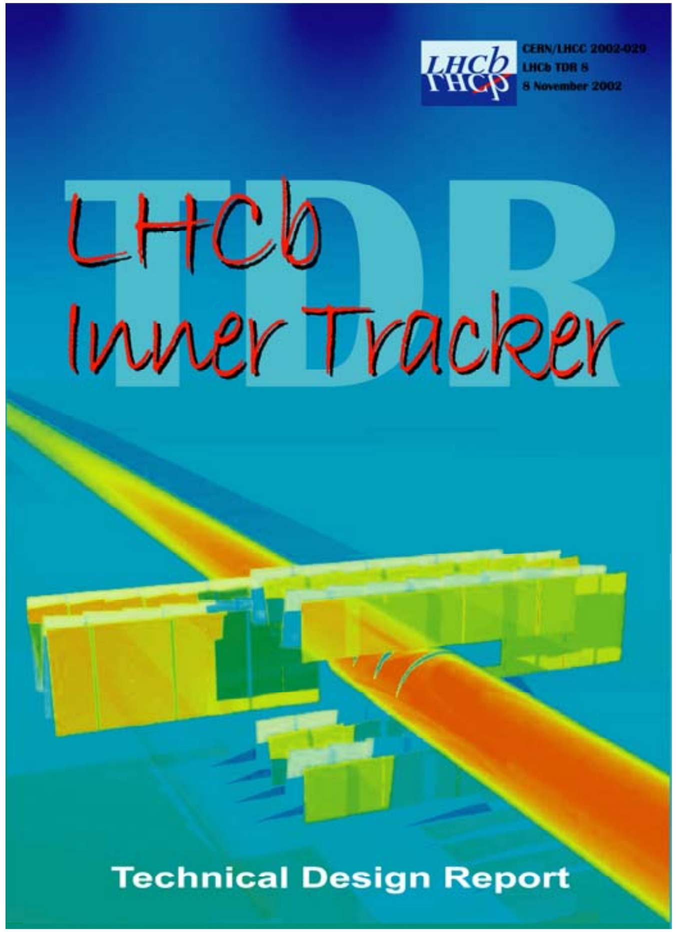
The LHCb Inner Tracker

Outline:
- Introduction
- Detector layout
- R&D
- Project organization

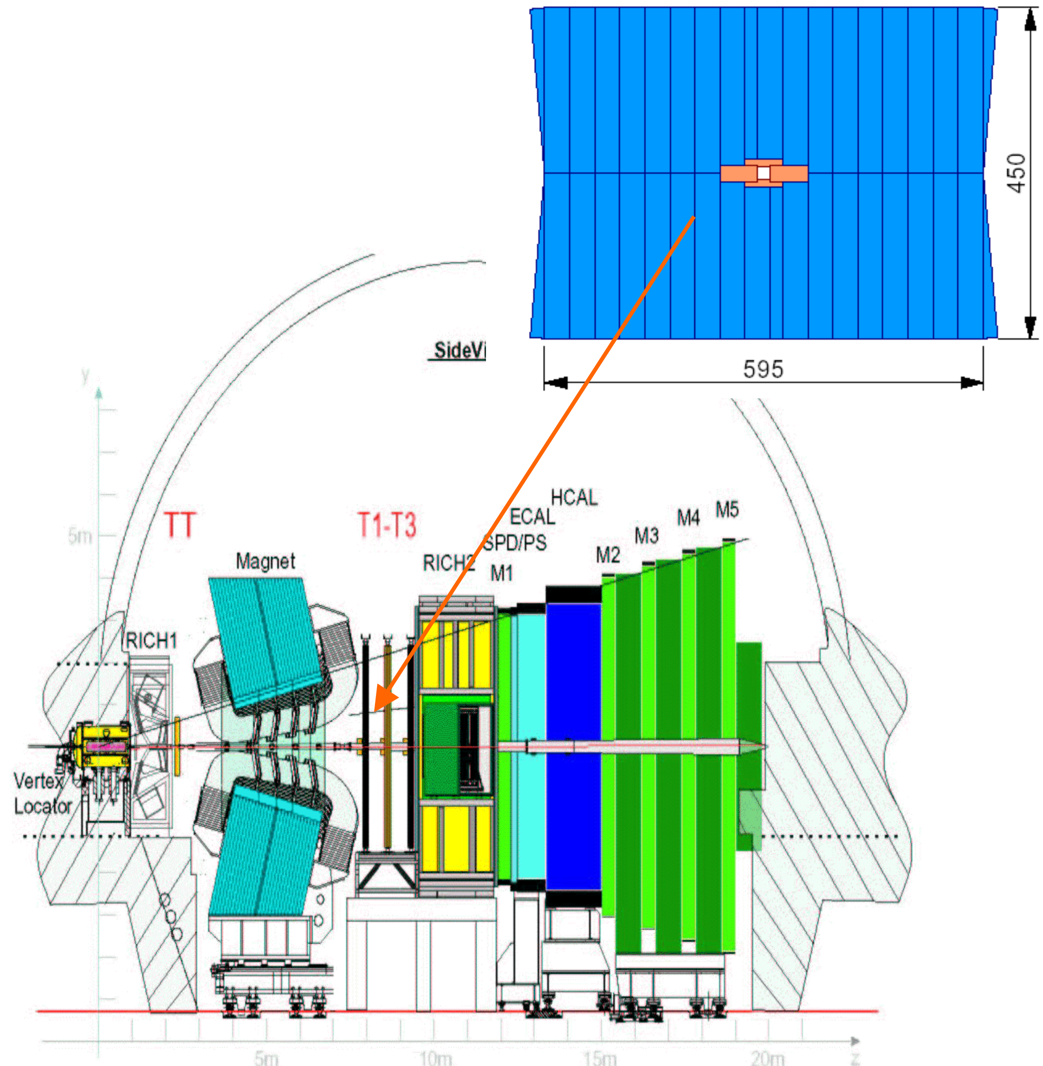


Frank Lehner
University of Zurich
on behalf of the
Silicon Tracker group
of LHCb

61st open LHCC session CERN Nov 27, 2002

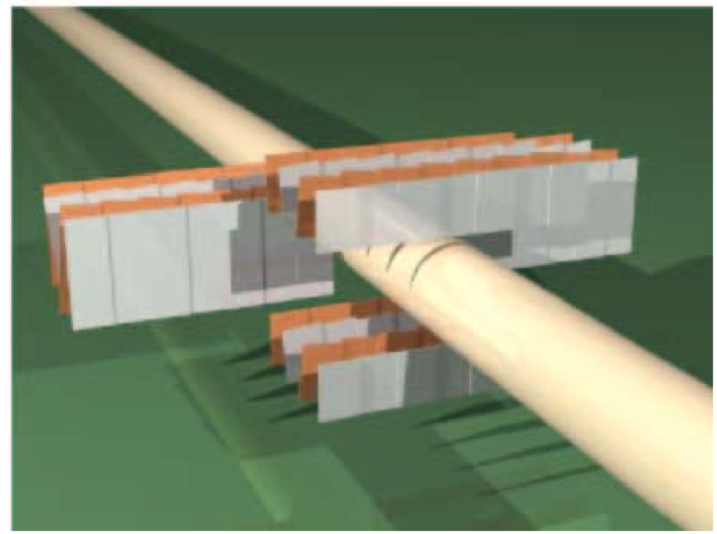
The LHCb Inner Tracker

- LHCb tracking stations behind dipole magnet
  - T1-T3
  - split between inner & outer part
- TDR describes the inner part of the 3 stations T1-T3
  - 'Inner Tracker'
  - 130k R/O channels
  - 4.2 m^2 silicon area
- in addition there is
  - large area station TT in front of dipole magnet
  - 170k R/O channels
  - 7 m^2 silicon area



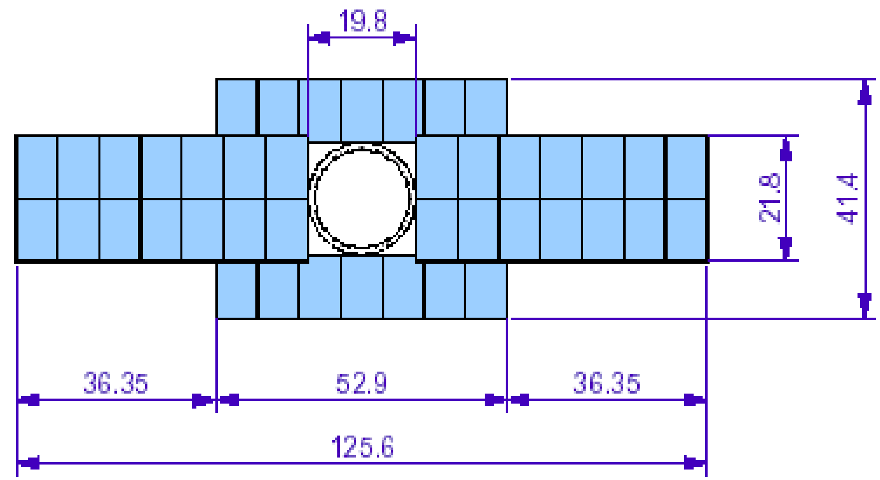
The LHCb Inner Tracker: Requirements

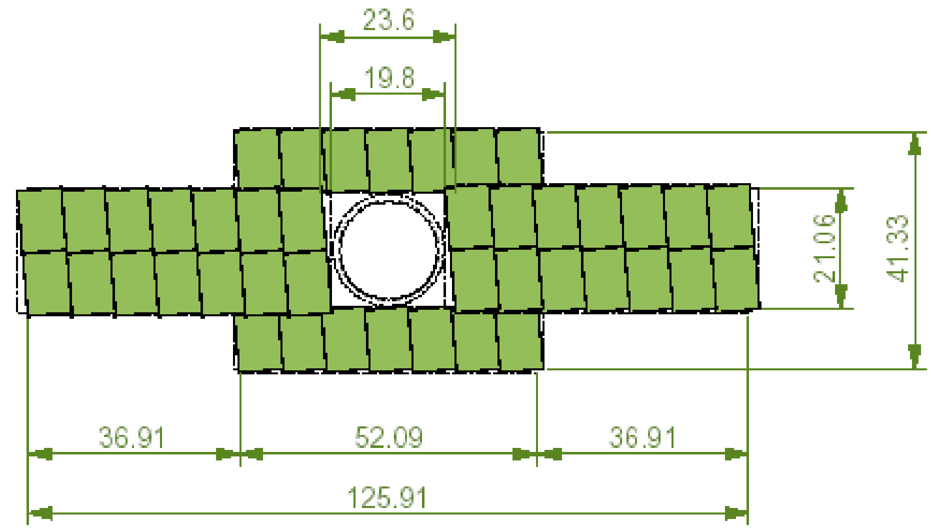
- provide reliable and robust tracking in charged particle environment w/ rates of up to ~10^5 cm^{-2}/s
  - achieve excellent momentum resolution of ~4‰
  - keep occupancies in Inner Tracker at tolerable level of few %
  - single hit resolution: ~70 μm
  - single hit efficiencies: close to 100%
  - minimize material
  - fast shaping (FWHM 35ns)



The LHCb Inner Tracker: Station layout

- three tracking stations along conical beampipe behind magnet
- Inner Tracker area
  - covers only 1.3% of sensitive overall tracker area
  - corresponds to 20% of all tracks within LHCb acceptance
- four detection layers each with small angle stereo-view: 0°, ±5°, 0°
- 11 cm & 22 cm long silicon ladders w/ pitch 198 μm
- conical beampipe => different layout in each station
- particle fluences higher in equatorial plane (bending plane of magnet)
- extend horizontal coverage of Inner Tracker
- accomplished by four independent boxes arranged in cross geometry

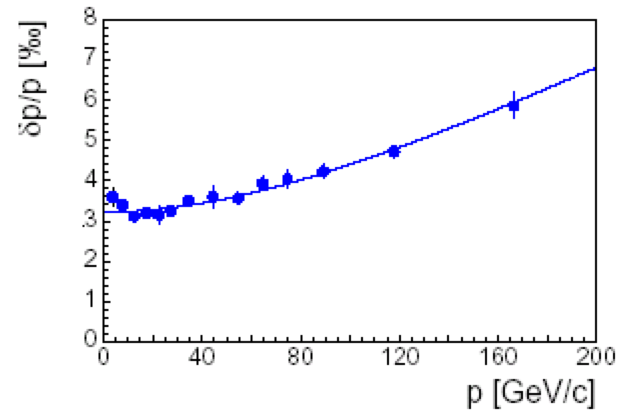


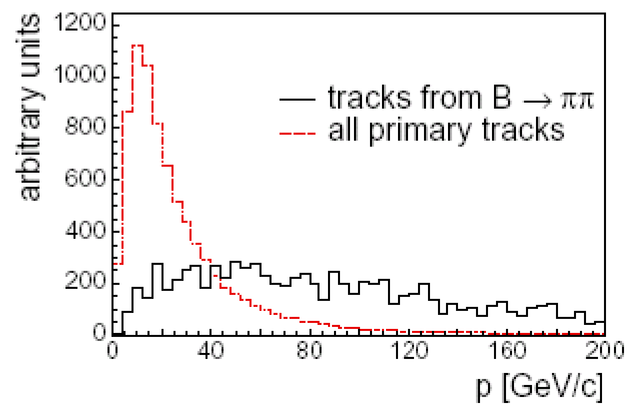


The LHCb Inner Tracker: MC Performance studies

- **GEANT detector simulation**
  - realistic description of active and inactive materials
  - silicon charge generation, collection & FE response tuned to lab and testbeam data
- **occupancies**
  - from B-> $\pi\pi$ studies at $L=2\cdot10^{32}\ cm^{-2}\ s^{-1}$
  - max 1.5% in left/right box of T1
- **material budget**
  - 2% for sensitive areas, 5% in hybrid region per station
  - averaged over detector acceptance:
    - ✓ 0.6% silicon & 0.8% 'dead' material per station
- **momentum resolution**
  - $(\delta p/p)^2 = A^2_{ms} + (B_{res} x p)^2$
  - dominated by multiple scattering up to p~100 GeV/c
- average momentum resolution does not improve by reducing pitch further

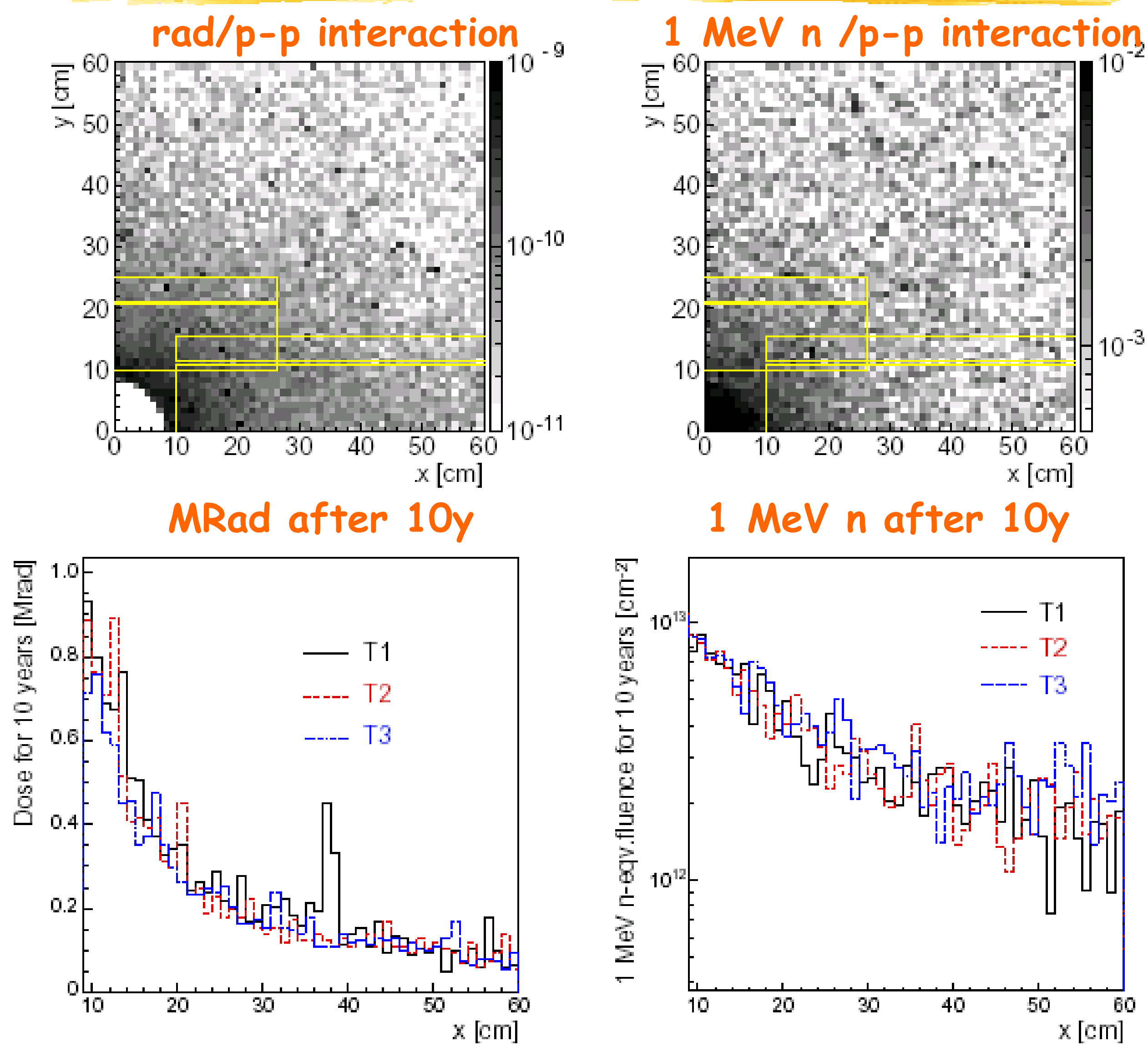
station	top/bottom		left/right	
	ave	max	ave	max
T1	0.26	0.41	0.65	1.5
T2	0.23	0.39	0.54	1.3
T3	0.20	0.26	0.51	1.2





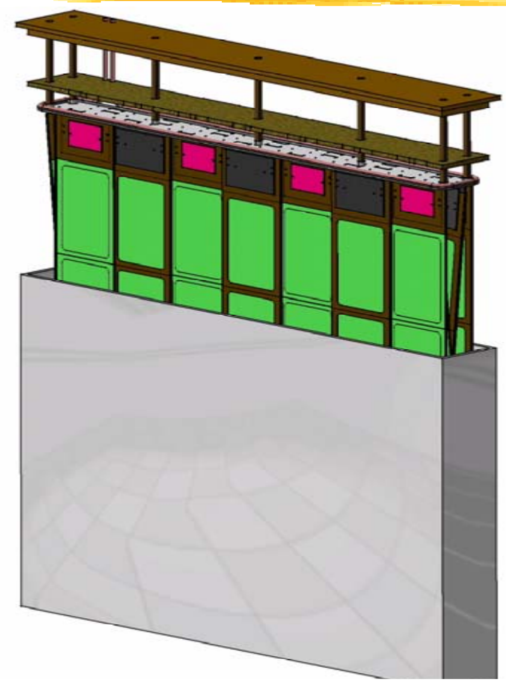
The LHCb Inner Tracker: Radiation environment

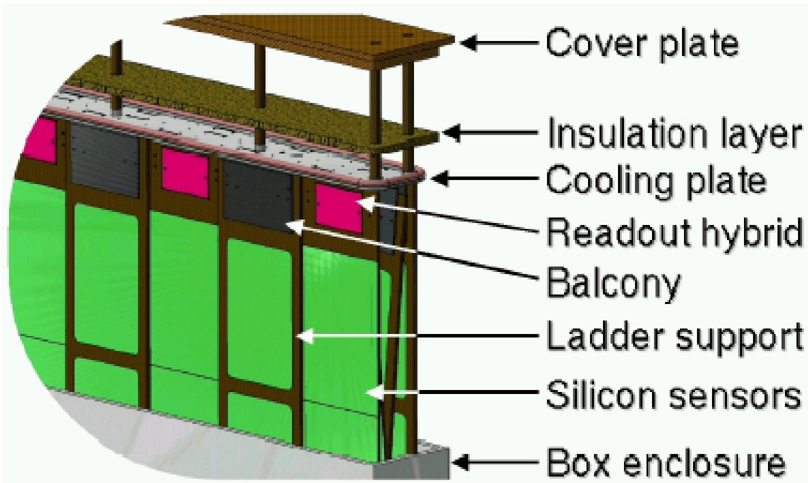
- **FLUKA** simulations for ionization deposition and NIEL damage
  - for hadrons, leptons & photons
  - assumed inelastic pp cross section 80mb
  - $1.6 \cdot 10^7$ p-p interactions/s
- no safety factor included
  - moderate radiation levels: up to 1 MRad (10y)
  - 10^{13} 1 MeV n cm^{-2} (10y)
- shot noise from leakage currents due to bulk damage (assume safety factor of 2)
  - S/N degradation is mitigated to < 10% over 10y of operation
  - if silicon kept at T=5°C



The LHCb Inner Tracker: detector box layout

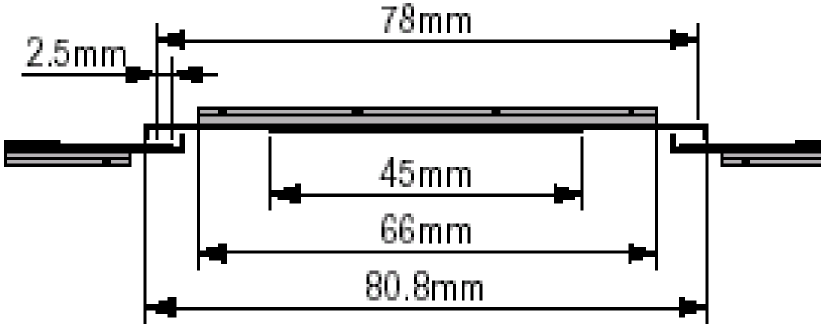
- each station has four independent boxes
  - modular design
  - stand-alone units in commissioning
- box houses 28 Si-ladders arranged in four detection planes
- ladder ends mounted to common cooling plate
  - circulation of coolant
  - common alignment reference
- cover plate provides mechanical rigidity, cable feed-through
- enclosure of lightweight insulation foam material + thin Al-foil
  - light tightness
  - thermal insulation
  - electrical shielding
- silicon sensors will be operated at ~5°C in dry (N_2) atmosphere

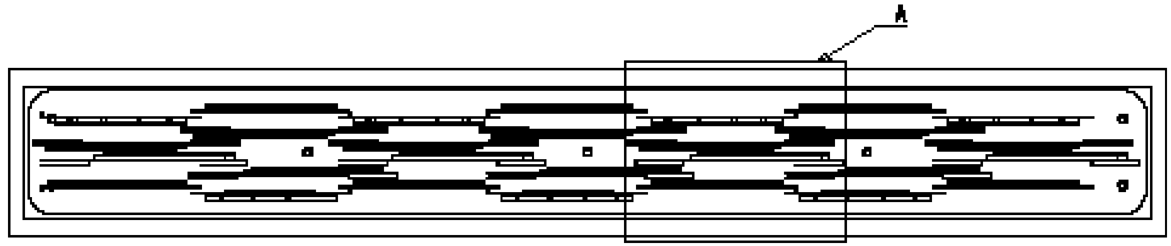


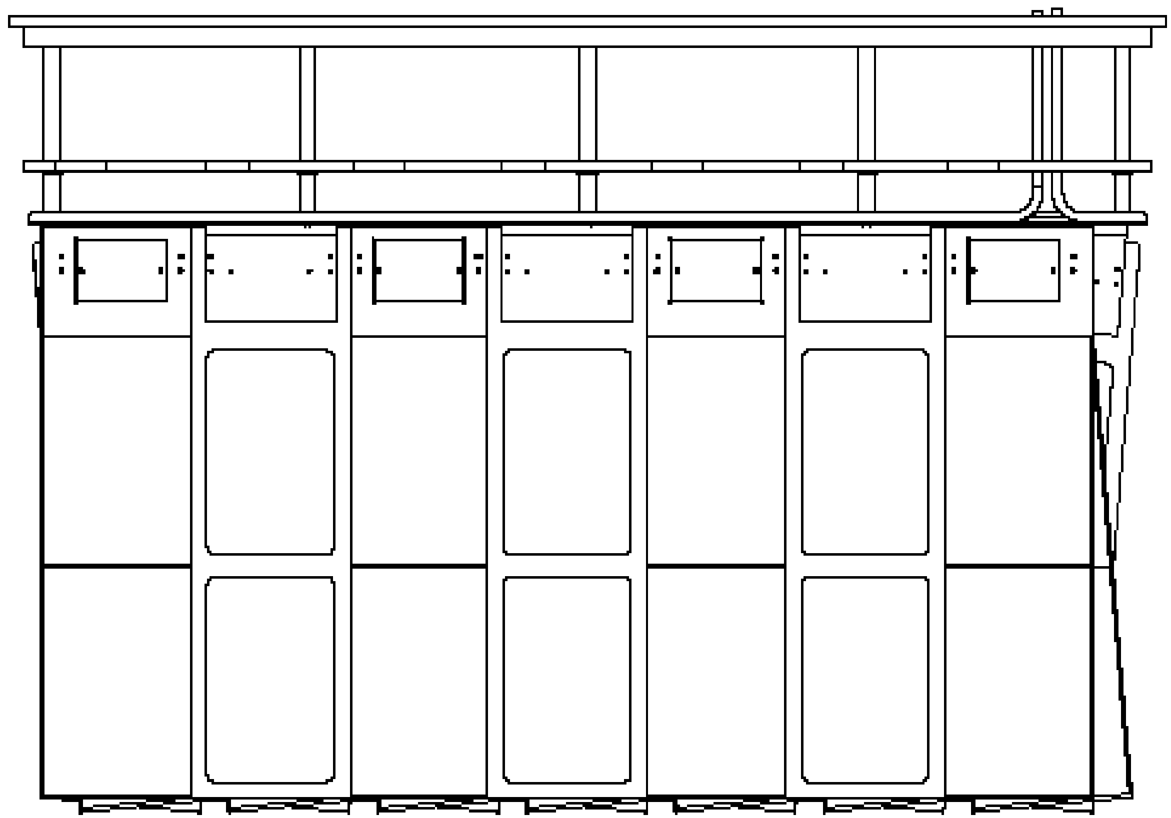


The LHCb Inner Tracker: detector station layout

- adjacent ladders within one detection plane are pairwise staggered
- ladder overlap 2.5 mm => redundant information for 2 strips on ladder
- orientation of adjacent ladders swapped => minimize z distance between staggered ladders

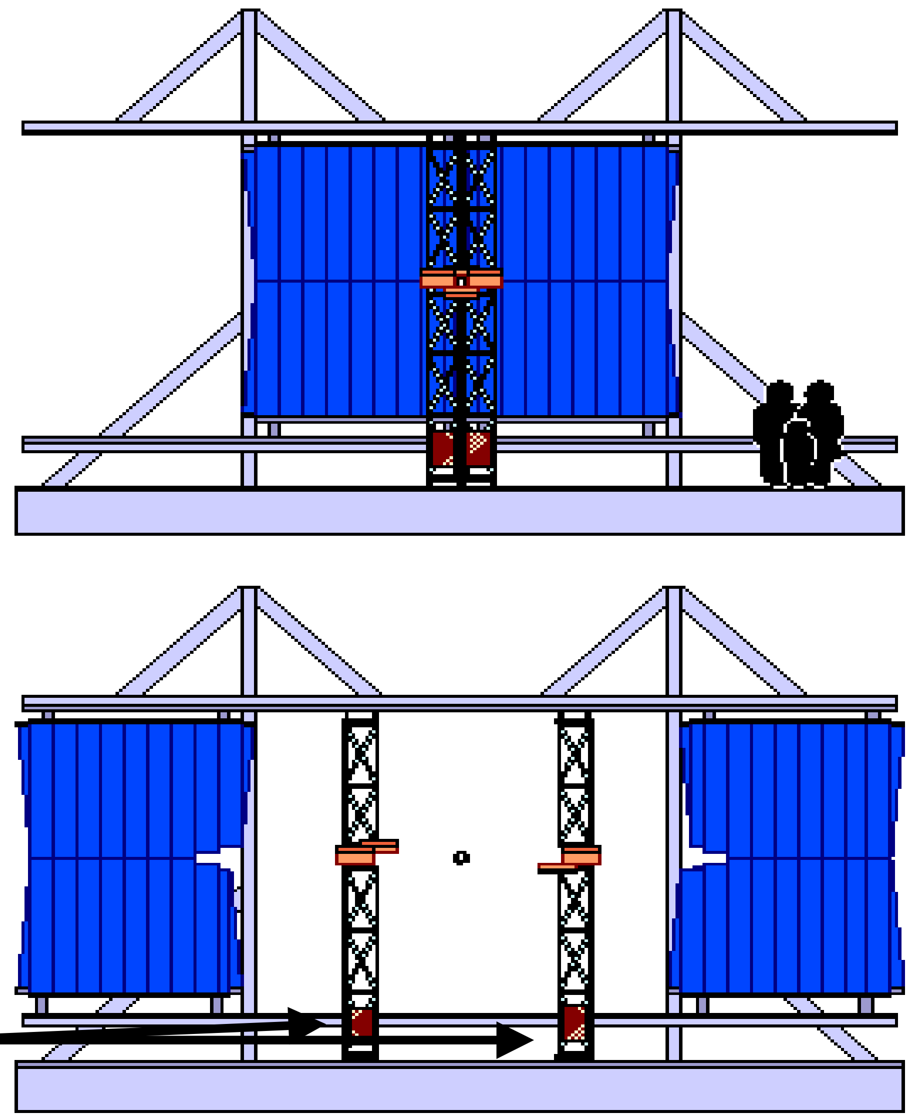






The LHCb Inner Tracker: Detector Design

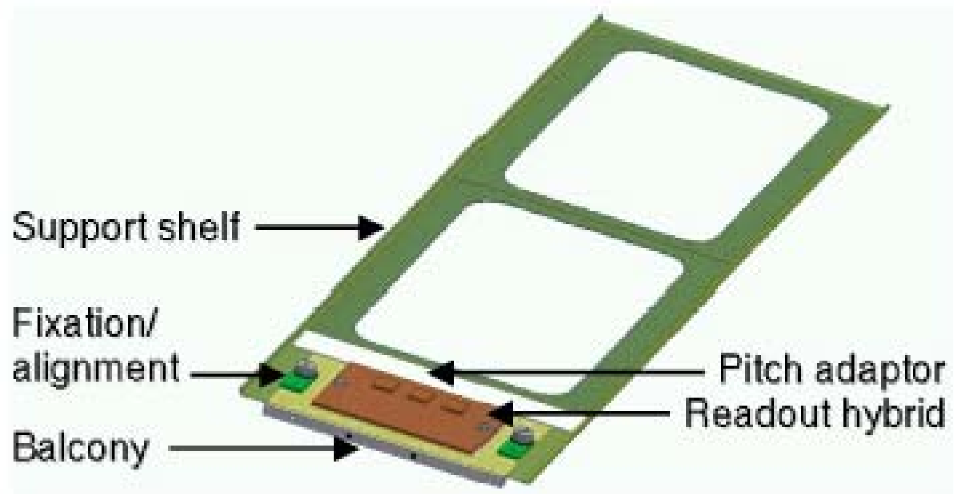
- independent support frame for Inner Tracker to allow independent movement for service and maintenance
- fixation of Inner Tracker to individual Outer Tracker rails
- part of R/O & service electronics located in service boxes outside acceptance

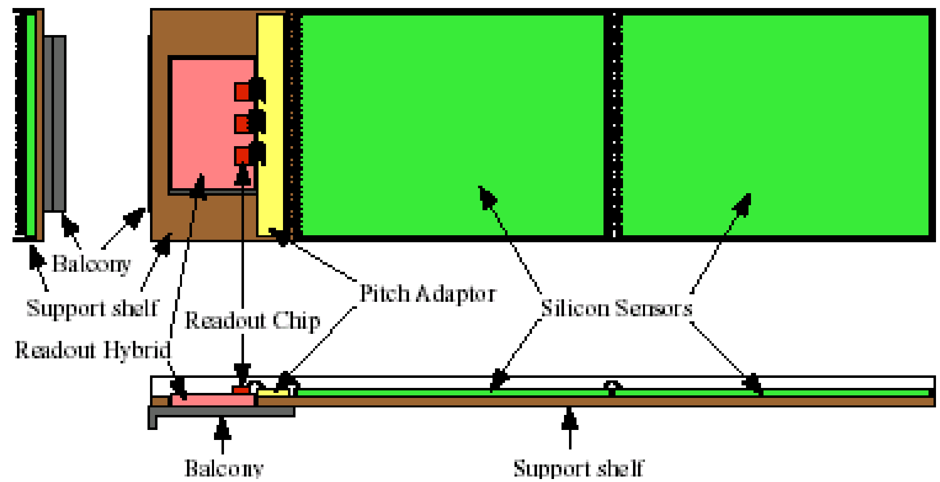


Service boxes

The LHCb Inner Tracker: ladder layout

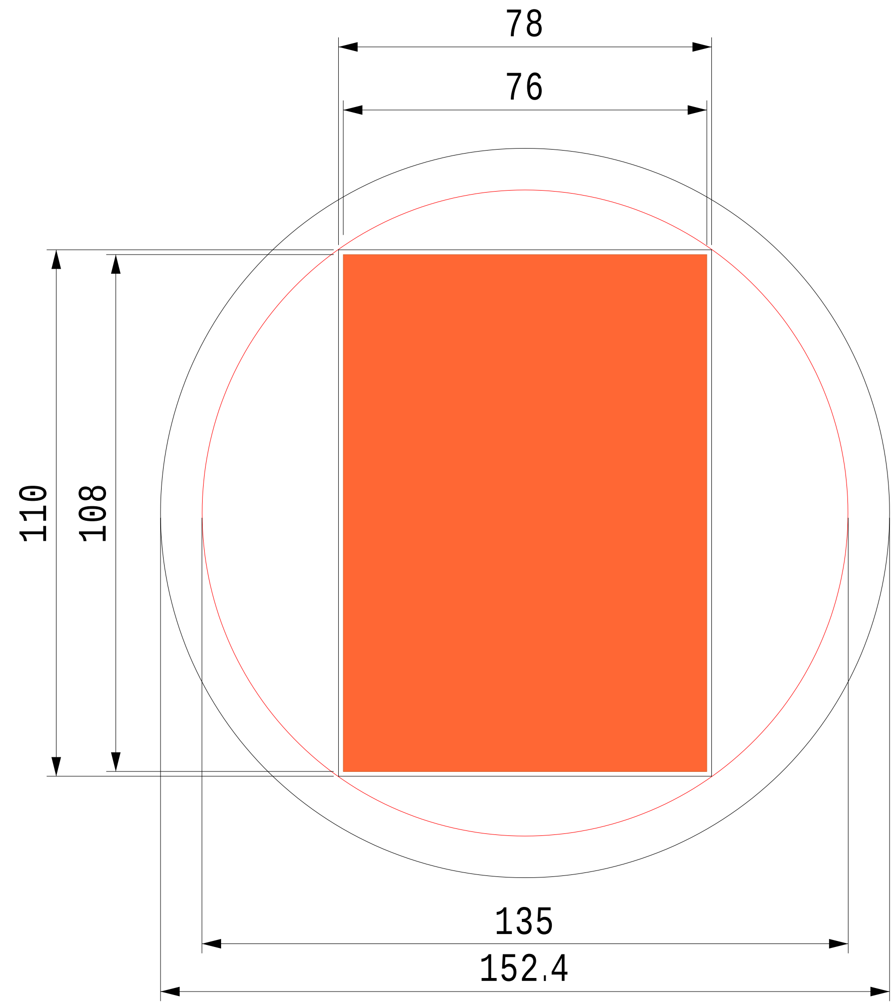
- single sensor and two sensor ladders
  - two sensors aligned head-to-head
- sensor support
  - U-shaped carbon fiber composite shelf with high thermal conductivity
- ceramic substrate piece at ladder end
  - Kapton based printed circuit
  - three readout chips per ladder
- cooling balcony
  - provide precision holes and guide pins to mount carbon fiber support
  - cooling balcony in direct contact with carbon support and ceramic for effective cooling
  - thermal decoupling between sensor & hybrid





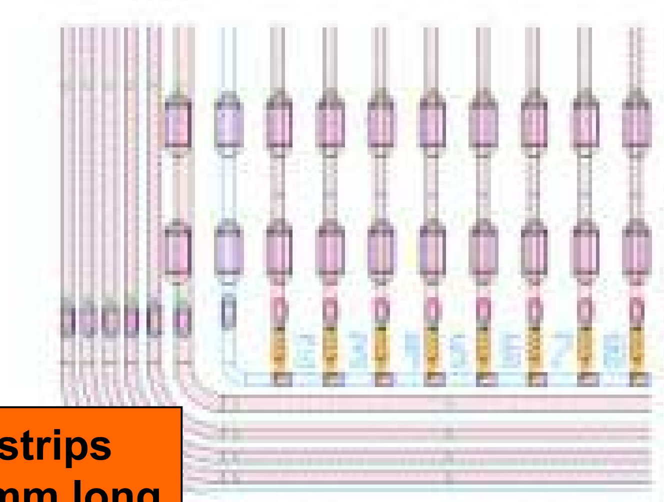
The LHCb Inner Tracker: silicon sensor layout

- employ 6"-wafers with p^+n strip technology
  - one sensor type only
- physical dimensions
  - 110 x 78 mm^2
  - thickness 320 μm
  - 1 mm dead area due to guard ring & HV protection
- single sided only
  - robust and simple design
  - high yield, low number of dead channels
- pitch 198 μm
  - number of strips: 384
  - matching FE chip granularity



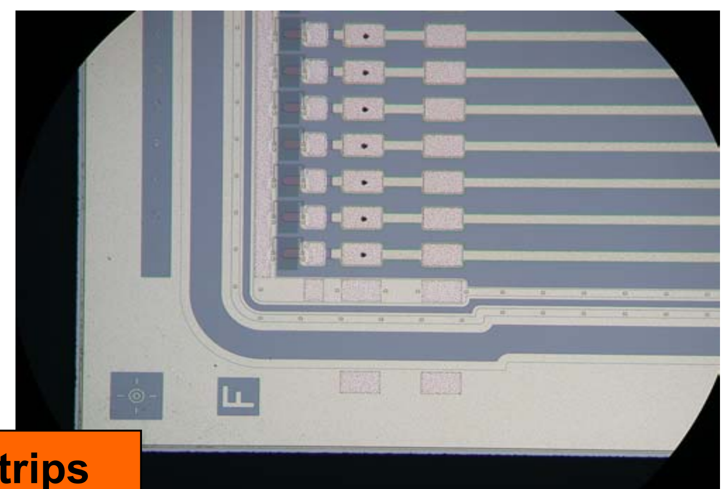
The LHCb Inner Tracker: silicon sensor R&D

- SPA (Kiev) prototype sensors:
  - 4"-wafer, 240 μm pitch
  - w/p = 0.2 - 0.3
  - multi-guard ring structure



64 strips
66.6 mm long

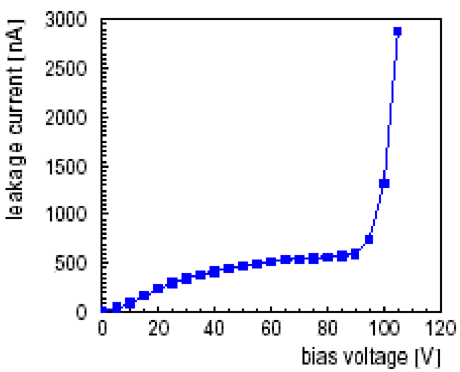
- Hamamatsu prototype sensors:
  - 6"-wafer, 'full-size' sensor: 198 & 237.5 μm pitch
  - w/p = 0.25 - 0.35
  - single guard ring design

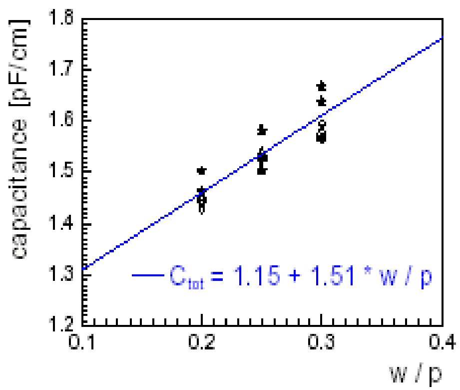


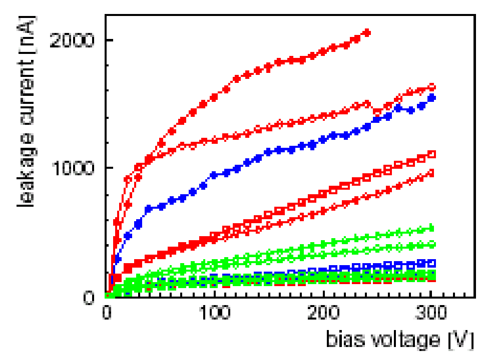
352 strips
108 mm long

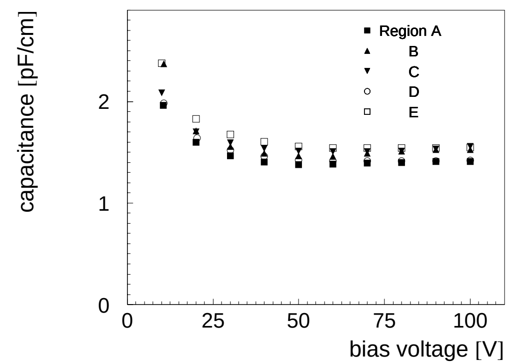
The LHCb Inner Tracker: silicon sensor R&D

- SPA:
  - characterized in lab & testbeam
  - depletion voltage: ~50-70V
  - total strip capacitances: 1.4-1.6 pF/cm
  - capacitances increase towards larger w/p
  - early junction breakdown at ~100V
- Hamamatsu:
  - characterized in lab & testbeam
  - depletion voltage ~70V
  - similar strip capacitances than SPA (C_{tot}=1.02+1.66·w/p)
  - high breakdown voltage, low currents <2 μA up to 300V



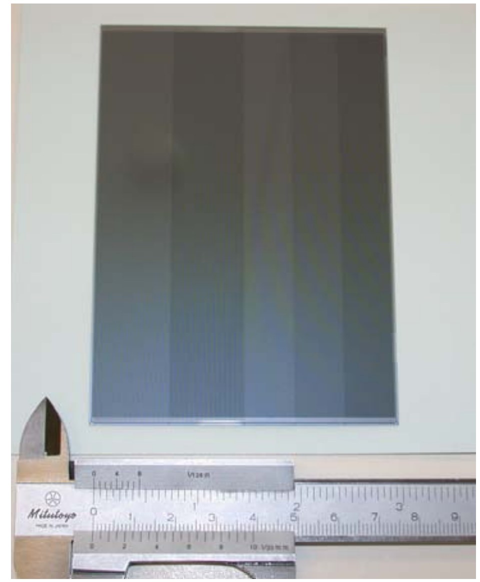


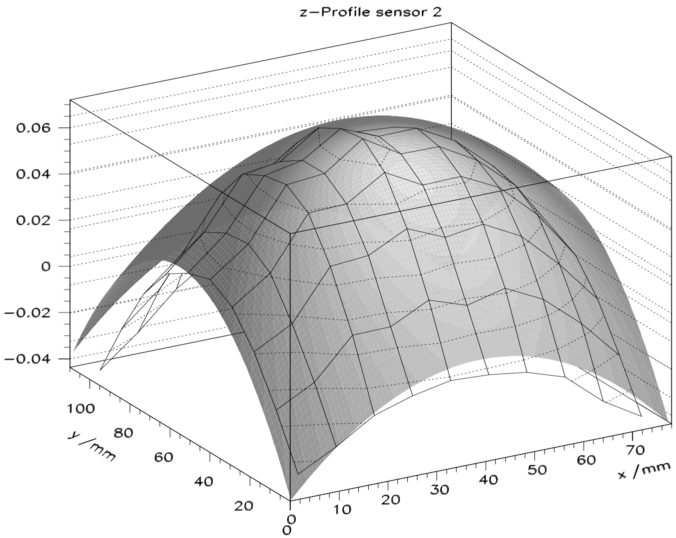


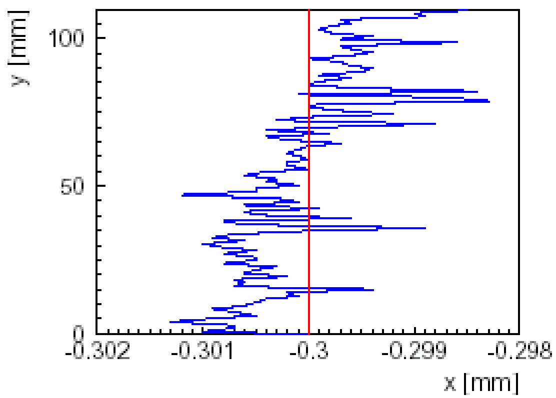


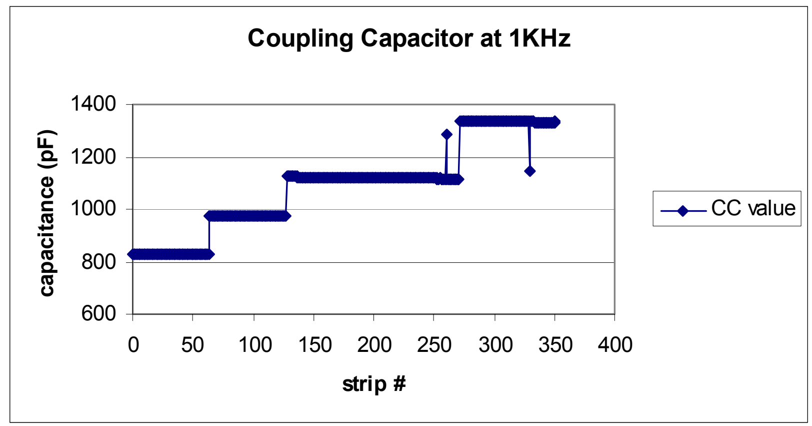
The LHCb Inner Tracker: silicon sensor R&D

- automatic probe station measurements for coupling capacitors integrity and pinholes
  - low number of dead strips < 1%
- metrology measurement
  - sensor warp < ±50 μm
  - dicing line accurate within 3μm
  - important for assembly procedure



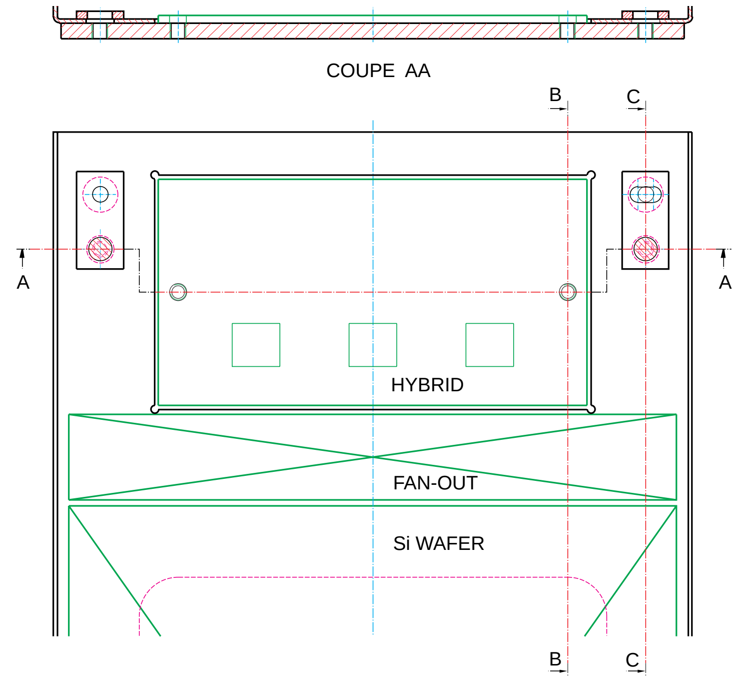


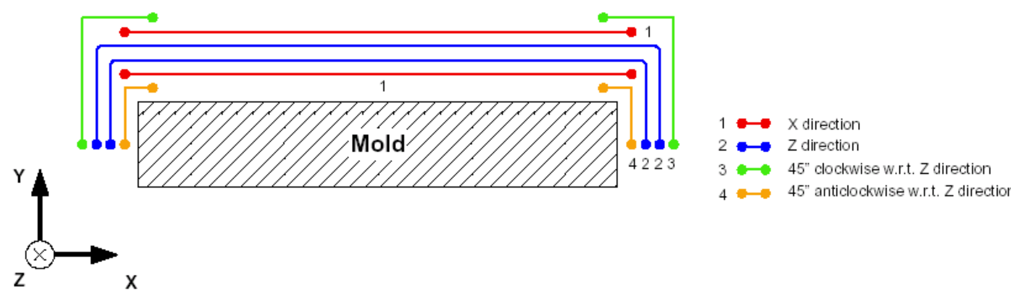




The LHCb Inner Tracker: ladder support R&D

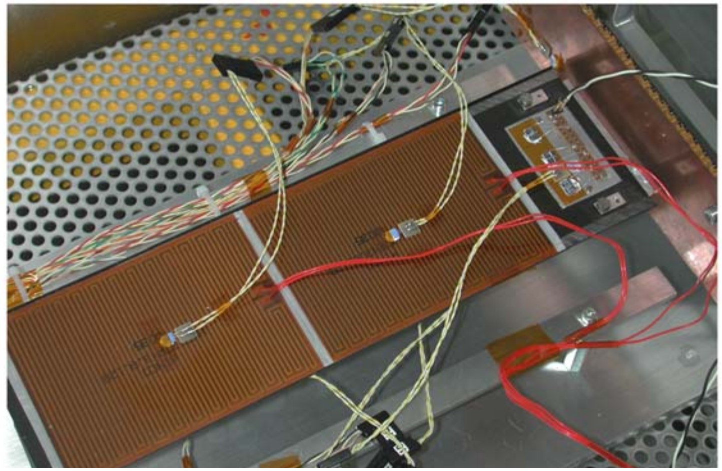
- ladder support requirements:
  - alignment <10μm, flat within ±50 μm
  - thermal conductivity >150 W/mK (suggested by FEA)
  - mechanical stiffness
  - high radiation length
- use carbon fiber composite
  - engineering & prototyping done at company in Lausanne
  - 4 layer composite with fibers running in different directions
  - first prototype batches from Amoco K1100 and Mitsubishi K13C2U composites produced
- last delivered batch of ladder supports show satisfactory flatness

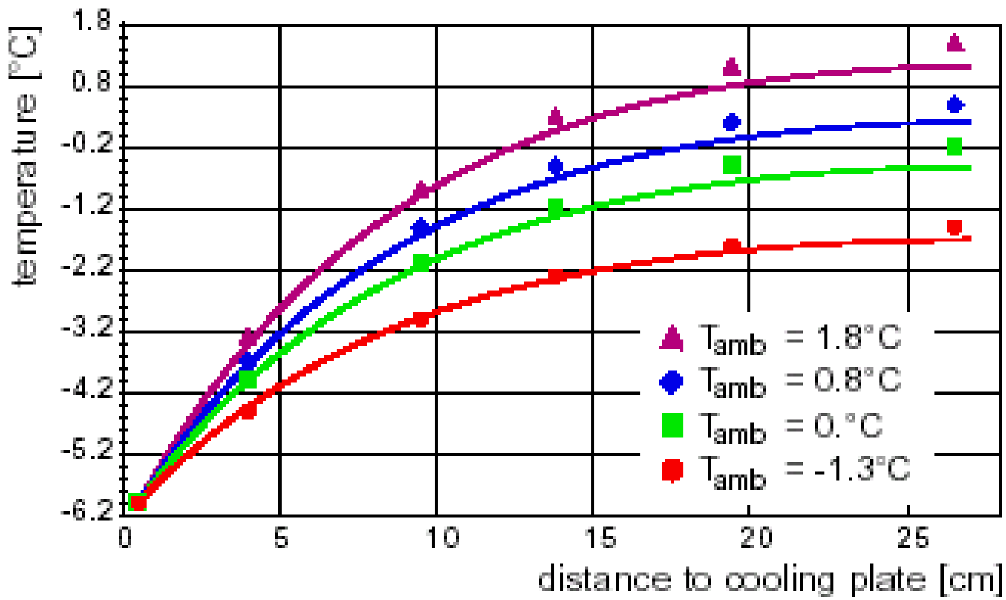




The LHCb Inner Tracker: ladder support R&D

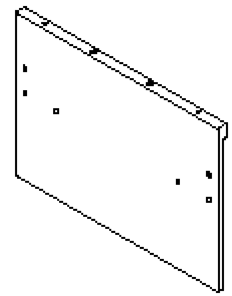
- ladder mock up to study thermal properties of carbon composite & contact joints to balcony
  - hybrid and silicon power dissipation simulated with Kapton heaters
  - ladder cooled through balcony
  - thermal probes to measure temperature distribution along carbon fiber support
  - measured λ~200 W/mK
  - good agreement to FEA

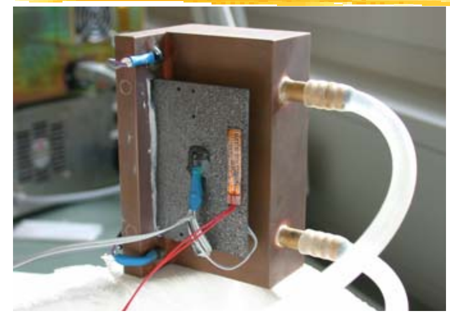


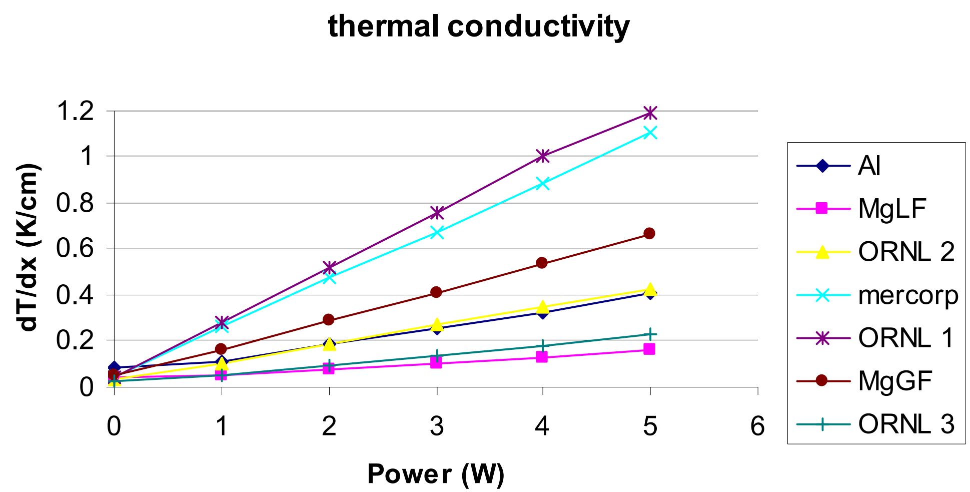


The LHCb Inner Tracker: balconies and material R&D

- cooling balconies (66 x 46 mm)
  - mounting & aligning of ladder CF composite support to cooling plate
  - precise within 5 μm, excellent machining required
  - high thermal conductivity
  - high radiation length
- extensive R&D on lightweight materials with high thermal conductivity:
  - MMC carbon fibers infiltrated with magnesium (X_0~17cm, λ~420 W/mK)
  - high density graphitic foams (X_0 up to 28 cm, λ up to 250 W/mK)
  - carbon-carbon composites
  - performed thermal and mechanical characterizations

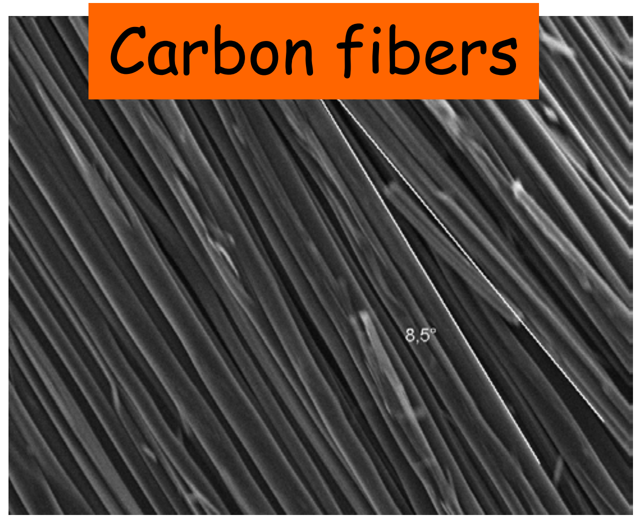


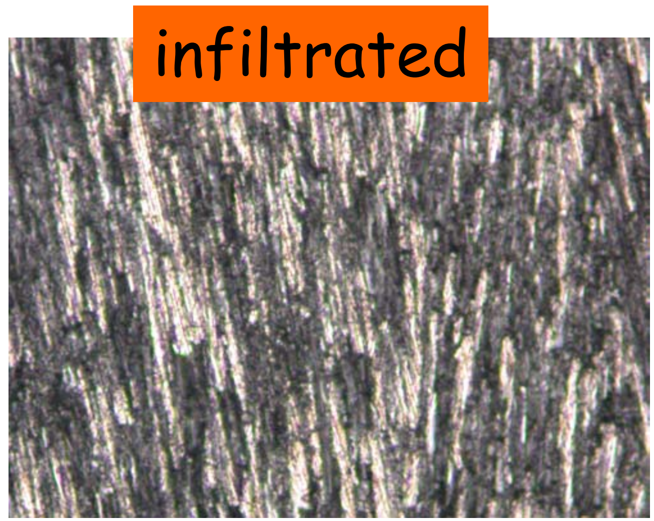




The LHCb Inner Tracker: material R&D

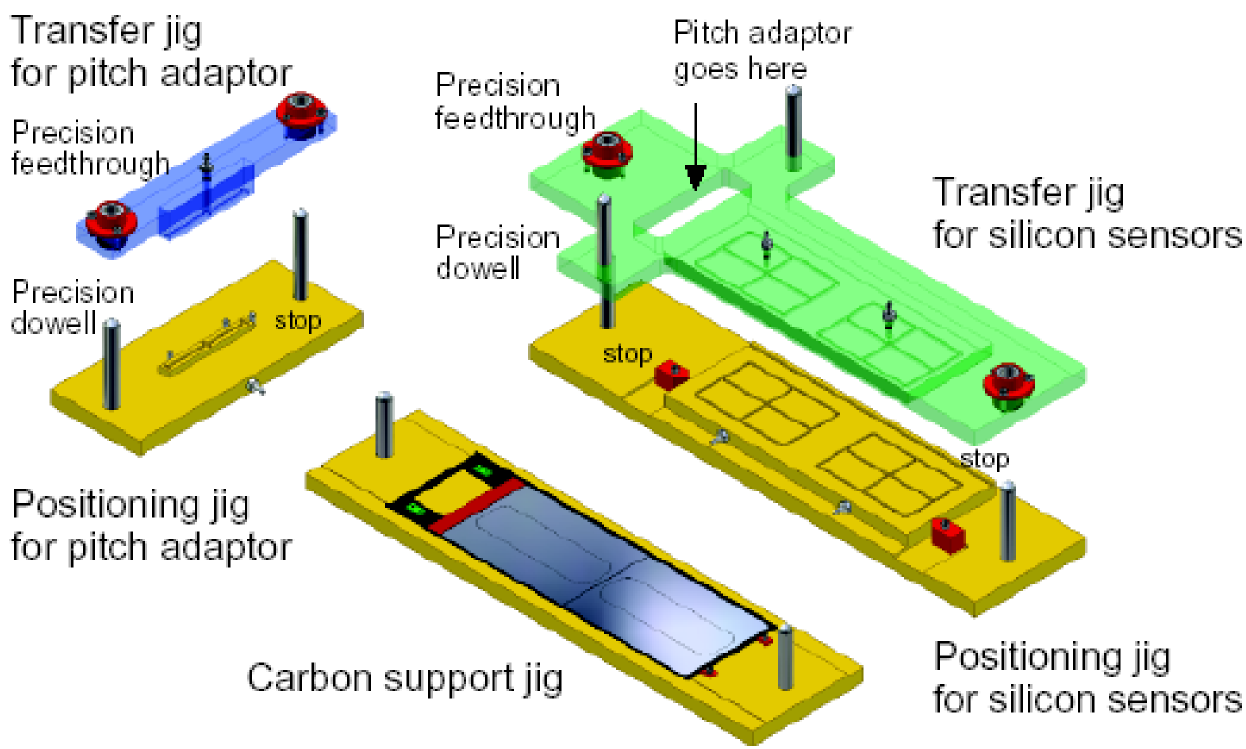
- balcony material option:
  - long (continuous) carbon fibers infiltrated with high purity magnesium alloy (Mg 91%, Al 9%)
  - developed together in collaboration with Swiss federal material R&D institute EMPA (Thun)
  - density ~ 2 g/cm^3, X_0~17cm (2x Aluminum)
  - thermal conductivity ~400 W/mK (> 2x Aluminum)
  - stiff and high E-modulus > 400 GPa
  - precise in-house machining of threads & holes possible for alignment features





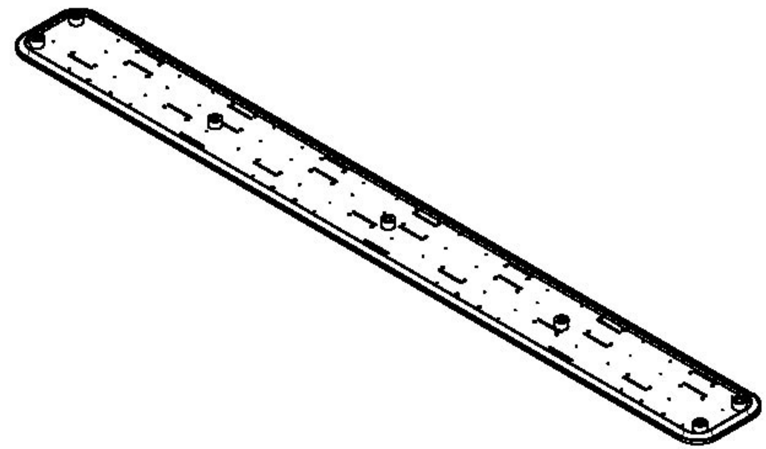
The LHCb Inner Tracker: Ladder assembly

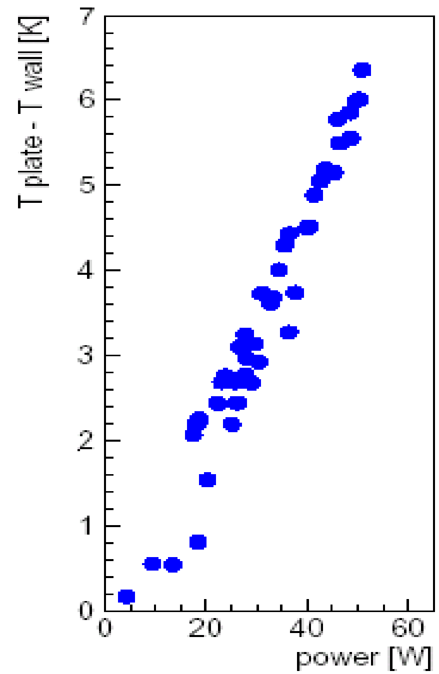
- total number of Inner Tracker ladders to be produced:
  - 336 + 15% spares
- ladder assembly
  - exploit accurate sensor dicing line for aligning
  - vacuum fixtures & jigs designed with guide pins for alignment transfer
  - optical metrology for precision control

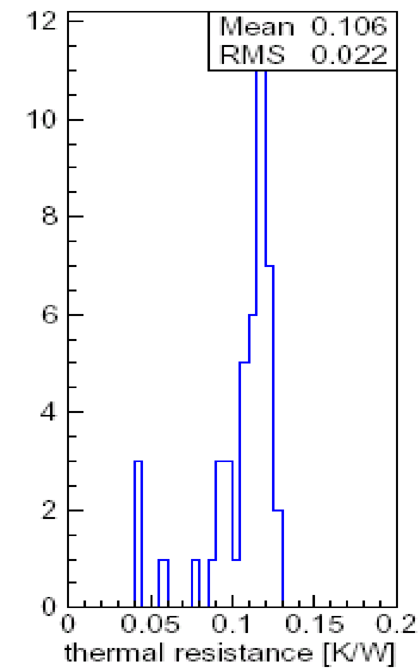


The LHCb Inner Tracker: cooling plate R&D

- cooling plate (560 x 55 mm)
  - provides mounting surface for all ladders within one box
  - align ladders to 10 μm by guide pins, flatness within 100 μm
  - embedded cooling pipe (OD 5mm) to circulate liquid C_6F_{14} at T=-15°C as coolant
  - design goal: keep ambient temperature in box at T~5°C
  - 1st prototype plate built out of 1.5 mm thick Al
  - measured thermal resistance 0.11 K/W ⇔ 8°C temperature drop for expected 75W power dissipation within one box



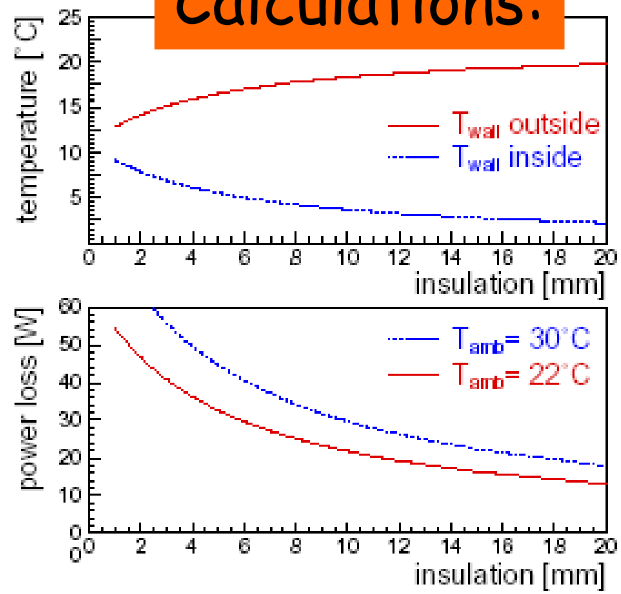




The LHCb Inner Tracker: detector box R&D

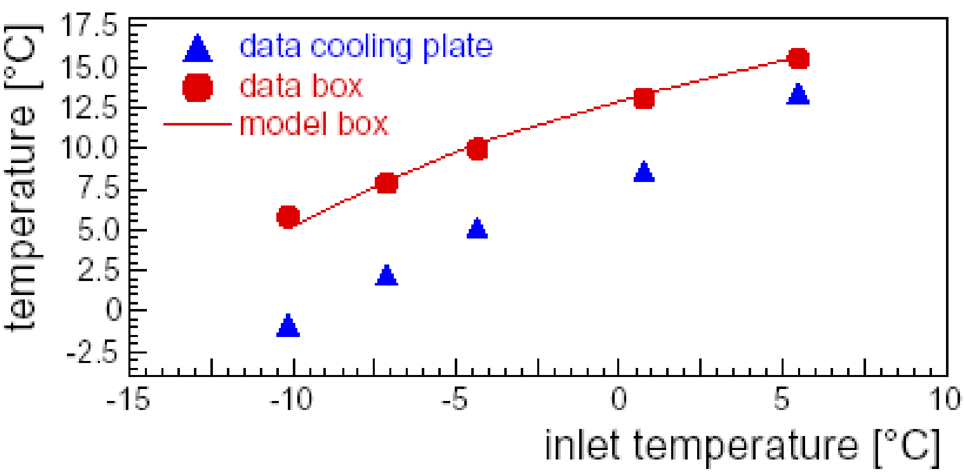
- box enclosure requirements
  - low density foam material
  - excellent thermal insulation
  - vapor barrier
  - compressive strength
  - electrical shielding
- use PUR foam material as core
  - stiffened with 100 μm Kevlar tape
  - 25 μm aluminum cladding inside and outside
  - wall thickness ~6mm, driven by thermal insulation loss to outside world and dew point considerations
- two box prototypes built

Calculations:



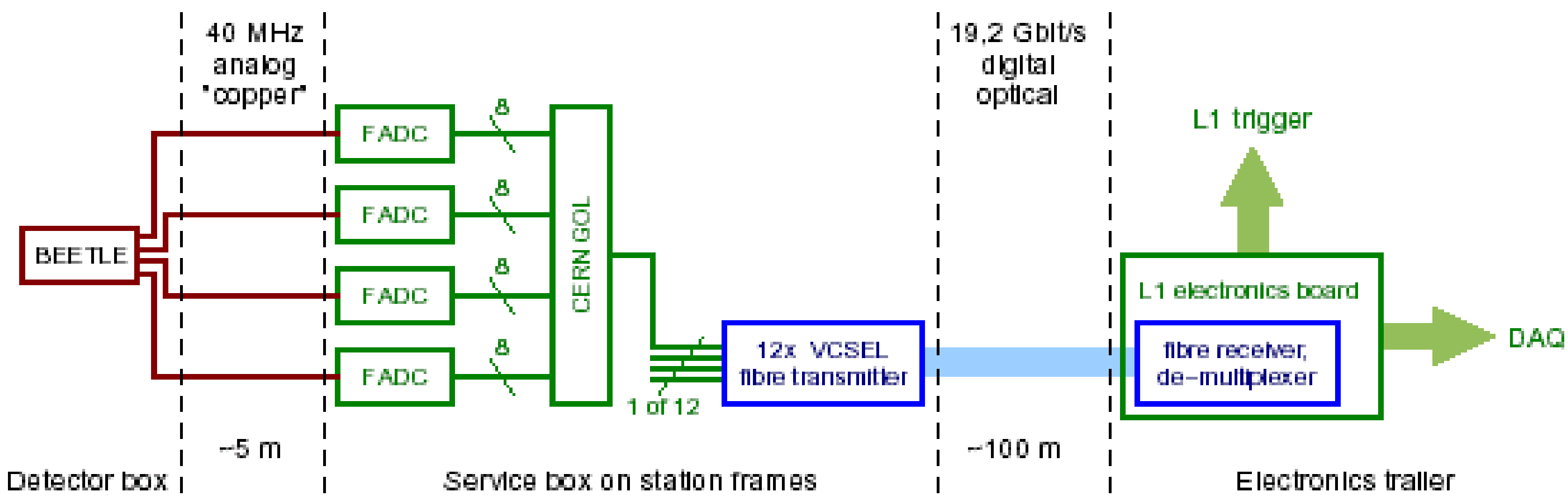
The LHCb Inner Tracker: detector box R&D

- **detector box cooling test**
  - several ladder mock-ups w/ Kapton heaters
  - apply full heat load as expected from FE chips
  - circulate C_6F_{14} at different temperatures
    - ✓ optimize mass/volume flow
    - ✓ understand heat transfer coefficients
  - measured data are well described by heat transfer
  - additional convective effects due to 'cold' ladder surfaces



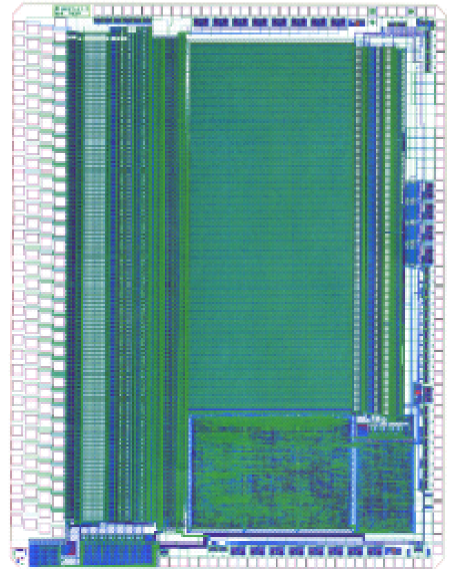
The LHCb Inner Tracker: R/O electronics layout

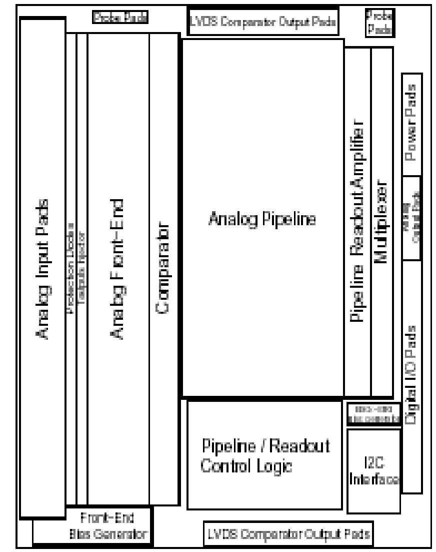
- **Beetle FE chip**
  - designed to LHCb specs
  - Radiation hard 0.25 μm CMOS
  - 4 analog output stages 32x multiplexed
- **Digitization**
  - FADC in service box outside tracking volume
  - 8-bit resolution
- **Data link**
  - serialization GOL chip 32-bit wide
  - digital-optical link over 100m
  - commercial VCSEL & optical fibers
- **L1 electronics**
  - common development for several LHCb subdetectors
  - in electronics hut
  - interface to L1 trigger and DAQ

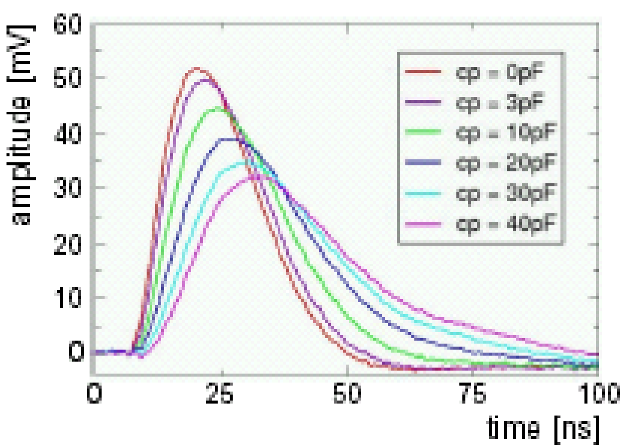


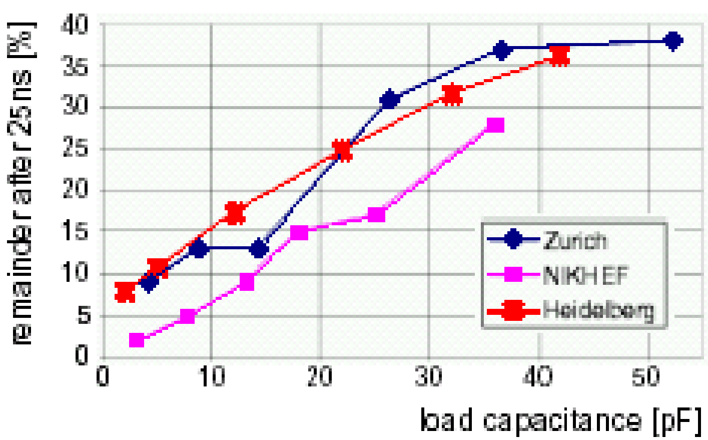
The LHCb Inner Tracker: Beetle chip

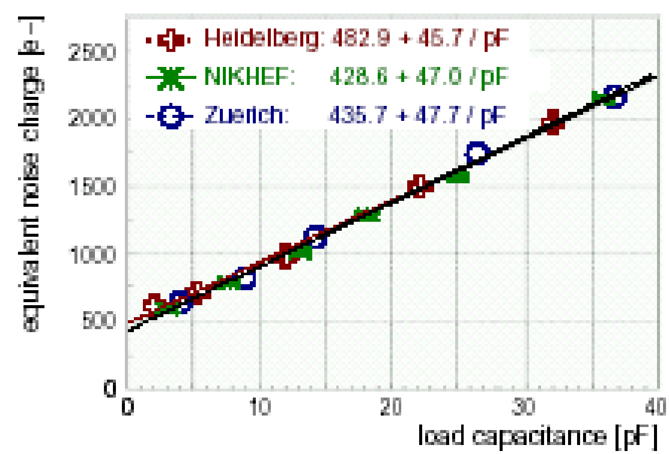
- 0.25 μm CMOS, 40MHz clock
- 128 channel preamplifier w/ 160 BC deep pipeline
- 32x multiplexed analog output for fast readout within 900ns
- Beetle 1.1 irradiated up to 45MRad (!),
  - fully functional,
  - no significant degradation observed
- most recent version Beetle 1.2:
  - SEU redundant logic
  - noise: 450e + 47e × C[pF]
  - remaining signal after 25 ns: ~30%





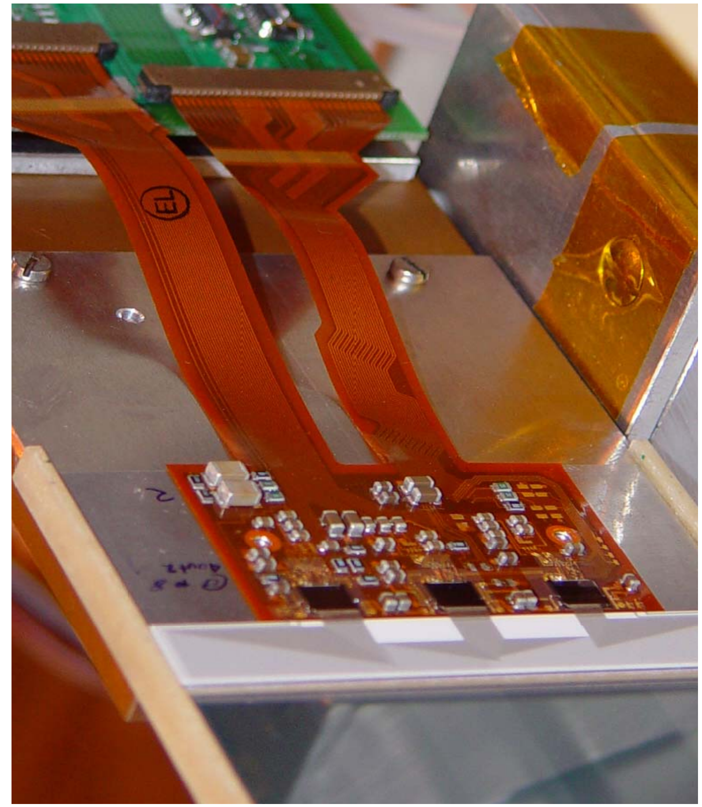


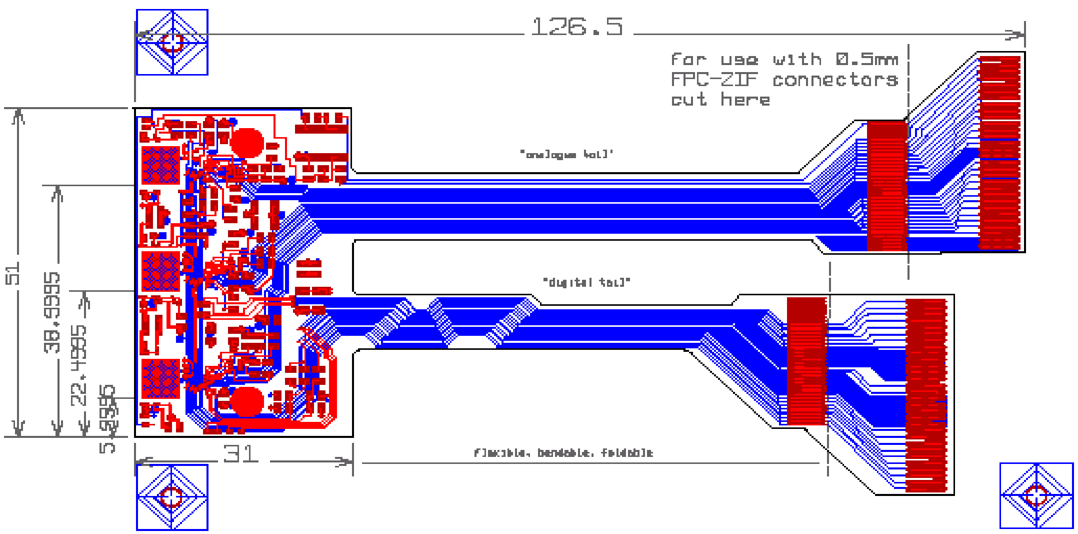




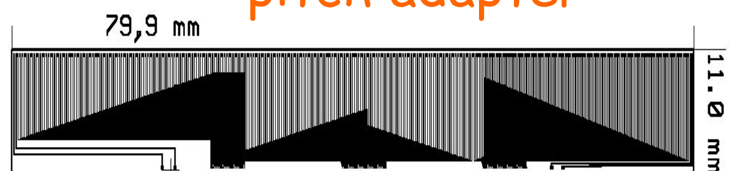
The LHCb Inner Tracker: hybrid

- 4 layer kapton flex circuit laminated to ceramic (AlN) substrate carrying 3 FE chips
- avoid crossing of analog and digital signals
- two separate 95 mm long flexible tails for analog & digital lines
  - allows routing through cooling plate
- pitch adapter to match 198μm wide pitch of sensors to 40μm pitch FE-Beetle bonding pad



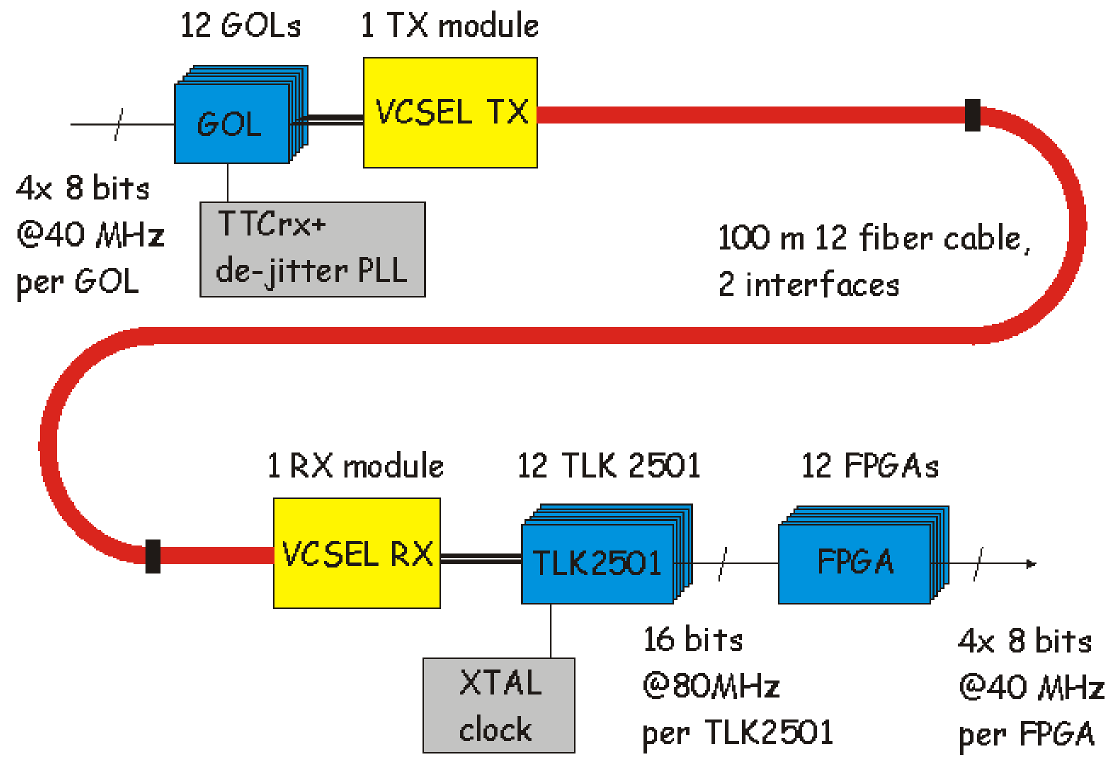


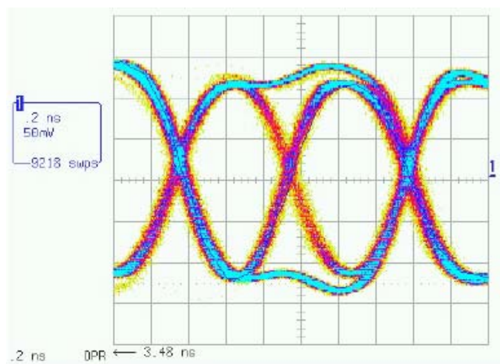
pitch adapter

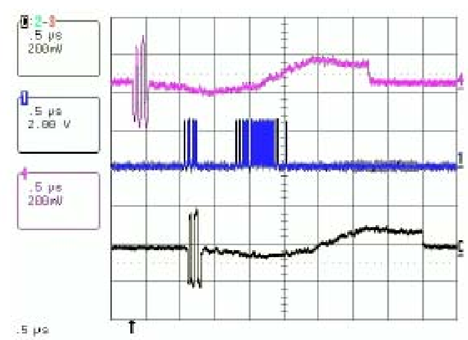


The LHCb Inner Tracker: R/O chain

- CERN GOL capable of serializing 32-bit wide date at 40MHz
- 1.6 Gbit/s optical link over 100m to L1 electronics in hut
- one digital optical link:
  12 x 4 x 8 bits =
  48 analog channels (4 hybrids)
- will use COTS devices wherever possible
  - optical transmitter modules w/ VCSEL diodes
  - optical fiber ribbon cable
- prototype link operating in lab
  - characteristic eye pattern at receiving end

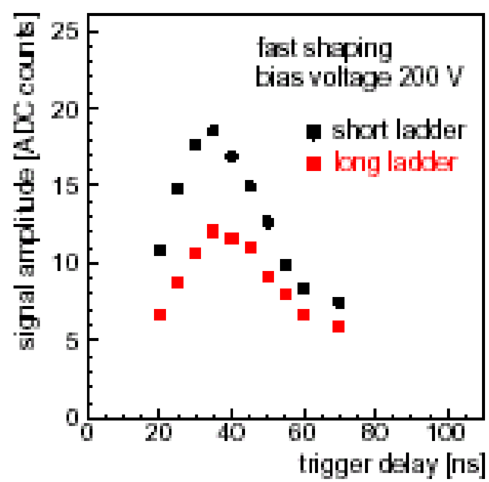






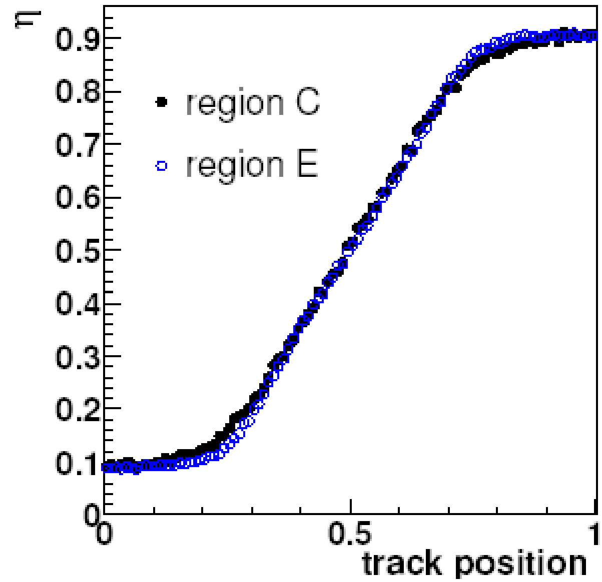
The LHCb Inner Tracker: CERN testbeam

- May/June 2002 testbeam at CERN X7
  - Hamamatsu 'full-size' sensors
    - ✓ 5 regions A-E with pitch 198 & 237.5 μm and different w/p
  - Beetle v1.1 R/O chip + hybrid
  - HERA-B silicon telescope + VDS DAQ
  - short ladder: 11cm strips, long ladder: 22cm strips
  - fast and slow shaping (~35 ns & 70 ns FWHM resp.)

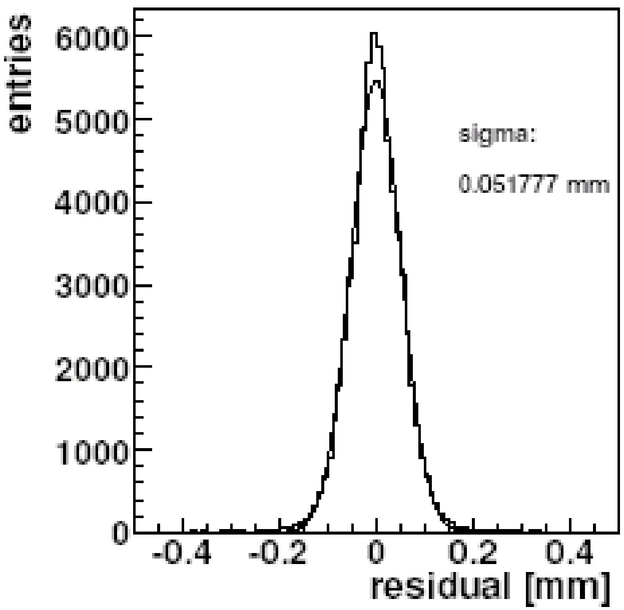


The LHCb Inner Tracker: CERN testbeam cont'd

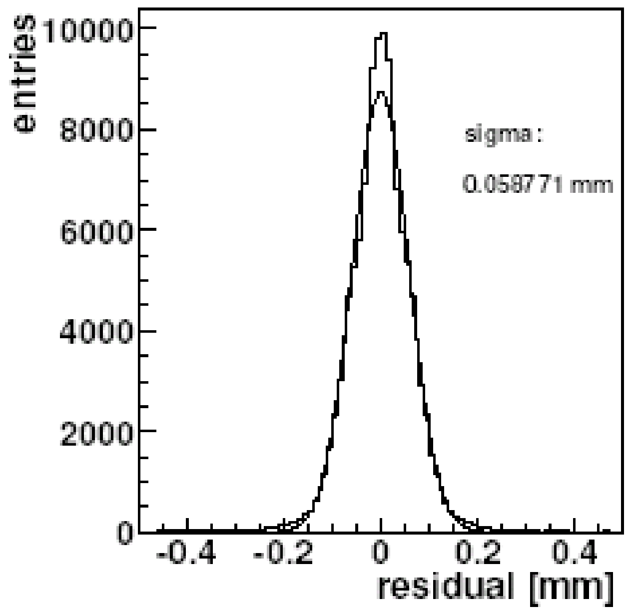
- charge sharing in silicon strip detectors
- achieved spatial resolution based on telescope track residuals:
  - 52 μm @ 198 μm pitch
  - 59 μm @ 237.5 μm pitch



pitch 198 μm

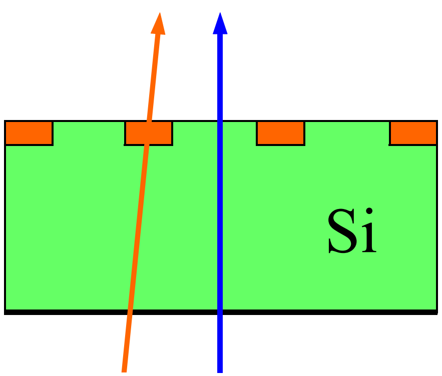


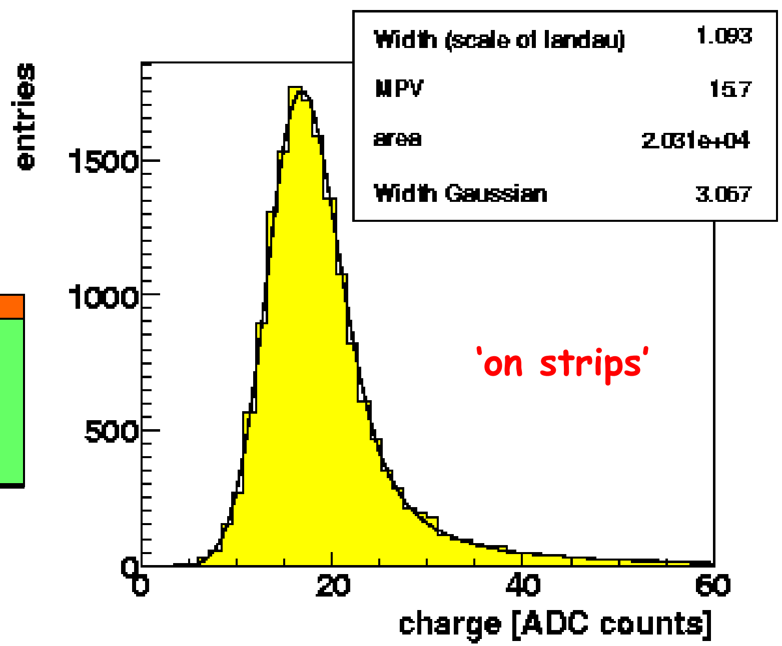
pitch 237.5 μm

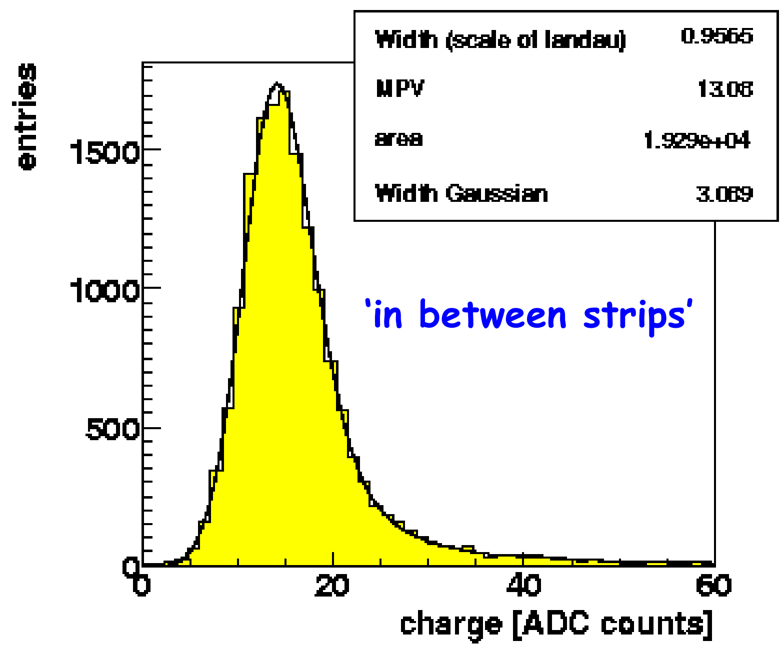


The LHCb Inner Tracker: CERN testbeam cont'd

- measured pulse height distributions for selected tracks
  - 'on strips' & 'in between strips'
  - fit w/ landau ⊗ gaussian
  - most probable value (MPV) as expected for tracks on strips
  - however, charge loss in between strips of ~18%
- S/N values of ~11 for tracks on strips for long ladder is in good agreement w/ expected noise performance of Beetle

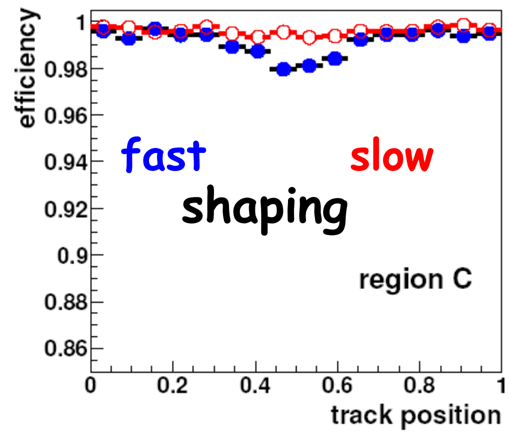


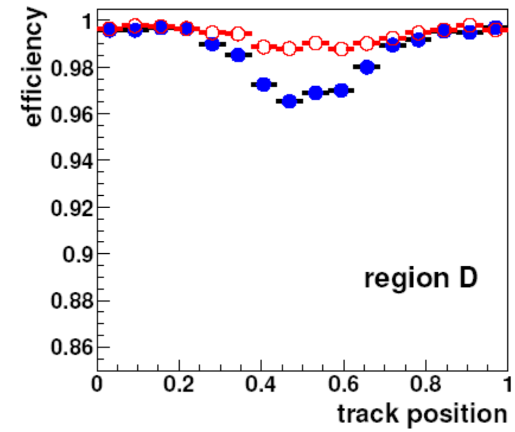


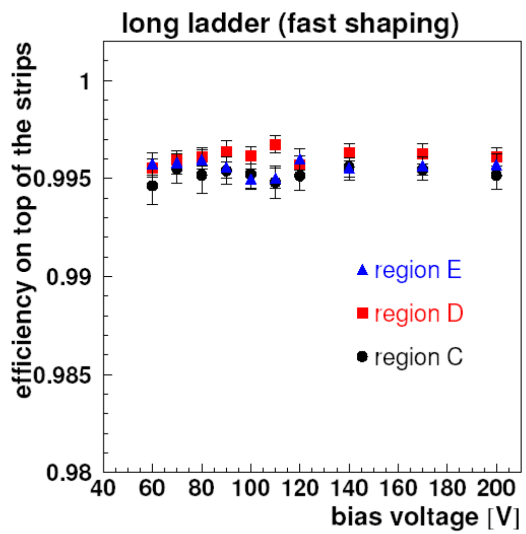


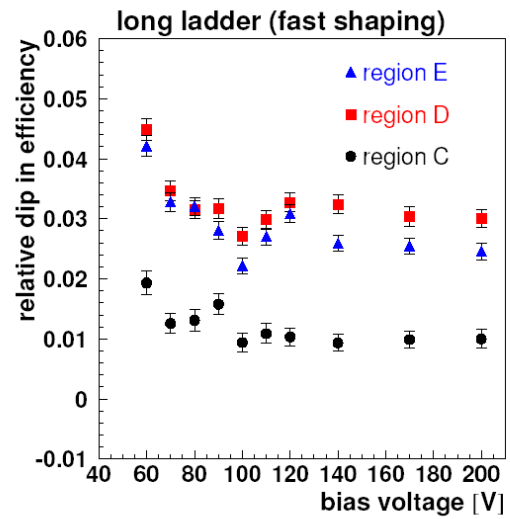
The LHCb Inner Tracker: CERN testbeam cont'd

- hit efficiencies
  - clustering algorithm adjusted to give noise rate of 0.1% per strip and event
  - compare to 0.6% per strip and event from physics
- efficiencies for fast shaping
  - close to 100% for tracks on strips
  - 96% - 98% for tracks in between strips
- efficiencies for slow shaping
  - improve to >99% everywhere
  - indicating ballistic deficit
- efficiency loss in regions D & E (with larger pitch) is more pronounced
  - prefer 198 μm pitch (region C) over 237.5 μm









The LHCb Inner Tracker: project organization

- schedule based upon current LHC schedule
- LHCb policy: all detector components ready at least 6 months prior to 1st LHC operation
- detailed time estimate for production based on experience from previous large-scale silicon detector
- 18 month (incl. contingency) reserved for ladder production
- full system ready for global commissioning in LHCb: Sept 2006

Milestone	Date
Project	
Final decision on production site(s)	06/2003
Engineering design finished	12/2003
First detector box in IP8, start of system commissioning	11/2005
Full system ready for integration into LHCb	09/2006
Silicon sensors	
Final order placed	03/2004
10% sensors delivered	09/2004
50% sensors delivered	01/2005
All sensors delivered	07/2005
L0 electronics	
BEETLE engineering run	03/2004
10% of hybrids assembled and tested	08/2004
BEETLE production run	12/2004
Readout link and service box	
Full prototype test of readout link	06/2003
L1 electronics	
Production of L1E boards started	03/2004
10% of L1E boards produced and tested	08/2004
50% of L1E boards produced and tested	04/2005
All L1E boards produced and tested	02/2006
Mechanics	
10% of ladder supports delivered	08/2004
Mechanics for first detector box ready	08/2004
Assembly	
Production sites ready	06/2004
Ladder assembly starts	09/2004
10% of ladders and first detector box assembled	01/2005
50% of ladders assembled	07/2005
All ladders and detector boxes assembled and tested	02/2006

The LHCb Inner Tracker: project costs

costs include 15% spares:

Item	Number of units	Cost (kCHF)
Silicon sensors	580	870
L0 electronics		320
Front-end chips	1160	
Hybrids	390	
Pitch adaptors	390	
Readout links	4640	560
L1 electronics		760
L1E boards	48	
Readout units	10	
Crates	6	
Mechanics		290
Ladder supports	390	
Balconies	390	
Cooling plate	12	
Insulation box	12	
Outer Tracker interfaces	6	
Infrastructure		350
High voltage		
Low voltage		
Cooling system		
Total		3150

The LHCb Inner Tracker: sharing of responsibilites

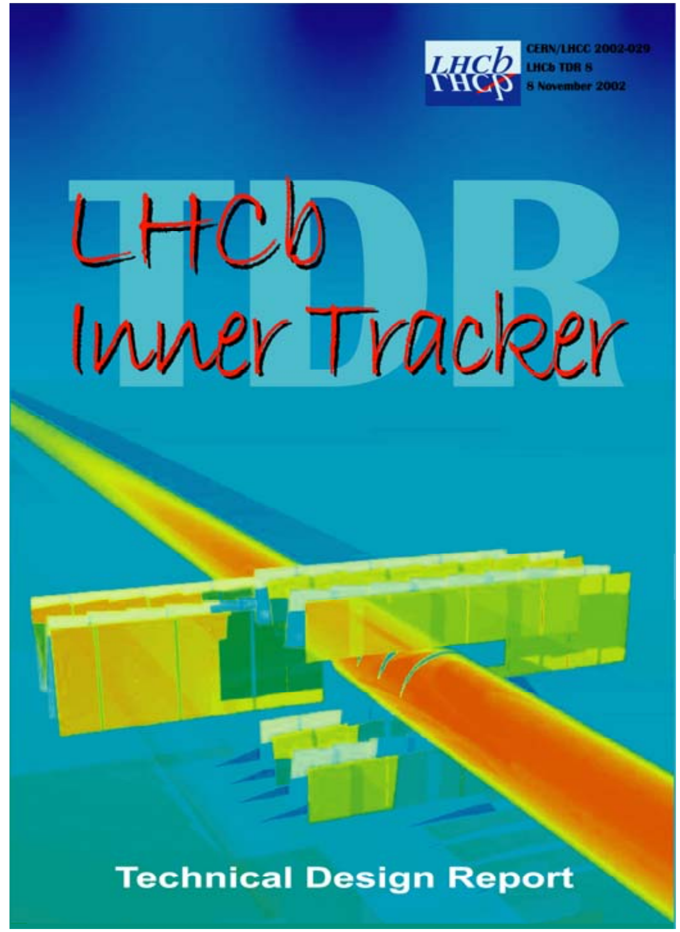
groups involved in Inner Tracker project:

- MPI Heidelberg
- Kiev
- U Lausanne
- Novosibirsk
- Santiago
- U Zurich

Task	Institute(s)
Silicon sensors	Zürich
L0 electronics	MPI Heidelberg
BEETLE chip, hybrid	
Readout link	Zürich
digitisation, optical links	
L1 electronics	Lausanne
DAQ interface, L1 trigger interface	
Mechanics	
ladder supports	Lausanne
station mechanics	Zürich
Infrastructure	
HV, LV, monitoring	Santiago
radiation monitor	Kiev
Assembly sites	
TT production	Kiev, Zürich
T1-T3 production	Lausanne, Santiago
Installation and commissioning	all

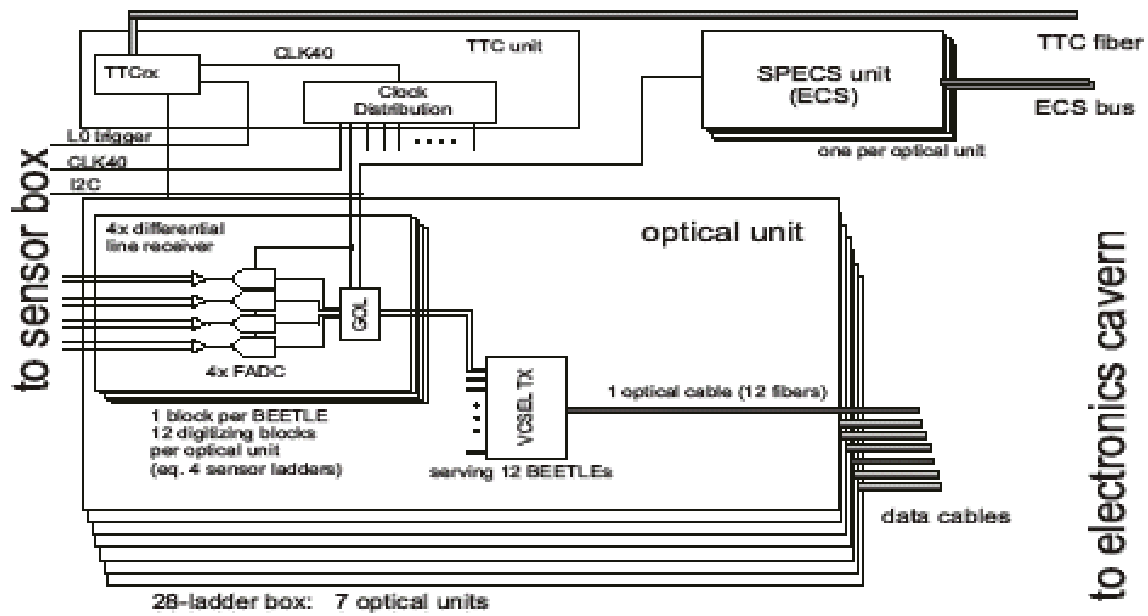
The LHCb Inner Tracker: Summary

- large surface silicon tracker
  - modular design
    - ✓ 12 detector boxes
    - ✓ 336 ladders
  - uses wide pitch (p=198 μm) silicon sensors
  - up to 22 cm long readout strips
  - short shaping FWHM~35 ns
- testbeam performance
  - spatial resolution of ~50 μm achieved
  - S/N of 11 for long ladders @ short shaping
  - single hit efficiencies ~99%



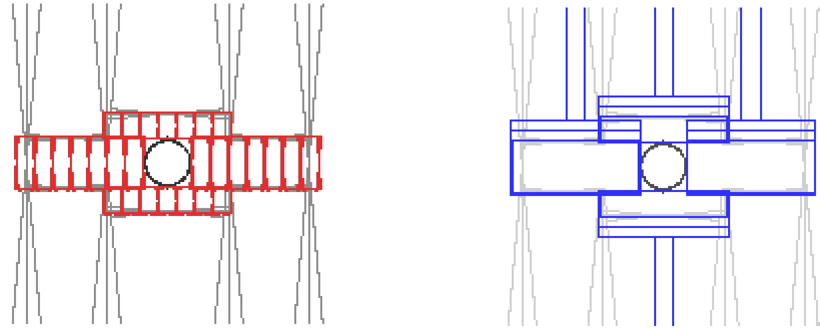
The LHCb Inner Tracker: Service Box design

- Service Box:
  - FADC, GOL & VCSEL drivers
  - TFC (TTCrx) & ECS interfaces
  - HV & LV distribution:
    - ✓ 1 HV channel per 4 ladders
    - ✓ HV individually switchable
    - ✓ LV regulations & control
  - slow control: temperature, coolant flow etc

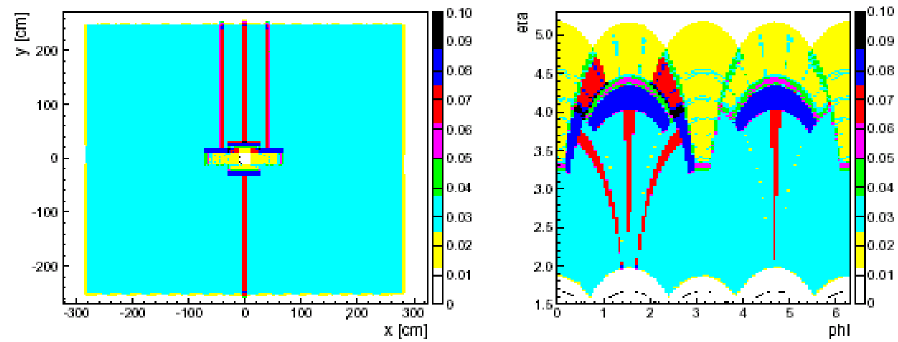


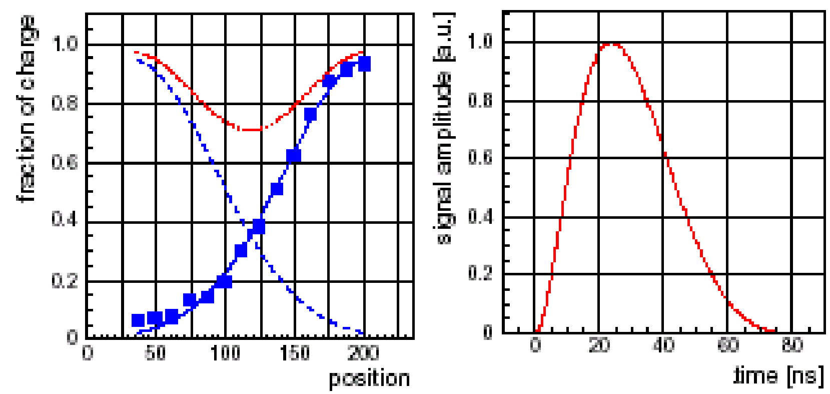
The LHCb Inner Tracker: Simulation

- GEANT in LHCb MC
  - detailed description of sensitive detector areas
  - 'dead material' of hybrid, cooling plate and service lines included (up to 8% X_0 per station)
- detector response
  - realistic charge deposition (Landau $\oplus$ Gaussian)
  - charge sharing incl. charge loss
  - strip noise 2000 e
  - folded w/ amplifier response having 35% remainder
  - clustering with fixed noise cut of 6000e



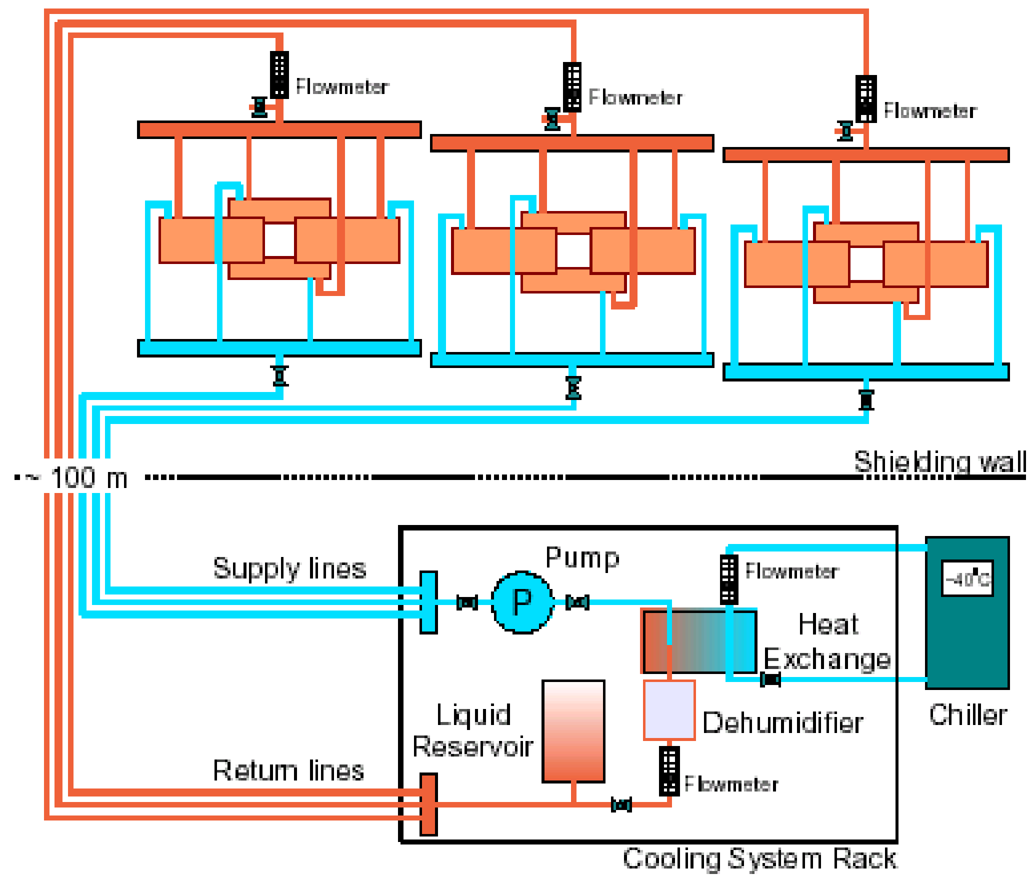
X_0:





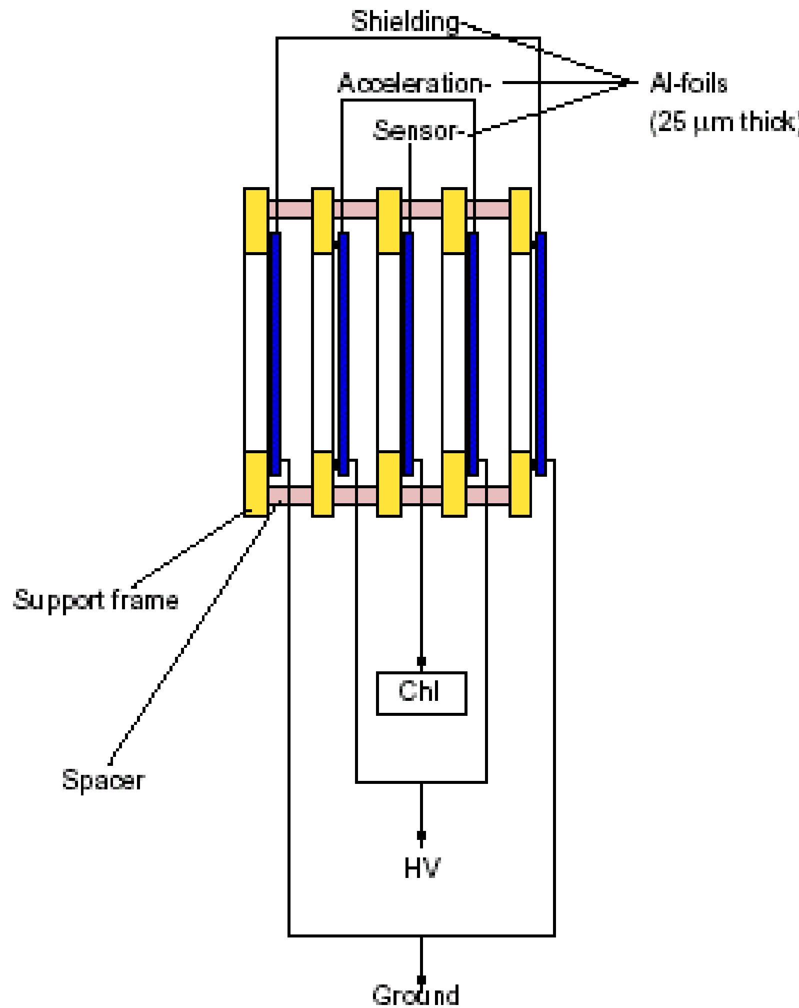
The LHCb Inner Tracker: Cooling design

- expected heat load per box:
  - 75W (Beetle FE-chip+insulation loss)
- conductive cooling with liquid coolant C_6F_{14}
- embedded pipe (OD 5mm) in cooling plate
  - circulate 150 l/h C_6F_{14} at T=-15°C
- parallel supply & return lines to stations T1-T3



The LHCb Inner Tracker: Radiation monitors

- simple & robust radiation monitoring using 'metal-foil' detectors
- successfully operated at HERA-B
- 5x 25 μm thin Al foils:
  - detection foil
  - acceleration foils
  - shielding
- charged particles induce secondary electron emission near metal surface
- charge integrators determine charge loss in detection foil



The LHCb Inner Tracker: history

- Changes since the LHCb technical proposal
  - MSCG/GEM option -> silicon strip detector
    - ✓ silicon strip technology proven as reliable, adopted as baseline in April 2001
  - rectangular 60x40 cm^2 layout -> cross shaped layout
    - ✓ extend horizontal coverage of inner tracker due to occupancies
  - reduced number of station 11 -> 10 -> 9 -> 4
  - add 'all-silicon' TT station in front of magnet (May 2002)

Efficiency versus S/N