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High Resolving Power Spectrometer for Beam Analysis*

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Abstract: We describe a system designed to analyze the high energy, closely spaced bunches from individual RF pulses. Neither a large solid angle nor momentum range is required so this allows characteristics that appear useful for other applications such as ion beam lithography. The spectrometer is a compact, double-focusing QBQ design whose symmetry allows the Quads to range between F or D with a correspondingly large range of magnifications, dispersion and resolving power. This flexibility insures the possibility of spatially separating all of the bunches along the focal plane with minimal transverse kicks and bending angle for differing input conditions. The symmetry of the system allows a simple geometric interpretation of the resolving power in terms of thin lenses and ray optics. We discuss the optics and the hardware that is proposed to measure emittance, energy, energy spread and bunch length for each bunch in an RF pulse train for small bunch separations. We also discuss how to use such measurements for feedback and feedforward control of these bunch characteristics as well as maintain their stability.

I. INTRODUCTION

Proposals for future linear colliders call for energies up to 1.0 TeV. From studies conducted at SLAC, one approach for the Next Linear Collider (NLC) is a pulsed machine operating at X-Band (11.4 GHz) with a pulse length of ≈100 ns. If one accelerates multiple bunches per pulse with less charge per bunch, this reduces the effects of wake fields and allows looser tolerances. To study multibunch effects as well as do the necessary R&D on the high power microwave tubes and transfer stuctures that are required, a test accelerator is being proposed (NLCTA). The QBQ spectrometer is part of this proposal intended to study such effects.

The matching section and spectrometer downstream of the last X-Band section in the NLCTA should allow one to measure the energy and phase space densities of the individual bunches in a train on a pulse-to-pulse basis. The energy of a single bunch and its spectrum as a function of bunch number, current, length and phase are important for studies of beam loading, timing and nonlinear RF effects. Similarly, transverse bunch offsets and profiles are important for studying long-range and short-range transverse wakefield effects and their corrections. Figure 1 shows the proposed system following directly after the last X-Band accelerating section.

The most important characteristic for the design (and cost) is the incoming emittance in the three coordinate dimensions. Because a significant improvement is possible in this area we studied several systems. The one described below can be operated in two distinctly different modes that are called the *high* and *low* emittance configurations that can be used alternately with the thermionic and RF guns that are expected to have very different emittances. The associated instrumentation and control requirements are also discussed.

II. MATCHING SECTION AND SPECTROMETER OPTICS

Figure 1 begins with four quads to measure and match the incoming beam with $\beta_x = \beta_y = 4$ m from the last X-Band section to asymmetric double concave waists with $\beta_x = 0.04$ and $\beta_y = 0.50$ m at 4.5 m from the linac. This measuring point (MK4) is 3 meters in front of the bending magnet of the double focusing QBQ spectrometer and there is a retractable screen (solid line) and wire scanner (dotted) at this point. A range of initial conditions were considered at QM1 e.g. for $\beta_{x,y} = 10$ m at 1.3 GeV we could use weaker quads but this worsens wake field effects.

The pole shapes of the bend and the two additional quadrupoles of the spectrometer focus the beam ($\beta_x = 0.22$ and $\beta_y = 0.18$ m) to a similar combination of monitors at the focal plane (MK6) ≈3.6 m after the 12° bend. Here we obtain a small monochromatic spot in the horizontal, dispersive direction as well as in the vertical to help separate bunches within a train. The vertical kicker (VK) is displaced roughly 90° in phase from MK4 and MK6.

Several different spectrometer designs were developed around an existing 12° dipole magnet which had been used previously. In one case, no matching was required to obtain a momentum resolving power of $RP \approx 5000$ with a single focusing QB configuration. For single bunch operation and fixed input conditions this configuration would be adequate as would a conventional SEM wire array at MK6 in Fig. 1. With the two-cell matching section, two additional, double focusing QBQ configurations were developed for differing beam emittances. Figure 1 shows the high-ϵ configuration for use with the thermionic gun whose normalized emittance is $\epsilon_{N_{x,y}} = 10^{-4}$m. At the focus MK6, the horizontal dispersion of $\eta_x = 1.1$ m and $\beta_x = 0.22$ m give a first order resolving power of:

$$RP_1 = \frac{\eta_x}{\sqrt{\beta_x \epsilon_x}} > 10^4 \left[\frac{1.3}{E(GeV)}\right]^{\frac{1}{2}} \left[\frac{10^{-4}}{\epsilon_{N_x}(m)}\right]^{\frac{1}{2}} .$$

This is only slightly worse using third-order TURTLE with full gaussian distributions i.e. $RP_3 = 1.1 \times 10^4$. In the vertical, the measured σ_y is essentially free of chromatic aberrations. The low-ϵ configuration has about half the dispersion but this still gives $RP_3 = 2 \times 10^4$ for the same ϵ_N and a much better value for the lower energies E and emittances expected for the RF gun ($\epsilon_N < 10^{-5}$ m).

The high-ϵ configuration has the first spectrometer quad excited to focus in the dispersive plane i.e. as FBD. The reverse is true in the low-ϵ or DBF configuration. In both cases the QBQ is a double-focusing, point-to-point system as shown in Fig. 2 but for the high-ϵ case R_{33} is demagnifying to simplify bunch separation in the vertical direction as discussed below. The differences here relate to variations in path length or flux closure as shown by a simple estimate of the resolving power:

$$\frac{p}{\Delta p} \approx \frac{\Theta_B \cdot L^*}{2\sqrt{\beta_x \epsilon_x}} = \frac{Flux Enclosed}{2(p/e)\epsilon_x} \approx 10^4 .$$

When spectrometer costs are dominated by the dipoles we would then expect the cost to be driven by the emittance and resolving power that is required.

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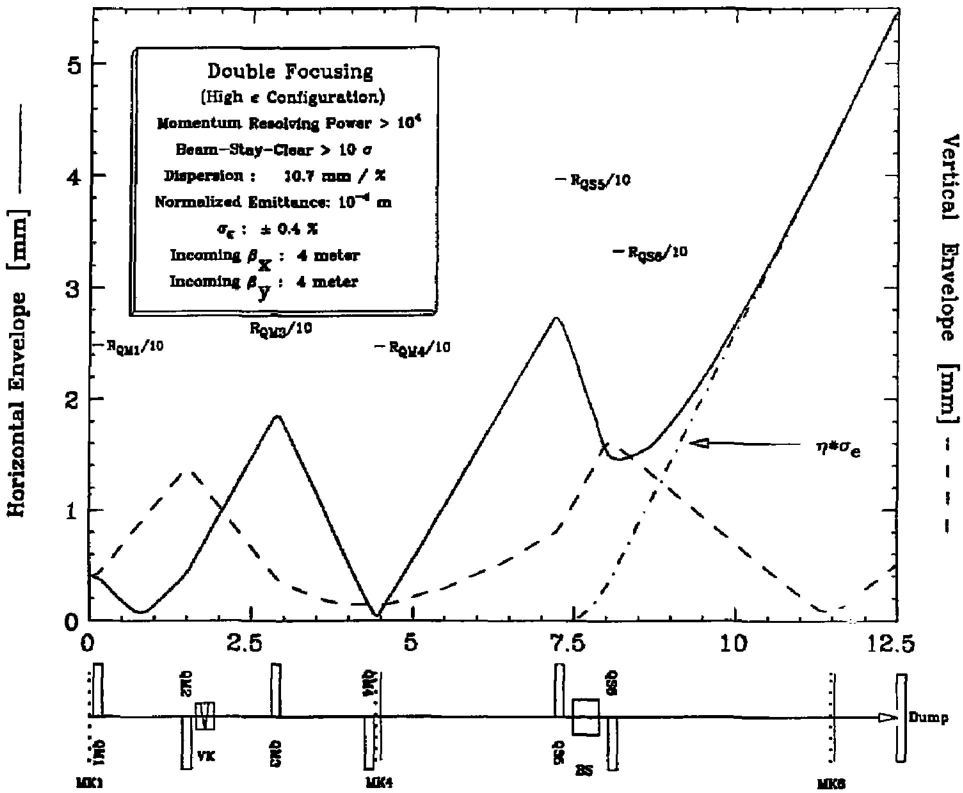

Figure 1: NLCTA Spectrometer and Matching Section Characteristics for the High-ε Spectrometer of Table I.

III. Beam Analysis Instrumentation and Hardware

Some of the required instrumentation is indicated at the bottom of Fig 1. Two dimensional wire scanners are shown as dotted lines and insertable screens as solid. A vertical kicker magnet is shown near QM2 for multi-bunch operation as well as a Faraday cup or reentrant dump at the very end. In addition to these elements there are also BPM's associated with each quad, some x/y steering magnets and two toroids - one before the bend and one after it. Finally there is also a straight ahead line with similar instrumentation and a dump. This leg could also include instrumentation for bunch length measurements and feedback for FFT's of coherent synchrotron radiation or fast pickup signals.

A. Vertical Kicker Magnet

To separate the bunches in a train spatially in order to observe all of them simultaneously, a kicker or transverse deflecting cavity (TM_{110}) can be centered $\approx 20-30$ cm on either side of QM2 where there is space and $\beta_y (\approx 36-44$ m) is large with a 0.6π phase shift to the image at MK4 or MK6. We need a separation of $\delta y_{i,i+1} \approx 6\sigma_y \leq 500\mu$m between bunches at the focal plane (MK6) to completely resolve them for the assumed values of ϵ_N and δ when there are no significant bunch offsets from the linac. There are several ways to accomplish this. One of the simplest is to modulate the phase of the last X-Band cell since we need only 10 MeV per bunch. However, due to other problems (both real and possible) we assume one or more vertical kicks. The frequency or rise time for linearity comes from using $\approx \pm 30°$ about the zero-crossing of a sinusoidal field for 10 bunches separated by 1.4 ns corresponding to a frequency $f \approx 12$ MHz (the 238-th subharmonic of S-Band). Perhaps the most practical approach is to use the current damping ring kicker design and simply run it at lower fields since it gives a total kick of $\delta y' \leq 8$ mr at 1.21 GeV while we need $\geq 50\mu r$ per bunch. This allows considerable flexibility in the number of bunches we can study and also gives us a know system whose study is also of interest. Because fast risetime and stability tend to be conflicting constraints, additional kickers or cavities could be be used for stability or to select specific bunches or to manipulate them in various ways.

B. Two-Dimensional Beam Profile Monitors

In addition to screens and TV cameras, it would be useful to have a 2-D pixel array of some kind that provides better resolution and saturation bandwidth than the normal screen provides. This is needed to study correlations between bunches in a single train. The constraints for different methods can be inferred from Fig. 3 for a bunch. *This plot shows 1000 rays traced with third-order* TURTLE assuming full gaussian distributions in all dimensions at 1.3 GeV for the thermionic gun. The assumed energy distribution was a 'Steining' type with $\delta^{max} = \pm 0.4\%$. When we set $\delta^{max} \approx 0$, we get $\sigma_x = 0.095$ mm and $\sigma_y = 0.083$ mm with no particles observed outside a radius r=250 μ. Again, a practical approach that should work well for these beam sizes at all of the locations indicated in Fig's. 1-2 is to use the current SLC wire scanners. No new design or redesign is necessary. These could be used to calibrate the screen and camera optics of a double or multiple camera arrangement that would allow one to observe all bunches simultaneously while zooming in on one or more for a detailed profile measurement. The screen should conform to the spectrometer focal plane.

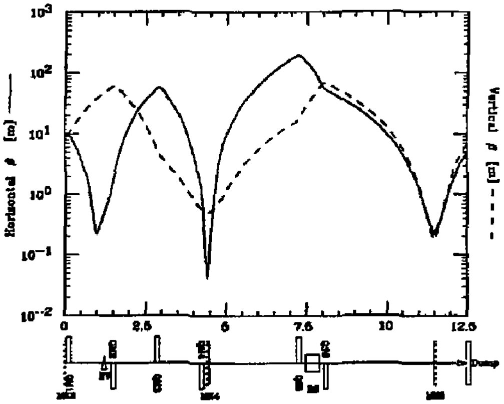

Figure 2: β-Functions for High-ϵ in Figure 1 and Table 1.

III. Summary and Conclusions

To summarize, the system is compact but leaves room for subsequent upgrades in energy or instrumentation. Such upgrades are especially relevant for the measurement hardware in the straight ahead line. The guidelines for the various designs were to obtain the best system in the shortest distance that is upward compatible i.e. that could progress from QB→QBQ(high-ϵ) →QBQ(low-ϵ) without vacuum chamber or magnet modifications where QBQ is always a double focusing, point-to-point system. We assumed similar quads as for the X-band lattice (L=15 cm) whose radii, for 10 kG pole tip fields at 1.3 GeV, are R_{QM}=1 cm and $R_{QS}\approx$4 cm. These radii provide a beam-stay-clear > 10σ for this pole tip field which depends on the initial βs assumed from the linac and the variations required for emittance measurements at MK4 in the matching section.

As discussed above, the cost of the system is driven by the required emittance and resolving power. This is true throughout the NLCTA and in this instance is easily estimated to be $\propto (RP\cdot\epsilon)^{\frac{1}{2}}$ which strongly emphasizes the importance of the RF-gun development work.

ACKNOWLEDGMENTS

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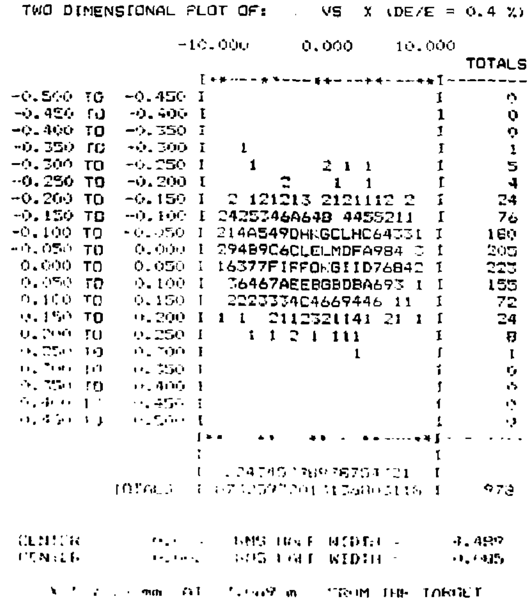

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TWO DIMENSIONAL PLOT OF:      VS   X (DE/E = 0.4 %)

                           -10.000      0.000     10.000
                                                          TOTALS
                          I**----*----**--- -**- ---**I--------
-0.500 TO  -0.450 I                         I         0
-0.450 TO  -0.400 I                         I         0
-0.400 TO  -0.350 I                         I         0
-0.350 TO  -0.300 I   1                     I         1
-0.300 TO  -0.250 I    1        2 1 1       I         5
-0.250 TO  -0.200 I          2   1  1       I         4
-0.200 TO  -0.150 I  2 121213 2121112 2     I        24
-0.150 TO  -0.100 I 2425346A648 4455211     I        76
-0.100 TO  -0.050 I 214A549DHKGCLHC64331    I       160
-0.050 TO   0.000 I 294B9C6CLELMDFA984 3    I       205
 0.000 TO   0.050 I 16377FIFFOKGIID76842    I       223
 0.050 TO   0.100 I  36467AEEBGBDBA693 1    I       155
 0.100 TO   0.150 I  2223334C4669446 11     I        72
 0.150 TO   0.200 I 1 1  2112321141 21 1    I        24
 0.200 TO   0.250 I    1 1 2 1 111          I         8
 0.250 TO   0.300 I             1           I         1
 0.300 TO   0.350 I                         I         0
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CENTER       [illegible]   RMS HALF WIDTH =      4.489
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[illegible] mm AT [illegible] m  FROM THE TARGET
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Figure 3: TURTLE Output for High-ϵ in Fig's. 1-2.

References

[1] R.A. Alvarez, K.L. Brown, W.K.H. Panofsky and C.T. Rockhold, Rev. Sci. Inst. **31**, 556, 1960.

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Table I: Characteristics of QBQ Spectrometer (Fig.1).

Characteristic	Value
Length of Matching Section[a]	4.5 m
Overall Length of Spectrometer	7.0 m
Nominal Dipole Strength (Θ_B)	0.21 (12°)
Entrance Angle=Exit Angle	0.17 (10°)
Object/Image Distance (L^*)	$\approx$3.0 m
Nominal Quadrupole Strength	1 m^{-1}
Momentum range	$\leq$ 1.3 GeV/c
Momentum Acceptance	5%
Momentum Dispersion	1.1 cm/%
Momentum Resolving Power	> 10^4
Horizontal Angular Acceptance $A_{x'}$	$\pm$14 mr
Vertical Angular Acceptance $A_{y'}$	$\pm$14 mr
Number of Bunches/Train[b]	10-20
Separation between Bunches	$\geq$1.4 ns

[a] This matches to variable input conditions on α, β.

[b] A train corresponds to one RF pulse of $\approx$100 ns.