THE BROOKHAVEN ACCELERATOR TEST FACILITY INJECTION SYSTEM

X.J. Wang
Department of Physics, UCLA, Los Angeles, CA 90024
H.G. Kirk, C. Pellegrini
Brookhaven National Laboratory, Upton, NY 11973
K.T. McDonald, D.P. Russell
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544

Abstract

The Brookhaven Accelerator Test Facility (ATF) consists of a 50 MeV/c electron linac and a high-brightness RF-gun both operating at 2856 MHz. An extremely short (a few picoseconds) electron pulse with a low transverse emittance is generated by the RF gun. In order to preserve both longitudinal and transverse emittances, great care must be taken in transporting the electron beam from the RF-gun to the linac. We describe the injection line, present first- and second-order lattice studies of the injection line, and study nonlinear effects on the emittance.

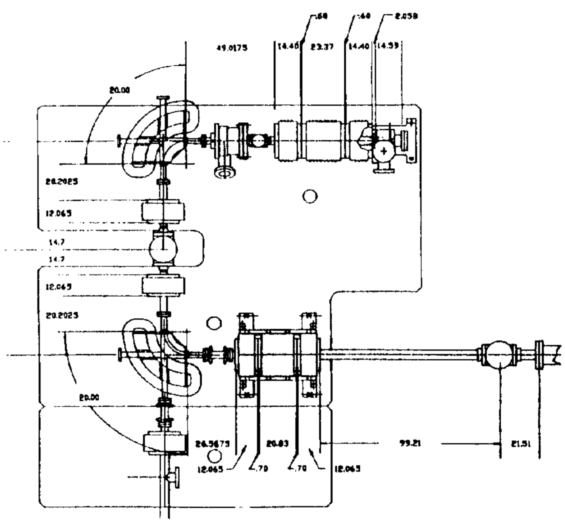

Figure 1: Detailed view of the gun-to-linac transport line.

Introduction

One of the most important developments in accelerator technology in the last few years is the photoinjector technology for high-brightness electron beams.[1] The Brookhaven Accelerator Test Facility is developing this technology to produce high-quality beams for FEL,[2] laser acceleration[3,4] and other experiments. This paper presents the design of the ATF injection system, and calculates the transverse emittance and bunch-length behaviour.

The basic objective of the ATF injection system (Fig. 1) is to transfer an intense, low-emittance electron beam from the electron gun to the linac without a significant increase in beam emittance or bunch length; to provide the possibility of measuring the transverse and longitudinal emittance;[5] and to perform momentum selection and magnetic pulse compression. The ATF injection system consists of two quadrupole triplets and a 180° achromatic double bend. The first triplet produces a waist at the median point between the dipoles, where a momentum-selection slit is located. The second triplet can be used to match the beam to the linac or to do emittance measurement. Several configurations of the injection system have been studied. First- and second-order beam properties of the injection line were calculated using the computer program TRANSPORT. The momentum resolution provided by the momentum-selection slit could reach ±0.1%. Higher-order effects on the beam emittance were first estimated with a one-dimensional model and then calculated using numerical integration methods.

Table 1: Initial beam parameters.

ϵ_x^a	0.84	ϵ_y^a	0.84
x_{rms}(mm)	4.1	x'_{rms}(mrad)	28.1
y_{rms}(mm)	4.1	y'_{rms}(mrad)	28.1
$\left(\frac{\Delta P}{P_0}\right)_{rms}$(%)	0.2	P_0(MeV/c)	4.5
Q(nano-C)	1.0	ℓ_{rms} (psec)	2.5

[a] 1-σ geometric emittance in mm-mrad.

First- and second-order lattices

Beam parameters at the exit of the RF-gun are given in Table 1.[6] We have studied several configurations of the injection line, depending on the quadrupole polarities and whether or not the first triplet is symmetric. Table 2 shows beam parameters for three typical configurations. The FDF configuration has a small horizontal amplitude overall while the vertical dimensions are very sensitive to field error and edge effects caused by strong vertical focusing. Second-order calculations show that correction sextupoles would be helpful for vertical control; but it is very difficult to find positions where the vertical betatron amplitude is large while the dispersion is nonzero so that second-order corrections be carried out.

Table 2: Beam parameters for three configurations.

	FDF	DFD	DFD′
X_{max}	13.823	16.168	19.212
Y_{max}	17.246	17.092	9.033
X_{waist}^a	0.078	0.153	0.120
Y_{waist}^a	1.263	0.152	0.326
X_{waist}^b	0.276	0.835	0.273
Y_{waist}^b	1.544	1.070	0.807
d_{max}	3.925	3.913	3.913
Y^c	3.311	7.028	3.750

[a] First-order calculation without energy spread (mm).
[b] Second-order calculation without energy spread (mm).
[c] Vertical beam size at the entrance of the first dipole (mm).

Many problems associated with the FDF configuration can be solved by reversing the polarities of the quadrupoles of the two triplets. This leads to our second configuration (DFD of Table 2). This design has larger betatron amplitudes in the vertical direction at the entrance of the first dipole and a larger horizontal beam size at the beam waist. This problem can be handled by making the first and the third quadrupoles of the first triplet nonsymmetric. As listed under configuration DFD′ of Table 2, the beam size can be reduced at the entrances of dipoles and at the waist. Fig. 2 shows the first-order beam sizes and dispersion for the DFD′ injection line as calculated by TRANSPORT.

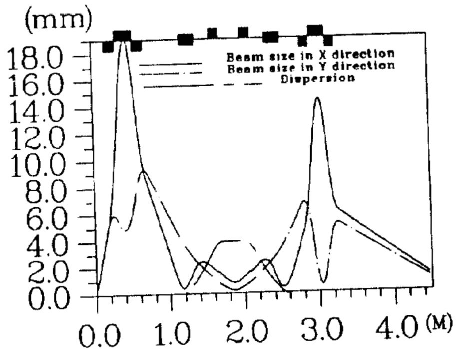

Figure 2: First-order calculation of the beam envelopes (in mm) and dispersion (in mm per % of $\Delta P/P$) for the ATF beamline configuration DFD$'$ with $\Delta P/P = 0.2\%$, prior the adjustment of the y waist.

Second-order calculations show that there is little change (compared to first-order) in the horizontal beam envelope, but a big distortion is observed in the vertical beam envelope. We have found that second-order effects in y can be reduced through the adjustment of the quadrupole parameters. Instead of locating the vertical beam waist in the halfway between the two dipoles as in the first-order design, we put it downstream at the entrance of the focusing quadrupole. Fig.3 shows the second-order beam envelopes after the adjustment of the quadrupole strengths to the DFD$'$ configuration.

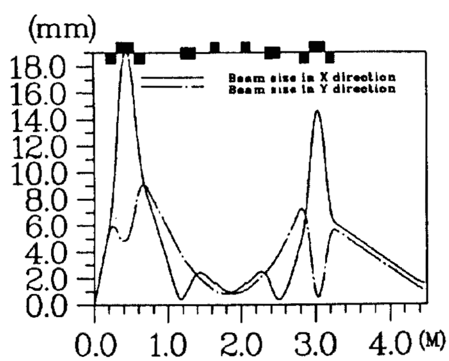

Figure 3: Second-order calculation of the beam envelopes (in mm) for the ATF beamline configuration DFD$'$ with $\Delta P/P = 0.2\%$, after the adjustment of the y waist.

Emittance growth in a transport line

Many studies of the emittance behaviour in a photoinjector RF-gun[7,8] have been done, but few reports exist for the emittance growth in the transport line of short, high-brightness electron bunches.

Emittance growth in the magnetic transport line is mainly due to:

- Mismatch caused by linear space charge.
- Nonlinear space charge.
- Chromatic effects.
- Nonlinear magnetic fields.

There are many theoretical[9] and experimental[10] studies of the space-charge effects on the transverse beam emittance in a transport line. We will now concentrate on chromatic and nonlinear magnetic fields effects.

In our emittance study, transverse geometric emittance is expressed as

$$\epsilon = \left(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2\right)^{\frac{1}{2}}. \qquad (1)$$

A simple one-dimensional model is used to estimate emittance growth due to higher-order effects. We will first consider the chromatic effects.

For simplicity, we now consider a zero-emittance beam with $x_0' = 0$ and nonzero x_0 passing through a thin lens. After the lens, we have $x = x_0$ and $x' = x_0' + \Delta x'$. Including the chromatic effect, we obtain

$$\Delta x' = -\frac{x_0}{f(1+\delta)},$$

where f is the focal length of the lens, and $\delta = \Delta P/P_0$.

If we assume no correlation between the transverse positions of the particles and their energies, then the emittance increase is

$$\Delta\epsilon \approx \left(\langle x_0^2\rangle^2\langle 1 - 2\delta + \delta^2\rangle - \langle x_0^2\rangle^2\langle 1-\delta\rangle^2\right)^{\frac{1}{2}}/f.$$

Thus

$$\Delta\epsilon = \langle x_0^2\rangle\delta_{rms}/f. \qquad (2)$$

We can use the same model to derive a similar formula for higher-order geometric effects. Let us assume that the quadrupoles have midplane symmetry and their fields up to fifth order are given by

$$B = G_1 x + G_3 x^3 + G_5 x^5, \qquad (3)$$

where G_{2n+1} is the magnetic-field coefficient of the corresponding magnetic field.

At the focal plane of the quadrupole, we can calculate the emittance introduced by nonlinear terms using the following relations

$$x = x_0 + f x'_{out} = -f S_3 x_0^3 - f S_5 x_0^5,$$

and

$$x' \approx -\frac{x_0}{f},$$

where $S_3 = G_3/(fG_1)$, $S_5 = G_5/(fG_1)$, and f is the linear focal length of the quadrupole.

Substituting x and x' into equation (1), we have

$$\Delta\epsilon^2 = S_3^2\left(\langle x_0^6\rangle\langle x_0^2\rangle - \langle x_0^4\rangle^2\right) + S_5^2\left(\langle x_0^{10}\rangle\langle x_0^2\rangle - \langle x_0^6\rangle^2\right) + 2S_3S_5\left(\langle x_0^8\rangle\langle x_0^2\rangle - \langle x_0^6\rangle\langle x_0^4\rangle\right).$$

To calculate the moments of x_n, we suppose that the beam has the initial distribution $f(x_0) = A\exp\left(-x_0^2/(2\sigma^2)\right)$, where σ is the r.m.s. beam size.

Case 1. $S_5 = 0$.

$$\Delta\epsilon = 4\left(\frac{\sigma}{d}\right)^4 \frac{d^2}{f}\frac{\Delta B_3}{B_0}\frac{1}{I_0}\left(I_6 I_2 - I_4^2\right)^{\frac{1}{2}}, \qquad (4)$$

where d is a radius at which the nonlinear field (3) is known: $B_0 = G_1 d$, $\Delta B_3 = G_3 d^3$; $I_{2n} = \int_0^{R/\sqrt{2}\sigma} x^{2n}\exp\left(-x^2\right)dx$, and R is the radius of quadrupole.

Case 2. $S_3 = 0$.

$$\Delta\epsilon = 8\left(\frac{\sigma}{d}\right)^6 \frac{d^2}{f}\frac{\Delta B_5}{B_0}\frac{1}{I_0}\left(I_{10} I_2 - I_6^2\right)^{\frac{1}{2}}, \qquad (5)$$

where $\Delta B_5 = G_5 d^5$.

We are now able to calculate the emittance growth due to higher-order effects. For the second quadrupole of the first triplet, $f_x = 15.82$ cm, $\sigma_x = 15.85$ mm (the average r.m.s. horizontal beam size inside the quadrupole), and $\delta = 2\times 10^{-3}$. Then the emittance increase caused by chromatic effect will be approximately 3.18 mm-mrad. The nonlinear fields of the second quadrupole are given in Table 3.[11] For $d = 4.57$ cm, the emittance growth caused by third- and fifth-order nonlinear field are approximately 1.5 mm mrad and 0.9 mm-mrad, respectively.

Table 3: Nonlinear fields for the first triplet.

	Q_1	Q_2	Q_3
$\Delta B_3/B_0\,(\%)^a$	0.04	0.32	0.04
$\Delta B_5/B_0\,(\%)^a$	0.54	0.15	0.54

[a] At 88.6% of aperture; $R = 5.16$ cm.

For very short bunches, second-order effects related to the divergence of the beam could be very important. Bunch lengthening caused by second-order geometric abberations in drift space can be calculated by:

$$\Delta \ell = \frac{L}{2}\left(x'^2 + y'^2\right) \tag{6}$$

for $x' = y' = 30$ mrad and $L = 1$ m, $\Delta \ell = 0.9$ mm.

Numerical study

We have developed a tracking program for emittance study. The Runge-Kutta method was adopted in our program to solve the initial-value problem for a system of ordinary differential equations. Chromatic effects are fully treated. We have also included nonlinear fields up to fifth order.

The emittance after each element in the first triplet is given in Table 4. We find that the results agree with our simple model to within 30% error. A ± 1.6 mm square slit is placed at beam waist to reduce the growth of both the transverse emittance and bunch length. A second slit at the exit of the second triplet, along with contoured edge of the dipoles, will restrict the emittance growth to within a factor of 2. Emittances after each element of the injection line are plotted in Fig. 4. About 75% of the beam particles survive the cuts, with 15% being lost at the first slit, and another 10% being lost at the second slit.

Conclusion

It has been shown that it is possible to preserve transverse emittance in a low-energy beam-transfer line by use of slits and contoured edges of the dipole magnets. Bunch lengthening is induced by the large beam divergence out of the RF-gun, thus requiring strong focusing.

This work is supported by the U.S. Department of Energy.

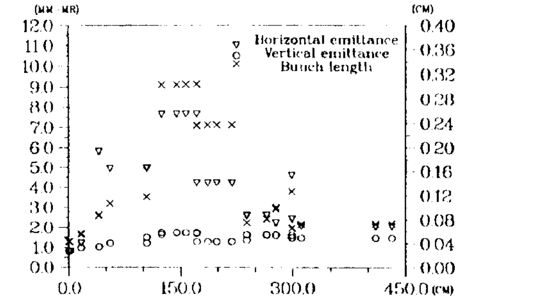

Figure 4: Emittance and bunch length vs. position.

References

1. J.S. Fraser *et al.*, p. 1705, Proceedings of the 1987 Particle Accelerator Conference (Washington, D.C.).
2. C. Pellegrini, Nucl. Instr. and Meth., **A272**, 364 (1988).
3. R.B. Palmer, Particle Accelerators, **11**, 81 (1980).
4. E.D. Courant, C. Pellegrini and W. Zakowicz, Phys. Rev. A **32**, 2813 (1985).
5. K.T. McDonald and D.P. Russell, "Methods of Emittance Measurement," Proceedings of the Joint US-CERN School on Observation, Diagnosis and Corrections in Particle Beams (Capri, Italy, 1988).
6. K. Batchelor, H. Kirk, J. Sheehan, M. Woodle and K. McDonald, "Development of a High Brightness Electron Gun for the Accelerator Test Facility at Brookhaven National Laboratory," Proceedings of the European Particle Accelerator Conference (1988); K.T. McDonald, IEEE Trans. Elec. Dev. **35**, 2052 (1988).
7. B.E. Carlsten and R.L. Sheffield, "Photoelectric injector design considerations," Proceedings of the 1988 Linac Conf. (Williamsburg, VA).
8. Kwang-Je Kim, "RF and Space-Charge Effects in Laser-driven RF electron guns", LBL Report LBL - 25807 (Aug. 25, 1988) .
9. M. Reiser, IEEE Trans. Nucl. Sci. **32**, 2201 (1985).
10. M. Reiser *et al.*, Phy. Rev. Lett. **61**, 2933 (1988).
11. T.R. Sherwood, "Harmonic Content of BNL Quadrupoles," BNL Internal Report MPS-LIN-Note 74-8.

Table 4: Transverse emittance after each element.[a]

z (cm)	ϵ_x^b	ϵ_y^b	ϵ_x^c	ϵ_y^c	ϵ_x^d	ϵ_y^d
0.0	0.798	0.812	0.795	0.815	0.795	0.815
2.058	0.798	0.812	0.795	0.815	0.795	0.815
16.458	0.803	0.813	1.203	0.977	1.211	0.979
40.428	3.749	1.016	4.096	0.814	5.805	1.021
55.428	3.616	0.944	3.046	1.111	4.928	1.207
104.446	3.616	0.944	3.046	1.111	4.928	1.207

[a] 1-σ emittance in mm-mrad.
[b] $\Delta P/P_0 = 0$, all nonlinear terms included.
[c] $\Delta P/P_0 = 0.2\%$, all nonlinear terms are zero.
[d] $\Delta P/P_0 = 0.2\%$, all nonlinear terms are included.