READOUT OF EXTRUDED SCINTILLATOR WITH EMBEDDED WLS FIBER & HIGH GAIN AVALANCHE PHOTODIODES

Rafe H. Schindler + Many Contributors
(SLAC, CALTECH, UMass)

MOST OF THIS WORK HAS BEEN DONE ONLY SINCE LAST SUMMER AS R&D FOR AN UPGRADE TO THE MUON SYSTEM IN BABAR

GOAL:

REPLACE ~9 to 12 of 19 LAYERS OF RPC IN THE BARREL MUON SYSTEM – BALANCE IN BRASS ABS.

EXISTING GAPS ARE 2.2 cm high  X 3.7m Long

DESired RESOLUTION ~ 4 cm in PHI
               ~ 20 cm IN Z

DESired EFFICIENCY ~100% - GEOM LOSS / Layer For Hits at Far (3.7m) end
BASIS OF IDEA

• BUILD SHORT (3.7m vrs 8m) VERSION OF MINOS SCINTILLATION SYS. WITH $\Delta t$ TO GET THE SECOND COORDINATE ALONG BAR

• MINOS USES ~300 Tons OF CHEAP CO-EXTRUDED SCINTILLATOR BARS (8m x 4cmx1cm) WITH A SINGLE 1.2mmØ Y11-175 multiclaid (polystyr., pmma, Teflon) WLS FIBER EPOXYED IN EXTRUDED GROOVE

MINOS:

• WLS FIBER $\rightarrow$ LONG CLEAR FIBER $\rightarrow$ PIXELATED PMT $\sim$3$\rightarrow$4 pe/fiber at $\sim$3.7 m INCL. CONNECTS & PMT QE

PMT IS MAIN PROBLEM FOR RETROFITTING OF BABAR

• STARTED LOOKING AT WHETHER SCINTILLATOR BARS COULD BE READ OUT SIMPLY BY ATTACHING A LARGE AREA APD (25mm² Hamamatsu S8664-55 APD for CMS) TO EACH END

• SIMULATION and LAB WORK SHOW WE WOULD NEED ~150mm² (~6 APD/end) TO GET ENOUGH SIGNAL WITH THESE DEVICES (low gain ~50X, high cap. 4pf/mm²)
• RETURNED TO MINOS IDEA OF COLLECTING LIGHT ALONG A BAR VIA DIFFUSE SCATTERING INTO EMBEDDED WLS FIBER WHERE $\lambda_{\text{att}} \sim 4 \text{ m}$ RATHER THAN TRANSPORT IN EXTRUDED SCINTILLATOR (where $\lambda_{\text{att}} \sim 20\text{cm to } 100\text{cm}$)

• THEN COUPLING FIBER(S) TO A SMALLER AREA / HIGH GAIN APD FOR READOUT

**MINOS PRODUCTION BARS SHOWING**

4 x 1 cm² CROSS SECTION WITH CO-EXTRUDED TiO₂
AND ~2mm GROOVE FOR WLS FIBER

ADVANTAGES: COMPACT, ROBUST, MECHANICALLY SIMPLE LITTLE AND VERY LITTLE DEAD SPACE
TO SET SCALE: WE FOUND AT LEAST TWO PRODUCERS OF SMALL HIGH GAIN APD’s THAT MIGHT WORK (RMD and ADV. PHOTONICS).

DATA FROM RMD SUGGESTED THAT BY COOLING APD TO ~0°C, THE DETECTION EFFICIENCY FOR MIN ION WILL BE ~100% EVERYWHERE.

QUESTION: UNDER BABAR CONSTRAINTS ON THICKNESS & LENGTH, COULD WE GET ENOUGH LIGHT USING THE INEXPENSIVE WLS ($1/m) & SCINTILLATOR ($10/Kg vrs $50 to $100/Kg) FOR HIGH EFFICIENCY DETECTION AND SUITABLE TIME RESOLUTION FOR Z-COORDINATE.
• MANY POSSIBLE WAYS TO INCREASE LIGHT YIELD OVER MINOS

- INCREASE # FIBERS PER BAR
- INCREASE BAR THICKNESS
- IMPROVE SCINTILLATOR & WLS
  - Cast vs Extruded (cost 4→8X to Get +30%) ❌
  - Improve Quality of Extruded Material ($\lambda=20\rightarrow\lambda=100$)
  - Improve Coating (Reflectivity→97%)
  - WLS – Scintillator Absorption Matching
    - Already Very Good
- SUBDIVISION OF BARS & WLS FIBERS INTO APD (WIDTH, THICKNESS AND FIBER POSITIONS)
### Cross-section and Cladding Thickness

<table>
<thead>
<tr>
<th></th>
<th>Single Cladding</th>
<th>Multi Cladding (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Round Fiber (D)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cladding Thickness</td>
<td>T = 3% of D</td>
<td>T = 3% (T_o) + 3% (T_i)</td>
</tr>
<tr>
<td>NA</td>
<td>NA = 0.55</td>
<td>NA = 0.72</td>
</tr>
<tr>
<td>Trapping Efficiency</td>
<td>3.1%</td>
<td>5.4%</td>
</tr>
</tbody>
</table>

| **Square Fiber (SQ)**|                 | Not available |
| Cladding Thickness   | T = 2% of S     |                |
| NA                   | NA = 0.55       |                |
| Trapping Efficiency  | 4.2%            |                |

3.1% $\rightarrow$ 5.4% TRAPPING GOING SINGLE TO MULTICLAD  
(already factored in from MINOS)

3.1% $\rightarrow$ 4.2% TRAPPING BY GOING FROM ROUND $\rightarrow$ SQUARE  
(potentially additional gain of 25%)

- SQUARE FIBERS IMPROVE GEOMETRICAL MATCH TO A SQUARE APD

- UNFORTUNATELY ONLY BICRON PROVIDES MULTICLAD SQR FIBER AND THE MATCHING OF ABSORPTION TO SCINT WAS FOUND TO BE POOR (NEEDS DEVELOPMENT)
QUANTUM EFFICIENCY OF READOUT DEVICE

WE EXAMINED SEVERAL APD ON MARKET – DEVICE FROM RMD APPEARED CLOSEST TO NEEDS & COST (More Later)

QE OF PMT & 2mm x 2mm RMD APD COMPARED WITH WLS EMMISSION SPECTRUM BELOW:

ABOUT A FACTOR OF 4X IN QUANTUM EFFICIENCY FOR APD OVER PMT AT ~520 nm

THIS QE IS TYPICAL OF Si APD DEVICES
GIVEN THE BABAR CONSTRAINTS, WHAT WE MIGHT EXPECT BASED ON MINOS AND OUR MONTE CARLO?

- REPLACE PMT WITH APD (~4X HIGHER QE)
- INCREASE # OF FIBERS TO 4 (~2X MORE LIGHT)
- INCREASE SCINT. THICKNS TO ~2cm (~1.5 X MORE LIGHT)
- IMPROVED SCINT. & WLS (1.3 X MORE LIGHT)

IMPLIES ~ 60pe at ~3.7m FOR MIN ION INTO A 2 x 2mm² APD

CLOSE TO SUFFICIENT TO MEET EFFICIENCY GOAL!

FOR POSITION RESOLUTION:

- POSITION in PHI (ϕ) set BY STRIP WIDTH (4 → 7 cm)
  - $\sigma_\phi \sim 1.2$ cm (inner layer)
  - $\sigma_\phi \sim 1.7$ cm (outer layer)

- PROPAGATION TIME OF 17cm/ns IN WLS FIBER IMPLIES $\sigma_z \sim 25$cm FOR EACH END IF $\sigma_t \sim 1$ns
  - APD Risetime ~5ns
  - Dispersion of Signal Edge in WLS (MC <1ns)
  - Risetime of Preamp (A250F) (thry < 25ns)

- MEASUREMENTS FROM BOTH ENDS MUST BE:
  - COMBINABLE TO $\sigma_z \sim 15$ cm

LOOKS OKAY TOO!
BABAR PROPOSAL:

- REPLACE 9 LYRS INSIDE FLUX RETURN STEEL WITH EXTRUDED SCINTILLATOR STRIPS READ OUT WITH WLS FIBER & AVALANCHE PHOTODIODES – OPER. IN 15Kg

- PHI COORDINATE FROM STRIP WIDTH, Z COORDINATE FROM TIMING

- GEOMETRY OF EACH Sextant
  - EACH LAYER IN EACH Sextant CONTAINS 3 ~ IDENTICAL MODULES SIMILAR TO MINOS IN CONSTRUCTION
  - EACH MODULE IS THE LENGTH OF THE STEEL (3.74 m) & CONTAINS 14 SCINTILLATOR STRIPS OF WIDTH 4cm to 7cm
    In PHI, & EXTENDS TO ~3 cm OF STEEL EDGE
  - SCINTILLATOR IS LOW-COST CO-EXTRUDED MATERIAL OF ~2 cm THKNS; EPOXIED INTO 0.5mm AL CRIMPED BOX
  - WLS FIBER IS 1.2mm KURARAY DBL–CLAD S-TYPE Y11(200)
  - EACH OF 14 STRIPS HAS 4 WLS FIBERS. EACH END GANGED INTO ONE 2x2mm² PIXEL OF 16 PIXEL RMD A1604 APD ARRAY, SPECIFIED TO HAVE 14 16 PIXELS MEETING NOISE SPEC.
  - 1 APD ARRAY, 1 PREAMP/DISCR. CARD RESIDE ON EACH END OF MODULE.
  - APD COOLING ACCOMPLISHED BY 4 Watt PELTIER DEVICE WITH HEAT TRANSFER VIA MODULE COVER. TWO TE COOLERS WILL BE PRESENT FOR REDUNDANCY. 1 cfh DRY AIR OR N2 Req. PER MODULE
ONE THERMO - ELECTRICALLY COOLED ARRAY/MODULE (4W)

HEAT TRANSFERRED TO EXISTING 15°C WATER ON FACE OF DETECTOR
START OF STUDY OF FIBER & MODULE LAYOUT

SIXTEEN SCINT. BARS, EACH 2 cm THICK

FOUR FIBERS PER BAR

CONNECTOR TO 4x4 APD ARRAY & THERMO ELECTRIC COOLER, PREAMP & DISCR CARD

PIECES BUILT UP TO MAKE FIBER OPTIC CONNECTOR

PREAMPLIFIER CARD
PROPOSAL (CONTINUED)

• **DAQ MIMICS DIRC TDC SYSTEM**
  - Discriminator output of each end pixel goes to DIRC style DFB (8 TDC/CARD) with $\sigma \approx 1$ns located on end of BABAR in reused IFB crates from IFR
  - TDC data goes to re-used IFR TPC - ROM

• **CALIBRATION**
  - Threshold digitally set in preamp / discriminator
  - LED in each APD block for stat chk & rough T₀
  - Gain adjusted via single high voltage / module end
  - Precise ΔT calibrated via dimuons / puncthru

• **SERVICES**
  - DRY N₂ TO EACH MODULE ~1cu ft/h (RE-USE IFR SYS)
  - CHILLED H₂O (15°C) TO @ MODULE TO REMOVE 4W+Preamp
  - FILTERED HV (0.1%) TO @ MODULE (~1850 v).
    (Re-Use IFR as Caan Regulation better than 0.5 v)
  - EXTERNAL LINEAR PROP. CTRL FOR TE MODULES POWER SUPPLIES (TEMP MEASURED VIA THERMOCOUPLES)
## STATISTICS OF A 9 LAYER REPLACEMENT

<table>
<thead>
<tr>
<th><strong>Statistics:</strong></th>
<th><strong>Full Barrel</strong></th>
<th><strong>Per Sextants</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambda=</td>
<td>6.29</td>
<td></td>
</tr>
<tr>
<td>Number of replaced layers:</td>
<td>9 Layers</td>
<td>9</td>
</tr>
<tr>
<td>Number of replaced sextants:</td>
<td>6 Sextants</td>
<td>1</td>
</tr>
<tr>
<td>Number of modules/sextant layer</td>
<td>3 Modules/Sext Layer</td>
<td></td>
</tr>
<tr>
<td>Number of strips/sextant/layer</td>
<td>42 Strips/Module</td>
<td></td>
</tr>
<tr>
<td>Number of compound strips (total):</td>
<td>2268 Compound strips</td>
<td>378</td>
</tr>
<tr>
<td>Number of modules (total)</td>
<td>162 Modules</td>
<td>27</td>
</tr>
<tr>
<td>Kg of scintillator:</td>
<td>11615 Kg</td>
<td>1936</td>
</tr>
<tr>
<td>Kilometers of WLS fiber</td>
<td>41 Km</td>
<td>7</td>
</tr>
<tr>
<td>Readout channels:</td>
<td>4536 Channels</td>
<td>756</td>
</tr>
</tbody>
</table>
FIRST GOAL OF R&D WAS TO ESTABLISH GEOMETRY WITH SUITABLE LIGHT YIELD

- PERFORMED MANY BASIC MEASUREMENTS TO STUDY GEOMETRY & PROPERTIES OF MINOS SCINTILLATOR + ROUND WLS + READOUT & COMPARE WITH MONTE CARLO

**BASIC SETUP:**

- ~2m LONG BARS & PMT/APD IN 4m LONG BOX
- 4 WLS (1.2mm) FIBERS BROUGHT OUT INTO SHORT ACRYLIC BLOCK FROM EACH END & POLISHED
- XP2262B PMT TO READOUT FIBERS – OPTICAL GREASE CONNECTION ON ONE END
- OTHER END OF FIBERS POLISHED AND TERMINATED INTO APD WITH AN OPTICAL GREASE JOINT
- TWO 4cm x 4cm x 1cm DEFINING COUNTERS (1cm Pb) (TO GENERATES TRIGGER & GATES)
- PMT SIGNAL SPLIT
  - → ADC (Lecroy 2249W) (50ns gate)
  - → AMPLITUDE - RISETIME CORRECTED DISCRIMINATOR (Philips 730)
  - → TDC (Lecroy 2228A)

- DEVELOPED TRANSPORT MC SIMULATION TO STUDY GEOMETRY, TIMING EFFECTS & COMPARE WITH DATA
FOR EACH CASE WE EVALUATED

- RELATIVE LIGHT YIELD,
- ATTENUATION LENGTH,
- TIME (POSITION RESOLUTION)

CASE #4 IS STUDIED IN THE MOST DETAIL INITIALLY

CASE #5 & #6 USED FOR FULL LENGTH (3.7m) PROTOTYPE

PHOTOELECTRON CALIBRATION OF ADC

COMPARISON WITH MC PREDICTIONS
LIGHT YIELD MEASUREMENTS OF 5 GEOMETRIES

RESULTS FROM LIGHT YIELD MEASUREMENTS (FIT TO PEAK)

<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>LY (42cm)</th>
<th>MC (LY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>1.47</td>
<td>1.53</td>
</tr>
<tr>
<td>3</td>
<td>1.81</td>
<td>2.00</td>
</tr>
<tr>
<td>4</td>
<td>3.02</td>
<td>3.13</td>
</tr>
<tr>
<td>5</td>
<td>2.96</td>
<td>3.06</td>
</tr>
</tbody>
</table>

CASE #4 at 42cm

TYPICAL COSMIC RAY SPECTRUM FOR CASE #4 AT 42cm FROM PMT

← 3X MINOS
ATTENUATION LENGTH MEASUREMENTS FOR 5 CASES

RESULTS FROM ATTENUATION LENGTH MEASUREMENTS

<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>LY (42cm)</th>
<th>λ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>217</td>
</tr>
<tr>
<td>2</td>
<td>1.47</td>
<td>208</td>
</tr>
<tr>
<td>3</td>
<td>1.81</td>
<td>238</td>
</tr>
<tr>
<td>4</td>
<td>3.02</td>
<td>213</td>
</tr>
<tr>
<td>5</td>
<td>2.96</td>
<td>208</td>
</tr>
</tbody>
</table>

LOSE ~5X IN LIGHT FROM 42cm TO 3.7 m ← WORSE THAN MINOS (~3.5X) SEE LATER DISCUSSION

BULK ATTENUATION LENGTH DEPENDS ON LENGTH OF TEST SAMPLES (λ DEPENDENT ABSORPTION)
TWO FULL LENGTH (3.7m) PROTOTYPE PROOF OF PRINCIPLE:

**ITASCA EXTRUSION**

**AMCRYST EXTRUSION**

**MINI-CONNECTORS WITH DOWEL REGISTRATION LIKE MINOS**

**WITH 4 WLS FIBERS**
3.7 METER LONG
2cm THICK BAR

BOTH SCINT.
HAVE A MID-PT
EPOXY JOINT –
MAY LOCALLY
EFFECT TIMING
RESOLUTION
• LIGHT YIELD & ATTEN. LENG. 3.7M LONG GEOM. 5 & 6:

• REQ. EXTERNAL TRIGGER HODOSCOPE TO DEFINE ~ 4cm REGION ALONG BAR

<table>
<thead>
<tr>
<th>DIST. TO PMT1 (cm)</th>
<th>Light Yield ITASCA (4cm)</th>
<th>DIST. TO PMT1 (cm)</th>
<th>Light Yield Ukrainian (5cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>504 +/- 10</td>
<td>46</td>
<td>697 +/- 10</td>
</tr>
<tr>
<td>89</td>
<td>398</td>
<td></td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>316</td>
<td>140</td>
<td>423</td>
</tr>
<tr>
<td>178</td>
<td>299</td>
<td></td>
<td></td>
</tr>
<tr>
<td>241</td>
<td>216</td>
<td>241</td>
<td>301</td>
</tr>
<tr>
<td>292</td>
<td>215</td>
<td></td>
<td></td>
</tr>
<tr>
<td>345</td>
<td>199</td>
<td>345</td>
<td>225</td>
</tr>
<tr>
<td>378</td>
<td>192</td>
<td>378</td>
<td>220</td>
</tr>
</tbody>
</table>

• <ATTENUATION LENGTH > (ITASCA) = 312 cm
• <ATTENUATION LENGTH > (UKRAINIAN) = 259 cm

FITS SHOW NON-EXPONENTIAL BEHAVIOR BECAUSE OF WAVELENGTH DEPENDENCE

NOTE VERY SHARP INITIAL LOSS (PREVIOUS 2m BAR RESULTS GAVE λ ~210 cm)

NOW GIVE CLOSE TO MINOS RESULT ~3X to ~3.5X LOSS OVER WHOLE BAR LENGTH

• AVERAGE LIGHT YIELD UKRAINIAN ~31% > ITASCA
SAMPLE SPECTRA AT 140cm FROM PMT (DEFINING HODOSCOPE)

NOTE SHARP FALLOFF AT SHORT DISTANCES
TWO EXPONENTIALS
- SINGLE SIDE EFFICIENCY:
  - REQ. EXT. TRIG. HODOSCP ~ 4cm RGN ALONG BAR
  - REQ. PMT2 TO SEE >10 adc cts (>1 pe) > PEDSTL
  - >1500 SAMPLES / POSITION

<table>
<thead>
<tr>
<th>DIST. TO PMT1 (cm)</th>
<th>Efficiency ITASCA (4cm)</th>
<th>DIST. TO PMT1 (cm)</th>
<th>Efficiency Ukrainian (5cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>0.994</td>
<td>46</td>
<td>0.998</td>
</tr>
<tr>
<td>89</td>
<td>0.994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>0.991</td>
<td>140</td>
<td>0.993</td>
</tr>
<tr>
<td>178</td>
<td>0.984</td>
<td></td>
<td></td>
</tr>
<tr>
<td>241</td>
<td>0.985</td>
<td>241</td>
<td>0.992</td>
</tr>
<tr>
<td>292</td>
<td>0.978</td>
<td></td>
<td></td>
</tr>
<tr>
<td>345</td>
<td>0.968</td>
<td>345</td>
<td>0.976</td>
</tr>
<tr>
<td>378</td>
<td>0.985</td>
<td>378</td>
<td>0.987</td>
</tr>
</tbody>
</table>

SINGLE SIDED EFFICIENCY OF FULL LENGTH BAR

![Graph showing efficiency vs. distance from PMT (cm)](image)
TIME/POSITION RESOLUTION MEASUREMENTS FOR 5 CASES

RESULTS ON SINGLE-SIDED POSITION RESOLUTION MEASUREMENTS (PMT)

<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>LY (42cm)</th>
<th>λ (cm)</th>
<th>σL (cm) Near to PMT (42cm)</th>
<th>σL (cm) Away From PMT (167cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>217</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>2</td>
<td>1.47</td>
<td>208</td>
<td>27</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>1.81</td>
<td>238</td>
<td>26</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>3.02</td>
<td>213</td>
<td>26</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>2.96</td>
<td>208</td>
<td>27</td>
<td>29</td>
</tr>
</tbody>
</table>

USES ONE END & NO PULSE HEIGHT INFO; SHOULDN'T IMPROVE WHEN BOTH ENDS USED

MC PREDICTS CONTRIBUTION OF RISE TIME FROM GEOMETRICAL & LIGHT PROPAGATION EFFECTS TO GO FROM 0.2 TO 1.5 ns SMALL

APD RISE TIME ~ 5 NS; RISE TIME SHOULD THEREFORE BE DOMINATED BY PREAMPLIFIER
ARRIVAL TIMES OF PHOTONS FROM MIN ION AT ONE END OF A 3.7m BAR (CASE #4)
**TIMING MEASUREMENTS (PMT) OF 2 FULL LENGTH BARS (GM# 5 & 6)**

- DONE AS BEFORE WITH DUAL LEVEL DISC+ TDC
- OBSERVE ~17cm/ns PROP. VEL. IN BOTH SCINT.

<table>
<thead>
<tr>
<th>DIST. (cm)</th>
<th>Pos. Resolution ITASCA PMT 1 (cm)</th>
<th>DIST. (cm)</th>
<th>Pos. Resolution ITASCA PMT 2 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>25.0 +/- 0.4</td>
<td>373</td>
<td>33.3 +/- 0.5</td>
</tr>
<tr>
<td>89</td>
<td>25.6 +/- 0.8</td>
<td>323</td>
<td>29.0 +/- 1.1</td>
</tr>
<tr>
<td>140</td>
<td>28.1 +/- 0.8</td>
<td>272</td>
<td>25.1 +/- 0.6</td>
</tr>
<tr>
<td>178</td>
<td>29.2 +/- 0.8</td>
<td>234</td>
<td>26.8 +/- 0.6</td>
</tr>
<tr>
<td>241</td>
<td>35.0 +/- 1.3</td>
<td>170</td>
<td>31.0 +/- 1.1</td>
</tr>
<tr>
<td>292</td>
<td>30.2 +/- 0.6</td>
<td>119</td>
<td>28.4 +/- 0.5</td>
</tr>
<tr>
<td>345</td>
<td>28.4 +/- 0.8</td>
<td>66</td>
<td>29.8 +/- 0.8</td>
</tr>
<tr>
<td>378</td>
<td>27.7 +/- 0.8</td>
<td>33</td>
<td>29.2 +/- 0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DIST. (cm)</th>
<th>Pos. Resolution AMCRYS PMT 1 (cm)</th>
<th>DIST. (cm)</th>
<th>Pos. Resolution AMCRYS PMT 2 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>24.5 +/- 0.4</td>
<td>371</td>
<td>28.6 +/- 0.5</td>
</tr>
<tr>
<td>140</td>
<td>28.9 +/- 1.1</td>
<td>277</td>
<td>23.0 +/- 0.8</td>
</tr>
<tr>
<td>241</td>
<td>28.4 +/- 0.4</td>
<td>175</td>
<td>27.7 +/- 0.5</td>
</tr>
<tr>
<td>345</td>
<td>26.7 +/- 0.7</td>
<td>71</td>
<td>25.1 +/- 0.6</td>
</tr>
<tr>
<td>378</td>
<td>26.7 +/- 0.9</td>
<td>38</td>
<td>24.2 +/- 0.7</td>
</tr>
</tbody>
</table>

RISE MAY BE ASSOCIATED WITH EPOXY JOINT
AVERAGED TIMING RESOLUTION OF BOTH ENDS

- \( \frac{\text{Pos}(\text{PMT1}) + \text{Total Length} - \text{Pos}(\text{PMT2})}{2} \) * 0.5
- Could improve with Weighted Average

<table>
<thead>
<tr>
<th>DIST. (cm)</th>
<th>Pos. Resolution ITASCA (cm)</th>
<th>DIST. (cm)</th>
<th>Pos. Resolution AMCRYS (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>17.8 +/- 0.3</td>
<td>46</td>
<td>15.1 +/- 0.2</td>
</tr>
<tr>
<td>89</td>
<td>16.2 +/- 0.5</td>
<td>140</td>
<td>14.3 +/- 0.4</td>
</tr>
<tr>
<td>140</td>
<td>17.8 +/- 0.4</td>
<td>140</td>
<td>14.3 +/- 0.4</td>
</tr>
<tr>
<td>178</td>
<td>16.6 +/- 0.8</td>
<td>241</td>
<td>15.6 +/- 0.3</td>
</tr>
<tr>
<td>241</td>
<td>17.9 +/- 1.3</td>
<td>241</td>
<td>15.6 +/- 0.3</td>
</tr>
<tr>
<td>292</td>
<td>17.1 +/- 0.6</td>
<td>345</td>
<td>14.5 +/- 0.3</td>
</tr>
<tr>
<td>345</td>
<td>17.1 +/- 0.8</td>
<td>345</td>
<td>14.5 +/- 0.3</td>
</tr>
<tr>
<td>378</td>
<td>16.8 +/- 0.8</td>
<td>388</td>
<td>14.4 +/- 0.4</td>
</tr>
</tbody>
</table>
ITASCA SCINTILLATOR

Position Resolution (cm)

Distance from PMT (cm)

σ ~ 17 cm
TWO SIDED TIME

AMCRYST SCINTILLATOR

Position Resolution (cm)

Distance from PMT (cm)

σ ~ 14 cm
TWO SIDED TIME
PHOTO ELECTRON CALIBRATION

MOVE XP2262B PMT + SPECIAL BASE BACK FROM FIBERS & FILTER DOWN THE LIGHT STRIKING TUBE.

RESULTS: ~ 10 ADC CTS per PHOTOELECTRON WITH PMT

IMPLICATION: GEOM. #6 GIVES ~ 700 ADC cts/MIN ION at ~46cm.

PMT QE~14% at 520 nm IMPLIES ~500 PRIMARY PHOTONS FROM THE 4 FIBERS REACH PMT

USING QE (APD) ~60% X 0.7 GEOM IMPLIES ~210 pe at 46cm. $\lambda_{\text{att}}$ IMPLIES ~65 pe FOR an APD at 3.7m
APD STATUS & ISSUES

- RMD’s PLANAR (NON-BEVELED EDGE) APD #S0223 (2x2mm², 0.7pf/mm²) IS BEST CANDIDATE ON MARKET (50µm DEEP DIFFUSED PN JUNCTION)
- USE THE 4 X 4 PIXEL ARRAY WHICH GIVES BEST COST / PIXEL
  - ASSUME YLD OF 14 of 16 MEET NOISE PERF
  - $85/working PIXEL IN LARGE (5K) QUANTITITES
- QE > 60% at >530 nm, G ~1000X, (0°C), AT ~1750v
- ~5 NS RISETIME AT 500nm
- RADIATION TESTED AT PSI – OK TO ABOUT 1 X 10¹² n/cm*

YOU CAN SEE FROM THEIR STANDARD PACKAGE THAT THERE IS NOT A LOT OF ROOM TO MAKE CONTACTS ETC…TO CERAMIC/LEADS

RMD GAVE US SUBSTRATES FOR PRACTICING & STUDYING THERMO-ELECTRIC ASSEMBLY
MEASUREMENTS OF SAMPLE APD’S FROM RMD:

- VARIATIONS FOLLOW THE WAFERS

- SMALL VARIATION IN BREAKDOWN VOLTAGE ACROSS PIXELS IN SINGLE ARRAY (~1v LEVEL) AS EACH ARRAY COMES FROM SINGLE 5cm WAFER

- GAIN VARIATIONS BETWEEN PIXELS LESS THAN 5% WITHIN ARRAY DUE TO DIFFERENCES IN LEAKAGE CURRENT & SERIES Ω

- EXAMPLES FROM SEVEN 2mm x 2mm PIXELS WE PURCHASED IN TWO BATCHES:

<table>
<thead>
<tr>
<th>RMD Serial#</th>
<th>BREAKDOWN VOLTAGE (210°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND-1873-1</td>
<td>1857 v</td>
</tr>
<tr>
<td>ND-1873-2</td>
<td>1855 v</td>
</tr>
<tr>
<td>ND-1885-1</td>
<td>1840 v</td>
</tr>
<tr>
<td>ND-1885-2</td>
<td>1840 v</td>
</tr>
<tr>
<td>ND-1885-3</td>
<td>1840 v</td>
</tr>
<tr>
<td>ND-1885-4</td>
<td>1840 v</td>
</tr>
<tr>
<td>ND-1885-5</td>
<td>1842 v</td>
</tr>
</tbody>
</table>
OUR MEASUREMENTS OF GAIN FROM THE LAST BATCHES OF 2mm DIODES SHOW SMALL VARIATIONS

(Note: ND-1885-5 WAS MEASURED EARLIER & SCALED FOR THIS PLOT, TEMP UNKN.)

IN PRACTICE, ONE HV CONTROL ON EACH 16 ELEMENT ARRAY SHOULD SUFFICE TO GIVE ADEQUATE GAIN CONTROL PER PIXEL

ROUGHLY: $\Delta \text{Gain}/\Delta V \ (G=1000,0^\circ\text{C}) = +5\%(-2\%)$
- **Each Pixel Irradiated With Fe55 (5.9 KeV X Rays)**
- **Each Pixel Was Biased At -1700 V**
- **Leakage Current & Peak Channel Noted**
- **You can see in the spectra and the data listed that the peak chan variation due to gain differences is less than +/- 5% : Most of this difference is probably due to difference in leakage current from pixel to pixel. Some of the variation could also be due to any slight variation in temp. While the measurements were being made; all the spectra were acquired over ~ 10-20 minutes**
FIRST COSMIC RAY SIGNALS WITH 4mm² APD (23°C)

TOP SCOPE TRACE IS PMT LOOKING AT FAR END OF BAR

BOTTOM TRACE IS APD OUTPUT FROM PREAMP AFTER DIFFERENTIATION & LOW FREQUENCY FILTER

BLOWUP OF TYPICAL PULSE SHOWING A250F PREAMP

\[ \tau_R \approx 100 \text{ ns} \quad (C_f = 0.25 \text{ pf}) \]

WILL INCREASE \( C_f \mapsto 1 \text{ pf} \) TO REDUCE \( \tau_R \mapsto 25 \text{ ns} \)
FIRST COSMIC RAY SPECTRUM

APD READOUT ON ONE END OF 2m BAR IN GEOMETRY #4

SPECTRUM TAKEN AT ROOM TEMP (VARIATIONS +/-2°C).

OBSERVED CHARACTERISTICS OF SPECTRUM & SCOPE:

- SMALL ELECTRONICS NOISE ON SCOPE ~4 mV
  
  APD PROVIDES GAIN ~1000

- BROAD PEDISTAL & BROAD SIGNAL PEAK

  ASSOCIATE WITH “EXCESS NOISE” OF APD
  (fluxuations in amplification of signal and dark currents)
NOISE IN APDS & WHY WE MUST COOL THEM:

- **4 PRIMARY SOURCES OF NOISE & PEAK BROADENING IN PLANAR APDS:**

  - **SMALL AS GAIN HIGH**
    - **USUAL ELECTRONICS NOISE FROM C & R AT INPUT OF FET** (measure at ~50v when fully depleted)

  - **PEDISTAL OR BASELINE WIDTH**
    - **FLUXUATIONS IN AMPLIFICATION OF DARK CURRENT (BULK) IN APD** DEPEND ON STATISTICAL NATURE OF IMPACT IONIZATION PROCESS (\(I_{\text{bulk}} \sim 4\text{pa/mm}^2\) at Hi-Gn)

  - **BROADENS PEAK FURTHER**
    - **FLUXUATIONS IN EDGE CURRENT (NOT AMPLIFIED)** \((I_e \sim 5\text{na/mm}^2 \sim \text{largest non-amplified “leakage” current})\)

    - **FLUCTUATIONS IN SIGNAL AMPLIFICATION WHICH DEPEND ON STATISTICAL NATURE OF IMPACT IONIZATION PROCESS** (at \(G=1000X, N_{pe} \sim 50 \rightarrow 50000e\))

- **COOLING THE APD HAS THREE EFFECTS:**

  - **REDUCES BULK LEAKAGE CURRENT** (halves @ -10°C)
    - **REDUCES AMPLIFIED NOISE CONTRIBUTION**

  - **INCREASES IMPACT IONIZATION PROBABILITY OF CARRIERS** (both \(\alpha_e\) and \(\beta_h\) increase as \(T\) decreases)
    - **GAIN INCREASES AT FIXED VOLTAGE**

  - **REDUCES EXCESS NOISE FACTOR** (\(F \sim \text{VARIANCE OF AMPLIFICATION}) \ (\Delta\alpha_e > \Delta\beta_h \text{ for a decrease in } T)\)
    - **REDUCES PED. & PEAK BROADENING**

**NET EFFECT OF COOLING IS INCREASE IN S/N BY REDUCING PEAK & PED WIDTH, AND INCREASING SIGNAL EFFICIENCY**
COOLING APD INCREASES GAIN AT FIXED VOLTAGE
~ 50V DECREASE WITH ΔT=-20°C)
FOR FIXED GAIN ~ 1000X

COOLING APD INCREASES GAIN & REDUCES PED & SIGNAL WIDTH → INCREASED EFFICIENCY AT FIXED DISC. THRESHOLD

FROM RMD STUDY (EFFIC. AT FIXED DISC THRESHOLD)
PELTIER COOLING & OPTICAL CONNECTS TO APD:

30W THERMO-ELECTRIC COOLER TO USED INITIALLY

4W to 8 W SMALLER ONES
15 x 15 mm FOR ACTUAL USE IN IFR

APD COOLER, MACOR APD HOLDER, HEAT SINK & FIBER OPTIC CONNECTOR BEFORE EPOXYING (FRONT VIEW)
FIRST DATA WITH APD AT 0°C : 3.7m LONG BAR

APD Cooled to ~0-Deg C.  HV = 1765 V,  PMT on One End
Defining Counters positioned at 380 cm from APD
Preamp Output Amplified x20 & Split (To Disc & Integ. ADC)

Note:
Integrating ADC Smears Spectra

Using 60 mV Discr. Threshold + Scalars at 3.8m pt:
Signal Efficiency > 98%  Background Rate < 1%
TIMING RESOLUTION IN PRESENT SETUP - POOR

Due to slow risetime of Preamp/amp
\[ \tau_r \approx 100 \text{ ns} \]

Single Side: Sigma (position) = 110 cm
At 380 cm From APD

Have modified AMPTEK 250F Preamp + Postamp
and will be re-measuring the time resolution.
NEXT STEPS:

- BETTER OPTICAL MATING TO APD

CURRENT SETUP HAS FOUR 1.2mm FIBERS ALIGNED ONTO 2mm x 2mm APD.

THE APD HAS A RESPONSE WHICH IS FLAT OVER THE CENTRAL PORTION, AND DROPS OFF BY THE EDGES

IN THE CURRENT SETUP, THIS MISMATCH RESULTS IN A LOSS OF LIGHT RELATIVE TO THE PMT MEASUREMENTS (~ 0.7)

THE OPTICAL CONNECTION WILL BE IMPROVED TO RECOVER A LARGE FRACTION (~85%) OF THE PRESENT GEOMETRIC LOSS

SETUP TO MEASURE RELATIVE TRANSMISSION OF FIBERS MODIFIED TO BETTER MATCH PIXEL
• INSTALL PELTIER COOLER PROPORTIONAL CONTROLLERS ALLOWING LONG & STABLE DATA TAKING RUNS WITH APDs ON BOTH ENDS. CAN THEN OPTIMIZE S:N

• AMPLIFIER IMPROVEMENTS & PEAK SENSING ADC TO DO COMPLETE TIMING & EFFICIENCY STUDY

BABAR’S MAJOR CONCERN WAS APD ROBUSTNESS

LITTLE INTEGRATED EXPERIENCE WITH RMD DEVICE & ESPECIALLY THE ARRAYS

• AS IN ANY SILICON (OR GAS) DEVICE PROVING OF ACCEPTABLE RELIABILITY OF A TECHNOLOGY IS A TWO STEP PROCESS

1) DEVELOP INFANT MORTALITY TEST PROCEDURE TO UNDERSTAND HOW TO WEED OUT EARLY FAILURES

ALREADY DONE BY RMD USING A 24hr BURN IN TEST

2) TEST LARGER SAMPLE TO ESTABLISH ACCEPTABLE MTBF

HAVE ORDERED 3 ARRAYS OF 16 pixels/array AND SETTING UP ACCELERATED TEST AT SLAC

RMD IS LOANING 3 ADDITIONAL ARRAYS IN RETURN FOR DATA

- TEST of ~96 PIXELS-