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=1.1x10^{33} cm^{-2} 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 ϒ(4S) resonance (E=5.29 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 half-angle) which separates the beams at the parasitic crossing-points in the interaction region.

The injector for CESR consists of a 150 keV e- gun, an 8-section S-band linear accelerator, and a 60 Hz synchrotron. The linac is incapable of providing the 45 bunches required to fill the CESR bunch pattern due to beam loading and positron target heating concerns. Instead, the gun provides charge in a bunch train pattern established by a control program which tailors the selected pattern as filling proceeds, based on the individual CESR bunch currents. For electron injection the beam is accelerated to 350 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 charge in the storage-ring.

For positron beam production, a 180 MeV electron beam strikes a tungsten target located midway along the linac. The positron beam is collected and accelerated to 220 MeV in the remainder of the linac and passed through an energy compressor cavity which performs phase-space rotation to reduce the energy spread to better match the synchrotron momentum acceptance. The positron beam is injected into the synchrotron in the direction opposite that for electron acceleration, accelerated to full energy, extracted, and delivered to CESR via another transfer line.

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 magnet is fired to further reduce the betatron amplitude of the injected beam at the expense of inducing a betatron oscillation in the stored beams. The linac, synchrotron, and CESR pulsed injection elements are cycled at 60 Hz.

3 LINAC IMPROVEMENTS

The Gun and Linac parameters are shown in Table 1. Recent improvements to the linac have focused on increased 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

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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 $\Delta E/E \cong 0.001$.

Table 1: CESR Injector and Injection Specifications and Performance

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

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

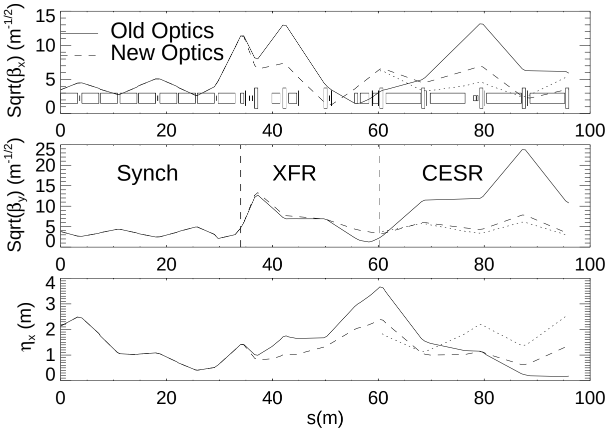

Figure 1: Extracted electron beam optics. The dotted line shows the CESR stored beam optics (starting at 60m). The old (unmatched) optics are compared to the new (matched) optics.

1 shows the optical functions of the extracted synchrotron beam from the synchrotron, through the electron transfer line and into CESR. Also shown are the CESR stored beam optical functions. The large mismatch is due to several effects, which have been present since CESR was constructed in 1978. First, the extracted synchrotron beam travels outside the good field region in the last two combined-function magnets in the synchrotron before entering the transfer line. This fringe-field was not properly handled in the original design [4], due in part to the lack of an accurate magnetic field profile. Secondly, the placement of transfer-line elements differs from the original design due to space constraints uncovered during construction. Finally, the synchrotron beam optics were modified in order to install extraction equipment when CESR was constructed.

New transfer line optics (shown overlayed in Figure 1) were designed to provide a better match to the CESR optics and to reduce the peak beta-functions in the transfer line. Matching of the dispersion was not possible given the constraints of existing quadrupole positions and number.

Until recently, the CESR operations cycle was as follows. At the end of an HEP run the beams were separated at the collision point, the electron beam was removed with a scraper, the positron beam current was topped up to the nominal value, the electron beam was injected and the beams brought back into collision for the next HEP run. Following the improved transfer line matching, as well as minor hardware modifications, a new operations cycle was implemented in which the electrons were saved at the end of a run, and both positron and electron beams currents were “topped-up.” This new operations cycle reduced the HEP off-to-on time by as much as 2-3 minutes. It also has the added advantage that the thermal heat load on the storage ring vacuum chamber components remains more stable.

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.

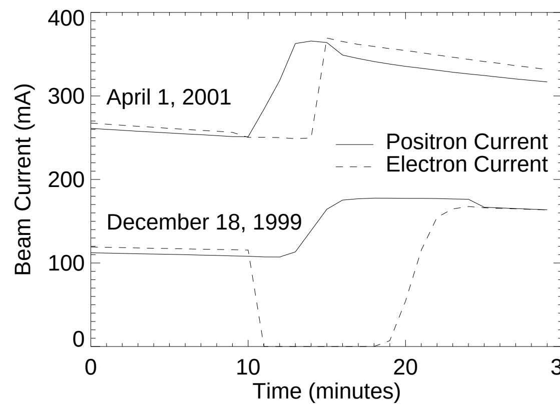

Figure 2: Comparison of CESR injection cycle before and after improvements.

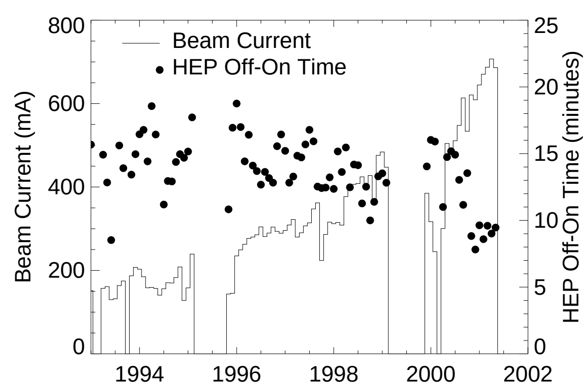

Figure 3: History of HEP Off-to-On time and CESR beam current. The reduction in fill-time is seen in late 2000.

6 REFERENCES

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