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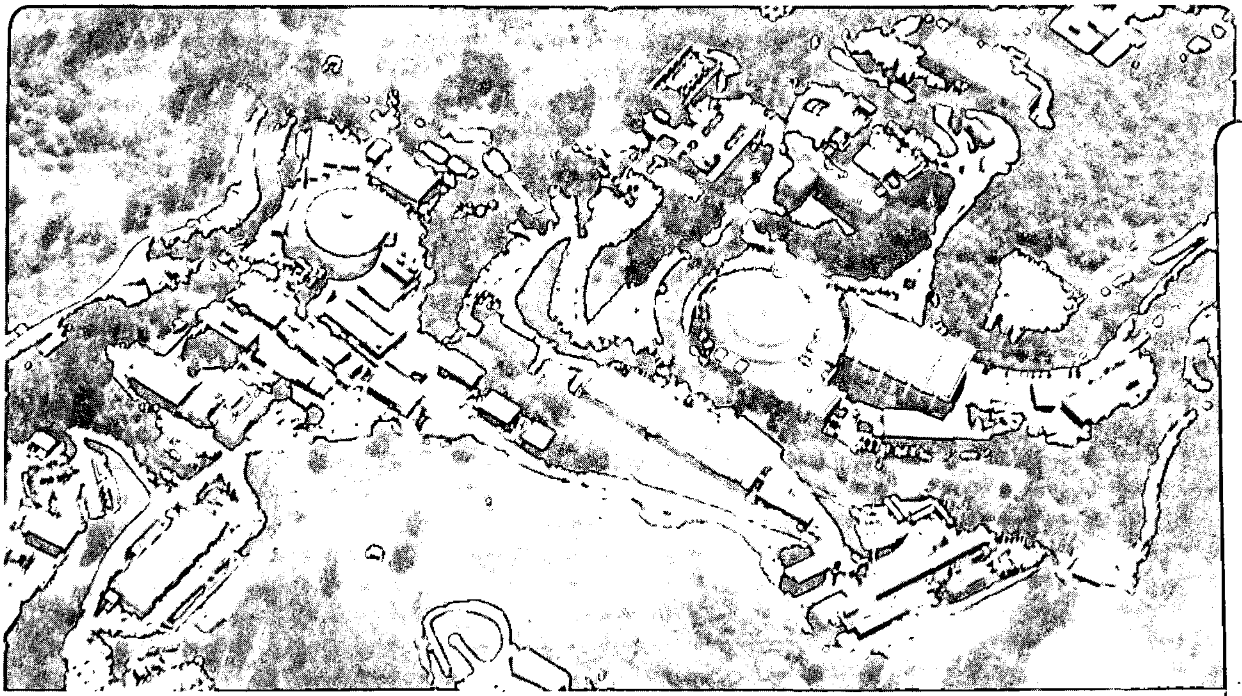

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DEVELOPMENTS IN WARM LIQUID CALORIMETRY*

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DEVELOPMENTS IN WARM LIQUID CALORIMETRY*

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Abstract

We provide an overview of some of the recent progress in warm liquid calorimetry and an assessment of the critical issues and present status of the R&D. Recent results are encouraging for the development of fast, hermetic, compensating warm-liquid calorimeters for use at the future (SSC/LHC) hadron colliders.

1. Introduction

The advantages of liquid ionization calorimetry are well known. Direct collection of charge leads to a stable, well calibrated and uniform response. There is flexibility and ease of segmentation in both depth and surface area, relatively high resistance to radiation, and, with the development of the electrostatic transformer, insensitivity to magnetic fields. A vigorous R&D program pursued world wide in the past few years has shown that some organic liquids at ambient room temperature (so-called "warm liquids") can make excellent calorimeters [1]—[3]. The yield of electrons, taking into account dE/dx, electron lifetime and drift velocity is comparable with that for liquid argon; and the relatively short drift times are an advantage in suppressing pile-up. Warm liquids can provide superior detectors, because they require neither cryogenic equipment nor thermal insulation; this enhances simplicity, flexibility, and hermeticity. Furthermore, as hydrogenous materials, organic liquids can provide a compensated response - equal sensitivity to hadronic and electromagnetic particles, leading to better resolution and linearity over a large energy range, without having to resort to expensive and exotic materials or techniques.

These features strongly suggest that warm-liquid calorimetry may result in a more effective and less expensive detector. Nonetheless, although very promising, this technology is still new and is as yet unproven for use in a large calorimeter system. One of the main immediate goals of the R&D program needs to be a "proof-of-principle" with the construction and testing of a large prototype test beam module, containing all the features necessary to satisfy the performance requirements at the SSC and the LHC. This is being pursued by a portion of the WALIC collaboration [3] as part of its comprehensive program to develop the warm-liquid technology.

2. Critical Issues

2.1 Liquid Purity

Much progress has been made in the routine production of high-purity warm liquids, particularly 2,2,4,4- TMP (C_9H_{20}) and TMS ($(CH_3)_4Si$). The ionization electron lifetime in the liquid is very sensitive to impurities. For signal collection to be insensitive to modest changes in the liquid purity, one would like purities corresponding to electron drift lifetimes of more than ten times the signal shaping time of 50-100 ns. To achieve this, the impurity concentration must be less than 100 ppb oxygen equivalent.

For TMP, the UA-1 collaboration [4] has achieved lifetimes of several hundred microseconds and the Saclay and LBL groups of the WALIC collaboration [3] have reached lifetimes of about 100 μs. For TMS, College de France [3] has obtained lifetimes of 100μs and the Penn and Japanese groups [3] have achieved lifetimes of the order of 1μs, with intentionally modest cleaning procedures for R&D purposes. The latter result can be easily improved upon.

With regard to choice of liquid, more of the WALIC R&D effort has focussed for the time being on TMP rather than TMS, simply because of the safety issue, since TMP has a much higher boiling point. However, TMS has better signal/noise properties because of its higher mobility. An even better and slightly safer liquid than TMS, but unfortunately much more expensive, is TMG. In a contribution at this conference, Yuta et. al. [5], report a lifetime in TMG of 16 ±7 μsec. These results indicate that liquid purification is a tractable issue.

2.2 Materials Compatibility and Long-Term Stability

This is one of the most important issues, since it has a profound impact on the design and costs of large warm-liquid calorimeters, especially for the "swimming-pool" type configuration, with the absorber immersed in the liquid.

UA-1 [6] has shown that their earlier TMP samples, with free electron lifetimes of about 15 μs, did not suffer any reduction in lifetime after three years in their sealed calorimeter boxes consisting of stainless steel and ceramic.

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This stability is much greater than is necessary for designs such as the swimming-pool which involve the recirculation and repurification of the liquid. The choice of this design concept, over that of the sealed UA-1 container, is dictated by the desire for significant reduction in the number of high voltage and signal feed-throughs, ease of construction, lower costs, and better hermeticity. Thus, it is essential to determine the compatibility of various materials (and their surface treatment) in contact with warm-liquid, that is, to determine if the needed liquid purity can be maintained.

Recent WALIC results on a variety of metals and plastics [3], [7], [8] are shown in Figure 1, where the ionization electron lifetimes in the liquid are plotted as a function of the contact time of the material with the liquid.

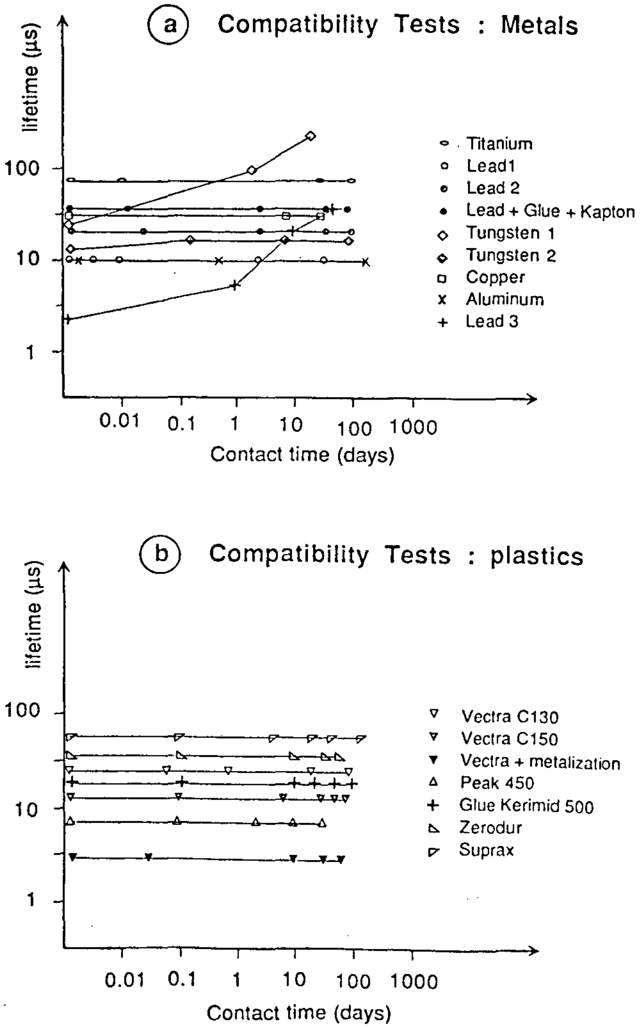

Figure 1. Material-Warm liquid compatibility tests on (a) metals and (b) plastics. Plots are of ionization electron lifetime in the liquid (µs) versus material-liquid contact time in days. All measurements are in TMS except for Aluminum and lead sample #3 which were done in TMP.

In all cases, there is no degradation of liquid purity with time. Moreover, in some cases, tungsten sample #1 and lead sample #3, the lifetimes rise dramatically, suggesting that these samples, subjected to their particular cleaning procedures, act as getters! This needs to be studied more systematically. In any case, the results indicate that there is a wide variety of materials compatible with warm-liquids, including all those specific materials being considered for a swimming-pool calorimeter, or for the so-called prism plastic calorimeter (ppc) design being developed by the College de France group [8]. Further independent tests by the Penn group [9] on Pb-TMS and by the Japanese groups [10] on Pb-TMG also demonstrate compatibility.

2.3 Radiation Resistance

The deterioration of warm-liquids due to radiation may not be as important for a swimming-pool calorimeter design, since the liquid can be recirculated and repurified whenever necessary. Nonetheless, radiation damage of the other material in the calorimeter may release contaminants into the liquid which may perhaps not easily get flushed out. This requires much more extensive investigation in the near future and is being pursued by the WALIC collaboration.

As far as the liquids per se are concerned, the most comprehensive study in TMP and TMS to date has been performed by R.A. Holroyd of BNL [11] in which he exposed the liquids to radiation from an intense Cobalt-60 source, up to doses of 10^5 grays (i.e. 10^7 rads). Even for this maximum dose, only about 1% of the liquid suffers from radiolysis decomposition. The conversion products are predominantly other saturated and unsaturated hydrocarbons or silanes, which do not attach electrons, and , therefore, do not significantly decrease the free-electron lifetime. The drift velocity of ionization electrons is very nearly unchanged and the electron lifetime in his setup drops from about 60 µs to about one µs at 10^7 rads, which is still quite acceptable. However, the gas pressure from radiolysis builds up linearly with dose. Since there have to be expansion tanks to accommodate possible temperature changes, the gas build up should not be a problem. In any case, significant radiolysis occurs only at 10^7 Rads, or above a radiation level that involves only a very small portion of the calorimeter in the very forward direction.

A new result presented at the conference by Yuta et al [10] is for radiation damage to TMG exposed also to a Cobalt-60 source. They report that the free ion yield, G_{fi}, extrapolated to a 2mm gap chamber, changes by only 2% at 1.2×10^3 grays· This is consistent with Holroyd's results.

To conclude, although prospects look very promising, let me re-emphasize the need for further tests of radiation resistance of entire calorimeter prototypes and not just of the liquid alone.

2.4 Fast Signal Response and Signal/Noise

Although liquid ionization calorimeters have been traditionally used with slow readout, their signals have a fast risetime, which can be exploited to obtain fast readout.

2.4.1 Ionization Current and High Voltage

Figure 2 shows the current signal versus time for a liquid ionization calorimeter, assuming uniform ionization in the gap. The current rises rapidly to a peak current, I_{max}, and then drops linearly (assuming very pure liquid) to 0 at a time, t_d, corresponding to the drift time for an electron to traverse the entire gap.

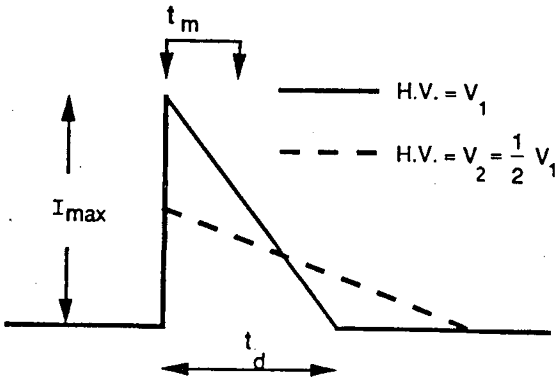

Figure 2. Induced current waveform as a function of time in liquid ionization chambers for a uniform energy deposition in the interelectrode gap, for two different voltages. t_d is the electron drift time across the gap, t_m indicates the signal measurement time interval and I_{max} is the peak ionization current.

The peak current, I_{max}, is a function of the density of ionization (dE/dx), the free electron yield (G_{fi}) and the drift velocity of the free electrons (V_d):

$$I_{max} = G_{fi} \times dE/dx \times V_d$$

In warm liquids, unlike liquid argon, V_d and G_{fi} do not saturate as a function of the applied electric field. Figures 3 and 4 show recent measurements of the dependence of these quantities on electric field [12], [13] for several warm liquids.

Thus, for higher electric field (see solid line in Figure 2), I_{max} increases and the drift time, t_d (= gap width/drift velocity) decreases. For the short shaping times ($t_m < t_d$) required at the SSC/LHC, it is clear from Figure 2 that signal/noise depends on the peak current, I_{max}, rather than the total charge. Moreover, to reduce pileup, it is necessary to reduce the drift time t_d. Thus for both effects, it is advantageous to operate warm-liquid calorimeters at higher fields than for liquid argon.

An important part of the WALIC R&D program has been the successful development of calorimeter prototypes which operate at high electric fields. To this end, a small, highly segmented, prototype TMP calorimeter (16 towers of 64 one-mm gaps) was constructed and tested at 60 kV/cm. Recently, a full-size tower for the large "proof-of-principle" swimming-pool TMP calorimeter module under construction (described below) has been tested extensively at 50 kV/cm! Although designed for electric fields greater than 80 kV/cm, the plan is to operate initially at 30-50 kV/cm.

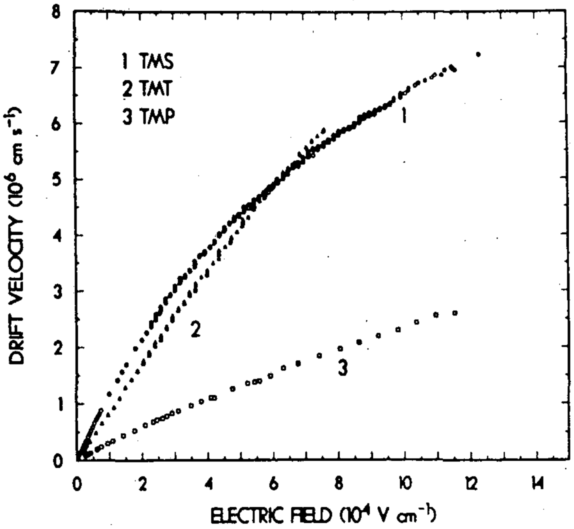

Figure 3. Electron drift velocity as a function of applied electric field in TMS, TMT and TMP. From reference [12].

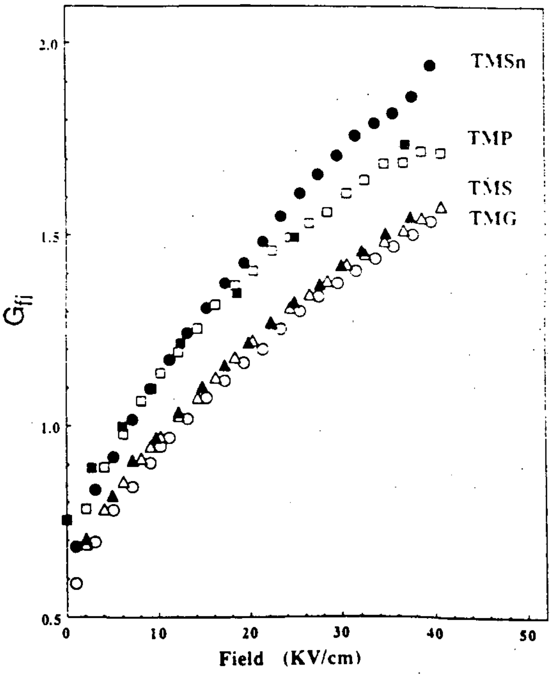

Figure 4. Free ion yield, G_{fi}, as a function of applied electric field for various warm liquids. From reference [13].

Figure 5 shows the results of a simple model calculation by Wenzel [14] that compares the multigap signal-to-noise (S/N) of liquid argon, TMP and TMS for various shaping times and voltages, under the particular assumption of fixed liquid depth of 10 cm and area of 0.01 m^2 per tower plate. For liquid argon the electric field is taken to be 10 kV/cm. The performance is not sensitive to this value. For TMP and TMS, there are two sets of curves, corresponding to high voltages of 5 kV and 10 kV across the gaps. It is desirable to maximize both S/N and, for pileup reasons, the so-called "ballistic factor", $B(\approx t_m/t_d)$, which measures the effective fractional charge utilization. Warm-liquid calorimeters (TMP or preferably TMS) operating at the achieved high voltages and indicated short signal shaping times would meet performance specifications at the SSC/LHC.

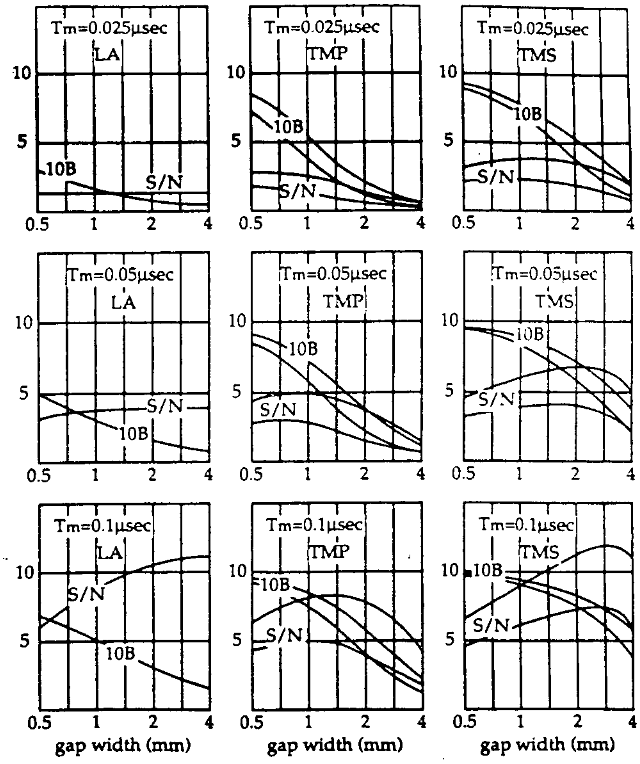

Figure 5. Signal-to-noise (S/N) and pile-up sensitivity ("Ballistic factor", B) for liquid argon, TMP and TMS, for various pulse shaping times, T_m. From reference [14].

2.4.2 Charge Transfer Time and the Electrostatic Transformer

As described in the fine article by Radeka and Rescia [15], one of the factors affecting the signal response speed from liquid ionization calorimeters is the charge transfer time from tower plates to the preamps. This transfer time depends on the tower impedance, as well as the length and impedance of the connecting cable. To minimize this, it is essential to reduce considerably the tower capacitance, C_d.

In typical liquid ionization calorimeters, C_d is of the order of 5nf, resulting in transfer times of about 500 ns, which is large compared to beam crossing times of about 16 ns at SSC/LHC. If the capacitance could be reduced to about 300 pf, then the transfer time would be correspondingly reduced to about 30 ns. In addition, the reduced capacitance would be a better match to the preamp capacitance, thereby improving the signal-to-noise as well.

One way to reduce the tower capacitance is to gang the drifting gaps in series rather than in parallel. Recall that for a tower with *n* gaps connected in parallel, the total capacitance, $C_d=nC$ where C is the single gap capacitance, while for *n* gaps in series the resulting capacitance is $C_d = C/n$. The WALIC collaboration has been developing and testing a scheme of ganging tower electrodes in combination of series and parallel connections to substantially reduce the overall tower capacitance. The arrangement would then act as an electrostatic transformer (EST) [16], so-called because it behaves from the preamplifier point of view very much the same as a ferrite-core transformer. This is discussed more fully in reference 16. Unlike the ferrite-core transformer, the operation of the EST is unaffected in the presence of a strong magnetic field. Considerable study has been made with computer simulations and testing with mockups and small calorimeter prototypes, [16], [17], yielding promising results. The aforementioned "proof-of-principle" hadronic test beam module is being constructed with the electrostatic transformer concept and will provide the first large scale beam test.

3. Compensation Studies

Recent Monte-Carlo calorimetry models [18] suggest that compensation — equal response to electrons and hadrons, e/h=1 — can be achieved for sampling calorimeters with hydrogenous active media (e.g., warm-liquids) and passive absorbers of material other than uranium, such as lead or iron, which are cheaper and easier to work with. To this end, the WALIC collaboration is presently running an experiment at Fermilab (E-795) to make a systematic study of calorimetry properties by measuring e/h as a function of absorber material (lead and iron) and as a function of absorber-to-TMP thickness. The TMP calorimeter is highly modularized, to allow for changes of configuration to be made simply. The TMP is isolated from the absorber by being contained in thin sealed boxes of stainless steel of the UA-1 type [1], [6]. Each box is 30 x 60 cm^2 with a 4-electrode plane in the middle of 2.5 mm of TMP, resulting in two 1.25 mm liquid gaps per box. The operating electric field was 6.5 kV/cm.

A key feature of the calorimeter is that each component (absorber plates, TMP boxes) is independently suspended by hanging frames from the support structure (Figure 6). After each change of configuration, the stack was recompressed. The TMP gap thickness was then monitored by measuring the capacitance of each electrode and found to be extremely stable. This was also confirmed by the signals from muon beams. The entire calorimeter is enclosed in a perforated aluminum Faraday Cage, which reduces the external electrical noise by a factor of 50,000. More details can be found in reference 19.

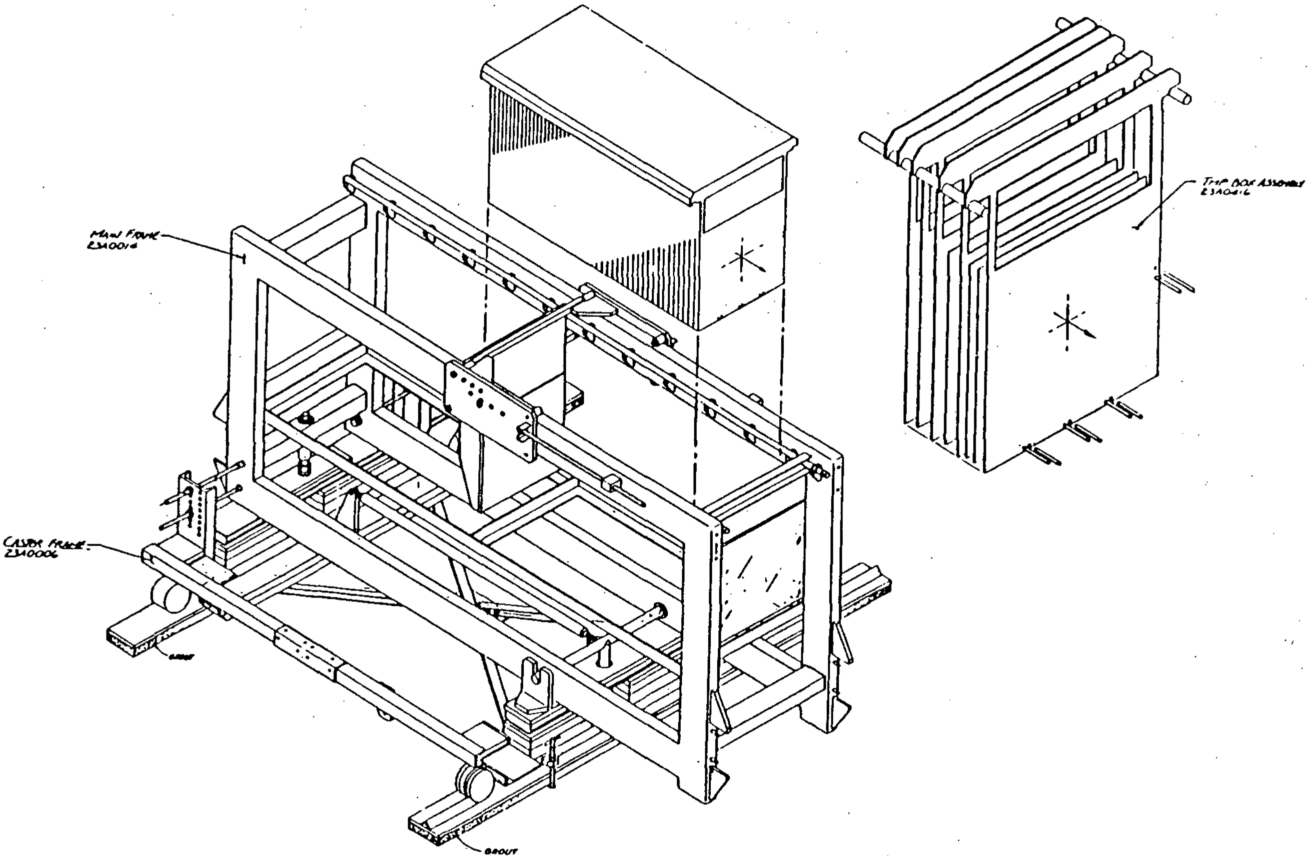

Figure 6. Isometric layout of WALIC hanging frame TMP calorimeter.

The first measurements were done with an electromagnetic configuration (e.m.) to measure the response to e.m. showers only. This consisted of a 6.35 mm lead plate followed by a single TMP box (4-electrode plane, 2.5 mm of liquid), repeated 26 times, for a total of 30 radiation lengths. In this configuration, the calorimeter was exposed to positron beams between 2.5 and 175 GeV/c and to a 175 GeV/c muon beam.

Figure 7 shows the response of the e.m. configuration (the sum of the signals from the 26 electrodes along the beam) to the 175 GeV/c muons and the pedestal noise. The signal/noise is about 3.8, as expected. This can be extrapolated to a full depth warm-liquid calorimeter for the SSC with a short 100 ns shaping time to give a signal/noise for muons of about 6.5!

Figure 8 shows preliminary results of linearity and resolution for this e.m. configuration, but with the data still uncorrected for the large beam momentum spread which explains the sizeable value of the constant term in the fitted resolution. These data have been compared to Monte Carlo data (Geant 3.14 which predicts a resolution of 18%/√E) and the agreement on the shape of the shower profiles is excellent.

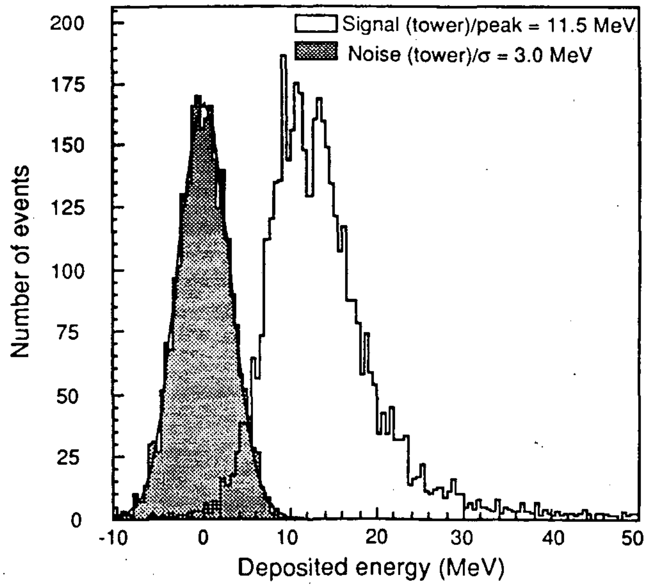

Figure 7. Muon signal and pedestal signal in a 26-plane tower.

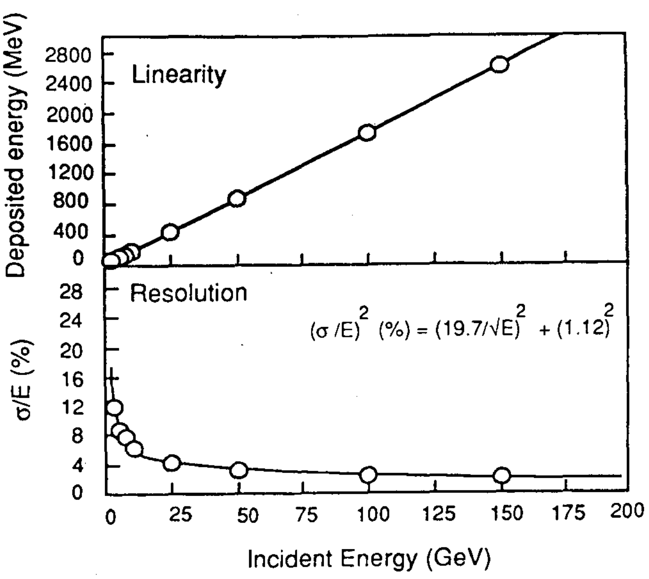

Figure 8. Signal response linearity and energy resolution as a function of incident positron beam energy, for the 26-plane electromagnetic (e.m.) configuration. Preliminary results.

To measure hadron showers, it was necessary to mount two TMP boxes in a detector plane hanger, one above the other, to cover a cross-section of 60 x 60 cm^2. With only one-half of the TMP boxes, comprising 34 TMP planes out of the eventual 68 planes (each 60 x 60 cm^2), several ("hadronic") configurations of lead and TMP, arranged to a depth of about 6.5 λ, were exposed to both positron and pion beams. Details are given in reference 19. Because of the limited number of TMP boxes, a number of the gaps contained "dummy TMP boxes" made up of CH_2 with the same nuclear content as the TMP planes in order to achieve the same shower development as if TMP planes were used. The beam energies were low for these first runs to avoid excessive leakage out the back because the calorimeter was only instrumented to half its depth. The full hadronic runs to study e/h will be done in the spring of 1991.

The analysis is still ongoing, but we show some preliminary results in Figure 9 for e/h for two extreme configurations to indicate some general features. First, it is important to remark that the TMP boxes were operated at an electric field of only 6.5 kV/cm, where the signal saturation, or Birk's constant (K_B), is very large according to measurements by the WALIC collaboration [20] and by Ochsenbein [21]. For these conditions, the response to hadron showers is expected to be substantially lower than at higher electric fields [18]. From Wigman's predictions [18] of e/h versus K_B, and the WALIC measurements of K_B [20], we obtain the curves in Figure 9, which agree quite well with the data. Wigman's predictions, together with the measured K_B dependence on electric field [20], [21], would suggest that one can achieve compensation, e/h ≈ 1, for a lead-TMP calorimeter if operated at high electric fields, 30 - 50 kV/cm, and with a lead-to-TMP ratio of about 4-5 to 1. These, in fact, are the design conditions for the "swimming-pool" test beam module now under construction, and to be tested in the coming year.

Another important feature of the next WALIC E-795 run at Fermilab, is the installation and testing of a small tungsten-TMP electromagnetic calorimeter in the "swimming-pool" configuration, built by the Harvard group. This is described in the paper by Brandenburg et al. [22] contributed to this conference.

Thus, the goal is to have by fall 1991 a complete data set on compensation measurements for lead-TMP and iron-TMP, as well as a comprehensive test of the tungsten-TMP e.m. calorimeter.

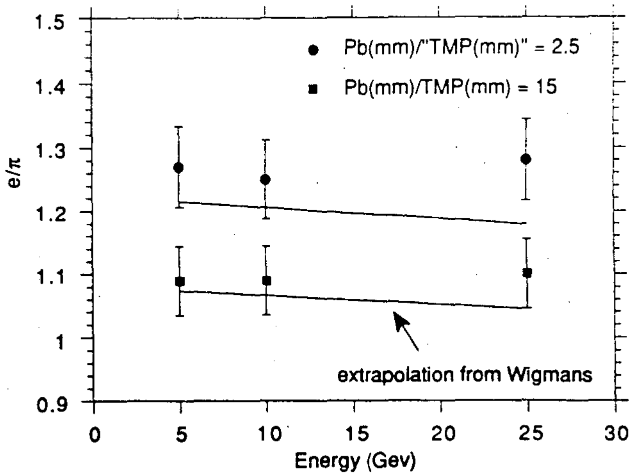

Figure 9. Preliminary results of e/π as a function of the incident beam energy for two extreme hadronic lead-TMP ratios of the calorimeter. The error bars represent 5% systematic errors.

4. "Proof-of-Principle" Test Beam Module

Even as each of the critical issues confronting this new technology gets successfully resolved, ultimately one needs to build and test a large "proof-of-principle" prototype. Part of the WALIC collaboration [3] is now building a large test beam module (TBM), designed in the "swimming - pool" configuration (the absorber inside the liquid volume), which is to satisfy the safety, hermeticity, hadronic compensation, resolution and time response requirements for an SSC/LHC detector. Furthermore, it is possible to extrapolate this design to a full-size SSC calorimeter module without major conceptual changes.

The design of the TBM itilizes many of the features that are envisioned being used in an actual calorimeter for an SSC detector, such as the "electrostatic transformer" readout, fine transverse segmentation in a tower configuration, and materials that lend themselves to efficient mass production techniques. The most time consuming part of the design phase of the TBM has been creating a module that uses only materials known to be compatible with TMP. It has also been a challenge to eliminate any volume that would trap air, since oxygen is very electro-negative and its presence would decrease the free-electron lifetime in TMP. Another design feature is that it can operate at electric fields up to at least 50 kV/cm.

The TBM is envisioned to consist of two modules, each one being about five interaction lengths deep, and 60 cm on each transverse side, comprising a five-by-five array of $12 \times 12\ \mathrm{cm}^2$ towers. The towers are read out in the electrostatic transformer configuration, summed so that there are four depths for the total of ten interaction lengths. An interesting feature of the design is that each layer of ten gaps is assembled from prefabricated, self-contained one-by-five arrays. A conceptual assembly drawing is shown in figure 10, and a detail of the tie-rod and insulator interface is in figure 11.

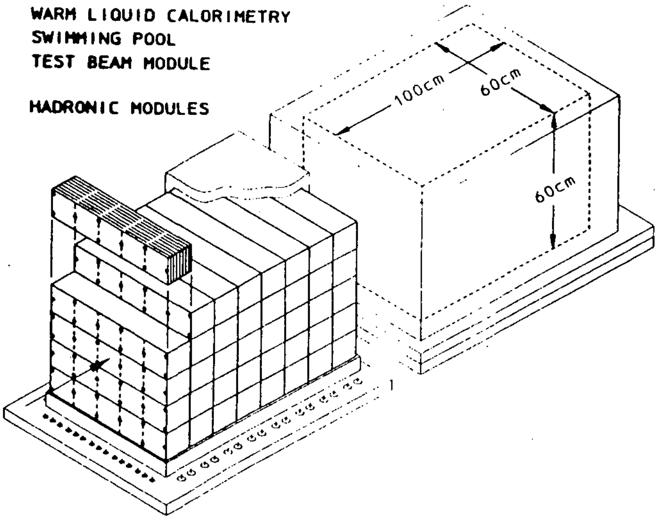

Figure 10. A conceptual drawing of a swimming-pool module (TBM) showing how a one-by-five preassembled tower module is assembled into the stack.

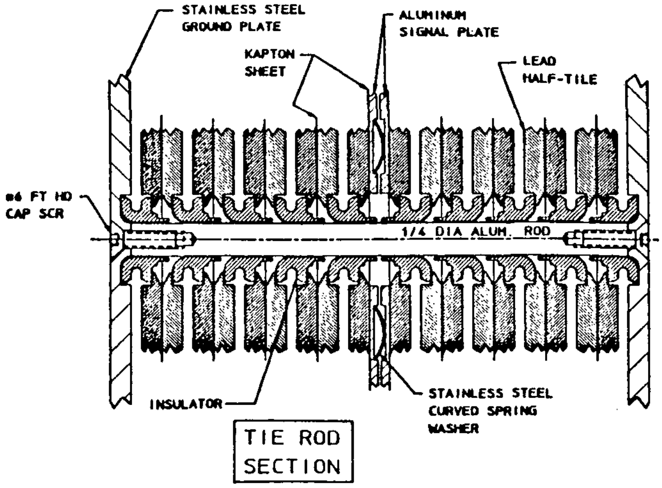

Figure 11. Detail of the ceramic insulator-lead tile interface of the test beam module (TBM).

The insulators were designed so as to maximize the surface leakage path in order to achieve the desired higher electric fields. The tiles are lead and ground plates are steel. High voltage tests performed so far in TMP have sustained 50 kV/cm across the gap. Each unit of this ten-gap building block has one signal plate in the center that collects the signal from two "electrostatic transformers" with a "turns ratio" of five. The advantage of this construction technique is that a one-by-five is small enough and sufficiently self contained that it can be built, cleaned, and tested independently of the final assembly of the large modules.

Figure 12 shows the voltage distribution and signal flow from the electrostatic transformer cell. The arrows in the TMP gaps show the direction of the ionization drift electrons across the gap.

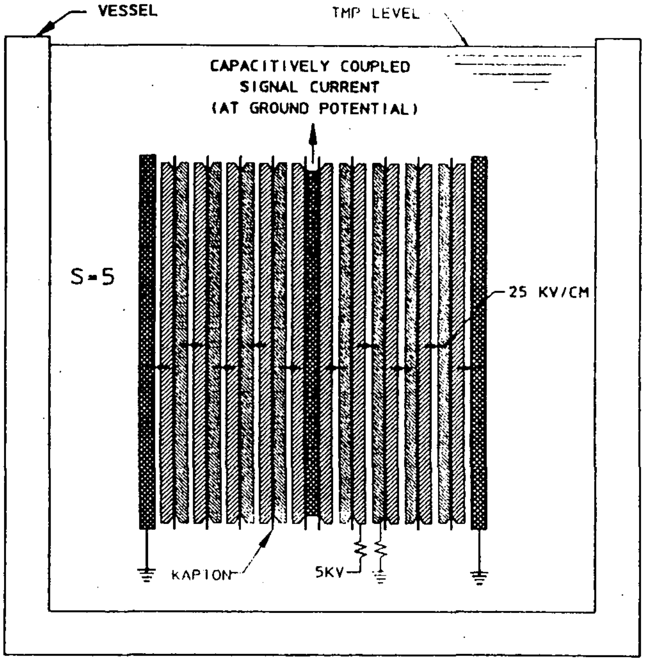

Figure 12. Electrostatic transformer cell configuration corresponding to the tower stack shown in Figure 11. The arrows in the gaps represent the ionization electron drift across the gap.

As mentioned earlier, all the components to be used in the test beam module have been tested for compatibility, with TMP and TMS. In addition, a ten-gap tower unit was recently tested by the Penn group [9] in TMS, using cosmic rays and they found no decrease of the free-electron lifetime.

If funds become too limited, only one of the two modules will be constructed and tested. In any case, several prototypes of TBM subsections are also being built in order to expose them to meaningful system radiation damage studies. These are intended to be completed in the coming year as well.

Finally, with the ideas incorporated in the test beam module, a detailed design of a full-size 4π warm liquid calorimeter for an SSC detector (SDC) has been made [23]. Among the outstanding features are the excellent hermeticity and the modularity which considerably eases the problems and schedule of assembly.

5. Conclusions

Considerable progress has been made recently in the development of warm-liquid calorimetry technology, which is very encouraging for application to SSC/LHC detectors. Nonetheless, more R&D needs to be done culminating in construction and testing of large "proof-of-principle" prototypes which satisfy performance requirements for the SSC/LHC colliders. These tests are planned to be done in the coming year, with at least two different design concepts: the swimming pool approach described above and the prism plastic calorimeter (PPC) [8] by the College de France group. In particular, there is still a great need for more extensive radiation-resistance studies of entire warm liquid calorimeter systems and not just of the liquid alone. This is especially crucial for consideration of this technology in a forward calorimeter whose the radiation levels are very high. However, radiation studies thus far, coupled with the fact that the liquid can be recirculated and repurified when necessary, hold out much promise for this technology. Nonetheless, this additional testing must be done. (Of course, the latter need applies even to all the other, more conventional, technologies).

Engineering design studies of full-size 4π warm liquid calorimeter have been made which exploit the hermeticity and modularity allowed by this technology.

Finally, there is an especially active R&D program being pursued which we expect will provide most of the remaining needed information soon.

6. Acknowledgements

I would like to thank all my colleagues in the WArm LIquid Calorimetry (WALIC) collaboration from France, Japan and the U.S. who have contributed significantly to the progress in this R&D program while making the whole research effort a lot of fun and a stimulating experience.

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