In-beam experience with CLAS12 SVT

Yuri Gotra
Jefferson Lab

SVT-EIC Workshop

09/02/2020

Outline

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  - Tracker integration
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  - Detector occupancy
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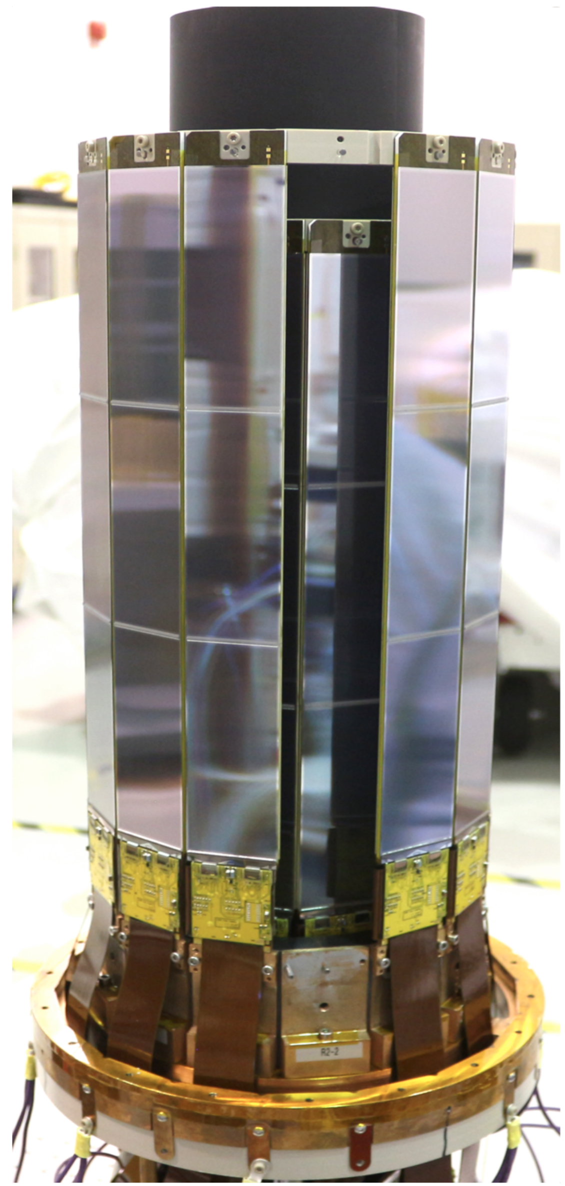
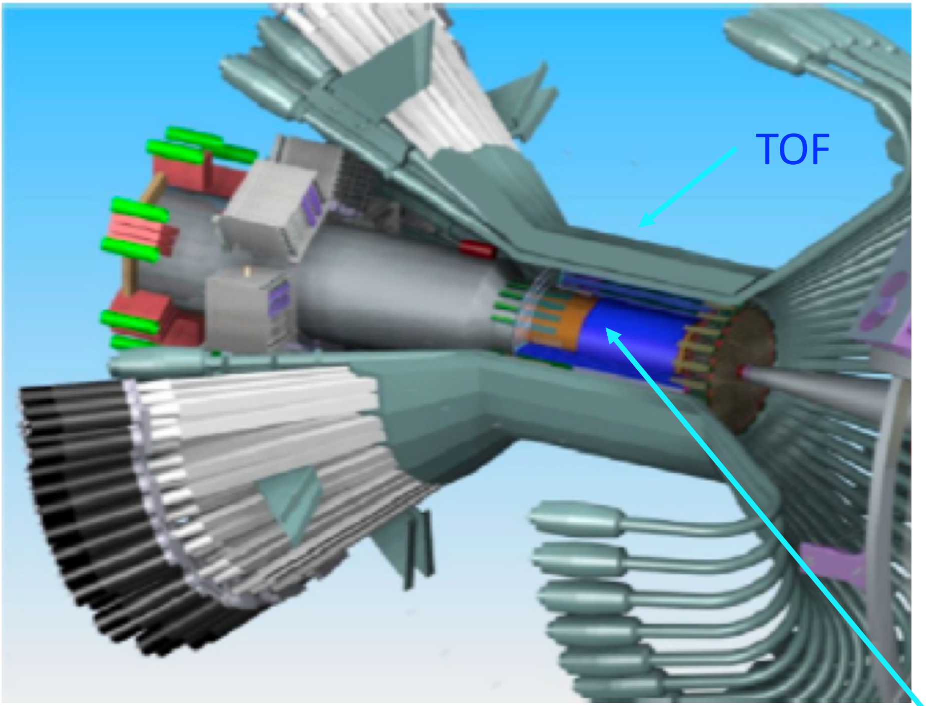
  - Survey and alignment
  - Tracking performance
- Summary and conclusions



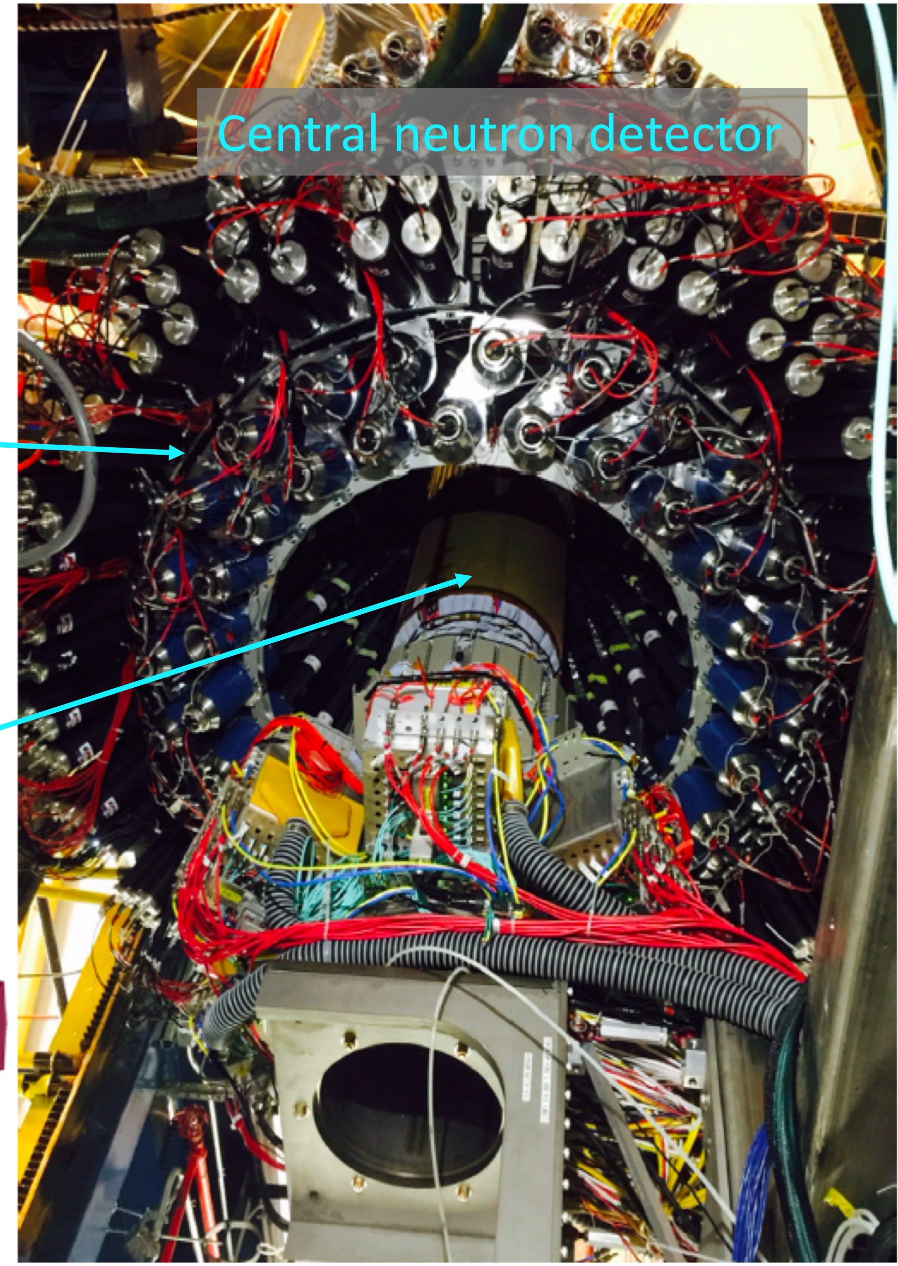
The CLAS12 Silicon Vertex Tracker, Nucl. Inst. and Meth. A 962, 163701 (2020)

CLAS12 Central Detector



Central Vertex Tracker

5 T Solenoid magnet

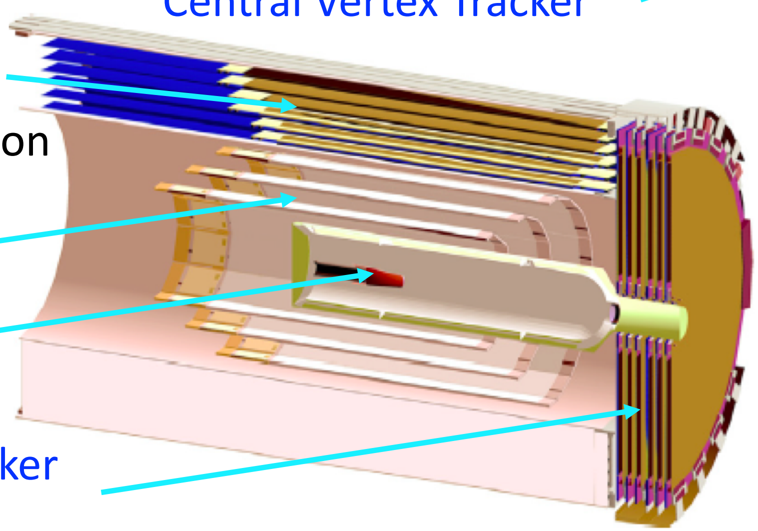


Barrel Micromegas tracker
3 XY and 3 Z layers
Improved V_z and θ resolution

SVT
3 double layers

Target

Forward Micromegas tracker
6 disks

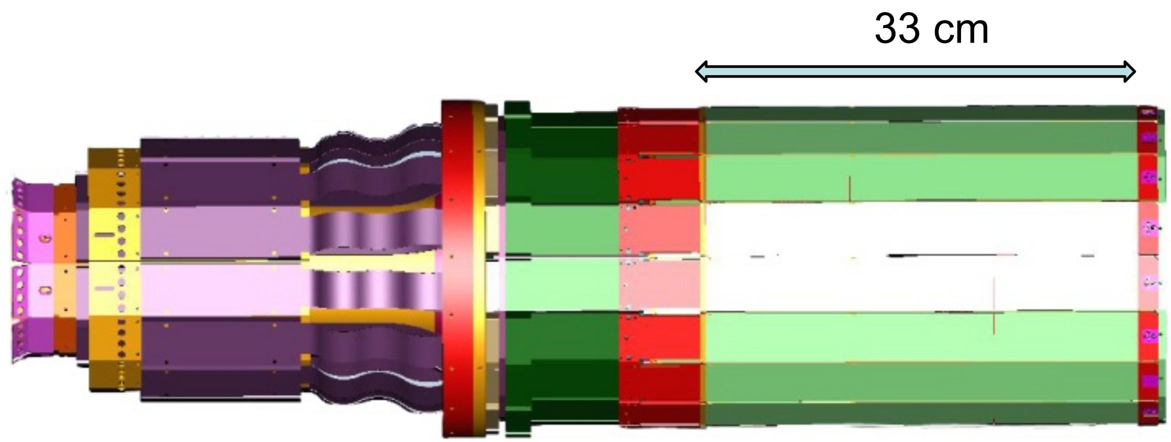


Motivation and Technical Specs

The **CLAS12 Silicon Vertex Tracker** system is a part of the central detector and will be used to measure the momentum and determine the vertex of charged particles emerging from the target. The SVT system includes 3 regions with 10,14, and 18 sectors of double-sided modules (silicon sensors on both sides of the backing structure) instrumented with digital readout ASICs, FSSR2s.

The system is designed to operate at a luminosity of 10^{35} $cm^{-2}s^{-1}$ and to have a momentum resolution of ~5% for 1 GeV particles emerging from the target at a θ of 90º.

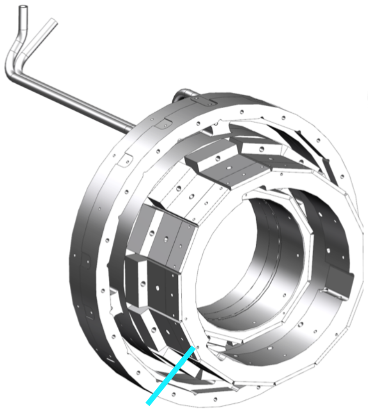
PARAMETER	DESIGN VALUE
Number of regions (radii, mm)	3 (65, 93, 120)
Sectors (modules)/region	10, 14, 18
Module dimensions (L x W x T)	41.9 cm x 4.2 cm x 0.39 cm
Number of silicon layers/module	2 (*U*, *V*)
Strip layout	(0º— 3º) Graded angle
Sensor thickness	320 μm
Readout pitch	156 μm (hybrid side)
Number of readout channels/module	512
Total number of readout channels	21,504
Readout ASIC	FSSR2
Backend electronics	Custom-made VXS cards
Angular coverage θ	35°–125°
Angular coverage Φ	~2π
Spatial resolution	50-65 μm
Momentum resolution	~5%
θ resolution	10–20 mrad
ϕ resolution	~5 mrad
Designed to operate at a luminosity of	10^{35} $cm^{-2}s^{-1}$

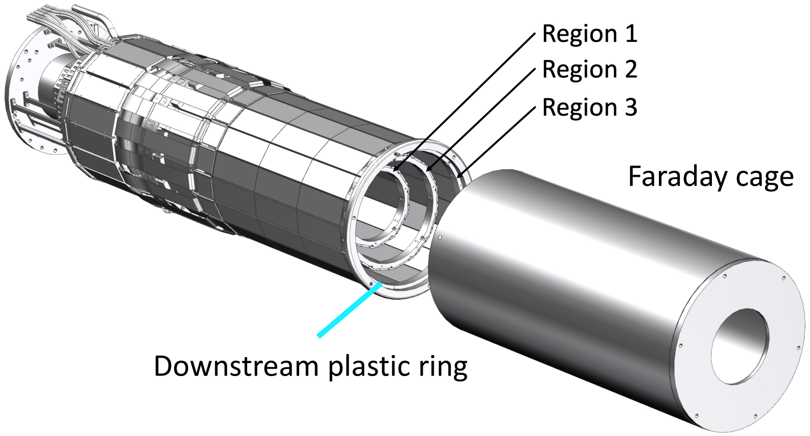


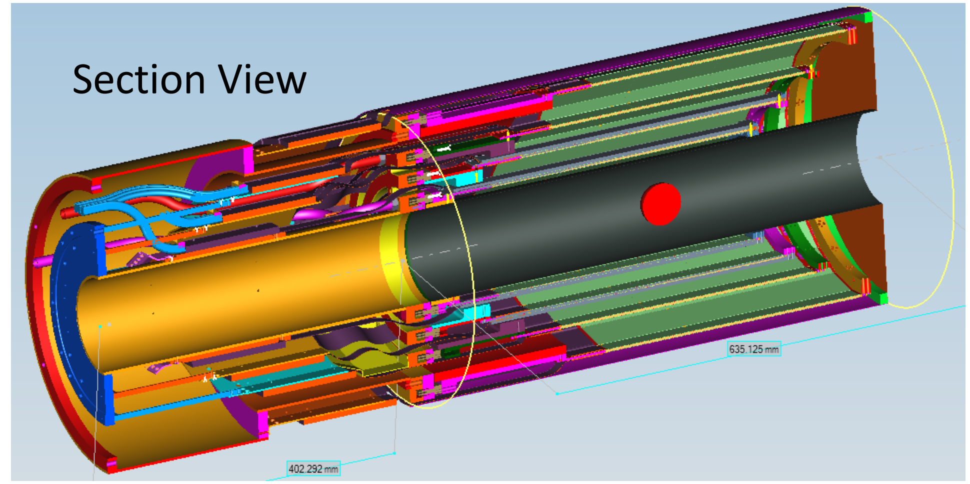
Tracking low energy hadrons:

- Multiple scattering
- Tight material budget
- Long light modules (~1% radiation length per region)
- Low-noise readout electronics
- No services in the tracking volume
- Cantilevered support
- Rigi-Flex hybrid board with extended L1 disconnect

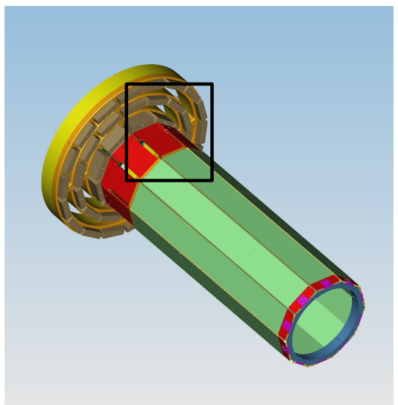
Design Overview: Mechanics

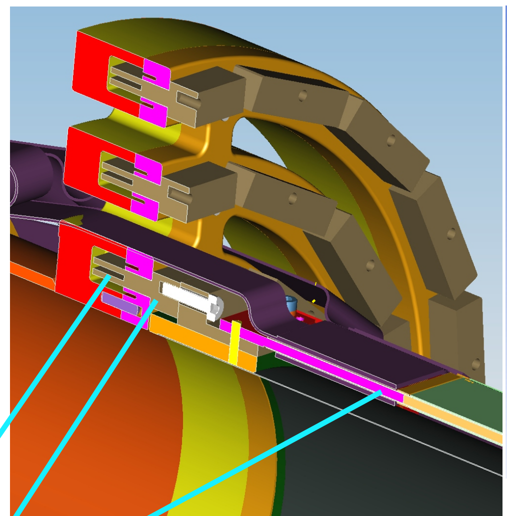






Cantilevered cylinders with support rings

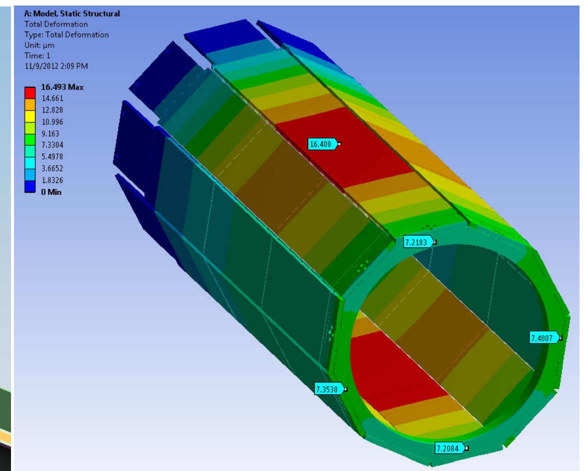




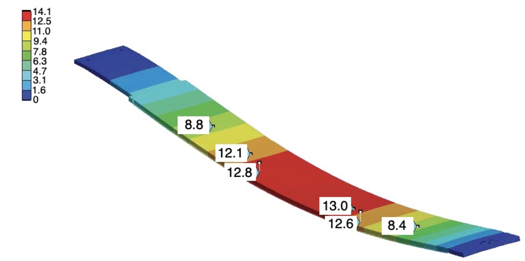
Coolant Channel

Module Support

Module



Max. Deflection: ~16 μm
(in horizontal modules)



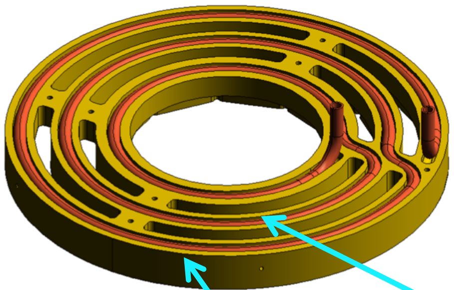
Max. Deflection: ~19 μm

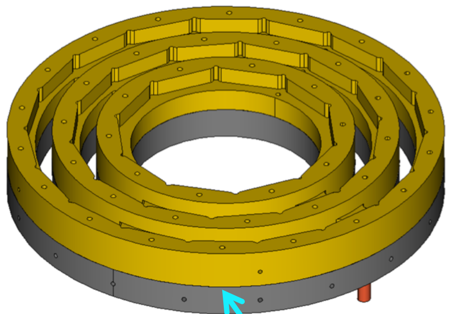
Max. Deflection in Downstream Ring: ~7 μm

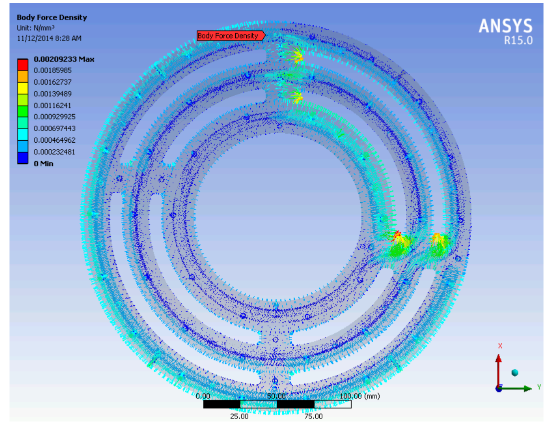
Design Overview: Cold Plate

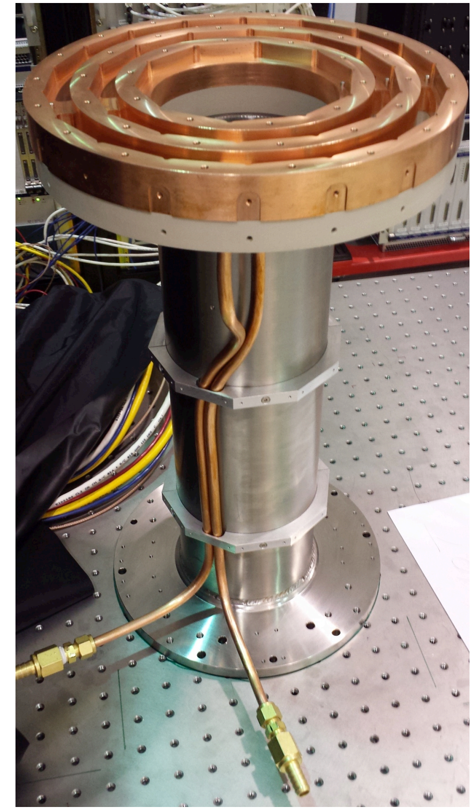
Metal cold plate with a copper tube eliminating leak path through cold plate

- ANSYS thermal analysis
- ANSYS quench analysis of eddy current forces





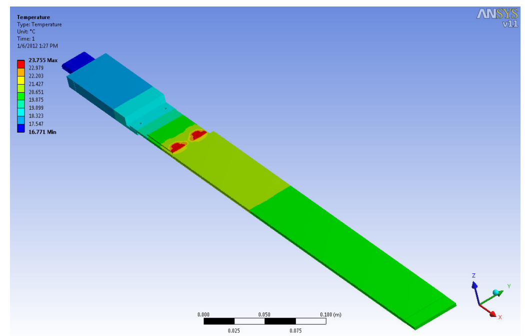


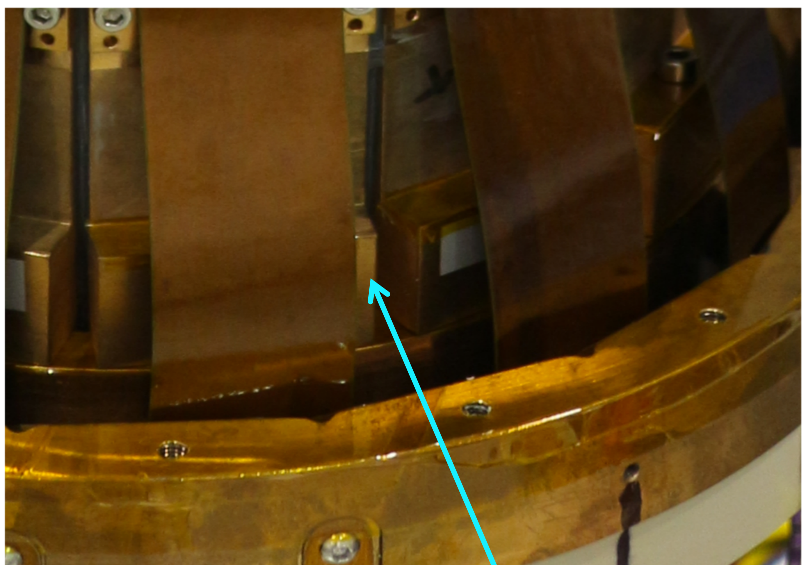


Brass Heat Sink Plate

Cover Plate (Plastic)

Copper tube brazed into channel

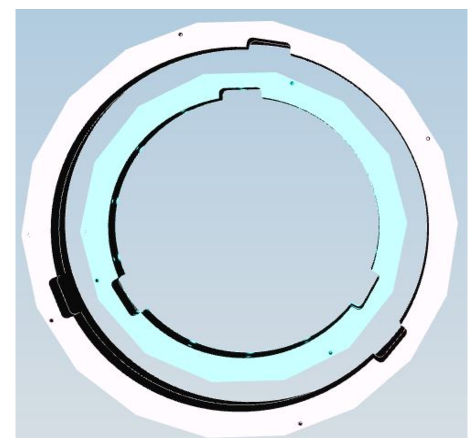




Heat Sinks

Heat output: 2 W per module

Hybrids @ 14 – 18 C (coolant @ 6 C)



The cut-outs in the upstream ring hold the ambient temperature and humidity sensors

Design Overview: SVT Module

Double-sided, all modules are identical

Sensor, 111.6 × 42 mm

- 3 daisy-chained per side
- Graded pitch, 156 – 202 µm

Pitch Adapter, 156 µm to 50 µm

- Metal on glass technology

Readout ASIC

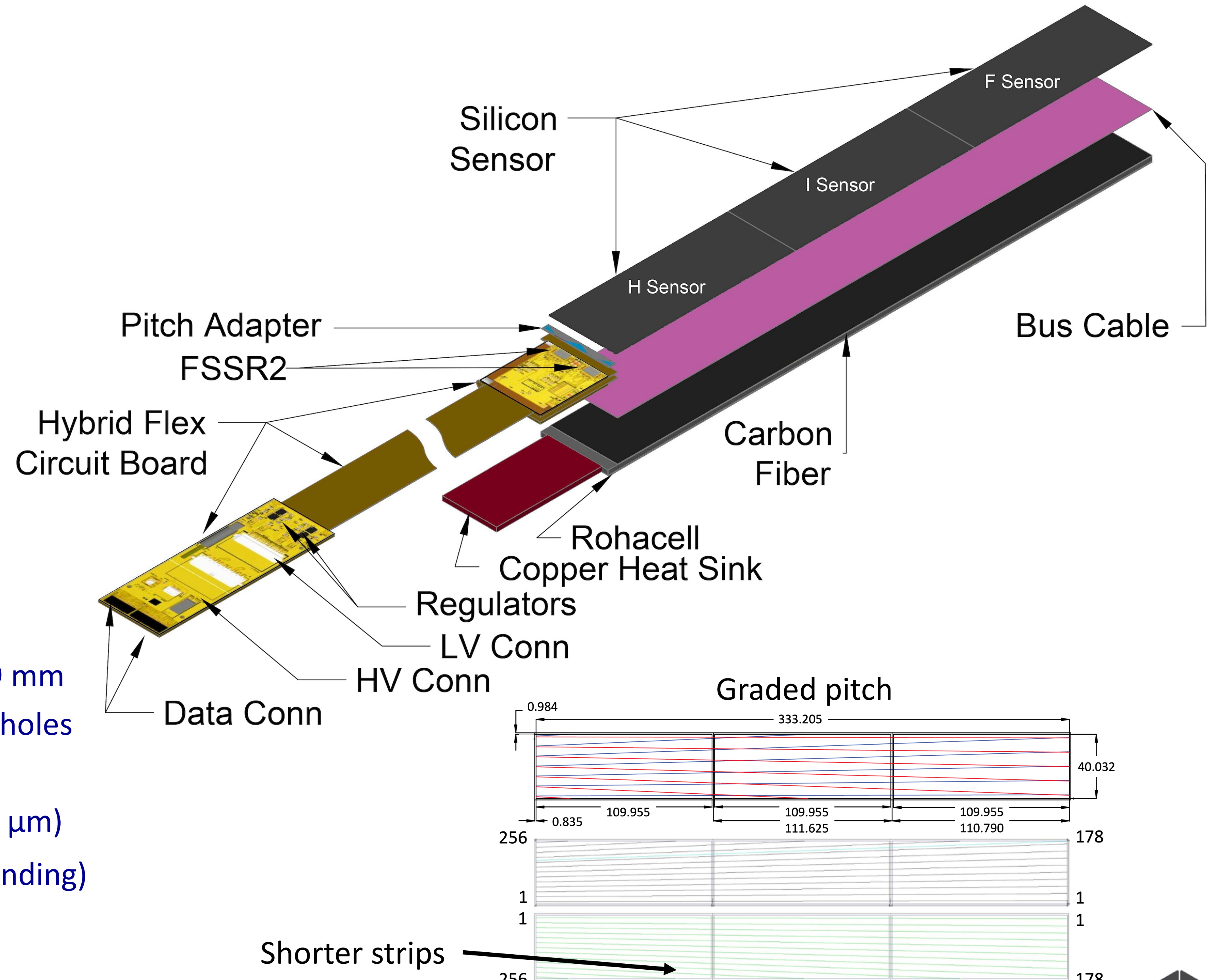
- FSSR2, developed for BTeV
- Self-triggered

Hybrid Flex Circuit Board (HFCB)

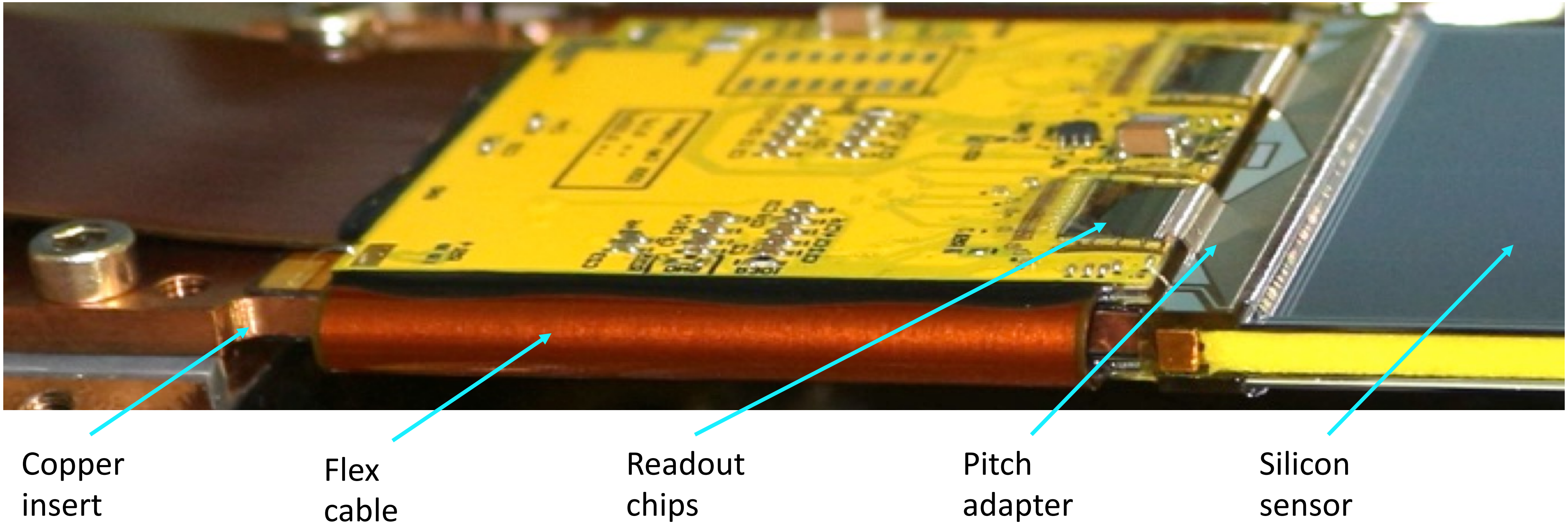
- Based on CDF and D0 designs
- 12 rigi-flex layers

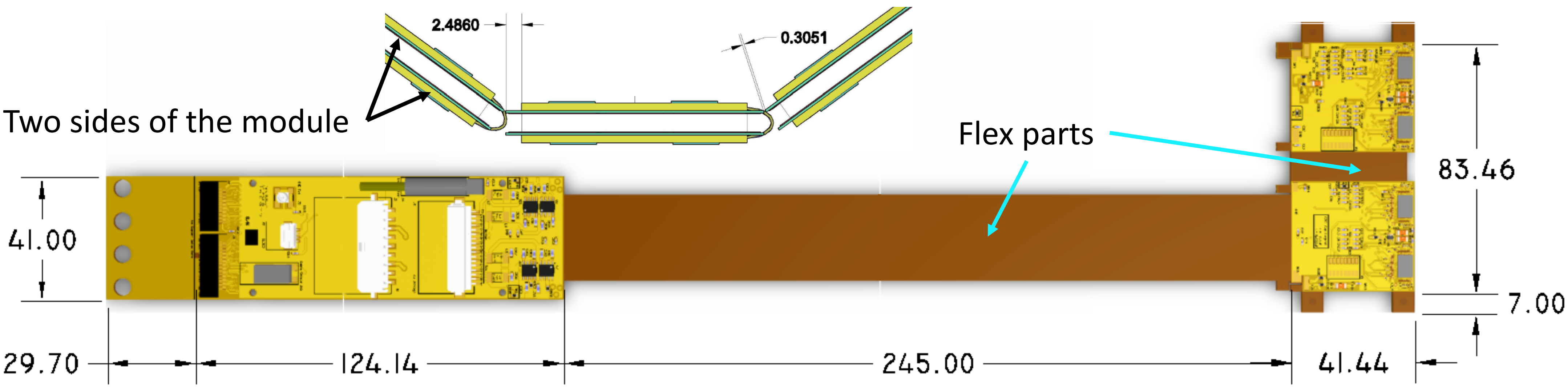
Composite Backing Structure

- Rohacell 71 core (2.5 mm)
- Carbon Fiber (K13C2U) skin, 0.19 mm
- Copper heat sink with mounting holes
- PEEK insert for downstream ring
- Bus Cable for HV distribution (78 µm)
  - co-cured with CF skin (grounding)

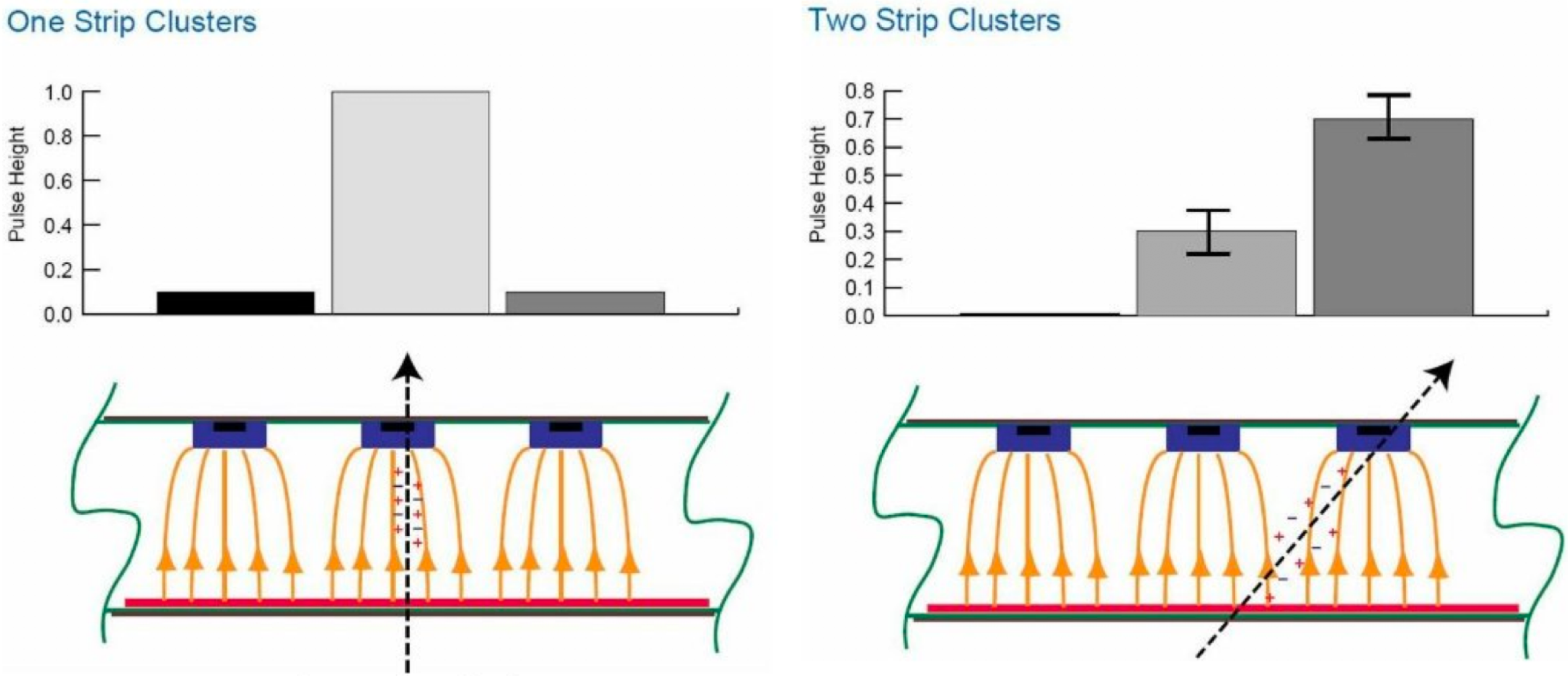


Rigi-Flex Hybrid Close-Up





SVT Sensor Spatial Resolution



Δs: strip pitch

$\sigma_x = \Delta s/\sqrt{12}$

centroid resolution

$\sigma_x \approx (\Delta s/2)(N/S)$

Readout pitch = 156-202 μm

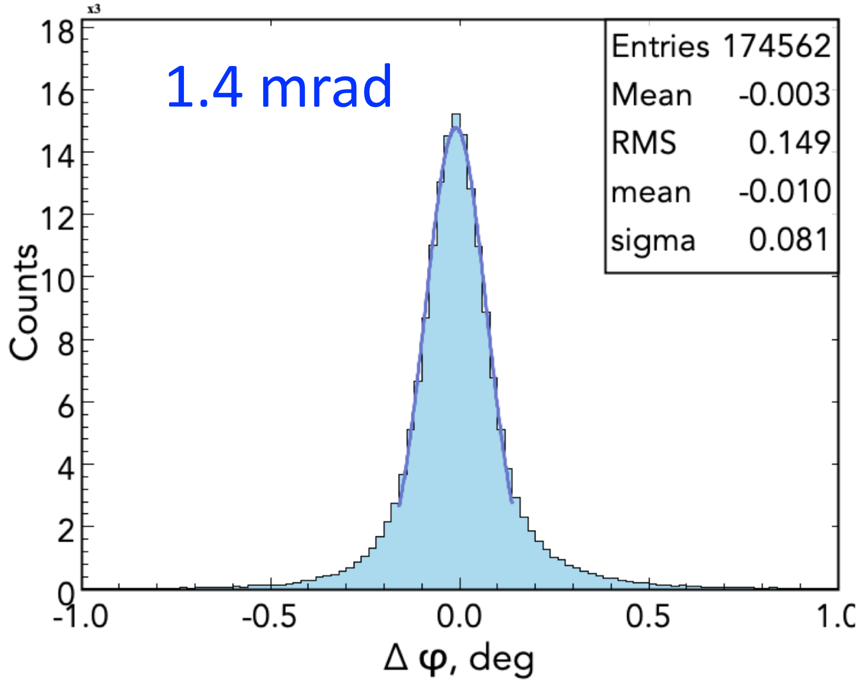
S/N = 15

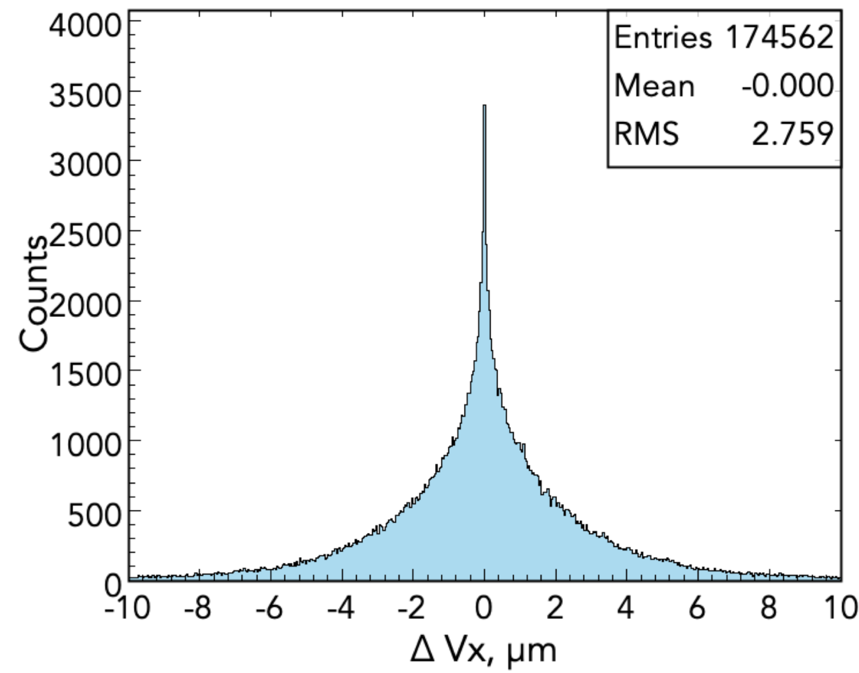
σ_x = 45-58 μm
(binary/digital readout)

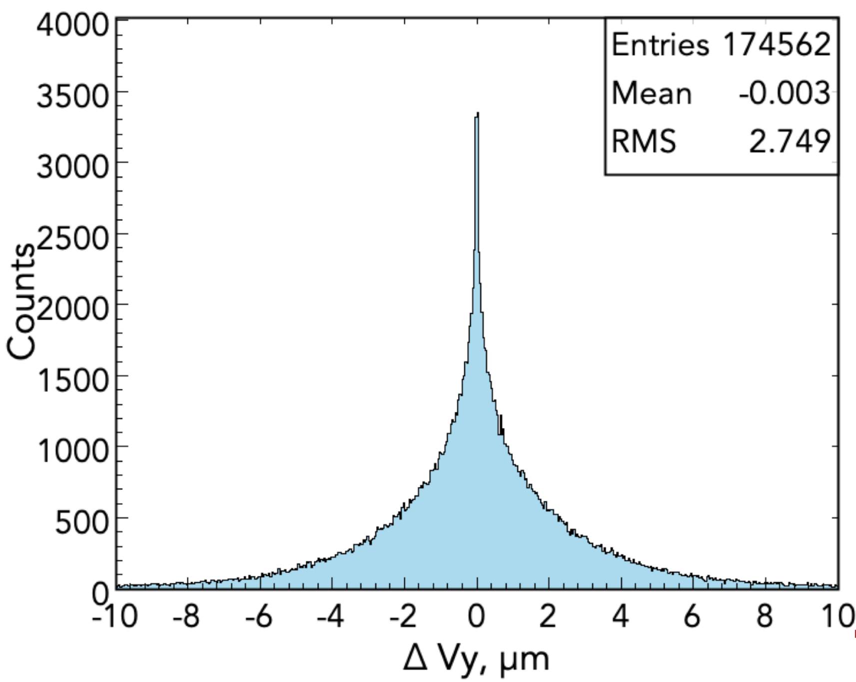
σ_x = 5-7 μm
(analog readout)

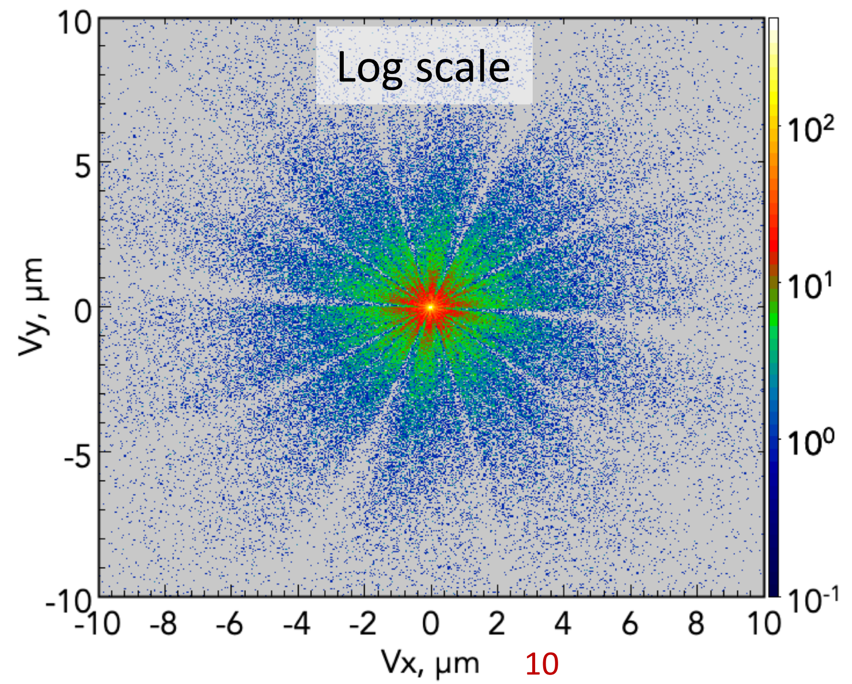
SVT: binary readout with 3 bit ADC

SVT Performance Estimates, Proton MC

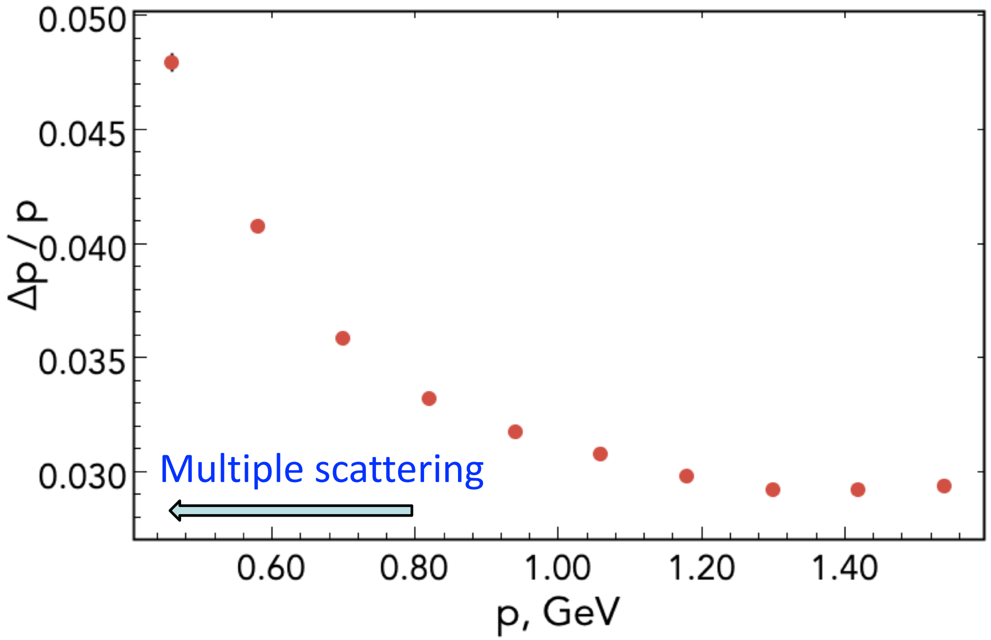


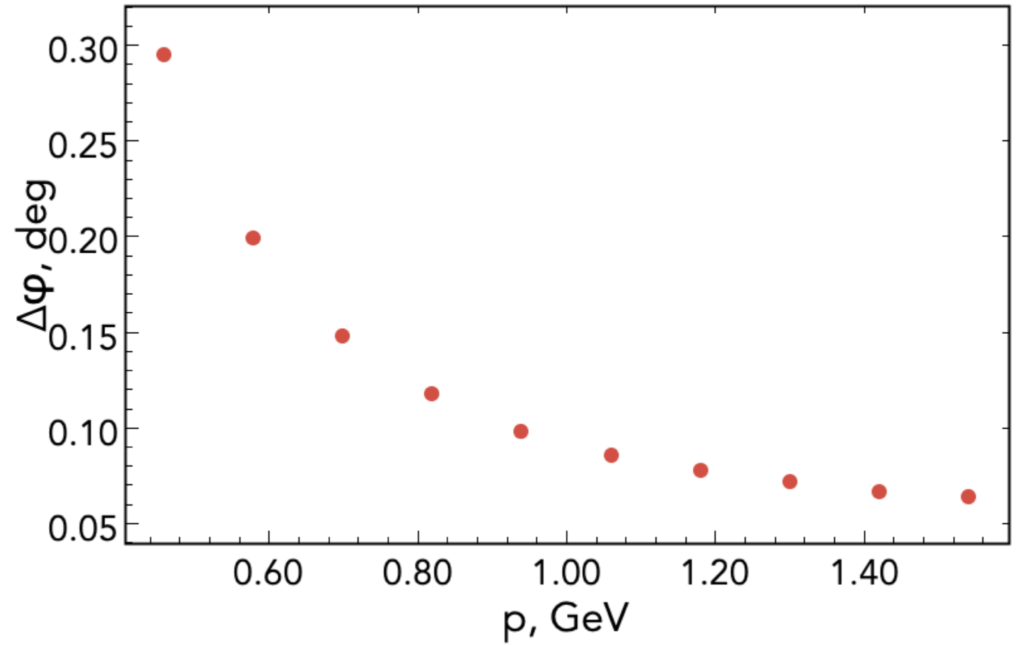


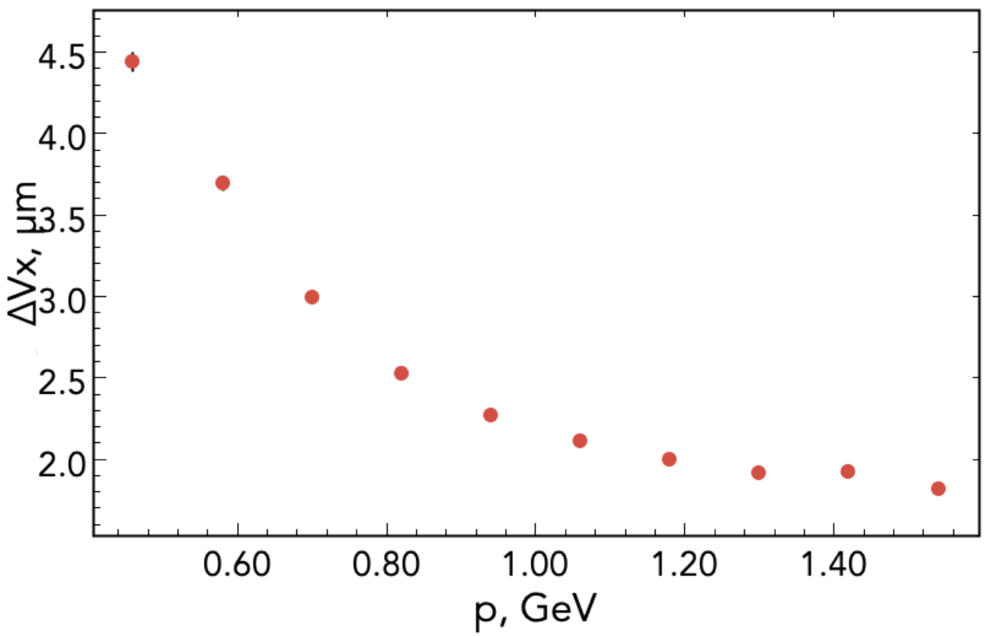


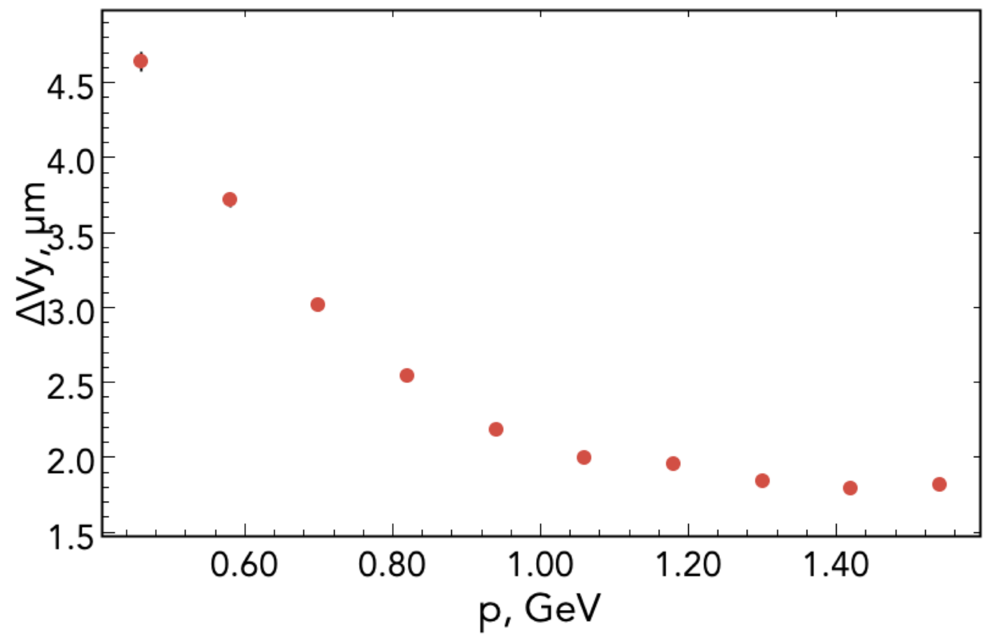


SVT Performance Estimates, Proton MC

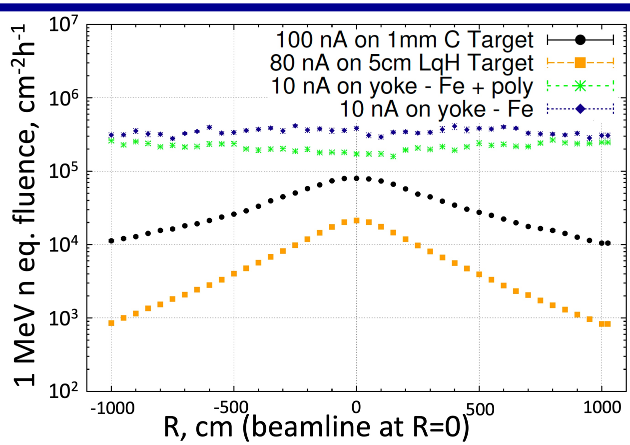


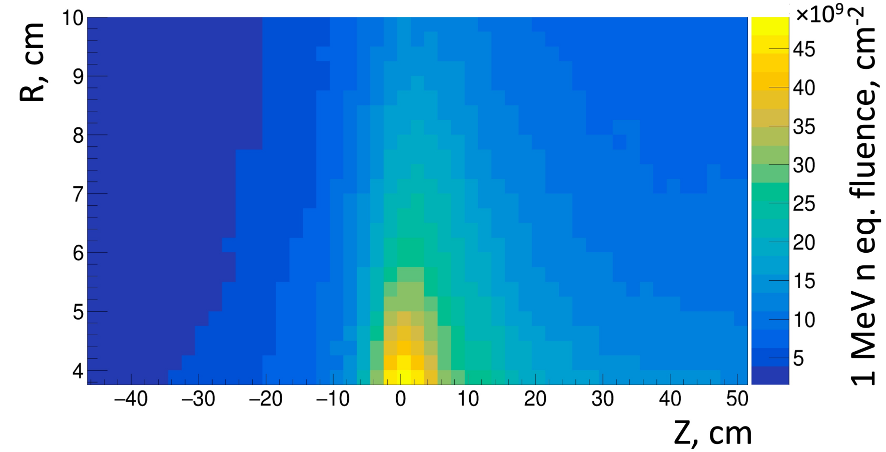




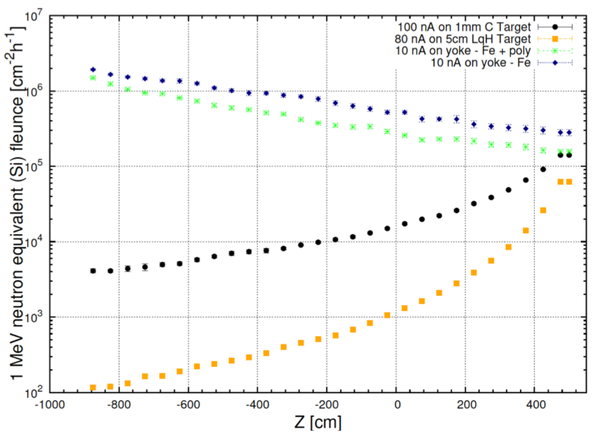


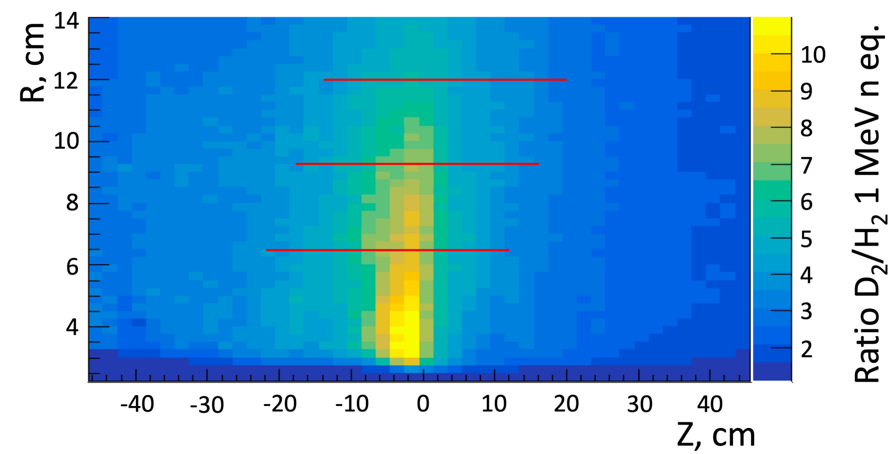
Simulations of Backgrounds and Dose Rates

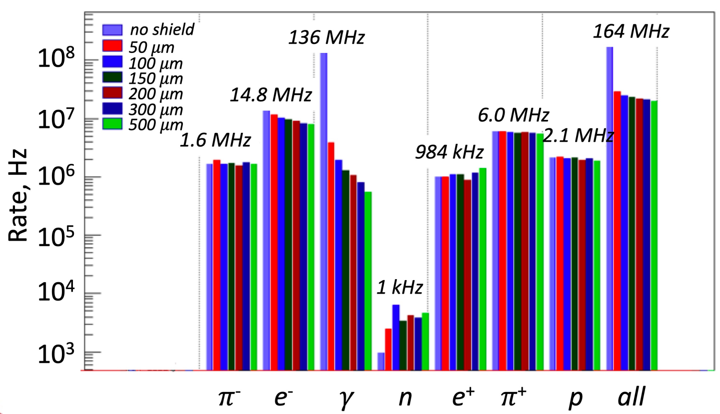




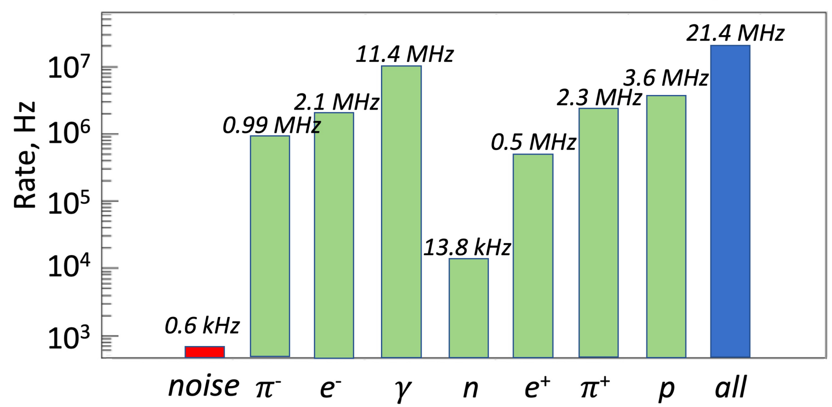
FLUKA



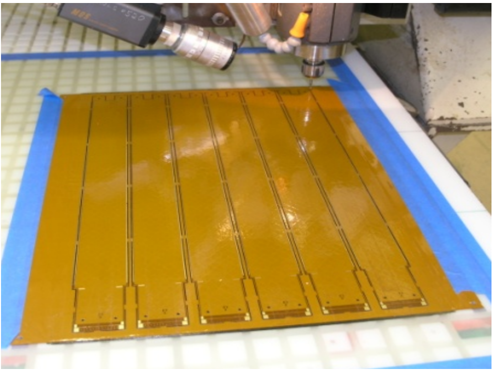




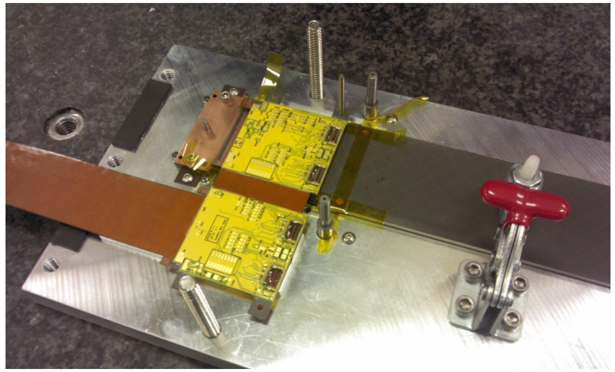
GEANT



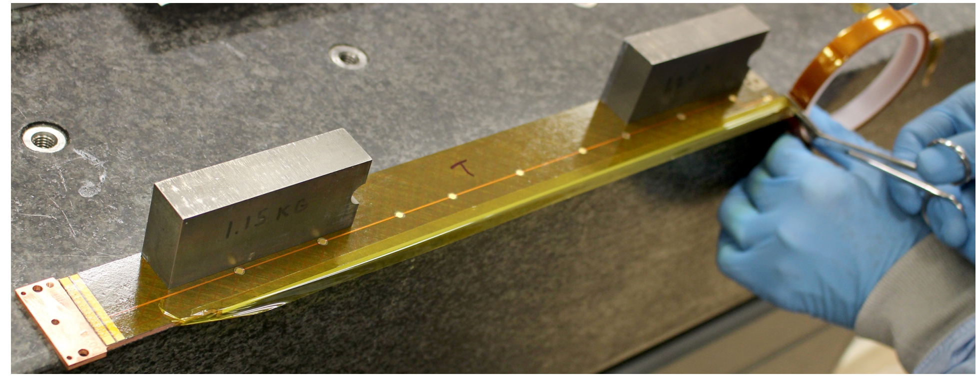
Module Assembly at Fermilab Silicon Detector Facility



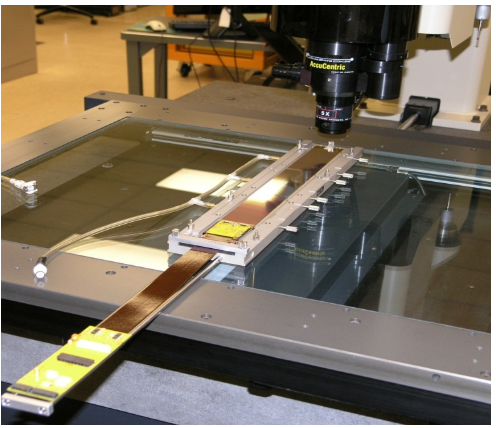
Routing skins



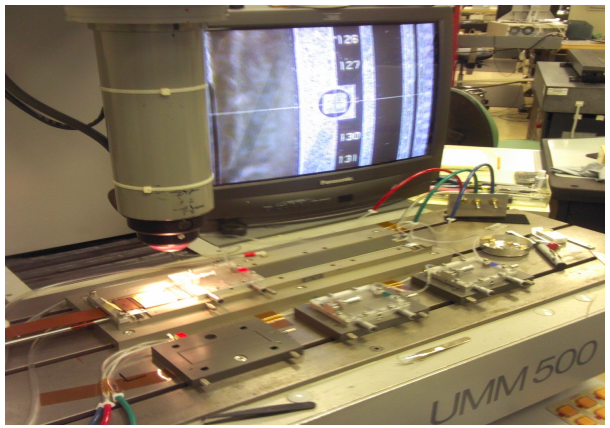
Hybrid placement



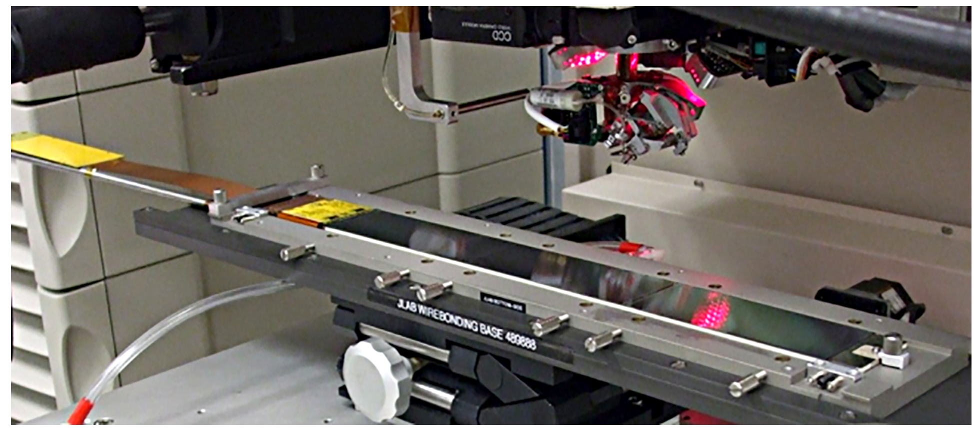
Preparing the backing structure



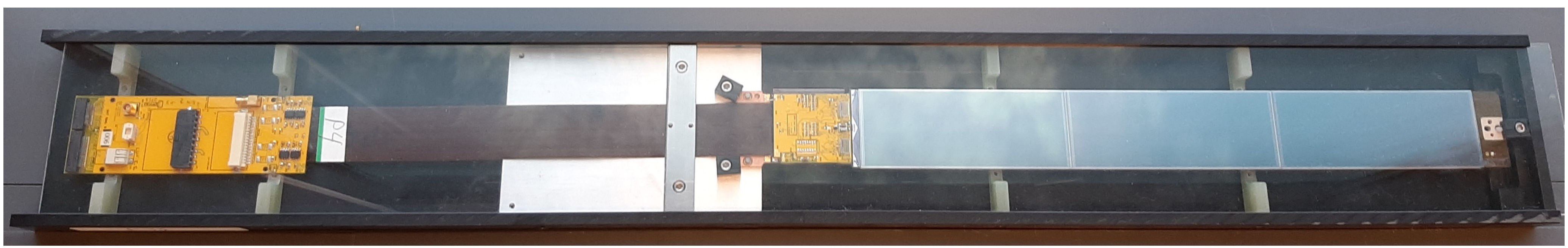
Optical survey



Sensor placement

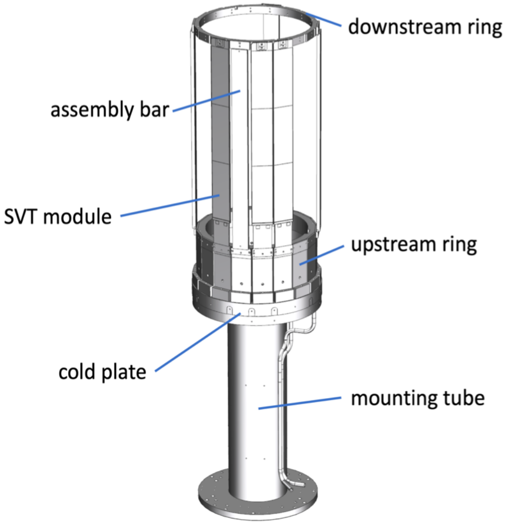


Wire-bonding

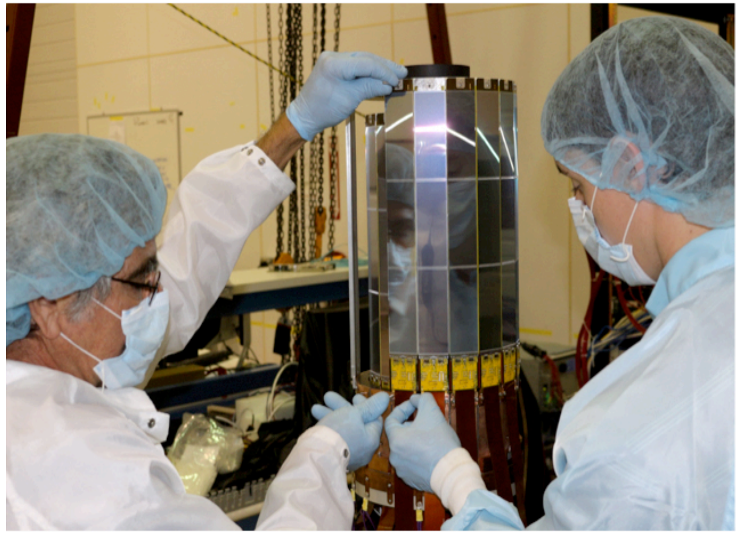


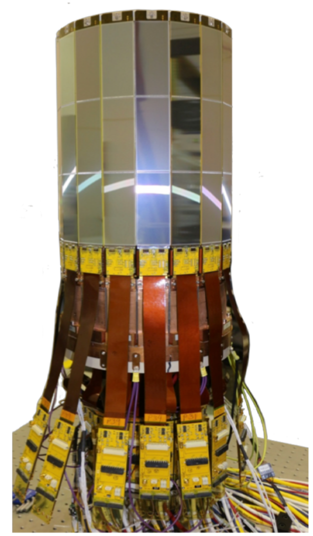
Assembled module

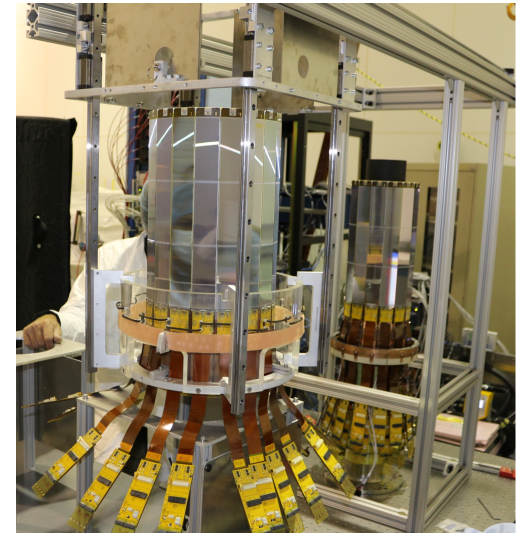
Tracker Integration at JLab



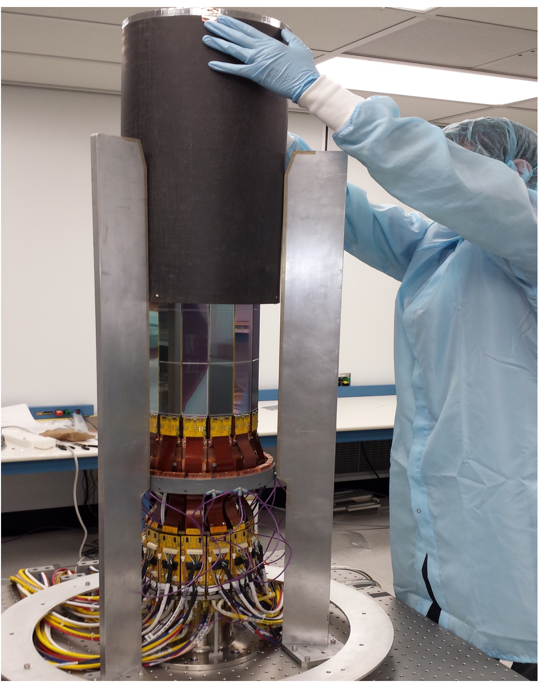
Assembly drawing



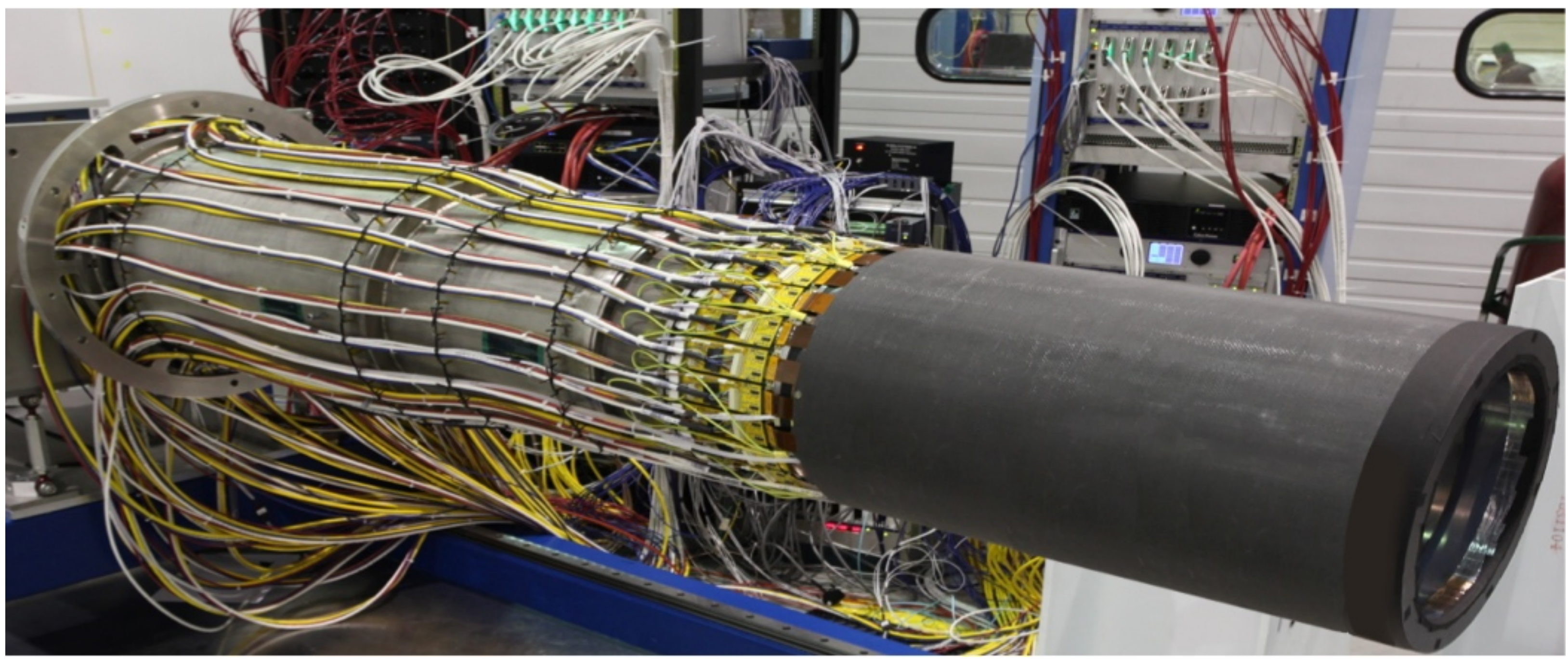




Barrel assembly

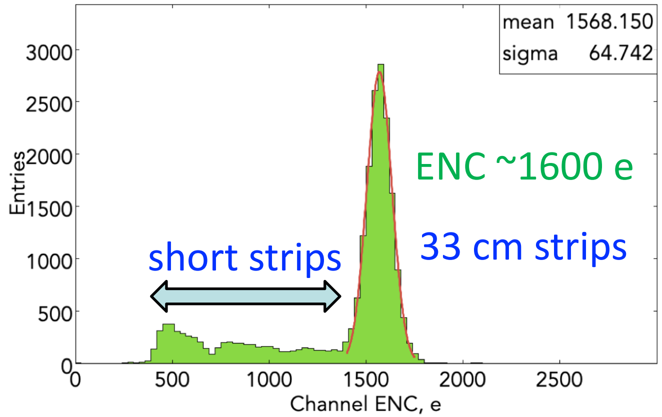


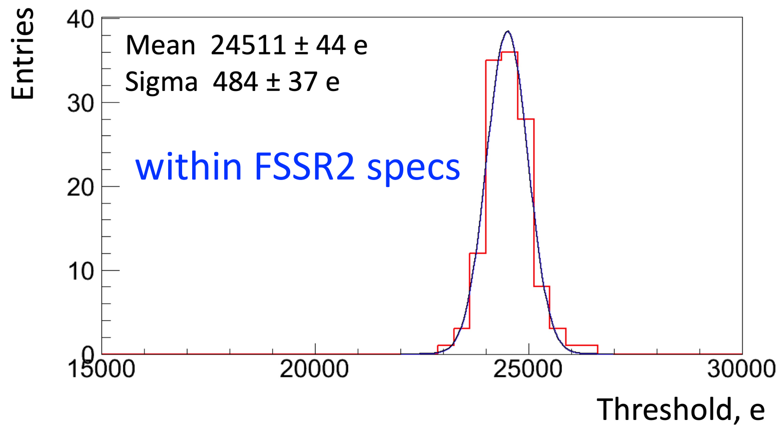
Faraday Cage



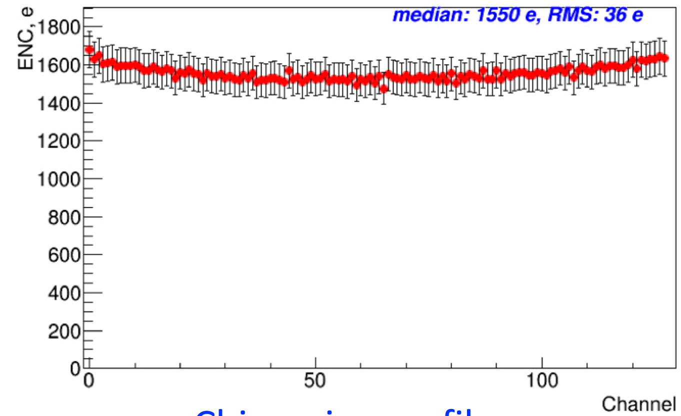
Assembled SVT barrel on the integration Cart

Calibration

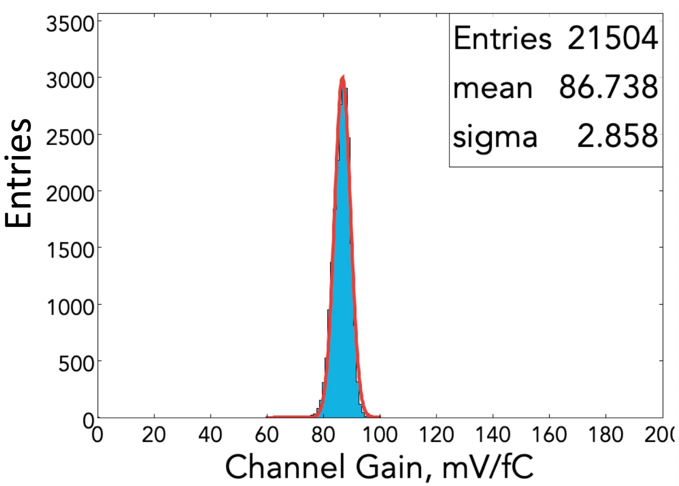


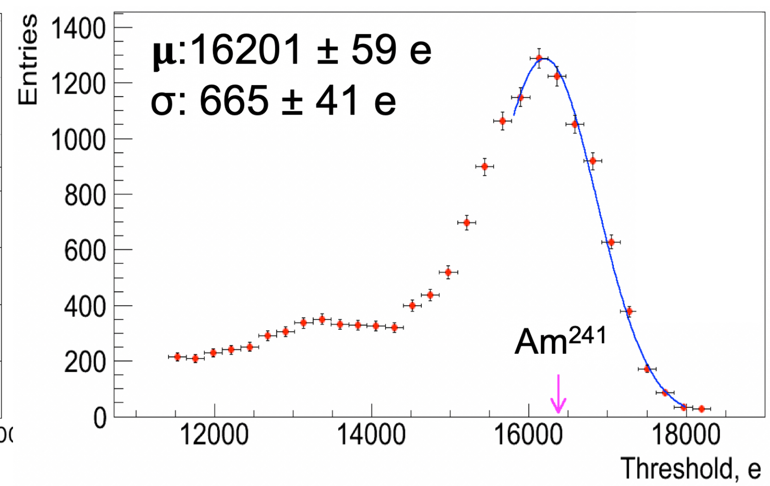


Threshold dispersion

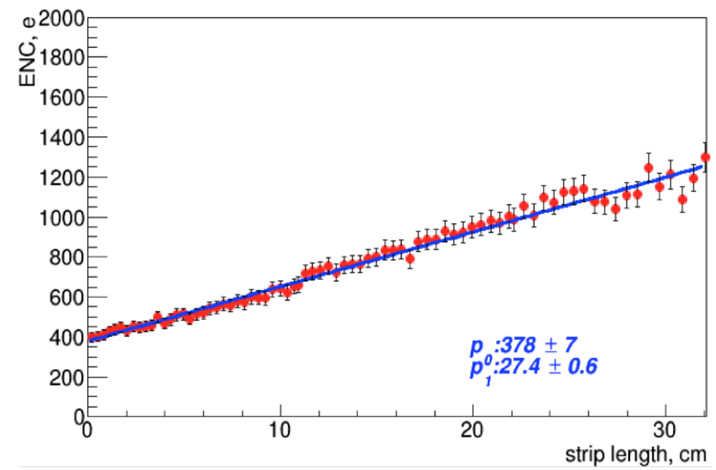


Chip noise profile





Gamma source calibration



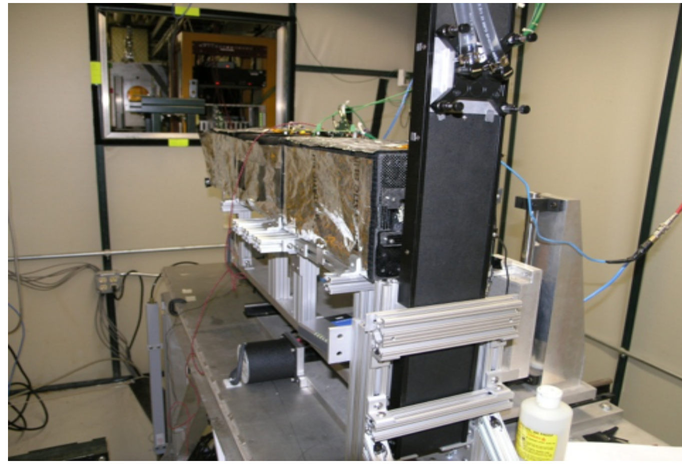
Noise vs. capacitive load

99.9% channels operational after tracker integration

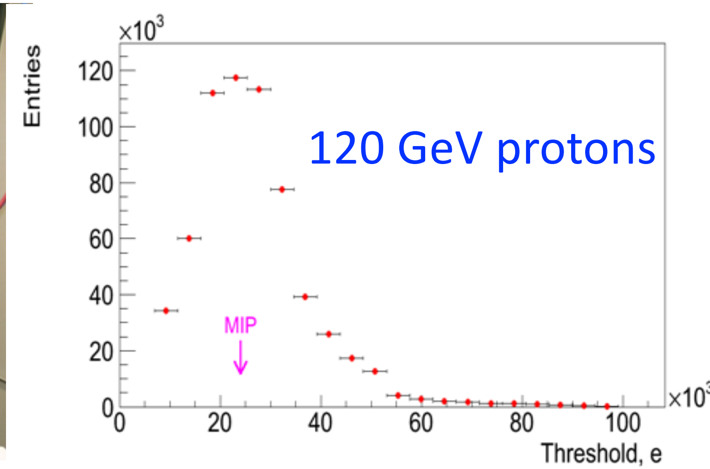
Excellent module assembly quality at FNAL SiDet

SVT Commissioning

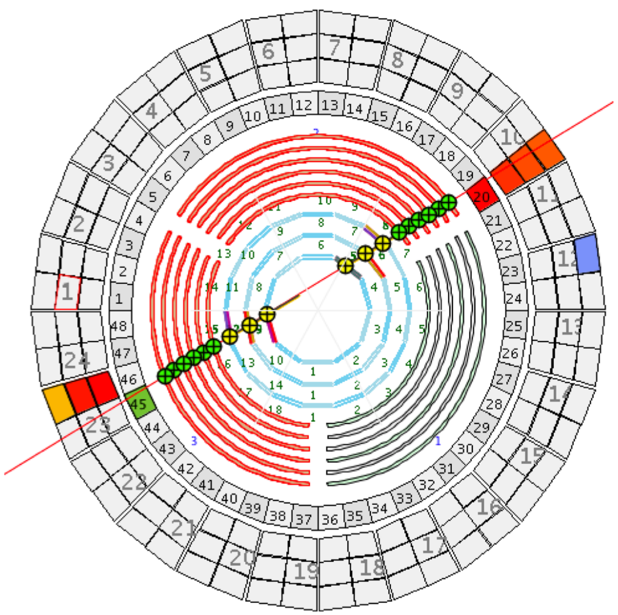
Cosmic test stand



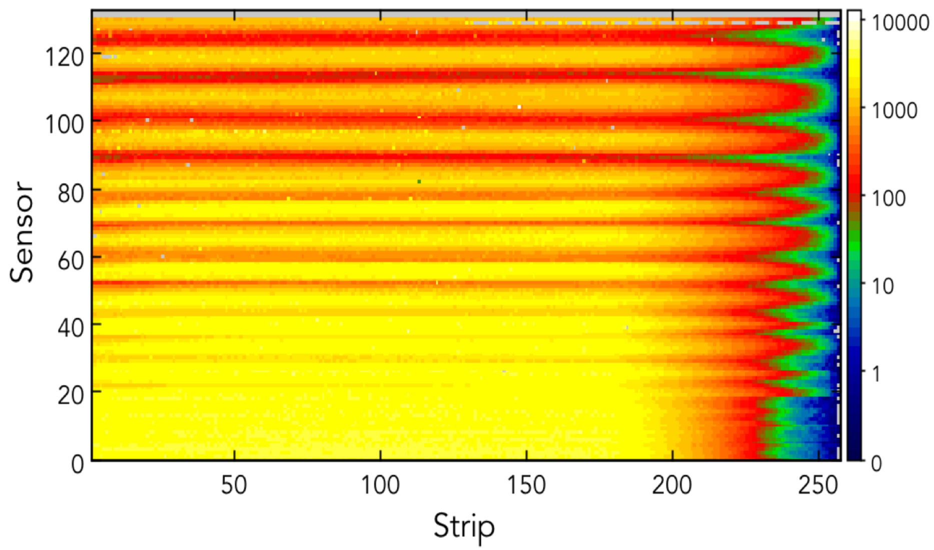
Beam test at FNAL



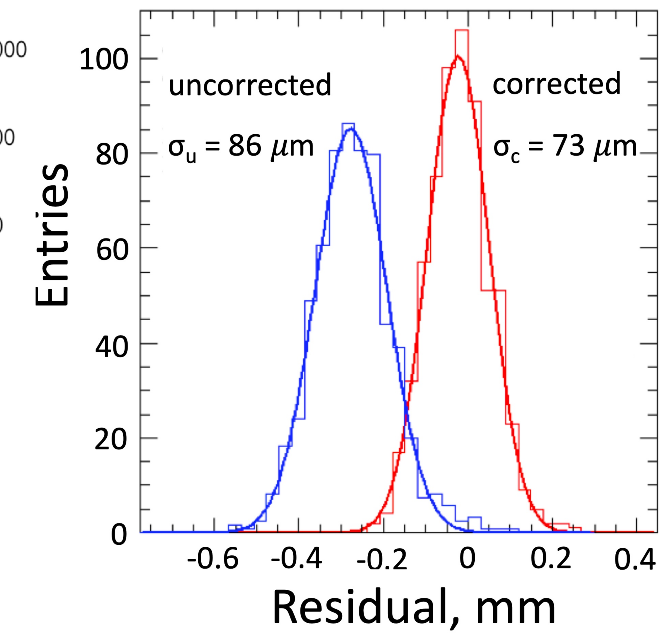
Energy Loss



Cosmic track in Central Detector

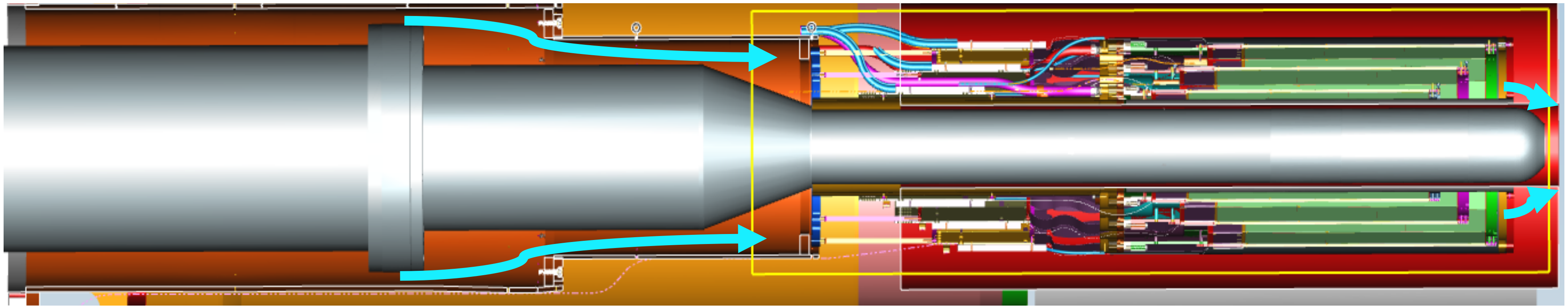


Cosmics hit map

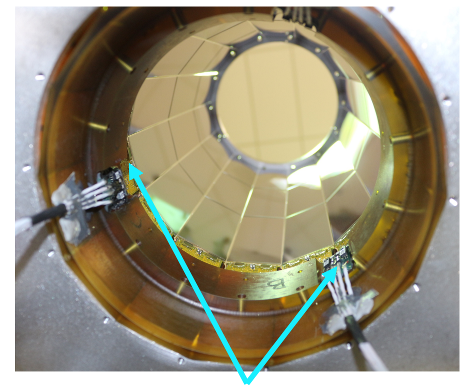


Cosmic alignment

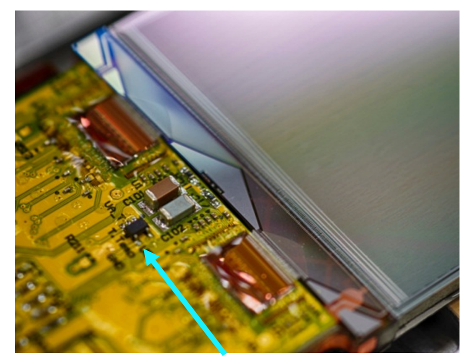
SVT Active Sensor Cooling System



- SVT is enclosed in a sealed enclosure purged with dry air
- Front-end electronics is cooled by liquid Dynalene through the cold plate
- The silicon sensors are cooled by dry air chilled by liquid coolant
  - Liquid coolant tube inside the dry air tube
- Sensors are kept below -10˚C to prevent reverse annealing
- Temperature and humidity inside the barrel is monitored
  - One temperature sensor on each side of the hybrid
  - 12 temperature and humidity sensors on the upstream rings
  - Environmental sensors are integrated in the SVT safety system

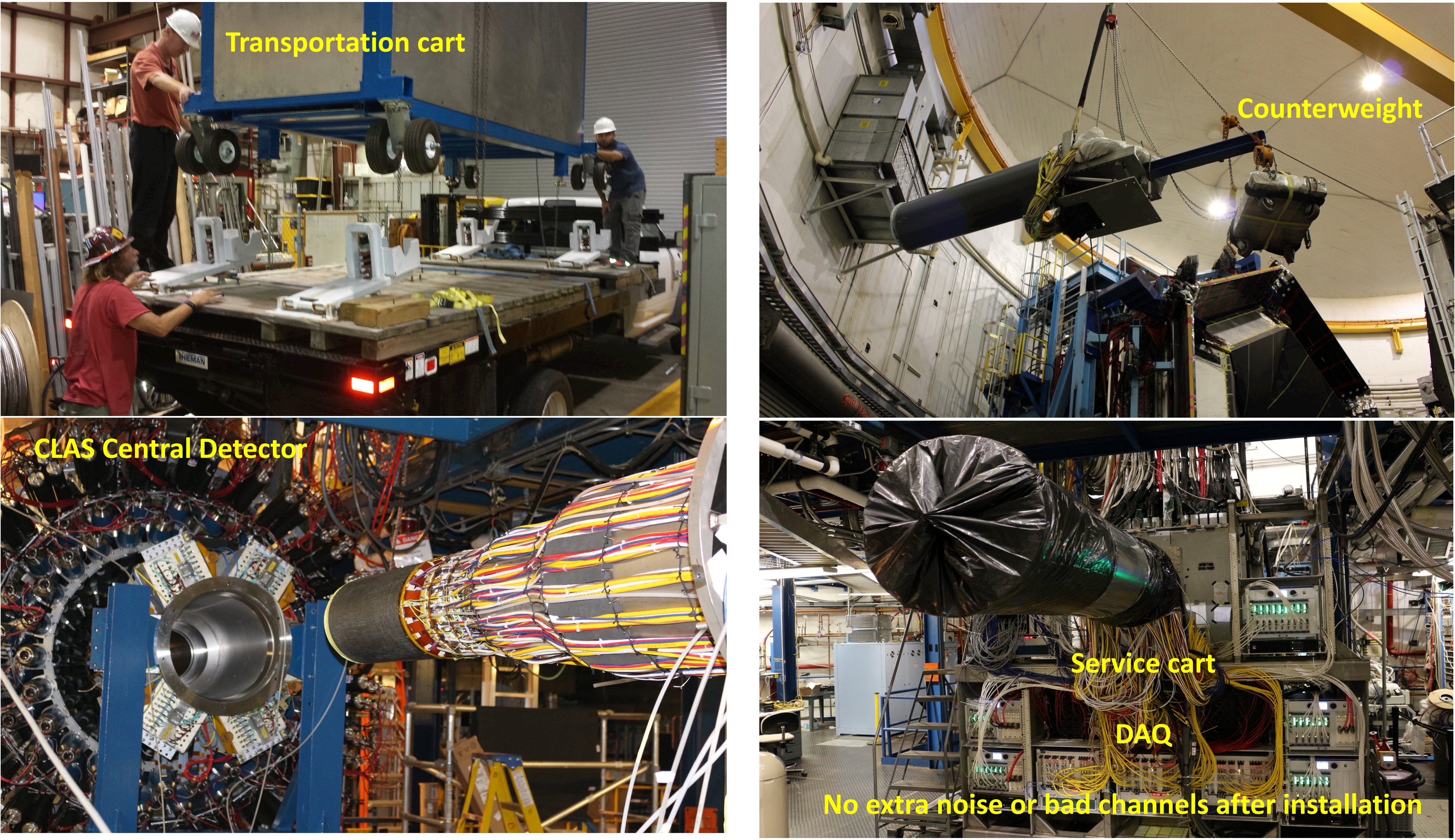


Ambient temperature and humidity monitors

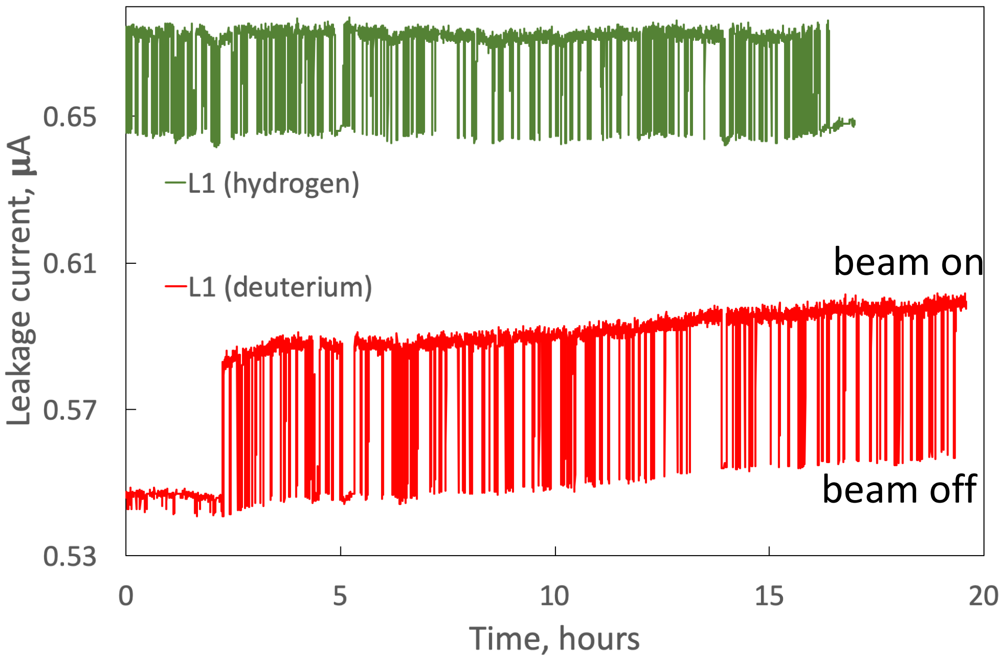


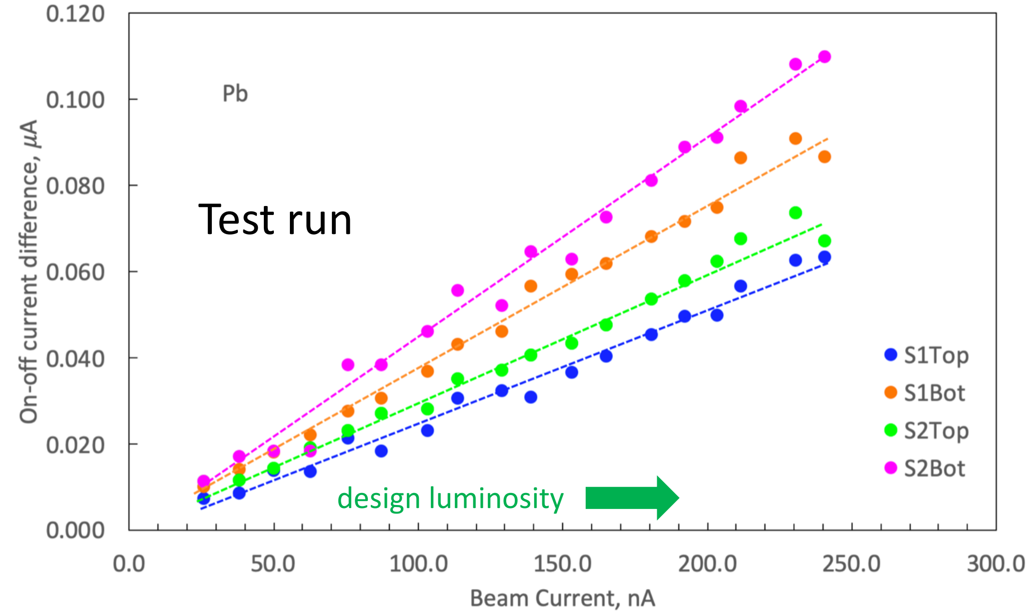
Temperature sensor (hybrid, each side)

Installation in the Experimental Hall



Sensor Leakage Currents and Fluence Estimates





Fluence estimates from increase of the SVT sensor leakage currents

CLAS production runs

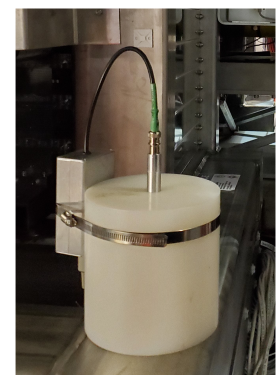
- 2017÷2019 physics runs:
  - 1.5×10^{11} 1 MeV neq cm^{-2}
- 2019 February - March liquid deuterium run:
  - 1.3×10^{8} 1 MeV neq cm^{-2} per hour

Expected SVT operating conditions:

- Accumulated dose (< 10^{14} 1 MeV neq cm^{-2})
- Occupancies (<2%)
- S.N.R. (>10)

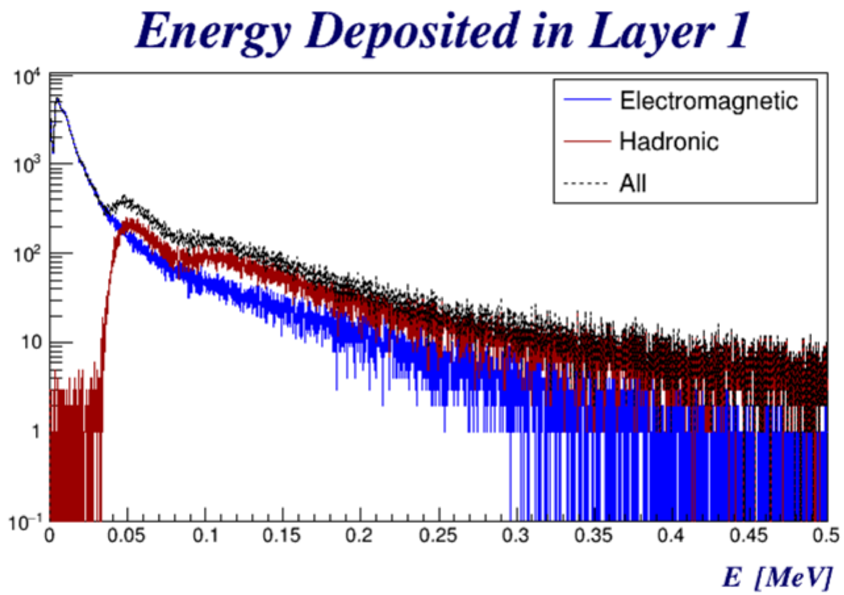
Radiation test run

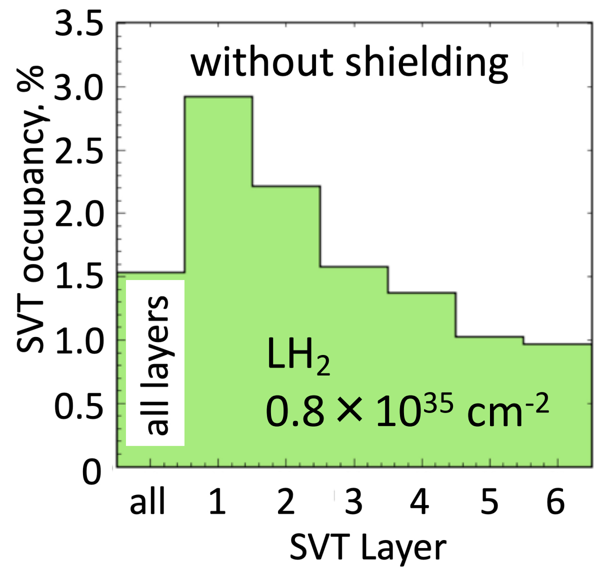
- Liquid deuterium:
  - 5×10^{8} 1 MeV neq cm^{-2} per hour
- Liquid hydrogen:
  - 1.8×10^{8} 1 MeV neq cm^{-2} per hour
- Lead:
  - 4×10^{8} 1 MeV neq cm^{-2} per hour

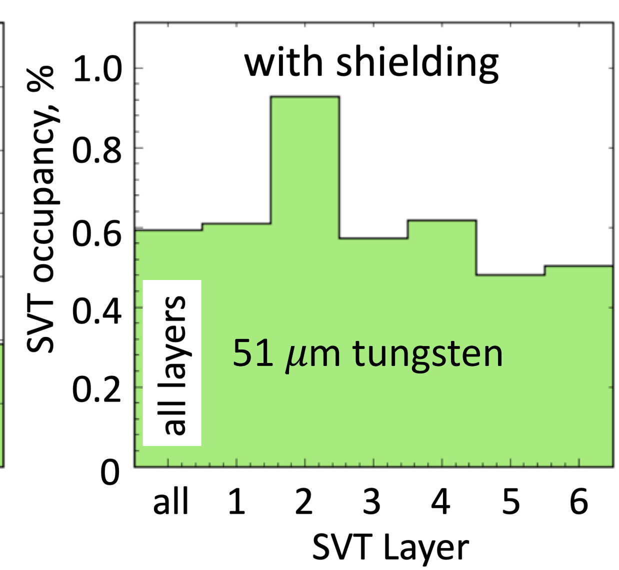


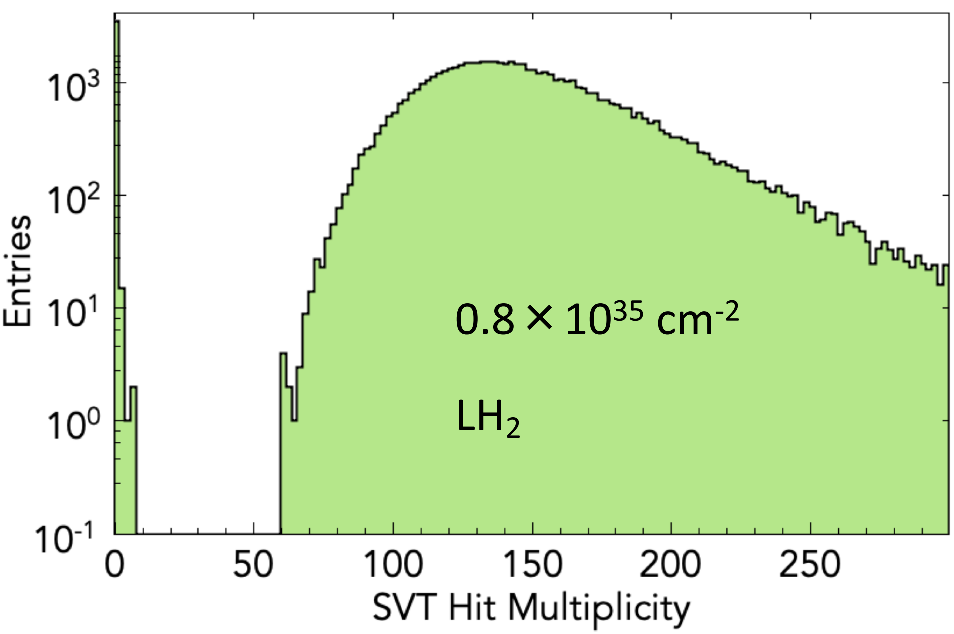
Neutron dosimeter

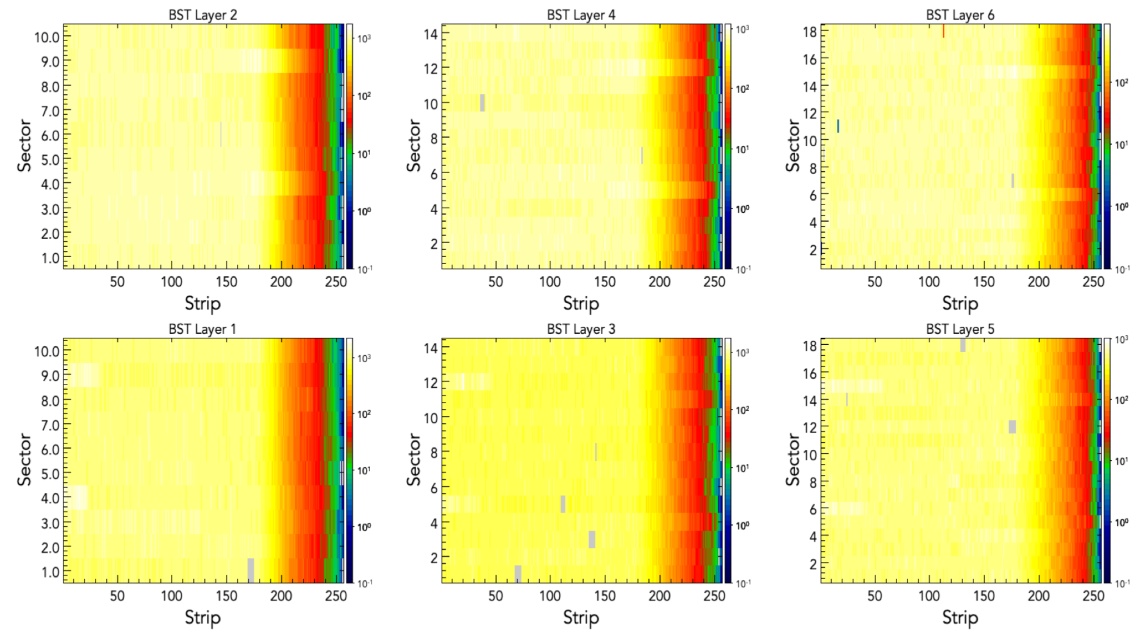
Hit Occupancies







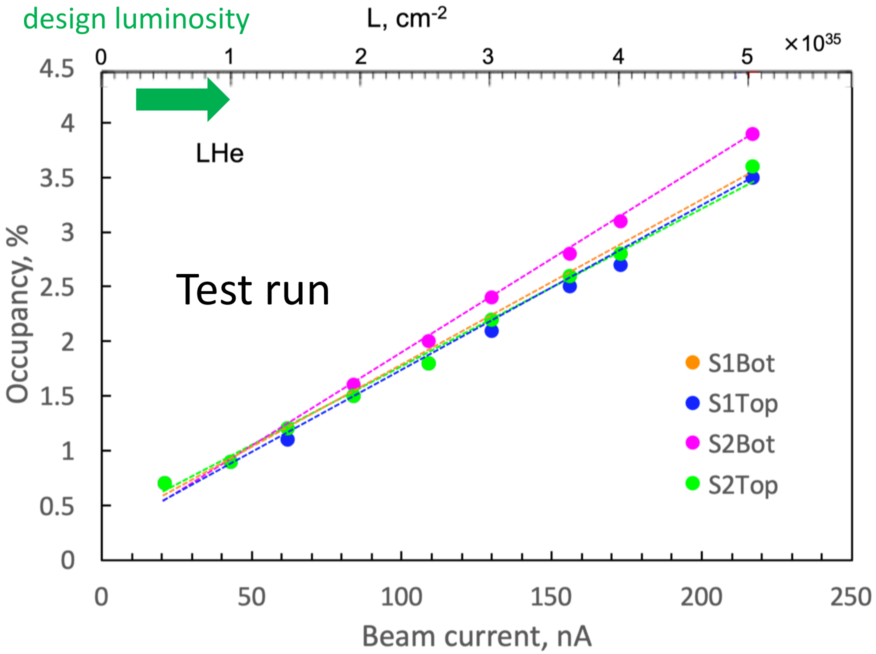


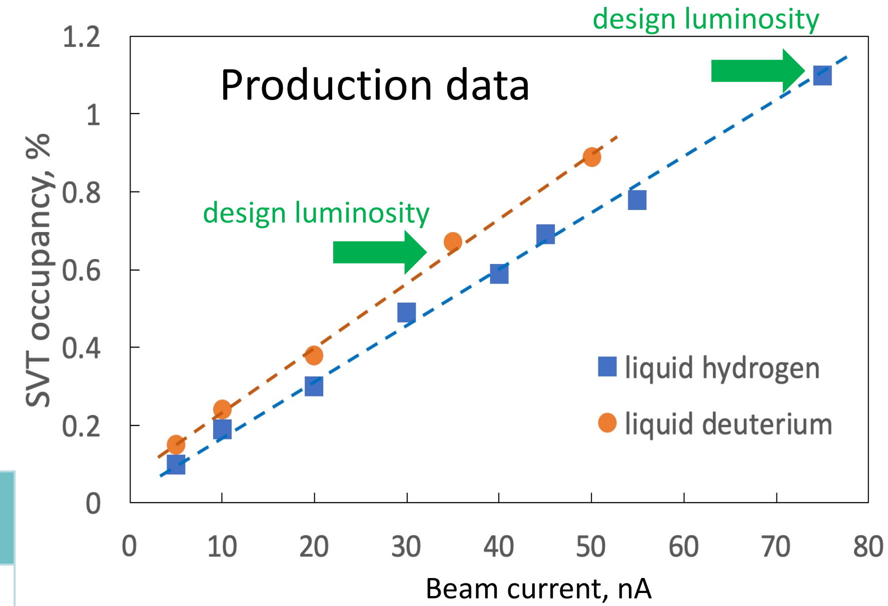


channel status table

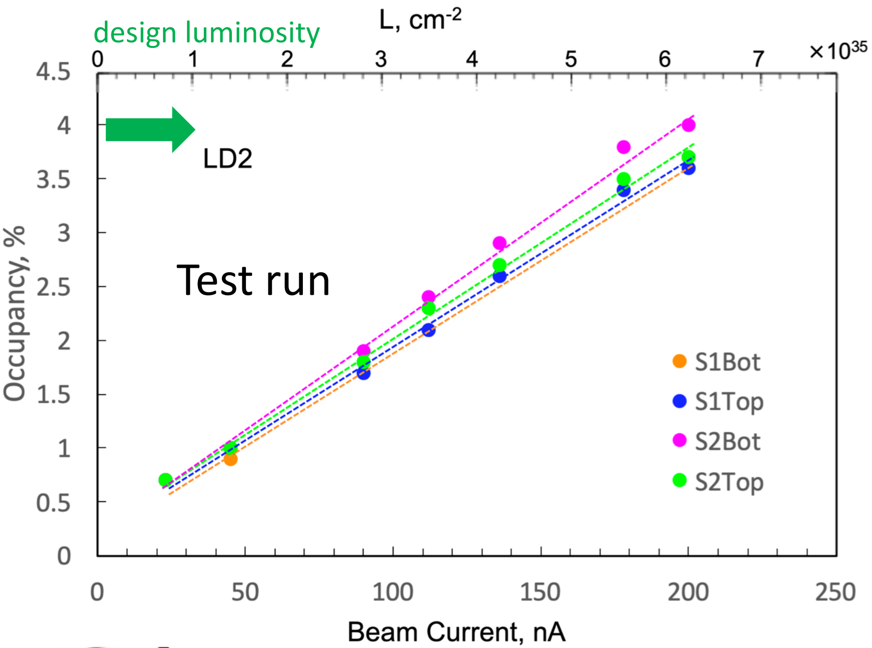
sector	layer	channel	status
4	1	3	0
4	1	4	0
4	1	5	0
4	1	6	0

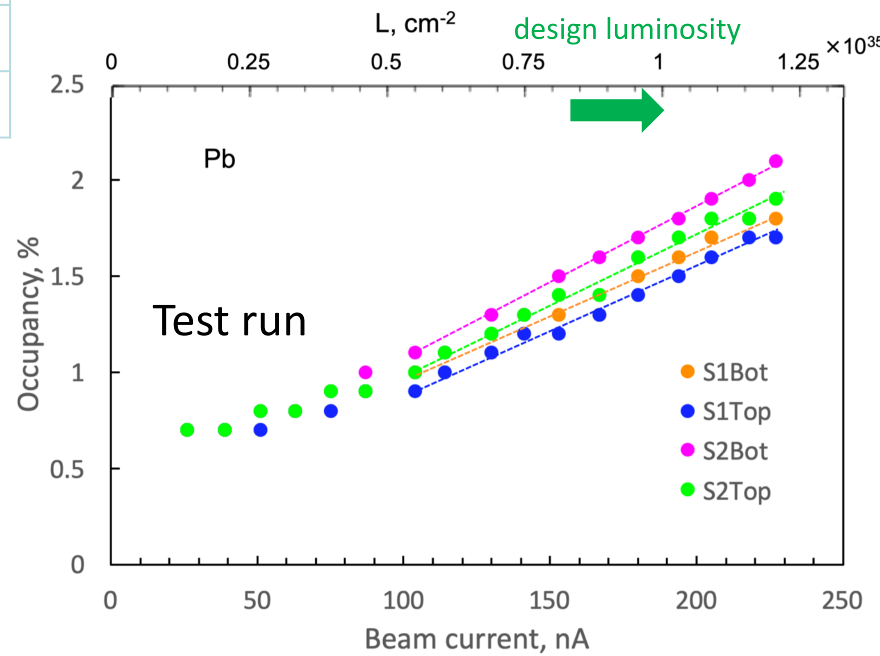
Hit Occupancies



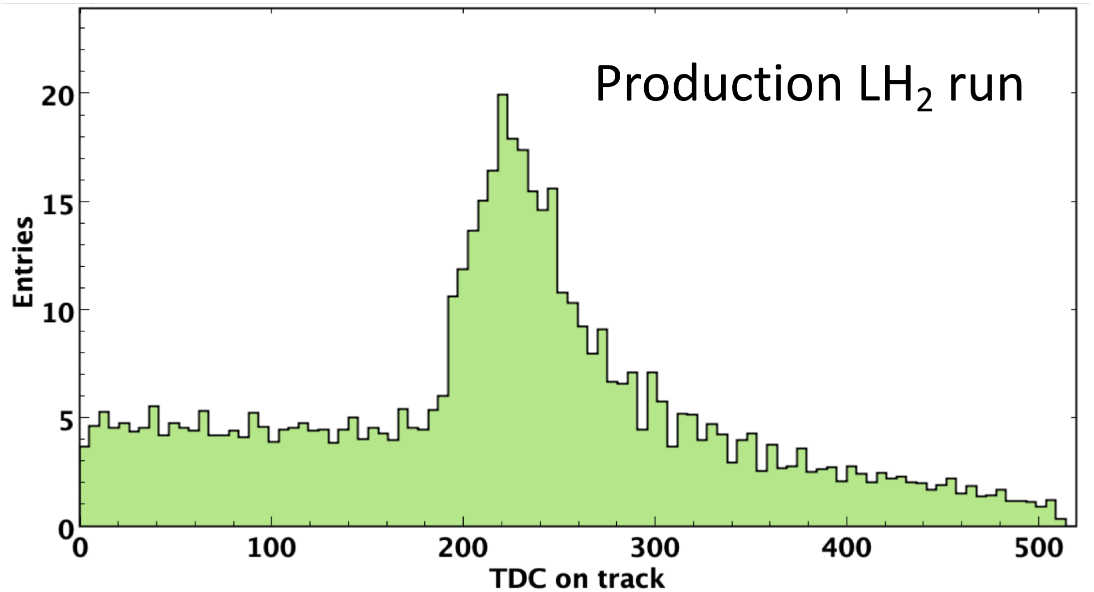


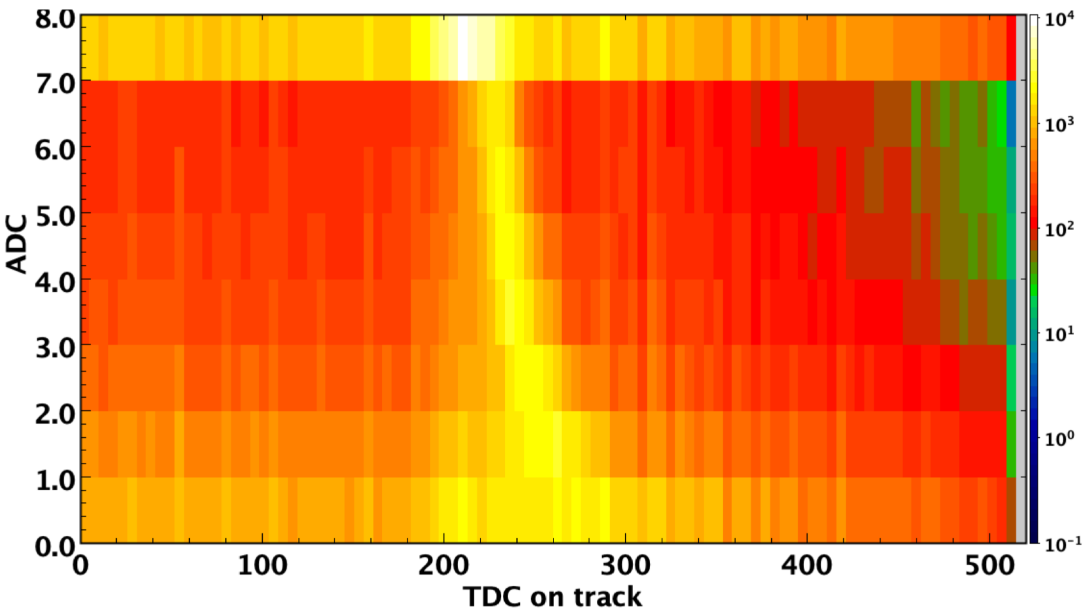
target	X/X_0 %	I, nA $L=10^{35}$
LD_2	0.65	32
LHe	0.66	42.6
Pb	2.2	188





Background Rejection with Hit Timing

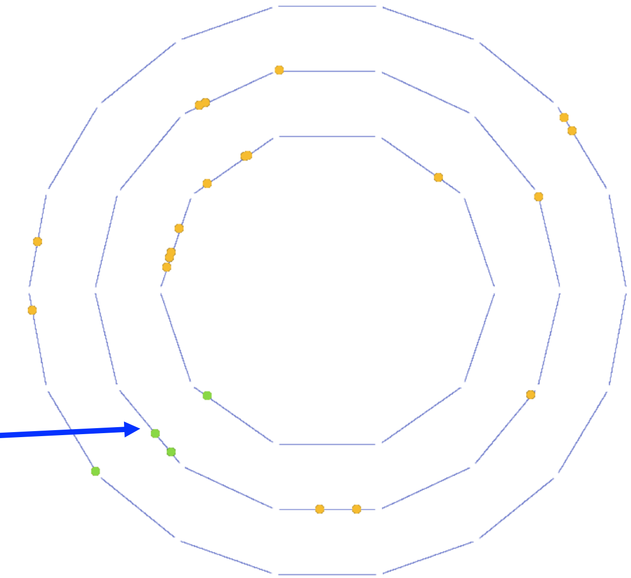




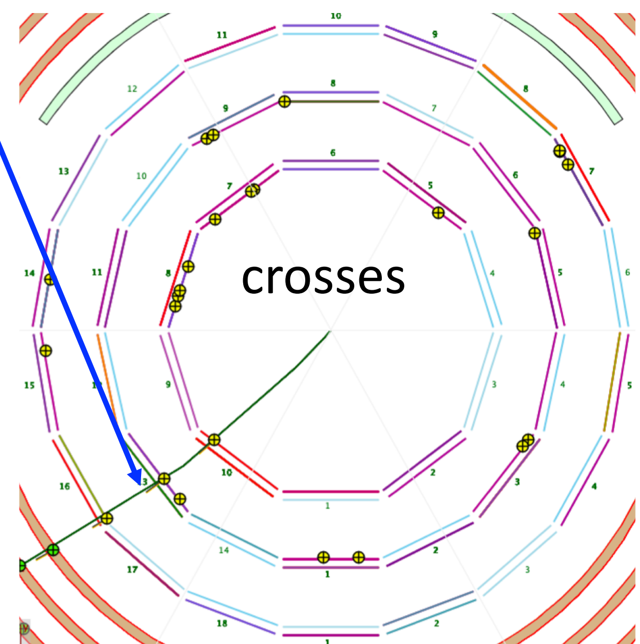
On time

Off time

Track

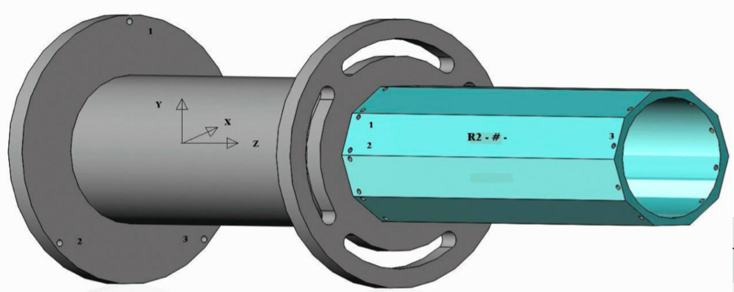


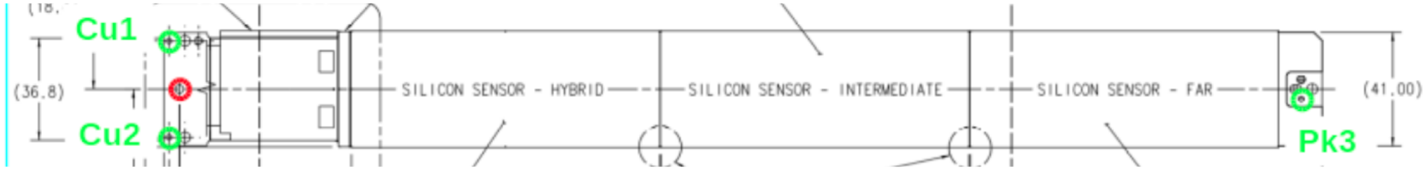
Cross – matched clusters on both sides



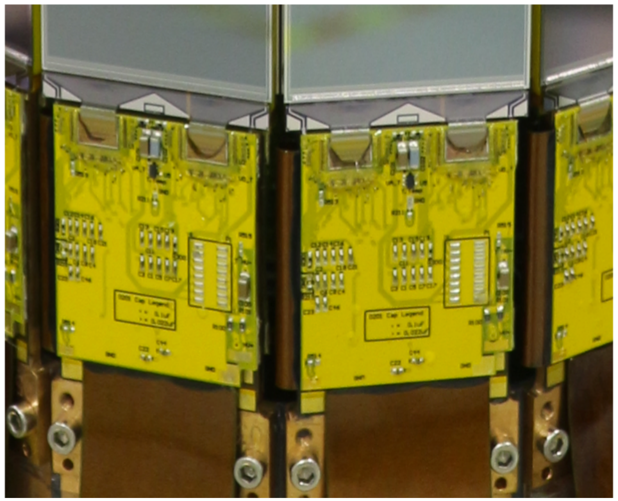
No hit timing in the FSSR2 ➪ TDC is implemented in the VSCM backend readout board

Tracker Survey

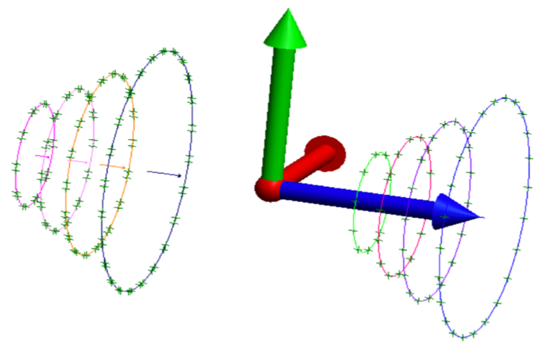


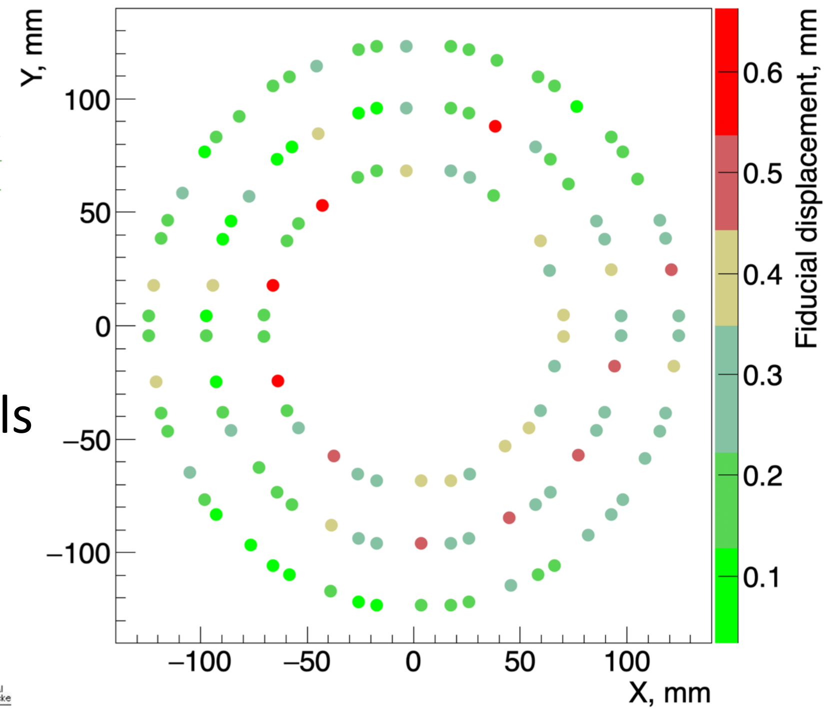


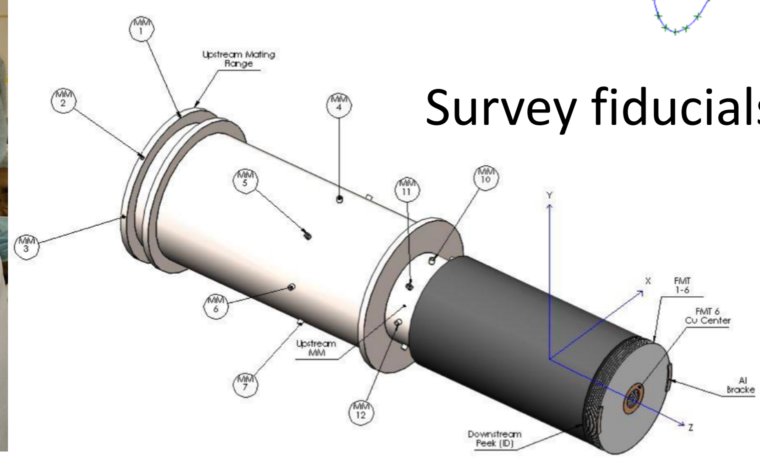
tag	tx	ty	tz	rx	ry	rz	ra
R1S01	0.177	0.184	0.183	0.312	0.000	0.950	0.164
R1S02	0.134	0.100	0.190	0.243	-0.177	0.954	0.102



	Cebaf Coordinates Ideal [μm]			Beam Following [millimeters]			BFS Angular [degrees]		
Component	ideal X	ideal Y	ideal Z	bfs dx	bfs dy	bfs dz	dYaw	dPitch	dRoll
TARGET	-80.60000	103.35526	-398.82153	0.13	-0.31	-29.97	0.0012	-0.0043	-0.0198
SVT	-80.60000	103.35526	-398.82153	-0.03	-0.38	-0.17	0.0083	-0.0115	0.0120

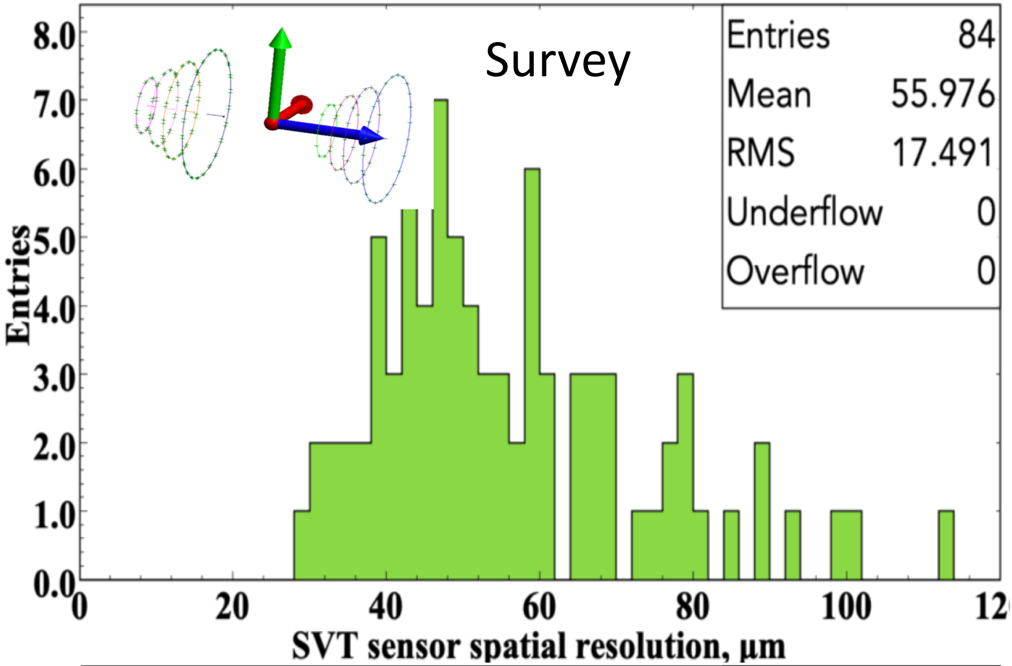


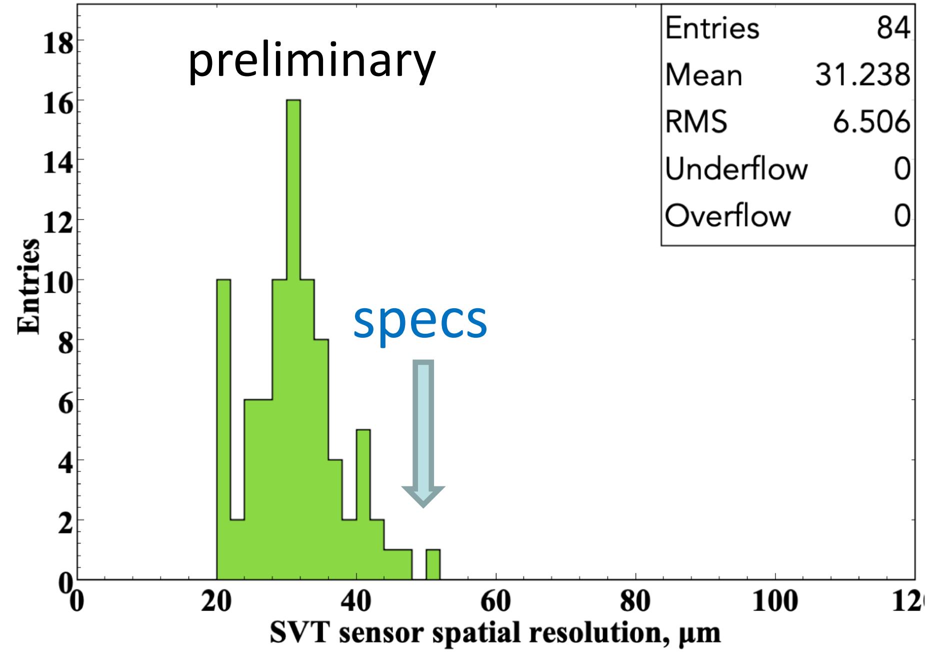


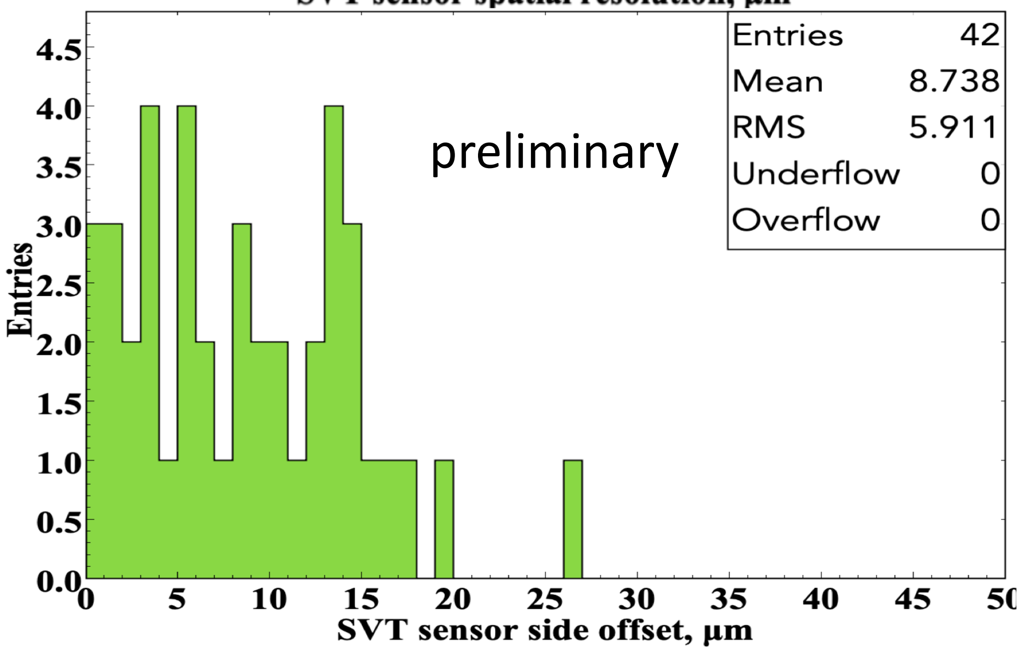


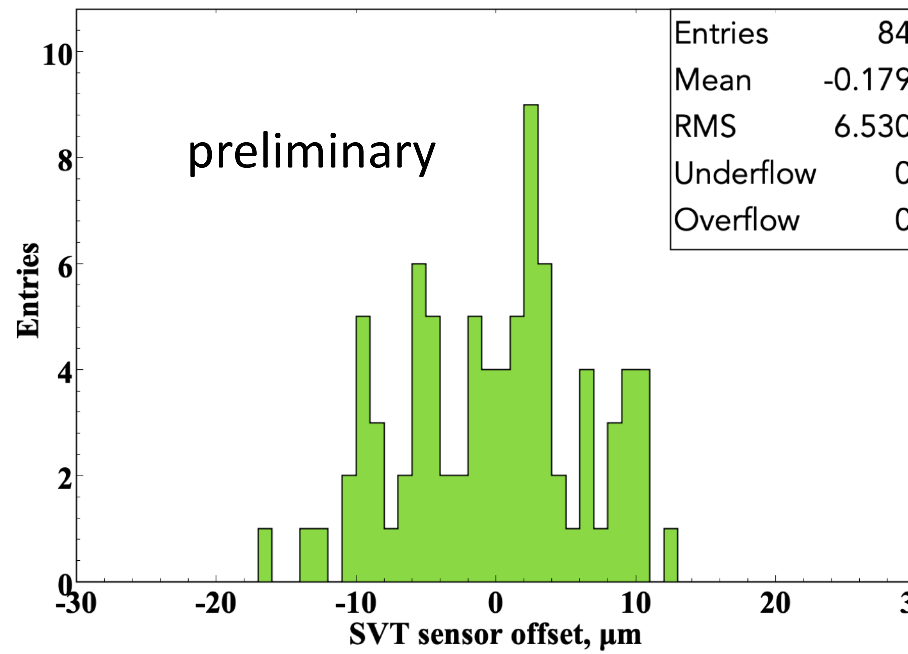
Survey fiducials

SVT Preliminary Alignment



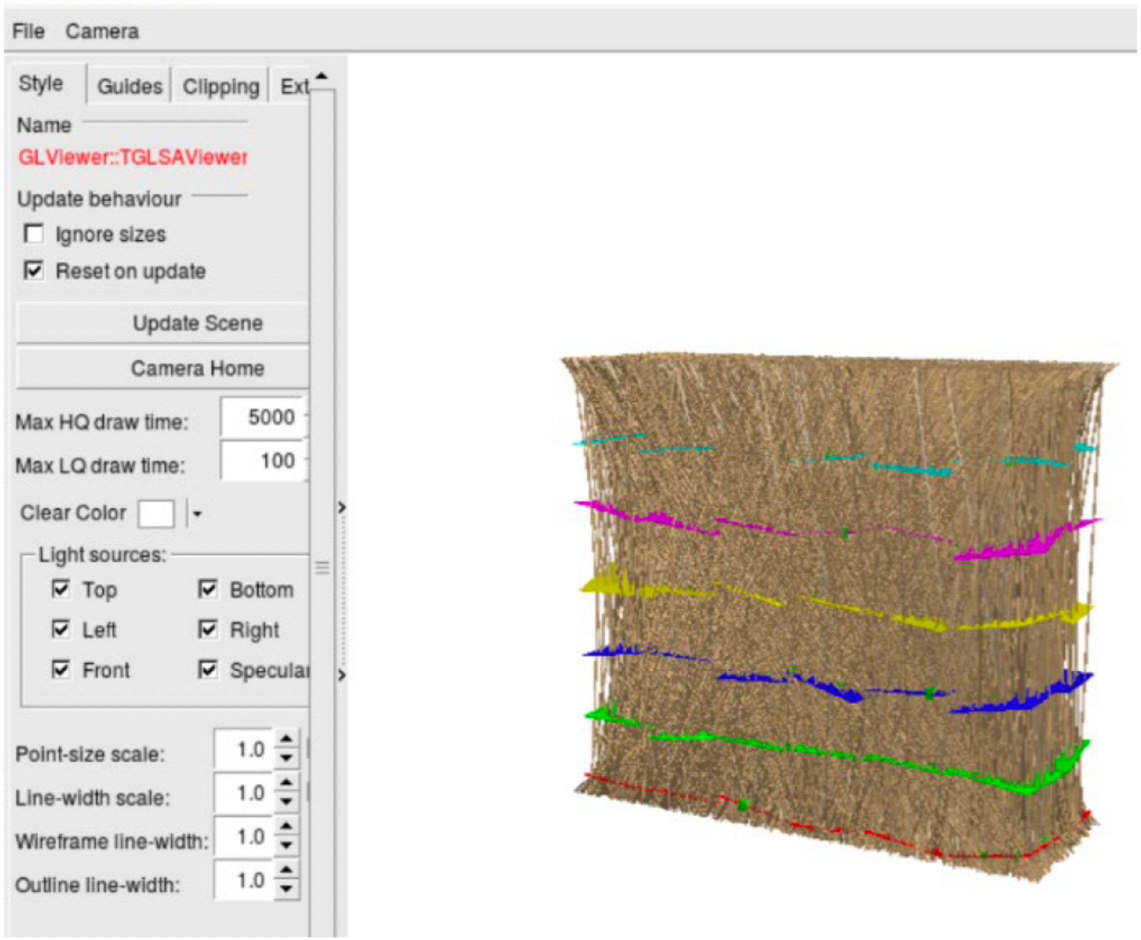


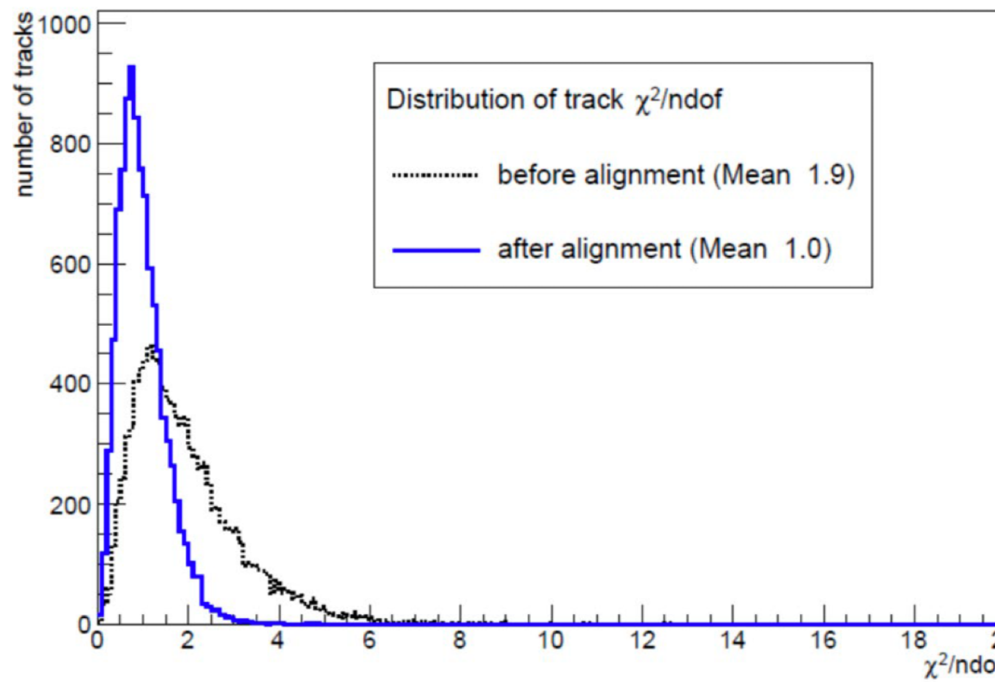




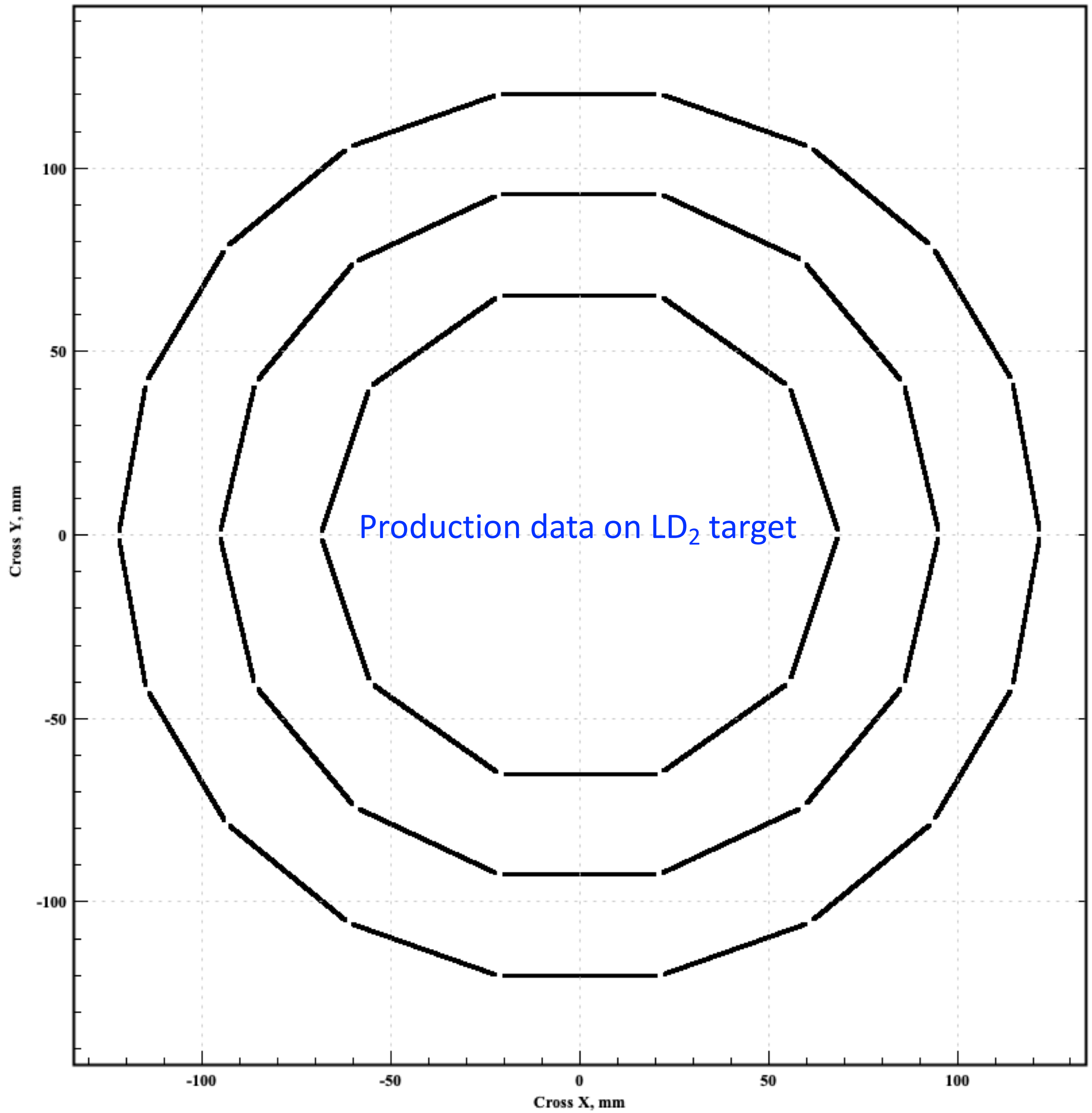
Alignment Algorithm

Alignment procedure based on the open source (GPL) project developed by the CMS:
https://kalmanalignment.hepforge.org
Experiment-independent algorithm based on the Kalman Filter.
The project contains a simulation package, the alignment algorithm, and a validation package.
The data-driven validation package shows track χ^2 improvement after alignment.

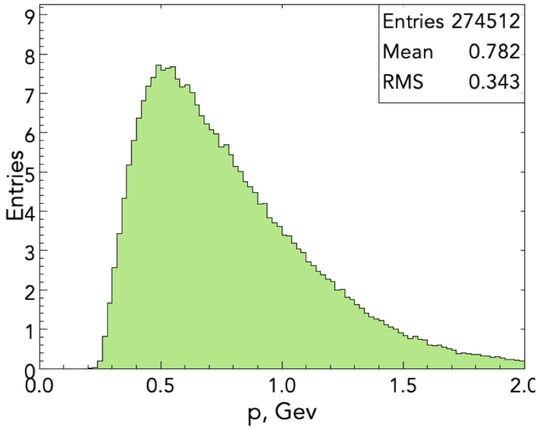


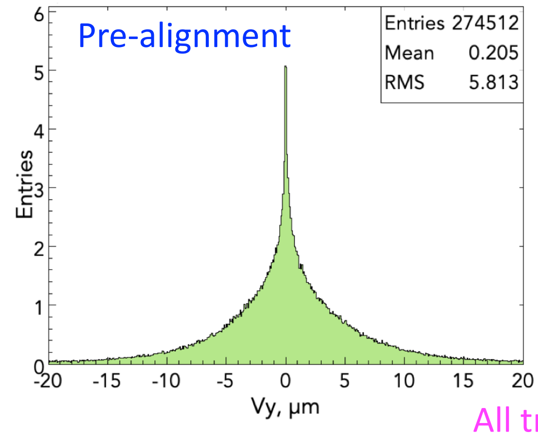


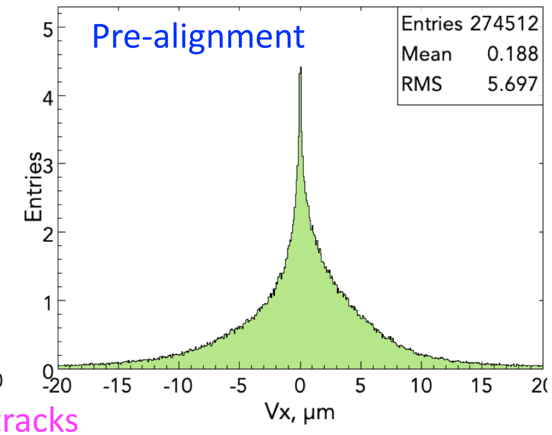
XY Projection of the Reconstructed Crosses

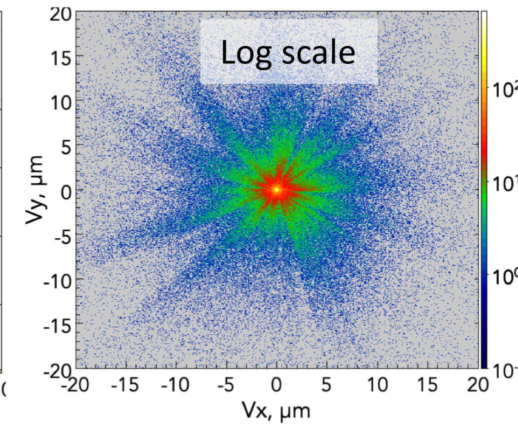


SVT Standalone Tracking Performance

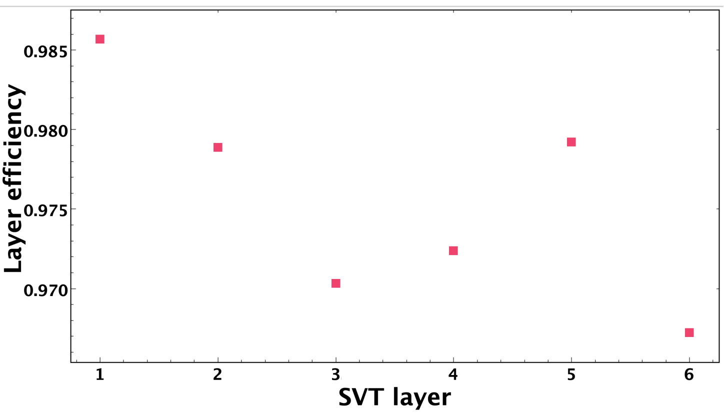


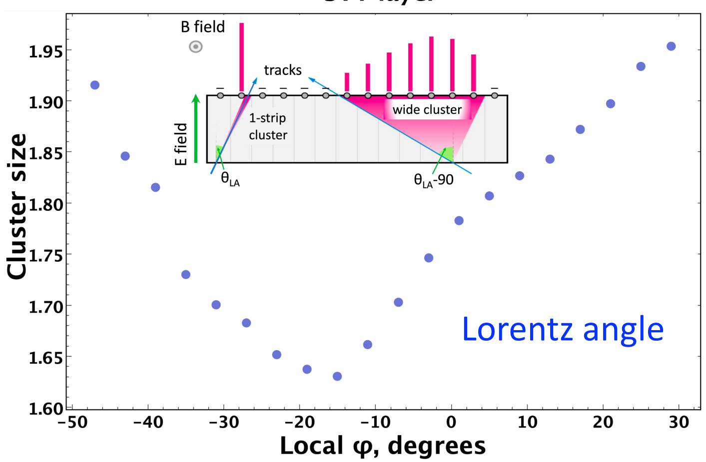


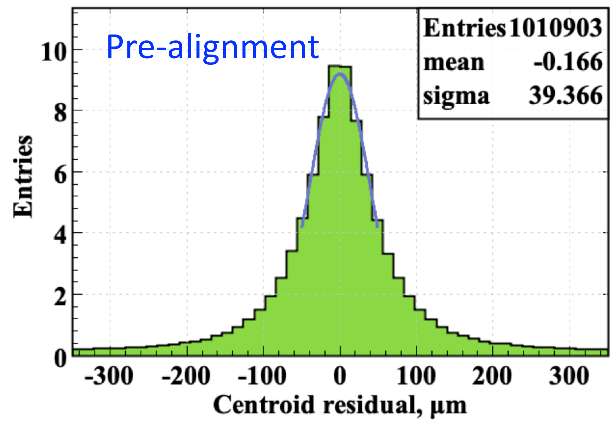


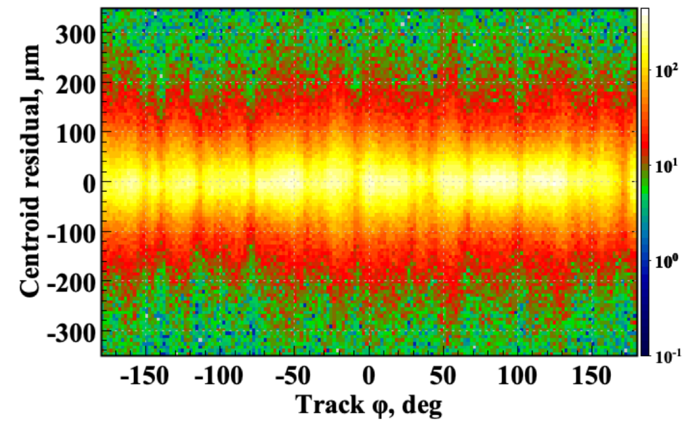


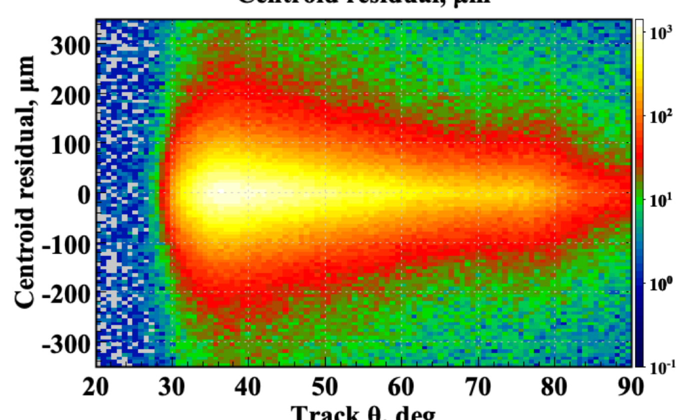
All tracks

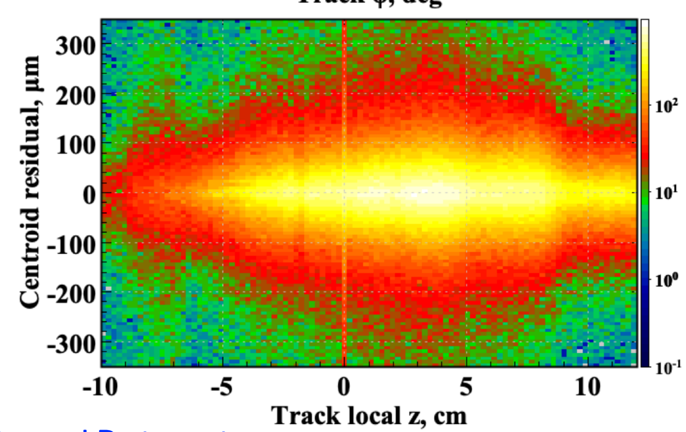






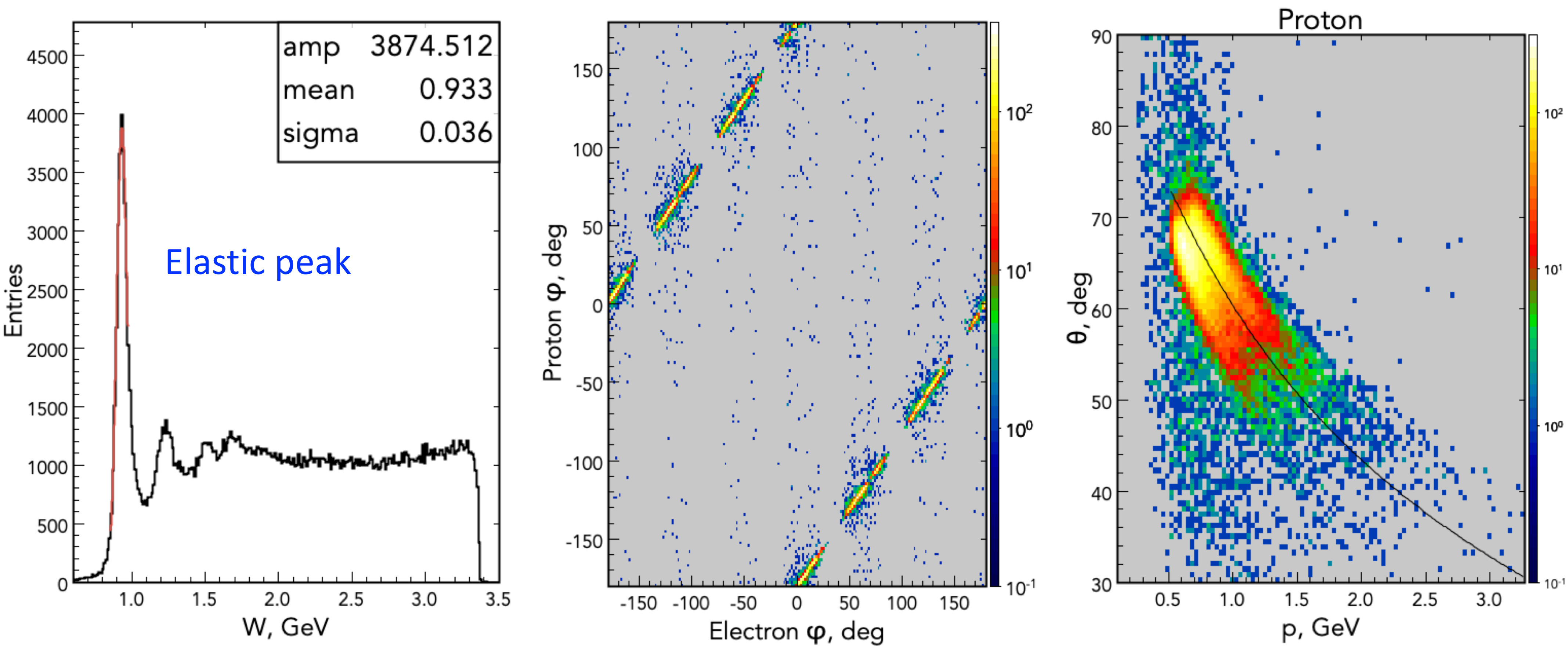






Production data on LD_2 target

Validation of SVT Tracking on 6 GeV Elastic Data



Azimuthal angle correlation between the forward electron and the central proton

Summary and Conclusions

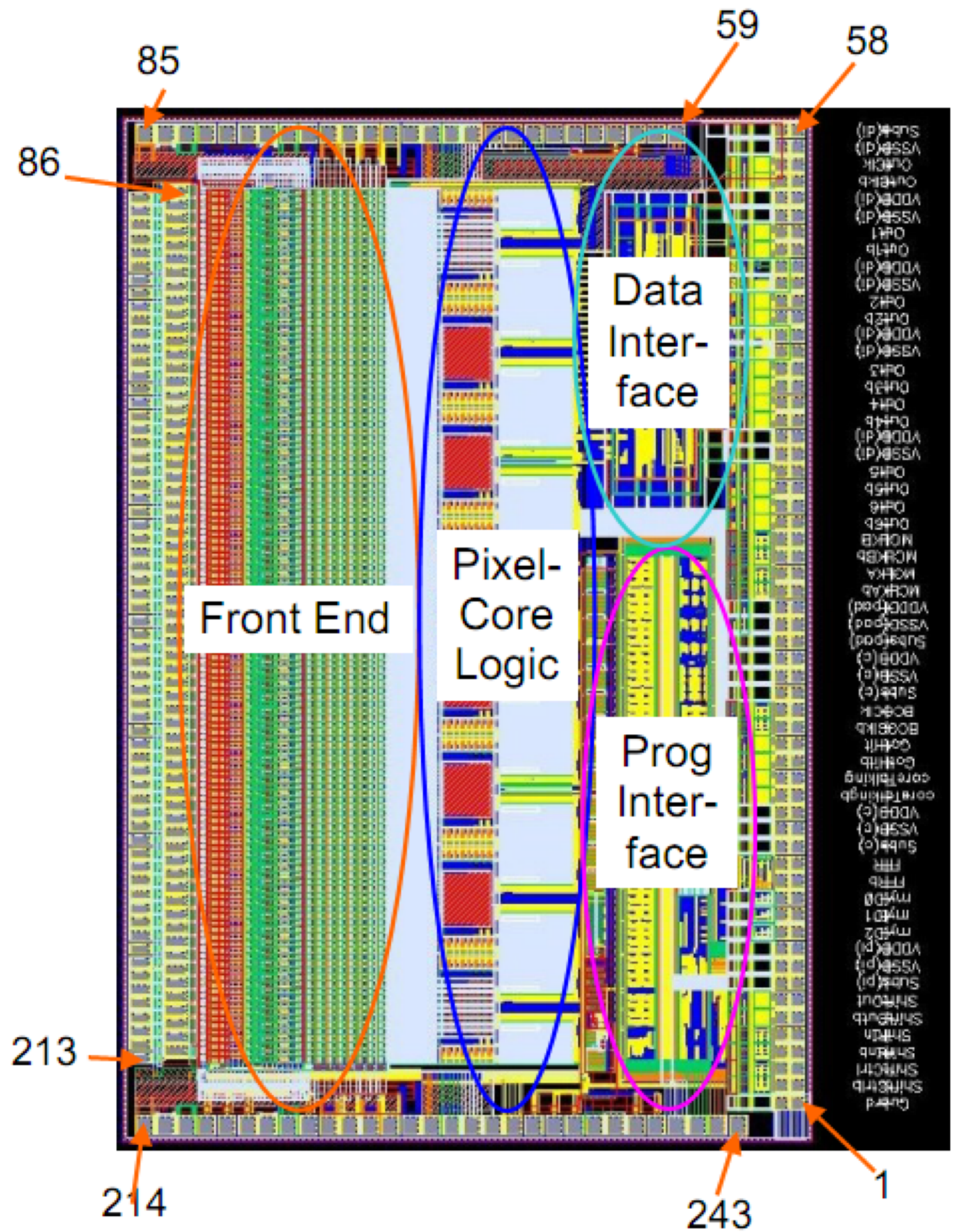
- Novel SVT design concepts successfully tested by operational experience
- Detector is fully calibrated and commissioned, no extra noise after integration
- SVT performance is better than the physics requirements
- All technical specs have been met
- SVT modules, DAQ, and services are fully functional
- Number of operational channels 99.8%
- Stable operation in production runs at design luminosity
- No Single Event Effect readout or data corruption issues were observed
- Radiation damage rates are acceptable
- Preliminary tracker alignment performed on cosmics and beam data
- Acquired operation experience during the 2 years of data taking

Parameter	Performance
Sensor spatial resolution	30 μm
Sensor S.N.R.	15
Internal alignment (preliminary)	10 μm
Transverse vertex resolution	< 5 μm

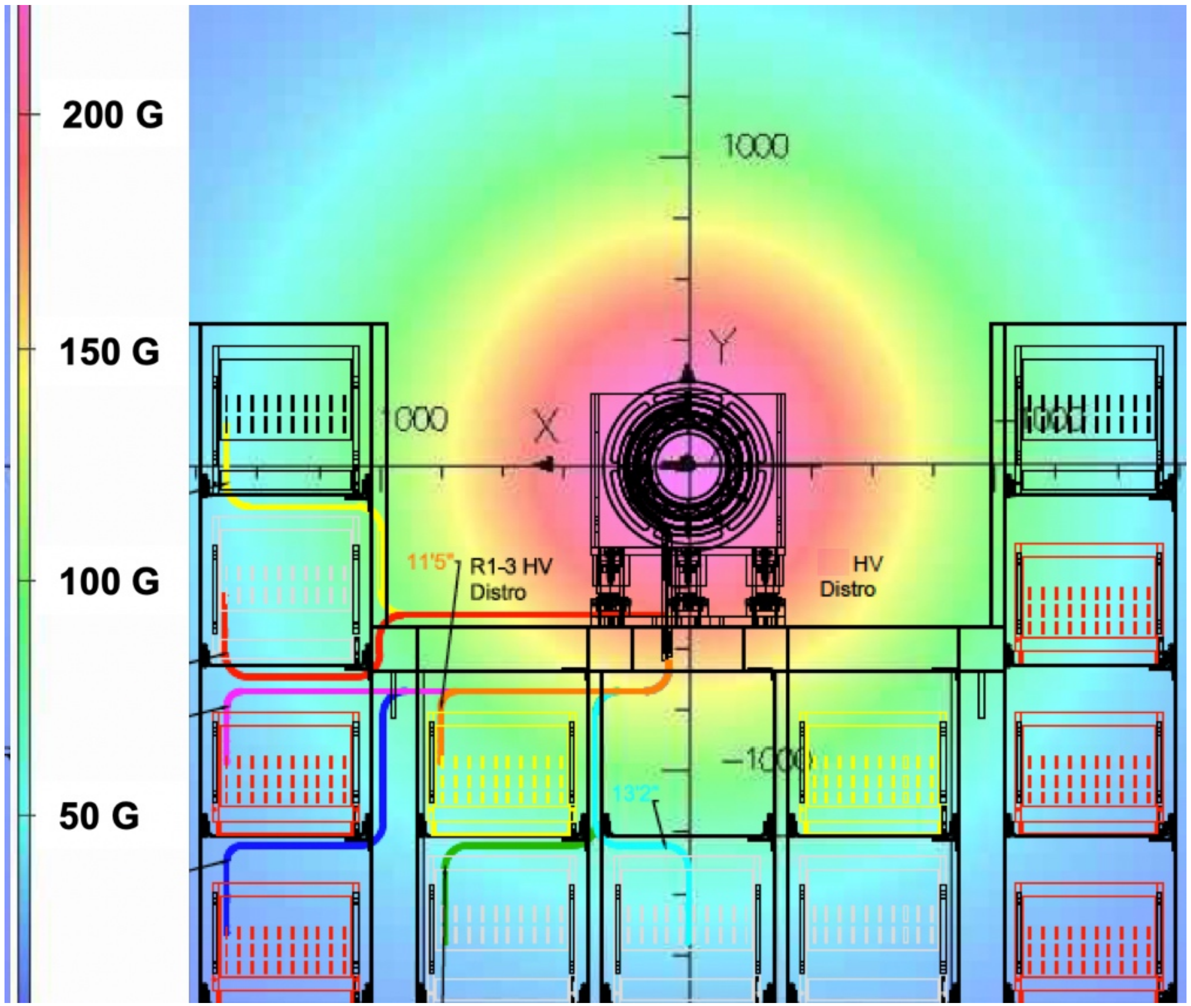
BACKUP

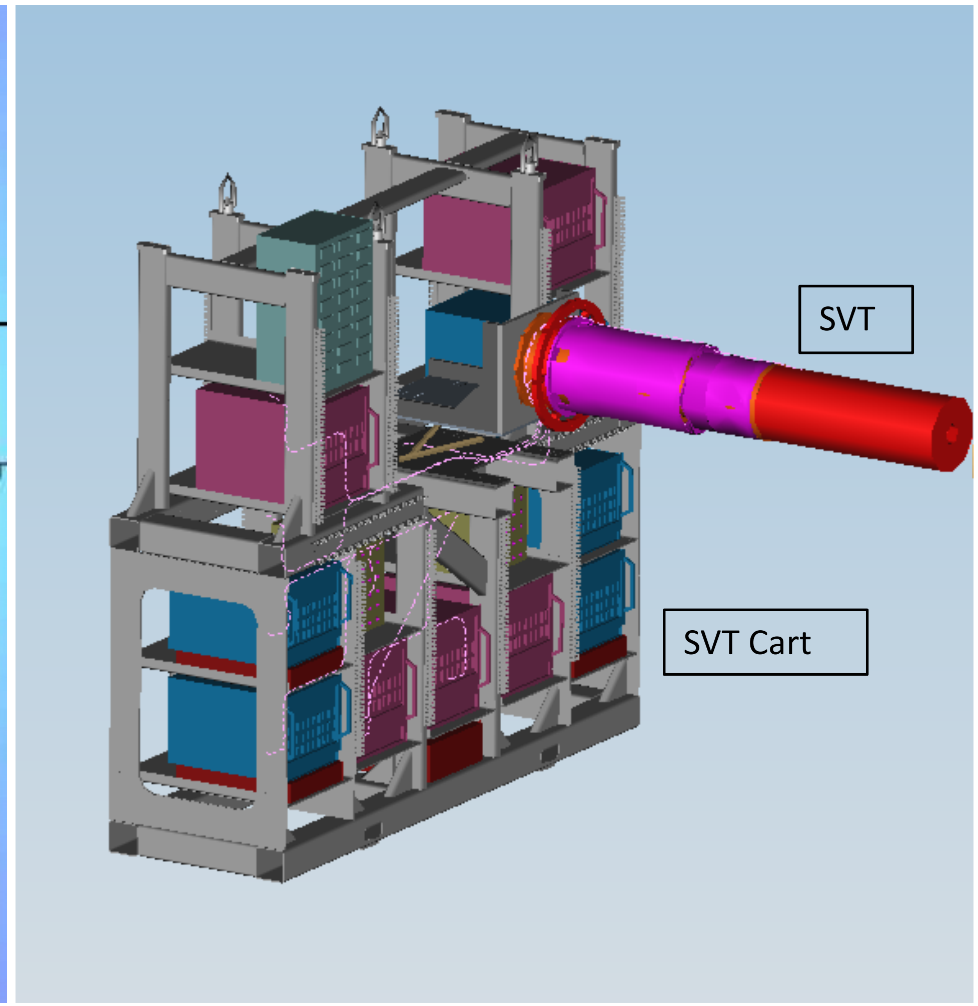
System Overview: Readout Chip

- **Fermilab Silicon Strip Readout Chip**
- 128 channels / chip, 50 µm input pitch
- Data-driven architecture - self-triggered
- 1 MHz input rate with < 2% missed
- Beam Cross Over (BCO) clock 128 ns
- DAQ synchronized with timestamp clock
- Zero-suppressed data readout
- 1-6 programmable serial outputs
- Double Data Rate (DDR) output
- Maximal data output rate 840 Mbits/s
- Anticipated data rate 200 Mbits/s
- Data readout clock 70 MHz
- 24 bit data format for 'hit' channel
  - 12 bit Address
  - 8 bit BCO clock counter
  - 3 bit ADC
  - 1 Sync
- Power consumption < 4 mW / channel
- 2.5 V supply separated on chip
- Radiation hardness 5 Mrad



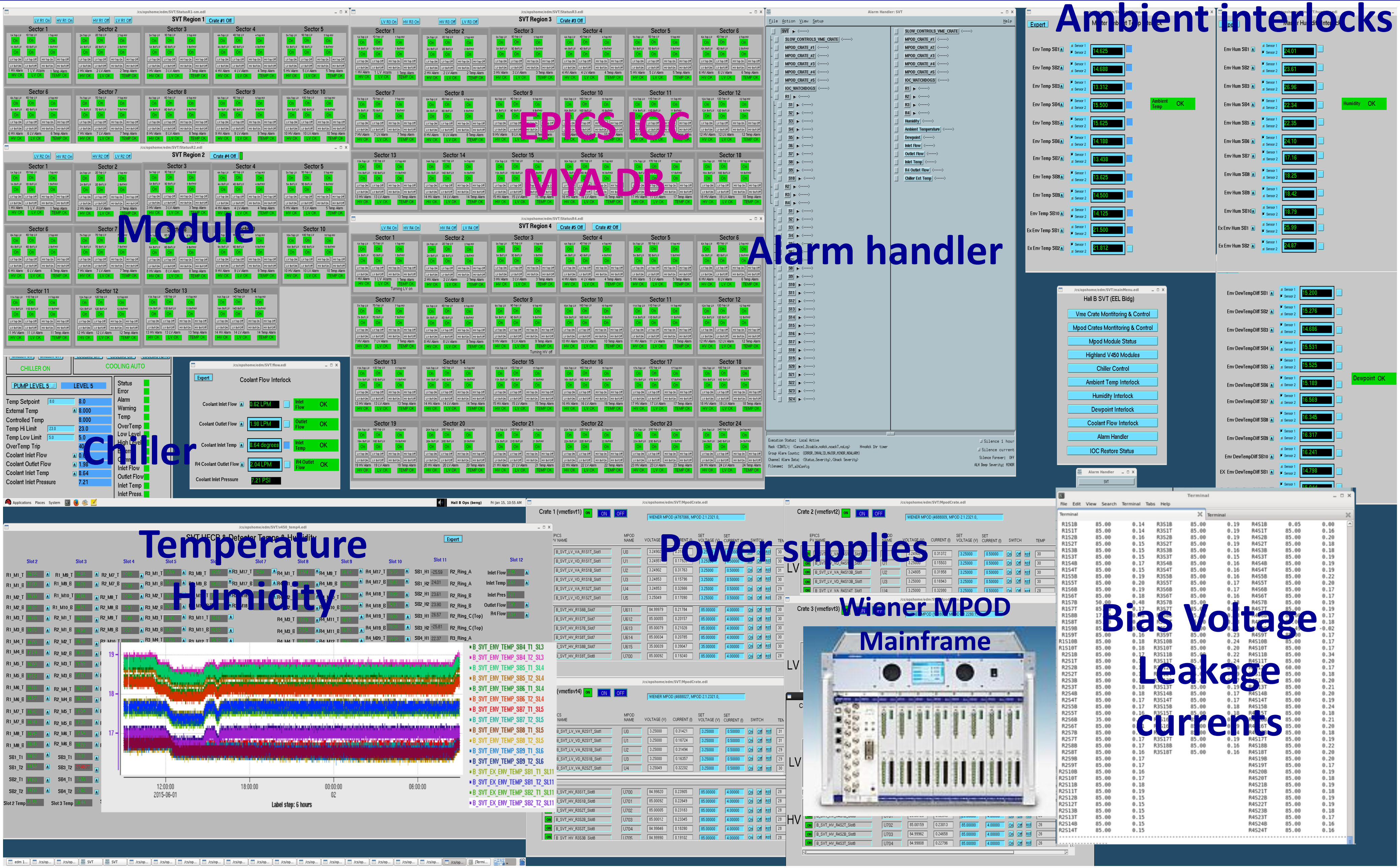
Solenoid Field Map at the Service Cart



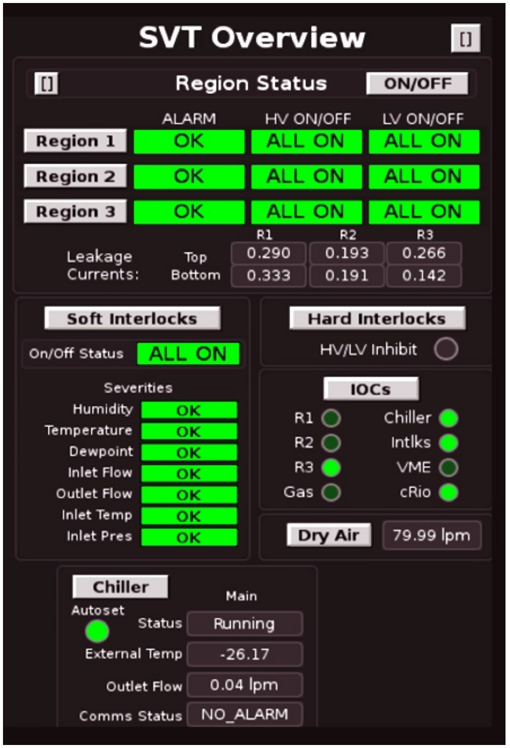


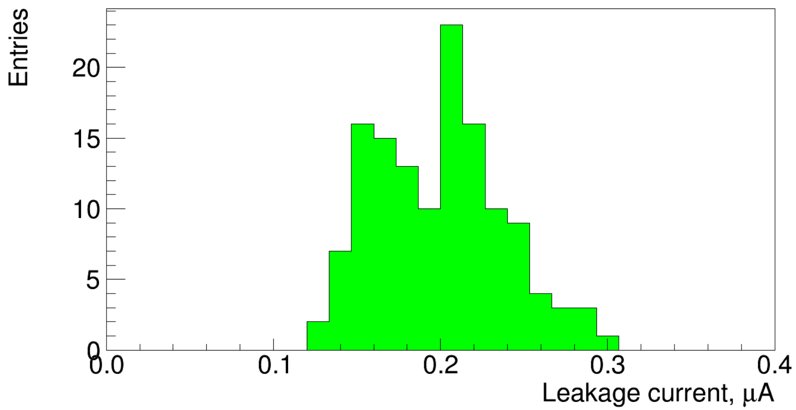
Crates are within the safe limits

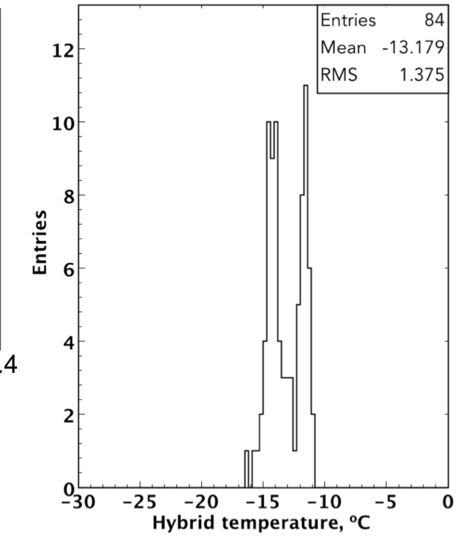
Slow Controls and Monitoring

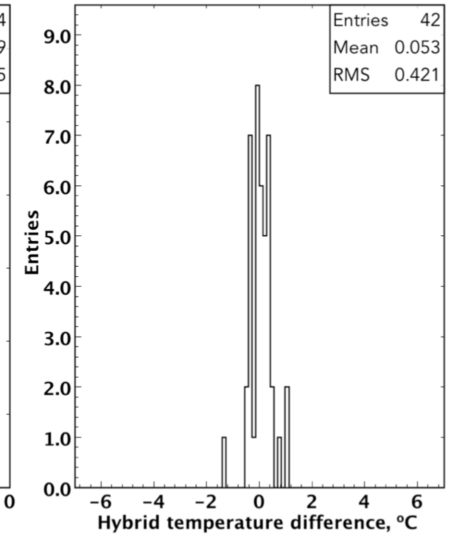


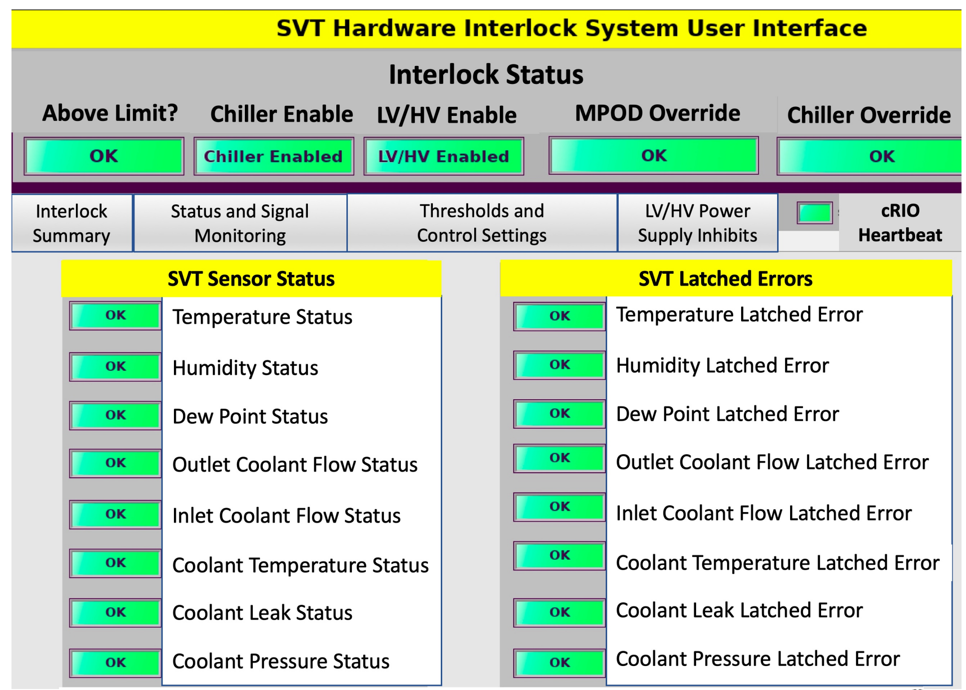
Monitoring and Interlocks

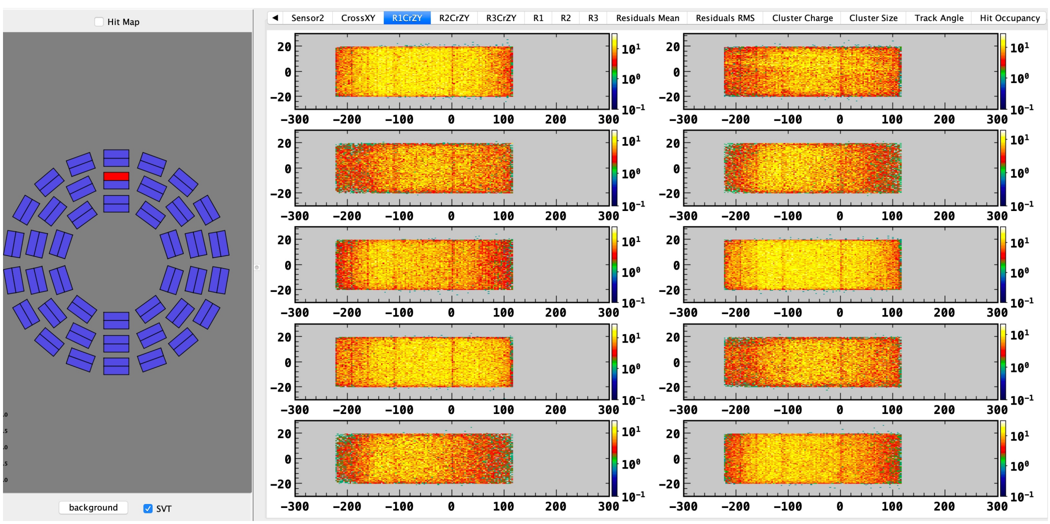












Fluence Rate Estimate

During the runs at constant luminosity the following changes in the sensor leakage currents were registered (normalized to 20°C):

- **liquid deuterium target, 157 nA, 4.9×10^{35}cm^{-2}, 283 min:** 365 nA (top), 413 nA (bottom)
- **liquid helium target, 108 nA, 2.5×10^{35}cm^{-2}, 249 min:** 110 nA (top), 120 nA (bottom)
- **lead target, 257 nA, 1.4×10^{35}cm^{-2}, 204 min:** 210 nA (top), 228 nA (bottom)

Temperature scaling of the leakage current to room temperature is done with:

$$I(20^{\circ}C) = I(T) \times R(T); R(T) = (293K/T)^2 \cdot e^{(-E/k(1/293K-1/T))}, \quad (1)$$

where E=1.4 eV.

The accumulated fluence is estimated with [9]:

$$\Phi = \Delta I/(V \times \alpha), \quad (2)$$

where ΔI is the change in leakage current, V is the volume of the sensor, and α(T=20°C)=4×10^{-17} A/cm. V=4 cm×33 cm×0.03 cm≈4 cm^3.

Running conditions of the SVT to ensure stable operation of the detector with tracking performance meeting the technical specs require hit occupancy below 2%, signal-to-noise ratio above 10 and accumulated fluence below 10^{14} 1 MeV neq cm^{-2}.

- **liquid deuterium target:** 2.3×10^9 1 MeV neq cm^{-2} (top), 2.6×10^9 1 MeV neq cm^{-2} (bottom)
- **liquid helium target:** 6.9×10^8 1 MeV neq cm^{-2} (top), 7.5×10^8 1 MeV neq cm^{-2} (bottom)
- **lead target:** 1.3×10^9 1 MeV neq cm^{-2} (top), 1.4×10^9 1 MeV neq cm^{-2} (bottom)

Fluence rate:

- **liquid deuterium target:** 4.9×10^8 1 MeV neq cm^{-2} per hour (top), 5.5×10^8 1 MeV neq cm^{-2} per hour (bottom)
- **liquid helium target:** 1.7×10^8 1 MeV neq cm^{-2} per hour (top), 1.8×10^8 1 MeV neq cm^{-2} per hour (bottom)
- **lead target:** 3.8×10^8 1 MeV neq cm^{-2} per hour (top), 4.1×10^8 1 MeV neq cm^{-2} per hour (bottom)

Results of the fluence rate estimates during the nuclear target test are comparable with the ones from the CLAS12 runs. The leakage currents for the unirradiated sensors (normalized to 20°C) were 300 nA. By October 2019 the currents increased to 25 μm.

During the period of 2017–2019 physics runs the accumulated fluence is Φ=$24.7\times10^{-6}/(4\times4\times10^{-17})$ ≈1.5×10^{11} 1 MeV neq cm^{-2}.

During the run on deuterium target in February–March 2019 (46 days×50% beam usage = 23 days or 552 hours):

- **Region 1:** ΔI=18 μA (at 20°C), Φ ≈1×10^{11} 1 MeV neq cm^{-2}
- **Region 2:** ΔI=12 μA (at 20°C), Φ ≈7×10^{10} 1 MeV neq cm^{-2}

The fluence rate in Region 2 sensors was 1.3×10^8 1 MeV neq cm^{-2} per hour, within the uncertainty of the rate estimates for the deuterium target during the nuclear target test.