Failure modes of resistive plate chambers

Outline

- Resistive Plate Chamber (RPC) operation
- Mechanical tolerances
- Failures due to resistivity changes – eg Oil bridges
- Aging in new production BaBar RPCs
- Malter effect
- Water in glass RPCs
- Conclusions
• Number of electrons at the head of shower is given by
  \[ n_e = e^{\alpha \ell} \]
  where \( \alpha \) is the Townsend coefficient (depends on gas and \( E \)) and \( \ell \) is the shower length

• Streamer mode (space charge dominated discharge) occurs when
  \[ \alpha \ell \approx 20 \quad \Rightarrow \quad n_e = 5 \times 10^8 \]

• Streamer is limited in part by the high resistivity of the bakelite
Typical gas mixture

- Argon to provide for efficient gas amplification
- Isobutane (or another hydrocarbon) to absorb UV photon
- Freon (e.g. 134a, C₄H₂F₄) “quench gas”, controls charge and physical size of streamers
- The detectors will operate over a very wide range of these gases.
- The Isobutane fraction can be as low as 4%

Caution: flammable mixtures easily produced, especially at low 134a fractions!

- Streamer production relatively tolerant to N₂, O₂ and H₂ O contamination
- The ratio of Ar/134a can vary from 10 to 0.25

- Streamer charge and size (area is in mm$^2$) increase with Ar fraction.

- Charge distributions of streamers is relatively narrow

- Fraction of double streamers small

- Charge distributions of avalanches exponential in parallel plate geometry
Bakelite (or glass) resistivity controls time needed (typically milliseconds) to rebuild field after a streamer occurs

In BaBar bakelite was required to have

\[ \rho = 28 - 120 \times 10^{10} \Omega \text{cm} \]

at 20° C. Resistivity of bakelite varies substantially with both humidity and temperature. Higher resistivities can be used for cosmic ray detectors.

The temperature effect is large:

\[ \Delta \rho / \rho \sim -10\% / ^\circ C \]

It is speculated that at high temperature streamers lower values of \( \rho \) can lead to large discharges and significant aging of the detectors.
Mechanical Tolerances

- Townsend coefficients rapidly increase with electric field (from Imonte simulation)

- If gap width increased, Townsend coefficient decreases faster than streamer length $\ell$ increases

- Chamber becomes inefficient when $\alpha \ell < 20$

- This analysis courtesy of C. Lu, Princeton
Basic result:

\[ \frac{dV}{d\text{ gap}} \approx 2300\text{V/mm} \]

In Babar a few "popped buttons" (unglued spacers) can easily lead to a 3mm gap width rather than the nominal 2 mm width.

• To avoid excess aging chambers should be kept no more than 500 V above streamer threshold

⇒ mechanical tolerance of only 200 \( \mu \text{m} \)
Problems associated with linseed oil coating

- Linseed oil coatings of inner surface lower the current drawn through the gas and singles of rates of the detectors by a factor of 5 to 10.

- The linseed oil is thought to provide two functions:
  - It makes a smooth inner surfaces leading to a more uniform electric field
  - It can absorb UV photons produced in the avalanche

- Main advantage of glass RPCs is that they avoid this coating
Babar problems
Possibly due to linseed oil bridges

- Temperature rose to 36° C in the experimental hall
- Currents increased ⇒ Many chambers temporarily disconnected
- Efficiency can be increased by lowering amount of Freon ⇒ See 200 and 420 days
- But efficiency still declines continuously
• Inefficiency appears to be mainly concentrated around edges of the chambers

• There is some evidence that the efficiency also occurs near the rows of spacers

• High voltage plateau’s become very broad
Efficiency Plateaus

During original testing

After operation in BaBar
Test Stand Studies

- Can we reproduce the problems in the lab?

- SLAC test stand shows that trigger chambers made prior to the BaBar production are sensitive to heat.

- Other tests (e.g. at Oregon) show that damage can be done to chambers at temperatures of only $28^\circ$ C

$\Rightarrow$ Problems could occur even at moderate temperatures!
Materials Studies and Models

- Effects of linseed oil columns will depend on the resistivity of the linseed oil:

  - A model of high and low resistivity linseed oil columns:

    ⇒ The resistivity of linseed oil depends on how it has cured and if contaminants are present

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resistivity $[10^9 \Omega \text{cm}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>polymerized US linseed oil (skin/oil mix)</td>
<td>145.9</td>
</tr>
<tr>
<td>US linseed oil (cured in air for 30 days)</td>
<td>42.3</td>
</tr>
<tr>
<td>US linseed oil (cured in air for 3 days)</td>
<td>27.9</td>
</tr>
<tr>
<td>uncured US linseed oil</td>
<td>14.4</td>
</tr>
<tr>
<td>uncured linseed (production oil)</td>
<td>7.7</td>
</tr>
<tr>
<td>uncured oil (removed from bad RPC)</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Unclear why oil removed from bad RPC has so low resistivity

LC Santa Cruz 13

David Strom – UO
Experience with prototypes for endcap replacement

- 24 endcap modules (12 chambers) were replaced with prototypes 12/00
- The prototype chambers have a single coat of 30% linseed oil, 70% pentane.
- Inner surface of opened chambers smooth
- Some damage seen in one of two chambers heated in test stand
  ⇒ Thinner linseed oil surface more sensitive to dust, contamination
- Modules in the shallow layers of the detector have stable, good efficiency

- Modules in the deepest layer of the calorimeter show significant damage after \( \sim 120 \) days of operation.
• The layer 18 prototypes were exposed to high levels of background from beam processes.

• Since detailed monitoring began, the charge through the gas has grown linearly with time.

• The decline in efficiency started at about 120 days corresponding to \( \sim 500 \text{ C/m}^2 \) (\( \sim 10^8 \text{ streamers/cm}^2 \)) in the gas.

• A model which takes the temperature of the leakage current into account and which assumes that

\[
I_{\text{leakage}} \propto Q_{\text{gas}}
\]

describes the data well.

\( \Rightarrow \) **Can this model explain the decline in efficiency?**
• Water vapor (70% relative humidity at 20°) was added to the gas of test stand chamber 6 on day 528. Rate was nominally 1 cm³/min, but was much lower for chamber 6 because it is somewhat leaky.

• **On day 529 a high rate of gas was flown through chamber 6** (flow rate off-scale on flow meters, ∼ 15 cm³/min)

• **Current immediately decreased in 6**

• **Efficiency immediately improved in 6**
Discussion

The observed behavior of chamber 6 is consistent with the Malter effect:

- Chamber current locally depletes charge carriers in linseed oil skin
- Ions collect on the insulating linseed oil surface.

- Accumulated ions will produce a large electric field across the linseed oil surface.

- Electrons can then be accelerated into the gas volume where avalanches are produced (Malter Effect).

- The large current from Malter electrons keeps the gap voltage below streamer threshold. A large current and inefficiency is observed.
• Adding water vapor to the gas decreases the surface resistivity of the linseed oil and prevents the accumulation of ions

• The Malter Effect also explains a common phenomena observed with many chambers: when the chambers are first switched on their efficiency decreases and the current increases

• The increased current occurs as the ions collect on islands of insulator on the linseed oil surface causing the Malter Effect

• As the chambers become drier, these islands become larger due to the depletion of ion conductivity (see Jerry’s Notebook).

• On 2 of 3 chambers tested, the water had no effect
Glass RPCs

• "Float glass" has resistivity of roughly $10^{12} \, \Omega \, \text{cm}$, comparable to the higher resistivity bakelite

![Graph showing the relationship between volume resistivity and temperature. The x-axis represents temperature in °C, ranging from -10 to 60, and the y-axis represents volume resistivity in $10^{\frac{1}{2}} \, \Omega \, \text{cm}$, ranging from $10^{-1}$ to $10^3$. The graph includes data points at various temperatures.](image)

Hoshi, et al.
In the Belle experiment, it was found necessary to control any moisture in the glass very tightly. Reportedly

- Water can combine with Fluorine which forms in the streamers to produce HF
- HF can etch the glass allowing for the adsorption of water onto the glass etch
- The water forms a conducting layer which ”shorts” the surfaces to nearby spacers, reducing the gap voltage below streamer threshold.
Gas without freon 134a can be used (Hoshi et al.,) eg:

4% isobutane, 10% O$_2$, 10% Ar and 76% CO$_2$ has 90% efficiency instead of 95% for freon based mixtures.

Caution: a simple analysis based on adiabatic flame temperatures and complete combustion indicates that this mixture may still be flammable.
Conclusion

- Results are mixed for large scale deployment of RPC

- Detectors are relatively inexpensive, but are not "easy to build" — careful QA/QC needed during production

- Double gap chambers are more robust against failure

- Must be able to replace faulty RPC chambers during the lifetime of the experiment.