



NUMI-L-676



MINOS

Extruded Polystyrene Scintillator for MINOS

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OUTLINE OF THE TALK

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MINOS

-
- Introduction/Physics of MINOS
 - The MINOS Scintillator Detector
 - Ingredients for the Scintillator
 - Scintillator Extrusion (Drying, Purging, Mixing, Co-Extrusion)
 - Light Yield Measurements
 - Effect of Air Exposure vs Inert Gas on Light Output (LO)
 - Effect of fluor concentration, groove depth and TiO_2 thickness on LO
 - Online Quality Control
 - Aging of the scintillator
 - Conclusions



MINOS & ITS PHYSICS GOALS

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1. MINOS is a long-baseline neutrino experiment.
2. Its main goal is confirm that atmospheric neutrino anomaly is due to neutrino oscillation.
3. Measure Oscillation Parameter(s).
4. And determine the Oscillation Mode(s)
 - a. ν_μ to ν_τ (Favoured by Super-K and MACRO)
 - b. ν_μ to ν_e (Limits from CHOOZ and PALO VERDE)
 - c. ν_μ to ν_s (Disfavoured by Super-K and MACRO)
 - d. ν_μ to $\nu_\tau + \nu_e$
 - e. ν_μ to $\nu_\tau + \nu_s$
 - f. ν_μ to $\nu_\tau + \nu_e + \nu_s$ (?) (A real challenge?)



MINOS PHYSICS GOALS – How to Get to it?

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1. Obtain Firm Evidence for Oscillation.

- a. Measure CC interaction rate.
- b. Measure CC energy distribution.
- c. Measure NC/CC rate ratio.
- d. Measure NC energy distribution.

2. Measure Oscillation Parameters from CC Energy Distribution.

(Statistical Measurement, Oscillation Mode Independent).

3. Precise Determination of Flavor Participation.

- a. Number of ν_{μ} events FAR/NEAR ratio to 1-2% . Probability of ν_{μ} to ν_{τ} oscillation.
- b. Number of ν_e CC events FAR/NEAR. Probability for ν_{μ} to ν_e oscillation down to 2% .
- c. Number of NC events FAR/NEAR. Probability for ν_{μ} to ν_s oscillation down to 4% .



WHAT MINOS CAN ACHIEVE ?

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1. NEUTRINO OSCILLATION seems to be a reality.
2. MINOS will provide conclusive evidence for oscillation.
3. MINOS will measure the oscillation parameters.
4. MINOS will determine the oscillation mode(s).
5. MINOS can answer other fundamental questions, such as
 - a. Distinguish between Neutrino Oscillation & Neutrino Decay Model.
 - b. Distinguish between Neutrino Oscillation & models with extra-dimensions with right handed neutrinos.



MINOS DETECTORS

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- Minos has two detectors. A far detector (5.4 kT) at Soudan, MN and a near detector (1 kT) at Fermilab, IL.
- The Major Parameters of MINOS Far Detector are:
 - 2 Supermodules, each of 2.7 kt and composed of 243 planes each
 - The shape of each plane is an 8 m wide octagon
 - Each plane is a sandwich composed of a steel plate and scintillator strips, each one having a 1 cm x 4.1 cm cross-sectional area
 - Light is read out via 1.2 mm diameter Kuraray wavelength shifting fibers and Hamamatsu M16 multi-pixel photocathode
- Relatively thin steel thickness was chosen to
 - Give good energy resolution for hadronic and electromagnetic showers
 - Give sufficiently frequent sampling for low energy running and for atmospheric neutrino studies
- Scintillator was chosen to
 - Give good energy resolution for hadronic and electromagnetic showers
 - Give fast timing important for non-accelerator physics, potential new physics



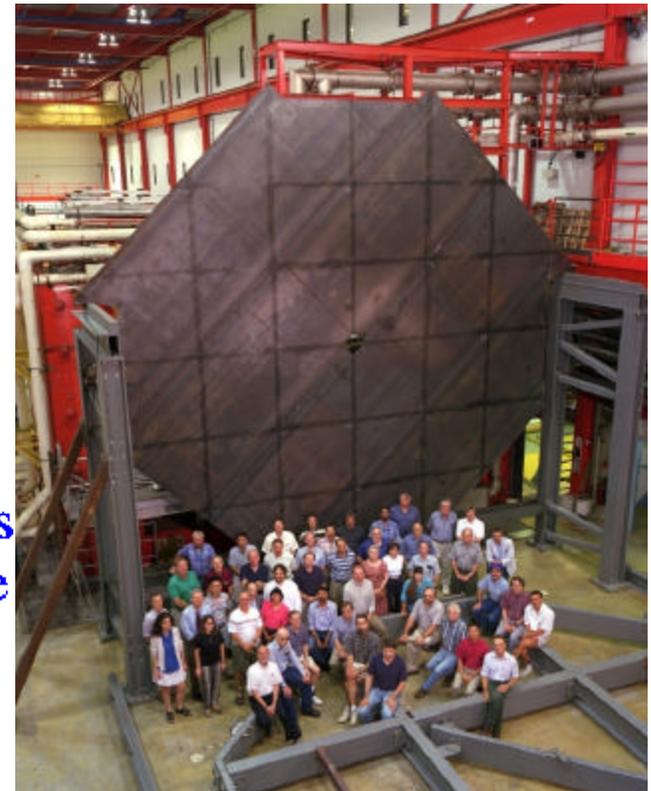
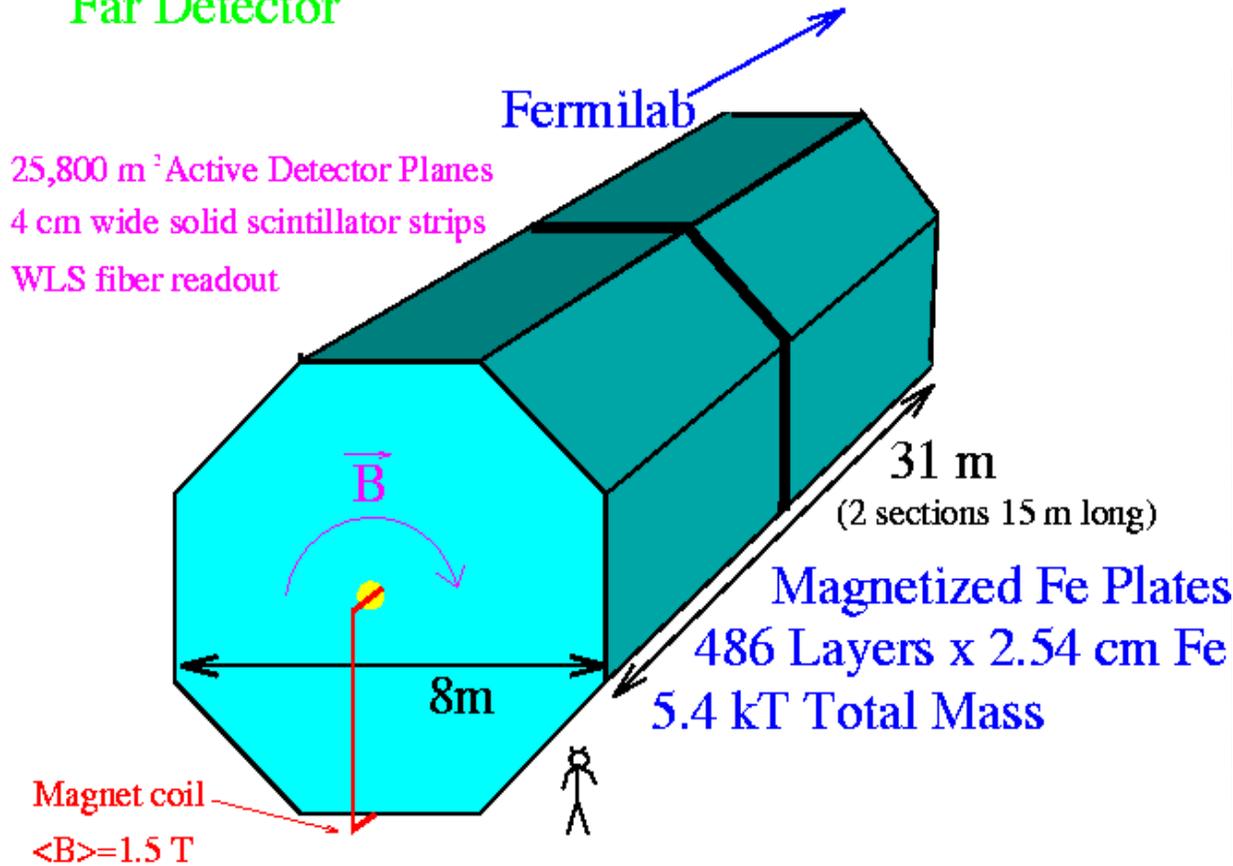
MINOS FAR DETECTOR

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Far Detector



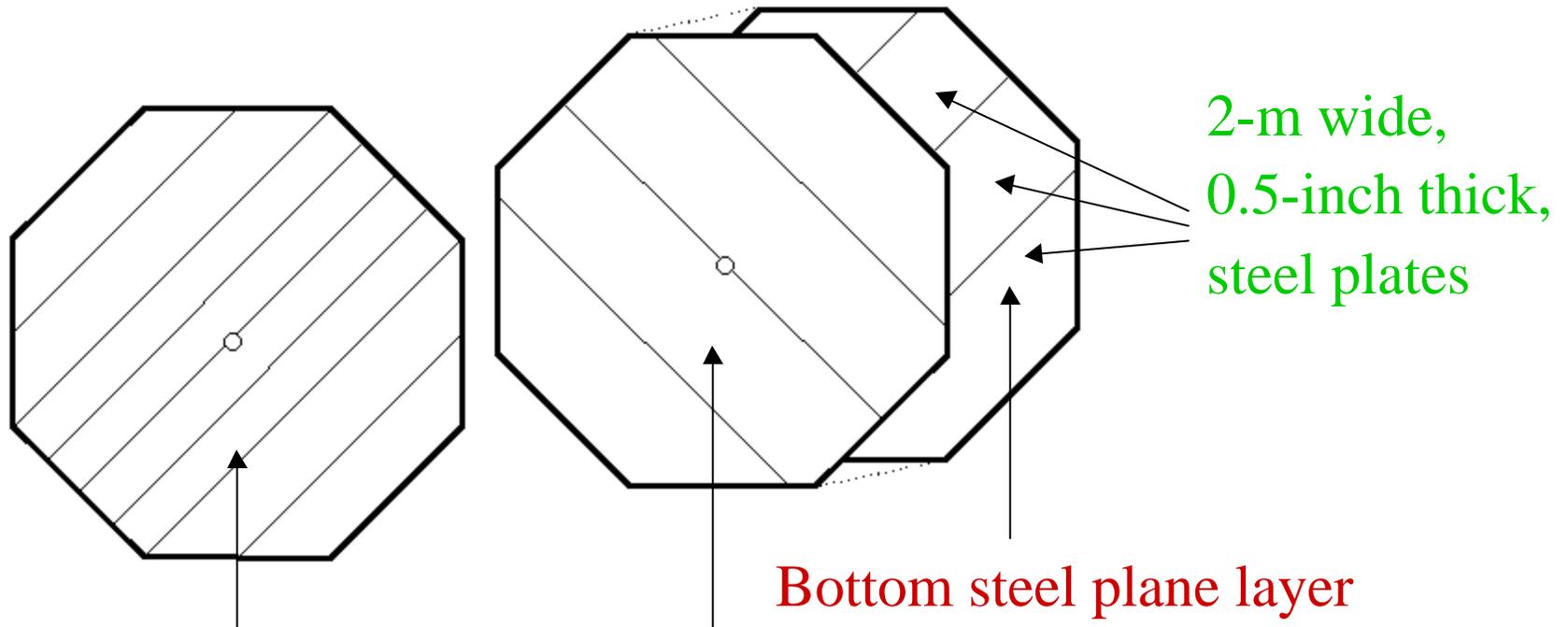


STEEL & SCINTILLATOR PLANE LAYOUT

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Scintillator plane

Orientations alternate $\pm 90^\circ$
in successive planes

Top steel plane layer

Bottom steel plane layer

2-m wide,
0.5-inch thick,
steel plates



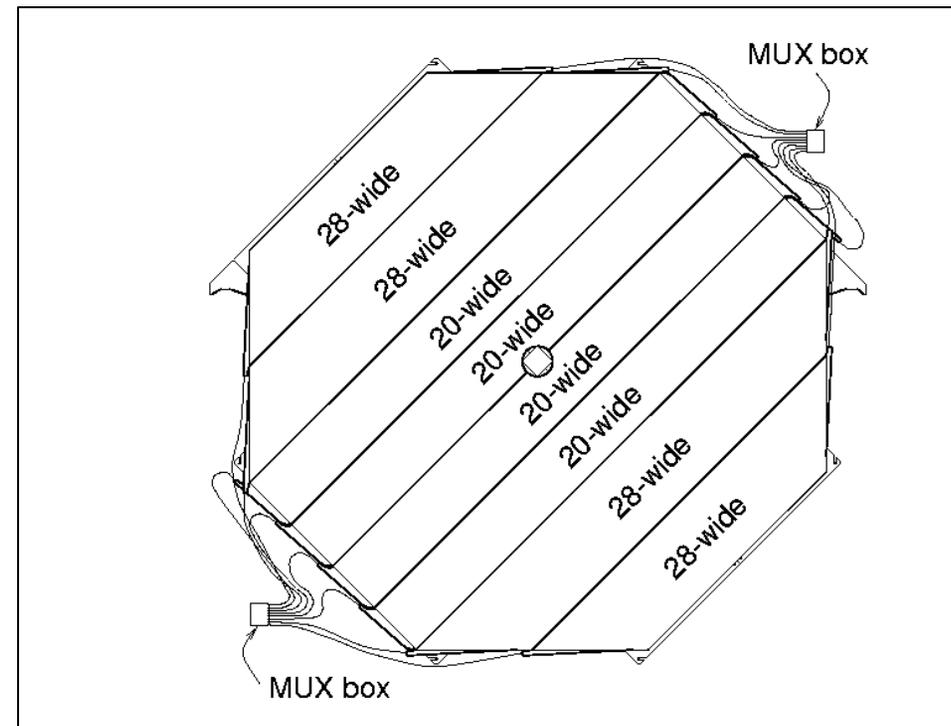
SCINTILLATOR MODULES ON STEEL PLANE (FAR DETECTOR IN MINNESOTA)

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- 8 modules cover one far detector steel plane
- Four 20-wide modules in middle (perp. ends)
- Four 28-wide modules on edges (45 deg ends)
- Two center modules have coil-hole cutout





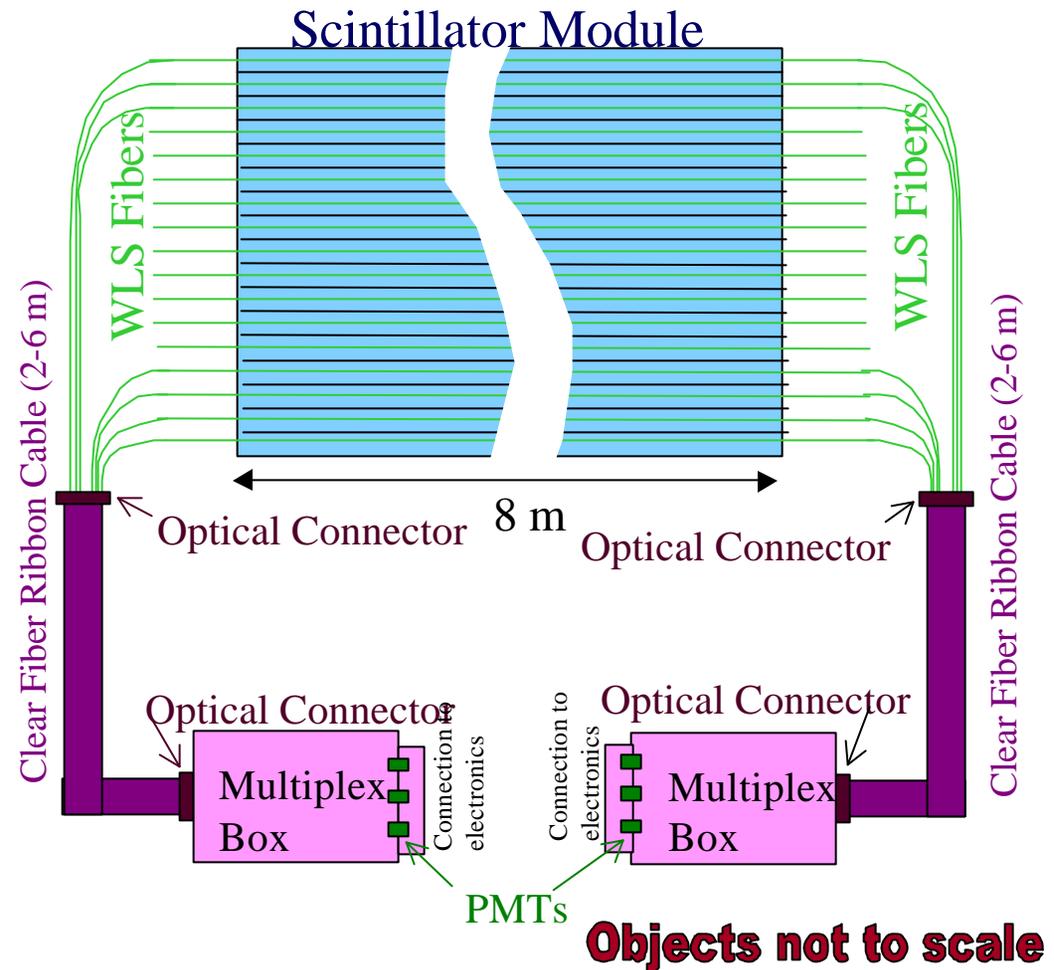
SCHEMATIC VIEW OF THE MINOS SCINTILLATOR SYSTEM

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- Extruded scintillator, 4cm wide
- Two-ended WLS fiber readout.
- Strips assembled into 20 or 28-wide modules.
- WLS fibers routed to optical connectors.
- Light routed from modules to PMTs via clear fibers.
- 8 Fibers/PMT pixel in far detector. (Fibers separated by ~1m in a single plane).
- 1 Fiber/PMT pixel in near detector (avoids overlaps).
- Multi-pixel PMTs (Hamamatsu M16)





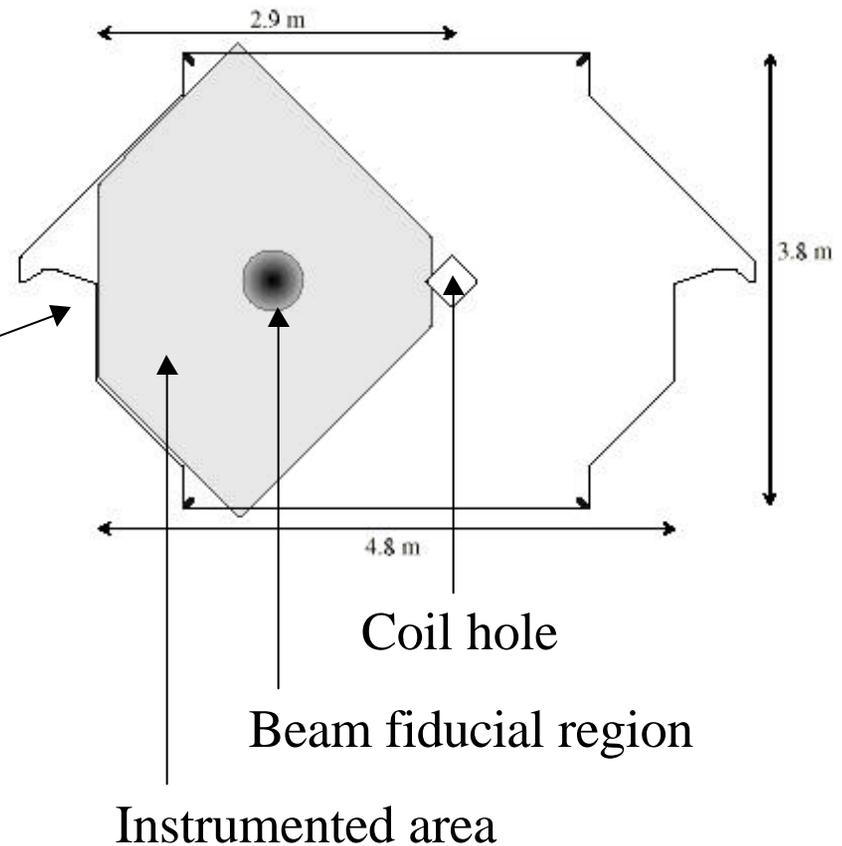
MINOS Near Detector

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MINOS Near Detector

- 16.6 m long, 980 tons
- 280 “squashed octagon” planes
- **Forward section:** 120 planes
 - 4/5 partially instrumented
 - 1/5 planes: full area coverage
- **Spectrometer section:** 160 planes
 - 3/4 planes not instrumented
 - 1/4 planes: full area coverage



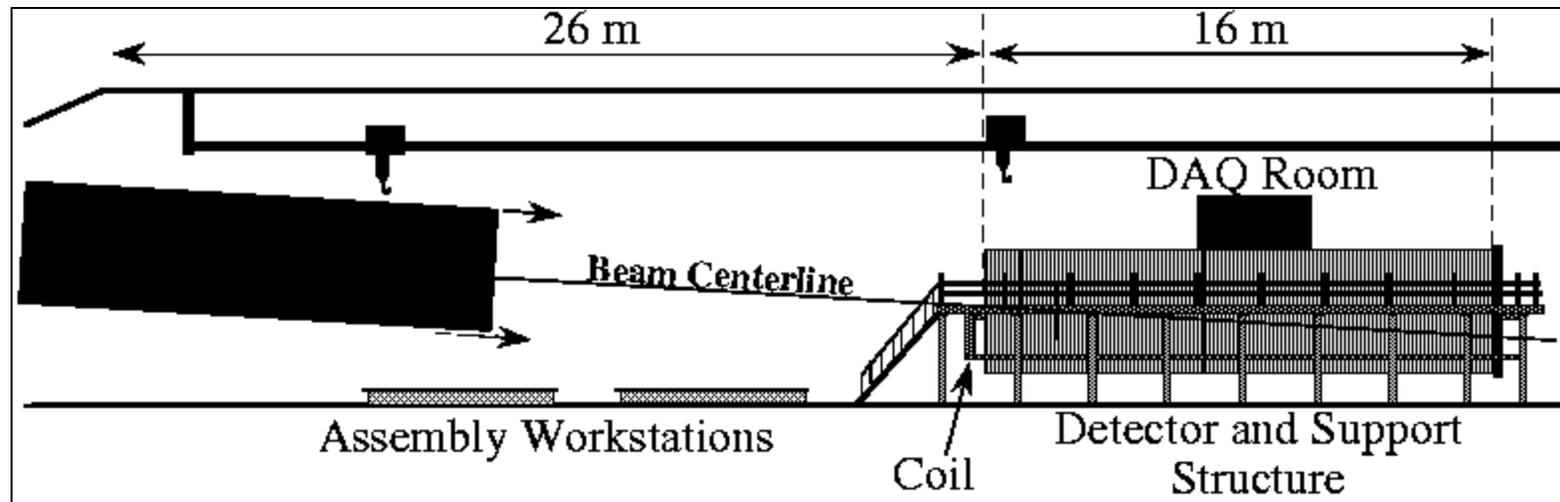


Near Detector Side View

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SCINTILLATOR STRIP w/WLS FIBRE READOUT

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- **MINOS scintillator strips are commercially extruded using**
 - DOW Styron 663 W general purpose Polystyrene without additives
 - PPO (2,5-diphenyloxazole) as primary fluor, and
 - POPOP (1,4-bis(5-phenyloxazol-2- yl) benzene as secondary fluor
 - Co-extruded with TiO_2 reflective cap
 - A groove for wavelength-shifting fiber having K27 dye as shifter
 - PPO and POPOP have reasonable match to K27 dye in fibre



SCINTILLATOR R&D

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- During last three years we have extruded and tested scintillators produced at extruders like RDN, Quick plastic, Polycast, and Itasca plastic.
- We have also tested scintillators extruded by Vladimir Technoplast (through IHEP, Protvino group) in Russia and from Kuraray Co. of Japan.
- We have Studied
 - a. Different Dimensions (4cm x 1cm with groove on side vs 2cm x 1cm with a hole)
 - b. Different Fluor Concentrations (varying amount of PPO and POPOP)
 - c. Quality of the Reflective Coating
 - d. Quality of the Groove
 - e. Optimum temperature for the production of the scintillator
 - f. Effect of the Environment (Presence of Air vs. Inert Environment)
- 4. The contract has been signed between MINOS and Itasca plastic for production of nearly 300 tons of scintillator.
- 5. The average cost of production is about \$10/Kg. Total cost about \$3M.



COST OF THE RAW MATERIAL & FINISHED PRODUCT

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1. Prices for pre-production quantities for testing.
 - a. DOW PS 663 about \$1.45/Kg. \$1.45/Kg of produced scintillator.
 - b. PPO about \$160/Kg. \$1.6/Kg of produced scintillator.
 - c. POPOP about \$1000/Kg. \$0.3/Kg of produced scintillator.
2. Final production prices are better.
 - a. DOW PS 663 about \$1.00/Kg. Itasca plastic buys it. \$1.00/Kg of produced scintillator.
 - b. PPO about \$123/Kg. Fermilab buys it. \$1.23/Kg of produced scintillator.
 - c. POPOP about \$650/Kg. Fermilab buys it. \$0.20/Kg of produced scintillator.
3. MINOS pays Itasca an extrusion price of \$6/Kg(\$0.70/ft) including all QC.
4. The overall cost of MINOS scintillator is ~ \$10/Kg.



PROCESS FOR EXTRUDING SCINTILLATOR

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1. Scintillator Extrusion. *Schematic diagram.*

- Take PS pellets.
- Dry the PS at about 170⁰F for 4-8 hours. *Figure.*
- Purge the dried PS with liquid Nitrogen for approximately 4 hrs.
- Mix about 100 lbs of dried PS with PPO and POPOP in a mixer for about 15 minutes. The purge with liquid Nitrogen continues. *Figure.*
- About 200 lbs of doped PS pellets is kept in a drum lined with polythene bag. The purge continues for another 4 hrs or more.
- About 100 lbs of doped PS pellet is put in the hopper. The purge continues. *Figure.*
- There are anywhere between 7 to 11 zones in the extruder. The temperature in these zones varies from 360 to 410⁰F (Ex: 360 - 365 - 370 - 375 - 393 - 405 - 390 F). The liquid Nitrogen purge continues in the extruder.
- Scintillator with a groove and co-extruded with TiO₂ coating comes out of the extruder and goes in the water bath. At this point the scintillator is very hot and rather soft. The dimension of the scintillator (41mm X 10mm) is not exact. Two more sizers inside the bath brings it to exact size.
- A puller pulls the scintillator out of the water bath and then the exact size scintillator is cut and online QC is done at the factory.



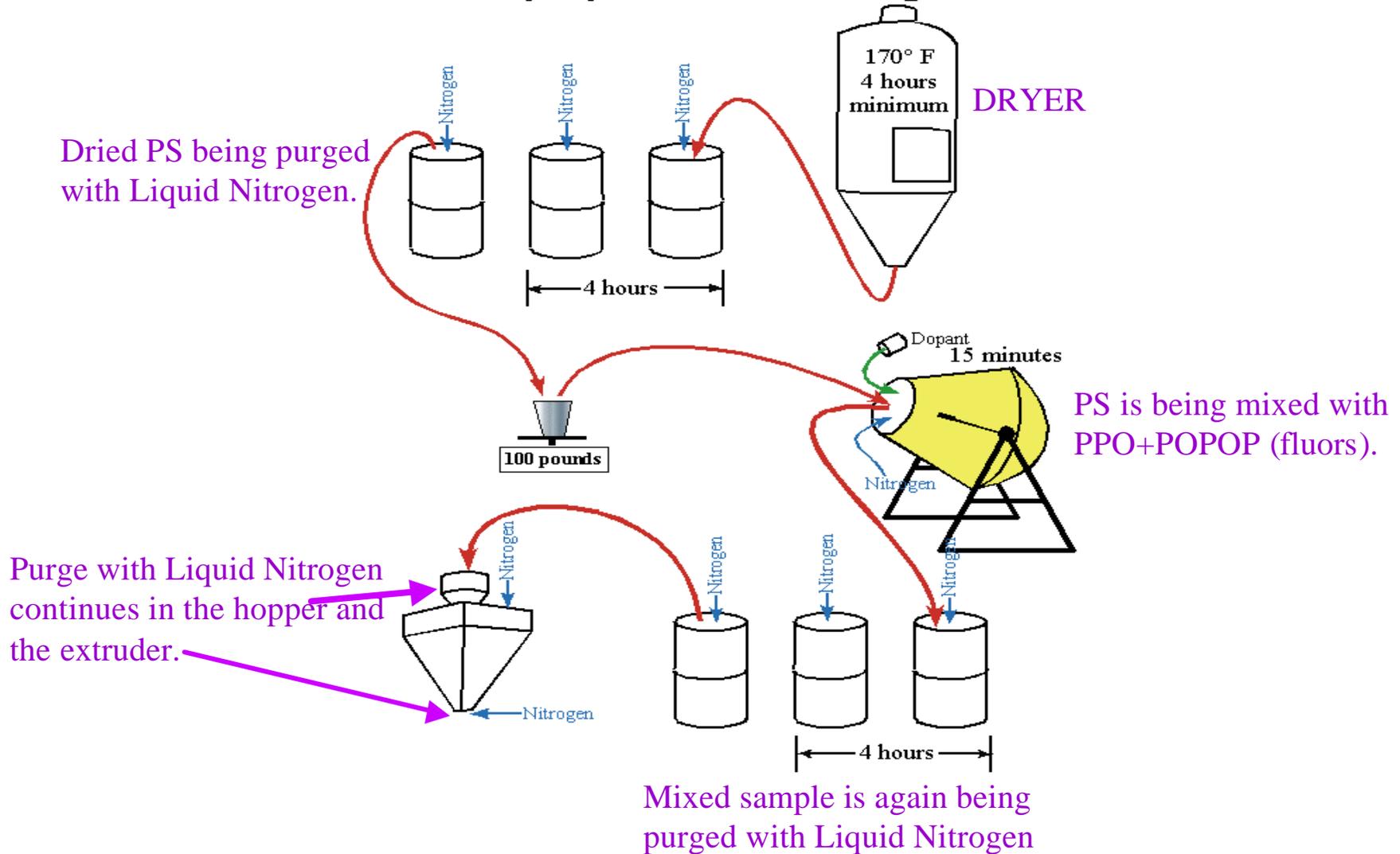
POLYSTYRENE THROUGH VARIOUS PHASES BEFORE EXTRUSION

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Polystyrene Handling



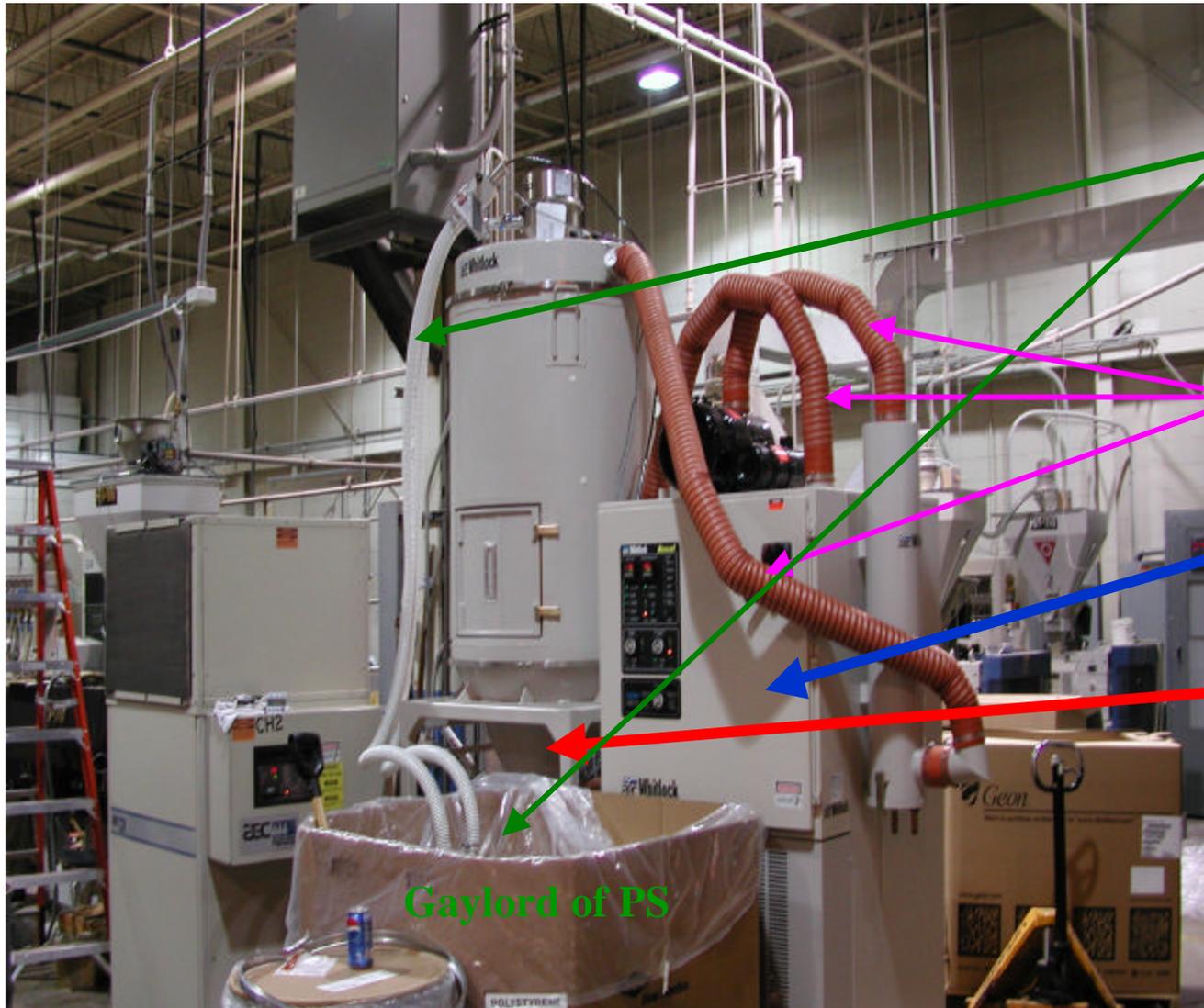


DRYING THE POLYSTYRENE PELLETS

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PS is being sucked from the Gaylord. Dry for 4-8 hours at ~170^oF. Total capacity of the dryer is about 800 lbs.

Circulate dry air.

Desiccant. Sucks up moisture.

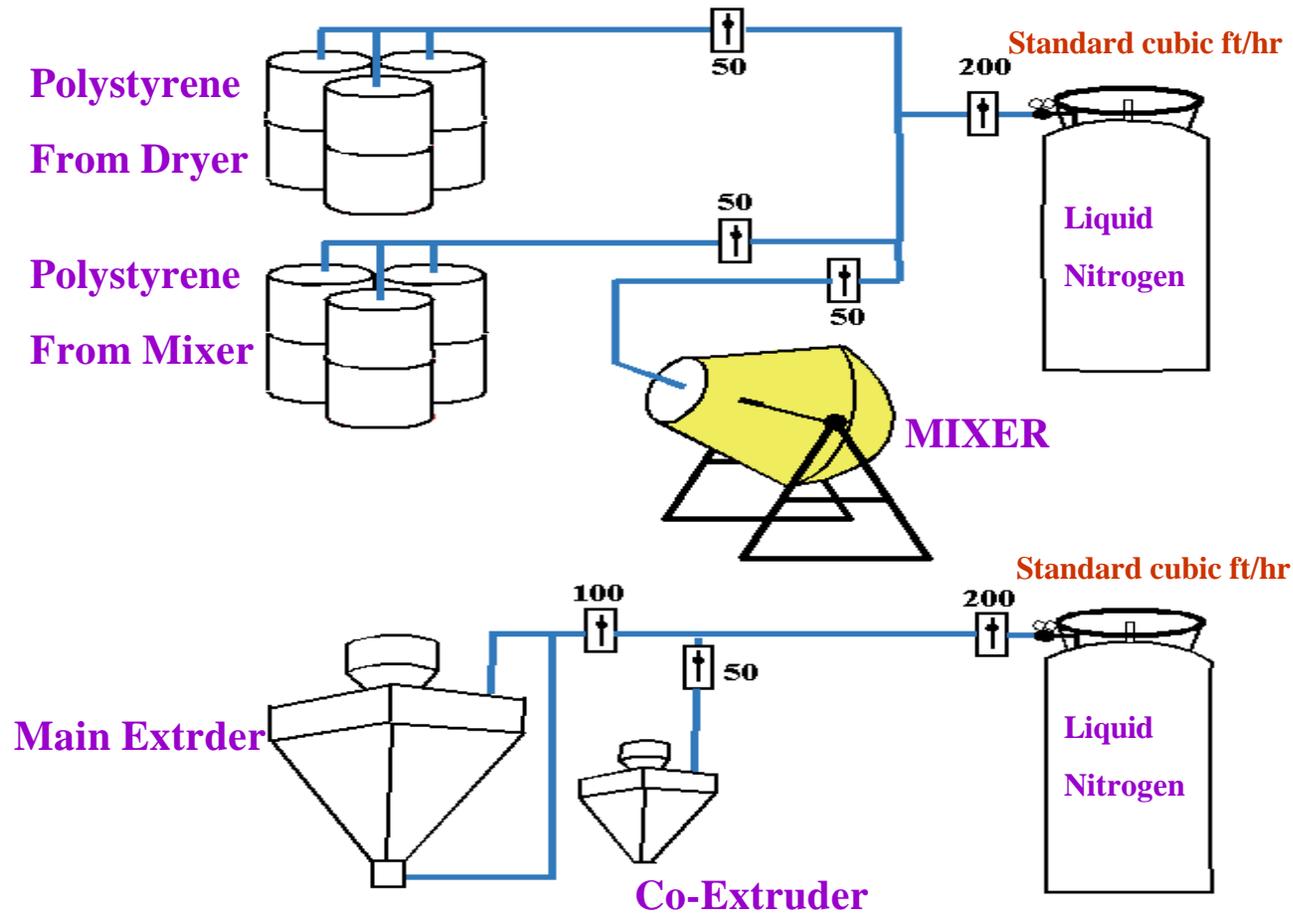
Dried PS goes here. Bucket underneath. About 200 lbs/container.

Gaylord of PS



INERT GAS FLOW THROUGH THE SYSTEM

Nitrogen Flows



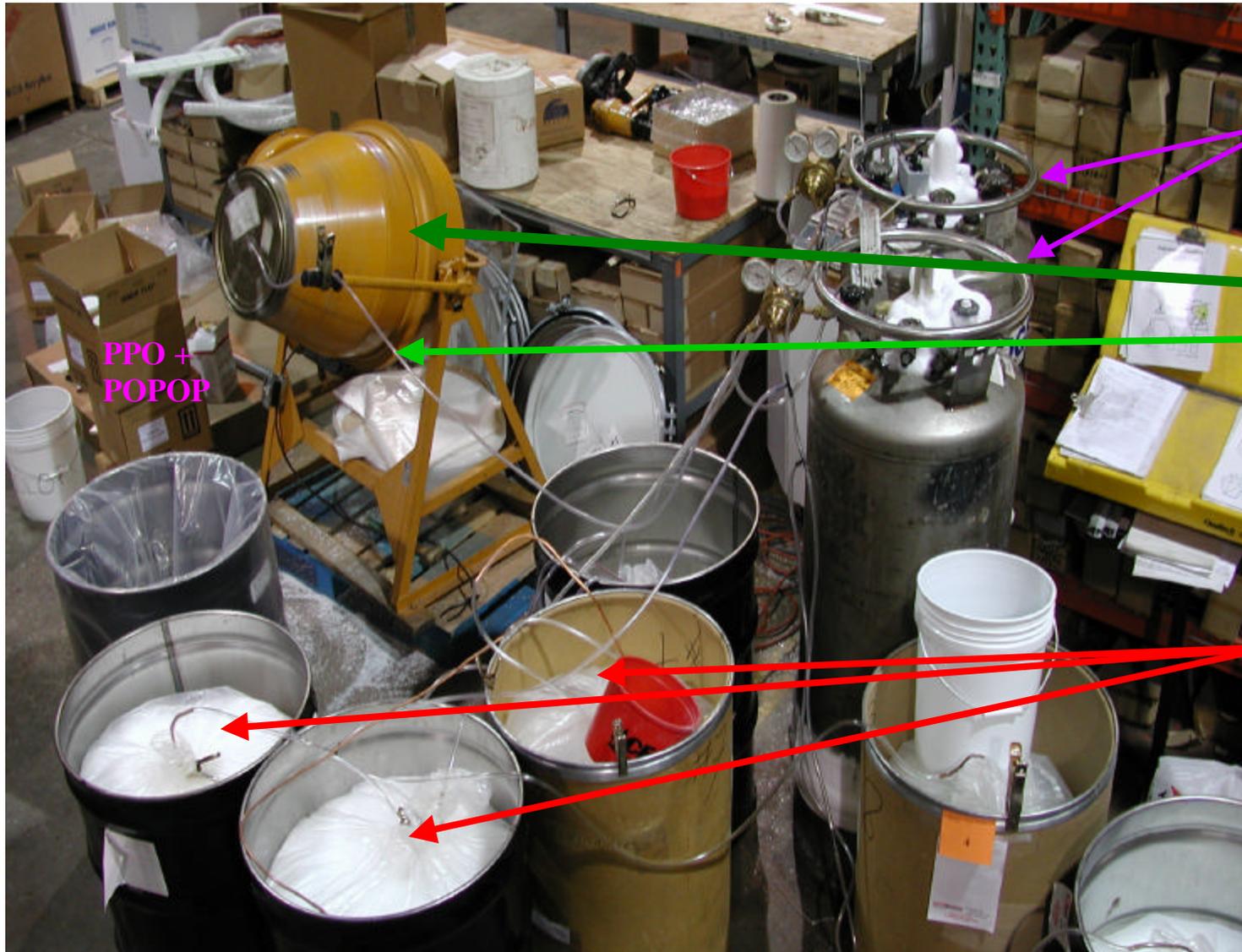


MIXING OF PS+PPO+POPOP

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LIQUID NITROGEN CYLINDERS

MIXER

Liquid Nitrogen flow continues in the mixer.

PPO + POPOP

Unmixed and mixed PS being purged.

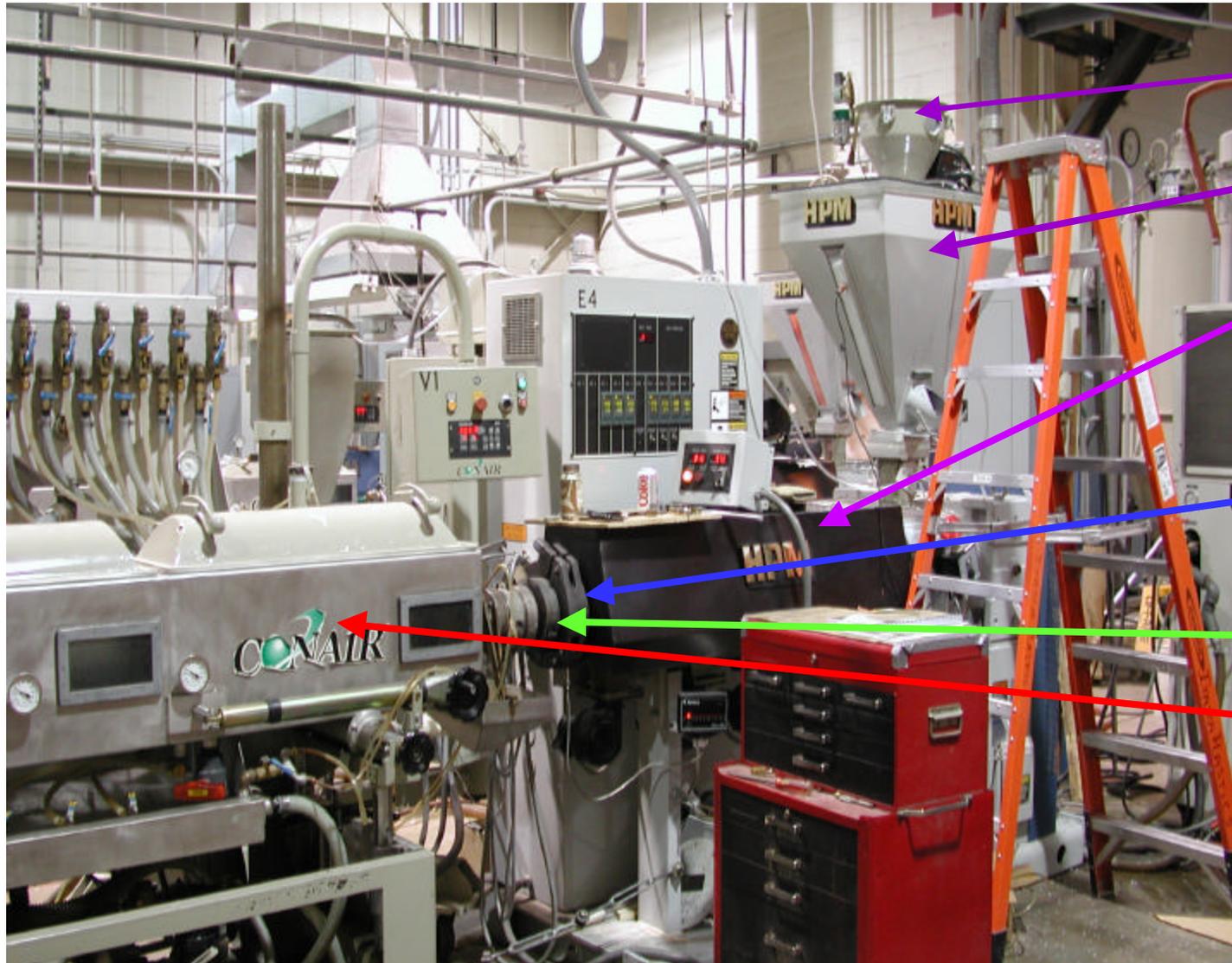


EXTRUSION DETAILS

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Doped PS goes here.

HOPPER

EXTRUDER.
About 7-8' long.

DIE

COEXTRUDER

WATER BATH.
About 25' long.

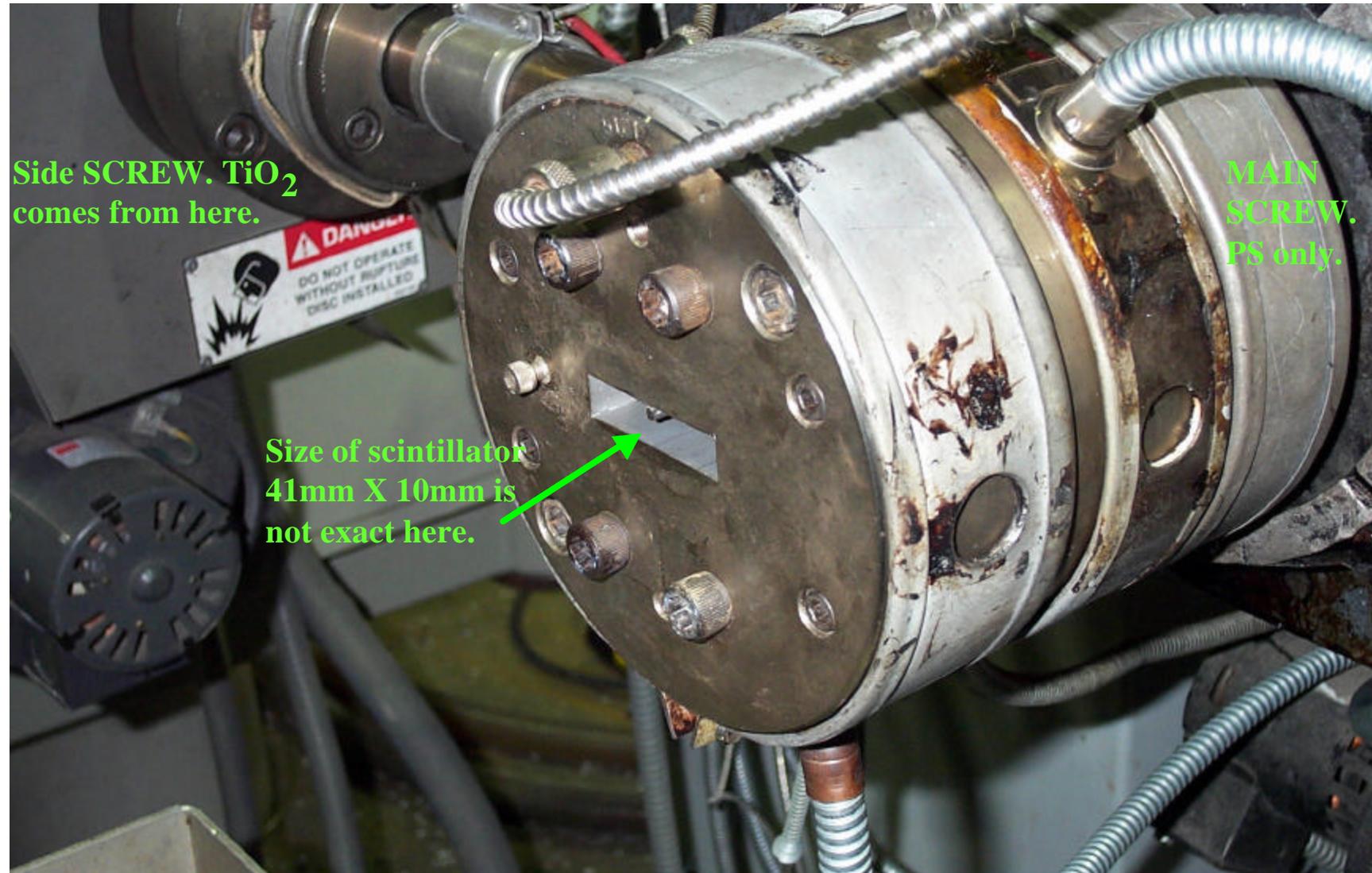


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SIDE VIEW OF THE DIE



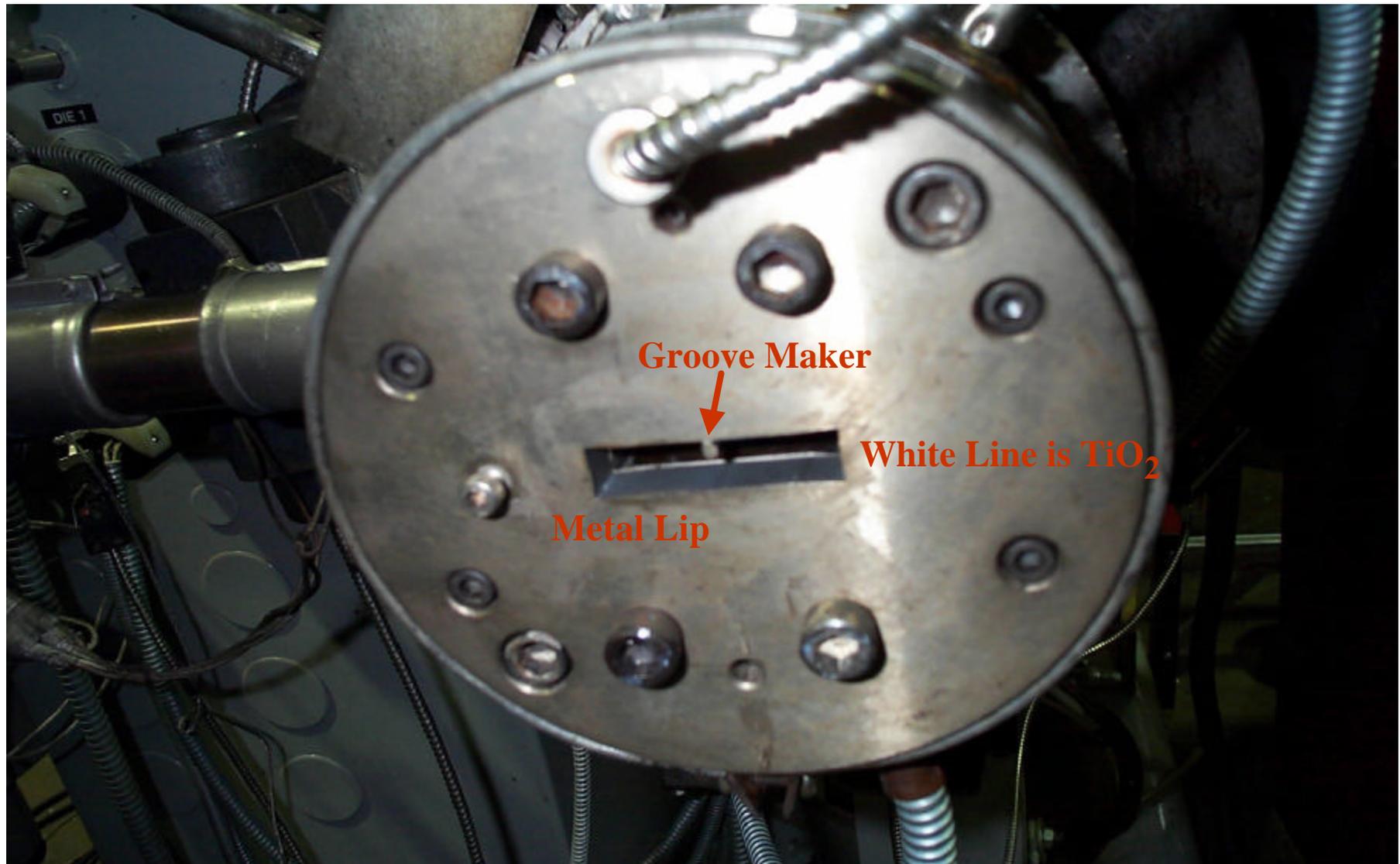


Main Screw – Side View

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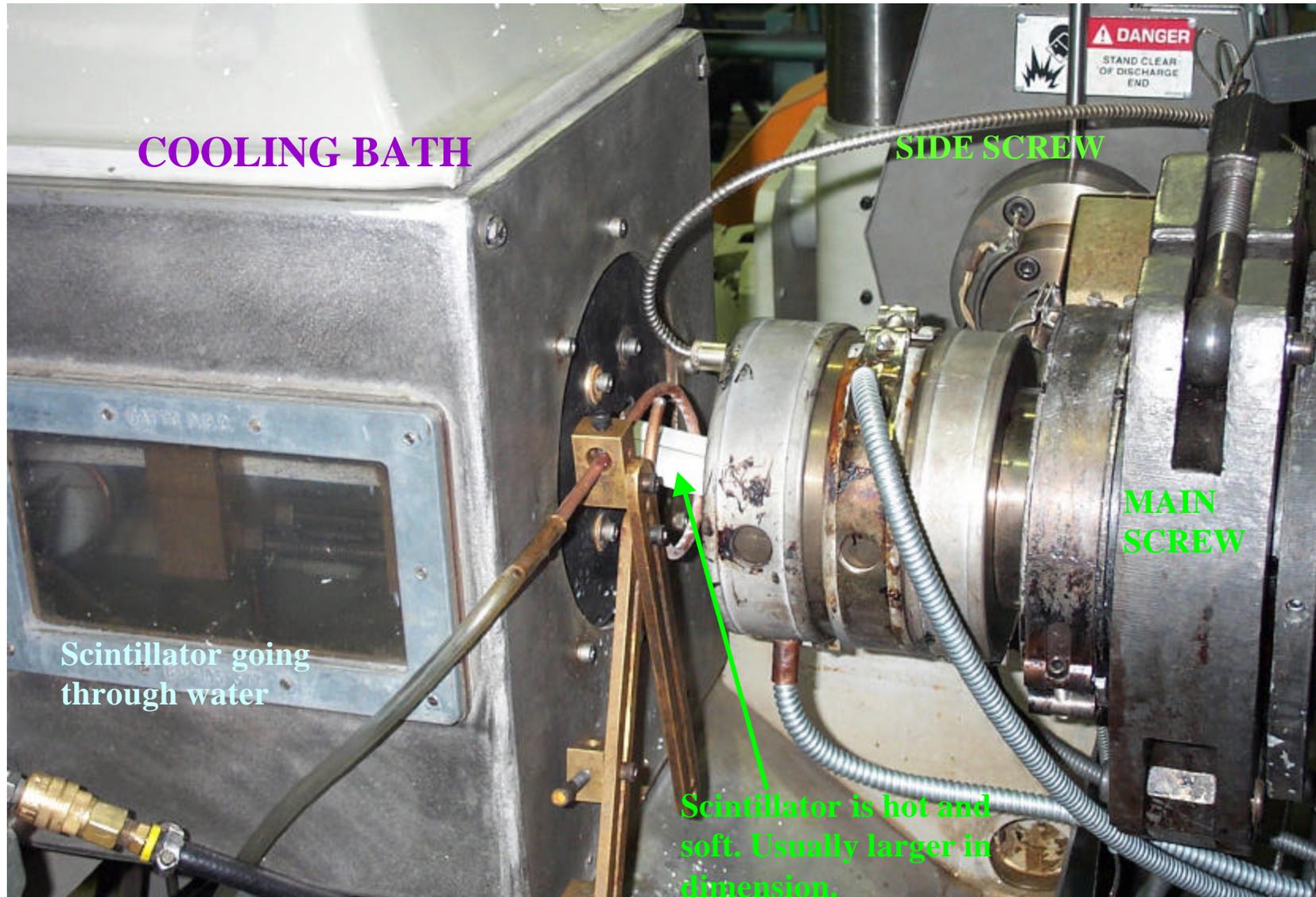


CO-EXTRUDED SCINTILLATOR THROUGH THE WATER BATH

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THE FINAL PRODUCT

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WATER BATH

PULLER

CUT SCINTILLATOR

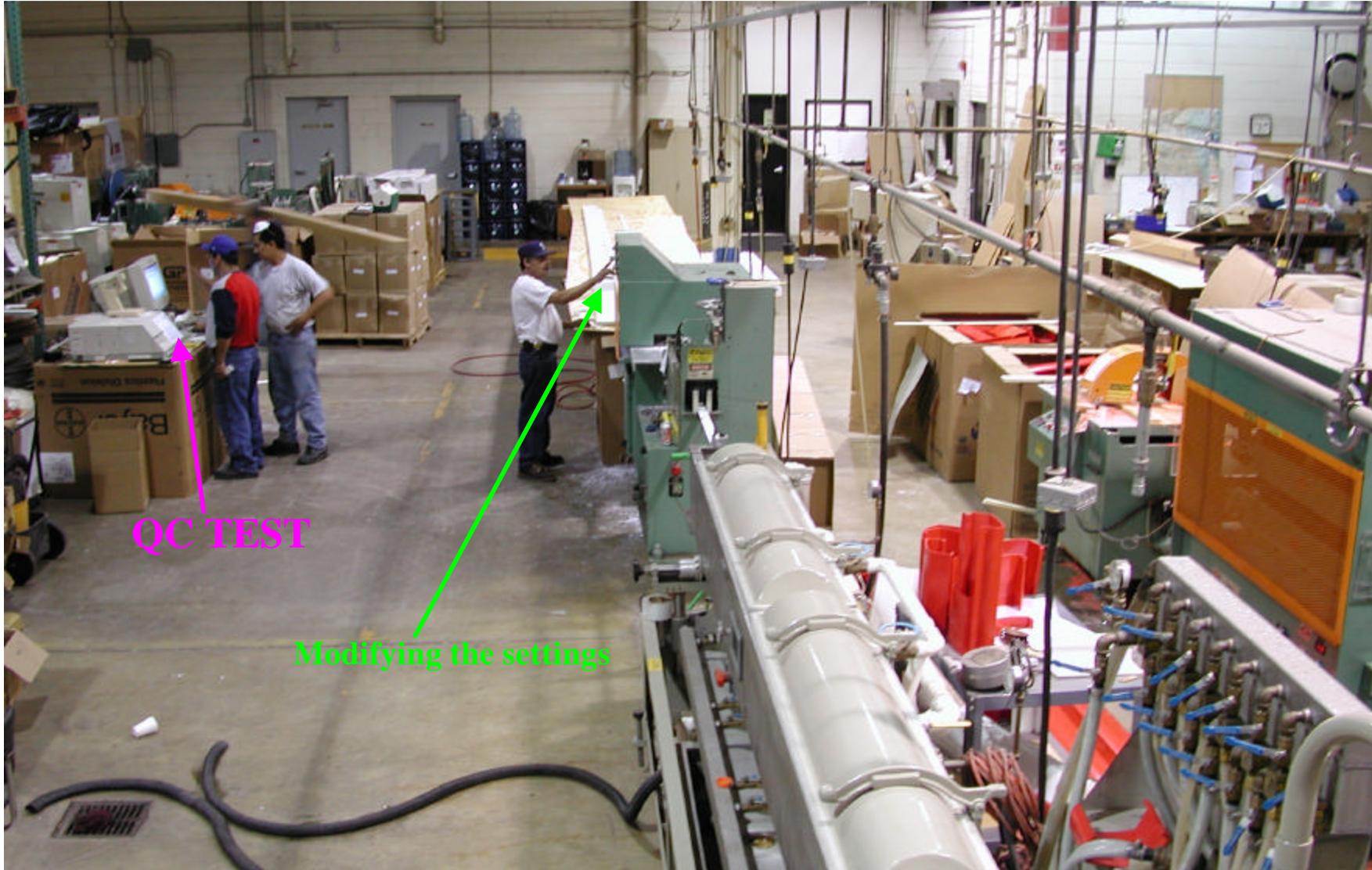


TECHNICIANS MODIFYING THE SETTINGS AND DOING QC

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QC TEST

Modifying the settings



LIGHT OUTPUT – MAY 2000 MODULE PRODUCTION

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AVERAGE SUMMED LIGHT OUTPUT > 7.0 pe

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Different Methods of Producing Scintillator

MINOS EXPERIENCE

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INITIAL METHOD USED BY MINOS FOR PRODUCING SCINTILLATOR

- A gaylord of Polystyrene (2000 lbs) is purged w/Ar/N₂ for 3-4 days before extrusion.
- Polystyrene in smaller quantities are put in dryer and heated at 170°F for 2-3 hrs. The Ar/N₂ purge may continue in the dryer. **Possibility of air presence.**
- **Warm polystyrene is mixed with PPO+POPOP. No Ar/N₂ purge while mixing in process.**
- **Warm PS+PPO+POPOP** to sit by the extruder for sometime, waiting to be placed in the hopper. **No Ar/N₂ purge there also.**
- **Ar/N₂ purge to resume in hopper and extruder.**

IMPROVED/CURRENT/FINAL METHOD OF PRODUCING SCINTILLATOR

- Step 1 is not necessary. During Step 2 there is no need to purge the polystyrene.
- **COOL** the **HOT** polystyrene for several hours. **Ar/N₂ purge to continue.**
- Mix PS+PPO+POPOP **at room temperature.** The process takes about 10-15 mts. **Ar/N₂ purge to continue while mixing is in progress.**
- **Doped PS purged with Ar/N₂ for ~4 hrs. Cool mixture goes in the hopper. Ar/N₂ purge to continue in hopper and extruder.**

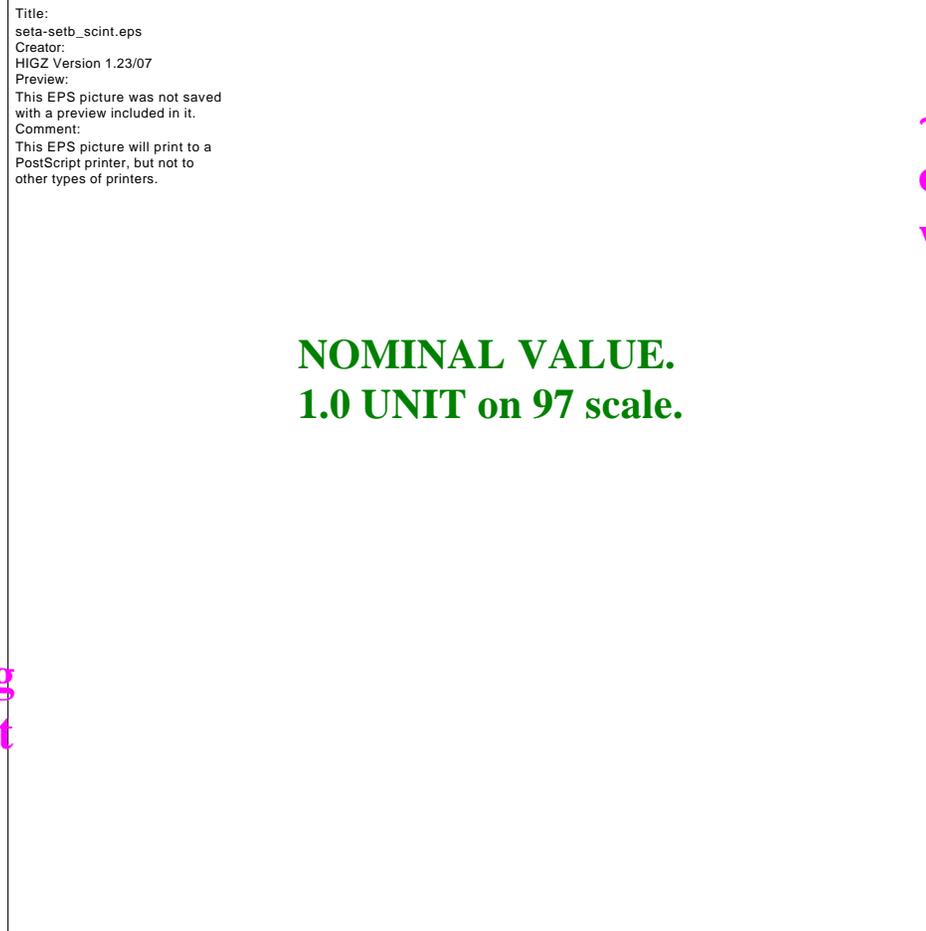


LIGHT OUTPUT COMPARISON USING DIFFERENT PRODUCTION MECHANISM

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**~25% higher light
output when no Air
was present.**

**Presence of Air during
extrusion reduces light
output. Extreme case
example.**



SCINTILLATOR PRODUCED AT ITASCA PLASTICS

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20 - 30 % EXTRA
LIGHT
2/2000 BATCH

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ABOUT 30% EXTRA LIGHT

5/2000 BATCH



FLUOR CONCENTRATION vs LIGHT OUTPUT

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S. N.	PROCESS	DATE	PPO(%)	POPOP(%)	RELATIVE LO
1.	Two Step	9/97	1.0 %	0.015 %	1.00 (Ref. Batch)
2.	Two Step	6/98	1.0 %	0.015 %	0.77-0.83
3.	One Step	6/98	1.0 %	0.010 %	0.82-0.84
				0.015 %	0.85-0.90
				0.030 %	0.93-0.97
				0.045 %	0.89-0.91
4.	One Step	6/98	1.5 %	0.010 %	0.86-0.90
				0.015 %	0.83-0.90
				0.030 %	~ 0.60
				0.045 %	~ 0.60
5.	Two Step	9/98	1.0 %	0.030 %	~ 0.90

For final scintillator production MINOS uses ONE Step process with 1% PPO and 0.03% POPOP and gets a relative light output of ~120% compared to standard test samples.



QUALITY OF GROOVE vs LIGHT OUTPUT

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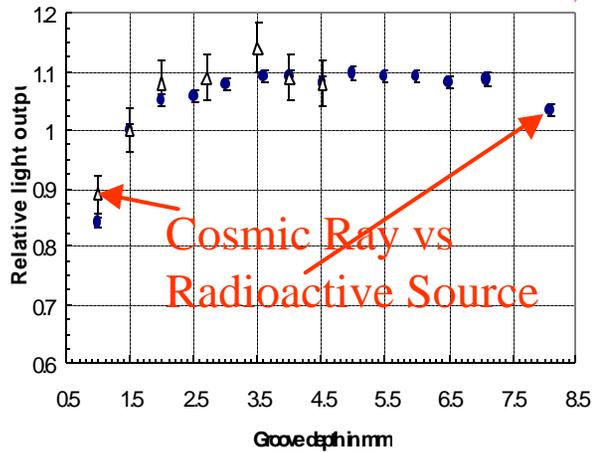
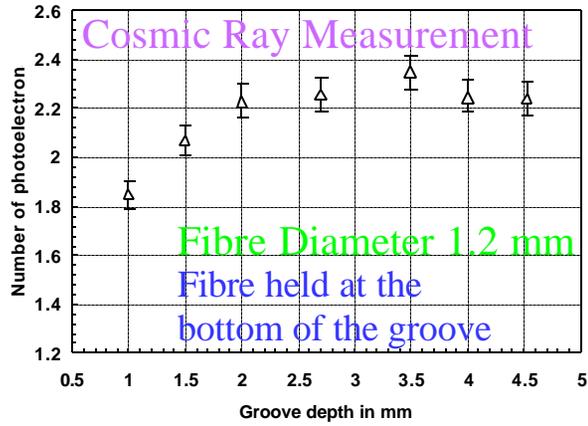
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EXTRUDED GROOVE VS MACHINED GROOVE

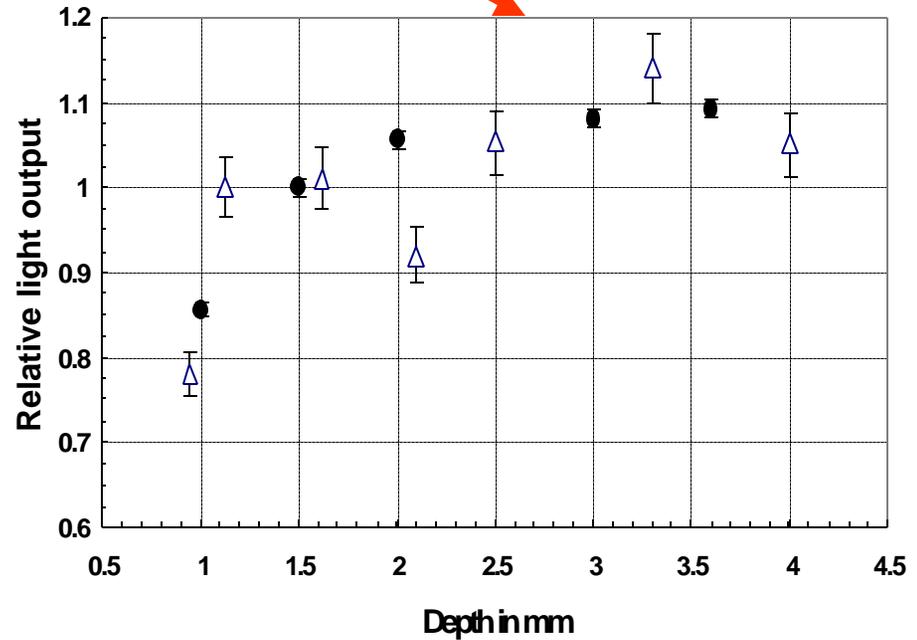
We have also compared light
output between extruded groove
and machined groove. Within
errors of measurement we do not
see any difference in light output.



LIGHT OUTPUT vs GROOVE DEPTH



LO vs Depth of Fibre Inside the Groove





EFFECT of TiO_2 THICKNESS on LIGHT OUTPUT

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- MINOS has produced scintillators with varying amount by TiO_2 by weight (for example 5%, 10% and 15%) and different thickness of the TiO_2 coating. For MINOS purpose, the optimum amount of TiO_2 is about 12% by weight. In terms of actual thickness the optimised value comes to about 0.25mm. The TiO_2 thickness usually varies between 0.25mm and 0.40mm.
- It was observed that light output did increase when the amount of TiO_2 was increased from 5% to 10%. But no significant light output increase was seen when the amount of TiO_2 was increased from 10% to 15%. For the same amount of TiO_2 the thicker coating gave higher light output compared to a thinner coating.
For Example : One particular batch of scintillator came with very thin coating. For 10% TiO_2 by weight, the measured thickness of TiO_2 coating was between 0.05mm and 0.10mm instead of usual 0.25mm. Light output was measured with these pieces. Afterwards few pieces were coated with several coatings of Bicorn TiO_2 paint and the average thickness of coated surface was about 0.20mm. The net increase in light output for different pieces was between 7 to 10%.
- We did encounter some problems with extrusion process when percentage of TiO_2 was increased. With 15% of TiO_2 there co-extrusion was less smooth than usual.



CORRELATION BETWEEN SOURCE MEASUREMENT AND SPECTROPHOTOMETER MEASUREMENT

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Light Output from 4PPT Module Tests

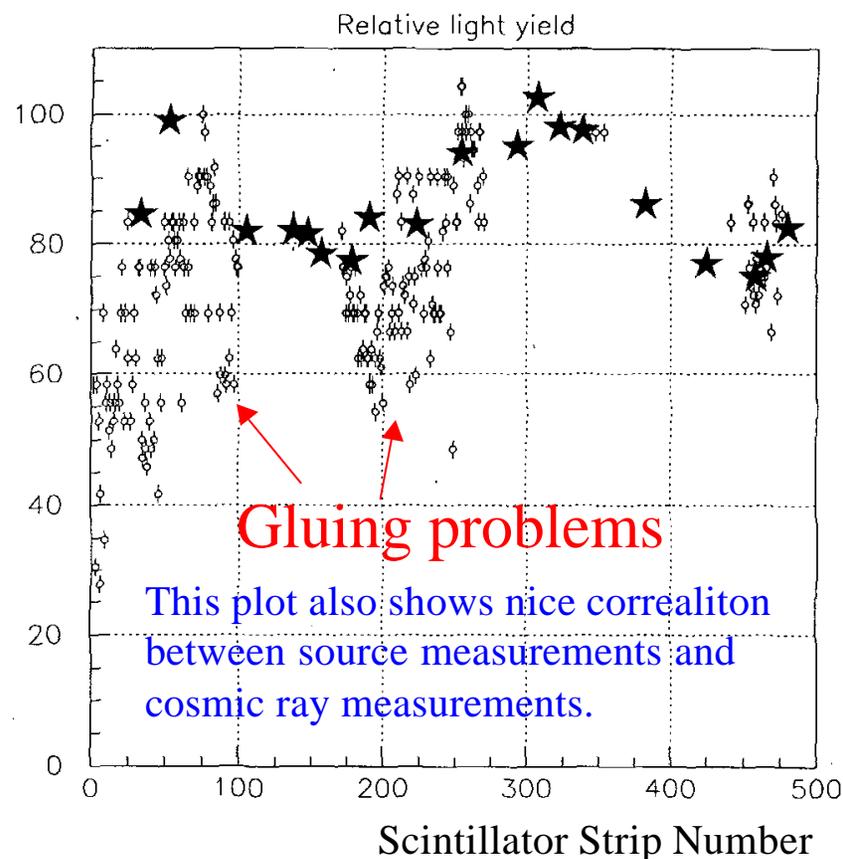
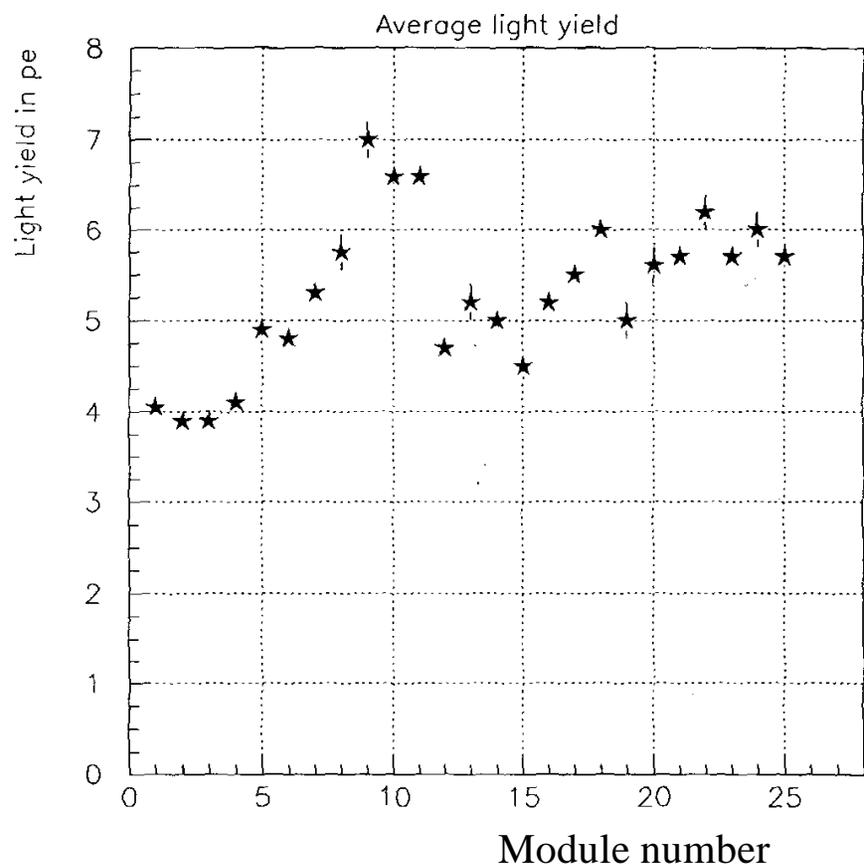
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Average light (summed at the center)
for all modules produced for 4PPT.
Average summed light output is 5.2 pe.

Light yield for strips in 4PPT
modules compared to light
measured for sample scintillators at
Caltech. We see good correlation.





AGING OF THE SCINTILLATOR

PRELIMINARY RESULT

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- Lifetime of the MINOS Detector ~ 8-10 yrs.
- Scintillators do age. Expect light loss as years go by.
- Aim – Sufficient light today. Sufficient light several years down the road.
- Method: Measure light output of identical scintillators kept at different environment and compare them to light output of the reference pieces. We kept the scintillators at room temp (22°C), 30°C , 40°C and 50°C . We also had samples which were kept at 50°C and very high humidity ($\sim 100\%$). The light loss for scintillator kept at 50°C was approximately 15% in six months and 20% in 8 months, which approximates to about 8yrs and 11yrs at normal room temperature. We expect to lose about 2% of light every year but may be not at an uniform rate.
- The scintillators usually yellows with time but in MINOS detector since the light travels only few centimeter inside the scintillator before it gets captured in the WLS fibre, the effect of aging of scintillator will be different on light output for detectors with different geometry.
- Detailed analysis to come soon.



WHY MINOS USES 1.2 mm DIAMETER FIBRE?

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Light Output is proportion to (Radius of fibre)^{1.4+-0.1}



CONCLUSIONS

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1. MINOS is the first large experiment to use co-extruded scintillator as active medium.
2. The scintillator extrusion process has been optimised and order has been placed with Itasca plastic for ~300 tons of extruded scintillator at a cost of ~\$10/Kg.
3. The scintillator is composed of PS + 1.0% PPO + 0.030% POPOP.
4. Light yield measurements have shown consistent (within +/-10%) and high light output.
5. It has been observed that presence of air during the extrusion process severely degrades light output.
6. Groove depth and thickness of co-extrusion needs to be optimised for particular needs. WLS fibre must be completely embedded inside the scintillator. The co-extrusion should be thick enough that no light leaks out of the scintillator.
7. We have established online quality control at Itasca plastic to monitor the quality.
8. We do understand aging of the scintillator. The scintillator will lose about 20% light in ~10 yrs. The light output from MINOS detector is more than necessary to do very good physics even after 10 years.