The design of the 3-way split has a long history and many participants. The original concept, including a sketch of a 3-way splitting magnet, was published by Andrews et. al. Proton Department work on a detailed design involved two steps: first, the design of a three-way splitting magnet with a 2 3/4" plate separating the East and West channels which left the rest of the geometry of Enclosure "H" intact and the design of new vertical bending magnets with a 5" good field region so as to accommodate the three beams; secondly, an attempt simultaneously to upgrade the West line in Enclosure "H" to 500 GeV and to minimize the thickness of the center plate.

The final 500 GeV system requires construction of four identical 3-way splitting magnets with a 2 1/8" plate separating the East and West channels (and one spare), six wide-gap modified B1 magnets for the vertical bends (and one spare), the addition of two EPB dipoles (one in the West line, and one in the East), a horizontal trim at the end of Enclosure "E" to achieve a Westward displacement of the Enclosure "H" lines of 0.3 mr and complete rearrangement of the dipoles in Enclosure "H".
Other Options

Two other options were thoroughly explored and discarded. The first involved building five non-identical 3-way split magnets, each built of the same laminations but with differing offsets of the magnetic channels from the zero-field hole in the center plate. The East-West vertical beam separation would have been $2-5/8"$. The complication of many different assemblies and the fact that spares would have to be assembled on the spur of the moment in case of failure (economic necessity precluding the assembly of five spares) outweighed the reduction of the required electrostatic split. The second option discarded required building three identical 3-way splitting magnets with 3" East-West vertical separation and also three "C" magnets made out of the same laminations with one end cut off. Again, the disadvantage of two styles of magnets and the problems of spares seemed to outweigh the reduction of the required splitting from $3\frac{1}{4}"$ to 3".

Three-Way Splitting Magnet

The dimensions and properties of the 3-way splitting magnet are shown in Table 1. Three factors allowed the reduction of the plate thickness from 2-3/4" to 2-1/8". First, the 3-way bend angle has been reduced from 6 mrad to 5 mrad. Secondly, the coil separation has been narrowed with subsequent shrinkage of the good-field region. However, careful attention has been paid to the question of what is a tolerable field deviation by concentrating on the average $dB/B$ (averaged over the curved trajectory through a four-magnet string) and calculating the effects of the deviation on a phase space boundary. Figure 1 shows
the average dB/B as a function of horizontal position for three vertical positions in the magnet string. Figure 2 shows the distortion of a large horizontal beam ellipse ($e_H = 0.5 \pi \text{ mm} -\text{mr}$) caused by the worst plane in the magnet, $y = 1.125''$ (near the top pole piece) where there are very few protons. The distortion adds less than 10% to the phase space area. Thirdly, the additional EPB dipoles in the East and West legs make up for the reduction in the 3-way bend angle and reduce the current in the West bend to 1640 amps at 500 GeV. Table II lists all the power requirements.

**Rearrangement of Enclosure "H"**

Enclosure "H" is rearranged in the following way. (See Fig. 3 and Table III.) The West line is packed with EPB dipoles from the SWIC at the end of the enclosure back to 200' from the front wall. The East and Center EPB dipole chains are interchanged in their position along the beam; specifically, the four East dipoles lie side by side with the first four West dipoles, leaving a gap of 1.7" for the P-Center beam (steel-to-steel). A special beam pipe for P-Center is needed for about 30' and special hanger bolts are needed for the first East and West EPB dipoles (see Fig. 4).

The extra 0.3 mr bend at the end of Enclosure "E" is necessary in order that the P-West beam leave Enclosure "H" within the aperture of the fixed 12" pipe. The interchange of the East and Center dipoles is then necessary in order to retain the correct positions of the East and Center beams in the 12" pipes at the end of Enclosure "H". With this deflection, the three beams enter Enclosure "H" 3" west of
the center of the 12" pipe from Enclosure "E". The beams leave "H" with the following offsets (from the 12" exit pipes): P-West beam: 2.7" east; P-Center beam: 2.0" west; P-East beam: 2.5" east.

**Electrostatic Septa Required**

Although the magnetic channel of the 3-way splitting magnet is 1.24" high, the field non-uniformity near the top pole piece is considerably worse than at the center plate, so we intend to center the beam in the lower 1-1/8" of the West magnetic channel (and upper 1-1/8" of the East channel), which requires 3\(\frac{1}{2}\)" vertical separation of the East and West beams. The distance from the center of the Lambertsons to the center of the electrostatic septa is 300 meters. The wire-cathode separation is assumed to be 2 cm.

The voltage is assumed to be either 70 kV (present operating limit) or 100 kV (a possible goal of the septum development program). The number of septa necessary for a three-way split must obviously be an even integer. Ignoring this quantization, the required number of septa at the two voltages is as follows:

- 5.1 septa at 100 kV at 500 GeV;
- 4.1 septa at 100 kV at 400 GeV;
- 7.3 septa at 70 kV at 500 GeV;
- 5.8 septa at 70 kV at 400 GeV;

The calculation included an empirical correction factor of 0.88 resulting from beam convergence.

However, if the vertical beam size remains at its present value (18mm full width at base), the required vertical separation of the East and West beams can be reduced to 2.85" with an increase in beam
scraping by about a factor of 2 (the tail is not quite flat). This is the appropriate way to plan to run occasionally at the peak energy of the machine. The septa requirements at 500 GeV become:

- 4.5 septa at 100 kV at 500 GeV;
- 6.4 septa at 70 kV at 500 GeV.

Final choice of the even number of septa necessary will depend on the ultimate machine energy and the results of the septum development program. Rounding off the above numbers suggests that what is needed is either 6 septa at 70 kV or 4 septa at 100 kV.

**Modified Bl Magnets**

The EPB dipoles presently used for the vertical bends have a good field region of 3" in the median plane and 2" at 3/8" off the median plane. In Enclosure "H", a good field region of 4.6" is required to accommodate the three beams. Such a magnet was designed using restamped Bl laminations and booster copper. The properties of the magnet are given in Table IV and the predicted field map in Fig. 5. The magnet has the further virtue that the current at 500 GeV is only 1066A. The vertical bending magnets at the end of Enclosure "E" are also replaced by these modified Bl magnets in order to keep the two vertical bends as a series dogleg.

**Contingency Plans**

This system also allows the following possibilities if unforeseen difficulties arise. Should the emittance in the horizontal plane increase drastically, or should the built magnet have a much worse field non-uniformity than predicted, the 3-way magnets can still move 6.0' upstream, providing another 0.6" separation of
the P-West and P-East beams at the first dipoles. New C-magnets made out of 3-way laminations can be designed instead of adding EPBs. The fourth 3-way magnet can be removed (if the field is too bad to accommodate the bending), C-magnets added, and the three beams can be rotated a bit at the end of "E" (by rotating the electrostatic septa) so as to put the beams into the good-field region of the 3-way magnets. Further clearance between the first East and West EPB dipoles can be gained by milling a 1/2" slot in the steel of the return leg (see Fig. 4).

Beam Monitoring Instrumentation

In the downstream branches, the existing flags and SWICs (one of each in each line) are relocated as shown in Fig. 3. For the upstream end of Enclosure "H", four new SWICs have been designed. Before and after the vertical bending magnets, 6" SWICs (3mm wire spacing) will display simultaneously profiles of the three beams (SWIC 318 and 319 on Fig. 3). Before and after the 3-way splitting magnets, special "triple-SWICs" will display each beam separately. Each element of these triple-SWICs has a sensitive area of 1 1/2" diameter (1/2mm wire spacing). This will allow simultaneous observation of widely differing intensity beams.

Acknowledgements

Stan Snowden initially did all the magnet designing and taught us all the tricks of shimming magnets and using the magnet design program LINDA. Lee Teng, Helen Edwards, Les Oleksiuk and Gene Fisk provided occasional advice and criticism. Ed Tilles and Research Services have carried out the engineering of the magnets.
Reference

3-Way Solit Magnet (1.24x3K120)

MAGNETIC FIELD

CENTRAL FIELD  7.0 kg
GOOD FIELD  2.8" x 1.125"
FIELD QUALITY ±1.15%

POWER:
DC Power  23.3 kw/gap
Current  1100 A/gap
Voltage  21.1 V/gap
Copper Temp. Ave.
Resist @ Temp.  0.0192 Ω/gap
Time Constant  0.28 sec
Inductance  5.3 mH/gap

COOLING:
Water Temp. Rise  11.2° C
Total Flow  2.6 GPM
Pressure  200 psi

COIL DATA:
Conductor O.D.  0.46" x 0.46"
Hole Diameter  0.23"
Turns  16/gap
Water Paths  1/gap
Ave. Turn Length  260"

WEIGHTS: (est.)
Coil & Insul.  445 lb
Core  6250 lb
Support  200 lb
Total Magnet Assembly  6900 lb

CALCULATION CONSTANTS:
\[ B = \frac{\theta}{mr} \]
Table II - Bend Angles, Currents, and Power for Enclosure "H"
3-Way Split at 500 GeV

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Name</th>
<th>No. Magnets</th>
<th>Bend Angle</th>
<th>B</th>
<th>Current</th>
<th>D.C. Power</th>
<th>Power Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Bend</td>
<td>MV320</td>
<td>3</td>
<td>8.568 mr</td>
<td>14.8kG</td>
<td>1066A</td>
<td>600 kW *</td>
<td>2 x 500kW transrex</td>
</tr>
<tr>
<td>East 3-Way</td>
<td>MH320E</td>
<td>4</td>
<td>5.070</td>
<td>6.95</td>
<td>1089</td>
<td>91.1</td>
<td>240kW transrex</td>
</tr>
<tr>
<td>West 3-Way</td>
<td>MH320W</td>
<td>4</td>
<td>5.070</td>
<td>6.95</td>
<td>1089</td>
<td>91.1</td>
<td>240kW transrex</td>
</tr>
<tr>
<td>East EPB dipoles</td>
<td>MH323</td>
<td>4</td>
<td>8.675</td>
<td>11.86</td>
<td>1145</td>
<td>83.9</td>
<td>500kW</td>
</tr>
<tr>
<td>Center EPB dipoles</td>
<td>MH322</td>
<td>2</td>
<td>4.635</td>
<td>12.67</td>
<td>1248</td>
<td>49.8</td>
<td>500kW</td>
</tr>
<tr>
<td>West EPB dipoles</td>
<td>MH321</td>
<td>9</td>
<td>24.526</td>
<td>14.91</td>
<td>1640</td>
<td>387.3</td>
<td>2 x 500kW</td>
</tr>
</tbody>
</table>

If the peak energy of the machine were to be 450 GeV, the extra EPB dipoles in the East and West line would not be necessary. Parameters at 450 GeV would be:

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Name</th>
<th>No. Magnets</th>
<th>Bend Angle</th>
<th>B</th>
<th>Current</th>
<th>D.C. Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>East EPB dipoles</td>
<td>MH323</td>
<td>3</td>
<td>8.675 mr</td>
<td>14.23kG</td>
<td>1509A</td>
<td>109.3 kW</td>
</tr>
<tr>
<td>West EPB dipoles</td>
<td>MH321</td>
<td>8</td>
<td>24.526</td>
<td>15.09</td>
<td>1670</td>
<td>357.0</td>
</tr>
</tbody>
</table>

(* ) Assumes MV310 in series with MV320
Table III - Equipment Location in Enclosure "H". The distance along the beam Z, is measured from the upstream wall of "H" to the upstream end of the magnet, or face of SWIC box. The offsets are measured from the present undeflected beam line entering Enclosure "H" (ref. print 0600 - LE - 24452). Positive offsets are to the East.

<table>
<thead>
<tr>
<th>Element</th>
<th>Beam Offset</th>
<th>Z</th>
<th>Element</th>
<th>Beam Offset</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWIC 318</td>
<td>-3.20&quot;</td>
<td>0 ft</td>
<td>MH323-1</td>
<td>4.17&quot;</td>
<td>200.145 ft</td>
</tr>
<tr>
<td>MV320-1</td>
<td>-3.21</td>
<td>3.976</td>
<td>-2</td>
<td>4.95</td>
<td>211.145</td>
</tr>
<tr>
<td>MV320-2</td>
<td>14.976</td>
<td>-3</td>
<td>6.02</td>
<td>222.145</td>
<td></td>
</tr>
<tr>
<td>MV320-3</td>
<td>25.976</td>
<td>-4</td>
<td>7.38</td>
<td>233.145</td>
<td></td>
</tr>
<tr>
<td>SWIC319</td>
<td>-3.33</td>
<td>37.080</td>
<td>MVT323</td>
<td>9.02</td>
<td>244.145</td>
</tr>
<tr>
<td>SWIC319E,C,W</td>
<td>38.559</td>
<td>40.059</td>
<td>SWIC323</td>
<td>249.145</td>
<td></td>
</tr>
<tr>
<td>Shield or Col.</td>
<td></td>
<td></td>
<td>Collimator</td>
<td>292.399</td>
<td></td>
</tr>
<tr>
<td>MH320-1</td>
<td>-3.3/</td>
<td>46.281</td>
<td>Wall</td>
<td>18.24</td>
<td>301.524</td>
</tr>
<tr>
<td>MH320-2</td>
<td>57.281</td>
<td>MVT322</td>
<td>-4.14</td>
<td>261.149</td>
<td></td>
</tr>
<tr>
<td>MH320-3</td>
<td>68.281</td>
<td>MH322-1</td>
<td>-4.16</td>
<td>266.149</td>
<td></td>
</tr>
<tr>
<td>MH320-4</td>
<td>79.281</td>
<td>MH322 2</td>
<td>277.149</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWIC320W,C,E</td>
<td>-3.53</td>
<td>90.385</td>
<td>SWIC322</td>
<td>288.649</td>
<td></td>
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<tr>
<td>MV1321</td>
<td></td>
<td>195.729</td>
<td>Collimator</td>
<td>289.649</td>
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</tr>
<tr>
<td>MH321-1</td>
<td>-12.03</td>
<td>200.145</td>
<td>Wall</td>
<td>-5.51</td>
<td>301.439</td>
</tr>
<tr>
<td>-2</td>
<td>-12.91</td>
<td>211.145</td>
<td></td>
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<td></td>
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<tr>
<td>-3</td>
<td>-14.16</td>
<td>222.145</td>
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</tr>
<tr>
<td>-4</td>
<td>-15.77</td>
<td>233.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5</td>
<td>-17.74</td>
<td>244.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6</td>
<td>-20.06</td>
<td>255.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-7</td>
<td>-22.75</td>
<td>266.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-8</td>
<td>-25.80</td>
<td>277.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-9</td>
<td>-29.21</td>
<td>288.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC321</td>
<td>-32.97</td>
<td>298.695</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>-33.86</td>
<td>301.480</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Beam Elevations, Inches Above 732' from Sea Level

<table>
<thead>
<tr>
<th>Place</th>
<th>P-West</th>
<th>P-Center</th>
<th>P-East</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Wall</td>
<td>9.264</td>
<td>7.752</td>
<td>6.238</td>
</tr>
<tr>
<td>End MV320-3</td>
<td>11.427</td>
<td>9.825</td>
<td>8.282</td>
</tr>
<tr>
<td>Downstream Wall</td>
<td>12.194</td>
<td>10.207</td>
<td>8.331</td>
</tr>
<tr>
<td>Slopes at MH320</td>
<td>+0.260mr</td>
<td>+.122mr</td>
<td>-.015mr</td>
</tr>
</tbody>
</table>
MAGNETIC FIELD

CENTRAL FIELD 16.0kG
GOOD FIELD 4.6" x 1.75"
FIELD QUALITY +0.14%, -0.06%

POWER:

Dc Power 109.0kW
Current 1116.0A
Voltage 97.5V
Copper Temp. Ave.
Resist @ Temp. 0.0876Ω
Time Constant 0.43sec
Inductance 0.0375H

COOLING:

Water Temp. Rise 15°C
Total Flow 9.6GPM
Pressure 200 psi

COIL DATA:

Conductor O.D. 0.46" x 0.46"
Hole Diameter 0.23"
Turns 68
Water Paths 8
Ave. Turn Length 278"

WEIGHTS: (est.)

Coil & Insul. 1,170 lbs
Core 10,300 lbs
Support 200 lbs
Total Magnet Assembly 11,670 lbs

CALCULATION CONSTANTS:

B =
θ =
Proton Department 3-Way split magnet

Average $\delta B/B$ as function of horizontal position at upstream end of 4-magnet string. The average is over the curved trajectory through the four magnets.
Distortion of horizontal phase space due to worst field contour \((y = 1.125\text{''})\) in Proton Department 3-Way Splitting Magnet.

\[\delta \Phi = 0.507 \frac{\delta \Phi}{\Phi_{\text{nom}} \%}\]

- Fig. 2
Fig. 4 - Cross section of beams at upstream end of MH 321-1 and MH 323-1
Field Uniformity of 2.28x5x120 Dipole (Modified Bl)

\( B/B \) as a function of horizontal position in magnet, \( x \), for three planes in the magnet.

\[ \frac{\delta B}{B} \]

\( x \) (inches)

\( y = \pm 0.125'' \)

\( y = 0 \) (median plane)

\( y = \pm 0.75'' \)

Fig. 5