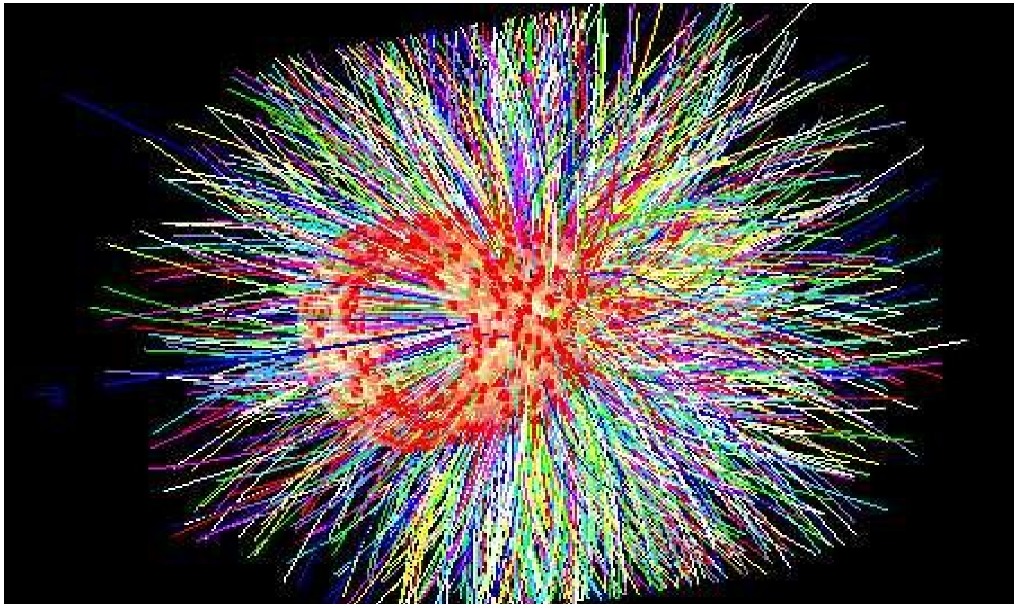
Upgrade of the ATLAS Silicon-Strip Detector for the High-Luminosity LHC



Conrad Friedrich, Ingo Bloch, Sebastian Gerhardt, Tai-Hua Lin, Laura Rehnisch, Malik Aliev, Heiko Lacker, Maik Daniels, Artem Kravchenko, Ingrid Gregor, ...

Deutsches Elektronen-Synchrotron DESY

Spring Block Course 2012 - March 13th 2012

GRADUIERTENKOLLEG Masse-Spektrum-Symmetrie

HELMHOLTZ GEMEINSCHAFT

DESY

Outline

Upgrades towards the HL-LHC

- motivation & current LHC upgrade schedule
- requirements & challenges for Detectors at the HL-LHC

Upgrade of the ATLAS Semiconductor Tracker (SCT)

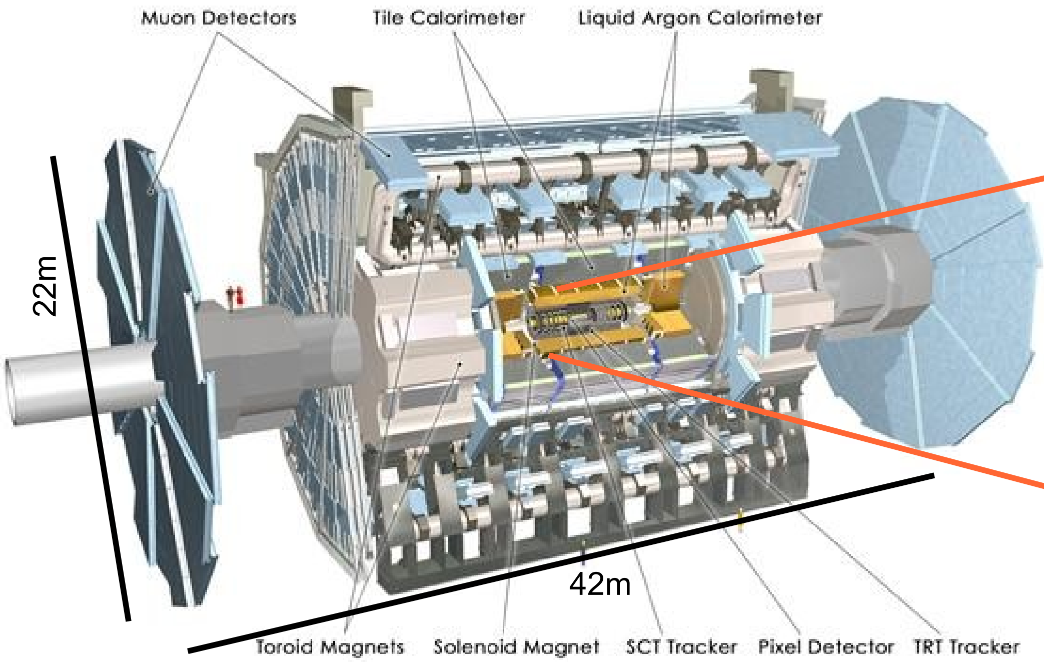
- Tracker upgrade: specs & baseline layout
- strip detector integration concepts (Staves, Supermodules, Petals)
- time-line & projects at DESY/HU

Prototyping

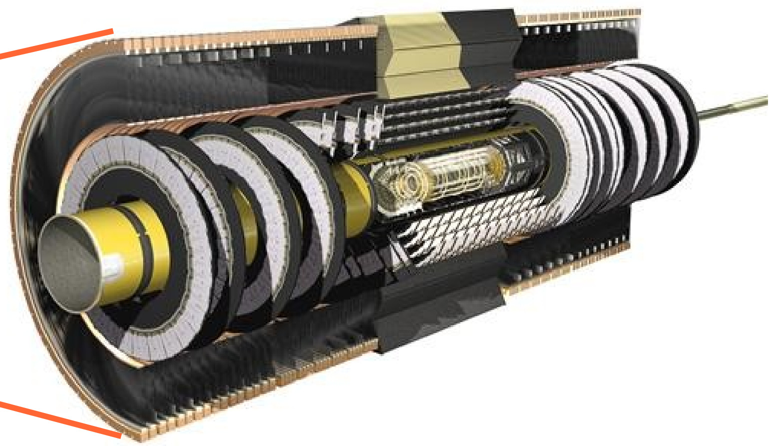
- construction of barrel module prototypes
- data acquisition & electrical testing

Summary & Outlook

ATLAS & Inner Detector



ATLAS Inner Detector



- Inner Detector consists of 3 sub-detectors embedded in a 2T axial field

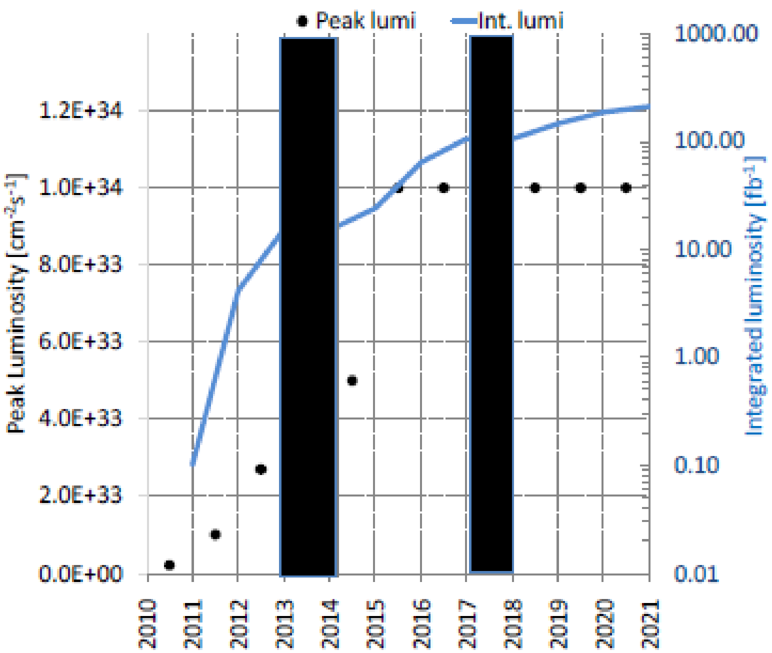
- Silicon Pixel Detector - 3 layers & 3 wheels - 1744 modules w. 50x400 μm² pixels
- Silicon Strip Detector (SCT) - 4 layers & 9 wheels - 4088 modules w. 12.6 cm long strips
- Transition Radiation Tracker (TRT) - 370.000 straws - 144 cm long drift tubes

high luminosity LHC (HL-LHC): motivation & physics goals

- **HL-LHC in short: increase recorded luminosity by a factor of 10**
  - improve precision in measurements within Standard Model & beyond
  - enlarge discovery reach in high-mass region
- **many studies require tracking performance to be kept at present value**

→ **Upgrade of detectors indispensable**

- **HL-LHC goals & target specifications:**
  - peak luminosity: **5×10^{34} cm^{-2} s^{-1}**
  - integrated luminosity: **~250 fb^{-1} per year**
  - record **~ 3000 fb^{-1} in approx. 12 years**



Phase 0 – 2014 (followed by 14 TeV running)

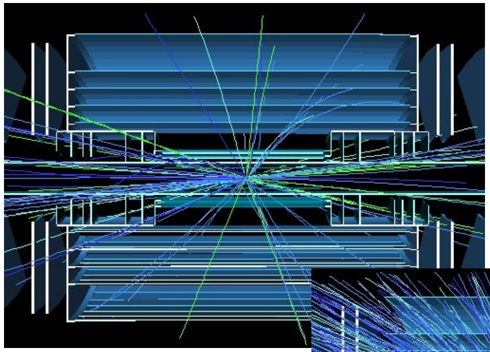
Phase 1 – 2018 (~200-300 fb^{-1} until Phae 2 shutdown)

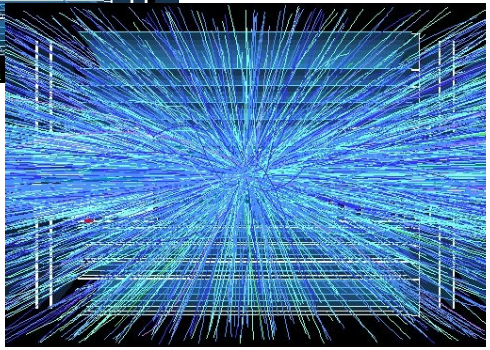
Phase 2 – 2022 → **Upgrades for high-luminosity LHC**

environment for new tracker at HL-LHC

- huge **increase in particle multiplicities** → **fluence ~200x higher** than at LHC
  - → **current tracker won't be able to stand cumulated radiation dose**
- **200 pile-up events per bunch crossing** (~23 at LHC design luminosity)
  - **occupancy will be too high** (i.e. TRT) → **higher granularity needed**

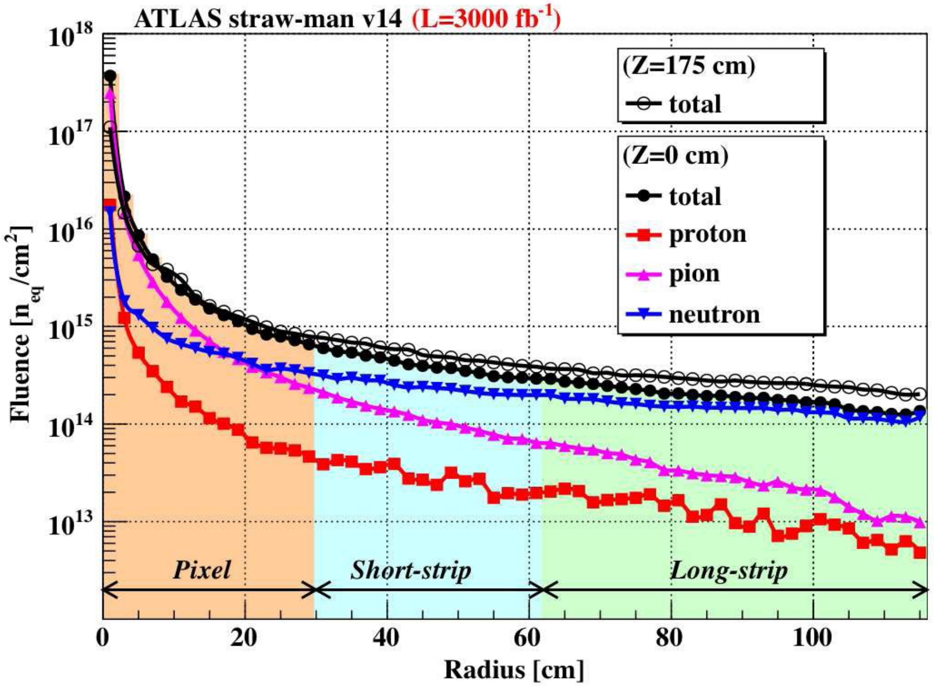
5 collisions (0.2 x 10^{34} cm^{-2} s^{-1})





400 collisions (10 x 10^{34} cm^{-2} s^{-1})

10^{16} 1-MeV n-eq cm^{-2} @ radii close to the beam-pipe

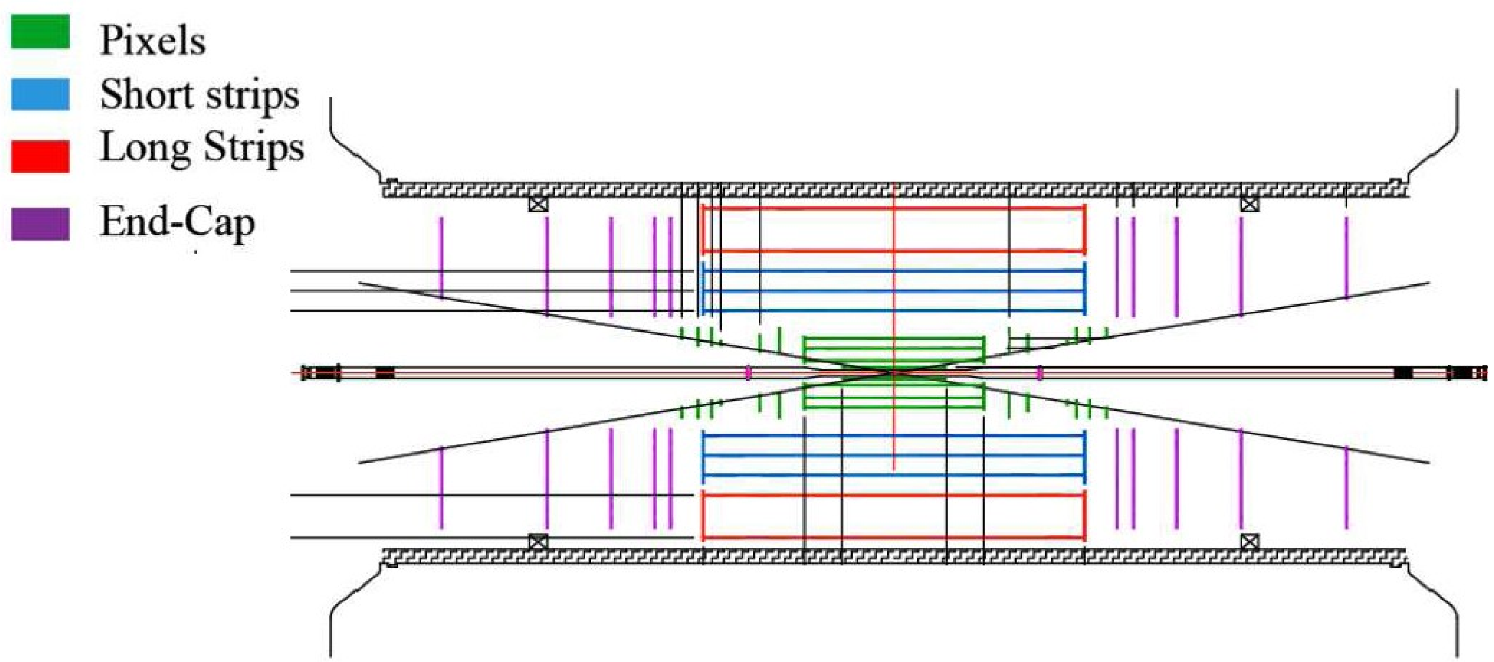


ATLAS Tracker Upgrade for HL-LHC

How could a new Tracker look like?

ATLAS Tracker Upgrade: straw-man layout

- whole Inner Detector is to be **replaced by an All-Silicon-Tracker** → no TRT
  - central barrel region: **4 pixel and 5 strip layers**
  - forward region: **6 pixel and 5 strip disks**
  - layout ensures 9-hit coverage in the pseudo-rapidity range $|\eta| < 2.5$



- **new tracker will consist of >100m² of silicon**
  e.g. Strip detector: channel number increased from 6M to ~40M @HL-LHC

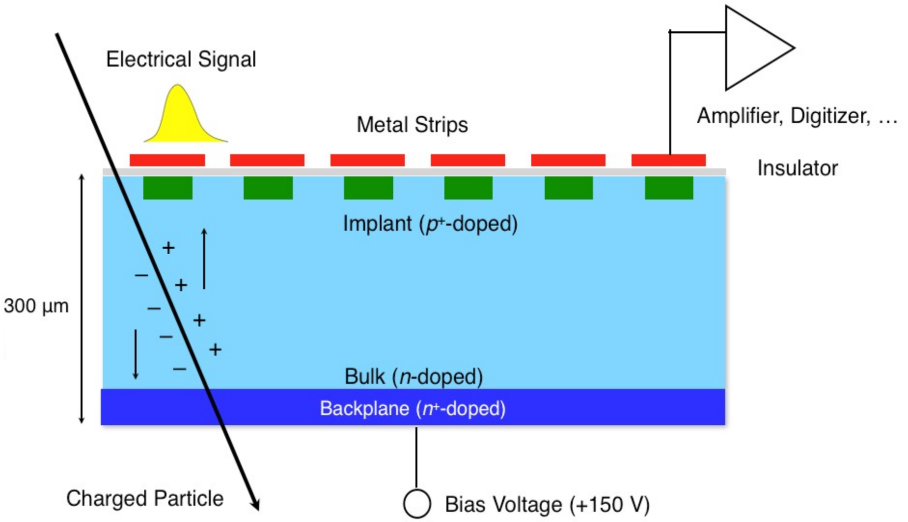
ATLAS Tracker Upgrade: specs & facts

- >100m² of silicon in total:
  - channels in Strip Detector: 6M @LHC → ~40M @HL-LHC
  - channels in Pixel Detector: 80M @LHC → ~500M @HL-LHC
- power consumption:
  - Strip Detector: 22 kW @LHC → ~50 kW @HL-LHC
  - Pixel Detector: 7 kW @LHC → ~30 kW @HL-LHC
- related issues / limiting factors:
  - How to get current needed to the electronics?
  - More modules result in more cables for power, data and detector control signals

    → new powering schemes needed (DC-DC or Serial powering)
  - Material Budget:
    Can we build a better/lighter tracker?

Silicon strip sensors

- short reminder:
  - passing ionizing particles create free charge carriers (e^-/h pairs) in depletion region / bulk
  - charges drift to p & n doped side (bias voltage)
  - usually one side is segmented (i.e. strips, pixels)
  - signal at strip is amplified by charge sensitive amplifier (100-10000e^- → ~1-1000mV)
  - usually test charges can be directly injected into amplifier inputs for calibration & testing

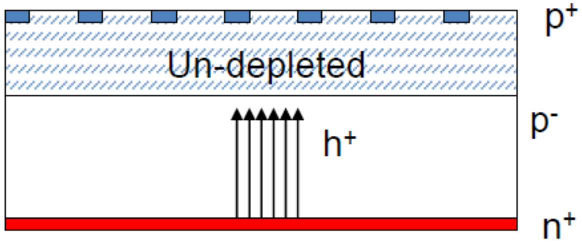


- current Strip Detector uses p-in-n Si-sensors
- advantages of n-in-p technology:
  - electrons are collected → higher mobility
  - ~33% smaller trapping constant
  - deposited charge can reach electrode even if sensor is under-depleted

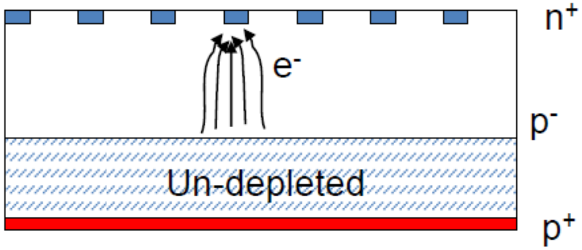
- typical thickness:	~300 µm
- energy loss of MIP per e/h pair: <E> = 3.6 eV (at 300°K), (gases: 20-40 eV)	
- total e-/hole pairs:	~25000
- drift times:	~8 ns e-, 25 ns holes

p in n

(both after type inversion)



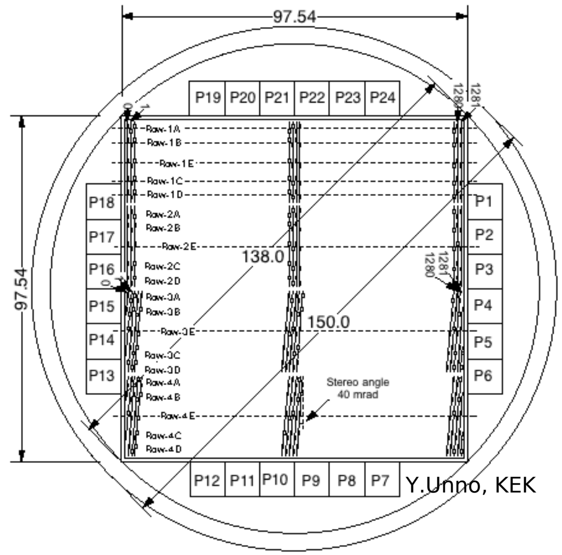
n in p



Barrel Sensor Prototypes

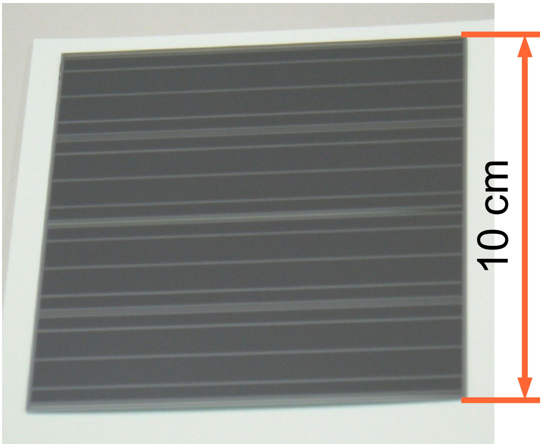
> sensor prototypes for SCT Barrel detector modules

- capacitively coupled, polysilicon biased n-in-p-type devices (produced by Hamamatsu)
- 4 rows of 1280 strips each
- 2 rows with tilted strips → stereo angle
- several thousand modules will be needed
- sensor specification have to be checked before module production



Axial-Stereo Sensor

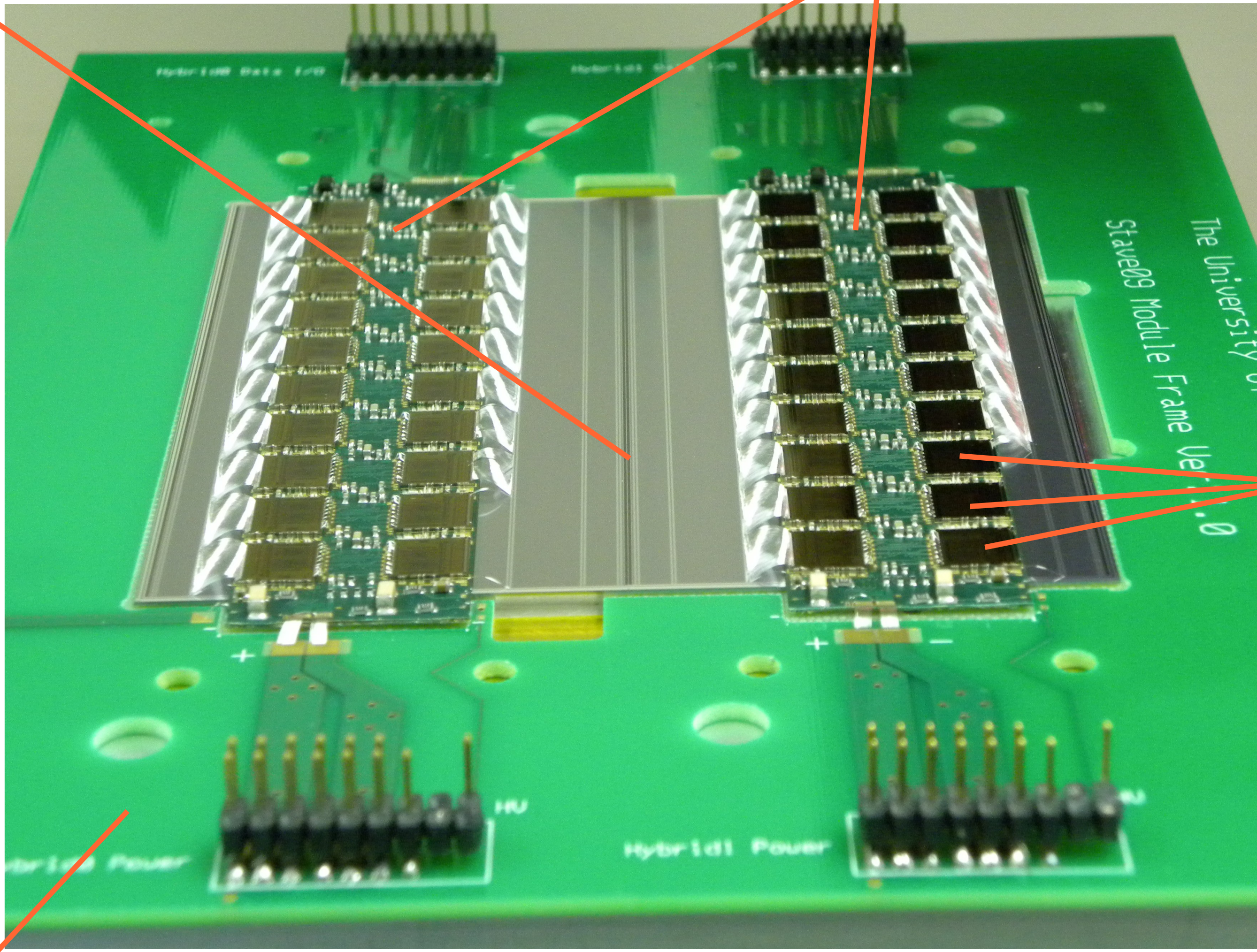
	ATLAS	ATLAS@sLHC
sensor size	6,4x6,4 cm²	9,75x9,75 cm²
type	p-in-n	n-in-p
# of strips	768	5120
pitch	80 µm	74,5 µm
length	12,6 cm	2,4 cm
max. V_{depl}	500 V	1000 V



Strip Detector Module (single sided version)

Sensor (4 rows of 1280 strips)

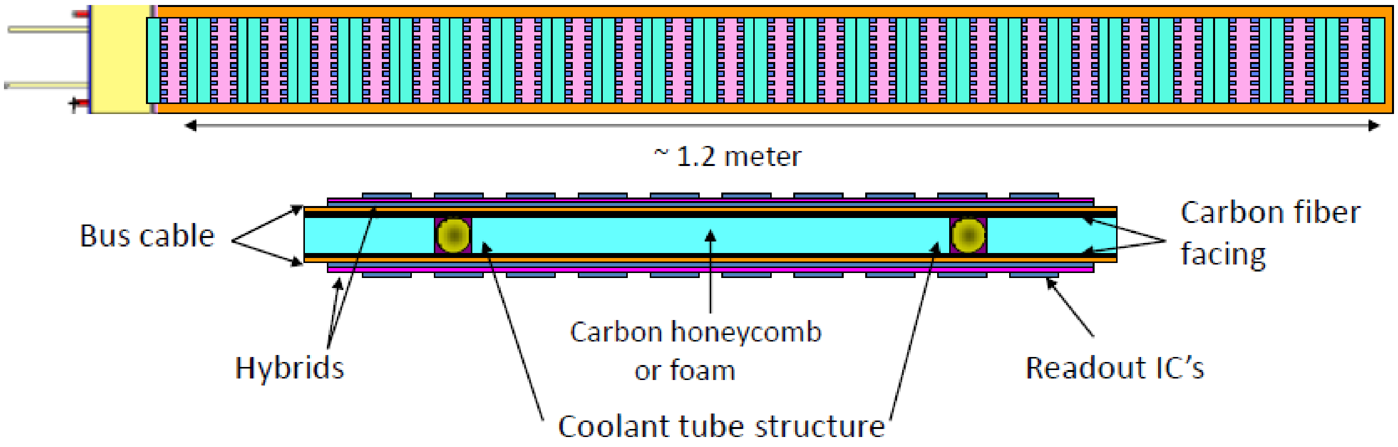
Hybrids

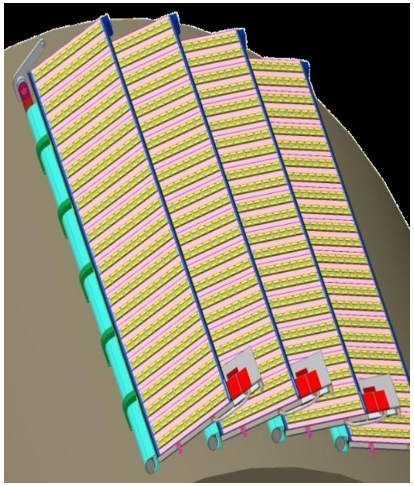


read-out chips (128 channels)

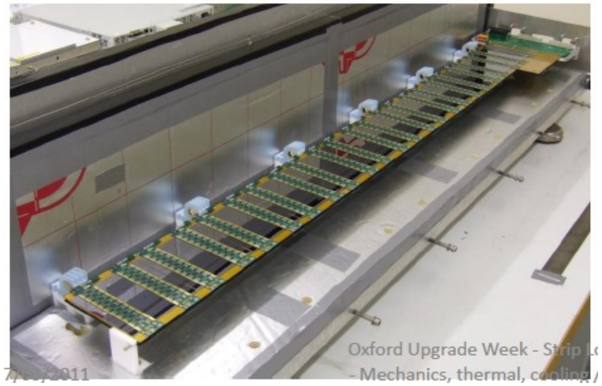
testing frame

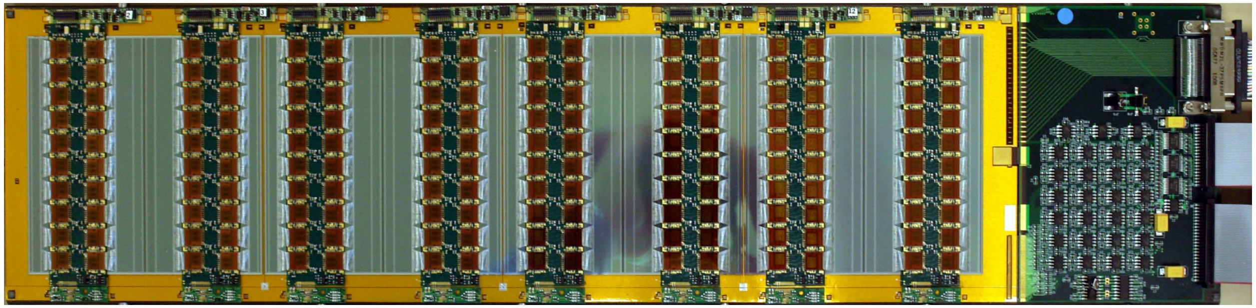
Integration concepts – Staves (baseline approach)



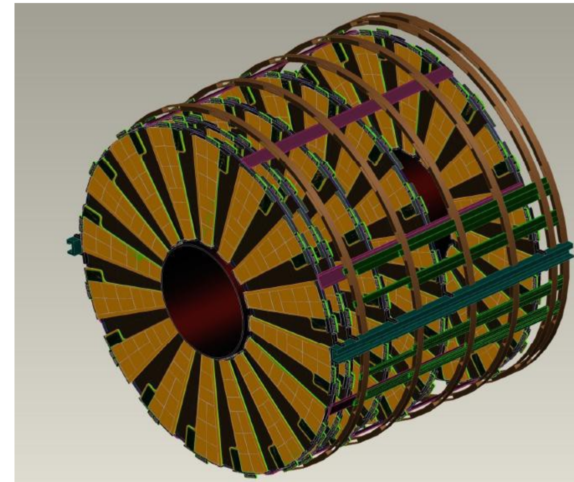


- Stave: 12 single-sided modules glued on common support & cooling structure from both sides

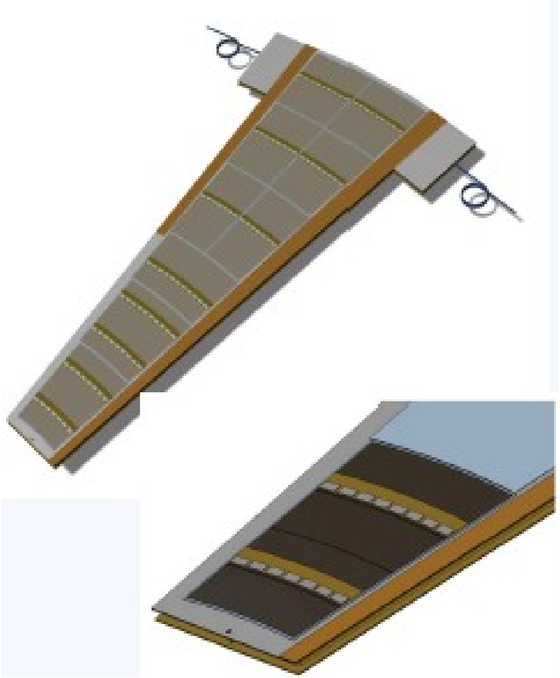


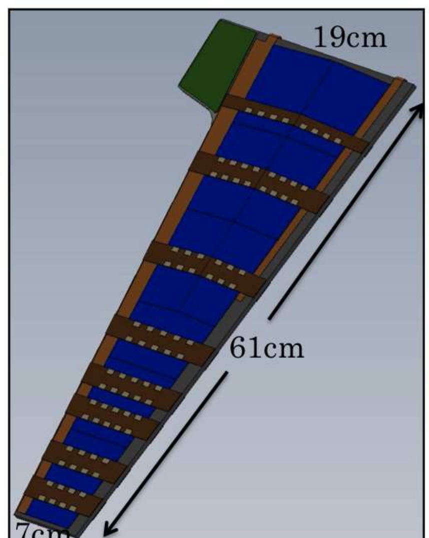


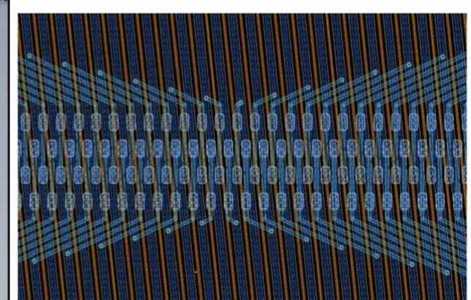
Integration concept - End-caps

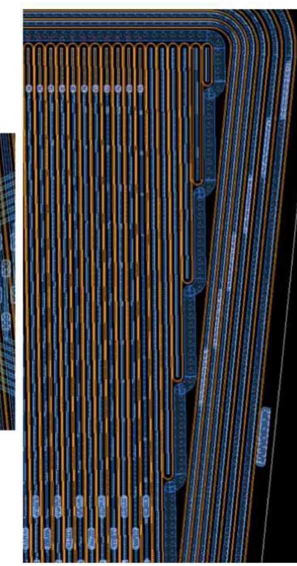


- layout closely follows the barrel stave concept
  - 5 discs on each end-cap, 32 Petals per disc
  - common mechanical & thermal support:
    carbon honeycomb core with embedded cooling loop
- major difference from Barrel Stave:
  9 different sensor & 11 hybrid layouts
  - sensors with radial strips, non-uniform pitch





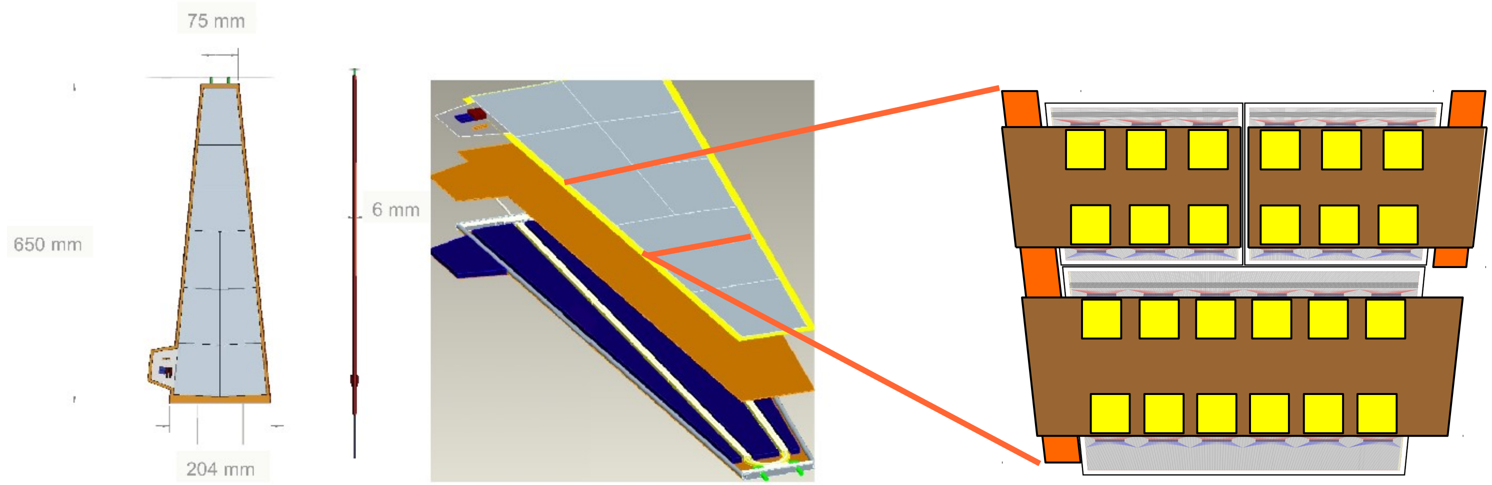




How are we involved?

SCT Endcap Upgrade – Petalets & Petal14 project

- DESY: probable macro assembly site of one Silicon strip detector end-cap
- Prototype Phase → Petal14 project:
  - show feasibility by design & construction of a full size & fully functional Petal prototype
  - collaborators: HU Berlin, Uni Freiburg
  - @ Zeuthen: sensor testing, module production & testing
  - @ Hamburg: petal assembly, macro assembly & testing
- step 0: gain expertise in barrel module production & stave community (Stave09)
- step 1: design & construct miniature prototype → Petalet:

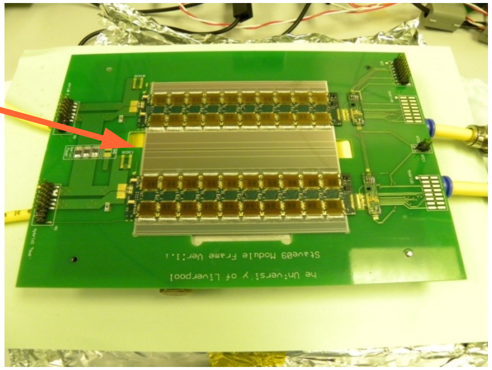


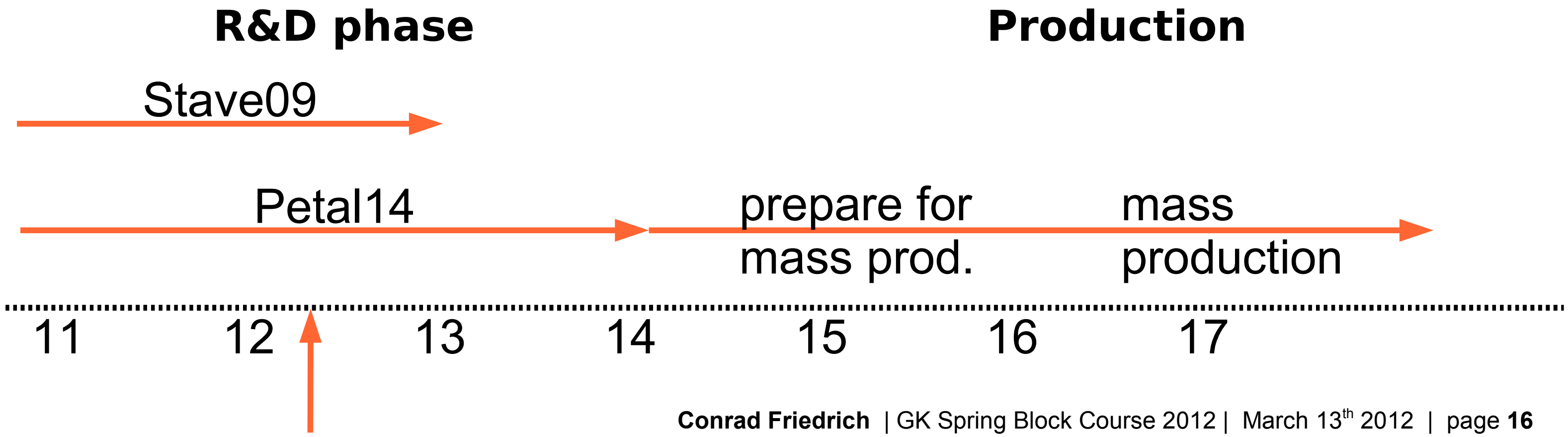
SCT Barrel Upgrade - Stave09 program

- **goal: build a full size stave prototype (24 modules)**

  7 sites are coming on-line for hybrid/module assembly and testing → DESY

- **barrel module production @ DESY**
  - assembly of modules for Stave09-Program
  - to gain expertise in: sensor testing, tooling,
  - mechanical module assembly (gluing / wire bonding),
  - electrical testing of hybrids & modules (DAQ),
  - tests of larger structures (Stavelets) → CERN





SCT Barrel Upgrade – Module Production

- **ingredients:**

  1 Si strip sensor (10x10 cm² n-in-p)

  2 hybrids (~10x2cm² flexible PCB)

  40 read-out chips (~1x1cm² ASICs)

  ~ 6.000 wire-bonds (25 um thick Al)

1. hybrid assembly:

1.1 – glue read-out chips onto hybrids

1.2 – chip to hybrid wire bonding

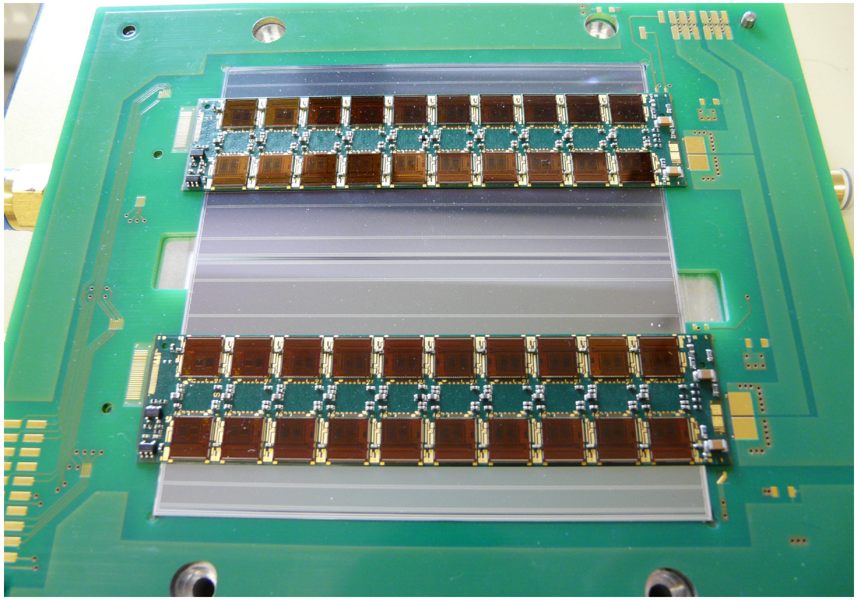
1.3 – hybrid testing (electrical / DAQ)

2. final module assembly:

2.1 – glue hybrids on sensors

2.2 – chips to sensor wire bonding

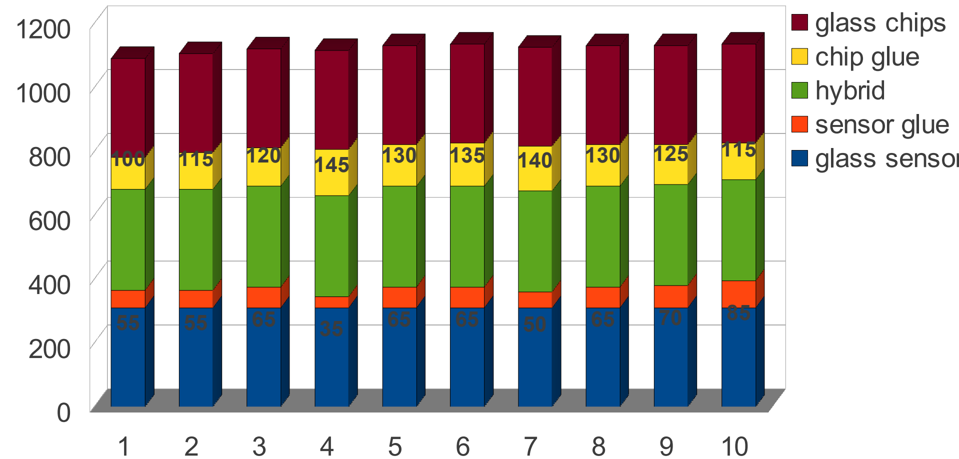
2.3 – module testing (electrical / DAQ)

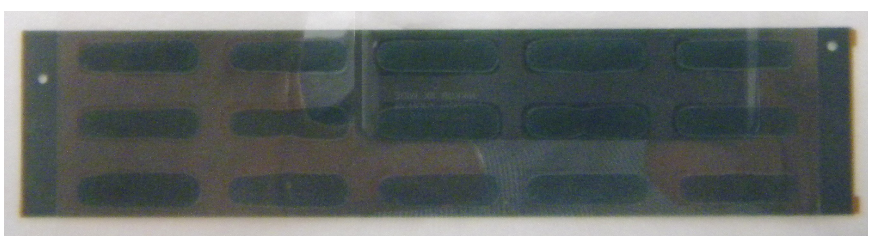


checking mechanical properties

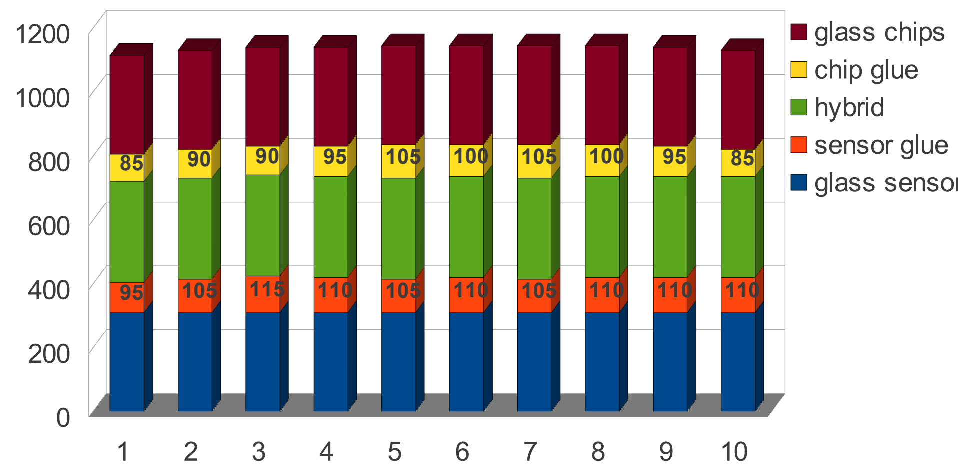
> gluing thickness of chips & hybrids in more detail

glue applied immediately





pre-curing time: 45 min



electrical testing / DAQ

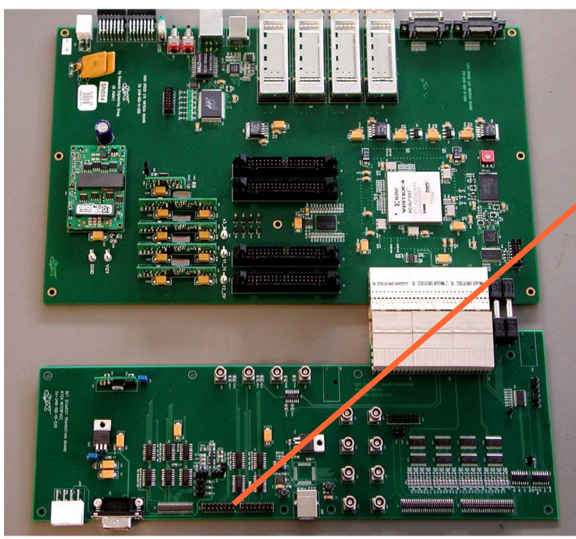
- moved to new lab & installed infrastructure:
  - vacuum system
  - chiller for water cooling (down to -30°C)
  - Nitrogen supply (for storage & to avoid condensation)
  - power supplies, ...
  - FPGA based read-out system (HSIO)
    (for read-out of up to 24 modules)

power & sensor bias

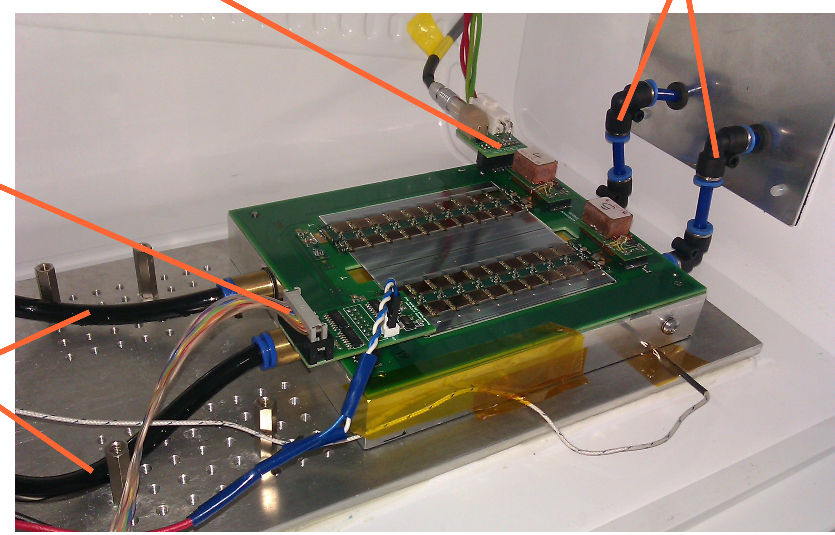
vacuum

data cable

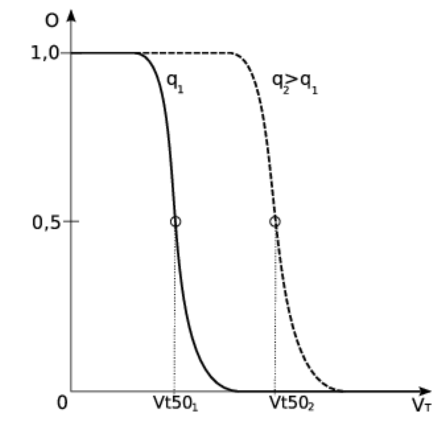
cooling



HSIO read-out system

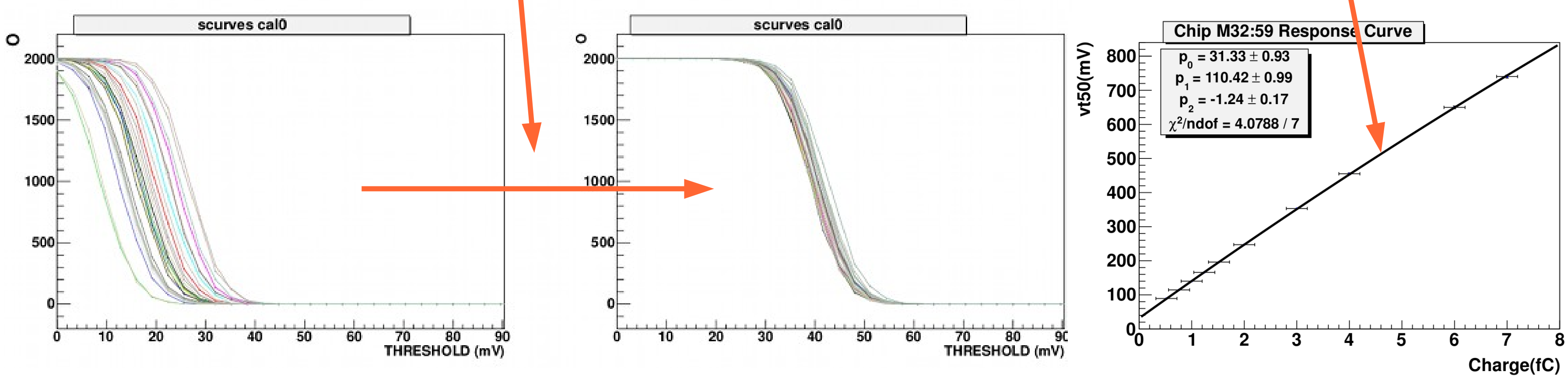


read-out architecture & electrical tests



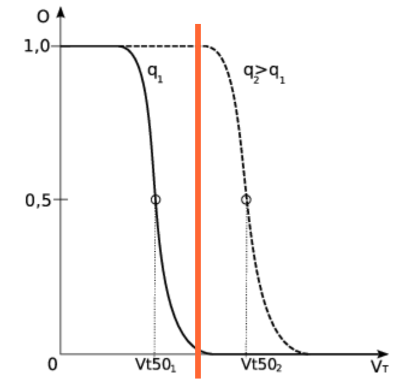
- **Binary readout (**digitization in the front-end electronics):
  - amplification of signal (charge sensitive amplifier)
  - discriminator compares signal with a threshold
    returns 1 (hit), if signal at strip is above threshold
  - hits & time-stamp buffered in FIFO & read-out if triggered

- **response certain charge should be uniform across all channels**
  - self-injection of different charges & scann over threshold → response curve
  - but amplifier response varies (manufacturing, supply voltage distribution, etc.)
    → **threshold calibration needed**



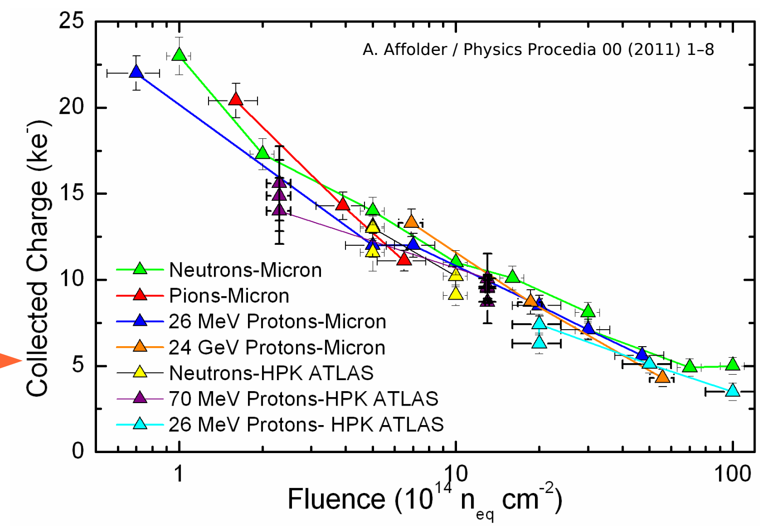
noise & noise occupancy

- **several noise sources contribute to noise signal at output:**
  - noise current of biasing circuit
  - shot noise from sensor leakage current
  - noise sources within the amplifier itself (thermal, shot, low-freq. noise)

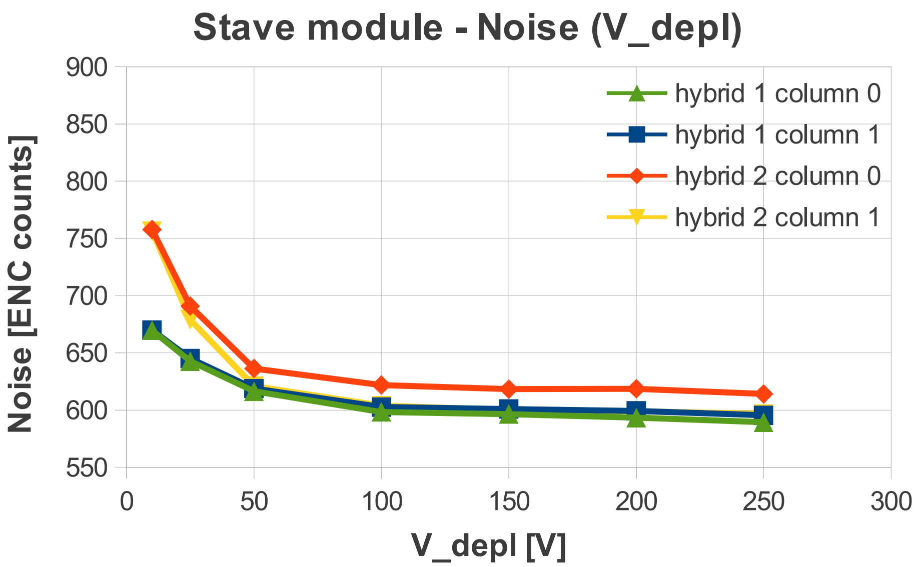


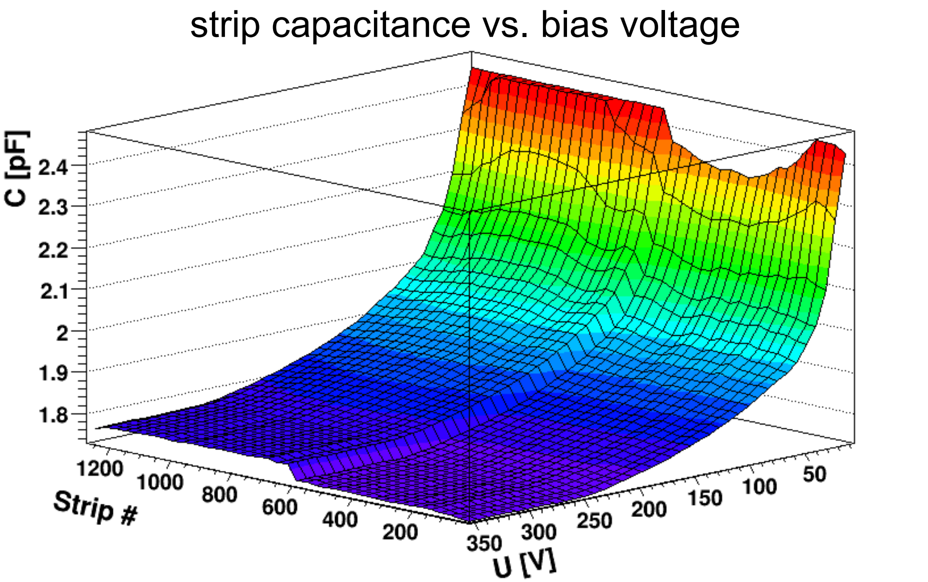
- **output noise** manifest as smeared out s-curves in threshold scan → **fit**
  - noise usually denoted as corresponding (input) noise charge at amplifier input: equivalent noise charge (ENC)
  - input noise typically at: ~ 600 ENC counts
  - typical threshold setting: 1fC (~ 6200e)
  - charge deposited: ~ 25000 e/h pairs

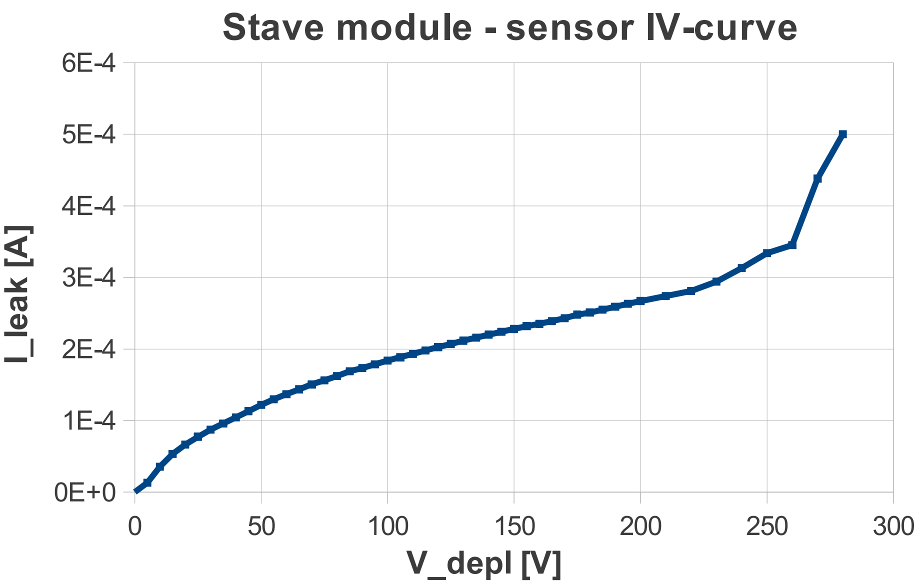
    → theoretical S/N ratio up to 40:1! (unirradiated)
  - but charge collection efficiency will drop

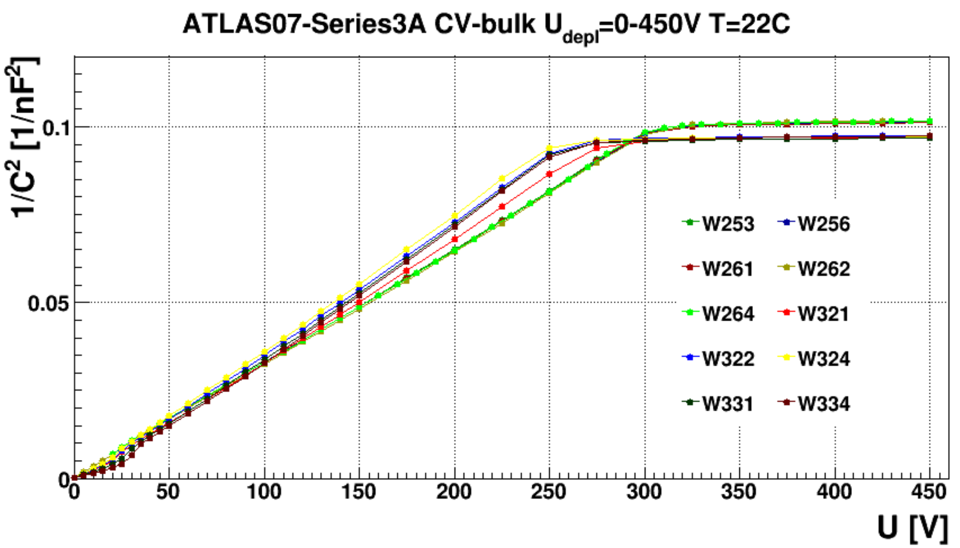


Noise dependence on depletion voltage

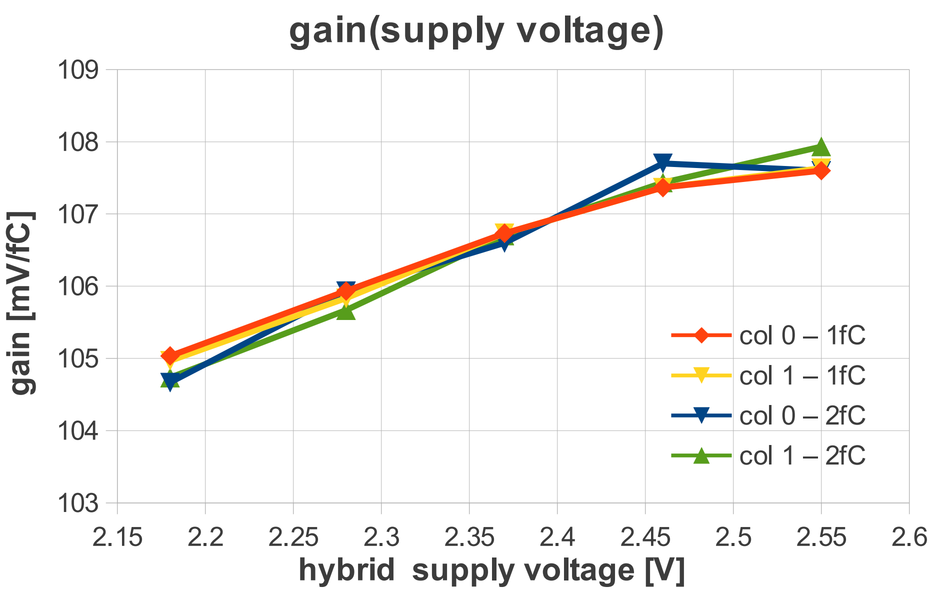


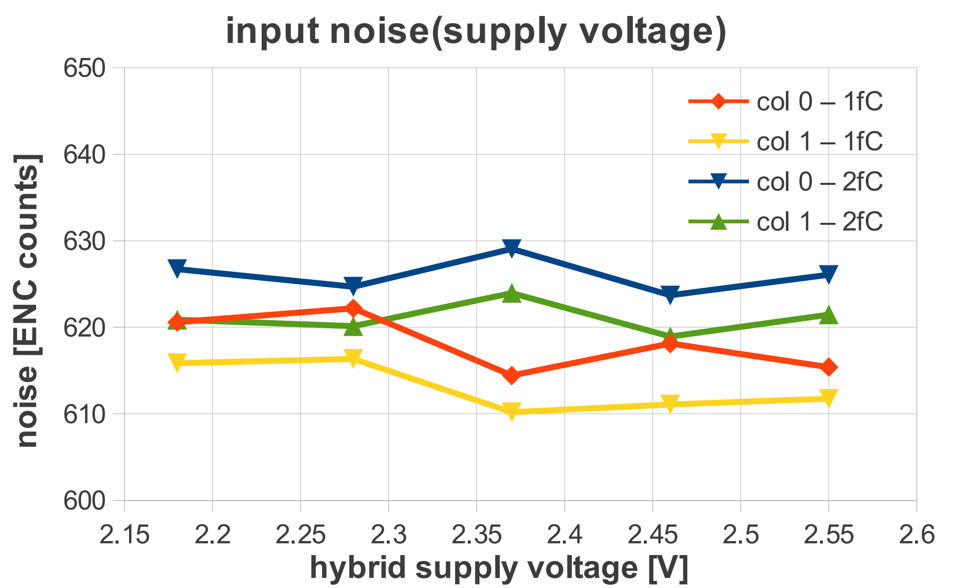


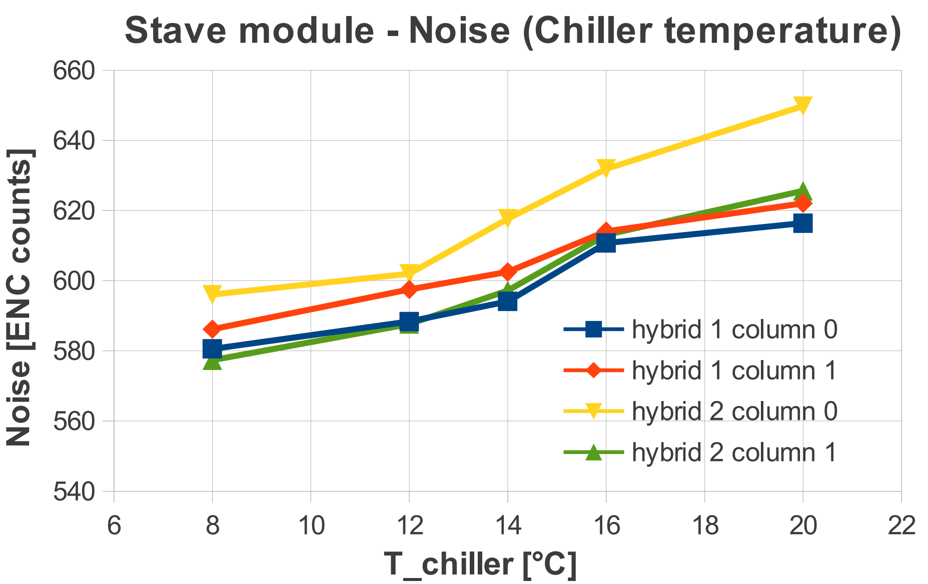


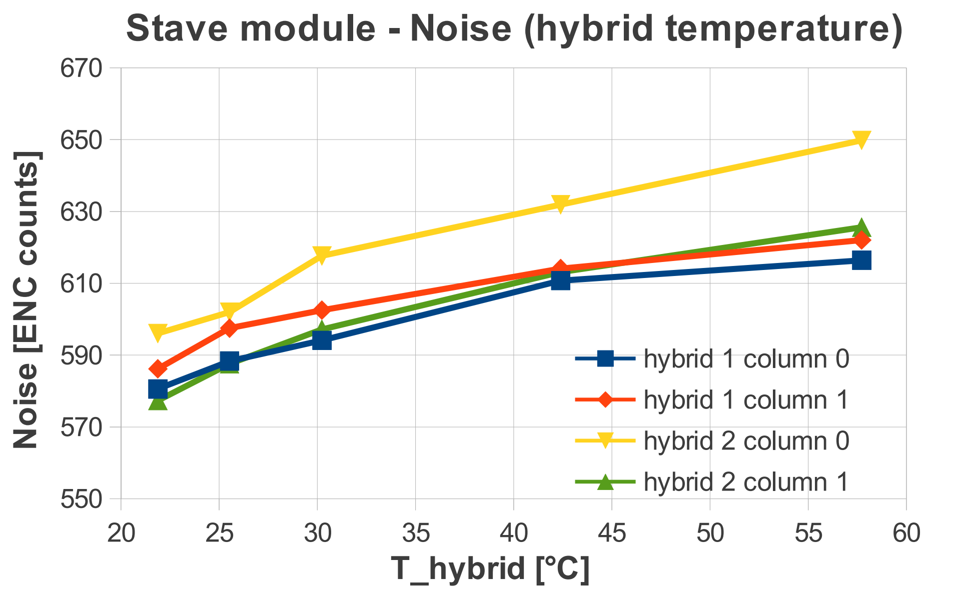


noise dependence on supply voltage & temperature



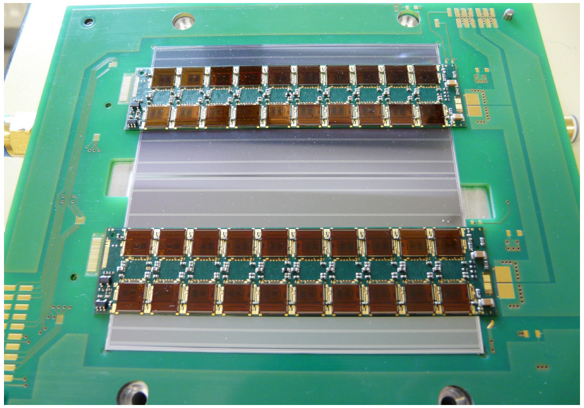






Summary

- current ATLAS Inner Detector will be replaced by an all-Silicon Tracker to account for:
  - larger track densities & pile-up
  - higher demands on radiation hardness
  - limits in power consumption & cooling, services and material budget



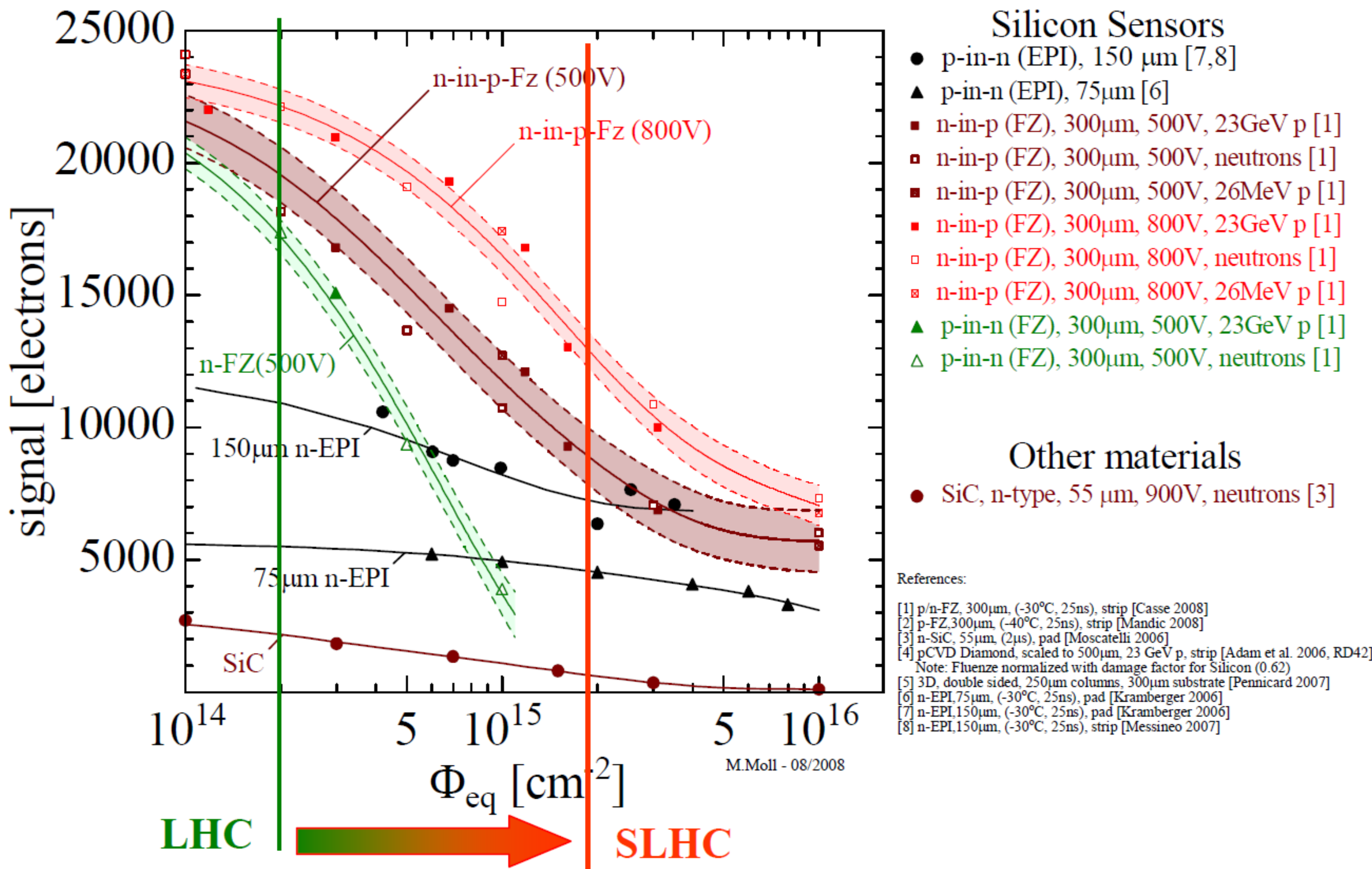
- our current focus → ATLAS Strip Detector Upgrade:
  - mechanical assembly of module prototypes (started with barrel modules)
  - DAQ / electrical testing
  - End-caps: design and construction of a Petal prototype in 2014
    starting with miniature "Petalet" - first sensors to arrive in summer

- 10 years to go for Phase 2 Upgrades, but still very ambitious time-line
  - start of mass production ~2016 (several 1000 modules have to be produced & tested)

backup slides

Backup 0: CCE

- **Signal comparison for various Silicon sensors**

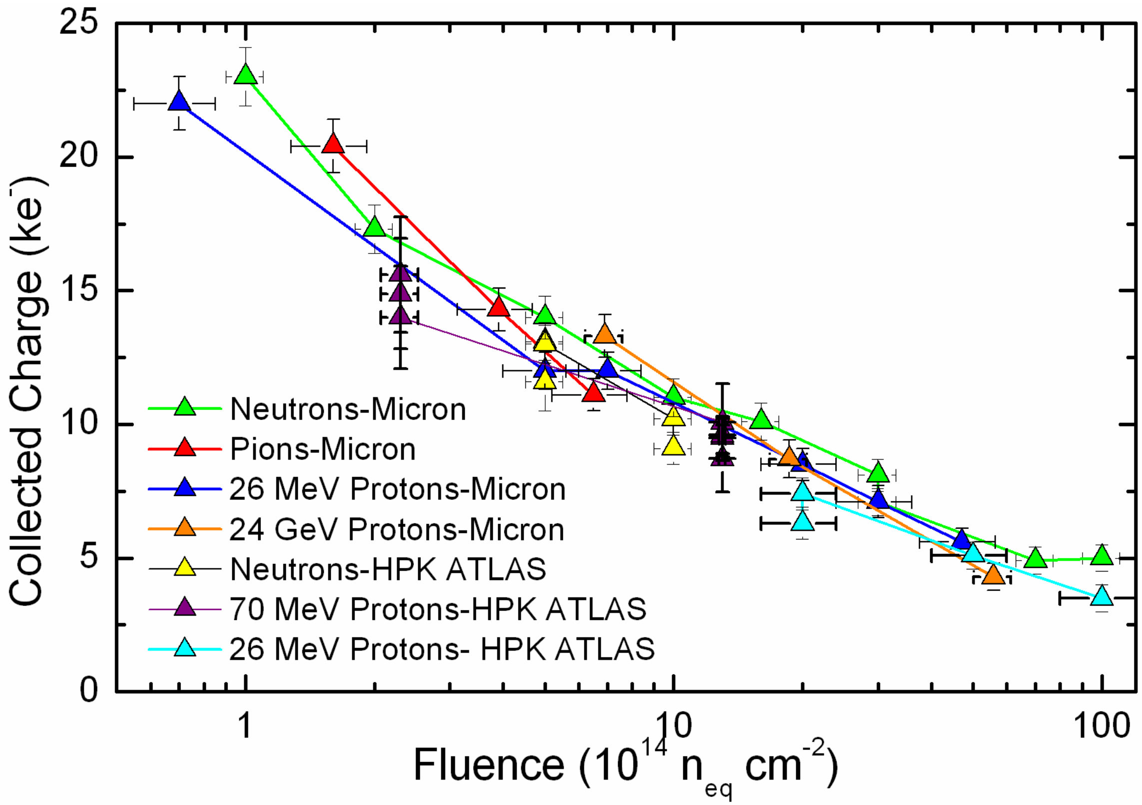


Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

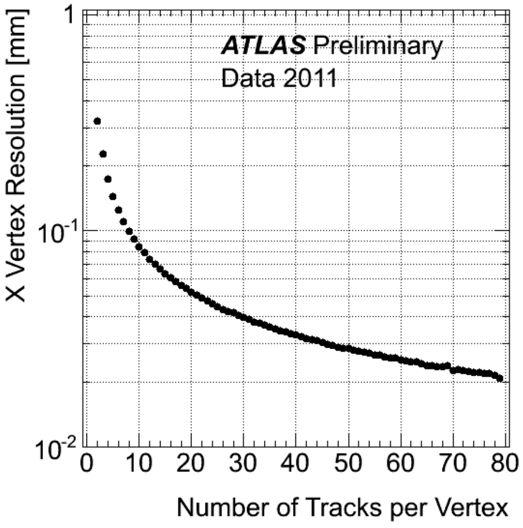
highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

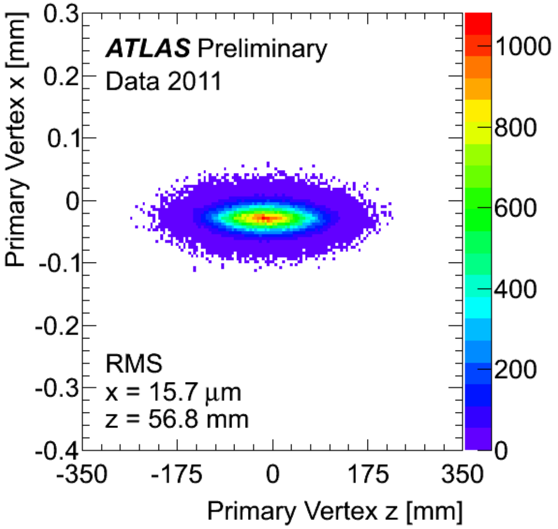
n-in-p technology should be sufficient for Super-LHC at radii presently (LHC) occupied by strip sensors

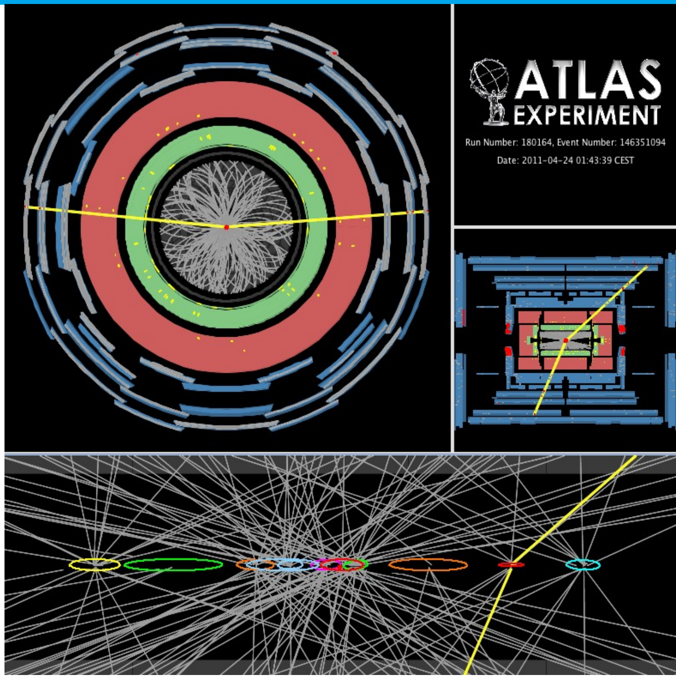
Backup 1: CCE2



Backup 1: current resolution



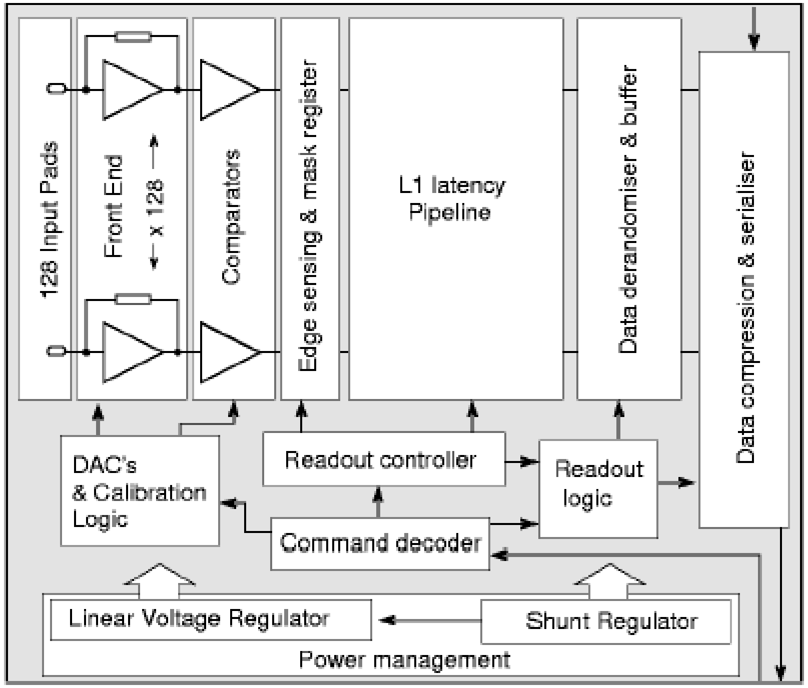


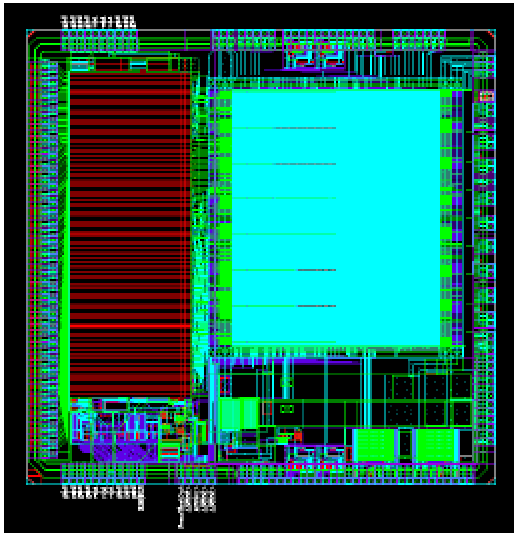


current detector sizes & resolution

Subdetector	r (cm)	Elements size	Resolution (X * Y)	hits/track (average)	channels
Pixel (silicon pads)	5 – 12.5	50 µm * 400 µm	10 µm * 115 µm	3	80 x 10^6
SCT (silicon microstrips)	30 – 52	80 µm * 12 cm (stereo)	17 µm * 580 µm	8	6.3 x 10^6
TRT (Transition Radiation)	56 – 107	4 mm (diameter)	130 µm	30	3.5 x 10^5

backup: ABCN-25





7.7 x 7.5 mm^2

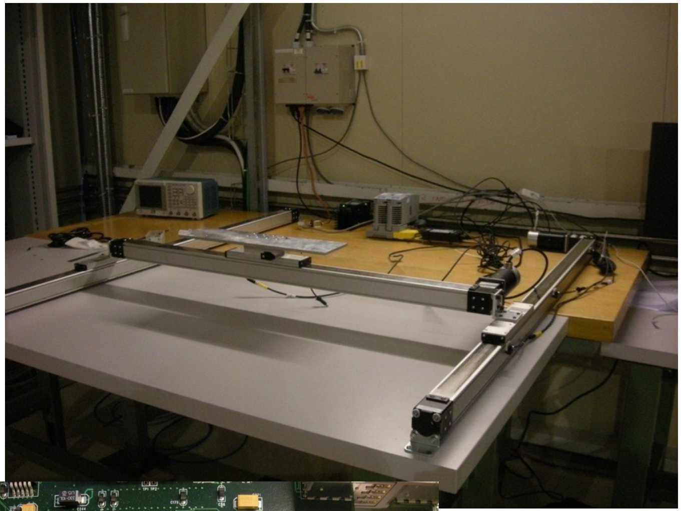
128 channels
35mA @ 2.0V Analogue
135mA @ 2.5V Digital

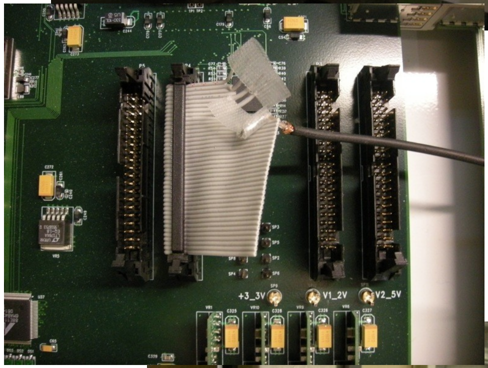
Backup: Trigger Upgrades

- **goal: preserve sensitivity to physics signatures**
  - use finer granularity and depth calorimeter information
  - learn from shower shape algorithms used at L2
  - match information from different detectors (improve electrons/muons with ID tracks)
  - build topological triggers (opening angles, invariant masses, etc.)
- **Track Trigger:**
- Self-seeded Standalone Approach (CMS Baseline)
  - dedicated tracker layers select hits from high pT tracks
  - read out only those hits to form tracks.
- Regional Readout L0+L1 Approach
  - regional readout seeded by L1Calo or L1Muon information (small fraction of ID)
  - may involve a two-stage L1 Trigger (L0 + L1) if the ID readout is not fast enough (may allow slower detectors to contribute also e.g. MDTs)
  - seeds useful for other detectors to refine processing (calo/muon)
- **many simulations & performance studies in progress**

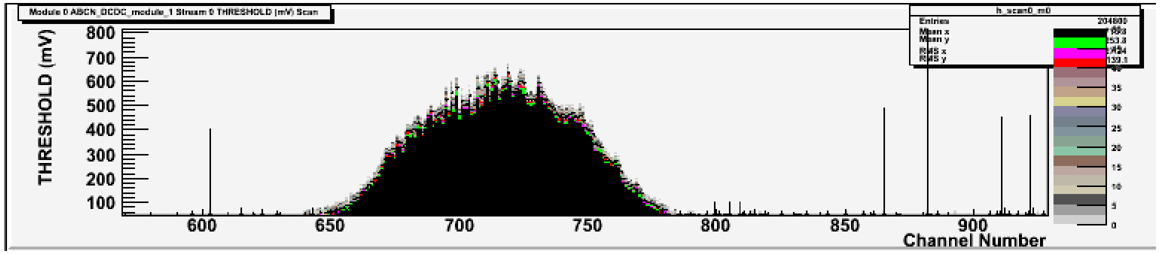
backup: laser test system

- laser triggered by L1A signal from HSIO
- charge injected into individual strips
- read-out - scanning through all channels
- status:
  - C++ software for motion control written & tested
  - design of base plate & dark box @ Freiburg
  - mountings for laser optics (collimator, lens, fibers) in production at CERN
  - measured focal width of laser
  - adjusted timings / delays for correct timing of read-out and tuned pulse shape for laser amp
- todo:
  - integrate motion & laser control into DAQ software & finish mechanical setup
  - measure final motion precision & repeatability: we need < 20um/step to hit in between strips

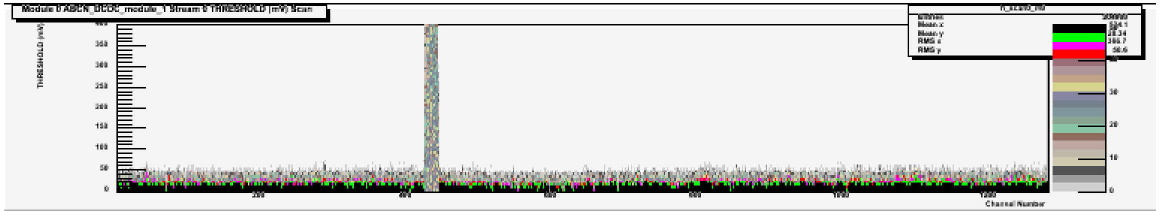




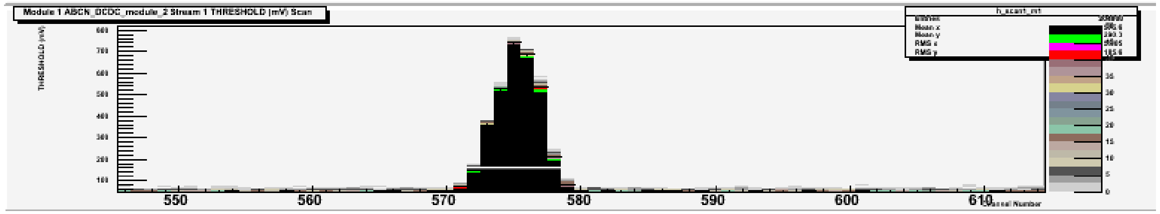
backup: laser focusing



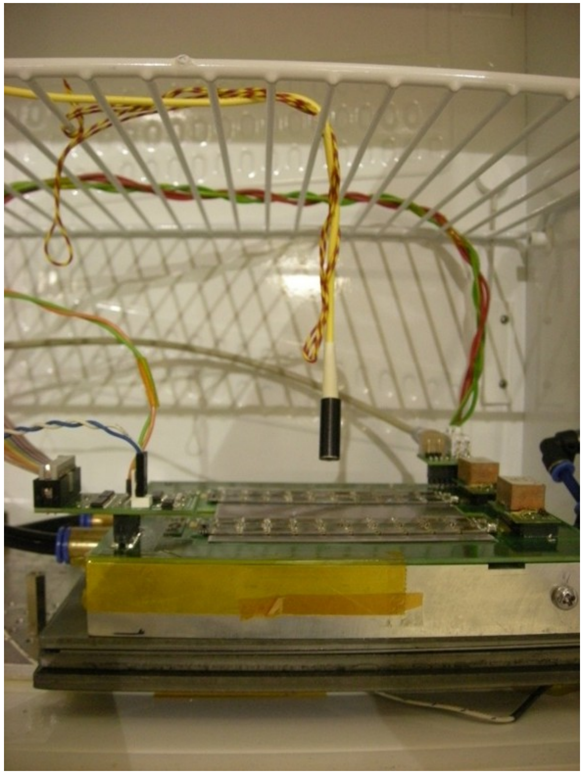
no collimator & lens



setup 1 - continuous operation → width ~20strips



setup 2 – pulsed operation → width ~1-3 strips



→ focal width < 1 strip feasible with precise mountings
(& proper adjustment of laser output power and threshold)