CMS Compact Muon Solenoid
Super LHC: Detector and Electronics Upgrade

Total weight: 12,500 t
Overall diameter: 15 m
Overall length 21.6 m
Magnetic field 4 T
SLHC & CMS Tracker

- Brief overview of present CMS Tracker

- Requirements for SLHC
  - Try to identify most important issues

- What have we learned so far from design and development of the Microstrip Tracker?
  - pixels: still in an earlier phase

- Many questions
  - Too soon for real conclusions
Silicon Tracker

- Two main sub-systems: Microstrip Tracker and Pixel Detector
  - Microstrip Tracker comprises 3 (topological) regions

Radiation environment
~10 Mrad ionising
~$10^{14}$ hadrons.cm$^{-2}$
Module components

- Pins
- Front-End Hybrid
- APV and control chips
- Pitch Adapter
- Kapton Bias Circuit
- Carbon Fiber/Graphite Frame
- Silicon Sensors

Kapton cable
Now incorporated with the hybrid.

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Modules and sub-structures

5550 TOB modules

688 Rods

288 TEC petals
Module types

~16000 modules (including spares)
to be produced over less than 2 years.

26 different types of modules in various combinations:
• 14 types of sensor masks
• 24 types of pitch adapters
• 3 types of hybrid layouts (but assembled differently with 4 or 6 APV chips, connector orientation up or down)
• 19 types of frames (e.g. different mechanical assembly jigs)

Very complex nesting of parts.
Design considerations of present pixel system

Pixel Detector designed 6 years ago with many speculative issues and unproven technologies

Today:
Technology realistic & feasible

• 3D –tracking points

• \( \sigma(z) \sim \sigma(r\phi) \sim 15\mu m \) for precise impact parameter in \( r\phi \) & \( z \)

• replace layers after \( 6 \times 10^{14}/cm^2 \) (assumed at the time for TDR)

<table>
<thead>
<tr>
<th>LAYERS:</th>
<th>( r = 4.3)cm</th>
<th>( 7.2)cm</th>
<th>( 11.0)cm</th>
</tr>
</thead>
</table>

\( \Rightarrow \) Area Barrel = 0.78 m\(^2\)
\( \Rightarrow \) Disk = 0.28 m\(^2\)
\( \Rightarrow \) Total ~ 1 m\(^2\)

Fluence & Rate limited \( \rightarrow r_{\text{min}} \)
Cost limited !! \( \rightarrow r_{\text{max}} \)

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Present CMS Sensors

- Silicon microstrip tracker
  - ~210 m² of silicon, 10M channels
    - 75000 FE chips, 40000 optical links

- Silicon sensors - main parameters
  - Substrate: <100>, n-type float-zone, phosphorus doped
  - p-side readout, AC coupled, with poly-Si bias resistors
  - 500µm 19100 units, 8 designs 3.5-7.5kΩ.cm
  - 320µm 6450 units, 8 designs 1.5-3.0kΩ.cm
  - \( V_{\text{depletion}} < 300V \)  \( V_{\text{breakdown}} > 500V \)
  - Defective strips < 1%. Rejects in modules < 2%

- Tender required companies capable to deliver >50% of requirement
CMS SLHC Tracker

- Major areas for discussion
  - Physics requirements
  - System issues
  - Electronic issues
  - Sensor issues
  - Mechanical issues - omit for time reasons

- Pixels will be more important at SLHC
  - rather key point…
    - since pixel technology is not yet proven on large scale
Tracker at $10^{35}\,cm^{-2}\cdot s^{-1}$

- Even more intense radiation environment
  - “only viable solution is to completely rebuild Inner Detector systems…”

- Working group concluded - three tracker regions
  - $R > 60\,cm$ push existing technology - ie microstrips
  - $20 < R < 60cm$ further developed hybrid pixels
  - $R < 20\,cm$ most likely new approaches required

- This probably does mean three trackers!
  - plus topographical divisions?
  - could need much larger community

- New CMS requirement - provide tracker data for L1 trigger
  - Major new challenge
Schedule for LHC Upgrades

From a talk by Jim Strait
to a DOE Meeting
18 April 2003

L at year end
Integrated L
Poisson Error
Time to Halve Error

[100 fb$^{-1}$]
[10$^{34}$ cm$^{-2}$s$^{-1}$]
[Arb. units]

[years]
Physics issues

- Higher luminosity and (eventual?) higher CM energy
  - $L \rightarrow 10^{35} \text{ cm}^{-2}\text{.s}^{-1}$ $E_{CM} = 28 \text{ TeV}$
  - NB Strong correlation between $L$ and beam lifetime

- Expect to be guided by LHC discoveries and success of machine operation
  - Electron and muon track reconstruction will still be important
  - Rarer channels to be studied?
  - More energetic jets with more particles and higher track density
  - Higher granularity will evidently help
    - but
  - No of channels, power & material budget are major concerns
What will remain the same?

- Specifications - no obvious reason for major change
  - momentum & spatial resolution
- Volume available
- Space & cooling in control room & cavern is also limited
  - increased off-detector electronics must be compensated by density
  - total power constraints will also not relax much
- Ability to cool system
  - No dramatic breakthroughs expected
- Budget?
  - Should expect it to be a constraint
What will not remain the same?

- Number of channels will increase
- Detector (sensitive) thickness and material *might* change

- Electronic technology changes are inevitable
  - and we are forced to follow them
- Off-line computing power will increase… as will…
- on-detector (ASIC) processing
  - limited by power dissipation
- off-detector (FED) processing
  - may be limited by increase in channels and complexity of data
System issues

CMS has pioneered automated module assembly
- Almost fully proven, and module assembly is now going quite fast
  - 15000 in ~2 years

But
- Significant development time to reach this point
- Many crucial, detailed, labour intensive tasks
- Some problems still occurring
- System assembly, installation and commissioning still ahead
  - Much less adaptable to automation
- SLHC tracker will be different - more modules &…
How much time is needed?

- For present system R&D started in ~1990
  - we did not understand electronic technologies as well as today
  - much time was spent on sensor development

- Where were we 5 years ago? (early 1999)
  - Sensors: MSGCs and silicon
  - Readout ASICs: 0.25µm had begun
  - Optical links: well advanced - but much done since
  - Hybrids, power, readout: barely started
  - Module assembly: automation demonstrated

- December 1999
  - MSGCs abandoned - despite much progress
  - 0.25µm CMOS adopted as baseline technology
One obvious conclusion

- 5 years is not a long time
  - Some things have taken longer than we expected, even when we thought we were finished

- We underestimate time for R&D to reach maturity
  - “90% of effort on last 10%”
  - especially affects evaluation and qualification
How to use available time?

- Possible date for upgrade 2015
  - for some assumptions see earlier slide

- Possible schedule - including contingency
  - 5-6 years R&D, depending on start, funding & people ramp
  - 2 years qualification of components in systems
  - 3 years construction

- Start date and funding are crucial assumptions!!
On-detector electronic issues

- Analogue readout was a good choice
  - but may need to reconsider digital for the future

- Optical data transmission (analogue) a big success
  - but links are the largest part of the electronics budget

- Investigating major design variants is lengthy and costly
  - often introduces new features, needing verification

- Radiation tolerance
  - Qualification is time consuming (x-ray systems & SEU)

- Automated testing
  - successful, but needs much preparatory effort & tools
Off-detector electronic issues

- Manufacture - now looks safe (but…!)
  - Large, complex boards are challenging
  - Special components (optical Rx, TTCrx,…) need care

- Processing power will increase
  - but constraints are harder to anticipate

- Components evolve fast (~5 years lifetime)
  - Functionality increases and design time
  - Technology changes - Pb free solder (2006), fpBGA assembly,…
  - Power is hard to predict reliably until design is well advanced
Relevant technology trends

- 0.25μm CMOS probably available until ~2009
  - 0.18μm and 0.13μm already available
    - essential design tools are increasingly complex
  - 300mm wafers next standard, already in use
    - implications for bump-bonding & other equipment, eg probers
- Supply voltage reduction (0.13μm 1.2V/1.5V)
  - challenge for design - dynamic range
  - trend to higher speed and lower power applications
    - not necessarily at the same time
- More digital logic possible in smaller area
  - programmable functions to tune, correct, test, debug,..
Potential benefits

- The current limiting factor for many detectors is power dissipation.

- Power (both Watts and Amperes) must be reduced using:
  - New architecture
  - New circuit design
  - New technology

Material budget in CMS tracker

All electronics related
0.13µm Good and bad news

- Radiation tolerance and noise
  - look excellent - without special design tricks
    - but care over details still required
  - SEU rate will be more of an issue

- Cost - significantly higher entry cost
  - how to plan development & NRE? - under discussion
  - but wafer costs probably scale with area, or even decrease

- Availability of engineers is a major concern
Front-end power in 0.13µm

- Simple assumptions eg. supply voltages scale, 80MHz
  - Scaled APV-type circuit (M. Raymond)
    - ENC ~ 700e for 2cm microstrip (+ leakage current)
  - power/channel : 2.3mW (0.25µm) => 0.4mW (0.13µm)

- Good news!!
  - but

- No of channels probably scales similarly…AND…

- Power in cables increases
  - $P_{\text{delivered}} = P_{\text{FE}} + I^2 R_{\text{cable}}$ and $P_{\text{FE}} = IV_s$
  - $V_s(0.13\mu m) \sim 0.5V_s(0.25\mu m)$
  - $P_{\text{cable}} = R_{\text{cable}} (P_{\text{FE}}/V_s)^2$ $R_{\text{cable}}$ likely similar to present value
Sensor issues for SLHC

- Radiation levels
  - $x5(\text{?})$ LHC - realistic allowance for machine performance

- Performance
  - Series noise ($C_{\text{det}}$) may decrease but parallel ($I_{\text{leak}}$) may not

- Power dissipation
  - Leakage current increase could dominate module power?

- Manufacturability & R&D
  - Will unusual materials be acceptable?
  - Are they available in required quantities?
  - Any special processing requirements?
  - Close collaboration with major manufacturers from early stage
Sensor prejudices

- Sensor material
  - silicon is still most robust, well understood and reliable material
  - no breakthroughs apparently (!) imminent …??
  - R&D on new materials takes much time (+ $$$) to mature
  - therefore …

- even innermost region still likely to be silicon?

- if this is not true…
  - need **quickly** to demonstrate alternatives and R&D required
  - must be capable of reaching maturity in 5-7 years
  - large scale, commercial manufacturing is **essential**
  - evaluate funding needed to bring to maturity
Pixel situation

- use 5x TDR fluencies

- old fluence limit of $6 \times 10^{14}/\text{cm}^2$
  $\rightarrow r_{\text{min}} \sim 26\text{cm}!!$ Problem!

- What can we do?
  - Change detector more often
  - Improve fluence limit off sensor

- Need to study sensors more!
  $\rightarrow$ RD50

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Fluence Limits of Silicon Pixel Sensors

• Double sided processed, $n^+$ on $n$ – silicon → expensive but high quality detectors

• So far many investigations for fluences $\sim 1 \times 10^{15} \text{ cm}^{-2}$, still quite ok!

• Reduced signal collection → partial depletion depth
  → trapping

• **Partial depletion depth** controlled by
  - High voltage capability
  - Oxygenation
  - Czochralski (lower costs)
  - Epitaxial silicon
  - Thinner detectors (e.g. 200µ → leakage current ??)
  - Reverse polarity ??

• **Trapping** so far not engineerable → final fluence limit for silicon detectors !!!

• Fluence $\sim 3 \times 10^{15} \text{ cm}^{-2}$ → $Q_{IR} = 25\% Q_{NIR}$ (very speculative !)

Is this enough signal charge for pixel ROC ?? (benefit from 0.13µ CMOS chips ?)

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Fluence Limits

- Oxygenated CMS pixel sensors

- Double sided processed $n^+$ on $n$ – silicon
  285$\mu$m thickness

- CMS Pixel test beam at CERN
  Summer 2003

- Shallow track method for depletion depth studies

- at 450V almost fully depleted

- see trapping!

$\Phi = 3 \times 10^{15}$ would imply a minimal pixel layer radius $\sim 8$cm!

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First conclusions (R. Horisberger)

- Current pixel system could possibly be extended and rebuilt for SLHC operation in a radial region of 8 cm to 16 cm.

- e.g. 3 Layers at: 8cm 11cm 14cm  
  **Pixel System #1**

- Silicon sensors could eventually be pushed to a fluence limit ~ $3 \times 10^{15} \text{cm}^{-2}$

- Pixel area stays 15000 $\mu \text{m}^2$  \(\rightarrow\) observe no benefit from smaller pixel

- The pixel ROC’s need some modifications to take the enormous data rate
Conclusions on pixels at intermediate radii
(R. Horisberger)

• The use of single sided processed n+ on p-silicon detectors could give a substantial reduction of the sensor costs.

• With n+ on p detectors partial depleted operation should be possible although high voltage issues at the guard ring region need R&D.

• Substantial cost reductions due to cheap module design decisions could result in module costs of 2100 SFr. With +20% add on  → ~100 SFr/cm²

• At this price level it becomes conceivable to cover intermediate radii:

  e.g. 2 Layers  18cm  22cm  Pixel System #2
Macro-pixels at large radii

• Need to cover the radial region 25cm to 60cm with tracking detectors that can deal with SLHC track rates

• Silicon strip detectors have sensor element area 10mm\(^2\) to 15mm\(^2\)

• For 10x luminosity increase occupancy requires a reduction of sensor element area by factor 10. \(\rightarrow\) Sensor element \(~1\)mm\(^2\) - 1.5mm\(^2\)

• Propose Macropixel detector with pixel size \(200\)um x \(5000\)um (Strixels)

• Use simple DC coupled \(p^+\) on n-silicon detector and route the strixel signals on thick polyimide (\(~40\mu\)) insulation to periphery and bumpbond to modified pixel ROC for cost efficient zero suppressed readout. \(\rightarrow\) \(~40\) SFr/cm\(^2\)

• With this price one can cover probably a 3 Layer system:

  3 Layers  30cm  40cm  50cm  \textbf{Pixel System #3}
Summary (R. Horisberger)

- Propose 3 Pixel Systems that are adapted to fluence/rate and cost levels

  - **Pixel #1**  max. fluence system  
    ~400 SFr/cm²
  
  - **Pixel #2**  large pixel system  
    ~100 SFr/cm²
  
  - **Pixel #3**  large area system  
    Macro-pixel  ~40 SFr/cm²

- 8 Layer pixel system can eventually deal with 1200 tracks per unit pseudo – rapidity

- Use cost control and cheap design considerations from very beginning.

- Can this be done for 2012/13 ????

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Sensor options

- Discussed in Working Group report
- 1. Those probably meeting *large scale* maturity criterion
  - defect engineered silicon / cryogenically operated silicon
- 2. Those probably *not* meeting maturity criterion
  - 3-d detectors/ diamond
- 3. Those not mentioned
  - disposable sensors + any other ideas?
- Each solution needs customised electronics
  - Not credible to develop electronics for all options
Quasi-conventional silicon

- Defect engineered material
  - eg Oxygen doped, Magnetic Czochralski
  - no special electronic implications, if manufacturers accept processes
    - would probably apply to diamond if large scale production possible

- Cryogenically operated
  - Pros: some evidence of improved radiation resistance
  - Cons: significant implications for electronic developments
    - no proven solutions based on widespread processes (CMOS)
    - all tests must be done at operating T, equipment not readily available
    - significant performance changes expected - not just analogue
    - less predictable at present, and time-consuming to prove
Disposable sensors

- If ultra-radiation hard sensors are not available?
  - possible alternative for innermost region?
  - assumed to be based on commercial electronic technology
    - eg MAPS or a-Si+CMOS

- Production cost of disposable sensors probably feasible
  - provided NRE/development costs contained
  - savings on assembly, etc might also be significant
  - Pros: continues trend to industrial-style assembly
  - Cons: which type of sensor and how?
    - need pixel sensor but not labour-intensive
    - handling of activated material
“Straw man” module

- Adapt sensor for commercial bump bonding
  - μstrips @ 100μm
  - Bond pads 200μm pitch (staggered)
- Heat sink + substrate to deliver service signals
  - Silicon?
- SAPV: 2 per die
  - Outputs in middle
  - Power rails bump bond to substrate
  - services via substrate surface
  - service chips at periphery
- Many questions to answer
  - But might be candidate for commercial assembly on large scale?
  - Is it possible with more conventional assembly?
New challenges

- Tracker input to L1 trigger

  Muon L1 Trigger rate at
  \[ L = 10^{34} \, \text{cm}^{-2} \cdot \text{s}^{-1} \]

  Note limited rejection power (slope) without tracker information

- Traditionally digitisation, rapid data transfer, off-detector processing
  - very significant changes will be required to adapt tracker readout architectures to trigger requirements
  - pixels are asynchronous, so even more difficult

(b) 

\[ p_T^{\mu} \text{ threshold [GeV/c]} \]
Conclusions (I)

- a replacement tracker must further develop automation
  - it will be large
  - limits on funding, manpower, time, maintenance,…
  - bottlenecks must be overcome early
  - modules must be simplified further - endcap remains most difficult
  - could task be sub-contracted?
  - disposable detectors might be necessary
    - but activation and personnel irradiation is a big issue
  - sensors must reach large scale maturity in ~5 years

- If not true, what is the alternative?
Conclusions

- Power will be a major concern
- Material budget should not increase
- Large systems are hard to build
  - Qualification must be taken seriously
- R&D duration is always underestimated
  - Reduce the number of (complex) module types
  - Increase automation of assembly
- Sensors are just one of many issues
- Electronic technology evolution will bring benefits
  - and also much difficult work