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Concluding remarks

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1. Introduction

Since there were no parallel sessions, the participants in this workshop were able to hear all the talks, so there was not the usual need for a summary talk. Furthermore, after 4 days of information-packed presentations, a serious summary talk in 30 min would have been impossible. One could only have picked out 'highlights', but what are gems of new information to one listener may already be known to another. Therefore, in the talk on which this paper is based, I tried to stand back a little from the 60 excellent presentations, in order to look for general trends, to think about lessons learned and ideas likely to help in the future. In this task, I was enormously helped by the spirit of the workshop. As at previous Vertex Workshops, we enjoyed a series of extremely comprehensive presentations including open discussion of problems. This information is particularly valuable in planning new projects and it is a sad fact that, when formal presentations are given at major conferences or project reviews, some problems are often buried. The Vertex Workshops provide a welcome contrast. Given the fact that vertex detectors push mutually incompatible requirements to the limit (requiring almost massless systems having micron stability, for example) it is not surprising that these limits are sometimes overstepped. The lessons learned can be of great importance to our community.

This paper is divided approximately into the topics of the workshop, but I have re-ordered the material to provide the most logical flow, and clearly separated the vertex/tracking from other applications. There is an ongoing trend for silicon microstrip detectors to expand out from the interaction region, taking over the general tracking functions from gaseous detectors. Neither during the workshop nor in this paper is a distinction made between vertex detectors (used for tagging heavy quarks and τ leptons) and tracking detectors, since in many cases the transition is progressive, from inner to outer layers.

2. Detector architectures

The first silicon vertex detectors (developed for charm tagging in the early 1980s) were microstrip detectors. Their development continues to be pushed, for example in extended guard ring structures permitting higher voltage operation, hence extended lifetime in high radiation environments. However, the trend to double-sided detectors has in some cases been reversed, for applications where the improved material budget does not justify the higher cost and complexity. An important point in designing microstrip detectors is the need to establish well-defined conditions for the potential in regions of exposed oxide surface. Lutz gave an unscheduled short talk to remind us of these requirements, which are well-documented [1].

For use as vertex detectors, silicon microstrips were closely followed in the 1980s by pixel detectors in the form of charge-coupled devices (CCDs). These

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provided greatly enhanced charm tagging since they determined unique space points on tracks and could be placed much closer to the interaction region with negligible cluster merging. Stefanov described new developments in this detector architecture.

Historically, hybrid active pixel sensors (HAPS) came next. Here, the pixellated sensor is bump-bonded to a readout chip over its full area. There are various readout schemes to cope with high rate conditions, the simplest being sequential row addressing to sense the stored signals, which are transmitted via column buslines to peripheral logic at the edge of the readout chip. Such detectors have proved extremely successful in environments with high rate and high hit density, and will provide reasonably efficient *b* tagging at the LHC. Rossi provided an overview of the status and prospects for this type of detector.

The next architecture used for high precision tracking was the monolithic active pixel sensor (MAPS) in which the functions of the HAPS are combined in a single chip. This was pioneered by Sherwood Parker's group, using fully depleted high resistivity silicon, as for microstrip and HAPS sensors. More recently, the MAPS technology has been extended to low resistivity substrate material compatible with standard VLSI processing, building on the development of CMOS imaging devices. Their extension for use as tracking detectors was reviewed by Turchetta.

The DEPFET pixel architecture has been developed in recent years, primarily for X-ray imaging. Lutz pointed out that this technology also has potential to be used for high precision tracking applications.

Finally, the silicon drift detector provides 2-D information with 1-D readout. This architecture has in the past been used for novel photodetectors, but its use for high precision particle tracking in a real experiment has now been demonstrated in the STAR detector at RHIC, as reported in this workshop by Bellwied.

3. Operating vertex/tracking detectors

We heard excellent reports from CDF, D0, BaBar, Belle, CLEO, HERA-B, H1, ZEUS, STAR, PHOBOS and ATHENA.

The first general comment one can make about these newly installed detectors is their great complexity. For the most part, increasingly complex designs are required by the physics goals and operating conditions. However, there were a few examples where the speakers felt that with hindsight, some design simplifications could have been made. While there will always be a temptation to implement some elegant new hardware or software feature, it is important to bear in mind the relative inaccessibility of a vertex detector once installed. The rule needs to be to follow the simplest and safest procedure which will do the job.

Next, even with an optimised design, numerous problems can arise during assembly and installation, and we heard about quite a number of these. Even minor errors can become showstoppers, at least until a long shutdown permits access. As the space-based detector community has found, even the strictest and most formal QC procedures can go drastically wrong; there is no limit to the capability of people (often tired and overworked) and nature, to subvert the most careful plans. However, it does seem that some tightening up of practices in our laboratories is desirable, given the great complexity of the current generation of detectors. It is suggested that, once a project moves from the R&D phase into construction, it would be advantageous to follow clearly defined procedures for all operations, even the most trivial. For the SLD vertex detectors, written procedures were prepared, studied and discussed by everyone from the project leaders to the clean-room cleaning staff. All work without exception had to be done in accordance with one of these agreed procedures, each of which had a corresponding checklist which was filled in and signed by the person doing the work. For each detector component (for example the CCD ladders which formed the units with which the 3-layer detector was assembled) a 'traveller' folder was used, which contained the total of completed check-lists from earlier work. If an accident happened or an irregular situation arose, the person concerned would not find their own solution, but would consult with the collaboration, as a result of which a special recovery procedure would be agreed after due reflection by all concerned. While one can never guarantee perfection, these procedures did lead to an extremely successful build programme, despite the fact that each ladder travelled between the CCD manufacturer, Brunel University, RAL, SLAC, MIT, Yale, MIT, Yale and finally back to SLAC, during the detector construction.

It is most impressive that some collaborations have produced beautifully working detectors in extremely challenging conditions. The HERA-B vertex detector is an excellent example embodying interesting solutions to the problems of RF shielding and cooling, while the detector is located inside a daring Roman pot extension to the machine vacuum.

However beautiful the design and however careful the assembly, a vertex detector is always vulnerable to accidents with the accelerator. Both the PHOBOS and Belle vertex detectors reported problems of this type.

A somewhat controversial issue was the required burn-in time for detector systems. The H1 detector modules were given two weeks, and this was justified by the observation of some problems which developed very slowly. Whether such problems are avoidable by an optimised design (e.g. to prevent surface charge spreading slowly and eventually creating high field at the detector edge) was unclear. There was also some disagreement about the optimum humidity conditions. Certainly for CCDs with well-defined surface passivation covering 100% of the area, completely dry nitrogen or vacuum is the safest environment, giving optimal protection to bond pads as regards corrosion. It was stated by some participants that microstrip detectors need a few percent humidity to prevent anomalous surface charge from developing. This sounds like a specific design issue which should be investigated; it clearly cannot apply to systems operating in space or in Roman pots!

The pioneering STAR tracking system which uses silicon drift detectors is working well. Its proponents are considering an upgraded version to be used as a high precision tracking detector at the future linear collider.

4. Future vertex/tracking detectors

We heard about upgrades to CDF and D0, detectors for the LHC (ATLAS, CMS, ALICE and LHCb) for BTeV and for the future e^+e^- linear collider (LC). Interestingly, apart from LHCb and upgrades to existing detectors, all future vertex detectors (strictly defined, i.e. for heavy flavour tagging) will probably be pixel-based.

For CDF and D0, the upgrades are driven by expected radiation damage to the present detector/readout systems. They plan in 2004 to install new detectors made with low resistivity single-sided sensors in place of the high resistivity double-sided detectors used at present. At the same time, largely by improving the layout of electronics, they aim to reduce the material budgets below the currently rather high values.

The giant silicon trackers for ATLAS and CMS (the latter uses 220 m^2 of sensors!) are nearing the start of production; they should be under way before the end of this year. The pixel detectors for these experiments are following closely behind, having been saved from major problems with their readout chips by the emergence of the deep submicron CMOS process. By design layout, these can be made extremely radiation tolerant.

The ALICE and BTeV pixel detectors share many design features with the LHC GPDs. These four collaborations are working closely together in solving some of the greatest engineering challenges in the history of particle detectors. Their major efforts will surely be justified by the physics prizes. Vertex detectors played a vital role in the discovery of the top quark, and this was probably only the first of many triumphs at the energy frontier.

The LHC GPDs are particularly challenging since they represent the hostile energy and luminosity frontier for hadron colliders. Another frontier will be opened up by the TeV-scale e^+e^- linear colliders. While the radiation environment is much less hostile than at LHC, the physics requirements create new challenges. Building on the SLD experience, the requirement is for the highest possible b and charm tag efficiencies, as well as measurement of more esoteric quantities such as the vertex charge and charge dipole. While the physics goals are clear, the means to get there are not. The technical challenges depend on which collider will eventually be built. The NLC vertex detector could be constructed with CCDs developed from those used for SLD, but at TESLA the time structure is much more demanding. At NLC, a readout time of 8 ms is sufficient, whereas at TESLA the inner layer needs to be read out within 50 μs. There are currently four suggestions for doing this, column parallel CCDs, MAPS, DEPFET and HAPS architectures. If each can be made to work, the choice will come down to the material budget. Over the sensitive volume, the suggested architectures are sketched in Fig. 1. The black lines represent sensor silicon (shown in the case of CCDs with or without mechanical support), and the dark grey lines represent 'readout' silicon which is part of the sensor die (for MAPS) and bump-bonded to it (for DEPFET and HAPS). The light grey areas indicate additional material needed for cooling. At this stage, much of this is conjectural and fluid. For example, the MAPS option may be configurable (like CCDs) with the readout all at the ladder ends. While these regions are less critical, being beyond the volume where multiple scattering degrades the impact parameter precision, they nevertheless threaten the precision measurement of Bhabha electrons, plus the fact that photon conversions or secondary interactions in this material certainly will degrade the measurement (by energy flow) of small angle jets. Consequently, if two vertex detector options were equivalent in precision and in the material in the tracking volume, the material in the endcaps would be decisive. It is believed that robust R&D programmes may permit the construction of prototype ladders with the different technologies by 2006. These will provide a sound basis for selecting the preferred option, and still have time to build the detector for the start-up of the linear collider around 2010.

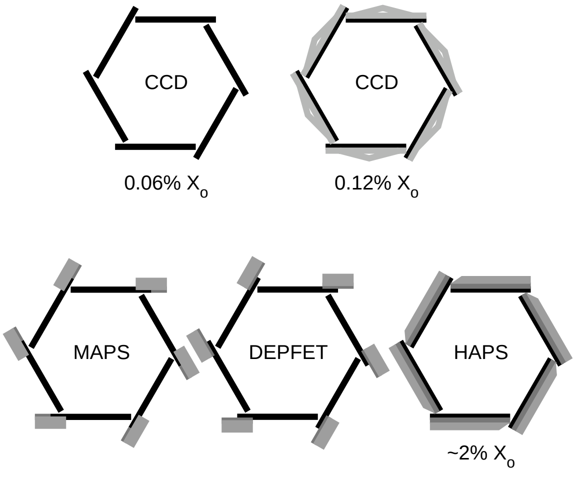

Fig. 1. $r\phi$ views of vertex detector architectures for the future linear collider. Some indications of layer thicknesses are indicated, but the R&D is only just beginning.

5. Triggering with vertex detectors

CDF is implementing a second level trigger based on impact parameters, but is hindered by the fact that the material budget is higher than originally expected. LHCb aims for a second level secondary vertex trigger using two or more close tracks. However, their detector is located in a field-free region, and they are hindered by the lack of momentum information. It is one thing to measure impact parameters, but to know their significance requires knowledge of the track momenta. The collaboration is investigating a modification to their detector to achieve this. CMS (also with a higher level trigger) aims to satisfy this requirement by combining information from the vertex detector with one or more layers of their microstrip tracker.

A particularly elegant trigger is proposed by BTeV. By embedding their pixel-based vertex detector in a magnetic field, simulations indicate that they can achieve extremely clean track finding plus measured momenta, hence precise measurement of the *impact parameter significance* of every track. Remarkably, it seems possible from their simulations to do this with a level-1 trigger. Hence they should have a very inclusive and democratic acceptance for an enormous sample of *B* decays.

6. Detector readout

The huge effort devoted by many groups and specialist manufacturers to the development of rad-hard BiCMOS electronics was a major learning experience. For relatively simple readout chips (such as those which provide binary readout for the ATLAS SCT) this route has been successful. Large scale production of their ABCD3T chip is now under way.

For more complex chips, yields have been too low and costs too high. Some manufacturers no longer support their rad-hard technologies. This problem, which posed a major threat to the hybrid pixel projects, has now been overcome with great success by a number of groups (CMS main tracker, ATLAS and CMS vertex detectors, BTeV vertex detector), which have switched to the deep submicron CMOS technology (0.35 or 0.25 μm). The design of these very complex mixed mode chips (analogue and digital) remains challenging. There are numerous issues such as the tight supply voltages (at high current), SEU protection given the very small parasitic capacitances, and achieving excellent radiation hardness by design. However, methods have been devised to overcome all these problems. In general, those who have designed in both architectures report that designing in DSM is much easier than for example in DMILL. The fact that they are working in the same environment as forefront IC designers, that they are using the most advanced design tools, that they can use 5–6 metal layers, in addition to the well-advertised advantages of extremely thin dielectric and a new level of component density, adds up to huge advantages. Overall, it is clear that the IC design engineers in our community are really enjoying this work, and are still only beginning to explore the full range of possibilities.

However, it was pointed out that there may not be good reasons to follow the industry to yet smaller feature sizes (e.g. 0.1 μm). Even tighter supply voltages, drawbacks for analogue designs due to increased spread in device characteristics, the fact that the radiation hardness with optimised 0.25 μm designs is probably adequate, and the fact that 50 μm square pixel HAPS designs are already possible, argues in favour of ongoing consolidation of the 0.25 μm designs. However, as the global IC industry continues to move briskly forward, one never knows what new opportunities may turn up.

7. Radiation effects in silicon detectors

This subject is now at a very advanced stage of development, with general agreement among the experts and continuing steady progress. After some exaggerated claims and unrealistic expectations over a number of years, it is now clear that there are no magic bullets. However, a combination of device engineering, defect engineering and optimal choice of operating temperature has led to silicon detectors (both strips and pixels) of ever-increasing radiation hardness. Since hybrid pixel detectors are mandatory for the highest flux environments, the recent developments have been particularly relevant to this architecture. These are the detectors which will need to be pushed even further if the LHC luminosity upgrades are eventually implemented.

Regarding device engineering, it is almost unanimously agreed that the "n-in-n" single-sided architecture is the most radiation resistant. This nomenclature is confusing to semiconductor engineers who use similar terminology to describe 3-component structures made with p-type, n-type or near-intrinsic ("in" or "ip") material. What strip detector people mean is simply highly doped n strips or pixels in a lightly doped n-type substrate, and they of course assume a p-type junction layer on the back of the wafer.

This n-in-n structure has two main advantages. Firstly, it involves the collection of electrons, of which the mobility is relatively unaffected by radiation, whereas hole trapping becomes extremely serious at high doses. Secondly, a relatively low resistivity n-type bulk substrate is the optimal starting material. Under irradiation, it progresses through type inversion, and eventually the collection of electrons degrades gracefully as the effective resistivity of the p-type material falls so low that full depletion is no longer possible. Starting with (for example) a more lightly doped n-type substrate or a p-type substrate would place one initially at some point along the route to detector failure.

It was clearly demonstrated at this workshop by Moll, by Watts and by Allport that highly oxygenated material (DOFZ: diffusion oxygenated float-zone) gives considerable benefits (by about a factor two) in the evolution of the effective dopant

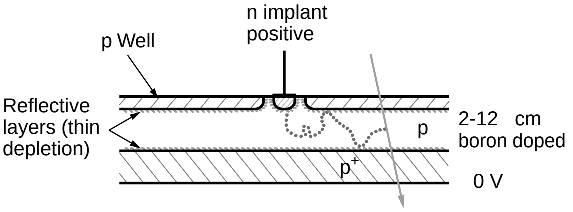

Fig. 2. Charge collection in a monolithic active pixel sensor (MAPS).

concentration with charged hadron fluence, which is the critical parameter for vertex detectors at hadron colliders. However, there is no benefit with respect to neutron irradiation. This contrast is due to the completely different energy loss mechanisms. Charged hadrons mainly produce low energy silicon recoil atoms from nuclear Coulomb scattering, while neutrons cause nuclear disintegration with high energy reaction products. The NIEL equivalence of radiation effects is now seen to be a dogma which could not have been expected to hold in general.

There was some discussion during the workshop of a suggestion to use the MAPS architecture for an upgrade LHC vertex detector. However, this seems pretty improbable. The charge collection (Fig. 2) is entirely by diffusion in the undepleted bulk material. Hence the charge collection efficiency is determined by the minority carrier lifetime. A calculation based on measured damage constants [2] indicates that in the LHC before luminosity upgrade, the carrier lifetime in the low resistivity epitaxial material used for CMOS sensors would be reduced to 0.6 ns after 1 year of operation at the inner layer radius of the ATLAS pixel detector, whereas the charge collection time by diffusion is around 100 ns. To have some hope, it would be necessary to consider a fully depleted detector of the type pioneered by the Hawaii group [3]. However, in this case, all the issues of type inversion previously mentioned would at first sight appear to disable such a detector.

8. Offline algorithms

We had two talks which neatly contrasted the situation at e^+e^- and hadron colliders. De Groot explained that the SLD experiment had established that if one has a pixel-based vertex detector of sufficient precision to make an efficient 3-D reconstruction of the B and D decay topologies, the possibilities for physics via pure, efficient flavour identification are very broad. It is expected that these capabilities will be enhanced at the future LC, since conditions will permit a smaller radius beam-pipe, and much progress has already been made with the development of superior detectors for this environment.

At hadron colliders, the hostile radiation environment forces the detector designers to use thick layers with relatively large pixels. Snider discussed the situation for the CDF microstrip vertex detector, which has additional pattern recognition problems compared with pixel detectors. He explained that under these conditions, flavour identification must be based primarily on statistical information (typically some number of tracks having impact parameter significance above some threshold). In these circumstances the possibilities for jet flavour identification are correspondingly reduced. Reasonable b tagging is still possible, but charm tagging and the higher goals of vertex charge determination are almost ruled out.

9. Other applications

We heard about the use of silicon detectors in a wide variety of applications. While these had nothing to do with vertex detectors, they were one of the most important parts of the workshop, in educating us as to the requirements for other scientific areas, and in forging links which could be of benefit to all of us in future technical developments.

For neutron scattering, the use of silicon is still only potential. The need is there, as Johnson explained; a requirement for 2-D detectors with much improved spatial and time resolution. Silicon pixel detectors faced with thin layers of converter (zinc sulphide, gadolinium, etc.) look promising.

For protein crystallography, Eikenberry described a HAPS-based detector with excellent rate capability. In principle, they would prefer significantly smaller pixels than the 217 μm square currently available. Also for crystallography, but now powder diffraction which needs only a 1-D detector, Schmitt described a microstrip system. For both these detectors, the rate advantage compared with earlier technologies is extremely valuable.

The CHICSI detector is a technically interesting sandwich of very thin (10–15 μm) and thick silicon, for measuring the energy loss and full energy of nuclear fragments. The use of wafer bonding has wide potential applications, including for vertex detectors.

Lutz described the pn CCDs used in the extremely successful XMM X-ray telescope, and the plans to upgrade to DEPFET-based pixel detectors for the gigantic follow-up XEUS telescope. One normally thinks of astronomical applications as involving long integration times, hence needing only slow readout, but there are some rapidly changing X-ray sources, such as neutron stars with a rotation period of less than 1 ms. For these sources, the extremely short readout time of the DEPFET pixel devices becomes important.

We heard of several other important and diverse applications, culminating in the use of silicon detectors to study the activity of living retinas. As Litke explained, the eye/brain complex of higher species is by far the most sophisticated pixel detector system on the planet. We are only beginning to understand the multi-level data processing which goes on in the everyday activity of looking at things. Whether the observer is a human being or an ant, the sophistication of this aspect of biological systems is staggering.

10. Non-silicon detectors

In previous workshops, much R&D was reported on gallium arsenide and other novel materials. It has proved extremely difficult to develop such detectors to the point where they are able to compete with silicon, particularly since the performance of silicon detectors of all types is continually being enhanced.

At this workshop there was only one non-silicon talk, given by Keil, on the topic of CVD diamond, which is still being pushed hard. There are complex effects due to the trapping of signal charge, but the work continues and there are ideas to enhance the charge collection efficiency significantly by defect engineering. The idea in this case is to reduce the nitrogen concentration.

The work on CVD diamond has been a long and heroic effort, which could still emerge as the winner in the development of vertex detectors able to operate in increasingly hostile environments.

11. Conclusions

For vertex detectors (strictly defined, meaning detectors used for tagging heavy quarks via their secondary vertices) the trend is towards pixel detectors. This follows naturally from the track record established by the NA32 and SLD detectors, now with the enhanced capability provided by at least three additional pixel architectures, all of which have contrasting capabilities to CCDs. In high flux hadron colliders, the hybrid active pixel architecture (HAPS) still seems to be the only plausible option. However, for the TeV-scale e^+e^- linear collider, all four architectures are being studied. Given the requirements of micron precision and stability, minimal material (including that related to cooling) in the detector active volume and beyond (including the very forward region) it is not at all clear which option will eventually be preferred. We are only at the beginning of a major international R&D programme; hopefully over the next 4 or 5 years at least one of the technologies will prove itself capable of satisfying the physics requirements.

The growth in the variety of silicon pixel detector options is driven more by other areas of science and technology than by particle physics. Since the 1970s, our field has been the beneficiary of enormous technological advances largely driven and funded by other application areas. While this will undoubtedly continue, the special requirements of the particle physics community have been the inspiration for developments in pixel detectors which otherwise would not have taken place. The ongoing synergy between vertex detectors, X-ray detectors and ultra-sensitive visible-light sensors is largely responsible for the rapid pace of development of these devices. Since pixel detectors are by design imaging devices, their scope for applications is immense. Advances in one area frequently spill over into others, often through the insight of device engineers in the manufacturing companies, who act as vital links between the often remote islands represented by different fields of science.

As the application of various pixel detector architectures grows, the role of silicon microstrip detectors is by no means diminishing. They will probably become completely displaced from the innermost regions of tracking systems, where the ultimate in track reconstruction capability, tracking precision and material budget are likely to be better served by pixel detectors. However, silicon microstrips have taken on an enormous new role as the detectors of choice for general tracking in the most hostile environments. In this application, their use does impose a considerable price in material budget, so the idea that they will take over completely from gaseous tracking detectors is surely an exaggeration. In environments where gaseous tracking devices are still viable, TPCs and other advanced gaseous detectors will continue to be preferred. Even for gaseous detectors the material in the endcap regions (mechanical supports, readout and cooling) is unwelcome, and reducing this is a very active area of research. So the choice between silicon and gaseous tracking detectors is application-specific and time dependent, since the R&D continues to advance in both fields.

In the early SSC studies, many distinguished physicists considered *any* form of tracking to be impossible. The seemingly insurmountable problems have been solved, and such systems are now under construction in the *more hostile* LHC environment, even down to a radius which will permit a respectable quality of b tagging. Is the world of vertex detectors likely to be dominated by silicon devices forever? At present, this would seem to be most probable, but one might be less sure if one looks back to the SLC detector workshop [4] in 1982. At that time, those of us proposing CCDs were generally considered over-ambitious. Silicon detectors in general were viewed as too unreliable, too small, too radiation sensitive, to ever be installed in the heart of a prestigious collider experiment. The favoured candidate for a vertex detector at the SLC, reflecting the dominant tracking technology of the day, was a rapid-cycling propane bubble chamber (Fig. 3)! It may be that some young physicist is about to come up with a technology which will sweep silicon vertex detectors aside. If anyone thinks they may have such an idea, please work on it! There is always room for a new idea.

Even if the future of vertex detectors will be evolutionary rather than revolutionary, huge improvements in performance can be expected, and will certainly open new windows on physics. These developments will not stop when the first generation systems are installed in any new detectors. Despite the fact that the vertex detector is the innermost, hence least accessible component of the overall detector, it is essential that the overall design should permit access for future repairs and occasional replacement with upgraded vertex detectors. This capability has in the past been essential for achieving greatly extended physics reach (e.g. at SLD), and this will surely continue to be important in the future. Collaborations which consider violating this requirement would create paralysis in the innermost component

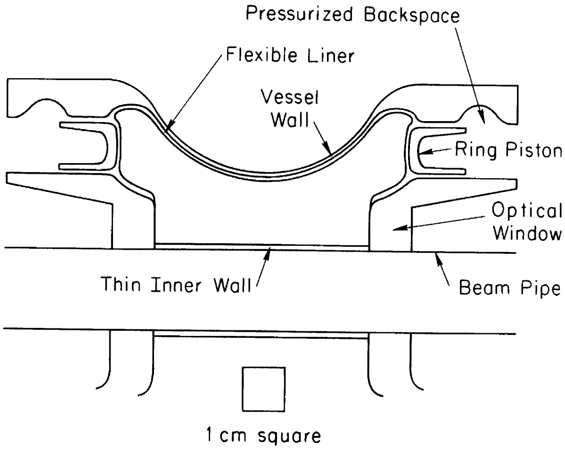

Fig. 3. The front-running candidate for a vertex detector at the SLC, at a workshop in 1982, a propane bubble chamber.

of their detector, one of the most critical tools for physics, and hence would eventually hinder their capability to do physics.

Acknowledgements

The Vertex Detector Workshops have a proud record as some of the most valuable around, both for their scientific content (the already-mentioned free exchange of information among friends) and for their collegial atmosphere. These aspects are of course connected, and this year we have to thank Roland Horisberger very specially for the tremendous effort he made in selecting a perfect venue, and in making all of us feel at home during our time there. This could not be done alone, and Roland was very ably assisted by Renate Berger, the workshop secretary, by Danek Kotlinski, who helped with many computing aspects, by his daughter Rahel and the team of PSI staff who made a wonderful barbecue in a fabulous setting above the lake. Roland took the opportunity to educate us in the fascinating history of Schwiez on several occasions. All of us had heard about William Tell, but we came away with an in-depth education on the fascinating history of the very heart of Switzerland since neolithic times. The staff of the Hotel Waldstaetterhof could not have been more friendly and helpful. Many of us, when we left, were determined to return soon for a vacation in this very beautiful part of the world. One should finally thank everyone who participated, who gave such excellent talks, and who contributed to one of the most intellectually stimulating and enjoyable events one could hope to attend.

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