IMPROVEMENTS TO THE CESR INJECTOR AND INJECTION PROCESS*

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Abstract
It is essential that the storage-ring beam injection time be minimized at an e⁺e⁻ collider factory in order to maximize the integrated luminosity output of the facility. We describe a program of improvements to the CESR injector chain and injection process which have resulted in a reduction in the CESR fill time of 40%. This has in turn allowed shorter high-energy-physics run lengths so that a higher average luminosity is maintained. Shorter fill times have resulted from increased linac beam intensity, stability and reliability, improved synchrotron transmission, faster machine condition switching time, improved CESR injection efficiency and a change to the CESR filling cycle in which both the positron and electron beam currents are topped up at the end of a run.

1 INTRODUCTION
The Cornell Electron Storage Ring (CESR) has been operating in a “factory” mode since October, 2000. This mode of operation is distinguished from past CESR operation by the emphasis on short high-energy-physics (HEP) run lengths and rapid and reliable injection to maintain a high average luminosity. In addition, the duty factor has been increased by reducing the scheduled interruptions to CESR operation.

Factory operation of a collider requires rapid and reliable injection to maximize the integrated luminosity output of the facility. Consider typical CESR parameters of peak luminosity, \( L = 1.1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1} \) and beam lifetimes of 120 minutes. For a run length chosen to maximize the integrated luminosity, and for 100% duty factor, one obtains a yearly integrated luminosity of 18.4 fb⁻¹ with a 30 minute filling time, 23.7 fb⁻¹ for 10 minutes, 26.3 fb⁻¹ for 5 minutes and 34.7 fb⁻¹ for zero filling time. Clearly, maintaining a short filling time is an essential component of successful “factory” operation of a collider.

2 CESR AND THE CESR INJECTOR
CESR is a single-ring e⁺e⁻ collider [1] operating on and near the \( \Upsilon(4S) \) resonance (\( E = 5.29 \text{ GeV} \)). CESR operates in a bunch-train mode in which each beam consists of 45 bunches arranged in 9 trains with 5 bunches per train. The bunches within a train are spaced by 14 ns, and the trains are spaced by 280 ns. The beams follow “pretzel” orbits to provide separation of the counter-rotating beams at the parasitic crossing points in the arcs of the machine. The beams collide with a small crossing angle (∼2.5 mrad).

3 LINAC IMPROVEMENTS
Recent improvements to the linac have focused on reduced linac beam intensity, improved reliability, and stability. The CESR linac had suffered from high klystron/modulator trip rates, which limited the linac availability during filling cycles. A program of pulse-forming-network improvements, klystron replacement, and klystron focus coil tuning has reduced the linac trip rates from several per hour to a few per day. The klystron replacement program has also provided ∼20% more RF power.

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power to ease beam loading and improve positron production and collection.

In addition, various thermal and “warm-up” effects affected the linac beam stability and reliability during filling cycles. One such warm-up effect was traced to the linac RF phase regulation. The RF phase is measured at the output of each klystron, rather than the input of each accelerating section. On initial turn-on of RF power, thermal expansion of the ≈15m waveguides resulted in waveguide temperature fluctuations of 14-20 °C, corresponding to 9-13 degrees at S-band. The “drifting” phases during initial turn-on resulted in “drifting” linac beam energy (by ∼1.3% per section). Two measures have been undertaken which have resulted in more stable linac beam intensity. First, cooling has been added to the exposed waveguide sections providing thermal stability to −0.5 °C. Secondly, a beam energy regulation technique has been implemented. The linac beam position is monitored in a dispersive region in each transport line which brings the beam to the synchrotron. The beam position is used to regulate the linac energy by adjusting the modulator high-voltage in a slow feedback loop. Typical linac beam energy stability is now ∆E/E ≅ 0.001.

Table 1: CESR Injector and Injection Specifications and Performance

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<thead>
<tr>
<th></th>
<th>Positron</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun charge per pulse</td>
<td>1.2x10^{12}</td>
<td>1.4x10^{11}</td>
</tr>
<tr>
<td>Linac Pulse Length [µs]</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Linac bunches per pulse</td>
<td>15</td>
<td>15-35</td>
</tr>
<tr>
<td>Linac beam energy [MeV]</td>
<td>220</td>
<td>350</td>
</tr>
<tr>
<td>Charge per pulse at synch injection [e]</td>
<td>1.1x10^{9}</td>
<td>7.0x10^{9}</td>
</tr>
<tr>
<td>Charge per pulse at synch extraction [e]</td>
<td>5.6x10^{8}</td>
<td>5.6x10^{8}</td>
</tr>
<tr>
<td>CESR peak filling rate [mA/min]</td>
<td>120</td>
<td>375</td>
</tr>
<tr>
<td>CESR average filling rate [mA/min]</td>
<td>35</td>
<td>90</td>
</tr>
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3 SYNCHROTRON IMPROVEMENTS

There is little radiation damping in the synchrotron, and adiabatic damping is inadequate to suppress coherent instabilities, or even to erase the effects of flutter in injection conditions on the extracted beam. A feedback system, modeled on the CESR wideband multi-bunch system [2], was installed to produce coherent transverse damping times <1 ms. This suppresses instabilities, permitting acceleration of large bunch charges. It also reduces flutter in the beam delivered to CESR, raising the transfer efficiency.

The new beam-position monitor system [3] has proved valuable in diagnosing major orbit-alignment problems (e.g., beam loss in mid-cycle). At high energy, the orbit is governed by the alignment of the combined-function magnets, which are positioned by motor-driven jacks (originally built-in but not utilized). The radial jack motors can now be adjusted remotely, while the accelerated beam is monitored. By various techniques we have located and eliminated several obstructions in the synchrotron's aperture.

At injection time, magnetic steering coils serve to correct the relatively much larger low-field errors. These correctors turn out to be extremely sensitive, especially for e^+, where for maximum yield one must accept particles even from the fringes of the distribution delivered by the linac. The parameters governing beam capture are not completely understood: best performance requires empirical "tuning," including the linac and its matching optics to the synchrotron. Sometimes, orbit centering by magnet moves appears to degrade the capture efficiency, because suitably placed magnetic correctors are not available to compensate. Peak performance has not so far been obtained with a well centered orbit.

Overall, however, the synchrotron's e^+ transmission efficiency has been raised from ∼35% to ∼50%, and the typical e^+ beam delivered to CESR has been almost doubled.

4 CESR INJECTION

CESR injection may be discussed in terms of two different types of filling operations. In the first, one beam species is injected into the storage ring while the other beam species is absent. This filling operation occurs at machine startup or following complete beamloss. These storage ring conditions are characterized by a small pretzel amplitude and great freedom to adjust the stored-beam tunes. In the second filling operation, one beam species is injected with the other species already at full single-beam current. This is the usual injection operation during routine running. The storage ring conditions are characterized by a large pretzel amplitude (≈2cm peak displacement) to separate the beams, and by little freedom in the choice of the stored-beam tunes. Generally, the first filling operation has been quite simple; injection efficiencies in this case can reach ∼80%. In contrast, the second filling operation has been more difficult, and has required much tuning to establish workable conditions.

The following injection-related observations have been made over several years of operation: i) as the stored beam current in CESR has increased the pretzel amplitude required to provide adequate separation of the beams during injection has also increased; ii) as the pretzel amplitude has increased the injection efficiency has decreased; iii) injection of electrons has been accompanied by high beam loss rates at the smallest vertical aperture in the machine (the wiggler vacuum chamber); iv) electron injection efficiency against a full stored positron beam routinely operated at ∼20% efficiency, compared to ∼50% in the absence of an opposing positron beam.

Several of these features pointed toward the possibility of an optics mismatch between the extracted synchrotron beam optics and the CESR optics. A reexamination of the synchrotron and transfer line layout and optics revealed a large optics mismatch at the CESR injection point. Figure
Figure 1: Extracted electron beam optics. The dotted line shows the CESR stored beam optics (starting at 60m). The old (unmatched) optics are compared to the new (matched) optics.

Figure 2: Comparison of CESR injection cycle before and after improvements.

Figure 3: History of HEP Off-to-On time and CESR beam current. The reduction in fill-time is seen in late 2000.

5 INJECTION PERFORMANCE
A comparison of a good CESR filling cycle from 1999 and a recent one is shown in Figure 2. The HEP off-to-on time has been reduced from 12 to 6 minutes as a result of the injector and injection improvements described above. It should be emphasized that this reduction in filling time is accomplished even at higher total beam currents. One expects that for operation at higher beam currents the filling time should increase since more current must be replenished at the end of a run. Figure 3 shows the history of the peak CESR HEP beam current compared to the average filling cycle time (HEP off-to-on time). The injector and injection improvements are seen as a reduction in the filling time in late 2000.

6 REFERENCES