Mu2e CD-2 Calorimeter
475.07.04 Photosensors

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Calorimeter L3 manager, calibration
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Requirements I – Calorimeter Photosensors

- Energy resolution at 100 MeV 5% (FWHM/2.35)
  - Driven by PID and trigger requirement, maintaining electron efficiency
  - Quantum efficiency
  - Light collection (photosensitive area and coupling to crystal)
  - Gain and noise
- Response variation correctable to 0.5%
  - Driven by 1% overall calibration requirement, negligible contribution to energy resolution
  - Temperature variation
  - Gain variation due to voltage instability
- Timing resolution better than approximately 0.5 ns
  - Enables suppression of energy deposits from backgrounds
  - Enables matching energy deposits in time with tracker
  - Determine direction of particle (cosmic ray background suppression)

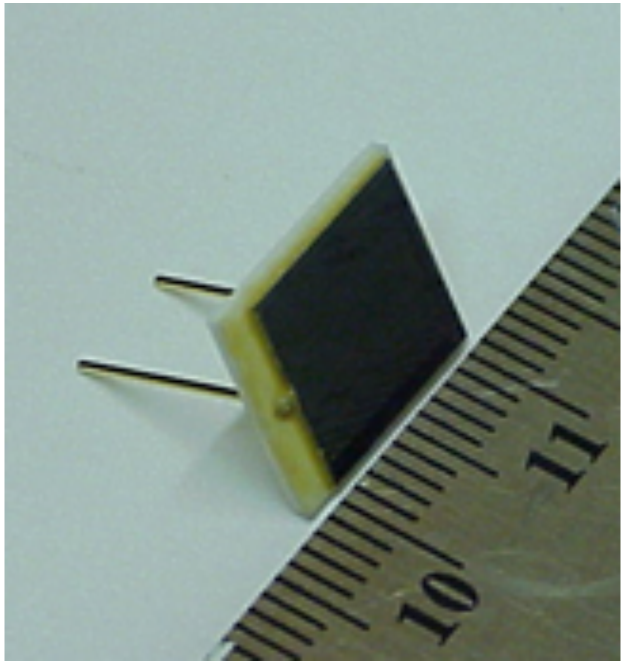
Requirements II – Calorimeter Photosensors

- Works in 1 Tesla magnetic field
- Radiation hardness
  - 50 Gy/yr
- Insensitive to nuclear counter effect
  - 2×10^9 n(1 MeV equivalent)/cm^2/year*
- Bias HV interlock with vacuum to prevent Crooke's tube breakdown

*New evaluation in progress

Design – Calorimeter Photosensors

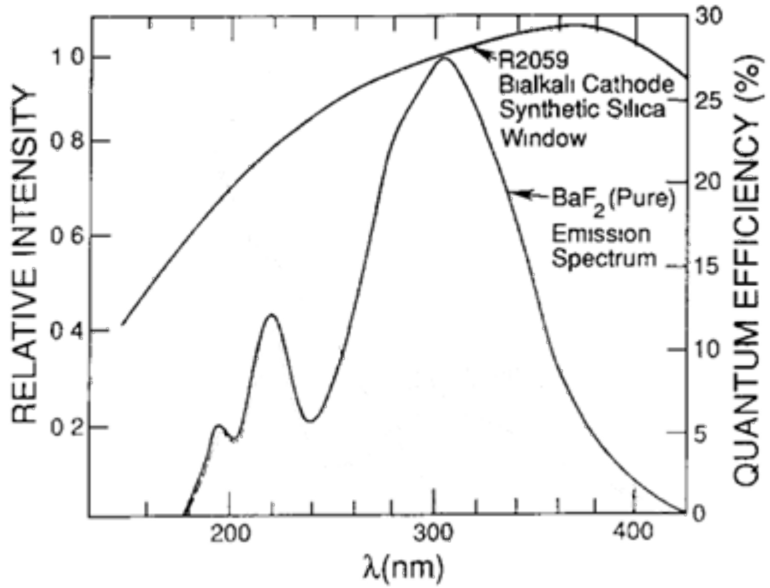
- Requirement to operate in a magnetic field, plus affordability, leads to use of solid state technology for photosensor
- Baseline choice is large area APD readout
- Two APDs/crystal
  - Greater light collection
  - Mitigate nuclear counter
- Challenges:
  - High QE at 220 nm
  - Solar-blindness to longer wavelengths
  - Large area for light collection

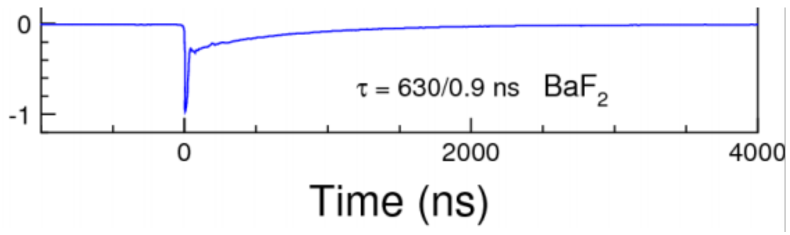


RMD 9x9 mm^2 APD

Design – Calorimeter Photosensors

- BaF2 emission spectrum:
  - Fast (0.9 ns decay time) short wavelength (220 nm) component, 4.1% of NaI
  - Slow (650 ns) longer wavelength (300 nm) component, 36% of NaI

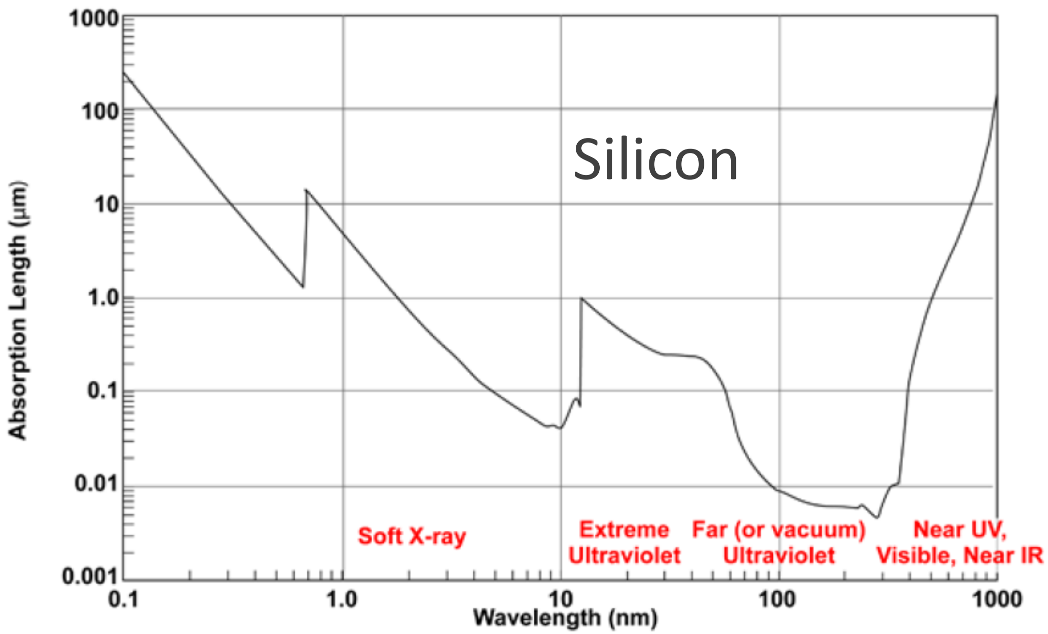




Fast component is among fastest crystals
To take advantage of this, need to suppress the slow component:
"solar-blind" photosensor

Design – Calorimeter Photosensors

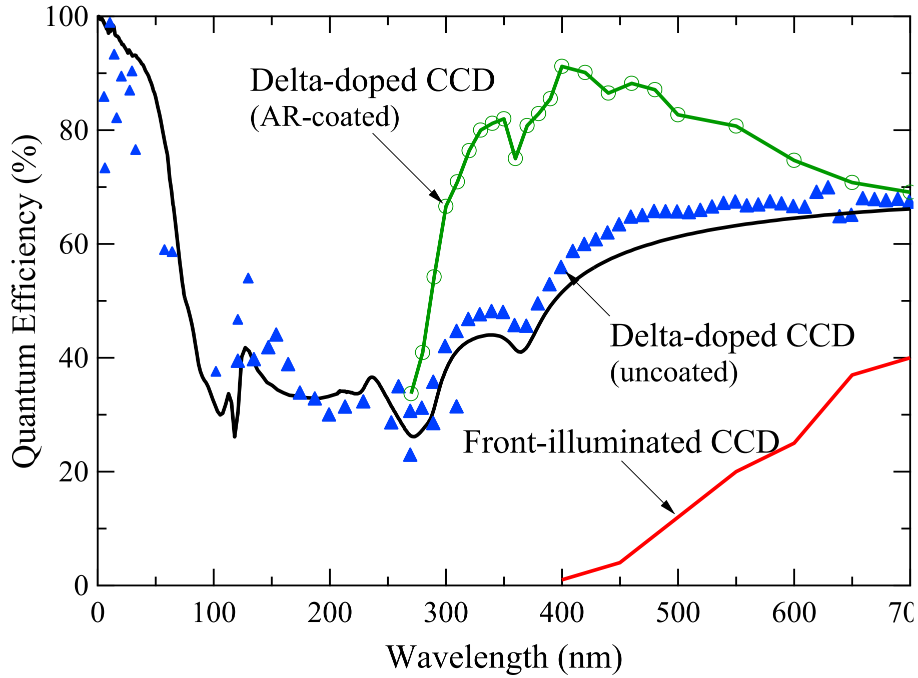
- Quantum efficiency at 220 nm
  - Silicon absorption length < 10 nm at 220 nm
  - Protective epoxy coating on off-the-shelf devices has strong effect
  - Sensitive region must be very close to surface



Design – Calorimeter Photosensors

- High QE in UV achievable by
  - removing protective layer
  - Delta doping
  - Antireflection coating
- Proven technology with CCDs
- Design antireflection coating to bandpass UV, creating solar blind device, using atomic layer deposition (ALD)
- Developing large area solar-blind APDs for mu2e (Caltech/JPL/RMD)

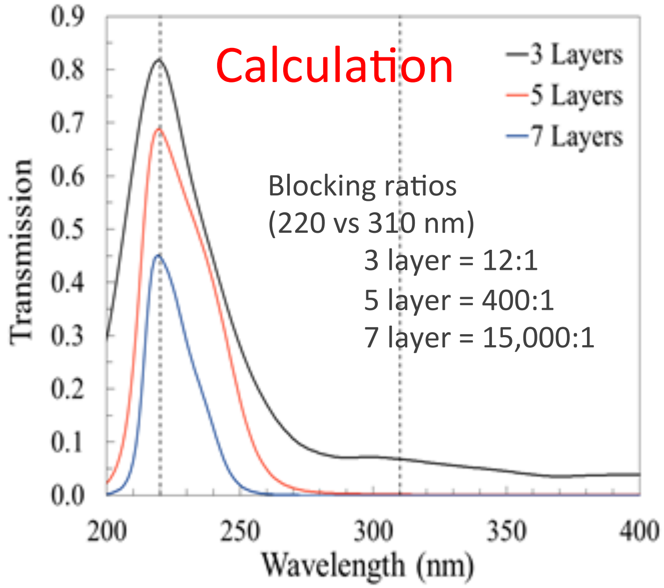
"Atomically precise surface engineering of silicon CCDs for enhanced UV quantum efficiency"
F. Greer, et al., *J. Vac. Sci. Technol.*, A 31, 01A103 (2013)

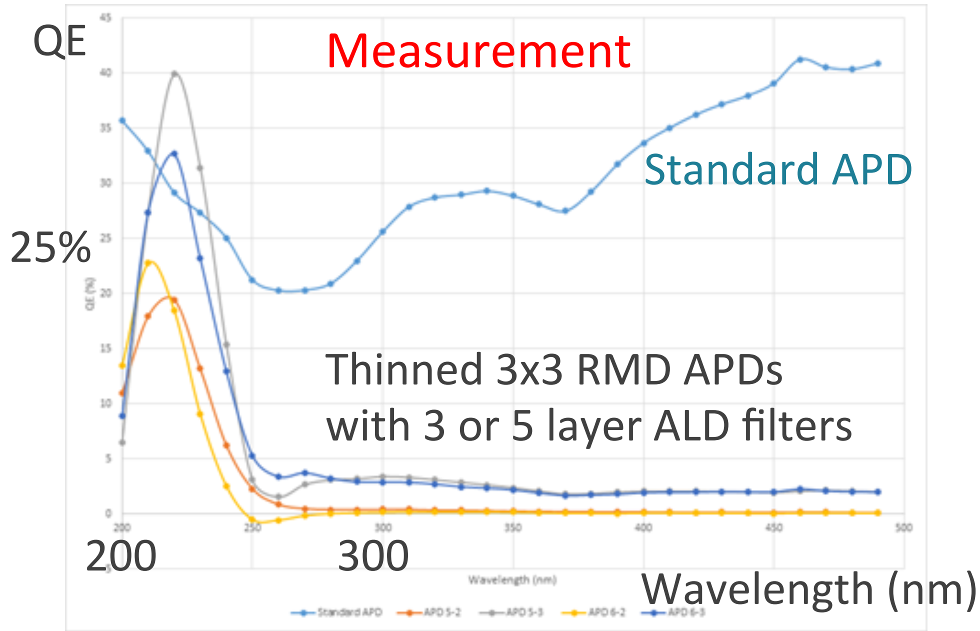


S. Nikzad, "Ultrastable and uniform EUV and UV detectors," *SPIE Proc.*, Vol. 4139, pp. 250-258 (2000).

Design – Calorimeter Photosensors

- Quantum efficiency nearly 70% possible at 220 nm for five layer coating (Al_2O_3/Al)
- 3 and 5 layer devices have been fabricated, encouraging results (no delta-doping yet)





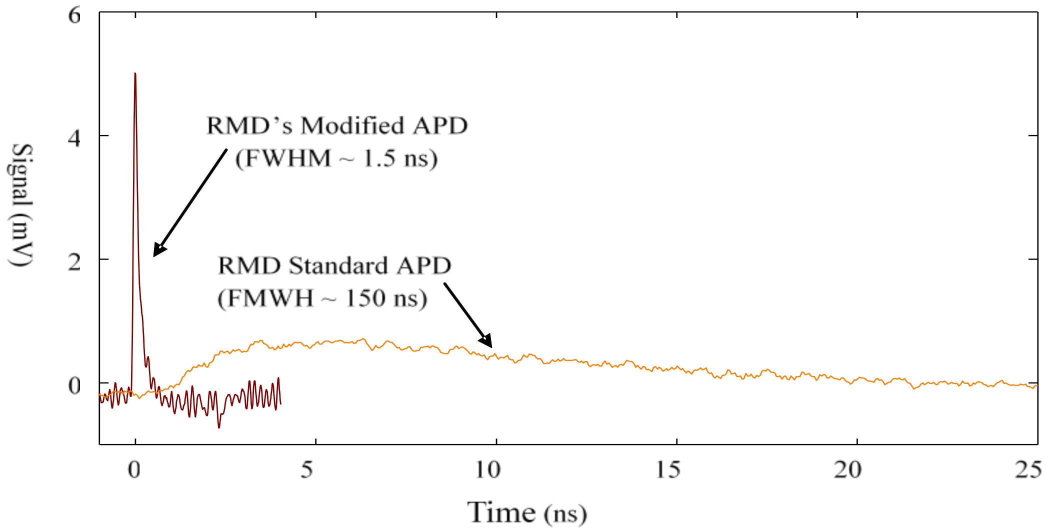
Design – Calorimeter Photosensors

- APD gain depends strongly on temperature and bias voltage
  - Operating voltage ~ 1800 V for gain ~ 500
  - Thermal contact via metallic cooling fingers
  - Monitor and correct for temperature variation
  - Stabilized and Monitored HV

Design – Calorimeter Photosensors

- Two large area (9x9 mm^2) APDs per crystal
  - Maximize light collection
  - Robustness against nuclear counter effect in presence of neutron flux
  - Operate at gain ~ 500
  - Thinning before ALD improves timing

- 3x3 mm^2 RMD APD
- 405 nm laser pulse
- 3 micron epitaxial layer on thinned APD



Changes since CD-1

- Crystal has been changed from LYSO to BaF2 due to the high cost of LYSO
  - This has implied redesign of the photosensor readout, from an off-the-shelf large area APD to development of a high QE solar-blind large area APD

Value Engineering since CD-1

- Crystal has been changed from LYSO to BaF2 due to the high cost of LYSO
  - Impacts photosensor
    - Small cost impact
    - Introduction of some risk

Performance

- Resolution
  - 30 pe/MeV → small contribution to overall resolution
  - Gain ~ 500 → ENE ~ 330 keV
    - Light yield decrease by 30-40% after > 10 Gy dose

      → ENE ~ 550 keV
- Timing and rate capability
  - Thinned APD very fast < 1 ns rise time
  - Good match to fast component of BaF_2
  - Reduces pileup contribution to resolution to acceptable level
  - Useable in higher rate experiment (mu2e-2)

Remaining work before CD-3

- Demonstration of large area solar-blind APD with high QE meeting requirements
- Characterization of radiation hardness (leakage current), gain dependence on voltage and temperature
- Vendor quote for production device
- Internal technology choice review
  - Spring 2015
  - Compare baseline with backup (pure CsI/MPPC)
- QA stations

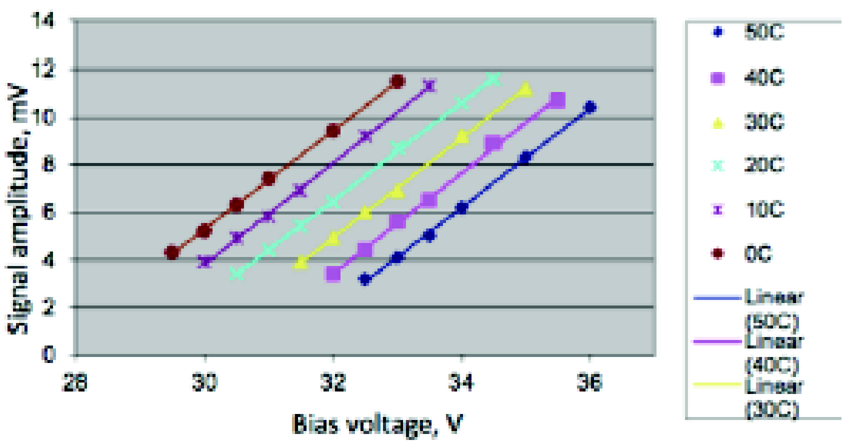
Organizational Breakdown - Calorimeter

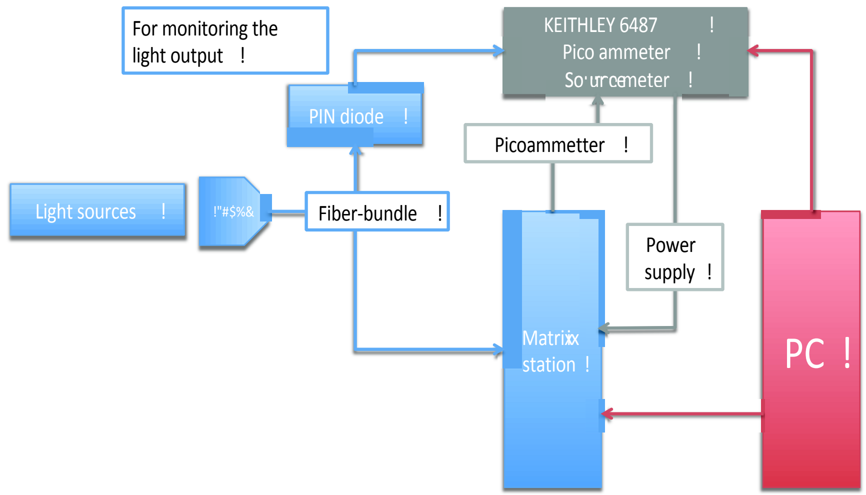
- L2 manager: S. Miscetti (Frascati)
  Deputy D.Hitlin (Caltech)
  - 7.1 Project Management
    S. Miscetti
    Frascati
  - 7.2 Crystals
    D.Hitlin
    Caltech
  - 7.3 Mechanics
    F.Happacher
    Frascati
  - 7.4 Photo Sensors
    I.Sarra
    Frascati
  - 7.5 Digitizer
    Spinella
    Pisa
  - 7.6 Calibration
    F.Porter
    Caltech
  - 7.7 FEE& Power
    G.Corradi
    Frascati
  - 7.8 Assembly & installation
    A.Saputi
    Frascati

- ❑ MoU agreement in progress between INFN and JINR.
- ❑ DOE/INFN Sharing under discussion. Presented at INFN HEP committee.

Quality Assurance – Calorimeter Photosensors

- Prototype devices are being made and will be tested
  - Iterations as needed
- Production acceptance testing
  - Leakage current
  - Gain, including temperature and bias voltage dependence
  - Operating margin





Quality Assurance – Calorimeter Photosensors

- Accepted APDs will be mounted on crystals and tested as a unit with readout electronics
  - Source calibration will be performed
- Calorimeter assembled and tested prior to installation in solenoid
  - Cosmic rays
  - 6 MeV source calibration

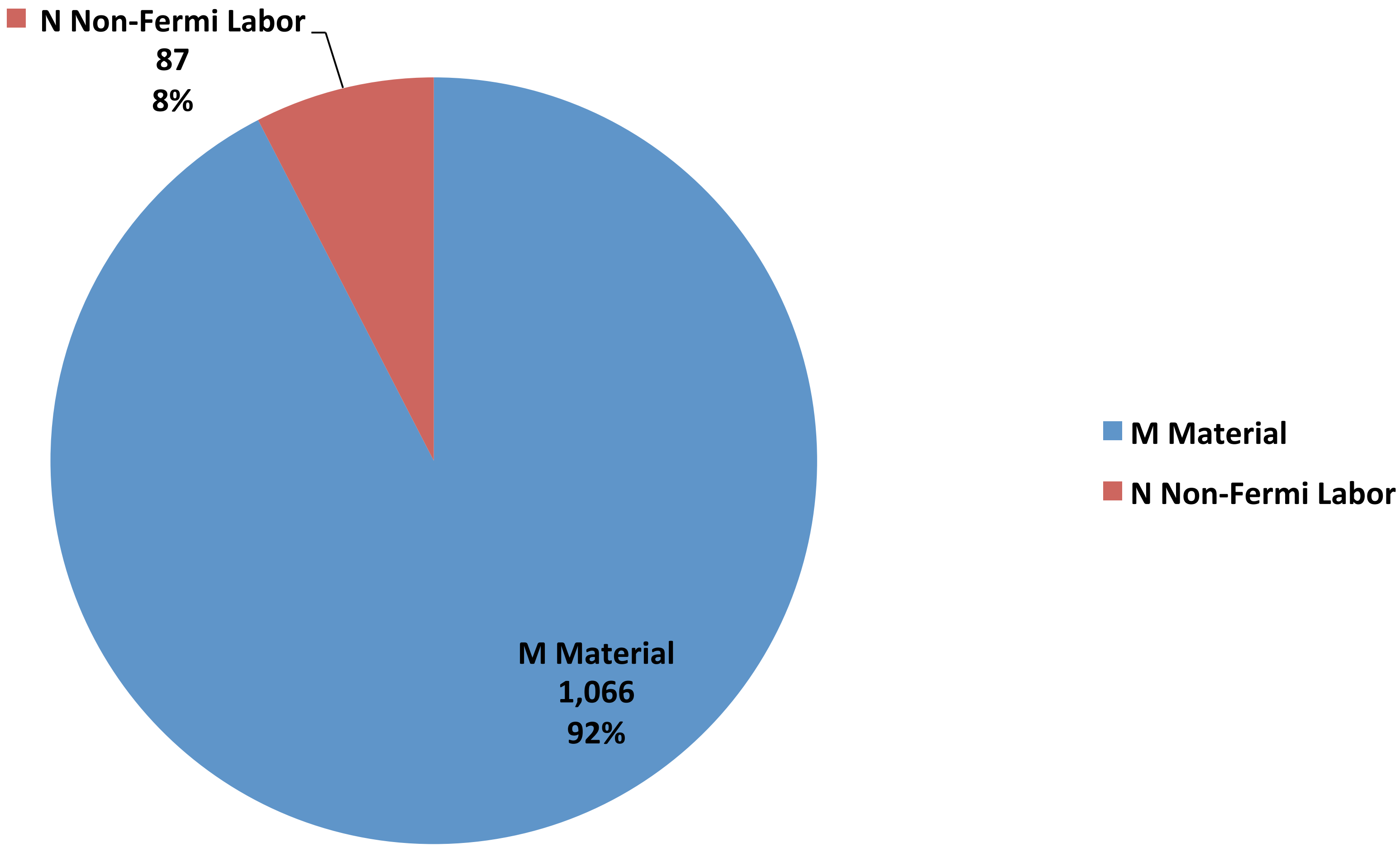
Risks

- Development risk (risk register CAL-148)
  - Unexpected problems could arise in device development
    - Each of the features is not new, but the combination is
  - Mitigation
    - Use of conventional APDs (impact on timing and high rate capability), use La doping to reduce long component in BaF2 (presently factor of ~4)
    - Also looking at Hamamatsu Photonics/MEG UV-sensitive MPPCs (12x12 mm^2)
    - Parallel R&D on CsI/SiPMs provides an alternative
    - Cost estimate is based on existing Hamamatsu devices, conservative based on informal vendor communication
    - Contingency (42% overall) reflects development stage of this item

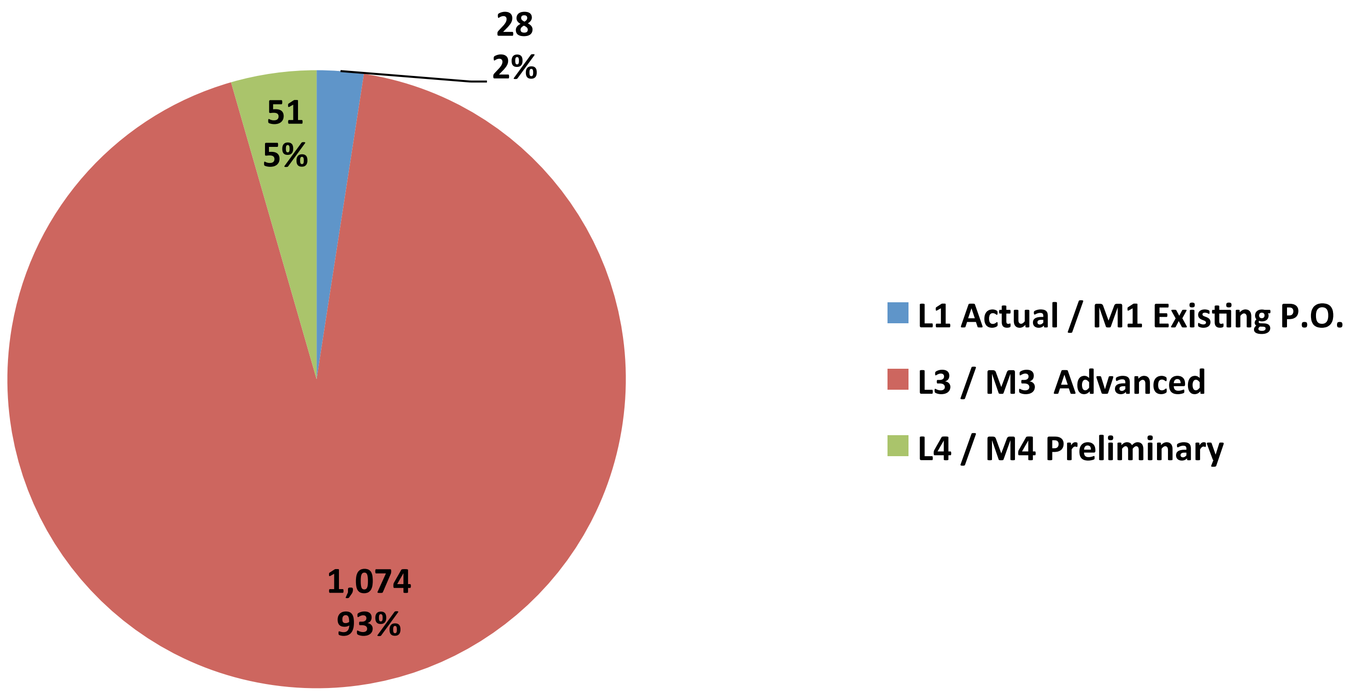
ES&H

- Bias is high voltage (1850 V)
  - Limited to non-lethal currents
  - At photosensor location, HV is inaccessible
- Toxic materials
  - Epoxy may be used to attach APDs to crystals
- Hazards discussed in the Mu2e Hazard Analysis document (Mu2e-doc-675)

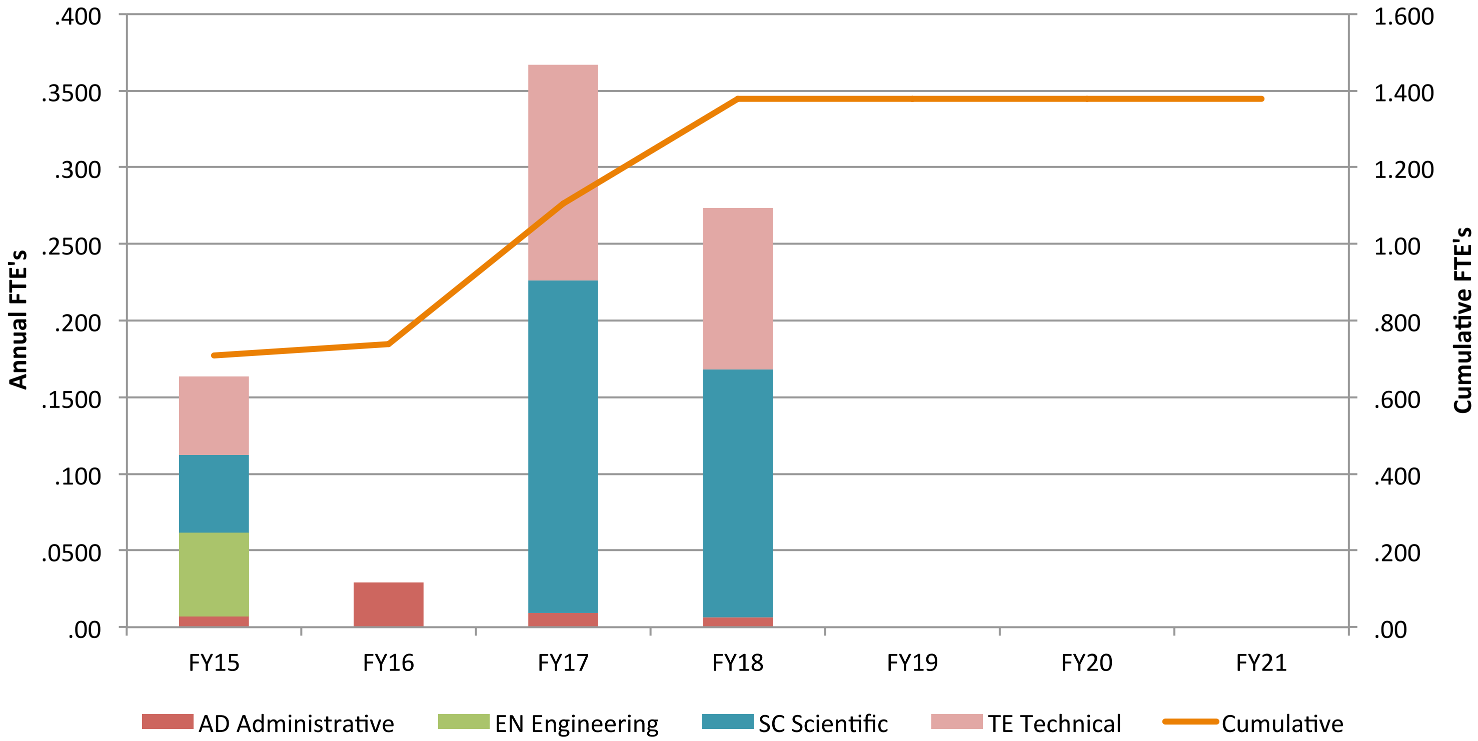
Photosensors: resource type



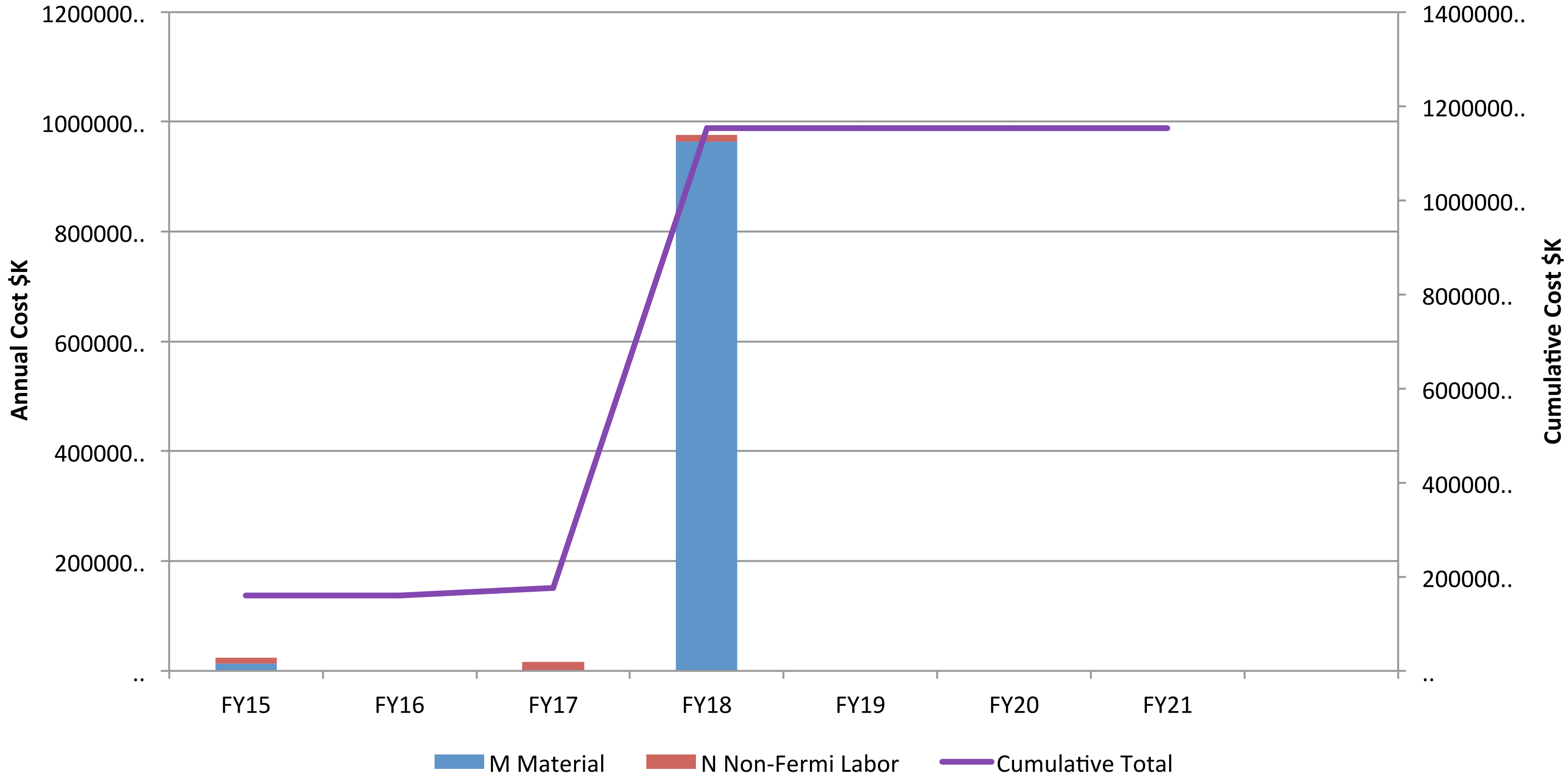
Photosensors: Quality of estimate



Photosensors: labor resources



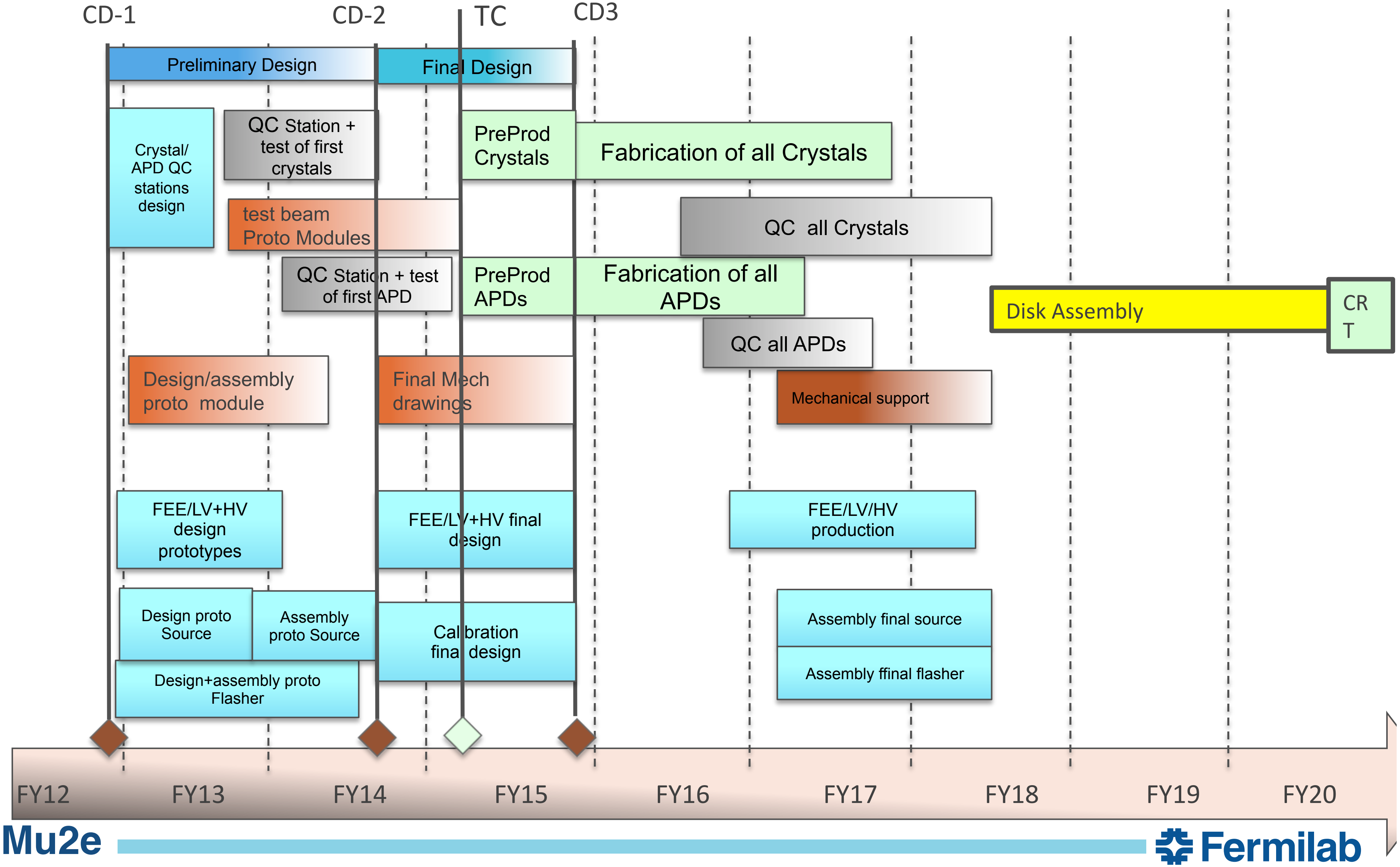
Photosensors: labor/material profile



Major Milestones

1. 47507.5.001320 **Final Design of FEE complete** 13 Feb 2015
2. 47507.2.001860 **Readiness Review for production crystals** 2 Sept 2015
3. 47507.2.011990 **PO issued for production crystals** 26 Jan 2016
4. 47507.4.000700 **PO issued for production photo-sensors** 1 Mar 2016
5. 47507.6.001510 **PO issued for source system material** 3 Jan 2017
6. 47507.4.000790 **QC of all photo-sensors complete** 13 Jul 2017
7. 47507.5.001590 **Assembly of full readout chain** 1 Mar 2018
8. 47507.2.092145 **QC of all crystals complete** 23 Apr 2018
9. 47507.8.002410 **Ready for cosmic ray system test** 19 Jul 2020

Schedule



CD-1
CD-2
TC
CD3
Preliminary Design
Final Design
Crystal/ APD QC stations design
QC Station + test of first crystals
PreProd Crystals
Fabrication of all Crystals
test beam Proto Modules
QC all Crystals
QC Station + test of first APD
PreProd APDs
Fabrication of all APDs
Disk Assembly
CR T
QC all APDs
Design/assembly proto module
Final Mech drawings
Mechanical support
FEE/LV+HV design prototypes
FEE/LV+HV final design
FEE/LV/HV production
Design proto Source
Assembly proto Source
Calibration final design
Assembly final source
Design+assembly proto Flasher
Assembly ffinal flasher
FY12
FY13
FY14
FY15
FY16
FY17
FY18
FY19
FY20

Summary

- BaF2 fast component at 220 nm, ~ 1 ns decay time
  - Excellent timing, pileup rejection
- Development of large area photosensor to match in progress
  - Speed achieved with thinning
  - QE achieved with delta doping and ALD layers
  - Slow BaF2 component suppressed with ALD layers
  - All features are individually proven, need to be combined in one device and tested
- Demonstration required for beginning 2015 internal technology review, on track to meet this schedule