# Advanced Scintillator Detector R&D

## Towards a 50 kt Ultra-High Segmentation Fe-Scintillator Detector

# Motivation

- Very Rich Physics program at a ν Factory
  - Long Baseline ν oscillation program at 20 GeV ν Factory pointing to a 50 kt detector
    - $\nu_e \rightarrow \nu_\mu$
    - $\nu_e \rightarrow \nu_\mu$
    - $\nu_e \rightarrow \nu_\tau$
  - Detector capabilities
    - Detect muons and determine sign
      - At as low a threshold as is possible
        - < 4 Gev/c
        - 2 Gev/c would be desirable
    - Detect electrons/positrons
      - Determine sign??
    - Detect τ leptons
      - This is a difficult task in a massive detector -τ detection best suited to specialized detectors
        - Kinematics can be used in fine-grained detectors, however
    - Compared to what is required at D0 or CDF (or LHC) – this is rather simple

# Detector Scenarios

- Options
  - Liquid Argon TPC
    - Fully reconstructed events – Bubble chamber-like event topologies
    - Excellent! Electron and hadronic calorimetry
    - External muon system required for muon sign and momentum
      - Unless very-large magnet used
  - Magnetized Fe-Scintillator
    - Unmatched muon detection capability
    - Electron/hadronic energy detection dependent on segmentation
  - Water Ĉerenkov
    - Scalable to very large detector
      - Best cost to size – Surface area detectors
    - Full containment excellent only for low energy $\nu$ beam
    - Poorest pattern recognition capabilities

# Detector Development at Fermilab

- Scintillation Detector work, however, has been a major R&D and construction effort over the last decade at Fermilab
  - CDF end-caps and shower max
  - CDF TOF
  - D0 Fiber tracker
    - VLPC Development
  - D0 Preshower detectors
  - D0 Central muon counters
  - CMS Calorimeters
  - MINOS

# Detector Development

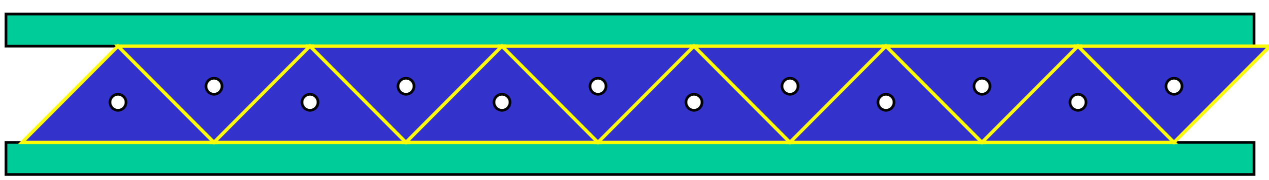
- This work has driven the development of significant infrastructure
  - Scintillation Detector Development Laboratory
    - Extruded scintillator
    - Fiber characterization and test
  - Thin-Film facility
    - Fiber processing
      - Mirroring and coatings
    - Photocathode work
    - Diamond polishing
  - CNC Routing
    - Tile-fiber detectors
  - Machine Development
    - Diamond polishing
    - Optical connector development
    - High-density Photodetector packaging (VLPC)

# Detector Development

- Detector R&D on scintillation detectors is appealing, since even if a large Fe-Scintillator neutrino detector is not the optimal choice for a future ν physics programs - the detector technology is general purpose
  - Not the case with LAr TPC or Water Ĉ
    - These are not likely to see major application outside ν physics
- Scintillation detectors
  - EM and hadronic calorimetry
  - Shower max detectors
  - Preshower detectors
  - Photon vetos
  - Fiber tracker
  - Muon tracking/hodoscopes
  - General purpose trigger hodoscopes
  - Time-of-Flight

# Strawman 50 kt UHS Fe-Scint ν Detector

- A detector with 10X the fiducial mass of MINOS
- $\frac{1}{8}$-$\frac{1}{4}$ $X_o$ longitudinal sampling (2.2-4.4mm Fe - ≈ 5-10 X MINOS)
- 1 cm transverse segmentation
  - 1 cm base triangles – yields about 1 mm position resolution for mips
    - From D0 preshower test data



- This begins to look like a magnetized Soudan with much better energy resolution
- What does this imply?
  - Scintillator
    - 0.3 kt → 12 kt (24)
  - Steel
    - Straightforward extrapolation
  - Photodetector
    - 1.5 X$10^5$ fibers → 25 (50) X $10^6$!
      - Note: MINOS reads out both ends of the fiber and then multiplexes fiber to photodetector 4:1
      - This example is non-multiplexed

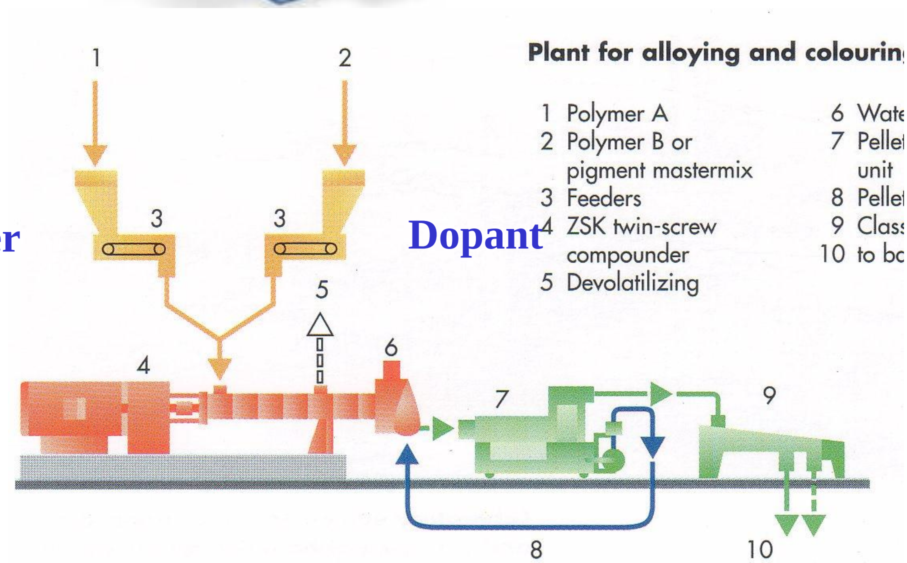
# Detector Issues

- Can this detector be built today?
  - NO!
- What are the issues? - There are three:
  - Scintillator
  - Fiber
  - Photodetector
- Lets take the first, first
  - Can we make this much scintillator?

# The History of Extruded Scintillator Work at Fermilab

- 1992
  - P860 – ν Oscillation exp. proposal Using Fermilab Debuncher
    - Considered Fe- Scintillator – MUCH TOO EXPENSIVE!
- 1993
  - R&D began in PDG on high-quality, low-cost extruded scintillator
    - Driving Motivation: Large-Scale neutrino oscillation experiments
- 1996
  - Triangular scintillator extrusions chosen for D0 preshower detectors
- 1998
  - MINOS selects extruded scintillator
    - First very-large application of technique
    - 0.3 kt of scintillator required
    - Price approximately 10% of conventional cast scintillator plate
- 1999
  - STAR experiment uses scintillator extrusions for shower max
- 2001
  - In-house facility approved for Fermilab

# Fermilab Facility




- All equipment for basic system has been specified – PO to be placed this week!
  - Up to 4X the production rate of MINOS
  - Expect better quality/uniformity
  - Some cost reduction over MINOS
    - $\leq$ $5/kg?
  - Can extrapolate to many kt with outside vendor involvement

# Scintillation Detectors

- The scintillator production will be challenging, but can be done

- The Fiber/Photodetector issues are more difficult

- Readout Optimization
  - For a given detector cell:

    dE/dx →

    → Scintillation light ($\varepsilon$)

    → Readout light (WLS fiber) ($\chi$ )

    → Signal Charge (photodetector) ($\theta$)

    $\varepsilon$ = Scintillation efficiency - 3%

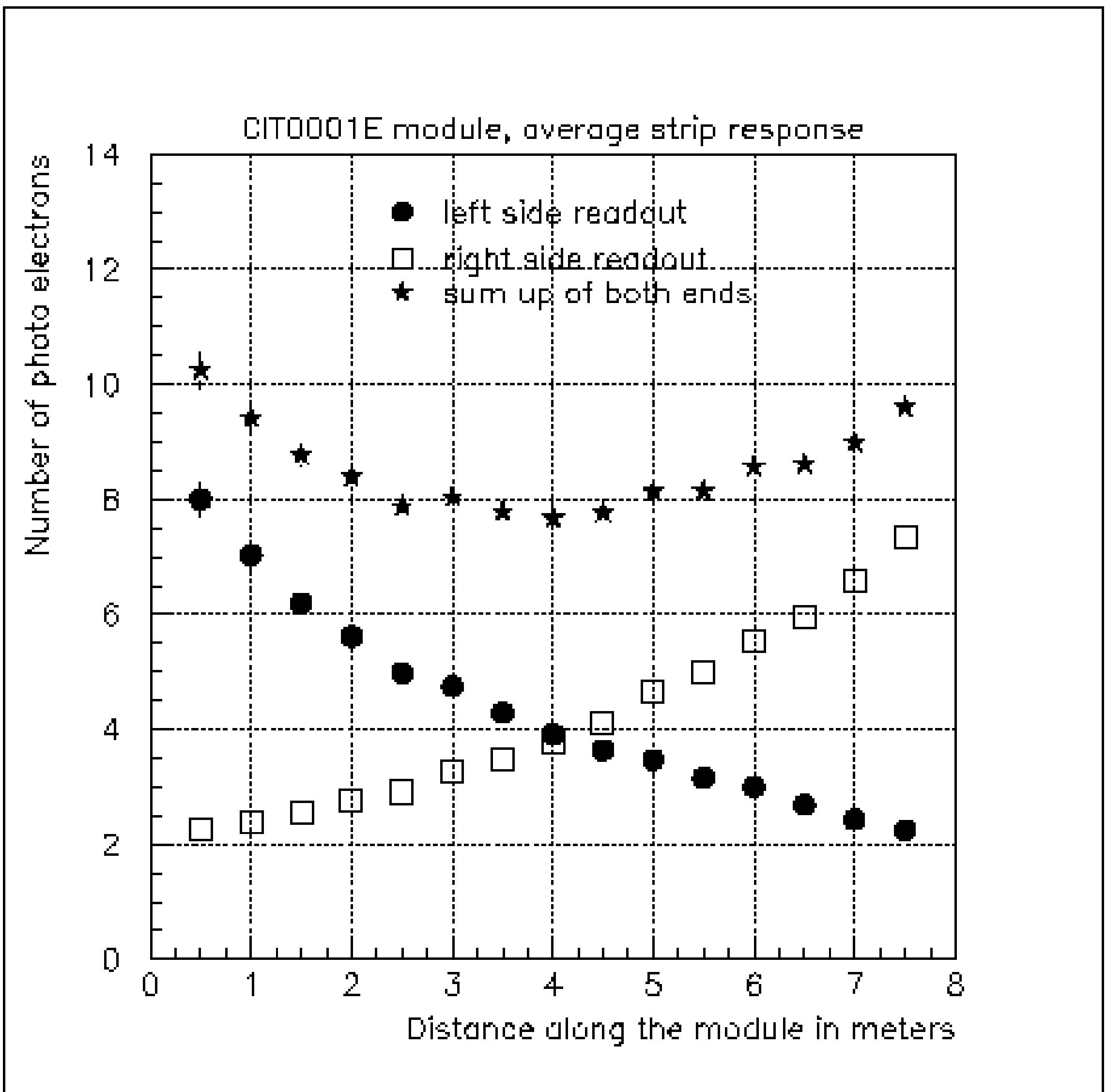
    $\chi$ = WLS fiber capture efficiency - 5%

    $\theta$ = QE X gain - 0.8 X 50k (VLPC)

Note: Both fiber and PD costs go like the cross-sectional area

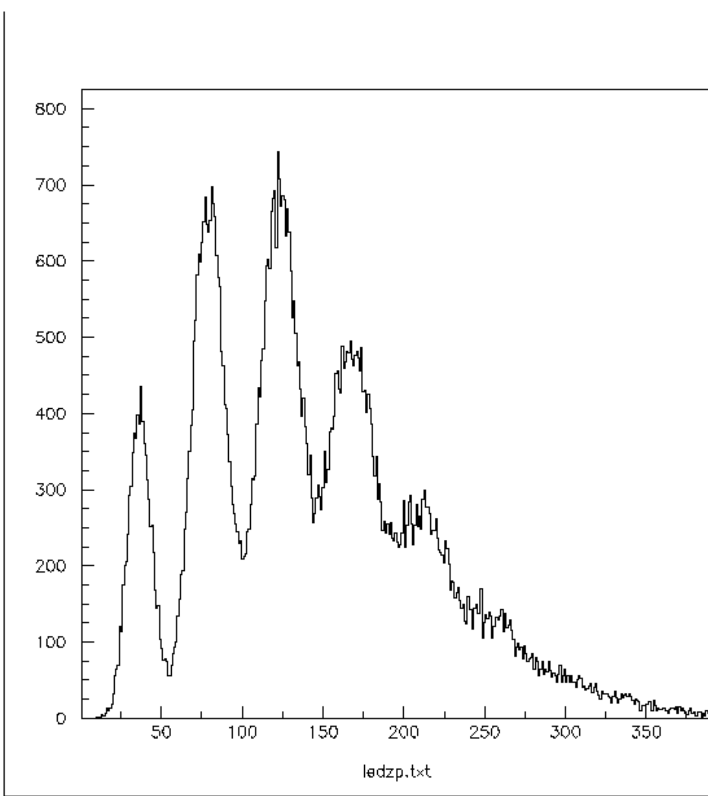
# Scintillation Detectors

- MINOS light yield (my apologies if this is not the latest&best data)
  - 1X4 cm extrusion
  - 1.2 mm WLS readout fiber to MAPMT

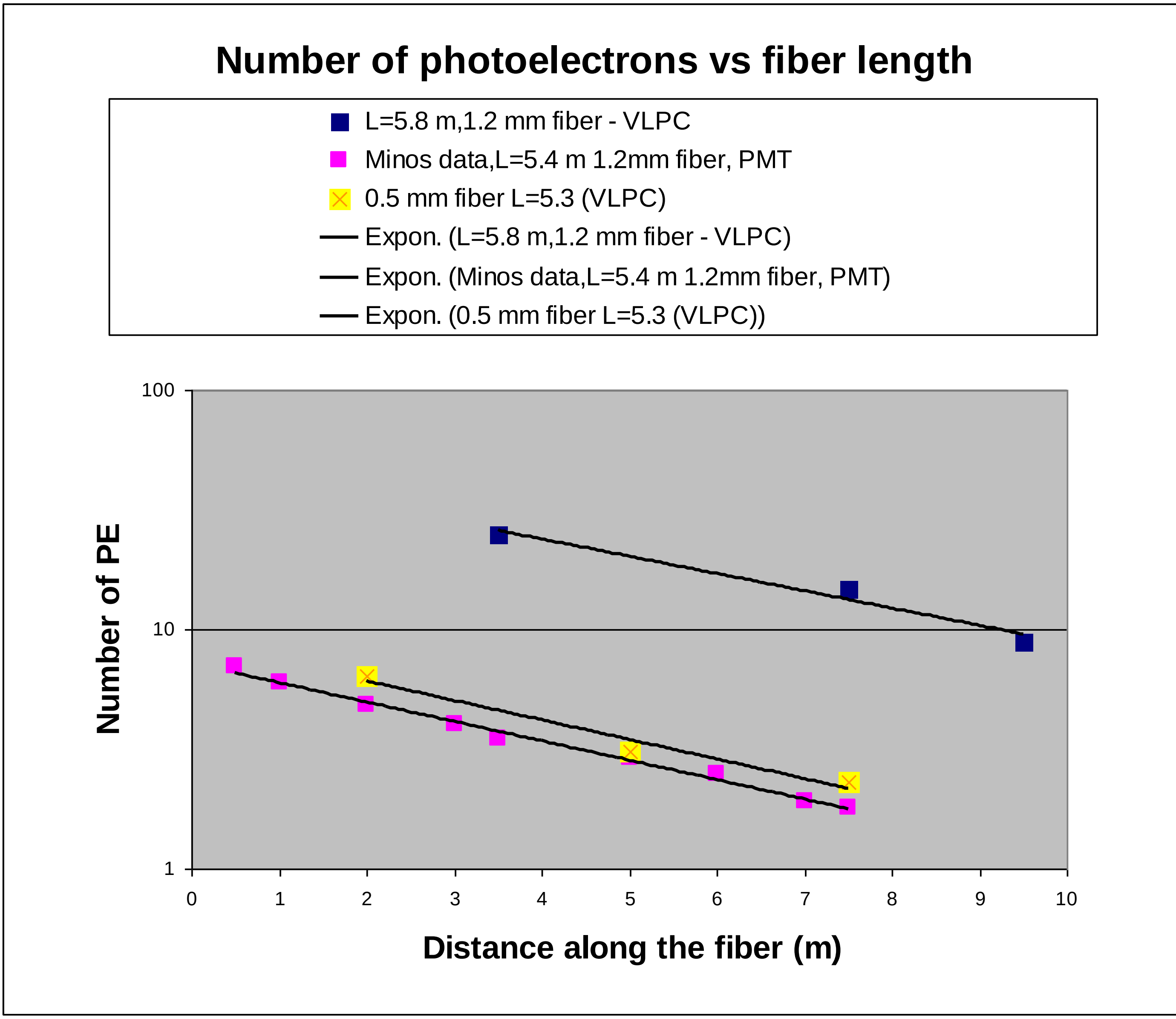


# Scintillation Detectors

- The product of Quantum Efficiency X Gain is the real figure or merit in this type of detector
  - Nothing is better than the VLPC
    - QE – 80-85%
    - Gain – Typically 50k
      - For low rate detectors (<500k pe/sec) – 100k



# VLPC Readout of MINOS extrusions

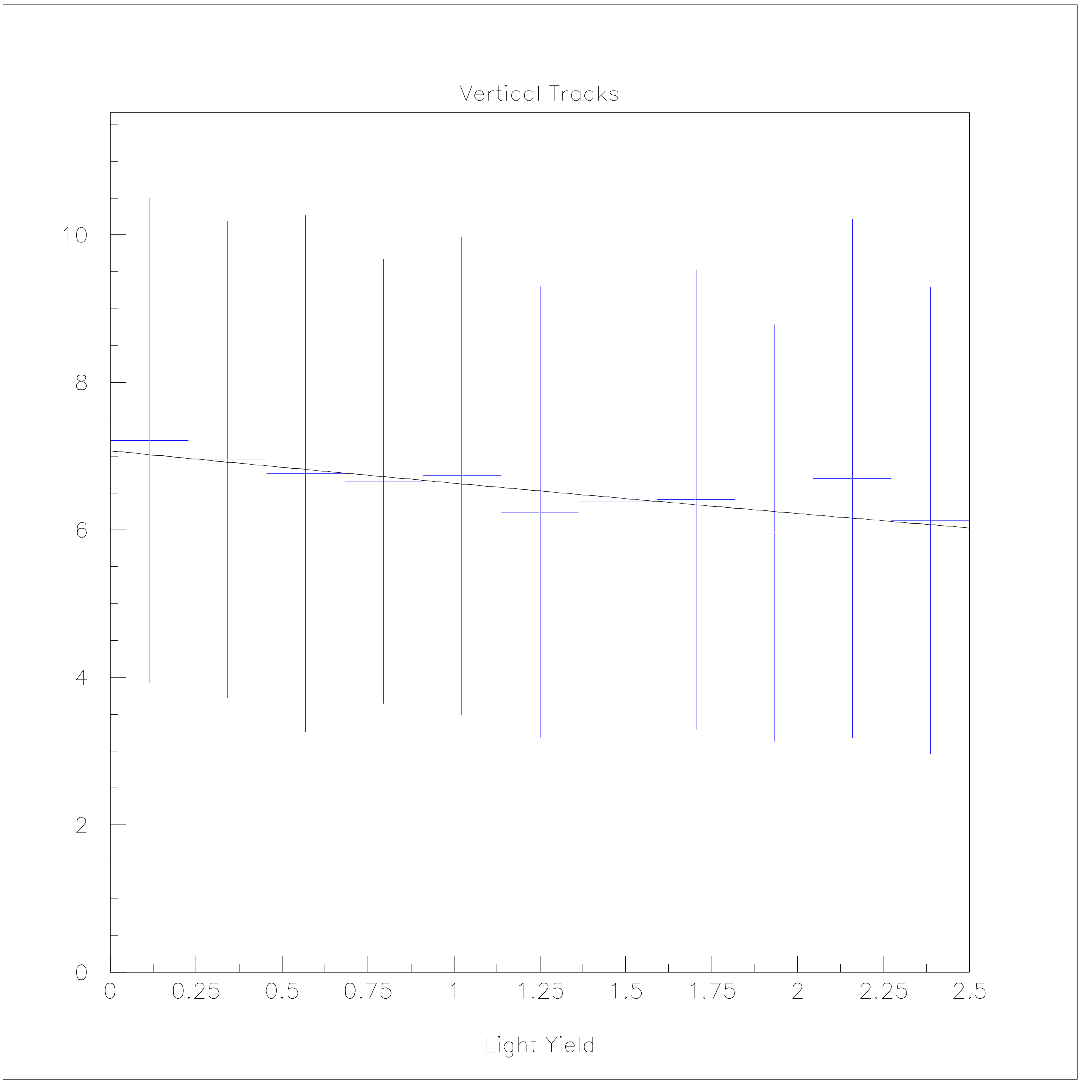



- MINOS 1 X 4 extrusion, 1.2 mm readout fiber
- 1.2 mm VLPC Data
  - Since the VLPC cassette uses 0.965mm fiber, this is corrected data [X$(1.2/0.965)^2$]
- 0.5 mm VLPC Data – No correction needed

# VLPC Readout of MINOS extrusions

- *A* number of caveats
  - These measurements do not use the latest VLPC type (Gen. VI) [1.25]
  - *A* 5 m waveguide was used for the VLPC data – likely only 2 m will be needed in a neutrino detector with distributed cryogenics [1.25]
  - The scintillator extrusion is not optimized for small diameter fiber and is wider than one that would likely be used in a final detector [1.25]
  - The proposed application would use single ended fiber with far end mirrored

# Single-ended fiber readout




- Results from D0 fiber tracker Cosmic Test
  - 2.5 m active fiber
    - 0.83 mm readout 1 end – far end mirrored
  - 11.5 m waveguide
  - Effective Attenuation Length = 16 m!

# Detector Optimization

- All of this indicates that the light yield for Fe-Scintillator detector with VLPC readout will be very high!
  - Even with 0.4 mm fiber – estimate at this time that the yield would be higher than MINOS baseline at all positions up to 8-10m fiber length.
- This has an enormous impact on fiber cost
  - For example – MINOS
    - $4M is reduced to roughly $450k
- The same is true for the photodetector
  - A 5 X 10 element array (.4mm) would cost the same or less than D0's 2 X 4 element array (1mm) - ≈$240

# Near-Term R&D Plans

- We plan to continue tests with the VLPC system – now using latest version (Gen VI)
  - Baseline measurements with 1.2 mm, 1.0 mm, and 0.5 mm readout fiber with MINOS extrusion.
    - Try for better optimization of VLPC
    - Measure Near/Far ratios
    - Measure single-ended 0.5 mm fiber with mirror
  - We have 1X2 cm extrusions available also and can setup for 0.5 mm tests with this cell geometry

# VLPC R&D

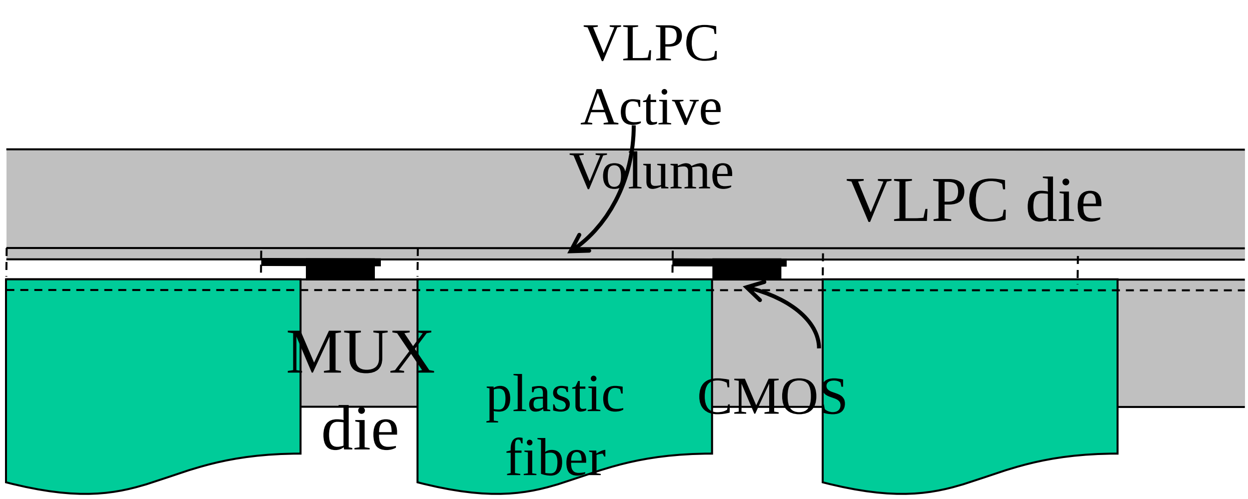
- Lawrence Semiconductor Research Laboratory (LSRL) has completed a SBIR Phase I grant to develop the next generation VLPC ($100k).
  - Collaborated with Boeing
    - Boeing now has LSRL make all the silicon epitaxy for their IR sensors – similar technology to VLPC
      - Better equipment than was used at Boeing for D0
      - Better yield/higher uniformity
      - 5” to 8” wafer ( D0 used 3” )
        - All projects to lowering cost
  - Very successful
    - Better uniformity demonstrated
      - X10
    - Much lower defect density (X40)
      - Higher yield
    - Produced enough epitaxial material in this phase to produce 320k pixels of the D0 type
      - Very low cost compared to D0

# VLPC R&D

- Phase II grant has been awarded $750k
  - Continue optimization
  - Process wafers from Phase I
    - Produced D0-type arrays for detailed device analysis
    - Produce higher density arrays
  - Goal: Demonstrate cost reduction at X10

# VLPC R&D

- The major difficulty to go to smaller VLPC pixel is the higher density
  - The D0 system uses "Cassettes" that hold 1024 channels each
  - To get to 10X the density – requires cold end electronics
    - Cannot individually bring signals out
  - This has been done at Boeing
    - For space applications
    - Will be expensive to develop
      - $1M estimated program cost
      - Maybe cheaper if some CMOS MUX design help can be provided by Fermilab or others
      - Part of program cost might be part of Phase II SBIR
    - However, Boeing believes that a X10 cost reduction from D0 is possible - $5/ch



# Conclusions

- Scintillator detector technology R&D will be part of Fermilab's program
  - Plastic Scintillator development
    - New scintillator systems
  - Scintillator extrusions
  - Co-extrusion of scintillator and WLS fiber readout
- Fe-Scintillator detector with high-QE, high-gain photodetectors is a good candidate for future neutrino detectors
  - Hard to beat LAr TPC in magnetic field
  - Optimization of scintillator/cell geometry/WLS fiber readout is needed
  - Significant R&D is required to develop a high-density, cost effective photodetector system