Mu2e CD3c Review
WBS 7.6 EMC Calibration

F. Porter
Mu2e EMC Calibration L3 Manager
4/19/16
DocDB 7141

EMC Calibration Team

Calorimeter experience from Crystal Ball, Mark II, BaBar, SuperB

BaBar source calibration system was Caltech responsibility

- Frank Porter (Caltech):
  - EMC Calibration L3 Manager
- Kevin Flood (Caltech):
  - Engineering physicist, source
- Jason Trevor (Caltech):
  - Engineer, source
- Bertrand Echenard (Caltech):
  - Simulation, source

- Pasha Murat (Fermilab):
  - Decays in orbit, pi^+ -> e nu
- Marco Cordelli (INFN-LNF)
  - Laser system
- Stefano Miscetti (INFN-LNF)
  - Laser system

Mu2e Calorimeter Organization

475.7
Calorimeter
L2 - S. Miscetti (LNF)
Deputy - D. Hitlin (Caltech)

475.7.1 Project Management
L3 – S. Miscetti – (LNF)
CAM – D. Hitlin (Caltech)

475.7.2 Crystals
L3 – D. Hitlin (Caltech)
S. Giovannella (LNF)
CAM - D. Hitlin

475.7.3 Mechanics
L3 – F. Happacher (LNF),
F. Raffaelli (Pisa)
CAM – D. Hitlin

475.7.4 Photosensors
L3 – D. Hitlin (Caltech)
I. Sarra (LNF)
CAM – D. Hitlin

475.7.5 Digitizer
L3 – F. Spinella (Pisa)
CAM – D. Hitlin (Caltech)

475.7.6 Calibration
L3 – F. Porter (Caltech)
M, Cordelli (LNF)
CAM – D. Hitlin (Caltech)

475.7.7 Frontend Electronics and Power
L3 – G. Corradi (LNF)
CAM – D. Hitlin (Caltech)

475.7.8 Assembly and Installation
L3 – A. Saputi (LNF)
CAM – D. Hitlin (Caltech)

Scope 475.7.6 - Calorimeter calibration

This task contains all aspects needed to build an operative calibration system both with the radioactive source for the determination of the absolute scale and with the laser system for a monitor of the photo-sensor gains. The laser system will be provided by INFN as in-kind contribution.

Requirements

The EMC requirements are described in docdb-864

R1) Online calibration sufficient for calorimeter trigger, online diagnostics

(R2) Precision commensurate with calorimeter resolution requirement of FWHM/2.35 ~ 5% at 100 MeV

(R3) Absolute precision and stability better than 1%

(R4) Independent calibration of each crystal

(R5) Track time dependence

(R6) Perform (source) calibration of entire calorimeter in ~10 minutes

(R7) Timing resolution better than 0.5 ns (driven by PID)

(R8) Position resolution < 1 cm

Design choice for calorimeter calibration

- Unchanged since CD-2 (2014) except for adjustments for change from BaF2 to CsI
  - Laser frequency changed from UV to blue/green

Our solution to calorimeter calibration requirements

- Pre-insertion calibration with 6 MeV source
- Weekly crystal-by-crystal calibration with 6 MeV source
- Monitor readout on shorter time scale with LASER pulsing system
- Higher energy with DIOs (Decays In Orbit)
  - Interpolation and extrapolation with source
  - Tracker can be used, low field for outer crystals
  - Absolute spectrum (at lower fields)
  - Check of MC extrapolation
- Cosmic rays as independent check
- $\pi^+ \rightarrow e^+ \nu_e$ as optional independent check (70 MeV e+)
- Monitor electronics gains with pulser
- Monitor temperatures

6 MeV Source

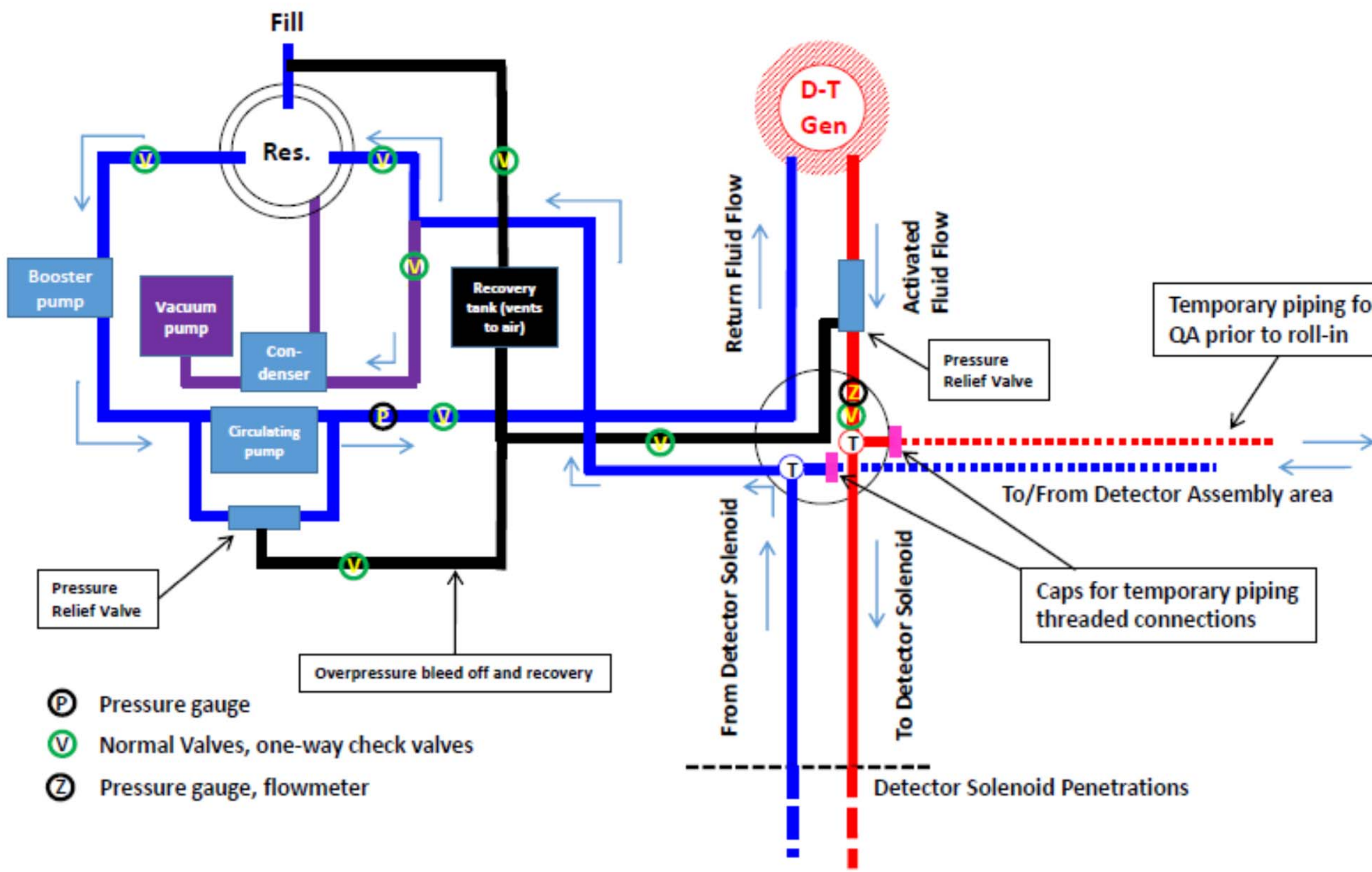
6 MeV source calibration

Reaction yielding 6.13 MeV photons is:

$$^{19}F + n \rightarrow \; ^{16}N + \alpha$$
$$^{16}N \rightarrow \; ^{16}O^{*} + \beta \quad t_{1/2} = 7 \text{ s}$$
$$^{16}O^{*} \rightarrow \; ^{16}O + \gamma(6.13 \text{ MeV})$$

- Low energy neutrons from a DT generator irradiate Fluorinert™ fluid outside detector
- Activated liquid pumped through pipes to front faces of crystals
- DT neutron generator d+t -> n(14.2 MeV): 10^9 n/s (ING-07)

Source plumbing schematic

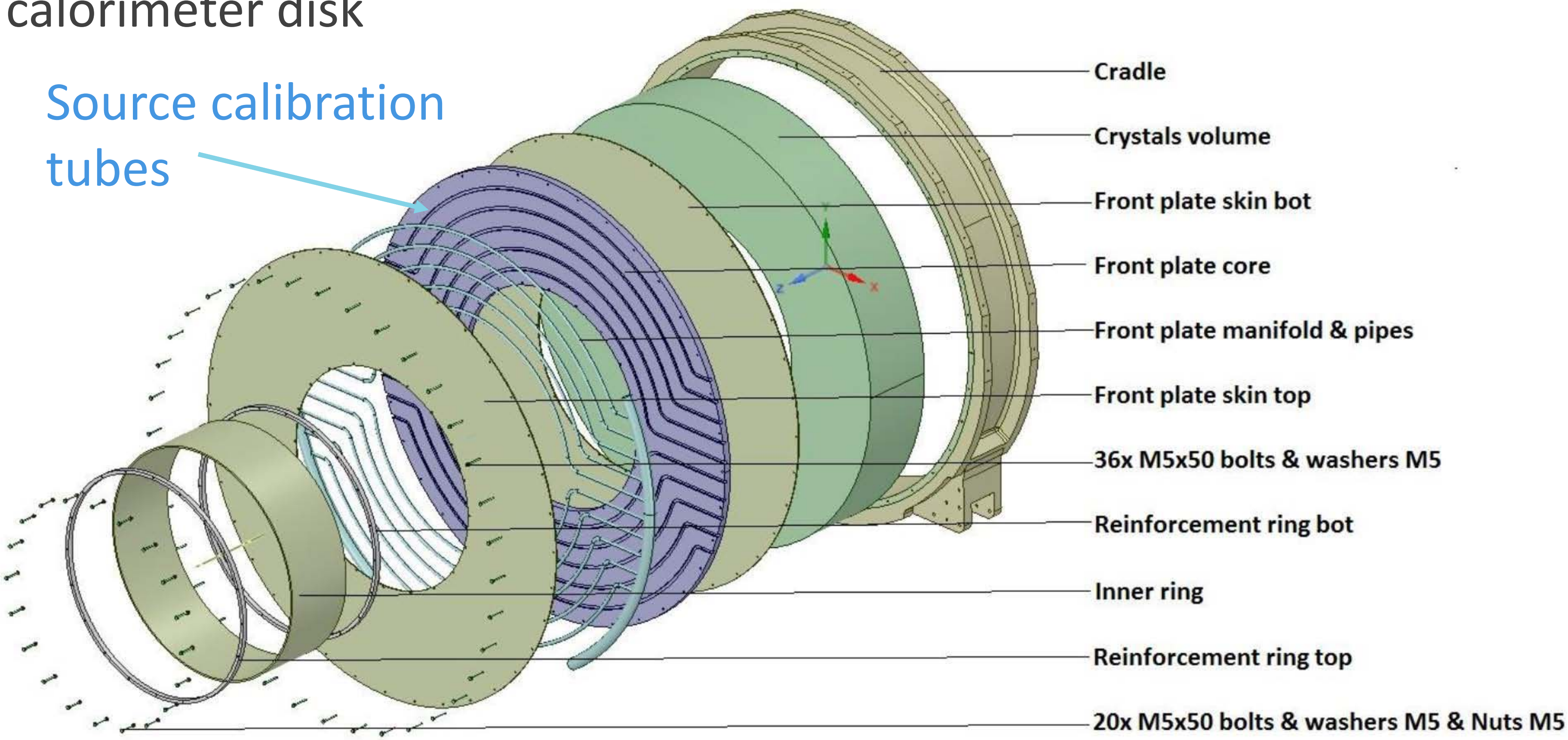


Source location on detector

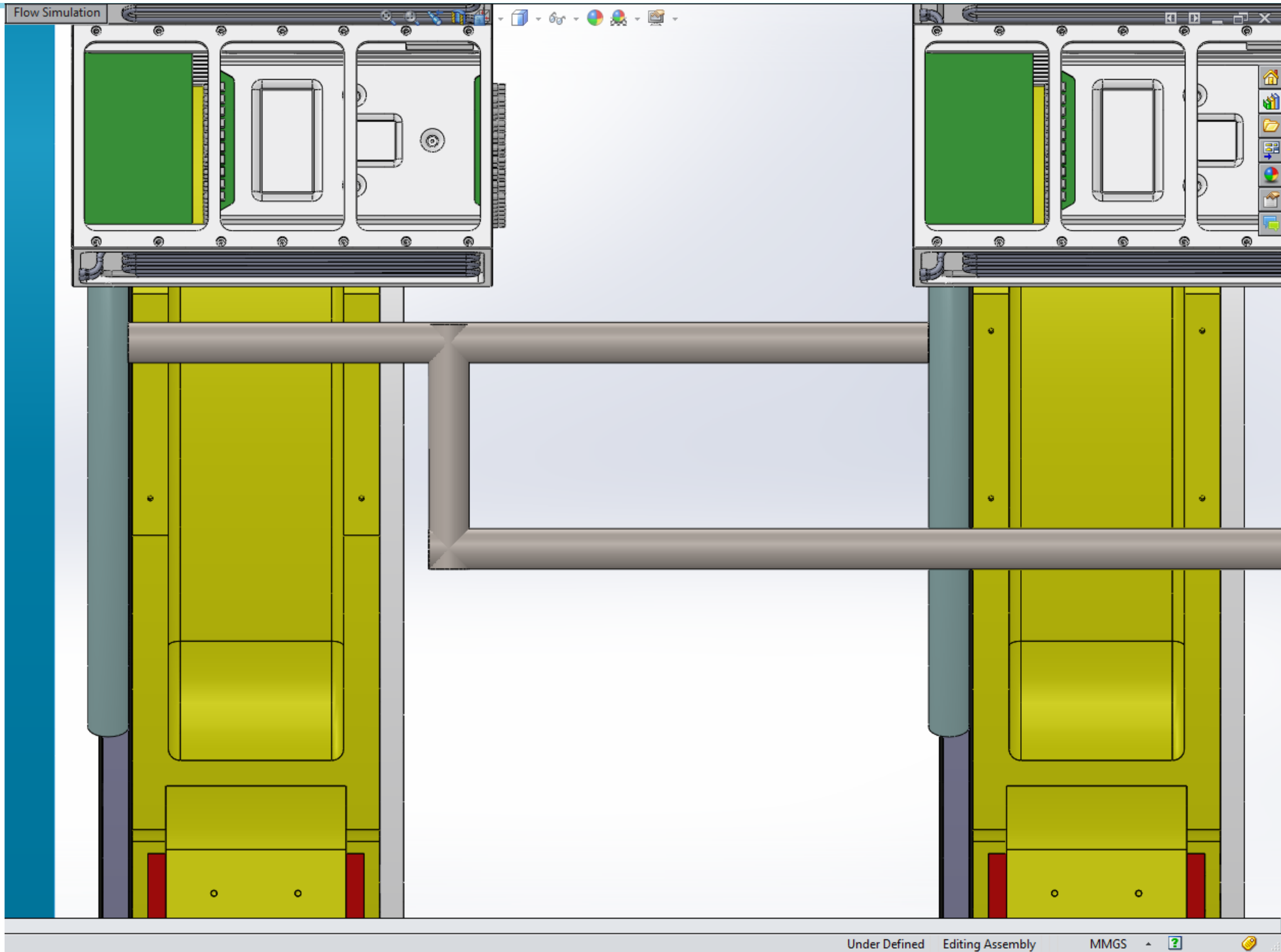
Exploded view of calorimeter disk

Milled Rohacell foam embeds tubes

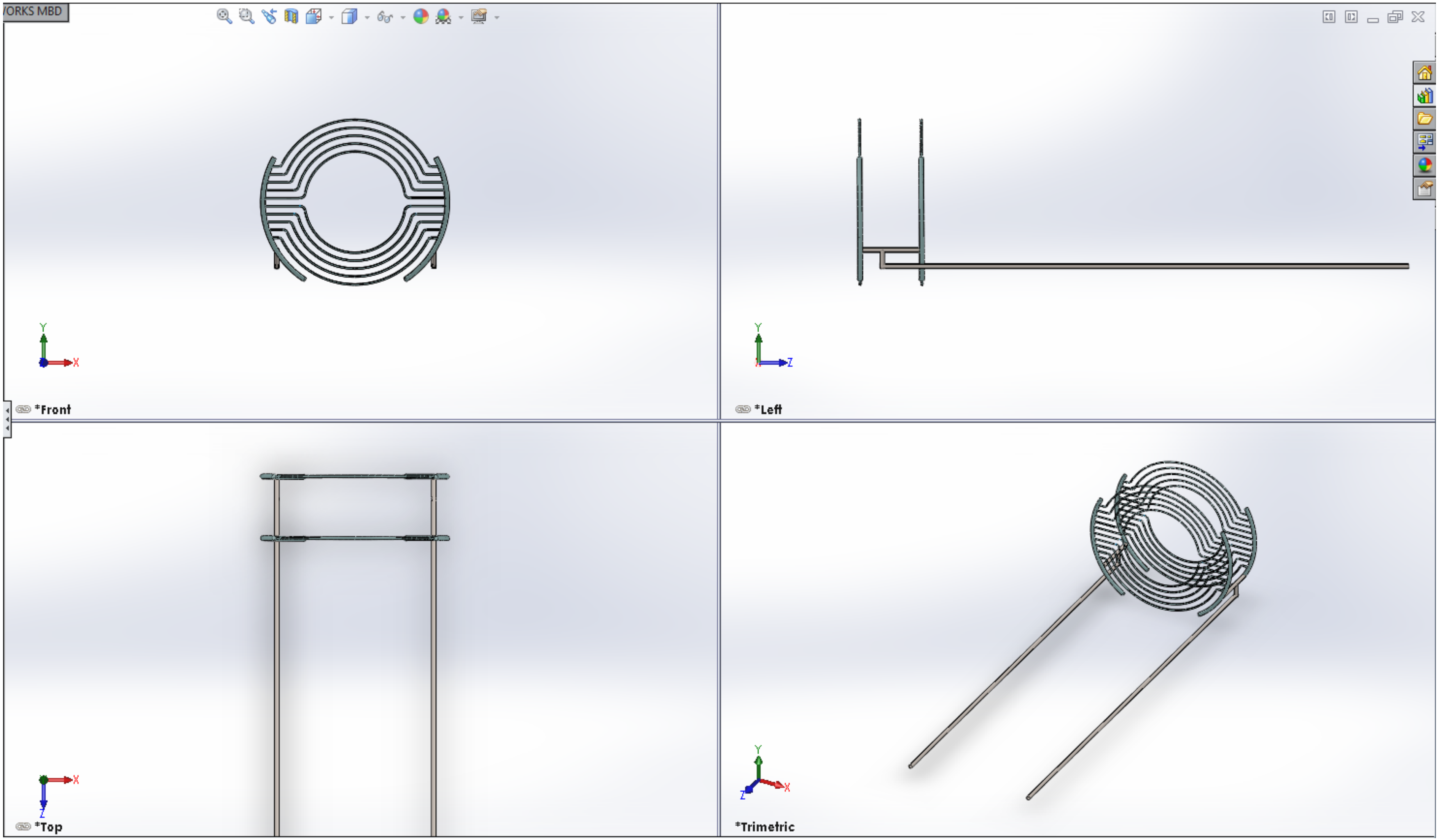
Source calibration tubes



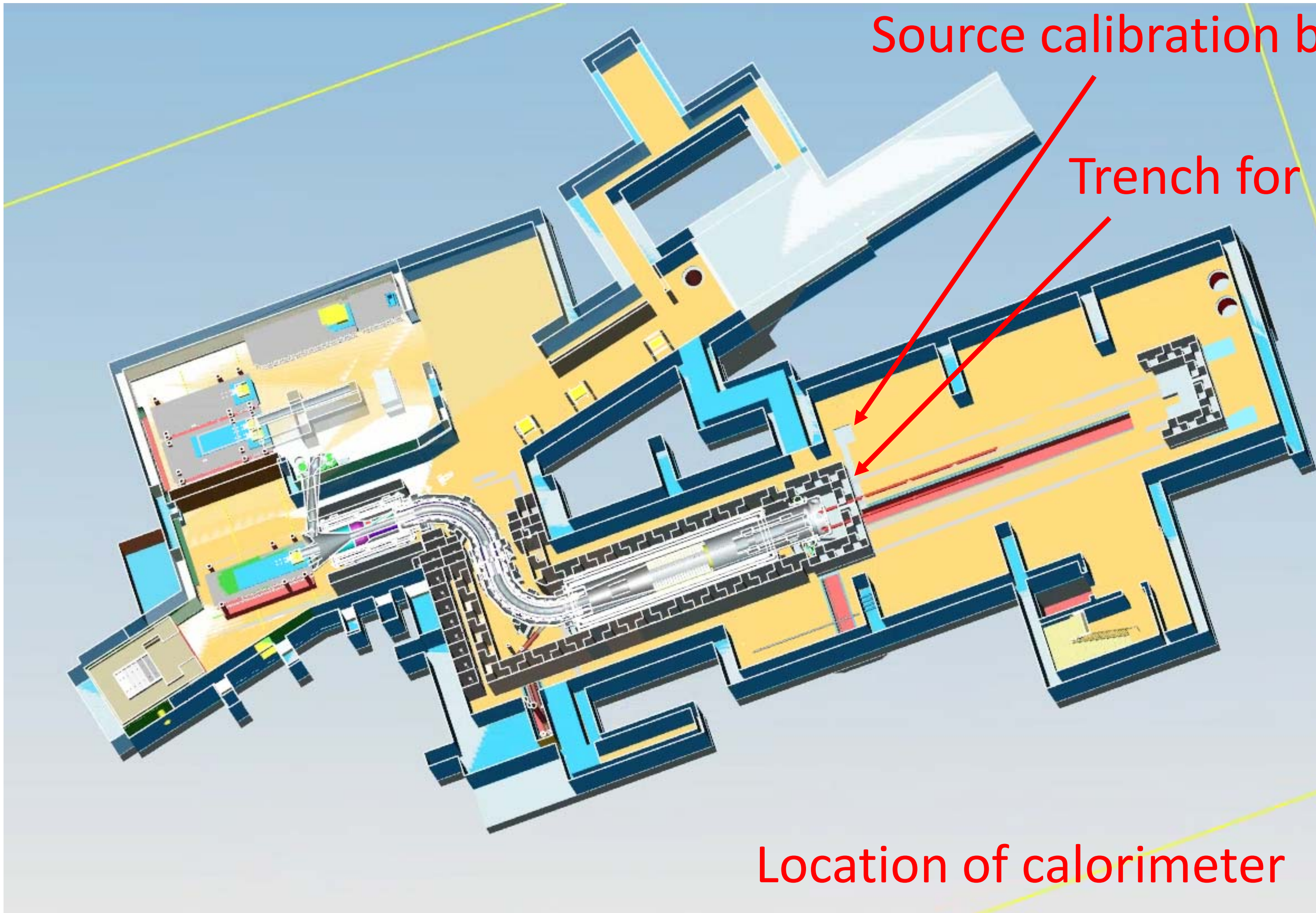
Plumbing detail between disks



On detector source plumbing

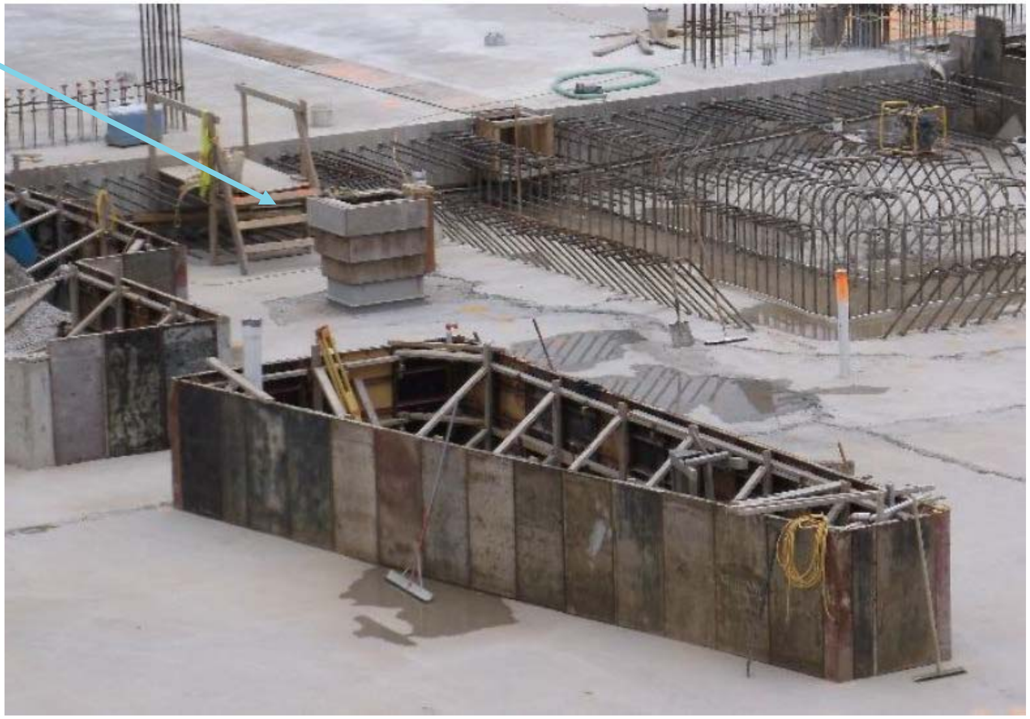


Detector hall plan



Source bunker

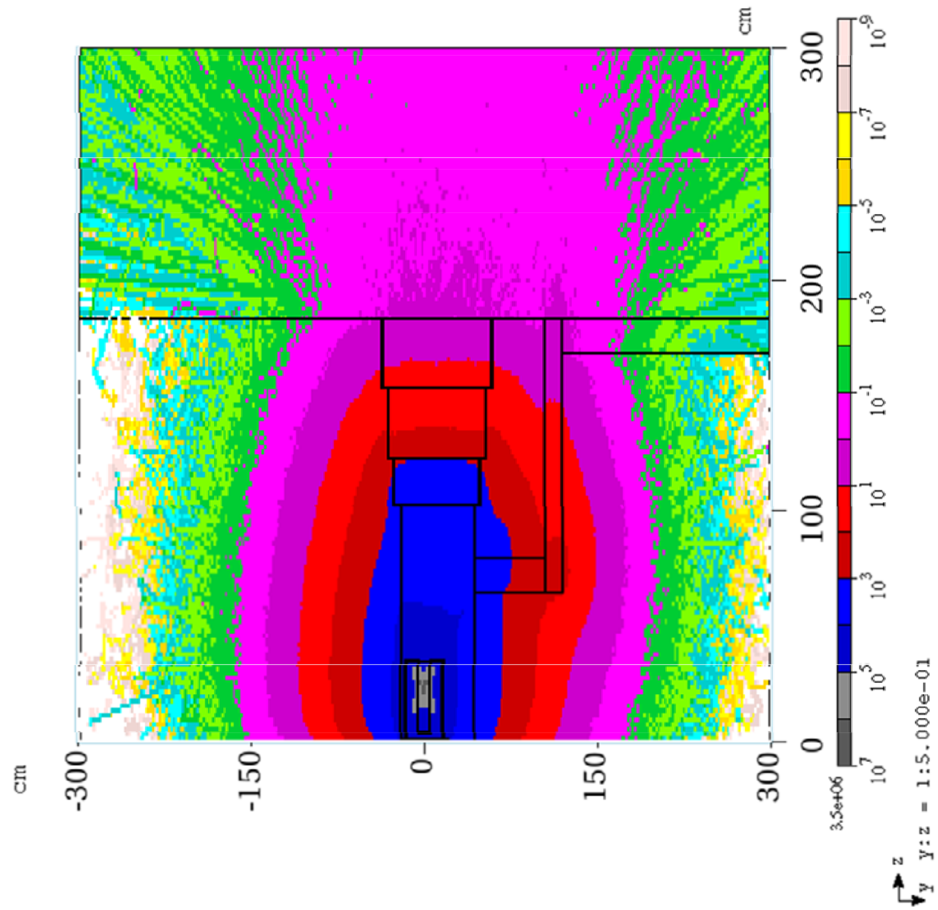
Outside view of the DT generator bunker

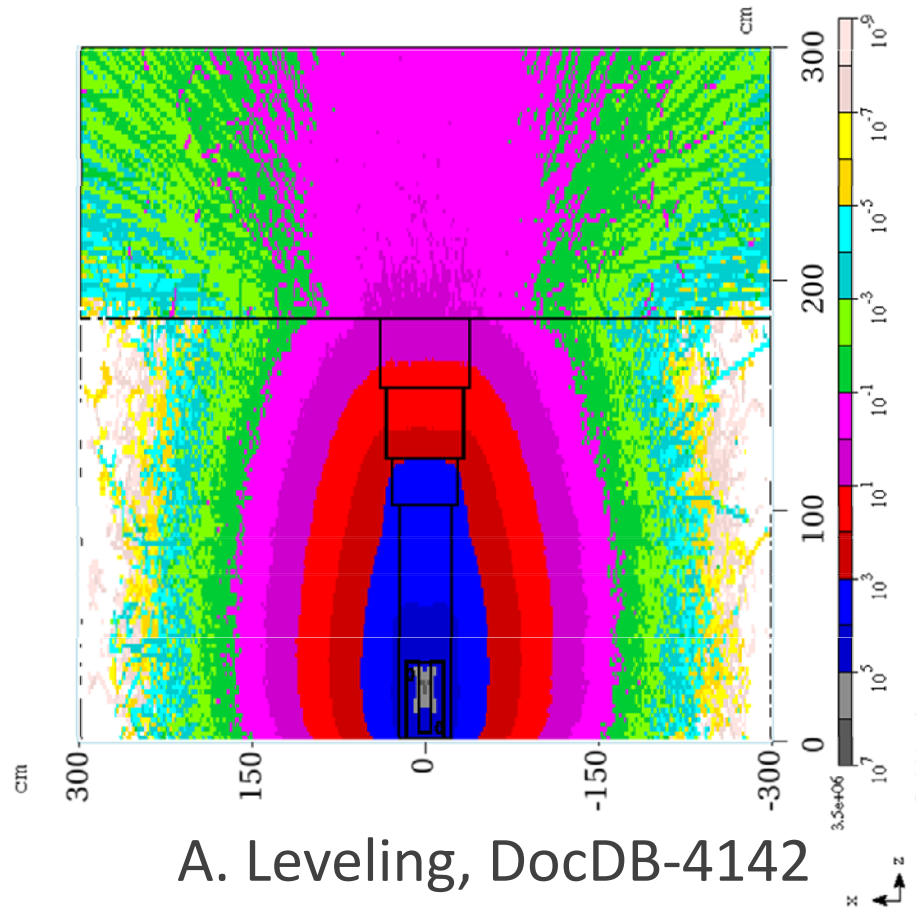


Performance - MARS simulation of source bunker

Total effective dose rate
millirem/hr-1E9n/s

- Shielding acceptable
- Total effective dose rate < 5 mrem/hr





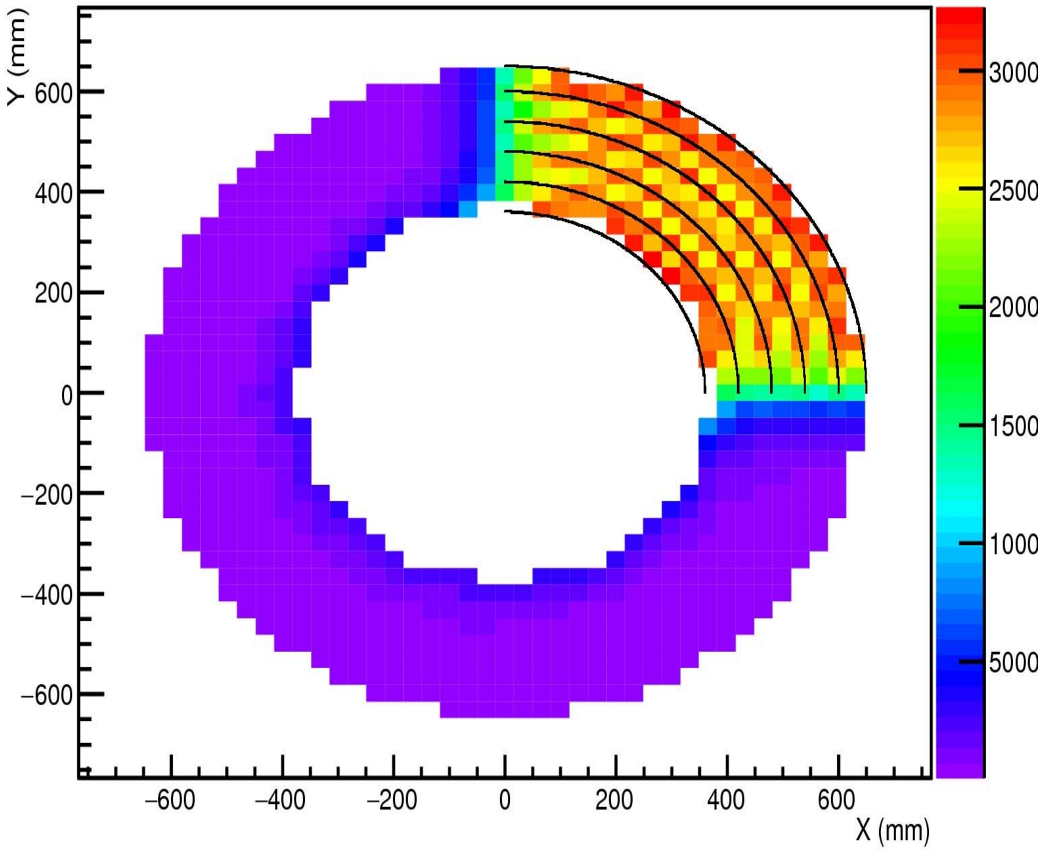
A. Leveling, DocDB-4142

Performance - Source calibration simulation

GEANT simulation includes crystal non-uniformity, photo-statistics (30 pe/SiPM), and electronic noise (100 keV/SiPM)

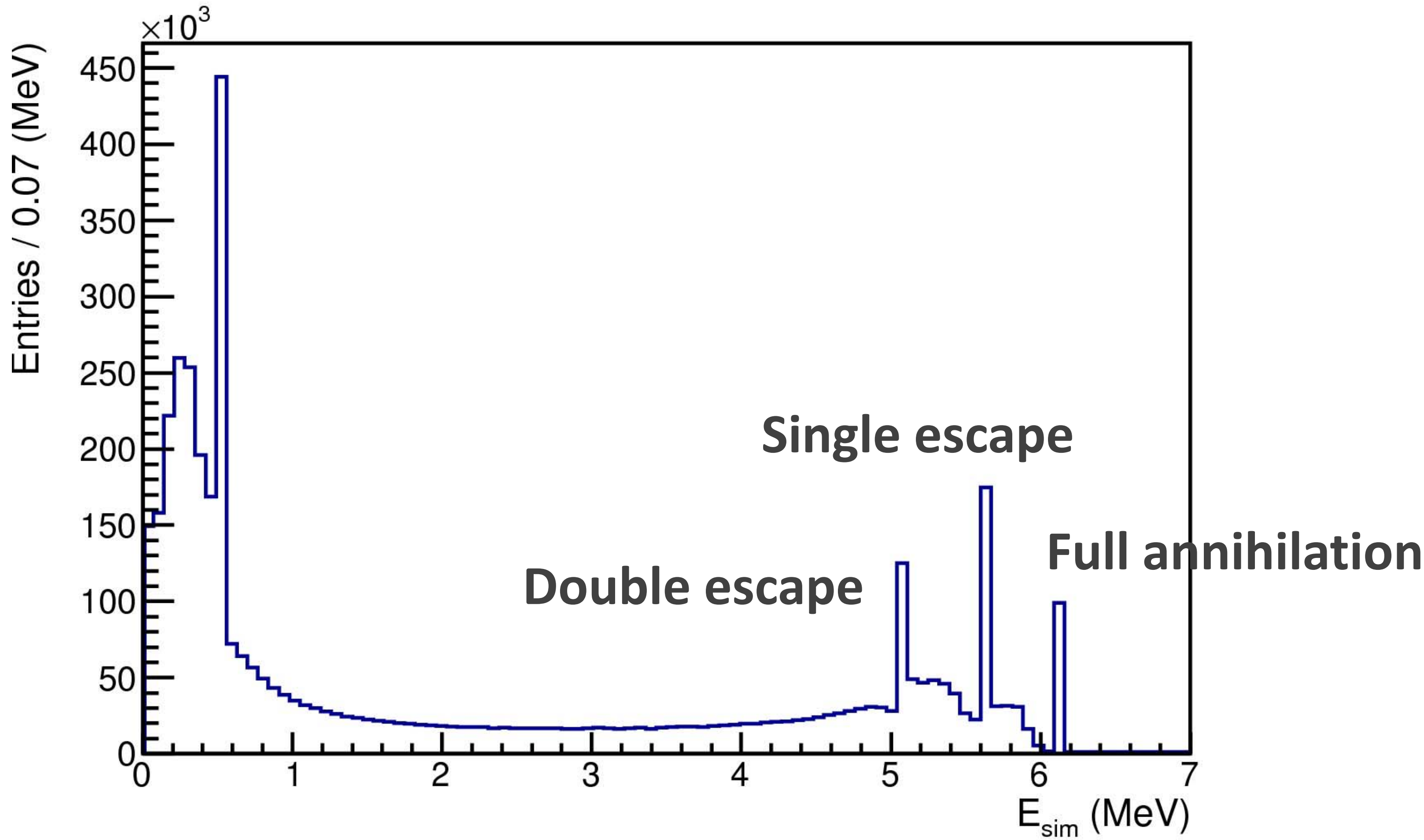
Location of generated photons

Reconstructed level, E > 4 MeV



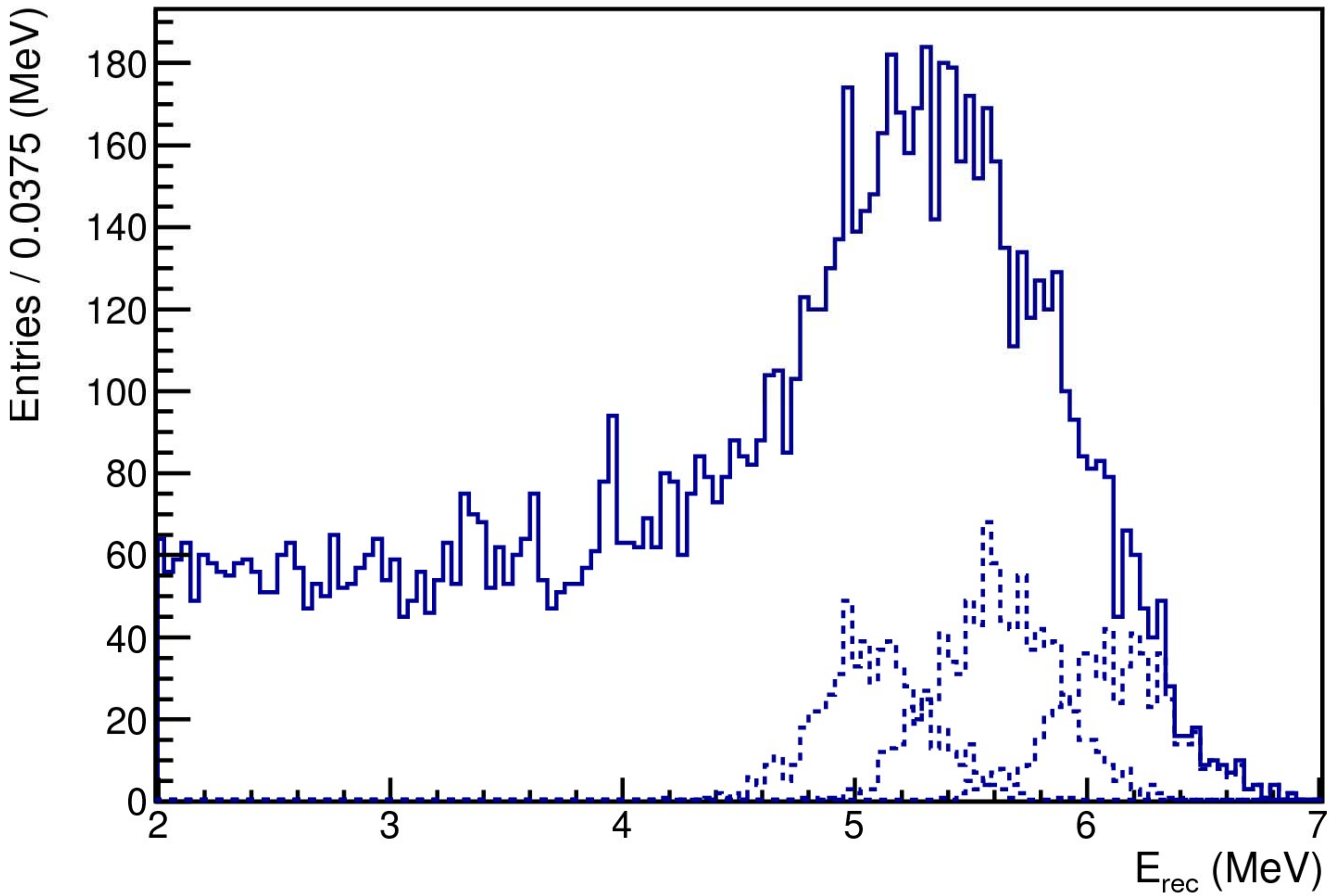
Tiny points = generated location of center of pipes, very fine binning

Energy of each crystal hit at the generator level



Full annihilation, single and double escape peaks + Compton

Spectrum corresponding to 10,000 calibration photons



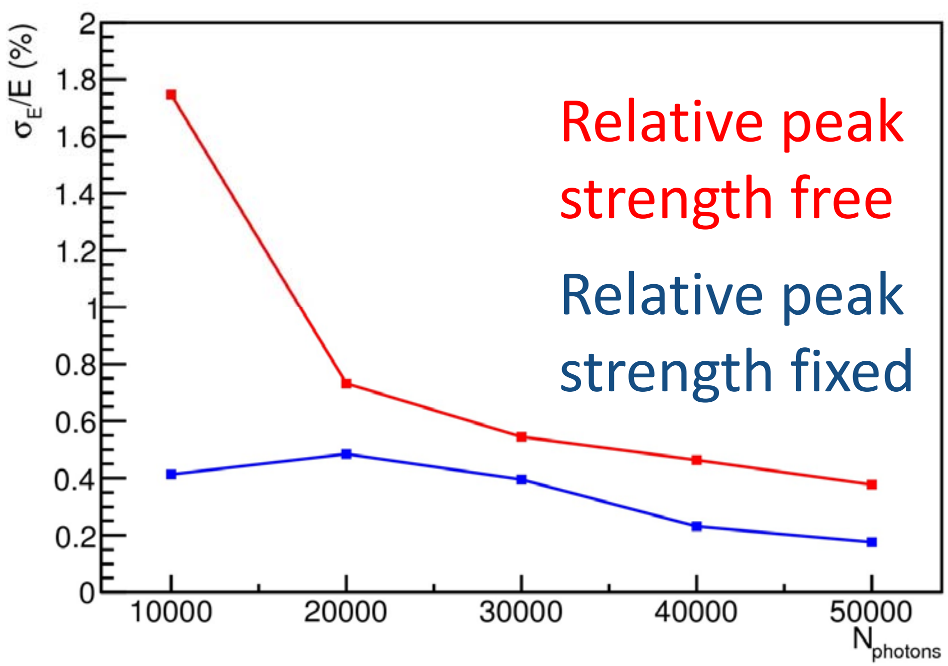
Performance - Source calibration simulation results

Source rate is ~10,000 entries/crystal/10 min

Precision (%) to have
10% effect on resolution

Resolution (%)	Calibration precision (%)
3	1.4
4	1.8
5	2.3

Precision (%)



Prototype source system at Caltech

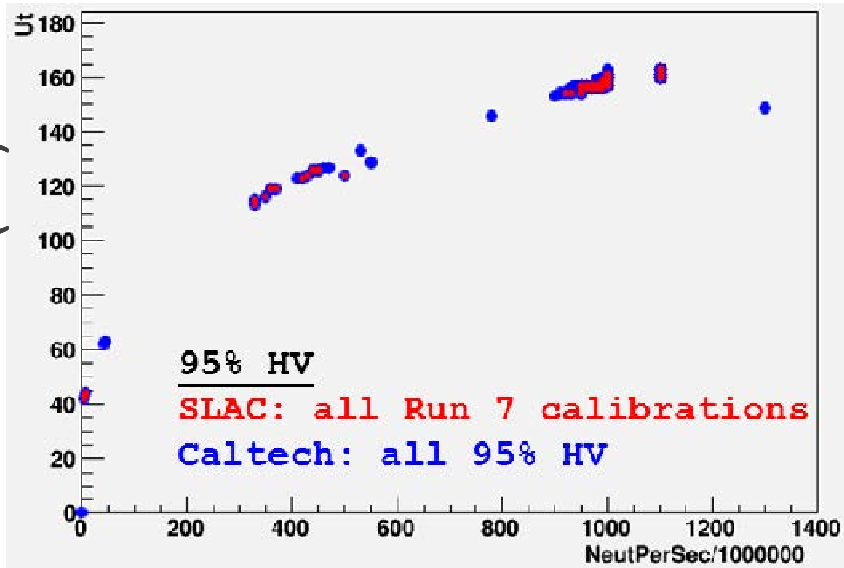
We have constructed and tested a prototype apparatus for the source calibration system at Caltech

- Uses salvaged components from BaBar at SLAC, including DT generator
- New generator bath, which will be used in final system
- Refurbished pump, to be used in final system
- Purchased FC-770 Fluorinert, to be used in final system
- Scavenged lead and paraffin for bunker, purchased some additional material

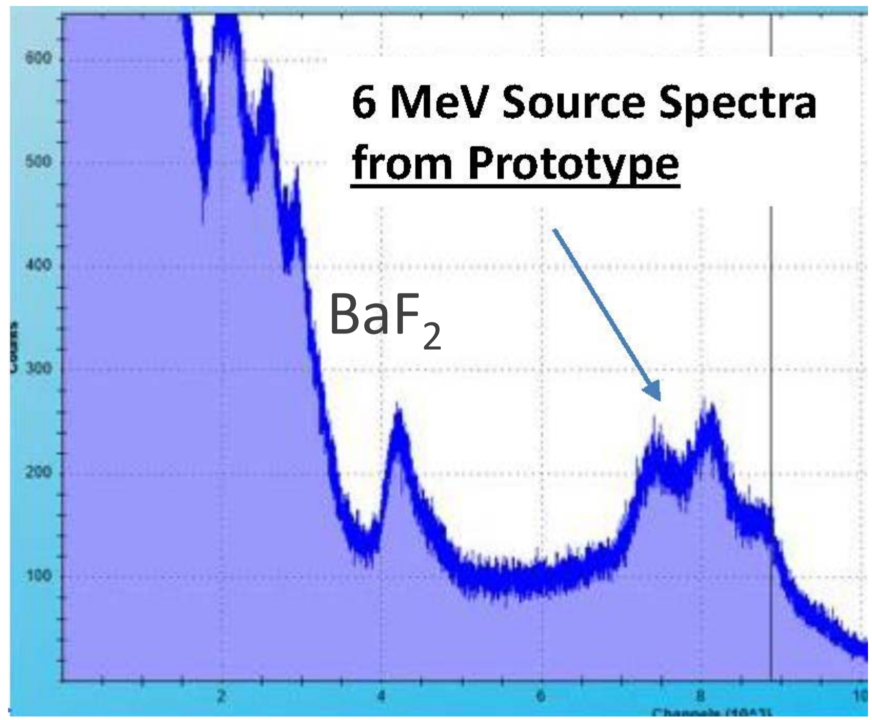
Prototype source system at Caltech

DT generator performance and source test

HV (kV)



n/s (10^6)



LASER System

Laser System requirements

- To keep the timing and energy resolution required we need also a continuous monitoring of the detector gain and of the timing offsets.
- ENERGY: While absolute energy scale will be provided by weekly calibration with the source, a control of faster gain changes (due to irradiation, increase of leakage current or temperature variation) will be performed to keep the detector equalization constant. Since we expect slow variation trends, the **relative gain change, at 0.5 % accuracy, can be tracked each hour.**
- TIMING: Similarly the determination of channel by channel timing offsets, T_0, and pulse height dependence, slewing, has to be determined to compensate for small differences on cable lengths, transit times of SIPM response or electronics delays/jitters. **Timing calibration to be kept below few tens of ps.** Final calibration of the timing scale between calorimeter and tracker will be provided "in situ" by means of DIO electrons.

Laser System specifications

- Laser system to **have enough power to get light to all 1374** crystals by means of an optical distribution system and to a **monitoring system that tracks the variation of the Laser light at the source**. We are tuning this system to get a **laser signal with a pulse height equivalent to 100 MeV electrons, 3000 Npe.**

- **The laser has to emit on blue or green wavelengths** to be in a region far from the CsI emission peak (310 nm), to be in a region where transmittance changes due to irradiation are small. This isolates photosensor gain variation.

- **The Laser has to be pulsed with a settable frequency below 100 Hz** by means of an external trigger. During running the Laser will be pulsed at a rate of 0.1 Hz and will be synchronized to be in the "beam-off" region.

- **Laser output to be controlled in amplitude to allow a measurement of the response linearity** for the photosensors and FEE chain.

- **The monitoring system will be based on PIN diodes** in a thermally controlled box

Laser System Scheme

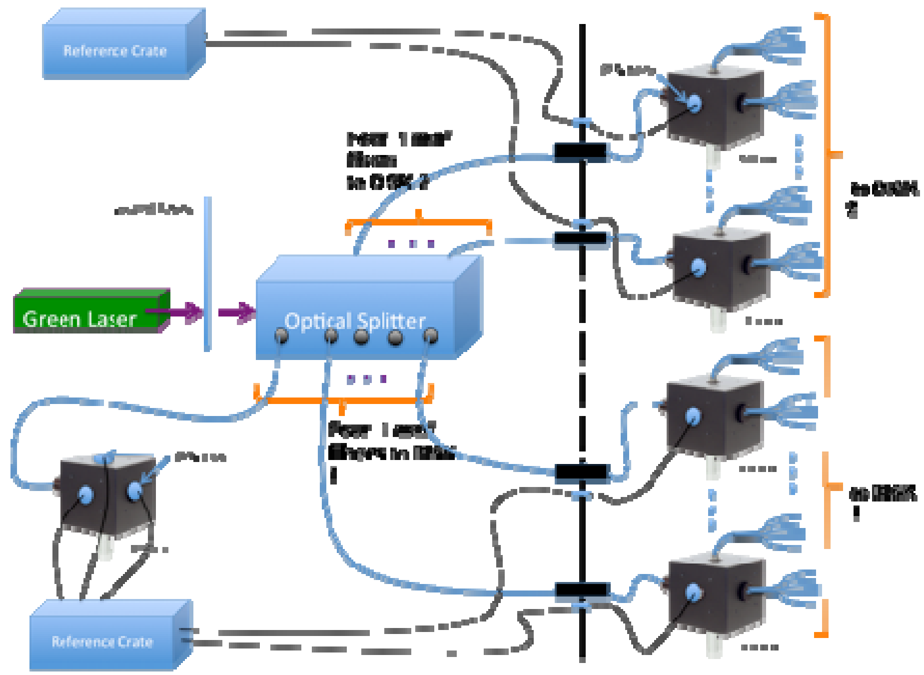
- ❑ The laser beam intensity is attenuated up to a factor of 10 by a graduated **neutral density filter**

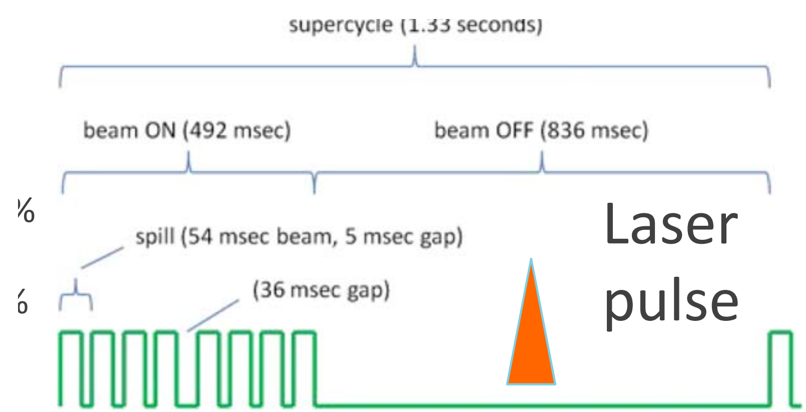
- ❑ The beam will be split, by means of semi transparent mirrors to 8 beams and focused by optical lens to 1 mm diameter Fused Silica fibers. 1/3 of the light will be sent to a 2” diffusing sphere with 3 pin-diodes for monitoring.

- ❑ Eight 60 m long fibers, routed from the counting room to the DS bulkhead brings the light to 8 2” diffusing spheres on the mechanical structure

- ❑ Each sphere, will have 1 pin diode for monitor and 3 bundles of 200 μm silica fibers. Each fiber will be inserted into a lodging in the back of the crystals close to the SIPM holders.

- ❑ Laser Trigger will be synchronized with the DAQ Clock signals and delayed into the beam-off region.





'igure 11.1. Mu2e Beam Structure.

Laser Model specifications

LaserHead+Laser
Controller Box
Diode Pumped Nd:Yag
Solid-State **Micro Laser**

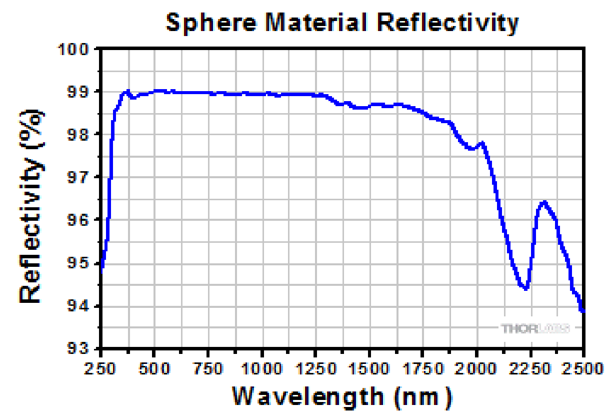
Table of Typical Micro Laser Models

Models	STA-01SH-1	STA-01SH-2	STA-01SH-3	STA-01SH-4	STA-01SH-5
Wavelength, nm			532		
Average output power (max), mW	40	25	50	20	100
Pulse energy, µJ	4	5	50	0.2	100
Pulse width (FWHM), ns	0.5	< 0.7	0.5	0.5	0.5
Repetition rate (max), kHz	10	5	1	100	1
Beam Profile			$M^2 < 1.1$		
Pulse spectral structure			single longitudinal mode		
Polarization ratio			> 100:1		
Beam Waist diameter inside the laser head $1/e^2$, µm*			25-200		
Pulse spectrum FWHM, pm			< 5 (near transform limited)		
Pulse to pulse energy stability RMS			< 0.5		
Power stability over six hours**			< ± 1,5%		
External power supply voltage, V AC			100-240		
Operating temperature, °C			15 - 40		
Interfaces			USB, External trigger (TTL rising edge) 1HZ...max repetition rate		
Laser head dimensions:					
diameter, mm			25		
length, mm			76.5		

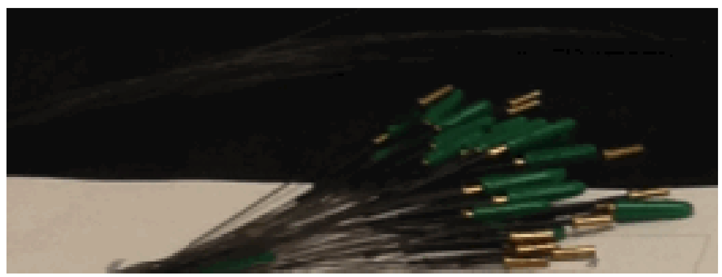
- ❑ Available @ different emission wavelengths → similar product also @ 355 nm.
- ❑ It is a good match between very high pulse-energy, good power stability, repetition rate and command from an external trigger. It has been used for the prototype phase.
- ❑ 5 µJ pulse → equivalent to 10^{13} photons produced at the source.
- ❑ Distribution losses are large but light output is more than enough for our purposes.

Light distribution system

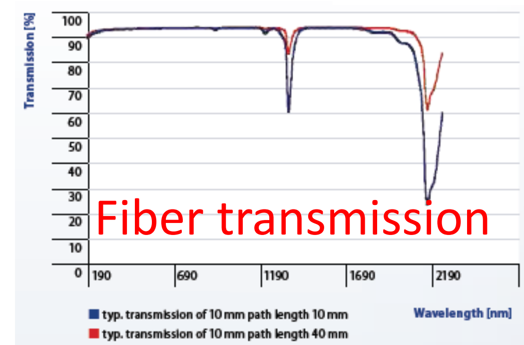
ThorLab-IS200 Sphere
- 1 input, 4 output ports
- PIN-diode ThorLab-SM05PD1A
- 3 Bundle of fibers with SMA connector in the port and final ferrule on each fiber.



- ✓ Loutput/μJ $=2\times10^{12}$
- ✓ T(filter+optical) = 10^{-3}
- ✓ Tfiber = 7×10^{-5}
- ✓ Ttotal = 7×10^{-8}



- ✓ LY = 10^5 Nphotons/pulse
- ✓ LY (NPE) = LY x QE = 3×10^4

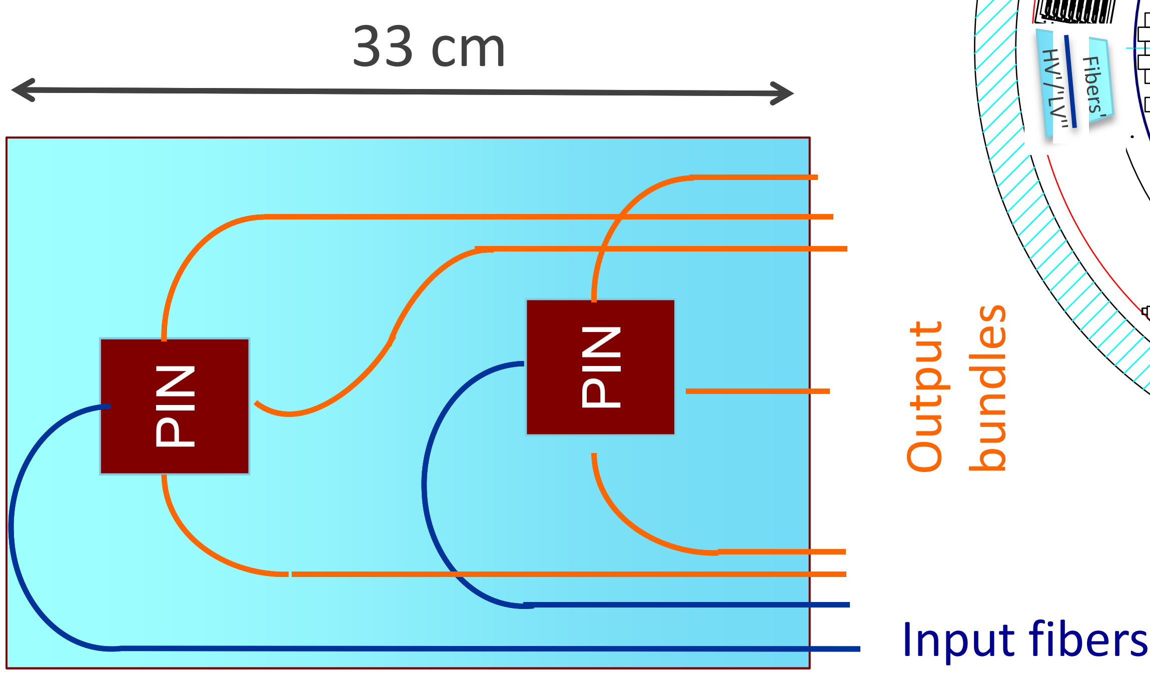


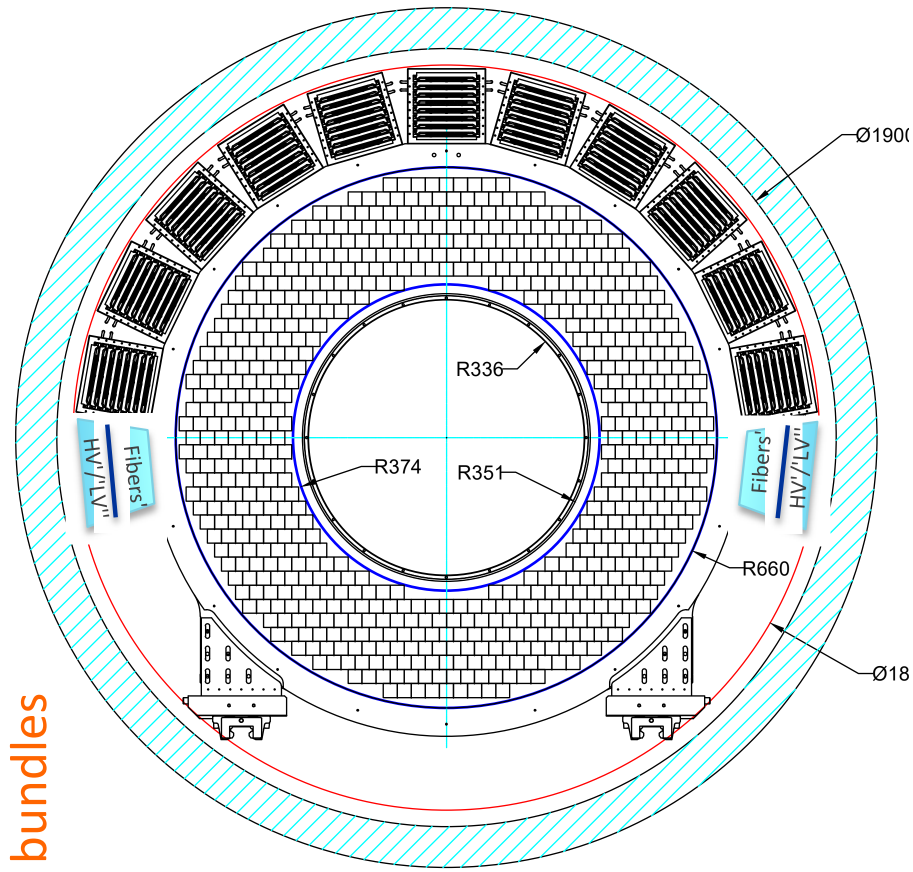
- Fused silica fibers have good transmission for the wavelengths under consideration (from 355 to 500 nm), high reliability and radiation hard for Mu2e.
- **We have tested them up to 90 krad and 10^{12} n/cm^2 seeing no deterioration.**

Fiber routing

After last round of optimization, the number of channels is frozen and we are completing the cable routing for the fibers:

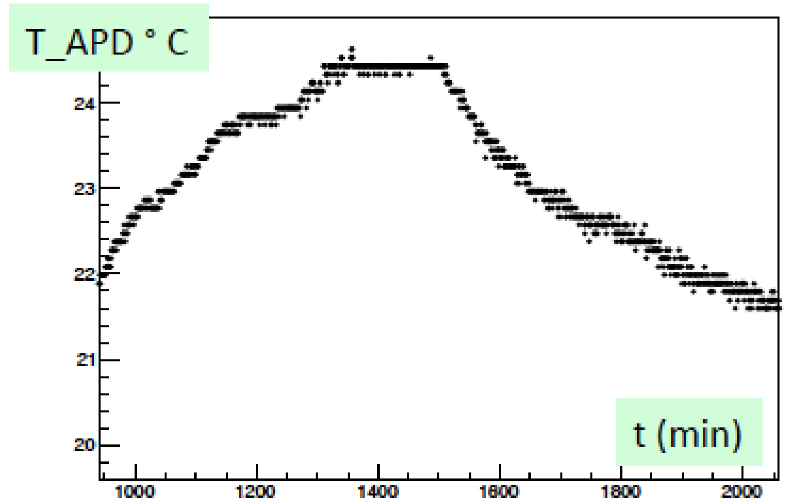
- 2 HV/LV/Fiber Box will be located at $\pm$ 7° in ϕ.
- 1 serving the Top area, 1 serving the Bottom area
- Each sphere will have 1 input and 3 output fiber bundles (225 total), serving 170 crystals+ 1 PIN Diode

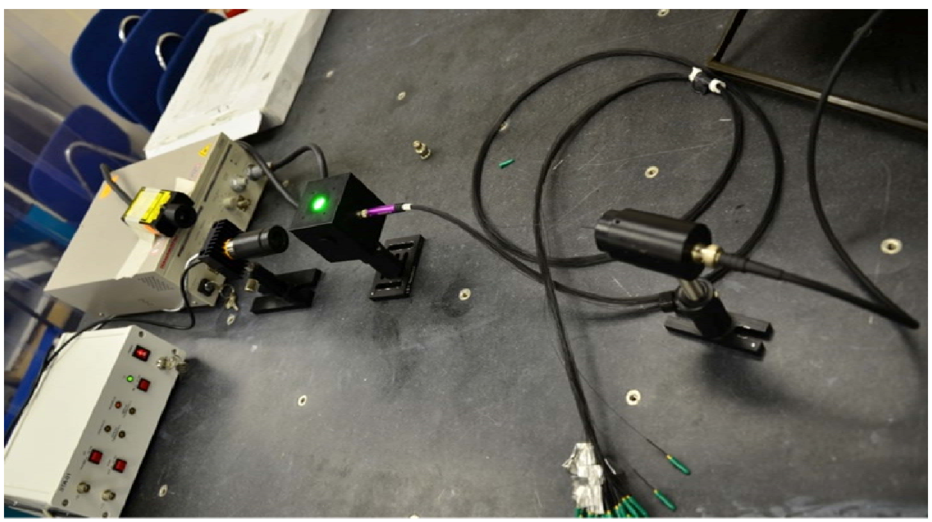


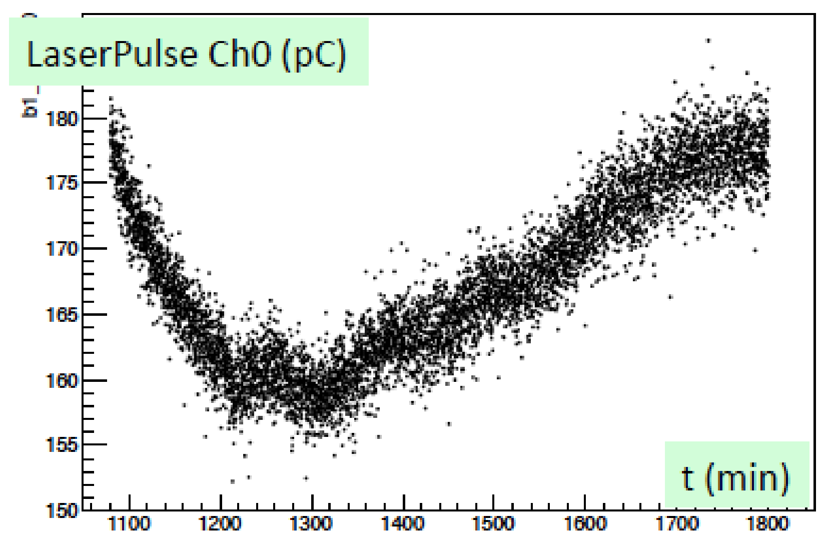


Performance – Laser System Prototype

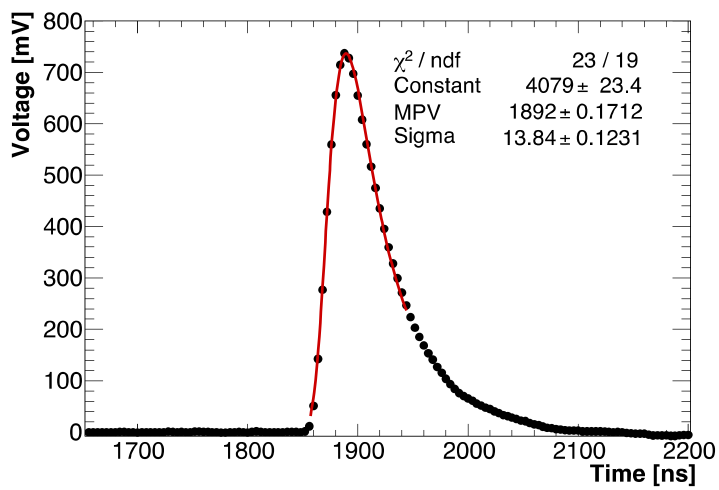
- A prototype of the laser system (below) was used to study, e.g., laser pulse stability.
- The plots (right) show the anti-correlation between temperature and APD gain, as well as the ~5% pulse-to-pulse variation.







Prototype system performance @ LYSO test beam for timing



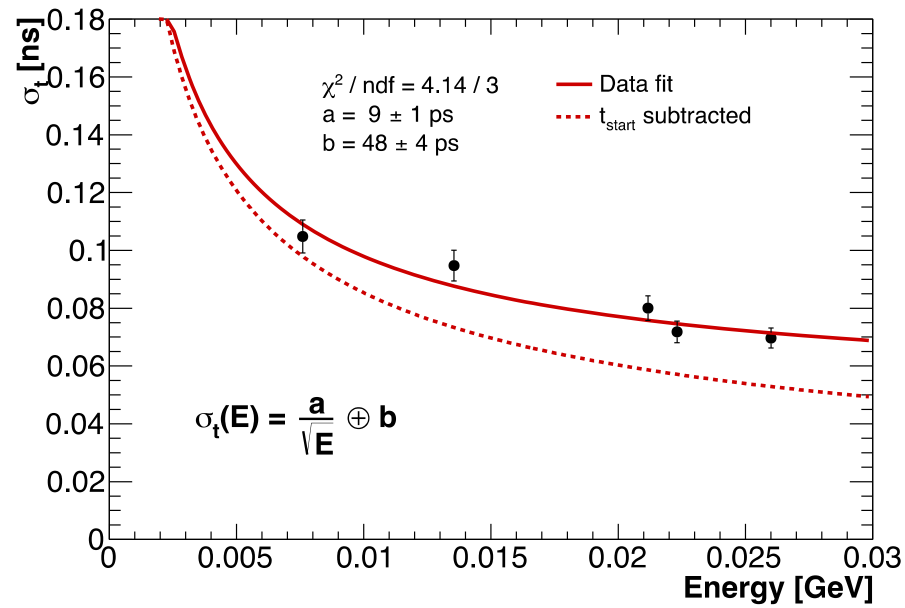


Figure 13: Time resolution for laser signals as a function of the equivalent deposited energy.

Performance Summary

- Calibration source system functional
  - Demonstrated feasibility and performance
  - Comfortable margins
  - Ready to proceed with final system
- Laser system meets specifications
  - Ample margin in both yield and timing
  - Ready to proceed with final system

Design Maturity

Calorimeter Subsystem	Design Completion	Remaining Work/Risks
Crystals	90%	Specification of CsI slow component - Low risk.
Photosensors	85%	SiPM packaging. Have one packaged SiPM from Hamamatsu but want to qualify other vendors - Low risk.
Mechanical Infrastructure	65%	Finalize cooling design. Optimizing tradeoffs between noise, radiation damage and operating temperature. x2 headroom - Low Risk
Front End Electronics	60%	• New pre-amp design for CsI/SiPM - Low Risk. • Front end board design with 20 channels. Moderate risk that we may have to back off to 18 channel boards. Adds a small amount of complexity.
Calibration	90%	Integration of source pipes. Finalize laser optics. – Low Risk
Overall Design	**80%**	

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Design Maturity and Path to Completion

- Working on integration of plumbing and installation in detector
- Finalize choice of laser
- Detailed integration of external source plumbing and controls

Fabrication Plan

- Prototype source system exists at Caltech
  - Some components will be re-used in final system
  - Reservoir purchased from outside vendor (DT generator bath has already been procured during prototype fabrication)
  - FNAL-specific plumbing fabricated and inspected on site
- LASER system will be built at INFN

Quality

- Source calibration included Mu2e Quality Planning Document
  - Available on web page (docdb 7053)

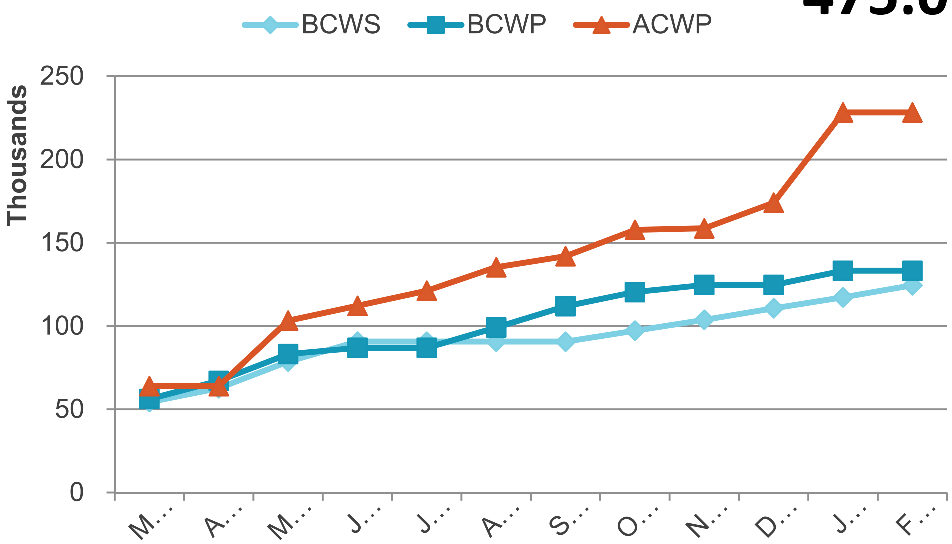
Deliverable	QA or QC Step?	QA or QC Process Documentation (DocDB #)	Inspection or Acceptance Criteria/Plan	Verification
Source vessels (reservoir and bath)	QC: Inspection and certification	DocDb 7053, 5868	Source vessels (reservoir and bath) inspected and certified with ASME code, 200 PSIG design pressure.	Vendor manufacturing standards
Source plumbing	QC: Inspection and certification	DocDb 7053, 5868	Welds inspected and certified according to ASME standrads.	Inspection by certified personnel
Source plumbing	QA: leak testing	DocDb 7053	After acceptance from inspection, system will be closed with detector in out position and pressure tested for leaks.	If leaks found, repairs made, and tests repeated until no further leaks.
DT generator	QA: neutron rate	DocDb 7053	At least 10^9 n/s averaged over 30 mins	Neutron rate to be measured upon receipt. After burn-in, generator will be run for 30 minutes at near maximum output and averaged rate measured.
Fluorinated fluid	QA: fluorine content	DocDb 7053, 5868	Must have F content comparable with FC-77	NMR, mass spectrometry evaluation of fluorine content

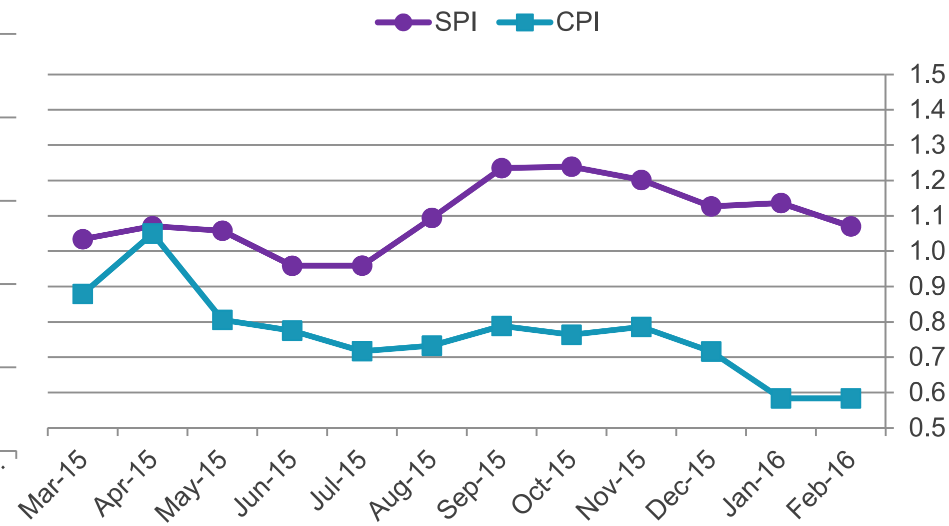
Quality Assurance/Quality Control

- Source vessels (reservoir and DT bath) inspected and certified with ASME code, 200 PSIG design pressure
- Welds inspected in accordance with ASME standards
- FC-770 Fluorinert (replacing FC-77 used in BaBar) has been tested with NMR and mass spectroscopy and determined to compare well in fluorine content with FC-77
- Prototype source calibration system will be further exercised at Caltech by developing calibration constants for crystal arrays, performance will be documented in database
- Italian prototype demonstrates good performance of the laser system and readouts

Cost and Schedule Performance

475.07.06 Calibration System





Performance

Mu2e Project																
February 29, 2016																
Currency in: $K	Current Period							Cumulative to Date								
Control Account, Work Package.CTC	**Budget**	Earned	Actuals	SV ($)	SV (%)	CV ($)	CV (%)	Budget	Earned	Actuals	SV ($)	SV (%)	CV ($)	CV (%)	SPI	CPI
475.07.06 Calibration System	7	0	0	(7)	-100%	0	0%	124	133	228	9	7%	(95)	-71%	1.07	0.58
475.394 475.07.06 Calibration System Design (PED)	7	0	0	(7)	-100%	0	0%	124	133	228	9	7%	(95)	-71%	1.07	0.58
475.395 475.07.06 Calibration System (Line Item: Construction)	0	0	0	0	0%	0	0%	0	0	0	0	0%	0	0%	-	-

Control Account, Work Package.CTC	BAC	EAC	VAC	% Spent	% Complete
475.07.06 Calibration System	567	695	(128)	33%	23%
475.394 475.07.06 Calibration System Design (PED)	230	358	(127)	64%	58%
475.395 475.07.06 Calibration System (Line Item: Construction)	337	338	(1)	0%	0%

Change Control

Control Account	CR #	CR Description	Prior Start	Revised Start	Prior Finish	Revised Finish	BAC Before	BAC After	Cost Increase /(Decrease)
475.07.06	2	Establish internal baseline and incorporate recommendations from Director's Review.	-	-	-	-	763,192.99	716,993.48	(46,199.50)
	3	New rate adjustments for labor fringe and overhead.	-	-	-	-	716,993.48	720,276.41	3,282.93
	4	Cost leveling; new CD-3c strategy	-	-	-	-	720,276.41	717,720.49	(2,555.92)
	8	FY15 Rate changes	-	-	-	-	717,720.49	717,549.22	(171.28)
	15	Establish CD-2 Baseline	11/23/2011	11/23/2011	8/6/2018	8/6/2018	717,549.22	566,980.60	(150,568.61)
	24	FY16 Rate Update	11/23/2011	11/23/2011	8/6/2018	8/6/2018	566,980.60	567,466.24	485.64
475.07.06 Total							4,202,713.19	4,006,986.45	(195,726.75)

Interfaces - internal

Item	Interface	Description	Owner	Reference Documents/ Drawings
107.03.1.3	Mechanics/Calibration Source	The calibration system will consist of a Fluorinert fluid which can be activated by means of a Deuterium-Tritium generator outside the DS to yield 6.13 MeV photons. The activated liquid is then pumped through pipes inside the DS in the front calorimeter face. A tight interface with the mechanical support of the calorimeter is needed. The capability of moving the disks one relatively to the others has to be inserted in the design of the Fluorinert piping.	475.07.03 475.07.06	

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Interfaces - external

Item	Interface	Description	Owner	Reference Documents/ Drawings
107.06.2.1	Calorimeter source DT generator	The Calorimeter Source DT generator has to be shielded and piping has to be placed in the pit. IFB penetrations and routing inside the DS. Interface with the routing of the tracking cooling pipe.	475.07.06 475.03 475.05 475.06	
107.06.2.2	Laser System	The Laser system is placed in the TDAQ room. Distribution optical fibers have to be rooted to the DS and vacuum penetration provided in the DS bulkhead. Interface with the routing of the tracking cabling. Its trigger signal has to be synchronized with the Beam signal to be delayed to the beam-off period.	475.07.07 475.03 475.05 475.06 475.09	

Interfaces are understood and under control

Integration

- Integration
  - Attend weekly EMC meetings.
  - Extensive interaction with EMC mechanical engineers
- For other subsystems (when appropriate)
  - Attend bi-weekly Mechanical Integration meetings
  - Attend Beam Line meetings

Environment, Safety & Health

- Radiation (Mu2e HAR: DocDB 675)
  - The DT generator is a radiation-producing device that must be licensed and appropriately shielded for safe operation
  - Bunker design for generator installation at FNAL has been simulated using MARS, acceptable levels of radiation in accessible areas. Survey with fluid to be performed
  - We have California licensing for operation of the DT generator at Caltech, and radiation survey records
  - Light flasher laser will be appropriately enclosed
  - Residual activity of the fluid is suppressed by its 7 s half-life
- Electrical
  - DT generator operates at ~100 kV, standard HV precautions and interlocks will apply. Under keyed control
- Chemical
  - The source calibration working fluid is Fluorinert™ FC-770, will be protected from accidental release to the environment..

Major Milestones

47507.6.001110	CDR component complete	12/21/2011
47507.6.001331	Proto source system assembled in Caltech	10/5/2015
47507.6.001364	Design of final flasher system by INFN complete	4/27/2016
47507.6.001510	PO issued for materials for final source system (pumps and distribution)	8/4/2017
47507.6.001542	Source system assembled in the pit	8/6/2018
47507.6.001551	Flasher System received at Fermilab from INFN	5/24/2018

Summary

- Comprehensive plan for calorimeter calibration
  - Design meets EMC requirements
  - Provision for cross checks and diagnostics
- Prototype source system is functional, performing to specification
  - Will be used for initial crystal-by-crystal calibration
- Laser system design advanced, prototype tests well
  - Meets requirements
- The EMC calibration system is ready for CD-3 approval

Additional Material

Calorimeter design review recommendation 13

- Explore the potential of the use of pi+ decays for the calibration of the calorimeter (and the experiment).
  - $\pi^+ \rightarrow e^+ \nu_e$ decay provides monochromatic source of positrons with $E = m_\pi/2$ when the pion decays at rest in the stopping target
  - Absolute energy calibration. Status in docDB 5391.
    - Requires reconfiguring the beam line for positive particles (by rotating the TS collimator)
    - reducing the detector magnetic field so that the 70 MeV positrons reach the radius of the tracker and calorimeter
    - changing the timing window, reducing the beam intensity, and perhaps other things
  - A substantial perturbation; would not be a frequent calibration method

Calorimeter design review recommendation 13 (continued)

- Primary motivation to consider this is to provide precise absolute calibration for the tracker
  - Could provide a calibration point at 69.8 MeV, somewhat higher than a Michel edge calibration
  - If justified for the tracker, then also of value for the calorimeter, even though not justified for the calorimeter alone. No requirement that the calorimeter calibration be independent of the tracker, but could provide a sanity check in unexpected situations
  - Calorimeter can be calibrated to needed precision at low energy with the source system, at higher energies by comparing DIO energies with the tracker momentum. Michel edge could be used for the calorimeter as for the tracker, for an independent absolute calibration

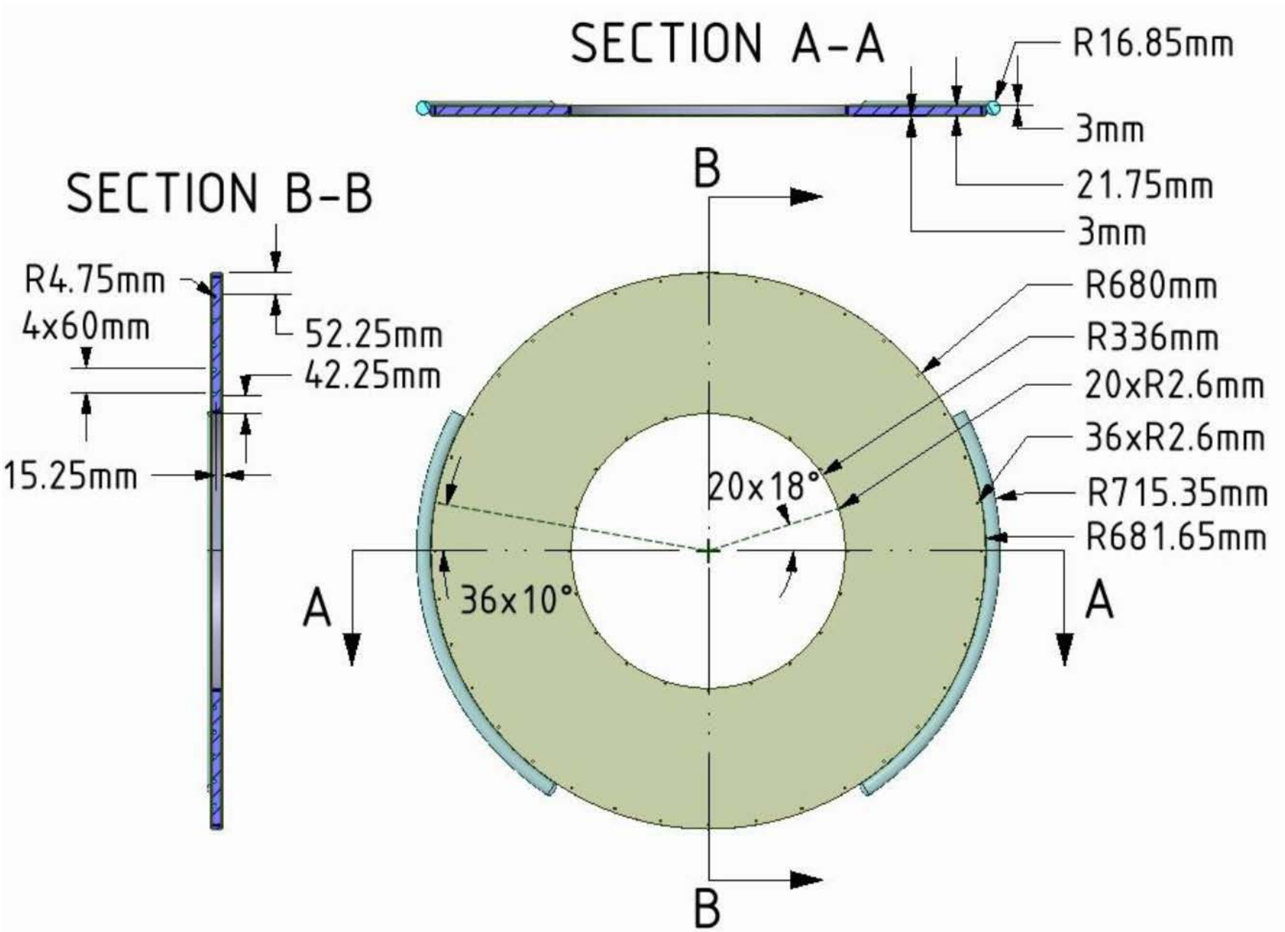
Calorimeter design review recommendation 13 (continued)

- Because the calorimeter is left-right symmetric, positrons should provide a valid calibration point
  - Need to extrapolate from 70% to full magnetic field (also for the tracker), studied in docDB 4550.
  - The 70% field requires a smaller extrapolation than the 50% field that would be used for a Michel-edge calibration. However, either extrapolation appears feasible

Calorimeter design review recommendation 13 (continued)

- Time required for pi^+ --> e nu calibration in the calorimeter
  - For a calibration of the global scale, time required is minor. For this purpose, rely on the crystal intercalibration determined from other means
  - For crystal-by-crystal calibration, need sufficient statistics of positrons hitting each crystal. Need ~100 events to calibrate a crystal to 1% at this energy, or ~200k events total. Estimated number of events in the pi+ --> e+ nu peak is 20k events/day (docDB 5998).
    - Thus, to accumulate sufficient statistics for the crystal-to-crystal calibration with pi+'s, translates into 10 days of data taking.

Structure of front plate, where source tubes reside

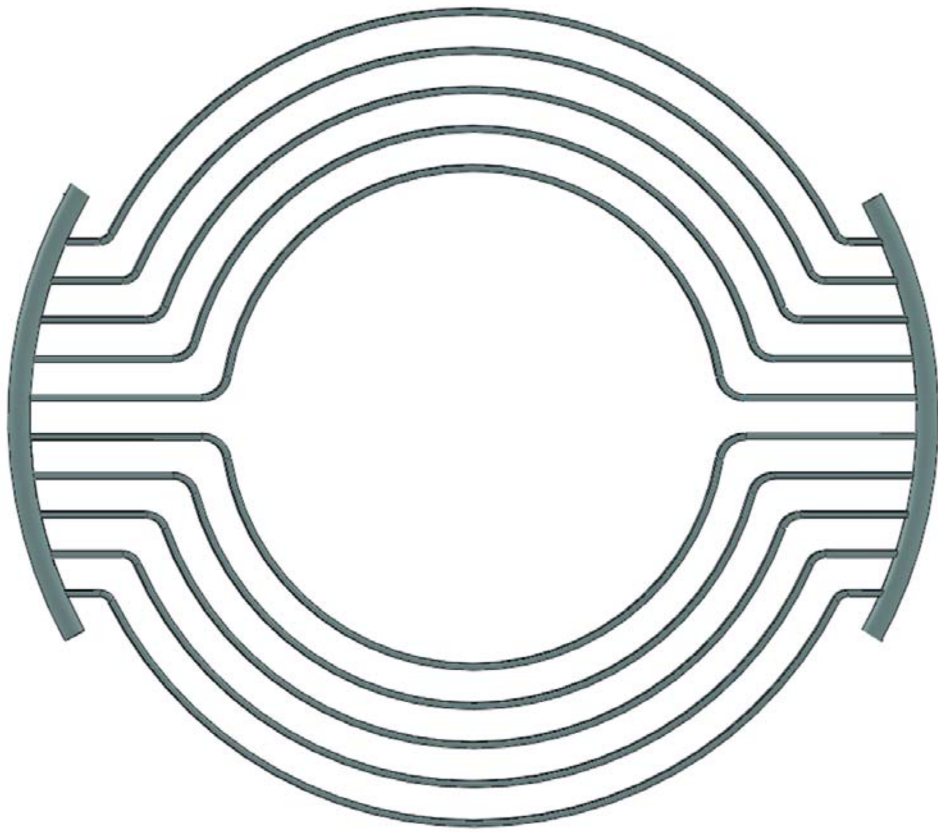


Front plate is a composite element with a sandwich structure. It is made up of a Rohacell foam core and two carbon's skins. The holes in Front plate (Φ=5,2 mm) will be obtained with a drilling operation in order to allow the integration of the bolts, both for skins and core. They have been thought to be a little bit greater than the external diameter of the bolts (M5).

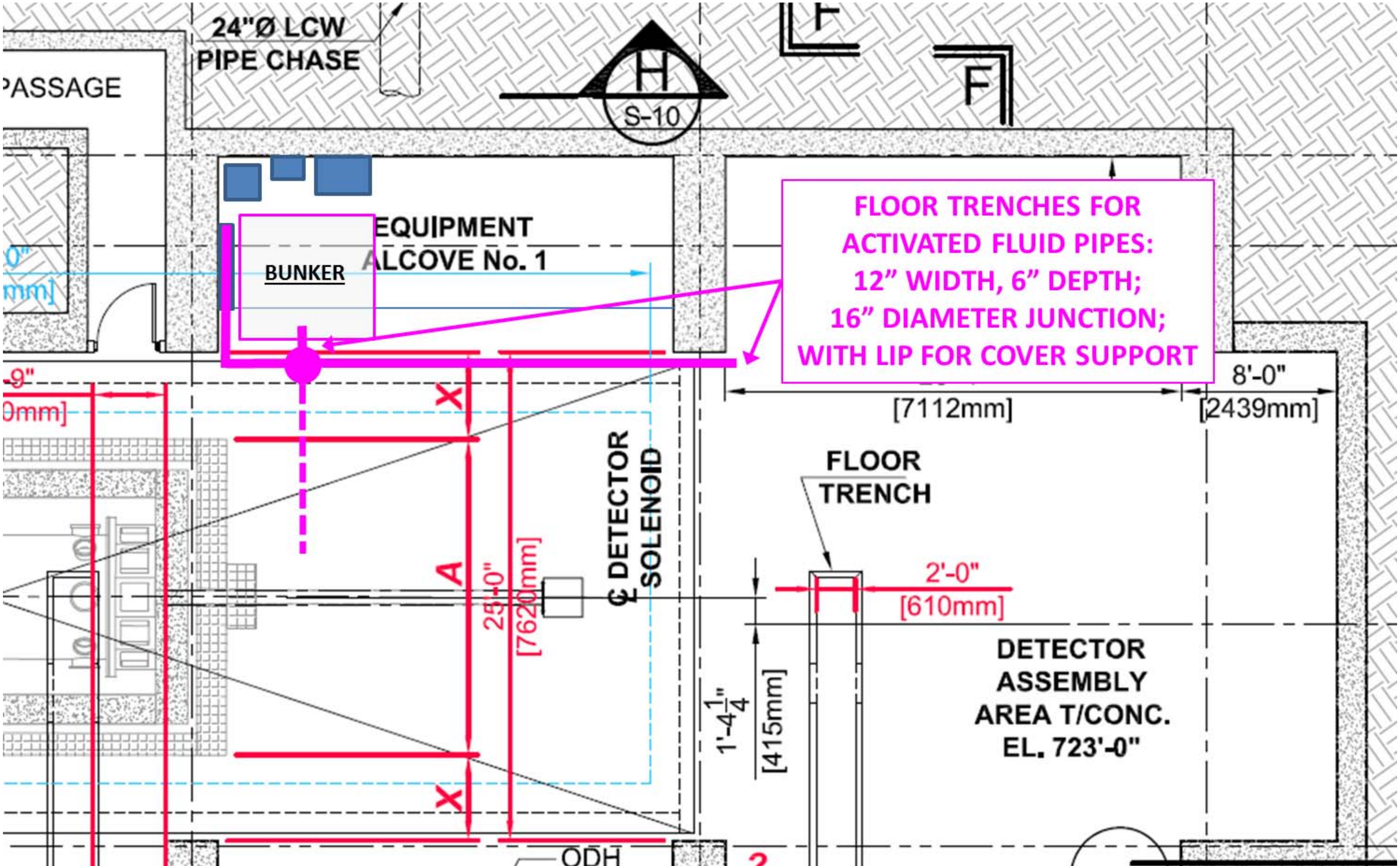
The foam will be milled to let the allocation of the pipes.

Manifolds and thin-wall tubing

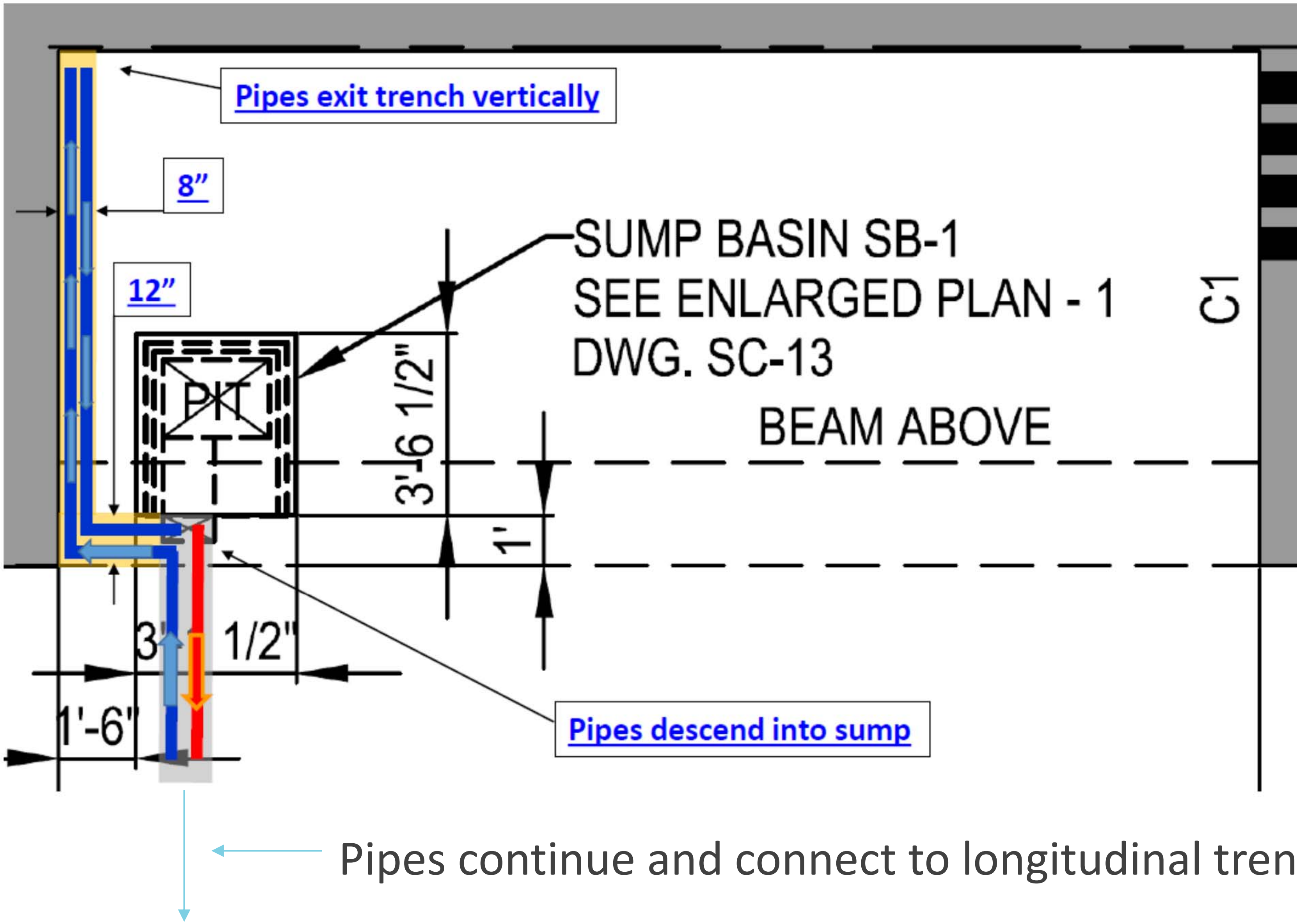
- The aluminum thin-tube array, with correct overall geometry, i.e. completed tubes attaching to the manifold, with the manifolds trimmed to length.



Proposed Source Calibration System Layout Outside Alcove No. 1

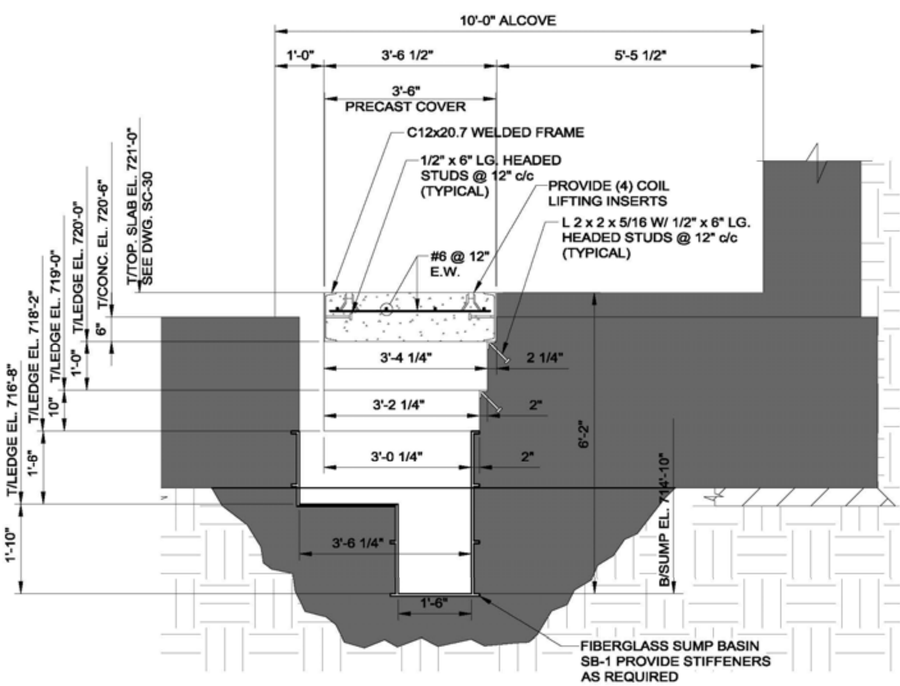


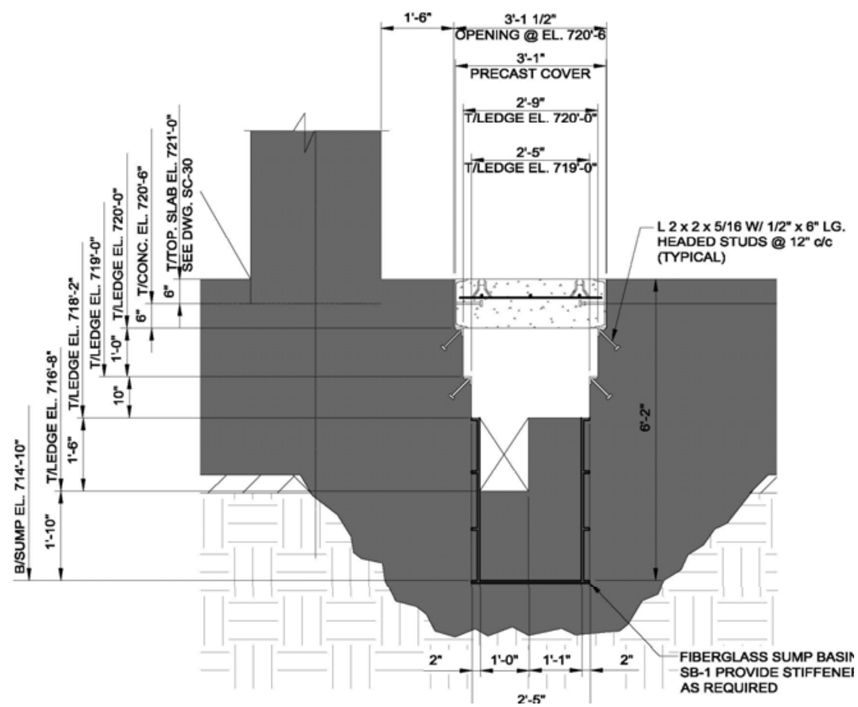
SC-2, Detail of Equipment Alcove With Additional Trench (in yellow)



Pipes continue and connect to longitudinal trench

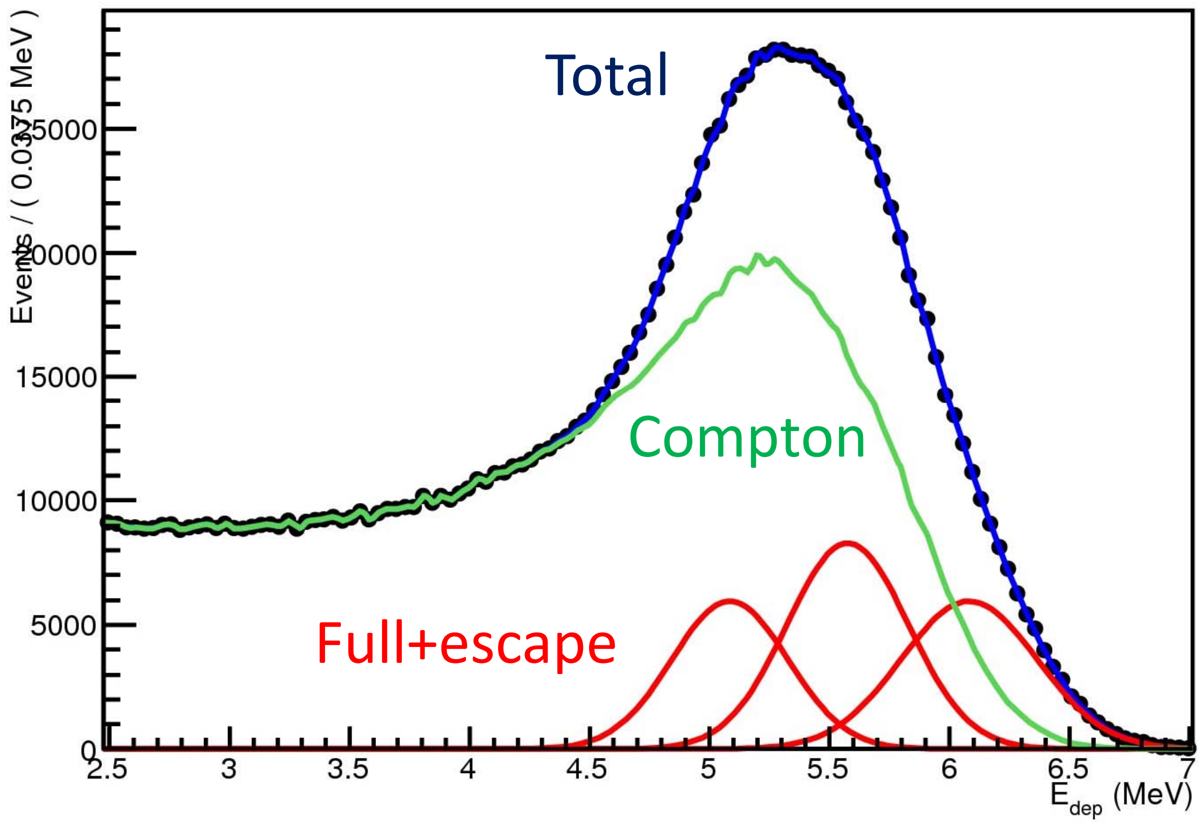
DT generator sump details





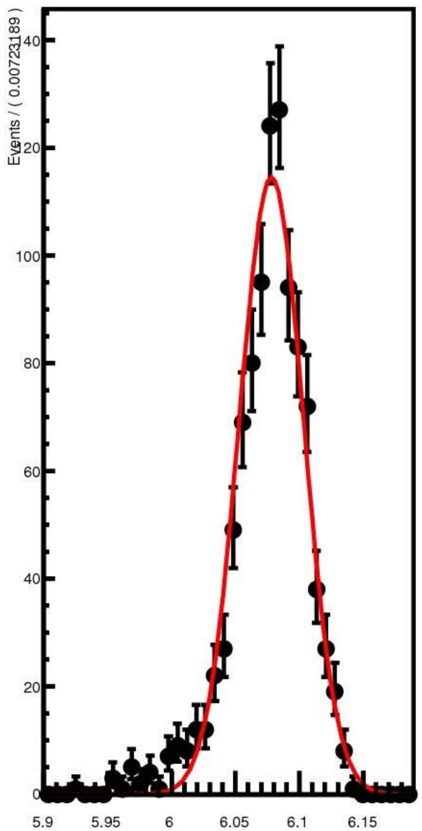
Fermilab

Energy of each crystal hit at the reconstructed level, break down the contribution of the full annihilation, single and double escape peaks. The rest is mainly from Compton scattering + leakage

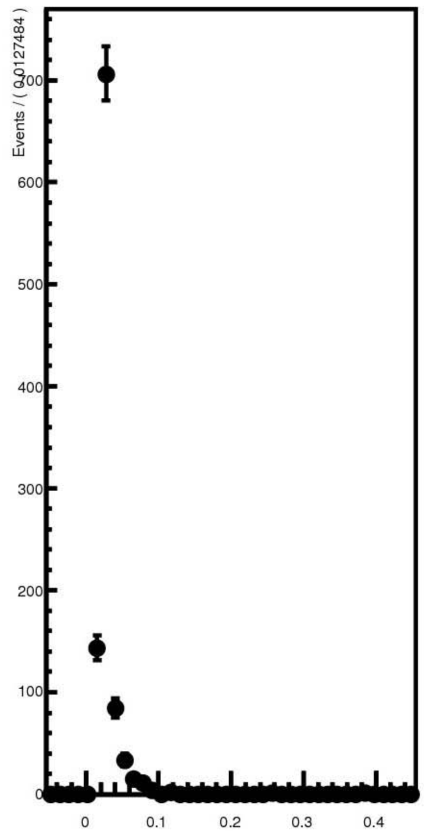


Source calibration – Distribution of fit results

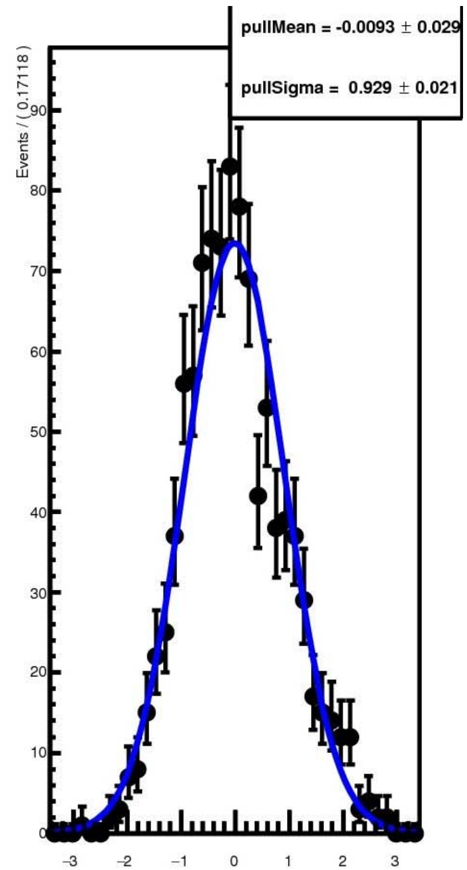
10,000 photon calibration



mean of Gaussian

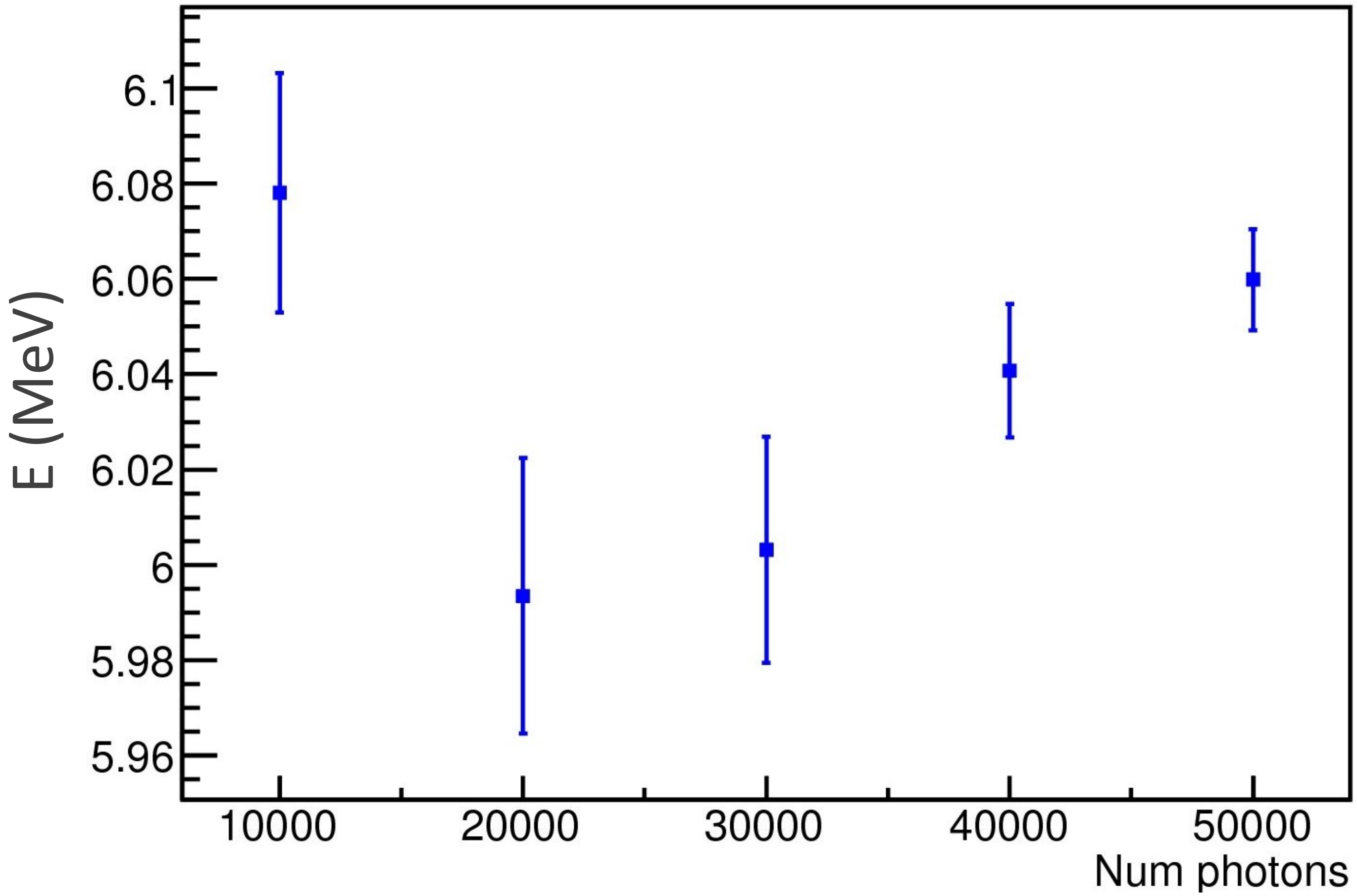


σ_{mean}



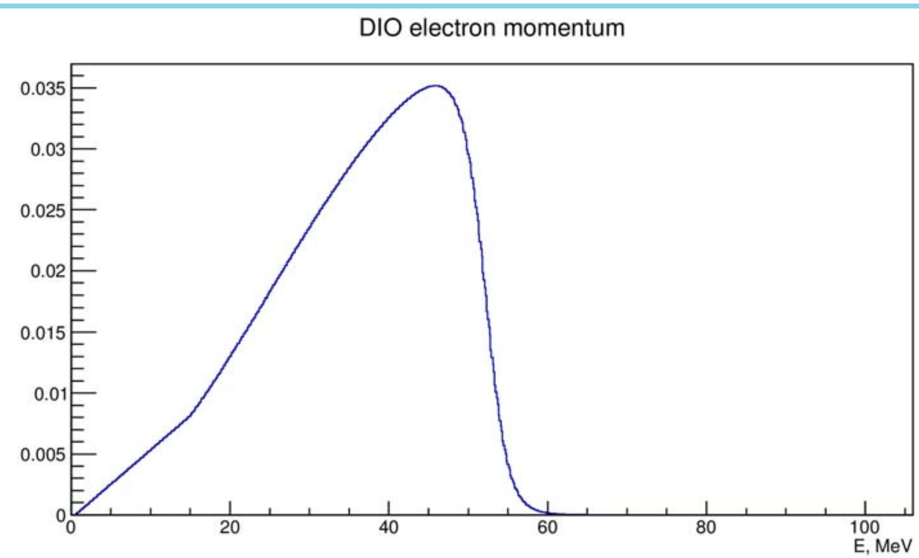
normalized error

Dependence of calibration on sample size



Decays in orbit

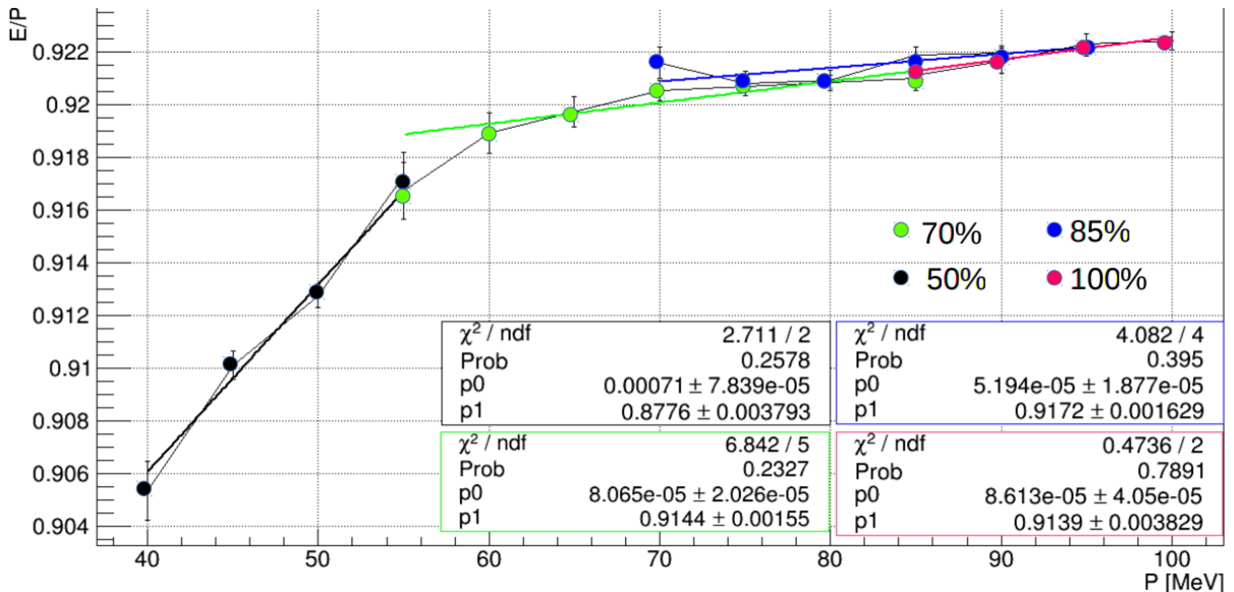
In-Situ calibration with DIO electrons



- Rely on the tracker momentum scal
- Use position of the E/P peak
- Magnetic field = 0.5T - uniform coverage
- muon beam intensity reduced by x200

- 200= 10 (N protons/bunch) *20 (beam off production target)
- 1000 electrons in each channel : need ~1 minute
- Calibration time driven by the operational procedures needed to change the field

In-Situ calibration with DIO electrons (E/p)



- Different colors correspond to different magnetic field values
- E/P increases with P, however the total change < 2%
- agreement better 0.1% in the overlap regions

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- To “transfer” calibration results to the nominal field of 1T, need measurements at two intermediate points – 0.7 T and 0.85 T
- Achieving accuracy $\sigma_T < 0.1$ ns, $\sigma_E/E < 1\%$ seems straightforward

Procurement plans

- Pressure vessel to surround DT generator is in hand
- Thin-wall aluminum tubing in hand
- Fluorinert fluid is in hand
- Pump is in hand and has been refurbished
- DT generator in hand for prototype, plan to purchase new one for installation at Mu2e
  - Purchase as late as possible, consistent with long lead time required
- New reservoir required
- Prototype gauges etc, to be reused; additional components to be purchased off-the-shelf
- Laser system procurement is Italian responsibility; most components are off-the-shelf

Reliability

- DT generator is most critical reliability concern
  - Experience with existing generator is good; has come back to design parameters after several years of storage
  - New generator to be procured and installed
    - Existing prototype generator may be available as temporary (and somewhat spent) backup in case of catastrophic failure
- Plumbing to meet or exceed ASME standards, including weld inspections
- Pressure vessels rated to 200 psi, lines designed to 150 psi; operation at ~70 psi

Risks

- CAL-170: Inability to purchase DT generator from Russia
  - US/Russian relations may preclude
  - Alternate US vendor exists
  - Keeping design flexible to accommodate either model
  - Exposure is $90k
  - No schedule impact
  - Ongoing discussions with both vendors

Schedule

- Crystal testing at Caltech (including source calibration)
  - First batch arrives at Caltech: Oct 2017
  - Begin wrapping, photodetector: Mar 2018
  - Last batch leaves Caltech: Jul 2019
- Final source system
  - Component POs (plumbing): Aug 2017
  - Source tubing, manifold on disk 1: Sep 2018
  - DT generator delivery (latest): Dec 2019
  - DT in sump (latest): Jun 2020
- Laser system at FNAL: May 2018
  - Distribution box on disk 1: Sep 2018
  - Test calorimeter: May-Jul 2020
- Calibration system test complete: Aug 2020