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Interlaced Beams of Unequal Energy and Pulse Length in the SLAC Linac for PEP-II and Experiment E-158*

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The two experiments, BaBar (PEP-II) and E-158, require quite different beams in the linac at the Stanford Linear Accelerator Center, SLAC. The first needs damped beams from the damping rings and low energies at the extraction points from the main linac. For E-158, an undamped, polarized beam bypasses the damping rings, and gets accelerated to energies of 45.6 and 48.7 GeV with 14% or 8% beam loading, resulting in beam charges of $6.5 \cdot 10^{11}$ and $4.0 \cdot 10^{11}$ particles. The linac betatron lattice must accommodate energy differences of up to 50%, 9 to 14 GeV at the one-third point in the linac. Gradually decreasing cell phase advance from about 100 degrees to 60 degrees near the PEP-II extraction points in the linac reduces the chromatic betatron mismatch of the PEP-II beams to an acceptable level. Additionally, pulsed correctors for steering and a pulsed RF phase shifter were installed to have more independent control for the different beams. Two new feedback systems have been implemented, which (a) stabilize the trajectory at the end of the linac, and (b) dithers the pulsed RF phase shifter to stabilize the beam phase with respect to the accelerator RF crest. A reduced intensity jitter from the gun and a skew quadrupole after the linac, which mixes the blown-up, stable *x*-emittance with the varying *y*-spot also stabilized the beam conditions on the fixed target.

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INTERLACED BEAMS OF UNEQUAL ENERGY AND PULSE LENGTH IN THE SLAC LINAC FOR PEP-II AND EXPERIMENT E-158*

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The two experiments, BaBar (PEP-II) and E-158, require quite different beams in the linac at the Stanford Linear Accelerator Center, SLAC. The first needs damped beams from the damping rings and low energies at the extraction points from the main linac. For E-158, an undamped, polarized beam bypasses the damping rings, and gets accelerated to energies of 45.6 and 48.7 GeV with 14% or 8% beam loading, resulting in beam charges of $6.5 \cdot 10^{11}$ and $4.0 \cdot 10^{11}$ particles. The linac betatron lattice must accommodate energy differences of up to 50%, 9 to 14 GeV at the one-third point in the linac. Gradually decreasing cell phase advance from about 100 degrees to 60 degrees near the PEP-II extraction points in the linac reduces the chromatic betatron mismatch of the PEP-II beams to an acceptable level. Additionally, pulsed correctors for steering and a pulsed RF phase shifter were installed to have more independent control for the different beams. Two new feedback systems have been implemented, which (a) stabilize the trajectory at the end of the linac, and (b) dithers the pulsed RF phase shifter to stabilize the beam phase with respect to the accelerator RF crest. A reduced intensity jitter from the gun and a skew quadrupole after the linac, which mixes the blown-up, stable *x*-emittance with the varying *y*-spot also stabilized the beam conditions on the fixed target.

1 INTRODUCTION

The simultaneous operation of the two different beam programs introduced complications with adverse impacts on both beams. The large PEP-II acceptance accommodates a wide range of parameters for the injected beams, allowing an optimization for E-158. An E-158 engineering run in the spring of 2001 uncovered many shortcomings [1] which were addressed in the fall before the 2002 data run. How these issues were identified and resolved will be discussed.

2 LINAC BETATRON LATTICE

The klystrons in the linac are pulsed devices and can produce beams with different energies. The biggest difference between the PEP-II beam and the E-158 beam occurs at the extraction point for the High Energy Ring beam (HER), where the HER and E-158 energies are 9 GeV and 14 GeV. Since the quadrupole magnets in the linac are not pulsed, the lattice has to be adjusted. A 90º lattice for a 14 GeV beam would be beyond 180º (stop band) for a 9 GeV beam. So the strong lattice, which reduces beam blow-up due to wakefields, has to be reduced to allow for the PEP-II extraction in Sector 4 (LER) und Sector 10 (HER). By minimizing the chromatic effects (*W*–function in MAD) and reducing the phase advance per cell to about 60-70º locally at the extraction points, a reasonable compromise was found for both beams. Fig. 1 shows the phase advance in *x* and *y* for the higher energy E-158 beam. Additionally, the linac lattice was stabilized with the Linac Energy Management (LEM) program for the E-158 beam instead of the lower energy PEP-II beam to adjust for different complements of linac klystrons.

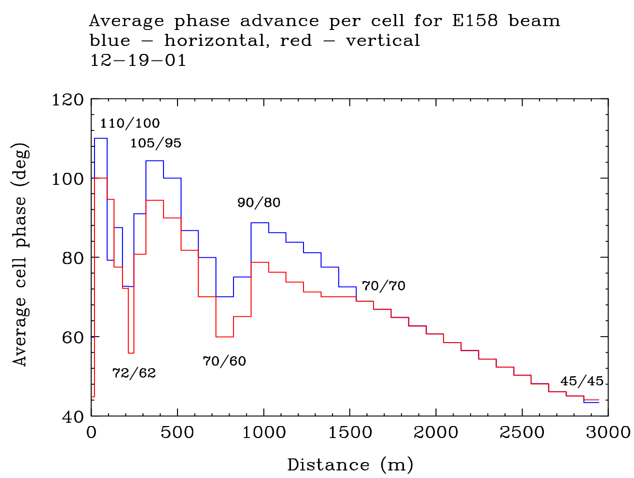

Figure 1: Betatron phase advance per cell in the linac.

3 PULSED DEVICES

Pulsed correctors and a pulsed phase shifter were added to have more independent control for the different beams.

2.1 Pulsed Correctors

Four correctors near the middle of the shared part of the linac (Sector 11) were equipped with pulsed power supplies. Some correctors had been moved from locations on the disk-loaded accelerator structure to locations with small stainless steel beam tubes to avoid the eddy currents in the copper. This was necessary for 120 Hz operation. Additionally, the two coils of each corrector were wired in parallel to reduce the inductance, resulting in an even faster rise time. Due to location constraints, one of the *x* correctors was installed at a low betatron point.

The correctors were incorporated in two feedback loops controlling the four transverse parameter *x*, *x'*, *y*, *y'* of the E-158 beam and the scavenger beam which produces the positrons for PEP-II. This setup worked well and corrected daily variations, but the power supplies for the different channels were unreliable, blowing fuses every week or two.

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2.2 Pulsed Phase Shifter

A pulsed phase shifter was added before Sector 2 to allow adjustments of the phase of all the following sectors to minimize the energy spread of the E-158 beam without changing the go-around time and therefore the phase of the combined scavenger-positron line.

This phase shifter was also controlled by a feedback system in which the phase was dithered by ±0.5º and the corresponding energy was recorded. The resulting slope was then kept constant by the feedback.

This was especially useful when other considerations were more important than the smallest energy spread. We reported earlier [1] that a positive phase could reduce the energy jitter (and the transverse jitter, too). For example, a higher intensity pulse creates a lower energy beam due to beam loading. This introduces a time-of-flight difference in the chicane, moving the beam later in time. When the phase offset is positive, the beam moves closer to the RF crest, compensating the beam loading.

The laser intensity jitter was substantially improved from 1.5% to 0.5% [2], making this compensation less critical.

3 SKEW QUADRUPOLE

A new skew quadrupole in the beam-line (A-Line) also helped to reduce the sensitivity to any linac variations. Since the strong bending in the A-Line generates an emittance blow-up of nearly 40 times in x, the spot at the target is very stable in x. In y, both the jitter and slow drift were much larger, requiring constant tuning. By mixing x and y, the skew quadrupole stabilized the y–spot on the target [3].

4 EXPERIMENTAL RESULTS

The beams were set up without difficulties, and currents up to $7.0\cdot10^{11}$ particles at 45.6 GeV or $4.5\cdot10^{11}$ at 48.7 GeV were achieved by using all of the available RF power. Typical numbers are summarized in Table 1.

Table 1: E-158 Beam Parameter Summary

Item	**Goal**	**May 2001**	**May 2002**
Beam Charge	$6.0\cdot10^{11}$	$2.4\cdot10^{11}$	$6.2\cdot10^{11}$
Intensity Jitter	2% rms	1.5% rms	0.5% rms
Position Jitter	<10%	<10%	5%
Spot Size Jitter	<10%	<10%	5%
Energy Spread	0.3%	<0.3%	0.1%
Energy Jitter	0.2%	<0.1%	0.03%
Beam Rate	120 Hz	30 Hz	120 Hz
Efficiency	43%	50%	70%
Polarization	75%	(67±8) %	82%

4.1 Injector

Improvements to the source laser increased the charge per pulse and reduced the jitter [2]. This resulted in improved beam stability through the entire linac and made higher current possible. With higher current, we were also able to shape the pulse intensity distribution to compensate beam loading more precisely.

4.2 Rate Changes

The linac repetition rate was initially 30 Hz; later it was raised to 60 Hz and finally to 120 Hz. Temperature effects were visible, since the beam extracts up to 550 kW of the RF power in the linac. Water temperature changes had a typical time structure of 2-3 min, but their effects were compensated by the energy and phase feedbacks.

After the repetition rate was raised to 60 Hz, the first few E-158 pulses following a PEP injection pulse (Pulse after PEP) differed from the average pulses and was also dependent on the rate (Fig. 2). The observed 6% change in intensity is much more than the usual 0.5%, resulting in a different energy downstream. This was traced back to the gun and its high voltage power supply. A 25 MΩ resistor in series with the gun limited the current, and the gun voltage actually dropped. This was temporarily fixed by firing the long pulse laser along with the PEP pulse, but shifted slightly in time. Later the 25 MΩ resistor was changed to 1 MΩ.

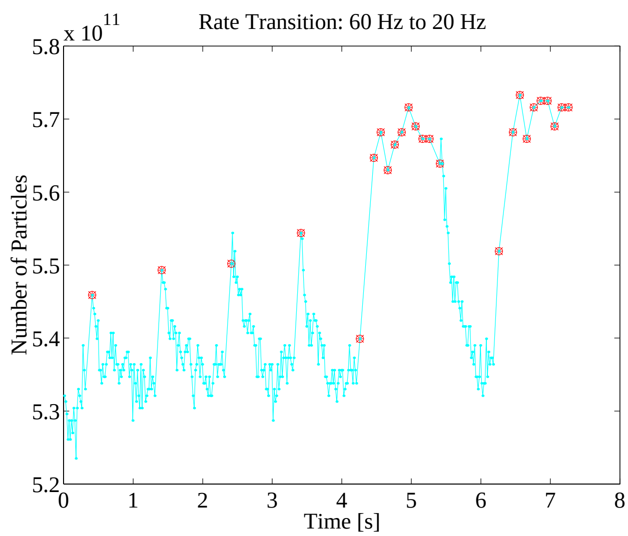

Figure 2: Different rates create different intensities. The rate changed from 60 Hz (58Hz for E-158, 2Hz for PEP-II) to 20 Hz for E-158 at around 4.5 and 6.5 sec. The pulse after PEP and the 20 Hz are marked in red (*). The higher intensities reduce the beam energy.

The next step to 120 Hz showed more effects like the ‘Pulse after PEP’ and less of the expected timeslot behavior. The higher rate pushed the temperature of the first klystron (K02) to a higher value. The resulting detuning led to a larger energy spread and 10% losses before the chicane (170 MeV point). Different rates resulted in different losses, changing the beam loading. Additional cooling fixed this problem.

One remaining problem was the residual magnetic field in the strong pulsed-magnets in the damping ring (linac) interaction point (DRIP), where the PEP beams are sent to the damping rings. This residual field kicks the first pulse following a PEP pulse by about 200 µm, which is nearly a sigma (Fig. 3).

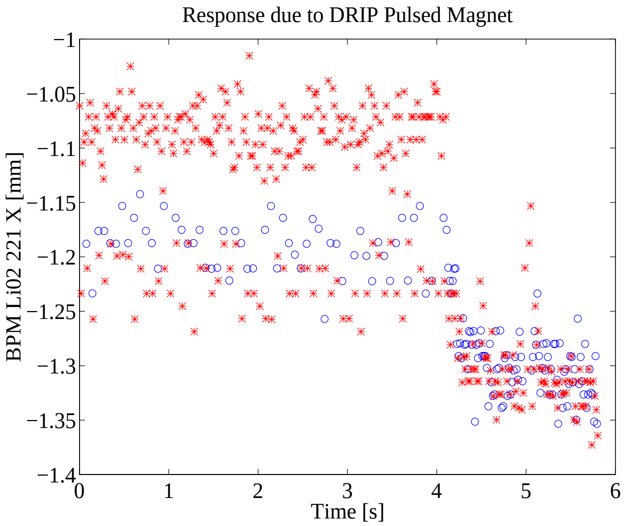

Figure 3: Pulsed magnets don't fully recover at 120 Hz. The transition from "75Hz" (60+15) to 116 Hz occurs at 4 sec. The 200 µm difference could not be fixed yet, but is reduced to only 30 µm at the end of the linac.

4.3 Beam Losses

Small losses of the E-158 beam along the 3 km long linac can be localized by a PLIC-cable (Panofsky Long Ion Chamber). The spikes in Fig. 4 show the losses at the injector chicane, the DRIP area, Sectors 4 and 10 (PEP-II extraction points) and the extraction area for the scavenger electron beam. Losses 20 times larger would trip the beam.

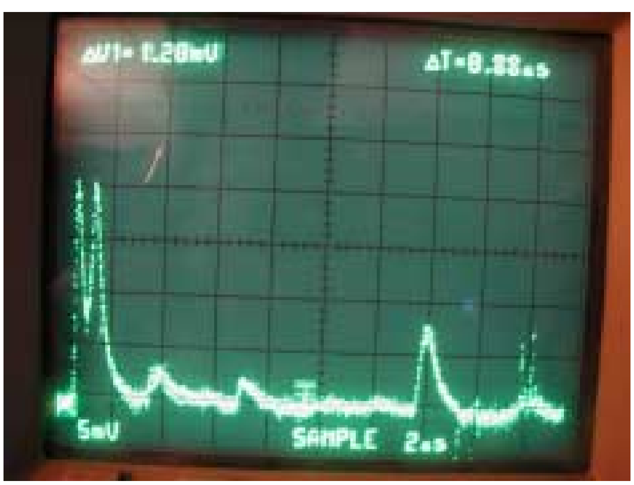

Figure 4: Beam loss along the linac.

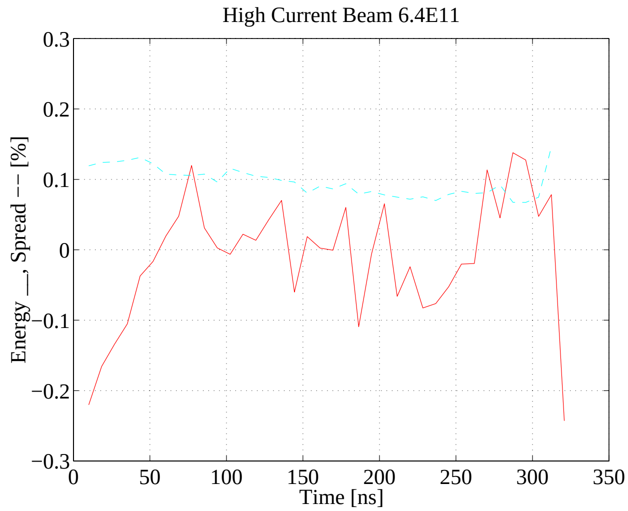

Figure 5: Energy and energy spread along the pulse. The finite rise time of the pulse creates a low energy tail.

4.4 Beam Loading Compensation

Figure 5 shows how well the beam loading can be compensated. It was measured with a gated camera (60 ns gate) looking at the synchrotron light from a bend magnet in the A-Line. An average energy spread of 0.1% was achieved, but there was a small low energy tail at the front of the pulse. We also observed that the front and rear of the pulse had different optimal linac phases for the smallest energy spread, meaning that when the center is on the RF crest, the front and rear are off by about ±2°.

5 SUMMARY

E-158 ran successfully together with PEP-II. Numerous improvements and tuning techniques were developed to decouple the operation of the two programs. In addition, most rate-dependent effects were eliminated during the run.

6 ACKNOWLEDGEMENTS

We greatly appreciate the efforts of the many SLAC support groups who helped to meet the demanding beam requirements for E-158. In particular, we would like to acknowledge the critical contributions of the Electronics and Software Department and the Klystron Department. We also wish to recognize the Accelerator Operators for consistently delivering high quality beams.

7 REFERENCES

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