Advanced Detector Technology

Luciano Musa - CERN
Silicon Tracker at the LHC Experiments (recap lecture 1)

Detector Technologies for the Central Trackers at the LHC Experiments

CMS Tracker
- Si-pixel, Si strip
- Phase-I upgrade: replacement of Si-pixel
- Phase-II upgrade: Si pixel + Si Strip (entirely new)
- 200 m² silicon strips

ATLAS Tracker
- Si-pixel, Si strip, TRT (gas, transition radiation)
- Phase-I upgrade: one more Si-pixel layer (BE)
- Phase-II upgrade: Si pixel + Si Strip (entirely new)
- 200 m² silicon strips

Detector Technologies for the Central Trackers at the LHC Experiments

ALICE Tracker
- Si pixel, Si drift, Si strip, TPC (gas), TRD (gas, trans. rad.)
- Phase-I upgrade: Si-pixels + TPC & TRD (new readout)
- 10 m² silicon pixels

LHCb Tracker
- Si strips (VELO), silicon+straw tubes
- Phase-I upgrade: Si pixel, scintillating fibers
- Pixels to cope with higher particle rates

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A Detector Based on a p⁺n Reversed Biased Junction (recap lecture 1)

p⁺n diode detector
- Reverse bias (positive voltage on n-bulk wrt p⁺ side)
- Increase reverse voltage to fully deplete the entire bulk of free charge carriers

⇒ Full volume is sensitive to a passing particle (ionization chamber)
- Highly n-doped layer to provide ohmic contact (n⁺)

Effective doping concentrations
- \(N_a = 10^{15} \text{ cm}^{-3}\) in p⁺ region
- \(N_d = 10^{12} \text{ cm}^{-3}\) in n bulk

Without applying any external voltage
- \(W_p = 20 \text{ nm}, \quad W_n = 23 \mu\text{m}\)

Applying an external voltage of 100V
- \(W_p = 400 \text{ nm}, \quad W_n = 363 \mu\text{m}\)

Voltage at which full thickness of the diode is depleted

\[
V_{fd} = \frac{e}{2\varepsilon_s} (N_D - N_A) d^2
\]

\(d\) ..thickness
\(N_D - N_A = N_{\text{eff}}\) ..effective doping concentration

\[
C = \frac{\varepsilon_0 \varepsilon_r}{2 \mu \rho |V|} \cdot A
\]

\(\rho\): resistivity of the bulk
\(\mu\): mobility of majority carrier
\(V\): bias voltage
\(A\): detector surface
Silicon Strips and Pixels (recap lecture 1)

- **Single sided strip sensor**
  - n⁺ ohmic bulk contact (0V)
  - N channels

- **Double sided strip sensor**
  - n⁺ strips
  - 2x N channels

- **Pixel Sensor**
  - n⁺ ohmic bulk contact (0V)
  - N² channels

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Double sided silicon strips for the CBM (FAIR)

Double Sided Strip Detector (DSSD)

Ambiguity at high occupancy

Nr. channels = 2 x N

n-side – strips parallel to edge (beam line)
p-side – stereo angle 15 degree

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Double Sided Strip Module

ATLAS Endcap Module Design

- 4 wedge shape silicon sensors
- 768 p-in-n strips, single sided
- supplied by Hamamatsu and CiS
- sensor alignment < 5μm
- 40 mrad stereo angle

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Pixel Chip (recap lecture 1)

Pixel detectors

- Truly two-dimensional sensitivity
- No two-hit ambiguity
- Single-sided process

Pixel Sensor Bump Bonded to the Readout Chip

- But nr. Channels $N^2$
- Minimum pitch limited by bump bonding technology
  $\Rightarrow$ position resolution $> 10 \mu m$
Lecture 2

- Silicon Tracking Detectors – Some Examples at LHC
- Silicon Tracking Detectors – New Developments
- Monolithic Pixel Detectors
- Application of HEP Silicon Detectors outside HEP

This lecture makes use of material from the following authors

- D. Bortoletto (Oxford University, UK)
- P. Riedler (CERN)
- Michael Moll (CERN)
- J: Christansen (CERN)
- Piero Giubilato (University of Padua, Italy)
Silicon Tracking Detectors

Some examples at LHC
The CMS Silicon Strip Tracker

- Size: 6m x 2.5m

- The largest silicon detector ever built
  - 207 m² of active silicon
  - 15’100 Si Modules
  - 75’000 APV FE chips
  - 9.6 M readout channels
  - 26 M wire bonds
  - 37.000 Optical links

- Required temperature: –10 °C on the Silicon surface

September 2007

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The CMS Silicon Strip Tracker – The Constituents

One Quadrant of Tracker in r-z  
11.4x10^6 microstrips  
Occupancy ~1%

TOB (Tracker Outer Barrel)  
6 layers, 5200 modules

SS Modules red  
DS Modules blue  
(100 mrad stereo angle)

hermetically closed system  
tracking combines to outer muon system resolution of p_t ~1.5% at 100GeV

TIB (Tracker Inner Barrel)  
4 layers  
2700 modules

TID (Tracker Inner Disks)  
2x3 disks  
800 modules

TEC (Tracker EndCap)  
2x9 disks  
6400 modules

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CMS Silicon Strip Sensors

- p-in-n type silicon
- 1.5 – 3.2 kΩ cm resistivity; 320 µm thickness
- 4.0 – 8.0 kΩ cm resistivity; 500 µm thickness

Strip length
From 10 cm (innermost) to 20 cm (outermost)

Strip pitch
From 80 µm (innermost) to 205 µm (outermost)
CMS Tracker Module

Sensor signal interconnection: Al wire wedge bonding

5200 TOB Modules
example: “stereo”-type
512 strips/sensor

6400 TEC Modules, 800 TID Modules
10 different geometries

2700 TIB Modules
768 strips/sensor
CMS Full Silicon Tracker – The largest Silicon Device
ATLAS Inner Detector (ID)

- 15 thousand silicon sensors
- 6 M silicon strips (80 μm x 12.8 cm)
- 80 M pixels (50 μm x 400 μm)

required temperature: \(-10^\circ C\) on the silicon surface

4 barrel layers
2 x 9 forward disks

16 thousand silicon sensors (60 m\(^2\))
ATLAS Inner Detector

Silicon Pixels, Silicon Strips and Transition Radiation Tracker

**Pixel Detector**
- 3 barrels, 3+3 disks: $80 \times 10^6$ pixels
- Pixel size: $50 \times 400 \ \mu m^2$
- $\sigma_{r\phi} = 10 \ \mu m$, $\sigma_z = 66 \ \mu m$

**SCT**
- 4 barrels, disks: $6.3 \times 10^6$ strips
- Strip pitch: $80 \ \mu m$
- Stero angle $\sim 40 mrad$
- $\sigma_{r\phi} = 16 \ \mu m$, $\sigma_z = 580 \ \mu m$

**TRT**
- Barrel: $55 cm < R < 108 \ cm$
- 36 layers of straw tubes
- $\sigma_{r\phi} = 170 \ \mu m$
- $400 \times 10^3$ channels
ATLAS SCT – Sensors

Sensors
- p-on-n single sided detectors
- thickness 285 µm
- 2-8 kΩcm
- Barrel
  - 64 x 64 mm²
  - 80 µm pitch
- Forward
  - 5 different wedge shaped sensors
  - Radial strips
  - 50 … 90 µm pitch
- 768 readout-strips
- AC coupled

4 barrel layers
2 x 9 forward disks
All 4088 modules double sided
ATLAS Semiconductor Tracker

SCT: 4088 modules; 6 million channels
Pixel Detectors
Primary and Secondary Vertex
Open charm (➔ QGP hard probe)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Decay Channel</th>
<th>cτ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D⁰</td>
<td>K⁻ π⁺ (3.8%)</td>
<td>123</td>
</tr>
<tr>
<td>D⁺</td>
<td>K⁻ π⁺ π⁺ (9.5%)</td>
<td>312</td>
</tr>
<tr>
<td>D⁻ s</td>
<td>K⁺ K⁻ π⁺ (5.2%)</td>
<td>150</td>
</tr>
<tr>
<td>Λ⁺ c</td>
<td>p K⁻ π⁺ (5.0%)</td>
<td>60</td>
</tr>
</tbody>
</table>

Example: D⁰ meson

Analysis based on invariant mass, PID and decay topology

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Invariant mass distribution of $K\pi^+$ pairs before and after applying selection criteria on the relation between the secondary ($D^0$ decay) and primary vertices

Example: $D^0$ meson

Analysis based on invariant mass, PID and decay topology
Very good MC description

ALICE
pp $\sqrt{s} = 7$ TeV

Very weak dependence on the colliding system

ALICE charged particles

120 $\mu$m at $p_T = 500$ MeV/c
What determines the impact parameter resolution?

Vertex projection from two points: a simplified approach (telescope equation)

pointing resolution = \((a \oplus b \text{GeV/p}\cdot c) \mu\text{m}\)

\[ \Delta v = \Delta x \cdot \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}} \]

From detector position error

From Coulomb scattering

first pixel layer

\[ \theta_m = \frac{13.6 \text{MeV}}{\beta \cdot c \cdot p} \cdot \sqrt{X_0} \]

\[ \Delta v = \theta_m \cdot r_1 \]

\[ X_0 = 0.3\% \]
## Hybrid Pixel Detectors at the heart of the LHC Experiments - Different sensor technologies, designs, operating condition

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ALICE</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nr. layers</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Radial coverage [mm]</td>
<td>39 - 76</td>
<td>50 - 120</td>
<td>44 – 102</td>
</tr>
<tr>
<td>Nr of pixels</td>
<td>9.8 M</td>
<td>80 M</td>
<td>66 M</td>
</tr>
<tr>
<td>Surface [m²]</td>
<td>0.21</td>
<td>1.7</td>
<td>1</td>
</tr>
<tr>
<td>Cell size (rφ x z) [µm²]</td>
<td>50 x 425</td>
<td>50 x 400</td>
<td>100 x 150</td>
</tr>
<tr>
<td>Silicon thickness (sens. + ASIC) - x/X₀ [%]</td>
<td>0.21 + 0.16</td>
<td>0.27 + 0.19</td>
<td>0.30 + 0.19</td>
</tr>
</tbody>
</table>

\[ \sigma_{rφ} \approx 10 – 20 \, \mu m \]

Spatial resolution better than pixel pitch x 1/√12 due to charge sharing.
ALICE Pixel Detector (SPD) – half stave

5 readout chips/sensor
0.25µm CMOS
13.68 mm x 15.58 mm
thinned to 150 µm

p-in-n silicon sensor
72.72 mm x 13.92 mm
200 µm thin
Sensor
- 47232 n-on-n pixels
- 250 µm thickness
- 50 µm (Rφ) × 400 µm (z)
- 328 rows (x_{local}) × 144 columns (y_{local})

16 FE chips
- bump bonded to sensor

charge amplitude via pulse width (ToT)
noise ~160e⁻ (on module)
Silicon Tracking Detectors
New Developments
Challenges for Silicon Sensors at the HL-LHC

HL-LHC: up to $7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$

Extreme rate conditions (3GHz/cm²)
Extreme radiation load

Radiation levels for 1st pixel layer after 3000 fb⁻¹

Non-ionizing energy loss (NIEL)
$\Phi_{eq} \approx 2 \times 10^{16} / \text{cm}^2$

Ionizing energy loss (IEL)
Dose $\approx 12 \text{ MGy}$
Radiation Damage to Silicon Sensors Induced by NIEL

Atomic displacement caused by massive particles (p, n, π)
- Charged defects $\Rightarrow$ change of effective doping concentration $\Rightarrow$ increase $N_{\text{eff}} (= N_D - N_A)$ and depletion voltage
- Shallow defects $\Rightarrow$ generation of trapping centers $\Rightarrow$ trapping of signal charge (at RT fast de-trapping)
- Midgap defects $\Rightarrow$ generation/recombination levels in band gap $\Rightarrow$ increase of leakage current

Increase of $I_{\text{leak}}$
more noise $\Rightarrow$ more power $\Rightarrow$ thermal runaway
$\Rightarrow$ more cooling $\Rightarrow$ more material

Change in $N_{\text{eff}}$
“type inversion” (“reverse annealing”)
Need higher $V_{\text{bias}}$ operation in partial depletion

from M. Moll

\[
V_{fd} = \frac{e}{2\varepsilon} \cdot |N_{\text{eff}}| \cdot d^2
\]
Sensor Radiation Damage

Macroscopic bulk effects

Depletion Voltage ($N_{\text{eff}}$)

Leakage Current

Charge Trapping

"Type inversion": $N_{\text{eff}}$ changes from positive to negative (Space Charge Sign Inversion)

Signal to Noise ratio is the quantity to watch (material + geometry + electronics)

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Device Engineering – p-on-n vs. n-in-p

**n-type silicon after high fluencies** (type inverted)

- p⁺on-n
- p'-strips
- Undepleted region
- Active region
- n'layer
- Traversing particle

**p-type silicon after high fluencies** (still p-type)

- n⁺on-p
- n'-strips
- Undepleted region
- Active region
- p'layer
- Traversing particle

**p-on-n silicon, under-depleted:**
- Charge spread – degraded resolution
- Charge loss – reduced CCE

**n-on-p silicon, under-depleted:**
- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (3 x faster than holes)

_from M. Moll_

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Silicon Materials for tracking Detectors

Signal comparison for p-type silicon sensors

**FZ Silicon Strip Sensors**
- n-in-p (FZ), 300μm, 500V, 23GeV p [1]
- n-in-p (FZ), 300μm, 500V, neutrons [1,2]
- n-in-p (FZ), 300μm, 500V, 26MeV p [1]
- n-in-p (FZ), 300μm, 800V, 23GeV p [1]
- n-in-p (FZ), 300μm, 800V, neutrons [1,2]
- n-in-p (FZ), 300μm, 800V, 26MeV p [1]
- n-in-p (FZ), 300μm, 1700V, neutrons [2]
- p-in-n (FZ), 300μm, 500V, 23GeV p [1]
- p-in-n (FZ), 300μm, 500V, neutrons [1]

References:
1. G. Casse, VERTEX 2008 (p/n-FZ, 300μm, -30°C, 25ns)
2. I. Mandic et al., NIMA 603 (2009) 263 (p-FZ, 300μm, -20°C to -40°C, 25ns)

**Silicon Sensors currently installed**

- Strips: ALICE, CMS, ATLAS: p-in-n
- LHCb: n-in-n, n-in-p

**Pixels**
- ALICE: p-in-n
- CMS, ATLAS: n-in-n

**Note:** Measured partly under different conditions! Lines to guide the eye (no modeling)!

- highest fluence for strip detectors in LHC
- use of p-in-n technology is sufficient
- n-in-p technology should be sufficient for HL-LHC at radii presently (LHC) occupied by strip sensors
Use of other Semiconductor Materials?

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>GaN</th>
<th>4H SiC</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ [eV]</td>
<td>5.5</td>
<td>3.39</td>
<td>3.3</td>
<td>1.12</td>
</tr>
<tr>
<td>$E_{\text{breakdown}}$ [V/cm]</td>
<td>10$^7$</td>
<td>4·10$^6$</td>
<td>2.2·10$^6$</td>
<td>3·10$^5$</td>
</tr>
<tr>
<td>$\mu_e$ [cm$^2$/Vs]</td>
<td>1800</td>
<td>1000</td>
<td>800</td>
<td>1450</td>
</tr>
<tr>
<td>$\mu_h$ [cm$^2$/Vs]</td>
<td>1200</td>
<td>30</td>
<td>115</td>
<td>450</td>
</tr>
<tr>
<td>$v_{\text{sat}}$ [cm/s]</td>
<td>2.2·10$^7$</td>
<td>-</td>
<td>2·10$^7$</td>
<td>0.8·10$^7$</td>
</tr>
<tr>
<td>e-h energy [eV]</td>
<td>13</td>
<td>8.9</td>
<td>7.6-8.4</td>
<td>3.6</td>
</tr>
<tr>
<td>e-h pairs/X$_0$</td>
<td>4.4</td>
<td>~2-3</td>
<td>4.5</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Diamond: wider bandgap
⇒ lower leakage current
⇒ less cooling needed
⇒ less noise

Signal produced by m.i.p:
- Diamond 36 e/μm
- Si 89 e/μm
⇒ Si gives more charge than diamond

GaAs, SiC and GaN
⇒ strong radiation damage observed
⇒ no potential material for LHC upgrade detectors
(judging on the investigated material)

Diamond (RD42)
⇒ good radiation tolerance (*CCE degradation similar to silicon*)
⇒ already used in LHC beam condition monitoring systems and partially in ATLAS IBL
⇒ considered as potential detector material for HL-LHC pixel sensors

poly-CVD Diamond – 16 chip ATLAS pixel module

single crystal CVD Diamond of few cm$^2$
Hadron fluency ($2 \times 10^{16} / \text{cm}^2$) → Silicon sensor bulk damage

- charge trapping reduces dramatically minority carriers lifetime (signal loss by recombination)
- Mitigation: reduce drift time (distance)

**Thin-planar sensor**
- drift length $L < 200 \mu m$ (now: $300 \mu m$)
- n-in-p (e signal)
- outer and possibly also innermost layers/rings

**3D sensor**
- shorter drift length $L$
- lower depletion voltage
- technically more challenging
- inner layer (at most one)

Reduction of Voltage for full depletion!!

3D pixel sensors installed in ATALS to partially populate the IBL
“3D” electrodes:
- narrow columns along detector thickness,
- diameter: 10µm, distance: 50 - 100µm

Lateral depletion:
- lower depletion voltage needed
- thicker detectors possible
- fast signal
- more complex, lower yield, higher cost
- higher capacitance (more noise)

3D is the most radiation hard technology to-day:
Similar performance than planar sensors, but less demanding in terms of bias voltage and cooling

HL-LHC needs
- More radiation hard (1-2x10^{16} n_{eq}/cm^2)
- Smaller pixels (reduce occupancy, 50-25µm)
- Thinner (reduce cluster size/merging, 200-100 µm)

Intensive R&D ongoing – decision will depend on performance, radiation tolerance, cost/yield
Extremely challenging requirements for HL-LHC

- **Extreme hit rates**: $3\text{GHz/cm}^2$, innermost layer for 200 pileup events (PU=200)
  - High granularity: small pixels: $50\times50\mu\text{m}^2$ ($25\times100\mu\text{m}^2$) with 25ns tagging
- **Extreme radiation load**: 1 Grad, $2 \times 10^{16} \text{1MeV } n_{eq}/\text{cm}^2$ over 10 years
- **High readout rate**: $\sim1\text{MHz} \Rightarrow$ very high data throughput, $O(1\text{Gbit/sec per cm}^2)$
- **Long trigger latency** $\sim10\mu\text{s}$ (hit buffering requirements increased by a factor 100)
- **Large chips**: $\sim 2 \times 2 \text{ cm}^2$ ($\sim 1$ billion transistors)
- **Low mass “low” power consumption**, “exotic = serial” powering scheme

**Baseline Technology: 65nm**

- **Pixel Readout chip for ATLAS and CMS at HL-LHC (RD53)**

- **Full scale demonstrator chip in 2017**

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Monolithic Pixel Detectors
CMOS Pixel Sensors
Beyond Hybrid Pixel Detectors ...

- Limited number of sensors producers (~10 world-wide)
- no industrial scale production → high cost

- Complex and costly interconnection between sensors and ASIC
- Interconnection technology (micro-bump bonding) limits:
  - pitch (currently ~30µm)
  - input capacitance → power

Lower production cost
Higher integration (pitch, x/X₀)
Lower power (x/X₀, cost)
ALICE Monolithic Pixel Detector

CMOS Pixel Sensor using 0.18μm CMOS Imaging Process

- High-resistivity (> $1k\Omega$ cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < $V_{BB}$ < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors

▶ full CMOS circuitry within active area

Fully depleted MAPS have also been recently developed by ALICE (see appendix and references)

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Pixel Sensor Chip (ALPIDE) – Main features

1. Overview

- ALICE experiment will fully replace its present Inner Tracking System (ITS) during the second long shutdown of the LHC in 2019/2020.
- New ITS will be fully equipped with monolithic CMOS pixel sensors.
- Development of dedicated pixel chip for the ITS upgrade – ALPIDE.
- Fabricated in TowerJazz 180nm CMOS Imaging Sensor (CIS) process.
- Chip development started end 2011, including 4 MPWs and 5 engineering runs, containing various small and full-scale prototypes.
- One of them: INVESTIGATOR.

Inner Barrel

- 7 layers, grouped into two barrels.
- Radial coverage 22mm - 406mm.
- ~10m² active area, ~25000 chips.
- ~12.5 Gigapixels with binary readout.

Outer Barrel

Ø M. Mager: The Upgrade of the ALICE Inner Tracking System with the Monolithic Active Pixel Sensor ALPIDE, Session N12: High energy physics instrumentation I: Silicon, Monday, Oct. 31, 18:00.


ALPIDE

- 1024 pixel columns.
- 512 rows.
- External trigger or Continuous.

IB: 50µm thick
OB: 100µm thick

130,000 pixels / cm²

27x29x25 µm³

Spatial resolution: ~ 5 µm (3-D)
Max particle rate: 100 MHz / cm²
Fake-hit rate: < 10⁻⁹ pixel / event
Power: ~ 300 nW /pixel
ITS Pixel Chip – role of diode capacitance

Low capacitance $\Rightarrow$ large S/N at low power

NWELL DIODE output signal = $Q / C$

- Minimize spread of charge over many pixels
- Minimize capacitance:
  - small diode surface
  - large depletion volume

Silicon strip capacitance: $> 10$ pF ($\sim 1.5$ pF / cm)

Hybrid pixel capacitance: $\sim 300$ fF

Monolithic pixel capacitance: $< 5$ fF

$C_d = 1$ fF: $1000$ e$^- \Rightarrow 160$ mV (almost a digital signal)
Blank Wafers QA at TMEC (SRP and XSEM measurements)

Resistivity: ITS5 run, T608519.1-6A1, 25 um epi

Wafer thickness: 97.22 µm

High-res epi: 25.28 µm
Other Applications

Space and medicine
• **0.15 T** (1200 kg NdFe permanent magnet, instead of planned 0.87 T niobium-titanium)
• 6.2 m² silicon tracker, 200 µm thick, 50 µm pitch double sided strips, 0.7 mW/channel (**200 W** total)
• Maximum Detectable Rigidity (MDR): about **2 T** (10 µm track resolution)

As it is difficult to foresee a more powerful magnet, to increase the detectable rigidity the way is to increase spatial resolution: we need a device of high granularity (**3 µm** for **1 µm** resolution) and ultra-low power consumption (**5 mW/mm²**).
Proton (ion) energy transfer is highly localized (Bragg peak): greater effectiveness and much lower collateral damage respect to traditional x-rays therapy.

The Bragg peak position (depth) in the body depends on the ion energy and the tissue density it traverses. Changing energy determines the aiming depth.

from P. Giubilato
Medical – proton therapy aiming limits

Aiming the Bragg peak requires fine tuning of the proton energy to account for the tissue densities they have to traverse to reach the tumor.

X-ray 3D CTs cannot distinguish tissue densities with the required precision, leading to Bragg peak aiming errors much worse than the Bragg peak intrinsic spread. But protons actually can (and with much less dose).

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from P. Giubilato

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NIM B 268 (2010) 3295–3305
The pCT works on the same principle as a “standard” x-rays CT: recording particles passing through the target from different angles to reconstruct a 3D image. Main difference is that, while photons are simply absorbed, protons also scatter.

At least $10^9$ proton tracks (energy loss, exit point & angle, entry point) have to be recorded to provide a detailed enough image. This leads to long exposure time (some 10s minutes) even with the best current state of the art prototypes.
References

Silicon Strip and Pixel Detectors

4. Garcia Sciveres M., Wermes N. “Advances in pixel detectors for experiments with high rate and radiation”
8. Proton Imaging: Proton imaging: "High-energy proton imaging for biomedical applications” Nature Scientific Reports - 6, Article number: 27651 (2016), doi:10.1038/srep27651
Appendix II
Fully Depleted CMOS Pixel Sensors
Applications, a drift field and hence depletion is required over the full around the collection electrode and signal charge generated outside the requirements. However, depletion in the sensor is limited to the region to well beyond.

Higher resistivity epitaxial layer for which the drift component in the devices with a higher radiation tolerance have been reported with a degradation after fluences in excess of primarily by diffusion, and often already show significant performance to non-ionizing energy loss (NIEL), traditional MAPS collect charge possible to use a deep nwell to obtain a standard triple well structure.

Outside of the pixel matrix it is also activity in the readout circuitry. In the standard process (Fig. 1), the onsets of punchthrough between deep pwell and substrate at around 10\(V\) reverse substrate bias for various collection electrode biases (Fig. 3), the peak positions indicate that increasing the higher implant in the modified process is higher than the lower one by several tens of percent.

Cluster size distributions indicate the full signal is collected on a single cluster (Fig. 4), with no sensor capacitance penalty, indicating the depletion dose there is no sensor capacitance penalty, indicating the depletion implant dose yields a slightly higher sensor capacitance, for a lower dose there is no sensor capacitance penalty, indicating the depletion.

Arrows point to the depletion boundary.

Tower Semiconductor Modified CMOS Imaging Sensor Process

**Standard Process**

**Modified Process (CERN & Tower Semiconductor)**

Used for ALPIDE (ALICE Pixel Sensors)
TJ standard process vs modified process - $^{55}$Fe spectra

(*) measurement limited by output buffer speed (~10ns)
Detection efficiency measurements in progress, first results encouraging

Standard process not working after $1 \times 10^{15}$ neq