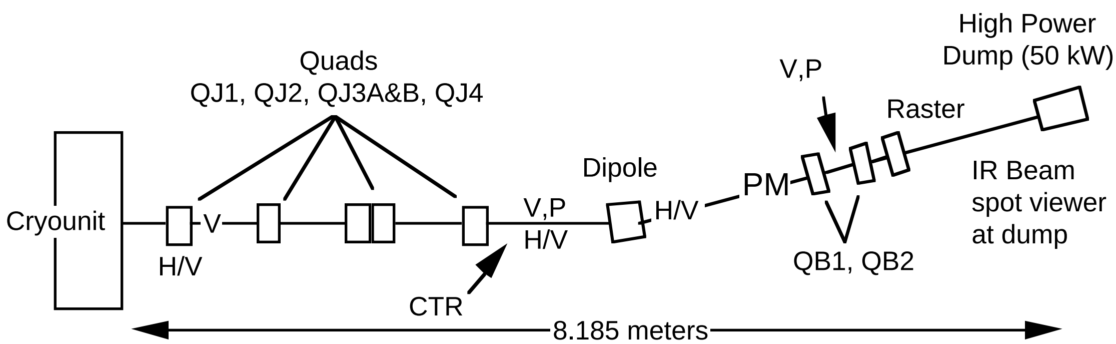
Summary of 10 MeV Beamline Specifications

D. Kehne
4/4/96

Abstract The field and alignment specifications for the magnets and diagnostics in the 10 MeV beamline of the FEL Injector Test Stand are presented and justified. Operation of the beam expander is also outlined.

I. Layout of 10 MeV Beamline

A schematic of the 10 MeV beam line in the test stand is shown in Fig. 1. It consists of 4 quadrupole magnets used for matching (QJ1-4), a dipole magnet, and 2 strong quadrupoles (QB1,2) used for expanding the beam to 50 sq. cm at the dump face. A raster magnet is used to further spread the beam to 200 sq cm. In addition, corrector pairs located at QM1, QM4, and after the dipole are to be used for compensating for stray fields and misalignments that cause the beam to wander off axis. OTR viewers will be placed immediately after QJ1, between QJ4 and the dipole, and between QB1 and QB2. Infrared cameras will be used to determine beam size and position on the dumpface.



V = OTR viewer

PM = Horizontal Stripline beam position monitor

P = profile diagnostic, wire scanner and/or OTR viewer

CTR = Coherent Transition Radiation Bunch length diagnostic

H/V = Corrector pair

Fig. 1. Schematic of the 10 MeV beam line for the 10 MeV Test Stand.

This tech note summarizes the magnet specifications for the quadrupole and dipole magnets and then details how each was determined.

II. DERIVATION OF NOMINAL PARAMETERS

A set of nominal parameters for the test stand magnets was first derived. These were then used as a baseline to study the effects of magnet and alignment errors. Derivation of the nominal parameters is described here.

MATCHING QUADS

The input beam conditions for the 10 MeV line were taken from the PARMELA runs done for the CEBAF UV FEL CDR. When properly set up, the beam envelope is parallel to the axis in both dimensions, i.e. it has zero slope. The values of β_x and β_y are 6.5 m. The matching quads will be used to compensate for deviations in the input conditions and to optimize beam conditions into the dump leg, if necessary. Quad scanning emittance measurements will also be performed here to give an upper limit on emittance. CEBAF type quad QJ will be used here. Also, space charge effects will be examined using the double strength quad QJ3A and QJ3B.

DIPOLE

The dipole is used to generate dispersion for the purpose of setting the beam energy, measuring the energy spread, and monitoring energy stability at high power. For this reason, the high power dump, capable of dissipating the necessary 50 kW of beam power, is placed on the spectrometer leg. An added benefit to this is that there will not be a straight flight path from the dump to the superconducting cavities. Space requirements limit the bend angle to 15˚. The nominal energy spread of the beam is $\sigma E/E \approx 0.5\%$. The specification for the rms energy stability is 0.2%. Assuming diagnostic position resolution to be 0.1 mm, the desired dispersion η is 0.5 m. The dispersion can be calculated using the equation

$$\eta = 2L\tan\left(\frac{\theta}{2}\right)$$

where η is the dispersion, L is the distance from the dipole to the point of measurement, and θ is the bend angle. Using this, η = 0.5 m, θ = 15˚, then L = 1.9 meters. The distance from the dipole center to the viewer is 1.85 m. At this position, a 0.1% change in $\Delta E/E$ corresponds to a 0.5 mm change in position. The full energy spread of 2% will cause the full beam to spread 1 cm. The distance from the dipole center to the BPM is 1.44 m giving a dispersion of 38 cm. In order to detect energy fluctuations to 0.001, the position resolution of the BPM needs to be < 0.38 mm. The dispersion at the dumpface with the expander quads off is 1.1 m and, according to DIMAD simulations, 4.5 m with them on.

The full aperture through the dipole will be 5 cm vertically and ≥ 5 cm horizontally. To maintain a 5-to-1 ratio in length to aperture, the length should be > 25 cm. According to PARMELA, the beam will expand to ~ 3 mm sigma in x and y at the dipole with the quads off. PARMELA also predicts that the maximum extent of the particles is $\pm 3\sigma$. This implies a full beam diameter of 18 mm. Assuming a maximum offset in the beam centroid of 2 mm, the "good field" aperture should be ≈±1 cm. PARMELA also predicts that, by using the 4 quads to keep the beam size small, the required good field aperture can be reduced to ≈ ±0.5 cm.

The errors induced by field nonuniformity should be significantly less than the energy resolution at either the BPM or viewer. Assuming an energy resolution described above (i.e. 0.1% energy change causes 0.4 mm change in BPM), the change in position due to field nonuniformity should be <0.1mm, assuming equal energy particles. The change in position x_1-x_2 can be calculated using the equation

$$x_1 - x_2 = \frac{L(B_1 L_B)}{B\rho}\left(1 - \frac{B_2}{B_1}\right)$$

where L is the distance from the dipole to the point of measurement, L_B is the dipole length, B_1 is the nominal magnetic field, B_2 is the perturbed field and $B\rho$ is the beam rigidity. The nominal field integral to bend a 10 MeV/c beam 15˚ is 8725 gauss-cm). Using the equation, Δx remains less than 0.1 mm at L=0.38 m (BPM location) if $\Delta B/B$ is $< 10^{-3}$. Thus, the specification for field uniformity is 10-3 over ±1 cm.

For a dipole in which the length of the iron is 15 cm, the effective length of the field is given by

$$L_{eff} = L_{iron} + 1.6 \times gap.$$

For a gap of 2 inches, the effective length is 23 cm. The nominal central field requirement would then be central field would then be 379 gauss. In simulations, field lengths of 15 and 25 cm were checked and are presented. A 15 cm dipole is also presented. Two CEBAF type BM (C-magnets) will be butted together to form window frame magnet for this dipole. The iron for this magnet is 15 cm and has a gap of 2". At its 3.5 amp maximum, a single BM produces 485 gauss peak field. Using the above equation, the maximum field integral that can be produced by the magnet is 10200 Gauss-cm [personal comm. J. Karn, G. Biallas, L. Harwood]. A field of 10500 Gauss-cm will bend a 12 MeV beam. If necessary, the magnet current can be increased somewhat. Field uniformity of the butted magnets should be adequate.

EXPANDER QUADS AND RASTER

The power density of the 5 mA, 10 MeV beam requires that the beam be expanded to 50 sq cm at the dump face. A raster magnet will then be used to further spread the beam to 200 sq. cm. It is desired to use two CEBAF type QB magnets to expand the beam and a standard CEBAF sextupole as a raster. Each has a bore of 2". Therefore, the beam envelope must be set up carefully to avoid beam scraping in this area.

1. In order to meet the 50 sq. cm specification for a round beam, the radius of a uniform beam should be 4 cm. Since the Dump has a 60˚ tilt with respect to vertical to further spread the beam, one beam dimension can actually be 1/2 the size of the beam in the other dimension. This provides additional dump space to accomodate unforeseen beam jitter. Alternatively, both beam dimensions can be reduced to 2.8 cm radius and still maintain 50 sq. cm on the dump. Since the first option is more sensitive, it was used to determine specifications. Also, even though the beam is not uniformly distributed at the dump, the full beam radius was assumed to be 2σ for current density calculations. However, pipe clearance calculations were performed using the outermost particles determined by PARMELA. Outermost particles predicted by PARMELA extend to $\approx 3\sigma$.

2. The raster magnet is used to kick the beam into a circular pattern at 60 Hz, smearing it over 200 sq. cm. This implies a radius of 8 cm for a uniformly distributed beam. Taking the dump face tilt into account implies a beam of radius 5.6 cm. Thus, the 4 cm beam edge needs to be rastered out 1.6 cm to 5.6 cm. The distance from the raster center to the dump face is 142 cm. Therefore, the required angular kick imparted by the raster is $\tan^{-1}(1.6/142) = 0.64˚ = 11$ mrad.

3. Setup of expander quads is done by using the first quad QB1 to roughly focus the beam in the x-dimension to the center of the QB2. This makes the horizontal beam size less sensitive to changes in the strength of QB2. QB2 can then be used to adjust the beam size in y. The process will be iterative but seems to converge rapidly, at least using simulation. Beam sizes can be measured between the quads and at the dump face. It is required that the beam size and position at the dump be measureable to within ±5.0 mm.

It is desired to use CEBAF type QJ and QB quadrupoles for the matching and expander quads respectively. A summary of QJ and QB quad parameters is shown in Table II.

Four lattice configurations have been generated. Each will be used for specific purposes. The first allows high power operation to running dump with all of the matching (QJ) quadrupoles off. The second also allows high power operation but maintains a smaller spot through the dump leg than with all quads. The QJ quads for this setup are at or slightly above their maximum set value. Since it pushes the limit on these quads, this quad set was used to generate most of the quad specifications. The third set generates a small beam β_x at the dump leg OTR viewer. This will allow more accurate energy and energy spread measurements when setting the cavitiy phases. The final setup generates a quad scanning emittance measurement in which only QJ3A and QJ3B are used. Beam size in the measurement plane ranges from ≈0.3 mm to 1.5 mm and from 1.5 mm to 3 mm in the other plane. The double quadrupole allows a smaller beam to be injected into the quad and focused to a smaller spot to explore space charge effects.

DIAGNOSTICS

The diagnostics include OTR viewers after QJ1, between QJ4 and the dipole, and between the two expander quads. A horizontal BPM will be placed on the dump leg to measure beam position (energy stability) during high power operations. Infrared cameras will determine the location and size of the beam on the dump. A slit emittance measurement device is nominally planned. The slit will sample small portions of the beam which then be meausred downstream using the second OTR viewer and harp. Signal levels will be very low.

NOMINAL PARAMETERS

The nominal values of the quads and dipole are shown in Table I. The nominal beam envelope (σ_x, σ_y) for Configuration 1 is shown in Fig. 2. This configuration generates equal x and y beam sizes at the dump. Also shown in Fig. 2 is the envelope that results when the expander magnets are turned off. The PARMELA simulations that generated the envelopes in Fig. 2 assumed a dipole length of 15 cm. This causes sharper focusing in the vertical dimension than a longer dipole and results in the value of QB2 to be significantly stronger than QB1. A simulation of the expander assuming a 25 cm long dipole is shown in Fig. 3. The value of QB1 and QB2 for this case was 67.5 Gauss/cm and -150 Gauss/cm. Furthermore, the y-envelope is larger than the x-envelope. In order for Configuration 1 (15 cm long dipole) to generate a comparable beam size at the dump, QB2 would have to be set to -270 G/cm. Though it is difficult to predict what the actual input beam conditions to the expander will be, the magnets have sufficient flexibility to set the proper beam size at the dump. Further flexibility can be obtained by adjusting the beam size prior to the dipole using the QJ matching quads.

Also shown in Fig. 3 is an estimate of the clearance of the pipe with the beam edge. PARMELA simulations show that the outermost particles of the beam fall at ≈3σ. The tightest spot occurs just after the raster where the pipe size increases from 1" radius to 4" radius. This area should be observed during initial high power operation.

Table I. Nominal settings for the various configurations.

Magnet	Configuration 1 Matching Quads OFF - High Power	Configuration 2 Matching Quads ON - High Power	Configuration 3 Low β at Dump leg viewer for E and $\Delta E/E$ meas.	Configuration 4 Emitt. Measurements - Quad Scanning
QJ1	0	23.4 gauss/cm (5.9 amps)	0	0
QJ2	0	-38 gauss/cm (9.6 amps)	0	0
QJ3A	0	42 gauss/cm (10.5 amps)	0	-12 - 12 gauss/cm (-30 - 30 gauss/cm for space charge studies)
QJ3B	0	0	0	-12 - 12 gauss/cm (-30 - 30 gauss/cm for space charge studies)
QJ4	0	-43 gauss/cm (10.6 amp)	8 gauss/cm	0
QB1	69.0 gauss/cm	95 gauss/cm (1 amp)	0	0
QB2	-200 gauss/cm	-105 gauss/cm (1.1 amps)	0	0
Dipole	15˚ Bend Angle	15˚ Bend Angle	15˚ Bend Angle	15˚ Bend Angle

Table II. Summary of CEBAF type QJ and QB quad characteristics.

	QJ	QB
Operating Range	±10 Amps	±10 Amps
(B'dL)max	± 600 gauss	±14400 gauss
Length	15 cm	15 cm
Random field errors	10^{-3}	10^{-3}
Systematic field errors	0.06 dodecapole, 0.02 icosapole	0.06 dodecapole, 0.02 icosapole

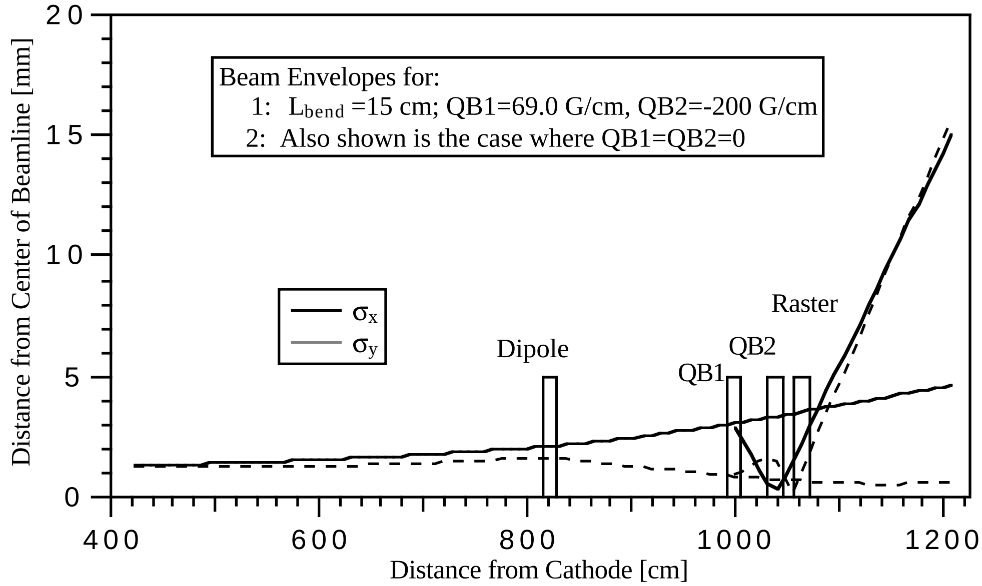


Fig. 3. Envelope for Configuration 1. The envelope resulting from turning off the expander quads is also shown (drift from dipole to dump).

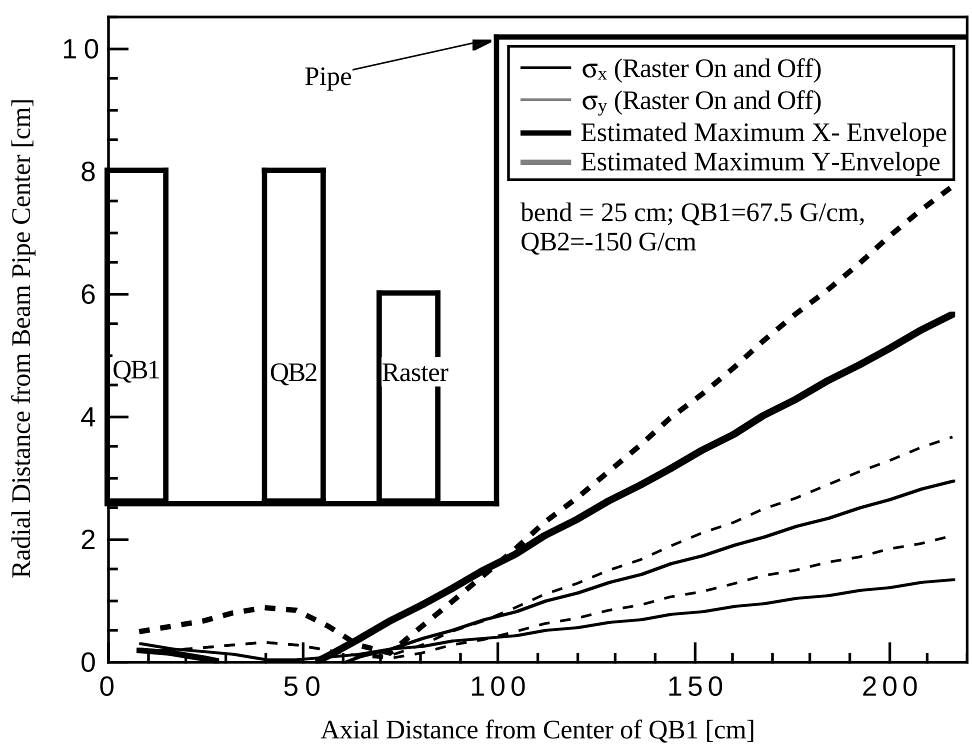


Fig. 3. Dump configuration with the beam being expanded. Conditions for the raster both on and off are shown. Note: Simulations predict no particles > 3σ at 2 inch to 8 inch pipe union and also at the dump .

III. DERIVATION OF SPECIFICATIONS

OVERVIEW

For the 10 MeV test stand, the primary constraint on the magnet specifications is beam loss. It is desired to have particles at all locations < 6σ from the pipe, where σ is the rms beam size for either x or y. Beam loss occurs when either the beam centroid excursion or beam size is large. The beam pipe radius is 25 mm. Therefore, the sum of rms beam size and the drift off axis should be < 4.2 mm. Beam centroid offset is generated by misalignments in magnets and stray fields present in the area of the beam.

In order to simulate the effect of stray fields similar to the earth's magnetic field, a kick was applied at the beginning of each drift. This kick was calculated using the equation

$$\theta[mrad] = \frac{0.3BL[gauss-cm]}{p[MeV/c]}$$

where B=0.5 gauss, L=the length of the drift, and p = 10 MeV/c. These kicks are summarized in Table III.

Table III. Summary of kicks used in DIMAD to simulate stray fields.

Location	Magnitude of kick [mrad]	Length of Drift [meters]
From Cryounit to QJ1	0.64	0.425
From QJ1 to QJ2	1.28	0.6*
From QJ2 to QJ3	0.9	0.85*
From QJ3 to QJ4	1.28	0.6*
From QJ4 to Dipole	1.71	1.14
From Dipole to QB1	2.45	1.62
From QB2 to Dump	2.45	1.65

* The kicks for the drifts from QJ1 to QJ2 and QJ3 to QJ4 (each 0.6 m) were calculated using the drift from QJ2 to QJ3 (0.85 m) and the kick from QJ2 to QJ3 was calculated using a 0.6 m drift instead of a 0.85 m drift. This error should not make a significant difference in the results.

SIMULATIONS TO DETERMINE SPECIFICATIONS

The following steps summarize the simulations that were performed to determine the specifications for alignment and field quality.

1. A DIMAD deck was written simulating the nominal setup of the injector. The input conditions (coming out of the cyrounit) were β_x = 6.5 m, β_y = 6.5 m, and $\alpha_x = \alpha_y = 0$.

2. Using DIMAD, random misalignments were generated in the 4 matching quads, the dipole, and the two expander quads. Misalignments included:
   a) transverse offsets in x and y,
   b) tilt arising from misalignments between the front and back ends of the magnet,
   c) longitudinal misplacement,
   d) rotation about the longitudinal axis.

The misalignments are uniformly distributed with the rms value being the input. Systematic quadrupole errors of 0.06 for dodecapole and 0.02 for icosapole were included but had no noticeable effect on the orbit.

3. 10 Random sets were generated with the misalignment errors given in Table IV.
For each set, the maximum positive and negative excursions were recorded for:
a) Uncorrected orbit - See Fig. 4a
b) Orbit corrected using feedback only from viewer locations - See Fig. 4b
c) Orbit corrected using feedback from quad centering as well as viewers - See Fig. 4c

With no correction, maximum orbits usually were near 50 mm with one as large as 100 mm. By simply adjusting the correctors so that the orbit was zeroed at the two viewers and the dump, the maximum orbit offsets were reduced to < 8 mm. Since the beam can be centered at the dump only if the beam is very near center of the quads, these large offsets plotted generally occurred between QJ1 and QJ4. By using quad centering techniques, the maximum beam orbit can be dropped below 2 mm. The alignment specifications are summarized in Table IV.

The resolution of the diagnostics were also determined using these runs. The resolution of the plotted orbit was ≈ 1 mm. Hence, alignment of the viewers should be ≈ ± 0.5-1 mm. This is roughly the accuracy during normal mounting procedures [P. Adderley, private comm.] and hence no special alignment techniques are necessary.

Table IV. Summary of the alignment specifications.

Parameter	Specification	Comment
Transverse	0.5 mm	RMS of uniform distribution
Tilt, front to back	0.5 mm front and back alignment	RMS of uniform distribution
Roll	1 mrad	RMS of uniform distribution
Longitudinal Placement	+/- 5 mm	RMS of uniform distribution

4. Using two of the nine DIMAD decks generated in step 3, random DC power errors were generated uniformly distributed over ±0.1%. For each of the two chosen sets, 9 sets of randomly mispowered magnets were generated and simulated. The variation in maximum orbit excursions was observed. For the 18 runs, all variations in orbit were < 0.2 mm. If the dump is excluded, the maximum variation in orbit was < 0.04 mm. Hence, power supply stability of ±0.1% is adequate for the test stand.

5. Random field errors as measured in existing QJ and QB magnets were then added at the nominal levels and are shown in Table II. Insignificant variations in orbit were observed.

6. Using the nominal setup, PARMELA runs were performed to generate beam envelope information. Field inhomogenieties were not included. They may be incorporated into the PARMELA code at a future date. PARMELA was used to see the effects of quad power fluctuations on the envelope, especially at the dump. When properly set up, the horizontal beam size is insensitive to large changes in QB2 and the vertical beam size is insensitive to changes in QB1. Changes of order 10^{-3} in QB1 cause

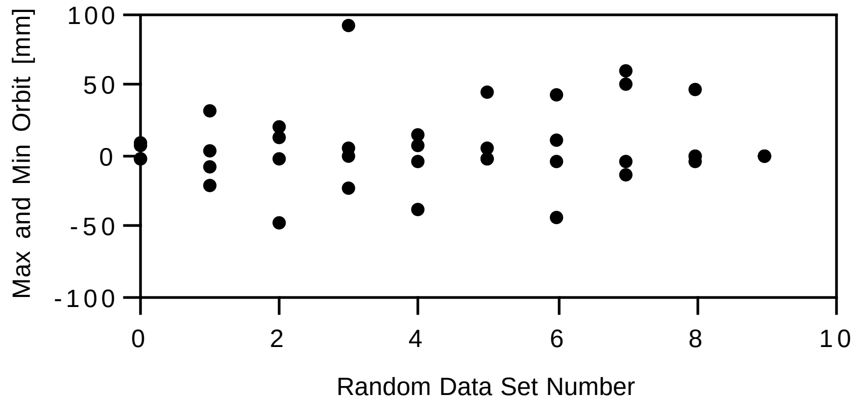
≈1 mm change in the horizontal rms beam size and the same change in QB2 causes similar ≈0.1 mm change in vertical position.

SPACING BETWEEN THE DOUBLE QUADS

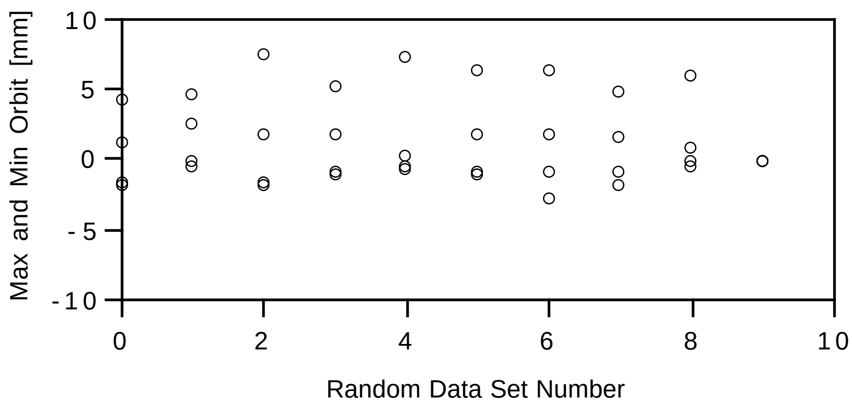
To avoid field interference between magnets, it is desireable to make the magnet separatin greater than twice the magnet bore[L. Harwood, private comm.]. The expander quads, where the separation to bore ratio is 5, satisfy this condition. The double QJ quad located at the third matching lens does not satisfy the condition. This magnet is doubled to provide the capability of focusing small beams (σ<0.5 mm) to smaller dimensions (σ<0.1 mm). It most likely will not be used as a double quad when running in the high power configuration. However, careful measurements of the double QJ quad are necessary.

IV. SUMMARY

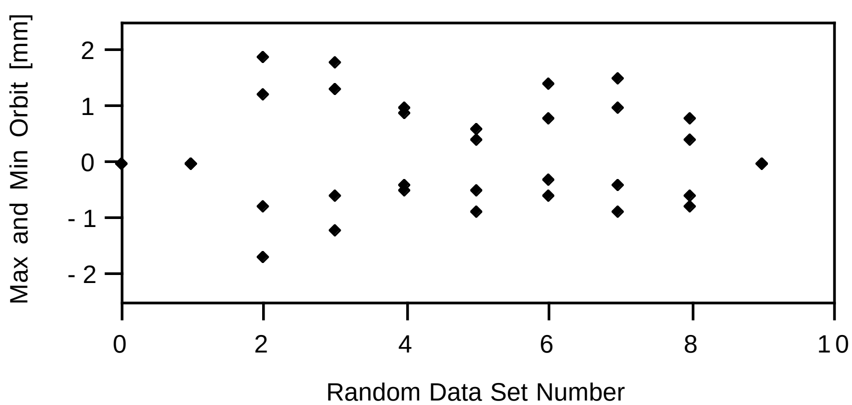
Alignment and field specifications for the 10 MeV Injector Test Stand have been presented. The field quality of the QJ, QB, and BM magnets are satisfactory.



(a)



(b)



(c)

Fig. 4. The 3 graphs shown plot maximum (positive) and minimum (negative) beam centroid offsets in the 9 DIMAD runs for (a) no correction, (b) orbit correction performed by zeroing beam at viewer locations, (c) orbit correction performed using both viewer location and quad centering.

The alignment specifications were derived in the following manner. A DIMAD deck was written simulating the nominal setup of the injector. Using DIMAD, random misalignments were generated in the 4 matching quads, the dipole, and the two expander quads. Misalignments included: 1) transverse offsets in x and y, 2) tilt arising from misalignments between the front and back ends of the magnet, 3) longitudinal misplacement, and 4) and rotation about the longitudinal axis. The misalignments are uniformly distributed with the rms value being the input.

DIMAD was run for 9 different sets of misalignments and the orbit was observed.