SPEAR-3
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STORAGE RING TRANSPORT SYSTEM

Introduction

The SPEAR rings are to be constructed in the north research area, at the end of the BSY (beam switchyard). We need an independent transport system to bring electrons and positrons from the collimators (C-0) at the entrance of the BSY to the SPEAR inflection points. The path goes along the existing A beam line, bending 24° from the accelerator center line, then bends another 24° to leave the BSY through the A" port. Outside the BSY wall, the single beam line splits, one line for injection into each ring. The angle between the single line emerging from the BSY and each injection line is 24°, the inflection angle into the ring is 7°. (Fig. 1.) The injection energy is 1.5 GeV, the total length of the beam from C-0 to injection is 400 meters.

A system using quadrupole doublets, singlets and zero-gradient bend magnets, reversing slowly in the single line is used. The transport system is only useful for one polarity of particles at a time and electron and positron operation must be separated in time by approximately one minute.

System Boundary Values

The vertical and horizontal phase-space admittance of the SPEAR lattice at injection[1] is an erect ellipse ± 1 mm. by ± 1.5 mrad. The momentum acceptance of the rings is ± 0.5%. The momentum bite of the transport system must be variable, with a resolution of 20% of total width, $\delta P/P = 0.1\%$. It is not necessary that the phase ellipse at injection be erect, or that the beam be completely achromatic as long as it fits in the ring admittance.

The full phase-space emittance area of the accelerator is assumed[2] to be 0.067π mr. cm in each plane. The size of the beam at C-0 is assumed to be

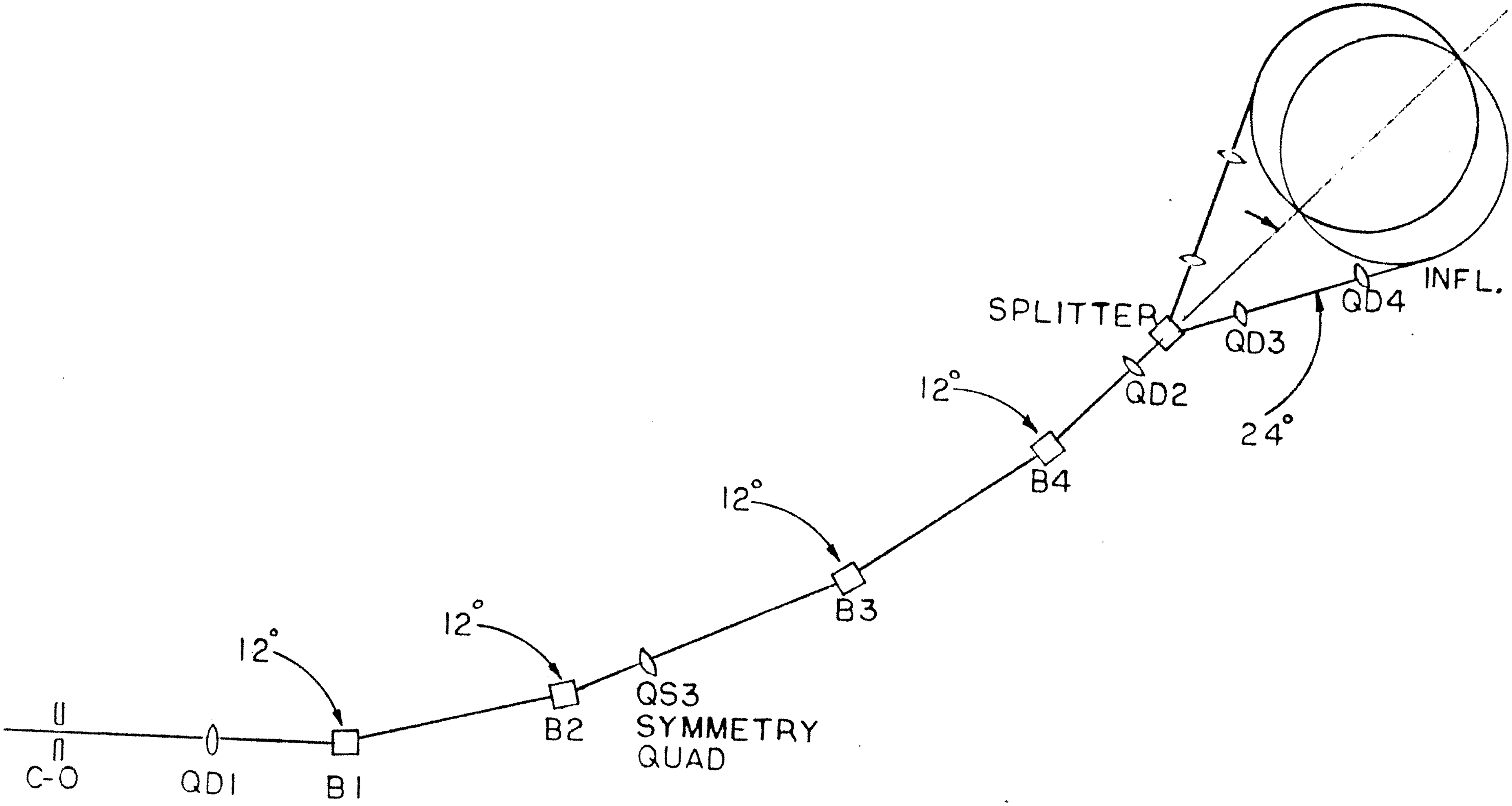

FIG. 1

BEAM LINE LAYOUT

± 5 mm, this being an everyday value for BSY operation. We put in a safety factor of 2 and assume, for design phase space, an erect ellipse ± 5 mm by ± 0.267 mr. This area matches the acceptance area of the rings.

The placement of bending magnets in the BSY is dictated by space available in the existing housing. The positions of the first two 12° bends are especially restricted because of A-beam equipment in the tunnel: the second pair of 12° bends are in a less-crowded area.

The location of the splitter vertex is dictated by real estate constraints. The intersection of the two injection lines, projected from the septum magnets, defines the splitter point. The beam line is defined by geometric constraints. The beam optics does not involve displacement of any of the bending points. Since all magnets are to be specially fabricated for this beam line, no element diameters are "given".

Design and Optimization

General

All optimization and testing in this design were done with the computer program TRANSPORT.[3]

We use radius = 3.5 cm as a beam-size limit in quadrupoles with one exception. Bending magnet apertures are kept as small as possible.

Design in the BSY (Fig. 2)

The BSY optics are similar to Karl Brown's original BSY optics.[4] There is a doublet (QD1/15Q1 and 2) outside the main bending system, imaging C-O horizontally and vertically on the single symmetry quad (QS1/15Q3). In order to keep the beam small in the bending magnets, the best location for the first doublet is half-way between C-O and the symmetry quad. The practical location is beside the existing BSY doublet Q10/Q11, 103 meters downstream of C-O. To

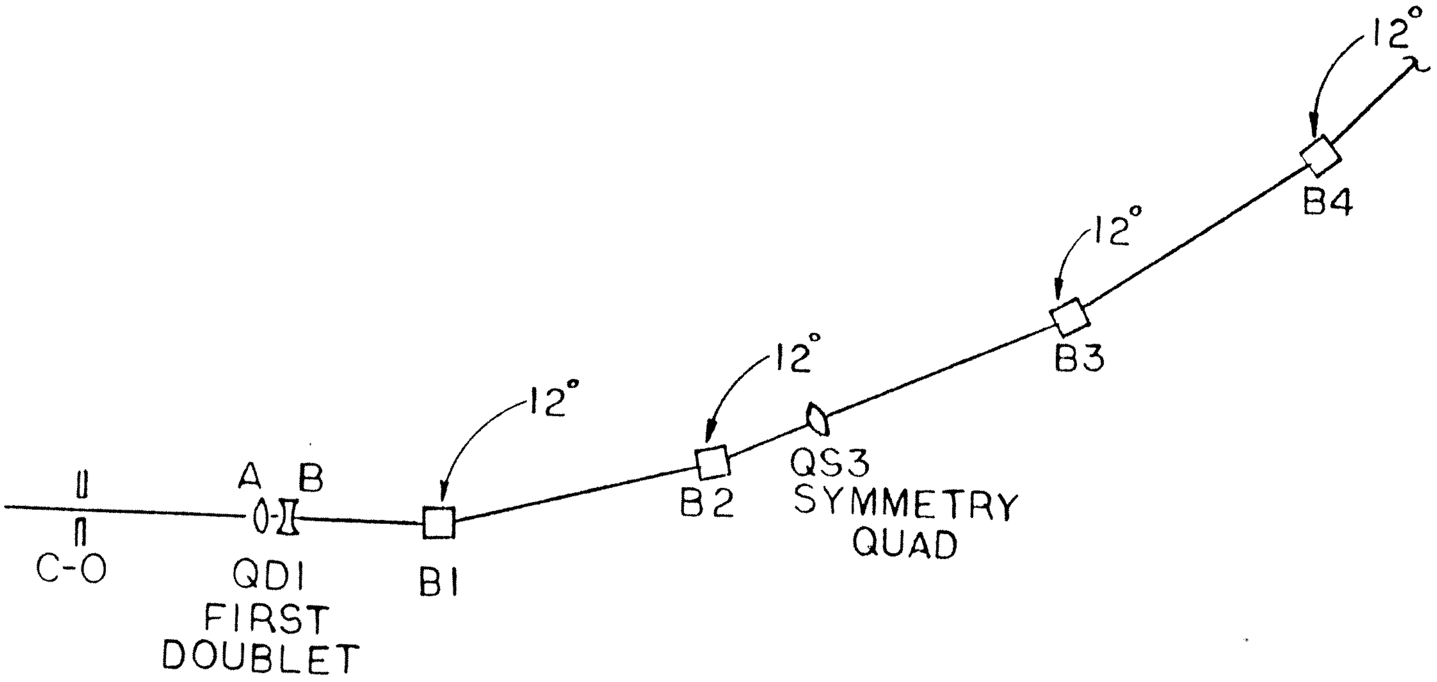

FIG. 2

BSY TRANSPORT SYSTEM

optimize this system, the following parameters are varied: (See Appendix.)

C-0 → End of BSY

FIT 1

(1) Gradient of QD1A

(2) Gradient of QD1B

(3) Position of QS3

(4) Strength of QS3

To fit the following constraints

Notation per SLAC-75

(1) Horizontal focus at face of QS1 $< x/\theta > = 0$

(2) Vertical focus at face of QS1 $< y/\varphi > = 0$

(3) Zero position dispersion at exit of bend system $< x/\delta > = 0$

(4) Zero angle dispersion at exit of bend system $< \theta/\delta > = 0$

The fringe-field focussing effects of the bending magnets are of the same order as the strengths of the lenses, and must be carefully calculated. The bending magnet effective length of 1 meter is constrained by edge focussing: if the length of the magnets is 0.5 meter, the edge focussing is so strong that the BSY system in its present form does not work.

The beam half-width at the symmetry quad QS1 is 9.5 cm. This is a large quadrupole aperture, but the low field requirement, 44 gauss/cm makes it practical to use an inexpensive current-sheet "Panofsky" quad. A system with more lenses would have a smaller beam size, but be more complex and expensive.

Splitter-to-Injection System

This beam is better considered backwards, from injection to the splitter. I shall discuss the injection point, at the end of the septum, as the beam origin, and the injection phase-space target as the initial beam. The problem now reduces to making the system achromatic to the end of the splitter, and keeping the beam size within aperture constraints.

Symmetry is not necessary for an achromatic bend system.

In an asymmetric achromatic bending system with two bends, α_1 and α_2 considering the horizontal transform matrix from α_1 vertex to α_2 vertex,

$< x/\theta > = 0$ point-to-point focus

$< \theta/\theta > = \frac{\alpha_2}{\alpha_1}$ angular magnification

In the ring-splitter beam, (Fig. 3) the distance between vertices is 83 meters and the angles are 7° and 24°. A system with only one lens in the horizontal plane would make the beam too large. I use two doublets, as far as possible from the bends to minimize their strengths. The beam between the lenses is approximately parallel in both planes.

The distance from the septum to the first doublet is set at 13 meters. The following parameters are varied (see Appendix).

(1) Gradient of QD4A

(2) Gradient of QD4B

Septum → Splitter
Fit 2

To fit the following constraints

(1) Point to parallel vertically $\langle \phi / \phi \rangle = 0$

(2) Zero angular dispersion horizontally $\langle \theta / \delta \rangle = 0$

The second constraint has almost the same effect as $< \theta/\theta > = 0$. To make this system more astigmatic and minimize quad gradients, the two doublets should be arranged DFOFD or FDODF*. To complete fitting of this sub-system, the following parameters are varied, plugging in the results from the last fitting (see Appendix);

(1) Gradient of QD3A

(2) Gradient of QD3B

(3) QD3 to splitter distance

Septum → Splitter
Fit 3

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*D is defocussing
F is focussing
0 is drift distance

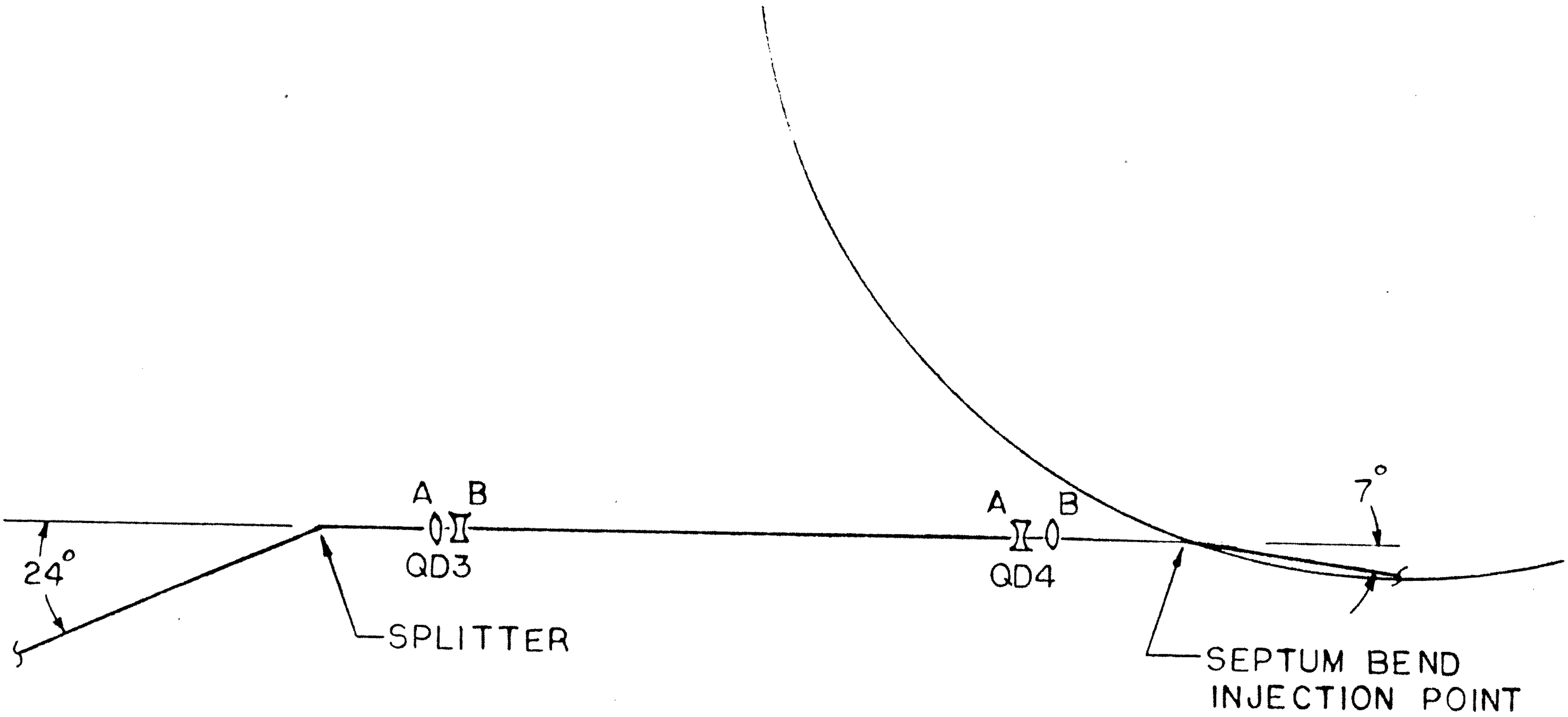

FIG. 3

SPLITTER TO RING SYSTEM

to fit the following constraints

(1) Zero horizontal position dispersion $< x/\delta > = 0$

(2) Zero horizontal angle dispersion $< \theta/\delta > = 0$

(3) Vertical focus at splitter vertex $< y/\varphi > = 0$

The third constraint is not critical at this stage and is set at the splitter vertex for symmetry with the horizontal plane. Three magnets comprise the splitter, one actual splitter and two post-splitters.

Phase-space Matching at the Splitter

General

The problem remaining is to match the BSY system to the splitter to ring system. The beam at the exit of the last bending magnet in the BSY has small divergence, approximately 0.3 mrad in both planes. The calculated angular admittance* at the splitter is approximately 4.5 mrad in both planes. We needed a strong lens multiplet to change beam divergence, and this needs to be close to the splitter. Phase-space matching theory shows that we need four independent variables to match a 4-emittance** to a 4-admittance. Since the principal planes of a doublet in orthogonal planes are not independent, a single doublet generally cannot fit a 4-emittance to a 4-admittance. In this case, the emittance and admittance are not fixed, but variable.

In the BSY system, a perfect horizontal focus at the symmetry quad is not necessary to stay within momentum resolution tolerance. The strong vertical focussing effect of bending magnet edges makes a vertical waist in the symmetry quad unnecessary also. We may adjust the beam size or divergence at the exit

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*The reasoning in this design is partially forward and partially backward. References to the ring to splitter beam are mixed with references to the splitter-to-ring admittance. The order of the component reference, splitter, ring or other, determines which direction one is looking, and whether admittance or emittance is appropriate.

**Four-dimensional emittance and admittance.

of the BSY system with the first doublet. Adjustments in the admittance of the splitter-to-ring system may be made by moving the doublets with respect to the bends or by other means, but the most fruitful adjustment is the location of the vertical image of the injection point in the splitter region. A good phase match needs intuitive fiddling as much as calculation and analysis.

Detailed Phase Match

The beam emergent from the BSY system, when allowed to drift (calculationally) to the splitter location has a size stigmatism of approximately 2.5: 1, horizontal: vertical. This is due to bending magnet edge focussing. The admittance of the splitter-to-ring system at the splitter is almost horizontal/vertical symmetric. A quad doublet strong enough to make the necessary angle charges for matching is stigmatic, and this stigmatism helps to match the two systems (Fig. 4). A splitter-doublet distance is fixed empirically at 2.1 meter. In order for us to have values at the upstream face of the phase match doublet (QD2/15Q4 and 5) for the BSY beam to match into, the ring-to-splitter beam must "look" further into the BSY system. Fitting a vertical and horizontal focus from the injection point to the symmetry quad in the BSY with QD2 gives a good approximation to what matched system should be. Using the numbers from successful fits 2 and 3, the following parameters are varied:

Septum → Symmetry
Fit 4

(1) Gradient of QD2A

(2) Gradient of QD2B

to fit the following constraints

(1) Horizontal focus at face of QS1 $< x/\theta > = 0$

(2) Vertical focus at face of QS1 $< y/\varphi > = 0$

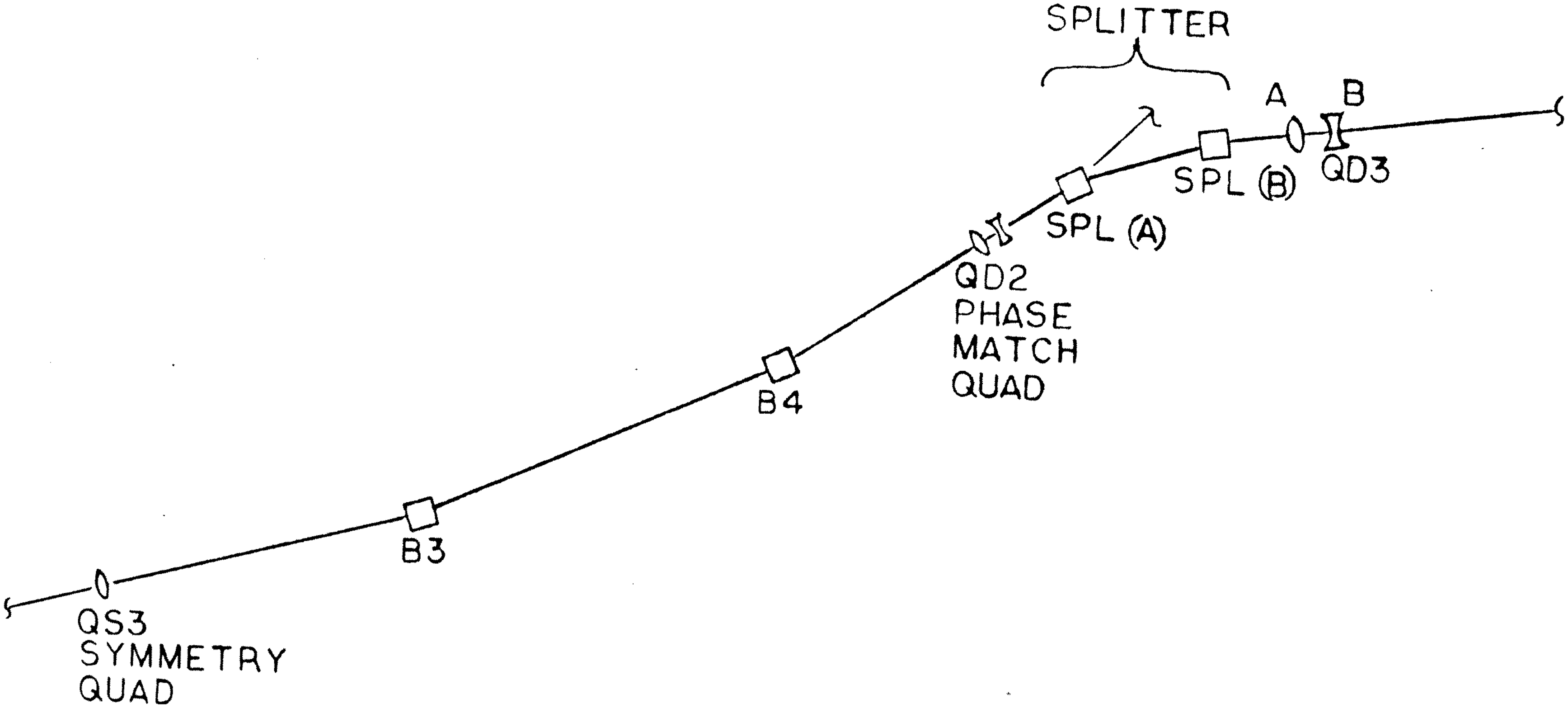


FIG. 4
PHASE MATCHING SYSTEM

The numbers to be taken from this fitting are the beam size parameters x, θ, y, φ at the upstream (from BSY) face of QD2A. The beam should be close to full aperture horizontally in QD2A. The divergence angles of the ring-to-splitter beam at the face of QD2A in Fit 3 should be within 10% of the divergence angles of the BSY beam at the same location. If this is not so, the vertical focus point of the ring-to-splitter beam needs to be moved in Fit 3. Fit 4 must also be repeated. TRANSPORT cannot directly optimize these parameters nor the QD2 to splitter distance.

The BSY beam is now adjusted to a 2-parameter size match at the face of QD2A while maintaining achromaticity.

The following parameters are varied

(1) Gradient of QD1A

(2) Gradient of QD1B

(3) Gradient of QS1

(4) Position of QS1

C-0 → End of BSY

Fit 5

To fit the following constraints

(1) Horizontal divergence at face of QD2A $\sigma(2, 2) = \theta$

(2) Vertical divergence at face of QD2A $\sigma(4, 4) = \varphi$

From Fit 4

(3) Zero position dispersion at end of BSY bend system $(x/\delta) = 0$

(4) Zero angle dispersion at end of BSY bend system $(\theta/\delta) = 0$

The final step images C-0 on the injection point with QD2.

The following parameters are varied:

(1) Gradient of QD2A

(2) Gradient of QD2B

C-0 → Septum

<u>Fit 6</u>

To fit the following constraints

(1) Horizontal focus at injection $(x/\theta) = 0$

(2) Vertical focus at injection $(y/\varphi) = 0$

The QD2 to splitter distance and the vertical image position of the injection point may need to be changed and fit steps 3-6 repeated to realize a good beam.

Undetermined Parameters

The most important unknown parameter in this design is the strength of the bend magnet edge focussing. A typical value has been assumed, but we await measurements on the actual magnets before this parameter is known well. The design in its present form can deal with any foreseeable value of fringe field.

REFERENCES

1. SPEAR Design Report, August 1969.

2. Dr. R. Miller, private communication.

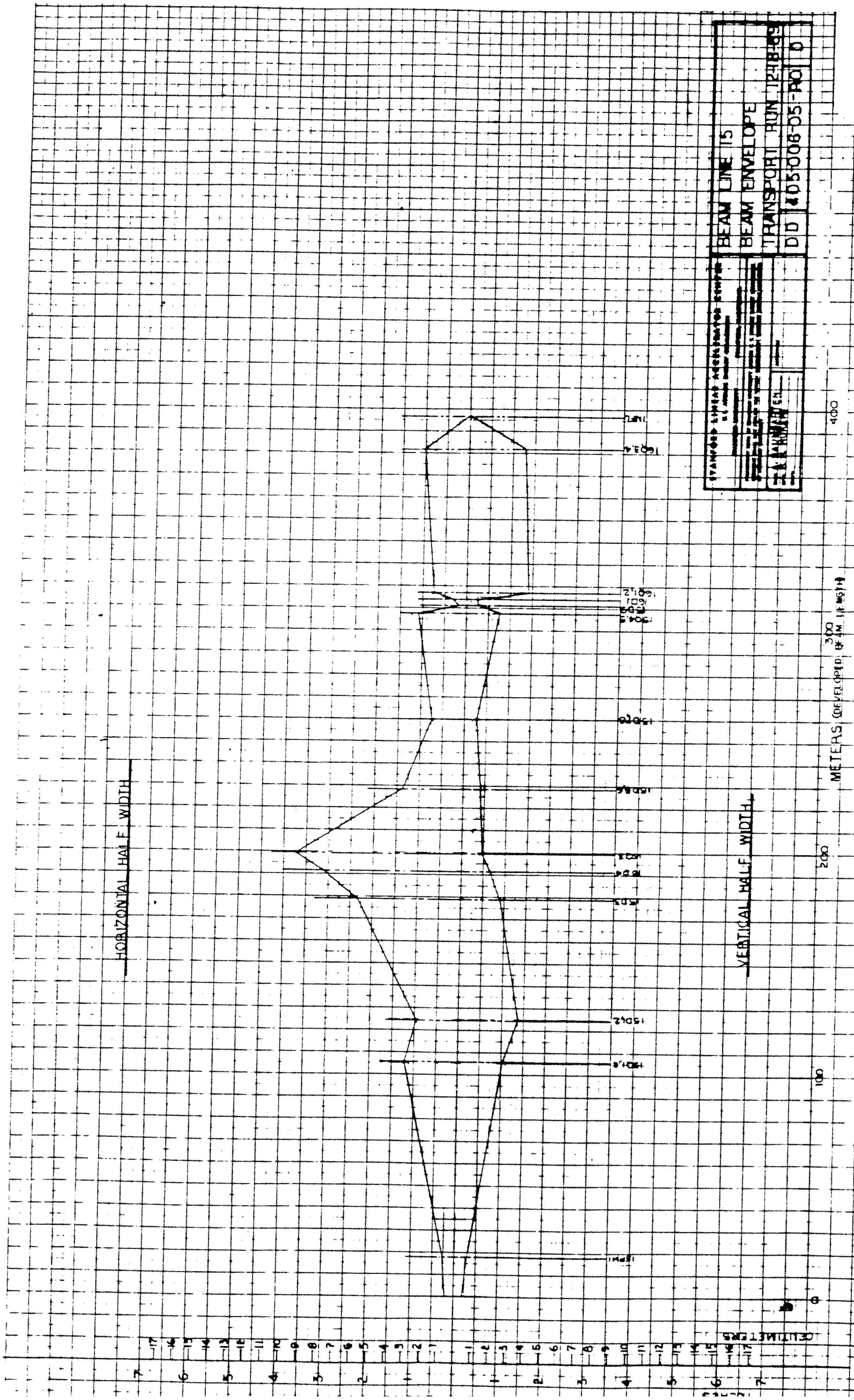
3. Transport/360 manual.

4. The STANFORD TWO-MILE ACCELERATOR - R. B. Neal pp 589 - 599.

APPENDIX

The appendix contains the six TRANSPORT fitting routines referred to in the text, plus a beam profile drawing.

The TRANSPORT output of the final beam is contained at present (April 1970) in SPEAR-22.


STANFORD LINEAR ACCELERATOR CENTER
BEAM LINE 15
BEAM ENVELOPE
TRANSPORT RUN 12-18-69
DD 405-008-05-R0 0
HORIZONTAL HALF WIDTH
VERTICAL HALF WIDTH
METERS (DEVELOPED)
0
100
200
300
400
CENTIMETERS

```
'FIT 1'

0

1.  .5 .267 .5 .267 0.0 .5 1.5 ;

16. 5. 3.81 'FRIN' ;

3. 16.894 ;

6. 0. 2. ;

2. .076 ;

4.  1. 0.13361 0. 'PB' ;

2. .076 ;

3. 86.344  ;

5.01 .5 -.8490  10. 'QD1A' ;

3. .5  ;

5.01 .5 .9888 10. 'QD1B' ;

3. 16.689 ;

2. 3.021197 ;

4. 1. 5.27815 0. 'B1A'  ;

2. 3.021197 ;

2. 3.021197 ;

4. 1. 5.27815 0.   'B1B' ;

2. 3.021197 ;

3.  53.154 'D4' ;

2. 3.021197 ;

4. 1. 5.27815 0. 'B2A' ;

2. 3.021197   ;

3. 11.802 ;

2. 3.021197 ;
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```
4. 1. 5.27815 0. 'B2B' ;
2. 3.021197 ;
3.4 7.3937  'VD1'   ;
10. -1. 2. 0. .1 'FIT1' ;
10. -3. 4. 0. .1 'FIT2' ;
```

$\langle x | \theta \rangle = 0$

$\langle y | \phi \rangle = 0$

```
13. 4. ;
5.01 .5 .4438 10. 'QS3' ;
3.9  28.0652 'VD2'   ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B3A' ;
2. 3.021197   ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B3B' ;
2. 3.021197 ;
3. 29.633  ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B4A' ;
2. 3.021197   ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B4B' ;
2. 3.021197 ;
10. -1. 6. 0. .1 'FIT3' ;
10. -2. 6. 0. .1 'FIT4' ;
```

$\langle x | \delta \rangle = 0$

$\langle \theta | \delta \rangle = 0$

```
13. 4. ;
13. 24. ;
SENTINEL
```

```
'FIT2'
0
13. 2. ;
1. .089 1.5 .089 1.5 0. .5 1.5 'BEAM' ;
2. 3.02119 ;
4. 1. 6.11275 0. 'INFL' ;
2. 3.02119 ;
16. 5. 2.54 'FRIN' ;
3. 13. 'LD2' ;
5.01 .5 3.0589 10. 'QD4B' ;
3. .5 ;
13. 3. ;
5.01 .5 -2.8417 10. 'QD4A' ;
13. 4. ;
10. -4. 4. 0. .1 'FIT1' ;   ⟨φ|φ⟩=0
10. -2. 6. 0. .1 'FIT2' ;   ⟨θ|δ⟩=0
13. 4. ;
SENTINEL
```

```
'FIT3'
0
13. 2. ;
1. .089  1.5 .089 1.5 0. .5 1.5 'BEAM' ;
2. 3.02119 ;
4. 1.  6.11275 0. 'INFL' ;
2. 3.02119 ;
16. 5. 2.54 'FRIN' ;
3. 13.  'LD2' ;
5. .5 3.0589 10. 'QD4B' ;
3. .5 ;
13. 3. ;
5. .5 -2.8417 10. 'QD4A' ;
13. 4. ;
3.9 62.8181  'LD1' ;
5.01 .5 -4.4785 10. 'QD3B' ;
3. .5 ;
5.01 .5 5.3799 10. 'QD3A' ;
3.4 3.1348  'LDS' ;
2. 6.19 ;
4. .75 14.41701 0. 'SPLA' ;
2. 6.19 ;
3. .5 ;
10. -3. 4. 0. .1 'FIT3' ;
```

$\langle y|\phi\rangle = 0$

```
3. 1.3 'BETW' ;
```

```
2. 12.3822 ;
4. .75 14.41701 0. 'SPLB' ;
10. -1. 6. 0. .1 'FIT4' ;   ⟨x|δ⟩ = 0
10. -2. 6. 0. .1 'FIT5' ;   ⟨θ|δ⟩ = 0
3. 2.1 'VDB' ;
13. 3. ;
5.01 .5 -9.1993 10. 'QD2B' ;
3. .5 ;
5.01 .5  8.8601 10. 'QD2A' ;
3.  45.9  'VDA' ;
13. 2. ;
16. 5. 3.81 'FRIN' ;
2. 3.02119 ;
4. 1. 5.27815 0. 'B4B' ;
2. 3.02119 ;
2. 3.02119   ;
4. 1. 5.27815 0. 'B4A' ;
2. 3.02119 ;
3. 29.633  ;
2. 3.02119 ;
4. 1. 5.27815 0. 'B3B' ;
2. 3.02119 ;
2. 3.02119   ;
4. 1. 5.27815 0. 'B3A' ;
2. 3.02119 ;
3.  28.0781 'VD2'  ;
5. .5 .4441 10. 'QS3A' ;
13. 4. ;
SENTINEL
```

```
'FIT4'
0
13. 2. ;
1. .089  1.5 .089 1.5 0. .5 1.5 'BEAM' ;
2. 3.02119 ;
4. 1.  6.11275 0. 'INFL' ;
2. 3.02119 ;
16. 5. 2.54 'FRIN' ;
3. 13.  'LD2' ;
5. .5 3.0589 10. 'QD4B' ;
3. .5 ;
13. 3. ;
5. .5 -2.8417 10. 'QD4A' ;
13. 4. ;
3. 62.8181  'LD1' ;
5. .5 -4.4785 10. 'QD3B' ;
3. .5 ;
5. .5 5.3799 10. 'QD3A' ;
3. 3.1348  'LDS' ;
2. 6.19 ;
4. .75 14.41701 0. 'SPLA' ;
2. 6.19 ;
3. .5 ;
3. 1.3 'BETW' ;
2. 12.3822 ;
4. .75 14.41701 0. 'SPLB' ;
3. 2.1 'VDB' ;
13. 3. ;
5.01 .5 -9.1993 10. 'QD2B' ;
3. .5 ;
```

```
5.01 .5  8.8601 10. 'QD2A' ;
3.  45.9  'VDA' ;
13. 2. ;
16. 5. 3.81 'FRIN' ;
2. 3.02119 ;
4. 1. 5.27815 0. 'B4B' ;
2. 3.02119 ;
2. 3.02119   ;
4. 1. 5.27815 0. 'B4A' ;
2. 3.02119 ;
3. 29.633  ;
2. 3.02119 ;
4. 1. 5.27815 0. 'B3B' ;
2. 3.02119 ;
2. 3.02119   ;
4. 1. 5.27815 0. 'B3A' ;
2. 3.02119 ;
3.  28.0781 'VD2'  ;
5. .5 .4441 10. 'QS3A' ;
10. -1. 2. 0. .1 'FIT1' ; <x|θ>=0
10. -3. 4. 0. .1 'FIT2' ;<y|φ=0>
13. 4. ;
SENTINEL
```

```
'FIT 5 AND FIT 6 COMBINED'
0
1.  .5 .267 .5 .267 0.0 .5 1.5 ;
16. 5. 3.81 'FRIN' ;
3. 16.894 ;
6. 0. 2. ;
2. .076 ;
4.  1. 0.13361 0. 'PB' ;
2. .076 ;
3. 86.344  ;
5.01 .5 -.8398  10. 'QD1A' ;
3. .5  ;
5.01 .5 .9755 10. 'QD1B' ;
3. 16.689 ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B1A'  ;
2. 3.021197 ;
2. 3.021197 ;
4. 1. 5.27815 0.   'B1B' ;
2. 3.021197 ;
3.  53.154 'D4' ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B2A' ;
2. 3.021197   ;
3. 11.802 ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B2B' ;
2. 3.021197 ;
3.9 7.3781  'VD1'   ;
13. 4. ;
5.01 .5 .4441 10. 'QS3' ;
```

```
2. 3.021197 ;
4. 1. 5.27815 0. 'B3A' ;
2. 3.021197    ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B3B' ;
2. 3.021197 ;
3. 29.633  ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B4A' ;
2. 3.021197    ;
2. 3.021197 ;
4. 1. 5.27815 0. 'B4B' ;
2. 3.021197 ;
10. -1. 6. 0. .1 'FIT3' ; ⟨x|δ⟩=0
10. -2. 6. 0. .1 'FIT4' ;⟨θ|δ⟩=0
13. 4. ;
13. 24. ;
3.  45.9  'VDA' ;
10. 2. 2. .282 .05 'FIT1' ; σ(2,2) = θ
10. 4. 4. .289 .05 'FIT2' ;σ(4,4) = φ
5.0 .5 4.8341 10. 'QD2A' ;
3. .5  ;
5.0 .5  -5.6782 10. 'QD2B' ;
3. 2.1 'VDB' ;
16. 5. 2.54 'FRIN' ;
2. 0. ;
4. .75 14.41701 0. 'SPLB' ;
2. 12.3822 ;
13. 4. ;
3. 1.880 'BETW' ;
2. 6.19 ;
```

```
4. .75 14.41701 0. 'SPLA' ;
2. 6.19 ;
3. 2.5716  'LDS' ;
5. .5 5.8490 10. 'QD3A' ;
3. .5 ;
5. .5 -4.8072 10. 'QD38' ;
3. 63.3812 'LD1' ;
5. .5 -2.8417 10. 'QD4A' ;
3. .5 ;
5. .5 3.05890 10. 'QD4B' ;
3. 13.  'LD2' ;
2. 3.0211975 ;
13. 3. ;
4. 1.  6.11275 0. 'INFL' ;
2. 3.0211975 ;
-10. -1. 2. 0. .1 'FIT5' ;  ⟨x|θ⟩ = 0
-10. -3. 4. 0. .1 'FIT6' ;  ⟨y|φ⟩ = 0
13. 4. ;
13. 24. ;
SENTINEL
```

```
'FINAL FIT WITH DOUB 2'
1
5. 'QD1A' ;
5. 'QD1B' ;
3. 'VD1' ;
3. 'VD2' ;
5. 'QS3' ;
-10. 'FIT1' ;
-10. 'FIT2' ;
-10. 'FIT3' ;
-10. 'FIT4' ;
10. 'FIT5' ;
10. 'FIT6' ;
5.01 'QD2A' ;
5.01 'QD2B' ;
SENTINEL
```