Chapter 7

Design of the Muon Detector

As described earlier, the BTeV muon system should have the following attributes:

1. Robust: It will be very difficult to access the detectors once they are installed.
2. High Rate Capability: Rates of a few kHz/cm^2 are possible in parts of the system (based on calculations of accelerator backgrounds).
3. Good Time Resolution: Timing information on hits with a resolution of 50–60 ns will allow rejection of hits due to accelerator backgrounds.
4. Magnetic: Two toroids of 1.5 Tesla field and roughly 1 m thickness (in each arm).
5. Fine-Grained Spatial Resolution: Tracking resolutions of 2–3 mm are required.
6. Longitudinal Compactness: Given the size constraints, the detectors should be of minimal thickness.
7. Minimal Neutron Susceptibility: We will avoid the use of hydrogenic detector elements.
8. Uniform Occupancy: A geometry designed to minimize pattern recognition confusion and minimize occupancy at smaller radii.

7.1 Detector Design and Fabrication

In this section we describe the detector system designed to satisfy these criteria.

7.1.1 Basic Building Block: Proportional Tube "Plank"

The basic building block in the construction of a detector station is a "plank" of 3/8" stainless steel proportional tubes (see Fig. 7.1). Thirty-two tubes are arranged in a double layer with an offset of half a tube ("picket fence" geometry) and are glued together at two or three points by aluminum ribs ("Fred Ribs" in the figure). This should provide an extremely

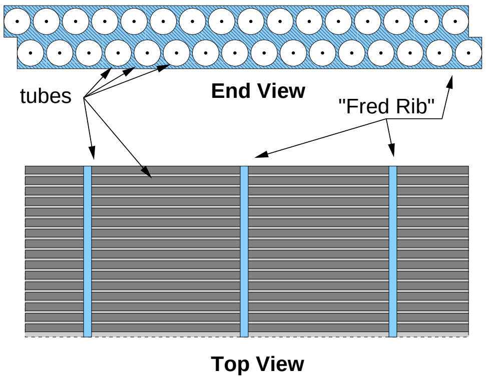

Figure 7.1: End and top views of one "plank" of proportional tubes. The plank is the basic building block of the muon system.

sturdy, self-supporting building block. Proportional tubes have been selected as the detector technology because they are robust and have the necessary rate capability. We intend to use a fast gas (such as 88% Ar, 10% CF_4, 2% CO_2, which has a drift velocity of roughly 9 cm/μs [1]) so the maximum collection time (drift plus charge integration) for a signal should be less than 60 ns. We intend to use thin walled (0.01") stainless steel tubes. This is a proven technology — it has been used successfully by the CDF collaboration where similar tubes [2] had a long lifetime with low failure rate.

The 0.5 cm wire spacing of this design has an effective spatial resolution of at most 1.5 mm, with no dead regions between tubes.

7.1.2 Design of a Detector Station

To minimize occupancy at small radii and to minimize pattern recognition confusion, each detector station will consist of eight overlapping pie shaped "octants," as shown in Fig. 7.2. Each octant is a single unit, which will be hung from a hanging frame. There are three views (r, u, and v) in each octant as shown in Fig. 7.3. The views stack on top of each other, and are built from the planks described above. We are considering adding a thin layer of aluminum between each view to act as a delta ray "shield." While the shield itself will generate delta rays, the idea is to regenerate them near the tubes so that they will tend to fire the same tubes as their parent muons. There will be 15 planks (butted up against each other) in each view of an octant (more than shown in Fig. 7.3).

Currently the angle of the u and v views with respect to the r view is $\pm 22.5^o$. The three views provide redundancy and allow studies to be made in which two views are beat against the third (such as in efficiency studies). The angle of 22.5^o is not yet set in stone, further Monte Carlo studies need to be performed. This geometry gives excellent resolution and redundancy in the bend direction ($\hat{\theta}$) of the toroids, and the resolution in the $\hat{\phi}$ direction is reasonable ($\sigma_\phi = 2.8$ mm, which is approximately twice the single plank resolution).

This octant geometry has several advantages. In all three views the planks are short near

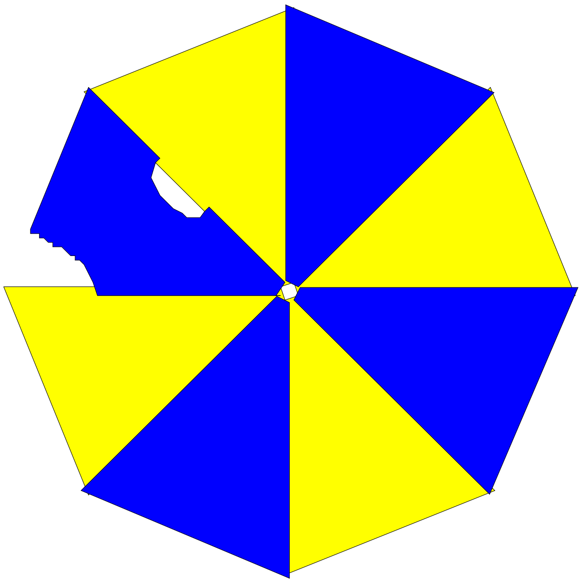

Figure 7.2: Beams-eye view of one muon detector station, which consists of eight overlapping octants arranged in two layers. One octant is cut away in places to show the overlap between adjacent octants.

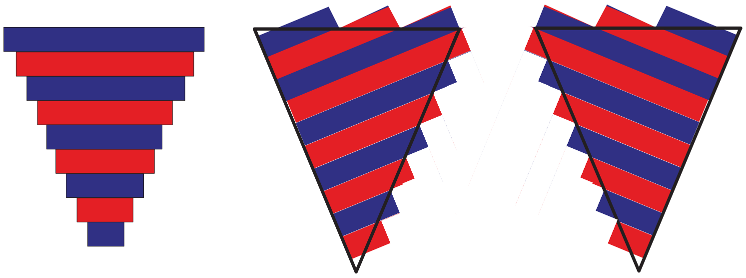

Figure 7.3: Arrangement of planks to form each of the three views in an octant. There will be 15 planks per octant (more than shown).

the beam pipe, and get longer at larger radii. This should result in approximately uniform occupancy as a function of r. This geometry should also help minimize pattern recognition confusion.

With 15 planks per view per octant, and 32 channels in a plank, the channel count for each octant will be 1440 and for each detector station will be 11,520, for a total of 34,560 channels in each arm and 69,120 channels in both arms.

7.1.3 Proportional Tube Details

Each of the 32 tubes in a plank will share a common gas manifold at each end. The wires will be held at positive high voltage and read out through a blocking capacitor by front-end electronics which will attach at one end. High voltage will be fed to the plank at the same end as the electronics. We intend to use a "fast" gas mixture of 88% Ar, 10% CF_4, 2% CO_2 or something similar. For more details on the front-end electronics, expected signals, etc., see the section on front-end electronics below.

The longest tubes in the system will be approximately 6 feet in length, and we are considering several different wire diameters (20–50 microns). We will decide on a wire diameter based on the results of beam tests to be performed this summer (1999, see description below). In any case, our calculations indicate that no wire supports are necessary. Again, we hope to get some feedback on that this summer.

The tubes will be strung individually and the wires held in place via a crimp pin. The arrangement is very similar to that used in the CDF system [2]. The crimp pins will extend out of the gas manifold and will attach to a circuit board which contains the blocking capacitors and an edge connector for the front-end cards.

7.1.4 Miscellaneous Mechanical Details

Because of the overlapping octant geometry of each detector station, there is plenty of room for cabling and front-end electronics everywhere except near the beam pipe. It is contention for space at small radii that limits the inner radius of the system to between 15 and 20 cm.

Weight is a potential concern because we are using stainless tubes. Using thin walled tubes reduces this concern significantly. We estimate the weight of the stainless tubes in one octant (all three views) to be 200 lbs, the same as if we were to use 1/32" thick aluminum tubes. However, the hanging frame used to support the octants and the delta ray shields will probably double the weight of each octant, so that each detector station will weigh 1.5–2 tons.

We plan on building at least 5 spare octants (10% of those in the total system), so that if one develops problems (more than a handful of broken wires, etc.) we can swap a new octant in and work on the problem octant "offline." We do not plan on restringing bad tubes – we will simply make a new plank.

The octants will be fabricated at Illinois (50%) and Vanderbilt (50%). We estimate the cost of the stainless tubing to be \$500,000. Wire will cost \$250,000. Machined parts such as the gas manifolds, gas connectors, wire crimp pins and feedthroughs will cost \$500,000. Including the hanging frame and contingency, we estimate the total cost of materials for the detector planes to be \$1.5 million, not including electronics.

7.1.5 Summary of Mechanical Design

A summary of the baseline BTeV Muon System is given in Table 7.1.

Table 7.1: Parameters of the baseline BTeV Muon System.

Transverse size	$\pm$ 200 mrads
Total Length	3.3 m
Rate Capability Req'd.	few kHz/cm^2
Steel Length	2 m
Toroidal Field	1.5 T
No. of Longitudinal segments (steel)	2
Plane size:	20 m^2
Tube cell size	1 cm (diameter)
Wire spacing:	0.5 cm
Spatial resolution	1.5 mm
No. of channels/octant (3 views)	1440
Octants per station	8
Total channels	35,000 per arm
Momentum resolution	$\sigma_p/p = 19\% \oplus 0.6\% \times p$
Total thickness/station	20 cm

7.2 Front End Electronics

In order to capture all the charge coming from a typical proportional tube for a single incident ionizing particle, one must integrate the charge due to the positive ion drift over a long period of time relative to the expected beam crossing for the BTeV experiment. The time needed to collect a portion of the total charge is a function of the gas used in the proportional tube, the geometry of the tube, and the high voltage bias of the center wire, relative to the outer conductor:

$$\frac{Q}{Q_o} = \frac{\ln(1 + t/t_o)}{2\ln(b/a)} \, [3], [4]$$

where Q is the charge collected in an amount of time, t, Q_o is the total charge from the ionization (depends on the gain of the tube), b and a are the outer and inner radius, respectively, of the conductors in the proportional tube, and:

$$t_o \sim \frac{a}{2v_d} \, [4]$$

where v_d is the drift velocity of the gas for the chosen value of the gain in the tube [1]. Alternatively, for a very fast signal, one could try to just capture the fast signal coming from the electron amplification, but this is only 1–2% of Q_o.

In BTeV we intend to use the muon proportional tubes in the Level 1 Trigger. The natural cutoff for integrating a signal then is on the order of a beam crossing, or 100 ns. However, we would like to reduce backgrounds associated with the collider beams, which pass through about 60–70 ns before interaction products arrive. For a fast gas like $ArCO_2CH_4$ [1], and a wire-to-wire spacing of 0.5 cm, the maximum drift time before the first signals from a track arrive is about 30 ns. This means that if we would like to be able to separate the various "crossings", our electronics should be able to resolve 2 hits occurring 30 ns apart (minimum).

7.2.1 Amplifier choice

Fortunately, electronics to amplify and digitize the analog signal from a chamber hit in a high rate environment were developed for the SSC [3], and continue to be refined for use in detectors for the LHC [5] and at Fermilab [6]. We will take full advantage of these developments.

We intend to mimic the setup used for the CDF COT [6]. There will be a PC board to deliver High Voltage to each Proportional Tube, and a PC board with electronics to amplify and digitize the tube signal. Both boards will be located directly at the end of a group of 16–32 proportional tubes.

We plan to utilize the ASD family of integrated circuits developed at the University of Pennsylvania to amplify and digitize the signals coming from the proportional tubes. These chips (and applications) are described in detail elsewhere [3],[6], but we briefly mention some more important features here.

The ASD8B, which is being used for evaluation and beam tests, amplifies the first $\sim$6 ns of the the chamber signal and outputs an LVDS (equivalent) differential logic signal. This chip, when mounted on a PC board, has a low effective threshold of about $\sim$1 fC. This is the threshold as quoted in the ASD8B reference and verified in tests that we performed on an evaluation board supplied by the University of Pennsylvania in December of 1998. The chip also features a double pulse resolution of $\sim$20 ns. This chip seems to be an ideal choice for the BTeV muon system, and it is important to determine if we have sufficient signal to utilize the ASD8B (or other ASD chip!).

7.2.1.1 Practical Considerations

To calculate the signal we expect in the proportional tube, we will use the data presented in reference [1]. For the same gain as quoted in the paper($\sim 1.8 \times 10^5$), we can use the quoted results to determine our operating parameters for different tube geometries and gas mixtures. In Table 7.2.1.1, we summarize the results for different gases and inner conductor radii.

In the table, we have made some assumptions. We've assumed that the most important factor in calculating the gain is sensitivity to a *single* ionization cluster of a *single* electron–ion pair; we haven't taken into account the effect of adding a termination resistor (see below); we haven't taken into account the effect of a magnetic field; and we've neglected aging effects in the tube. We've also taken for granted that the electronics will be located at the end of the proportional tubes: lowering the electronic noise and increasing the amount of signal we get in the small integration time available. Even so, we can learn a great deal from looking at the table.

Table 7.2: Operating parameters for different gases and inner wire radii (a). The values of t^M_{drift} assume a wire space of 0.5 cm.

Gas	$E_{field}\|_a$	v_d	V_{bias}	Q_{6ns}	t^M_{drift}	a
$\frac{ArC_2H_6}{50/50}$	$150(\frac{\mathrm{kV}}{\mathrm{cm}})$	$4.8(\frac{\mathrm{cm}}{\mu\mathrm{s}})$	3545(V)	7.8(fC)	50(ns)	50(μm)
$\frac{ArCO_2}{80/20}$	164	2.4	3768	5.9	100	50
$\frac{ArCO_2CF_4}{88/2/10}$	150	8.7	3454	9.5	30	50
$\frac{ArC_2H_6}{50/50}$	150	4.8	1656	8.8	50	20
$\frac{ArCO_2}{80/20}$	164	2.4	1806	7.1	100	20
$\frac{ArCO_2CF_4}{88/2/10}$	150	8.7	1656	10.4	30	20

7.2.1.2 Amplifier Observations

A smaller wire size is desirable from an electronics standpoint: the operating voltage (V_{bias}) is lower and the integrated charge collected (Q_{6ns}) is a little higher. The lower operating voltage gives us more flexibility in the choice of a decoupling capacitor, allowing the option of surface mount components in the high voltage system. The higher integrated charge means we can safely raise the threshold of the electronics without losing signal, allowing greater flexibility in our noise budget. Additionally, it is expected that the gain of a tube has less sensitivity to the operating voltage with a smaller wire [1].

Also evident is the advantage of having a fast gas. Not only can one integrate more charge in a smaller period of time, one has less sensitivity to beam "crossings". We can achieve our goal, stated previously, of the first signal to arrive after a maximum time of about $t^M_{\mathrm{drift}} = 30$ ns.

Another way to look at the table is to reason that all the combinations calculated will produce a working detector, and that using the ASD chip allows us a lot of flexibility in our choice of wire diameter, gas, and operating voltage.

At most, a termination resistor will raise our noise by 1 fC and lower our gain by a factor of 2. This is to be offset by the expectation that about 10 primary ion-pair clusters will be produced, on average, for a MIP passing through 1/3 cm of gas volume.

One final consideration in evaluating the ASD8B for BTeV is that the process used to make the chip is obsolete and the chip will not be available in production quantities [7]. We will have to use an improved version (ASDQ) at a slightly higher cost. It integrates for a slightly longer period, has the same double pulse resolution, and has a higher noise level of $2 - 3$ fC.

7.2.1.3 Front–end Readout

As mentioned previously, the ASD chips produce differential logic signals (LVDS) suitable for driving long (10 m) cable lengths. The LVDS signal consists of 1 bit/channel signifying whether or not a channel is on or off. If we choose to do any logic on the ASD board, we must first convert the LVDS, perform the required function, and finally redrive the signal. This option, though decreasing cable cost, will require more power to be delivered to the front-end, more power to be dissipated in a small area near the detector, and will increase the amount of noise on the board. This option was not used on CDF and is not recommended by the designer of the ASD8B chip [7].

Finally, reading out the raw hits provides for maximum flexibility in designing, prototyping or even upgrading and good utility in re-using these electronics or interchanging electronics with other BTeV detectors. Cards designed with a similar philosophy have been in continual use for 25 years in high energy physics experiments. For the reasons given, we intend to read out the raw hits from the front-end electronics.

7.2.1.4 Feasibility

By utilizing existing electronics packages and packaging for the front-end of the BTeV muon system we will save considerable time and developmental costs. For instance, the major modification needed to utilize the 24 channel CDF COT front-end card for BTeV, is to remove one of the chips from the CDF COT circuit board to accommodate the smallest muon drift tube channel count footprint of 16 channels.

Additionally, such a scheme is easily utilized by other detectors, such as the straw tracker, and we can benefit from standardization. To use this scheme and front-end board in other BTeV gas tracking systems, one has to consider what information is needed for tracking, and build a suitable post front-end circuit board to suit those needs. The front-end can be used right away.

7.2.2 Post Front-end Considerations for the Muon System

As stated, we intend to do no post processing on the front-end amplifier board. We still need to read the signals out, and we would like to keep costs to a minimum.

In order for the front-end to operate correctly, we will need to provide a mechanism to modify the threshold for a channel. Rather than include a digital to analog converter on the front-end card, we would rather provide a single analog threshold for each chip (8 channels) and provide a digital mask for channels that fire continuously.

To reduce cable cost and logistics for long cable runs, we will convert the parallel bitmap coming from the front-end to a serial signal that can be transmitted on a single fiber optic cable. A single optical cable will read out 96 channels and do so in the 132 ns between beam crossings. (The hard limit is 132 bits for a 1 Gbit/s optical link.)

Converting the data from parallel to serial destroys the fine timing information of the front-end signal but allows us to apply a gate to the signals coming from the front-end. By applying this gate we provide both the means to compress the bitmap information in time for the conversion and the ability to filter out-of-time hits from the information sent to the trigger and the DAQ.

All these actions are to be done on a circuit board that intercepts 96 channels of input

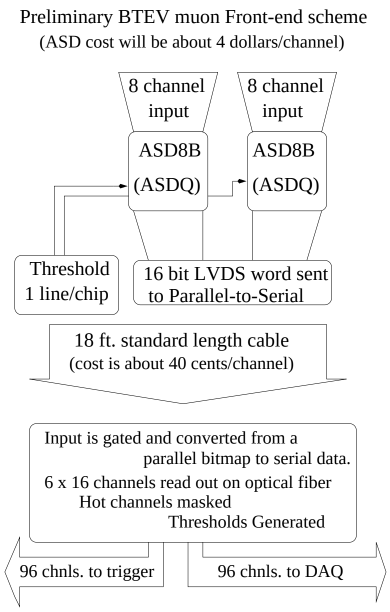

Figure 7.4: Schematic diagram of the front-end and post front-end circuit boards for the BTeV Muon Proportional Tube system. Some highly preliminary cost estimates are included in the figure.

from 6 frond-end cards, and converts the signals for later use. Schematically, the front-end and post front-end card are shown in Fig. 7.4.

7.3 Trigger Electronics

7.4 Test Beam Plans and Goals

During the 1999 test beam running we will investigate the stability, reliability and operating characteristics of our proportional tubes with various tube lengths (1,3,6 feet) and with various wire diameters (20, 30, 50 micron). We will analyze the response of the system at different incident beam angles and will record rate capability, noise, efficiency and resolution. We also will test the performance of prototypes of the front-end electronics and a prototype trigger processor.

We will construct a tracking system consisting of ten planks of proportional tubes. The planks are identical in design to the ones described above: 32 tubes arranged in two, offset layers. The tubes will be 0.01" thick walled stainless, with an outer diameter of 3/8". We will have enough front-end boards to read out half (160) of these channels.

Our Run Plan is:

1. One week to install planks, trigger scintillators and DAQ. The planks will have been

tested in a cosmic ray test stand at Vanderbilt prior to installation. The DAQ software will have been tested with partial electronics prior to installation.

2. One week of running with Beam #1 (see below) to bring the system up and adjust timing in electronics, etc.

3. One to two weeks of running with Beam #1 to take main data sample. We require several 1-3 hour runs with access time between, to rotate a station or to move other portion of a plank into the beam.

4. Two days of data taking with Beam #2 and Beam #3.

5. After taking a few days to analyze the data and reach conclusions, we may go back and repeat some or all of the above. A third iteration could be necessary. Up to 4 weeks of data taking has been requested.

Beam Requirements:

1. A 1 kHz pion beam with energy of 100 GeV or higher and with a beam spot diameter of 4–8 cm.

2. A beam consisting primarily of muons. Provided that the rate is at least 100 Hz with a beam spot area of 15×15 cm^2, either a beam derived from hadrons hitting a dump or a halo muon beam will be adequate. Muon purity around 99% is desirable. It would be ideal if this could be achieved by moving the stations downstream of the Mtest dump during this part of the test.

3. A 10–100 kHz pion beam for rate studies. This might require a somewhat higher allocation of protons to Mtest area than normal for a small period of time. Depending on the situation, we may require a special high intensity run of 10^{12} protons per pulse for 1 day.

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