The LHCb Inner Tracker

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

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on behalf of the
Silicon Tracker group
of LHCb
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 m² silicon area
- in addition there is
  - large area station TT in front of dipole magnet
  - 170k R/O channels
  - 7 m² silicon area
The LHCb Inner Tracker: Requirements

- provide reliable and robust tracking in charged particle environment with rates of up to \( \sim 10^5 \text{ cm}^{-2}/\text{s} \)
  - achieve excellent momentum resolution of \( \sim 4\% \)
  - keep occupancies in Inner Tracker at tolerable level of few \%
  - single hit resolution: \( \sim 70 \, \mu\text{m} \)
  - 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→ππ studies at L=2·10^{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**
  - \((\frac{\delta p}{p})^2=A_{ms}^2+(B_{res}xp)^2\)
  - dominated by multiple scattering up to \(p\sim100\ \text{GeV/c}\)
- average momentum resolution does not improve by reducing pitch further
The LHCb Inner Tracker: Radiation environment

- **FLUKA** simulations for ionization deposition and NIEL damage
  - for hadrons, leptons & photons
  - assumed inelastic pp cross section 80 mb
  - $1.6 \times 10^7$ 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=5ºC
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 \(~5{\degree}C\) 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
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 mm²
  - 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

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

64 strips
66.6 mm long

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 ($C_{\text{tot}}=1.02+1.66\cdot w/p$)
- 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 $\lambda \sim 200$ W/mK
  - good agreement to FEA
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 ($X_0$~17 cm, $\lambda$~420 W/mK)
- high density graphitic foams ($X_0$ up to 28 cm, $\lambda$ 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/cm³, X₀ ~17 cm (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 C₆F₁₄ 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: $450e + 47e \times C[pF]$
  - 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 198\(\mu\)m wide pitch of sensors to 40\(\mu\)m pitch FE-Beetle bonding pad
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.)
charge sharing in silicon strip detectors
achieved spatial resolution based on telescope track residuals:
- 52 \, \mu m @ 198 \, \mu m pitch
- 59 \, \mu m @ 237.5 \, \mu m pitch

pitch 198 \, \mu m

pitch 237.5 \, \mu m
The LHCb Inner Tracker: CERN testbeam cont’d

- measured pulse height distributions for selected tracks
  - ‘on strips’ & ‘in between strips’
  - fit with landau \( \times \) 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

![Graphs showing pulse height distributions for 'on strips' and 'in between strips']
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

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
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<tbody>
<tr>
<td>Project</td>
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<td>Final decision on production site(s)</td>
<td>06/2003</td>
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<tr>
<td>Engineering design finished</td>
<td>12/2003</td>
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<tr>
<td>First detector box in IP8, start of system commissioning</td>
<td>11/2005</td>
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<td>Full system ready for integration into LHCb</td>
<td>09/2006</td>
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<td>Silicon sensors</td>
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<td>Final order placed</td>
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<td>10% of hybrids assembled and tested</td>
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<td>BEETLE production run</td>
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<tr>
<td>Readout link and service box</td>
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<td>Full prototype test of readout link</td>
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<td>Production of L1E boards started</td>
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<td>Mechanics</td>
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<td>10% of ladder supports delivered</td>
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<td>Mechanics for first detector box ready</td>
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<td>Assembly</td>
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<td>Production sites ready</td>
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<td>Ladder assembly starts</td>
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<td>50% of ladders assembled</td>
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<td>All ladders and detector boxes assembled and tested</td>
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## The LHCb Inner Tracker: project costs

Costs include 15% spares:

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<th>Item</th>
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<td><strong>Total</strong></td>
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The LHCb Inner Tracker: sharing of responsibilities

groups involved in Inner Tracker project:
- MPI Heidelberg
- Kiev
- U Lausanne
- Novosibirsk
- Santiago
- U Zurich

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<th>Task</th>
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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
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 $T=-15^\circ C$
- 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 $\rightarrow$ silicon strip detector
    - silicon strip technology proven as reliable, adopted as baseline in April 2001
  - rectangular 60x40 cm² layout $\rightarrow$ cross shaped layout
    - extend horizontal coverage of inner tracker due to occupancies
  - reduced number of station 11 $\rightarrow$ 10 $\rightarrow$ 9 $\rightarrow$ 4
  - add 'all-silicon' TT station in front of magnet (May 2002)
Efficiency versus S/N