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.

**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....
High Threshold Cerenkov Counter (HTCC)
- 5 T SC Solenoid
- Central TOF
- Silicon Vertex Tracker (SVT)

Low Threshold Cerenkov
- Forward TOF
- Pre-Shower Calorimeter
- Electromagnetic Calorimeter

SC Torus Magnet
- Drift Chambers
- Moeller Shield

Beam-line:
- Raster magnets
- Beam Position
- Targets
- Moeller System
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 $\beta$ vs. $p$ measurement (particle ID)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESIGN VALUE</th>
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<tbody>
<tr>
<td>Number of regions (radii, mm)</td>
<td>4 (65, 93, 120, 161)</td>
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<tr>
<td>Sectors (modules)/region</td>
<td>10, 14, 18, 24</td>
</tr>
<tr>
<td>Module dimensions (L x W x T)</td>
<td>41.9 cm x 4.2 cm x 0.39 cm</td>
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<tr>
<td>Number of silicon layers/module</td>
<td>2 ($U$, $V$)</td>
</tr>
<tr>
<td>Strip layout</td>
<td>($0^\circ$—$3^\circ$) Graded angle</td>
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<tr>
<td>Sensor thickness</td>
<td>320 μm</td>
</tr>
<tr>
<td>Readout pitch</td>
<td>156 μm (hybrid side)</td>
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<tr>
<td><strong>Number of readout channels/module</strong></td>
<td><strong>512</strong></td>
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<tr>
<td><strong>Total number of readout channels</strong></td>
<td><strong>33,792</strong></td>
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<tr>
<td>Readout ASIC</td>
<td>FSSR2</td>
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<tr>
<td>Backend electronics</td>
<td>Custom-made VXS cards</td>
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<tr>
<td>Angular coverage $\theta$</td>
<td>35°–125°</td>
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<tr>
<td>Angular coverage $\Phi$</td>
<td>$\sim2\pi$</td>
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<tr>
<td>Spatial resolution</td>
<td>50-65 μm</td>
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<tr>
<td>Momentum resolution</td>
<td>$\sim6%$</td>
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<tr>
<td>$\theta$ resolution</td>
<td>10–20 mrad</td>
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<td>$\phi$ resolution</td>
<td>$\sim5$ mrad</td>
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<tr>
<td>Tracking efficiency</td>
<td>$&gt;90%$</td>
</tr>
<tr>
<td>Designed to operate at a luminosity of</td>
<td>$10^{35}$ cm$^{-2}$s$^{-1}$</td>
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</tbody>
</table>
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 Design
- 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

- **B-field direction**
  - Outside view LAYER B
  - View of LAYER A from outside
  - Intersecting strips in the BST

- **Dimensions**
  - 156 µm graded pitch
  - 202 µm

- **Angles**
  - 3° stereo angle
  - 2°

- **Reg 1**
  - 300 µm
  - 2.4860
  - 0.3051
**Design Overview: Mechanics**

- **R4 support tube**
- **R1-3 tube support flange**
- **Mating Flange**

Max. Deflection:
- ~16 \( \mu \text{m} \) (in horizontal modules)
- ~7 \( \mu \text{m} \) (in downstream ring)
- ~19 \( \mu \text{m} \)

*Images showing different components and deflection measurements.*
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
- Copper tube brazed into channel

Cover Plate (Plastic)

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

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

- Output of HV filter, return jumpers
- Polyimide Alignment Tabs
- FSSR2 ASICs
- Diagnostic Header
- Input of HV filter
- HV+ Tab
- HV ground
- Decoupling capacitors
- Temperature and RH sensors
- Clocks Termination
- Input of HV filter
- HV+ Tab
- 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

- 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

Separate circuits for LV analog and LV digital
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
- Optical survey
- Sensor placement
- Sensor wire bonding
Mounting the SVT Module

- Handle screw
- Guide pin
- Mounting screw
Region Assembly (Vertical)

CF Faraday Cage

R1  R2

R3  R4

U.S. DEPARTMENT OF
Office of
Energy Science

Jefferson Lab
Region Disassembly Fixture

Lifting Frame

SVT Lifting Cradle

Region Storage Cart

Region lifted and secured
Survey of Module Position

Position of each module measured using Faro-Arm

Module position measurement accuracy 20 μm
Integration with Support Tube

Vertical position of SVT after assembly

Horizontal position of SVT after rotation

CF Faraday Cage
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

Counterweight

No extra noise
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

Fiber Optics (from global trigger crate)

1Gbit Ethernet to Event builder

High Density Round Shielded (100 Ohm twisted pair)

Data cable (5 m)
Slow Control and Monitoring

- EPICS IOC
- MYA DB
- Module
- MEDM GUI
  (transition to CS Studio)
- Alarm handler
- Ambient interlocks
- Chiller
- Temperature
- Humidity
- Power supplies
- Wiener MPOD
- Mainframe
- Bias Voltage
- Leakage currents
Online/Offline Control and Monitoring

Micromegas Layers

COATJAVA Clas Offline Analysis Tools

Channel Occupancy map (cosmic run)

EVIO/Hipo Data Format

<table>
<thead>
<tr>
<th>Partition</th>
<th>Channels</th>
<th>% operational</th>
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<tbody>
<tr>
<td>Region 1</td>
<td>5120</td>
<td>100</td>
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<tr>
<td>Region 2</td>
<td>7168</td>
<td>99.98</td>
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<tr>
<td>Region 3</td>
<td>9216</td>
<td>99.96</td>
</tr>
<tr>
<td>Region 4</td>
<td>12288</td>
<td>99.99</td>
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</table>
Channel Calibration

Occupancy scan

Response plot

Gain dispersion

Threshold dispersion

Noise vs. channel, U1/U3

Noise vs. channel, U2/U4

Shorter strips

γ source

Cosmic muons

120 GeV protons
SVT Calibration, Noise and Gain, R1-R4

1. Median ENC: 264 chips
2. MIP: 24 ke

S.N.R. > 15
- Short strips

- Good agreement with published FSSR2 results

ENC vs. strip length (capacitive load) in one chip

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

HFCB noise

hfcb2p2, u1, BCO 128 ns, 125 ns, Low gain, BLR On
Simulation & Reconstruction

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

\[ \alpha(\text{pt})/\text{pt as a function of } p \ (\text{GeV/c}) \]
\[ \delta(\phi) \ (\text{mrad}) \text{ as a function of } p \ (\text{GeV/c}) \]

```
• Java based CLAS Event Display
• Vertex reconstruction
• Vertex resolution
```
Alignment with MillePede for fitting many parameters: \( N_{\text{sectors}} \times N_{\text{layers}} \times N_{\text{trans}} \times N_{\text{rot}} = 66 \times 2 \times 3 \times 2 = 792 \)

- 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 $\sigma$ from the fit
- Code for Type 2 events (all sensors) is being tested
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
### Sensor Specifications – Mechanical

- **Outer Size (BST)**: $42.000 \times 111.625$ mm
- **Active Area (BST)**: $40.032 \times 109.955$ mm
- **Thickness**: $320 \, \mu m \pm 25 \, \mu m$
- **Dicing Tolerance**: $\pm 20 \, \mu m$
- **Flatness**: $<200 \, \mu m$
- **# of readout strips**: 256
- **# of intermediate strips**: 256
- **Implant strip pitch**: $78 \, \mu m$
- **Readout strip pitch**: $156 \, \mu m$
- **Implant strip width**: $20 \, \mu m$
- **Aluminum strip width**: $26 \, \mu m$
- **Overhang of Al strip**: $3 \, \mu m$ (on each side)
- **Ratio implant width to pitch**: 0.256
- **Angle of strips**: $0^\circ$ (strip #1) to $3^\circ$ (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/cm²
- **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; $(C_{tot} = 2C_{int} + C_{back} @ 1$ MHz)
- **Poly-silicon bias resistor**: 1.5 MΩ
## Radiation doses in sensors

### lh2

#### Layer 1a Fluences:

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

### iron

#### Layer 1a Fluences:

<table>
<thead>
<tr>
<th>particles</th>
<th>GeV/s</th>
<th>mrad/s</th>
<th>rad/year</th>
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<tbody>
<tr>
<td>pi-</td>
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<td>0.178654</td>
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<tr>
<td>e-</td>
<td>554</td>
<td>0.272492</td>
<td>8593</td>
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<tr>
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<td>e+</td>
<td>145</td>
<td>0.071363</td>
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<td>23496</td>
<td>11.5503</td>
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### lead

#### Layer 1a Fluences:

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<th>mrad/s</th>
<th>rad/year</th>
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<tbody>
<tr>
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<td>e-</td>
<td>1954</td>
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<tr>
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### carbon

#### Layer 1a Fluences:

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<th>mrad/s</th>
<th>rad/year</th>
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<td>47</td>
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<td>19468</td>
<td>9.57049</td>
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</tbody>
</table>

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:

<table>
<thead>
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<th>particles</th>
<th>GeV/s</th>
<th>mrad/s</th>
<th>rad/year</th>
</tr>
</thead>
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<td>e-</td>
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<td>gamma</td>
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<td>n</td>
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<td>20</td>
<td>0.635616</td>
<td>20044</td>
</tr>
</tbody>
</table>

**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

ENC $[e \text{ rms}]$ vs. $C_D [\text{pF}]$

- $t_p = 85 \text{ ns}$
- $y = 221.07 + 26.387x \quad R = 0.9995$
- $y = 216.22 + 33.228x \quad R = 0.99863$

**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

$p20 \text{ U2, BCO 128ns, BLR on, low gain, 125ns}$

$p = 378 \pm 7$
$p^0 = 27.4 \pm 0.6$