STD6 Symposium
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Design and Production of the LHCb Silicon Tracker

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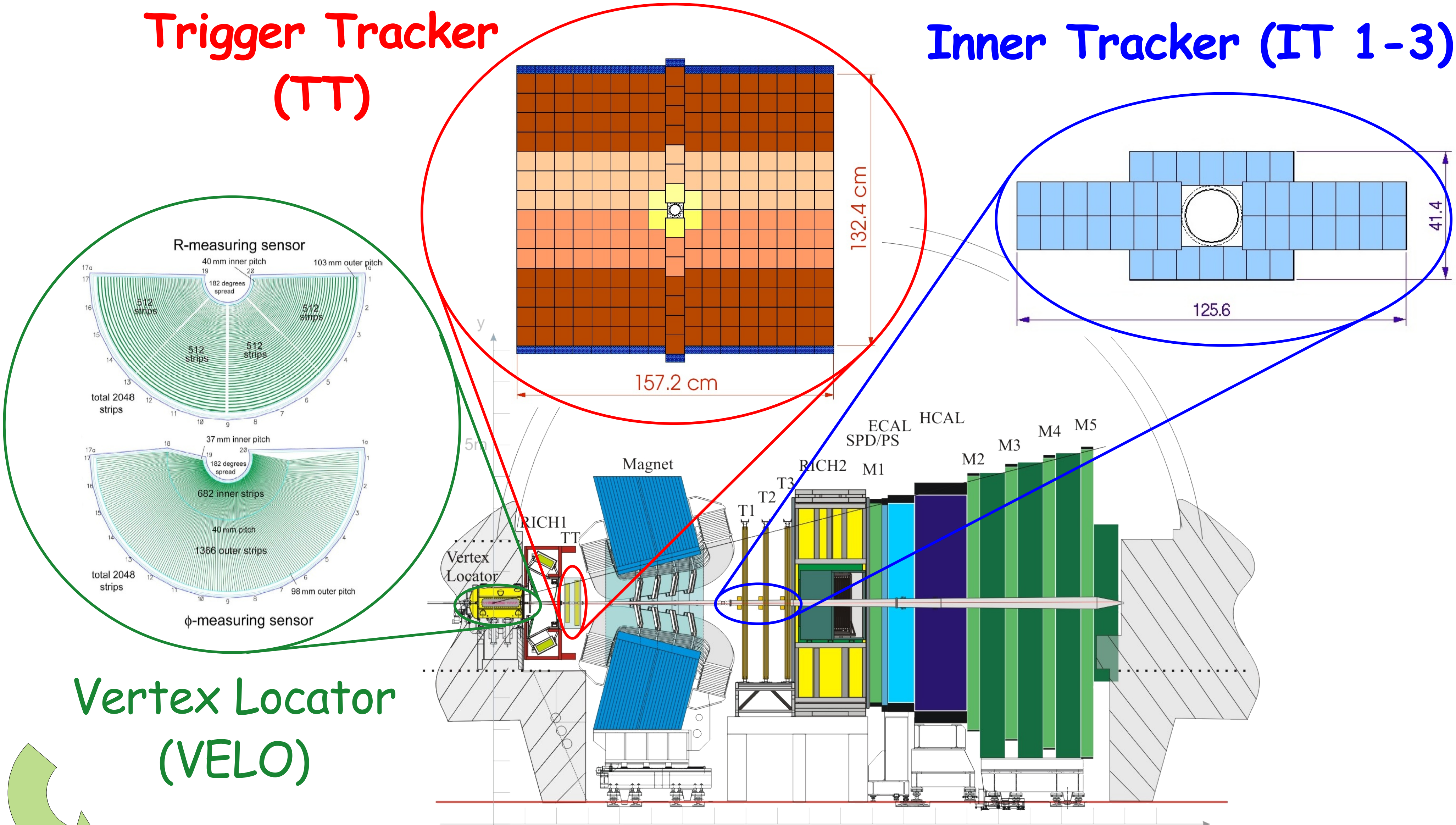
"Point Lobos" Ashok Sadrozinski, 2005

LHCb Silicon Detectors

Trigger Tracker (TT)

Inner Tracker (IT 1-3)



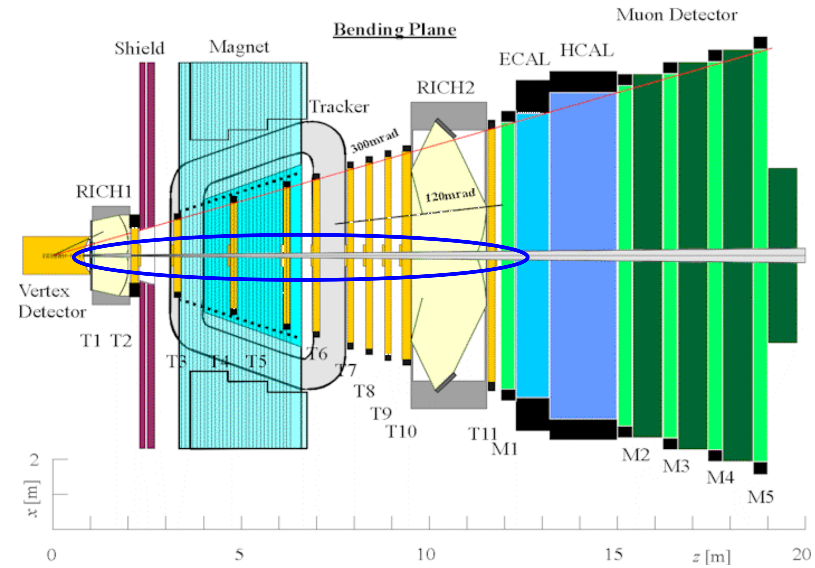
Vertex Locator (VELO)

Martin van Beuzekom's talk at 9:20 tomorrow morning

A Short History

<u>Once upon a time</u>...

- LHCb "classic": 11 tracking stations
- each station: Inner & Outer Tracker
- Inner Tracker: some variety of Micro-Pattern Gaseous Detector (MSGC+GEM, 3GEM, Micromega, Microwire)



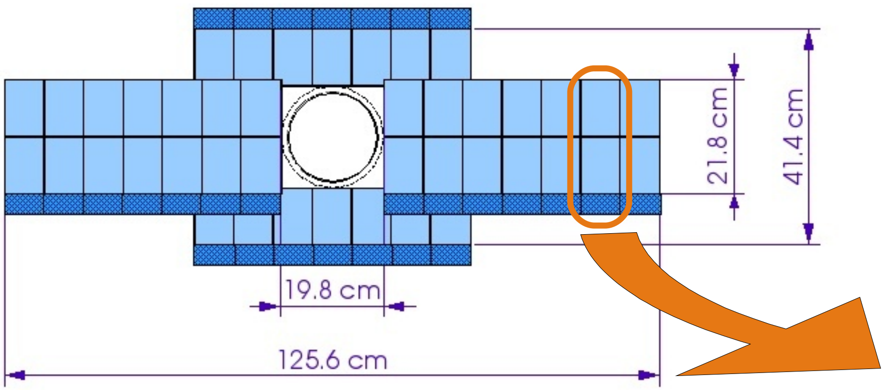
<u>2000</u>: start to investigate viability of a silicon micro-strip Inner Tracker

- adopted as baseline solution (for the 11-station detector) in May 2001
- Technical Design Report submitted in Nov 2002

<u>2002:</u> experiment-wide effort to reduce material budget (LHCb "light")

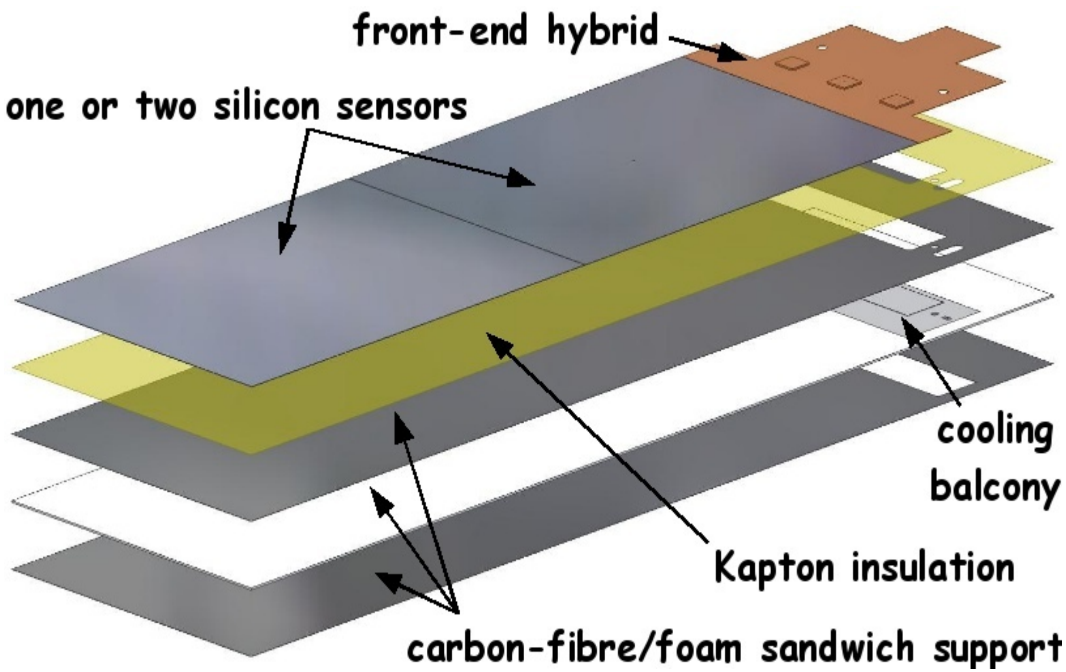
- reduce number of tracking stations from eleven to four
- the first of these all-silicon (→ Trigger Tracker)
- "Re-optimised Detector" Technical Design Report submitted in Sep 2003

Inner Tracker



Three stations with four layers each:

- 1-sensor ladders above/below beam pipe
- 2-sensor ladders left/right of beam pipe



Concerns in design phase:

- material budget
  - sensors as thin as possible
    320 μm for 1-sensor ladders
    410 μm for 2-sensor ladders
  - supports / cooling etc
- cost (number of r/o channels)
  - large pitch (197 μm)
- modularity (11 stations !)

~ 4.2 m^2, 504 silicon sensors,
336 modules, 130k readout strips

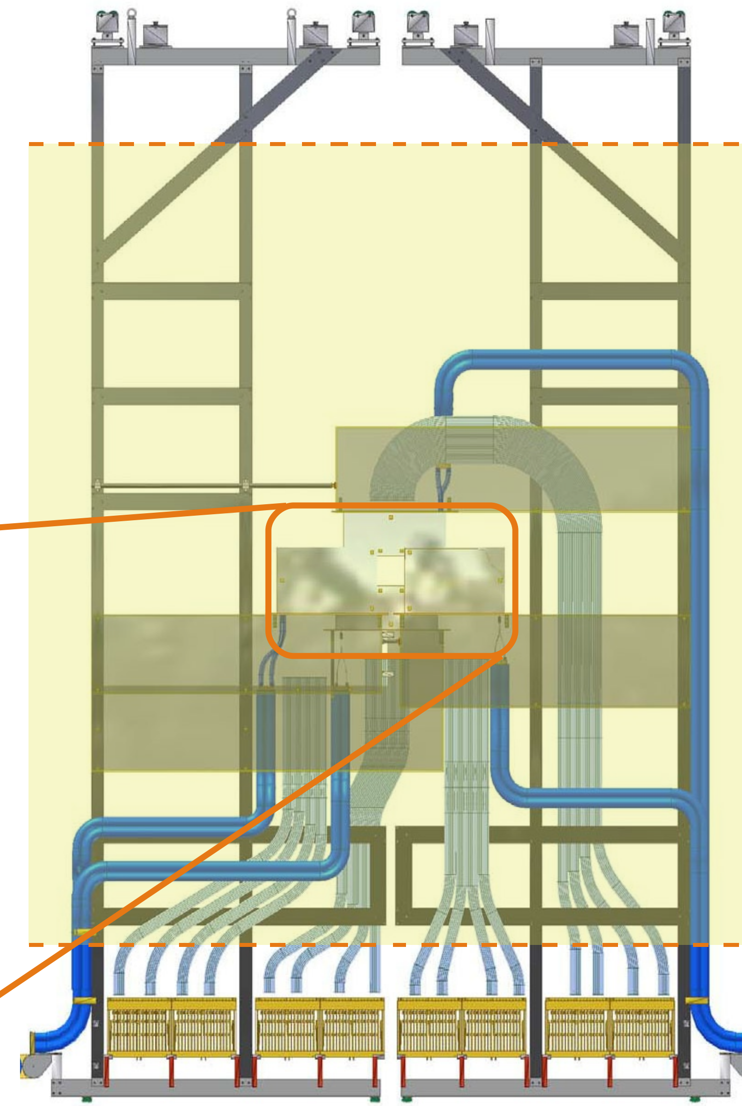
Inner Tracker Station

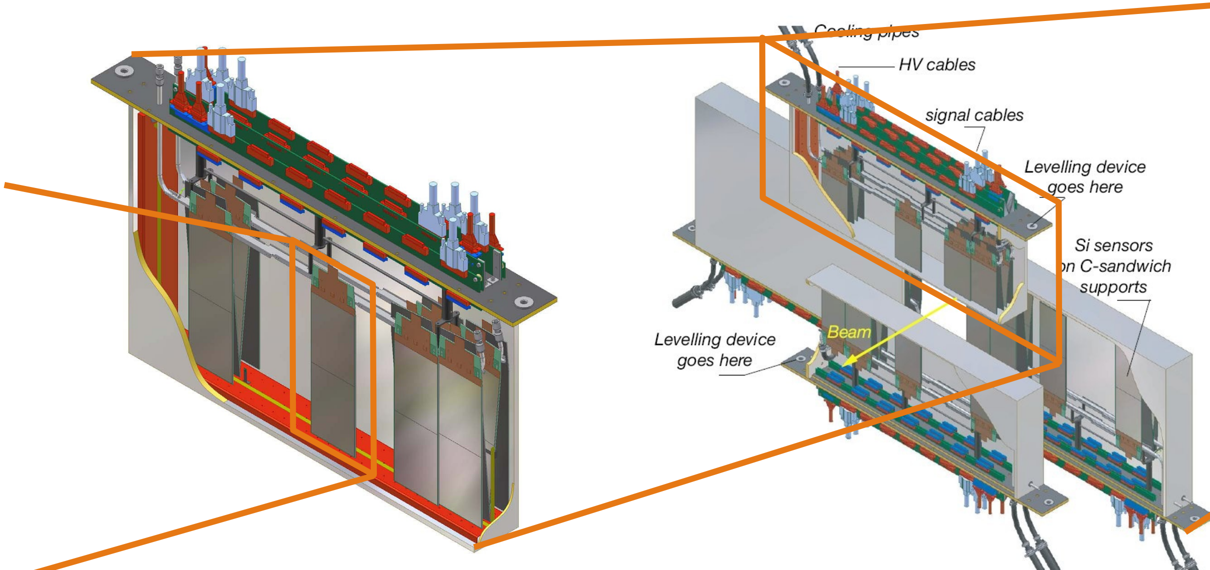
Four individual detector boxes surrounding LHC beam pipe:

- mechanical support of detector modules
- cooling (front-end hybrids and ambient)
- thermally and electrically insulating box

Two support frames on precision rails:

- mechanical support of detector boxes, cables
- retractable for detector maintenance





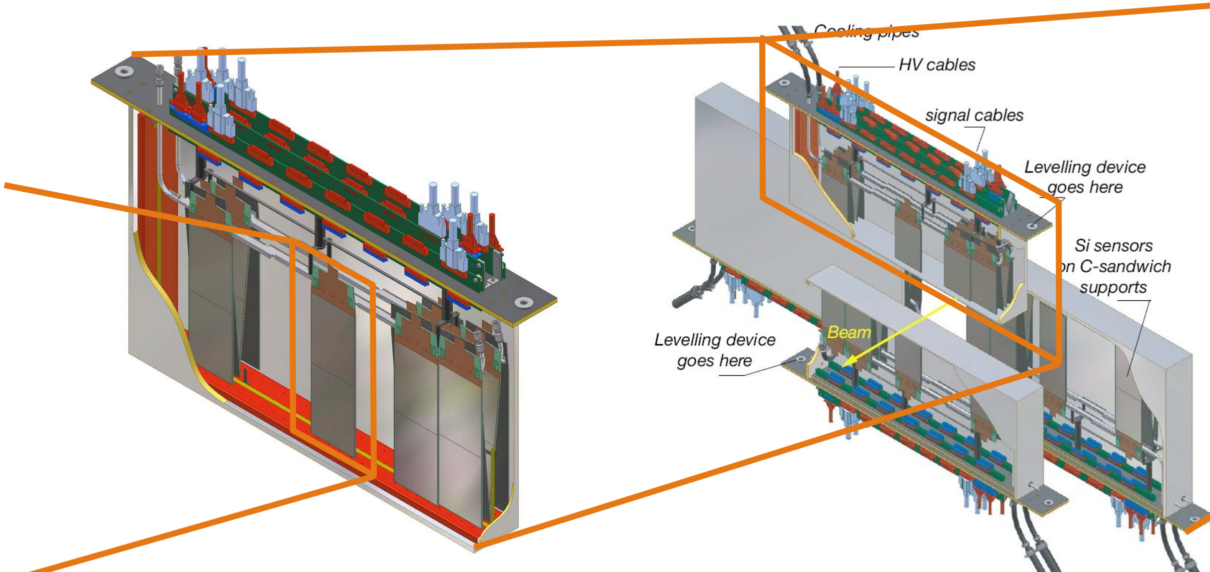
Inner Tracker Station

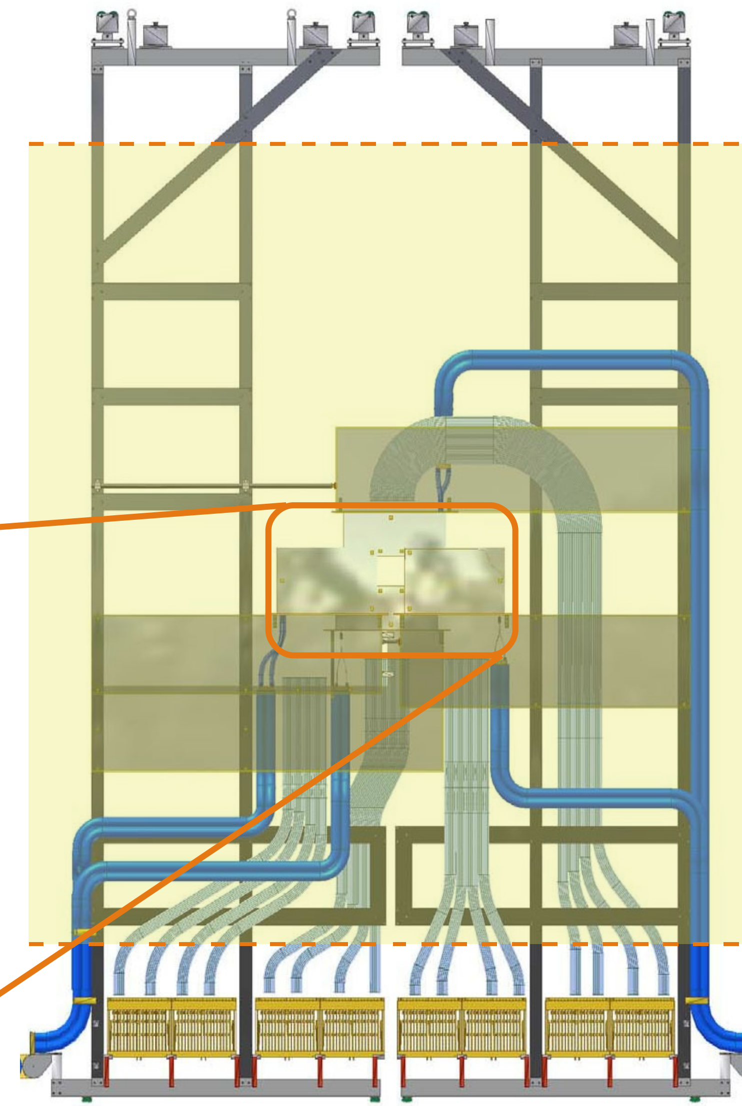
<u>Material budget per Inner Tracker station</u>:

- active region: 2 - 2.5 % (dominated by silicon)
- frames: ~ 6 %
- connectors: ~ 4 %
- cables: ~ 8 %

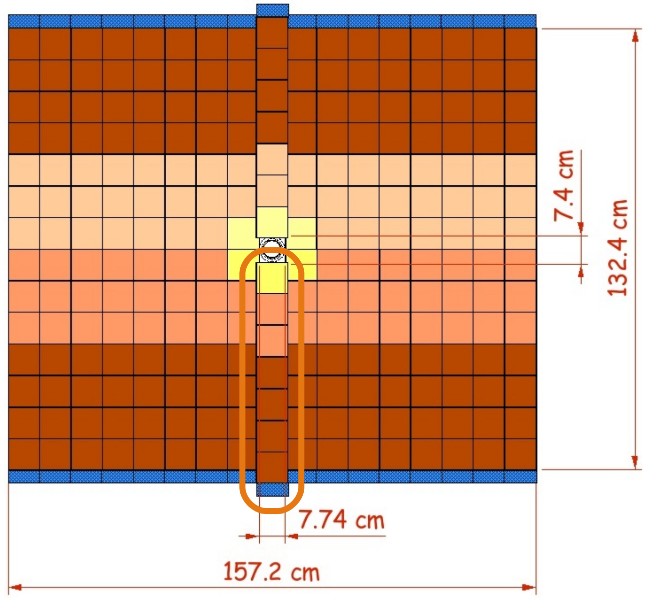
} inside LHCb acceptance

- "dead" material further out than active region (LHCb physics are forward peaked)



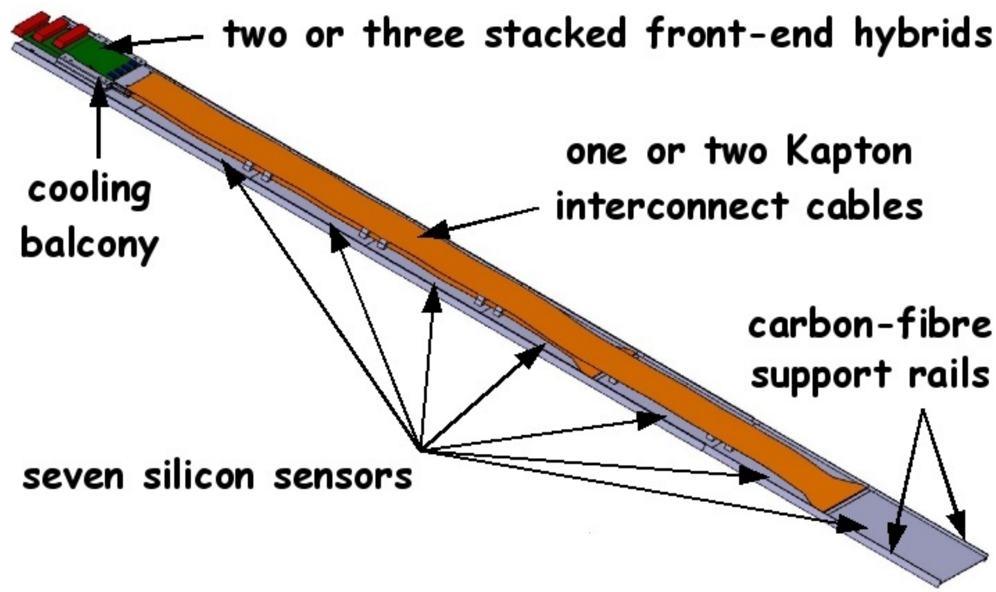


Trigger Tracker



One station with four detection layers:

- 7-sensor long "half-modules"
- 1-/2-/3- and 4-sensor long readout sectors
- all r/o hybrids at one end of the module
- "inner" r/o sectors: Kapton interconnects



Concerns in design phase:

- material budget:
  - r/o electronics outside acceptance
- cost (number of r/o channels)
  - large pitch (183 μm)
  - long strips (up to 37 cm)
- S/N for very long readout strips

~ 8.2 m^2, 896 silicon sensors, 280 r/o sectors, 143k r/o strips

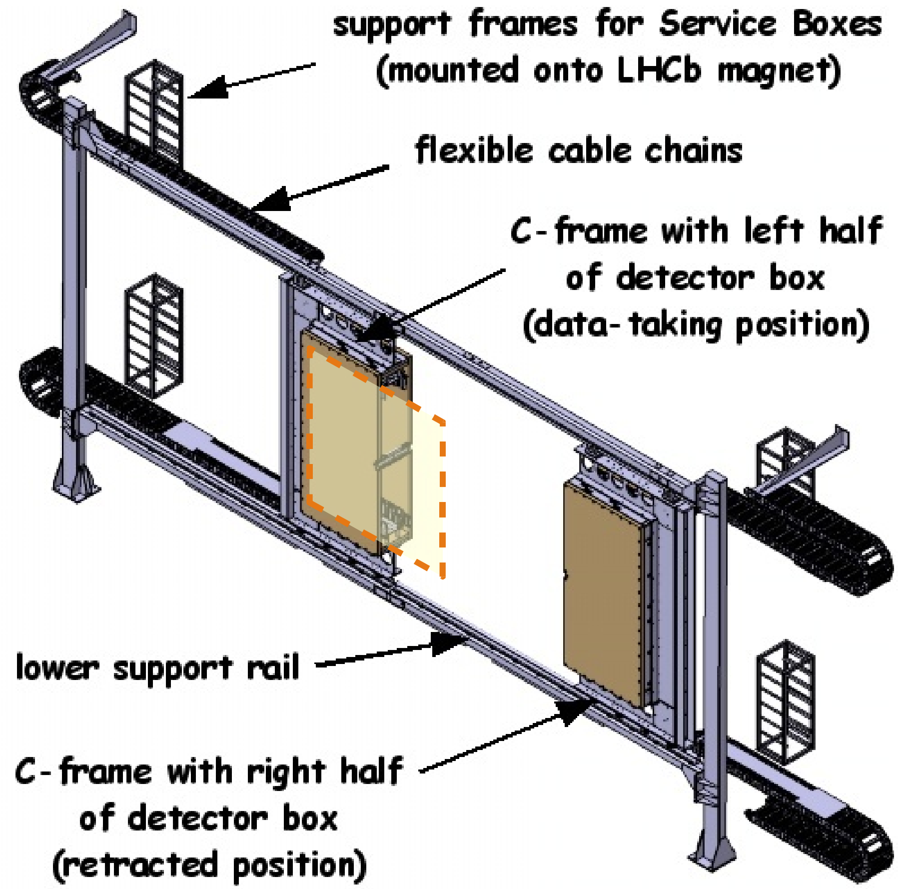
Trigger Tracker Station

Two half stations, retractable for detector maintenance:

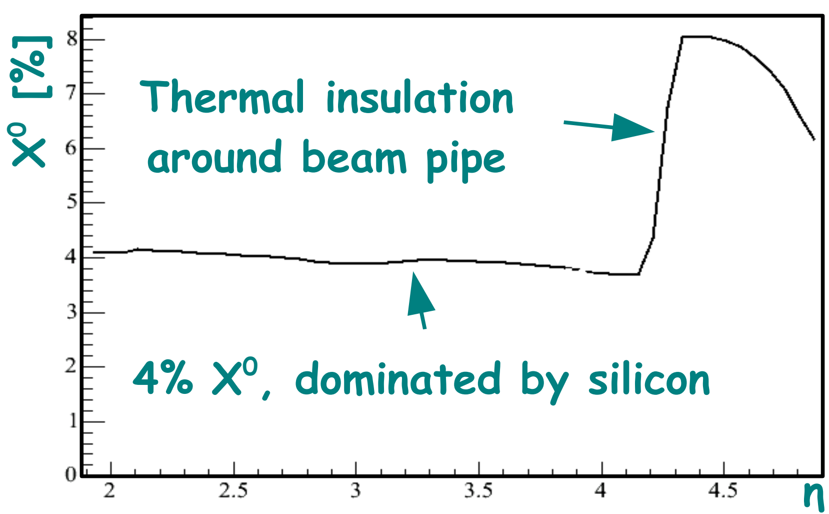
- support rails, frames and cables
- cooling (front-end hybrids and ambient)

} outside of LHCb acceptance

- thermally and electrically insulating box
  - lightweight polyurethane foam sheets clad with thin aluminium / Kevlar foils
  - one large volume when closed



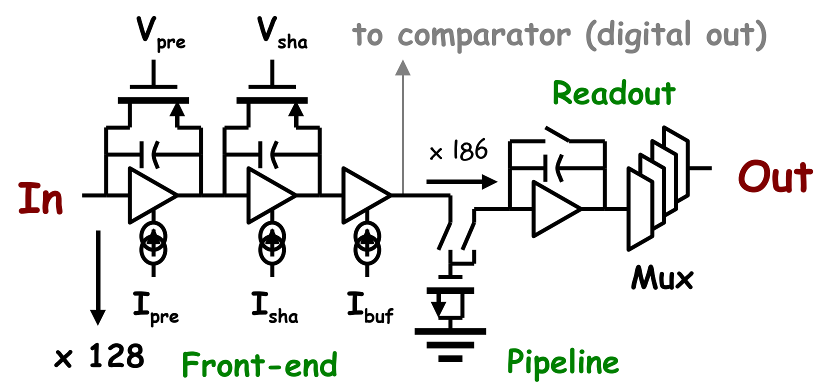
Material budget inside acceptance:



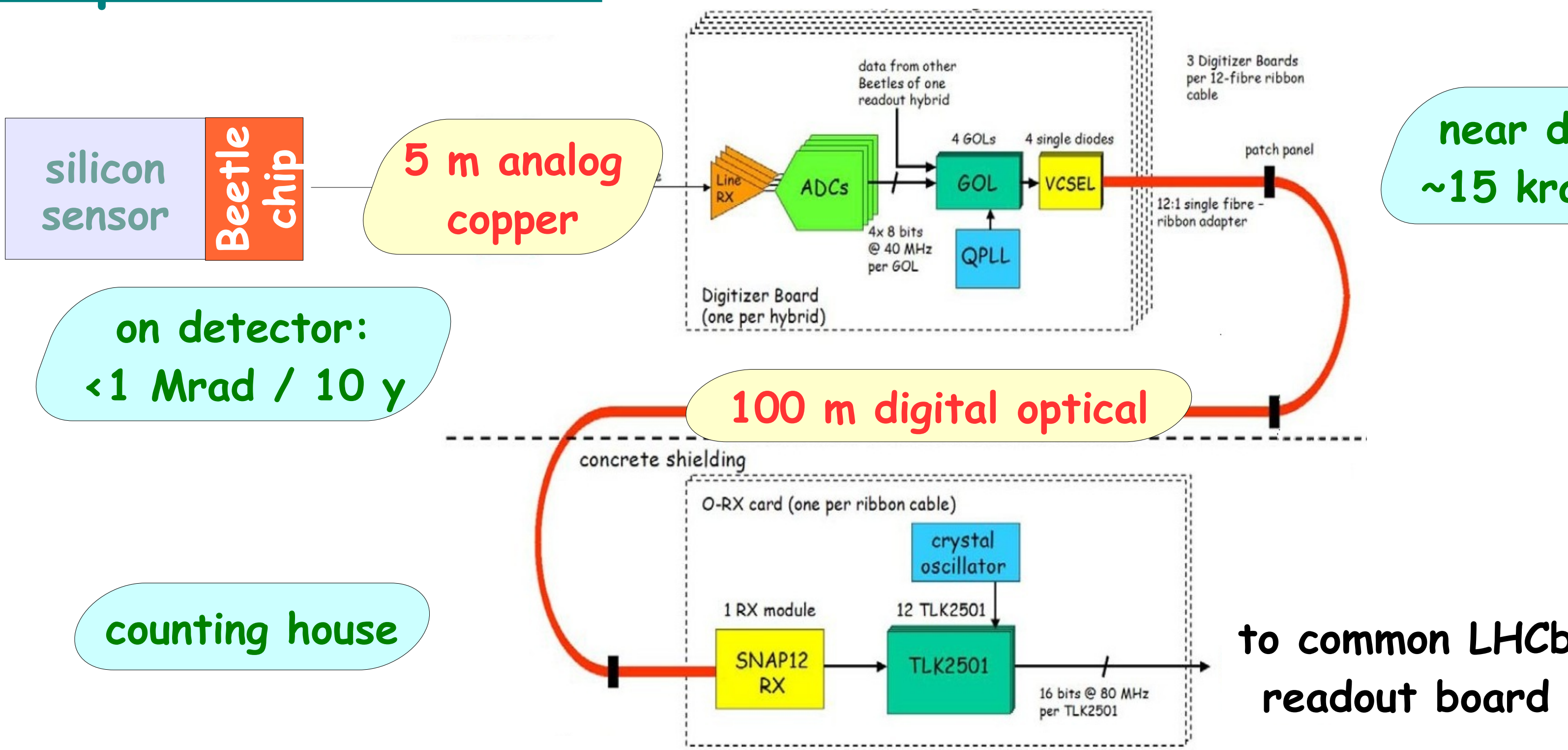
Silicon Tracker Readout

"Beetle" front-end readout chip:

- radiation-hard design in 0.25 μm CMOS
- analog pipeline, multiplexed analog readout
- adjustable shaping time of ~ 25 ns (via V_{fs})



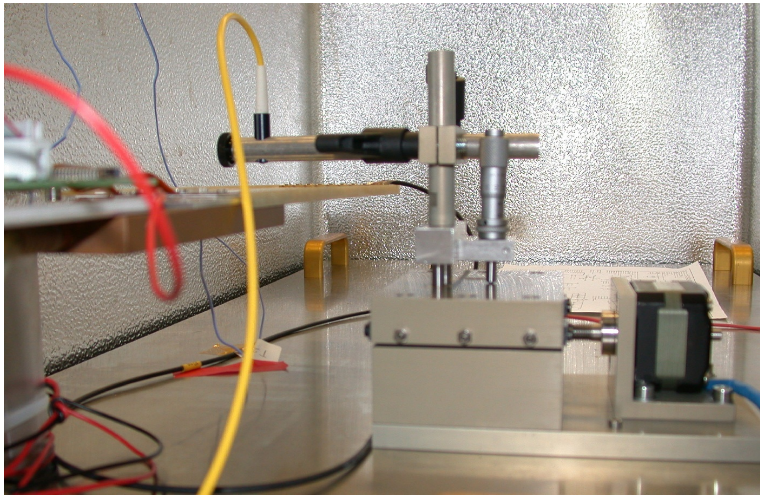
Digital optical readout link:



Silicon Tracker R&D

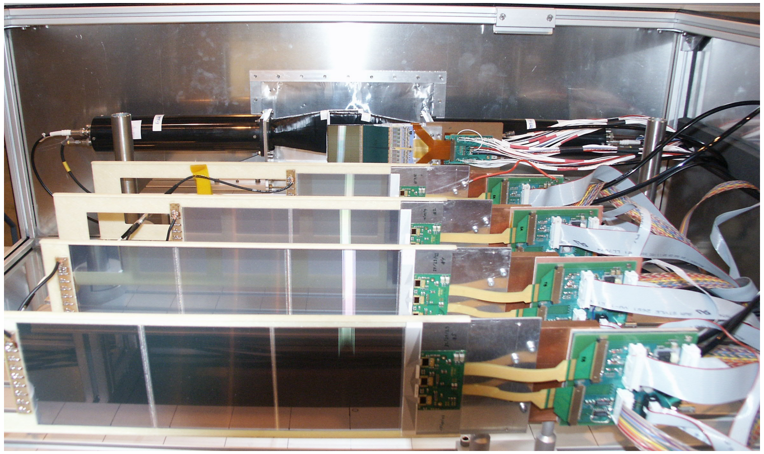
<u>Main concern</u>: detector performance

- required sensor thickness for Inner Tracker
- S/N for long r/o strips of Trigger Tracker (up to 37 cm, read out at 25 ns !)
- signal integrity for Trigger Tracker readout sectors with Kapton interconnect



<u>Infra-red laser test stand</u>:

- pulsed infra-red laser, focussed to ~ 10 µm
- signal shape, charge sharing, CCE as function of inter-strip position of charge deposition



<u>Test beams</u> (120 GeV/c pions from SPS):

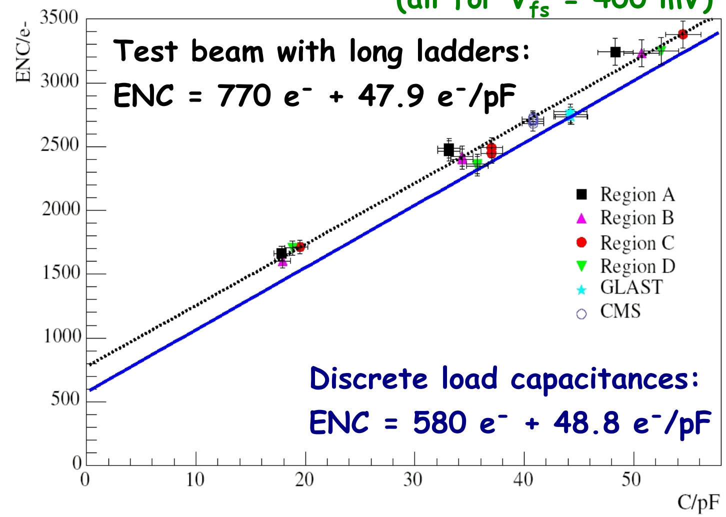
- beam telescope to determine particle impact position on detector under test to ~ 15 µm
- S/N and detection efficiency as function of inter-strip position

Main Findings from R&D

1) S/N scales linearly with detector capacitance:

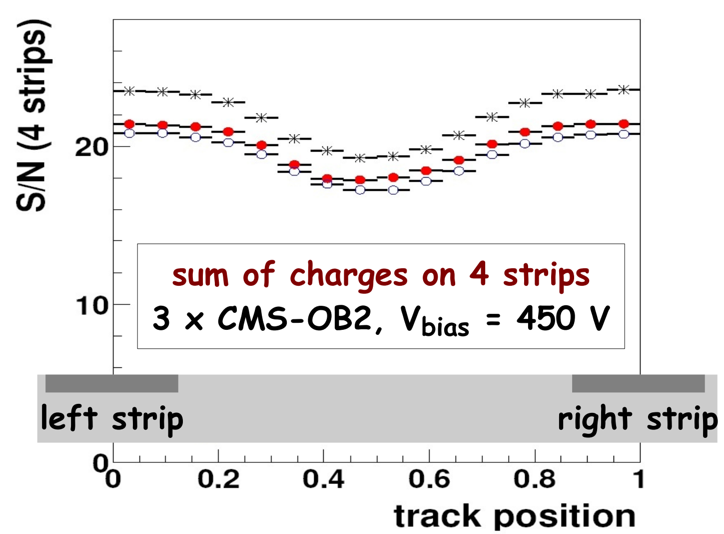
- no significant contribution from strip resistance even for the longest readout strips (33 cm)
- confirmed by a combined SPICE simulation of r/o strips and Beetle front-end amplifier
- careful: strong dependence on interplay between noise spectrum of detector (resonances) and bandwidth of amplifier → do not generalise !

(all for V_{fs} = 400 mV)



2) significant loss of CCE in between strips:

- independent of strip length and shaping time
- depends ~ linearly on (pitch-width) / thickness
- interpreted as being due to charge trapping at silicon bulk / oxide interface between strips

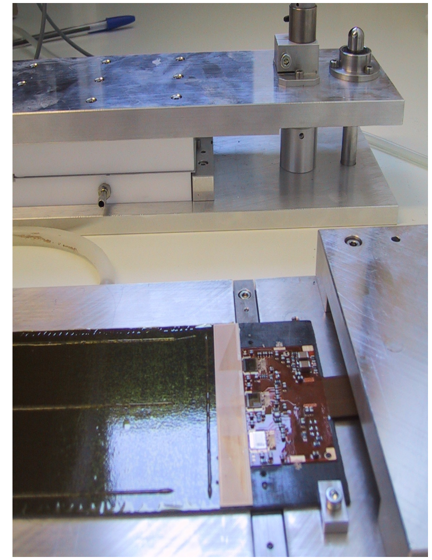


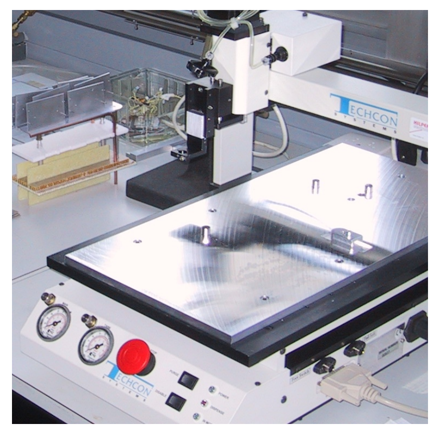
3) no deterioration of signal integrity due to Kapton interconnects

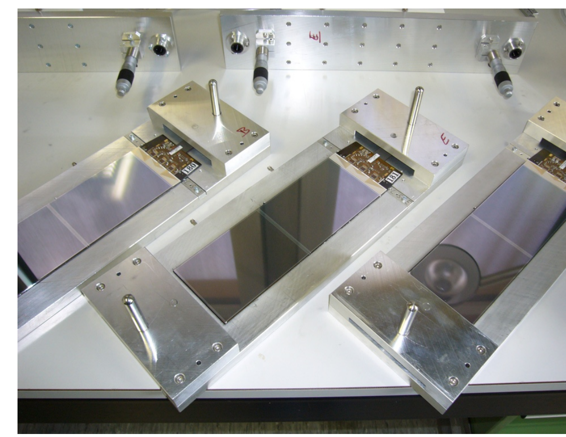
Inner Tracker Production

<u>Main production steps</u>:

- position hybrid & pitch adaptor, glue them to the sandwich support
- r/o functionality test
- position silicon sensor(s), glue it/them to the support
- measure sensor alignment
- bond hybrid & pitch adaptor, bond bias and GND to the sensor
- r/o functionality and HV test
- bond all readout strips
- 24h burn-in test:
  - IV curves, strip noise to identify bad strips (shorts, opens, pinholes)
  - several temperature cycles between 20°C and 5°C



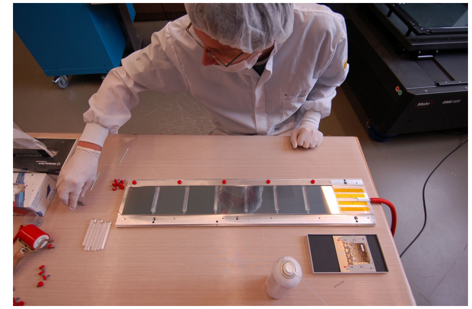


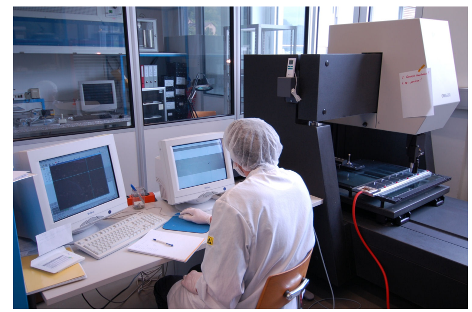


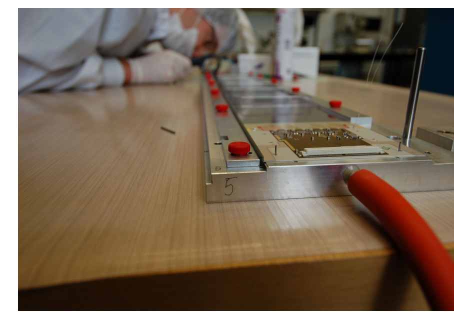
Trigger Tracker Production

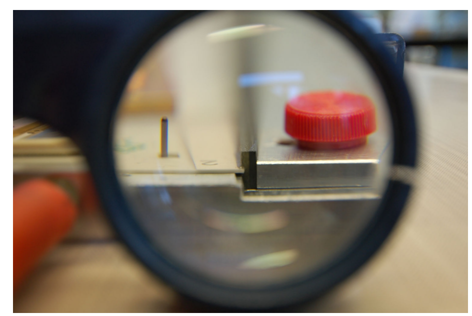
"Stage I" production steps:

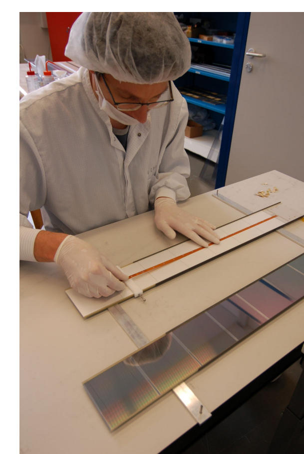
- place seven sensors and lower hybrid (use sensor edges for positioning)
- verify and correct alignment (CMM)
- glue support rails along the edges
- measure final sensor alignment
- glue bias voltage cable along back of module, apply GND and bias connections (using silver glue)
- bond sensor(s) to pitch adaptor
- 24h burn-in test:
  - IV curves, CCE curves, pulse-shape scans
  - analysis of strip noise to identify bad strips
  - several temperature cycles between ~20°C and 5°C







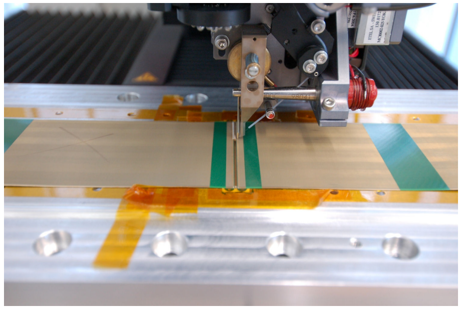
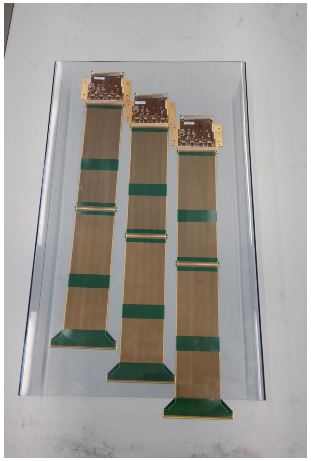
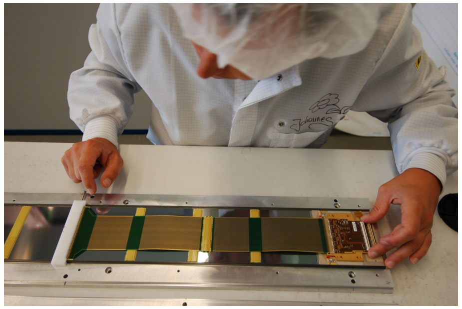




Trigger Tracker Production

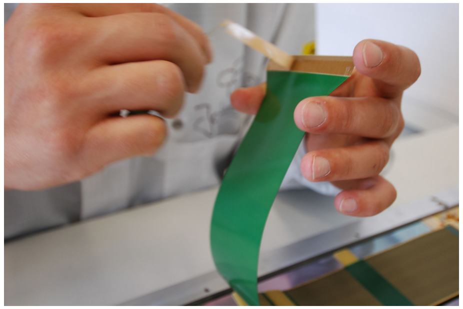
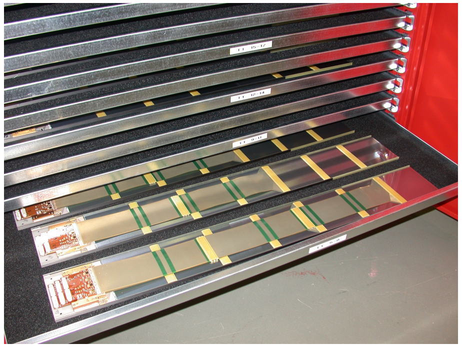
“Stage II” production steps:

- glue Kevlar protection caps over bonds
- assemble and bond Kapton interconnect cable and upper hybrid
- mount interconnect & hybrid onto detector module, bond cable to sensor
- solder GND connections to lower hybrid
- 36h burn-in test with similar programme as after stage I

“Stage III” production steps:

- for modules with three read-out sectors, repeat stage-II steps for 2nd interconnect and 3rd hybrid

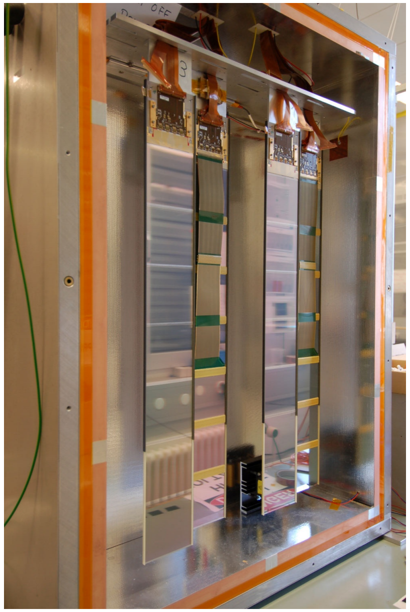



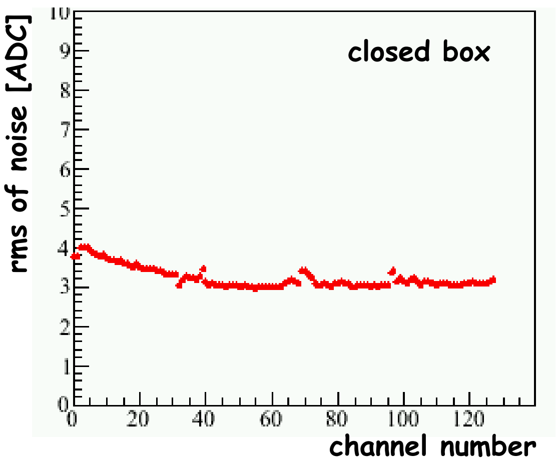
- 36h burn-in test with similar programme as after stage I and II

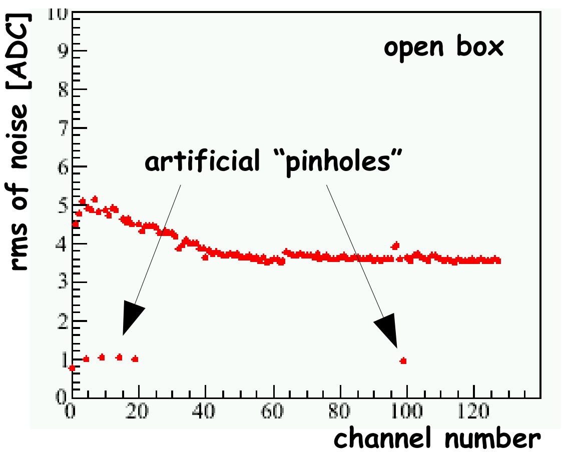
Burn-In

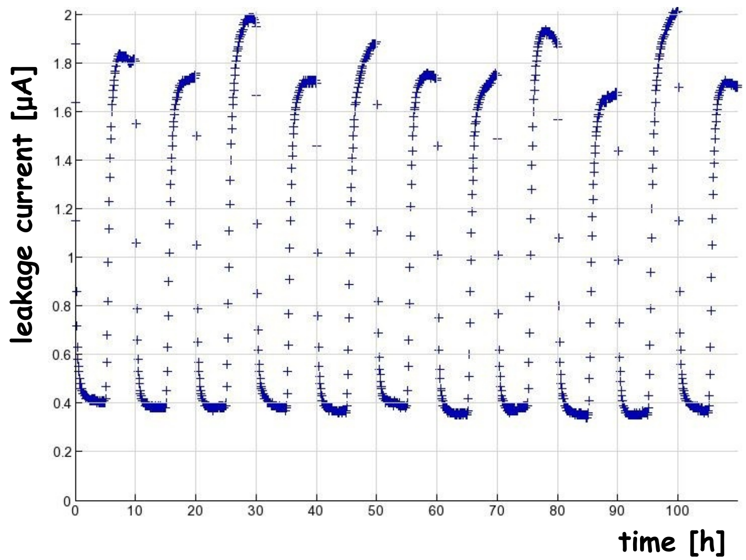
Example: TT burn-in test stand

- fully automatic operation (LabView)
- temperature cycling between r.t. and 5°C
- continuous monitoring of leakage currents
- pulsed IR diodes to generate charge at defined positions on the sensors
- also: excercise final readout link
- also: test final cooling concept









Comments on Production

Module production largely "manual" and run by small production teams

- IT: 6 physicists / technicians from Lausanne and Santiago de Compostela
- TT: 5 physicists / technicians from Uni Zürich

Small team means flexibility in decision making processes

- short production meetings to discuss problems and decide the programme for the coming week
- lots of ad-hoc decisions in the production room

Small team means simple logistics

- hybrids from MPI Heidelberg, silicon sensors (from HPK) via Uni Zürich
- IT assembly in Lausanne, bonding and testing at CERN (40 km distance)
- TT production entirely at Uni Zürich

But it also means lack of redundancy in manpower and equipment

- we have been lucky no accidents happened (except for one broken hand)

Comments on Planning

Projected production speeds could be reached and maintained

- Inner Tracker:
  - producing 12 modules / week using five production templates in parallel
  - currently about 230 modules out of 380 fully produced and tested
- Trigger Tracker:
  - produced 5 modules / week in stage-I, using two templates in parallel
  - stage-I production finished last week, stage-II/III by end October
- as expected, testing takes up more resources than the actual production

Transition from prototyping to production much slower than expected

- unforeseen problems when building the first “final” modules
- problems at vendors when going from prototype to series production
- training of unexperienced bonders can take a lot of time
- should have known all this and reserved more time in our project planning
- finally we are okay since LHC schedule slipped by a similar amount of time

Module Quality

Fraction of "problematic" modules so far quite low

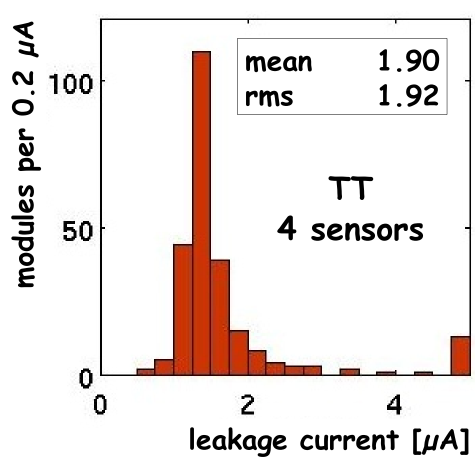
- 5 (IT) + 4 (TT) modules lost (damaged sensor, pitch adaptor or r/o hybrid)
- 1 + 0 modules with more than 2 bad strips (could be used if needed)
- 1 + 3 modules probably repairable (strange IV curve or r/o problem)
- planned for 50 + 20 spare modules (15 %)
  - hopefully no need to install these problematic modules
  - have a closer look at them once the main production is finished

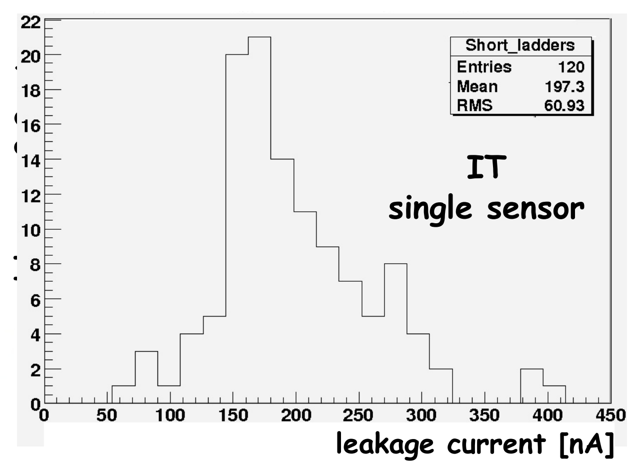
Fraction of bad strips so far quite low ("bad" = interrupt, short, pinhole)

- IT: 82 out of ~ 85 k tested
- TT: 141 out of ~ 134 k tested

Leakage currents very low

- normally < 500 nA per sensor at 500 V (HPK sensors !!!!)

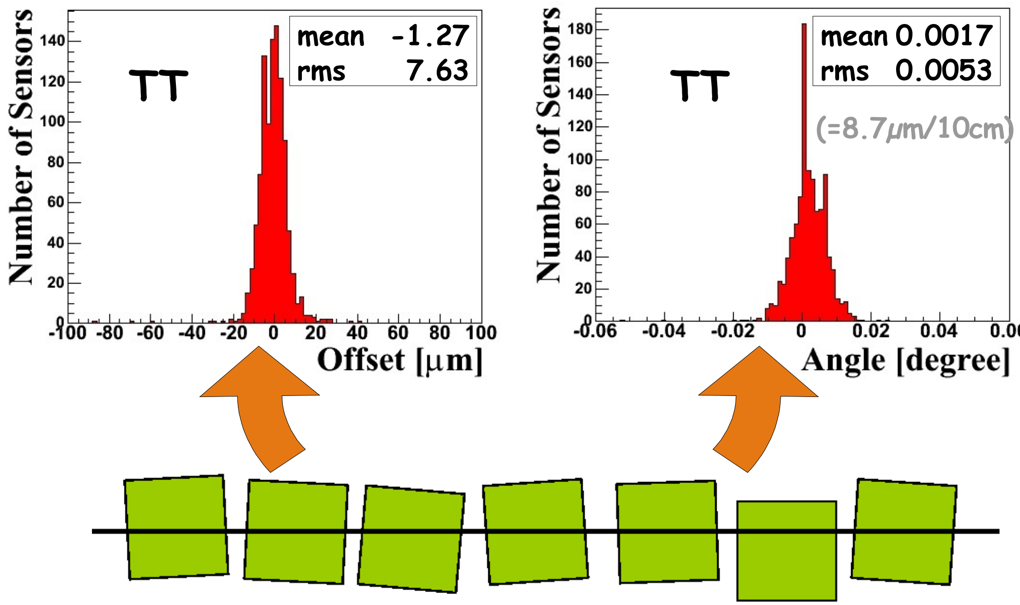


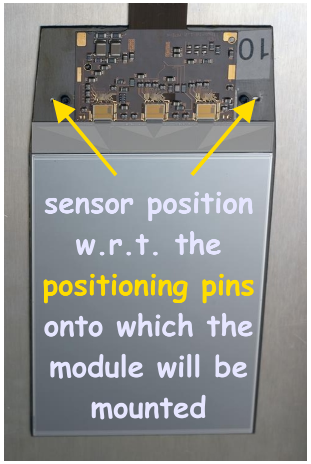


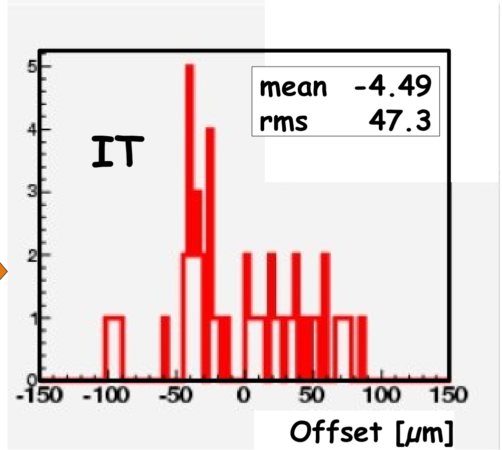
Module Quality

Positioning precision (benchmark: expected spatial resolution of ~ 50 µm)

- excellent relative positioning of the sensors on a module
- each module can be treated as one unit in software alignment, no need to align individual sensors
- positioning of sensors on supports worse than what we had hoped for (true for IT, not measured for TT)
- mainly due to worse than expected tolerances on production templates
- each module has to be aligned individually in software
- no problem: had always been foreseen





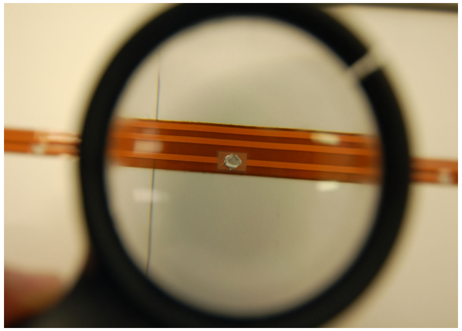


Silver Glue

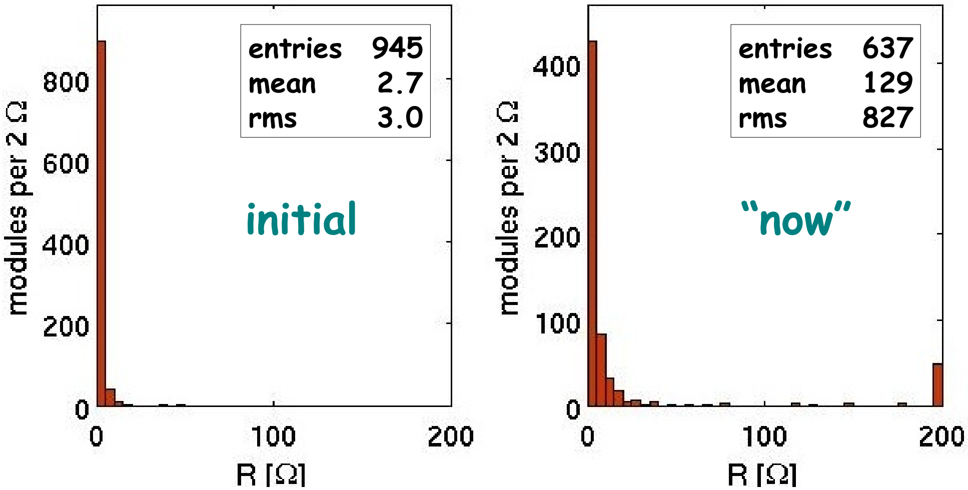
<u>Latest "discovery": silver glue on aluminium is a bad idea</u>

(not entirely unexpected since similar effects were already observed by CMS)

- TT: use dedicated bias voltage cable along the back of the module
- used silver glue to connect bias voltage to the backplane
  - TT9-75: Elecolit 340 (one-component "silver paint")
  - TT76-155: Elecolit 325 (two-component epoxy)



- measured resistance of all connections
  - shortly after module production
  - again after a few weeks / months
- find significant increase of resistance
  - for both types of silver glue
  - typically a few hundred Ohms now
  - but the trend is worrisome



- decided to provide additional bond connections on all sensors

Summary

Where we could have done better:

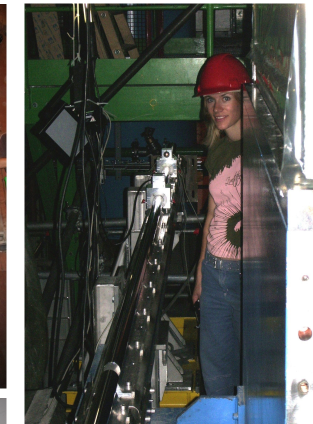
- underestimated the transition from prototyping to production
  → should have tried to build a "final" module much earlier on
- may have spent too much effort on optimisation of sensor thickness (IT)
  → material is anyway dominated by supports, cooling, cables
  → having two types of sensors (320/410 μm) is a complication
- ended up having two types of TT modules for no good reason at all
  → unnecessarily complicates logistics, production of spares

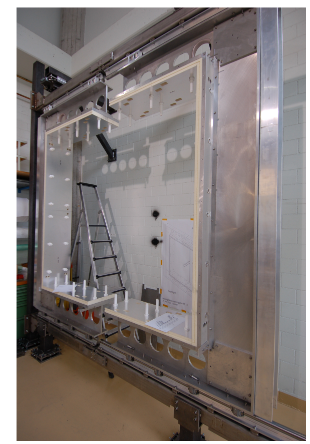
What we might have gotten right:

- relatively simple and robust module design (despite a few "ad-hoc" fixes)
- good sharing of responsibilities between participating groups
- entire production of all r/o hybrids in a single company (RHe, Germany)
- investment in automated burn-in test stands, using final components

Summary








Other activities:

- TT support frames installed
- IT support frames assembled and to be installed soon
- IT detector boxes being assembled
- TT detector station being assembled
- r/o electronics being produced
- work on monitoring / control software

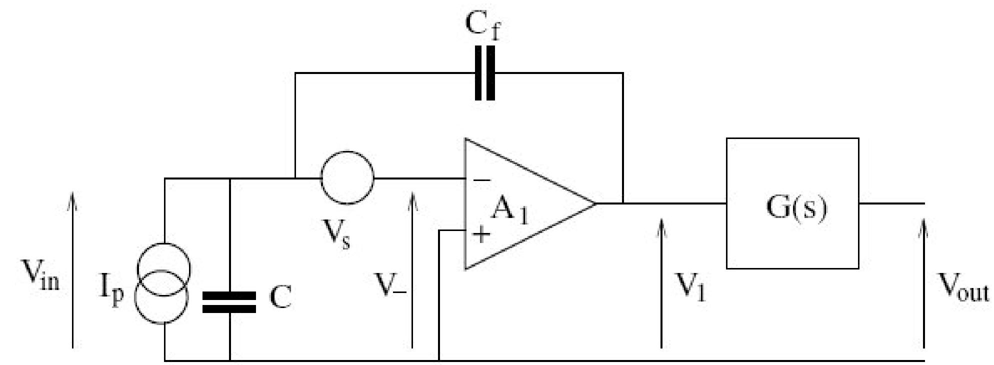
Main tasks for the coming year:

- finish module production and testing (TT: October, IT: February)
- station assembly and installation in the experiment (TT: Dec, IT: Dec-Feb)
- detector integration and "commissioning" without beam (Jan-Aug)
- hall closes end Aug, single p beam Nov/Dec, first p-p collisions end 2007

Extra slides

Noise Model

Charge-sensitive amplifier:



- G(s): transfer function of shaper
- C : load capacitance
- V_s : serial noise of input FET
- I_p : parallel noise from leakage currents

$$ENC^2 = \int_0^\infty \frac{1}{2\pi} \cdot \left(\frac{8\,kT}{3\,g_m} (C + C_f)^2 \omega^2 + 2\,eI_p \right) \cdot \frac{\left| L\,(V_0 \cdot v(t)) \right|}{V_0}\, d\omega$$

- calculate serial noise using measured Beetle response function $V_0 \cdot v(t)$

=> good agreement with values measured on a test bench

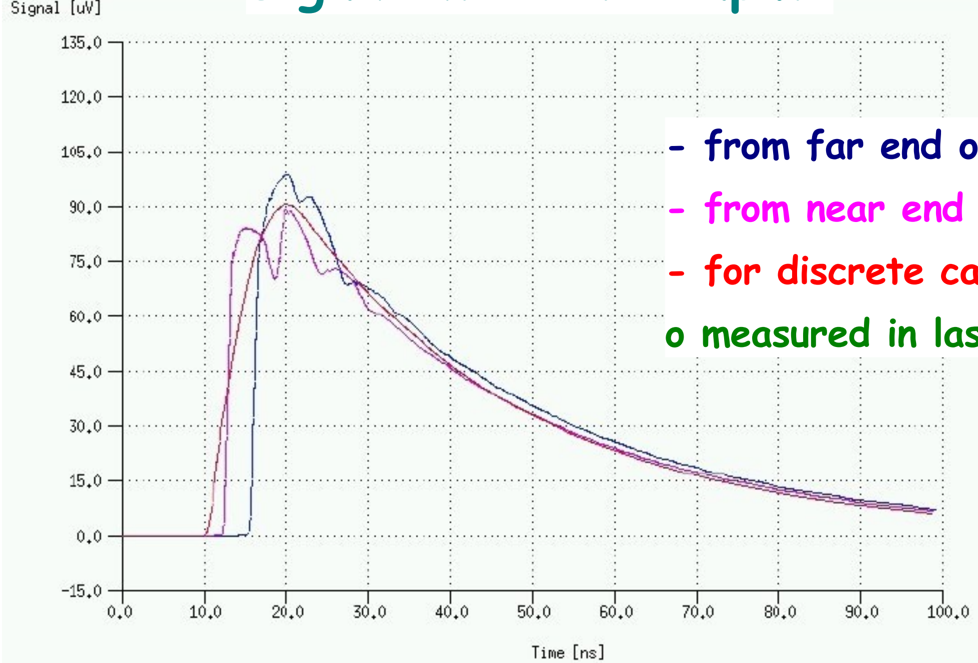
V_{fs} [mV]	0	100	400	1000
calculated serial noise [e/pF]	51.2	50.9	49.0	43.0
measured serial noise [e/pF]	52.6	51.9	49.4	45.2

Calculated Signal Shapes

Spice simulation of long readout strips (10 RLC elements / cm):

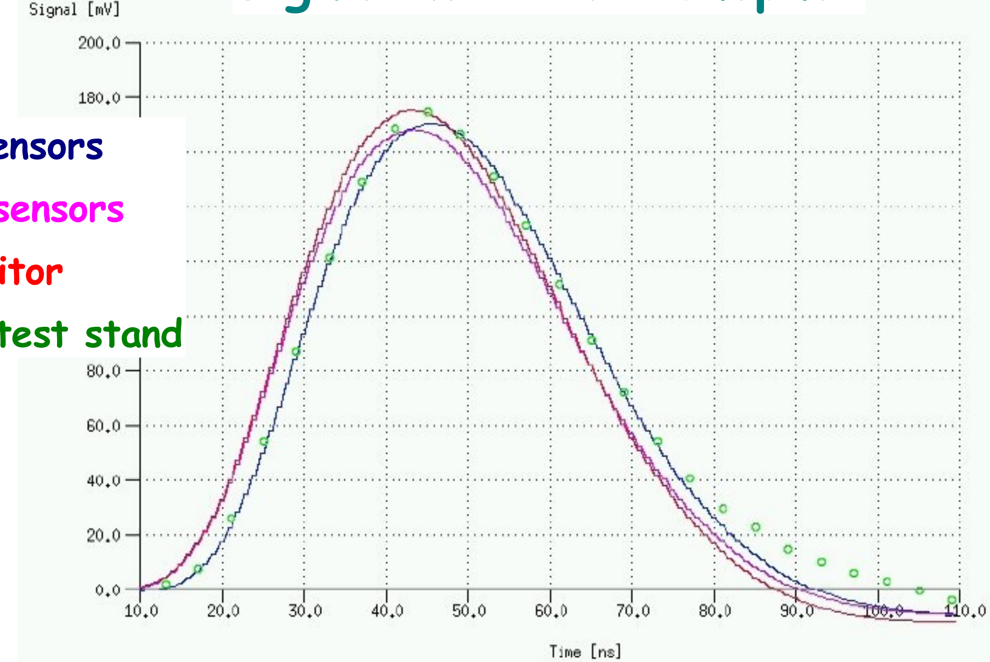
- Example: 3 sensor long CMS-OB2 ladder with Kapton interconnect cable
  => R,L,C determined separately for sensor and interconnect cable !
- Beetle output signal determined using measured Beetle response function
  => signal from far end: peaks ~ 3 ns later, pulse height is ~ 4% smaller

Signal at Beetle input:



- from far end of sensors
- from near end of sensors
- for discrete capacitor
o measured in laser test stand

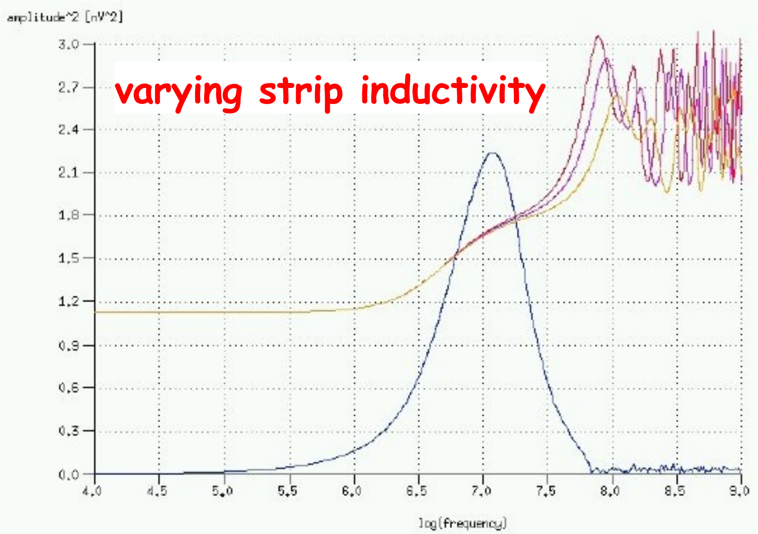
Signal at Beetle output:



Serial Noise

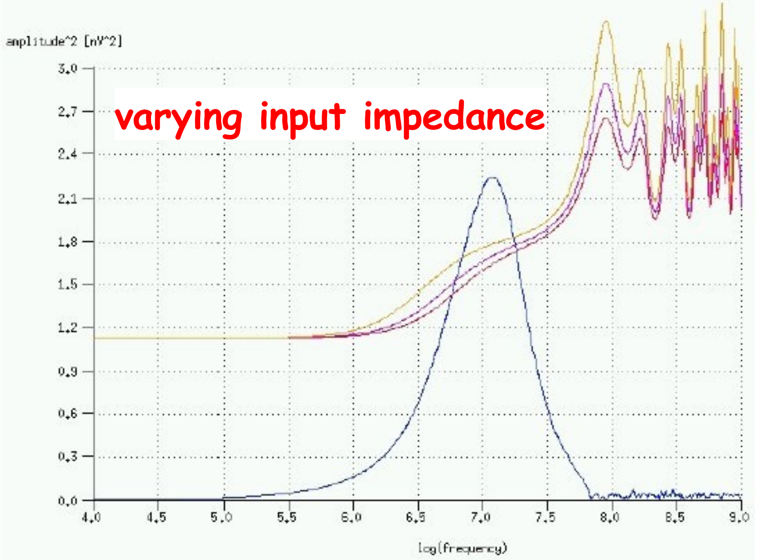
Noise spectrum from the same spice simulation:

- FET equivalent noise resistor (68 Ω)
  - "white" noise spectrum
- strip lines:
  - negligible noise at low frequencies
  - resonating behaviour above 100 MHz (lowest Eigenfrequency of the system)



Beetle frequency response spectrum:

- peaks around 10 MHz
  - in rising part of noise spectrum
  - sensitive to details of simulation
  - e.g. significant systematic effect from effective Beetle input impedance



Serial Noise

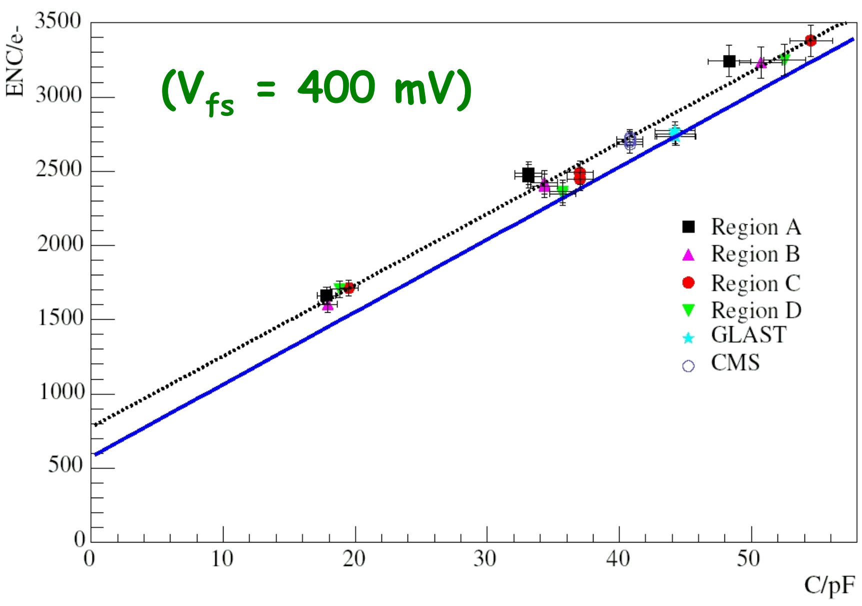
Convolution of squared noise spectrum and Beetle response spectrum

- for 3 x CMS + cable: 3800 e-
- discrete capacitance of 57 pF: 3300 e-

} ~ 15 % increase due to strip resistances

but: significant uncertainty on this result !!!!

Measured noise as a function of load capacitance:



- Test beam with long ladders:
  ENC = 770 e^- + 47.9 e^- / pF
- Test bench measurements with discrete load capacitances:
  ENC = 580 e^- + 48.8 e^- / pF
- good agreement of slopes, no indication for any effect from strip resistances

CCE Loss in Between Strips

Sum of the signals on four strips closest to particle impact point

- to avoid any possible bias due to clustering algorithms
- example: module of three CMS-OB2 sensors, V_{bias} = 450 V ($V_{fd} \approx$ 250 V)
- similar results for other testmodules / strip geometries
- relative CCE loss depends ~ linearly on the ratio (pitch-width) / thickness