Luminosity

shift
beam-beam tune
bunch current
beam current
energy spread

bunch trains
bunch length
radiation damping time
efficiency

CESR-c parameters

NSF Site Visit - March 5, 2002

& CESR Working Group

David Rubin

Accelerator Physics Challenges and Early Results
To get from CESR (5.3) to CESR-c (1.88) we scale current with energy and then introduce wigglers to keep everything else the same.

I. Emittance and Damping rate
- Without wigglers: \( \epsilon \sim E^2 \) and \( \frac{1}{\tau} \sim E^3 \)
- Restore to typical 5.3GeV values with 14 - 21 wigglers

II. Dynamic Aperture
- Compensation of wiggler focusing
- 9-5 bunch trains
- Wiggler compensation
- Solenoid compensation
- Linear optics
- Without wigglers: \( \epsilon \sim E \) and \( \frac{1}{\tau} \sim E^3 \)

III. Energy calibration
- Timescale scattering, multibunch instability, parasitic beam-beam
- 4mA/bunch, 180mA/beam injection
- Beam current
- Wiggler nonlinearities

IV. Beam current
- CESR-c parameters

V. To get from CESR (5.3) to CESR-c (1.88) we scale current with energy
Emittance and Damping

- Emittance is generated by emission of photons in bending magnets
- At lower energy and lower bending field emittance shrinks
  \[ \text{I}_{\text{bmax}} \sim x \cdot h \cdot e \]
  (beam-beam interaction at IP)

- Control emittance or beam current will be limited
- Flexible control will permit optimization for best performance
- Control emittance or beam current will be limited

- On the other hand
  \[ \frac{1}{I_{\text{total}}} \sim \frac{1}{I_{\text{max}}} \]
  (parasitic beam-beam interaction and aperture for pretzel orbits)

At lower energy and lower bending field emittance shrinks
- Emittance is generated by emission of photons in bending magnets
And radiation damping is critical to the injection process.

- Beam-beam interaction
- Intra-beam scattering
- Impedances

Radiation damping limits destabilizing effects of:

- Beam-beam interaction
- Intra-beam scattering
- Impedances

Radiation damping time in CESR at 1.88 GeV without wigglers is \( t = 500 \text{ms} \) at 1.88 GeV without wigglers.

Damping time in CESR at 5.3 GeV beam energy is \( t = 22 \text{ms} \).

Without wigglers radiation damping time \( t = 5 \times 10^{-3} \).
Linac synchrotron injector can deliver trains of bunches at 60Hz

Emittance and Damping
Emittance and Damping

With the installation of high field wigglers, that time can be reduced to an acceptable level. With the installation of high field wigglers, all of its energy is radiated away.

The radiation damping time is that time required for the beam to radiate. Reduced damping time with wigglers and filling time is < 1 hour.

At 1.88 GeV, without wigglers, rep rate is reduced to ~ 3 Hz. Typical time to refill CESR (5.3 GeV) at 60 Hz is 5 minutes.

Radiation damping and injection.
Emittance control and reduced damping time

- Total length = 18.2 m
  - $B_w = 2.1 T$, $E/E \approx 8.1 \times 10^{-4}$ at 1.88 GeV
  - $t \approx 55$ ms
  - 30 Hz injection

We choose spread peak field ultimately limited by acceptable energy

But peak field is most effective field

To increase emittance and especially damping rate, high

- Neatly independent of $L_w$ (nearly independent of $L$)

Choice of wiggler parameters

Emittance control and reduced damping time - Conclusion
Linear Optics

Requirements

- Accommodate optical effects of wigglers
- Emittance $100 \text{nm} < 250 \text{nm}$
- Betatron phase advance suitable for electrostatic separation
- Compensate transverse coupling of 1T CLEO solenoid $= 10 \text{mm}$
- Of 9 trains with 5 bunches/train in each beam
March 5, 2002

CESRF Accelerator Physics

\[ B^2 (\text{CLEO}) = 1.7 \]
\[ E = 1.89 \text{GeV/beam} \]

\[ \text{Interaction Region} \]
\[ \text{Final focus} \]
- Superconducting/pm quad hybrid
- H and V SC quads share a single cryostat
- 20cm long high gradient permanent magnet nose piece V quad

\[ \text{All quads (skew and erect) rotated} \quad 4.5^\circ \text{about beam axis for zeroth order compensation of CLEO solenoid} \]
- Skew quads permit fine tuning of compensation over wide range of energy and solenoid strength

\[ 1.5 < 5.7 \text{GeV/beam} \]

Energy reach

\[ E = 1.89 \text{GeV/beam} \]
\[ B_z (\text{CLEO}) = 1 \text{T} \]

Final Focus

Interaction Region

Linear Optics
Graded tilt except for wigglers - very similar to 5.3 GeV optics

\[ \frac{1}{Q_v} \sim \frac{B_0^2}{L} \]

Wiggler focusing is exclusively vertical

For typical quadrupoles, \( Q_v \sim 1.2 \) for 14 wiggles

In CESR all quadrupoles are independent and the strong localized vertical focusing is easily compensated (1.5 -> 2.5 GeV)

\[ f_v = \frac{0.073}{1.3} \text{m}^{-1} \text{ for } B_0 = 2.1 \text{T, } L = 1.3 \text{m and } E = 1.88 \text{GeV} \]

For typical quadrupoles, \( Q_v \sim 1.2 \) for 14 wiggles.
 CESR Accelerator Physics

Linear Optics

<table>
<thead>
<tr>
<th>Lattice parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>x [mm]</td>
</tr>
<tr>
<td>y [mm]</td>
</tr>
<tr>
<td>φ [mrad]</td>
</tr>
<tr>
<td>β [mm]</td>
</tr>
<tr>
<td>β∗v [mm]</td>
</tr>
<tr>
<td>β∗h [mm]</td>
</tr>
<tr>
<td>Crossing angle [mrad]</td>
</tr>
<tr>
<td>Qv</td>
</tr>
<tr>
<td>Qh</td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
</tr>
<tr>
<td>Number of trains</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
</tr>
<tr>
<td>Number of trains</td>
</tr>
<tr>
<td>Number of wigglers</td>
</tr>
<tr>
<td>Wiggler Peak Field [T]</td>
</tr>
<tr>
<td>Wiggler Length [m]</td>
</tr>
<tr>
<td>Bunch Length [mm]</td>
</tr>
<tr>
<td>Accelerating Voltage [MV]</td>
</tr>
<tr>
<td>1.89 Beam energy [GeV]</td>
</tr>
</tbody>
</table>
March 5, 2002

CESRc Accelerator Physics

Machine studies test optics

Linear Optics - results

Measurement of lattice parameters is in good agreement with design.

- Measure and correct betatron phase and transverse coupling
- Measurement of lattice parameters is in good agreement with design

Beam energy = 1.84 GeV
Substantial but readily compensated

Effect on linear optics of a single wiggler is substantial but readily compensated.

<table>
<thead>
<tr>
<th>Number</th>
<th>CHESS/east</th>
<th>CHESS/west</th>
<th>CESR-c</th>
<th>Length [m]</th>
<th>Peak Field [T]</th>
<th>Period [cm]</th>
<th>N-POLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.073</td>
<td>0.023</td>
<td>1.1</td>
<td>0.81</td>
<td>1.17</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>1</td>
<td>2.1</td>
<td>7</td>
<td>1.3</td>
<td>3</td>
<td>2.355</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Linear Optics - Results

Permanent magnet wigglers for CHESS x-ray physics in CESR provide an opportunity to test our understanding of wiggler optical effects.
Design test lattice including x-ray wigglers

Closed phase bump remaining

Compensate 14 adjacent quadrants adjusted to east wiggler strength reduced to zero

Phase error due to 20% reduction in strength of east wiggler.

Linear Optics - results
Linear Optics - Conclusion

- Measured parameters of 1.84 GeV test optics as designed
- Vertical focusing of 14 CESR-c wigglers readily accommodated
- 1T solenoid field compensated 1.55 - 2.5 GeV
- Linear optics design meets specification for $E_{\text{beam}} > 5.72 \, \text{GeV}$
Dynamic Aperture

- Dynamic aperture is increased
- Required sextupole correction is reduced
  - Chromaticity generated in IR decreases with energy
  - Especially true at low energy
  - Compact final focus designed to minimize peak $\sigma$ in IR
  - Interaction Region

Dynamic Aperture
We need to determine optimum period and required field uniformity.

But the larger excursion of wigglers yields greater sensitivity to horizontal roll-off. Longer period results in weaker cubic nonlinearity.

Finite pole width roll-off in vertical field with horizontal displacement.

\[ y = -B_0 L^2 (B r)^2 + \frac{2}{3} \frac{1}{p L} \epsilon \frac{(B r)^3}{L_0^2} \]

Wigglers cubic nonlinearity scales inversely as square of period.

Dynamic Aperture
Procedure for determining wiggler period and field quality specifications

1. Design linear optics to minimize effect of cubic nonlinearity
   - Minimize vertical wiggler locations
   - Minimize nonlinearity
   - Arrange betatron phase so that there is some cancellation

2. Determine dynamic aperture with particle tracking
   - Assumes infinitely wide pole
   - Using analytic "hard edge" model that includes cubic nonlinearity

3. Yields minimum period consistent with good dynamic aperture
   - \( l = 40 \text{ cm} \)

Dynamic Aperture
Dynamic Aperture

Plot indicates maximum stable amplitude after 1000 turns.

- Number = 14 (7 poles)
- \(l = 1.3\) m
- \(E_{beam} = 1.88 GeV\)
- \(B_0 = 2.1\) T
- \(E/E_0 = 0.003\)
- \(E/E_0 = 0.006\)

Wiggler parameters

- Tracking with "Perfect" wigglers

- is < 10° (outside physical aperture)

- Rigidity parameters

March 5, 2002
4. Include multipole fields in each pole to model horizontal roll-off in the vertical field.
5. Tracking study indicates that unless $B/B \leq 0.3\%$ at 4 cm, the dynamic aperture is degraded.
6. Shape profile of wigglers pole to achieve required level of uniformity.
7. Compute dynamic aperture by tracking with field map as wigglers model.

Dynamic Aperture
Dynamic Aperture

Through the mapped field, the dependence of horizontal kick on horizontal displacement is determined by integration through the mapped field. The vertical field vs horizontal displacement at the center of the central pole and in the midplane is shown.

Dependence of horizontal kick on horizontal displacement.

$\frac{B/\beta_0 B_0}{4 \text{cm}} \approx 0.3\%$
Dynamic Aperture

Compressed field map

Tracking is based on computed field map.

For good lifetime, stable amplitude required.

In units of rms beam size, stable amplitude for various energy offsets.

Jagged curves indicate largest stable amplitude for various energy offsets.

Smooth curves correspond to stable amplitude required for good lifetime.

Ax / Sigx

Ay / Sigx

Optics: BMAD RK

A1 wigglers ON

Ax = 0.266, Ay = 0.596, OX ~ 0.09

Dynamic Aperture
Dynamic Aperture

Wiggler specifications

- Dynamic Aperture

\[ \frac{B}{B_0} < 0.3 \% \text{ at } 4 \text{ cm} \]

- 40 cm period

Check accuracy of finite element calculation of fields

Comparison of measured and computed fields for

- Presently testing 3-pole model with 20 cm period
- In 3-20 model, pole is not shaped to minimize roll off

Dynamic Aperture
Dynamic Aperture

March 5, 2002

CESR Accelerator Physics
Dynamic Aperture

$B_y = 2.17$ at $x = 0$

Magnet center $B_y$ vs $x$ in midplane at

Difference between measured and calculated field ~0.1%
Dynamic Aperture

Feb 20 2002, ST
Vertical field integral vs horizontal position.
3x20 model magnetic measurement (long flipping coil)

Dynamic Aperture

Peak field at 2.1T
Integrated field with corresponding to the black points

March 5, 2002
CESRc Accelerator Physics
Dynamic Aperture

March 5, 2002

Dynamic Aperture

Calculation and measurement are close but we would like to do better and are investigating discrepancy. If measurements indicate that we have not achieved the requisite uniformity we will add pole face trim coils to correct it. We are assembling a second model with 3.40 cm poles with the refined pole shape. If measurements indicate that we have not achieved the requisite uniformity we will add pole face trim coils to correct it.
Detuning of the pair of x-ray wigglers in CESR at 1.84GeV, is approximately twice that of 14 CESRc wigglers.

<table>
<thead>
<tr>
<th>Period [cm]</th>
<th>CHESS/east</th>
<th>CHESS/west</th>
<th>CESR - c</th>
<th>Cubic nonlinearity [m⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>29</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td>12</td>
<td>23</td>
<td>33</td>
<td>22</td>
<td>32</td>
</tr>
<tr>
<td>40</td>
<td>42</td>
<td>72</td>
<td>14(11.9)</td>
<td>167</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ D_{\text{Q/m}} = B_0 \frac{B \Delta L}{2 \pi} \left( B \Delta L \right)^2 \]

PM x-ray wigglers in CESR provide an opportunity to test understanding of dynamics.

**Dynamic Aperture - Beam measurements**
Dynamic Aperture - beam measurements

CHESS/west wigglers

CHESS/east wigglers

measured

calculated

88.7(4)

79.0(4)

87.1(2.6)

91.6(5) [Hz/mm²]

16.6(5)
Measured in CESR by kicking the beam to large amplitude and recording trajectory one turn by one turn. The dynamic aperture was calculated numerically.

\[ \theta = 0.749 \]

Dynamic Aperture - Beam measurements.
Standard optics at 1.84GeV
So we have confidence in our model of both wigglers and
Nonlinear phase space -
Amplitude dependence of tune in PM wigglers
There is good agreement between measurement and calculation of:
• That we can inject and store beam with good lifetime at 1.84GeV
• Vertical detuning is more severe in CESR at 1.88GeV with existing PM wigglers than it will be with CESR-c wigglers
Total Length = 18.2m
$B/B < 0.3\%$ at 4cm
$B = 2.1T$
$N = 7$
$\Delta = 4\text{cm}$
Tracking studies indicate dynamic aperture is good if

Dynamical Aperture - Conclusions
Last night we stored $I \approx 177 \text{ mA}$ in 36 bunches at 1.84 GeV. We conclude that the feedback provides all of the damping are at the same rate. The feedback gain scales with current as does growth rate which is in agreement with the measurements at 1.84 GeV. We measured this with broadband feedback. The threshold for multi-bunch instability at 1.84 GeV is $I_{\text{threshold}} \approx I/E^4$. The damping rate is $\tau_d \approx E^{-3}$. With fixed impedances, growth rate is $\tau_g \approx E^{-3}$. Multibunch instabilities are not a serious problem.
March 5, 2002

CESRc Accelerator Physics

Lifetime limit due to Touschek scattering?

Emittance will increase further with
installation of CESR-c wigglers.

Bunch current [mA]

Loss rate versus bunch current

Beam Current

Emittance will increase further with
larger horizontal emittance

Longer lifetime with permanent
magnet wigglers closed is consistent

Measured lifetime at design bunch current of 4mA

is 40 minutes at 1.84 GeV

Loss rate [1/min]

(CESRc MS Jan 7 2002, ST)
Bunch lengthening is anticipated to be small to 10mm zero current length with respect to design gradient of 10MV to 1OMV.

Increasing accelerating voltage is observed to decrease bunch lengthening.

Increasing accelerating voltage is observed to decrease bunch length.

Beam Current
Current is limited by some combination of long range tune shift and parasitic beam-beam effects.

- Increase in beam separation (x)
- Reduce loss from tails and permit
- Lower emittance at 1.89GeV
- 3mA at 1.89GeV
- Limiting bunch current of 8.5mA at 5.3GeV corresponds to

\[ \frac{E}{q} X_{eq} \sim \Delta a \]

- Long range tune shift
- Loss of tails to collisions with counterrotating core
- Current is limited by some combination of long range tune shift and parasitic beam-beam effects.
Beam Current - conclusion

- Multibunch feedback demonstrated effective to at least 60 mA/beam
- Measured lifetime >40 minutes with 4 mA/bunch and will increase with wiggler generated horizontal emittance
- Measured lifetime >40 minutes with 4 mA/bunch and will increase with wiggler generated horizontal emittance

- Current limits at 5.3 GeV are:
  - Synchrotron radiation heating of vacuum components
  - Beam-beam limit 4 mA/bunch

- Filling time of ~5 minutes to 180 mA with replacement of transfer line windows

- RF window power
- Synchrotron radiation heating of vacuum components
- Beam-beam limit 4 mA/bunch

- No significant bunch lengthening expected with 10 MW accelerating field
- Will not be an issue at 1.89 GeV

With flexibility to optimize emittance, parasitic beam-beam limit 4 mA/bunch

Filling time of ~5 minutes to 180 mA with replacement of transfer line windows

Conclusion:

- Beam Current - conclusion
March 5, 2002

CESRe Accelerator Physics

Identification of \( (2S) \) yields calibration of beam energy

Energy Calibration
Except for 14 wigglers, CESR is ready to run at 1.89 GeV

Beam energy is calibrated at 1.84 GeV by identification of $y(2s)$
and extrapolated to target values in wiggler loaded machine

177 mA in a single beam at 1.84 GeV

Multibunch feedback system has been tested and we have stored
Because all CESR quadrupoles (and sextupoles) are independent, no special
and tested at 1.84 GeV
Linear optics that match parameter list have been designed
and 1-1.77 CLEO solenoid
IR optics exist for 1.55 $< E_{beam} < 5.72$ GeV
and key aspects of wiggler optical properties have been tested at 1.84 GeV

Good dynamic aperture
 Adequate damping and emittance control
Wiggler parameters are specified for

Summary