ATLAS Tracker Upgrade @ HL-LHC

Birmingham Seminar 8/3/16
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ATLAS Tracker Upgrade @ HL-LHC

• Physics Motivation
• HL-LHC & Technical Challenges
• Trigger
• ITk
  – Challenges
  – Strips
  – Pixels
• Outlook
Ladies and gentlemen, I think we’ve got it!

Discovery of a Higgs-like particle coupling to gauge bosons
Why More Luminosity?

• LHC is parton-parton (mainly gg) collider.

  – More luminosity = more collisions at high parton-parton CMS energy $\sqrt{s}$.

• More events for precision physics.
• Larger window for searches.
Higgs Physics

• We know it is a boson, spin =0.

• Does it couple to mass as expected?
  – SM predicts all BR now that we know $m_H$.

• VV scattering at high energy?
  – Does Higgs mechanism prevent unitarity violation at high energy?

• Higgs self coupling
  – Required for SSB and $\Rightarrow$ HH production.
Higgs Coupling

• Run 1, precise results only for $\gamma/W/Z$, evidence for $\tau$
• HL-LHC: 3000 fb$^{-1}$
• Many improvements including measure BR($H \rightarrow \mu\mu$)
VV Scattering

- WW and ZZ
- ZZ good mass resolution → sensitivity to resonances
- Need 3000 fb$^{-1}$ for good sensitivity.
Higgs Self Coupling

- Higgs potential:
- After SSB $\Rightarrow H^3$ term $\Rightarrow$ HH production.
- Destructive interference in SM
- Small $\sigma \sim 40$ fb
- Different channels, $bbbb$, $bb\gamma\gamma$, $bbWW$ etc.
- Needs HL-LHC.

$$L = -\frac{1}{4} \lambda^2 \phi^4 + \frac{1}{2} \mu^2 \phi^2$$

$$\phi = \varphi_0 + H$$
New Dark Age

• “What we know is a drop, what we don't know is an ocean.”

• New dark age, we understand 5% of the energy in the Universe.

• Positive spin: lots for physicists to discover!
SUSY & Exotics

• Hierarchy problem still exists
  – Why $M_H << M(GUT)$ or $M(\text{Planck})$?
  – Natural explanation requires new physics @ TEV scale.

• Astrophysical evidence for dark matter very strong
  – Search in events with MET

• SUSY still an option for solving both these problems

• Extend reach for SUSY and exotics with HL-LHC.
HL-LHC

- Many improvements for \( L = 7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \rightarrow \) very high pile up \(<\mu> = 200.
- New superconducting triplets \( \rightarrow \) low \( \beta^* \). Needs \( \text{Nb}_3\text{Sn} \) (cf \( \text{NbTi} \) in LHC).
- Injector upgrades
- Crab cavities
- Luminosity Levelling
- High availability
- Aim \( \int Ldt = 3000 \text{ fb}^{-1} \)

- **HL-LHC, Rossi & Bruning, ECFA 2014**
HL-LHC goal could be reached in 2036
ITk Design Challenges

• Challenges for tracking detectors:
  – Radiation damage
  – Hit occupancy
  – Data rates.

• Aim to maintain performance of current detector.
  – Higher trigger rates but keep thresholds low.
  – More granular detector elements to keep low occupancy.
  – More rad-hard technology.

• Improvements:
  – Extend $\eta$ coverage
  – Lower radiation length for tracker
• Importance of keeping low thresholds on leptons.

• Different options considered for trigger:
  – 1 MHz full readout
  – L0/L1 using L1track to reduce rate before full readout.
  – All options ➔ higher data rates.
Material Budget

• Main limitation in performance of current ID
  – Degrades track resolution (multiple scattering)
  – Degrades EM calo resolution for electrons
  – Decreases efficiency for electrons and pions.
  – Need to build thinner \(X_0\) & \(\lambda_0\) detector.

• ITk goal: <1.5 \(X_0\)
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Radiation Levels

- **Ionizing dose**
  - Strips < 500 kGy (Si)

- **Hadron Fluence**
  - Strips < $1.2 \times 10^{15} \text{n}_{eq} \text{cm}^{-2}$

¼ detector in R-z plane
ITk Layout

- Layout still evolving but all silicon tracker with extended $\eta$ coverage.
- Pixels (strips) at low (high) radius.
- Very Forward pixels.
ITk Strips Design

• Some key components
  – Sensors
  – ASICs
  – Optoelectronics

• Build up systems
  – Modules
  – Staves/petals
  – Structures

• System Issues
  – Powering
  – Reliability
Si Radiation damage

- High energy particles $\rightarrow$ complex lattice defects
- Mid-band states increase leakage current
  
  $$I(T) = AT^2 \exp\left(\frac{-E_g}{2k_BT}\right)$$
  
  – Shot noise
  
  – Thermal runaway: $I$ increases $T$(Si) $\rightarrow$ $I$ $\rightarrow$ increases $T$
  
  – Cool Si $T$=-25°C
- Acceptor concentration $N_a$ increases $\rightarrow$ higher depletion thickness $d$ of Si
  
  $$V_{dep} = \frac{N_a ed^2}{2\varepsilon}$$

- Charge trapping $\rightarrow$ signal loss.
Silicon Sensor

- $n$-in-$p$ (SCT $p$-in-$n$)
- Signal (mainly) from electrons (faster than holes)
- Depletes from junction → can operate under-depleted.
- Cheaper than $n$-in-$n$.
- Sufficient signal for maximum strip fluence.
ABC130* ASIC

- Keep SCT binary architecture: discriminator per channel.
- Many improvements
  - Allow for L0/L1 trigger, new deep buffer.
  - 130 nm technology (more rad-hard).
HCC130* ASIC

- Star connections from ABC130* \( \rightarrow \) allows higher data rates (cf Daisy Chain).
- Allows full readout at 1 MHz.
- Higher rates possible with L0/L1.
Radiation Effects on ASICs

- Large increase in digital current with dose (TID).
- Electrical & Thermal problem.
- “Well-known” effect in 130 nm process.
- Very rate and temperature dependent.
- Optimise temperature scenario for early running to minimise effect.

2.25 Mrad/hr -15C

2.3 kRad/hr -10C.
Optical Links

VL+ 10 Gbps rad-hard optical links

10 Gbps IpGBT ASIC

Very small form factor optical transceivers
Radiation Effect VCSELs

- Vertical Cavity Surface Emitting Lasers
  - data transfer detector $\rightarrow$ counting room
- Radiation damage $\rightarrow$ threshold shift
- Measure and model annealing $\rightarrow$ predict damage.
- Small threshold shifts after annealing.

Fractional threshold current increase

![Graph showing fractional threshold current increase vs. neutron fluence](image)
Strip Barrel Module

Schematic

- 10 ABC130* + HCC*/hybrid

Thermo-mechanical module
Low $X_0$ Tracker

- Glue modules directly to mechanical support.
- Carbon fibre sandwich, provides rigid, lightweight 0 CTE support structure.
- Evaporative CO$_2$ cooling.
Staves

- Barrel staves

- Module rotated ➔ stereo reconstruction
- Opposite stereo angle for modules on bottom of stave.
- Services:
  - Bus tape provides LV/HV and data transmission to/from EoS
  - Embedded cooling tubes
  - EoS: optoelectronics: data to/from counting room.
Barrel Stave

- Schematic
- Tape co-cured to carbon fibre

Cross-section

- Cu tracks 100 µm track and gap
- 3 layer carbon fibres (0°, 90°, 0°)

14 modules = 1.4×0.1m²

Similar build on other side
Data Transmission

• Data transmission 1.4m @ 640 Mbps point to point.
• Constraints: space and thickness.
• Design optimisation
  – $Z_0=100 \, \Omega$ (reflections)
  – Low loss and dispersion.
  – Use FEA:
    • E and B fields $\rightarrow$ C and L.
    • Attenuation and dispersion
    • Signal integrity, eye-diagram

\[ Z_0 = \sqrt{L/C} \]
Signal Integrity

- Data @ 640 Mbps:
  - Dispersion, but clean eye @640 Mbps
- Distribute Timing, Trigger & Control (TTC) → hybrids on FE modules @ 160 Mbps.
- 28 capacitive loads → reflections.
  - $T \sim 1/(1+\omega CZ_0)^2$
- Split TTC into 4 groups → improves signal integrity.
- Strong reflections but clean eye for worst case 10 loads.
Module Powering

• Can’t afford one cable per module.
  – Too high current $\rightarrow$ IR drop $\rightarrow$ cables too big!

• DC-DC for strips.
DC-DC Powering

• Challenges
  – Need coil to operate in B field.
  – Radiation tolerance
  – EMI

• Prototypes used to demonstrate good system noise performance with “stavelet” (4 modules).

• UpFEAST: rad-hard versions for HL-LHC being developed by CERN. cern.ch/project-dcdc
Reliability

• What could possibly go wrong?

How can we ensure we have a reliable system?
• **Replaceability**
  – Not feasible for ITk strips on-detector components.

• **Redundancy**
  – Q: when should you use redundancy?
  – A: safety or mission critical.
  – Redundancy in # of layers. Validate design assuming 10% dead.

• **Reliable components**
Reliable Components

- Conservative design
- QC on all components
- QA on batch basis
- QA: more extreme stress test than anticipated in operation. e.g.
  - Elevated temperature and/or voltage
  - Rapid thermal cycling
  - Vibration
- Failure analysis on failed components in R&D ➔ improve reliability.
- Check quality on batch basis in production.
Pixels

- Hybrid Pixels
- Challenges
  - Radiation hardness
  - Higher granularity
  - Higher data rates
- Solutions
  - Thin sensors and larger fields
  - New ASIC 65nm
  - High speed electrical readout
Hybrid Pixel

- Good for HL-LHC radiation levels
- $n$-$in$-$p$ cheaper $n$-$in$-$n$
- Thinner $\rightarrow$ improves efficiency @ lower HV.
- Reduce inactive regions
- Avoid HV breakdown, even with higher HV
Pixel Radiation Damage

- High efficiency after $2 \times 10^{16}$ n cm$^{-2}$ for very large HV
- Charge amplification?
- Main effect is charge trapping $\rightarrow$ thinner sensors $\sim 100$ um
- 3D
Readout & Powering

• Inner layer chip data rates ~ 100 Gbps/chip.
  – Store data on chip, readout triggered events → rate 2-4 Gbps
  – Improved architecture for pixel chips, RD53. Rad-hard 65 nm CMOS
  – Electrical readout over few metres → optical transceivers. Challenging!

• Powering
  – DCDC converters too bulky → use serial powering.
Outlook

• Physics case for HL-LHC
• ITk strips: TDR, final R&D, pre-production in 2019
• ITk pixels: more R&D, TDR 2017 (smaller detector, shorter production time)
• Questions?
BACKUP
### Safety factor of 1.5 for fluence.

<table>
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<tr>
<th>Module Type</th>
<th>Fluence $10^{14}n_{eq}cm^{-2}$</th>
<th>Charge $ke^-$ 500 V</th>
<th>Charge $ke^-$ 700 V</th>
<th>Noise $e^-$</th>
<th>S/N 500 V</th>
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</tr>
</tbody>
</table>
Is there still the need for ELTs and guard rings?

The leakage current is the sum of different mechanisms involving:
- the creation/trapping of charge (by radiation)
- its passivation/de-trapping (by thermal excitation)

These phenomena are Dose Rate and Temperature dependent!

Source-Drain leakage is eliminated by the Enclosed Layout Transistor (ELT)...

Inter-diffusion leakage is eliminated by p+ guard rings...
From Thin Planar to 3d sensors

Common advantages: Short drift path, Higher fields at same $V_{bias}$

Thin planar sensors:
- Low total leakage after irradiation
Drawback:
- Smaller initial signal (76e⁻/µm)
- Design limits for small pixels
- Thinning of handling wafer
  → Candidate for larger areas

3D sensors:
- Thick sensor possible with low depletion voltage
Drawback:
- Higher Capacity
- Low yield
- Are very small pitches possible?
  → Candidate for 1st layer

Paula Collins
ECFA High Luminosity LHC Experiments Workshop
CMOS

• Fall forward options being considered
  – CMOS strip sensors as replacement for strip detectors
  – Full MAPS for outer pixel layer(s)
CMOS Sensors

CMOS Imagers

- Cheap
- Diffusion $\Rightarrow$ too slow for LHC
- Not rad-hard

HV/HR

- High voltage or higher resistivity $\Rightarrow$ larger depletion depth
- Fast signal
- Radiation-hard?
CHESS1

- Radiation damage studies
- Measure depletion region with edge TCT

Scan laser spot vs depth, measure I

- Depletion depth increases at first

Sufficiently radiation hard for outer layers.
Further Information

- ECFA 2016 talks
  - ATLAS Upgrade
  - ATLAS strip tracker: Ingrid Gregor
  - Pixel tracker: Joern Grosse-Knetter

- ATLAS ITk strip TDR