Table 1: Beam Bending Experiment Component Specifications

Class	Type	Length	Field	Comments	Number
Dipole	Sector	0.15 m	1 kg	entrance, exit angles equal 1/4 bend angle	4
Dipole	Rectangu-lar	~0.5 m pole width	1 2/3 kg	semi-circular orbit with 0.2 m radius	1
Quadrupole		0.15 m	k_{max} ~ 25/m^2	QJ needs 20 A to meet spec at 10 MeV	8
Sextupole		0.15 m	k_{max} ~ 80/m^3		4
H+V Correc-tor			900 g-cm		7
Beam Viewer					7
BPM					3
Profile Moni-tor					3
Magnetic Shielding	As in CEBAF injector				

C6x, C6y, C7x, and C7y as needed to optimize centering.
2. Activate MQ1-MQ4 and verify beam centering by observation on VB.

D. Steering to high power dump

This procedure is yet to be completed, but will be conceptually similar to the above.

Status

The status of the design at the date of this writing is as follows:

- there is a completed layout
- there are matching quad solutions for Liu input conditions for both straight ahead and backleg emittance measurements
- there are baseline geometry element specifications (element lengths, positions, field/gradient integrals, entry/exit angles, *etc.*)
- a preliminary layout of the diagnostic and correction system has been completed; preliminary estimates of required corrector strengths have been made

At the present time, the following issues are still outstanding:

- a careful layout of the diagnostic and correction system must be completed
  - simulations of orbit analysis and correction must be performed
  - final diagnostic type, number and location must be determined
  - orbit correction methods must be developed and tested
  - required corrector strengths must be detailed and finalized
- error studies must be performed and engineering specifications for beamline components (field quality, excitation stability, *etc.*) must be developed
- a high order chromatic scan using TLIE must be completed
- detailed operational procedures must be completed

References

[1] H. Liu, private communication.

[2] *ibid*.

```
I =100.1000   radius =    .156000E-02   error =    .263723E-13
I =   .0000   radius =    .204000E-02   error =    .312624E-13

 emittance     =  1.884187488942059E-07
 beta  at quad =  2.77145867974746
 alpha at quad =  4.10168826231486
 gamma at quad =  6.43121498850406
 beta*gamma-alpha**2 =  1.0
 error function      =  3.126236043182323E-14

I =800.6000 rmeas=.249000E-02 rtest=.247245E-02 betaharp =.324438E+02 test emittance = .1911E-06
I =700.5000 rmeas=.194000E-02 rtest=.195473E-02 betaharp =.202791E+02 test emittance = .1856E-06
I =600.4000 rmeas=.143000E-02 rtest=.145490E-02 betaharp =.112342E+02 test emittance = .1820E-06
I =500.3000 rmeas=.980000E-03 rtest=.100016E-02 betaharp =.530903E+01 test emittance = .1809E-06
I =400.3000 rmeas=.690000E-03 rtest=.687009E-03 betaharp =.250496E+01 test emittance = .1901E-06
I =300.2000 rmeas=.760000E-03 rtest=.728457E-03 betaharp =.281633E+01 test emittance = .2051E-06
I =200.1000 rmeas=.112000E-02 rtest=.108497E-02 betaharp =.624752E+01 test emittance = .2008E-06
I =100.1000 rmeas=.156000E-02 rtest=.155240E-02 betaharp =.127904E+02 test emittance = .1903E-06
I =   .0000 rmeas=.204000E-02 rtest=.205707E-02 betaharp =.224581E+02 test emittance = .1853E-06

           ave emit = 1.901250991495402E-07    deviation = 7.695823871783932E-09
-------------------------
```

Beamline Setup

Refer to the layout of Figure 1 for the following setup procedure.

A. Steering into arc/onto straight ahead

1. Turn off quads, sextupoles, and set dipoles to nominal values for transport to either straight ahead dump or
2. Center beam in cryounit using chopper modulator and V1
3. Thread beam to PM2 and thence to V3 (or, for straight ahead, to VS) using C1x and C1y.
4. Activate QM1 - QM4 and verify beam centering by observation on PM2 and V3 (or VS).
5. With beam centered in QM4, read BPM offsets for PM2, record, and load. Setup complete.

B. Steering around arc

1. Using C2x and C2y, steer to center at V3; verify centering in S1.
2. Using C3x and C3y, steer to center at PM4 and V4; verify centering in S2 and read, record and load PM4 offsets.
3. Using BB and C4y only (do NOT use C4x, EVER!) steer to center at V5. Verify centering in S3.
4. Using C5x and C5y, thread beam to PM6 and thence to V7; verify centering in S4 and MQ1. Read, record, and load PM6 offsets.
5. Using C6x and C6y, thread beam to V7 and VB. Examine C2x, C3x, C5x, and C6x values for correlations that may indicate a mis-excitation of the BSA1, 2, 3, 4 buss. If encountered, correct and resteer. Setup complete.

C. Steering through backleg.

1. With beam steered as above, verify centering in MQ1, 2, 3 and 4 using VB. Adjust

From the simulation results below, the "measured" beam parameters are as follows:

$$\varepsilon_x = 0.268 \text{ mm-mrad}, \beta_x = 2.304 \text{ m}, \alpha_x = -1.686$$

$$\varepsilon_y = 0.188 \text{ mm-mrad}, \beta_y = 2.771 \text{ m}, \alpha_y = 4.102$$

The agreement is, again, quite good. We note that the CEBAF emittance code assumes not only linear transport, but also evaluates the data using a thin lens model. The agreement is, in this case, even more reassuring.

Output of CEBAF Emittance Analysis Code

```
 quadrupole mq1 at 10 mev
-------------------------
  case number  1 plane: x

  s11 =  6.176910409350956E-07
  s21 =  4.521255922034055E-07
  s22 =  4.472588679104479E-07

I =800.6000   radius =    .262000E-02   error =    .510741E-14
I =700.5000   radius =    .209000E-02   error =    .563673E-14
I =600.4000   radius =    .159000E-02   error =    .117911E-13
I =500.3000   radius =    .114000E-02   error =    .142973E-13
I =400.3000   radius =    .870000E-03   error =    .144410E-13
I =300.2000   radius =    .940000E-03   error =    .170590E-13
I =200.1000   radius =    .132000E-02   error =    .230729E-13
I =100.1000   radius =    .183000E-02   error =    .255368E-13
I =   .0000   radius =    .240000E-02   error =    .329867E-13

 emittance     =  2.680489592626257E-07
 beta  at quad =  2.30439634100538
 alpha at quad =  -1.68672765395977
 gamma at quad =  1.66857155178222
 beta*gamma-alpha**2 =  .9999999999999996
 error function      =  3.298674365372295E-14

I =800.6000 rmeas=.262000E-02 rtest=.263360E-02 betaharp =.258754E+02 test emittance = .2653E-06
I =700.5000 rmeas=.209000E-02 rtest=.208449E-02 betaharp =.162101E+02 test emittance = .2695E-06
I =600.4000 rmeas=.159000E-02 rtest=.156514E-02 betaharp =.913882E+01 test emittance = .2766E-06
I =500.3000 rmeas=.114000E-02 rtest=.111783E-02 betaharp =.466160E+01 test emittance = .2788E-06
I =400.3000 rmeas=.870000E-03 rtest=.863083E-03 betaharp =.277902E+01 test emittance = .2724E-06
I =300.2000 rmeas=.940000E-03 rtest=.966833E-03 betaharp =.348730E+01 test emittance = .2534E-06
I =200.1000 rmeas=.132000E-02 rtest=.134906E-02 betaharp =.678962E+01 test emittance = .2566E-06
I =100.1000 rmeas=.183000E-02 rtest=.184351E-02 betaharp =.126788E+02 test emittance = .2641E-06
I =   .0000 rmeas=.240000E-02 rtest=.238195E-02 betaharp =.211666E+02 test emittance = .2721E-06

           ave emit = 2.676448758499011E-07    deviation = 8.120514917383608E-09
-------------------------
  case number  2 plane: y

  s11 =  5.221947770500044E-07
  s21 =  -7.728349707394164E-07
  s22 =  1.211761482003599E-06

I =800.6000   radius =    .249000E-02   error =    .758153E-14
I =700.5000   radius =    .194000E-02   error =    .108719E-13
I =600.4000   radius =    .143000E-02   error =    .160307E-13
I =500.3000   radius =    .980000E-03   error =    .176244E-13
I =400.3000   radius =    .690000E-03   error =    .176413E-13
I =300.2000   radius =    .760000E-03   error =    .198456E-13
I =200.1000   radius =    .112000E-02   error =    .258132E-13
```

monitor is varied in a controlled fashion and the profile response measured, thereby specifying the beam phase space incident on the quad.

The DIMAD model injected 5000 particles into the beamline on the design acceptance ellipse, using a truncated (4 sigma) six dimensional Gaussian load. To investigate the possible existence of H/V coupling, split horizontal and vertical emittances were used: $\varepsilon_x = 0.28$ mm-mrad, $\varepsilon_y = 0.18$ mm-mrad. Bunch length and momentum spread were as specified in the design by Liu. The program was then used to track the particle through the line to the final position, where the "particle distribution analysis" operation was employed to determine the rms spot size. The results are presented in Figure 5, where the simulated "measured" data points are shown as triangles and diamonds, and predicted results from an ideal linear model (based on the linear lattice functions only, exclusive of any nonlinear aberrations in the beam line) are shown as curves. Despite the presence of residual aberrations in the transport, the agreement between the nonlinear DIMAD tracking simulation and the linear model is good.

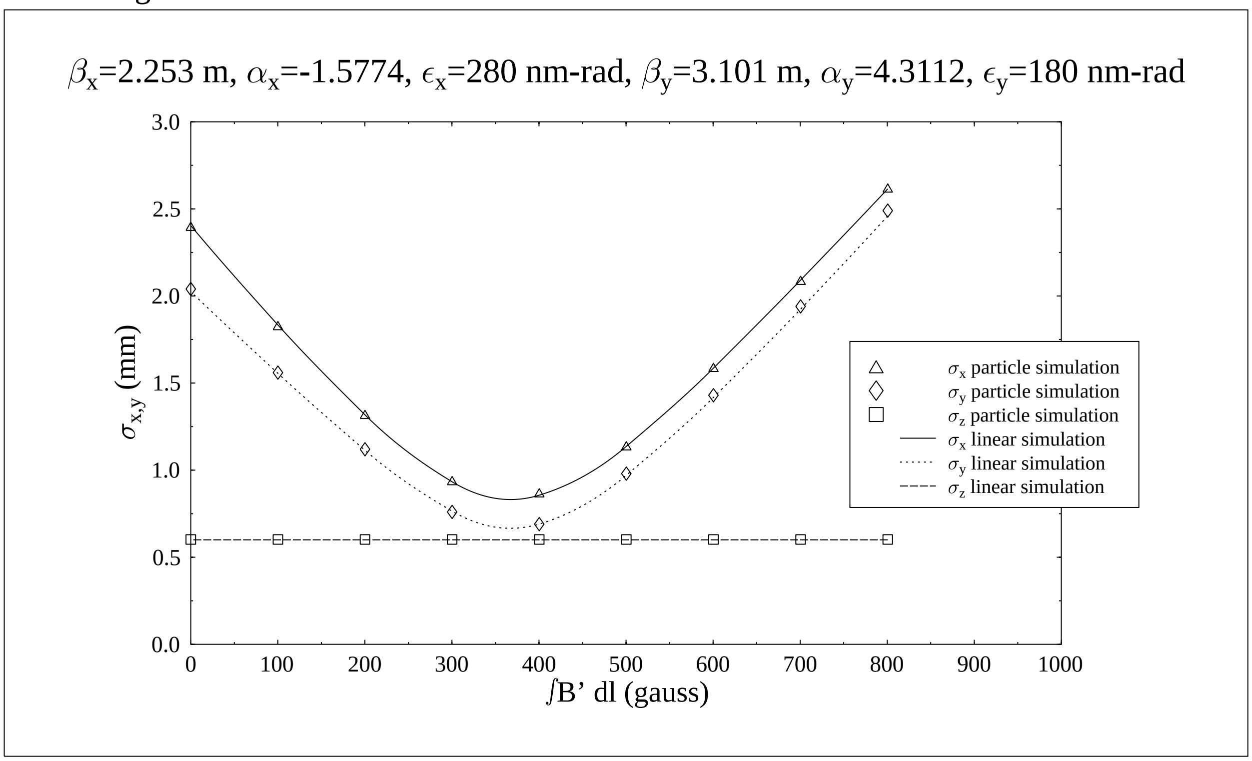

Figure 5: Results of simulated emittance measurement.

Evaluation of the simulated emittance was performed using a CEBAF standard code. The results are given below. From linear theory, the beam parameters upstream of the quadrupole are as follows:

$$\varepsilon_x = 0.28 \text{ mm-mrad}, \beta_x = 2.253 \text{ m}, \alpha_x = -1.5774$$

Figure 4 presents the result of a DIMAD "line geometric aberration" computation, in which seven beam phase spaces at momentum offsets of -3%, -2%,..., 2%, and 3% are injected on the beamline acceptance ellipse at five times the design emittance (a 1 mm-mrad geometric emittance was used). The resulting phase space images characterize both geometric and chromatic distortion introduced by the beam line; as can be seen by the figure large amplitudes and momentum offsets do not have an untoward impact on the beam phase ellipse.

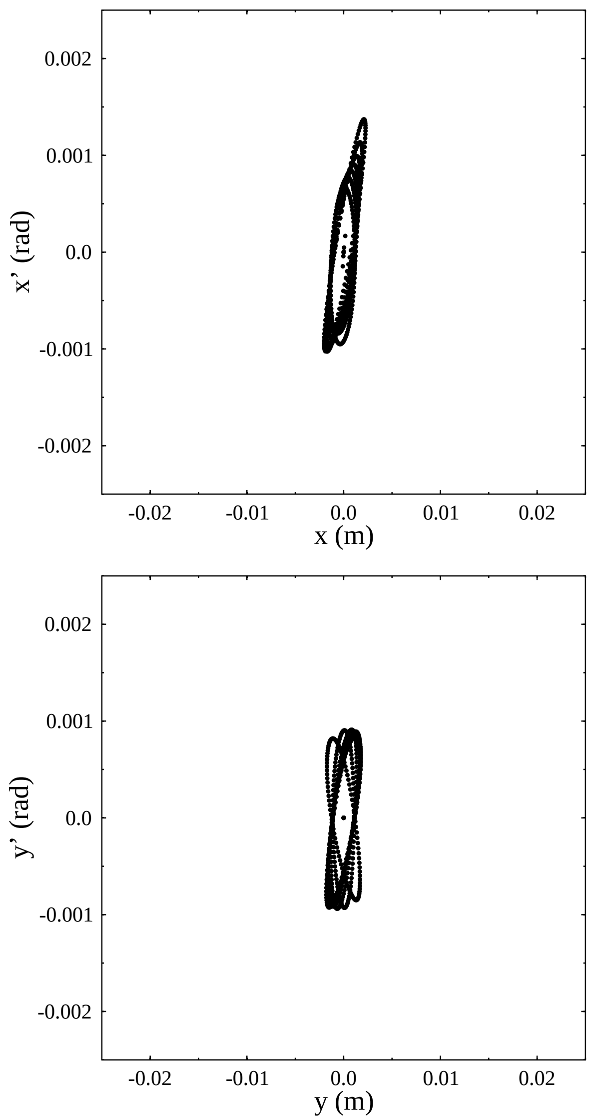

Figure 4: Result of DIMAD line geometric aberrations computation on a ±3% momentum bite, at a geometric emittance of 1 mm-mrad (~five times nominal).

The purpose of this beam line is to measure beam properties in the injector test stand. We have therefore simulated, using DIMAD, an emittance measurement at the backleg beam properties analysis station. The measurement modeled using the quad/profile monitor method, in which a single quadrupole upstream of a profile

Figure 3 provides the result of a DIMAD detailed chromatic analysis across a 6% full momentum bite. The betatron functions vary by only ±50% on this momentum range; the variation of path length with momentum offset is also acceptably small.

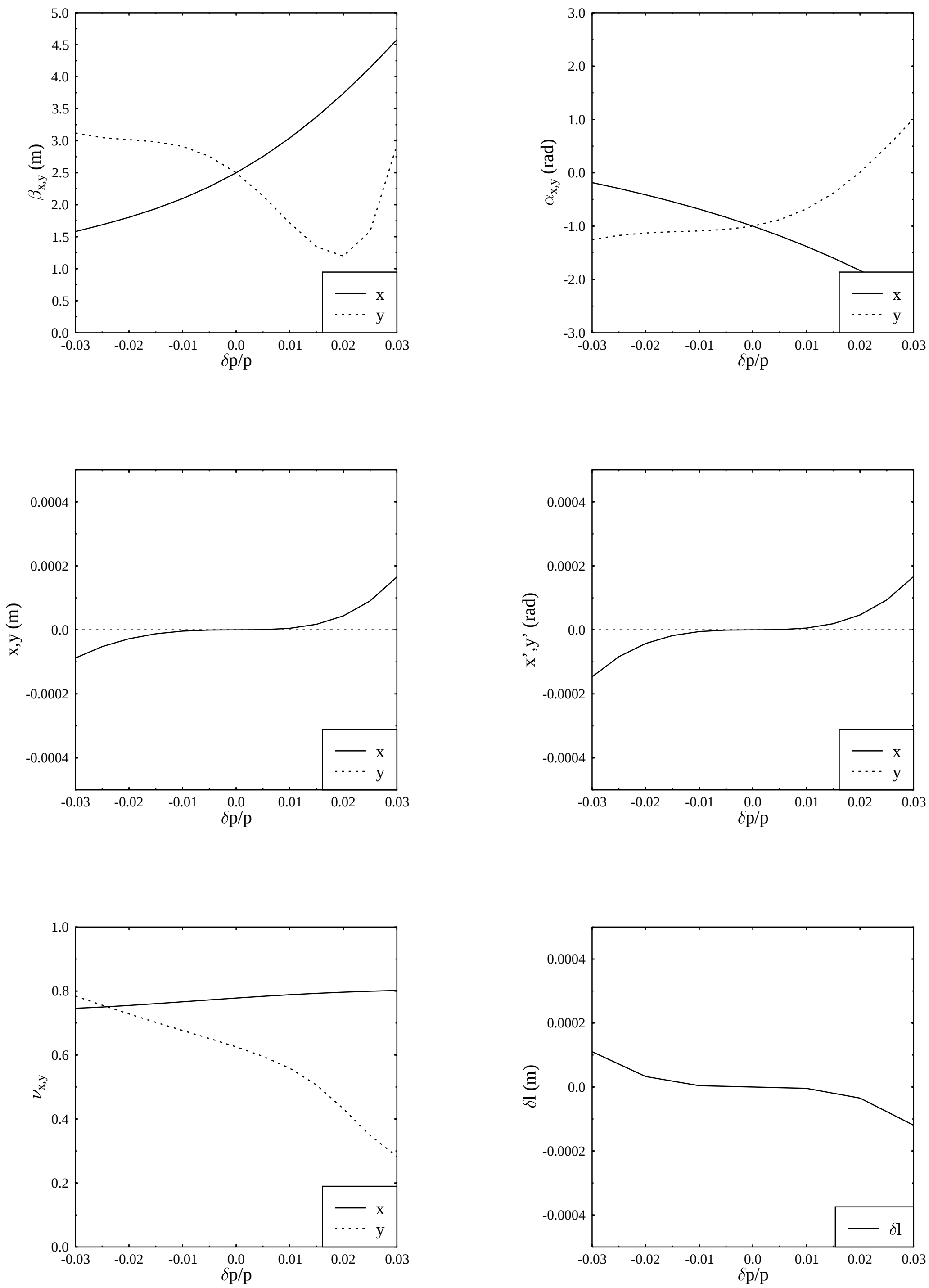

Figure 3: Results from DIMAD momentum scan of beamline from injector to back-leg beam properties analysis station.

The plots show that all peaks are of modest amplitude and that spot sizes will remain small through the system. The average M_{12} and M_{34} matrix elements are on the order of 1 m; the minimum value between any corrector and downstream monitor is ~3/4 m. This may be used to set a specification on the required corrector strength. If we demand each corrector be able to scan the 1.5" aperture at the next monitor, then the maximum required corrector field integral is, at 10 MeV, as follows.

$$L = \Theta B\rho = \frac{(1.5/2)\text{ in } \times 0.0254\text{ m/in}}{0.75\text{ m}} \times 33.3564\text{ kg-m/(GeV/c)} \times 0.010(\text{ GeV/c}) \approx 900\text{ g-cm}$$

The second order matrix transform for the sextupole-corrected beam line (injector to back-leg beam properties measurement station) is given below. Chromatic and geometric aberrations are thereby observed to be small through second order.

```
        FIRST ORDER MATRIX

  .1086793E+00  -.3968750E+01   .0000000E+00   .0000000E+00   .0000000E+00   .2924342E-15
  .2877025E+00  -.1304934E+01   .0000000E+00   .0000000E+00   .0000000E+00   .9490006E-16
  .0000000E+00   .0000000E+00  -.4371158E+00  -.2859595E+01   .0000000E+00   .0000000E+00
  .0000000E+00   .0000000E+00   .1128739E-02  -.2280339E+01   .0000000E+00   .0000000E+00
 -.4163336E-16   .2220446E-15   .0000000E+00   .0000000E+00   .1000000E+01  -.1734723E-16
  .0000000E+00   .0000000E+00   .0000000E+00   .0000000E+00   .0000000E+00   .1000000E+01

             SECOND ORDER TERMS

    .1135790E+01   .1134041E+02   .0000000E+00   .0000000E+00   .0000000E+00   .5341936E+01
                  -.9172638E+02   .0000000E+00   .0000000E+00   .0000000E+00  -.3227068E+02
                                  .3241164E+01   .3146644E+02   .0000000E+00   .0000000E+00
                                                -.1317335E+03   .0000000E+00   .0000000E+00
                                                                .0000000E+00   .0000000E+00
                                                                               .2979905E-16
    .8440198E+00  -.4347486E+01   .0000000E+00   .0000000E+00   .0000000E+00   .2292022E+00
                  -.9535967E+02   .0000000E+00   .0000000E+00   .0000000E+00  -.2965724E+02
                                  .2468101E+01  -.4138934E+01   .0000000E+00   .0000000E+00
                                                -.9717203E+02   .0000000E+00   .0000000E+00
                                                                .0000000E+00   .0000000E+00
                                                                               .3531747E-15
    .0000000E+00   .0000000E+00  -.3547957E+00   .5107515E+02   .0000000E+00   .0000000E+00
                   .0000000E+00   .5696064E+02   .2247286E+02   .0000000E+00   .0000000E+00
                                  .0000000E+00   .0000000E+00   .0000000E+00  -.9663209E+01
                                                 .0000000E+00   .0000000E+00   .1335990E+03
                                                                .0000000E+00   .0000000E+00
                                                                               .0000000E+00
    .0000000E+00   .0000000E+00   .3040199E+01   .2160787E+02   .0000000E+00   .0000000E+00
                   .0000000E+00   .2531881E+02  -.1315747E+03   .0000000E+00   .0000000E+00
                                  .0000000E+00   .0000000E+00   .0000000E+00  -.8987891E+01
                                                 .0000000E+00   .0000000E+00  -.8732541E+01
                                                                .0000000E+00   .0000000E+00
                                                                               .0000000E+00
   -.7403557E+00   .4919407E+01   .0000000E+00   .0000000E+00   .0000000E+00   .1508165E-14
                   .4038501E+02   .0000000E+00   .0000000E+00   .0000000E+00   .3738567E-14
                                  .1969581E+01   .3663106E+01   .0000000E+00   .0000000E+00
                                                 .1680717E+03   .0000000E+00   .0000000E+00
                                                                .0000000E+00   .0000000E+00
                                                                               .1196959E-15
```

Beamline Performance

The linear lattice and dispersion functions for the recirculation transport are given in Figure 2. We note that the peak values are modest and the spot size remains small for the nominal geometric emittance of 0.2 mm-mrad.

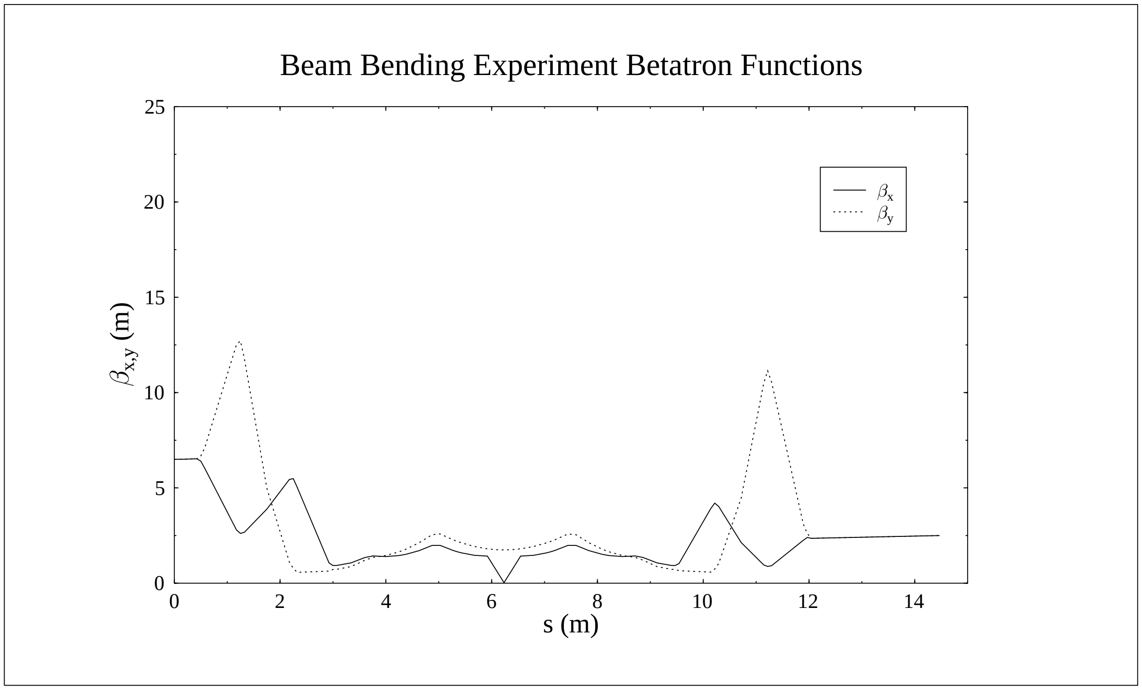

Figure 2a: Beam envelope functions for beam bending experiment; initial conditions are those from Liu, following injector.

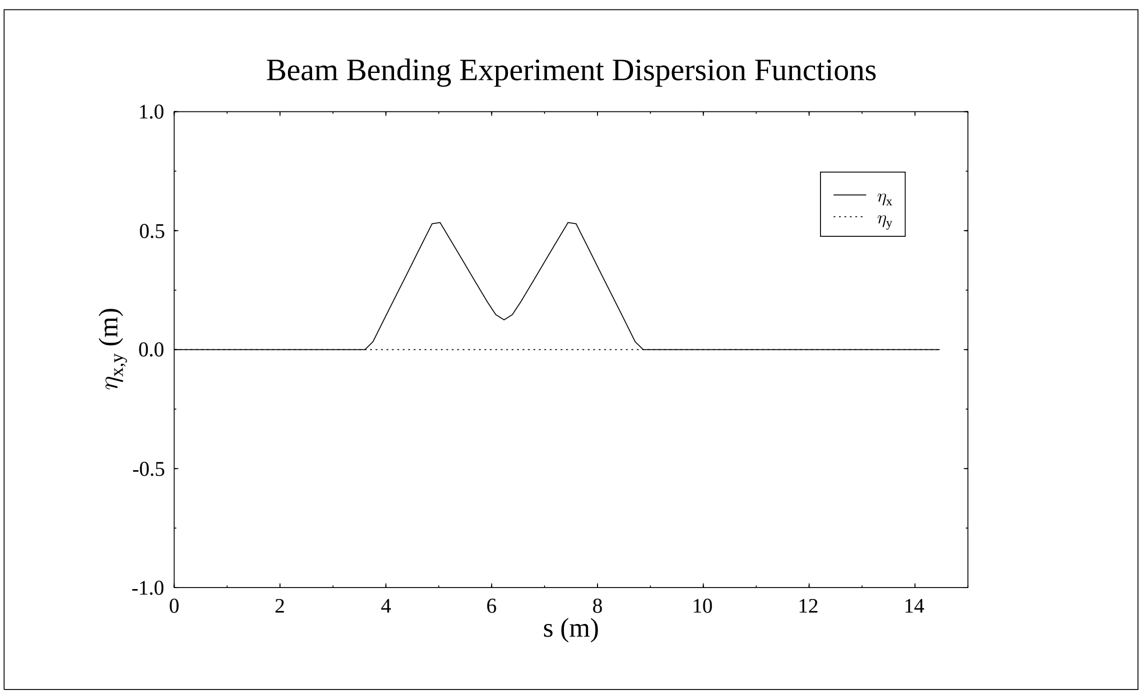

Figure 2b: Dispersion for beam bending experiment.

Betatron matching to either the straight-ahead beam properties analysis station or into the arc (fitting to arc “matched” betatron envelope function values) is provided by a four quadrupole telescope (QM1 - QM4 in Figure 1). Simulation with DIMAD using the aforementioned initial conditions indicates that both emittance measurements and matching to the arc are readily achieved. Betatron matching out of the arc to the backleg beam properties analysis station is achieved similarly (using the MQ1-MQ4 telescope of Figure 1). Beam envelope control required for emittance measurements is, in DIMAD simulation, again readily obtained.

The arc is betatron stable from the center of the final upstream matching quad to the center of the first downstream matching quadrupole, linearly achromatic, and linearly isochronous. Two sextupole families (S1 - S4 and S2 - S3 in Figure 3) are used (together with the reflective symmetry of the beam line) to set T_{166}, T_{266}, and T_{566} to zero; other aberrations are reduced (though not zero) through the choice of bend radii, chicane dipole entry/exit angles, and bend angles of the chicane dipoles.

Orbit analysis and correction is accomplished through a set of beam viewers, monitors and steering elements. These are also shown in Figure 1. Steering element specifications are evaluated in the following section; placement has been made so as to support the set-up procedure given later in this note.

The present beamline footprint, exclusive of the backleg beam properties analysis station, is 6 m x 1.5. Table 1 lists and specifies beamline magnetic and diagnostic elements. DIMAD input and output files for the present transport system design may be found on the cebafh cluster in the following files:

input: ~douglas/CEBAF_optics/TLFEL/bbex/bates091895

output: ~douglas/CEBAF_optics/TLFEL/bbex/bates091895out

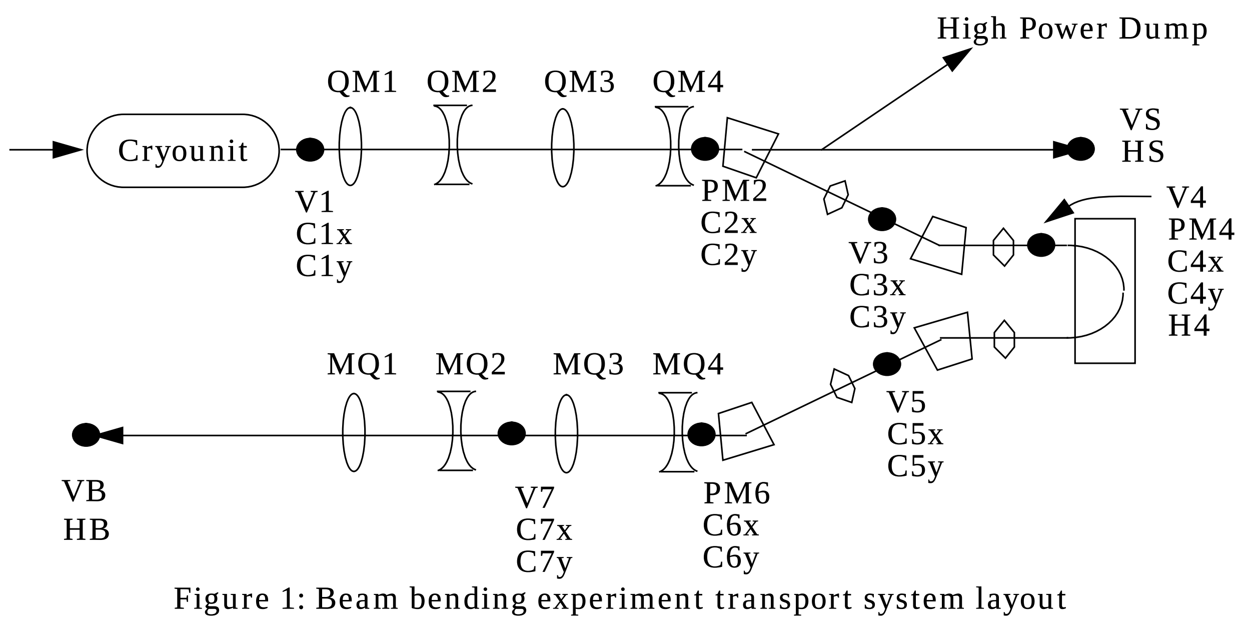

Figure 1: Beam bending experiment transport system layout

Beam Bending Experiment Transport System

D. Douglas, R. Legg, R. Li, D. Neuffer

Requirements

The beam bending experiment transport system is designed to propagate beam from the back end of the cyrounit in the injector test stand through various beam analysis stations. It is intended to meet the following requirements:

- low loss transport of 10 MeV beam from the cryounit (with initial beam envelope conditions of $\beta_x = \beta_y = 6.5$ m, $\alpha_x = \alpha_y = 0$ and geometric emittance of ~0.2 mm-mrad [1]) to one of a) a high power dump, b) a straight ahead transverse emittance and bunch length analysis station, or c) around a test bending arc to a back-leg transverse emittance and bunch length analysis station,
- implementation of an isochronous, achromatic Bates-like test arc for initial beam properties testing,
- appropriate matching of beam envelopes defined above to either the straight-ahead beam properties analysis station or into the test arc,
- appropriate matching of beam envelopes out of the test arc onto the backleg beam properties analysis station,
- momentum acceptance of ±1% (this is $4\sigma_{\delta p/p}$ of the anticipated momentum spread [2]),
- implementation of beam steering/orbit correction systems,
- modest optical aberrations,
- compensation of chromatic aberrations through the use of sextupoles,
- beam envelope function variations of ~25-50% at beam properties analysis stations across the full momentum acceptance, and
- footprint of 6x1.5 m, exclusive of backleg beam properties analysis station.

Design

A design meeting the above requirements has been developed. A Bates-like 180^o achromatic and isochronous recirculation arc is led and followed by four-quad telescopes used for betatron matching. The system, with nomenclature employed in this report, is shown in Figure 1.

The arc proper employs four identical sector dipoles with reduced pole face rotations (entry/exit angles 1/4 the full bend angle), and a single 180^o bend at a 0.2 m radius. This dipole geometry was chosen so the chicane dipoles focus equally in both transverse planes, providing optimum aberration control and reduction of betatron mismatch in this case of small bend radii and beamline footprint.