Mass production of large-area lithium-drifted silicon detectors for the GAPS silicon tracker

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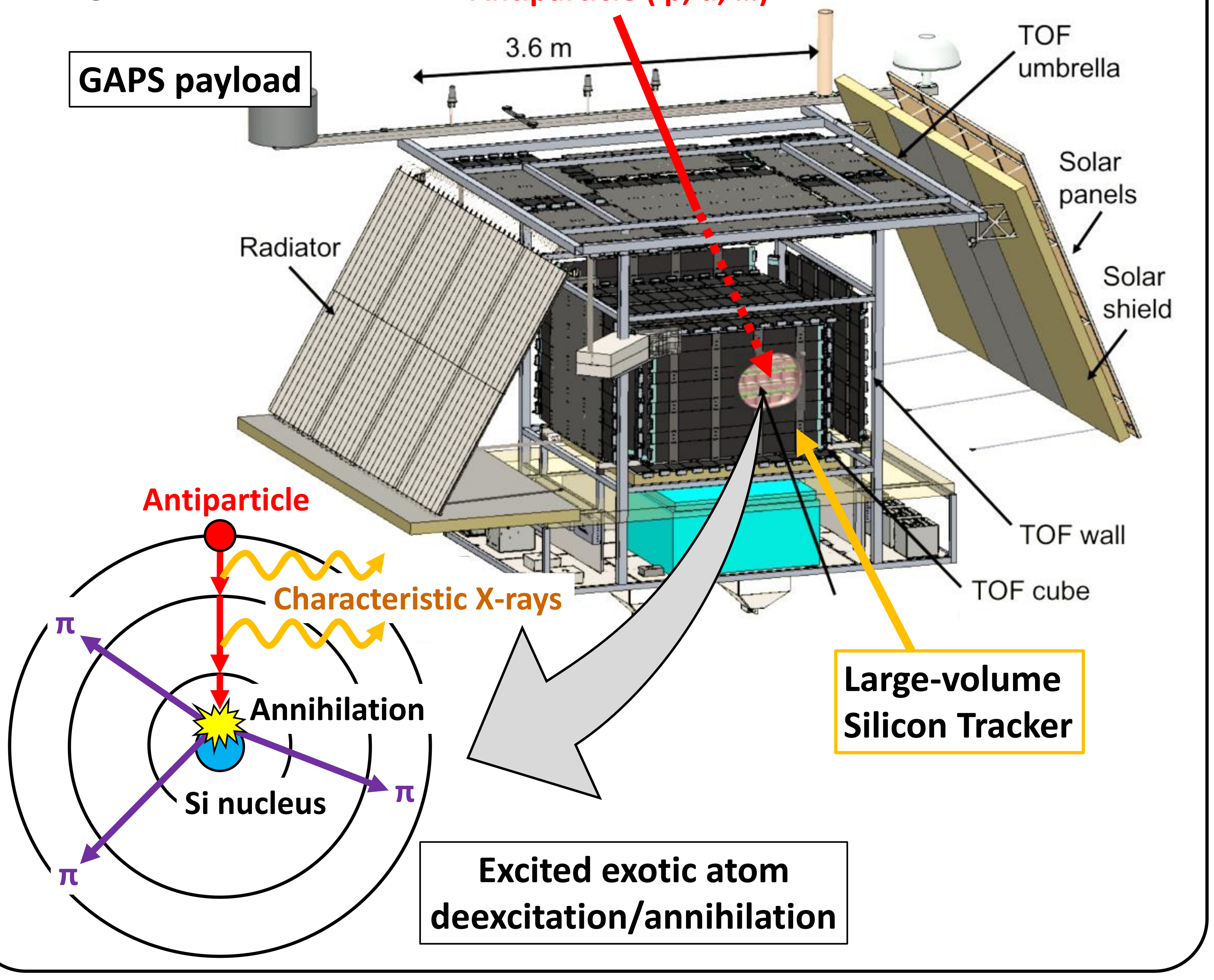
Mass-production of large-area lithium-drifted silicon (Si(Li)) detectors has been done for the General Antiparticle Spectrometer (GAPS). GAPS aims for a high-sensitivity observation of cosmic-ray antiparticles, especially antideuterons which are predicted to be a distinct signal of the dark matter. A large-volume silicon tracker plays an essential role in the novel GAPS detection technique, which is based on exotic atom physics. We established a fabrication method for the large-area Si(Li) detector and produced >1000 detectors. In this report, statistical characteristics of the detectors are discussed based on the performance parameters. The results ensure that a silicon tracker with large and high-quality sensitive volume is achieved with our detectors.

1. GAPS experiment

[P. von Doetinchem et al. (2020) JCAP; M. Kozai et al. (2020) J. Phys. Conf. Ser.; T. Aramaki et al. (2016) Astropart. Phys.]

- International collaboration between Japan, US and Italy
- High-sensitivity observation of low-energy antiparticles ($\bar{p}$, $\bar{d}$, …) in cosmic-rays
- First flight using NASA long-duration balloon in Antarctica is scheduled in late 2022.
- Novel detection technique based on exotic atom physics
  1. Incident antiparticle forms an excited exotic atom with silicon nucleus.
  2. Characteristic X-rays and annihilation particles (mainly pions) from exotic atom enable an efficient identification of the antiparticle.
- Payload size: H ~4 m x W ~4 m x L ~6 m
- Weight: ~3.5 metric ton

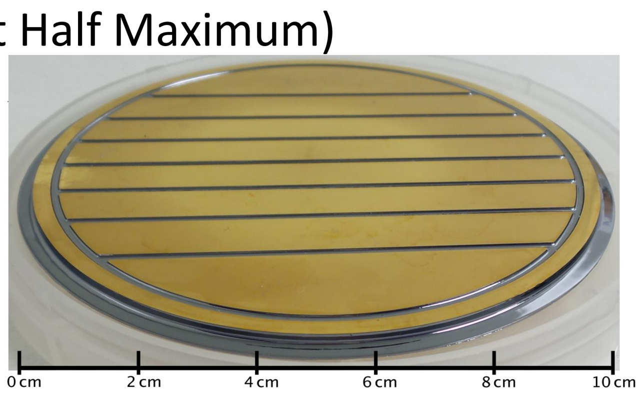


2. Large-area lithium-drifted silicon (Si(Li)) detectors

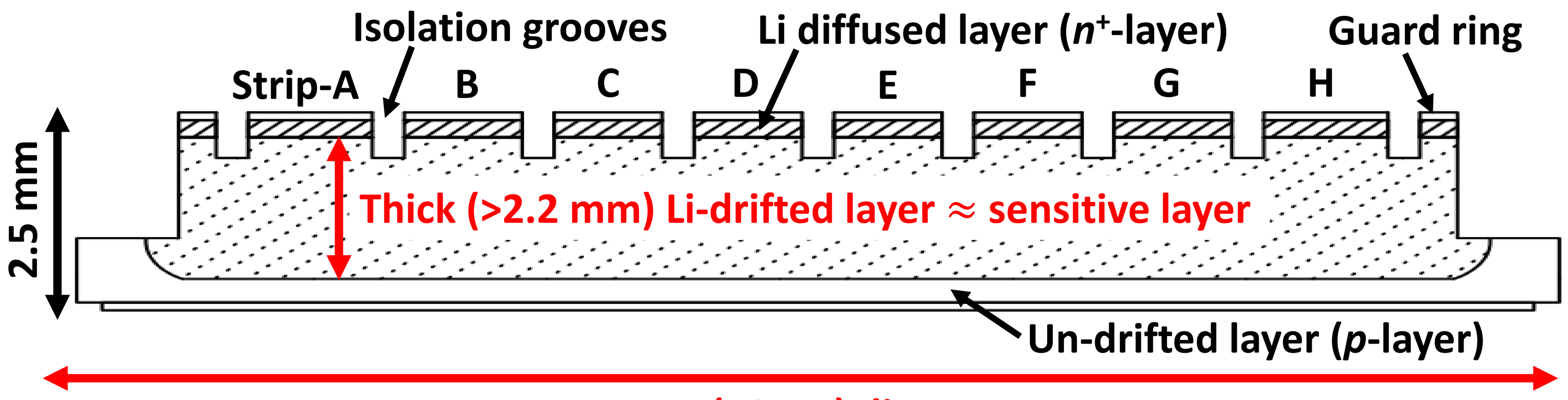
[M. Kozai et al. (2019) NIM A; F. Rogers et al. (2019) JINST; N. Saffold et al. (2021) NIM A; K. Perez et al. (2018) NIM A]

The silicon detector was a key development in realizing the novel detection concept. We developed a fabrication method for large-area Si(Li) detectors for the tracker.

- **Basic Si(Li) fabrication process**
  1. Procuring a boron-doped silicon wafer.
  2. Evaporating/diffusing Li ions onto a side of the wafer to form an n^+-layer.
  3. Drifting Li ions toward the *p*-side by applying a bias voltage to the heated wafer.
  4. The thick drifted layer functions as a sensitive layer.
- **The GAPS Si(Li) detector features:**
  - ✓ Large (10 cm) diameter with ~9 cm sensitive area.
  - ✓ 2.5 mm thickness with ~90% sensitive layer.
  - ✓ Segmentalized into 8 strips with equal area.
  - ✓ Energy resolution of <4 keV FWHM (Full Width at Half Maximum) for 20-100 keV X-rays.
  - ✓ Relatively high operating temperature (~-40°C), which allows use of a low-power cooling system. [S. Okazaki et al. (2018) Appl. Therm. Eng.]



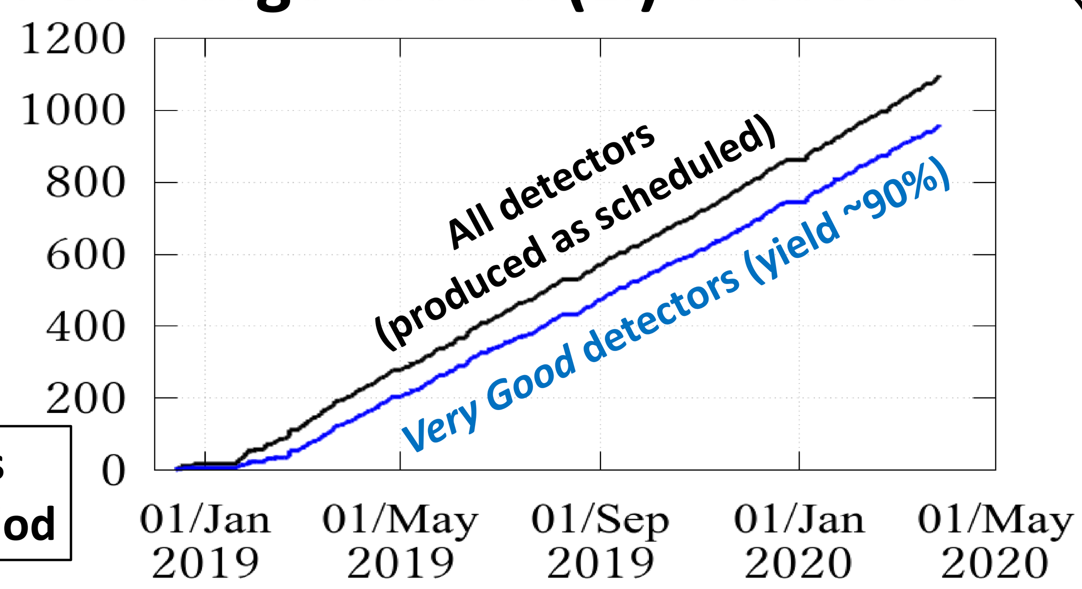
Cross section of the detector



3. Mass-production of the large-area Si(Li) detectors

Rapid mass-production was one of the key issues to construct the large-volume silicon tracker. We established a fabrication method and produced >1000 detectors for the first flight.

Cumulative number of detectors during the mass-production period



- Leakage currents (LCs) and capacitances of all strips at room temperature (RT) were measured for all detectors just after each detector was fabricated.
- *Very Good* detectors are defined using the LCs and capacitances at RT as below. They enable distinct identification of the exotic-atom products during flight.
  - ✓ ≥7 strips in 8 strips have LCs ≲7 uA at the bias voltage of 250 V. LC of 7 uA at RT corresponds to ≲5 nA at the operating temperature (~-40°C).
  - ✓ All strips and guard ring have LCs ≲50 uA at 250 V, or their change ratios are ≲0.05 uA/V in the range of 200-300 V.
  - ✓ All strips have capacitances between 35 and 42 pF.
- ~90% detectors in ~1100 detectors were classified as *Very Good* grade. This high yield rate enables construction of the large-volume silicon tracker.
- Majority of the detectors failing the *Very Good* criteria will still function as particle trackers. Detailed grading is now performed based on the measurements at the operating temperature (~-40°C).

4. Preliminary results of the statistical study

Fig. A displays the strip LCs and capacitances at RT. The LC is a major factor limiting the energy resolution. The LC distribution has a maximum at ~2 uA, several times smaller than the *Very Good* criterion at 7 uA. This performance margin will provide high reliability or designing flexibility of the tracker.

Fig. B shows the strip LCs and capacitances of the *Very Good* detectors, split into each strip position. There is no significant dependence of the performance on the position. Especially the variations (FWHMs) in the capacitance are within 38-40 pF (~5%) in all histograms. This indicates that Li ions were very uniformly drifted in all strips and detectors by our custom material and methods. The uniform drifting had been a major issue in previous studies of large-area Si(Li) detectors.

[e.g., Onabe et al. (2002) Ioniz. Radiat.; Miyachi et al. (1994) Japan. J. Appl. Phys.]

Fig. A: Histograms of strip LCs and capacitances of All (black) and *Very Good* (blue) detectors.

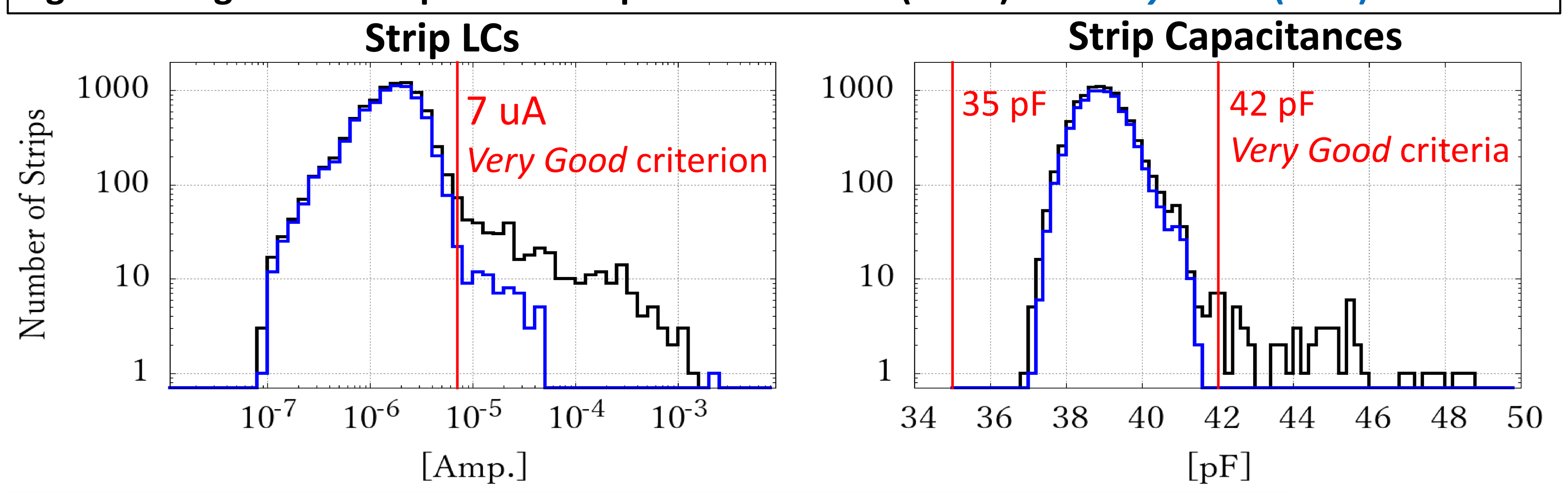
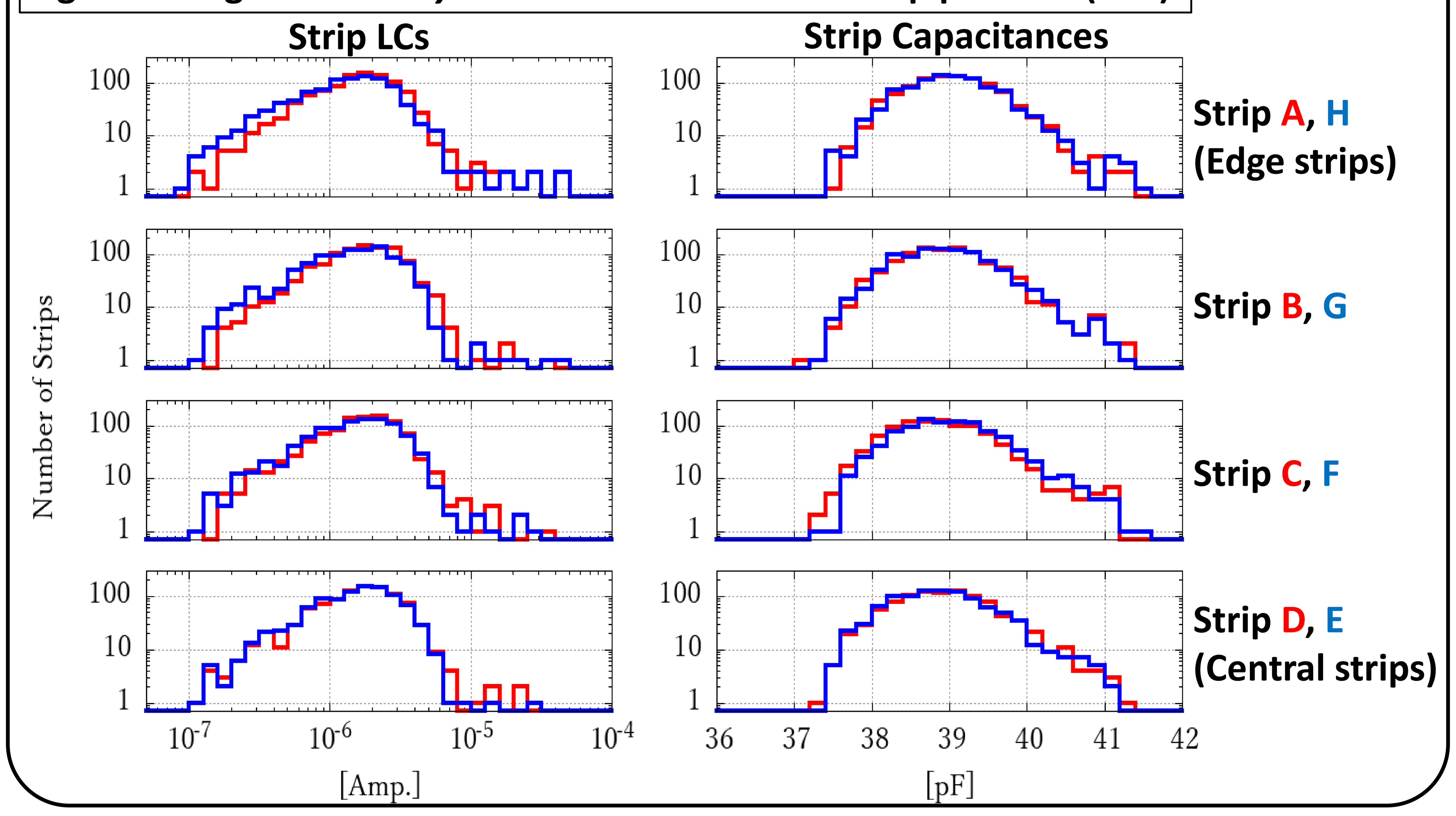


Fig. B: Histograms of *Very Good* detectors in each strip position (A-H).



Summary

Mass-production of large-area Si(Li) detectors has been done to construct a large-volume silicon tracker for GAPS. Stable production was performed as scheduled and ~90% of the fabricated detectors meet the criteria imposed from scientific requirements. Distribution of the capacitance indicates that lithium-drifted layers, i.e. sensitive layers, have uniform depths in all detectors. Ongoing investigation analyzing fabrication data along with the performance data will provide further insights into the fabrication process.

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