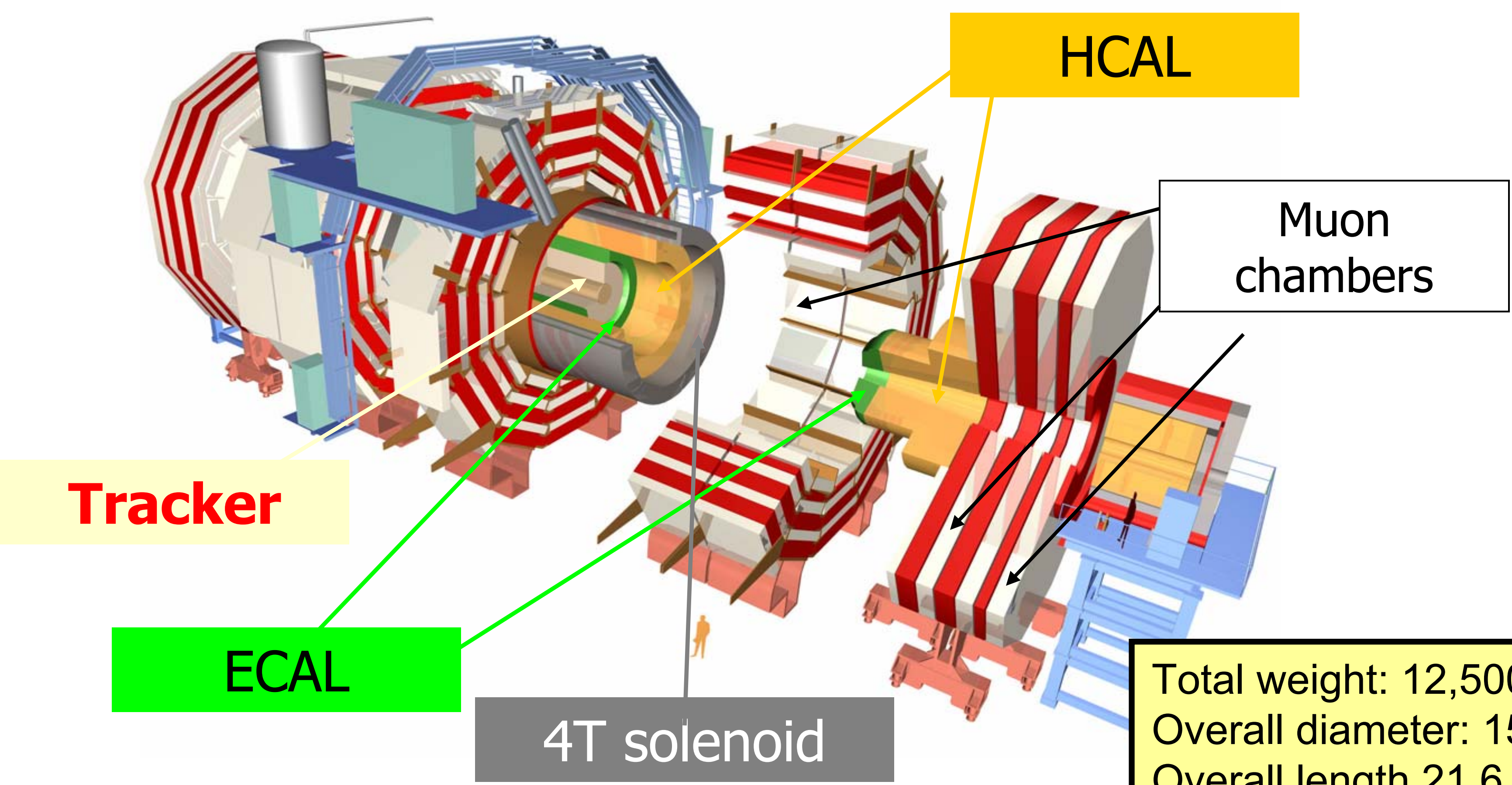
CMS Compact Muon Solenoid
Super LHC: Detector and Electronics Upgrade



HCAL

Muon chambers

Tracker

ECAL

4T solenoid

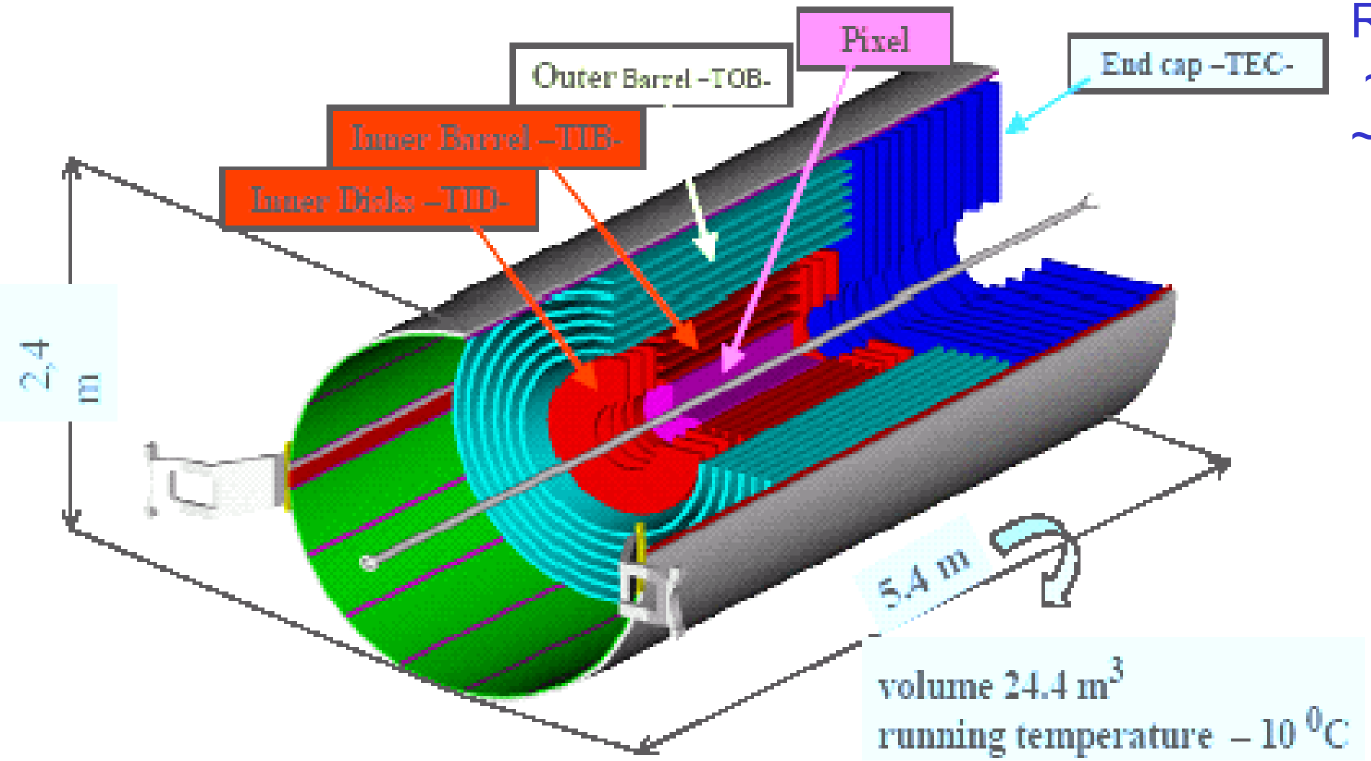
Total weight: 12,500 t
Overall diameter: 15 m
Overall length 21.6 m
Magnetic field 4 T

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

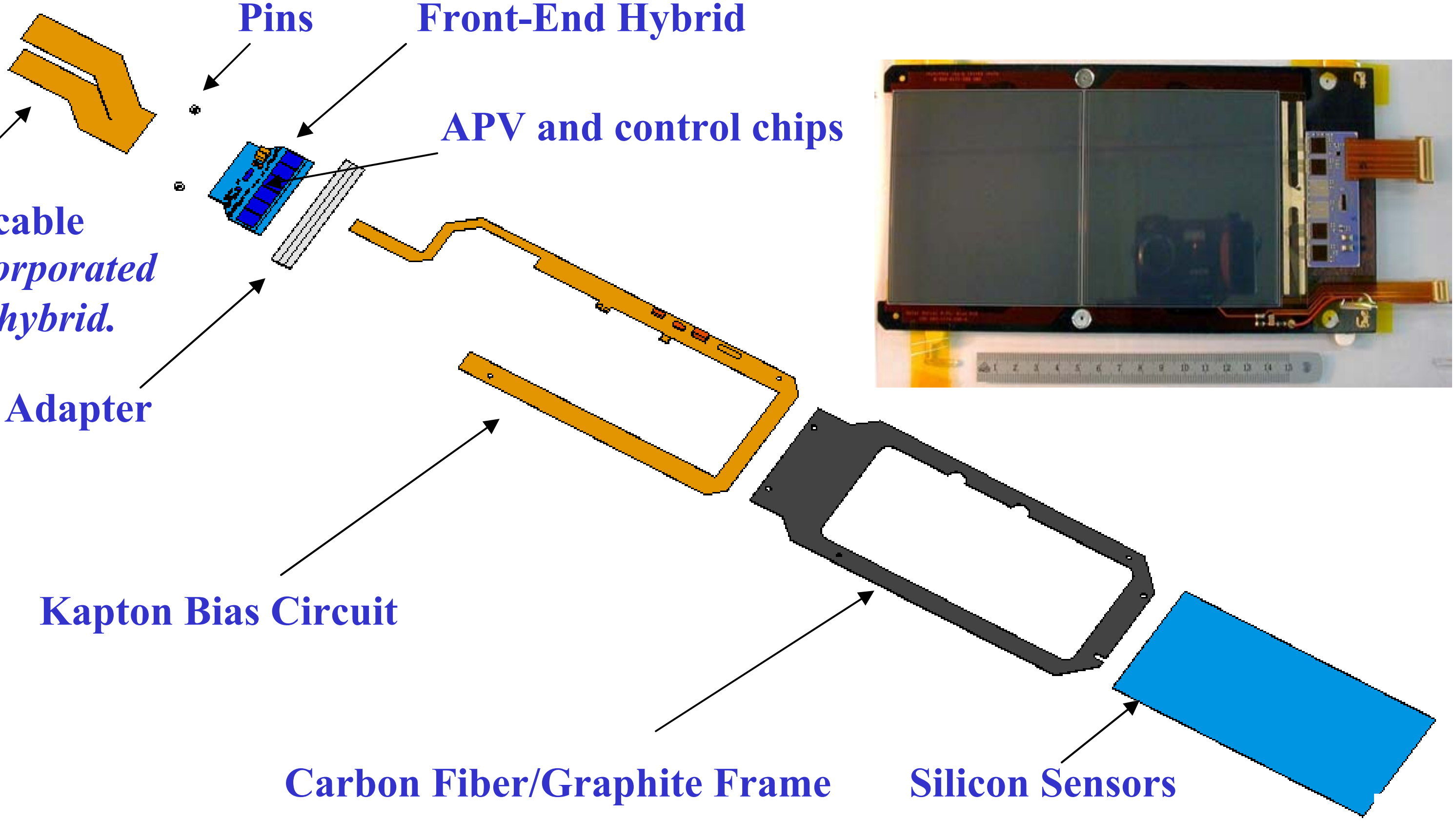


volume 24.4 m^3
running temperature – 10 ^{0}C

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

Geoff Hall

Module components



Pins

Front-End Hybrid

APV and control chips

Kapton cable

Now incorporated with the hybrid.

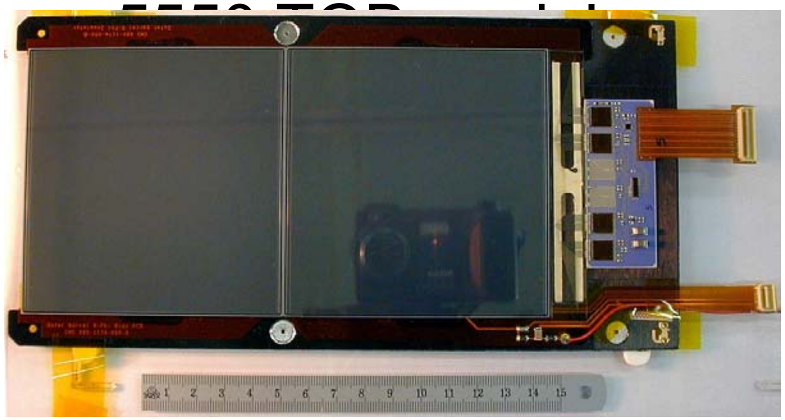
Pitch Adapter

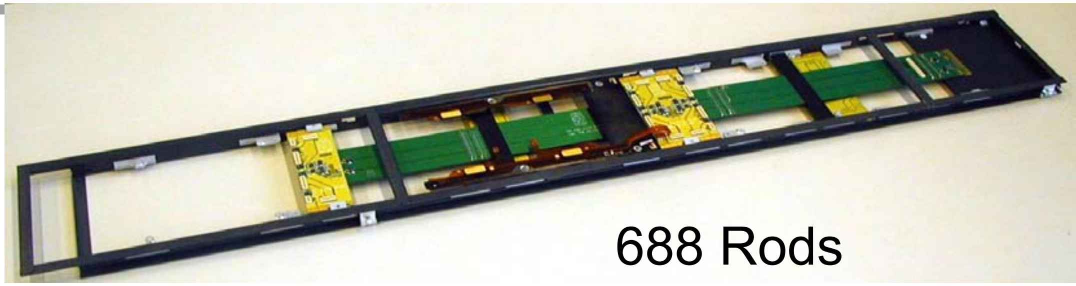
Kapton Bias Circuit

Carbon Fiber/Graphite Frame

Silicon Sensors

Modules and sub-structures





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:

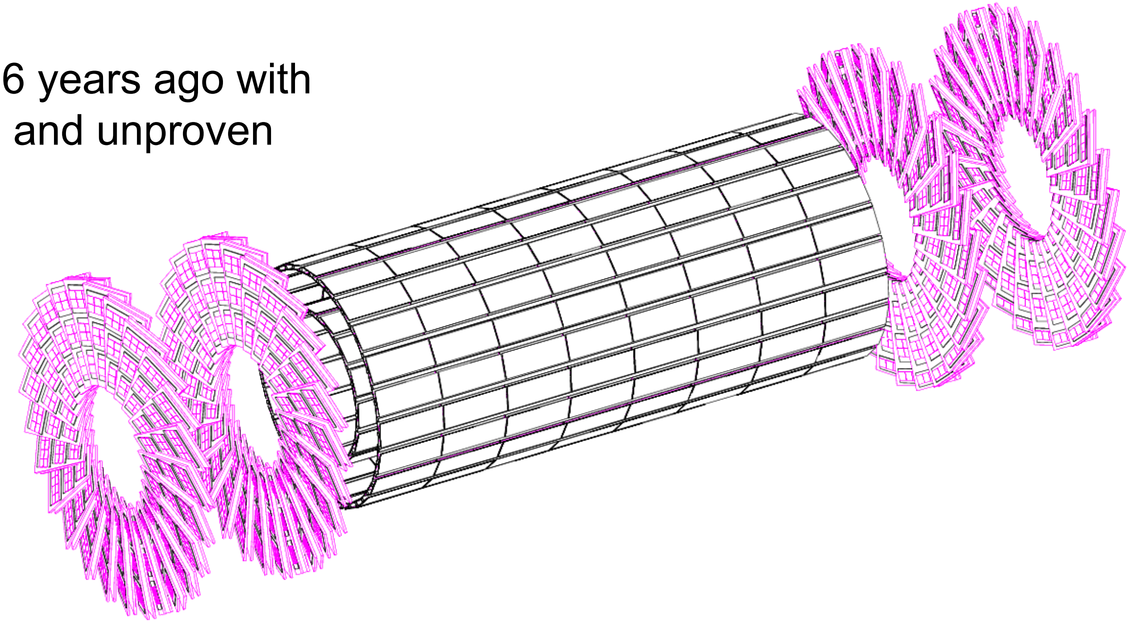
- 14 types of sensor masks
- 24 types of pitch adapters
- 3 types of hybrid layouts (but assembled differently with 4 or 6 APV chips, connector orientation up or down)
- 19 types of frames (e.g. different mechanical assembly jigs)

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
- $\sigma(z) \sim \sigma(r\varphi) \sim 15\mu m$ for precise impact parameter in $r\varphi$ & z
- replace layers after 6x $10^{14}/cm^2$ (assumed at the time for TDR)

LAYERS: r = 4.3cm 7.2cm 11.0cm → Area Barrel = 0.78 m^2
Disk = 0.28 m^2
Total ~ 1 m^2

Fluence&Rate limited → r_{min}

Cost limited !! → r_{max}

Present CMS Sensors

- Silicon microstrip tracker
  - ~210 m^2 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
  - $V_{depletion} < 300V$ $V_{breakdown} > 500V$
  - 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 $10^{35}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}$

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

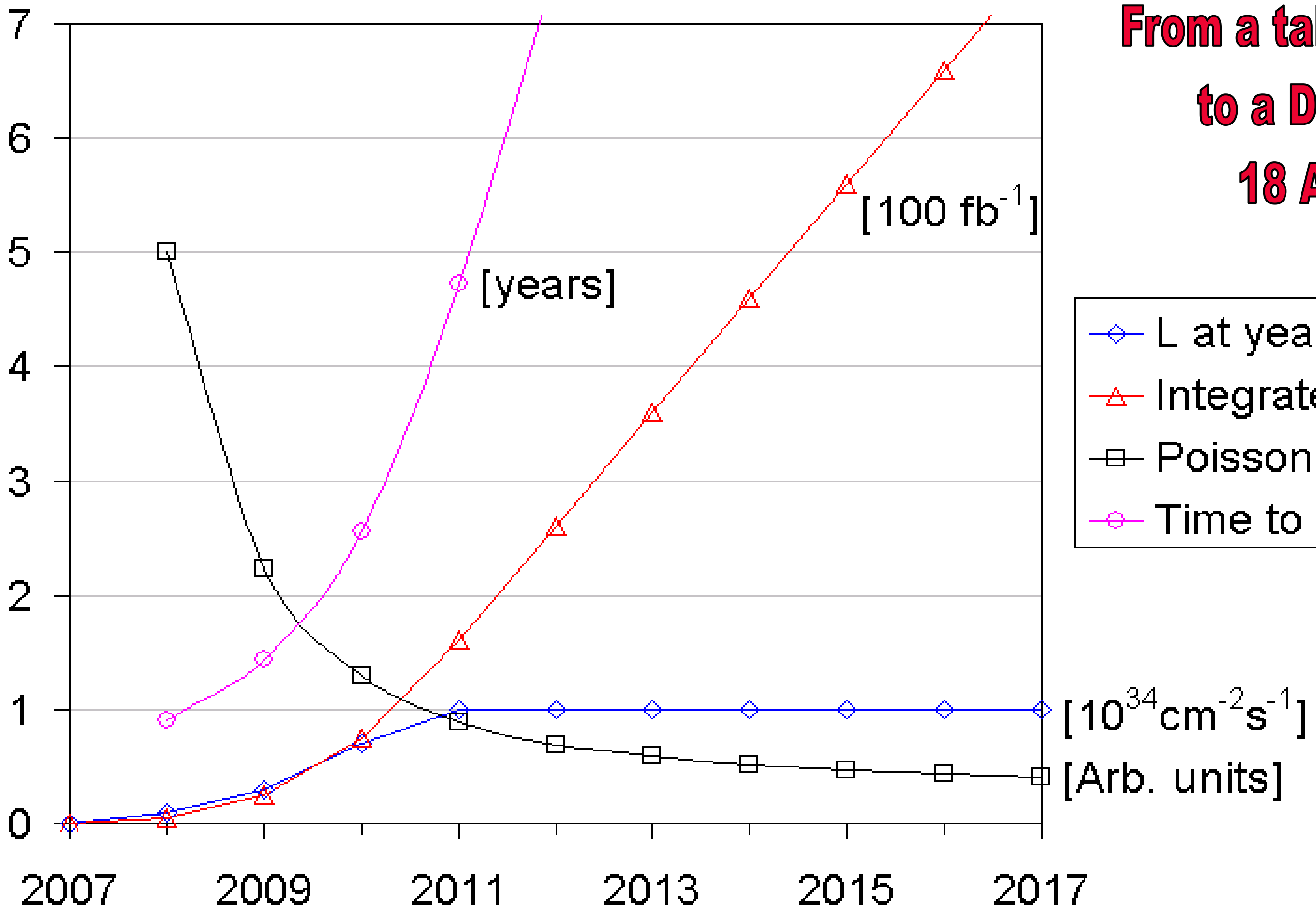
- Working group concluded - three tracker regions

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

Physics issues

- Higher luminosity and (eventual?) higher CM energy
  - L => 10^{35} $cm^{-2}.s^{-1}$ E_{CM} = 28 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

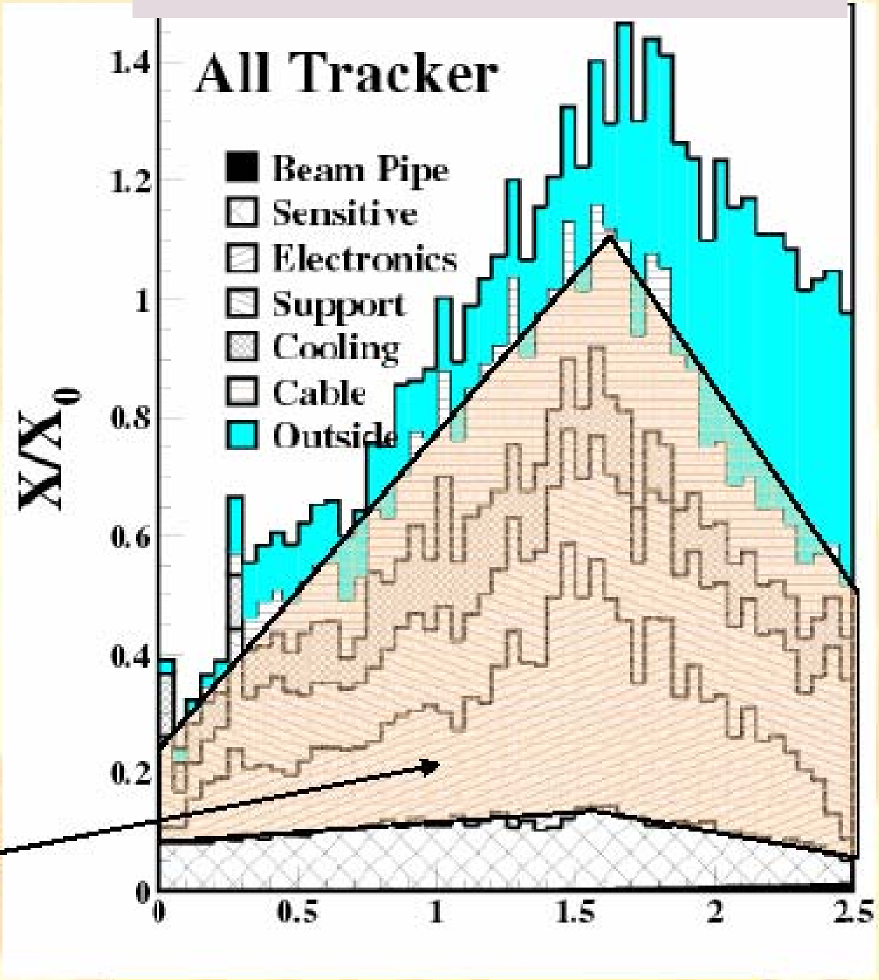
Relevant technology trends

- 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

Sandro Marchioro
LECC Amsterdam 2003

- 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



All electronics related

Material budget in CMS tracker

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
  - $P_{delivered} = P_{FE} + I^2R_{cable}$ and $P_{FE} = IV_s$
  - $V_S(0.13\mu m) \sim 0.5V_S(0.25\mu m)$
  - $P_{cable} = R_{cable}(P_{FE}/V_s)^2$ R_{cable} likely similar to present value

Sensor issues for SLHC

- Radiation levels
  - x5(?) LHC - realistic allowance for machine performance
- Performance
  - Series noise (C_{det}) may decrease but parallel (I_{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

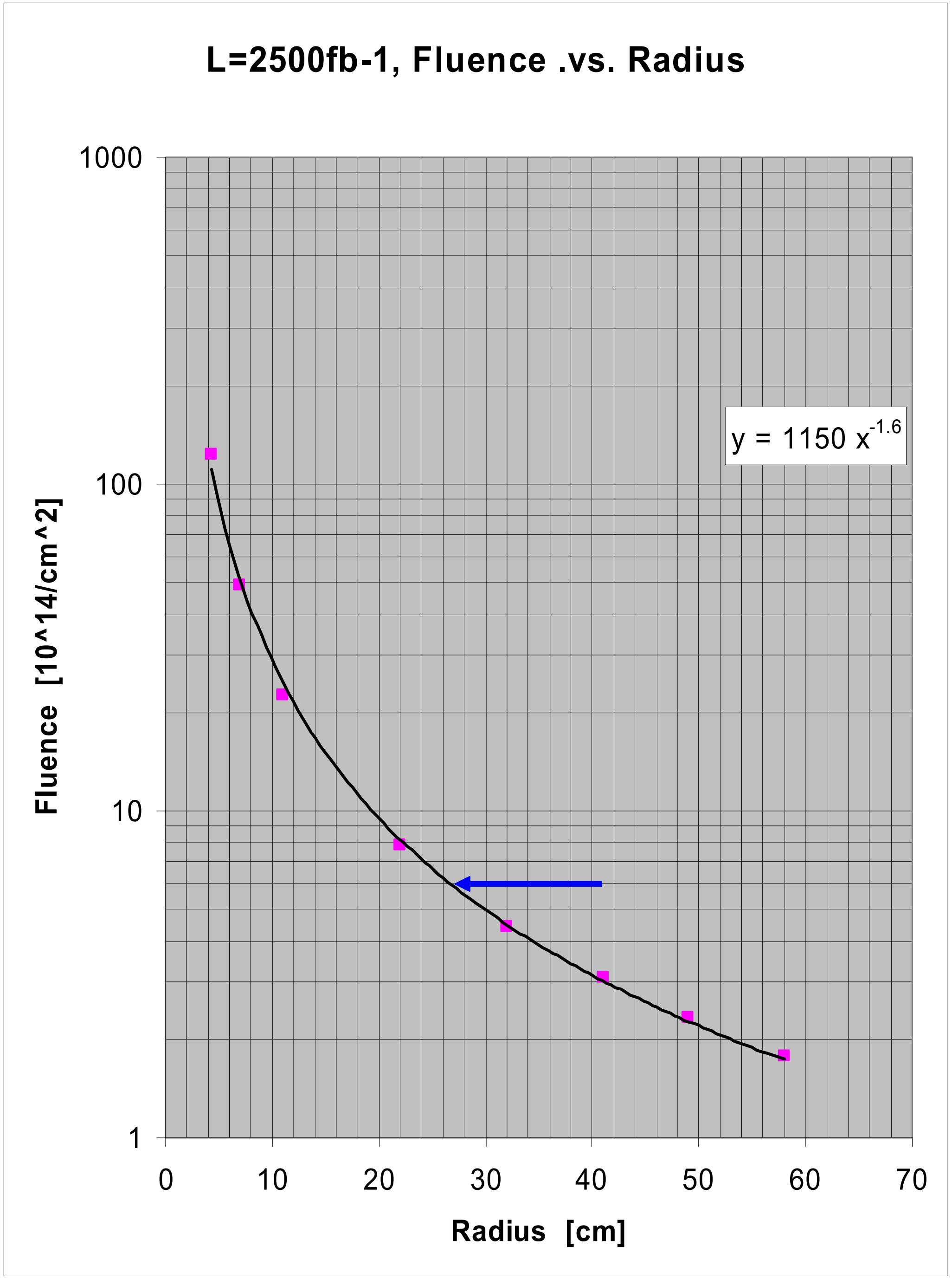
- use 5x TDR fluencies

- old fluence limit of $6x10^{14}/cm^2$
→ r_{min} ~ 26cm !! Problem!

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

- Need to study sensors more !

→ RD50



Fluence Limits of Silicon Pixel Sensors

- Double sided processed , n$^+$ on n – silicon → expensive but high quality detectors
- So far many investigations for fluences ~ 1x 10 ^{15} 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 ~ 3x 10^{15} cm^{-2}** → Q_{IR} = 25% Q_{NIR} (very speculative !)

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

Fluence Limits

- Oxygenated CMS pixel sensors

- Double sided processed
  n$^+$ on n – silicon
  285µ thickness

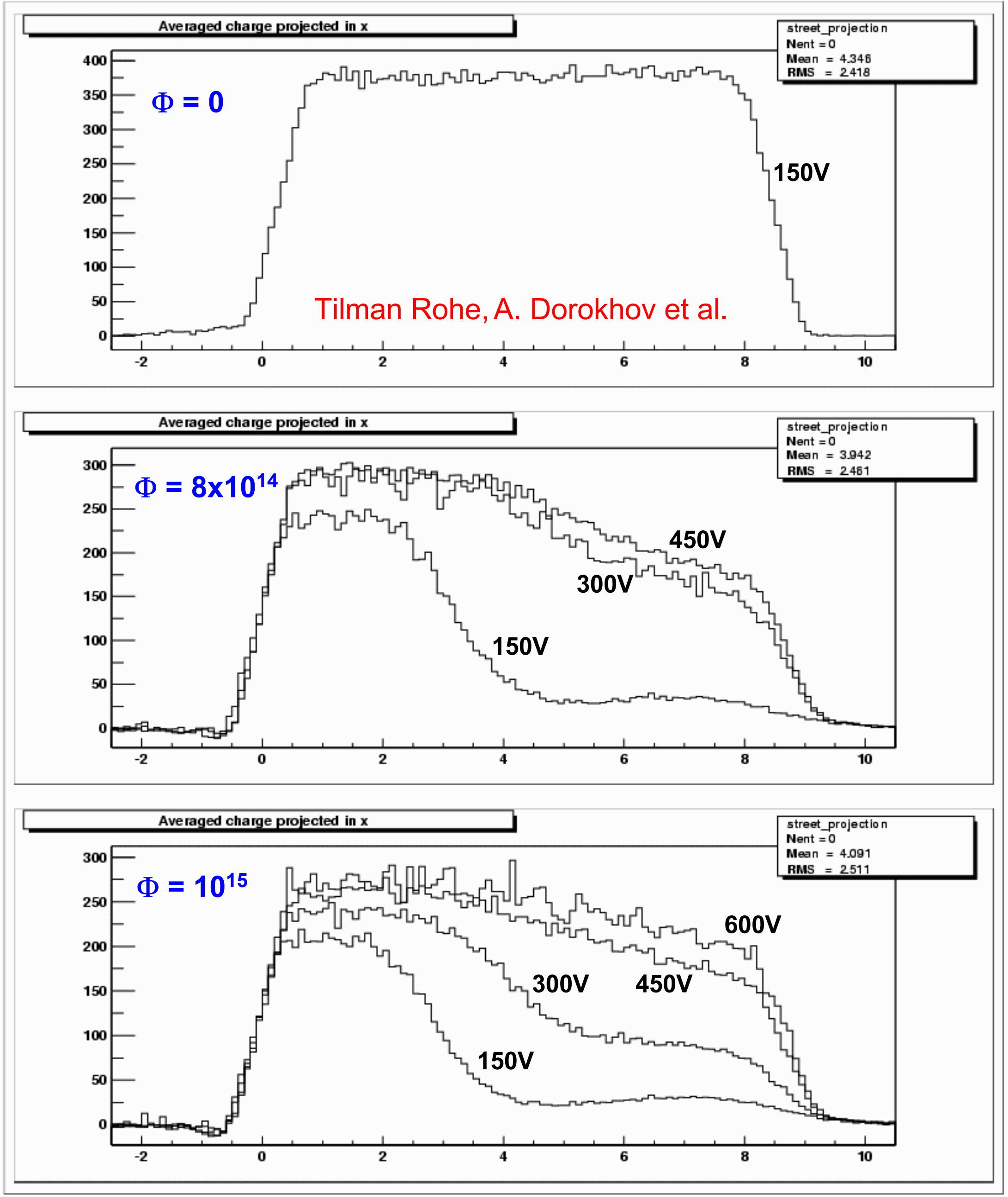
- CMS Pixel test beam at CERN
  Summer 2003

- Shallow track method for depletion depth studies

- at 450V almost fully depleted

- see trapping !

Φ = 3x 10^{15} would imply a minimal pixel layer radius ~ 8cm !



Tilman Rohe, A. Dorokhov et al.

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 ~ **$3x\ 10^{15}\ cm^{-2}$**
- Pixel area stays 15000 μm^2 → 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/cm^2

- 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. → Sensor element ~ 1mm^2 - 1.5mm^2

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

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

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

3 Layers 30cm 40cm 50cm **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/cm^2

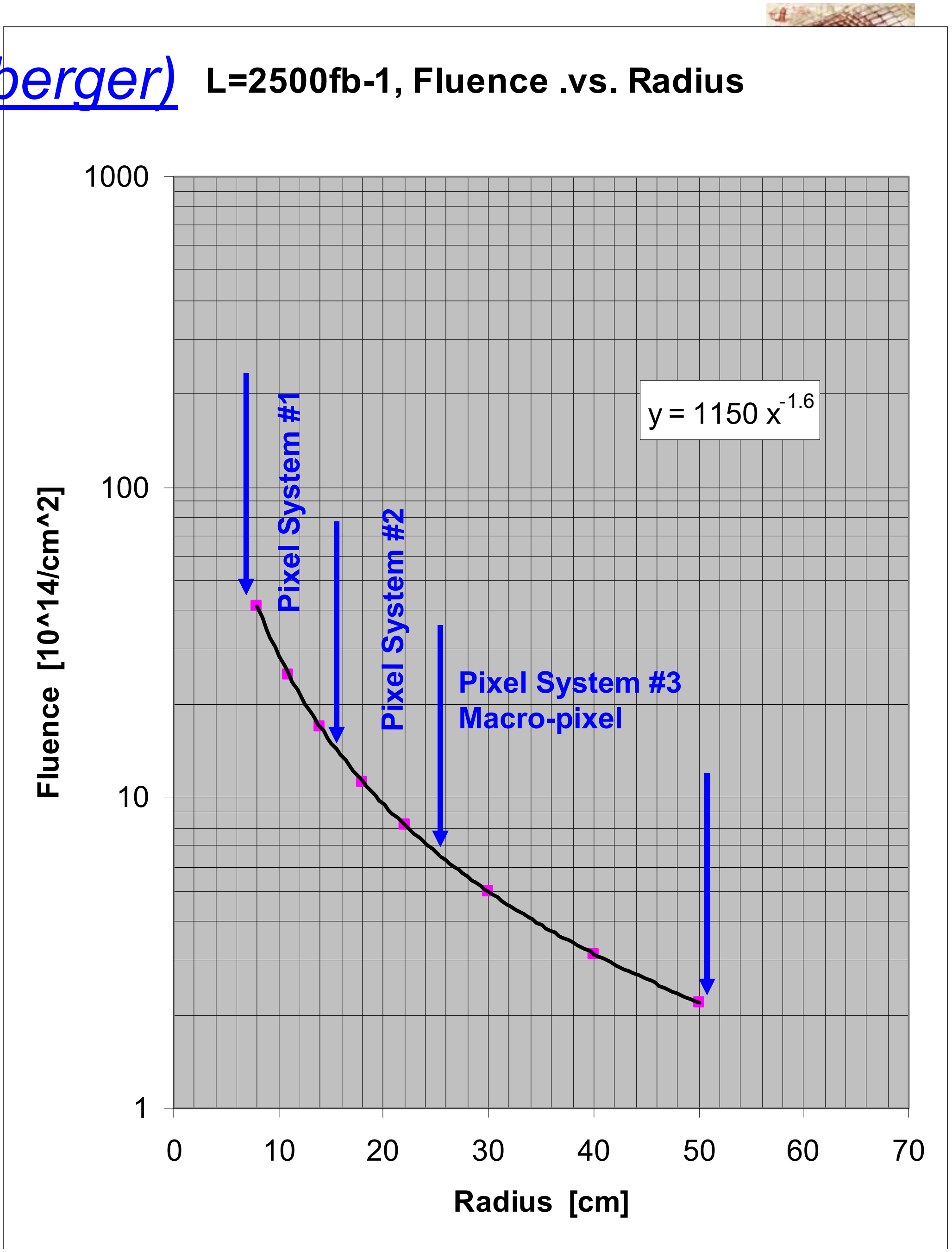
- **Pixel #2 large pixel system**
  ~100 SFr/cm^2

- **Pixel #3 large area system**
  Macro-pixel ~40 SFr/cm^2

- **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 ????**



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

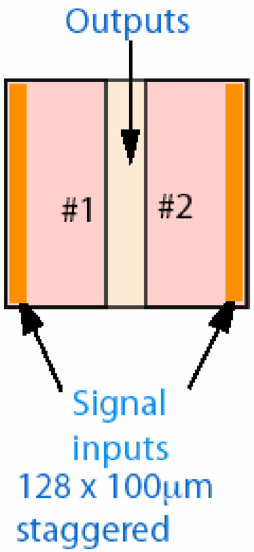
- Cryogenically operated
  - Pros: some evidence of improved radiation resistance
  - Cons: significant implications for electronic developments
    - no proven solutions based on widespread processes (CMOS)
    - all tests must be done at operating T, equipment not readily available
    - significant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

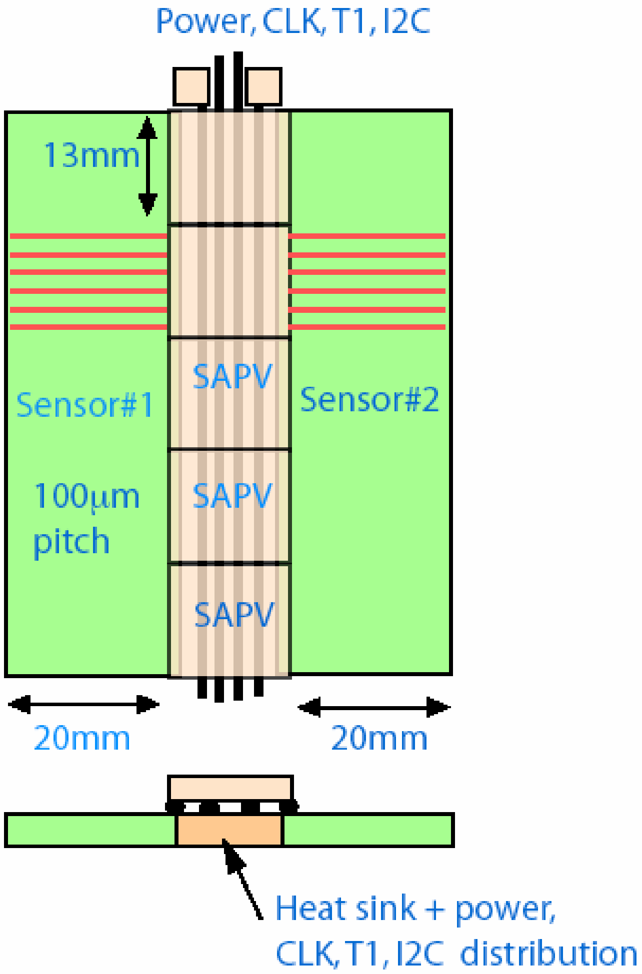
Disposable sensors

- 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?





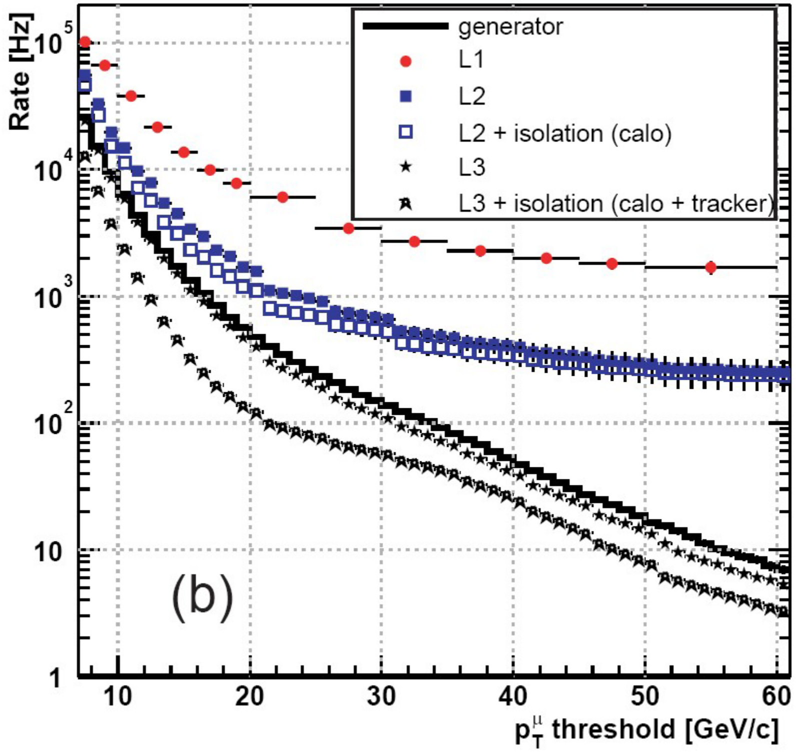
New challenges

- Tracker input to L1 trigger

Muon L1 Trigger rate at

$L = 10^{34}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}$

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

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