Development of Radiation Hard Tracking Detectors

1) LHC Upgrade environment
2) New tracker materials?
3) Radiation damage in Si
   a) Effects
   b) Present microscopic interpretation
4) Bias Dependence of collected charge
5) Thin sensors and Pixel sensors

Hartmut F.-W. Sadrozinski,
SCIIP UC Santa Cruz, 1156 High Street, 95064 CA, USA
LHC vs time: a wild guess ...

\[ L = 10^{35} \]
Need to Upgrade

Integrated Luminosity (fb⁻¹)

L = 10^{35}

Time to half Stat. Error

ID dies of radiation damage

LHC + sLHC
Fluence in Proposed sATLAS Tracker

Radial Distribution of Sensors determined by Occupancy < 2%

Long Strips  
Short Strips  
Pixels


5 - 10 x LHC Fluence

Mix of n, p, π depending on radius R

Strips damage largely due to neutrons

Pixels Damage due to neutrons+pions

**Design fluences for sensors** (includes 2x safety factor):
- Innermost Pixel Layer: $1 \times 10^{16}$ neq/cm$^2$
- Outert Pixel Layers: $3 \times 10^{15}$ neq/cm$^2$
- Short strips: $1 \times 10^{15}$ neq/cm$^2$
- Long strips: $4 \times 10^{14}$ neq/cm$^2$
RD50 – CERN R&D Collaboration
“Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders”

Started in 2002, now 261 Members from 50 Institutes

42 European and Asian institutes
Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Laappeenranta), Germany (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), Lithuania (Vilnius), Netherlands (NIKHEF), Norway (Oslo (2x)), Poland (Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool)

8 North-American institutes
Canada (Montreal), USA (BNL, Fermilab, New Mexico, Purdue, Rochester, UC Santa Cruz, Syracuse)

Detailed member list, Progress Reports, Workshop papers etc. :
http://cern.ch/rd50
RD50 started when the design of the LHC tracking detectors based on large-scale silicon strip and pixel sensor were frozen.

The performance of the LHC Si sensors (p-on-n FZ strips, n-on-n oxygenated FZ DOFZ) was limited by radiation damage. The aim of RD50 is to develop Radiation-Hard Semiconductor Devices for High Luminosity Colliders -- like the LHC Upgrade, the Super-LHC (sLHC).

The program of RD50 was laid out and is progressing along these lines:

• Extend the radiation testing to the predicted sLHC fluences (10^{16}, neutrons!)
• Search for alternative sensor materials to Si (more radiation-hard)
• Develop new experimental methods to help gaining insight into the radiation damage mechanism
• Understand on the microscopic level the observed radiation damage effects
• Optimize sensor geometry for radiation tolerance
• Start to transfer fabrication to commercial manufacturer in anticipation of large-scale production
### New Materials: Diamond, SiC, GaN

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<th>4H SiC</th>
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#### Key Points:
- **Wide bandgap (3.3eV)**: lower leakage current than silicon
- **Signal**: diamond 36 e/μm, SiC 51 e/μm, Si 89 e/μm
  - more charge than diamond
- **Higher displacement threshold than silicon**: radiation harder than silicon (?)

R&D on diamond detectors: RD42 – Collaboration
http://cern.ch/rd42/
New materials for Tracking Sensors?

Comparison of measured collected charge on different radiation-hard materials and devices

No “Wunder” material found, so investigate in depth
best known and developed material: Si.
Erosion of collected charge @ $\Phi > \sim 10^{15}$ neq/cm$^2$ : is S/N ok?

At a fluence of $\sim 10^{15}$ neq/cm$^2$, all planar semiconductor sensors lose sensitivity:
on-set of trapping!

Solution for Pixels: 3-D sensors, which provide shorter drift distance

Plot (Sept. ‘06) outdated:
much new Si data will be discussed

Not shown: GaN, other exotics

Line to guide the eye for planar devices

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<tr>
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Properties of Silicon Strip Detectors SSD

Reverse Bias of junction: only thermal current generation
Scale : Band gap 1.12eV vs. kT = 1/40eV: huge Boltzmann factor
  Cooling needed only in ultra-low noise applications.
Wafer thickness 300um = 0.3%RL: 23k e-h pairs (small fluctuations)
Depletion Voltage ~ thickness² : < 100V
Collection Time of e-h pairs: ~ 20ns
Position Resolution: 10-100um
Area is given by wafer size: 4” & 6” => Ladders

Depletion region. Charged particle traversing region produces ~80 electron/hole pairs per micron.

Determine location of single particles on the micron scale
If you still have Questions…

Visit your Favorite Web Site

Britney Spears Guide to Semiconductor Physics

http://britneyspears.ac/lasers.htm
Radiation Damage in Silicon Sensors

- **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
  - displacement damage, built up of crystal defects, proportional to fluence

  I. **Change of effective doping concentration**
     - type inversion, higher depletion voltage, under-depletion
     - loss of active volume ⇒ decrease of signal, increase of noise
     - Different for neutron and proton irradiation

  II. **Increase of leakage current**
     - increase of shot noise, thermal runaway, power consumption…
     - need for cooling (Diamond has advantage, RD42)
     - Universal if fluence is scaled according to NIEL

- **Surface damage due to Ionizing Energy Loss (IEL)**
  - accumulation of +charges in oxide (SiO₂) and the Si/SiO₂ interface, saturates
     - interstrip capacitance, strip isolation, breakdown behavior, …

- **Important latent effects:**
  - Space charge sign inversion (SCSI)
  - Annealing

Influenced by impurities in Si – Defect Engineering is possible!

~ Same for all tested Silicon materials!
Radiation Damage Induced Defects in Bandgap

*particle* → *Si$_s$*

- **Frenkel pair**
  - Vacancy + Interstitial
  - $E_K > 25$ eV
  - $E_K > 5$ keV

**Point Defects** (V-V, V-O ..)

Initial distribution of vacancies after $10^{14}$ particles/cm$^2$

- **10 MeV protons**
  - 36824 vacancies

- **24 GeV/c protons**
  - 4145 vacancies

- **1 MeV neutrons**
  - 8870 vacancies

Main radiation induced defects in Si

- $\overline{V}$-O
- SD/TD
- $V_2^-$
- $C_i$-O$_i$
- $V_2$-O

More point defects

Mainly clusters

[Mika Huhtinen NIMA 491(2002) 194]
Radiation Damage caused by Defects

Charged defects $\Rightarrow N_{\text{eff}}, V_{\text{dep}}$
- e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h) $\Rightarrow$ CCE
- shallow defects do not contribute at room temperature due to fast detrapping

Generation $\Rightarrow$ leakage current
- Levels close to midgap most effective
Radiation Damage – Leakage Current

- **Damage parameter** $\alpha$ (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current per unit volume and particle fluence

$\alpha(60^\circ C, 80 \text{ min}) = (3.99 \pm 0.03) \times 10^{-17} \frac{A}{cm}$

- $\alpha$ is constant over several orders of fluence and independent of impurity concentration in Si

  ⇒ can be used for fluence measurement

- **Leakage current decreasing in time (depending on temperature)**

- **Strong temperature dependence:**

  $$I(T) \propto T^2 \exp\left(-\frac{E_g}{KT}\right)$$

**Consequence:**

Cool detectors during operation!
Radiation Damage – Effective Doping

Change of Depletion Voltage $V_{\text{dep}}$ in high resistivity n-type FZ Si

- Full depletion voltage too high to fully deplete detectors at very high fluences ($>1000\text{V} @ 10^{15}\text{cm}^{-2}$)
- "Type inversion": $N_{\text{eff}}$ changes from positive to negative (Space Charge Sign Inversion)

Short term: “Beneficial annealing”
Long term: “Reverse annealing” 3x stable component

- time constant depends on temperature:
  - $\sim 500$ years (-10°C)
  - $\sim 500$ days (20°C)
  - $\sim 21$ hours (60°C)

- Consequence: Detectors must be cooled even when the experiment is not running!
Defect Engineering of Silicon

Influence the defect kinetics by incorporation of impurities or defects: Oxygen

Initial idea: **Incorporate Oxygen to getter radiation-induced vacancies** ⇒ prevent formation of Di-vacancy ($V_2$) related deep acceptor levels

- Higher oxygen content ⇒ less negative space charge

One possible mechanism: $V_2O$ is a deep acceptor

\[
\begin{align*}
V & \xrightarrow{O} VO & \text{(not harmful at RT)} \\
VO & \xrightarrow{} V_2O & \text{(negative space charge)}
\end{align*}
\]

\[\begin{array}{c}
E_c \\
\hline
VO \\
V_2O(?)
\end{array}\]

\[\begin{array}{c}
E_V
\end{array}\]

**Graph:**
- Carbon-enriched (P503)
- Standard (P51)
- O-diffusion 24 hours (P52)
- O-diffusion 48 hours (P54)
- O-diffusion 72 hours (P56)

**Figure:**
- Carbonated
- Standard
- Oxygenated

**DOFZ (Diffusion Oxygenated Float Zone Silicon)** RD48 NIM A465 (2001) 60
- MCz (Magnetic Czochralski) has even higher O content NIM A568, 1, (2006), 83-88
Difference in p and n irradiation in n-type Si

n-type MCz Si after 24GeV p and after reactor neutrons:
Oxygen not effective for neutrons

Electric field distribution by TCT
(loffe-St Petesburg on SMART n-MCz Si single pad diodes)

"Double Junction" develops mostly from back in neutron irradiated silicon, probably due to a high generation of cluster, behaving as a source of quasi-midgap acceptors.

M. Bruzzi 6th International "Hiroshima" Symposium STD06, Carmel Sept. 06

Hartmut F.-W. Sadrozinski, SLAC AIS Jan 9, 2008
Charge Trapping

Collected Charge is limited by:

- Partial depletion
- Trapping at deep levels

Collected Charge: \[ Q = Q_0 \cdot \varepsilon_{\text{dep}} \cdot \varepsilon_{\text{trap}} \]

\[ \varepsilon_{\text{dep}} = \frac{x}{W} = \sqrt{\frac{V_{\text{bias}}}{V_{\text{dep}}}} \]

\[ \varepsilon_{\text{trap}} = e \frac{\tau_c}{\tau_t} \]

\[ 1/\tau_{e,h} = \beta_{e,h} \cdot [\Phi_{\text{eq}}/10^{16} \text{ cm}^{-2}] \]

\[ \beta_{e,h} = 3 \]

\[ \tau_t = 3 \text{ ns for } \Phi = 10^{15} \text{ cm}^{-2}, \]

\[ \tau_t = 0.3 \text{ ns for } \Phi = 10^{16} \text{ cm}^{-2} \]

Annealing favorable for electrons
not favorably for holes

Bias dependence of charge collection:
increase depleted region & speed up collection

Trapping is the ultimate limitation for the active region in all semiconductors
(even for Diamond!)
Device engineering: Collection at junction
p-on-n versus n-on-p (or n-on-n) SSD

n-type silicon after high fluences:

- p^+on-n
- Charge spread – degraded resolution
- Charge loss – reduced CCE

p-type silicon after high fluences:

- n^+on-p
- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (fast)

Be careful, this is a very schematic explanation, reality is more complex, e.g. DJ!
Charge collection efficiency CCE on p- and n-side after Inversion

Advantage of collecting on the n-side after inversion was established long time ago:

- Double-sided n-type SSD
- 106 Ru telescope
- \(5 \times 10^{13} \text{p/cm}^2\)

This motivated the n-on-n development for (ATLAS SCT), ATLAS & CMS Pixels, LHCb Velo

Paradigm Change for Upgrade Tracker:

Collect electrons, use n-on-p sensors (expect be much cheaper than n-on-n)
## SSD Development for ATLAS Upgrade Tracker

### Development of non-inverting Silicon strip detectors for the ATLAS ID upgrade

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Hartmut F.-W. Sadorzinski, SLAC AIS Jan 9, 2008
Investigation of p-type Sensors

Ljubljana Univ., SCIPP - UC Santa Cruz, Univ. of Liverpool

– What collected charge can we expect at fixed bias 500 V for different materials? (ATLAS wants / needs to continue the use of present cables which are rated to 500V!)
– How much does charge collection depend on different readout (pads, strips, binary, analog)
– What is the most promising Si wafer material?

• All detectors studied are with n⁺ readout (n-on-p and n-on-n) – “electron collection”

Bias Voltage Dependence of Depletion after Neutron irradiation

The depleted sensor thickness \( x: \) can be measured two ways:

Capacitance-Voltage C-V measurement:

\[
C(V) = \epsilon \frac{A}{x(V)} \quad \text{for un-irradiated sensor:} \quad V = q \frac{Neff}{2\epsilon} x^2 \rightarrow 1 / C^2 \sim V
\]

Collected Charge vs. Bias \( Q(\text{CCE}) \) – V measurements

\[
Q(V) \sim x(V) \quad \text{for un-irradiated sensor} \quad Q(V) \sim \sqrt{x}
\]
**RD50 MICRON 6” project**

- 36 processed, 20 received
- Fz (topsil) and MCz (Okmetic) wafers of p&n type material
- n-on-n, n-on-p, p-on-n structures (pixels, strips, diodes)

**Strips:** ATLAS strips geometry 80 μm pitch (w/p~1/3)

**Pads:** 2.5 x 2.5 mm², multiple guard rings

**MCz wafers have very high oxygen content**

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**Neutron and Proton and Pion (Aug. ’07) irradiation of SSD and Diodes**

- **Liverpool:** CCE with SSD and diodes
- **UCSC:** CCE with SSD, both p-type and n-type, C-V, i-V on SSD and Diodes
- **Ljubljana:** CCE with Diodes, C-V, i-V on SSD and Diodes
C-V Measurements after Neutron Irradiation

- all detectors have negative space charge (decrease of $V_{fd}$ during short term annealing)
- Leakage current agrees with expectations ($\alpha \sim 3.5-5.5 \times 10^{-17} \text{A/cm}$)

Defect Introduction Rate consistent with microscopic picture:
- MCz (p and n type): 55 V/$10^{14}$ cm$^{-2}$ ($g_c \sim 0.8$ cm$^{-2}$) – lower stable damage than seen before?
- Fz (p and n type): 125 V/$10^{14}$ cm$^{-2}$ ($g_c \sim 1.8$ cm$^{-2}$) – in agreement with previous results

Charge collection (CCE) in all p-type wafers and n-type FZ should be similar at these fluences. Expect that n-type MCz should perform better – do we see this performance in CCE? Expect that MCz should be advantageous at very high fluences.
Charge Collection CCE for p-type Sensors

$\Phi = 5 \times 10^{14} \text{ n cm}^{-2}$
fluence motivated by long strip (10 cm) region of straw-man design

$\Phi = 1 \times 10^{15} \text{ n cm}^{-2}$
fluence motivated by short strip (2.5 cm) region of straw-man design

13-14 ke$^-$ collected at 500V

8.5-10 ke$^-$ collected at 500V

No effect on CCE seen for different resistivities or FZ/MCz (as expected)

A. Affolder ATLAS Tracker Upgrade Workshop, Valencia 12$^{th}$-14$^{th}$ Dec. 2007
Bias Dependence of Charge collection CCE

- $V_{fd}$ from CV (denoted by arrows) agrees well with the kink in CCE
- The slope of charge increase with voltage is directly related to $V_{fd}$:
  - increase of $V_{fd}$ can be measured by the change of slope and vice versa
  - Similar $V_{fd}$ = similar slope -> same E field
- High resistive non-depleted bulk is well reflected in linear increase of charge – different from un-irr.
- N-type FZ and all P-type show similar behavior, and N-type MCz has best depletion characteristics, as predicted from C-V

G. Kramberger
ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007
Fz-p vs. MCz-n Difference due to Depletion Voltage

Big difference in the charge collection between MCz n-n and Fz n-p
~14000 e vs. ~8000 e at 500V!

Fully depleted detector – one can see kink in Q-V plot

The difference in CCE is related to the difference in $V_{fd}$
Depletion Voltage from C-V vs. from Q(CCE)-V

$V_{fd}$ from saturation in C-V and Q(CCE)-V curves (80min @ 60$^\circ$C – end of beneficial annealing)

The correlation holds for all investigated fluences in range of full depletion voltages up to 1000V!

G. Kramberger
ATLAS Tracker Upgrade Workshop, Valencia 12$^{th}$-14$^{th}$ Dec. 2007

$V_{fd}$ from CV underestimates the onset of saturation in CCE by max. 100-150 V!

- after $V_{fd}$ the collected charge continues to increase due to shorter drift
- due to growth of depletion depth from electrode side the offset is smaller than in inverted p-on-n!

Advantage of charge collection on the junction
The CCE for n-type MCz follows the annealing trend of the depletion Voltage $V_{fd}$:
• initial rise (beneficial annealing) increase in collected charge by $\sim 10\%$ (@500V)
• decrease by again 20-30% (@500V) during the reverse annealing 10000 min

Increases for p-type FZ-p by 30% and then slow decrease to the pre-anneal value

After depletion annealing of trapping visible
Annealing of p-type FZ and DOFZ sensors
(p irradiated)

- p-type strip detector (280 μm) irradiated with 23 GeV p 
  (7.5 \times 10^{15} p/cm^2)
- expected from previous CV measurement of \(V_{\text{dep}}\) on n FZ:
  - before reverse annealing: \(V_{\text{dep}} \sim 2800\) V
  - after reverse annealing \(V_{\text{dep}} > 12000\) V
- no reverse annealing visible in the CCE measurement!

Data: G.Casse et al., to be published in NIMA

G.Casse et al., 10\textsuperscript{th} European Symposium on Semiconductor Detectors, 12-16 June 2005
CCE vs. Annealing (n irradiated)

Stable plateau of increased signal between 20-100 days (30% for this piece)

(Current decreases by ~30% over same time period)

At sLHC fluences for p-type sensors, the entire annealing process is much less pronounced than for n type FZ. It opens the possibility that sensors need to be cooled only during operations to control the leakage current, but not during beam-off time to prevent anti-annealing.
Mitigation of Radiation Damage in Si

- **Increase depleted region at fixed bias: Wafer materials**
  - Oxygen  
    - But neutrons
  - Epi  
    - But neutrons, protons
  - MCz  
    - But special wafer processing
  - N-type wafers: low resistivity  
    - But SCSI, annealing
  - P-type wafers: high resistivity  
    - Need experience, good annealing

- **Decrease drift distance to decrease trapping: Geometry**
  - Thin  
    - But inferior at low / medium, no advantage at high fluences
  - 3-D  
    - But high capacitance, need experience

- **Reduce trapping with beneficial annealing: Carrier**
  - Collect at (main) junction  
    - n-on-p or n-on-n
  - Collect electrons  
    - less trapping, good trapping annealing
Wafer Scorecard

• Materials: $\text{Neff} = \text{Neff}_0 + g \Phi_{eq}$

• For p-type: need $\text{Neff}_0$ low: high resistivity
• For n-type, need $\text{Neff}_0$ high: low resistivity

FZ and Mcz data verified for neutron irradiation, some proton data puzzling. Will soon have proton and pion data to check the advantage of MCz.
Charge Collection in Irradiated SSD

N-on-p strip sensors are sufficiently radiation-hard for the sLHC
No obvious advantage for MCz over FZ. 7500 e after $10^{16}$ n/cm$^2$!
Charge Collection in Upgrade Strips

ATLAS bias voltage is constraint to < 500V (cables!).

N-on-p strip sensors are sufficiently radiation-hard for the sLHC?

Hartmut F.-W. Sadrozinski, SLAC AIS Jan 9, 2008
Efficiency vs. Collected Charge

- For tracking sensors with binary readout, the figure of merit is not the collected charge, but the **efficiency**.
- **100% efficiency** is reached at a signal-to-noise ratio of $S/N \approx 10, S/Thr > 2.5$
- For **long strips** (5e14 cm$^{-2}$) with a signal of about 14ke, the usual threshold of 1fC = 6400 e can be used.

![Efficiency vs. Collected Charge Diagram]

**Long strips efficient at 1fC threshold**

Hartmut F.-W. Sadozinski, SLAC AIS Jan 9, 2008
Efficiency vs. Collected Charge

- For **short strips** (1e15 cm$^{-2}$) with a signal of about 8ke, the efficiency at 500V is only 70%.

- The threshold needs to be reduced to about 4500 e, i.e. electronics must be designed for a noise of ~700e.

**Median Pulse Height vs. Efficiency**
(n-on-p FZ, 1e15 n)

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**Short strips efficient if threshold can be lowered**

Hartmut F.-W. Sadrozinski, SLAC AIS Jan 9, 2008
Thin and Pixel sensors
Thin Sensors

Benefits of thin sensors:
Can be fully depleted at high fluences (important for p-on-n sensors?): Thin detectors allow very high effective doping densities in n-type detectors and thus “delay” of inversion to very high fluences. \( V_{\text{bias}} = \frac{q\cdot N_{\text{eff}}}{(2\varepsilon)x^2} \)
Less material (sensor only a fraction of the total material budget)

Disadvantage of thin sensors:
Signal lower for much of the operation
Thick sensor can be operated under-depleted (current is lower)

Simulations 2005:

Measurements 2007
(G. Casse, Affolder, P.P. Allport, IEEE 07, N07-06)
Planar electrodes replaced by columns through the wafer
- diameter: 10mm, distance: 50 - 100mm
De-couple deposit and charge collection

Lateral depletion assures Radiation Hardness
- Low depletion voltage: Increase active thickness
- Short drift distance and fast signal: Decrease trapping

Introduce by: S.I. Parker et al., NIMA 395 (1997) 328

No proton irradiation
No radiation hardness with MIP (only laser)
Grain size: \(~100-150\mu m\)

- large band gap and strong atomic bonds promise fantastic radiation hardness
- low leakage current and low capacitance both give low noise
- Ionization energy is high: \(\text{MIP} \approx 2x\) less signal for same \(X_0\) of SI
  - Diamond: \(~13.9\text{ke}^-\) in 361 \(\mu m\) (140 enc; bare threshold \(~1500\text{e}\))
  - SI: \(~22.5\text{ ke}^-\) in 282 \(\mu m\)
- Grain-boundaries, dislocations, and defects can influence carrier lifetime, mobility, charge collection distance and position resolution
- Available Size \(~2 \times 6\) cm\(^2\) (12cm diameter wafer; \(~2\)mm thick)

M. Mikuz ATLAS Tracker Upgrade Workshop, Valencia 12\(^{th}\)-14\(^{th}\) Dec. 2007

H. Kagan

Hartmut F.-W. Sadorzinski, SLAC AIS Jan 9, 2008
Pixel Sensor Efficiency: Signal/Threshold

Signal is Landau (here Diamond):

Efficiency requires
Signal/Threshold > 2

Threshold
“bare” threshold is set as low as the system permits
Bare Threshold ~ 1500e for Diamond
~ 2500e for Silicon
(why does it not scale with noise?)

In order to fit the hit into the beam crossing of 20 ns,
the signal has to exceed the threshold by the “overdrive”.
In-time Threshold = bare threshold + overdrive

Signal needs to be > 2x In-time Threshold:

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Bare [e]</th>
<th>Overdrive [e]</th>
<th>In-time [e]</th>
<th>Required Signal [e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si planar</td>
<td>2500</td>
<td>1300</td>
<td>3800</td>
<td>7600</td>
</tr>
<tr>
<td>Si 3D</td>
<td>2500 (?)</td>
<td>1800</td>
<td>4300</td>
<td>8600</td>
</tr>
<tr>
<td>Diamond</td>
<td>1500</td>
<td>800</td>
<td>2300</td>
<td>4600</td>
</tr>
</tbody>
</table>
Need comparisons of CCE(V) with (m.i.p.) and S/N after $10^{16}$ neq/cm$^2$ of protons

Preliminary results show marginal performance for 3D.

Need to optimize FEE?

Planar n-on-p adequate for all but innermost Pixel Layer
Planar (protons!) and diamond are not adequate for innermost Pixel Layer
RD50 provided the bases for understanding the use of tracking detectors at the LHC upgrade.
No magic new semiconductor tracking material found.

Paradigm change in Si at fluence of about $10^{15}$ neq/cm$^2$:
At lower fluences depletion of sensors important.
MCz seems to be favored, at least for neutrons
Strong annealing in n-type FZ, little annealing in p-type and n-type MCz.
Collect electrons in n-on-p (cheaper than n-on-n) because of high mobility.
Collected charge almost independent of wafer type except n-type FZ.
At higher fluences trapping dominates
but high resistivity MCz p-type could have depletion advantage at very high fluences.

A straw-man tracker layout at the sLHC looks like this:
Planar n-on-p sensors with long and short strips at large and medium radius and the outer pixels.
At small radii, the pixel sensors might need to be made from 3D sensors, but we need more high fluence proton data with planar p-type MCz.
Thanks to

the foundries and institutes who supplied sensors,

RD50 collaborators in Ljubljana, Liverpool, Louvain, CERN, Karlsruhe, PSI, UCSC for carrying out the irradiations, and analyzing the data.

the many students who spend their evenings and nights taking and analyzing the data.
References

ATLAS Tracker Upgrade Workshop Valencia Dec 11-14 2007
http://indico.cern.ch/conferenceTimeTable.py?confId=21398

ATLAS Upgrade Website
http://indico.cern.ch/categoryDisplay.py?categId=350

RD50 Website
http://rd50.web.cern.ch/rd50/

LHC Machine Operations Website
http://lhc-operation.web.cern.ch/lhc-operation/
To keep ATLAS running more than 10 years the inner tracker will have to go ... (Current tracker designed to survive up to $730 \text{ fb}^{-1} \approx 10\text{ Mrad}$ in strip detectors)

For the luminosity-upgrade the new tracker will have to cope with:

- much higher occupancy levels $3000 \text{ fb}^{-1}$
- much higher dose rates $\sim 300\text{ Mrad}$
- same performance

To build a new tracker for 2015, major R&D program already needed. Steering group (lead Nigel Hessey) and several working groups. Formal proposal submittal structure.

Timescales:
- R&D leading into a full tracker Technical Design Report (TDR) in 2010
- Construction phase to start immediately TDR completed and approved.

The intermediate radius barrels are expected to consist of modules arranged in rows with common cooling, power, clocking and cooling. The TDR will require prototype super-modules/staves (complete module rows as an integrated structure) to be assembled and fully evaluated. All components will need to demonstrate unprecedented radiation hardness.
many strategies to follow up, new techniques, many unknown parameters ….
needs first beam

25 ns vrs 50 ns … 12ns, 75ns gone!
LHC nominal and ultimate L strategy -> new large aperture triplet
Early separation scheme, magnets inside the detector … small crossing angle
Beam-beam effects: unclear can be tolerated, wait for LHC beam
Luminosity leveling: new … more fill lifetime, less peak luminosity
Crab cavities,…: new magic technology, need substantial R&D

ATLAS message is always the same:
we prefer more constant luminosity, less pile up at the start of the run, higher luminosity at the end
Current Inner Tracker Layout

Pixels (50 μm × 400 μm): 3 barrels, 2×3 disks
- Pattern recognition in high occupancy region
- Impact parameter resolution (in 3d)

Radiation hard technology: n+-in-n Silicon technology, operated at -6°C

Strips (80 μm × 12 cm) (small stereo angle): “SCT” 4 barrels, 2×9 disks
- pattern recognition
- momentum resolution
- p-strips in n-type silicon, operated at -7°C

TRT 4mm diameter straw drift tubes: barrel + wheels
- Additional pattern recognition by having many hits (~36)
- Standalone electron id. from transition radiation

Mean Occupancy in Innermost Layer of Current SCT

Pixels: 1.8 m², ~80M channels
SCT: 61 m², ~6.3M channels
TRT straws: ~400k channels

Hartmut F.-W. Sadrozinski, SLAC AIS Jan 9, 2008
New SLHC Layout Implications

Strawman 4+3+2

Pixels: 
Short (2.4 cm) \(\mu\)-strips (stereo layers): 
Long (9.6 cm) \(\mu\)-strips (stereo layers):

\[ r = 5\text{ cm}, 12\text{ cm}, 18\text{ cm}, 27\text{ cm} \quad z = \pm 40\text{ cm} \]
\[ r = 38\text{ cm}, 49\text{ cm}, 60\text{ cm} \quad z = \pm 100\text{ cm} \]
\[ r = 75\text{ cm}, 95\text{ cm} \quad z = \pm 190\text{ cm} \]

J. Tseng

Short and Long Strip Occupancy

1.6%  Only LO MC (Pythia). May need to include \(\times 2\) safety factor?
1.2%  
0.8%

Including disks this leads to:

- Pixels: 5 m\(^2\), \(~300,000,000\) channels
- Short strips: 60 m\(^2\), \(~28,000,000\) channels
- Long strips: 100 m\(^2\), \(~15,000,000\) channels

Hartmut F.-W. Sadrozinski, SLAC AIS Jan 9, 2008