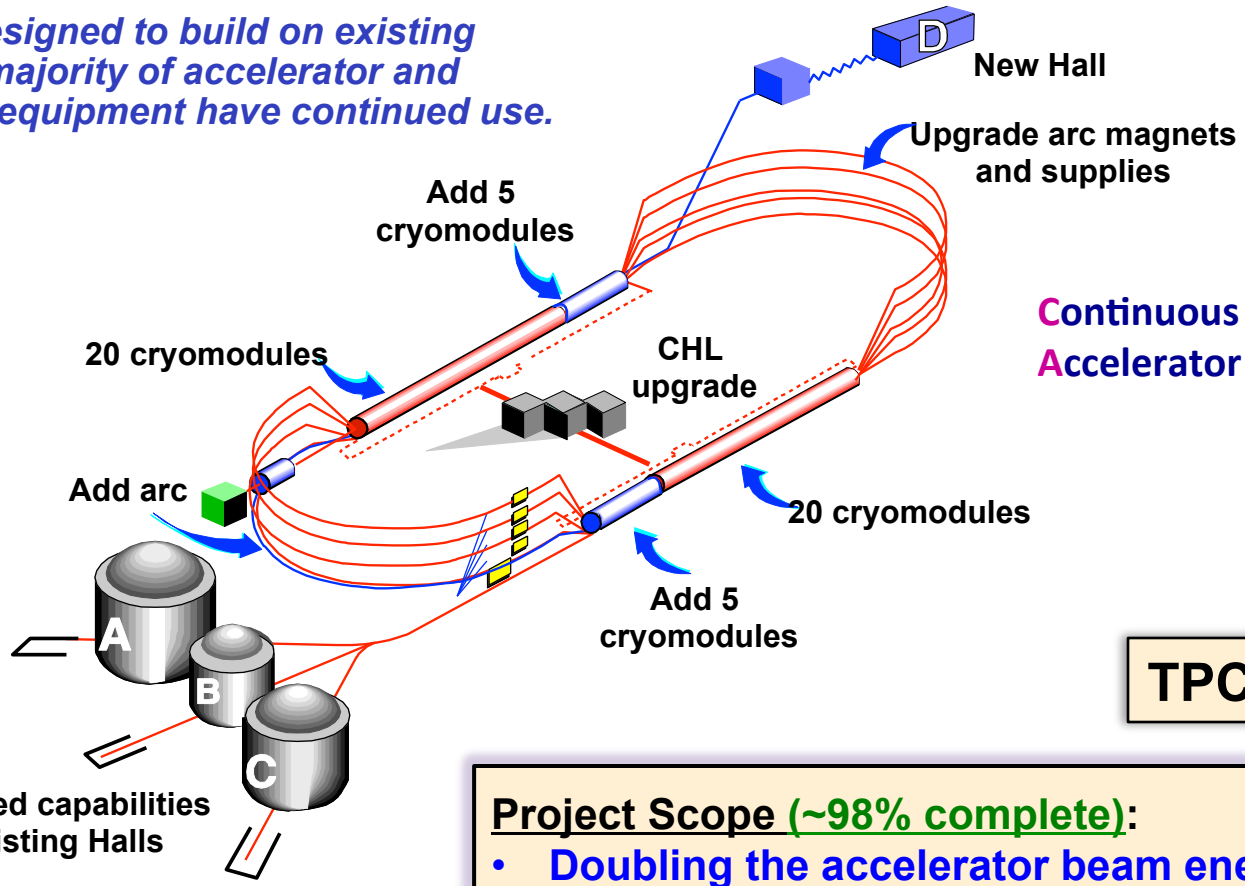
CLAS12 Silicon Vertex Tracker

Yuri Gotra
on behalf of CLAS collaboration

Jefferson Lab - 12 GeV Upgrade Project

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.



Continuous Electron Beam Accelerator Facility CEBAF

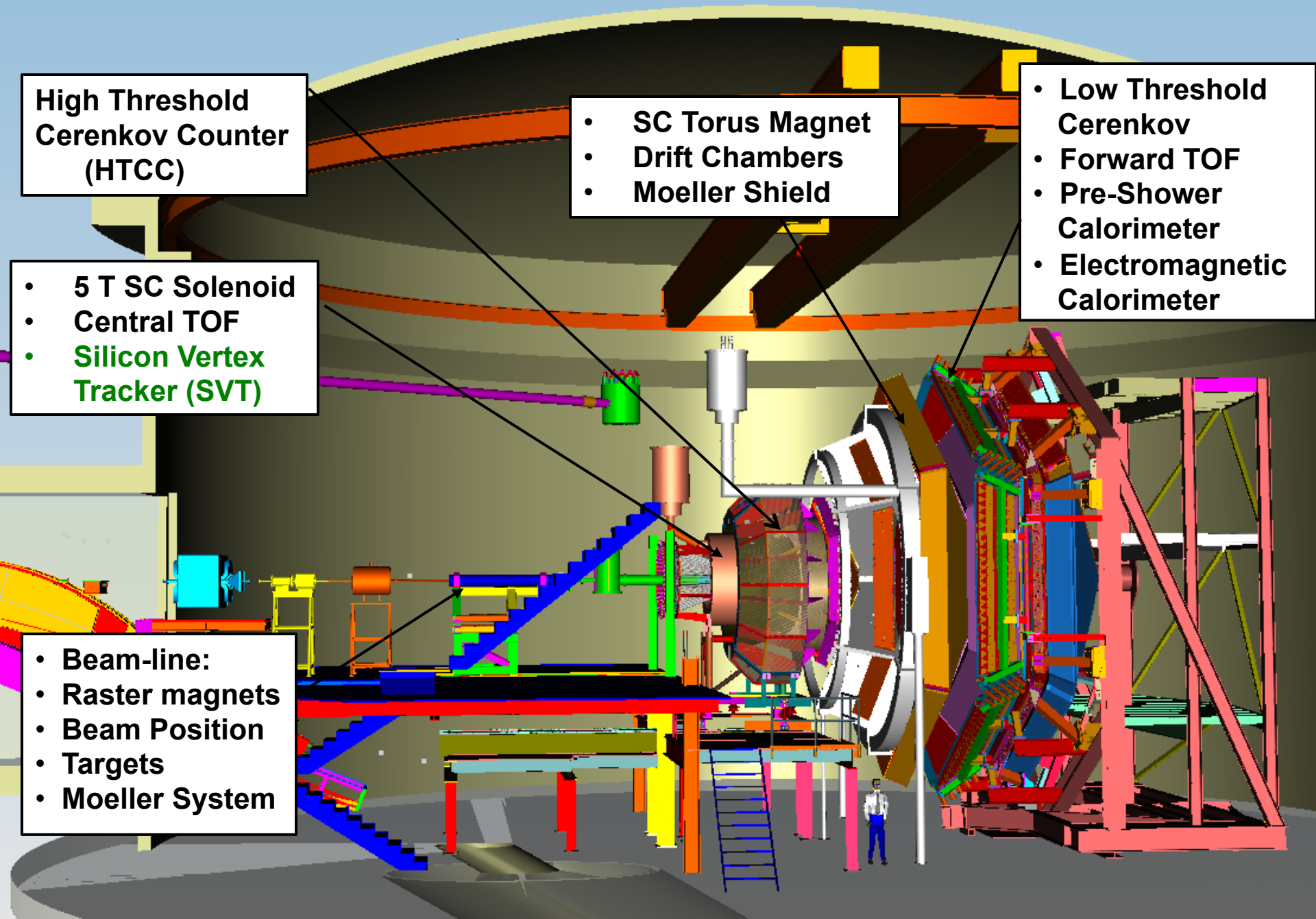
TPC = $338 M

Project Scope (~98% complete):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - DONE
- Upgrades to Experimental Halls B & C - ~97%

Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

CLAS12 in Hall B



CLAS12 SVT Physics Requirements and Technical Parameters

SVT provides standalone tracking capabilities in the central detector region

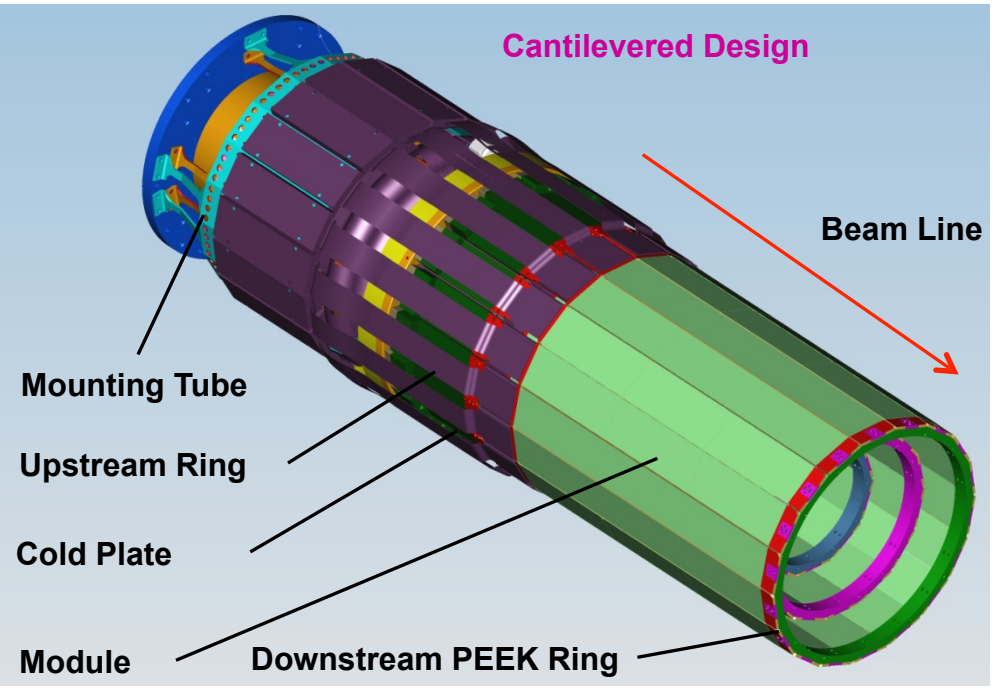
- **Measure recoil baryons & large angle pions, kaons**
- **Match up tracks with hits in the CTOF for β vs. p measurement (particle ID)**

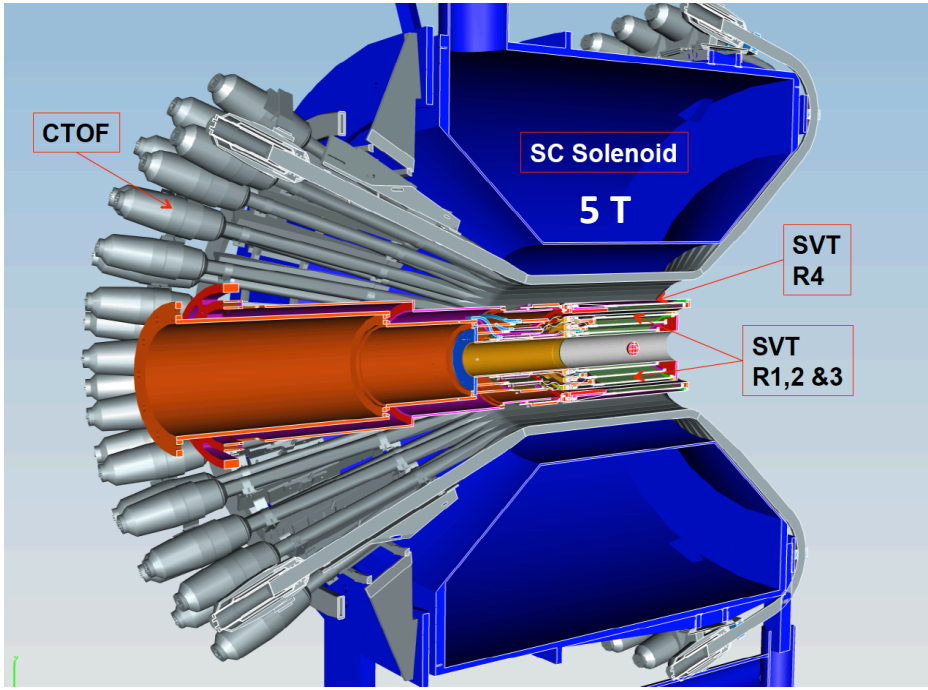
PARAMETER	DESIGN VALUE
Number of regions (radii, mm)	4 (65, 93, 120, 161)
Sectors (modules)/region	10, 14, 18, 24
Module dimensions (L x W x T)	41.9 cm x 4.2 cm x 0.39 cm
Number of silicon layers/module	2 (*U, V*)
Strip layout	(0°— 3°) Graded angle
Sensor thickness	320 µm
Readout pitch	156 µm (hybrid side)
Number of readout channels/module	**512**
Total number of readout channels	**33,792**
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	~6%
θ resolution	10–20 mrad
ϕ resolution	~5 mrad
Tracking efficiency	> 90%
Designed to operate at a luminosity of	10^{35} $cm^{-2}s^{-1}$

Design Solutions

- Four regions (radii 65, 93, 120, 161 mm)
- 1% of radiation length per region
- 66 sectors/modules (10, 14, 18, 24)
- Two concentric barrels (MicroMegas upgrade)

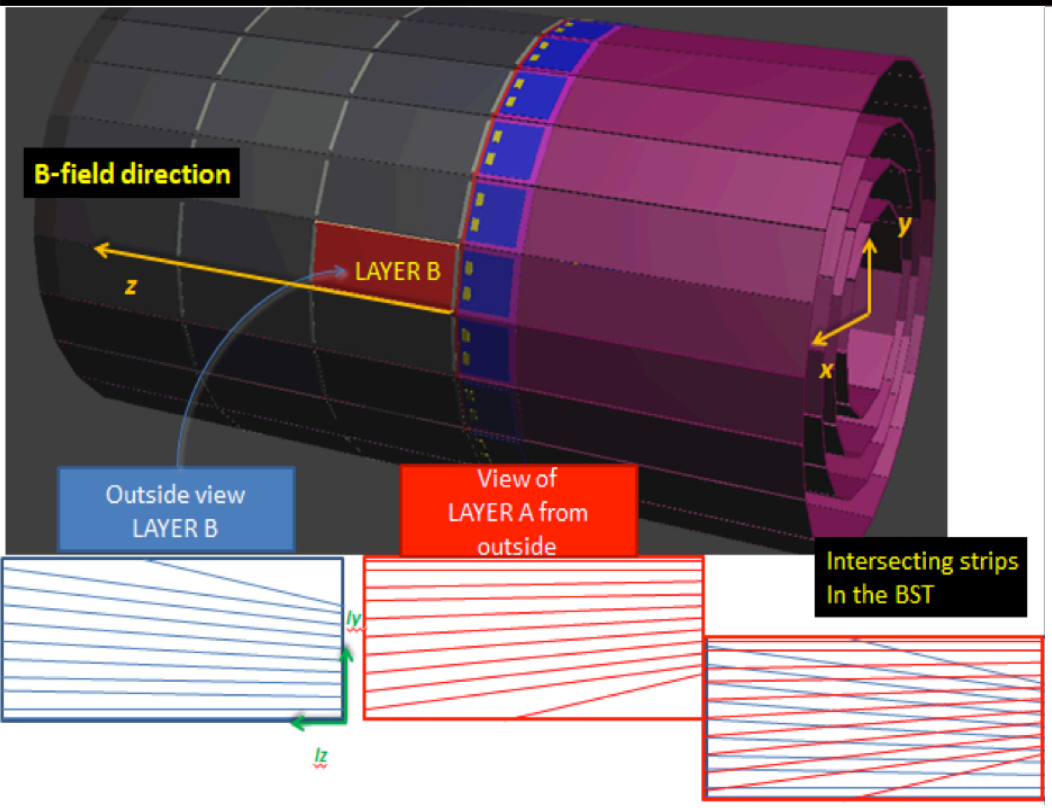
- Silicon area ~1.5 m²
- Channels: ~34,000
- Bonds: ~200,000

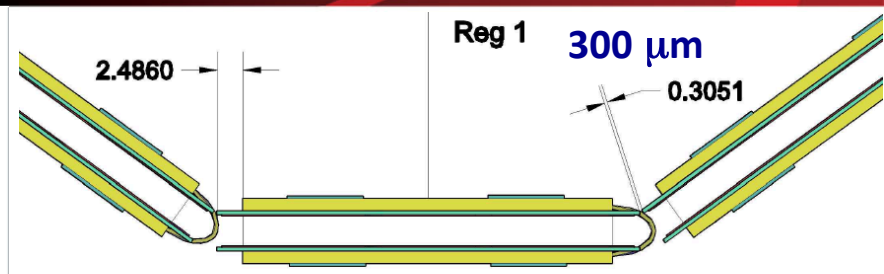


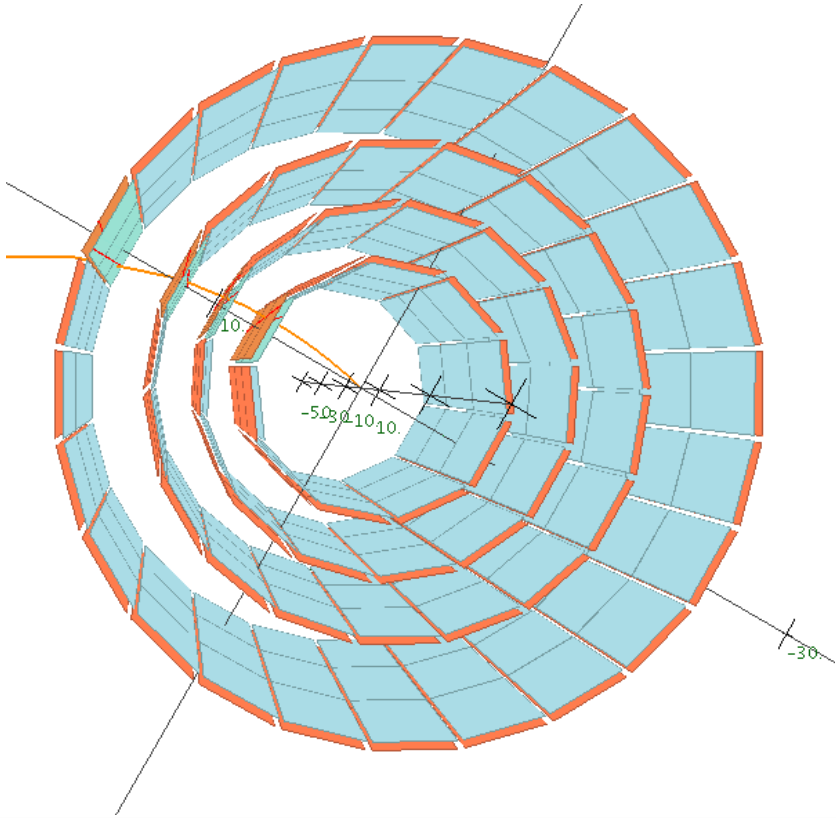


- Cantilevered cylinders with support rings
- Double sided modules with 3 daisy chained sensors
- Single sided sensors with graded pitch
- Rigi-flex hybrid with extended L1 disconnect

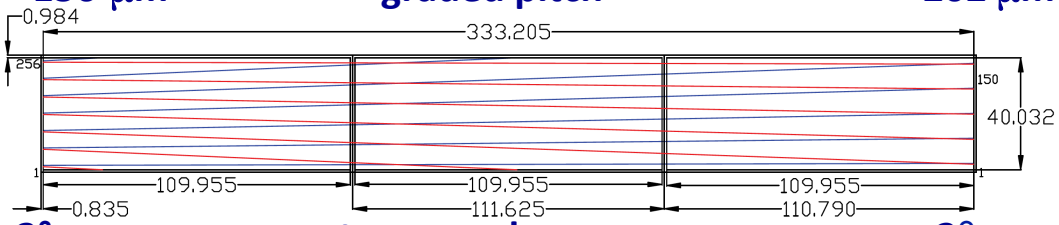
Design Overview: Layout





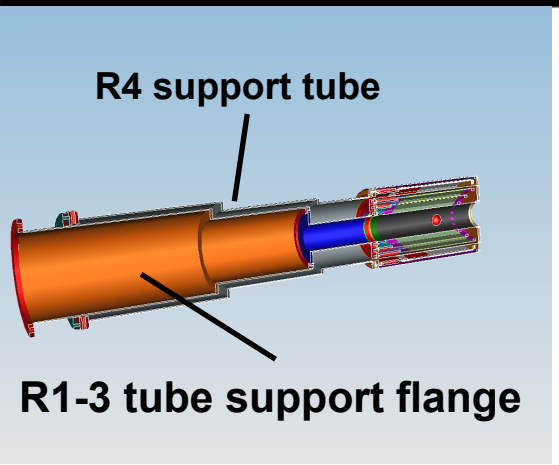


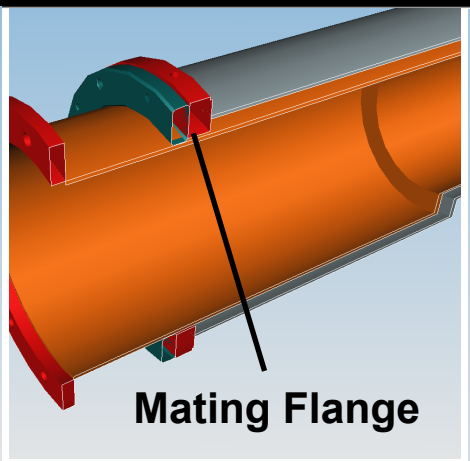
156 μm graded pitch 202 μm

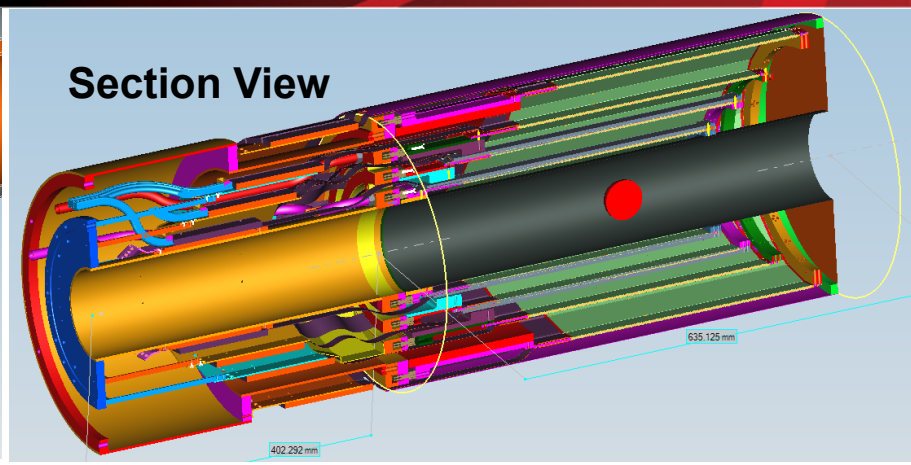


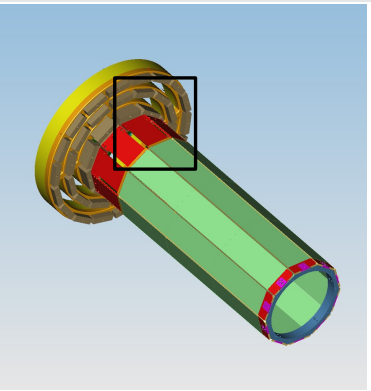
3° stereo angle 2°

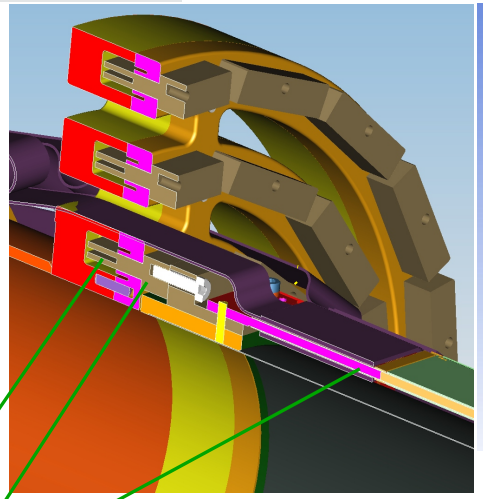
Design Overview: Mechanics

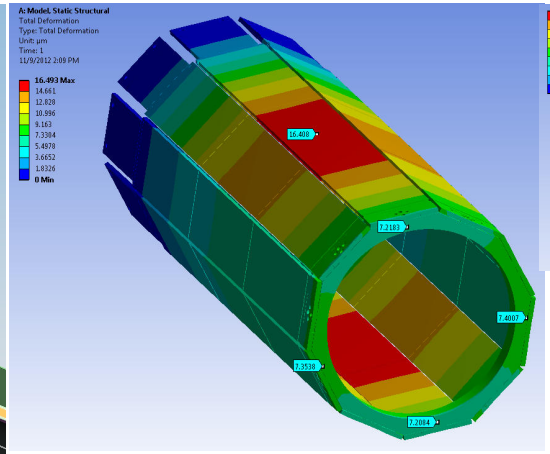






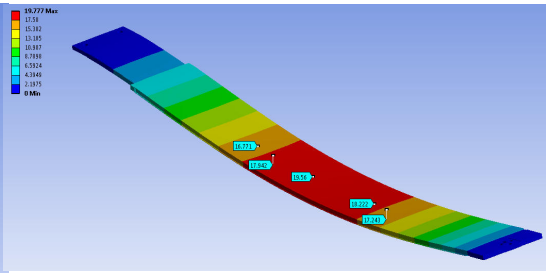






Max. Deflection: ~16 µm
(in horizontal modules)

Max. Deflection in
Downstream Ring: ~7 µm



Max. Deflection : ~19 µm

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

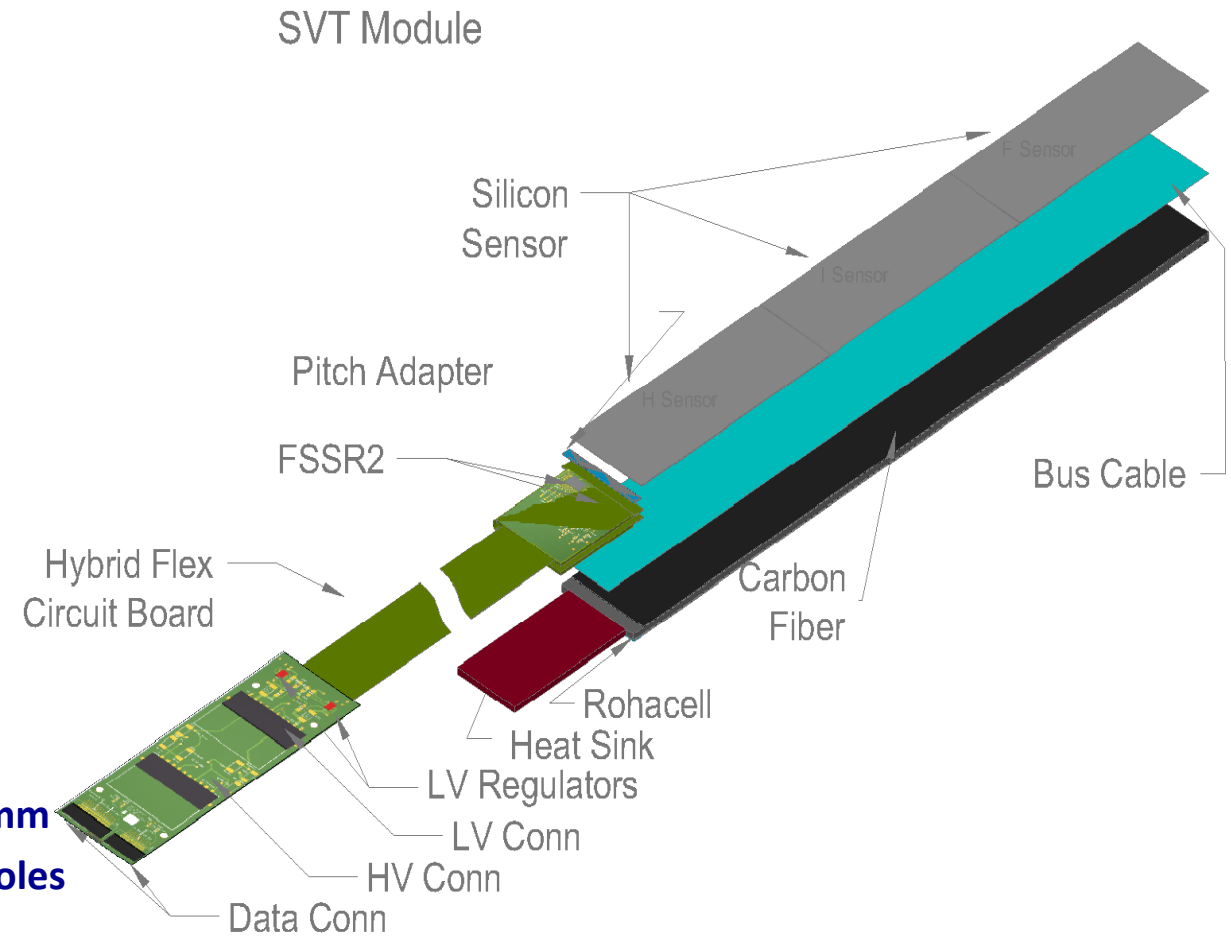
- **FSSR2, developed for BTeV**
- **Self-triggered**

Hybrid Flex Circuit Board (HFCB)

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

Composite Backing Structure

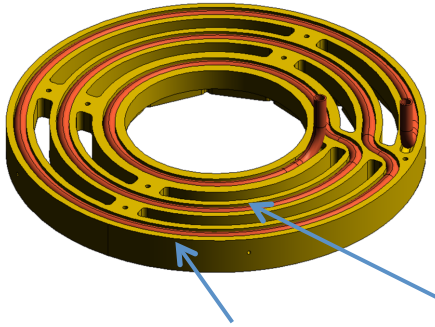
- **Rohacell 71 core (2.5 mm)**
- **Carbon Fiber (K13C2U) skin, 0.19 mm**
- **Copper heat sink with mounting holes**
- **PEEK insert for downstream ring**
- **Bus Cable for HV distribution (78 µm)**
  - **co-cured with CF skin (grounding)**

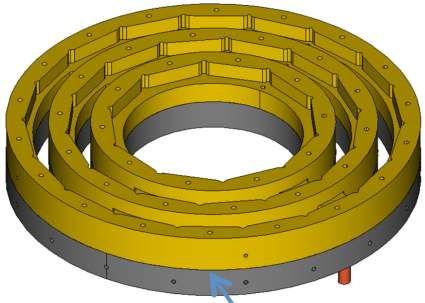


Design Overview: Cold Plate

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

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

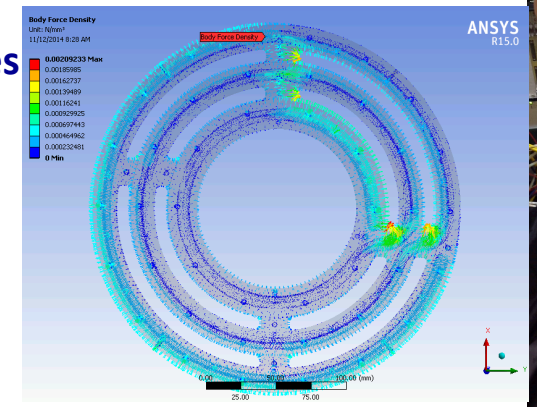


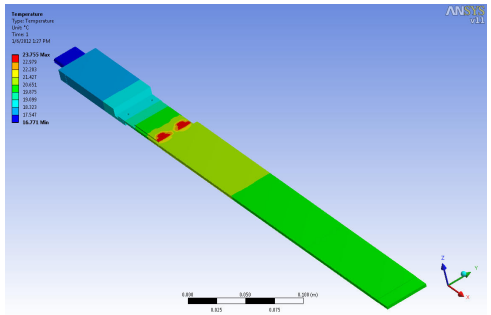


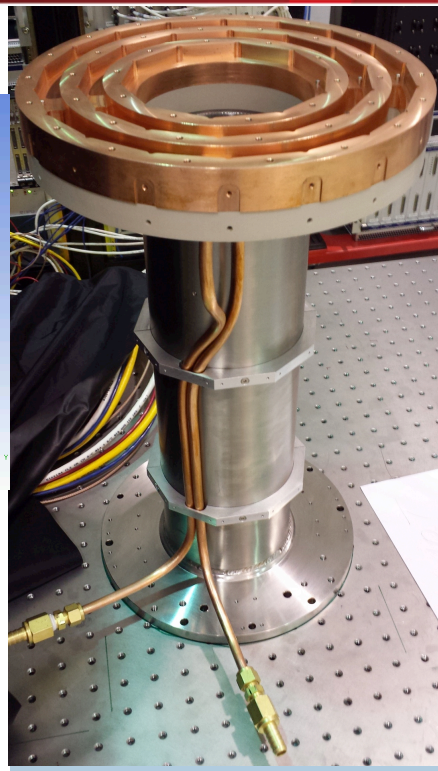
Brass Heat Sink Plate

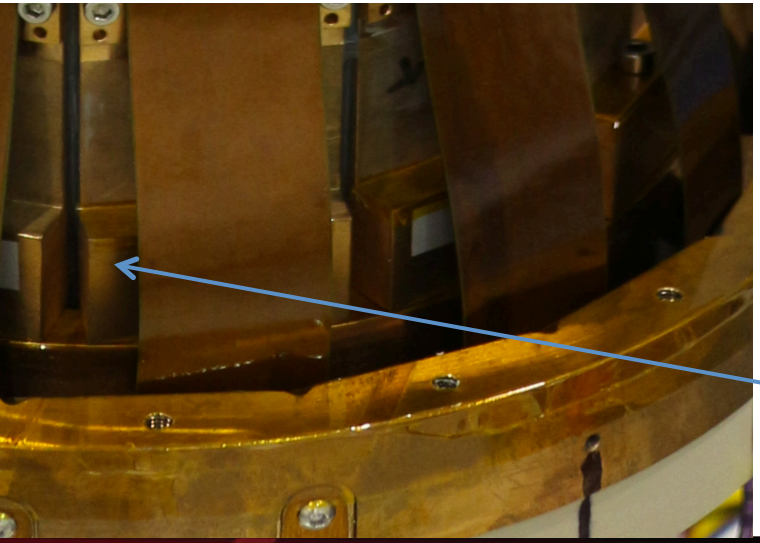
Cover Plate (Plastic)

Copper tube brazed into channel





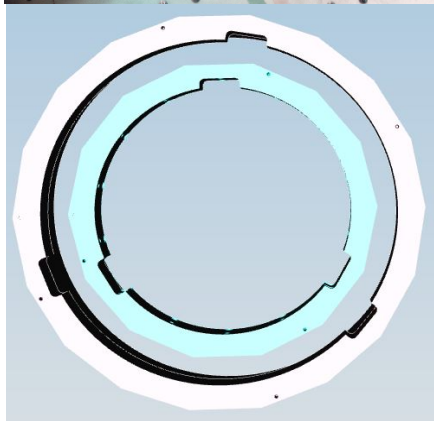




Heat Sinks

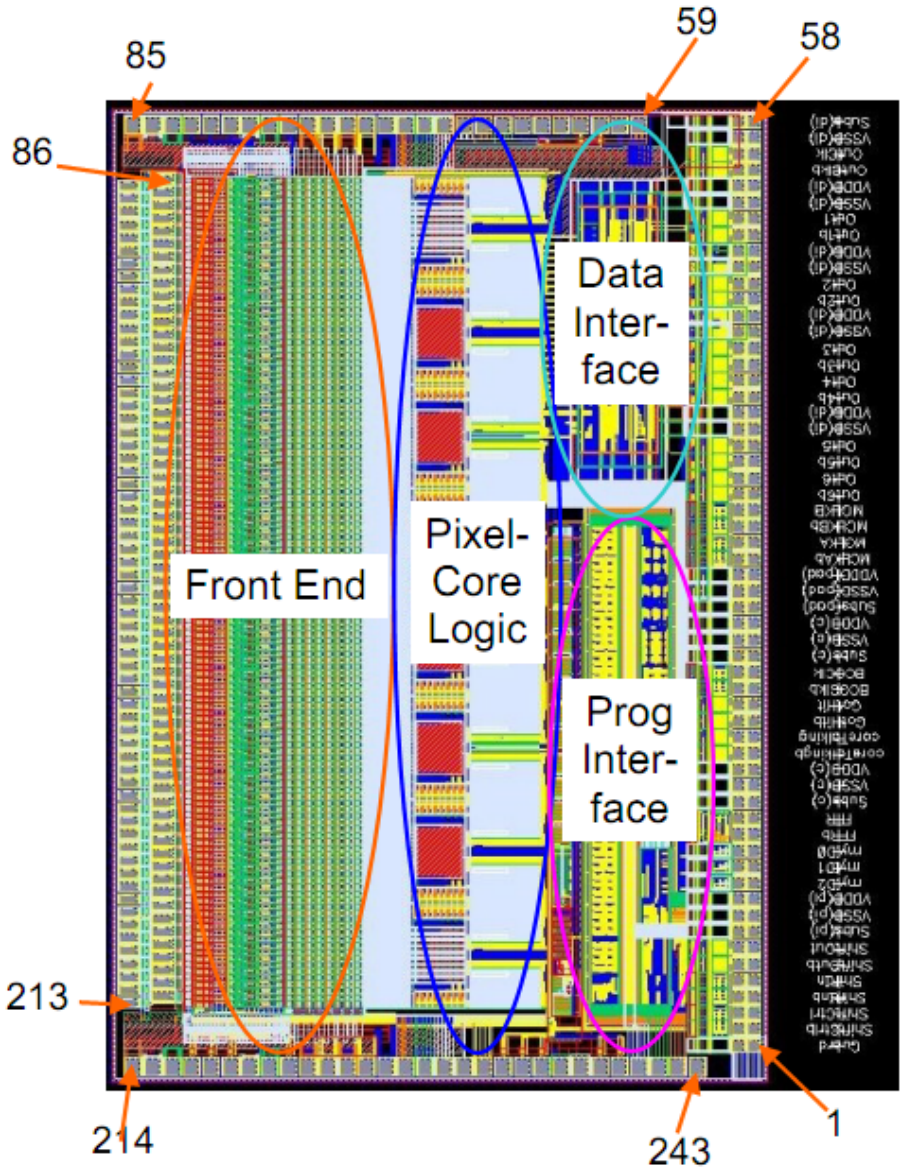
Heat output: 2 W per module
Hybrids @ 14 – 18 C (coolant @ 6 C)

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

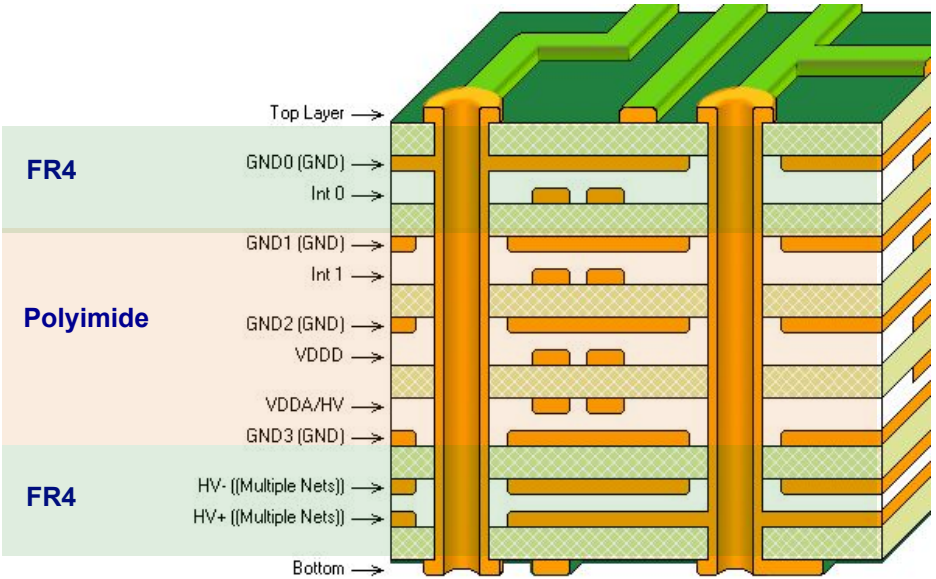


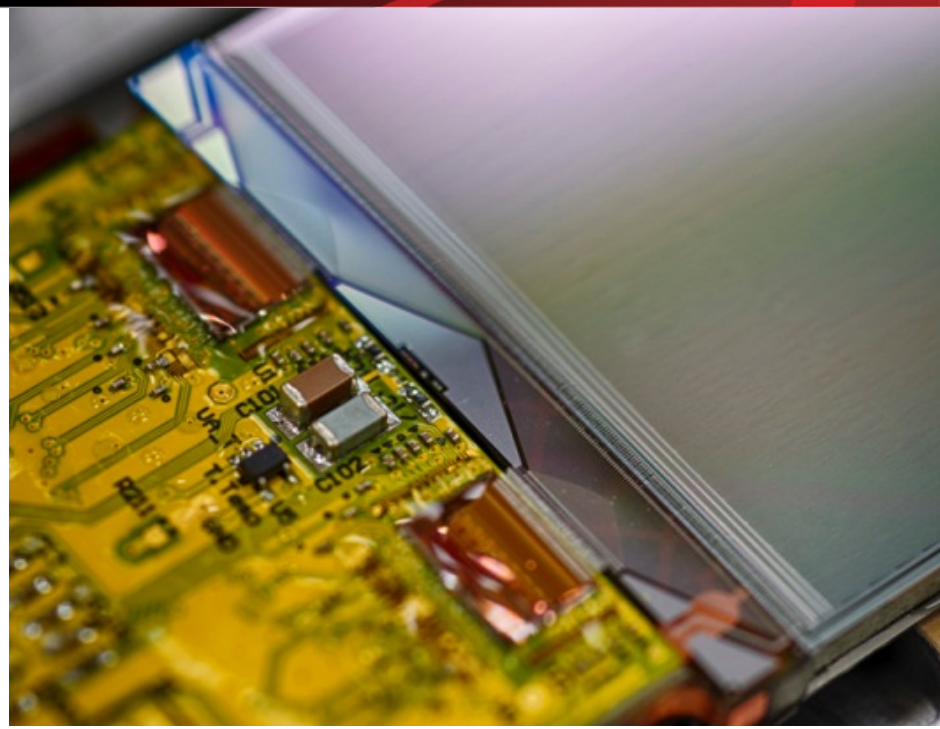
Design Overview: FSSR2

- 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: from 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: use 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

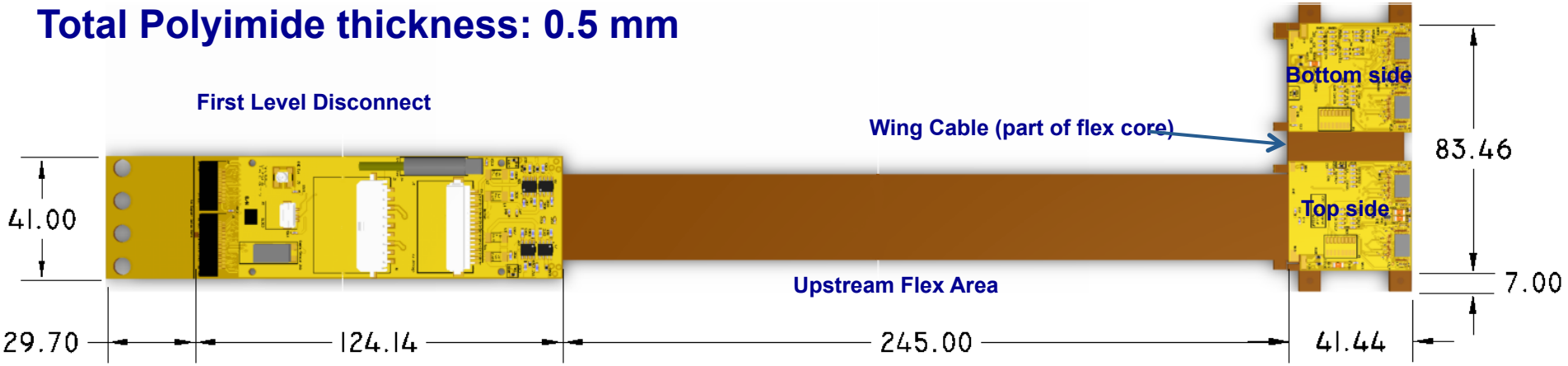


Design Overview: HFCB





12 Layer Stack-up
Total thickness: 1.42 mm
Total Polyimide thickness: 0.5 mm



Hybrid Area Features

Decoupling capacitors

Output of HV filter, return jumpers

FSSR2 ASICs

Polyimide Alignment Tabs

Diagnostic Header

Temperature and RH sensors

Clocks Termination

Input of HV filter

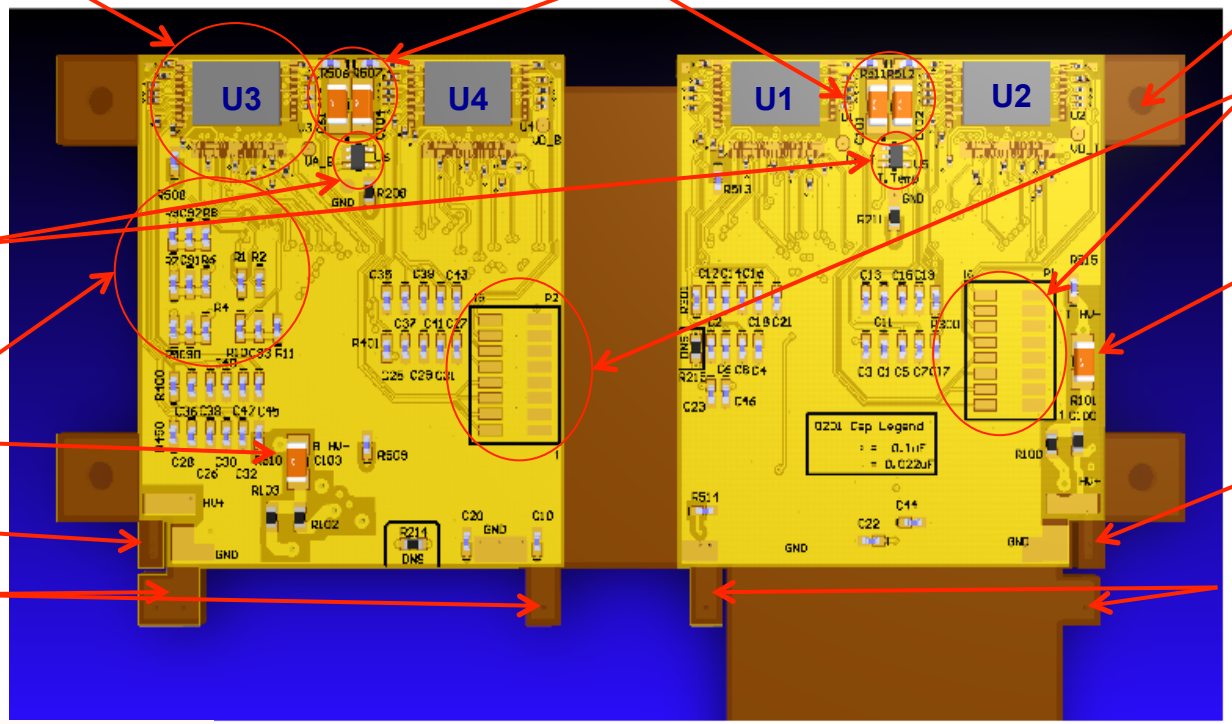
Input of HV filter

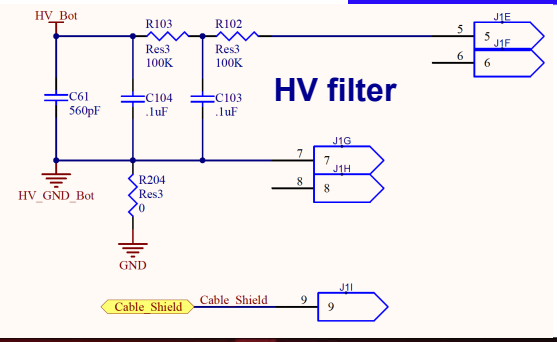
HV+ Tab

HV+ Tab

HV ground

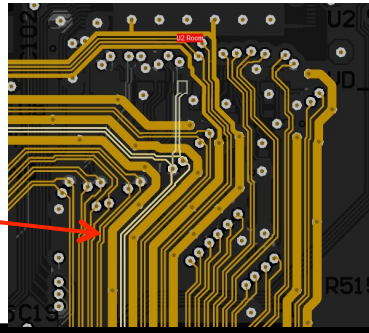
HV ground



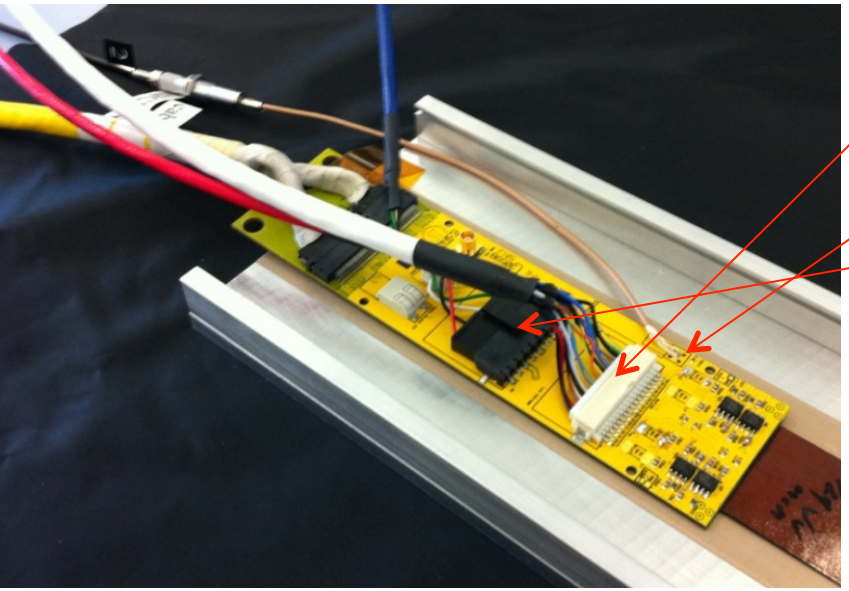


Analog LV capacitors return to the FSSR2 substrate
Digital LV capacitors return to LV plane

Stitched guard traces separate clock pairs from other LVDS signals

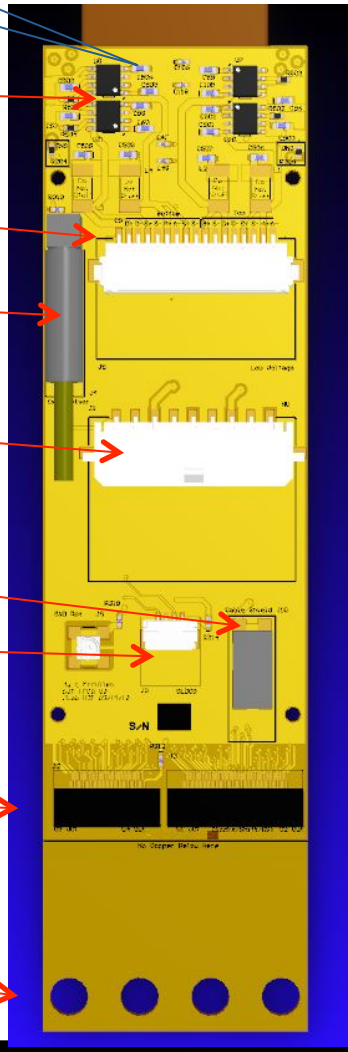


HFCB: First Level (Dis)Connect



Separate circuits for LV analog and LV digital

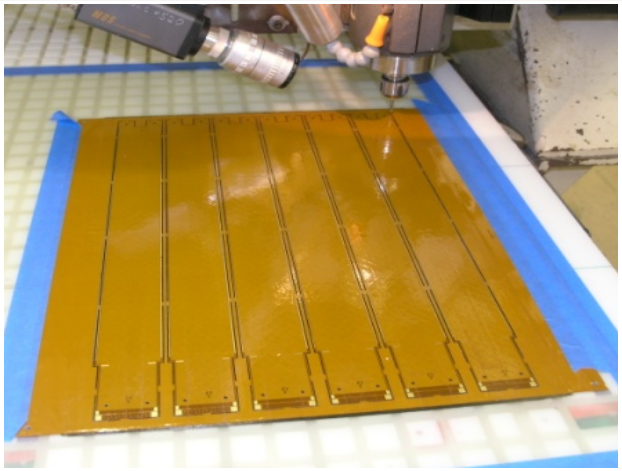
HFCB L1C



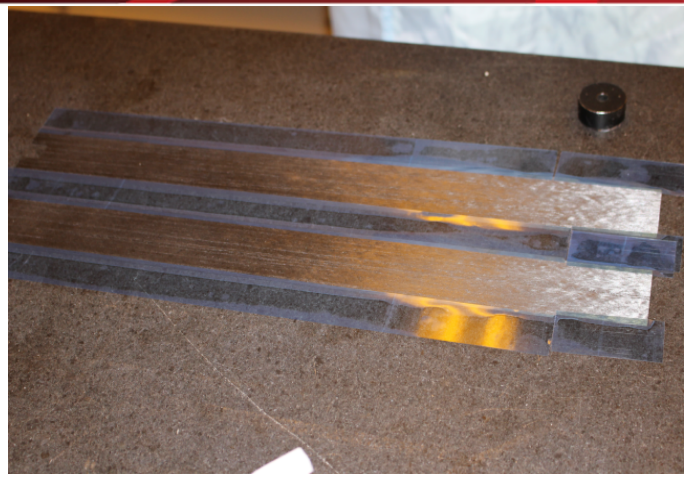
Regulators	Ti Linear LDO 2.5V
Low Voltage	Amp 17 Pin
External Pulser	Sabritec NDL-Q Triax
High Voltage	MicroFit 9 Pin
Cable Shield	Wago 2 pos Terminal
Slow Controls	Molex Clik-mate 4 pin
Data Connectors	Nanonics 37 and 51 Pin
Cable strain relief	

Backing Structure Assembly

Bus Cable Panel

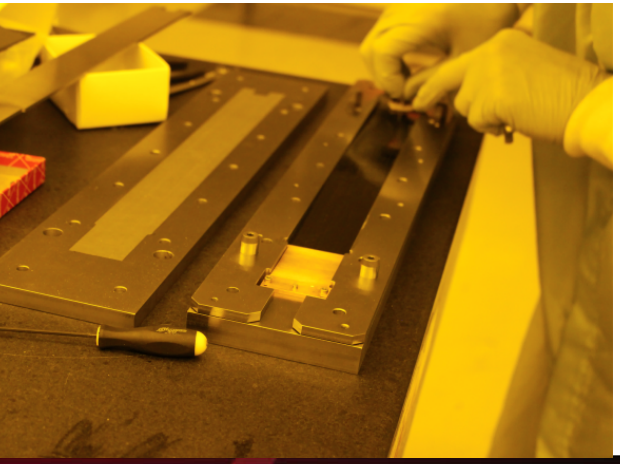


Routing co-cured skins

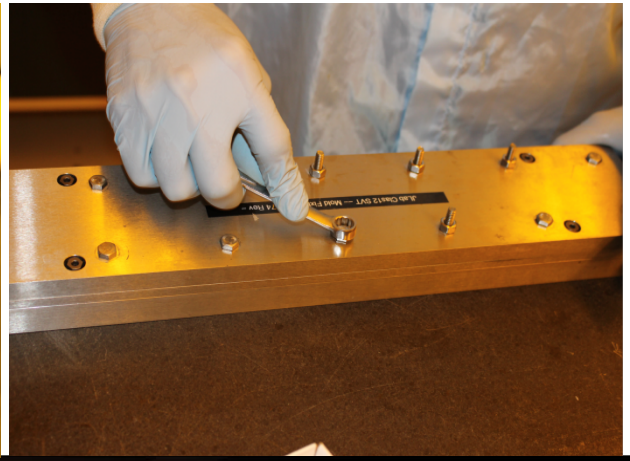


CF skins ready for assembly

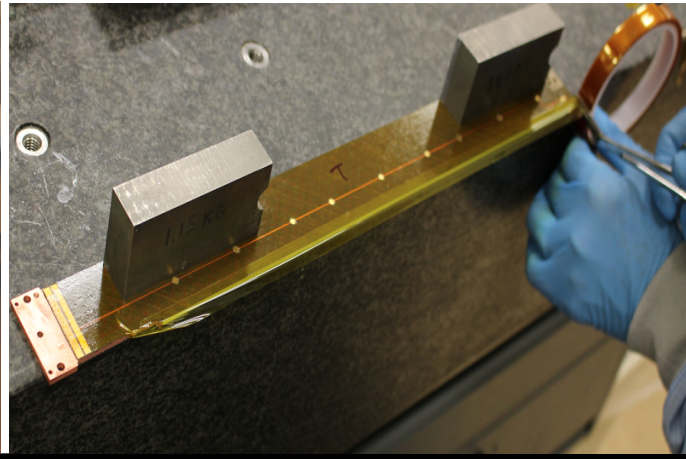
Mounting the parts in the mold



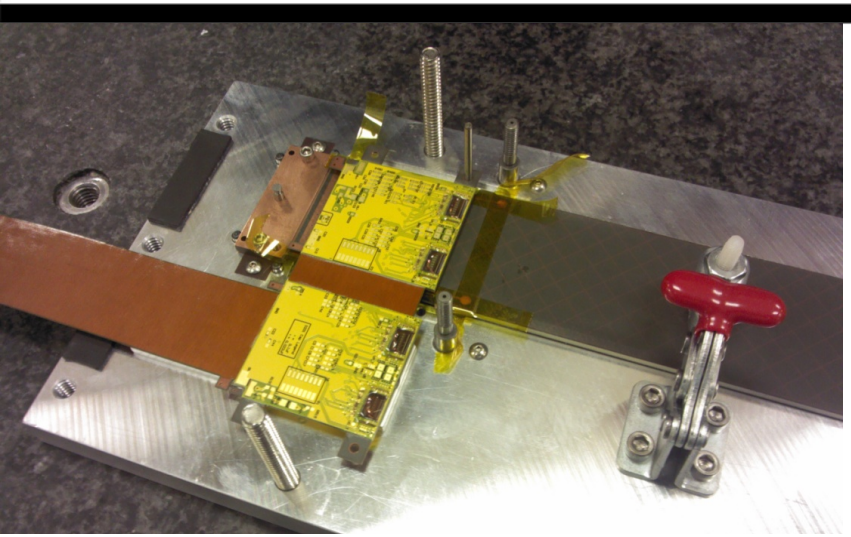
Preparing for epoxy curing



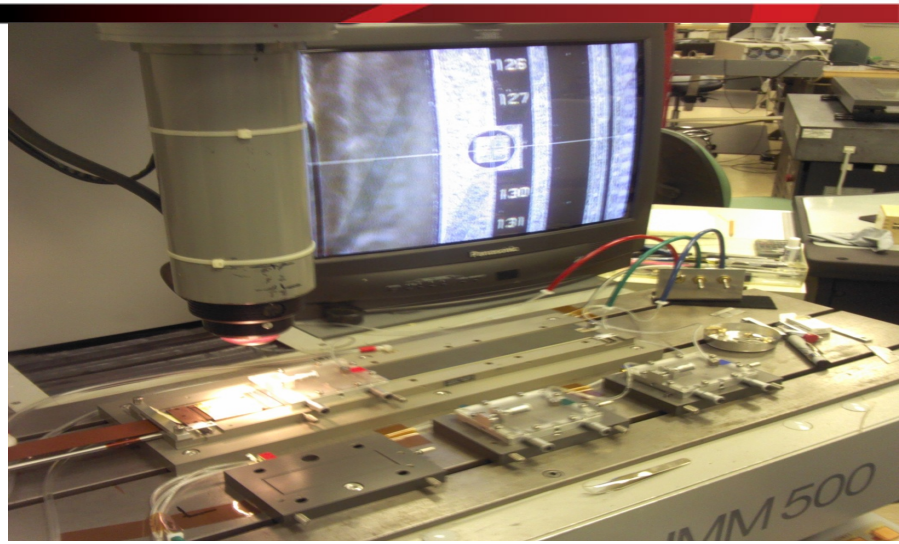
Isolating the edges



Module Production at Fermilab

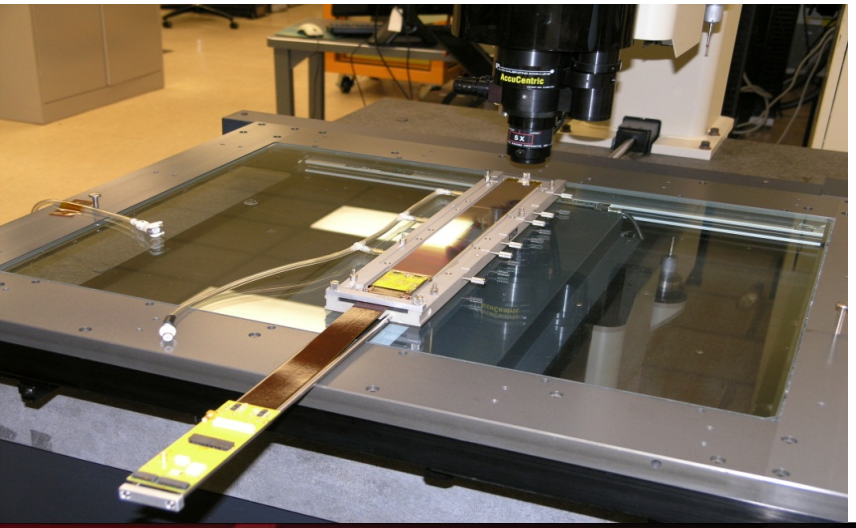


Gluing HFCB to the backing structure

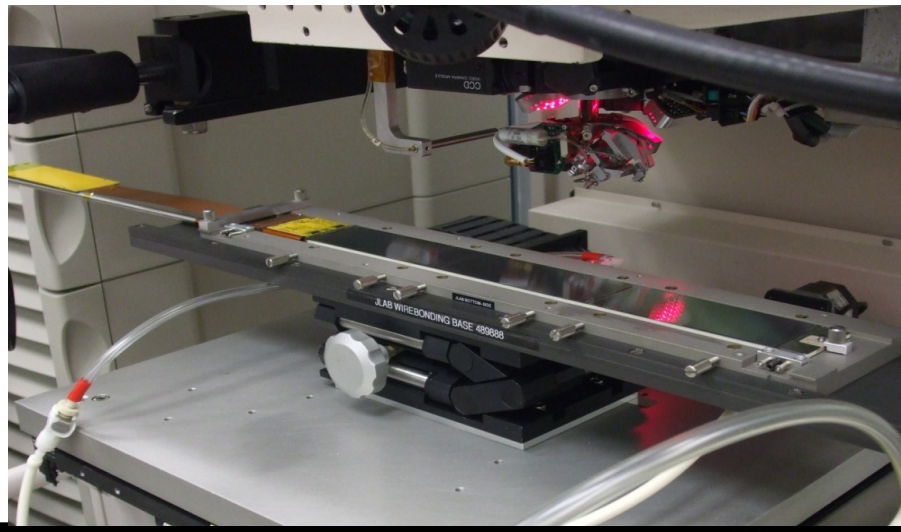


Sensor placement

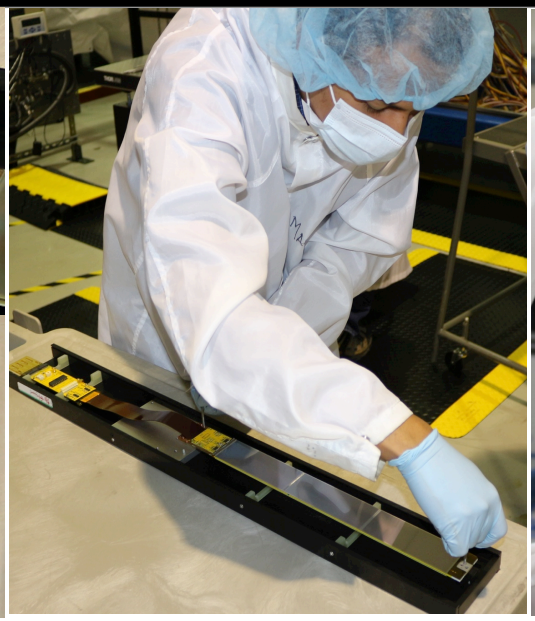
Optical survey

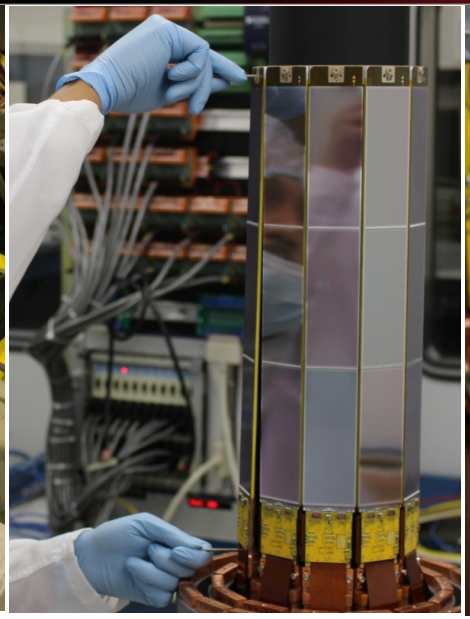


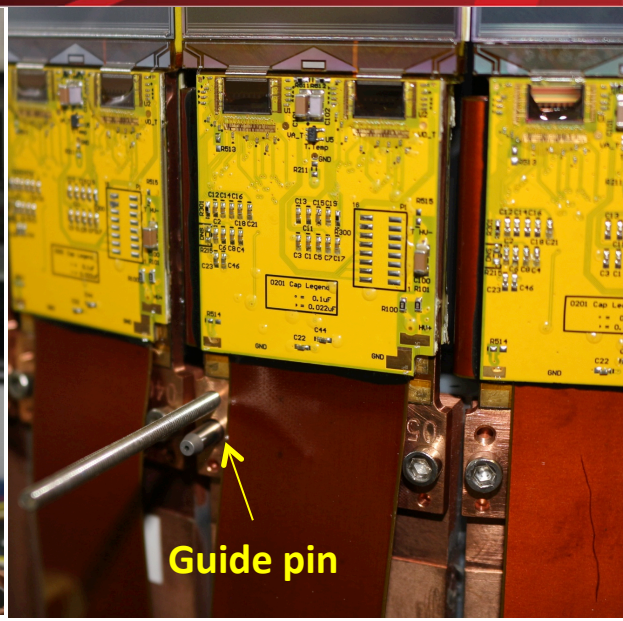
Sensor wire bonding

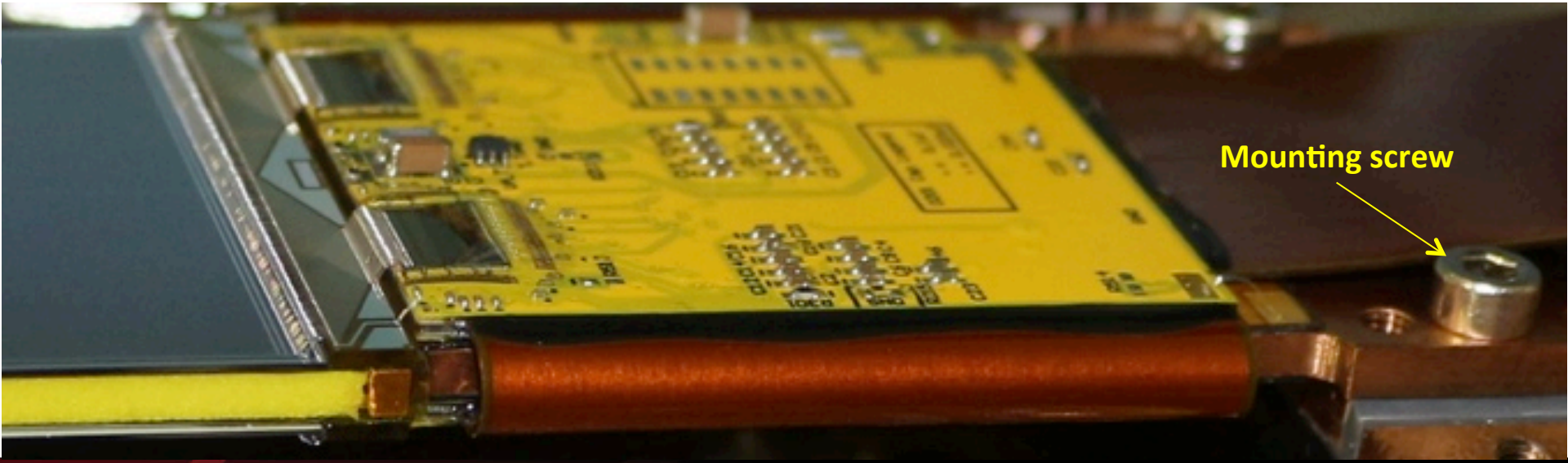


Mounting the SVT Module





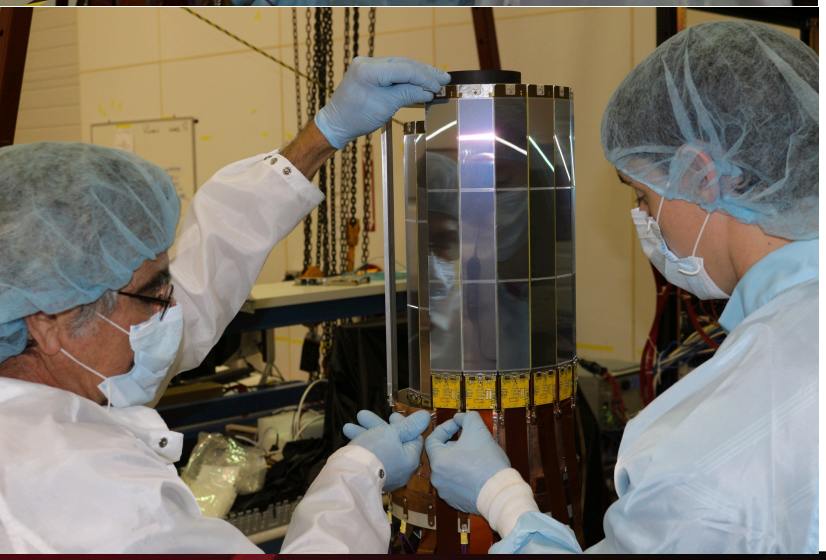




Region Assembly (Vertical)

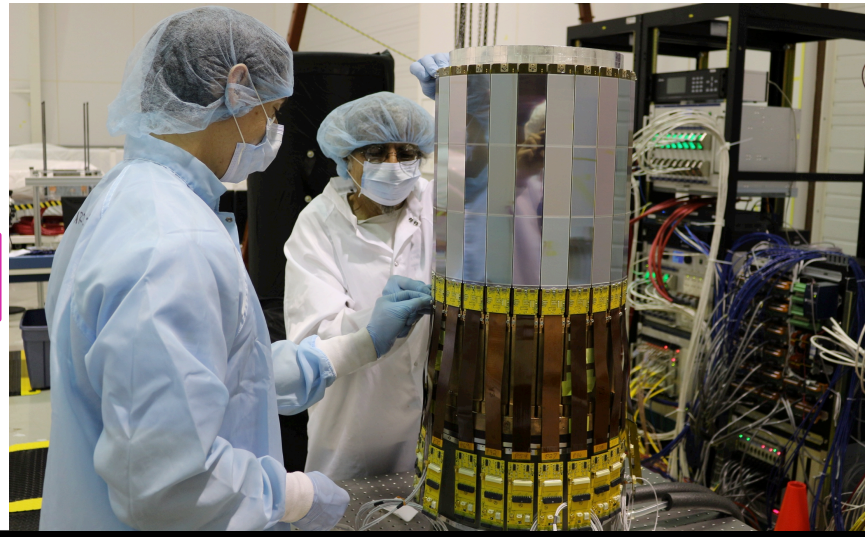
R1

R2

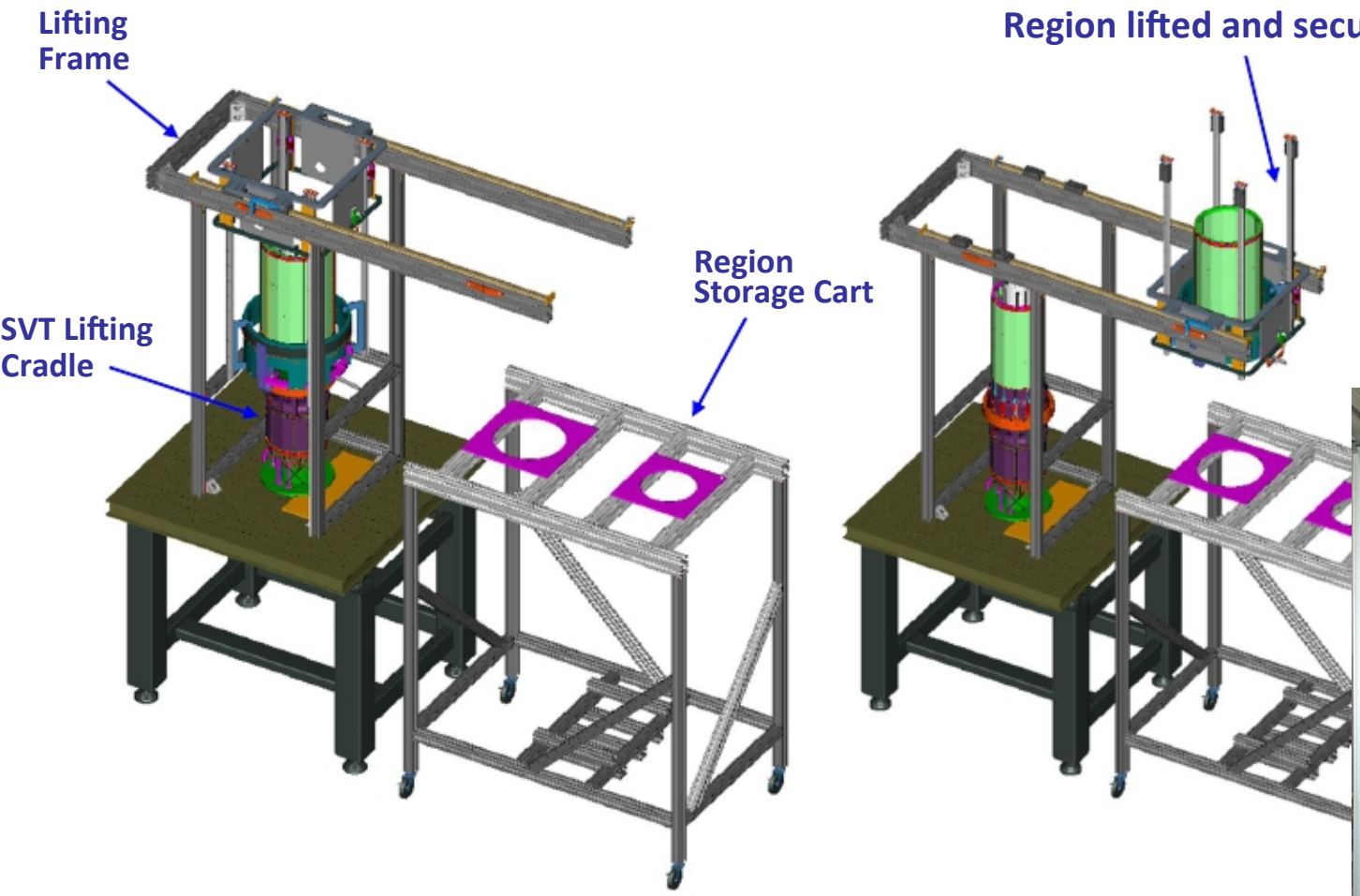


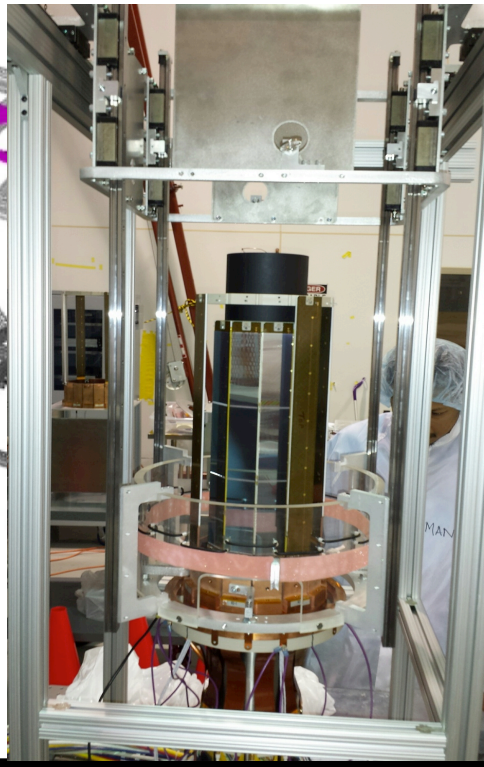
R3

R4



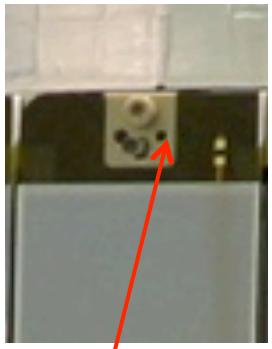
Region Disassembly Fixture



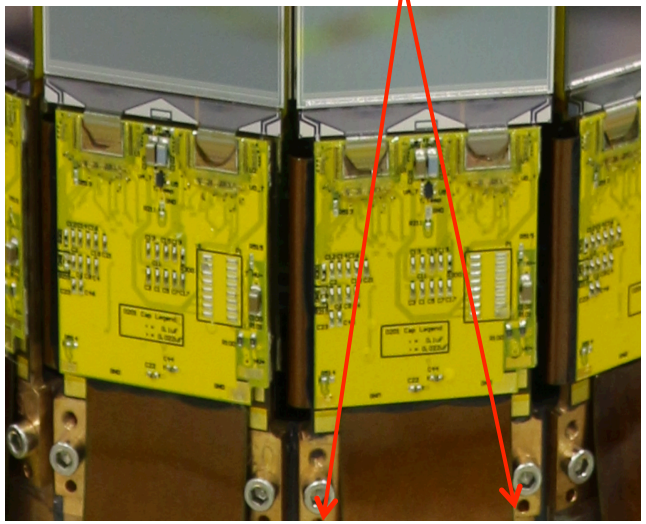


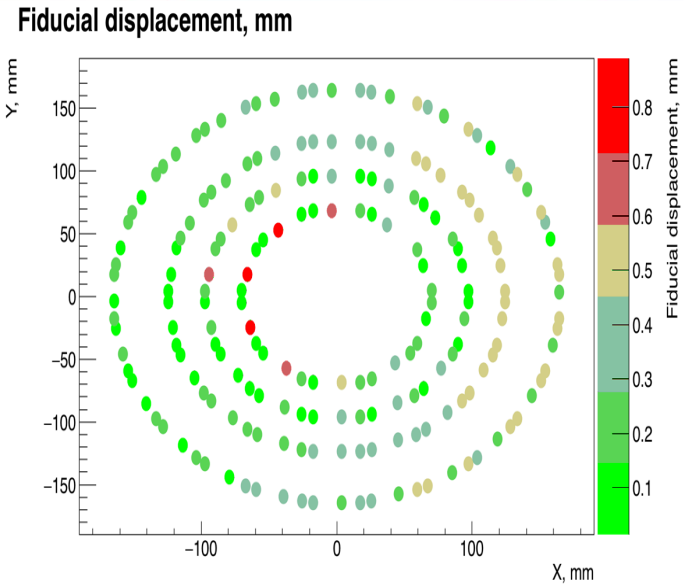
Survey of Module Position

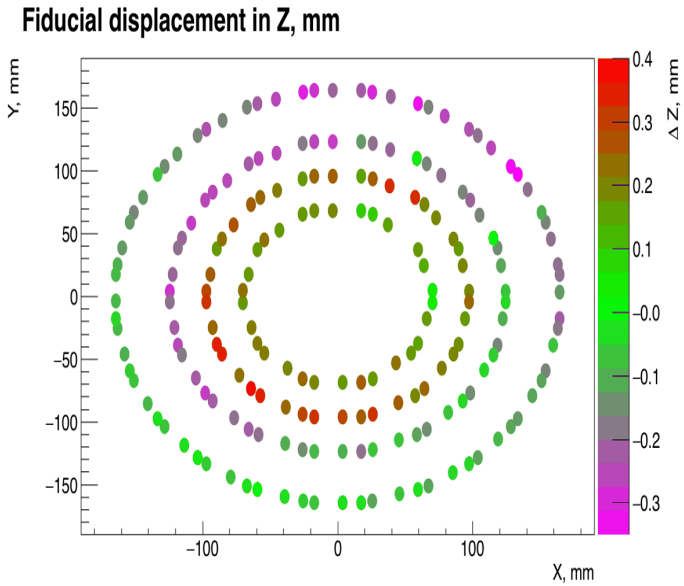
Position of each module measured using Faro-Arm



Fiducials

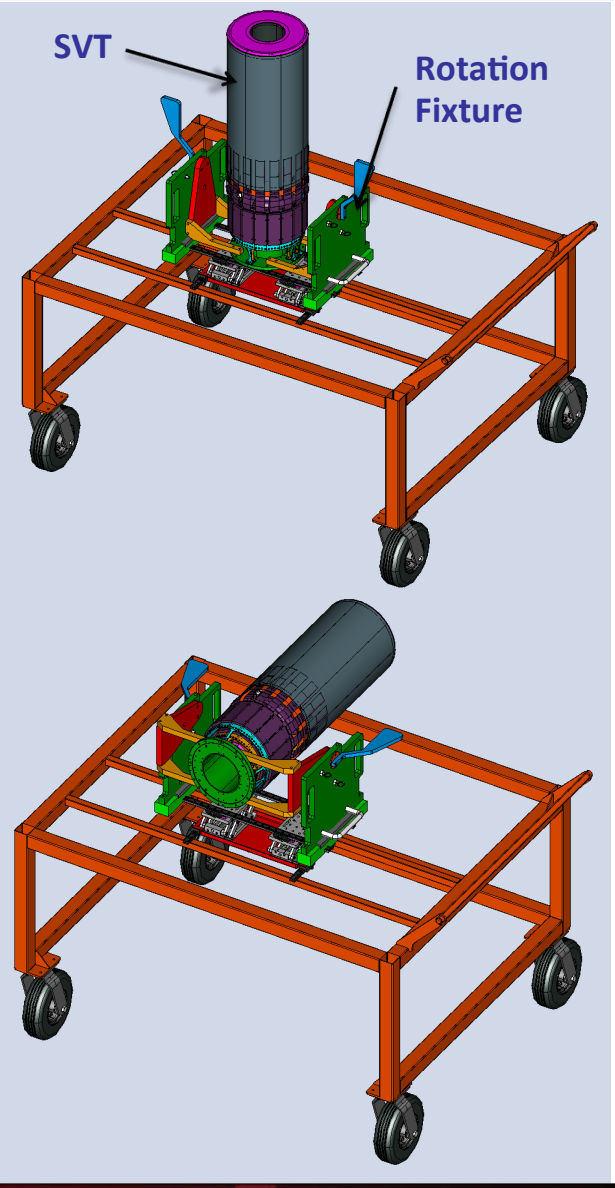




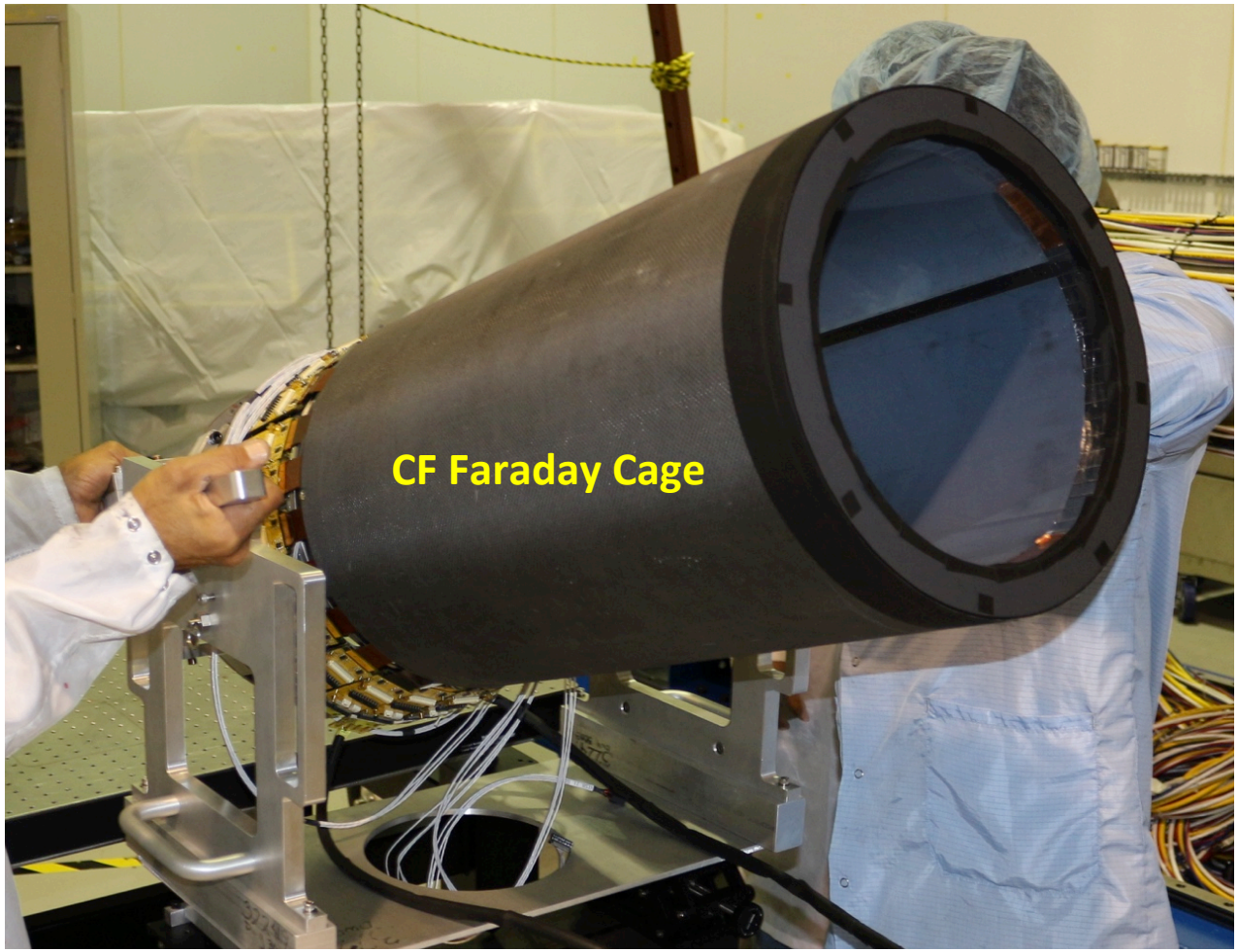


Module position measurement accuracy 20 µm

Integration with Support Tube

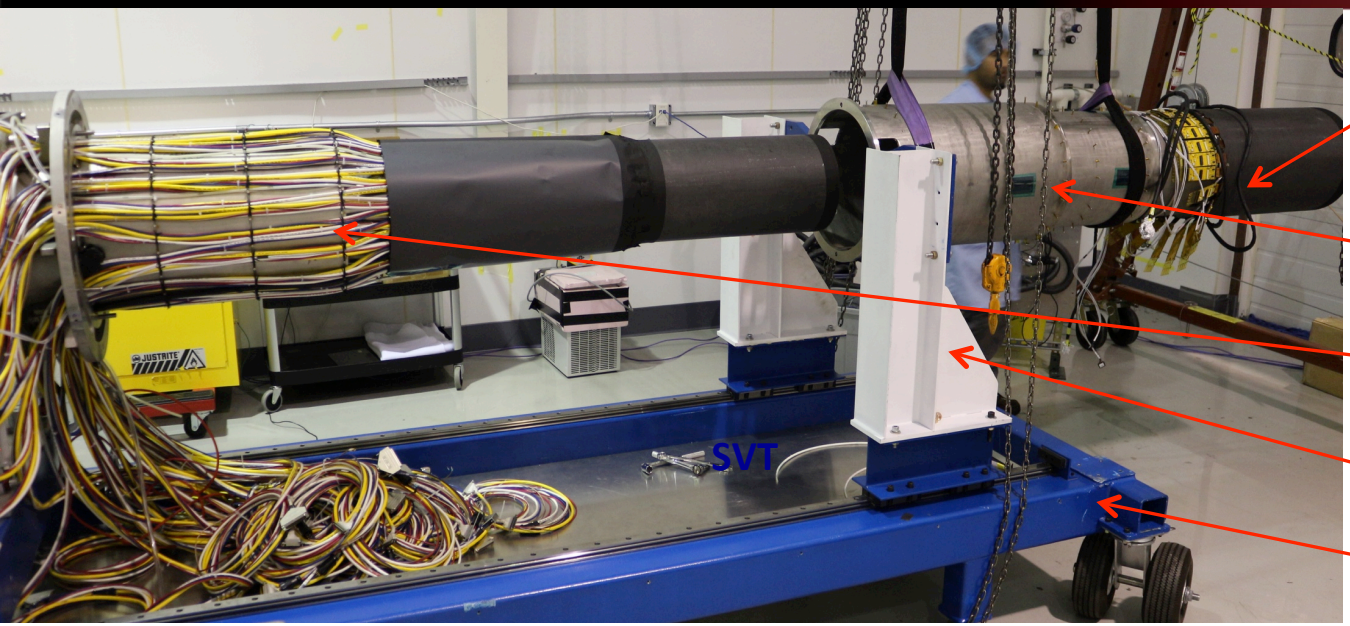


Vertical position of SVT after assembly



Horizontal position of SVT after rotation

Region 4 Integration



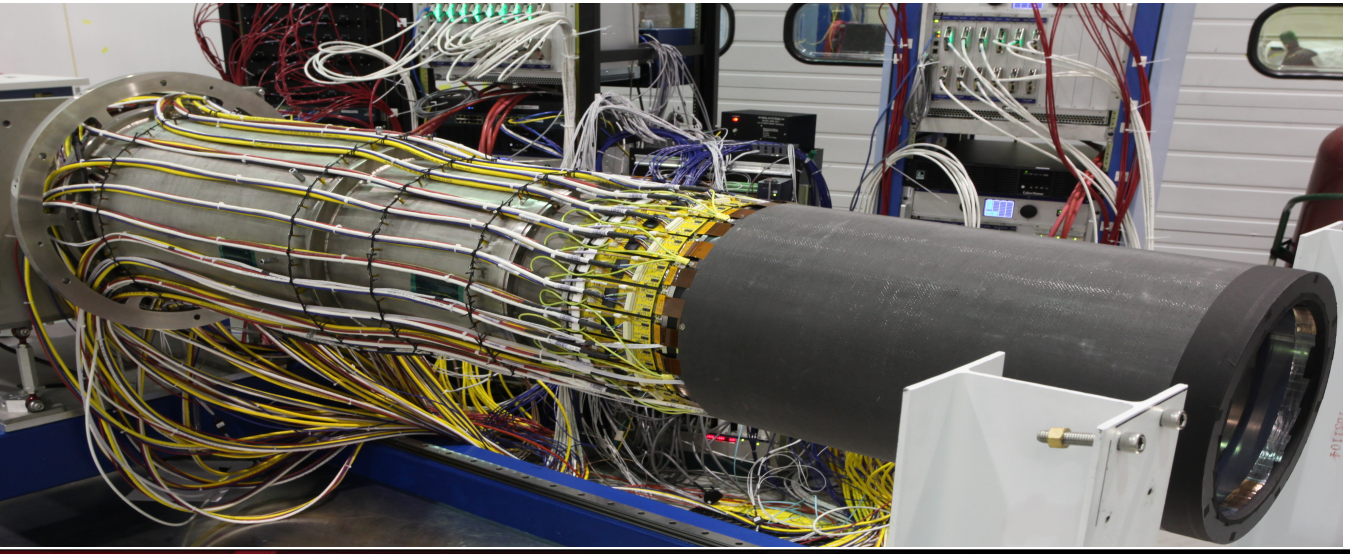
Region 4

R4 Support Tube

R1-R4 Support Tube

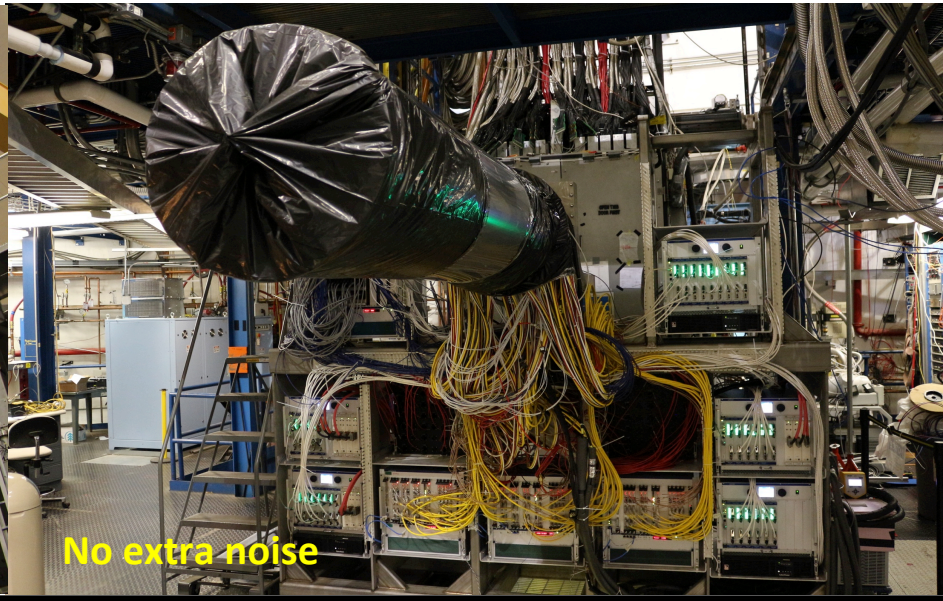
R4 Integration Adapter

Integration and Transport Fixture



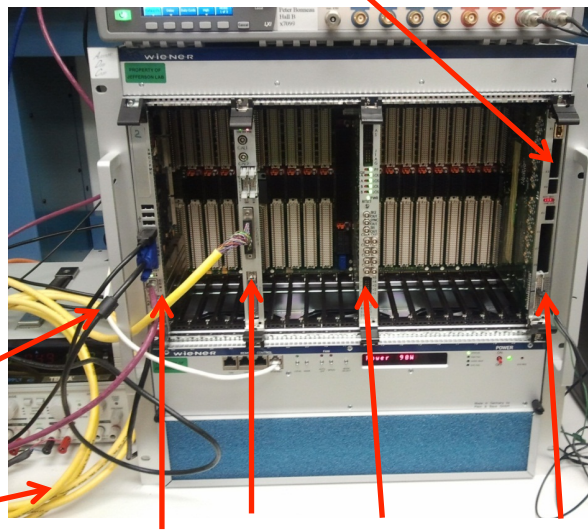
SVT integrated

Installation in the Experimental Hall

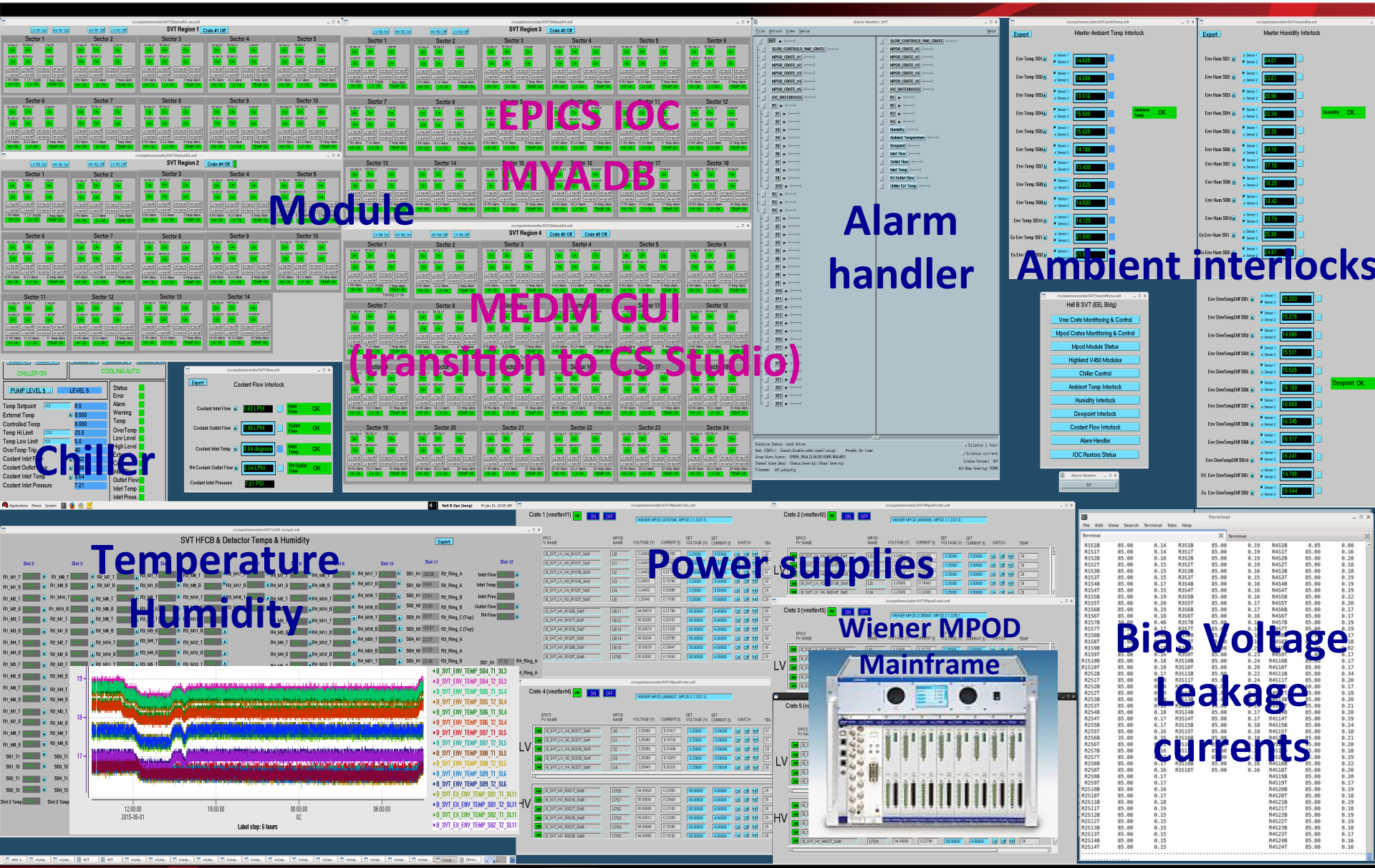


DAQ Components

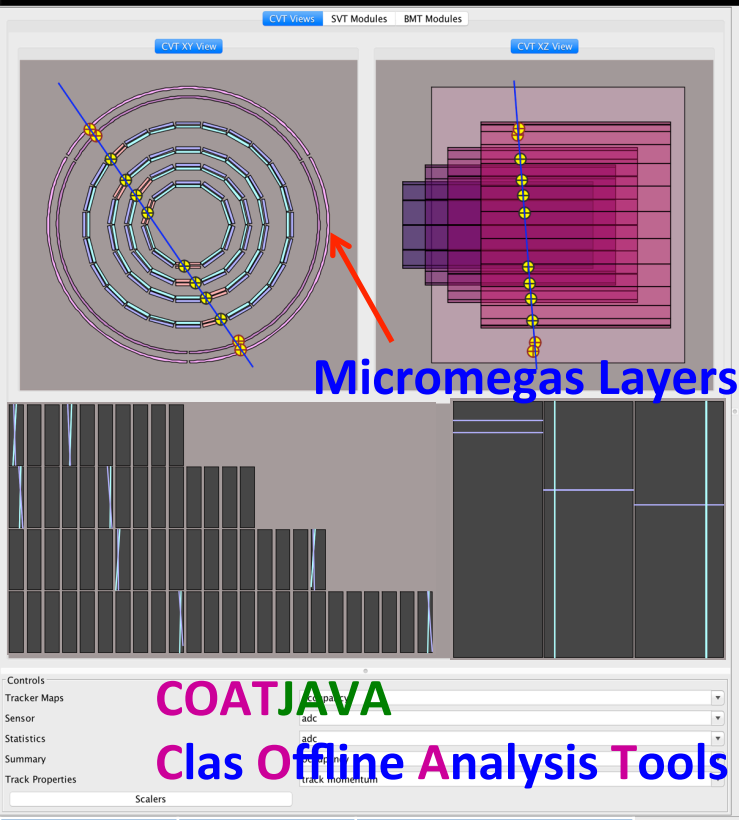
- CPU: Commercial VME Controller (Intel 2.53GHz Core i7, 4GB DDR3 SDRAM)
- Crate: Commercial VXS Crate (Wiener 21 Slot VXS Crate)
- SD: Signal Distribution (trigger, clock, and sync via intra-crate copper backplane)
- TI: Trigger Interface (trigger, clock, and sync via inter-crate fiber optic)
- VSCM: VXS Silicon Control Module
  - Each card controls 2 SVT module
  - VSCM and FSSR2 clocks are synchronized
    - uses global clock (125 MHz)
    - generates BCO clock (~8 MHz) for FSSR2 chips
    - clocks synchronous across all chips/boards/crates within 4 ns
    - clock counters are synchronously reset
  - Converts FSSR2 Data Driven to Trigger Event
    - stores FSSR2 hits in 16 µs buffer using BCO timestamp
    - receives global fixed latency trigger signal
    - extracts FSSR2 hits in 16 µs to report for event
    - converts global time to BCO time

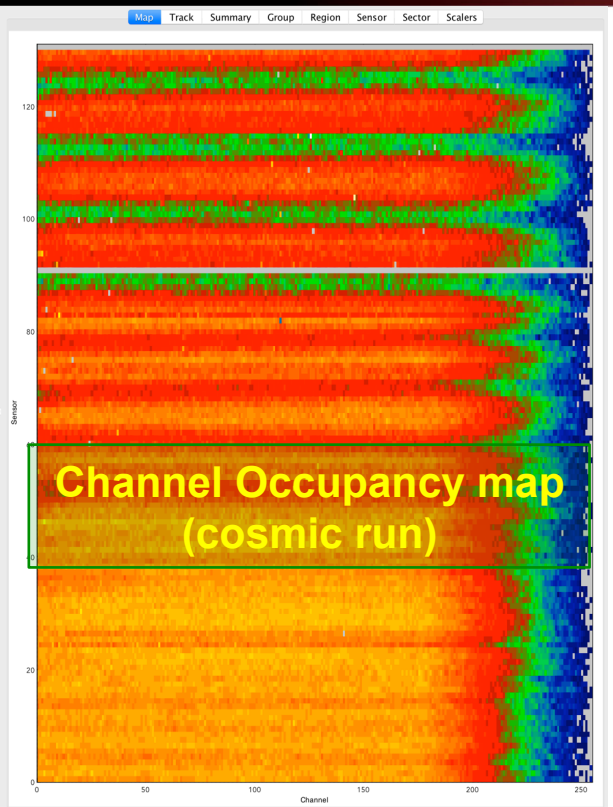


Slow Control and Monitoring

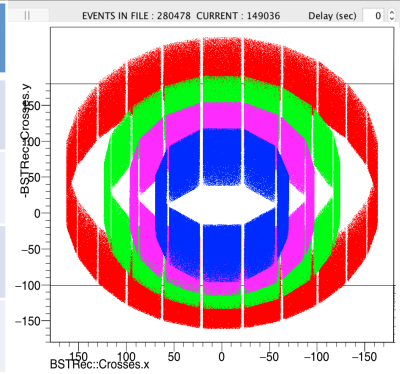


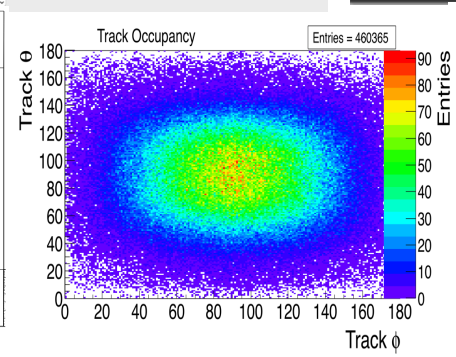
Online/Offline Control and Monitoring

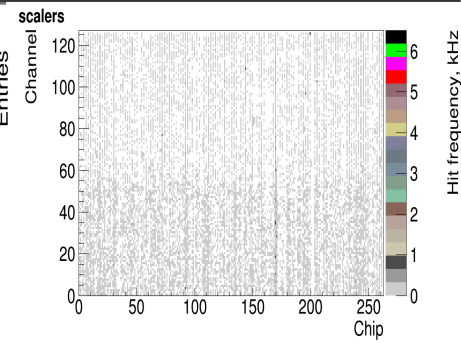




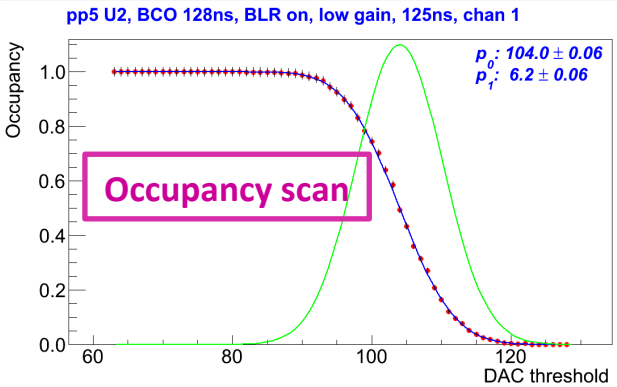
Partition	Channels	% operational
Region 1	5120	100
Region 2	7168	99.98
Region 3	9216	99.96
Region 4	12288	99.99

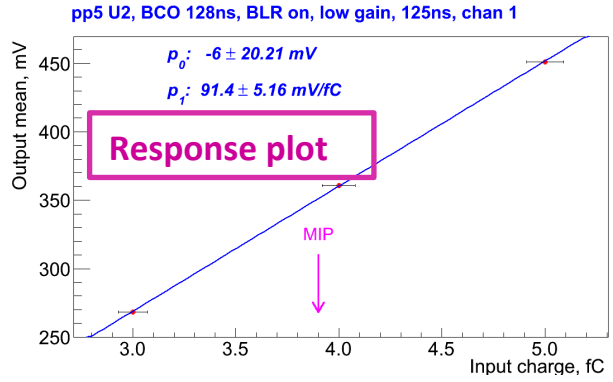


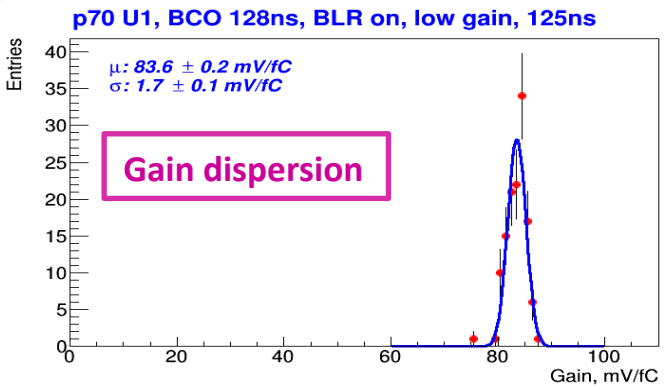


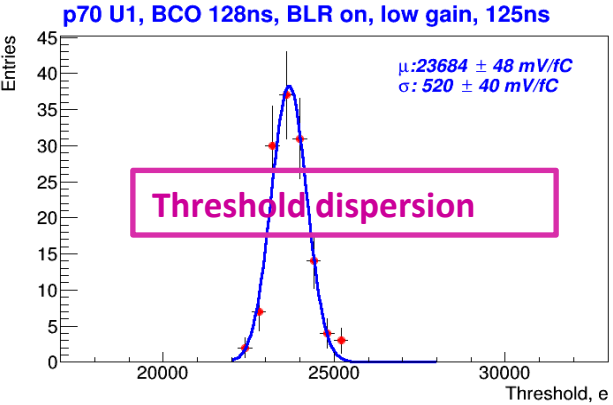


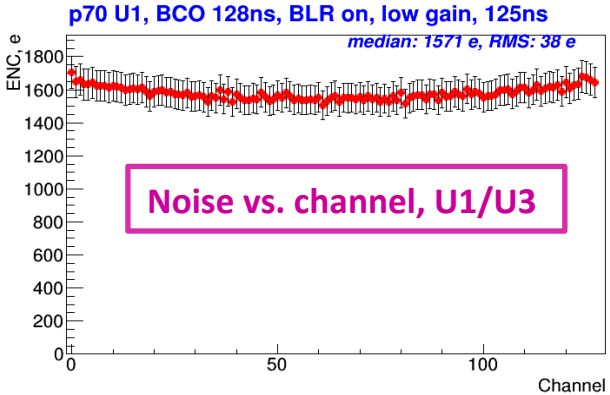
Channel Calibration

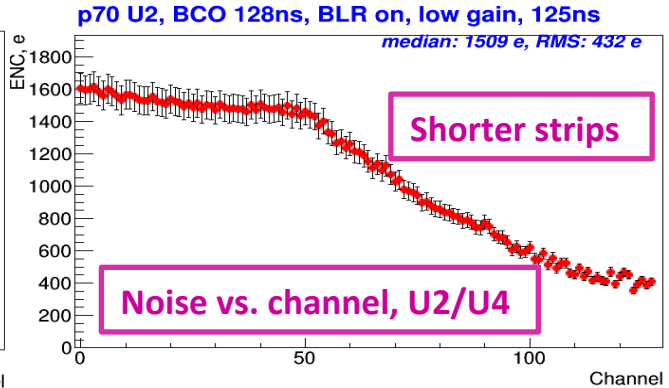


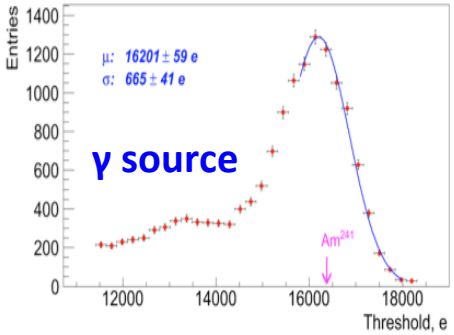


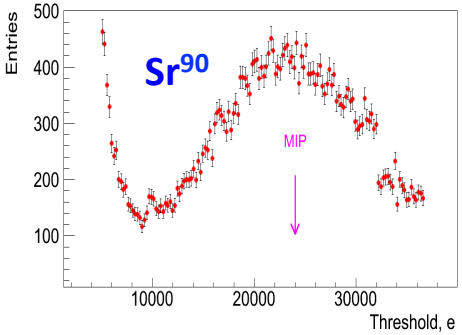


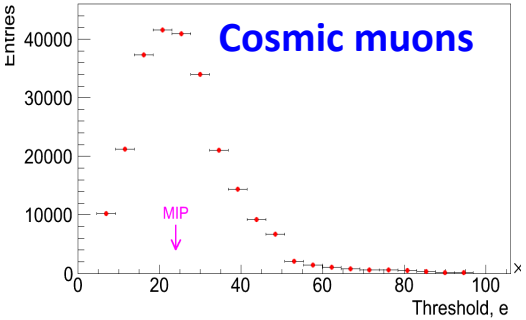


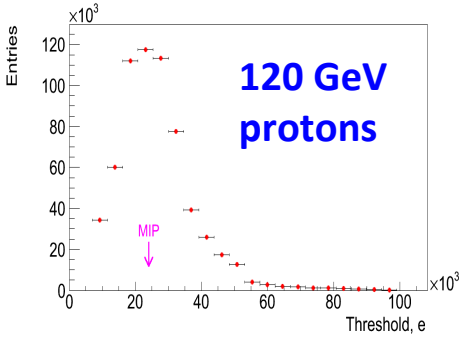




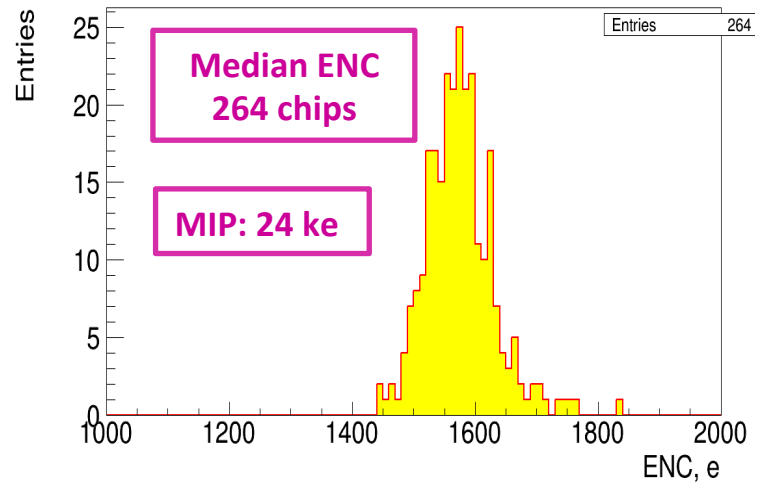


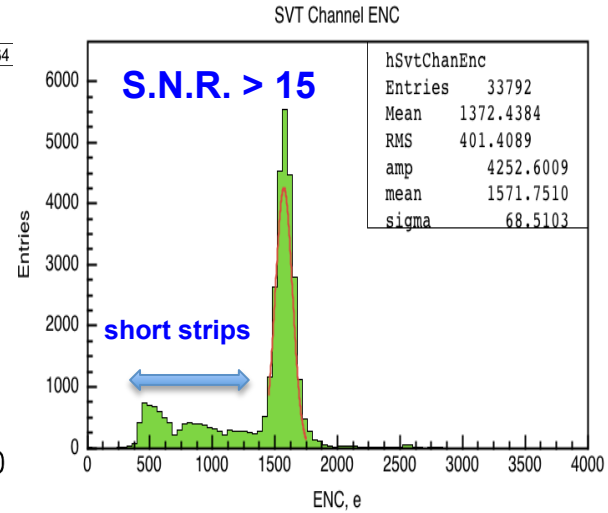


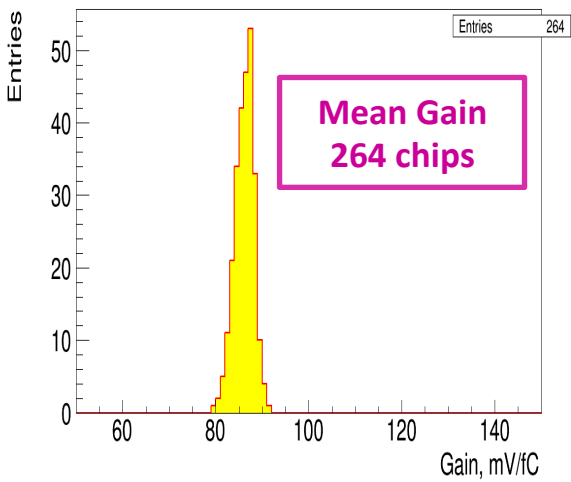


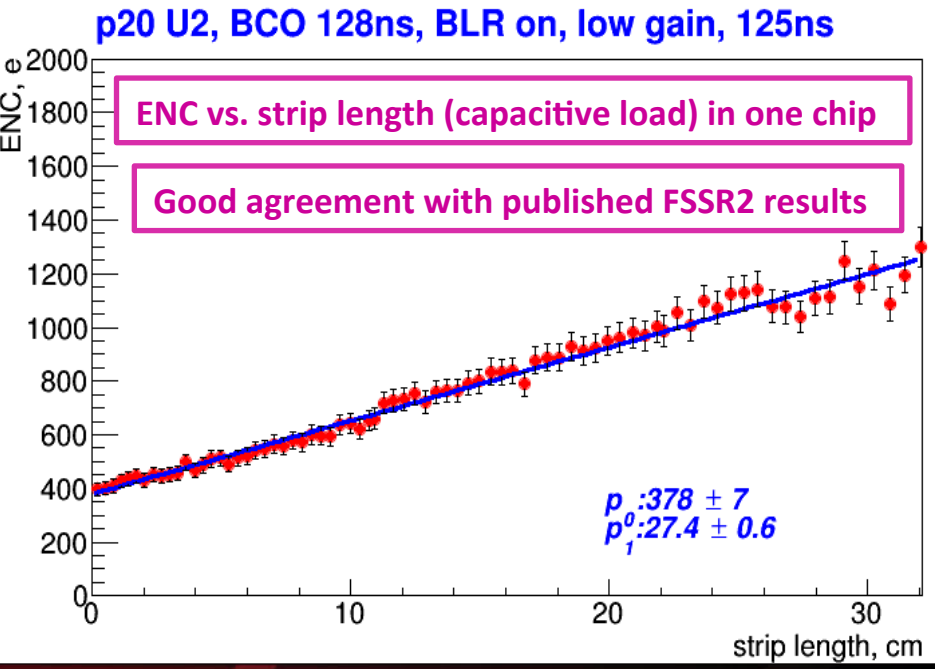


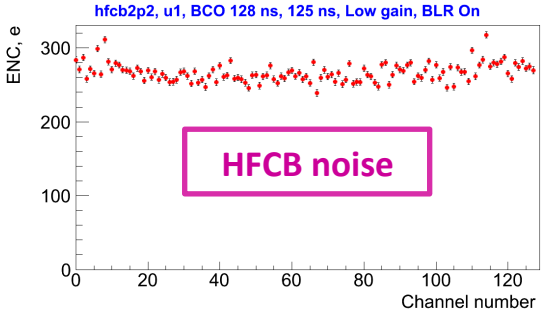
SVT Calibration, Noise and Gain, R1-R4







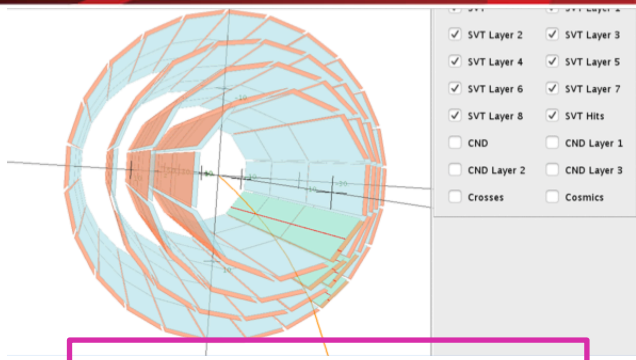




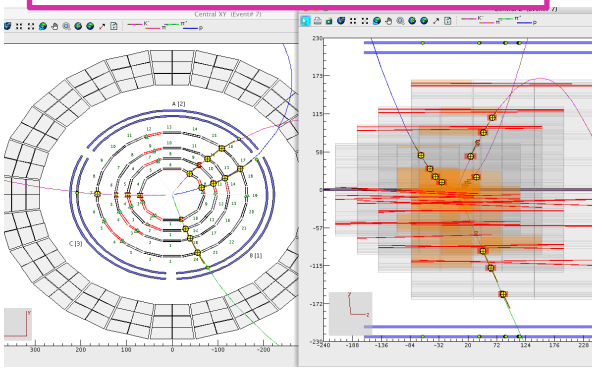
Detector/module	Strip length, cm	ASIC	ENC, e
ATLAS Barrel	13	ABCD3A	1500
CMS TOB OB1	18	APV25	1100
CDF Run 2b L0	24	SVX4	1600
CLAS12 SVT	33	FSSR2	1600

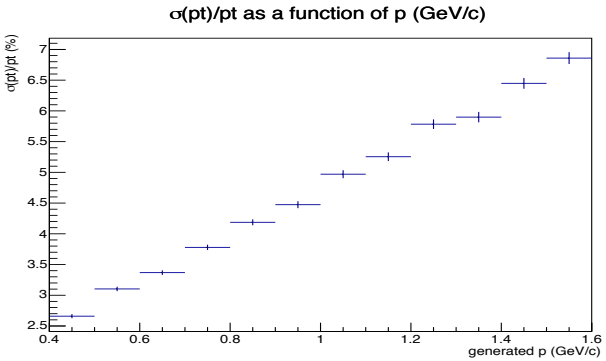
Simulation & Reconstruction

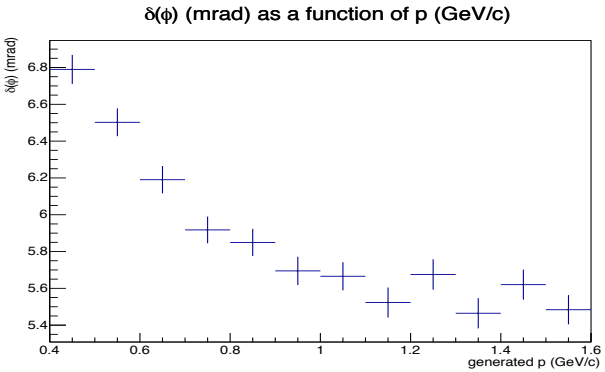
- Geant-4 simulation with full digitization
- Java code integrated in Service Oriented Framework
- Pattern Recognition in r−ϕ view
- Cut-based algorithm
  - Require 3 out of 4 intersections
  - Allows skipped region
- Global & adaptive (Kalman Filter) fitting
- Validated on cosmics & simulated events

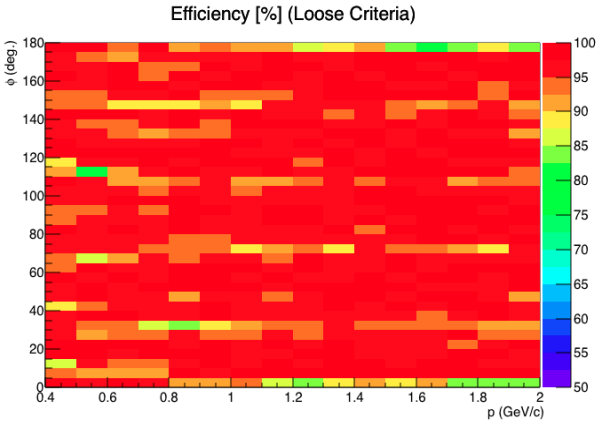


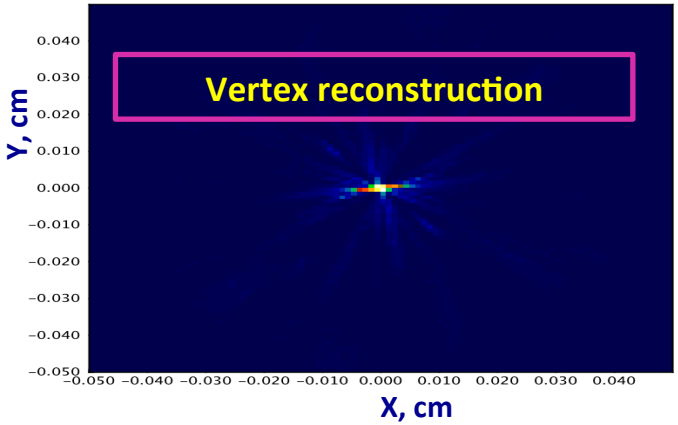
Java based CLAS Event Display

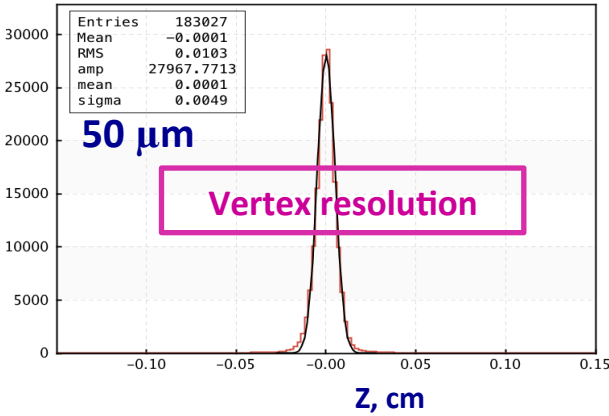












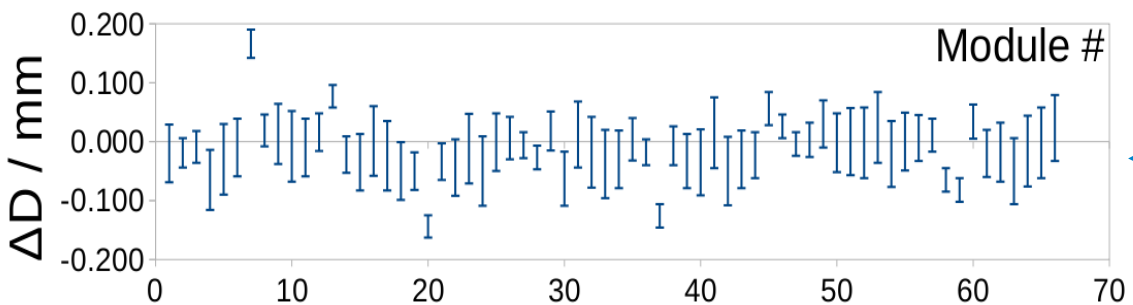
Alignment Procedure

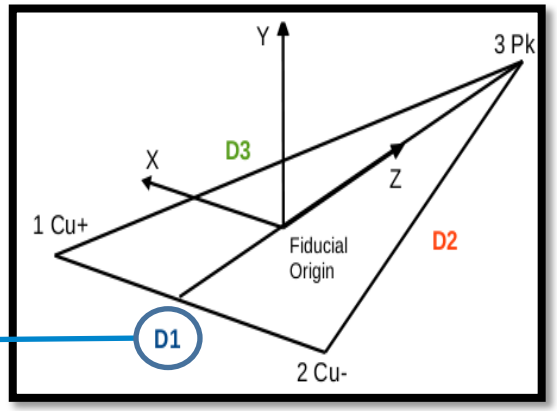
Alignment with MillePede for fitting many parameters: $N_{sectors} \times N_{layers} \times N_{trans} \times N_{rot} = 66 \times 2 \times 3 \times 2 = 792$

- **Uses matrix form of least squares method and divide the elements into two classes**
  - **Global parameters – the geometry misalignments. Same in all events**
  - **Local parameters – individual track fit parameters. Change event-to-event**
- **Calculate first partial derivatives of the fit residuals with respect to the local (i.e. fit) parameters and global parameters (geometry misalignments)**
- **Manipulate the linear least squares matrix to isolate the global parameters (geometry) and invert the results to obtain the solution**

Geometry package

- **Java utility to access geometry for GEMC simulation and reconstruction**
- **Generate shifts from ideal geometry to measured fiducial results**
- **Process fiducial survey data in alignment shifts – validate with simulated tracks**
- **Put full inventory of material in GEMC simulation**
- **Calculate ideal fiducial location on each module**
- **Ideal geometry defined with parameters from engineering drawings**

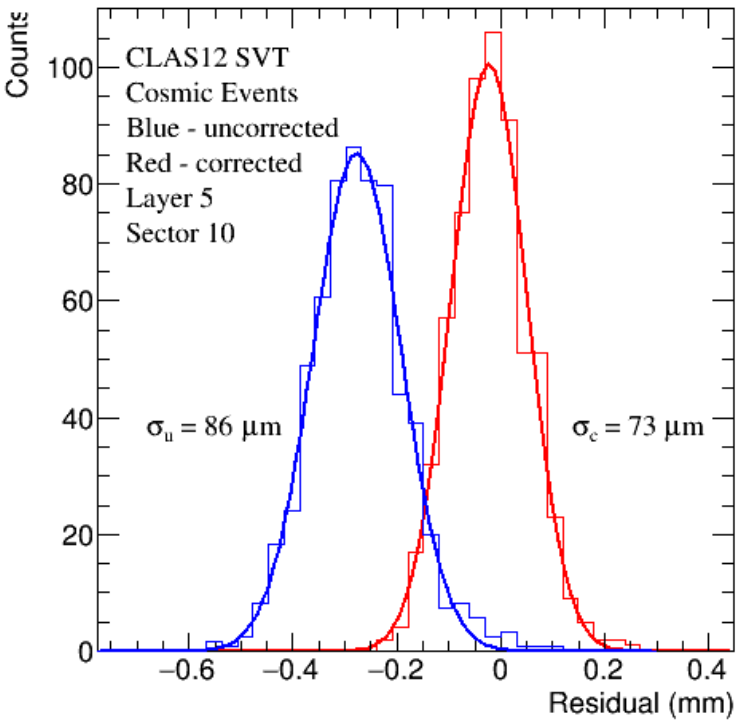


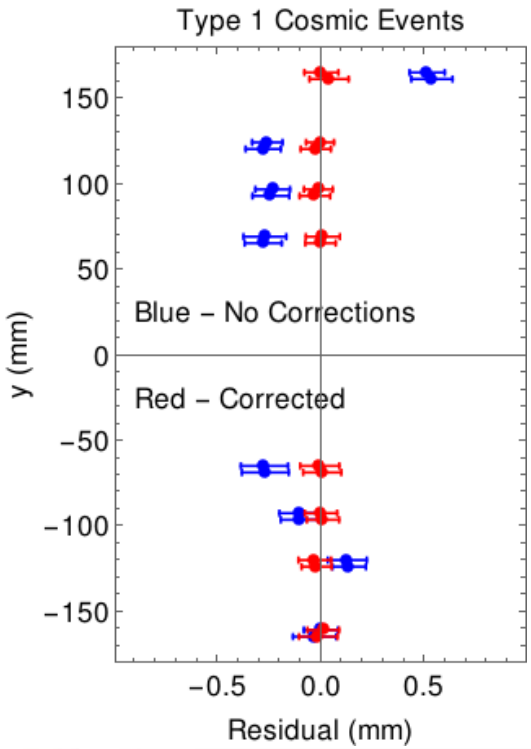


Fiducials form triangle on a sensor

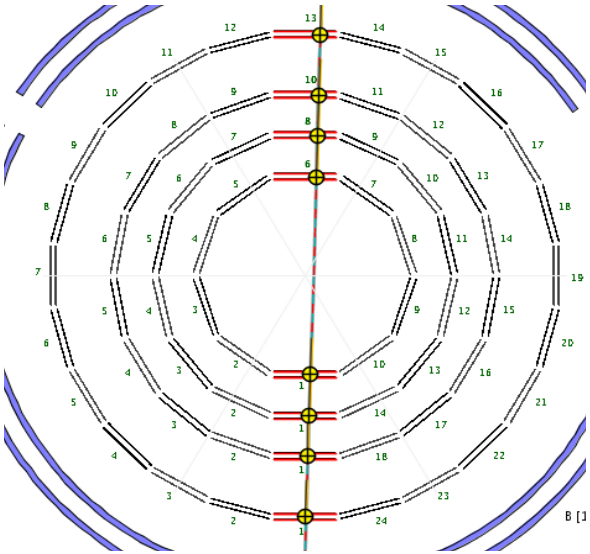
Alignment Status

- Validated on GEMC simulated sample
  - Code reproduces shifts of 2 – 500 microns
- Applied to Type 1 cosmic ray data sample
  - Fixed layer 4 in millipede fit to SVT residual
  - Good agreement between millipede misalignment and residuals
  - MillePede misalignments along the plane of the sensor
  - Error bars are the Gaussian width σ from the fit
- Code for Type 2 events (all sensors) is being tested





Type 1 tracks: horizontal sensors



Summary

- SVT is fully integrated, surveyed and calibrated
- No extra noise observed after integration
- Noise performance on par with leading silicon trackers
- Checkout of the detector services complete
- Checkout of detector safety system complete
- Checkout of DAQ and trigger complete
- Validation of data integrity and reconstruction chain complete
- CoatJava based calibration and monitoring suite developed
- 20 M tracks cosmic alignment sample collected
- SVT alignment in progress

BACKUP

Sensor Specifications – Mechanical

• Outer Size (BST)	42.000 x 111.625 mm
• Active Area (BST)	40.032 x 109.955 mm
• Thickness	320 µm ± 25 µm
• Dicing Tolerance	± 20 µm
• Flatness	<200 µm
• # of readout strips	256
• # of intermediate strips 256	
• Implant strip pitch	78 µm
• Readout strip pitch	156 µm
• Implant strip width	20 µm
• Aluminum strip width 26 µm	
• Overhang of Al strip	3 µm (on each side)
• Ratio implant width to pitch	0.256
• Angle of strips	0° (strip #1) to 3° (strip #256)

Sensor Specifications: Electrical

Full depletion voltage	40<V<100 (25° C@<45% RH)
Interstrip capacitance	<1.2 pF/cm
Leakage current (@ depletion V)	<10 nA/cm^2
Strip to back side capacitance	< 0.2 pF/cm
Interstrip isolation (@150 V)	>1 GΩ
Resistance of Al strips	< 20 Ω/cm
Coupling capacitance	> 20 pF/cm
Total (strip) capacitance	≤ 1.3 pF/cm; ($C_{tot} = 2*C_{int} + C_{back}$ @ 1 MHz)
Poly-silicon bias resistor	1.5 MΩ

Radiation doses in sensors

---
lh2
Layer 1a Fluences:
---

particles	GeV/s	mrad/s	rad/year
pi-	148	0.0729397	2300
e-	245	0.120444	3798
gamma	9363	4.60273	145151
n	21	0.0105842	333
e+	77	0.0380637	1200
pi+	451	0.221867	6996
p	3835	1.88562	59464
all	15303	7.52308	237247

---
iron
Layer 1a Fluences:
---

particles	GeV/s	mrad/s	rad/year
pi-	363	0.178654	5634
e-	554	0.272492	8593
gamma	5585	2.74589	86594
n	108	0.0531899	1677
e+	145	0.071363	2250
pi+	650	0.31982	10085
p	13452	6.61283	208542
all	23496	11.5503	364249

---
lead
Layer 1a Fluences:
---

particles	GeV/s	mrad/s	rad/year
pi-	464	0.22821	7196
e-	1954	0.960597	30293
gamma	9896	4.86486	153418
n	262	0.129285	4077
e+	396	0.194996	6149
pi+	794	0.390489	12314
p	17821	8.76063	276275
all	35236	17.3215	546252

---
carbon
Layer 1a Fluences:
---

particles	GeV/s	mrad/s	rad/year
pi-	229	0.112763	3556
e-	209	0.102942	3246
gamma	5236	2.57438	81185
n	47	0.0232453	733
e+	58	0.0286764	904
pi+	365	0.1798	5670
p	9967	4.89975	154518
all	19468	9.57049	301814

302 krad / year (2 years on the floor) for carbon target

2.2 Mrad for 15 years

Within acceptable limits of 5 Mrad

Radiation Doses in FSSR2

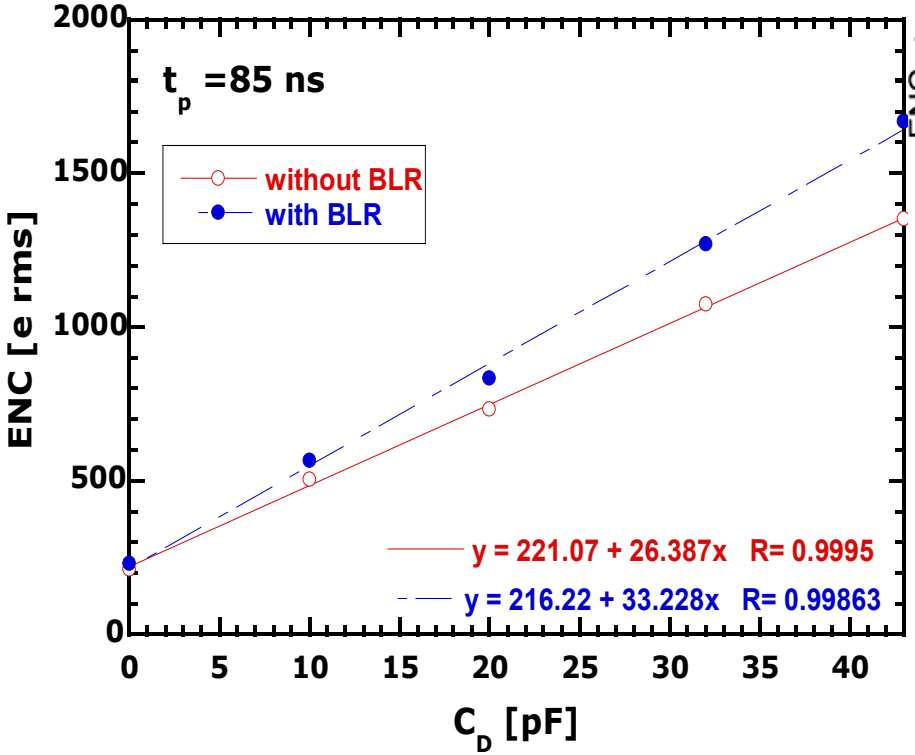
```
-----------------------
iron
Layer chip_r1 Fluences:
-----------------------
```

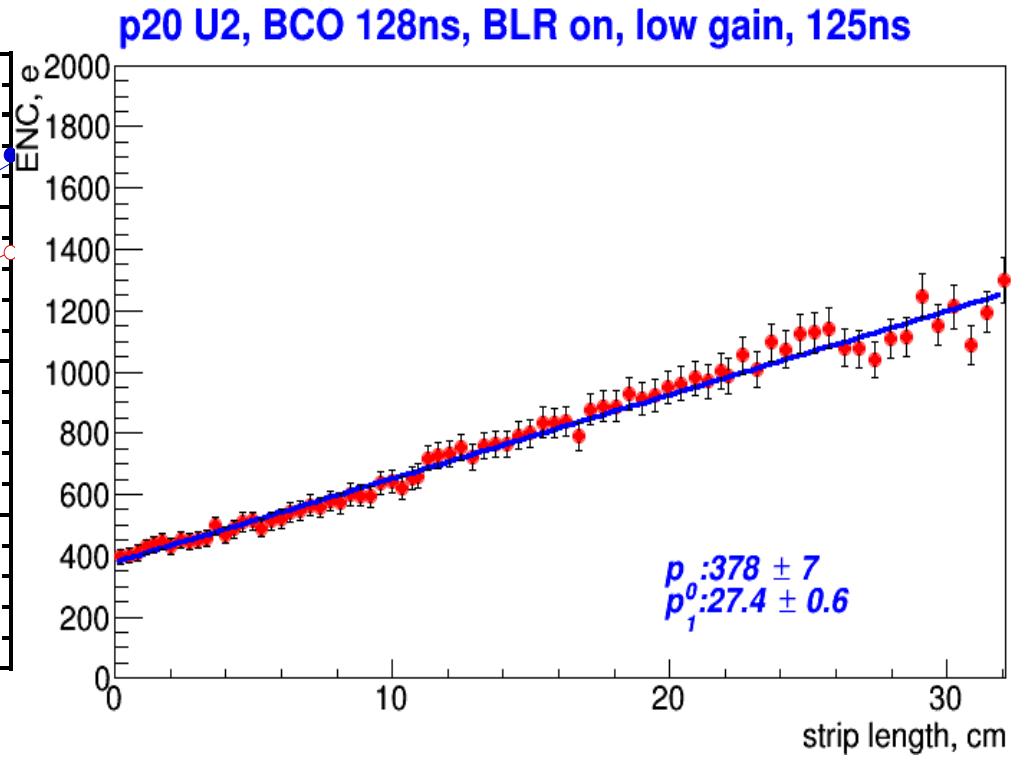
particles	GeV/s	mrad/s	rad/year
pi-	0	0.0146573	462
e-	8	0.257076	8107
gamma	2	0.0822083	2592
n	0	0.00509819	160
e+	0	0.0307166	968
pi+	0	0.0261282	823
p	3	0.0949537	2994
all	20	0.635616	20044

20 krad / year (2 years on the floor)
0.15 Mrad for 15 years on iron

Within acceptable limits of 5 Mrad

ENC vs. preamp load





FSSR2 testing @FNAL by FNAL
Single chip on a PCB
Load from capacitors

SVT module testing @FNAL by JLab
Four chips on a hybrid
Bonded to sensors