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BEAM STABILIZATION IN THE SLAC A-LINE USING A SKEW QUADRUPOLE*

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Abstract

The E158 experiment at SLAC is a precision measurement of the left-right asymmetry in Møller scattering at low Q^2 utilizing a high-current long-pulse polarized electron beam scattering off unpolarized electrons in a liquid hydrogen target [1]. Tolerances on beam size and position/angle stability for E158 are extremely tight, but the electron beam is subject to intensity jitter, dispersion, and wakefield effects in the linac which tend to make it unstable. Horizontal emittance growth due to synchrotron radiation in the transport line from the linac to the target ("A-line") reduces the sensitivity of the horizontal beam parameters at the target to incoming changes, but instability in the vertical plane was observed during the E158 pilot run. A skew quadrupole recently installed in the A-line 90 m upstream of the target has been used to couple the projected transverse emittances, increasing the vertical emittance of the beam and thereby reducing its sensitivity to incoming changes. Simulations of the performance of this skew quadrupole, along with measured beam data with and without the skew quadrupole, will be presented.

1 A-LINE BEAM TRANSPORT

The SLAC A-line transports polarized electron beams from the linac to End Station A, guiding the beam through a total horizontal bend angle of 24.5 degrees [2]. The bulk of the bending is provided by two sets of six identical dipole magnets. A quadrupole doublet before the first set of dipoles brings the beam approximately to a focus at a high-dispersion point between the two sets of bending magnets. A pair of symmetry quadrupoles here is used to restore the dispersion to zero at the end of the second set of dipoles, which is followed by three matching quadrupoles that are used to vary the spot size and angular divergence of the beam at the target. A fourth matching quadrupole is available for added flexibility, but is not used during normal E158 operation. The optics of the A-line is shown in Fig. 1.

Electrons that are longitudinally polarized in the linac will precess as they traverse the A-line to an orientation at the target that depends on their energy. For E158 the linac is operated at either 45.45 GeV or 48.74 GeV. At these energies the spin orientations are parallel to the momentum at the target.

Incoherent synchrotron radiation (ISR) emitted by the beam in passing through the A-line bend magnets causes both energy loss and horizontal emittance blowup. The emittance blowup at these energies is significant. At the end of the linac, the normalized emittance of the E158 beam has been measured to be $\gamma\varepsilon_x = \gamma\varepsilon_y = 132$ µm.

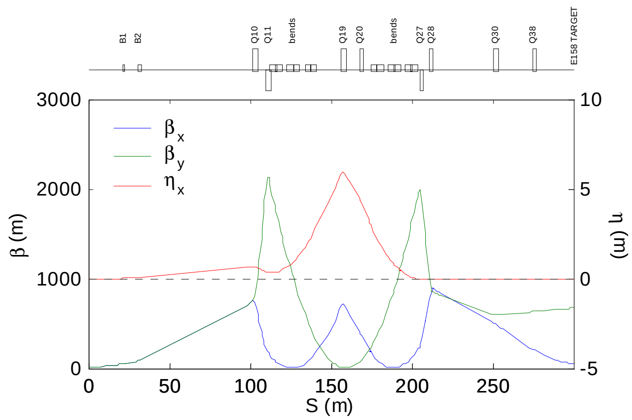

Figure 1: A-line optics from end of linac to E158 target.

Table 1: A-line ISR energy loss and emittance growth.

E_i (GeV)	ε_{xi} (nm)	E_f (GeV)	ε_{xf} (nm)	$\varepsilon_{xf}/\varepsilon_{xi}$
45.45	1.48	45.16	36.15	24.4
48.74	1.38	48.35	48.96	35.4

Table 1 lists the beam energy and horizontal geometric emittance at the end of the linac (subscript *i*) and at the E158 target (subscript *f*) for each operating point.

At 45.45 GeV ISR increases the horizontal emittance by a factor of almost 25. This increase in emittance causes the horizontal position, angle, spot size, and divergence of the beam at the target to be insensitive to changes in beam conditions at the end of the linac. However the vertical beam parameters at the target remain sensitive to changes occurring upstream.

The high charge of the E158 beam (6.2×10^{11} electrons in each 290 nsec long pulse) often leads to substantial jitter at the end of the linac due to large position-intensity correlations arising from a combination of intensity jitter, dispersion, and wakefield effects in the linac [3]. In order to reduce the vertical sensitivity to this jitter a skew quadrupole, installed near the end of the A-line, is used to couple some of the horizontal emittance growth into the vertical plane. Simulations illustrating the effectiveness of this scheme are described below.

2 SIMULATIONS

Beam transport through the A-line at the 45.45 GeV operating point, including ISR, is simulated using the particle tracking program *ELEGANT* [4]. Tracking begins

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at a point downstream of the end of the linac where $\beta_x = \beta_y = 14$ m, $\alpha_x = \alpha_y = 0$.

To investigate the effects of incoming emittance fluctuations and mismatches, we blow up either the horizontal or vertical emittance and introduce beta mismatches with a representative sampling of phases. The beta mismatch (B) and its phase (ψ_B) are defined in terms of the matched Twiss parameters α_0, β_0, and γ_0 as follows:

$$\mathrm{B} \equiv \mathrm{BMAG} = \frac{1}{2}\left(\beta_0\gamma - 2\alpha_0\alpha + \gamma_0\beta\right) \geq 1$$

$$\frac{\beta}{\beta_0} = \mathrm{B} + \sqrt{\mathrm{B}^2 - 1}\cos\left(2\psi_{\mathrm{B}}\right)$$

$$\alpha - \left(\frac{\beta}{\beta_0}\right)\alpha_0 = \sqrt{\mathrm{B}^2 - 1}\sin\left(2\psi_{\mathrm{B}}\right).$$

For these simulations we double the incoming emittance and choose B = 1.25 so that, for some ψ_B, either the initial beam size or the initial beam divergence will be increased to at least twice its nominal value.

To investigate the effects of position and angle jitter we introduce horizontal or vertical incoming betatron oscillations with one sigma (beam size) amplitude and a representative sampling of phases.

2.1 Without skew quadrupole

Fig. 2 (left) shows simulated 1-σ beam ellipses at the target for initial emittance blowup and beta mismatches in either the horizontal or the vertical plane. Matching quadrupoles Q27, Q28, and Q30 have been set to give $\sigma_x = \sigma_y = 1$ mm at the target for the matched case. The vertical beam size at the target varies by a factor of 2. Fig. 2 (right) shows the sensitivity of the centroid position of the matched beam to incoming betatron oscillations as described above.

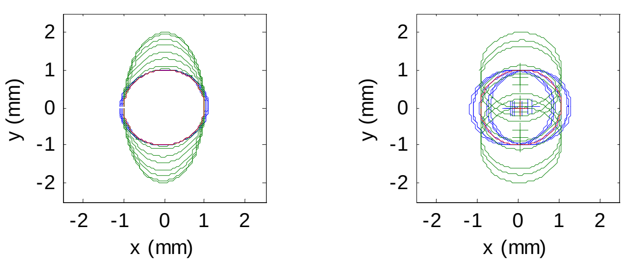

Figure 2: Simulated beam profiles (left) and beam positions (right) at the target with no skew quadrupole. Left: red ellipse is matched with nominal emittance; blue ellipses have horizontal mismatches; green ellipses have vertical mismatches. Right: red ellipse is on-axis; blue ellipses have horizontal betatron oscillations; green ellipses have vertical betatron oscillations.

Fig. 3 shows beam images from a profile monitor near the target, acquired under both stable and jittery conditions during the E158 pilot run. These observations agree well with the simulations illustrated in Fig. 2.

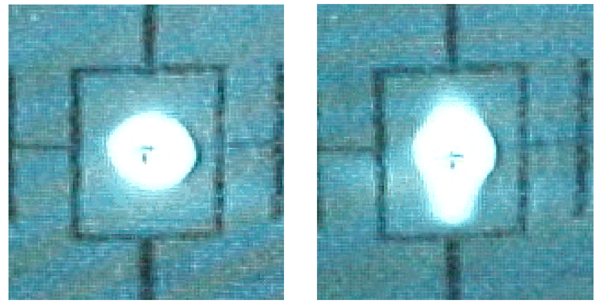

Figure 3: Observed beam profiles near the target under stable (left) and jittery (right) conditions. The square box is 1 cm x 1 cm.

2.2 With skew quadrupole

A skew quadrupole is introduced at a zero dispersion location which gives maximum emittance coupling. The vertical emittance growth generated by the skew quadrupole depends on the initial uncoupled emittances, the skew quadrupole strength f, and the values of β_x and β_y at the skew quadrupole:

$$\frac{\varepsilon_y}{\varepsilon_{y_0}} = \sqrt{1 + \frac{\varepsilon_x}{\varepsilon_{x_0}}\frac{\beta_x\beta_y}{f^2}}.$$

Fig. 4 shows $\sqrt{\beta_x\beta_y}$ along the A-line, indicating the selected location for the skew quadrupole between Q27 and Q28.

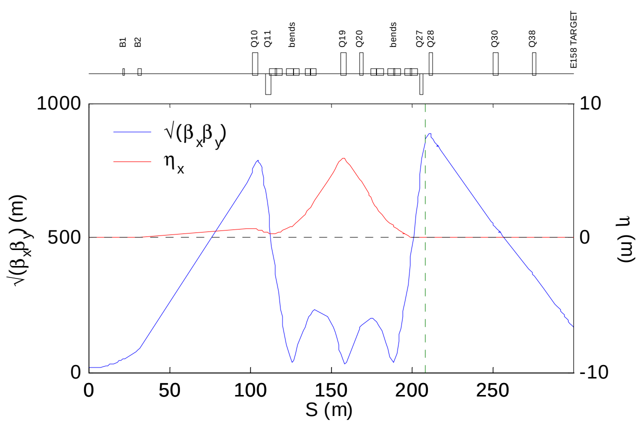

Figure 4: Selection of optimum skew quadrupole location (chosen location indicated by green vertical dashed line).

The strength of the skew quadrupole ("SQ27.5") is adjusted to minimize sensitivity to incoming vertical changes. Q27, Q28, and Q30 are then set to restore $\sigma_x = \sigma_y = 1$ mm at the target. At the 45.45 GeV operating point the vertical emittance downstream of SQ27.5 is increased by a factor of 7.2 at the optimum setting.

Fig. 5 (left) shows simulated 1-σ beam ellipses at the target for initial emittance blowup and beta mismatches in either the horizontal or the vertical plane, with SQ27.5 set optimally as described above. Both the horizontal and vertical beam size at the target now vary by at most 20%. Fig. 5 (right) shows the reduced sensitivity of the centroid position of the matched beam to incoming betatron oscillations.

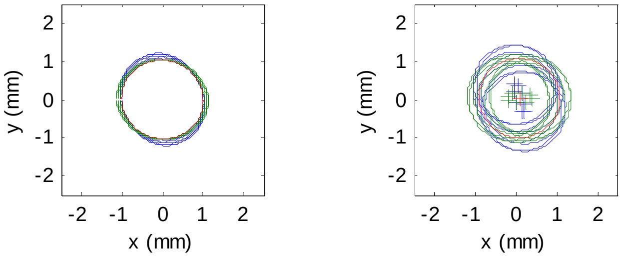

Figure 5: Simulated beam profiles (left) and beam positions (right) at the target with skew quadrupole set optimally. Left: red ellipse is matched with nominal emittance; blue ellipses have horizontal mismatches; green ellipses have vertical mismatches. Right: red ellipse is on-axis; blue ellipses have horizontal betatron oscillations; green ellipses have vertical betatron oscillations.

3 OPERATIONAL EXPERIENCE

SQ27.5 was installed in the A-line in December 2001. The skew quadrupole has an effective length of 55 cm, a pole-tip radius of 4 cm, and a maximum pole-tip field of 2 kG at 25 amperes.

Fig. 6 shows recently measured beam profiles, acquired under typical conditions. Fig. 6 (a) shows the beam spot on a profile monitor near the target with SQ27.5 turned off; Fig. 6 (b) shows the vertical beam profile as measured on a nearby wire array. Note the pronounced tail in the vertical distribution. Fig. 6 (c) shows the beam spot when SQ27.5 is turned on to its optimum value; Fig. 6 (d) shows the corresponding wire array measurement of the vertical distribution, showing that the tail has been corrected. Stable spot sizes and elimination of spatial tails are very important in reducing systematic effects for the E158 parity violation experiment [5].

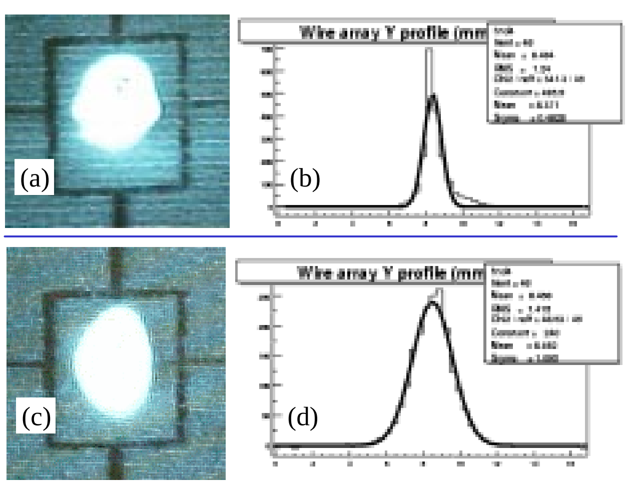

Figure 6: Observed beam profiles near the target with SQ27.5 off (top) and on (bottom).

Fig. 7 (left) shows representative vertical position jitter measured at the target during the pilot run (May 2001) at a beam current of 2×10^{11} e-/pulse. Performance improvements in the injector [6] and the linac [7], together with the use of the new skew quadrupole, have dramatically reduced this jitter. Fig. 7 (right) shows the measured jitter now (February 2002), with SQ27.5 set optimally. The beam current is 4×10^{11} e-/pulse. The observed jitter amplitude is now well within the requirements for E158.

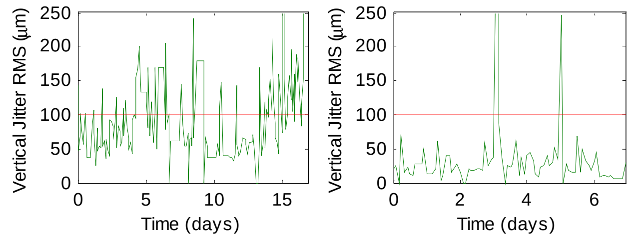

Figure 7: Measured vertical beam position rms at the target during the E158 pilot run (left) and now (right). The red lines indicate the experimental requirement of rms jitter less than 100 μm.

An additional benefit provided by the skew quadrupole is improved vertical betatron phase advance (from $\Delta\psi_y = 3°$ to $\Delta\psi_y = 63°$) between two BPMs, located 2 m and 43 m upstream of the target, which are used in the determination of detector sensitivities to beam conditions at the target via dithering measurements. In the dithering analysis, detector and BPM sensitivities to incoming beam parameters (x, x', y, y', energy) are measured by dithering these quantities at the end of the linac. The measured sensitivities are then used to correct the detector data for beam fluctuations pulse-by-pulse.

4 CONCLUSIONS

A skew quadrupole installed in the SLAC A-line is used to couple some of the horizontal ISR emittance growth into the vertical plane, reducing vertical beam sensitivity at the target to incoming conditions from the linac. Along with performance improvements in the injector and the linac, the A-line skew quadrupole provides an important contribution to the performance of the E158 physics run.

5 REFERENCES

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