A Barrel IFR Instrumented with Limited Streamer Tubes

Proposal from the BaBar Collaboration

to the

SLAC Experimental Program Advisory Committee

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The LST Team

M. Andreotti, D. Bettoni, R. Calabrese†, V. Carassiti,
G. Cibinetto, A. Cotta Ramusino, E. Luppi, M. Negrini, L. Piemontese
Ferrara University and INFN
R. Baldini, A. Calcaterra, U. Denni, P. Patteri, A Zallo
Laboratori Nazionali di Frascati dell'INFN
R. Capra, M. Lo Vetere, S. Minatoli, S. Passaggio, C. Patrignani, E. Robutti
Genova University and INFN
T. Allmendinger, K.K. Gan, K.Honscheid, H. Kagan, R. Kass, J.Morris,
C. Rush, S.Smith, Q. Wong, M.Zoeller
Ohio State University
R. Frey, N. Sinev, D. Strom, J. Strube
University of Oregon
C. Fanin, M. Morandin, M. Posocco, M. Rotondo, R. Stroili, C. Voci
Padova University and INFN
J. Biesiada, G. Cavoto*, N. Danielson, R. Fernholz, Y. Lau, C. Lu, J. Olsen, W. Sands, A.J.S. Smith†
Princeton University
S. Morganti , G Piredda, C. Voena
Roma "La Sapienza" University and INFN
D.B. MacFarlane, H.P. Paar
University of California at San Diego
R. Boyce , P. Kim, J. Krebs , R. Messner, M. Olson , Z. Szalata , T. Webber , W. Wisniewski, C. Young
Stanford Linear Accelerator Center

† Contact persons
* Also INFN Rome

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I. Introduction

We propose to replace the present Resistive Plate Chambers (RPC) in the gaps of the BaBar Instrumented Flux Return (IFR), used to detect muons and neutral hadrons, with plastic Limited Streamer Tubes (LST). After extensive detector R&D and testing, we are persuaded that LST's are the most straightforward, practical and reliable detectors among the various available options to instrument the barrel region, access to which has been and will continue to be difficult and in some cases impossible. To support our conclusions we have surveyed the major HEP experiments of recent years and have found that LST's have a good record for satisfactory performance with high efficiency and reliability over many years. Prominent examples include ZEUS, LEP experiments, MACRO, CLEO, SLD, and PHENIX. Nevertheless, it is highly desirable that the new detector for the barrel be designed with sufficient modularity to permit, wherever possible, the replacement of occasional ailing modules without the need for additional or extended shutdowns beyond those normally foreseen. The proposed LST system lends itself nicely to this requirement, and has been designed keeping it firmly in mind.

The BaBar IFR faces several challenging experimental conditions, requiring a detector with a high degree of reliability and redundancy, and easy maintainability. BaBar takes data for a very large part of the year and in factory mode, so that long stops for maintenance of any type must be avoided. Therefore, as much of the detector and electronics as possible should be located in regions of easy access for repair. For example, it should not be necessary to open doors to disconnect a HV channel or replace a front end circuit.

In the following we will describe the basic features of the proposed LST system as optimised for use in the present iron structure, assuming that the principles of operation of the tubes are well known. A preliminary design has been made, both of mechanics and module construction and of the readout electronics. However, the choices of some parameters remain to be made, depending on the outcome of tests of prototypes now underway, and of the Monte Carlo studies being carried out now by the Collaboration.

The main choice we still have to make is the one between the baseline configuration, a single layer of "large cell" tubes, and an alternative configuration, a double layer of smaller cells. The final decision will be made in about one month.

References:

This document presents a summary of the proposed LST construction project. Detailed explanations of the physics motivation for the upgrade, the need to replace the RPC's, and the choice of LST technology, are given in the "Report of the IFR Barrel Replacement Review Committee," which was recently distributed to the EPAC.

II. IFR constraints and LST parameters

The Flux-Return Geometry

The present muon and neutral hadron detector consists of 19 layers of RPC's, interspersed between the iron slabs of the flux return. The gaps between the slabs are nominally 35mm, but have been measured with a gauge only to exceed 22mm over the whole 3.75m long gaps, and 29mm over the first 85mm at the front and back ends. (No check has been made with a thicker gauge because 22mm was sufficient for the original RPC's.) The iron slabs are not of uniform thickness, the first 9 being 2cm thick, followed by 4 of 3cm, 3 of 5cm and 2 of 10cm. Various iron plates are bolted to the barrel at the ends of the gaps to close the magnetic circuit. Of these, the "filler plates" are reasonably easy to remove even after the detectors have been installed. However, the "corner pieces" will be removed only once, and even then in the forward end of the detector only, to remove the old RPC's, replace them with new detectors or, in layers 5, 7, 9, 11, 13 and 15, with 2-cm thick brass absorber plates. Layer 18 is covered at both ends by a slab of iron, which needs the corner pieces to be taken out before it can be removed. In other words, once installed, layer 18 will never be removed. (Layer 19 is NOT ACCESSIBLE). Four cable conduits are installed on each end of each sextant for IFR cables. Two of them are near the centre of the sextant, 6"x 2" cross section; the other two, laid behind the corner pieces, are 3cm x 3cm and are now used for HV and gas lines; they will probably not be accessible in the back end.

The LST Concept

A "standard" LST configuration consists of a silver plated wire 100 μm in diameter, located at the centre of a cell of 9x9mm^2 section. A plastic (PVC) extruded structure, or "profile", contains 8 such cells, open on one side (Fig. 1). The profile is coated with a resistive layer of graphite, having a typical surface resistivity between 0.2 and 1 MΩ/square.

Figure 1. Photo of a standard LST, partially inserted in the sleeves (shown on the left).

The profiles, coated with graphite and strung with wires, are inserted in plastic tubes ("sleeves") of matching dimensions for gas containment. Other components needed for the complete detector are: end pieces with gas inlets, HV and ground connectors; spacers installed typically every 50cm to fix the wires at the centre of the cell; small printed circuit boards and their supports at the two ends of the profile, for soldering the wires and providing electrical connections.

The signals for the measurement of one coordinate can be read directly from the wires, but it has become customary instead to read both coordinates with strip planes, thereby avoiding the complications of feedthroughs and DC-blocking capacitors. For such tubes the operating voltage is typically 4.7kV; the efficiency plateaus are at least 200V wide; the signals on the wire are of the order of 200/300mV (into 50Ω), typically 50ns at the base, sometimes with an afterpulse. The gas mixtures are strongly quenching: the original one (25% Ar, 75% n-pentane) being explosive has been replaced in accelerator use (SLD, ZEUS) by a non-flammable one based on CO_2.

The LST geometrical efficiency is limited by the ratio of active versus total volume in the cell. For example, in the standard LST tube (a cell of 9x9 mm^2 with 1 mm plastic walls), the efficiency cannot be greater than 90 % for perpendicular impacts. Fortunately this effect is mitigated by the fact that most tracks do not impinge perpendicularly. Furthermore, if the gap between iron slabs is wide enough, the inefficiency can be greatly reduced by using larger cells or, alternatively, a double-layer geometry.

Design and Performance Issues

The LST tubes are somewhat fragile mechanically so careful design, handling, and operation are of paramount importance in preventing failures. The "mortality" of the LST's depends on the cell size, on the care and attention given during construction and installation, and on the strictness of the acceptance tests. Given these constraints, we are designing a highly efficient detector and are planning the implementation of stringent quality checks during production and commissioning**.**

This means:

- Minimize dead spaces. These include the profile walls, separation between tubes, dead areas at the tube ends, both inside the sleeves and outside, for electronics, gas and cabling.
- Reduce tube mortality and/or introduce redundancy to decrease its effect on detector efficiency.
- Arrange tubes into modules that can be extracted and replaced without removing corner pieces.
- Feed each tube with one or more independent HV channels.
- Locate HV distribution boxes and front end electronics on the outside of the detector to avoid having to open doors for repairs.

LST Experience in Other Experiments

Several major experiments have used LSTs. In general the tubes consist of 8 cells 9mm by 9mm, with the exception of MACRO where the cell was 29mm by 27mm. We summarize below the failure rates experienced by some of the major LST systems. Most of the information comes from private communication.

- ZEUS: 3400 tubes, length up to 10m, high radiation induced by a depleted uranium calorimeter. The mortality in the first two years was about 6% mainly due to the short conditioning and selection time before installation; afterwards the failure rate was less than 2% in 7 years.
- DELPHI: 19000 tubes, length up to 4.1m, infant mortality ~1%.
- OPAL: 6700 tubes, length 3m to 7.3m. Failure rate 6% in 10 years.
- SLD: 10000 tubes, length 1.9m to 8.6m. Failure rates 10% in 10 years for the Barrel due to low initial experience and to mechanical problems during installation, 3% for the endcaps (shorter tubes).
- MACRO: 6000 tubes, length 12m, cell size 2.9x2.7cm. Infant mortality ~0.1% of wires, only 6 wires (out of 49,536) disconnected per year.

III. LST Design and Project Status

Overview

A vigorous R&D program underway during the past year has provided much insight into the characteristics of the LST detector that we propose to build. We have focused on two options, which we shall refer to as "*large cell*" (single layer 15x17mm^2 LST) and "*small cell*" (double layer 8x9mm^2 LST). We have also performed studies on 9x9 mm^2 cells, which we shall refer to as "*standard cell*" LST's because this configuration has been widely used in recent experiments. Initially the small cell option looked more promising, but significant new information collected over the past few months now strongly points toward the large cell as the better match to our requirements, making it the baseline. Particularly important are the lower cost and the expected superior cell reliability. Furthermore the total thickness of one LST layer is 1.2mm smaller in the case of the large cell. Therefore, barring any surprise in the last phase of the R&D program, the large cell will be the chosen solution. This decision will be made by the end of June, 2003.

In the following subsections we shall discuss the components of the system in some detail, beginning with the tubes and a comparison of the large cell and small cell options, and then proceeding to describe the construction of tubes into modules, the cathode-strip readout, the installation procedures, the electronics, the high-voltage and gas systems.

The Tubes

Two solutions are considered for the preparation of 8-cell plastic profiles into tubes, each aiming at increasing the reliability of the system and at reducing the impact of dead spaces. In both designs we plan to use PVC, which has become the standard material for extruded LST profiles. Its advantages are ease and reliability of extrusion and low cost, combined with more- than-adequate aging performance for the IFR environment, even with an order of magnitude increase of the present luminosity (See section on R&D). In both options the streamer coordinates z (along the beam direction) and Φ (azimuthal angle around the beam direction) are read out by detecting signals induced on strips. The Φ-strips are etched on a layer glued externally on one side of the tubes. The z strips will cover the whole sextant, and are installed into the magnet gaps prior to insertion of the LST modules. (See installation section).

Large-Cell Tube

In the current baseline design, we shall use a single layer of tubes of large cell size (15x17 mm^2) shown in Fig. 2. This option also gives higher geometrical efficiency and improved reliability of operation, compared to a single layer of standard cells, as confirmed by the very good operation of tubes in MACRO. We plan to supply independent high voltage (HV) to each pair of cells (*i.e.*, 4 independent HV channels for each tube). A set of dies for such tubes is being fabricated now. The set of small components (end caps, wire holders, etc) has been designed and the quantity needed for 10 prototype tubes has been fabricated by a rapid mold factory. Ten complete tubes of this type have been ordered from the vendor, Pol.Hi.Tech. (PHT) of Carsoli, Italy, and they should be ready by mid-June. In parallel, a few 70-cm long large-cell profiles have been built in our workshops for preliminary tests. The first such profile has been coated with graphite at PHT with good results.

Figure 2. The large-cell sleeve (top) and profile (bottom). Dimensions are in mm.

Small Cell Tube

In a second design, two profiles are inserted back to back into a single large sleeve, as shown in Fig. 3. The cells have dimensions 8mm x 9mm. In this configuration, to provide a backup in case one tube fails, each layer of a tube has an independent HV cable. The Φ and z strips, owing to the high resistivity of the graphite coating, pick up the signals from both tubes. It has already been verified experimentally that, if the profile next to a strip is turned off, the signal from the other profile still gives a good signal even though it is farther away. This design, beside granting good redundancy, also reduces the effect of dead spaces, since it shrinks the range of track angles for which a particle crossing the dead areas (plastics) escapes detection. The design calls for a total thickness of the detector of 23.2 mm at most. A few initial prototype tubes were made by PHT for testing the readout of this “twin profile” solution. Tospeed up construction these tubes were fabricated by recycling, and shaving old PVC profiles to obtain 8mm high cells in order to fit in the guaranteed 22mm gaps. The plateaus of these tubes have not been good, and subsequent measurements have shown that the mechanical precision was not adequate. A new set of prototypes is being carefully built with the proper dies and will be tested for reliability, mortality, range of HV plateau with cosmic rays and occurrence of double (or multiple) pulsing. We have also placed an order for 20 tubes of this type, and the set of small components (end pieces etc.) needed have been designed and fabricated. Such tubes are expected to be ready for test in the second half of June.

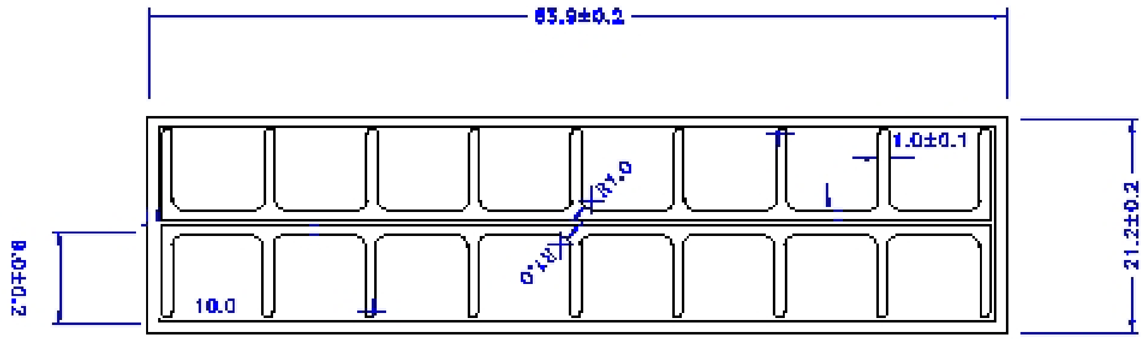


Figure 3. Double-layer design: two small-cell tubes in same sleeve (dimensions are in mm).

To validate the capability of PHT to fabricate high-quality tubes and to gain early experience operating LST's, we ordered and have received a set of twenty-two 4m long tubes of standard (9x9 mm^2) cell configuration. Eleven such tubes have silver coated wires, eleven have gold coated wires. The cathodes have been coated with water-based paint, and the resistivity has been measured, yielding good results (Fig. 4). Efficiency plateaus measured at the firm are good, and these tubes are being tested thoroughly at our labs (see R&D section).

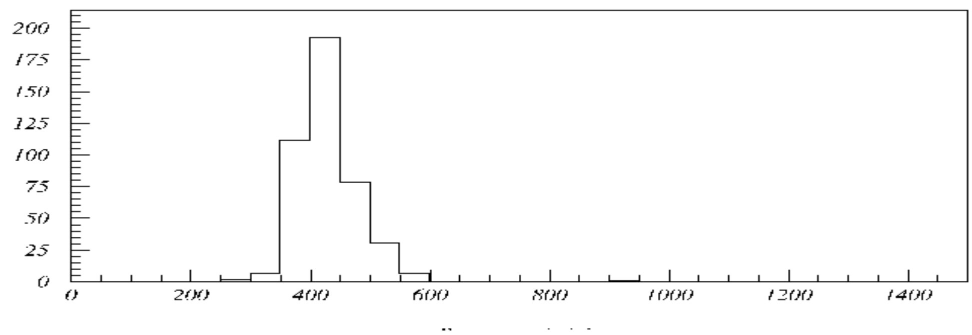


Figure 4. Distribution of resistivities (in kΩ/cm^2) measured in the 9x9 mm^2 cell tubes.

Comparison of Large and Small Cells

In comparing the two options we have considered various aspects and grouped them into three categories: performance, cost and schedule.

Performance
The relevant aspects considered are reliability, efficiency, drift time and occupancy.

Reliability
The most common failure mode for LSTs is associated with an increase of the dark current that leads to non recoverable damage. Standard LST's used in various environments have shown a mortality of 0.5% per year. On the contrary large cell systems have shown much higher reliability: for example, the MACRO experiment reported a total number of failures that is of the order of 0.1 % in equivalent units. These results are not unexpected. The reliability of LSTs mostly depends on the regularity of the cell shape, on the quality of the graphite coating and on the precision of the wire position along the tube. In all cases a larger cell presents an electrostatic design that is much more favorable. For example, the same misplacement of the wire reduces the width of the high-voltage plateau in the small cell LST by a larger amount than in the large cell. In addition the size of the large cell allows for stronger plastic parts to keep the wire in position. Particularly important in this respect are the wire holders: in the standard and small-cell LST plastic holders are melted around the wires, while in the large cell the holders are equipped with plastic clips that guarantee a more reproducible and precise wire positioning.

We can estimate the relative efficiency loss in the single and double-layer options in the following way. A Φ road defined by the width of a small-cell tube will comprise 16 cells (two layers of 8 cells) in the small-cell design, and 4 cells in the large-cell design. We plan to have one high-voltage channel per 8-cell layer for the small-cell design, and one channel per two cells in the large-cell option. Therefore, the loss of one cell results in a relative efficiency loss of ~5% for the double-layer (nominally from 95% to 90% because the second layer would still be on) or ~50% for the single layer (2 of the 4 cells are lost). The net efficiency loss would be $N_c p_c \varepsilon_c$, where N_c is the number of cells, p_c is the probability for a single cell to fail, and ε_c is the resulting loss in efficiency. Assuming the same failure rate, the small-cell design would be 2.5 times more reliable than the large-cell option. However, we know from previous experiments that the failure rate for the large-cell tubes is 3 to 5 times better than small-cell tubes, so that our baseline large-cell design should be at least as reliable as the double-layer option.

Efficiency
The cell efficiency was studied by a simple Monte Carlo simulation, reproducing tracks going through standard-cell LST, small cell and large cell. The results are shown in Fig. 5, where the inefficiency is plotted as a function of the minimum track path inside the cell required to generate sufficient ionization to produce a signal (~3mm should be sufficient).

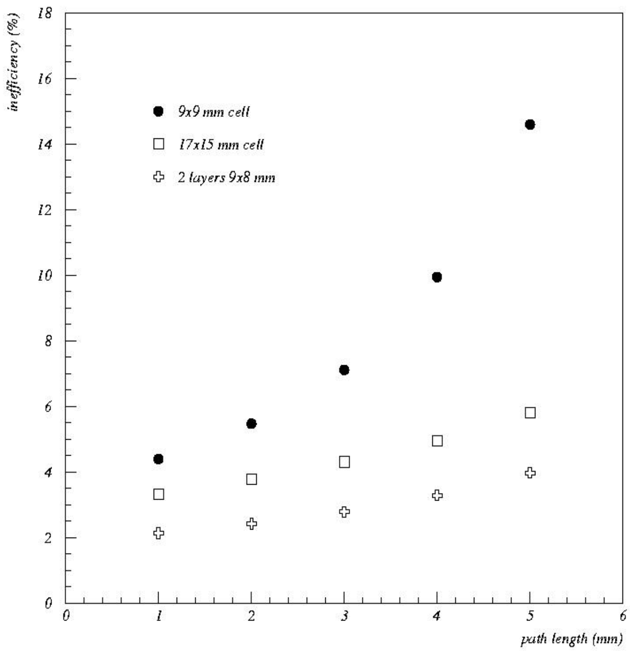


Figure 5. Monte Carlo results for efficiency vs path length for various cell geometries.

For a path corresponding to an inefficiency of 10% in the standard LST case, the inefficiency decreases to 3.3% for the small cell and to 5% for the large cell. Results from measurements made with cosmic rays on standard tubes and on the first batch of double layer prototypes are consistent with these numbers. A measurement with large cell prototypes will be performed soon.

In addition the overall efficiency of the detector depends on the dead space at both ends of the LST and in between the LST. In the current design, these effects are very similar for both options.

Drift time and occupancy

The longer drift time (up to ~300 ns) of the large cell is not expected to cause any significant increase of random coincidences with the first level trigger, since the width of the coincidence window is determined to a large extent by the trigger jitter. Given the low level of background expected in the Barrel IFR detector (< 2 Hz/cm^2) the worst case strip occupancy, in the innermost layers, is expected to be less than 0.5% per strip (slightly lower for the ϕ strips of the large cell option which has a smaller pitch).

Cost

The smaller number of LST's in the large cell option leads to a decrease of the total production cost of approximately 30 %. The number of spare LST's needed is also expected to be smaller for the large cell and that should further decrease the total cost. Savings are also expected in the gas distribution system due to the smaller number of gas connections.

Schedule
Prototypes of both types of LST's have been produced by PHT. Extrusion dies are now available while final molds of the small parts have to be ordered before production can take place. The modification of the graphite coating machine, required for the large cell, has already been carried out and the same "wave" coating technique used for small and standard cell tubes has been verified to work also for the large cell, on the basis of a few 70-cm long prototype profiles. Large cell production needs in addition the replacement of the cleaning machine and the modification of the stringing machine originally used for the production of the MACRO tubes. Despite this additional preparatory work, PHT has confirmed that production of either option can begin on October 1, 2003. Due to the smaller total number of large cell LST's to be produced, the total production time for the large cell can be shorter, thus providing a useful contingency to recover any unforeseen delays.

Conclusions
Both LST designs that we have considered represent viable solutions for the proposed upgrade of the Barrel IFR. However, for the reasons given above the large cell is our baseline option. A final decision will be taken after an evaluation of results from the final prototypes by the end of June.

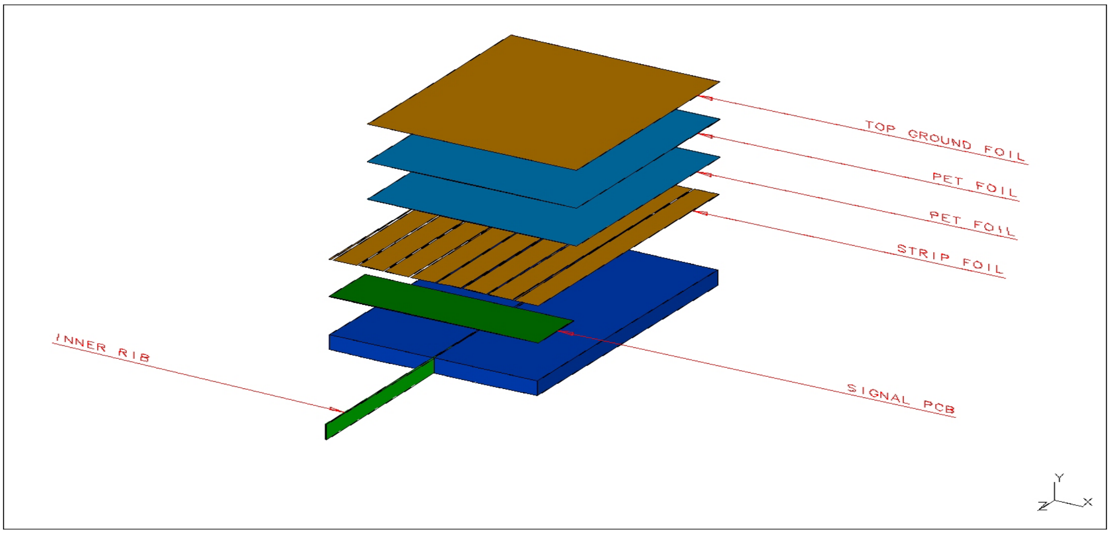


Figure 6. Assembly of large-cell tubes and ϕ strips into 2-tube module.

Assembly into Modules
In both large cell or small cell options we plan to assemble several tubes into modules to strengthen the mechanical structure. In order to fill completely the available space we are also preparing 7-cell profiles. The present design, shown in Fig. 6, calls for a layer within a sextant being split into several modules, each 2 tubes wide (there are 20 tubes per outermost layer). The Φ strips will be glued to each module; z strips will be made on one single layer, which will not be glued to the tubes, but inserted separately into the magnet gaps before the modules. Thin (less than 1mm) steel strips will be glued to the inner sides of the tubes to add rigidity to the module. This feature will help considerably in module handling, transport and installation.

Cathode-Strip Readout

The charge produced in the LSTs by ionizing radiation is collected through Φ and z segmented cathode strips capacitively coupled to the wires. The cathode strips are a composite structure only 1mm thick, stratified as follows (see Fig. 7 for details):

- The strip, which is facing the tube, onto which the signal charge is induced.
- The insulator foil, made out of two layers of PET with a total thickness of 500µm.
- The ground plane, which shields the strips and forms with them a transmission line that guides the signal to the collection junctions. The impedance and the parasitic capacitance vary with the strip width and are on the order of a few (~5) Ω and ~1nF/m respectively. The overall length of a z strip plane is 3700mm; the width is that of the layer, ranging from 1900mm for layer 1 to 3130 mm for layer 18.

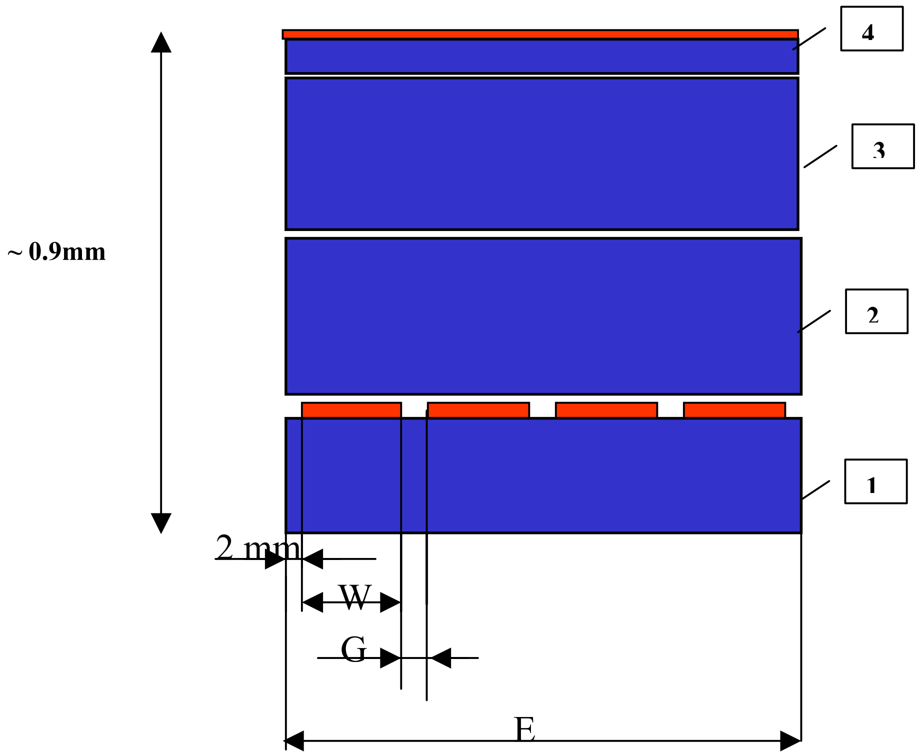


Figure 7. Φ-strip construction details: 1) PET 190 µm with copper lamination machined in strips of width W and separation gap G. Currently G=2mm; W=36mm for the z strips, 36mm or 40mm for the Φ strips according to the version of LST. 2),3) PET 250 µm 4) PET 50µm with solid copper lamination.

At present we plan to build the z strips in three sections that will be assembled together after arriving at SLAC. Figure 8 shows one such section. One can see that embedded in the cathode strip plane there are also flexible Printed Circuit Boards (PCBs) with copper traces in the z direction. The traces are interrupted at specific positions by holes. Underneath each of these interruptions is a corresponding hole in the insulator foil, centered with respect to one of the cathode strips. The end of one copper trace is then soldered to the cathode strip below. The strip signal is carried along the copper trace to one end of the flexible PCB where it will be fitted to a transition board (not shown in the drawing) with connectors mating to the microribbon-twisted - pair flat cable going to the front end electronics cards.

The flexible PCB will be backed by another PCB with a solid ground plane (not shown in the picture for clarity) to be joined to the rest of the cathode strip ground plane. The impedance of the signal traces is matched to that of the strips.

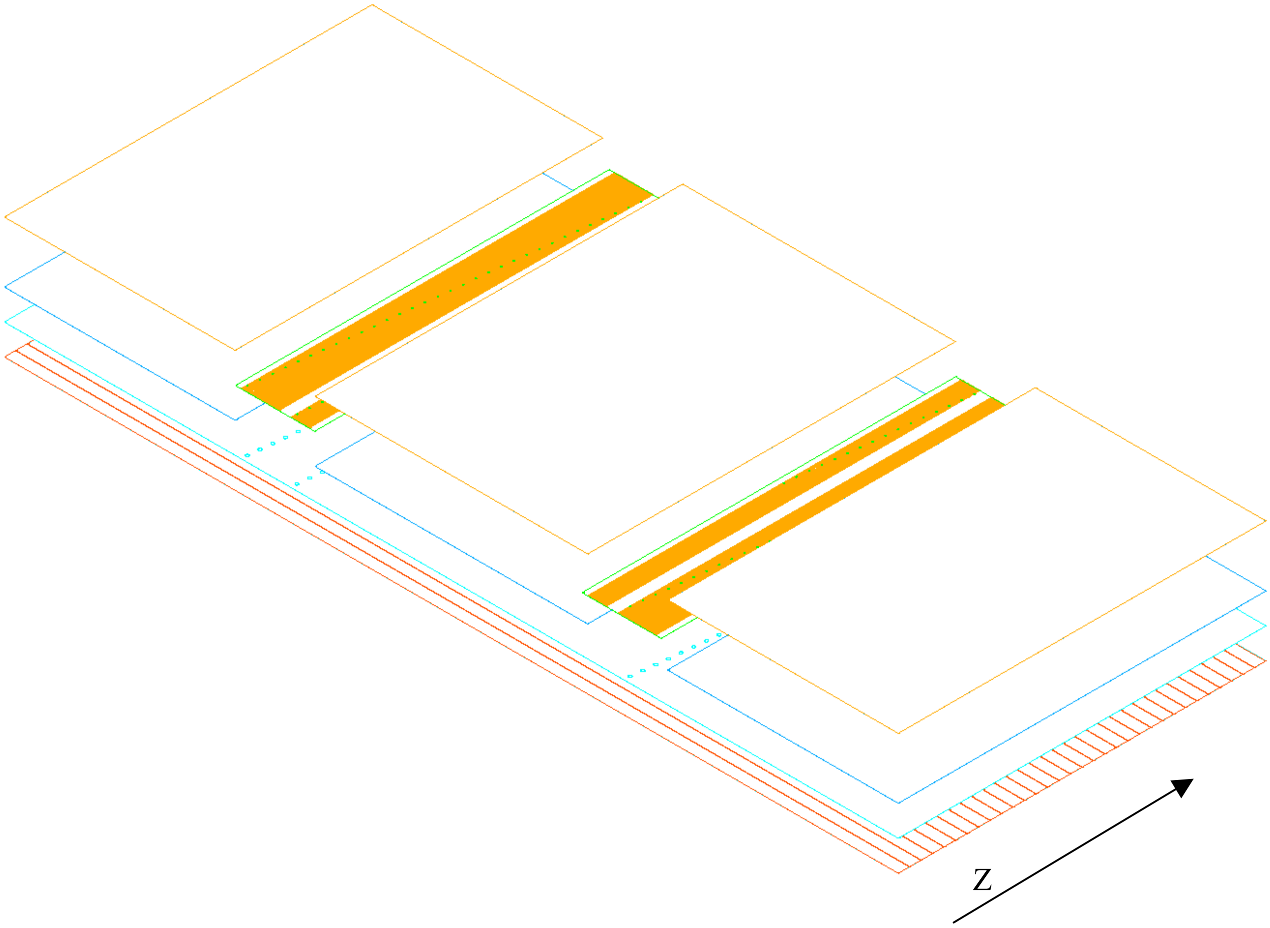


Figure 8. Construction of the z strips.

The structure of the Φ cathode strip plane is simpler than that of the z strip plane since it does not have the embedded flexible PCB. A transition board with connectors mating to a microribbon-twisted pair flat cable carries the signal to the front end cards fitted directly at the end of the Φ cathode strip plane. Figure 9 shows the layout of the prototype transition board.

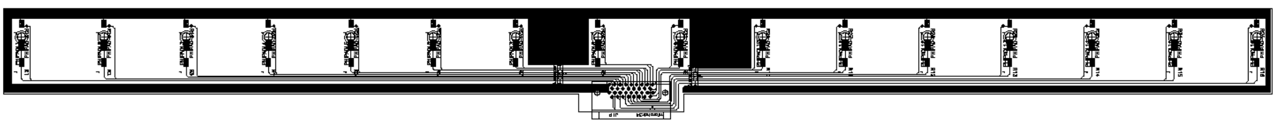


Figure 9. Transition board to bring to a connector the signals from 16 strips.

Installation into BaBar

Installation begins with the insertion into each gap of a z-strip covering an entire sextant. These strips will be attached to the iron and supported by gravity. Then, as shown in Fig. 10, the modules are brought onto a supporting structure and inserted into the gap on top of the strip layer. We have decided to leave a space of about 3 cm at one edge of each sextant layer for contingency in providing services and any extra cabling needed.

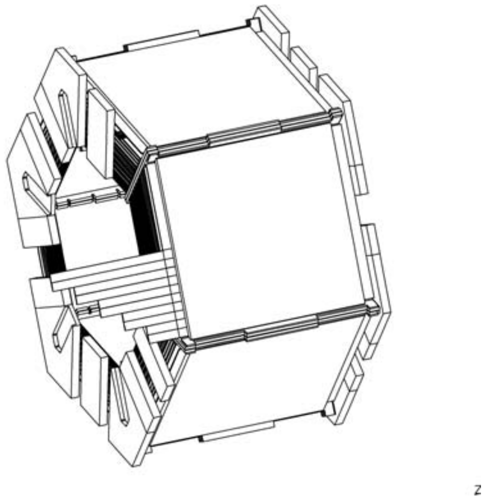


Figure 10. Installation of LST modules

Front-end Electronics

We plan to build new Front End Cards (FEC) rather than recycling the existing IFR FEC's. The new FEC's will have a different input section but will have the same interface to the existing IFR-FIFO boards, which will be used for the readout of the LST's and are well integrated in the BaBar DAQ. The data format will be the same as it was in the RPC system. This choice allows us to use the present DAQ software and electronics also with the LST system. Compared to the old FEC's, two new functions are provided: a) front-end amplification and b) a settable threshold.

As already mentioned, we plan to locate the electronics just outside the detector in a set of 12 crates (assuming the whole detector will have ~11000 channels). The new system will be based on boards which serve 64 channels: 4 input connectors, 64 amplifiers and comparators, and a Field Programmable Gate Array (FPGA) which will contain all the digital logic (delay, gate with the trigger, latch) for the 64 channels. The crates will have the added functionality of a DAC/ADC card to provide the thresholds, controlled by EPICS. Sufficient room is available in the existing cable conduits to carry all the signals from the strips to these crates, using microribbon cable, for the present configuration (12 layers, 192 channels per layer).

The baseline plan is to route the utilities (gas, HV) to the detector layers of a sextant, as well as the signals from the z cathode strip planes throughout 2 dedicated conduits (dim. 2"x 4") located at the backward end of each sextant. The Φ-strip signals will be routed throughout 2 dedicated conduits (dim. 2”x 4”) located at the forward end of each sextant. The baseline plan includes suitable fixtures fastened to the LST endplugs to help in an orderly routing of the utilities and the signal cables at the detector layer. These structures will occupy about 8cm at the backward end and 3cm at the forward end.

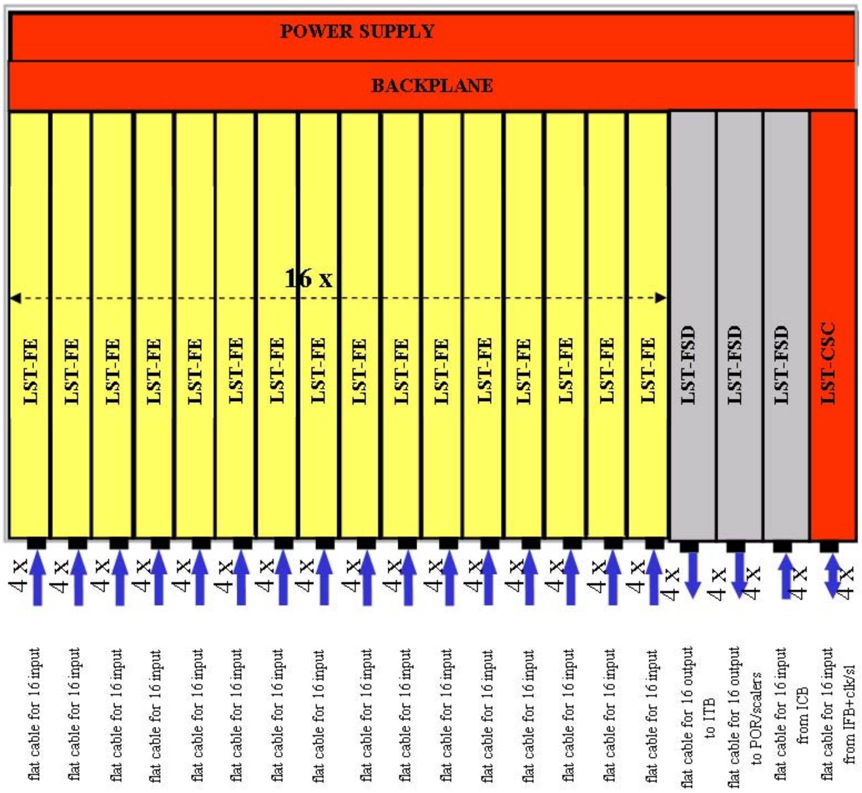


Figure 11. Layout of the LST front-end crate.

The layout of a front end crate is shown in Fig 11, and the block diagram of the LST Front End Card is shown in Fig. 12. The FPGA implements all the digital functions now implemented on 4 RPC FEC cards and also contains a microcontroller core which controls the thresholds and provides self-diagnostic features.

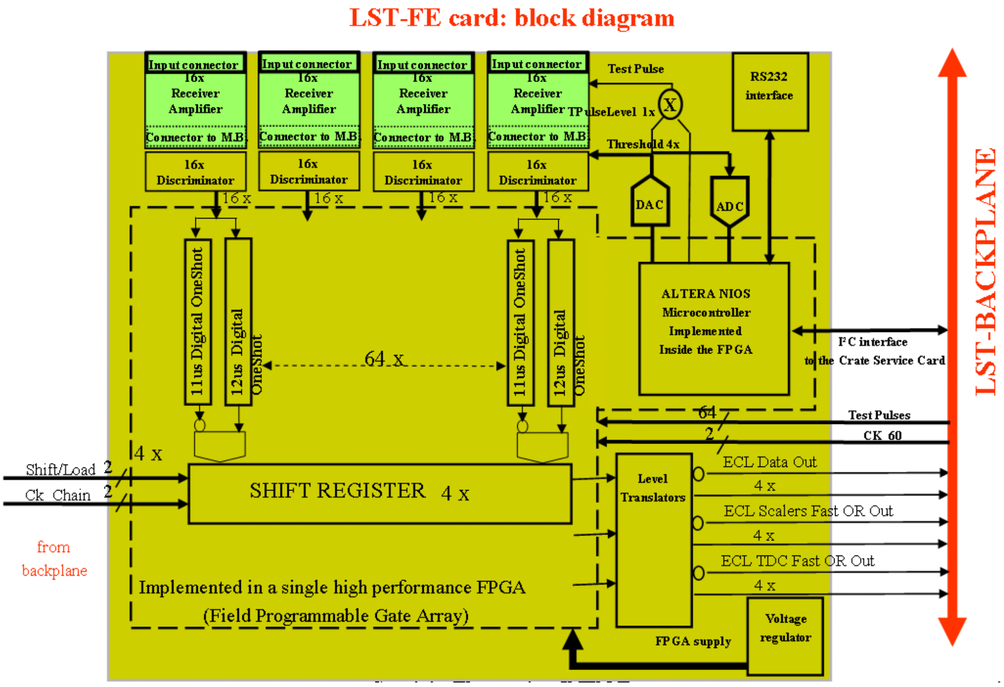


Fig. 12:Block diagram of the FE card.

We now briefly report on the performance of a Φ cathode strip plane, coupled to a prototype standard LST tube being tested in Ferrara. The Φ strip plane tested is a prototype made by General Tecnica to our specification. The overall length is 3.7m and the strip pitch is 42mm, half of the double layer LST's width. The measured strip parameters were: Z = 5 Ω; C = 3.2 - 3.5 nF.

The Φ strip signals were transmitted to a two-stage amplifier/discriminator described below, which has the baseline schematic shown in Fig. 13.

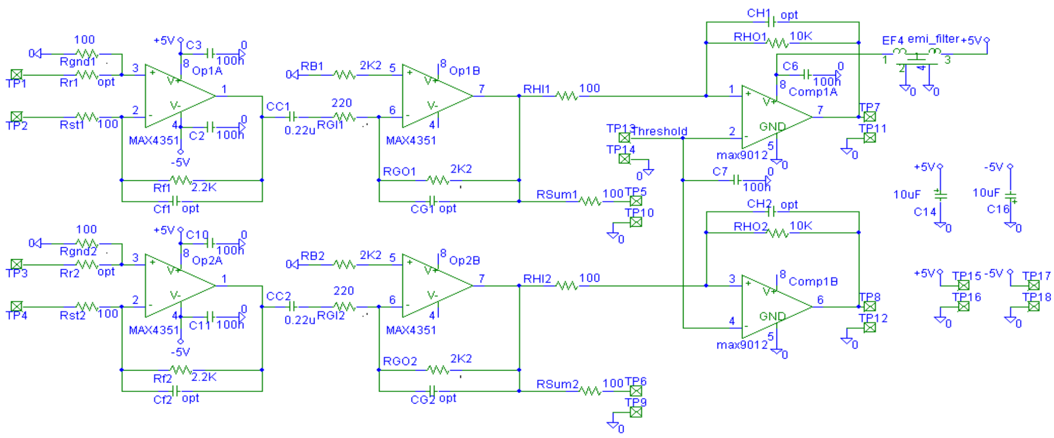


Figure13. Schematics of the prototype dual amplifier/discriminator

The first amplifier stage is an integrator with a 50ns time constant, AC-coupled to the second stage with a 10x gain. The overall sensitivity is 0.2V/pC. A suitable hysteresis network is provided around the discriminator. Its effects on the amplifier's output, evident on the waveform presented in Fig. 14, are of no consequence to the overall performance. The amplifier input impedance matches the single-ended characteristic impedance of the microribbon cable.

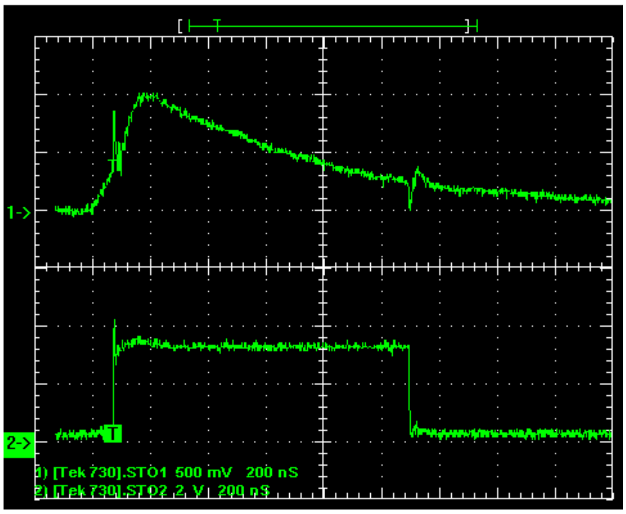


Figure 14. Response of the amplifier and discriminator to a 5 pC signal.

High Voltage System

A multi-channel High Voltage (HV) system is required to operate the LST detector. HV values around 5 kV are typical, with single tube currents less than 150 nA. In the baseline design, each single-layer tube will have four independent HV connections. For the double-layer solution the baseline is to use two HV connections per tube, one for each layer. This approach of multiple HV sections will help to reduce detector inefficiencies should cells in a tube develop HV problems. Each HV channel will include a current monitor with a resolution of better than 10 nA and a protection circuit that automatically limits the current and prevents a tube from getting permanently damaged. In addition, the HV system provides a mechanism to completely disconnect individual tubes.

In the baseline design, each HV section of a tube will be connected to separate channels of the high-voltage power supply. As an alternative we also consider solutions with two or more (tube) HV sections ganged together and controlled by a single power-supply channel. In this scenario we would still maintain separate HV cables to each section, allowing us to disconnect a cable should parts of a tube develop a high-voltage problem.

The HV system will consist of the following building blocks that will be discussed in greater detail in the following sections:

- HV power supply with current monitor and over current protection;
- HV distribution;
- HV cables from the electronics house to the detector;

- HV connector including HV capacitor.

The general requirements for the HV system are summarized in Table I.

	Double Layer	Large Cells
Individual LST tubes	2106	1164
HV Channels (Power supply) (depending on design choices, ie the number of tube sectors ganged together)	1053 - 4212	1164 - 4656
Worst case rate per tube (2 Hz/cm^2)	6.2 kHz	11 kHz
Max. tube current	620 nA (per layer)	1140 nA
Max. current per HV channel	620 – 2480 nA	285 – 1140 nA
Typical rate per tube (0.2 Hz/cm^2)	620 Hz	1.1 kHz
Typical tube current	62 nA (per layer)	110 nA
Typical current per HV channel	62 – 248 nA	28 – 110 nA

Table I. High Voltage System Requirements

Over-Current Protection

Limited streamer tubes, especially during the very first part of their life, have a certain probability of having self-sustained discharges resulting in a large current flow. It has been shown that leaving an LST in such a condition results in permanent damage. To prevent this problem, limited streamer tubes are usually conditioned over extended periods before being installed in the detector. Nevertheless, discharges will still happen from time to time. To protect the detector under these circumstances a passive circuit was developed by the University of Padova for the LST's of the ZEUS experiment. Figures 15 and 16 show the circuit diagram and performance, respectively. The circuit has been tested successfully at OSU and will be adopted for the baseline proposal.

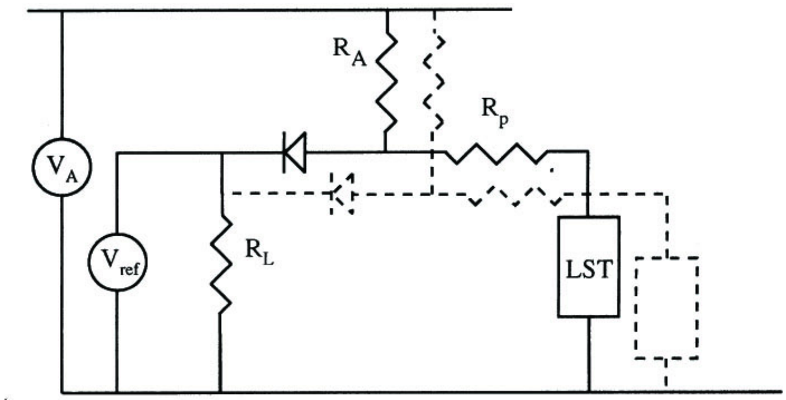


Figure 15. The Zeus over-current protection circuit.

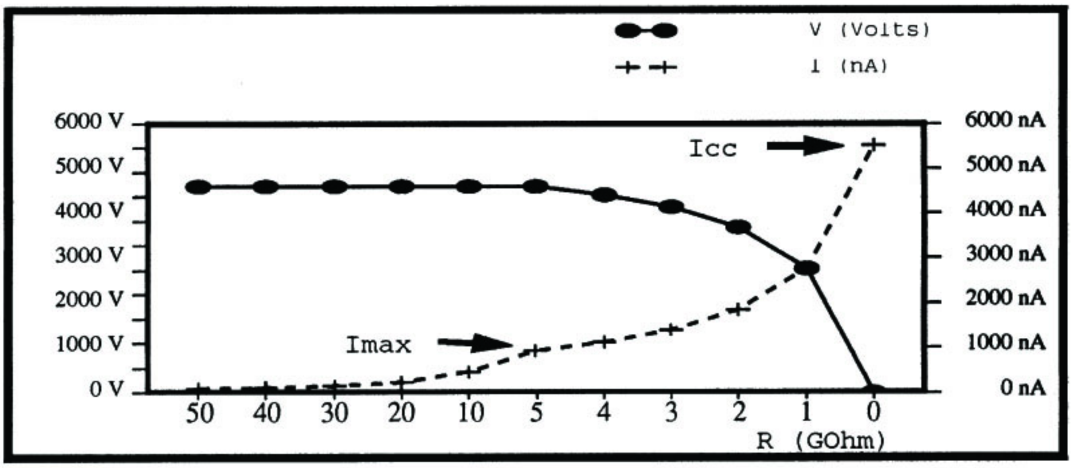


Figure 16. High voltage as function of chamber current using the ZEUS protection circuit.

HV cables

We shall use a multi-conductor HV cable made by Kerpen-Kabel. A picture of the cable is shown in Fig. 17. The outer jacket is halogen free and flame retardant. It comes in 25-wire or 37-wire configurations (others available on request) and is rated for 6 KV (wire to wire). Factory tests are performed at 12 KV. We have obtained a 25m-long sample of this cable which will allow us to perform our own measurements and to set up a complete HV test stand with cable lengths comparable to those we will encounter in IR-2. The baseline design is one high-voltage cable per gap per sextant.

Figure 17. HV cable.

HV Connector and Capacitor

The baseline solution includes a direct capacitive coupling between anodes and cathodes, similar to other LST detector designs. For example, SLD used a 2 nF capacitor between ground and HV mounted on a separate HV board close (< 1 m) to the detector. A schematic drawing of the SLD strip read-out is shown in Fig. 18 (from NIM A290 353-369). We studied the effect of the HV capacitor on the signals picked up by the strips and concluded that a 500 pF – 1000 pF capacitor has to be used. The exact value will be determined experimentally once the final design choices have been made and the prototype tubes become available. The 155 Ω resistor was included by SLD to reduce cross talk between channels. Its value was determined experimentally. Again, we will study this with our LST prototypes.

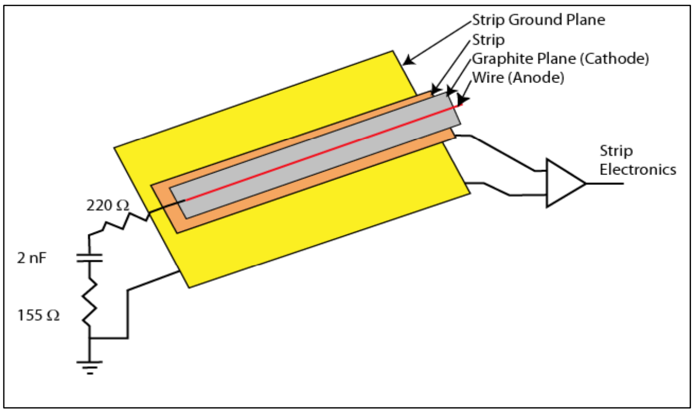


Figure 18. SLD streamer tube readout.

Inserted in the endcaps of each large-cell tube are four 2-mm plugs and one 2-mm jack used for high voltage and ground connections. The double-layer design would use two HV plugs, with the ground connection (one jack) being shared by both layers. The left picture in Fig. 19 shows the design for an integrated HV connector with capacitors and jacks for HV and ground connections for the small-cell configuration (the 155 Ω resistor will be added eventually). A similar solution for the large cell tubes will be available in early summer. The right picture in Fig. 19 shows the complete connector with a simplified model of a tube endcap.

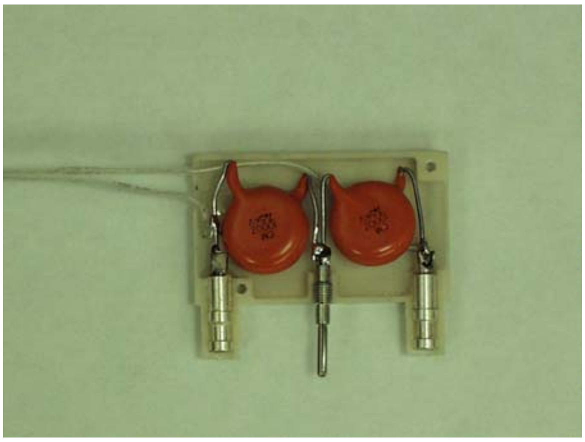


Figure 19. Opened prototype HV connector (left), connector plus endcap (right).

HV Power Supply and Distribution

The high voltage power supplies for the LST detector have to provide regulated HV up to 5 KV, current monitoring, and over-current protection. While the CAEN SY546 system could provide an adequate HV solution for the LST detector there are still many outstanding issues (repairs, availability, affordability, protection circuit) that make this an unlikely solution. We have therefore decided to adopt a custom-designed HV system as our basline proposal.

Custom-Designed HV System

A custom high-voltage power system tailored to the needs of the BaBar LST detector has been designed at OSU. The system is quite similar to the SY546 system, with a number of output channels sharing a common high-voltage setting. Here are a few of the relevant features:

- Self-contained unit ("Pizza Box") with 96 channels;
- Outputs protected against discharge (ZEUS protection circuit);
- Integrated controller for ramping, current monitor, HV setting etc. (1.5 V resolution);
- Individual current measurement for each channel (10 nA resolution);
- Fast Ethernet Interface to control system;
- 2 NIM inputs for a general inhibit and an automatic ramp-down of the high voltage during injection;
- Significantly reduced cost per channel compared to CAEN SY546 system;

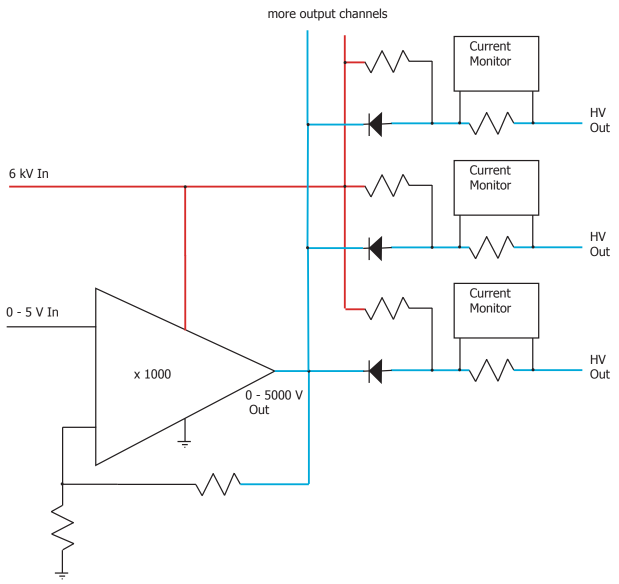


Figure 20. Schematic (left) and photo (right) of the protopye custom-designed HV system.

Figure 20 shows a schematic of the circuit and a photo of a prototype HV board. Several high-voltage transistors are configured as an op-amp that provides an adjustable output voltage for 48 channels. As in the SY546 system, the output channels are set to the same voltage but current monitoring and over-current protection are implemented on a channel-by-channel basis. As indicated in Fig. 20, the current-limiting circuit from ZEUS is integrated in this design. Not shown in the figure is the digital part, which includes a Xilinx FPGA and a micro-controller with an integrated FastEthernet interface. A first prototype with 5 channels (photo in Fig. 20) has been built and tested successfully (linearity of current monitor, output protection, noise and ripple). The current-monitor circuit is based on a VCO chip (voltage to frequency converter), which offers fast response time on the order of a few microseconds. A complete 96-channel prototype power supply is under construction.

CAEN SY546 HV Supply

The alternative proposal is to use a commercial system available from CAEN. This system, the SY546 developed for the LVD experiment at the "Gran Sasso" laboratory, consists of 4u highcrates hosting 8 HV boards. Each board has one HV regulated power supply that feeds 12 output channels. All outputs are set to the same voltage but the current of each channel is individually monitored and alarm thresholds can be set for each of them.

The SY546 system is no longer in the CAEN catalogue, but the Padova group has learned from CAEN that they are willing (and able) to produce this system for BaBar should we decide to go this route. Initial cost estimates are $160,000 for 1000 HV channels. We have obtained several 06-channel SY546 crates from LVD that we will use for the quality control work at PHT, and an additional crate was sent to OSU for evaluation purposes. We have obtained two PCI-based system controller modules and the development of the control software has started. We have also learned that an opto-coupler component in the SY546 modules is failing. For a nominal fee this can be repaired by CAEN. Although the SY546 power supply has a built-in trip mechanism that shuts off an output channel should the current rise above a preset threshold, it does not include the over-current protection circuit discussed above. We are investigating if and how this circuit can be added to the SY546 HV boards.

Detector Control

The Experimental Physics and Industrial Control System (EPICS) will be used to monitor the LST system. The Detector Control system is logically divided into high voltage (HV), gas, and environmental subsystems, and we plan to use the existing IFR input/ouput controllers for the LST EPICS system. Existing DCH HV software (EPICS panels, state machines, etc.), which has proven to be effective and highly reliable over the last four years of BaBar operation, will be the template for the LST HV system, thus minimizing the necessary software development effort. Figure 21 lists the parameters that are available in the current design. The HV control system will be implemented in the form of a state machine that will control ramping between programmable setpoints (V0/V1). As an example of the flexibility of this system, it would be straightforward to configure the state machine to automatically adjust the HV as a function of gas pressure (to ensure stable running at the plateau). Further tests with the prototype tubes will determine if such a feedback system is necessary.

Parameter	Description
V	Voltage monitor (per board)
I	Current monitor (per chan)
Vmax	Maximum allowed voltage
Status	Channel Status (see table)
V0/V1	V0 and V1 setpoints
I0/I1	I0 and I1 setpoints
Trip Time	Max time for I > I0/I1 before trip
Ramp Up/Dn Rate	dV/dt for ramping up/dn

Status	Description
Vmax	Channel is at maximum voltage
Tripped	Channel is tripped
Over/Under Voltage	Channel is over/under voltage (V0/V1)
Over/Under Current	Channel is over/under current (I0/I1)
Ramping Up/Dn	Channel is ramping up/dn
On/Off	Channel is on/off

Figure 21. List of available HV parameters for the monitoring system.

RUNNABLE/INJECTABLE flags will be defined by a separate state machine, using input EPICS data from the entire system. For example, the status of the RUNNABLE flag could depend on the number of HV channels that are OK, with a granularity either at the layer or sextant level. For the INJECTABLE flag we plan to lower the HV by 300-500V during injection to minimize aging of the LST's. The definition of these flags is determined in software and the final configuration will be determined before data taking (Fall 2004).

Although the gas system design is still evolving, it is clear that control and monitoring will involve several features: the control and status of valves; gas flow, pressure, and mixture; temperature; and humidity. In particular, sensors that monitor gas bubblers near the detector inputs will be monitored in EPICS, giving quick diagnostic information in the case of disruption in gas flow to a single layer. Here, the EPICS software for the IFR gas system provides a general design template.

Monitoring of the voltage and ambient temperature of the front end electronics will also be available in EPICS. We plan to recycle the IFR temperature monitors, which, in principle, provide two temperature measurements per layer. However, we anticipate the need for only a few measurements per sextant. Alarms for the HV, gas, and environmental systems can either be hardwired (SIAM'S) or defined in software. A summary of the LST system status will be available in EPICS and forwarded to the BaBar Alarm Handler.

Access to archived data is critical to the ability to maintain the detector at its optimal performance. Archiving of all EPICS data for the LST system, in particular the currents for each channel, will be provided by the existing OdcArchiver processes. Retrieval of this information is via standard tools. Having this data available will allow experts to carefully monitor trends in detector performance at the tube level, giving the ability for the operations team to identify potentially failing tubes in time to apply preventive measures.

Gas System

The components of the gas mixture, $Ar/C_4H_{10}/CO_2$ (2.5/9.5/88), will be mixed in the existing gas shack before the mixture is piped to IR-2 and distributed to the modules. The system will include the following features.

Mixer: A system with mass-flow meters, shut-off valves, and mass-flow controllers is suitable for our purpose. A buffer tank would not be needed. We have begun to develop this system, and expect that it will cost less than $40k.

Safety: The system will be similar to the SLD system. It uses redundant gas flow measurements to ensure that the gas mixture sent to IR-2 stays within non-flammable limits. This can be integrated with the existing gas shack safety system to shut off the gas flow in the event that the mixture strays from normal. We have contacted the designers of the gas shack safety system, who have assured us that this is possible.

Storage: Argon and isobutane are already available and we could tee from the current feeds. CO_2 will require a new setup. All the existing storage space near the gas shack is in use. This issue requires further investigation but appears soluble.

Pipe to IR-2: We will install two new supply gas pipes from the gas shack to the detector hall, and use an existing exhaust line.

Distribution: We will re-use as much of the existing RPC gas distribution infrastructure such as bubbler boxes, manifolds etc as possible. Additional hardware requirements are being defined.

R&D Progress

Our R&D program has been concentrated on several critical issues:

- Selection of safe gas mixture;
- Comparison of electric field variation for large and small cell configurations;
- Rate capability;
- Wire surface quality and uniformity;
- Aging test for LST with PVC and ZEUS gas mixture;
- Performance of the double layer configuration and standard prototypes.

Selection of Safe Gas Mixture

Three collider experiments have used safe gas mixtures instead of the regular flammable binary gas mixture:

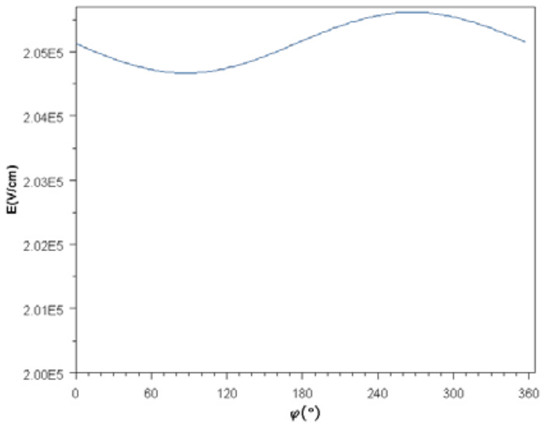
1. SLD: Ar/ IsoButane/CO2 (2.5/9.5/88)
2. ZEUS: Ar/ IsoButane/CO2 (3/8/89)
3. PHENIX: IsoButane/CO2 (9/91)

Initial studies on the 9x9mm^2 prototype tubes suggest that the SLD gas mixture provides a wider plateau region compared to the ZEUS mixture. We therefore plan to use the SLD gas mixture as our baseline proposal.

Study of Electric Field

We have performed a study of the difference of the electric field distributions of four geometries: a) large 15x17mm^2 cell (baseline), b) standard 9×9mm^2 cell, c) smaller 8×9mm^2 cell with anode wire at the center, and d) 8×9mm^2 cell with the wire equidistant from the three conductive walls. The CERN program Garfield and the ANSYS Finite Element Analysis program were used to study the relative variation of the electric field, $(E_{max}-E_{min})/E_{max}$, on the anode-wire surface. For a tube cell with four conducting walls, the electric field on the anode wire surface should be constant. However, for a coverless cell as used in all LST's the electric field varies around the circumference of the wire.

In Figure 22 we show the results for small- and large-cell geometries. The electric-field variation is significantly reduced with the large-cell design, which should lead to increased stability of operation with respect to the small-cell tubes. Table II summarizes the results of this study.



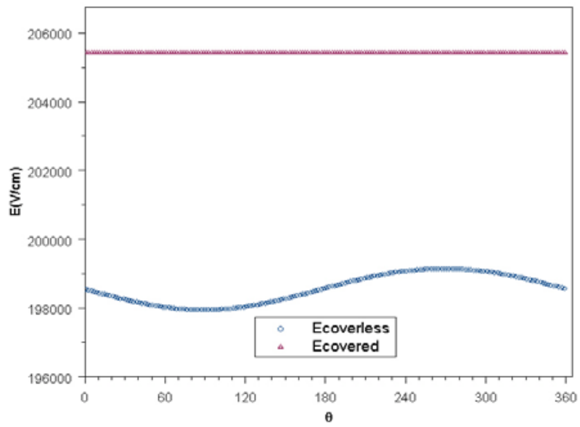


Figure 22. Electric field around the anode wire for large (left) and small (right) cells.

	ST type (standard cell)	SC type (anode at center)	SE type (anode equally distant to conductive walls)	Large cell
Cell size	9X9mm^2	9X8mm^2	9X8mm^2	17X15mm^2
V_a (V)	4700	4700	4700	5500
Emax (V/cm)	199,137	199,704	196,126	205,608
Emin (V/cm)	197,938	198,002	194,352	204,660
(Emax – Emin) / Emax	0.6%	0.85%	0.9%	0.46%
ΔV(V)*	28.3	40.0	42.5	25.0

Table II. Comparison of electric field variation in four different cell geometries.

Rate Capability

The highest expected rate in the barrel LST at a luminosity of 4×10^{34}/cm^2/sec is ~ 2 Hz/cm^2. This is much less than in the IFR *endcap* layer 18, where the rate will be 100 Hz/cm^2. To test the capability of the LST's we have compared charge spectra under varying dose rates. Fig. 23 shows that the charge spectrum remains essentially unchanged up to an effective rate of 111 Hz/cm^2, which indicates that the LST modules are a safe option, eventually even for the endcap detector.

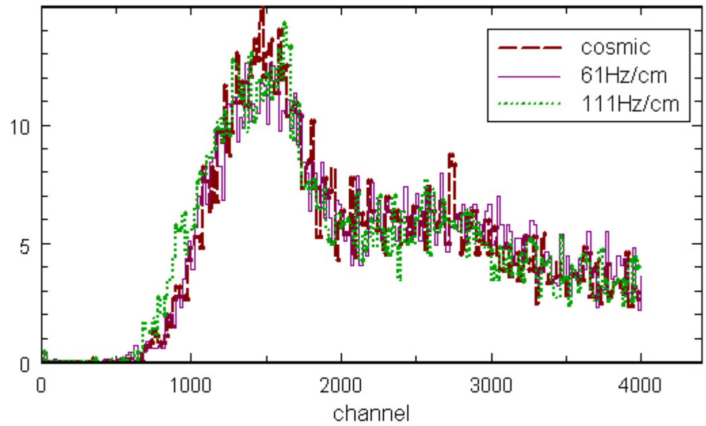


Figure 23. Measured charged spectra for various dose rates.

Wire Surface Quality and Uniformity

The surface quality of Au- and Ag-coated wires was studied with a Phillips XL30 FEG-SEM electron microscope and PGT-IMIX PTS EDX x-ray analysis system at the Princeton Image and Analysis Center. The wire diameters are 101μm (Au) and 107μm (Ag), and both Au and Ag coatings appear smooth under the microscope. From the known composition and diameter of the wire, we estimate a significantly thicker coating for Au (2.8μm) than for Ag (1.5μm). We calculate that a variation in total wire diameter of 5% leads to a voltage difference of 200V, which would significantly affect the parameters of the plateau. We have therefore set a requirement on wire diameter of (100 ± 1)μm.

Aging Study

Jerry Va'vra estimates that by 2010 the accumulated charge dose for barrel IFR layer 1 will be ~50mC/cm^2. To study the impact of such a dose, an aging test is being conducted with a standard LST tube with a graphite-coated PVC profile, strung with 100mm Au-coated Cu-Be wire. The PVC envelope was heat-sealed and the wires were heat-fastened onto plastic supports. No glue was used.

Figure 24 shows the results of the aging test. Through May 14, 2003, the accumulated charge dose has reached 750mC/cm^2, with no significant degradation in performance. After an initial decrease of the streamer signal at a rate of –70% per C/cm^2 of dose, the tube's performance has been stable. Even assuming the initial rate of decrease, the barrel LSTs should function with high performance for the expected lifetime of the experiment.

Looking further, we note that the estimated total charge dose in layer 18 of a forward *endcap* LST would be 2 C/cm^2. We plan to continue our aging tests to see if LST's with PVC can reach this limit. In addition, when the large-cell prototypes become available we plan to begin more aging tests as soon as possible.

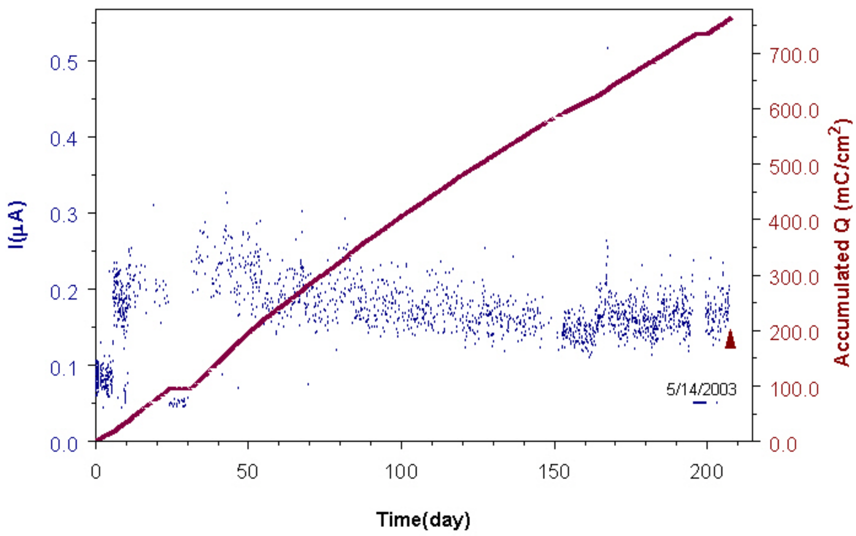


Figure 24. Results of LST aging test.

Performance of the Double-Layer Configuration

Due to the intrinsic dead space of the LST chamber, the efficiency of a standard tube is limited to ~90%. The baseline proposal solves this problem by having larger cells, while the alternative proposal solves it by having two layers of small-cell tubes. Monte-Carlo calculations show that the efficiency of the double-layer design can easily pass 96% and maintain a total thickness within 23mm. We propose to read out both Φ and z coordinates from strip planes, therefore we have to check if the induced signal at the far-side strip is still large enough to be recorded. The test results are summarized in Table III, which shows good efficiency even at the far-side strip.

HV on	Efficiency (%)
Both layers	96.4
Top layer	92.5
Bottom layer	89.8

Table III. Efficiency for double-layer configuration (signals are read out from the top strip only).

The distribution of strip signals has been studied for both Φ and z strips. For the double-layer configuration it is found that disitributions are much narrower when the near-side layer is on, compared to the case when only the far-side layer is active. Figure 25 shows the distribution of charge on z strips when either one or the other layer is active. For these studies, the strip pitch was 2.9cm and the strip signal was amplified (x10). We have also studied the effect of grounding the conductive support rib between tubes. We find that grounding the rib shields the strips on the opposite side of the hit cell, so we have decided to isolate the rib from ground in the final setup. Table IV summarizes the results of the study on Φ strips.

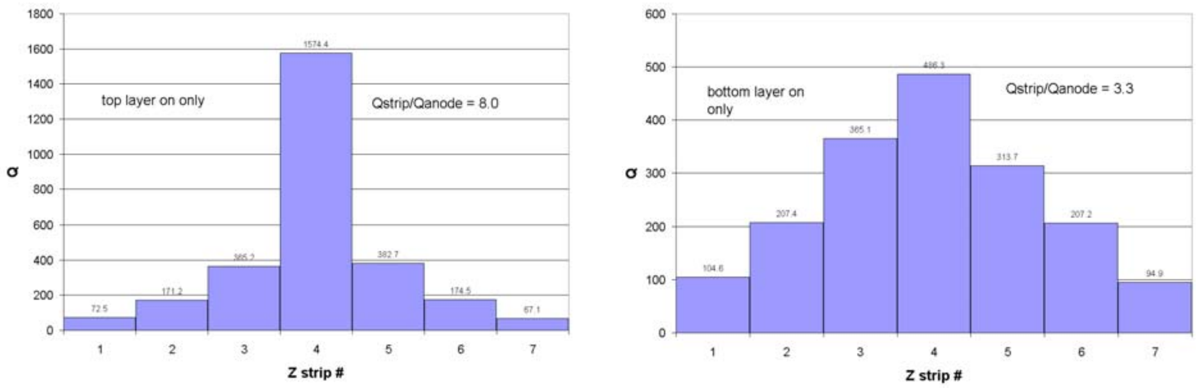


Figure 25. Charge distribution on z strips for near layer (left) and far layer (right) active.

Performance of Standard Prototypes

Standard prototypes have been tested at Ferrara (6 tubes arrived on May 3), Princeton (10 tubes arrived on May 9), and OSU (6 tubes arrivied on May 12). Similar procedures for initial gas flow and HV training were performed at all three institutions: flow gas for 2-3 days, then 2-3 days to raise HV gradually up to ~5000V. One tube at Ferrara and one tube at OSU failed to hold voltage at the plateau.

Layer	Cu tape	Ground	Source at	Qn / Q0	Qstrip/Qanode	Qstrip
Bottom	No	No	#5(Rme)	0.33	2.54	1244
	No	No	#7(Rhi)	0.188	2.94	2032
Bottom	Yes	No	#5	0.425	3.2	1416
	Yes	No	#7	0.3	3.3	1648
Bottom	Yes	Yes	#5	0.065	1.66	713
	Yes	Yes	#7	0.054	1.84	931
Top	Yes	No	#5	0.17	5.9	3005
	Yes	No	#7	0.19	5.9	2540
Top	Yes	Yes	#5	0.033	4.7	2471
	Yes	Yes	#7	0.04	4.59	1932

Table IV. Results of conductive rib and Q-distribution studies for the Φ strips. Q_n/Q_0 is the ratio of charge on the adjacent strip to the charge on the hit strip, Q_{strip}/Q_{anode} is the ratio of charge collected on the strips to the charge collected on the anode wire, and Q_{strip} is the total charge collected on the strips.

HV plateau curves have been measured at Ferrara, Princeton, and OSU after the tubes were conditiosed. Figure 26 shows the results obtained at Ferrara using the SLD gas mixture, a threshold of 30mV, and a deadtime of 400ns. Good plateaus (~400V wide) were obtained for Au-coated wires, while Ag-coated wires have smaller, but still reasonable, plateaus. Initial results at Princeton and OSU were not as good. The left plot in Fig. 27 shows the plateau curves for six of the Princeton tubes; obtained after ~6 days of HV training with the ZEUS gas mixture, a threshold of 30mV, and a deadtime of 300ns. No obvious plateau region is seen. Similar results were obtained with the tubes at OSU using the same gas mixture, threshold, and deadtime.

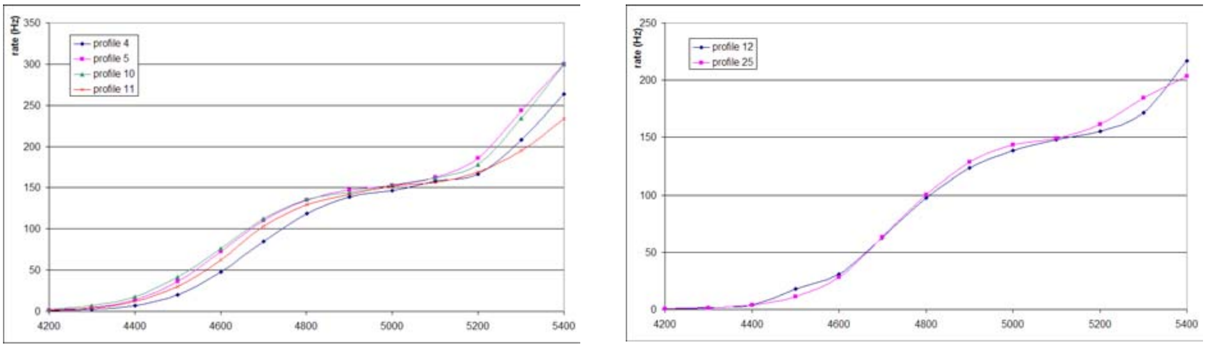


Figure 26. Results of plateau test at Ferrara for tubes with Au- (left) and Ag-coated (right) wires. The SLD gas mixture was used.

Further tests were performed to understand the apparent discrepancy between results at Ferrara vs. Princeton/OSU. To check that the tubes had not been damaged in transit to the US, four of the Princeton tubes were tested with the binary gas mixture, Ar/C_4H_{10} (31/69), used for the measurements at PHT. The results show good plateaus in three of the four tubes (right plot in Fig. 27), confirming the results obtained at the manufacturer. It was also found that lowering the discriminator threshold to 5mV improved the length of the plateau region significantly.

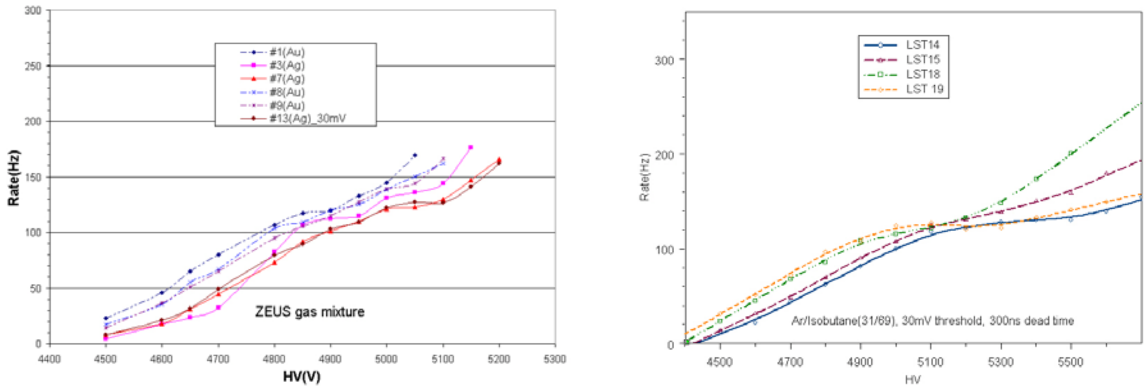


Figure 27. Results of the plateau test at Princeton using the Zeus (left) and binary (right) gas mixtures.

The fact that Princeton tubes with the binary gas mixture give similar results to those obtained at PHT seems to indicate that differences between results at Ferrara and Princeton/OSU are not due to damage or defects caused by the longer shipping distance. We suspect that the SLD gas mixture used at Ferrara, with a higher isobutane concentration, probably explains the better plateau results. However, the thresholds and deadtimes were different as well, so we plan to remeasure all tubes using a consistent set of conditions: SLD gas, 30mV threshold, and 300ns deadtime.

Summary of R&D progress since the collaboration decision in December 2002 to pursue the LST solution.

- Aging tests have shown that the performance of PVC tubes is still satisfactory after operation with an irradiation well above what can be expected from an upgraded PEP II. We have therefore decided to use PVC beause it is cheap, and easier to extrude than other plastics: standard-cell tubes made of PVC have been coated with the water-based carbon paint with good result: average resistivity has been within the desired range, and there is no evidence of "bald spots," which cause tube failure.
- The $8x9mm^2$ tubes made by modifying old standard profiles have shown only sporadically good plateaus. Further measurements have shown that the mechanical properties (ie, dimensions) were well out of tolerances.
- To check on the quality of the tube preparation procedures we have ordered twenty 4m long profiles of standard cell size: ten with silver coated wires, and ten with gold coated. 19 such tubes have shown good plateaus at Pol.Hi.Tech (PHT) and have been delivered to us for detailed testing. They have been coated with the "standard" water based paint, and the resistivities have been measured; their distributions are good. We have measured plateaus again, with good results.
- We are working with PHT to improve the cleanliness of the tubes: we especially fear the possible presence of hair (not so much thick human hair, rather thin wool or fiber). PHT has prepared two enclosures – one for the coating and the other for the stringing – where we want to keep at least "Class 100.000 conditions," *i.e.* more than an order of magnitude fewer particles than in normal atmosphere. Quotes are being obtained from specialized firms to equip such enclosures with all the necessary equipment: absolute filters, proper floor treatment etc.
- We have ordered dies for the extrusion of proper profiles and sleeves for small (8x9) and large (15x17) cells. The other pieces needed for the construction of the tubes have been designed and fabricated. We expect 10 large cell tubes by the first week of June, and 20 small cell ones a week later.
- We have prepared QC specifications for the tube production (see Appendix).
- Detailed plans have been made for the division of layers into modules, the preparation of modules, and the handling of the tubes and modules, including tests of acceptance.
- Prototypes of Φ-strips have been ordered and have been received. Prototypes of z-strips – complete with their signal cables - have been ordered and should be delivered this week. Components for the production of 16 front end electronics channels have been ordered and have been received. A prototype card has been made and tested with the signals from a standard cell LST read by the prototype Φ-strips, with good results.
- The program for the FPGA's, which read out the LSTs exactly in the same way as the present RPC FEC cards, has been written and simulated: it performs as expected (ie, it reads the LST data into the BaBar DAQ).

- Two alternative solutions have been identified for the HV system, one custom made and the other built by CAEN. They are being evaluated.

Simulation

LST MonteCarlo simulation will be based on the current BaBar software infrastracture, which uses Geant4 for the tracking and the interactions of the particles through the detector. It will reuse most of the current code, taking advantage of its object-oriented design. Most of the changes will be concentrated in the geometrical and physical description of the new active detectors. The conversion of the Geant information into realistic detector hits (streamer probability, strip multiplicity, etc.) will be based on prototype data. One of the early application of the simulation will be the study of the physics impact vs. the active length of the tubes.

Schedule and Cost

The schedule for this project is prepared using Microsoft Project. The format is in the Gannt style with heirarchial organization using the Work Breakdown Structure.

The first level in the schedule structure is, of course, the LST project itself. The second level of structure comprises the major subtasks of this project such as tube production, high voltage system, quality control, and so forth. Each of second level structures is actually a stand-alone project file, or *subproject*. This allows the organizer of the *master project* to let the person responsible for each major subtask to create their own task list and schedule independently from the remainder of the project.

Once the subprojects are created, they are collected by the organizer of the master project and merged into single file. It is the responsibility of the master project organizer to resolve any scheduling conflicts between the subprojects and then set a master project baseline against which future progress will be measured.

At the same time that the task scheduling is being devised, the cost of each subproject is determined. At the subproject level, the costing exercise is straightforward since the subproject is locally contained. At the master project level, however, this is no longer true. The master project spans two countries and different institutions such as universities and national laboratories. So, both different currencies and different accounting practices have to be taken into account.

The different accounting practices come into play when calculating labor costs. For this reason, both labor hours and the “dollar value” of the labor is given. By focusing on the number of man-hours for a given task versus another task, it is expected that a truer comparison of the actual effort expended by each university or laboratory may be made.

We are actively working to fill out the WBS and thereby obtain a reviewable cost estimate. This should be ready by the end of June.

Milestones

June 15, 2003 : Large-cell Prototypes tested at PHT. Final test with full-width strips.

June 30, 2003: Decision between large cell and small cell tube configuration.

Aug 1, 2003 : Start tender for the full tube production. Place separate orders for materials and molds.

Aug 1, 2003: First prototype module assembled in U.S.

Oct 1, 2003 : Pol.Hi.Tech starts full tube production.

Dec 30, 2003 : First 1/3 tube production done, ready for QA and long term test.

Feb 1, 2004 : Full production finished at PHT, first 1/3 production ready for shipping.

Feb 10, 2004 : All module components for 2 sextants available at US assembly sites.

March 1, 2004 : Module assembly begins at Princeton and OSU.

Mar 1, 2004 : All tubes ready for shipping to USA.

May 1, 2004 : 1/3 of modules shipped from Princeton /OSU to SLAC.

July 1, 2004 : Begin installation of first two sextants into BaBar.

Sept 1, 2004 : All modules shipped to SLAC.

July 1, 2005 : Begin installation of last four sextants.

APPENDIX -- LST QC AND TEST PROCEDURES

I. At the Production Site

Quality Control (QC) procedures have been discussed in several meetings with the company which will manufacture the detectors (PHT). For some of the procedures described below the equipment will be provided by BaBar. Acceptance criteria for the various stages will be established in agreement with the company. After a description of the general infrastructure we will give a brief discussion of the main QC steps, i.e.:

- Inspection of profiles
  - –Mechanical
  - –Graphite coating
  - –Resistivity Measurement
- Inspection of jackets, endcaps, circuit cards
- Gas tightness (leak test)
- Wire check
- HV conditioning and plateau measurement
- Long range tests

General Infrastructure

QC data and any other relevant information will be collected by hand or, whenever possibile, automatically, by means of DAQ stations located on site. In order to make data entry easier and quicker, barcode labels will be used to identify the various parts and components, as well as some of some QC tests (e.g. the quality of the graphite coating, see below).

All QC operations will be carried out by BaBar physicists and PHT personnel. BaBar will organize shifts to guarantee the presence of the appropriate number of people during the production of the detectors (probably 3-4 each day).

The DAQ stations will be connected with each other by means of a wireless Local Area Network. The output of the DAQ stations will be simple text files reporting a common reference record (e.g. the barcode of the tube under construction) plus all the relevant quantities related to the test underway (e.g. the resistivity values). At the end of each test the station(s) will send the files to a central server which will then put this information in the local “production” database.

At the end of each day, all data files will sent to a server outside the production site, to be imported in the “official” (off-site) LST database. To this end, a (maybe slow) connection with the internet will be available.

DAQ and test stations. There will be four dedicated DAQ/test stations dedicated to the following tasks:

- Measurement of the resistivity of the graphite-coated profiles.
- Wire/tube association.
- HV conditioning and plateau measurements
- Long range tests.

In addition there will be 1 or 2 general purpose, portable stations which will be used for other operations such as reporting the results of the visual inspection of the graphite coating, the gas tightness tests, the measurement of the wire position and the capacitance measurements. All these operations will be described below. The DAQ software will be written using Labview.

Local Production Database. The local production database will be populated by automatic insertion of data produced by the DAQ stations, as well as by data typed in manually by operators, whenever necessary. The database will reside on a central server, which will also be used for network management and for backups. Relational databases such as mySQL are being considered.

Inspection of Comb Shape Profiles

Mechanical. Every profile shall be visually inspected to make sure there are no observable bents, dents, cracks. This check will be carried out by the company which fabricates the profiles before they are delivered to PHT. After delivery, profiles will be measured on a sampling basis, to make sure that their dimensions are within the required mechanical tolerances.

Graphite coating. After coating, all profiles will be visually checked. Big defects will be corrected, smaller, acceptable defects will be recorded together with their position along the tube.

Resistivity measurement. The surface resistivity is monitored by measuring the resistance between a pair of appropriate electrodes. The resistivity will be measured in an automatized way at 50 cm intervals along the tube's length, for each of the 8 cells, on the bottom of the cell. In addition, we are considering the possibility of also measuring the resistivity of the side walls. The tube will be accepted if the resistivities measured lie within a predefined range.

Inspection of parts

Jackets will be checked visually for mechanical integrity. Measurements will be made to make sure that they have the correct dimensions. These checks will be made on a sampling basis after production.

Endcaps. The electrodes and the gas inlet and outlet are visually inspected to insure they are in good integrity and there is no crack in the endcaps.

Circuit Cards. The solder joints are visually inspected to check for cold solder joints and for sharp wire ends. The entire circuit is then checked for proper continuity.

Gas tightness

Gas leakage test is performed by completely submerging the tubes in water at 15-20 mbar overpressure in a "knife.edge" fashion. Less than 1 small bubble per minute is required. Leaking tubes are fixed with PVC glue if possible and tested again. If accepted, the information that the tube has been repaired will be registered and the position in which the repair has occured will be clearly marked. Tubes exceeding the 1 small bubble per minute limit will be rejected.

Wire Check

Wire quality. At the beginning of each new spool a sample of wire will be sent to Princeton to be checked (mechanical check, diameter measurement). A wire sample from each spool will be kept and appropriately identified, in order to keep track in which tubes it is used. To this end a dedicated DAQ station will register, for each tube, the 8 spools whose wires are used to string the tube.

Wire position. Each strung profile shall be visually inspected, to make sure the wires are correctly positioned in the wire holders. In addition to that the possibility is being considered to measure the distance between the wire and the bottom of the profile for a sample of tubes.

Wire connection and wire tension. Tests and measurements shall be carried out to ensure that no wires are broken, that they are all connected and that they all have the proper tension. To this end the capacitance between pin and ground at one end of the chamber will be measured.

Electrical conditioning and Plateau measurement

An **electrical conditioning** is performed for each tube for a minimum of 7 days (even if the drawn current becomes acceptable in less than 7 days). A current limiting power supply will be used. The tubes will be fluxed with a ternary gas mixture (88 % CO_2, 9.5 % Isobutane, 2.5 % Argon).

- Each tube will be kept one day (24 H) under the ternary gas mixture flux for at least 6 volumes.
- Each tube will take a minimum of 8 hours and a maximum of 24 hours to reach 2500 V; they will take a minimum of 8 hours and a maximum of 24 hours to go from 2500 V to 4900 V. The total time being a maximum of 48 h to reach 4900 V.
- Each tube drawing a current greater than 5 μA is rejected.
- The tubes are kept at 4900 V for 4 days (96 H). The current drawn must not exceed 2 μA for the first day and, for the remaining 3 days, must not exceed 150nA for more than 5% of the time. Tubes failing these tests are rejected.

Plateau. For each tube the plateau will be measured using the ternary gas mixture. The exact specifications for the plateau measurements will be established after the prototype tests being done in Ferrara and Princeton.

Long Range Tests

Each tube will be kept at the maximum operating voltage (as resulting from the plateau curve) for a period of thirty days, during which the current drawn by the tube must not exceed 100 nA for more than 5 % of the time it is monitored. In addition no observed activity allowed in the second half of the history.

II: Q/C During Module Assembly at Ohio State and Princeton

This document outlines the quality control procedures and tests we will perform at Ohio State and at Princeton before and after the tubes are assembled to modules. Some test details will be defined after we complete our prototype studies.

1. **Inspection of Shipping Boxes**
    - Every shipping box shall be visually inspected for any transport damages.
    - The bar code tag on the shipping box will be scanned and the appropriate information in the QC database will be updated (arrival time, location, possible damage etc.)

2. **Tube resistance and capacitance**
   With the tubes still in the shipping box but with the box endplates removed we perform the following tests on each tube.
    - Measure the resistance between anode and cathode. A small value indicates a broken wire or a similar problem.
    - Measure the capacitance between anode and cathode. While a study showed that this will not be sensitive enough to control wire tension this test will help to find tubes where one or more wires are not properly connected to the HV pc board. For a 3.7 m long tube with two layers of eight 9x8 cells the capacitance between anode and cathode

will be around 340 pF. For each wire that is not connected to the HV board this will be reduced by ~40 pF.

3. **Leak check (still under consideration)**
We are considering performing a second leak test (the first being done at Pol.Hi. Tech). Options include to submerge the tubes in water (that causes all kinds of problems and forces us to remove the tubes from the shipping box), to flush the tubes with argon and to use a leak detector around the endcaps (this is rather time/labor intensive and not suited for production quantities), or to monitor the pressure inside a tube with the gas outlet blocked (is that sensitive enough?).

4. **Long term test, burn in**
With the tubes in the shipping box connect gas lines and HV. All tests will be performed with our standard Ar:Isobutane:CO_2 (2.5:9.5:88) gas mixture.
    - Flush for one day and about 10 volume exchanges
    - Turn on HV and monitor tube current. Since we don't know how well the tubes survived being shipped across the Atlantic we assume here that a few days of HV conditioning/burn in will be required. This will follow the same procedure developed for LST conditioning at Pol.Hi. Tech.
    - Tubes that don't reach 4900 V after 48 hours or that draw a current larger than 5 μA will be rejected.
    - Tubes are kept at 4900 V for four days (96 hours). The current drawn must not exceed 2 μA for the first day and, for the remaining 3 days, must not exceed 100nA for more than 5% of the time. Tubes failing these tests will be rejected.

5. **Signal Shape Test**
    - The (anode) pulse shape of each tube will be studied with an oscilloscope.
    - Pulses should be ~40 ns wide and 30 – 50 mV high.
    - Rejection criteria: anomalously shaped pulses or no pulses at all.
    - We are still investigating if pulse shapes (or the average over several pulses should be recorded in the QC database. Maybe it will be sufficient to just record the average pulse height.)
    - This test will be performed with the tubes in the shipping box.
    - Shielding either integrated in the box or around it will be required.

6. **Plateau Curves**
    - For each tube the plateau curve will be measured using the singles rate of the anode wires.
    - For the large cell solution with multiple HV sections we will determine the plateau curve for each section.
    - We will require a minimum width for the plateau region, with the exact criteria being decided after gaining further experience with the prototype tubes and SLD gas mixture.
    - The counting rate at the plateau region should be fairly stable (need to confirm this). Once the average counting rate for a test site has been determined we can use deviations from this value to identify tubes with bad cells.

- The plateau curves will be measured without a pre-amplifier and with a discriminator threshold of 30 mV and a pulse width of 300 ns.
- This test will be performed with the tubes in the shipping box.
- For each tube the plateau curve(s) and the counting rate(s) will be recorded in the QC database.

7. **Tube Efficiency**
    - For QC tests 7 and 8 and of course for the following module assembly the tubes have to be out of the shipping box. Careful handling guidelines will be established once we gain experience with the prototypes.
    - For a sample of tubes we will determine the efficiency using a cosmic ray telescope.
    - The results will be recorded in the QC database.

8. **Scan Test with radioactive source**
    - This test consists of producing an exceptionally high rate using a radioactive source. This results in a high rate of charge exchange on the cathode which will allow us to identify non-uniformities in the graphite coating, in particular so called bald spots or graphite islands.
    - A radioactive source (OPAL used 10 μCi (or 370 KBq) ^{60}Co, we are planning to use several 5 μCi ^{137}Cs sources. A 1 mCi ^{90}Sr source is also available.
    - The source will be moved above each cell in every tube at a rate of approximately 10 cm/second to achieve a tube current of ~300 nA.
    - While the source moves over the cells the tube current is monitored and the values are recorded on a computer (and eventually the QC database). This requires a HV power supply with fast current readback.
    - Following the OPAL procedures we will classify the test results in 6 categories:
        a. Perfect behavior
        b. No peaks exceeding 1 μA.
        c. No more than 2 peaks exceeding 1 μA; no peaks above 2 μA.
        d. More than 2 peaks exceeding 1 μA or duty factor > 50%; no peaks above 2 μA.
        e. Worse than (d) but current returns to normal level spontaneously when the source is removed.
        f. Non-self extinguishing discharges.

    - Only tubes with a grade of (c) or better was accepted by OPAL. We will adjust these criteria once we gain experience with our prototypes.

9. **Inspection of Φ strips**
    - Visual inspection. Look for bents, cracks, and transport damage.
    - Measure resistivity (to find shorts) and capacitance between ground and signal traces.

10. **Long term test II (one week)**
    - After assembly the modules are returned to the shipping box
    - Attach gas lines and HV supply.
    - Flush for one day and about 10 volume exchanges

- Turn on HV and monitor current in each tube.
- Modules don't reach 4900 V after 48 hours or that draw a current larger than 5 μA will be rejected.

Modules are kept at 4900 V for five days (120 hours). The current drawn by each tube must not exceed 2 μA for the first day and, for the remaining 4 days, must not exceed 100nA for more than 5% of the time. Tubes failing these tests will be rejected.