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The Performance of the Barrel CRID at the SLD; Long-term Operational Experience

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THE PERFORMANCE OF THE BARREL CRID AT THE SLD; LONG-TERM OPERATIONAL EXPERIENCE

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Abstract

The Barrel CRID detector has been operating successfully at SLD for the past 7 years. It is an important tool for SLD physics analyses. We report results based on long term operational experience of a number of important quantities such as the Cherenkov quality factor, N_0 , of the device, fluid transparency, electron lifetime, single electron detection efficiency, anode wire ageing, TMAE purity, long term stability of the gas refraction index, liquid radiator transparency, Cherenkov angle resolution and the number of photoelectrons observed per ring.

1. INTRODUCTION

The concept of the CRID at SLD benefited from the pioneering work of J. Seguinot and T. Ypsilantis [1]. The design is similar to that of the DELPHI RICH [2] and each group benefited from the work of the other. The early R&D developments of the Barrel CRID are summarized in ref.3, and its electrostatic design is described in ref.4. The detector main operating features and early CRID performance are described in ref.5. In addition, every year since 1986 we have presented some partial results at the IEEE conference. This paper summarizes our long term experience at a time when the SLD experiment is approaching the end of operation.

The CRID includes 40 TPC's, 40 liquid radiator trays containing liquid C_6F_{14} , a vessel containing a gas radiator composed of 87% C_5F_{12} +13% N_2 , and a system of 400 spherical mirrors [6]. The photoelectron drifts to a wire chamber where its position is reconstructed using a combination of drift time (z-coordinate), wire address (x-coordinate) and charge division (y-coordinate) with a precision of $-1 \times 1 \times 2$ mm. The TPC gas is C_2H_6 +TMAE (-0.1%). The maximum drift length is 1.2 m, and the maximum operating voltage is 55kV, which gives a drift field of 400 V/cm. The system operates at 35°C with the TMAE bubbler temperature set at 26-27°C, and has -3720 anode wires, -7440 amplifiers, -64000 field shaping electrodes and 6520 corona-preventing field wires.

2. SYSTEM PERFORMANCE

2.1. The single electron detector

2.1.1. General performance

The single electron detector is based on single stage MWPC wire amplification with an average total gas gain $\sim 3 \times 10^5$. The present CRID operating point corresponds to a single electron efficiency of about 85-90% [7]. To limit the avalanche photons from entering the TPC drift volume, a system of Cu-Be blinds

was constructed. The avalanche photons cause after-pulses. The measured rate of after-pulses per avalanche caused by the secondary avalanche photons is less than 1% at the operating point. The Cu-Be blind structure gives a factor of 7-8 reduction in the rate of after-pulsing. In order to have good electron transmission to the anode wire, the ratio of the drift field within the detector to that in the TPC is maintained at a value close to 6. This makes the structure relatively insensitive to misalignments. The fact that the system of 3720 anode wires has been stable throughout 7 years of TMAE operation demonstrates that the design and the choice of operating conditions are sound.

2.1.2. Charge division performance

Initial experience and the very good charge division resolution, $\sigma_z/l \sim 0.7\%$, obtained in early R&D tests [4,8], led to the choice of 7 μ m carbon wire, even though such a thin wire is weak and difficult to handle. However, as a result of wire ageing arguments, the wire gas gain is set at as low a value as possible. This is the dominant factor in defining the observed charge division resolution, $\sigma_z/l \sim 2.5\%$ [9], which is nevertheless sufficient for the physics analysis.

2.1.3. Wire ageing

The TMAE molecule is very susceptible to polymerization. The prediction from the R&D ageing tests [10] is that a modest detector current of about 5-10nA would cause a 50% gain drop in about 1-2 years. Fig.1a shows the wire ageing at SLD and indicates a decrease in gain of about 20-30% in a three year period; this result is consistent with the R&D data (a typical current 2-4nA per detector). From pulse height distribution measurements, we estimate that a 30% average gain decrease reduces the detection efficiency by about 5%. The rate of wire ageing was studied by monitoring the average single electron pulse height using UV fibers.

To regenerate the wire gain, we have shown in R&D tests that we can either wash the detectors with alcohol, or evaporate the deposits by passing a small ($\sim 10\text{mA}$) current which heats the carbon wires to a temperature above 300°C . However, after ~ 7 years of running there is strong evidence that the wires have weakened to the point that they may be unable to tolerate this current without running a substantial risk of breakage. Tests with a detector which was removed from the SLD recently, indicate that such a procedure would be too risky. Therefore, the only option available is to clean the wires by washing the whole anode plane in ethanol. This was done to some detectors being repaired in the lab. Fig.1b indeed shows that there is an improvement in the relative average pulse height after such washing.

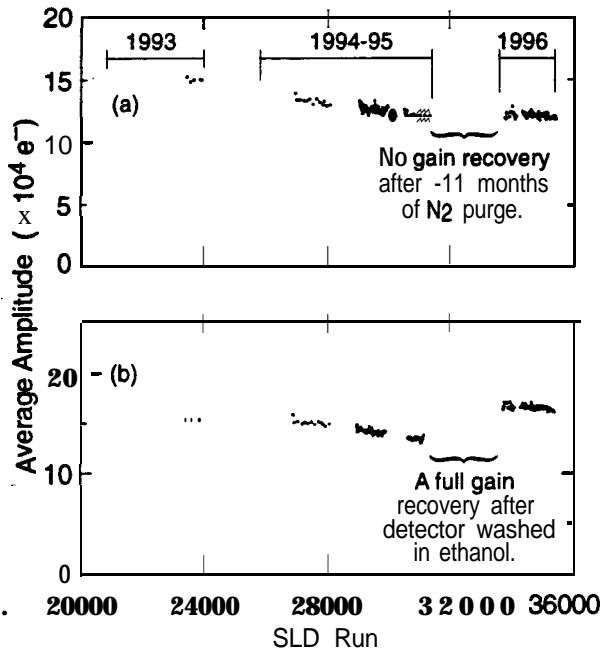


Fig.1. Wire ageing in the SLD CRID between 1993 and 1996 with: (a) a detector which was never removed, and (b) a detector which was removed after the 1995 run and washed in ethanol. The average pulse height is monitored using the UV fiber single photon calibration pulses [7].

2.1.4. Malter effect

During the period from 1991 to 1993, our UV fiber trigger rate was set to the 120Hz SLC repetition rate. This caused local rates on some anode wires as high as 10Hz per cm of wire length. It was discovered [11] that this caused damage (probably in the form of an insulating film) to cathodes corresponding to wire locations aligned with the UV fiber fiducials. The damage would show up as a burst of charge every 15-20 minutes. Since then these wires cannot take a very high UV fiber rate. After the problem was discovered, the UV fiber trigger rate was reduced by a factor of 2000, and this yielded a reduction of the burst rate by more than a factor of 20. The total charge dose from the UV fiber source before the first bursts were discovered was estimated to be only about $2 \times 10^{-7} \text{C/cm}$, which is an exceedingly small amount. Of course, the subsequent burst charges increased the total charge dose rapidly. So far, during hadronic trigger running, this has

not caused a problem due to sufficiently low charge density. However, it is obviously a concern for times when the SLC background is very large. A similar concern may come from background muon aligned with the TPC axis.

2.1.5. Wire breaking

The $7 \mu\text{m}$ diameter carbon wires are definitely too fragile for the long term operation of such a large system as the CRID. They break at a rate of 3-5 per run, and this creates geometrical inefficiencies at a level of 5-10%. We try to repair detectors with broken wires during a run in order to minimize their impact. It is not clear why such breakage occurs, but we think it is due to material fatigue resulting from the total accumulated dose. This dose can be enhanced by excessive SLC noise during some periods (remember any single SLC pulse can create a very large background), due to background muons depositing charge axially in the TPC. ($>10000e^-$ per track), or due to the charge created by bursts related to the Malter effect. In retrospect, a choice of anode wire diameter between 20 and $33 \mu\text{m}$ diameter would have been better (the wire ageing is also slower with thicker wire [10]).

2.2. Electronics performance

We placed the amplifiers, analog storage (HAMU), ADC's and control and multiplexing circuitry on the detector [12]. Only a few serial optical fibers lead to the Fastbus located in the electronics control room. The amplifier charge gain is about $-2.7 \mu\text{V/electron}$. To limit heating problems, amplifiers are water cooled, and all components except the first the JFET use pulsed power. The analog storage needs to be calibrated every few days; the amplifier gain is calibrated once per run.

The amplifier-detector combination has cross-talk at a level of $+1.1\%$ for the first neighbor and about -0.25% for a distant neighbor [13]. This may seem small, but a typical charged track deposits about 1000 electrons in the TPC so that the cross-talk problem becomes significant. The amplifier recovery from such charge deposits creates spurious pulses, and also affects the measurement of real pulses. This is a complication for CRID analysis in the core of a jet, where many tracks overlap; for example, it causes a typical loss of 10-20% of the photoelectrons per liquid ring.

Any fault with the electronics located on the detector usually means that we have to wait for an SLD door opening in order to make repairs. Typically, we have -1% dead electronics channels randomly distributed at any given time during the run; from time to time some other larger segments fail, for example an ADC board, and this causes an additional $-1-2\%$ dead channels which tend to be clustered. However, it should be pointed out that it took several years before the electronics was debugged to this level. This is the price of placing complicated, inaccessible electronics on the face of the detector.

2.3. TPC gas

The C_2H_6 gas¹ is cleaned in the standard way, i.e., we use mechanical filters,² Oxisorbs³ and 13X molecular sieves.⁴ In

¹ Purchased from AlphaGaz Co. with purity specification: 99.995%.

² Mechanical Wafeguard filter, 0.05 micron, Milipore Co., U.S.A.

³ Oxisorb made by Messer Griesheim GmbH, 4000 Dusseldorf, Germany.

⁴ 13X Molecular Sieve made by Union Carbide Co., Danburg, CT 068174001, U.S.A.

addition, we use electropolished stainless steel tubing as is common practice in Silicon Valley industry.

We had serious problems with sulfur contamination. Our initial 1991 ethane supply was contaminated at a level of only 1-3 ppm, but that was sufficient to completely plug the ethane pressure regulator after one year of operation. The sulfur impurity level varies with the oil well which is the source of the ethane (as much as 200ppm of sulfur has been reported). Sulfur can exist in ethane as elemental sulfur (dissolved in ethane liquid), CS_2 , H_2S , SO_2 and COS. During the 1993 physics run we tried using a nickel getter⁵ to remove this contaminant. This caused day-to-night variations in drift velocity, which could not be corrected by means of a simple pressure and temperature correction. Instead, we had to rely on the W fiber drift velocity off-line calibrations. There was also a small release of oxygen from the nickel getter over a period of time, which prompted us to introduce another Oxisorb cartridge on the gas pad. This experience illustrates that some very active substances used in modern cleaning filters, such as nickel, can give rise to very complicated chemistry. As a result, in 1994, we decided to buy sulfur-free ethane in Europe. The sulfur level was specified to be less than 1ppm. The 1994 and 1995 physics runs went without any problem. However, in the 1996 and 1997 runs the same plug-up problems developed despite very tight sulfur specifications. For example, we see elemental sulfur deposits in the gas regulator (see Fig.2), and we also clearly recognize the characteristic smell of SO_2 . This indicates that the gas company's certification documents cannot be trusted. Each gas delivery must be checked independently. It was sulfur, and not TMAE, which was the biggest source of grief for long term operation of the CRID.

The TMAE⁶ is cleaned by the CRID group by (a) washing it with oxygen-free deionized water, (b) filtering through silica gel and 3A and 4A molecular sieves, and (c) pumping [14] it at elevated temperature ($\sim 60^\circ\text{C}$) and at a pressure of a few Torr for 12-24 hours.



Fig.2 Sulfur deposits in the ethane gas pressure regulator.

This operation was perfected over many years, and resulted in the production of TMAE of consistently good quality by removing various contaminants, such as TMO, which is

⁵ Nickel catalyst N1-0104T-1/8 made by Engelhard Co., Iselin, NJ 08830-0770, U.S.A.

⁶ TMAE stands for Tetrakis dimethylamino ethylene and was purchased from RSA Co., U.S.A.

soluble in water (it has a $\sim 40\times$ higher electron capture rate than oxygen [15]). Before the TMAE is used in the TPC's, it is qualified in a small ionization chamber (ELM) [16]. Fig.3 shows an example of electron lifetime after TMAE washing with two different bubblers before use in the 1997-98 physics run. One can see a clear improvement in TMAE purity when pumping is used compared to simple filtering. When the TMAE washing is finished, the electron lifetime is almost the same in the TMAE laden gas as in the carrier gas, in this case CH_4 [7].

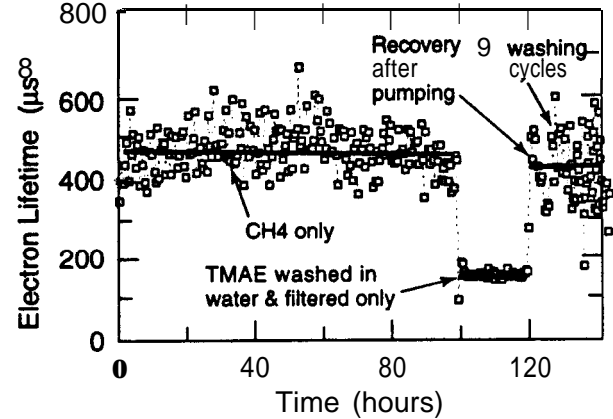


Fig.3 TMAE washing: (a) measured electron lifetime with CH_4 only, (b) with CH_4+TMAE where TMAE was just washed in water and filtered, (c) as (b) but also pumped for 12-24 hours at a pressure of a few Torr at 60°C [7].

2.4. Gas radiator

Our gas radiator recirculation system operates as a heat engine. We believe that the simple distillation and condensation cycle in our heat engine recirculation system helps maintain the required purity of the radiator gas. The returning gas mix from the vessel enters a -90°C tank where the C_5F_{12} liquefies, and the N_2 gas is vented; this also serves to remove some gaseous impurities. The C_5F_{12} liquid is then evaporated again and mixed with new N_2 gas. The overall flow generates one complete volume change every 10-11 hours. In parallel, the C_5F_{12} liquid is circulated through a system of silica gel,⁷ elemental copper (RIDOX),⁸ and Oxisorb filters. The idea is that the silica gel protects the other filters.⁹ We do not regenerate any of these cartridges for fear of possible dissociation of C_5F_{12} molecules during the heating process.

We monitor the radiator transmission using two methods: (a) we pump a return gas mixture from the vessel to a gas rack monochromator, where it is measured in a 20cm long W cell, or, (b) we take a liquid C_5F_{12} sample from the -80°C tank directly into either a 1cm thick W cell or a small glass bottle, and then take this liquid to another monochromator. Fig.4

⁷ Silica Gel Sorbead R was purchased from Adcoa Co., Gardena, CA 90247, U.S.A.

⁸ Elemental Copper is made by Engelhard Co., Elyria, OH 44035, U.S.A. (the process is called Q-5)

⁹ The procedure recommended to us by 3M Co., St. Paul, Minn. 55144-1000, U.S.A.

shows that the measurement of the 87% C_5F_{12} +13% N_2 gaseous sample using the 20cm long cell is consistent with 87% C_5F_{12} + 13% N_2 gas, 87.5 cm

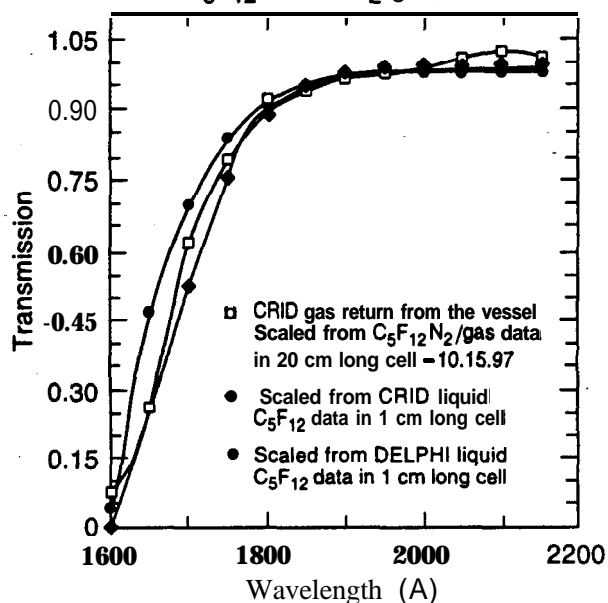


Fig.4 The transmission of C_5F_{12}/N_2 gas, taken from the vessel return and measured in a 20cm long cell, compared to liquid measurements properly scaled [7].

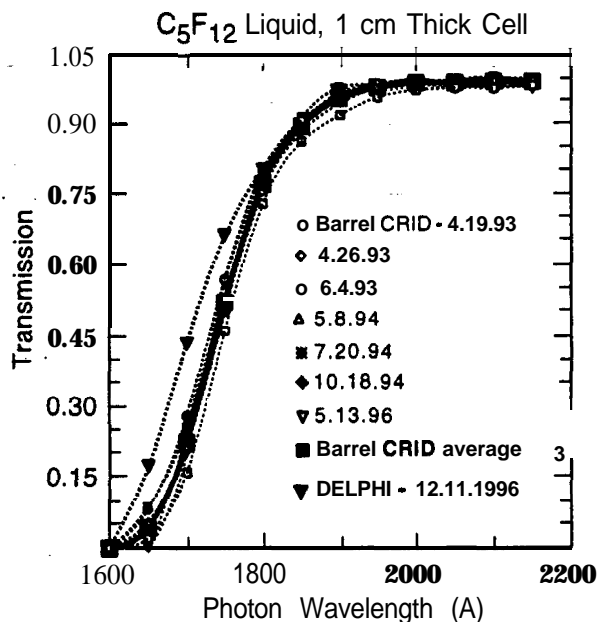


Fig.5 The transmission of C_5F_{12} liquid taken from the $-80^\circ C$ tank and measured in a 1cm thick cell. Six SLD measurements from different periods, and their average are compared to the current DELPHI results [7].

that using the 1cm thick liquid sample, after both have been scaled to the average photon path length 67.5cm. Both CRID measurements are only slightly worse than the results from the DELPHI 1cm thick liquid sample, which was obtained by fractional distillation [17]. This indicates that the results of our

C_5F_{12} purification procedure is nearly the same as that obtained by the DELPHI group. Fig.5 shows good reproducibility of the transmission measurements using liquid samples from the $-80^\circ C$ tank, taken during different periods.

Any instability in the 87% C_5F_{12} +13% N_2 mix causes instability in the refractive index or the Cherenkov angle. The gas radiator mixture in the vessel is continuously monitored by sonar [18]. The data are then used in the off-line analysis. Fig.6 shows the time history of the Cherenkov angles in this radiator obtained from off-line reconstruction, in comparison to

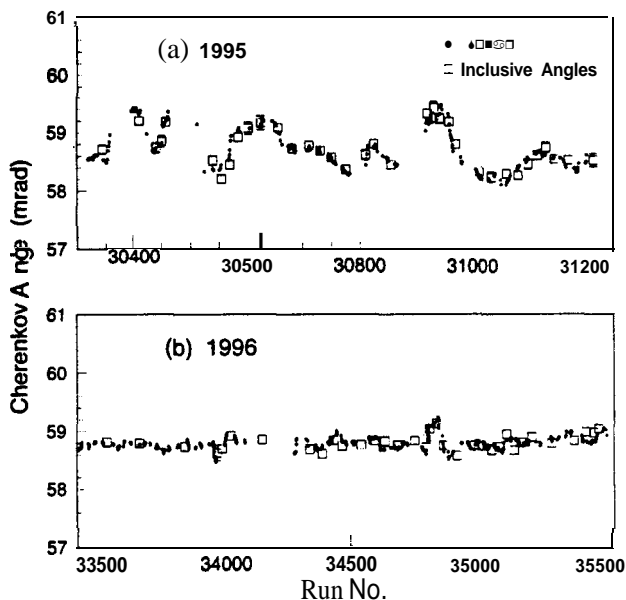


Fig.6 The $\beta \sim 1$ Cherenkov angle measured from ring reconstruction (squares) compared to the value expected from the gas index measured by sound velocity in the CRID vessel and corrected for atmospheric pressure (dots).

the angles obtained from the sonar measurements. Both agree very well. Therefore sonar can be used to correct the data during periods when we do not have high statistics in Z^0 events.

2.5. Liquid radiator

The C_6F_{14} liquid is initially de-oxygenated and purified by bubbling N_2 gas through it. During the run, the liquid is purified by pumping it through Oxisorb. The recirculation flow is one radiator volume every 2 hours. The Oxisorb is changed every 3 months. In this system the Oxisorb is not protected by silica gel. However, we do know that the 3M company uses silica gel to clean the liquid before shipping, and our experience to date is satisfactory. We have never experienced problems with 'improperly fluorinated C_6F_{14} molecules such as those experienced by the DELPHI group (17,191, which caused severe transmission problems in the early period of their running. However, Fig.7 shows that our simple filtering method is not equivalent to cleaning by fractional distillation, which DELPHI presently uses to separate C_5F_{12} and C_6F_{14} molecules, because of leaks between the liquid system and the gas radiator. Fig.7 also shows that by the time of the Bari RICH conference both experiments had similar transmission; at that time DELPHI did

not yet use the distillation process. After the process was introduced one can see a steady improvement. One can also see

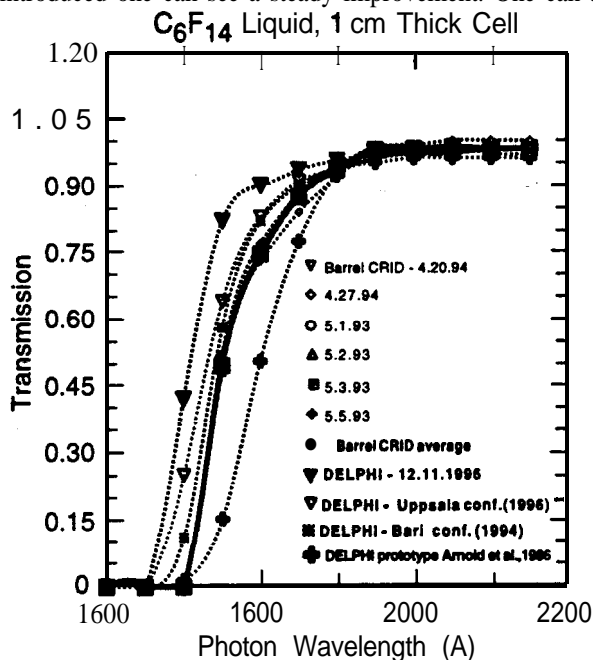


Fig.7 The transmission of C_6F_{14} liquid measured in a 1cm thick cell. Six SLD measurements from different periods, and their average are compared to the current DELPHI and older DELPHI prototype results [7].

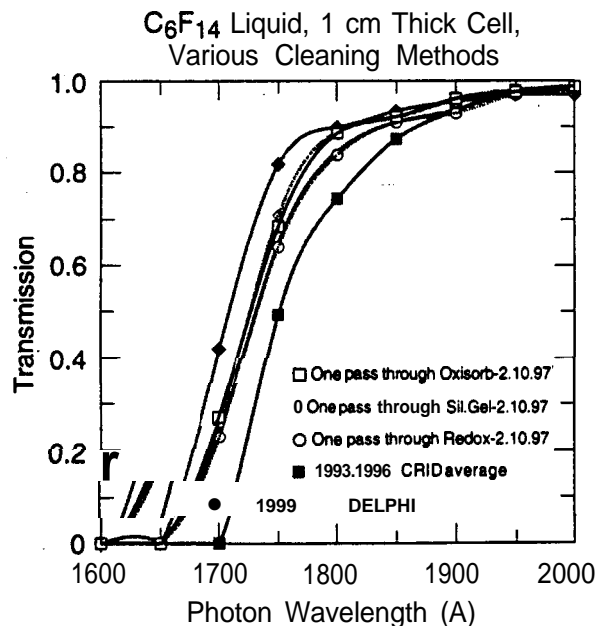


Fig.8 Attempt to take the liquid from the CRID system and pass it once through an Oxisorb, or Silica gel, or RIDOX [7].

that the **early** DELPHI prototype from 1986 had even worse C_5F_{12} transmission. We were interested to test whether the transmission might be **improved** by a different kind of filtering. Fig. 8 shows an attempt to take the liquid from the CRID system and pass it once through an Oxisorb, or Silica gel, or RIDOX filter. It is interesting to note that silica gel is

equivalent to Oxisorb; on the other hand, **RIDOX** filtering is worse. This indicates that our purity could be improved if we increased our filter capacity substantially, at least in principle. However, probably the best way to clean the commercially **available** C_5F_{12} or C_6F_{14} molecules is to distill them.

2.6. High voltage

In the early days we worried that any corona on field wires might cause a very large photon background in nearby TPCs. This did not occur, mainly because of our conservative **design** for the electric gradient on the field cage wires ($<20\text{kV/cm}$). To define the drift field in the TPC's we decided to use a simple geometry for the field cage wires rather than a volume degrader. Our experience with high voltage is excellent indicating that it is not necessary to build a volume degrader for voltages up to 60kV and distances of **8-10cm** to ground, provided that a gas with good dielectric properties fills the volume.

We had good experience with all high voltage cables used both for the 55kV TPC operation (inside the radiator vessel we use -3m long 100kV Belden polyethylene cable, outside we use -30m long 125kV silicone Alden cable) and for the 1.5-5kV MWPC detector operation (in this case, we use ~30m long 10kV Belden polyethylene cables), and also with all power supplies made by the CAEN and Gamma H.V. Research companies. We had good experience also with thin film resistors used for TPC field grading and spark gaps used to protect them in case of a spark.

2.7. Material stability

2.7.1. Materials exposed to TMAE

Generally, all materials exposed to TMAE are in excellent shape after -7 years of SLD operation and 10 years after the initial construction. This includes hard epoxies (DP-190 or Epon826+Versamid140), Cu-Be electrodes of the detector (they are as shiny as new), Viton O-rings¹⁰ used to seal the MWPC detector to the TPC (in the early days we worried about the longevity of such a soft material in TMAE), TMAE bubblers, etc. This comes from visual inspection of both TPCs and the MWPC detectors, and also from the fact that the oxygen level in the return gas from all TPC's is the same as seven years ago, i.e. below lppm. Perhaps the only weak part of the entire system exposed to TMAE is the Alodined plating of an aluminum surface within the MWPC detector and the TPC detector enclosure; this plating seems to come off relatively easily when rubbed with a Q-tip dipped in ethanol.

2.7.2. Materials exposed to C_5F_{12}

We see clear signs that this particular molecule, which is a solvent, leaches a small amount of plasticizer from the RF gasket¹¹ used to seal the radiator vessel's sector covers. The plasticizer is deposited on the clamps located a few mm away. However, because we keep a slight positive pressure in the vessel ($\sim 0.5\text{Torr}$), this effect is believed not to be harmful to sensitive components within the vessel.

2.7.3. Materials exposed to C_6F_{14}

We do not see any obvious deterioration. In the early period of **CRID** running we have seen pollution leaching from the

¹⁰ Viton O-ring, Parker Co., Part number : VO747-75, Cure 4Q87.

¹¹ "Elastomet" rubber gasket filled with 5056 aluminum wire made by Nova-tronix Inc., Santa Clara, CA 95054, U.S.A.

DP-190 epoxy into the C_6F_{14} liquid, thereby affecting the UV transparency. To solve this problem, it was found necessary to circulate C_6F_{14} liquid continuously and filter out this pollution using an Oxisorb filter.

However, based on our lab tests, the liquid trays, which were built using G-10 panels and quartz windows, do change shape under gravity; it is possible that this effect results in poorer angular resolution than expected for Cherenkov rings in the liquid (we have to add $\sim 10\text{mrad}$ in quadrature with the resolution obtained in Monte Carlo simulation to reproduce the data).

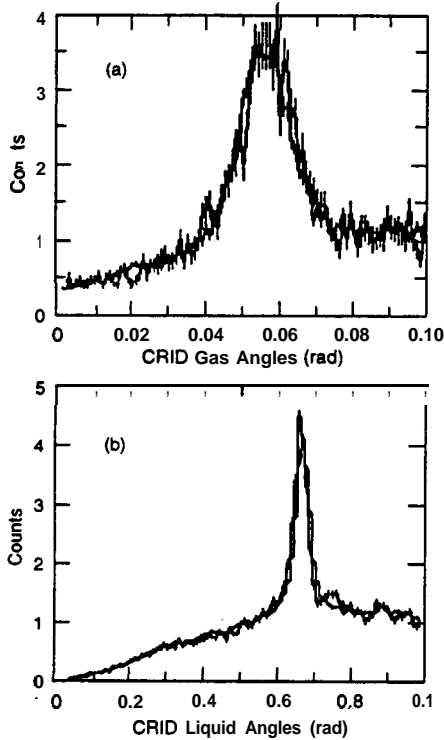


Fig.9 On-line monitoring of the Cherenkov angles at the end of each run (-4 hour running period).

2.8: CRID monitoring

There are several levels at which the CRID system is monitored: (a) the absolutely critical variables, such as TPC or gas radiator pressure, are tied to an automatic hardware control which protects the basic integrity of the system by switching off the gas flow [20]; (b) a very important part of the safety system is the SIAM alarm system, which allows monitoring of about 80 variables; some critical variables are connected to an auto-dial paging system, and some can cause an automatic TMAE bubbler bypass; without the SIAM system the CRID would not have been successful; (c) another important feature of the CRID is slow self-monitoring of each TPC by measuring, for example, the Cherenkov angle distribution at the end of each 4 hour running period (see Figs.9a, b), the average TPC \bar{z} -coordinate formed from single electron pulses plotted as a function of time (see Fig.9c), the average number of hits per gas or liquid Cherenkov ring, etc.; in a way, this is the final arbiter of performance; (d) in addition, there is an extensive on-line monitoring system [21] which gives quantities such as the electron lifetime in selected TPCs, the

mix ratio in the radiator vessel based on sonar, various averages, etc.

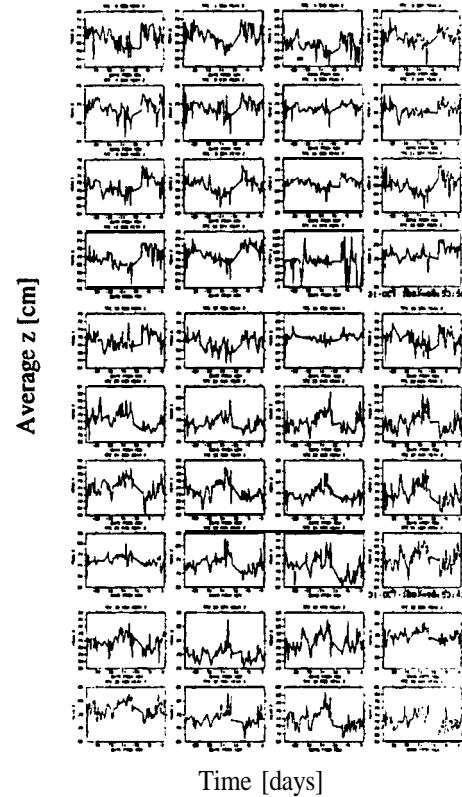


Fig.9c The time dependence of the average TPC \bar{z} -coordinate formed from single electron pulses for each TPC.

2.9. Simple estimate of N_0

It is useful to define a “starting efficiency”, which can then serve as a limit on how well one can do in the best possible circumstance. It is limited only by the TMAE quantum efficiency and basic material transmissions. For liquid rings, the “starting efficiency” is defined by the wavelength dependent transmission through quartz, $T_{\text{quartz}}(E)$ [corrected for photon path length $4\text{mm}/\cos(38.5^\circ)$; and applied twice], C_6F_{14} liquid, $T_{C_6F_{14}}(E)$ [corrected for photon path length $1\text{cm}/\cos(38.5^\circ)$], and the TMAE quantum efficiency, $\epsilon_{\text{TMAE QE}}(E)$. For gas rings, the “starting efficiency” is defined by the transmission through the quartz window, $T_{\text{quartz}}(E)$ [assume 4mm photon path length; applied once], $87\%C_5F_{12}+13\%N_2$ gas, $T_{C_5F_{12}/N_2}(E)$ [corrected for $\sim 67.5\text{cm}$ photon path length $\sim 1.5 \times 45\text{cm}$], the mirror reflectivity, $R_{\text{mirror}}(E)$, and the TMAE quantum efficiency, $\epsilon_{\text{TMAE QE}}(E)$. There are many corrections which degrade the “starting efficiency.” They are derived from a collection of efficiencies, such as those measured during the construction period (transmission of quartz, mirror reflectivity and TMAE quantum efficiency [22]), and those measured during the run (MWPC chamber efficiency, UV transmission of fluorocarbons, oxygen and water effects), together with estimates of other factors, such as absorption by the field cage wires, electron lifetime, TPC gaps, TMAE absorption length, etc. We call the degraded efficiency a “final

efficiency." The "starting" and "final" efficiencies are shown in Figs.10 and 11, and Table 1 lists estimates of the total degradation factors between the "starting efficiency" and the "final efficiency;" these factors are 0.52 for the liquid rings and 0.70 for the gas rings. For more detailed discussion of the Barrel CRID efficiencies and degradation factors see ref.7.

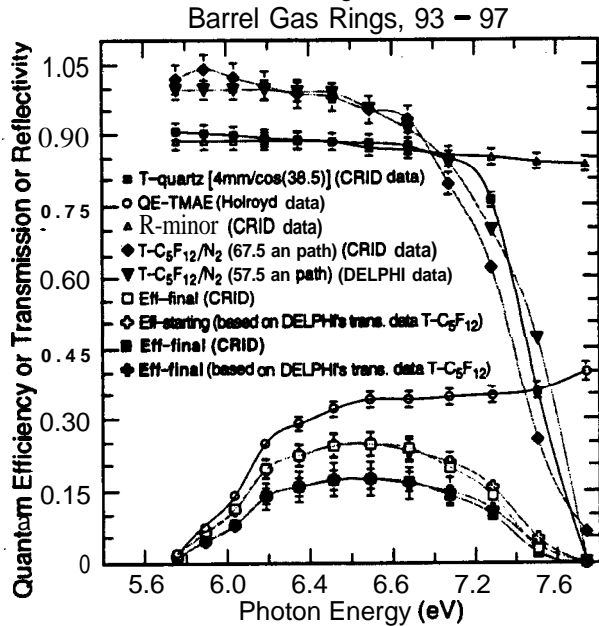


Fig. 10 Barrel CRID gas rings with the C₅F₁₂/N₂ radiator: transmissions for quartz (4mm) and the 87% C₅F₁₂+13% N₂ gas radiator [for an average photon length ~1.5x45 cm], reflectivity of mirrors, TMAE quantum efficiency (Holroyd), and the "starting" and "final" efficiencies [7].

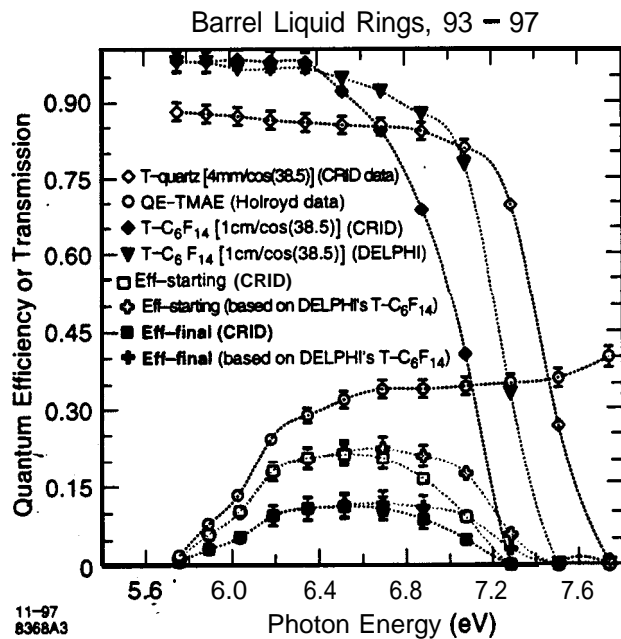


Fig.11 Barrel CRID liquid rings: transmission for quartz (4mm) and the C₆F₁₄ liquid radiator (1cm), TMAE quantum efficiency (Holroyd), and the "starting" and "final" efficiencies [7].

The above mentioned method does not include effects such as those due to the confusion in the middle of jets (the cross-talk and amplifier recovery cleaning cuts, and small electron losses due to the Lorentz angle in the liquid rings). Therefore, it is expected to be useful only for simple events, such as di-muons, where we observe 16- 17 photo-electrons per full liquid ring, and -10 per gas ring; this is consistent with the simple calculation at the level of 10%. Notice that we could increase the total number of photo-electrons per liquid ring by 2-3 if we were to achieve DELPHI's C₆F₁₄ purity, which was obtained by fractional distillation instead of filtration.

Table 1

| Parameter | Gas Rings | Liquid Rings |
|--|-----------|--------------|
| Total fraction of photoelectrons contributing to the "final efficiency" compared to the "starting efficiency" $Eff_{final} / Eff_{starting}$ | 0.70 | 0.53 |
| Mean photon energy [eV]: | 6.70 | 6.50 |
| Mean refraction index : | 1.001646 | 1.2720 |
| Mean Cherenkov angle [mrad] ($\beta=1$ particle) : | 57.33 | 666.24 |
| Calculated for radiator length [cm]: | 45 | 1 |
| N_0 [cm ⁻¹] | 80 | 42 |
| Expected average number of photoelectrons per full ring ($\beta=1$ particle) [7]: | 11-12 | 16 |
| Measured average number of photoelectrons per full ring (di-muons) [21]: | 10 | 16-17 |

3. RESULTS AT SLD

Fig. 12a shows the Cherenkov gas ring angular resolution for di-muons [21]. This particular resolution is obtained by making circle fits to gas rings, and represents the "internal resolution" (3.6mrad) of the CRID; it indicates that the TPCs are reconstructing data with a resolution close to design value. Fig.12b shows the same for full liquid rings close to a 0° dip angle. The expected resolution is about 12mrad. This means that we have to add about -10mrad in quadrature to explain the data; this ~10mrad represents systematic errors due to misalignments, for example, distortions in liquid trays. Fig.12c shows this resolution as a function of dip angle. We see about 10 photoelectrons per gas ring, and 16- 17 photoelectrons per liquid rings for di-muons [21], i.e. close to expectation for simple events - see Table 1.

The most important fact is that the CRID contributes to more than a dozen SLD physics analyses. As an example, Fig. 13 shows the charged hadron fractions from Z⁰ decays as a function of momentum. One can see that pions are identified between 350MeV/c and 35GeV/c, kaons between 750MeV/c and 35GeV/c, and protons between 750MeV/c and 45GeV/c. Fig.14 shows the cross sections for the production of various particles at the Z⁰ as a function of the variable x_p [23]. This graph includes also ϕ and K^{*0} production, for which the CRID particle identification is essential for reduction of background.

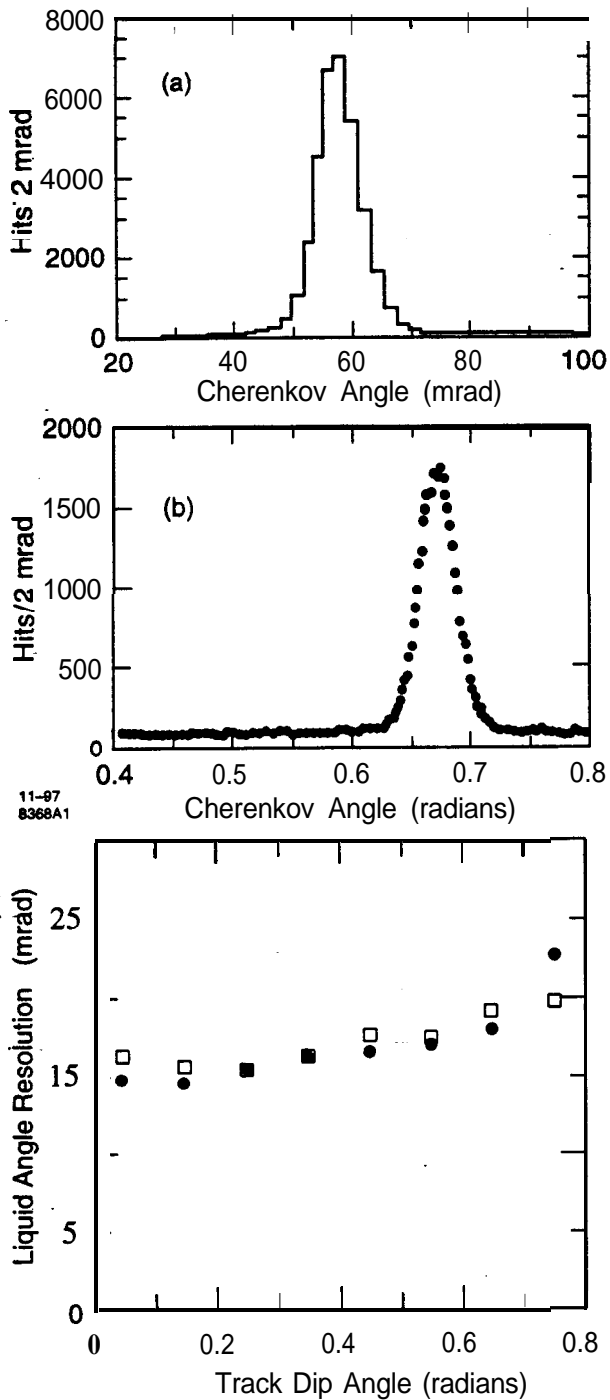


Fig.12 Cherenkov angle resolution in $e^+e^- \rightarrow \mu^+ \mu^-$ events for: (a) gas rings (~ 3.6 mrad; residuals from the fitted circle to show the internal TPC resolution), (b) liquid rings (~ 15 mrad; inclusive resolution) at 0° dip angle, and (c) liquid rings as a function of dip angle (squares are from hadronic events, while dots are from $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow e^+e^-$ events) [21].

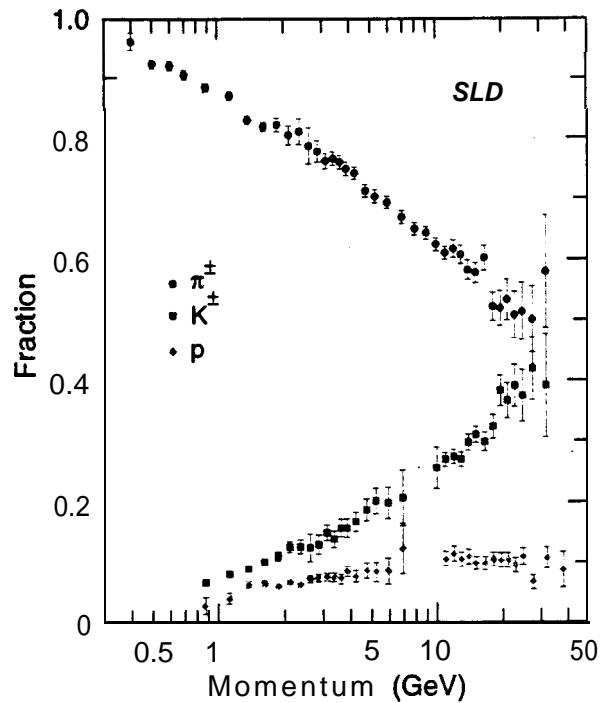


Fig.13 Particle fractions from Z^0 decays as a function of momentum [23].

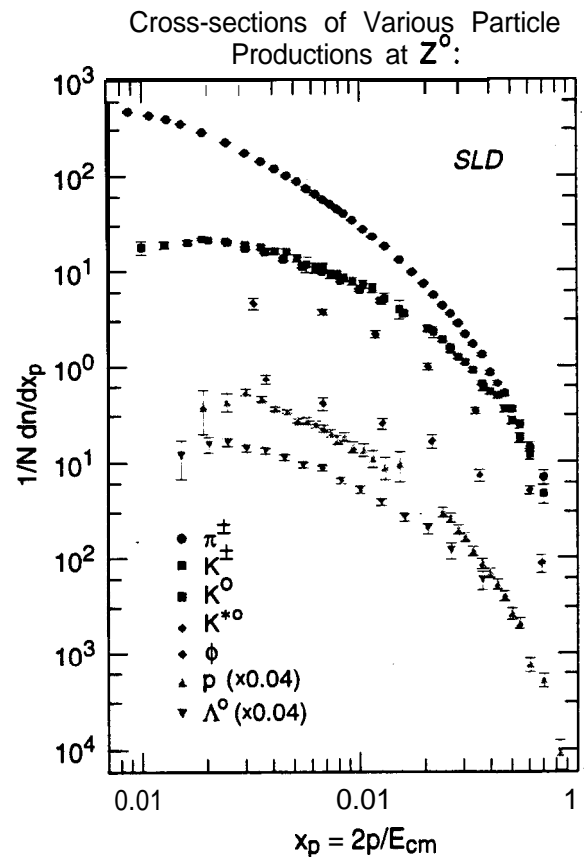


Fig. 14 Cross sections for the production of various particles productions at the Z^0 [23].

4. CONCLUSIONS

A major achievement of the first generation photon detectors, such as the CRID, was to convince the many skeptics in the high energy physics community that the RICH concept can be implemented to yield useful physics. The members of the SLD collaboration are "embracing" the CRID as an important tool in a wide range of physics analyses.

REFERENCES

- [1] J. Sequinot and T. Ypsilantis, **Nucl. Instr.&Meth.**, **142(1977)377**.
- [2] DELPHI Proposal, LEPC 83-3 and LEPC 84-16, and **Nucl. Instr.&Meth.**, **A343(1994)68**.
- [3] D.W.G.S. Leith, **Nucl. Instr.&Meth.**, **A265(1988)120**.
- [4] K. Abe et al., Fifth International Conference on Instrumentation for Colliding Beam Physics, Novosibirsk, Russia, March 15, 1990.
- [5] K. Abe et al., **Nucl.Instr.&Meth.**, **A343(1994)74**.
- [6] K. Abe et al., **Nucl.Instr.&Meth.**, **A300(1991)501**.
- [7] J. Va'vra, CRID note 89, January 1997, including addendum to it, which includes an update after the gas rack monochromator has been rebuilt.
- [8] D. Aston et al., **Nucl.Instr.&Meth.**, **A283(1989)582**.
- [9] F. Suekane and Y. Iwasaki, CRID Note #79, March 24, 1993.
- [10] J. Va'vra, IEEE Trans. **Nucl. Sci.**, NS-34, p.486, Feb. 1987; CRID Note #36, SLAC (1987); and IEEE Trans. **Nucl. Sci.**, NS-35, p.487, Feb. 1988.
- [11] J. Va'vra, **Nucl.Instr.&Meth.**, **A367(1995)353**.
- [12] E. Spencer et al., IEEE **Trans.Nucl.Sci.**, NS-35, p.231, Feb.1988; P. Antilogus et.al., **SLAC-PUB-5120**, Oct. 1990; K. Abe et.al., **SLAC-PUB-5679**, Nov. 1991.
- [13] P. Rensing, Ph.D. thesis, SLAC Report 421, Stanford, August 1993.
- [14] D. Anderson, IEEE Trans. **Nucl. Sci.**, NS-28, p.842, Feb. 1981.
- [15] R.T. Rewick, T. Weber, M. Cavalli-Sforza, M.L. Schumacher, and S. Shapiro, **Anal.Chem.**, **60(1989)2095**.
- [16] M. Cavalli-Sforza, CRID Note#15, May 1986.
- [17] G. Lenzen, private communication and E. Schyns, Ph.D. thesis, WUB-DIS-96-22, Wuppertal, Germany, 1997.
- [18] G. Hallewell et al., SLAC-PUB-4405, 1987.
- [19] S. Ilie and G. Lenzen, DELPHI 93-33 RICH 54.
- [20] P. Antilogus et al., **Nucl.Instr.&Meth.**, A293 (1990) 136.
- [21] T. J. Pavel, Ph.D. Thesis, SLAC Report 491, August 1997.
- [22] R.A. Holroyd, J.M. Preses, C.L. Woody, and R.A. Johnson, **Nucl.Instr.&Meth.**, **A261(1987)446**.
- [23] D. Aston, D. Muller and T. Pavel, SLD Physics Note 58, November 1996.