LOW DIVERGENCE BEAM IN PROTON WEST

D.G. Ryan
McGill University

and

C.T. Murphy

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Abstract

This note describes the procedure used to obtain a 400 GeV low divergence external proton beam in Proton West suitable for running experiment #177.

Introduction

The purpose of E-177 is to measure p-p elastic scattering at 200 and 400 GeV for momentum transfers in the range from -4 to -20 $(GeV/c)^2$. The apparatus consists of a 4" long transmission target and MWPC spectrometers for the scattered and recoil particles. Elastic events are identified using the usual momentum-angle, angle-angle and coplanarity constraints. The experimental resolution achievable in the determination of t depends on the measurement resolution of both spectrometers and on the beam spot size and divergence at the target. Thus the beam properties must be controlled so as not to deteriorate the t resolution and the selection of events using the elastic constraints, particularly that of coplanarity.

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Constraints on the beam spot size and divergence in both planes are determined by the measurement resolution of the scattered particle spectrometer. For resolution purposes this spectrometer consists of MWPC's with 16 wires per inch at a maximum spacing of 15 m and having a mean distance of 42.5 m from the target. The measurement resolutions for this system are $\sigma_H = \sigma_V = 0.32$ mm and, in both planes, $\sigma_\theta = 0.043$ mr. When referred back to the target these quantities correspond to $\sigma_H = \sigma_V = 1.8$ mm and $\sigma_\theta = 0.043$ mr. As we will be using FWHM as a measure of beam properties these quantities become $\delta_H = \delta_V = 4.2$ mm and $\delta_\theta = 0.10$ mr.

Resolution considerations thus require that in both planes the beam spot size at the target should be less than 4.2 mm and the divergence less than 0.10 mr. If possible these conditions should be met with waists in both planes at the target position. Of course the beam emittance in both planes must satisfy the requirement that $\varepsilon_{H,V} < \delta_\theta \cdot \delta_{H,V} < 0.42$ mm-mr. (Note that phase space areas will be defined using the method of Murphy[1] where the measured FWHM's of SWIC histograms are taken to be the half-widths of the projections of an elliptical phase space, which has been estimated to contain $\sim$85% of the proton flux.) Additional requirements are that the beam should have low halo for operation at high intensities and that the beam properties should be relatively independent of tuning conditions in the switchyard area.

Proton West Beam

The above conditions are satisfied by the Proton West (PW) beam which is derived from electrostatic septa and the 3-way split[2] in Enclosures E and H. It is then passed through a series of refocussing and collimation stages[3] before entering the PW target area. A complete listing of all the elements in the beam is given in Table I. Since focussing elements are of prime importance here, all bending magnets and trim magnets have been replaced by drift spaces of equivalent lengths. Table II lists the quadrupoles by location, name and type, and also gives the constants used for converting gradients to amperes. Note that these constants require the use of the physical length of the quadrupole as its equivalent length. Also given in Table II are the correction factors required to obtain the SET TO (ST) or READ BACK (RB) values for the computer controlled power supplies. In the case of the pretarget (PT) quadrupoles this factor was measured using a precision current shunt while for the PW-A and PW-C quadrupoles it was arbitrarily set at 0.96* since all four quadrupoles seemed to require the same correction.

Preliminary calculations using the programs BETRAF[4] and TRANSPORT[5] indicated that it was not possible to obtain a double waist at the E-177 target position with the required properties. This is due primarily to the large distance between the PW-C and PT quadrupoles. However a satisfactory compromise was to require the following:

*This value has since been measured using a precision shunt and should be 0.943.

(i) a horizontal waist at the target with 0.1 mr divergence and (ii) a vertical waist downstream of the target with 0.1 mr divergence.

The starting condition assumed was that the proton beam could be represented by erect ellipses in both planes at the approximate centre of the 3-way splitting magnets in Enclosure H. The properties of the ellipses are as follows:

$$\varepsilon_H = 9.0 \text{ mm} \times 0.035 \text{ mr} = 0.32 \text{ mm-mr}$$

and

$$\varepsilon_V = 6.0 \text{ mm} \times 0.02 \text{ mr} = 0.12 \text{ mm-mr.}$$

These values were found to produce a good fit to the beam sizes as measured in the quadrupole enclosures.

Alignment

Before quadrupole tuning is started the beam should be roughly aligned so as to be centered in the enclosures and PW. For this the procedure given in Table III should be followed. It should be carefully repeated after final quadrupole currents are obtained. Note that the crew chief must centre the beam vertically in SC321W. A setting between 0 and -5 wires is satisfactory but must remain constant. The correct line in PW is the centre of the E-177 beam aperture collimator and the centre of SC616 at the beam dump. The nominal position on SC602 is established by scanning with ST603 and ST604 until minimum counting rates are achieved in the scattered particle spectrometer. If all SWIC's have been properly aligned the beam should now also be centered in SC615.

Collimators

Before quadrupole tuning the PW-A collimators should be set such that the apertures are approximately twice the FWHM of the beam size as measured on SC331W. This immediately removes large displacement particles and prevents misleading minima from being obtained. The other collimators are left open until the final focus and alignment has been obtained at which time they are adjusted to minimize beam halo.

Beam Tuning

The general procedure employed was to vary quadrupole currents until minimum beam sizes were achieved at the SWIC's and then to change the currents by calculated amounts so as to place waists at the correct locations. Table IV lists the steps required to reach the desired focus and these will now be discussed. All final calculated values were obtained from TRANSPORT.

I. PW-A

The polarities of the PW-A quadrupoles are set at horizontally focussing followed by vertically focussing as this optimizes the vertical backup collimator in PW-B. The currents in both quadrupoles are set by requiring simultaneous minimum spot sizes in both the horizontal and vertical planes on SC334W. Note that in general a minimum beam size at a given location in a drift space requires an upstream waist of a smaller dimension. Experimentally the condition is best achieved by alternately varying the two quadrupoles until a double minimum is obtained. With TRANSPORT the condition is achieved by varying the waist positions until minimum spots are obtained. Figure 1 shows the final tune curves for the two quadrupoles. The sensitivity of setting is 0.5 A or ∿1%. The calculated currents for this condition are given in Table V, which also gives the currents for the parallel to point requirement. The vertical waist coincides with the minimum spot while the horizontal waist is 23' upstream.

It was decided to leave this condition rather than moving the horizontal waist because it did give the minimum spot in PW-B and also provided a very easy retune if conditions changed in the switchyard area. In fact once a complete tune had been achieved with stable beam it was only necessary that subsequent small adjustments be made to the PW-A quadrupoles if conditions seemed to have changed.

II. <u>PW-C</u>

The PW-C quadrupoles were left with the symmetric polarities, i.e., vertically focussing followed by horizontally focussing. This minimizes the beam envelope size through that enclosure. The quadrupole currents were adjusted to minimize the beam spot on SC600. Again the calculated values were obtained by varying the waist positions to achieve a double minimum and the currents are given in Table V. The horizontal and vertical waist positions were found to be 80' and 214' upstream respectively.

Next the horizontal waist was moved further upstream requiring that the PT quadrupoles maintain a horizontal waist at the E-177 target position. This was continued until a divergence of 0.10 mr was obtained at the E-177 target. The vertical waist was left at the position which gave the minimum spot size on SC600 since this is the best that can be done. The resulting calculated currents are given in Table V and the horizontal waist is now 280' upstream from SC600.

III. PT

With this beam entering the PW target area, the PT quadrupoles can produce a horizontal waist of divergence 0.10 mr at the E-177 target position but for a divergence of 0.10 mr the vertical waist must be allowed to move downstream to the position of SC615, i.e. about 90'. Calculated spot sizes in both planes at the target are approximately 3 mm under these conditions and the currents are given in Table V. Also given are the calculated currents required to produce simultaneously a horizontal minimum on SC602 and a vertical minimum on SC615. These minima correspond to horizontal and vertical waists which are 23' and 6' upstream of the respective SWIC's.

Results

The final calculated beam envelopes for the horizontal and vertical planes are shown in Figure 2. The arrows indicate the position of the waists. Also shown in the figure are the experimental SWIC sizes as observed in March and November 1976. The corresponding currents are given in Table V. Both the currents and SWIC sizes show good agreement with the calculated values. The measured beam sizes in both planes at the E-177 target position are approximately 4 mm. Note that changes in the quadrupole currents as indicated in Table IV affect primarily the horizontal plane. Vertical minima should remain at SC600 and within a few feet of SC615. This was verified experimentally by reminimizing the values of QV335 and QV602 after moving the horizontal waists.

Beam emittances in PW can be determined using SC602 and SC616 for the horizontal plane and SC615 and SC616 for the vertical plane assuming that waists in the respective planes are located at SC602 and SC615. For example, the divergence in the vertical plane is given by

$$y_0' = \frac{\sqrt{(y+y_0)(y-y_0)}}{\Delta z}$$

where y is the size on SC616, y_0 is the size on SC615 and Δz is the distance between them. Using the data of Nov. 1976 gives

$$y_0' = 0.14 \text{ mr}.$$

The emittance is then

$$\varepsilon_V = 2 \text{ mm} \times 0.14 \text{ mr} = 0.28 \text{ mm-mr} .$$

Similarly in the horizontal plane

$$x_0' = 0.12 \text{ mr}$$

and

$$\varepsilon_H = 3.5 \text{ mm} \times 0.12 \text{ mr} = 0.42 \text{ mm-mr.}$$

Both these values are larger than the observed emittances in Enclosure H, particularly that in the vertical plane. This unequal growth may be related to the fact the beam is split by electrostatic septa in the vertical plane and may not be a true ellipse. Also contributing to the growth will be any residual ripple in bending magnet currents, particularly that in the West bend and vertical dogleg, as well as multiple scattering in vacuum windows in Enclosure H. However, the requirement of producing a beam in PW at the E-177 target location with a size of ∿4 mm and divergence of ∿0.1 mr has been adequately achieved.

References

1. C.T. Murphy, Fermilab TM-454 (1973).

2. B. Cox, C.T. Murphy and J. Peoples, Fermilab TM-491 (1974).

3. B. Cox and C.T. Murphy, Fermilab TM-492 (1974),
   B. Cox and C.T. Murphy, Fermilab-PUB-76/31-EXP (1976),
   B. Cox and C.T. Murphy, Nucl. Instr. and Methods 136, 35-39 (1976).

4. J. Sandweiss, I.O. Skillicorn and M.S. Webster, Brookhaven National Laboratory Report H-11 (1962), (See also Appendices by M.S. Webster and Hugh N. Brown).

5. K.L. Brown, F. Rothacker, D.C. Carey and Ch. Iselin, Fermilab Report NAL-91 (1974).

TABLE I

Proton West Beam Line Elements

≠E-177 BEAM

	0					
	(FIRST TRY-NO DIPOLES)					
	15.		8.00000	≠IN ≠	.02540 ;	
	13.		3.00000;			
	1.000000		.30000	.03500	.60000	.02000
	(START AT 3-WAY SPLIT)					
	3.0	≠S320≠	230.80000;			
	3.0	≠S321≠	2380.80000;			
	3.0	≠H--A≠	8358.80000;			
	3.0	≠S331≠	174.60000;			
	3.0		9.00000;			
	5.0A	≠H331≠	120.00000	6.00000	3.81000;	
	3.0		15.20000;			
	5.0A	≠H331≠	60.00000	6.00000	3.81000;	
	3.0		69.30000;			
	3.0	≠TRIM≠	40.00000;			
	3.0		14.30000;			
PW-A	5.0B	≠V331≠	120.00000	-5.00000	3.81000;	
	3.0		11.20000;			
	5.0B	≠V331≠	120.00000	-5.00000	3.81000;	
	3.0		12.00000;			
	3.0	≠BEND≠	120.00000;			
	3.0		26.40000;			
	3.0	≠A--B≠	2379.20000;			
	3.0	≠A--B≠	74.00000;			
	(HORIZONTAL WAIST)					
	10.0	≠F1 ≠	2.00000	1.00000	0.00000	.00010;
	3.0	≠A--B≠	26.00000;			
	3.0	≠S334≠	249.00000;			
	(VERTICAL WAIST)					
	10.0	≠F2 ≠	4.00000	3.00000	0.00000	.00010;
	3.0		117.00000;			
	3.0	≠BEND≠	120.00000;			
PW-B	3.0		12.00000;			
	3.0	≠BEND≠	120.00000;			
	3.0		30.00000;			
	3.0	≠B--C≠	1758.00000;			
	3.0	≠S335≠	166.40000;			
	3.0		16.00000;			
	3.0	≠BEND≠	120.00000;			
	3.0		12.00000;			
	5.0C	≠V335≠	120.00000	-5.50000	3.81000;	
	3.0		12.40000;			
	5.0C	≠V335≠	120.00000	-5.50000	3.81000;	
	3.0		11.30000;			
PW-C	3.0	≠TRIM≠	40.00000;			
	3.0		71.50000;			
	5.0D	≠H336≠	60.00000	6.50000	3.81000;	
	3.0		14.80000;			
	5.0D	≠H336≠	120.00000	6.50000	3.81000;	
	3.0		27.60000;			
	3.0	≠C-W1≠	1000.00000;			
	3.0	≠C-W2≠	1000.00000;			
	3.0	≠C-W3≠	1000.00000;			
	3.0	≠C-W4≠	1000.00000;			
	3.0	≠C-W5≠	1000.00000;			
	3.0	≠C-W6≠	800.00000;			
	(HORIZONTAL WAIST)					
	10.0	≠F3 ≠	2.00000	1.00000	0.00000	.00010;

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 3.0                       12.00000;
 3.0          ≠BEND≠      120.00000;
 3.0                       30.00000;
 3.0          ≠B--C≠     1758.00000;
 3.0          ≠S335≠      166.40000;
 3.0                       16.00000;
 3.0          ≠BEND≠      120.00000;
 3.0                       12.00000;
 5.0C         ≠V335≠      120.00000     -5.50000     3.81000;
 3.0                       12.40000;
 5.0C         ≠V335≠      120.00000     -5.50000     3.81000;
 3.0                       11.30000;
 3.0          ≠TRIM≠       40.00000;      (PW-C)
 3.0                       71.50000;
 5.0D         ≠H336≠       60.00000      6.50000     3.81000;
 3.0                       14.80000;
 5.0D         ≠H336≠      120.00000      6.50000     3.81000;
 3.0                       27.60000;
 3.0          ≠C-W1≠     1000.00000;
 3.0          ≠C-W2≠     1000.00000;
 3.0          ≠C-W3≠     1000.00000;
 3.0          ≠C-W4≠     1000.00000;
 3.0          ≠C-W5≠     1000.00000;
 3.0          ≠C-W6≠      800.00000;
    (HORIZONTAL WAIST)
10.0          ≠F3  ≠        2.00000      1.00000     0.00000     .00010;
 3.0          ≠C-W6≠      200.00000;
 3.0          ≠C-W7≠      600.00000;
    (VERTICAL WAIST  )
10.0          ≠F4  ≠        4.00000      3.00000     0.00000     .00010;
 3.0          ≠C-W7≠      400.00000;
 3.0          ≠C-W8≠     1000.00000;
 3.0          ≠C-W9≠     1164.40000;
 3.0          ≠S600≠       31.00000;
 3.0                       10.00000;
 5.0E         ≠H600≠      120.00000      7.50000     5.08000;
 3.0                       21.50000;
 5.0E         ≠H600≠      120.00000      7.50000     5.08000;
 3.0                      128.50000;
 5.0F         ≠V602≠      120.00000     -8.50000     5.08000;
 3.0                       22.00000;
 5.0F         ≠V602≠      120.00000     -8.50000     5.08000;
 3.0          ≠E-95≠      814.50000;      (PW)
 3.0          ≠S602≠      535.00000;
 3.0          ≠E177≠      161.00000;
    (HORIZONTAL WAIST)
10.0          ≠F5  ≠        2.00000      1.00000     0.00000     .00010;
 3.0          ≠S615≠     1079.00000;
    (VERTICAL WAIST  )
10.0          ≠F6  ≠        4.00000      3.00000     0.00000     .00010;
 3.0          ≠S616≠     1644.00000;
    (END AT DUMP )
SENTINEL
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TABLE I (Continued)

TABLE II

Proton West Quadrupoles

Location	Name	Type	Constant (kg/in)/A	Correction (ST or RB)/A
PW-A	QH331 QV331	3"	0.052	0.96
PW-C	QV335 QH336	3"	0.052	0.96
PW or PT	QH600 QV602	4"	0.0054	1/0.92

TABLE III

Beam Alignment Procedure

	Adjust	to center (plane)	SWIC	Position (wires)	Comment
1.	H320WH	H	SC321W	0	Vertical must be centered by crew chief.
2.	H321AH	H	SC331W	0	
3.	TV321H	V	SC331W	0	
4.	TH331H	H	SC335W	0	No adjustment for SC334W.
5.	TV331H	V	SC335W	0	Repeat until both are correct. (steps 5–6)
6.	BV331H	V	SC334W	-6	
7.	TH336H	H	SC600	$-9^{(1)}$	Check SC616 and if not centered repeat by varying values on SC600. (steps 7–10)
8.	TV335H	V	SC600	$+3^{(1)}$	
9.	ST603H	H	SC602	$+3^{(2)}$	
10.	ST604H	V	SC602	$0^{(2)}$	

Notes: (1) These are the nominal values required.

(2) These values are obtained by varying ST603H and ST604H for minimum counting rate in the scattered particle spectrometer.

TABLE IV

Suggested Beam Tuning Procedure

1. Set all beam transport elements at their nominal values. Align beam as per procedure in TABLE III. Close PW-A collimators such that apertures are twice FWHM of beam size as measured on SC331W. Leave other collimators open.

2. Vary PW-A quads for minimum spot on SC334W.

3. Vary PW-C quads for minimum spot on SC600. Start with values of 57.7 and 69.1.

4. Move horizontal waist upstream by increasing experimentally obtained values for PW-C quads by 2.66% and 5.83%.

5. Vary PT quads for minimum spot horizontally on SC602 and vertically on SC615. Start with values of 692. and 672.

6. Move waists downstream by decreasing experimentally obtained values for PT quads by 7.69% and 4.53%.

7. Re-align beam and adjust PW-B and PW-C collimators for minimum halo.

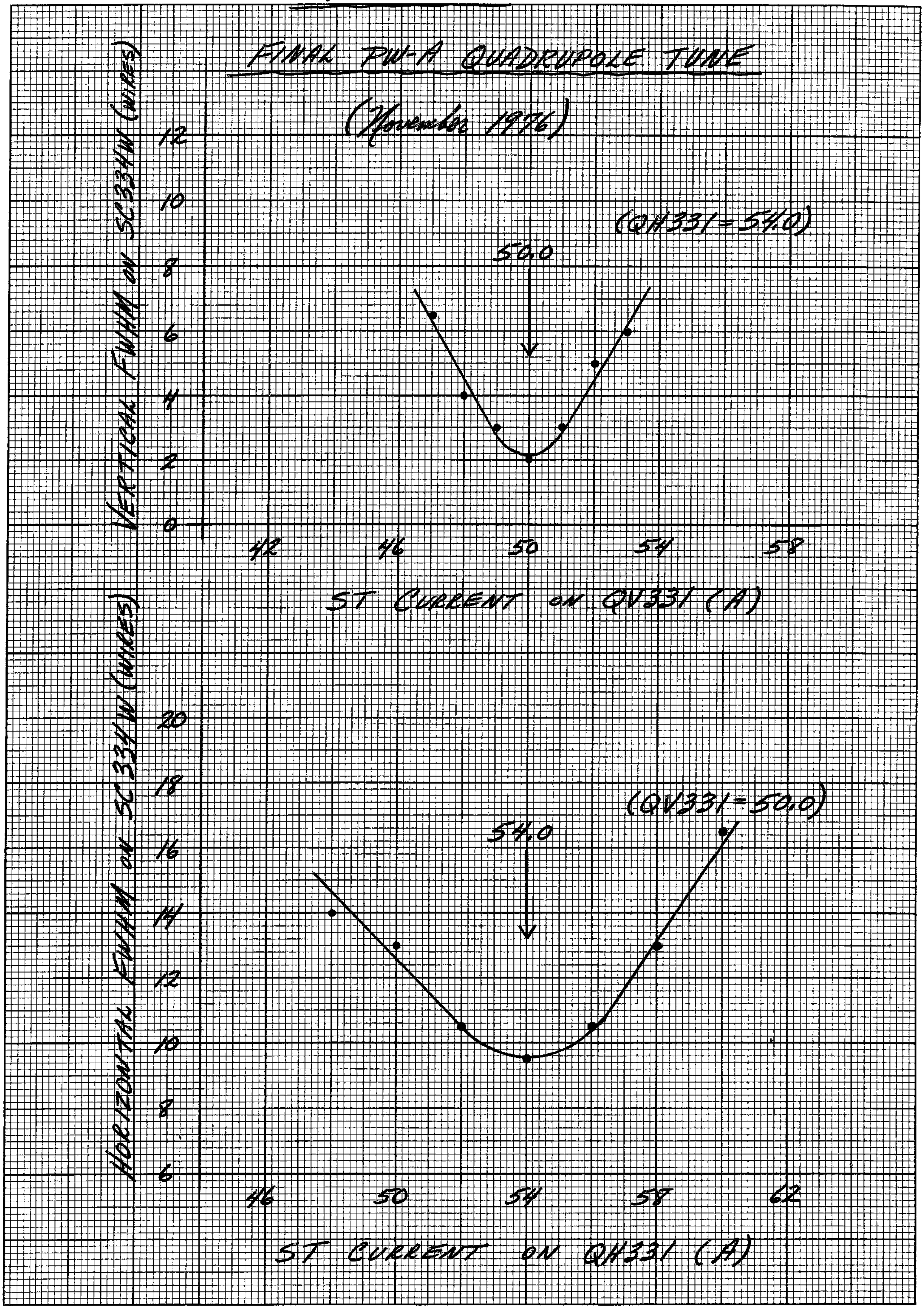
TABLE V

Calculated and Measured ST or RB values (nominal amperes)

Quadrupoles	Condition	Calculated	March 1976	Nov 1976
QH331	Minimum size at SC334W.	61.5	61.2	54.0*
QV331		50.7	52.0	50.0
QH331	Parallel to point.	56.7		
QV331		47.6		
QV335	Minimum size at SC600.	57.7		
QH336		69.1		
QV335	Horizontal waist moved upstream.	59.2	58.4	59.5
QH336		73.2	72.8	72.5
QH600	Horizontal minimum at SC602.	692.		
QV602	Vertical minimum at SC615.	672.		
QH600	Horizontal waist at E-177.	639.	625.	637.
QV602	Vertical waist at SC615.	641.	609.	640.
Beam Intensity per Pulse			1×10^{11}	4×10^{11}

* This is the measured value when MQ310=70.0, which is required to run P-East at high intensity ($\sim 5 \times 10^{12}$). With MQ310 at its normal value of 72.0, the required setting was determined to be 62.0.

FIGURE 1


FINAL PW-A QUADRUPOLE TUNE
(November 1976)
VERTICAL FWHM ON SC334W (WIRES)
12
10
8
6
4
2
0
(QH331=54.0)
50.0
42
46
50
54
58
ST CURRENT ON QV331 (A)
HORIZONTAL FWHM ON SC334W (WIRES)
20
18
16
14
12
10
8
6
(QV331=50.0)
54.0
46
50
54
58
62
ST CURRENT ON QH331 (A)

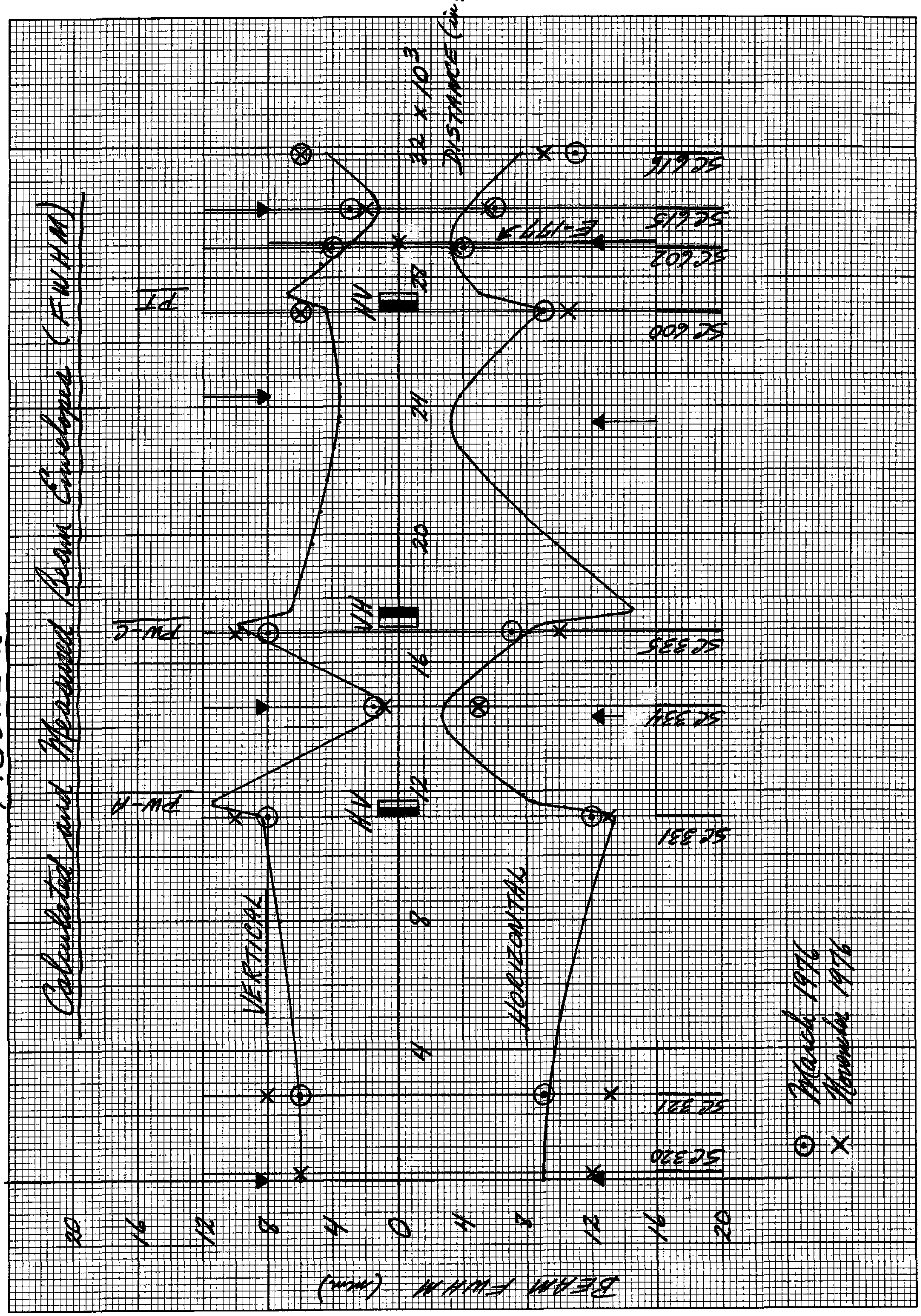


FIGURE 2

Calculated and Measured Beam Envelopes (FWHM)