カロリメータ関連アレコレ

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EIC日本グループ会合
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前置き

- EIC 日本グループ会合に参加させて頂いて
  - 検出器の話題：カロリメータ (Si/W, 結晶)、シリコントラッカー
  - 知っている情報や思いつきをコメントしてきました。

- ご興味がありそう・参考になりそう、と思える話題をピックアップ
  - シリコン検出器の放射線耐性
  - LGAD

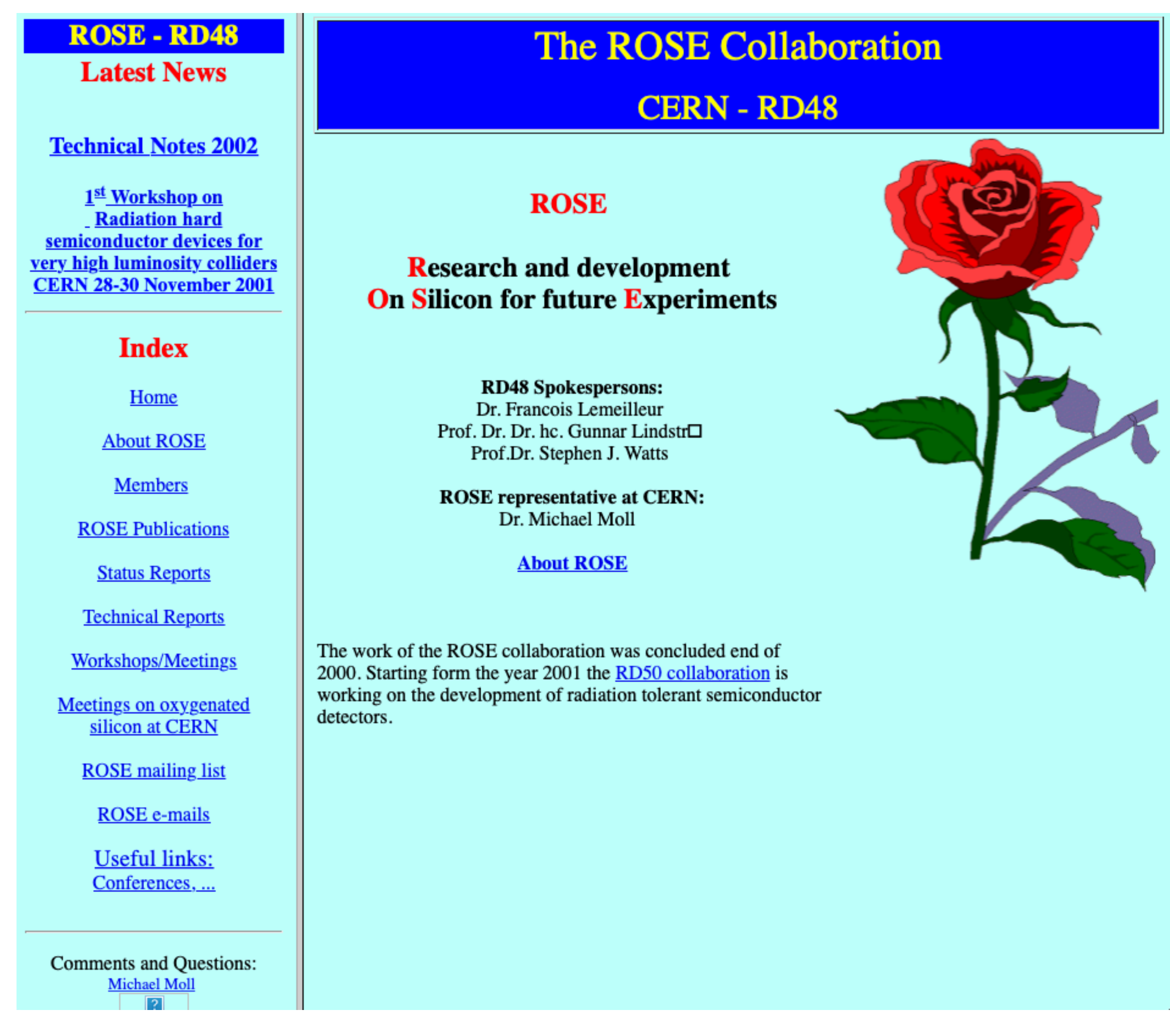
  - 無機結晶
    - スライド多くなったので、次回以降に
    - COMET LYSO + APD, CMS LYSO 案 etc を例に
    - GSO, LGSO もオモシロイ結晶かと
      - 国産：OXIDE

シリコン検出器の放射線耐性

- A long time ago in US far, far away…
  - Before SSC, 70年代くらいか
  - シリコンは放射線耐性が低いと考えられていた
  - 理解は進んでいなかったが、意外にイケるのではないか

- 現代的な理解：CERN RD48 (ROSE) からだと思われる
  - 1996年形成、LHC 実験のため
  - Hambrug グループ主導
  - 成果まとめ　“Hambrug Model”
    - Michael Moll の博士論文
      Radiation Damage in Silicon Particle Detector
      http://mmoll.web.cern.ch/thesis/
  - 後継：CERN RD50
    - HL-LHC 実験のため
    - 有用な情報がいっぱい
      https://rd50.web.cern.ch

https://rd48.web.cern.ch



結論その１：Leakage Current

- バルク損傷のよる増加
  - n/p型・結晶生成方法によらない
  - “Density の増加は 1 MeV-eq neutron fluence に比例”
  - $\alpha = 4\mathrm{x}10^{-17}$ A/cm
    - “80 min, 60°C” 条件
  - Damage = stable + annealing

逆手に取って、増加からfluence測定可能

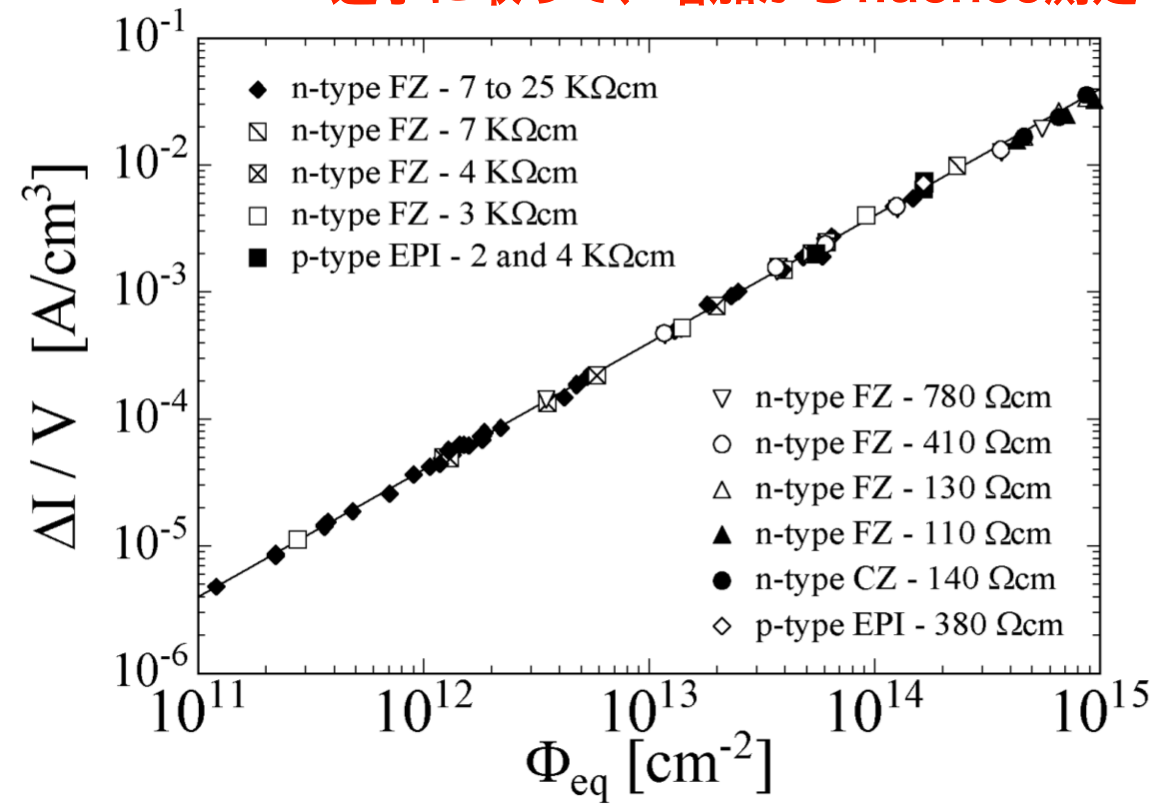
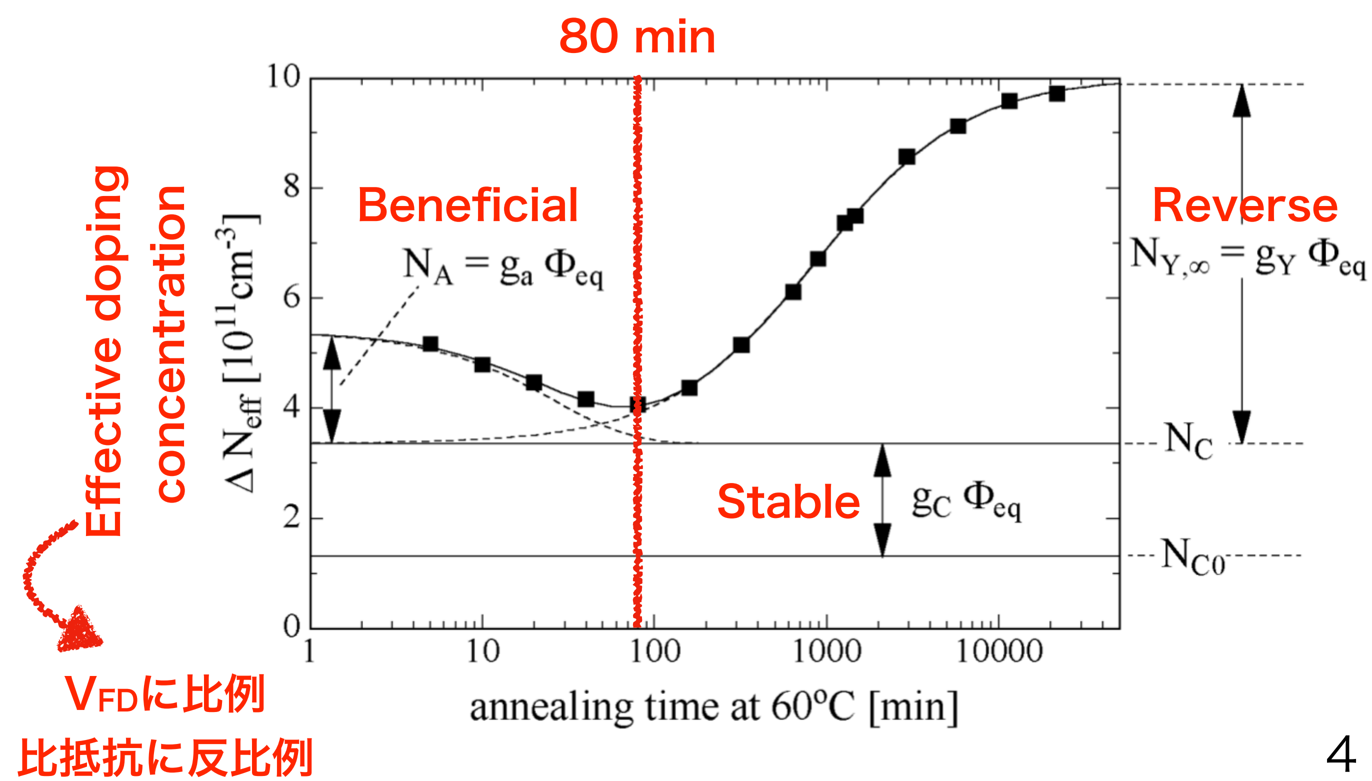


Figure 5.1: Fluence dependence of leakage current for silicon detectors produced by various process technologies from different silicon materials. The current was measured after a heat treatment for 80 min at 60°C $\{\alpha(80\,\mathrm{min}, 60°\mathrm{C}) = (3.99 \pm 0.03) \times 10^{-17}\mathrm{A/cm}$; for details see Fig. 5.6}.

- 条件：Annealing
  - 損傷 = stable + annealing
  - Annealing は温度・時間に依存
    - Beneficial
    - Reverse
  - “80 min, 60°C”
    - Beneficial annealing が最大



結論その2：Full Depletion Voltage

- バルク損傷による型変換
  - n型からp型へ
    - Effective doping concentration の変化として理解
  - 条件：”80 min, 60°C”
    - Beneficial annealing 最大
  - 特徴
    - 型変換する fluence では V_{FD}はゼロ
    - 型変換後は、早く増加

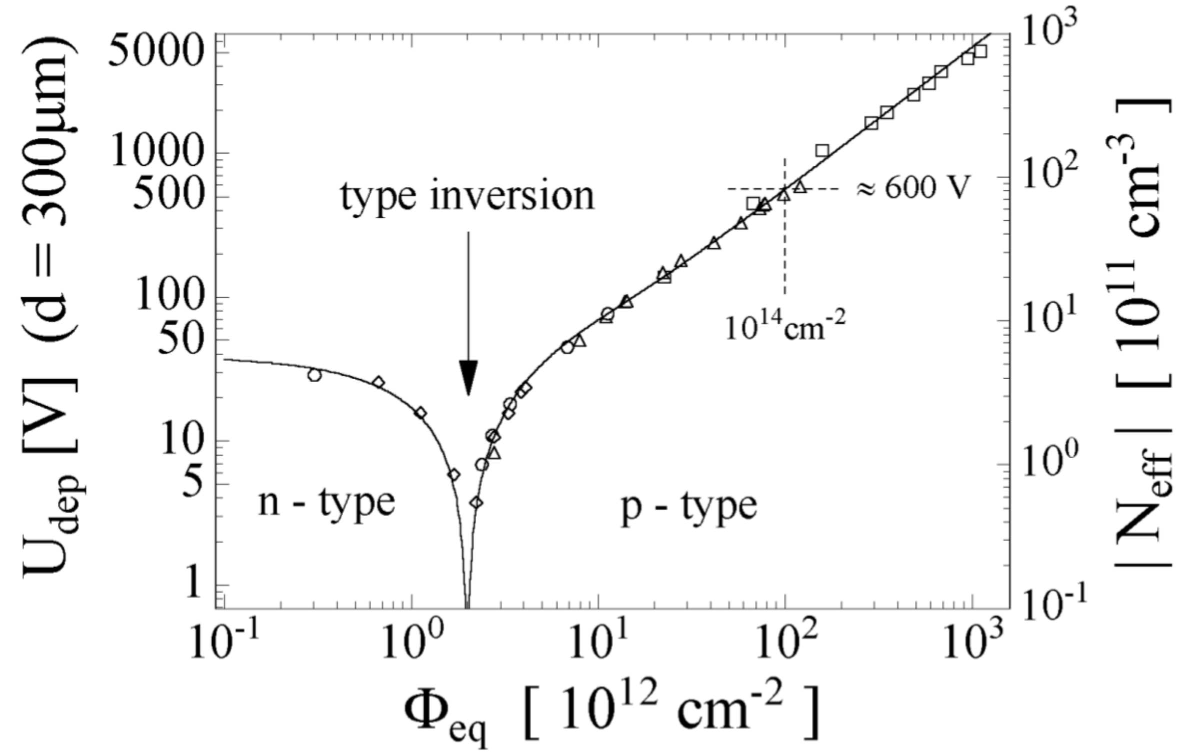


Figure 5.8: Change in the depletion voltage respectively the absolute effective doping concentration as measured immediately after irradiation [Wun92].

- シリコン検出器の特徴の一般論
  - n型：型変換する
    - 初期値を大きく取る (V_{FD} 大) → 遅く型変換、検出器としての放射線耐性は見かけ上は向上
    - 型変換後も空乏化できれば良い → 耐圧・カレントリミットに注意、部品・バイアス性能
  - p型：型変換しない
    - 高比抵抗の材料入手が難しかった → 最近は問題なし
  - 冷却シナリオ
    - Beneficial annealing (BA) を活かす → 休止期間は常温に戻す、BA 後は冷却維持

結論その3：NIEL

“1 MeV Equivalent” の換算

基準：中性子、1 MeV が 1

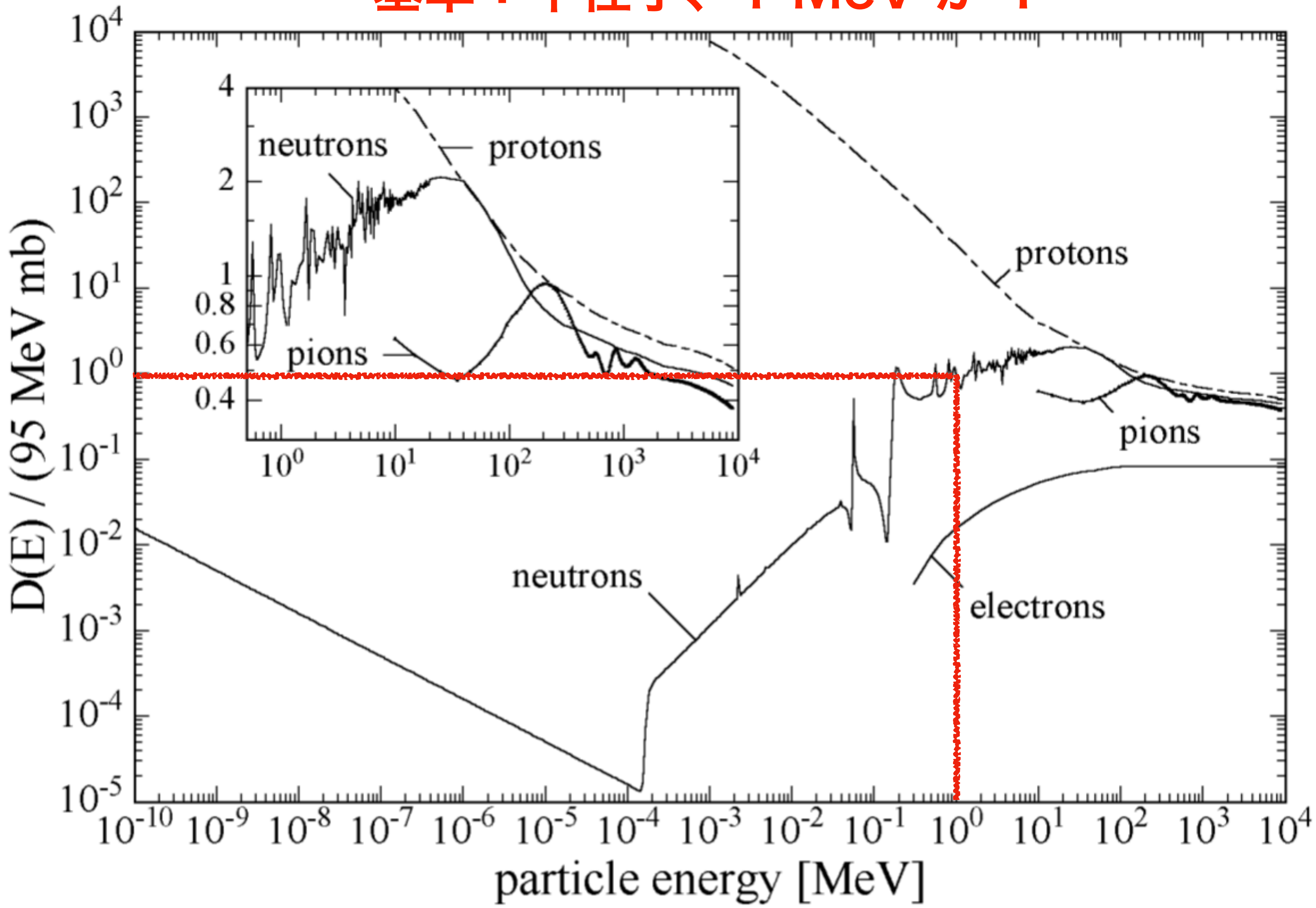


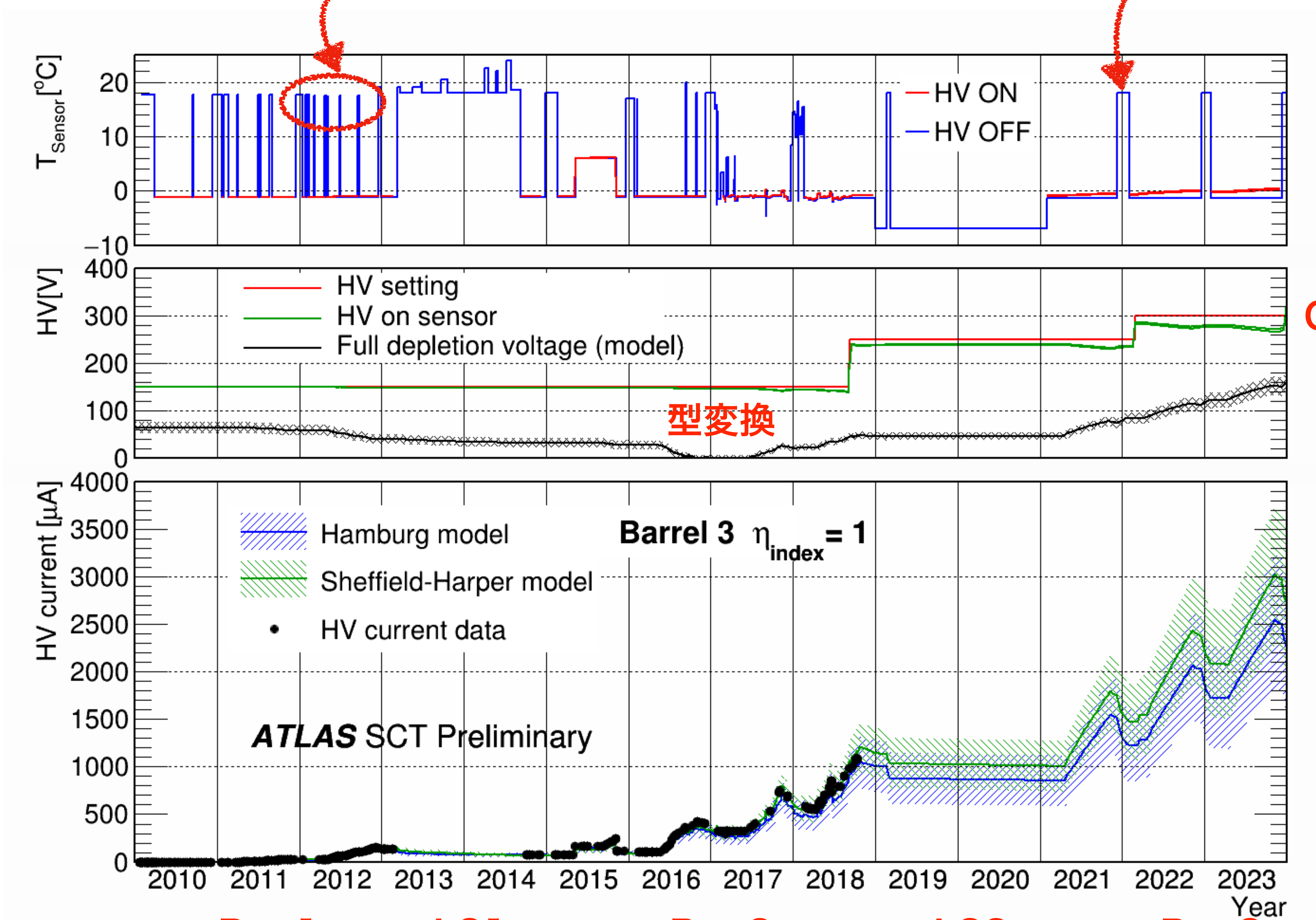
Figure 3.2: Displacement damage functions $D(E)$ normalized to 95 MeVmb for neutrons (10^{-10} to 20 MeV [Gri96], 20 to 400 MeV [Kon92], 805 MeV to 9 GeV [Huh93b]), protons [Huh93b, Sum93, Huh93a], pions [Huh93b] and electrons [Sum93]. Due to the normalization to 95 MeVmb the ordinate represents the damage equivalent to 1 MeV neutrons (see text). The insert displays a zoomed part of the figure.

例：ATLAS SCT のオペレーション

印加 HV・冷却シナリオ

オペレーション上の温度サイクル

計画 annealing



Over-depleted
を維持

Current limit
に注意

Run1 LS1 Run2 LS2 Run3

LGAD : Low Gain Avalanche Detector

- 近年の注目
  - Gain がある
    - 信号大 → 薄くできる、エレキがラクに
  - 早い
    - 通常のシリコンは数 ns → 数十 pc
    - トラッカーの場合、”4D” = 3D 位置 + 1D 時間 と言われたりする

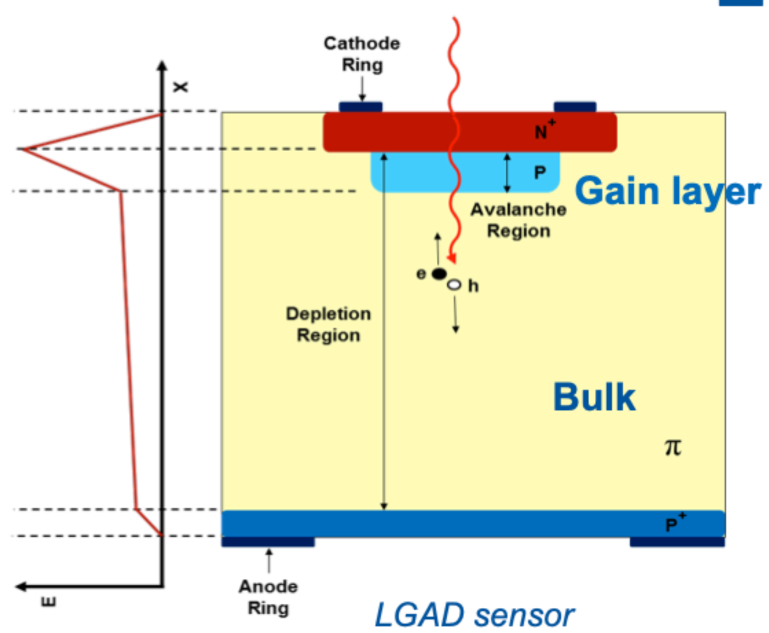
- 適用例
  - Low-mass tracker
  - 高速・省スペース要求がある検出器
    - シリコンカロリメータ
    - TOF

測定器開発プラットフォームから

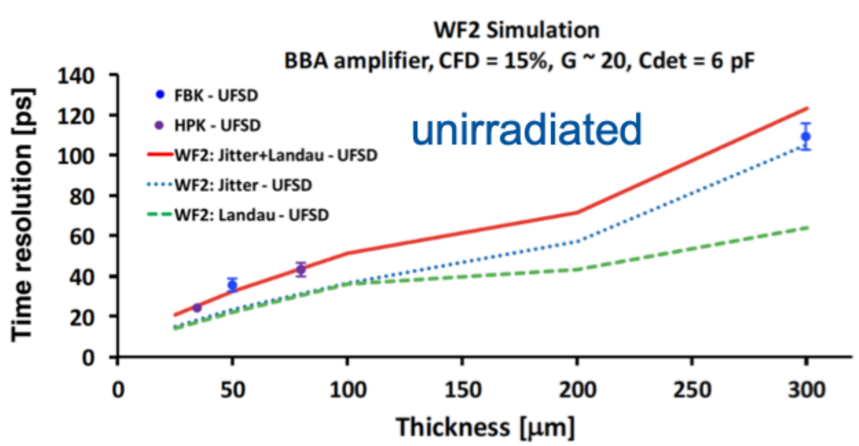
H. Pernegger のスライド
CERN RD

発想は APD
比較的マイクロパターンが可能

LGAD timing sensors



N. Cartiglia, H. Sadrozinski



Low Gain Avalanche Detectors (LGAD):
Multiplication of charges (~10-100x) in thin gain layer → fast rise time, increased S/N

- Several vendors: CNM, FBK, HPK　　CNM が先行
- Reached **~30 ps** for few mm^2 size sensors → considered for HL-ATLAS/CMS/LHCb **timing layers**
- Limiting factors for time resolution:
  - Weighting **field uniformity** → favors larger pixels
  - **Radiation effects** → ok up to ~10^{15}, mitigation measures under study for higher fluences
  - **r/o electronics + clock distribution** → IC work package
- R&D to achieve radiation hardness
  - Variation in doping to limit gain loss after irradiation
- RD for **larger fill factors** (currently ~70-00 μm inactive region between pixels):

F. Carnesecchi / Frontier Detectors – Elba 2018

https://kds.kek.jp/event/33154/contributions/160269/attachments/128157/156287/KEK-Workshop-TrackersPernegger-Dec2019-V2.pdf

例：ATLAS HGTD

https://cds.cern.ch/record/2721909?

- High Gain Timing Detector
  - HL-LHC アップグレード
  - Endcap LAr の前
- LGAD をハイブリッドピクセル風に
  - 1.3 mm 角, 300 μmt
  - ~30 psec
  - Gain ~20

Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	± 3.5 m
Weight per end-cap	350 kg
Radial extension:	
Total	$110\,\mathrm{mm} < r < 1000\,\mathrm{mm}$
Active area	$120\,\mathrm{mm} < r < 640\,\mathrm{mm}$
Pad size	$1.3\,\mathrm{mm} \times 1.3\,\mathrm{mm}$
Active sensor thickness	50 μm
Number of channels	3.6 M
Active area	$6.4\,\mathrm{m}^2$
Module size	30 x 15 pads ($4\,\mathrm{cm} \times 2\,\mathrm{cm}$)
Modules	8032
Collected charge per hit	> 4.0 fC
Average number of hits per track	
$2.4 < \|\eta\| < 2.7$ ($640\,\mathrm{mm} > r > 470\,\mathrm{mm}$)	≈ 2.0
$2.7 < \|\eta\| < 3.5$ ($470\,\mathrm{mm} > r > 230\,\mathrm{mm}$)	≈ 2.4
$3.5 < \|\eta\| < 4.0$ ($230\,\mathrm{mm} > r > 120\,\mathrm{mm}$)	≈ 2.6
Average time resolution per hit (start and end of operational lifetime)	
$2.4 < \|\eta\| < 4.0$	≈ 35 ps (start), ≈ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	≈ 30 ps (start), ≈ 50 ps (end)

Table 2.1: Main parameters of the HGTD.

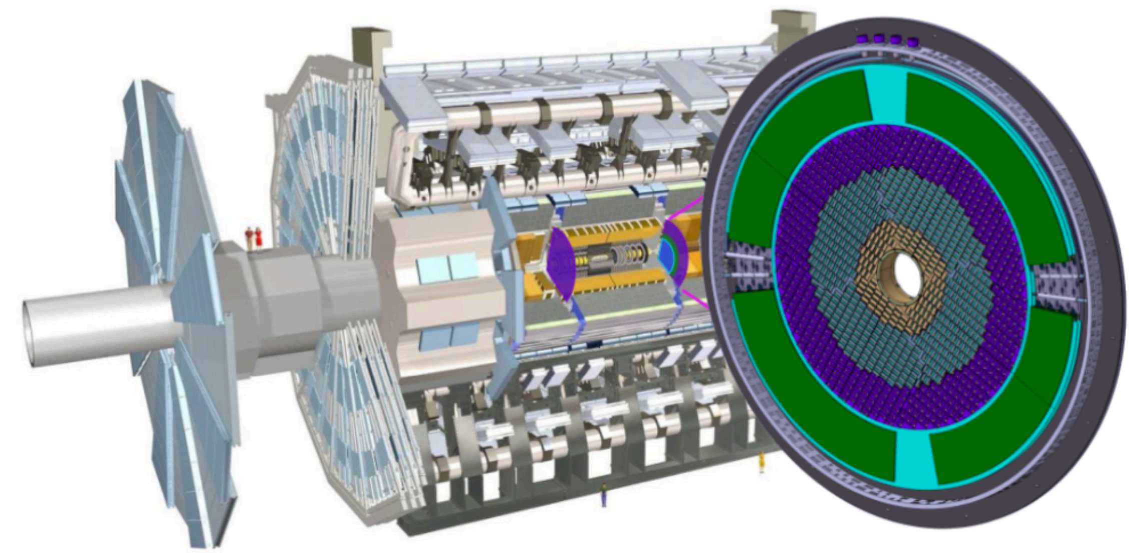


Figure 2.3: Position of the HGTD within the ATLAS Detector. The HGTD acceptance is defined as the surface covered by the HGTD between a radius of 120 mm and 640 mm at a position of $z = \pm 3.5$ m along the beamline, on both sides of the detector.

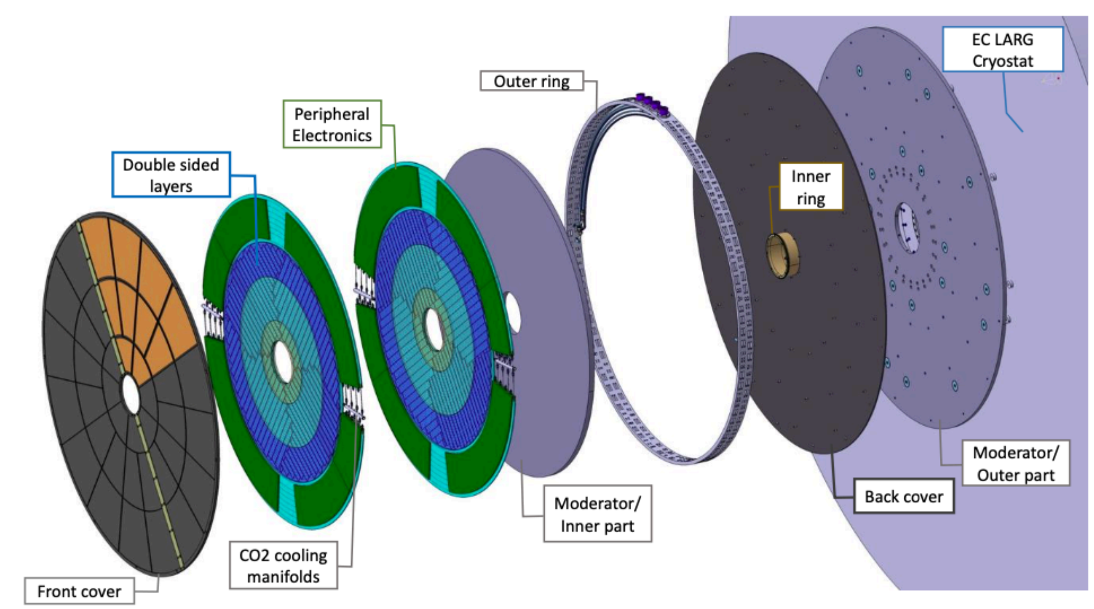


Figure 2.4: Global view of the HGTD to be installed on each of two end-cap calorimeters. The various components are shown: hermetic vessel (front and rear covers, inner and outer rings), two instrumented double-sided layers (mounted in two cooling disks with sensors on the front and back of each cooling disk), two moderator pieces placed inside and outside the hermetic vessel.

ATLAS HGTD：モジュール構造

見た目はハイブリッドピクセル

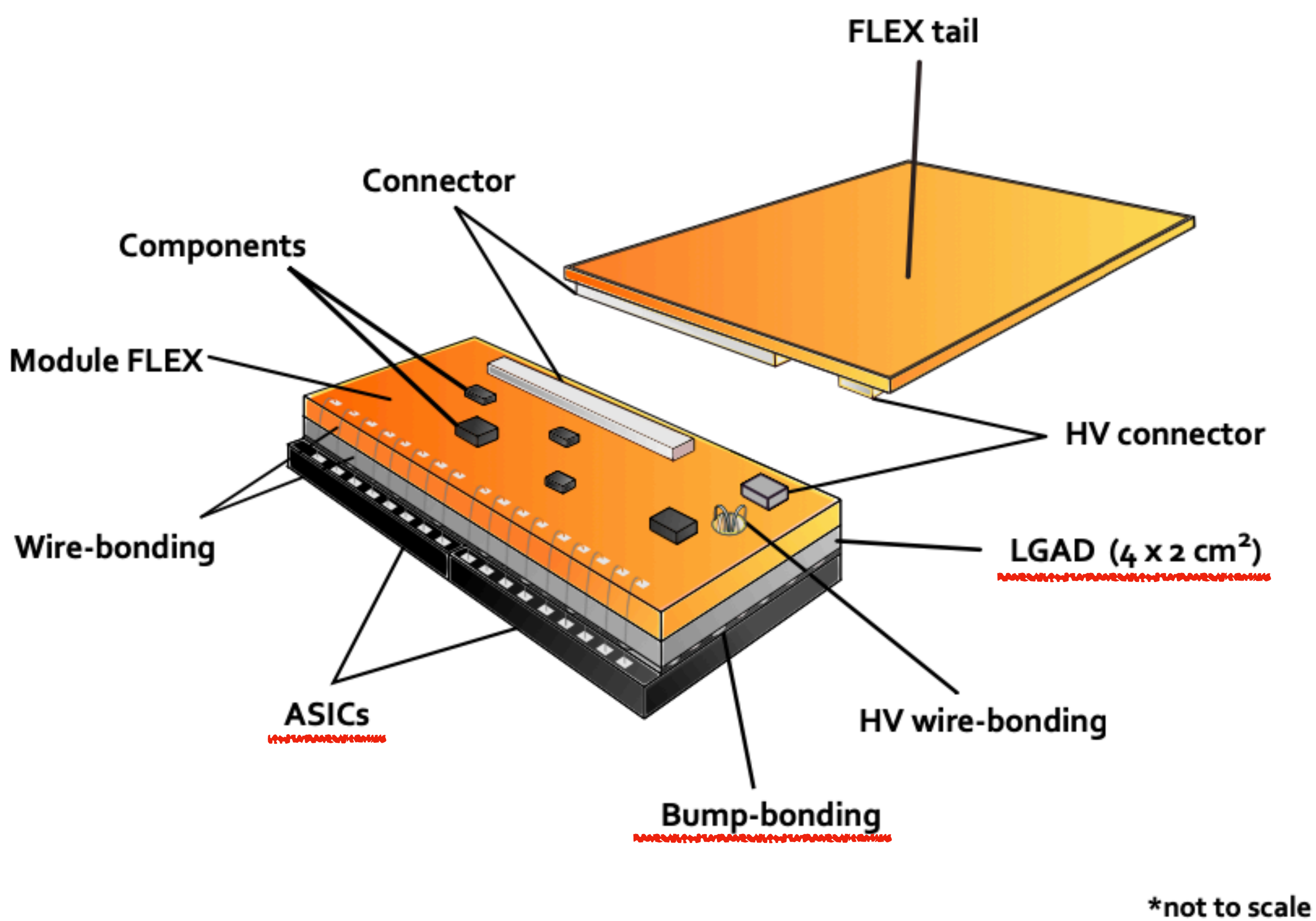


Figure 4.3: View of an HGTD hybrid module equipped with its read-out flex cable tail. The bare module, glued on the flex cable, is made of a $4 \times 2\,\mathrm{cm}^2$ sensor with two bump bonded ASICs. The signal lines of the ASIC are wire bonded on one side of the module flex, while the bias voltage of the sensor is provided to the back-side of the sensor through a hole in the module flex.

ATLAS HGTD：時間分解能 (1/2)

放射線損傷依存性、HPK の結果もアリ

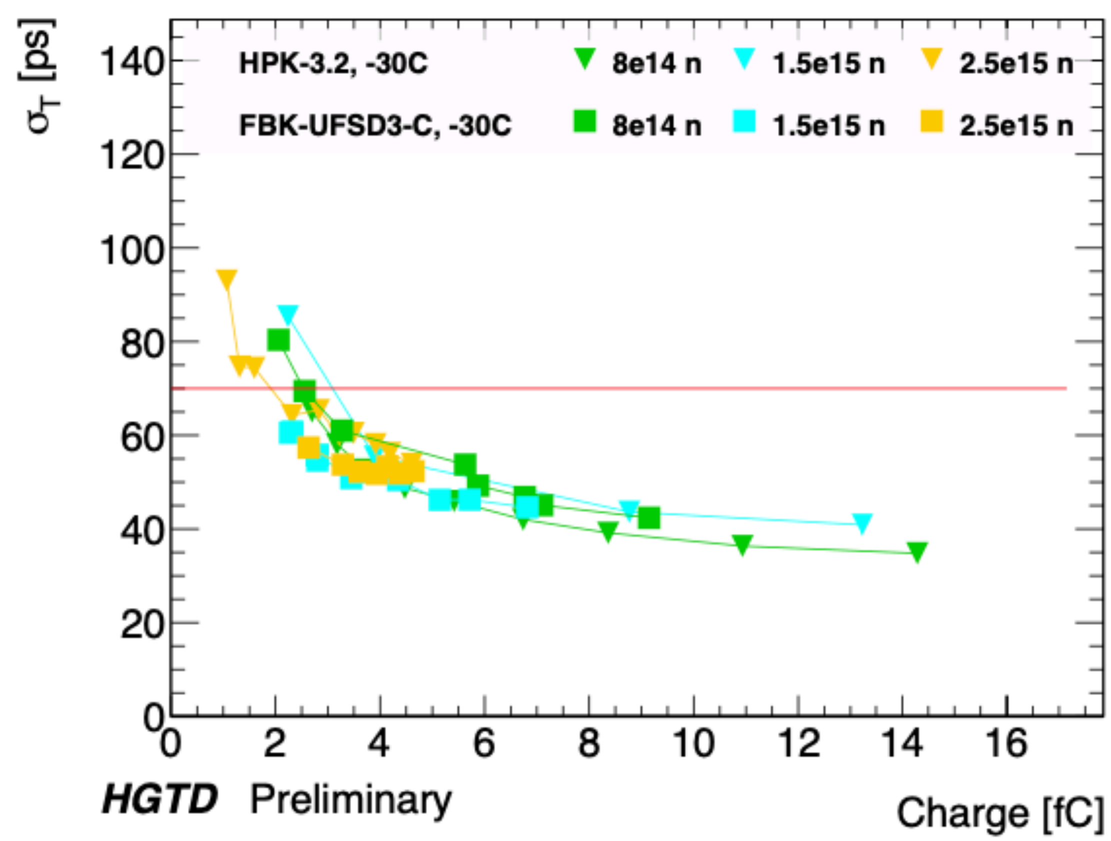


Figure 4.5: Time resolution as a function of the collected charge for neutron irradiated LGADs from different producers (HPK, FBK) with a 50 µm active thickness. These measurements have been made at –30 °C, in the laboratory with a β source using a custom electronics read-out board (not the ALTIROC therefore optimistic with respect to the expected electronics jitter contribution). The typical error bar is about 3 ps. The red line shows that in these conditions better than 70 ps time resolution is obtained at 4 fC

ATLAS HGTD：時間分解能 (2/2)

放射線損傷依存性、HPK の結果もアリ

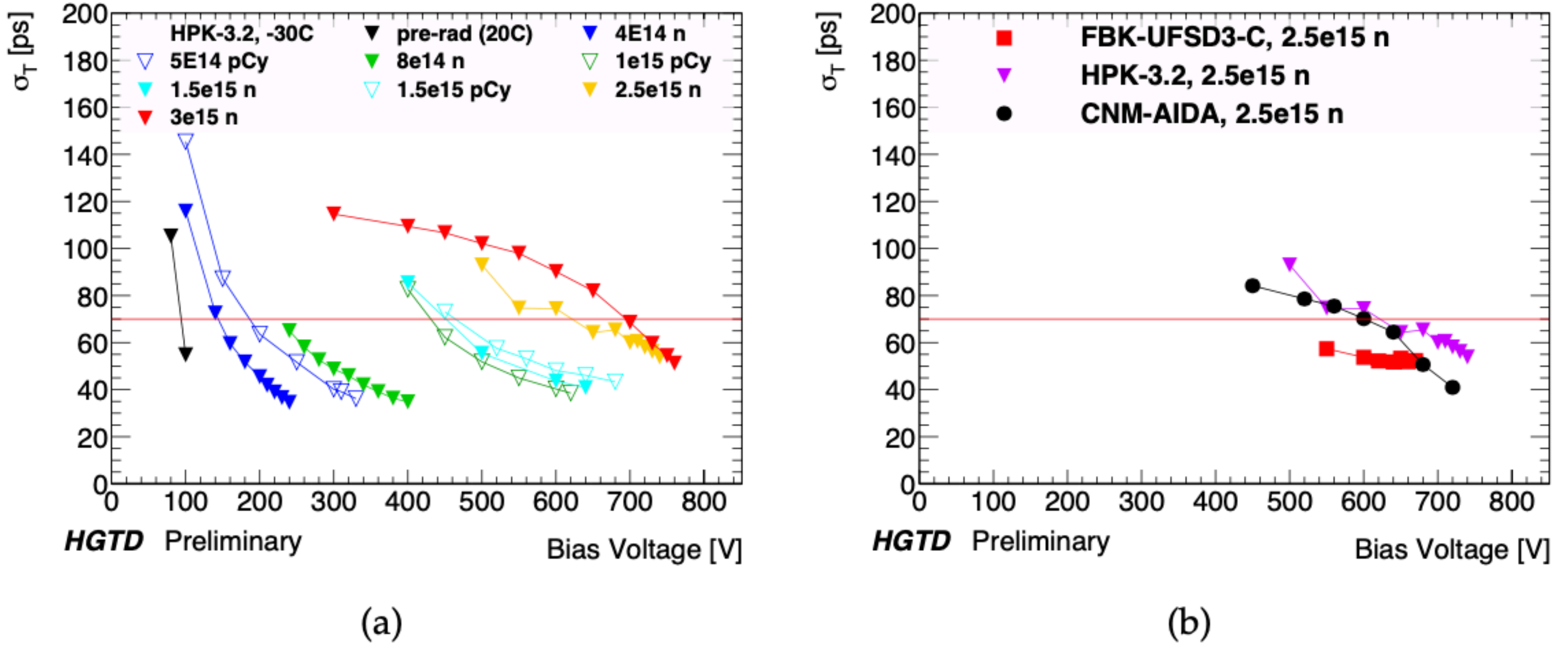
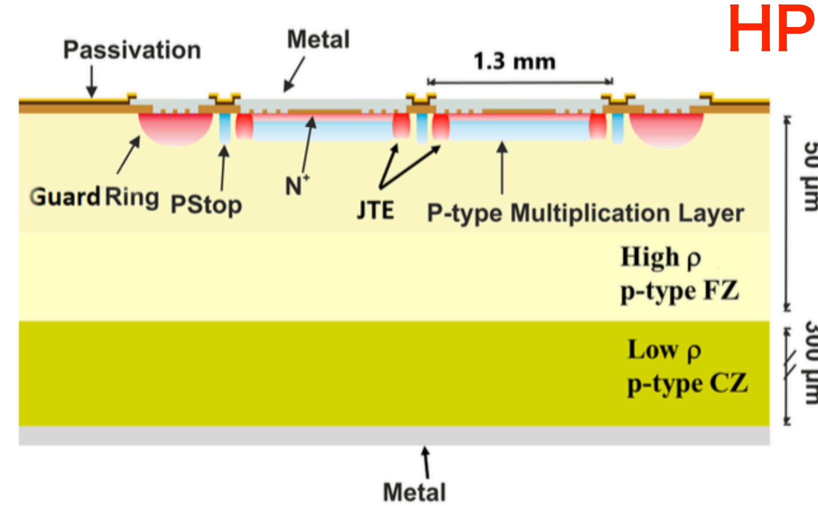


Figure 5.11: Time resolution as a function of bias voltage for different fluences for HPK-3.2 (a) and for all vendors at the maximum HGTD fluence (b) measured on custom-made HGTD-specific readout boards. Solid markers indicate n irradiation (*n*), open markers p irradiation at CYRIC (*pCy*). The red line represents the maximum allowed time resolution (70 ps) in the lifetime of HGTD. Measurements were performed at −30 °C except for the pre-rad measurement that was done at 20 °C.

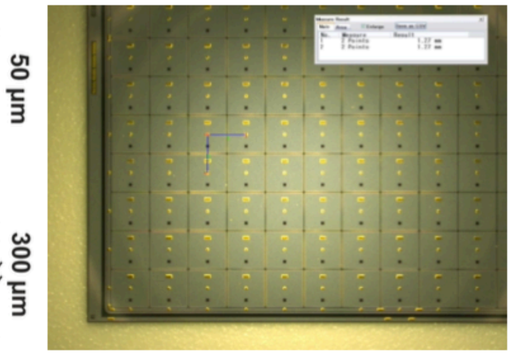
ATLAS HGTD：Sensor

- 1.3 mm 角、300 μmt
  - ちょっと分厚いか…
    - カロリメータにはOKか
    - トラッカーにはもっと薄く
- Gain
  - 初期 20
  - 損傷受けて (それでも) 8 へ
- 時間分解能
  - 35 ps → 70 ps

HPK製：R&D 可能かも



(a) Cross section of a 2 × 2 array.



(b) Photo of a 15 × 15 array.

Figure 5.1: (a) Cross section of a 2 × 2 array including a JTE around each sub-pad (SiSi wafer, CNM design) [63]. (b) Microscope photo of an HPK-3.1 15 × 15 array.

Technology	Silicon Low Gain Avalanche Detector (LGAD)
Time resolution	≈ 35 ps (start); ≈ 70 ps (end of lifetime)
Time resolution uniformity	No requirement
Min. gain	20 (start); 8 (end of lifetime)
Min. charge	4 fC
Min. hit efficiency	95%
Granularity	1.3 mm × 1.3 mm
Max. inter-pad gap	100 μm
Max. physical thickness	300 μm
Active thickness	50 μm
Active size	39 mm × 19.5 mm (30 × 15 pads)
Max. inactive edge	500 μm
Radiation tolerance	$2.5 \times 10^{15}\, n_{eq}\, cm^{-2}$, 1.5 MGy
Max. operation temperature on-sensor	−30 °C
Max. leakage current per pad	5 μA
Max. bias voltage	800 V
Max. power density	100 mW/cm^2

Table 5.1: Sensor parameters and requirements.

ATLAS HGTD : ASIC

- TOA と TOT を利用
  - TOA : Time-Of-Arrival
    - Leading edge
  - TOT : Time-Over-Threshold
    - Charge と相関
- つまりは…
  - leading edge + slewing correction で時間分解能を出す作戦

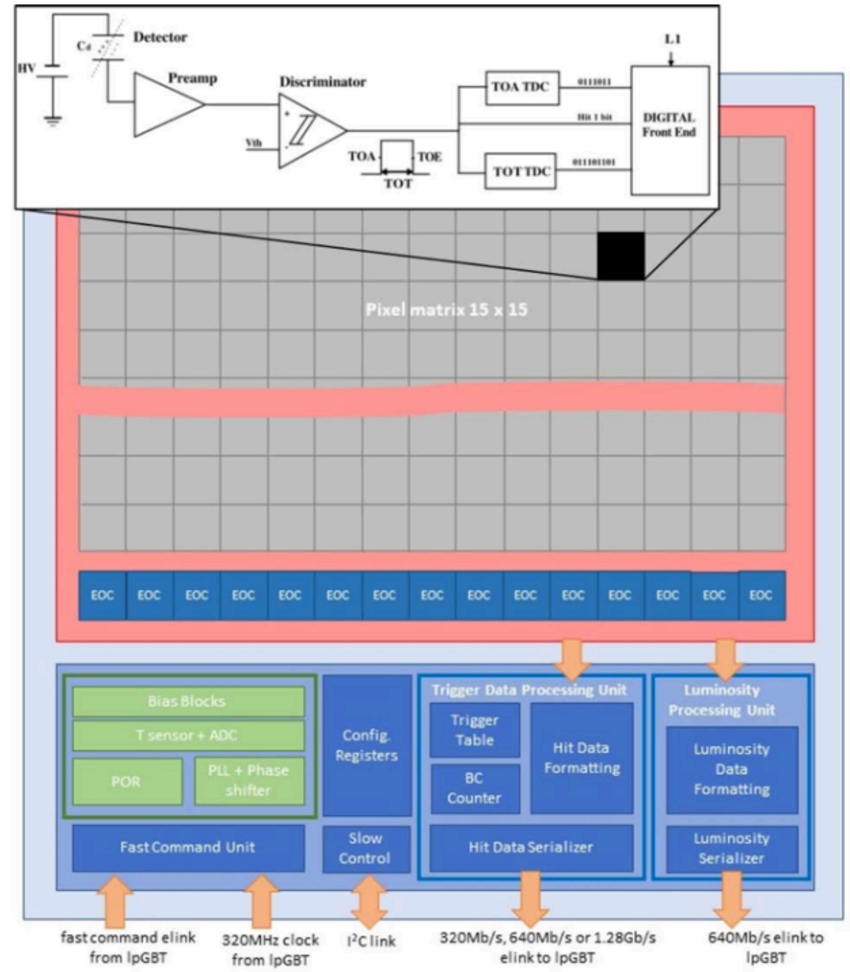


Figure 4.6: Global architecture of the ALTIROC ASIC. The schematic of one Front End electronics channel is displayed on top of the channels matrix, with the preamplifier followed by a discriminator, two TDCs, and a digital front end block.

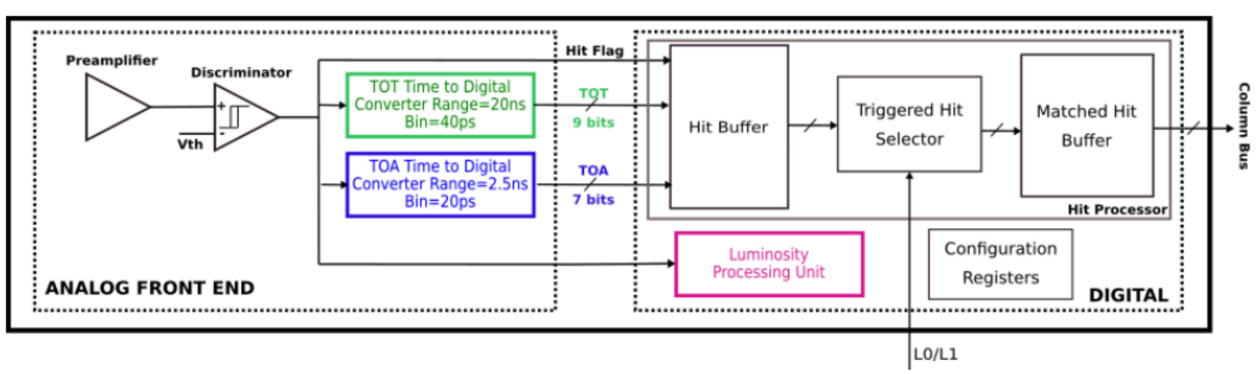


Figure 6.1: Schematic of the single-channel readout electronics. Two main blocks are identified, the analog and the digital part. The input pulse from the sensor enters the preamplifier on the left. The TOA and TOT data are read out by the column bus on the right.

Maximum leakage current	5 µA
Single pad noise (ENC)	$< 3000\ e^- = 0.5$ fC
Cross-talk	< 5%
Threshold dispersion after tuning	< 10%
Maximum jitter	25 ps at 10 fC 70 ps at 4 fC
TDC contribution	< 10 ps
Time walk contribution	< 10 ps
Minimum threshold	2 fC
Dynamic range	4 fC–50 fC
TDC conversion time	< 25 ns
Trigger rate	1 MHz L0 or 0.8 MHz L1
Trigger latency	10 µs L0 or 35 µs L1
Clock phase adjustment	100 ps

Table 6.2: Performance requirements for the HGTD ASIC. The values given for the noise, minimum threshold and jitter have been specified considering a detector capacitance $C_d = 4$ pF.