to avoid difficult *in-situ* aluminum welds. SLDJT(s) will be added at one end or both ends (depending on local vacuum chamber constraint situation) of wiggler assembly cluster to allow the installation and thermal expansion of the vacuum chambers.

Ion pumps will be installed on both ends of the long wiggler cluster or on one end of single wiggler to maintain adequate pressure at and near the wiggler assemblies. At locations with limited space, compact non-evaporable getter cartridges will be used for pumping.

Most of the SR generated by the wigglers in the straight sections will hit the water-cooled outer wall of the bending chambers. However, due to the long period of the wiggler, and therefore SR with a large opening angle (≥ 20 mrad), the edge of the wiggler SR can hit the un-cooled inner wall of the straight chamber and/or the bending chamber, when a wiggler

magnet is more than 4 m away from the beginning of a bending chamber. Thermal and mechanical analysis, using ANSYS, predict that the temperature rise and thermal stress on the un-cooled inner wall are all well within tolerable level. If necessary, water-cooled masks, with a masking height up to 5 mm, may be added on both ends of the wiggler cluster to prevent the wiggler SR from hitting the bending chamber inner wall.

4.4 Instrumentation and Control Systems

4.4.1 Accelerator Control system

The accelerator control system has been developed in house during the 22 years of CESR operation. A diagram showing the major components of the hardware is presented in Figure 44. All application programs run on Digital Equipment Corporation VAX or Alpha processor based work stations, shown on the left side of the figure. VME crate resident interface hardware connects the available processor buses to a 4 Mbyte Multi-Port Memory (MPM) which holds the real time database as well as data transfer control registers and semaphores for resource access control. Connections between the MPM and other VME based hardware are parallel cables.

Five byte-parallel differentially driven buses (X-bus) connect remote interface crates to 68020 based bus controllers. These processors, in addition to coordinating data transfer between MPM and hardware registers, perform scaling and offset of data and implement hardware specific instructions, effectively hiding the individual hardware characteristics from the VAX resident software.

This system is readily maintainable by a minimal staff (~ 2 full time equivalents) and has proven itself to be robust and expandable. Updating the database takes less than 2 minutes, and under some conditions can be done with a stored beam.

CESR-c will use the control system as is with minor expansion (for example monitoring and control of wiggler cryostats and power supplies.)

4.4.2 Instrumentation for 5.3 GeV Operation

CESR has an array of instrumentation and diagnostic equipment. In addition to spectrum analyzers, complex FFT analyzers, oscilloscopes, and sampling oscilloscopes, we have a 32 channel 10 Msample/s transient digitizing system for diagnosis of transient events and a synchro-scan (dual sweep) streak camera for picosecond resolution bunch measurements.

Custom instrumentation includes a beam position monitor system with detectors at every quadrupole (~ 100 total), and a $20\ \mu\text{m}$ short term repeatability. Access to individual pick up buttons makes possible measurement of transfer functions between different detectors' buttons. These measurements are used to determine betatron phase advance and coupling functions with high resolution.

Electron and positron beam synchrotron light is brought to optics boxes and used for beam profile monitoring, both 2-d qualitative monitoring with TV cameras and 1-d (vertical) quantitative monitoring for beam diagnostics and tuning.

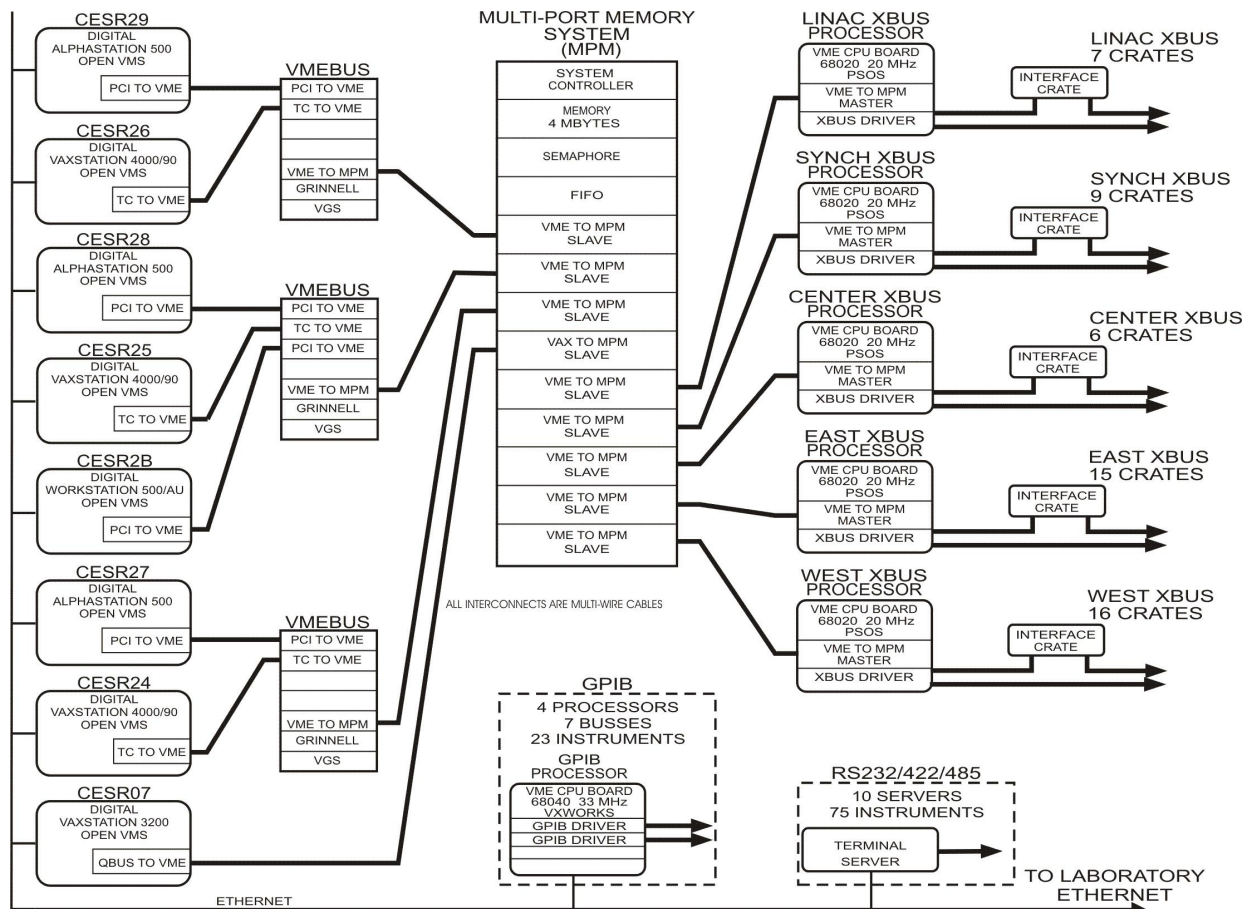


FIGURE 44. CESR control system hardware configuration.

4.4.3 Instrumentation Needs for 1.5–5.6 GeV Operation

A new CESR beam position monitor system is presently being installed in stages. The new system is capable of recording the beam position for a single turn and will enhance the lattice diagnostic and correction capabilities in this new energy region. The system is based on controllable gain amplifiers followed by a 60 Msample/s 12 bit ADC and a large buffer memory. The combination gives 16 bit resolution and provides a time stamp for accurate betatron phase measurements.

Measurement of the vertical beam size in CESR-c will be particularly important for luminosity tuning, and will be carried out using two different techniques. An interferometer will be installed in the present optical synchrotron light monitor systems which will provide measurements with an uncertainty of approximately $10\text{ }\mu\text{m}$ with a few Hz update rate. A system using prototype Si strip detectors that were manufactured for the Si vertex detector for the CLEO III detector will be installed in the unused CHESS wiggler beam lines in front of the collimators used for their focused X-ray beams. This system should be capable of providing $10\text{ }\mu\text{m}$ resolution with an update rate of 10 kHz or more depending on the x-ray beam flux. The combination of the two systems will provide much improved measurements of the vertical beam size in CESR-c that can then be used to maximize luminosity.

General instrumentation in terms of spectrum analyzers, digital oscilloscopes for wave-

form recording, etc will be acquired as needed. In some cases, dedicated custom interface boards to VME will be designed and installed to meet special needs. As an example, the same technology as used in the BPM system provides an excellent digital oscilloscope.

4.5 Feedback System

4.5.1 Present Feedback Systems

CESR operates routinely with three beam stabilizing feedback systems in action. These systems provide damping of dipole oscillations in the horizontal, vertical and longitudinal directions of motion bunch by bunch for as many as 182 bunches per beam. The system operates with a minimum bunch-to-bunch spacing of 14 ns.

The present systems are the result of feedback system development in CESR over the last 17 years and they have been designed to counter two known coupled bunch dipole instabilities. The first of these occurs for positrons in the horizontal plane and is believed to be due to the high voltage in the distributed vacuum pumps interacting with photoelectrons in the vacuum chamber. For this instability the most unstable mode of oscillation has a very non-linear current dependence, starting with no growth rate at zero current rising to $+300 \text{ s}^{-1}$ at 80 mA total beam current in 9 trains of bunches and then falling to near zero at 150 mA [17,18]. The peak instability growth rate is roughly proportional to the high voltage on the vacuum pumps, so a program of reducing the voltage during operations and using horizontal bunch by bunch feedback is able to control this instability. The second instability is longitudinal in nature being caused by higher order modes (HOMs) in the vacuum chamber components interacting with the beam [19] and is stabilized using longitudinal dipole bunch by bunch feedback which has a damping rate which exceeds the instability growth rate at all currents.

All three feedback systems [20,21] use capacitive beam position monitors (BPMs) at an electrostatic pretzel node as inputs to a bunch by bunch digital signal processor, which provides a filtered position error signal at the betatron or synchrotron tunes. In the case of the horizontal and vertical feedback systems, this error signal is used to amplitude modulate a bipolar pulse which is in turn amplified and sent to the respective horizontal or vertical stripline kicker. In the longitudinal case the BPM signal is mixed with a 500 MHz CESR RF reference to give a phase (or temporal) error signal. After digital processing, the longitudinal error signal controls the amplitude of a pulse modulated 1142 MHz carrier. This signal, after passing through a TWT power amplifier, is applied to three coupling ports on a low Q , 1142 MHz accelerating cavity. In addition to producing the beam stabilizing feedback, the digital processors also provide the bunch by bunch current monitor for CESR and a beam loss trigger signal to initiate beam loss diagnostics. The processors also store up to 32k samples of position data with full flexibility in choice of bunches sampled and turns between samples.

All three systems provide damping proportional to the total beam current for bunch currents in the range of 0.4 mA to 12 mA (6×10^{10} to 1.8×10^{11}). In this linear regime of operation the feedback systems provide damping of dipole coupled bunch oscillation with a rate of $6000 \text{ s}^{-1} \text{ A}^{-1}$ for the horizontal plane, $4000 \text{ s}^{-1} \text{ A}^{-1}$ for the vertical plane and $5000 \text{ s}^{-1} \text{ A}^{-1}$ for the longitudinal plane. All three of these damping rates are maintained in the presence of injection and other routine operational transients and are well in excess of

any observed instability generated growth rate.

4.5.2 Feedback Needs for 1.5-5.6 GeV Operation

Operating CESR at lower energies implies that the destabilizing kicks produced by the interaction of the beam's co-moving RF fields with the HOMs caused by discontinuities of the vacuum chamber components will be higher, inversely proportional to energy. Likewise the feedback system's kicker will provide a larger feedback kick compared to higher energies - also inversely proportional to energy. Since at all but the very lowest currents the feedback system's damping of dipole motion vastly exceeds the radiation damping of CESR, the net effect is that, if the beam's spectral excitation of the HOMs remains constant at all energies, then the feedback system will be equally effective, allowing the same maximum current to be stored independent of energy.

There are two major effects that can change the beam's spectral excitation of the HOMs. The first of these is due to a significant increase in the beam's spectral amplitudes at higher frequencies caused by reducing the longitudinal bunch length. Since the present bunch length of CESR gives a characteristic frequency roughly the same as the beam pipe's cutoff frequency and since HOMs above the cutoff frequency have generally much lower Q 's and R/Q 's, this is not likely to increase the instability growth rate by more than a factor of 3. Measurements of longitudinal instability threshold currents vs. bunch length show no significant dependence at all. The second mechanism for changing spectral excitation of the HOMs is caused by shifts of the HOM frequencies in the various vacuum chamber components which have relatively large Q 's and R/Q 's. These frequency shifts can arise from changes in dimensions of vacuum chamber components caused by variations in beam induced heating. The repeatability of the measurements of the instability threshold currents vs. different spacings of bunches in the 9 trains over time and many different sets of conditions suggests that this is not likely to change the instability strength a large amount.

The present feedback systems should be sufficient to stabilize dipole coupled bunch instabilities over the entire energy range. Furthermore, the instability caused by the beam interacting with photoelectrons trapped by the distributed vacuum pumps will be eliminated at the lowest energies since the vacuum pumping will be very small and the pumps will, therefore, be turned off. The longitudinal and transverse feedback damping can be increased by switching to a higher output power amplifier or, in the longitudinal system, by switching to a higher frequency cavity. A longitudinal bunch by bunch quadrupole feedback system can also be added. This could be implemented using another digital signal processing channel and the existing longitudinal feedback cavity's field being amplitude modulated and operating at the zero crossing phase.

At some point in low energy operation it may be advantageous to run with minimal beam energy spread, *i.e.*, without wigglers. In this configuration the horizontal emittance will be so small that bunch currents will be limited to very low values (0.5 – 1 mA) by the horizontal beam-beam space charge effects. Luminosity could be increased by adding bunches between the existing bunches. The feedback system would then have to operate with about half the present bunch spacing (faster rise times, wider effective bandwidth). The kickers have been switched from bi-polar to uni-polar operation and additional processing channels have been built. Initial tests are underway.

4.6 Injection System

4.6.1 Present Injection System Operation

The CESR Injector chain consists of a 150 kV e^- gun, an 8-section S-band linear accelerator and a 60 Hz synchrotron with 10 GeV peak energy. The gun provides charge in a bunch train pattern with 14 ns spacing between bunches in the train. For electron injection this beam is accelerated to 300 MeV in the linac, injected into the synchrotron, accelerated to full energy and extracted in a single turn for delivery to CESR via a transfer line. The extracted beam is transported to a thin-walled septum magnet for injection into CESR. This process repeats at 60 Hz for accumulation of beam current in CESR.

Positron beam production proceeds by striking a 150 MeV electron beam on a tungsten target located midway along the linac. The positron beam is collected and accelerated in the remainder of the linac to 200 MeV, and passed through an energy compressor which performs phase-space rotation to reduce the energy spread. The positron beam is injected into the synchrotron (in the direction opposite that of the electron beam), accelerated to full energy, extracted and delivered to CESR.

A set of fast “bumper” magnets in CESR creates a closed horizontal orbit bump (lasting 4 turns) which brings the stored beam near the injection septum to minimize the oscillation amplitude of the injected bunch. After one revolution in CESR a one-turn kicker is fired to further reduce the betatron amplitude of the injected beam, at the expense of inducing betatron motion of the stored beams. The linac, synchrotron and CESR pulsed injection elements are cycled at 60 Hz. The CESR injector and injection specifications and performance are summarized in Table 15.

CESR presently operates in a “topoff” mode as follows. At the end of a data-taking run, the beams are separated, the positron current is “topped-up” to the operating current, the electron current is “topped-up”, the beams are brought back into collision and data-taking resumes. CESR injection is performed in the standard colliding-beam optics, although efficient injection requires operation with tunes, closed orbit, coupling and chromaticities which are different from those used for colliding-beam conditions. The present CESR operations cycle at 700 mA total beam current consists of 45 minute data-taking runs followed by ~ 7 minutes to topoff the beam currents and bring the beams back into collision.

4.6.2 Injection System Operation for 1.5-5.6 GeV

No modification of the existing injection hardware is required for operation in the range 1.5 - 5.6 GeV. In fact, the injector was operated in the range 3-10 GeV in the 1970s. Recently, we have established 1.5 GeV multibunch positron and electron beams in the synchrotron with intensities $\sim 90\%$ of that routinely achieved at 5.3 GeV. Furthermore, we have extracted a 1.9 GeV positron beam into the synchrotron-CESR transfer line for observation on a phosphor screen. Some minor adjustments to regulation circuits have been required to achieve stable operation of a few power-supplies at the lower currents required for low-energy extraction.

We are proceeding with hardware improvements to increase the positron production and positron injection efficiency into CESR. These improvements will enhance the positron injection rates at all CESR operating energies. Central to this upgrade program is a new tungsten positron converter with improved cooling capability (to handle increased bombard-

TABLE 15. Injector and injection specifications and performance.

	Positron	Electron
Gun charge per bunch	3×10^{11}	1×10^{10}
Linac pulse length [μ s]	2.5	2.5
Linac bunches per pulse	15	15-35
Linac beam energy [MeV]	200	300
Charge per bunch at injection [e]	2×10^8	2×10^9
Charge per bunch at extraction [e]	1×10^8	1×10^9
CESR peak fill rate [mA/min]	120	350
CESR average fill rate [mA/min]	35	90

ing electron intensities) and improved positron collection efficiency. In addition, a one-turn kicker is being constructed for installation in an optimum location in CESR to reduce the betatron amplitude of the injected positron beam.

The injector requirements for low energy CESR operation are modest. Assuming beam lifetimes of 3 hrs, fill rates comparable to those presently achieved, peak single-beam current of 230 mA and the present operations cycle with 45 minute run length yields a total injection time of 2.3 minutes. Allowing 1 minute for switching between the various machine conditions yields 3.3 minutes for HEP off to on time, or a duty factor of 93%.

4.7 Safety Systems

4.7.1 General Safety

The Laboratory of Nuclear Studies (LNS) and the Cornell High-Energy Synchrotron Source (CHESS) are located on the Cornell University Campus. They operate under Cornell's Health and Safety Policy: "Cornell University strives to maintain a safe living, learning, and working environment. Faculty, staff, students, and other members of the Cornell community must conduct university operations in compliance with applicable federal, state, and local regulations, University Health and Safety Board requirements, and other university health and safety standards." As part of the implementation of this policy, the University has a Department of Environmental Health and Safety. Their staff provides substantial support to the Safety Programs of our laboratories.

LNS operates with both a Safety Committee and a Safety Director. The Safety Director screens new installations and apparatus for compliance with health and safety regulations, for conformance to any safety standards that might apply, and for protection from any hazards these do not adequately address. Depending on the scale of the project or nature of the hazard, the Safety Committee or an ad hoc committee may be asked to conduct a formal review. Representatives from the Department of Environmental Health and Safety are invited to most Safety Committee meetings and reviews. CHESS has its own Safety Committee. The laboratories share portions of Wilson Laboratory and have fully coordinated safety programs. This includes participation of safety personnel of each lab in reviews of

hazards in either lab.

The areas where CESR-c may raise new safety concerns are radiation and cryogenic safety.

4.7.2 Radiation Safety

Cornell University is licensed by the New York State Department of Health, by authority of 10NYCRR Part 16, to operate the accelerators that make up and fill CESR. The University Radiation Safety Committee and the Cornell Radiation Safety Officer prepare and enforce rules that implement the requirements of these regulations. Radiological monitoring of CESR is done by employees of the Laboratory of Nuclear Studies and reviewed by Cornell's Department of Environmental Health and Safety. The laboratory's radiation safety program is administered by a laboratory Radiation Safety Officer, a Radiation Safety Technician and other laboratory personnel as needed and is reviewed by the LNS Safety Committee.

Cornell has an aggressive ALARA (As Low As Reasonably Achievable) program that seeks to minimize exposures to occupational workers (with an investigation trigger of one-tenth the whole-body dose allowed under federal and state regulations). The radiation badges worn by LNS and CHSS personnel show exposures much lower than ALARA levels and nearly all are less than the dose limits for the general public (< 100 mrem/year).

4.7.2.1 Radiation Safety at 5.3 GeV Operation

The radiation from CESR is synchrotron x-rays formed in the bending magnets and electromagnetic shower products, such as gammas or neutrons, from lost particles either from stored beam or injection. The CESR tunnel extends into the side of a valley with nearly all of the storage ring about forty feet underground. Thus, the earth provides a natural shield for most of the accelerator. The experimental hall is constructed on the grade side of the ring and provides the only break in the earth shielding. The walls of the hall were built thick enough to shield against the much higher radiation levels generated in the past by the extracted beams from the original Wilson Synchrotron. Concrete shielding block walls define the radiation area within the experimental hall. Inside the high radiation areas, additional shielding reduces the radiation levels from the injector and other high loss rate points near their source. We shield to keep levels outside the controlled access areas to less than 2 mrem in one hour.

The system of shielding, gates and light beams isolate the high radiation areas from the rest of the facility. Entry can be made only by a system of access keys which, in hardware, either disable all or parts of the accelerator or enable local area monitor trip circuits (depending on the location of the particular area). Keys can be released only by the CESR Operator. Electronic radiation monitors are placed near the shielding around the perimeter of CESR. Neutron and gamma levels are continually recorded by a computer. Hardware interlocks in each monitor trip the accelerator or injector if either level exceeds a threshold (usually 2 mrem /hr.) Inspection of graphs of the history of these monitors show average rates much less than the trip levels. Radiation survey badges are also placed around the building to monitor integrated doses near the accelerator. All of the badges from outside the controlled access areas register less than 100 mrem/year.

The personal radiation badge exposures serve as feedback on the effectiveness of these measures. Each badge monitors x-ray, gamma ray and neutron exposures. Our median and average doses to LNS and CHESS personnel are much less than the ALARA levels and the even more conservative dose limits for non-radiation workers (< 100 mrem/year).

CHESS will be rebuilding its A-Line optics with a front-end mirror that will intercept the bremsstrahlung radiation from the CESR beams before it can enter the CHESS areas. This will reduce neutron production in CHESS experimental apparatus and reduce levels inside the CHESS experimental area we were most concerned about for the future (a controlled access area, now usually less than $1/2$ mrem/hr).

4.7.2.2 Radiation Safety at 1.5-5.6 GeV Operation

The impact of operating at higher or lower energies will be influenced not only by the beam energy directly, but also by the amount of current that can be stored in CESR and the quality of the vacuum at that energy. The number of gammas and neutrons generated by showers from lost beam particles will be proportion to the beam power. The total energy of synchrotron x-rays increases as the fourth power of the beam energy and the critical energy, as the cube.

At energies above 5.3 GeV the increased power lost to synchrotron x-rays will limit the ability of the RF to support additional beam current. Since our shielding is sized to reduce the neutron flux from lost particles; we have much more x-ray stopping power than we need. The increased number of x-rays may lead to operations difficulties from radiation damage of electronic equipment and cabling inside the shielding. There is an ongoing program to identify and repair weak spots in x-ray shielding inside the accelerator enclosure. The lost particle flux and the resultant neutron generation will change only slightly with a small change in energy.

At lower energies synchrotron x-ray radiation problems will markedly decrease. The radiation from lost beam particles will fall from both reduced current in CESR and reduced beam energy (beam power is energy times current). The reduced beam current and x-ray flux (which produces the gas responsible for lost particles) will give an order of magnitude reduction in the production of gas which will more than compensate for any reduction in pumping as the magnetic field in the distributed ion pumps drops at the lower energy. Tests with the distributed pumps disconnected showed vacuum chamber wall pumping continuing for at least a month. The pumping in the area where people work, near the IR, will still be working at 1.5 GeV (lump pumps, hard-bend pumps and Ti sublimation pumps). Therefore we expect reduced radiation levels in these areas at the lower energies.

In summary, operation slightly above or substantially below 5.3 GeV is not expected to increase the radiation hazard during operation.

4.7.3 Cryogen Safety

The installation of superconducting wiggler magnets in the tunnel raises the question of the safe use of liquid cryogens in the tunnel. Because of cryogens ability to displace air in a relatively limited volume, their use in accelerator tunnels must be implemented with great care.

There are several precautions that will be observed. Supply rates and local inventories will be hardware limited to necessary amounts. The tunnel normally has a high ventilation rate to replace any accidental release of cryogenics with fresh air. All normal exhaust of evaporated cryogenics will be through an exhaust line out of the tunnel. All reasonably anticipated events that might result in a venting of a cryogen will be engineered to vent outside the tunnel. This would include quenches, simple vacuum failures, simple operational errors, warm ups. This will be accomplished by having a set of pressure relief systems that discharge into an appropriately sized and engineered vent line (which might also be the exhaust line). These measures are beyond the active or passive operational controls that serve to limit quench conditions or overpressures.

There will be a Safety Review of the detailed plans to ascertain that the final installation will be safe.

4.8 Conventional Systems

4.8.1 Power and Water

The RF and magnet power requirements for low energy operation are drastically reduced compared to recent running at 5.3 GeV, and operation up to 5.6 GeV or higher will continue with limits to beam current to keep within power limits, both source and sink.

The wiggler units themselves will operate from the installed refrigerators. The only additional power needed will be for a small (20 kW) power supply for the main wiggler current plus low level electronics. This can be readily supplied from the existing power distribution system. A small amount of local water cooling may be needed for solid state switches, but total requirements will be less than 10 gpm and have no impact on the overall water system load.

4.8.2 Cryogenic System Modifications Needed for 1.5-5.6 GeV Operations

Operation of CESR over the extended energy range has only a modest impact on the cryogen plant, principally because the expected heat loads associated with the wigglers are small. As remarked in Section 4.1.3.5.1 they demand less than 100 W from our capacity. The principal modification of the existing installation is the insertion of “tees” in the transfer lines just upstream of the satellite valve boxes, which serve the RF cavities.

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