ATLAS Tracker Upgrade @ HL-LHC

Birmingham Seminar 8/3/16

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(Oxford)

ATLAS Tracker Upgrade @ HL-LHC

- Physics Motivation
- HL-LHC & Technical Challenges
- Trigger
- ITk
  - Challenges
  - Strips
  - Pixels
- Outlook

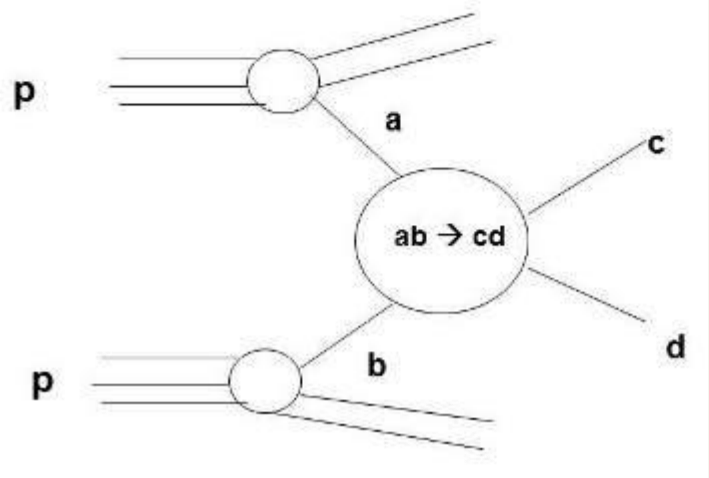
CERN, 4 July 2012

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.**



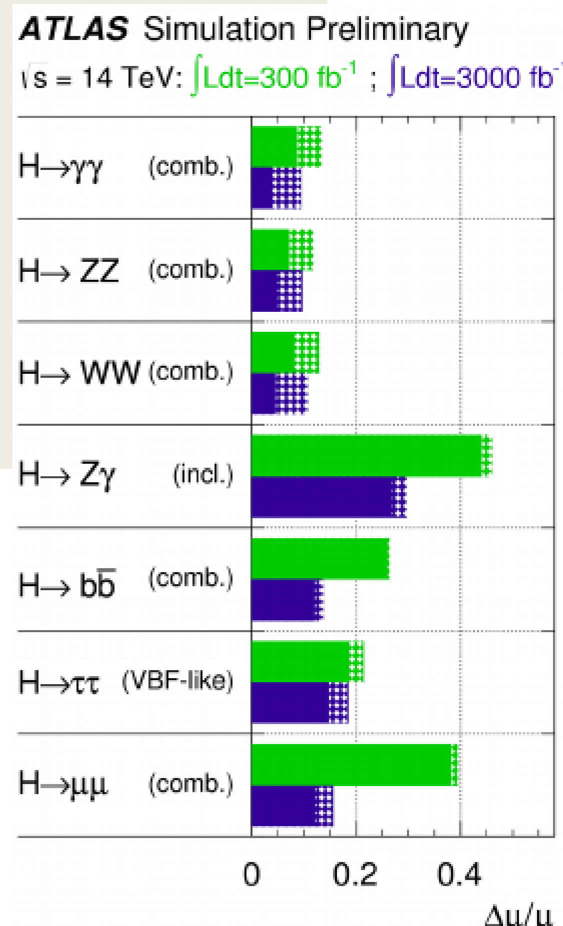
  - **More luminosity = more collisions at high parton-parton CMS energy $\sqrt{s}$.**
- **More events for precision physics.**
- **Larger window for searches.**

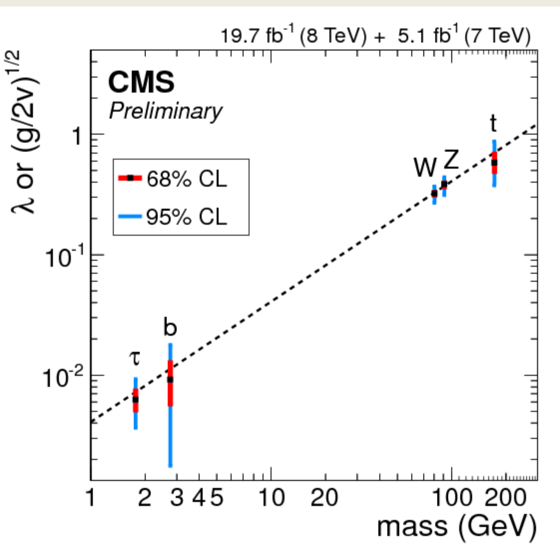
Higgs Physics

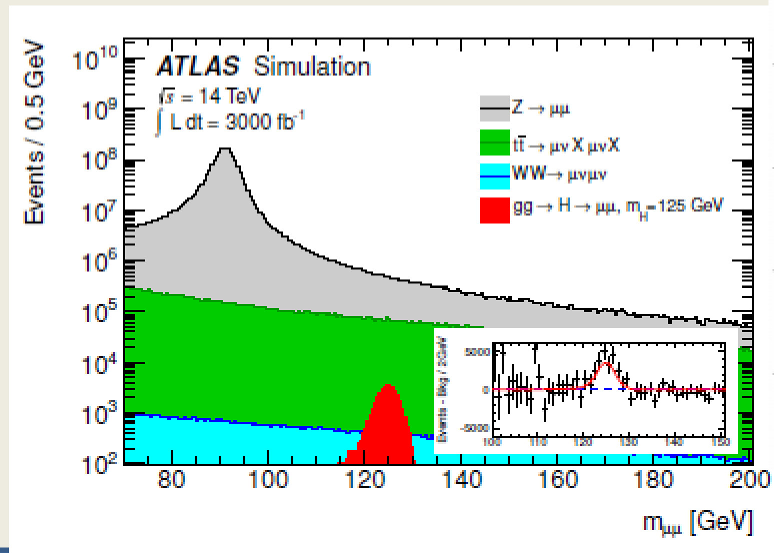
- We know it is a boson, spin =0.
- Does it couple to mass as expected?
  - SM predicts all BR now that we know m_H.
- VV scattering at high energy?
  - Does Higgs mechanism prevent unitarity violation at high energy?
- Higgs self coupling
  - Required for SSB and → HH production.

Higgs Coupling

- Run 1, precise results only for γ/W/Z, evidence for τ
- HL-LHC: 3000 fb^{-1}
- Many improvements including measure BR(H→μμ)

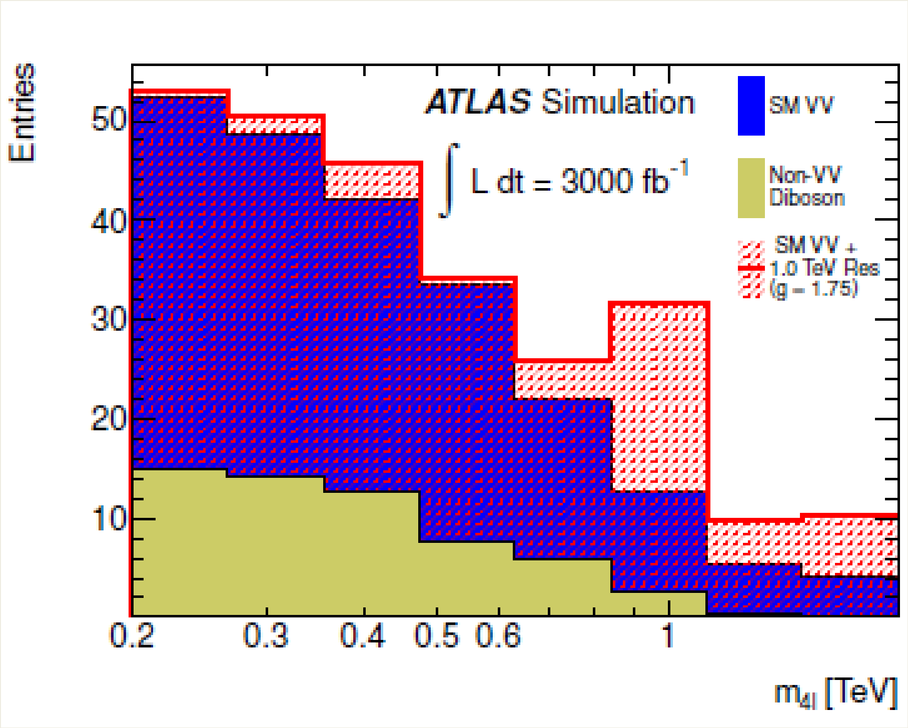






VV Scattering

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

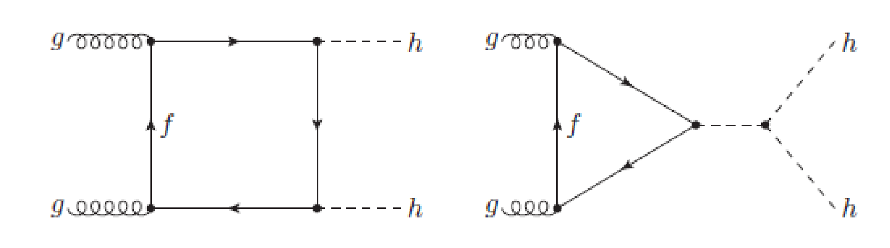


Higgs Self Coupling

- **Higgs potential:**
- **After SSB ➔ H^3 term ➔ HH production.**
- **Destructive interference in SM**
- **Small σ ~ 40 fb**
- **Different channels, bbbb, bbγγ, 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

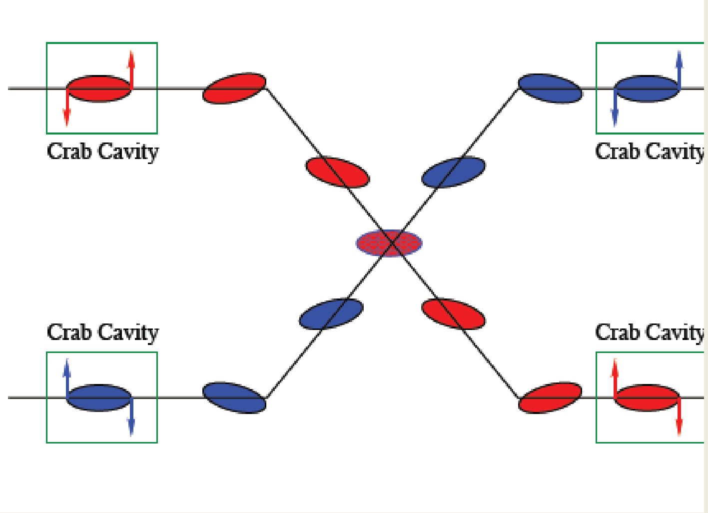
- "What we know is a drop, what we don't know is an ocean."
- New dark age, we understand 5% of the energy in the Universe.
- Positive spin: lots for physicists to discover!

SUSY & Exotics

- **Hierarchy problem still exists**
  - **Why M_H << M(GUT) or M(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.**

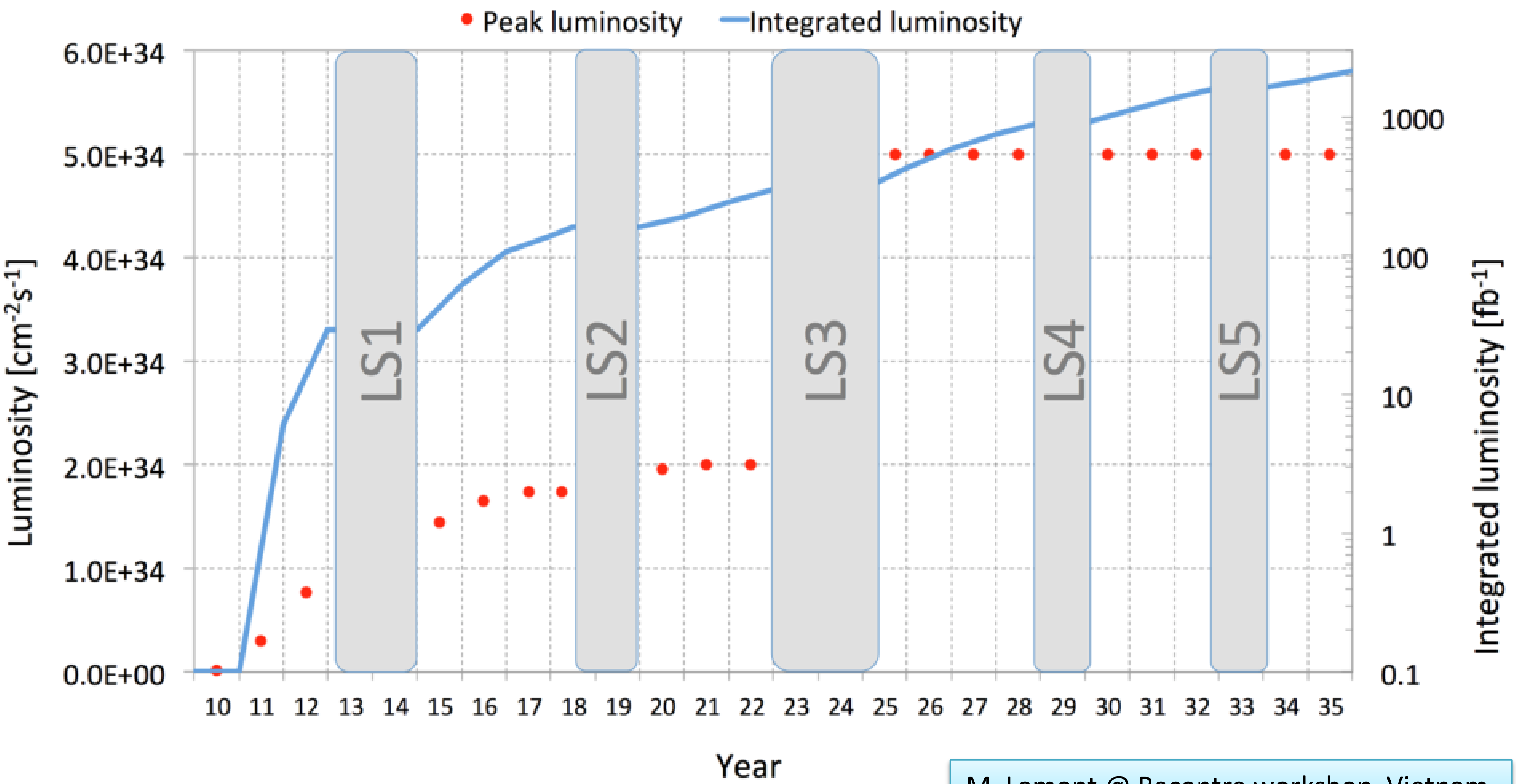
HL-LHC

- Many improvements for L=7 10^{34} $cm^{-2}s^{-1}$ ➔very high pile up $\langle\mu\rangle=200$.
- New superconducting triplets ➔ low β^*. Needs Nb_3Sn (cf NbTi in LHC).
- Injector upgrades
- Crab cavities
- Luminosity Levelling
- High availability
- Aim $\int Ldt = 3000\ fb^{-1}$



- HL-LHC, Rossi & Bruning, ECFA 2014

HL-LHC goal could be reached in 2036



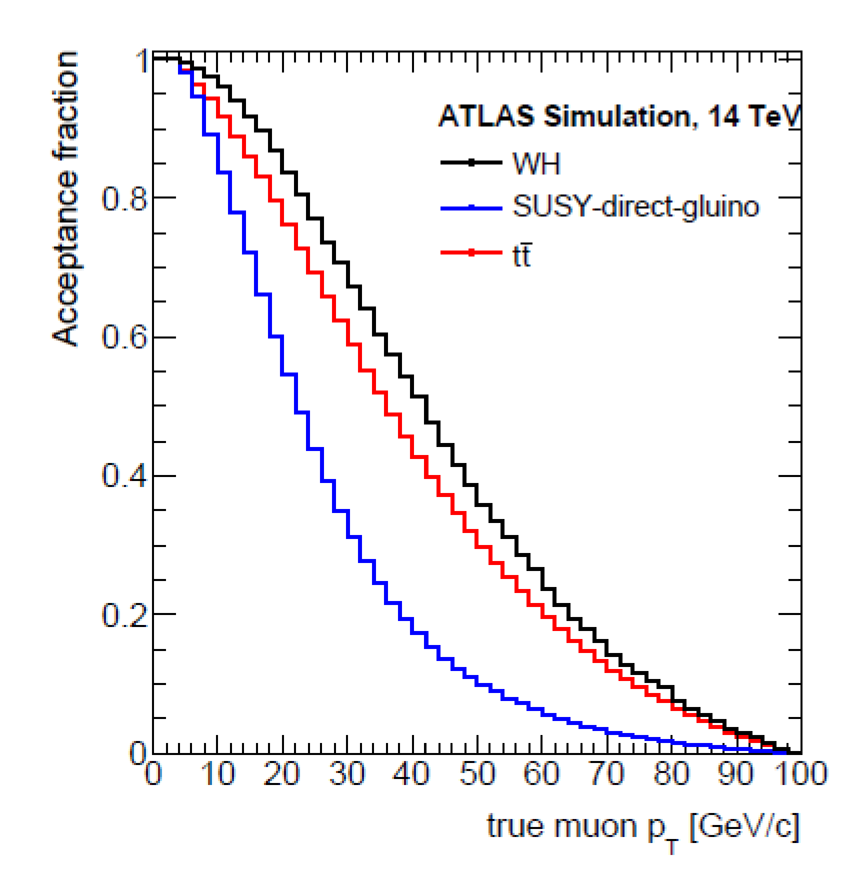
M. Lamont @ Recontre workshop, Vietnam

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 η coverage
  - Lower radiation length for tracker

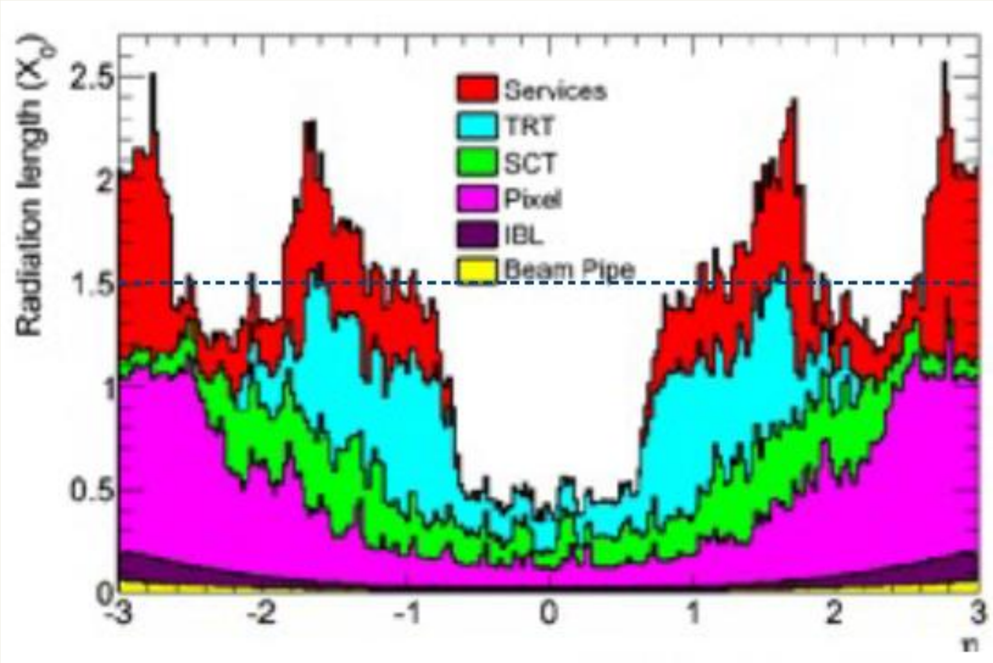
Trigger

- **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 & λ_0) detector.**
- **ITk goal: <1.5 X_0**



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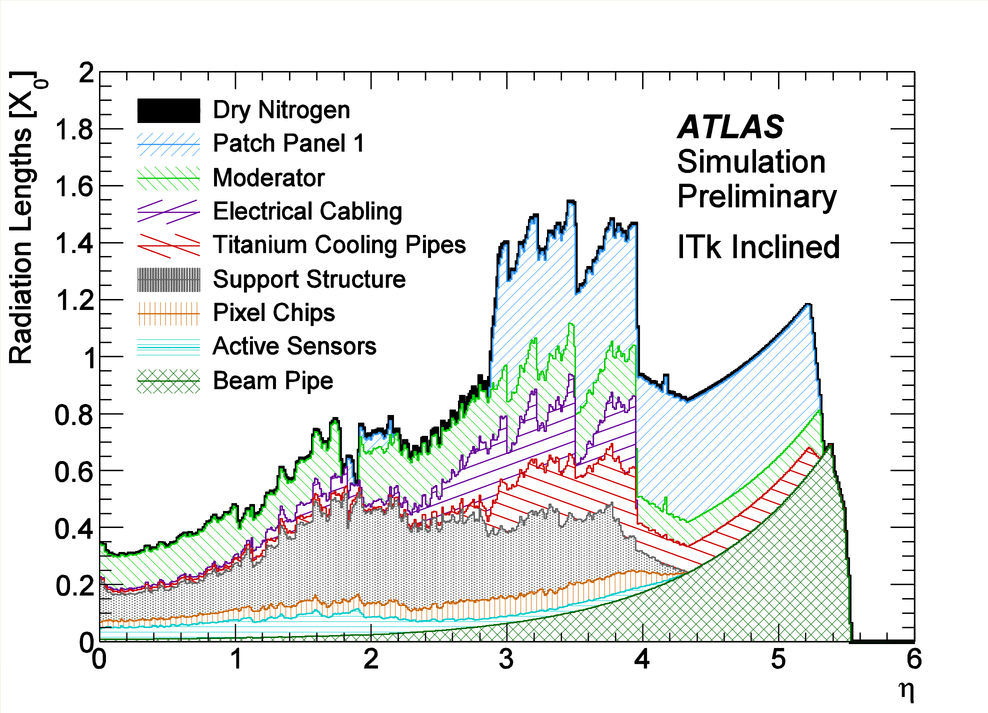
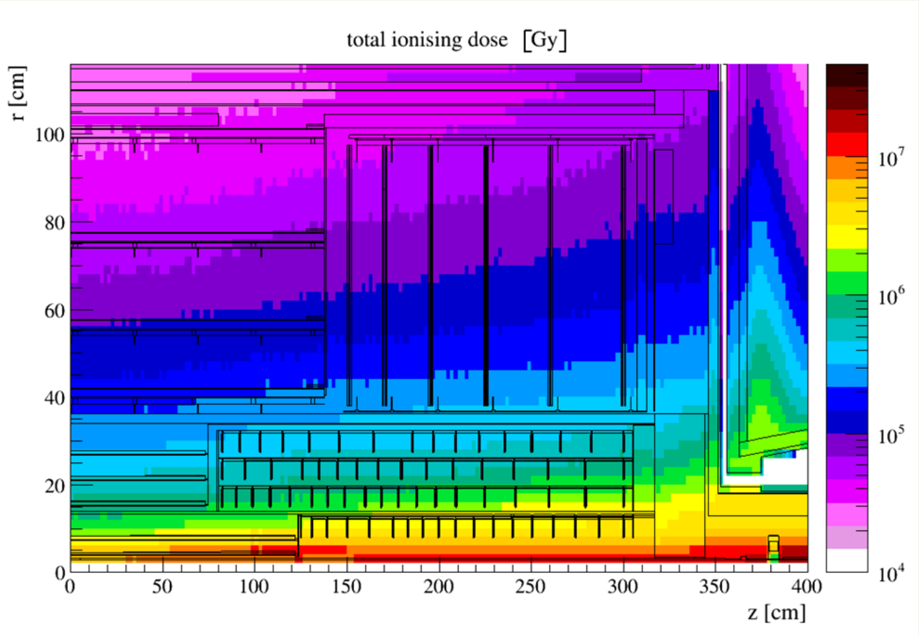
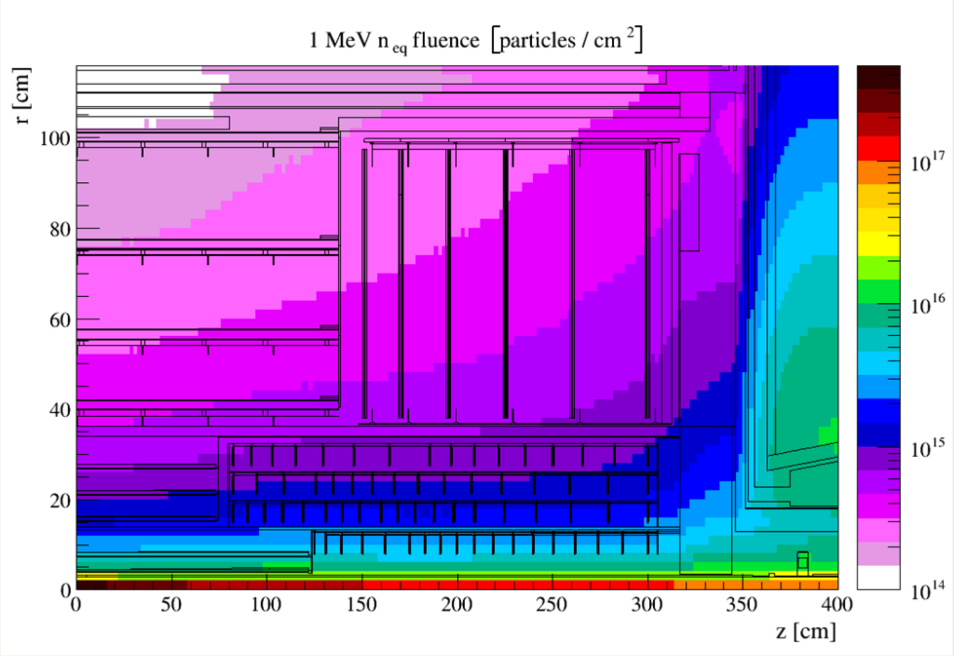


Radiation Levels

- **Ionizing dose**
  - **Strips <500 kGy (Si)**
- **Hadron Fluence**
  - **Strips < 1.2 10^{15} n_{eq} cm^{-2}**

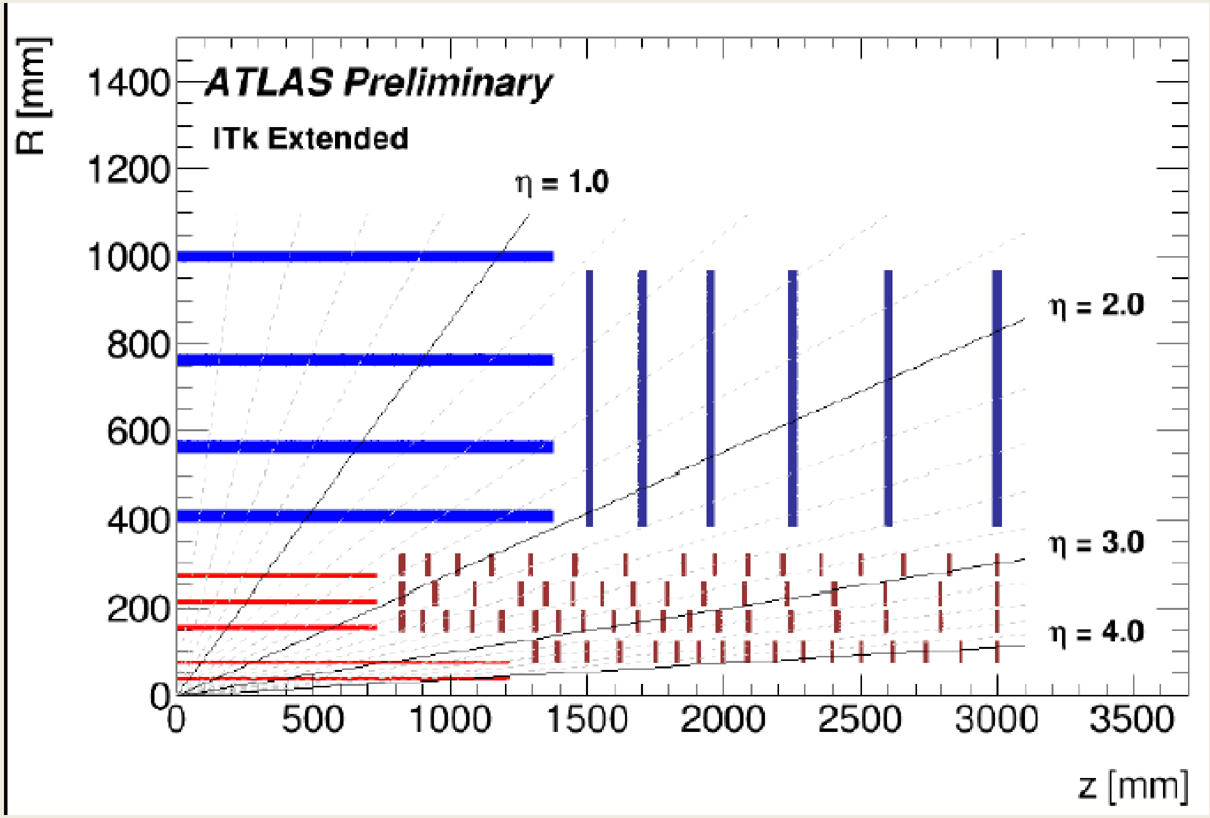




¼ detector in R-z plane

ITk Layout

- Layout still evolving but all silicon tracker with extended η 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

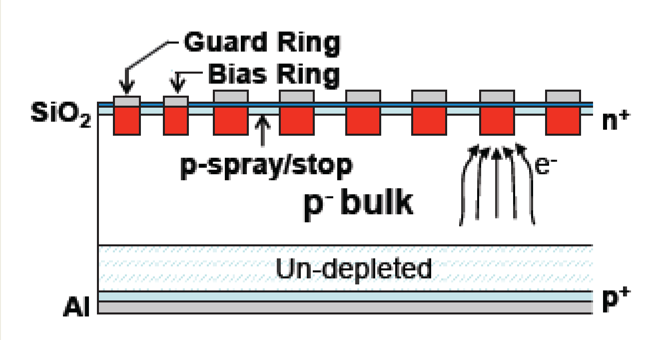
- High energy particles → complex lattice defects
- Mid-band states increase leakage current

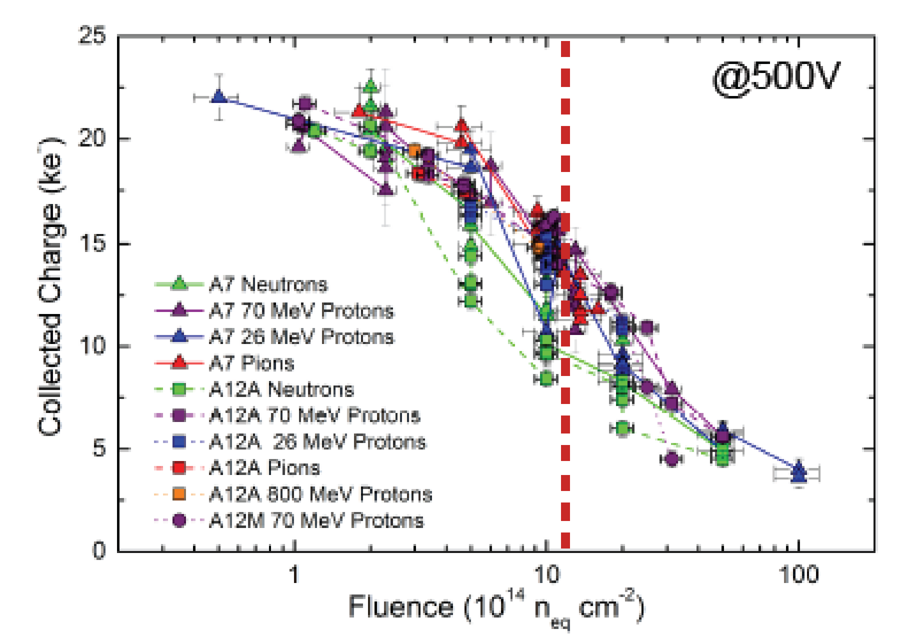
$$I(T) = AT^2 \exp\left(\frac{-E_g}{2k_B T}\right)$$

  - Shot noise
  - Thermal runaway: I increases T(Si) → I → increases T
  - Cool Si T=-25°C
- Acceptor concentration N_a increases → higher depletion thickness d of Si $V_{dep} = \frac{N_a e d^2}{2\varepsilon}$
- Charge trapping → signal loss.

Silicon Sensor

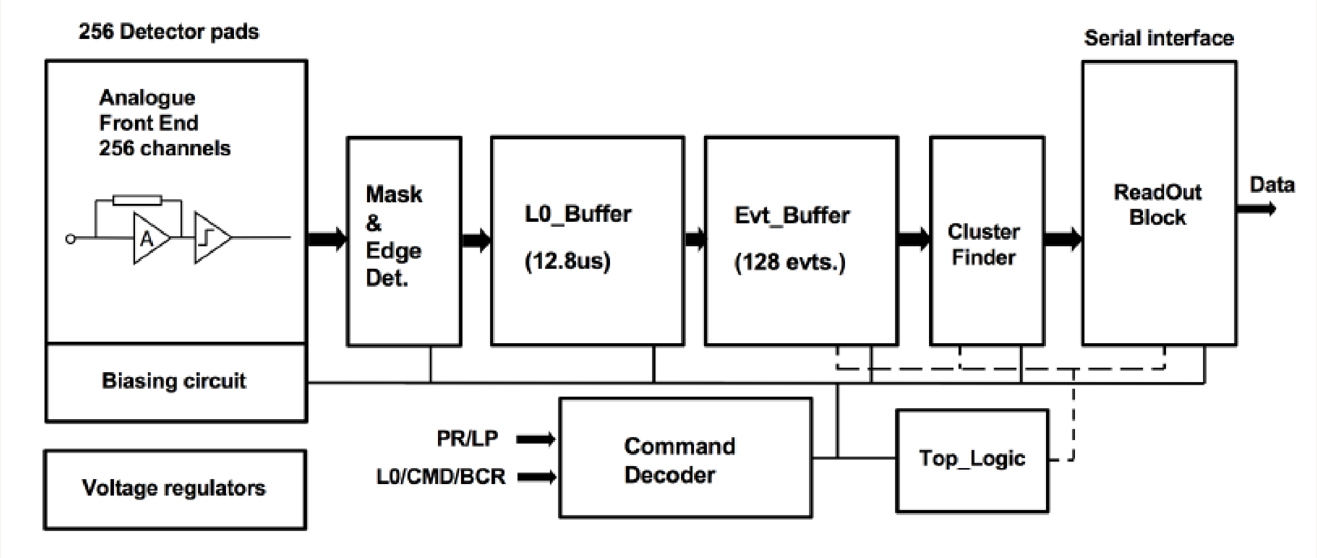
- *n*-in-*p* (SCT *p-in-n*)
- Signal (mainly) from electrons (faster than holes)
- Depletes from junction ➔ can operate under-depleted.
- Cheaper than *n*-in-*n.*
- Sufficient signal for maximum strip fluence.





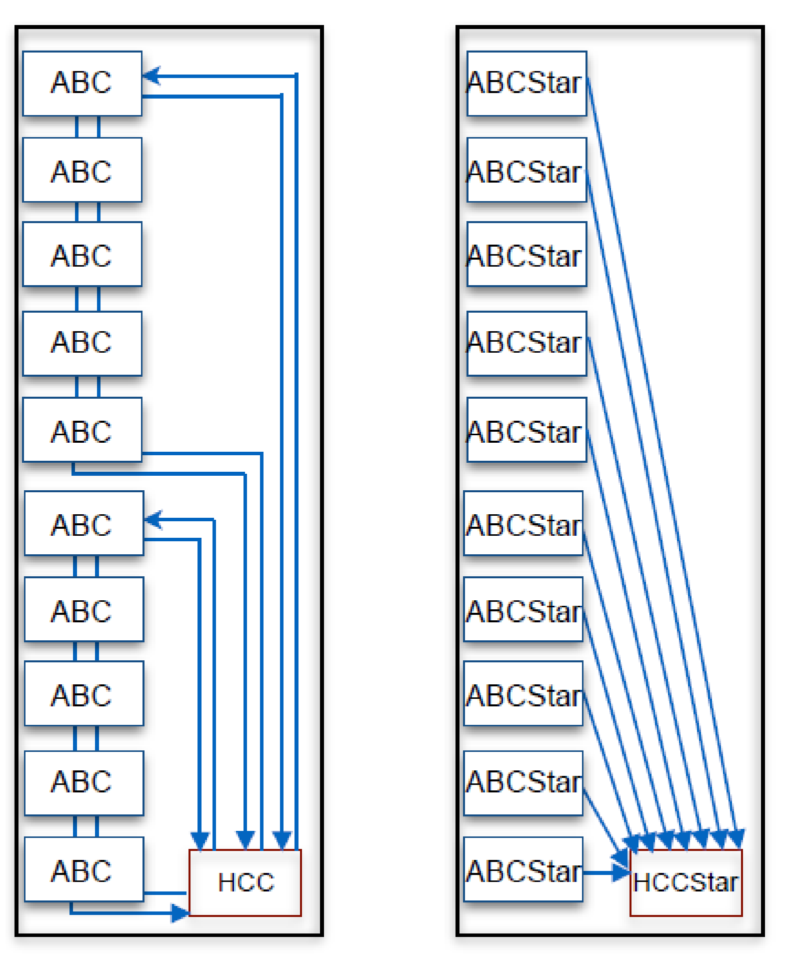
ABC130* ASIC

- 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

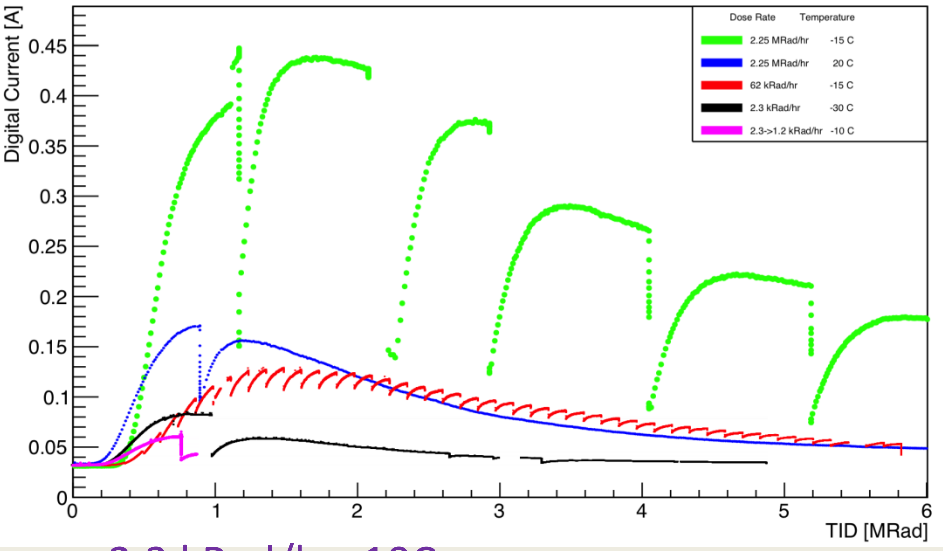
- **Star connections from ABC130* ➔ allows higher data rates (cf Daisy Chain).**
- **Allows full readout at 1 MHz.**
- **Higher rates possible with L0/L1.**



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

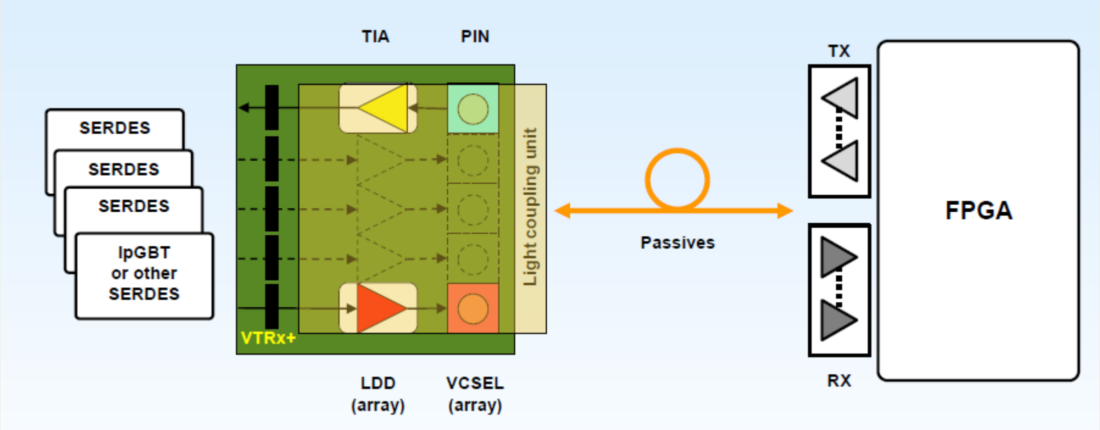


2.3 kRad/hr -10C.

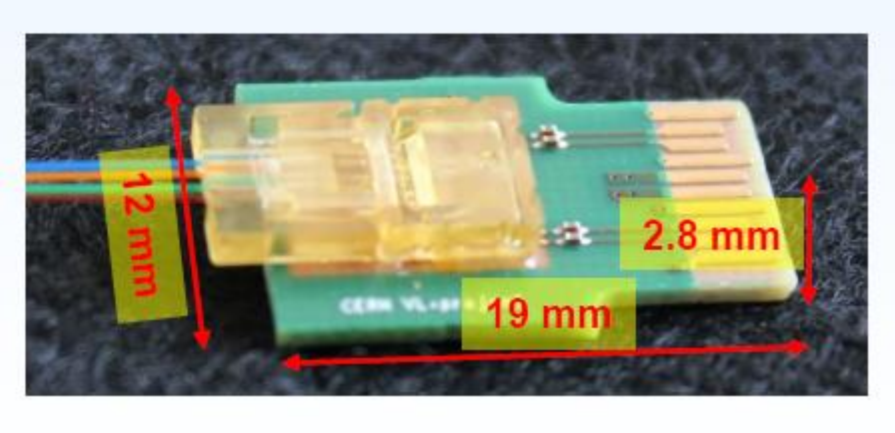
Optical Links

VL+ 10 Gbps rad-hard optical links

10 Gbps lpGBT ASIC



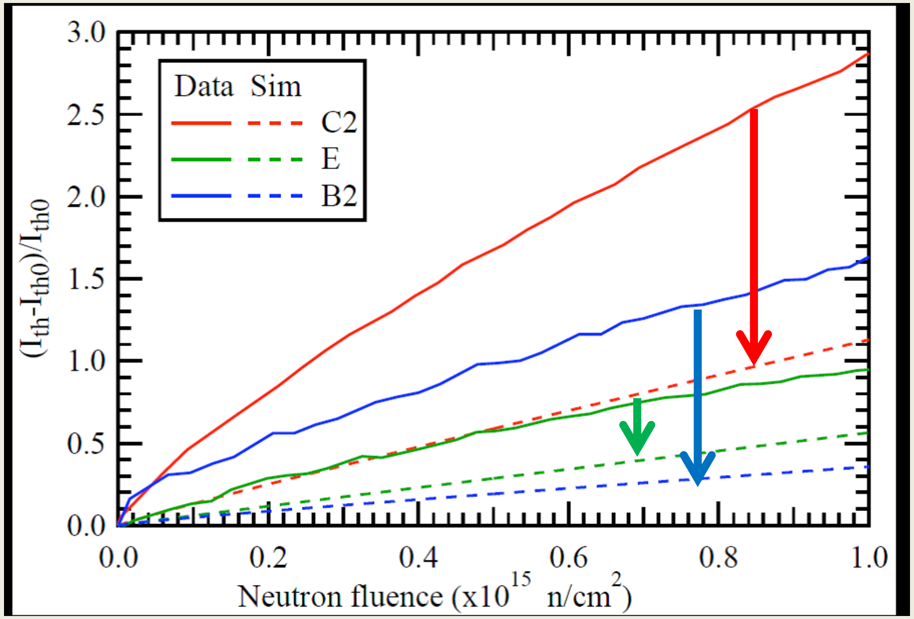
Very small form factor optical transceivers



Radiation Effect VCSELs

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

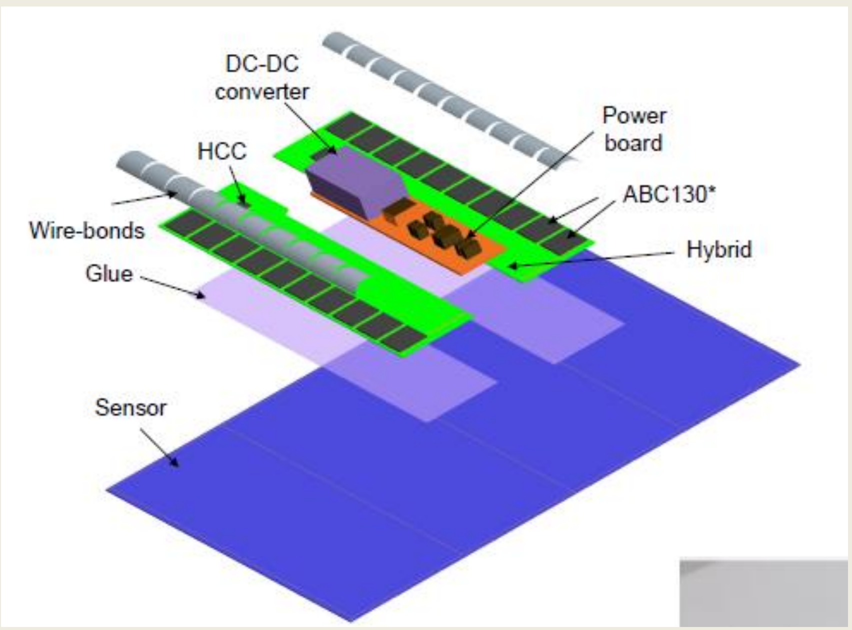
Fractional threshold current increase



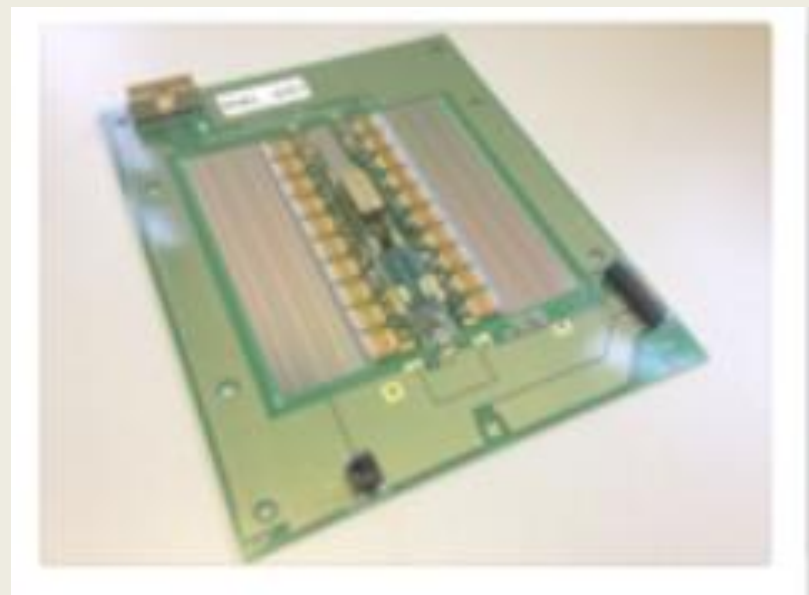
Strip Barrel Module

Schematic

- 10 ABC130* + HCC*/hybrid

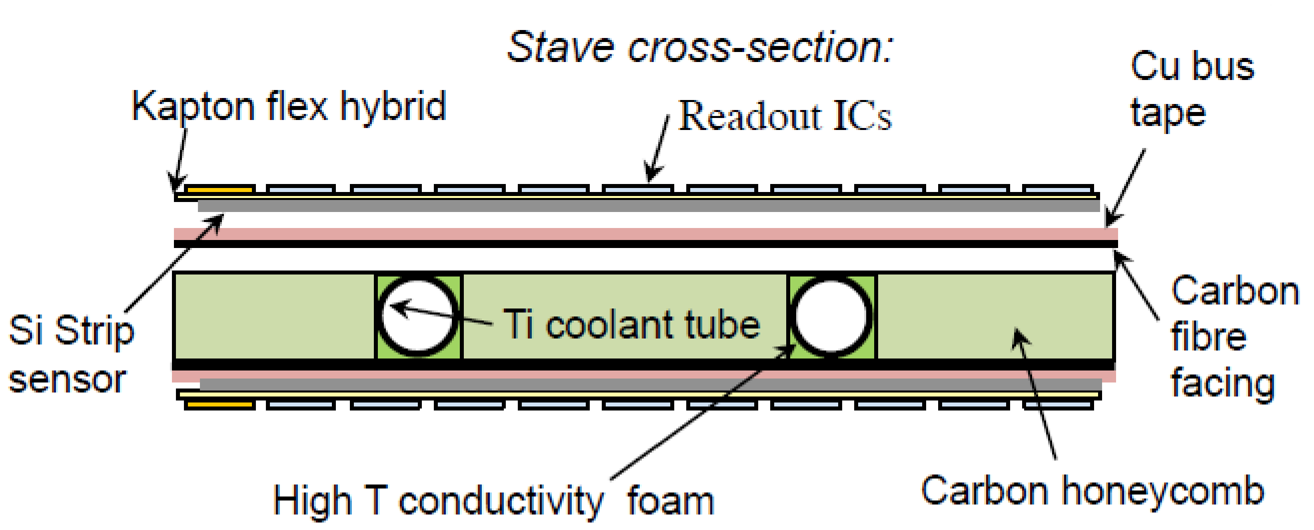


Thermo-mechanical module



Low X_0 Tracker

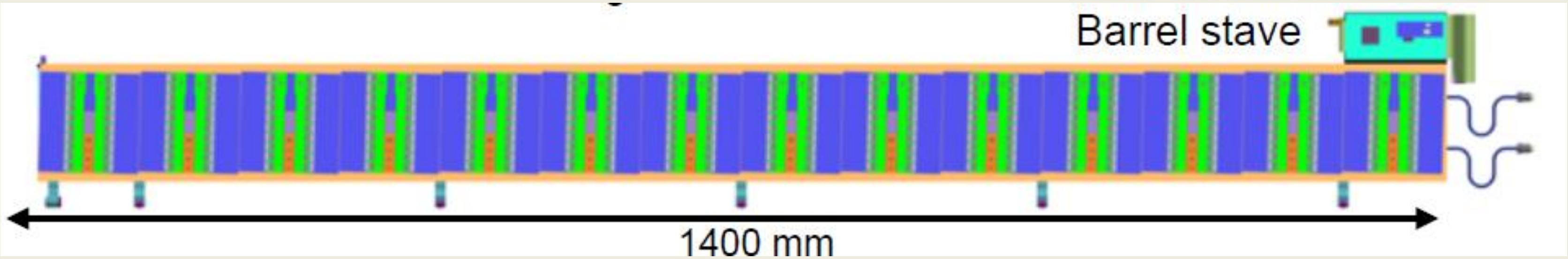
- Glue modules directly to mechanical support.



- **Carbon fibre sandwich, provides rigid, lightweight 0 CTE support structure.**
- **Evaporative CO_2 cooling.**

Staves

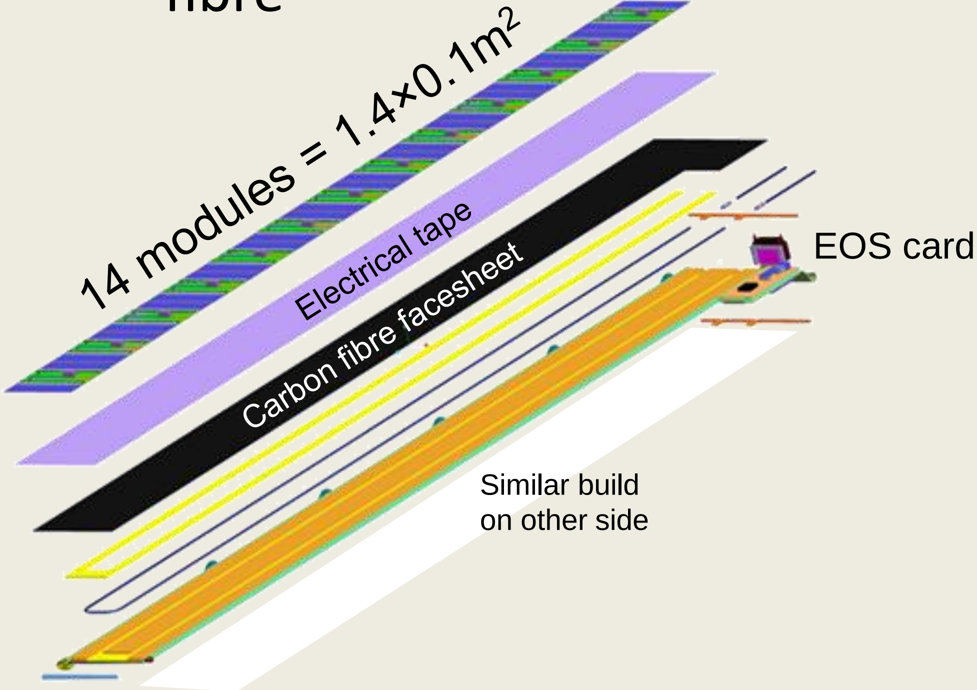
- Barrel staves



- **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.**

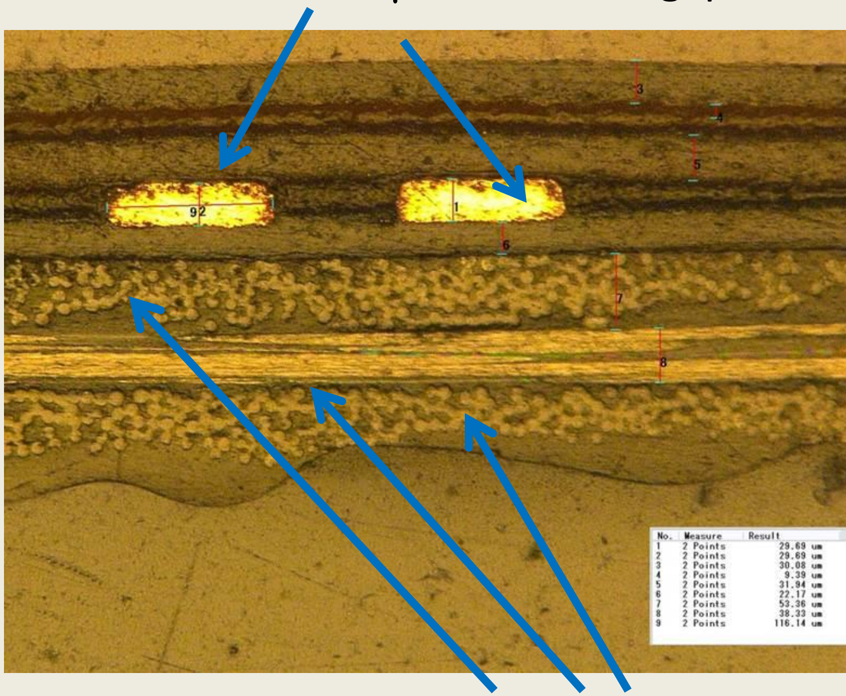
Barrel Stave

- Schematic
- Tape co-cured to carbon fibre



- Cross-section

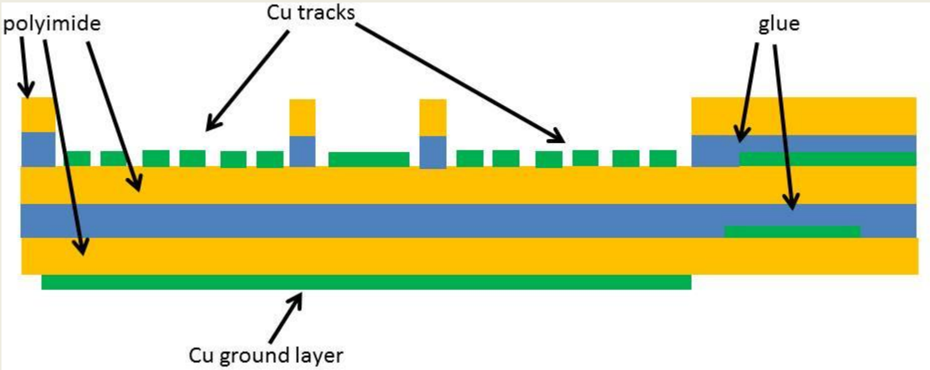
Cu tracks 100 μm track and gap



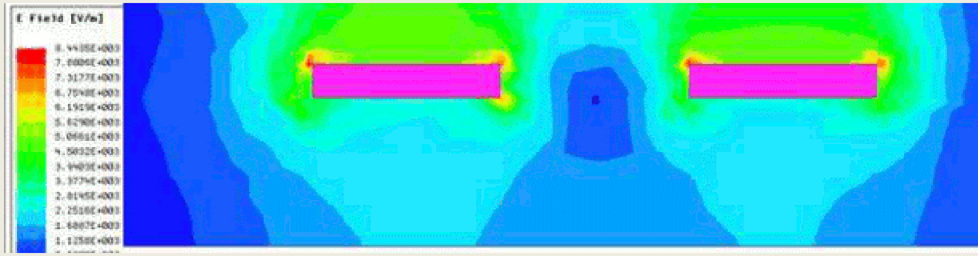
3 layer carbon fibres (0°,90°,0°)

Data Transmission

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



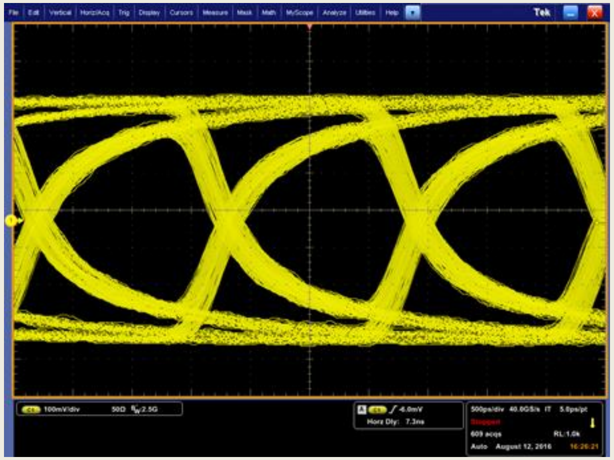
Differential pair: E field

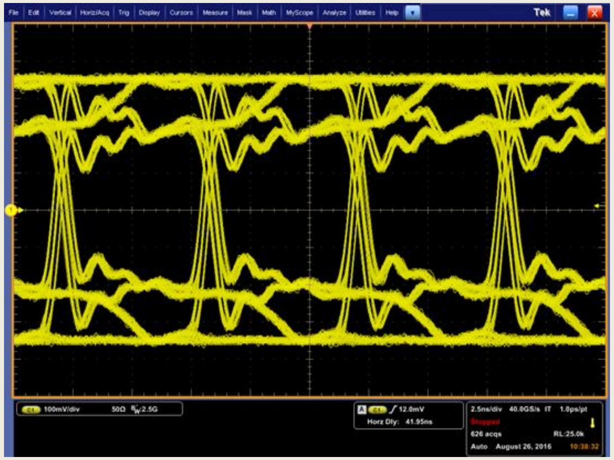


$$Z_0 = \sqrt{L/C}$$

Signal Integrity

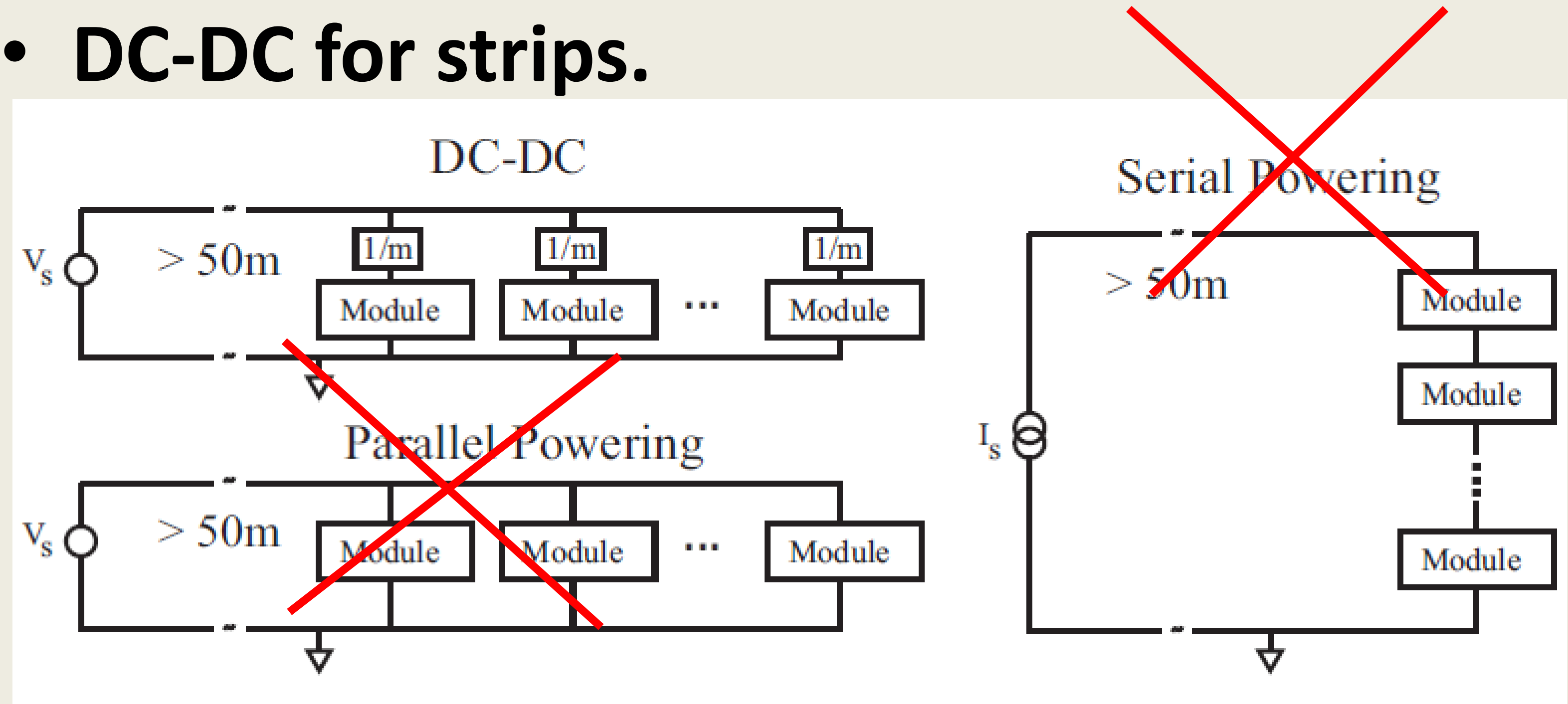
- **Data @ 640 Mbps:**
  - **Dispersion, but clean eye @640 Mbps**
- **Distribute Timing, Trigger & Control (TTC) → hybrids on FE modules @ 160 Mbps.**
- **28 capacitive loads → reflections.**
  - **$T \sim 1/(1+\omega C Z_0)^2$**
- **Split TTC into 4 groups → improves signal integrity.**
- **Strong reflections but clean eye for worst case 10 loads.**





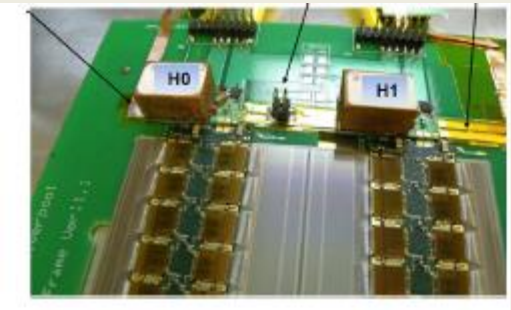
Module Powering

- **Can't afford one cable per module.**
  - **Too high current → IR drop → cables too big!**
- **DC-DC for strips.**



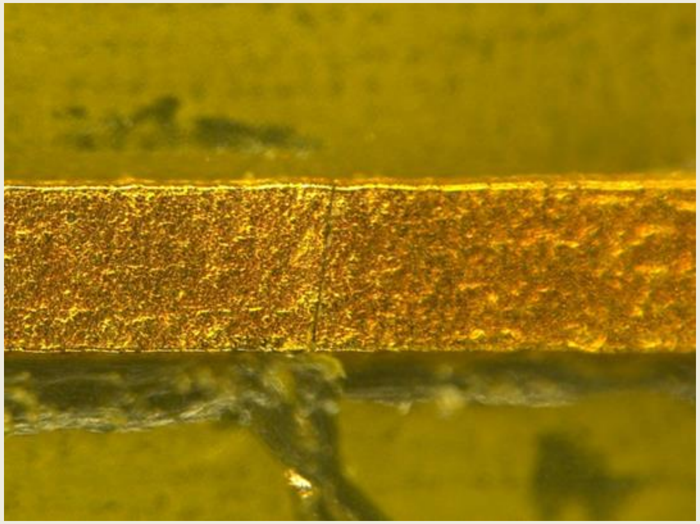
DC-DC Powering

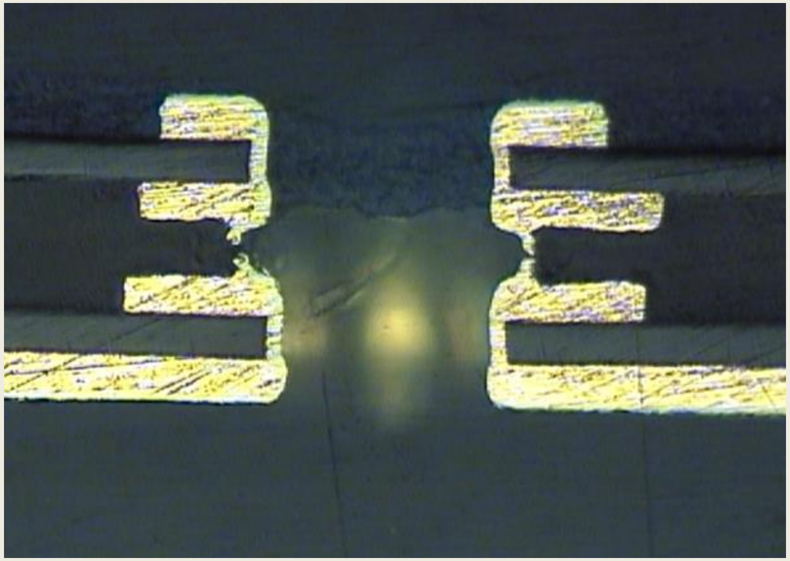
- Challenges
  - Need coil to operate in B field.
  - Radiation tolerance
  - EMI
- Prototypes used to demonstrate good system noise performance with “stavelet” (4 modules).
- UpFEAST: rad-hard versions for HL-LHC being developed by CERN. *cern.ch/project-dcdc*



Reliability

- What could possibly go wrong?





How can we ensure we have a reliable system?

Reliable Designs

- Replaceabilbity
  - 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

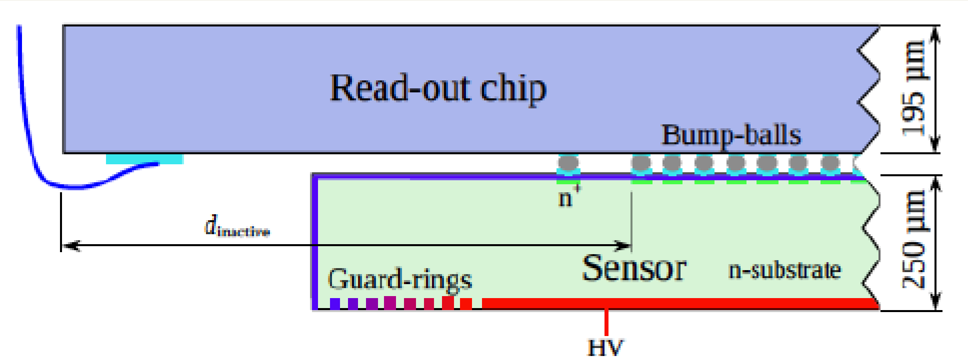
- Conservative design
- QC on all components
- QA on batch basis
- QA: more extreme stress test than anticipated in operation. e.g.
  - Elevated temperature and/or voltage
  - Rapid thermal cycling
  - Vibration
- Failure analysis on failed components in R&D ➔ improve reliability.
- Check quality on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

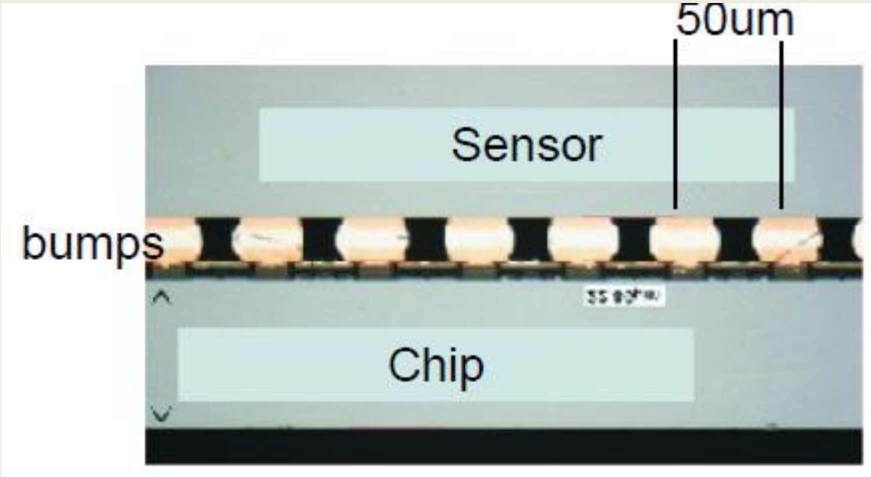
Pixels

- 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

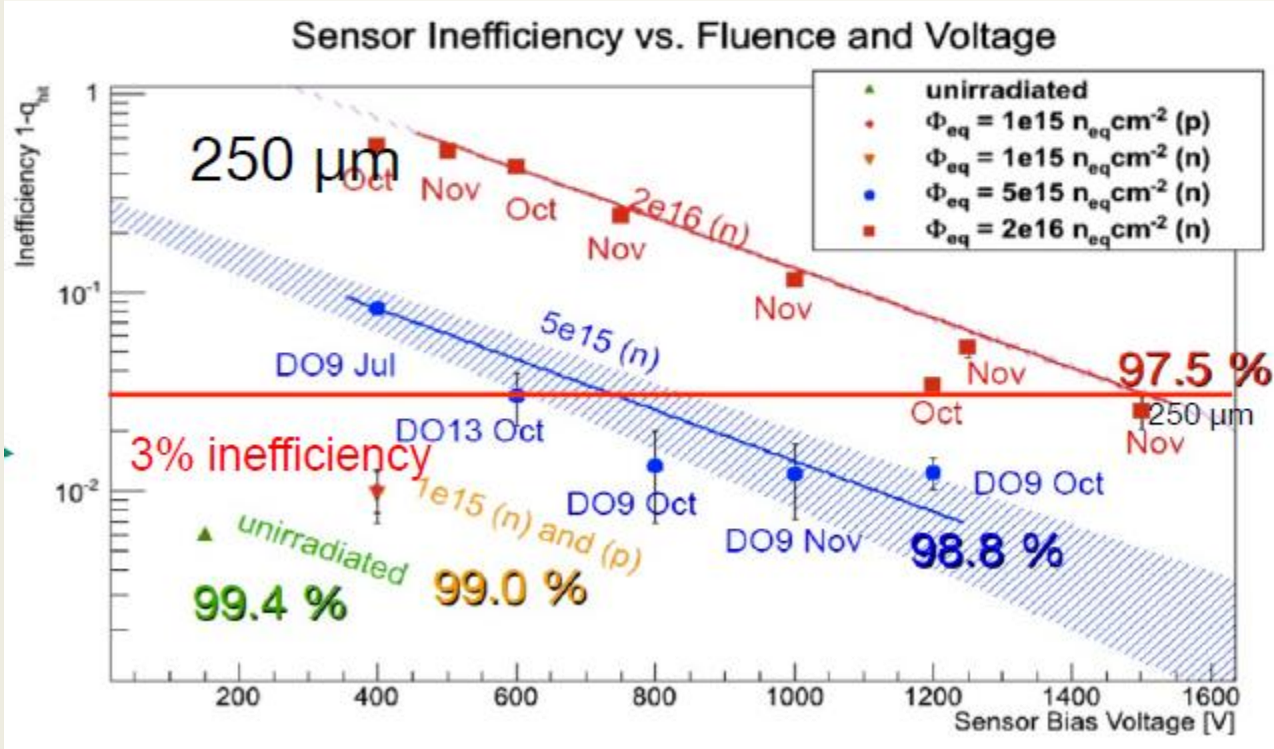
- Good for HL-LHC radiation levels
- *n-in-p* cheaper *n-in-n*
- Thinner → improves efficiency @ lower HV.
- Reduce inactive regions
- Avoid HV breakdown, even with higher HV





Pixel Radiation Damage

- **High efficiency after 2 10^{16} n cm^{-2} for very large HV**
- **Charge amplification?**
- **Main effect is charge trapping ➔ thinner sensors ~ 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

S/N at end of life

Module Type	Fluence $10^{14} n_{eq} cm^{-2}$	Charge ke^- 500 V	Charge ke^- 700 V	Noise e^-	S/N 500 V	S/N 700 V
SS	8.1	13.7	16.1	630	21.8	25.6
LS	4.1	17.3	19.5	750	23.1	26.0
R0	12.3	11.5	14.0	650	17.7	21.5
R1	10.1	12.5	15.0	640	19.6	23.4
R2	8.7	13.3	15.7	660	20.3	23.9
R3	8.0	13.8	16.2	640	21.4	25.1
R4	6.8	14.6	17.0	800	18.4	21.3
R5	6.0	15.3	17.6	840	18.3	21.1

Safety factor of 1.5 for fluence.

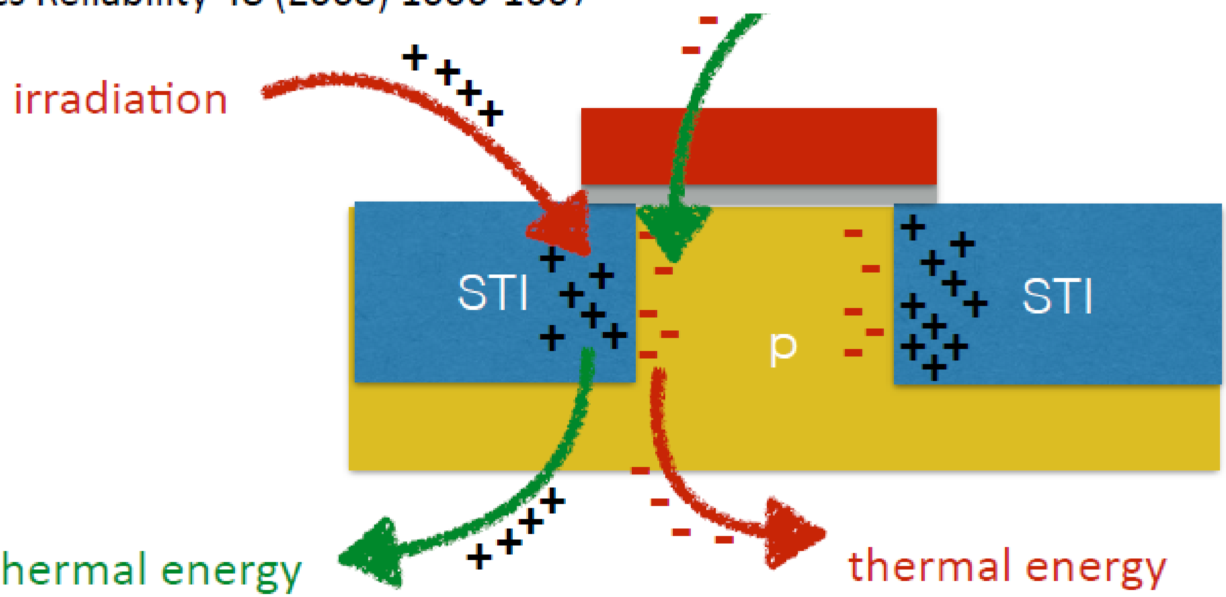
Is there still the need for ELTs and guard rings?

The leakage current is the sum of different mechanisms involving:

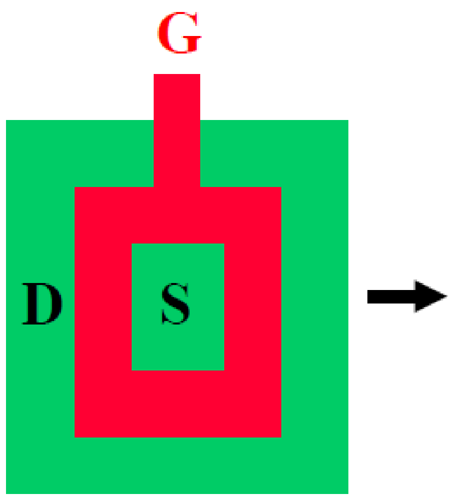
- the creation/trapping of charge (by radiation)
- its passivation/de-trapping (by thermal excitation)

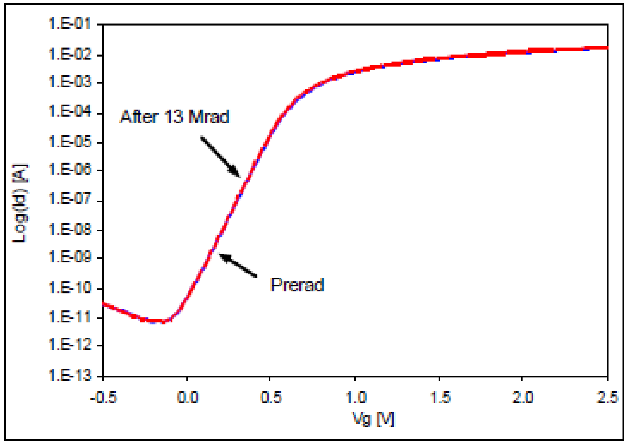
These phenomena are Dose Rate and Temperature dependent!

- F.Faccio, G.Cervelli, “Radiation-induced edge effects in deep submicron CMOS transistors”, IEEE Trans. Nucl. Science, Vol.52, No.6, December 2005, pp.2413-2420
- F.Faccio et al., “Total ionizing dose effects in shallow trench isolation oxides”, Microelectronics Reliability 48 (2008) 1000-1007

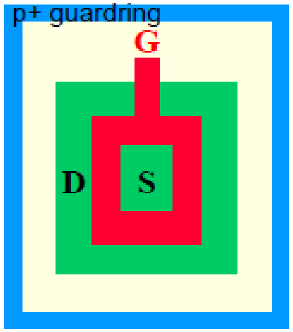


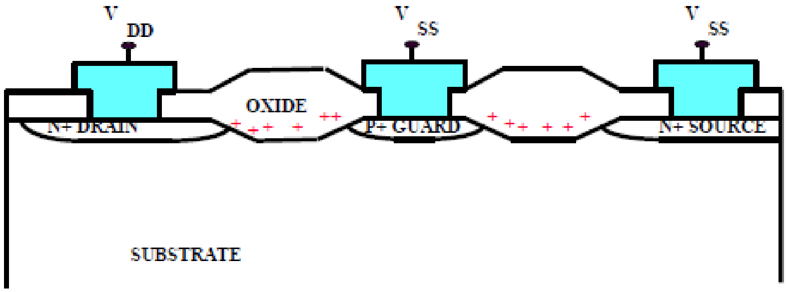
Source-Drain leakage is eliminated by the Enclosed Layout Transistor (ELT)...





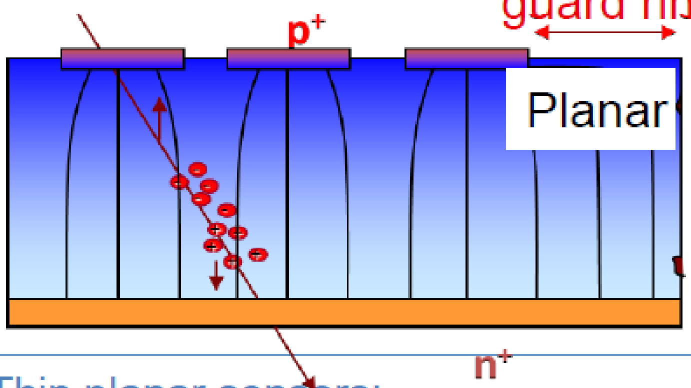
Inter-diffusion leakage is eliminated by p+ guard rings...

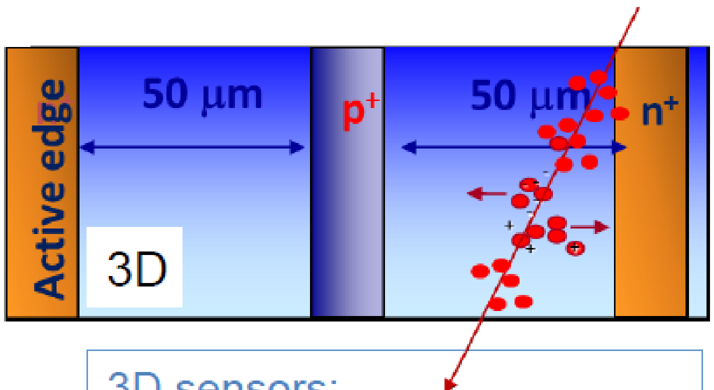




From Thin Planar to 3d sensors

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?

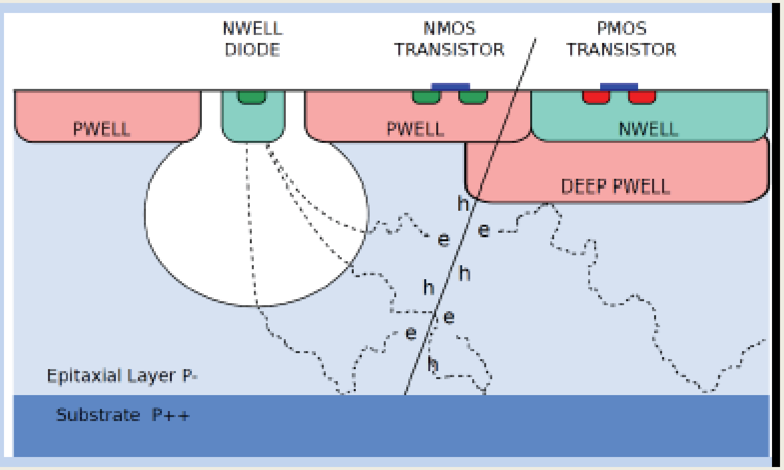
→ Candidate for 1st layer

CMOS

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

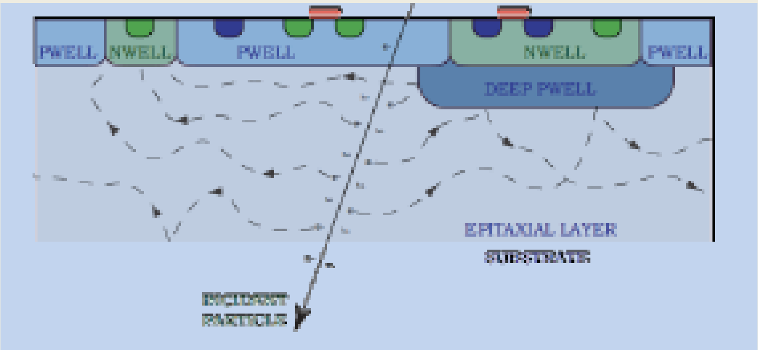
CMOS Sensors

CMOS Imagers



- Cheap
- Diffusion ➔ too slow for LHC
- Not rad-hard

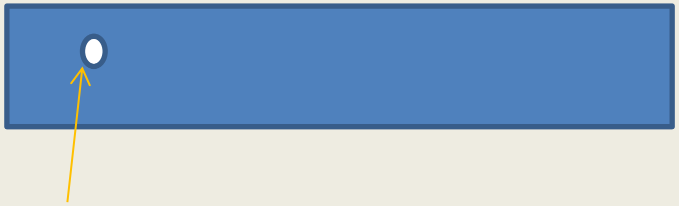
HV/HR



- High voltage or higher resistivity ➔ larger depletion depth
- Fast signal
- Radiation-hard?

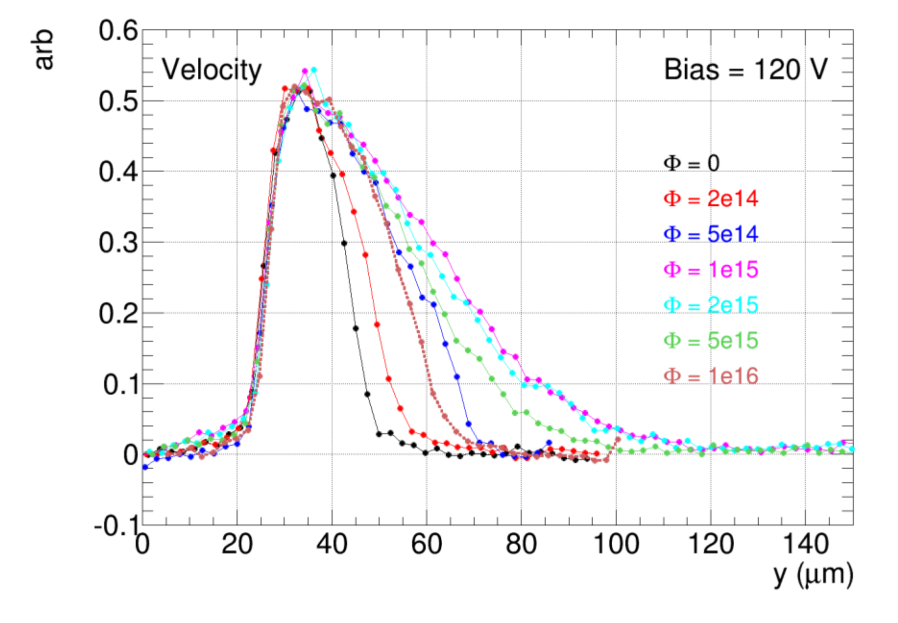
CHESS1

- 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