Silicon Detector Systems

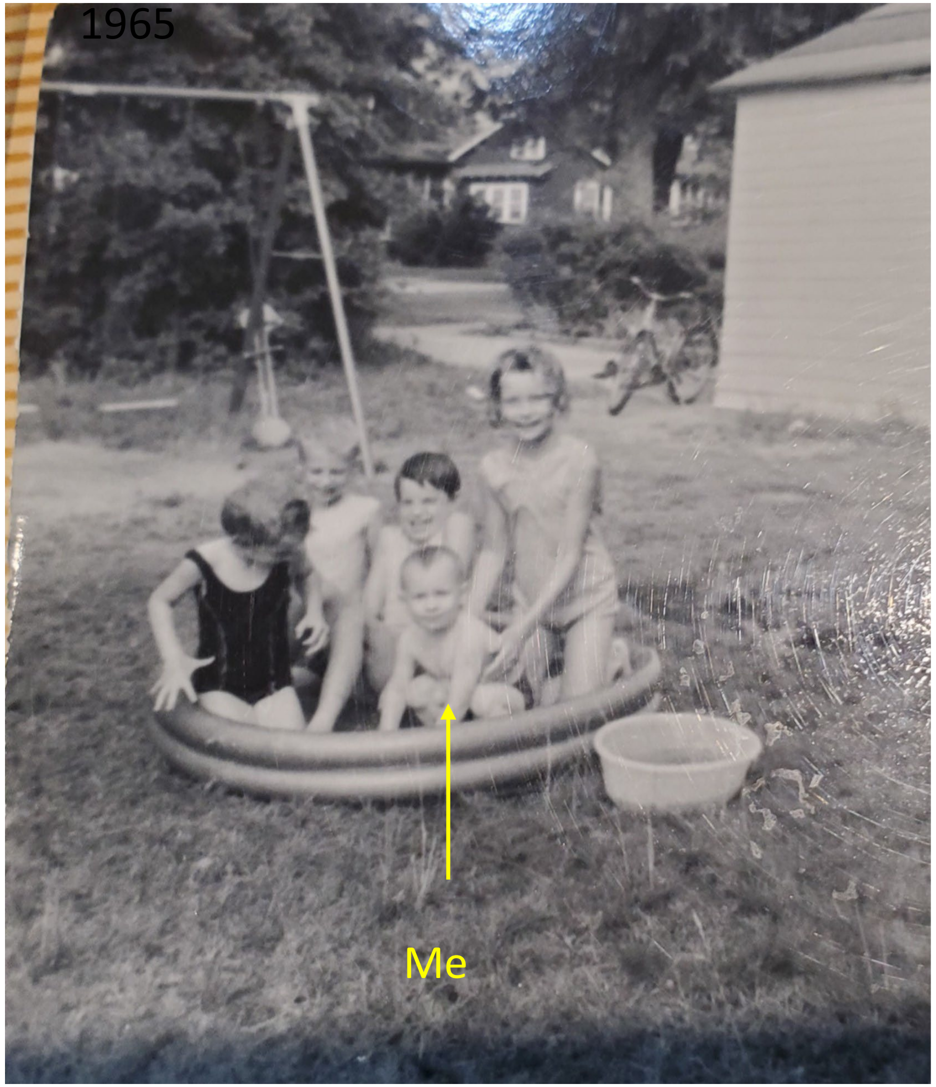
Cleanroom for silicon detector testing; located in back of physics building

David Lynn, BNL Physics Department Summer Lectures, July 22, 2022

Brief Biography

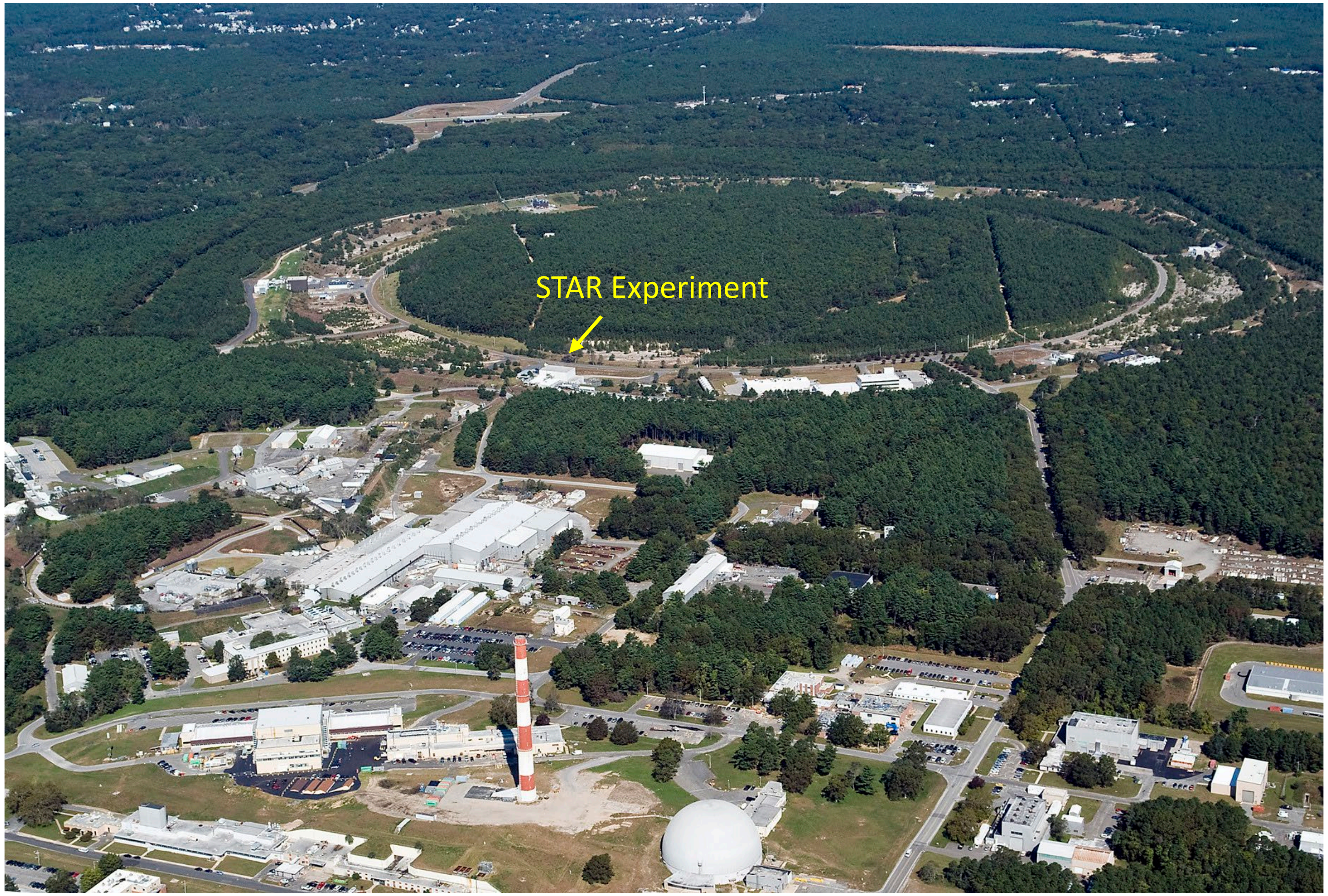
- Born Philadelphia 1963. Lived either near Philadelphia or Nashville.
- Went to Massachusetts Institute of Technology 1982-1986. Was planning on majoring in Electrical Engineering even though I had no idea what that was (this was before the Internet (gasp!)).
- Everybody at MIT had to take a physics class, even English majors.
- I decided I liked it and majored in Physics and Math instead.
- Went to UCLA in 1986 for a PhD in physics. Was there for 1 ½ years before joining a research group. Was sent to Lawrence Berkeley Lab to build a small silicon detector and take to Geneva, Switzerland for an experiment there. Later built a larger silicon detector as part of my thesis.
- Came to BNL in 1995 after graduating from UCLA. Since them have been involved in four silicon detector projects.
    1. STAR Silicon Vertex Tracker
    2. E896
    3. PP2PP
    4. ATLAS Silicon Detector Upgrade (presently my main job)

Lynn siblings in family pool, Circa 1965



Relativistic Heavy Ion Collider (RHIC)

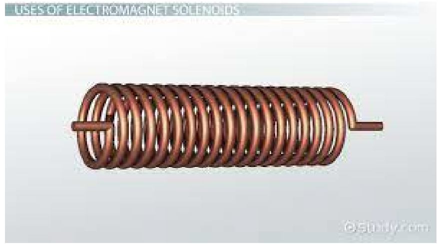
- Located at BNL
- 2.4 miles circumference
- Collides gold ions vs gold ions (this field is called heavy ion physics)

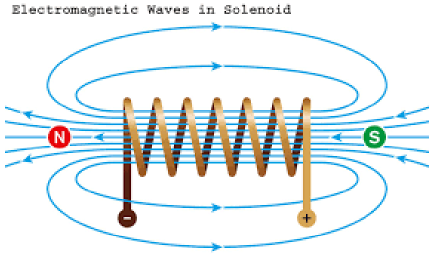


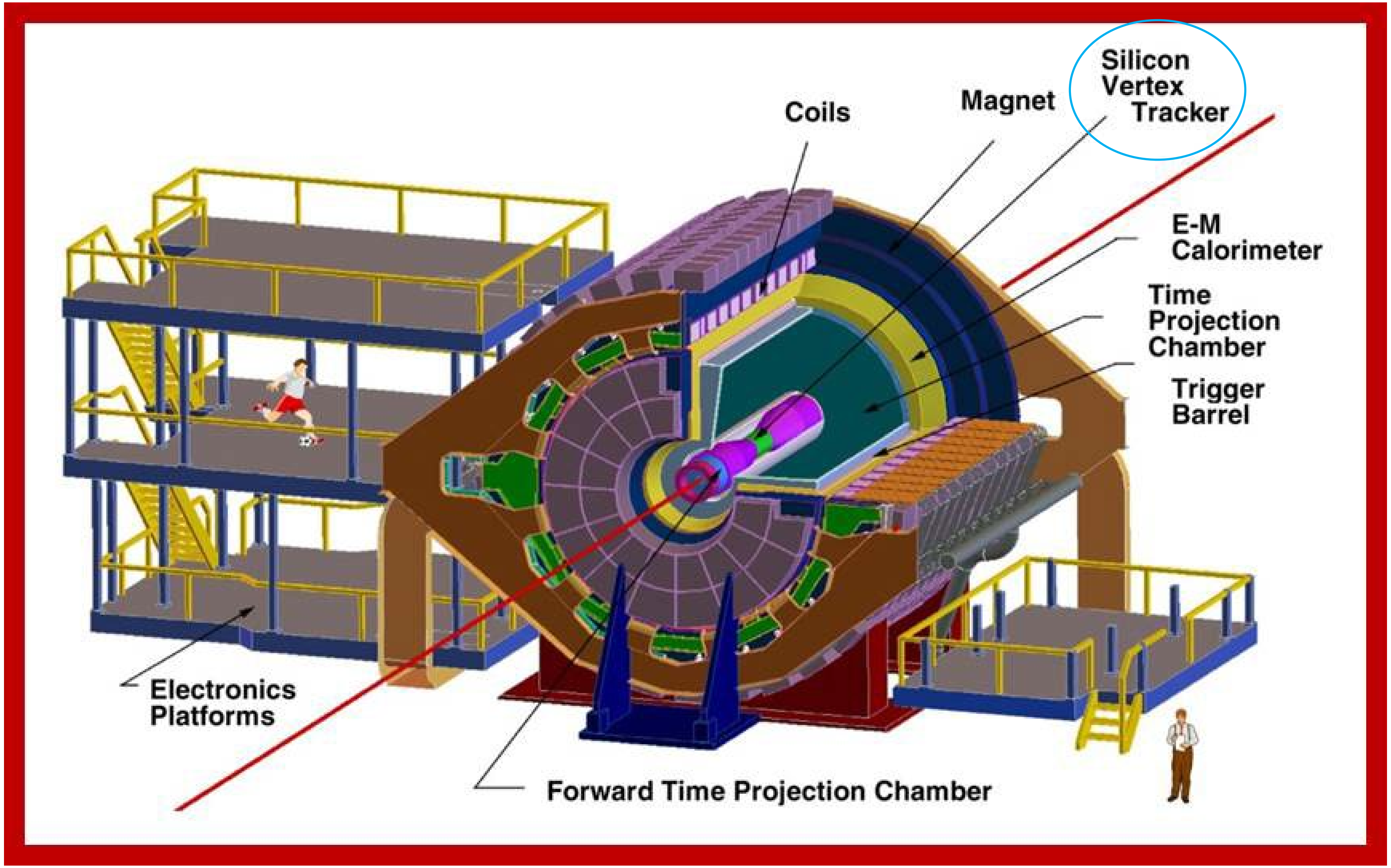
Main physics goal:

Create and study quark-gluon plasma

STAR (Solenoidal Tracker at RHIC) Dectector



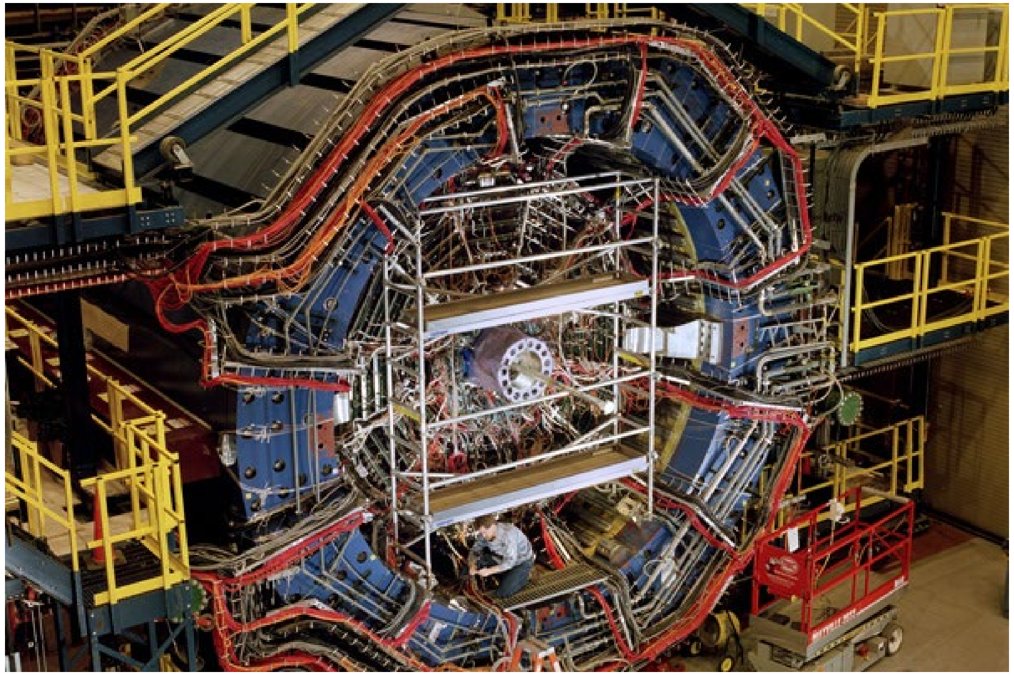




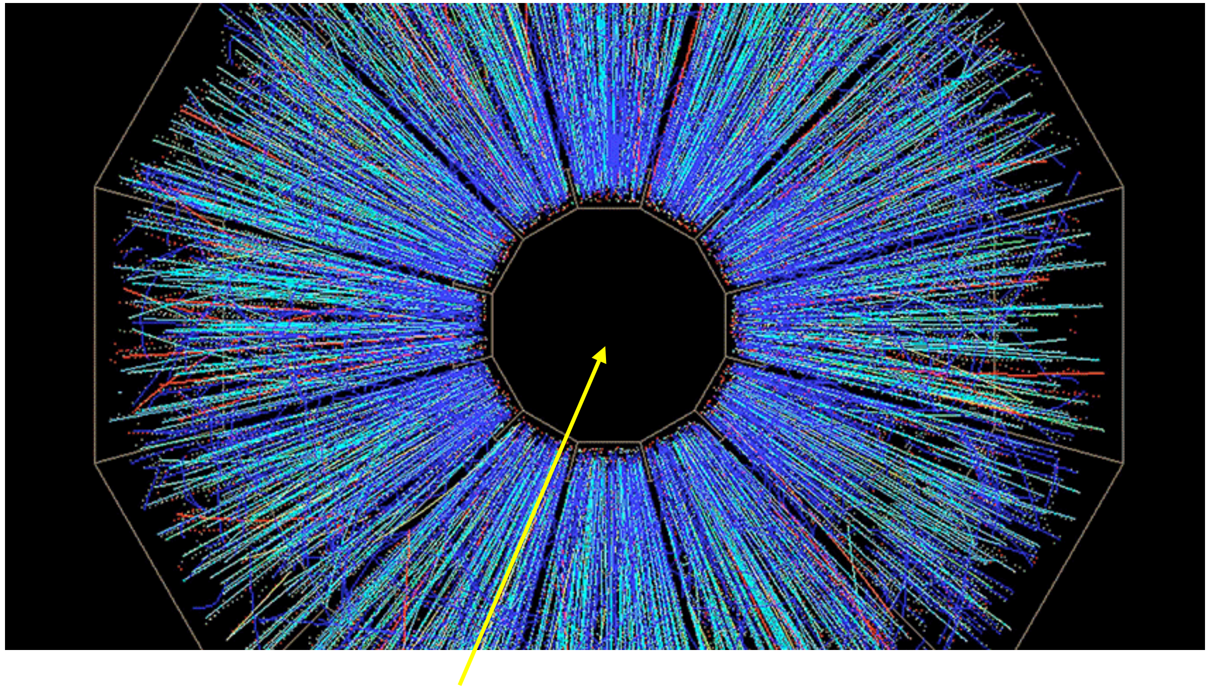
Silicon tracking detectors typically are the closest detector to the collisions

STAR (Solenoidal Tracker at RHIC) Detector

Photo of STAR Detector



Thousands of "tracks" of charged particles created by gold-gold collisions and recorded in STAR Detector

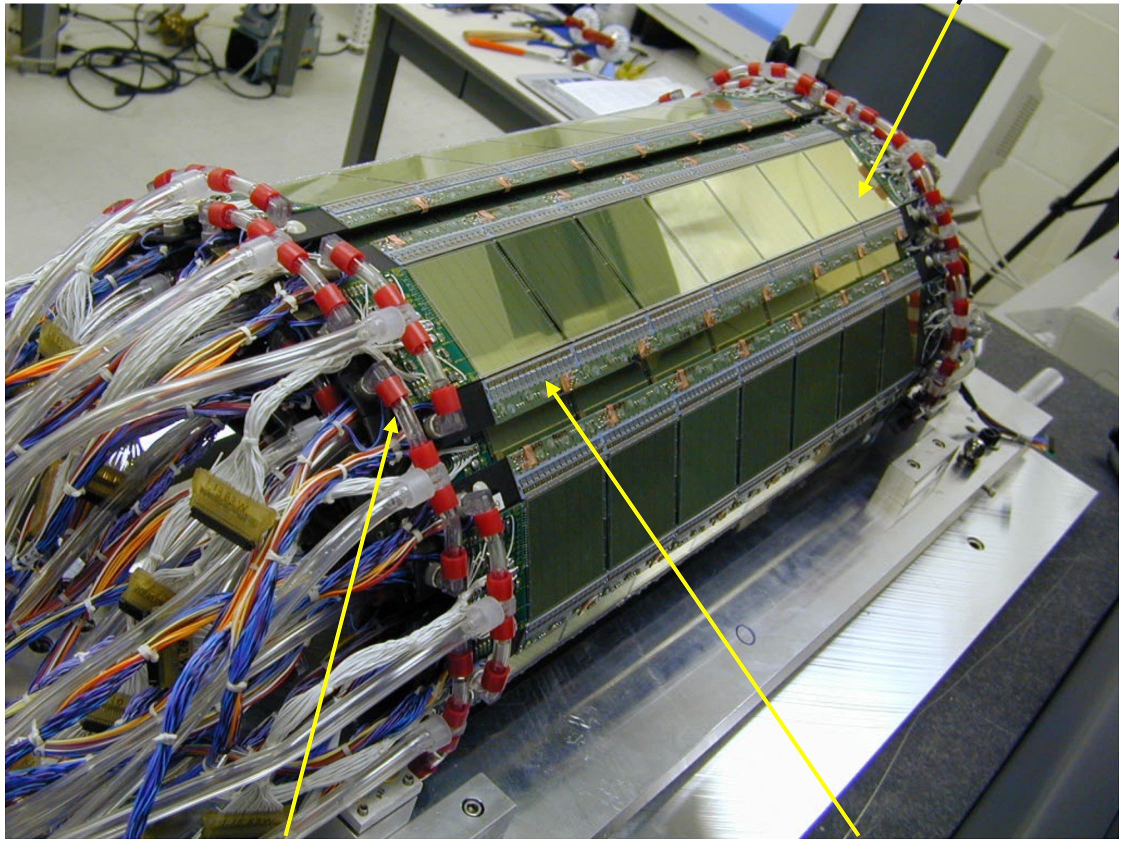


Silicon detector goes in here

Star Silicon Vertex Tracker at Relativistic Heavy Ion Collider at BNL

- 0.7 m^2 of silicon drift detectors. Detect passage of charged particles (e.g. protons, electrons, but not neutrons)
- Barrel geometry
- ~ 5 million dollars (in 1997)

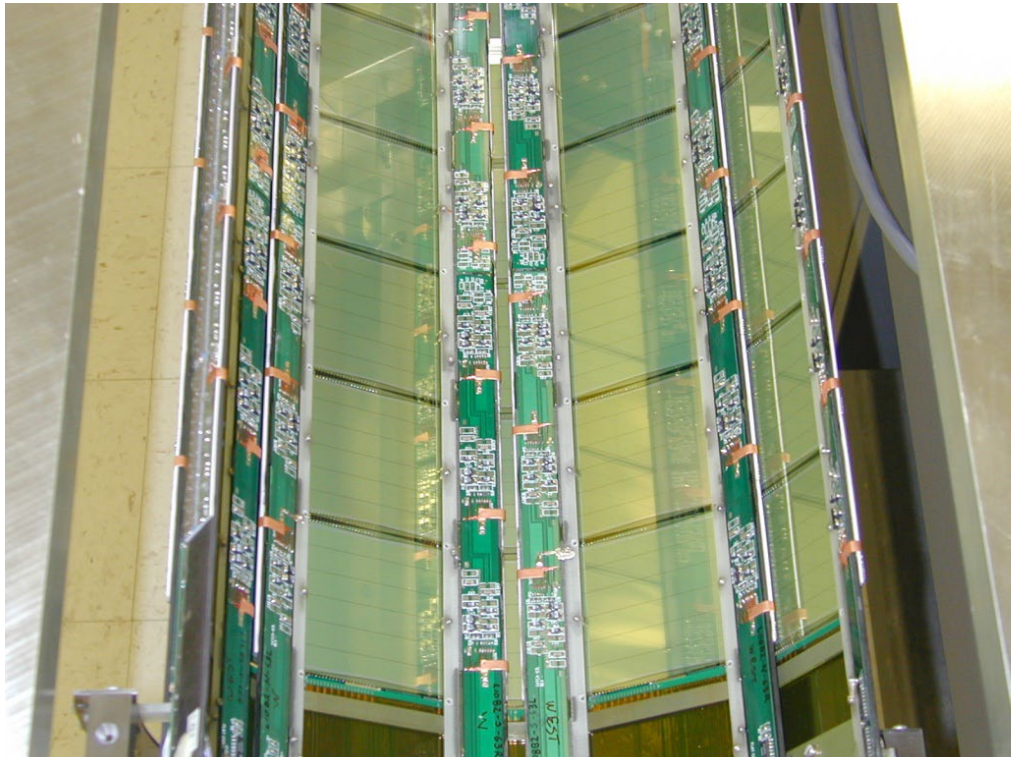
6 cm x 6 cm x 300 um silicon sensor



Cooling tubes

Amplifying electronics

Photo from inside



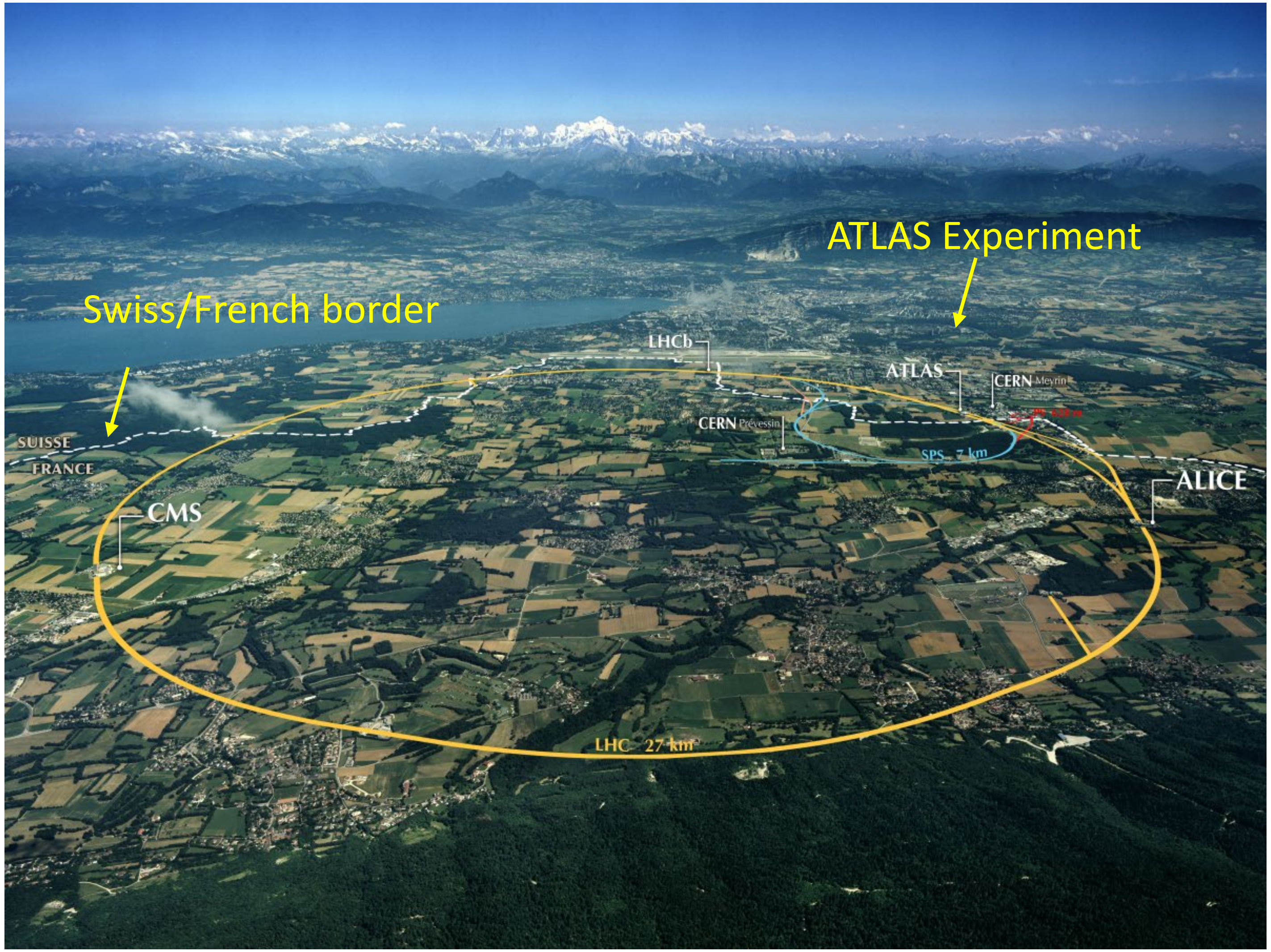
Extremely delicate! Cannot touch detectors or electronics. Only can touch support structure!

Silicon Vertex Tracker Being Installed at RHIC

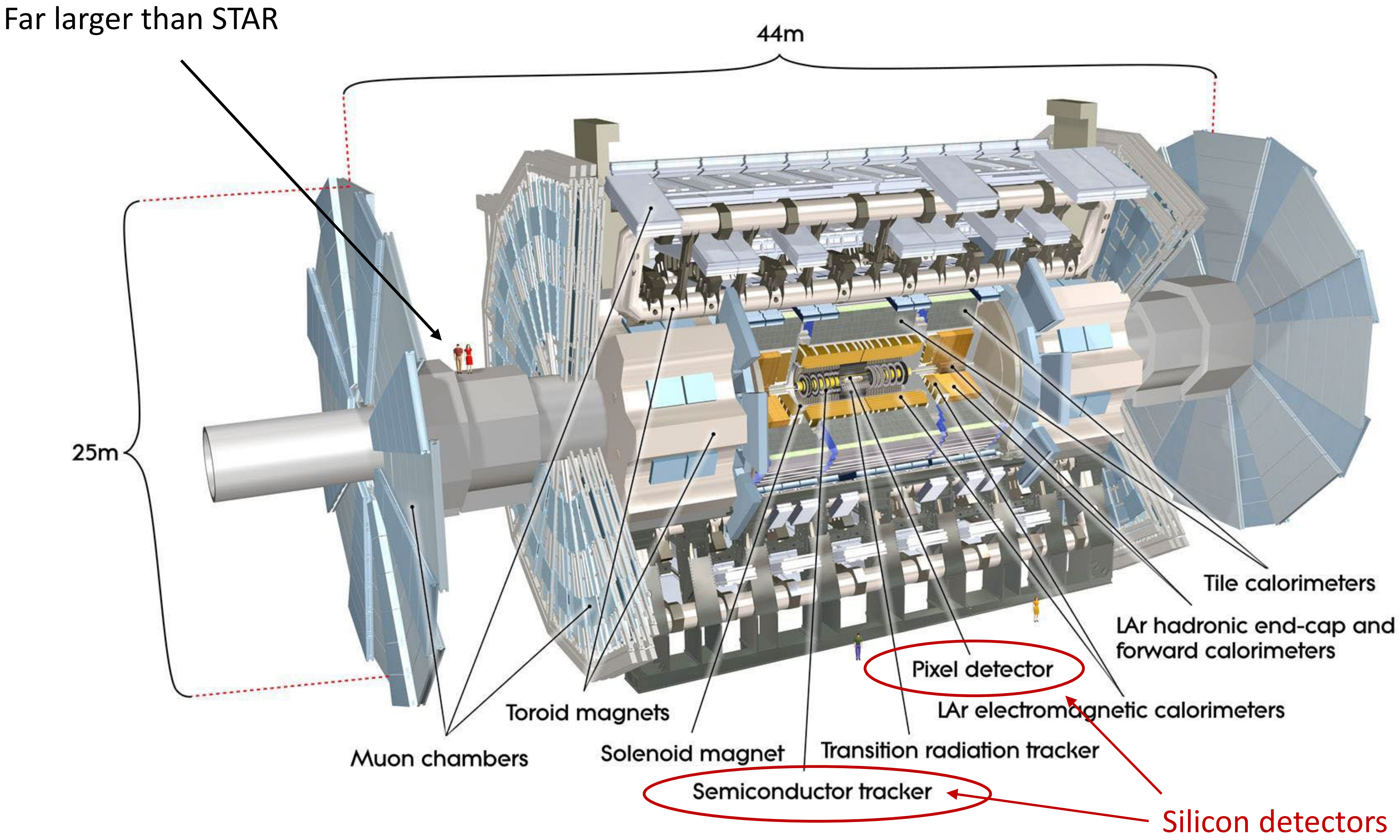
Half of Silicon Vertex Tracker Installed at RHIC

CERN (Conseil Européen pour la Recherche Nucléaire) Large Hadron Collider (LHC)

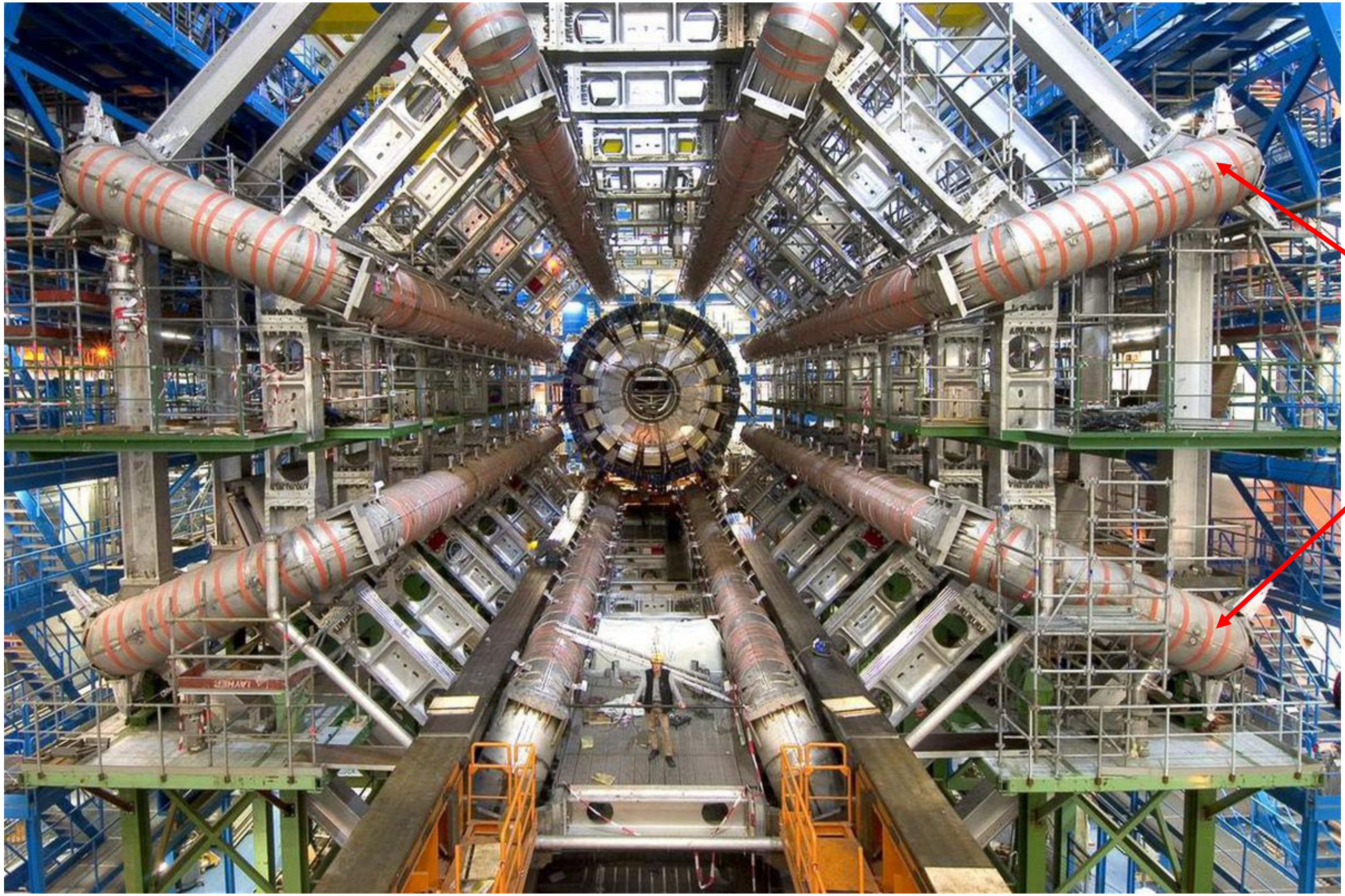
- Located near Geneva, Switzerland
- Tunnel goes through both France and Switzerland (Swiss are good at building tunnels)
- 16.8 mile circumference
- Located underground
- ATLAS experiment ~ 70 meters underground
- ATLAS = A Toroidal LHC Apparatus
- Collides protons on protons



ATLAS (A Toroidal LHC Apparatus)



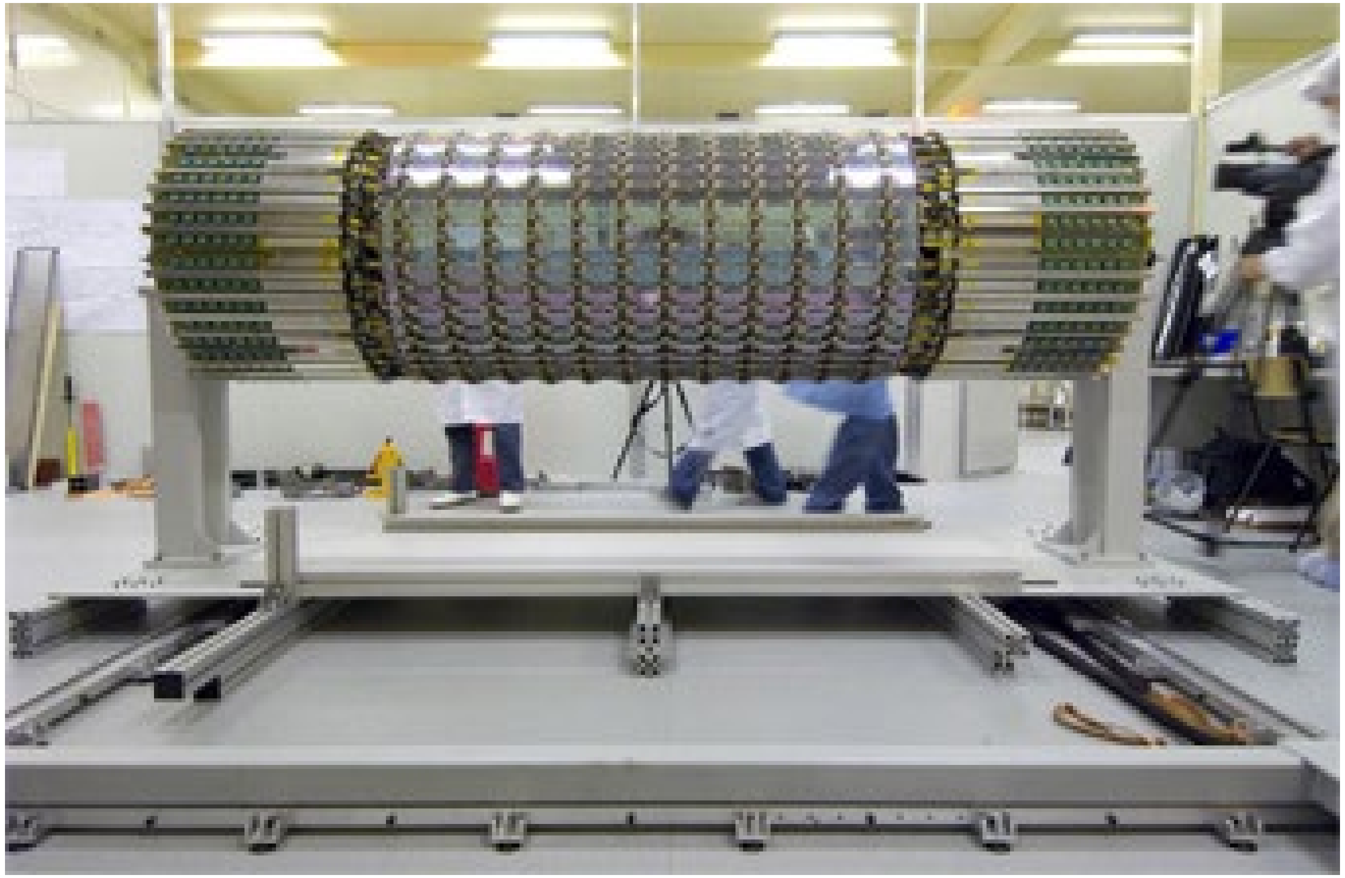
ATLAS under construction



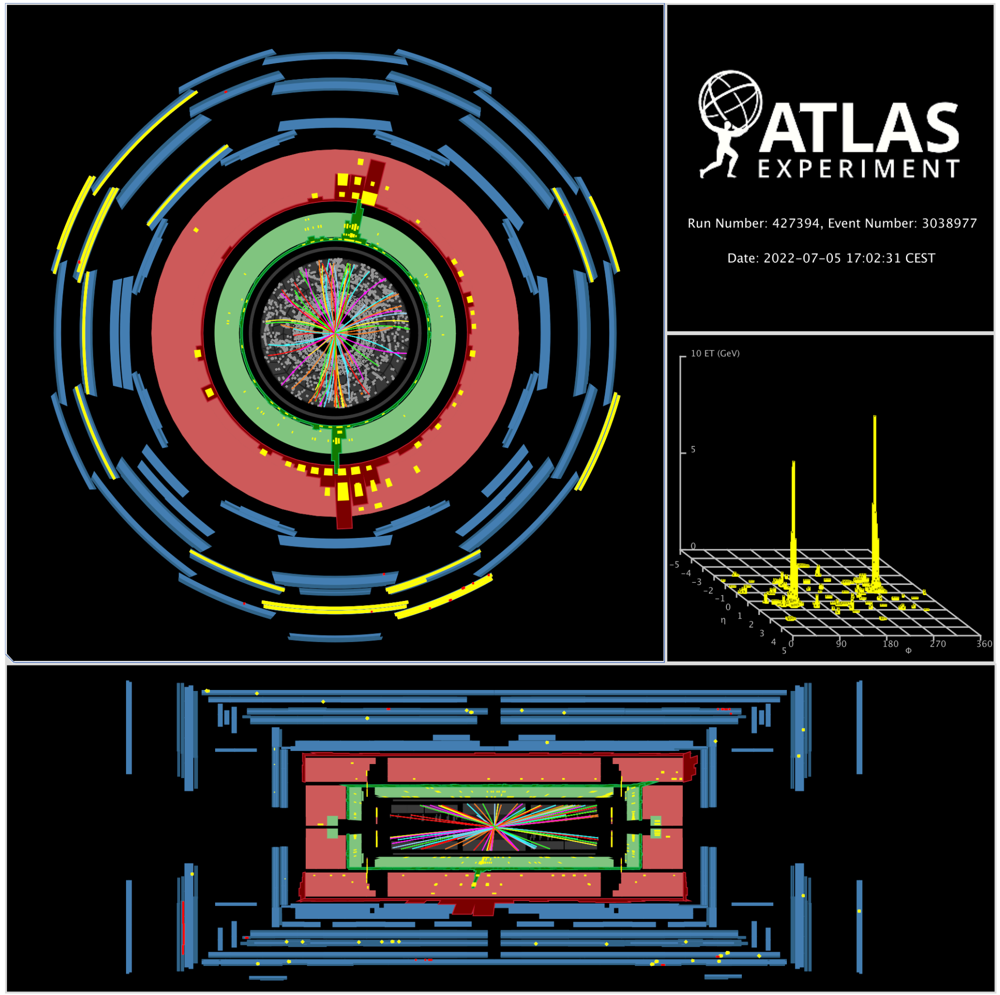
Toroid magnets

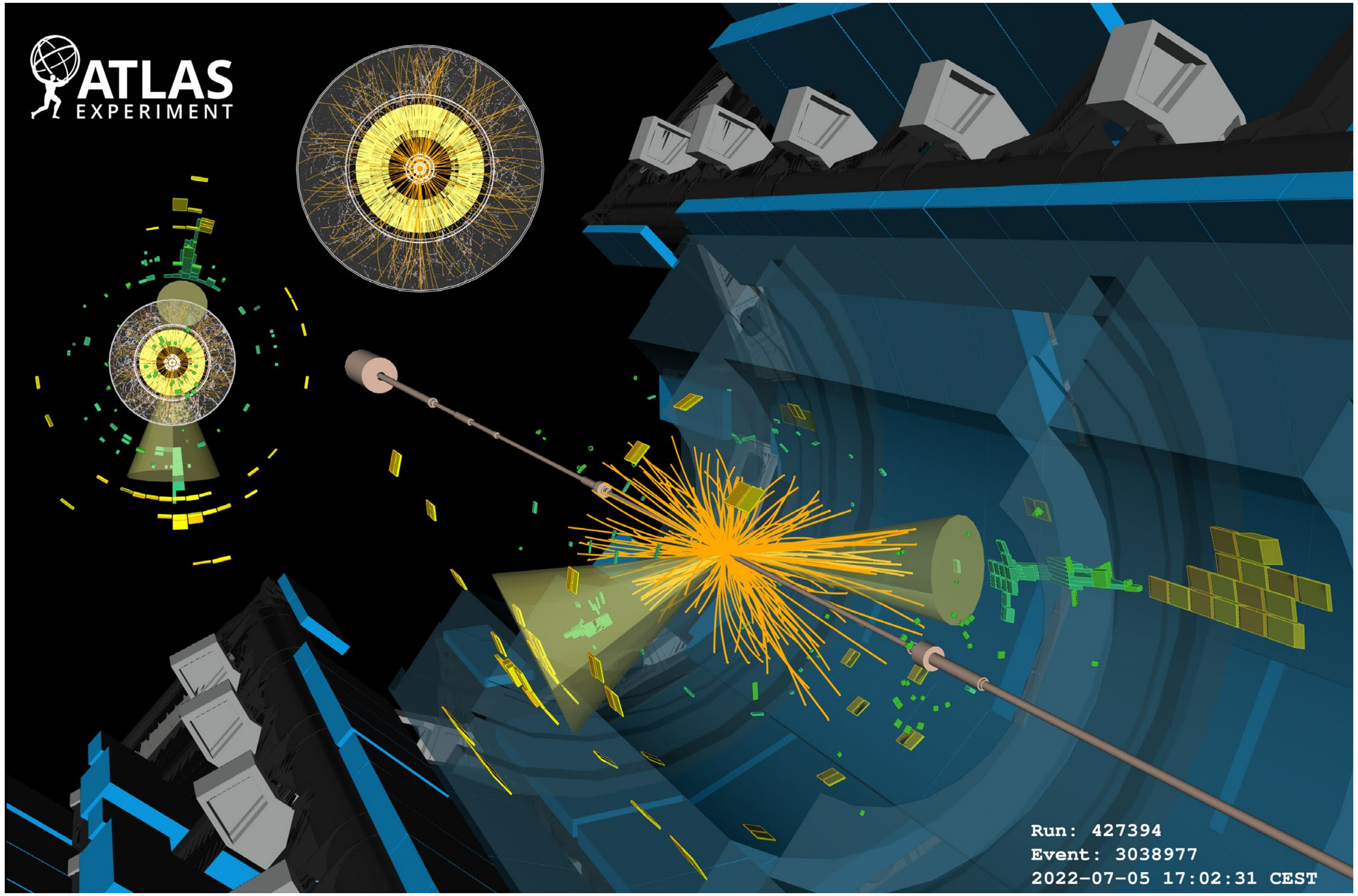
ATLAS Silicon Semiconductor Tracker

- 61 m^2 of silicon
- Currently operating
- Cost = ? At least tens of millions of dollars



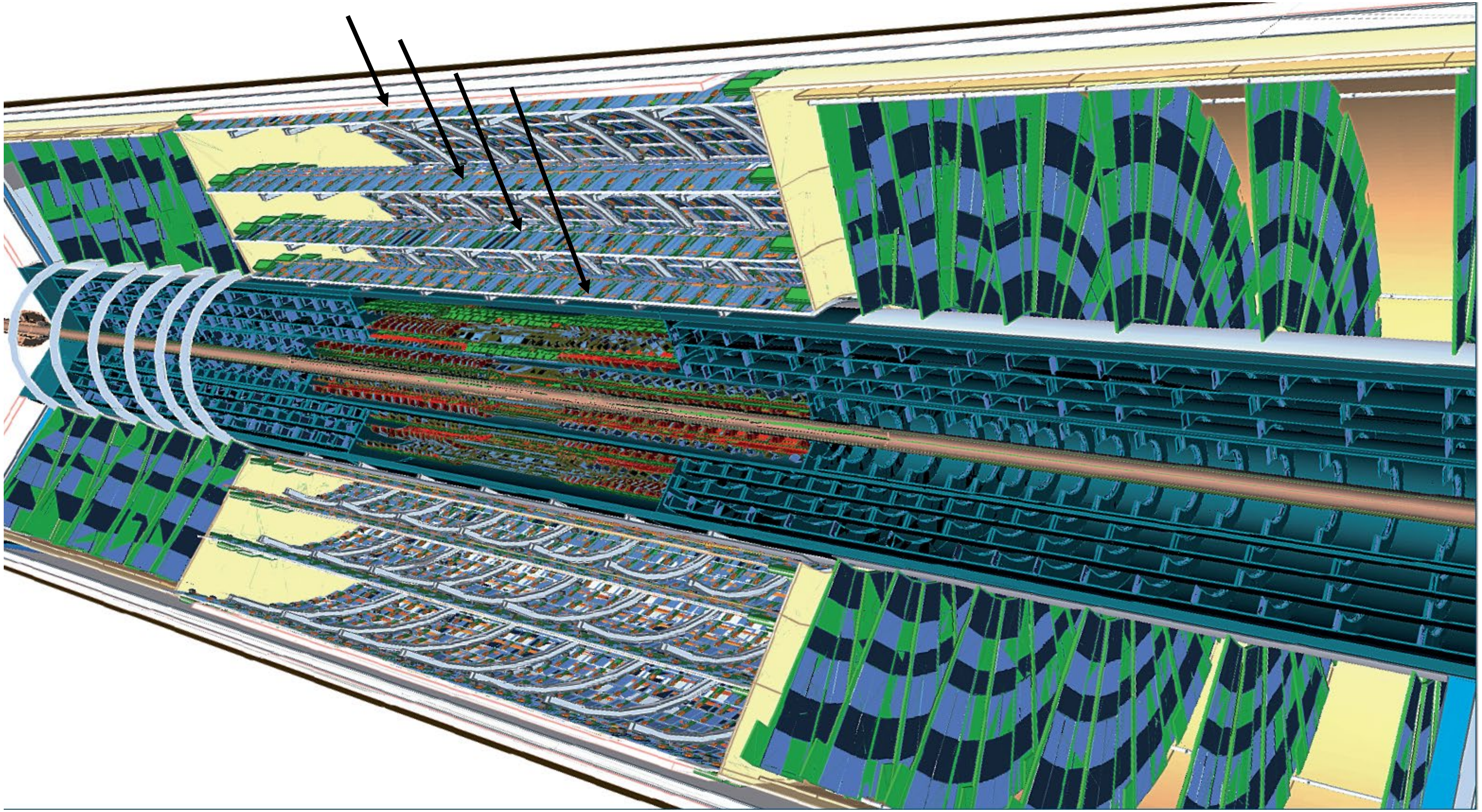
Particle reconstruction from tracks from Run-3 data (just a couple of weeks old!)





ATLAS Silicon Strip Upgrade (my current project)

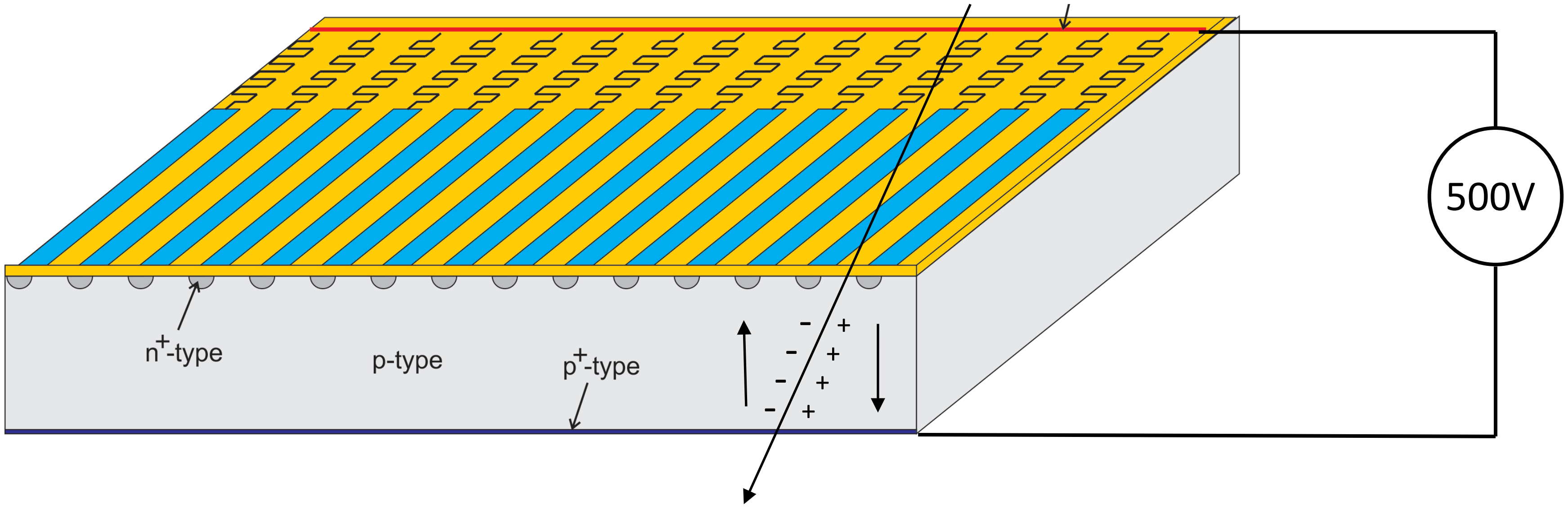
162 m^2 of silicon strip sensors
Cost > $100 million



What Are Silicon Detectors?

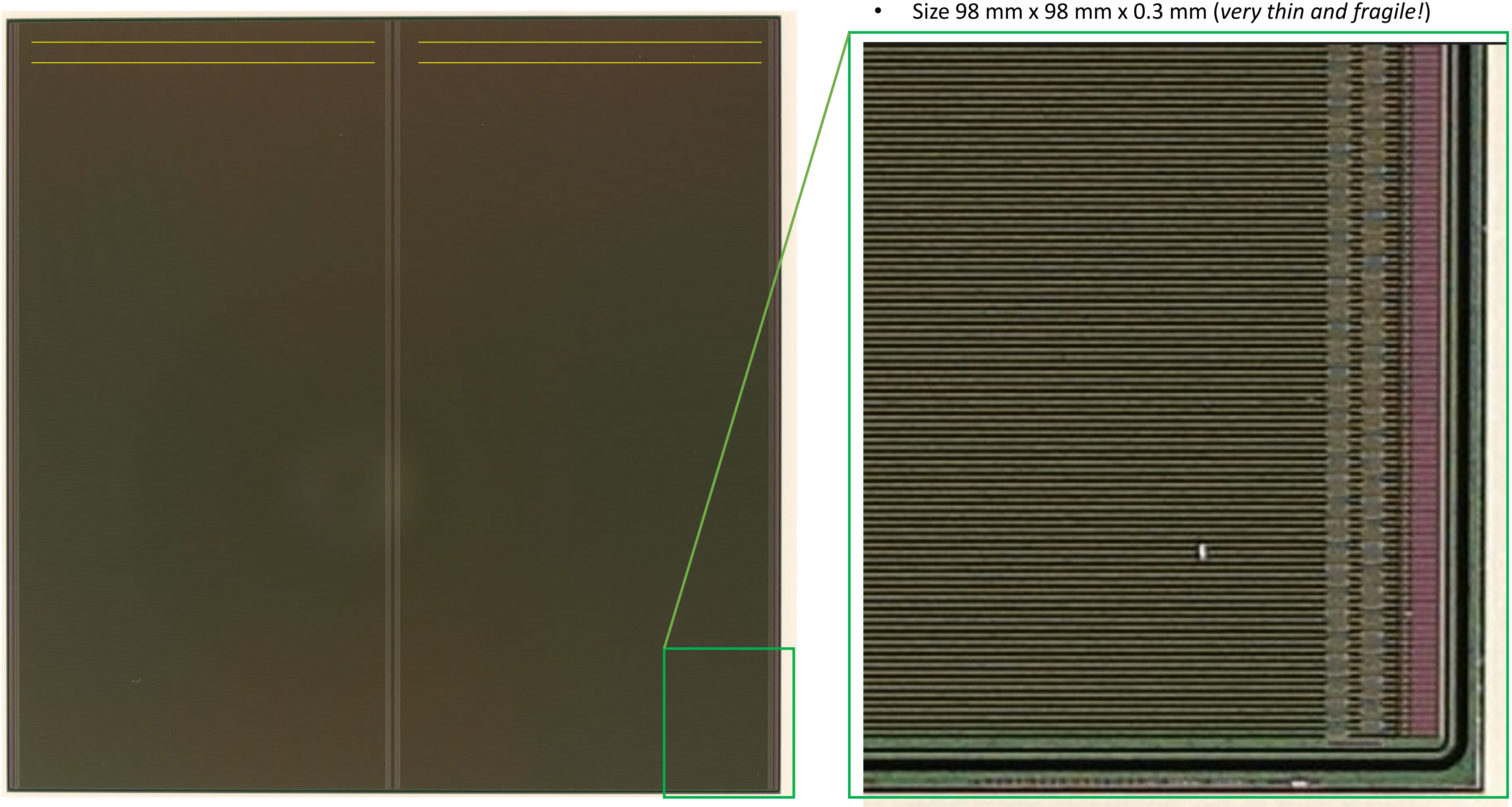
- There are a variety of silicon detectors, but we will focus on silicon *strip* detectors.
- The are sensors made out of silicon, not to detect silicon.
- The detect the ***position*** passage of charged particles passing through them.
- They also can detect photons, either being absorbed in the sensor, or Compton scattered.
- The sensor is simply a large collection of reverse biased diodes (but with a “strip” geometry”. Ionized electrons generated from passing charged particles are driven to the diode strips by voltage applied across thickness of detector.

Diode symbol



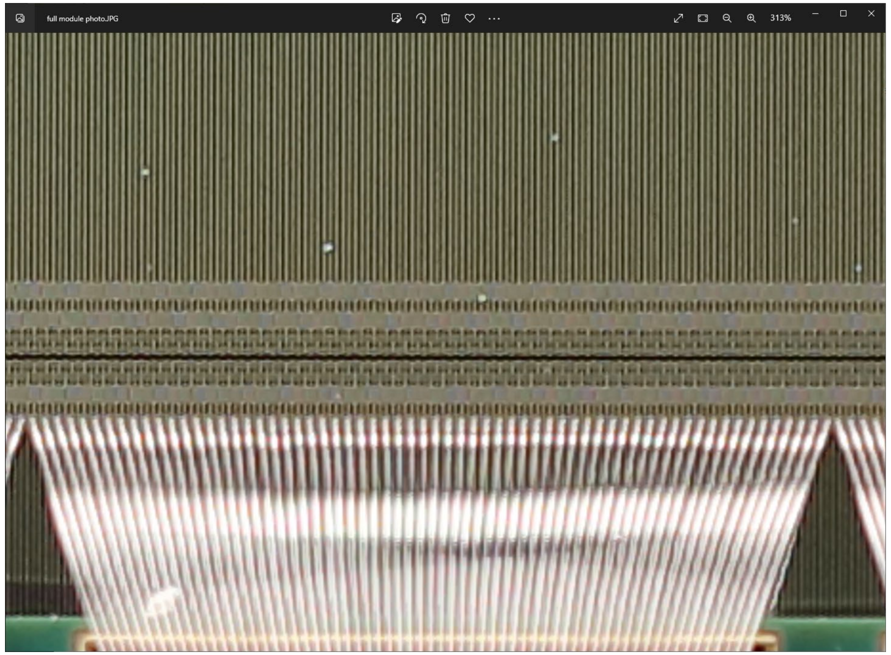
Silicon Strip Sensor for ATLAS Upgrade

- 2 rows of 1280 diode strips (detecting elements)
- Spaced **75 um** (3 thousandths of an inch)
- Size 98 mm x 98 mm x 0.3 mm (*very thin and fragile!*)

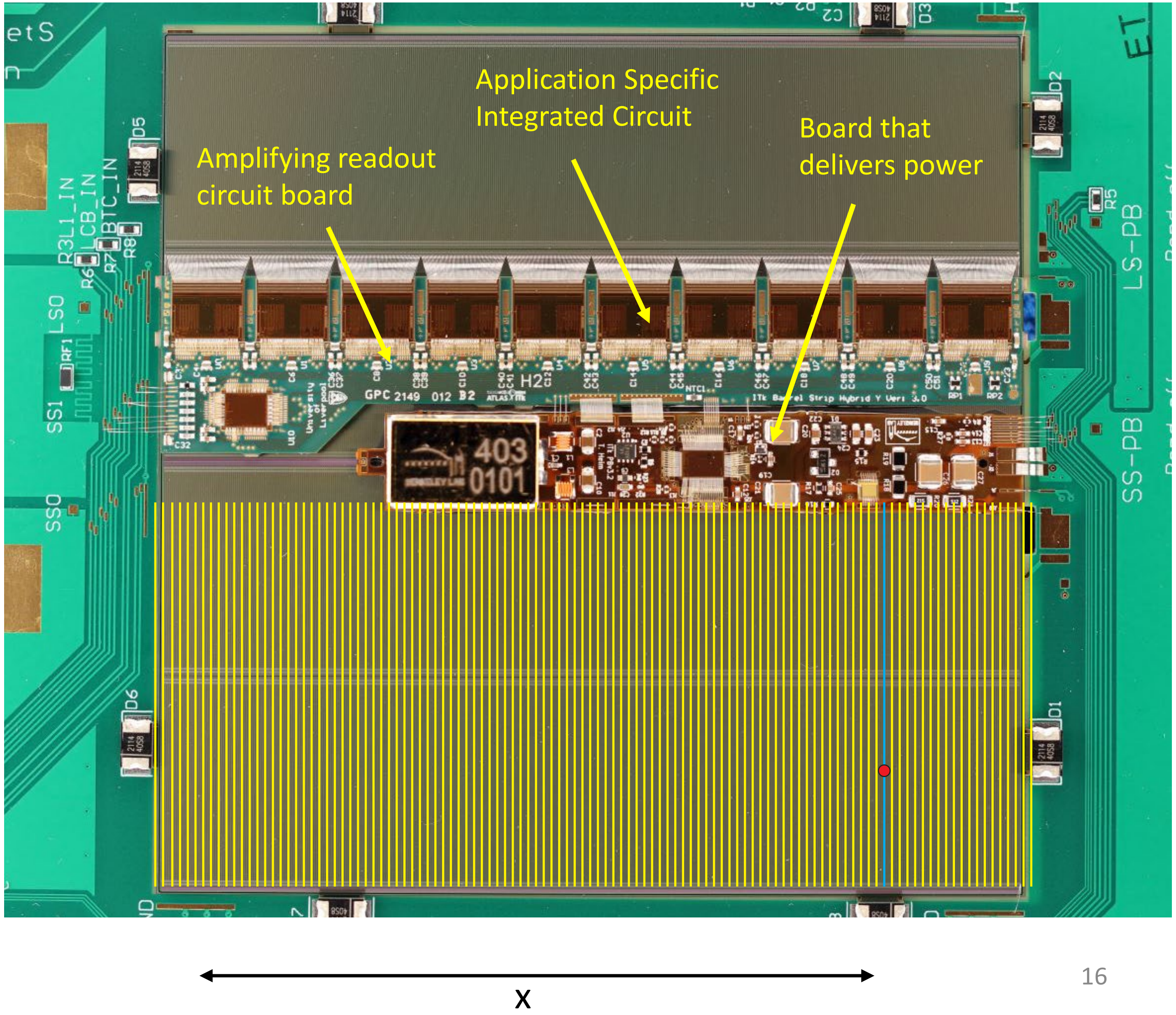


Silicon Strip Module (sensor + amplifying circuit board + board that provides electrical power)

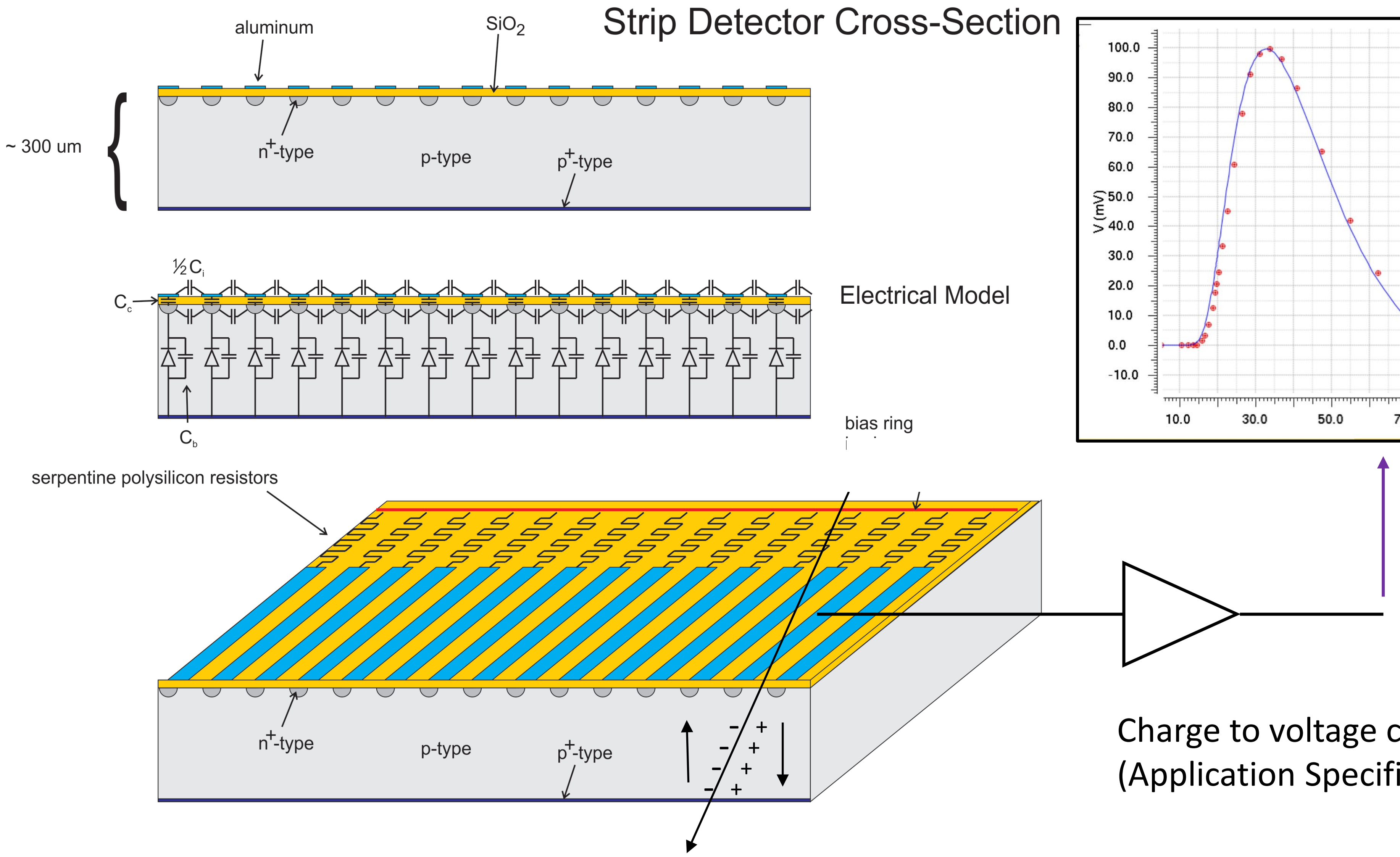
- 1280 “strips” spaced 75 um (3 thousands of an inch) apart
- A charged particle (like a proton or electron)goes through sensor and leaves ionized charge on a strip. Which strip is “hit”give the position of the charged particle in x direction.

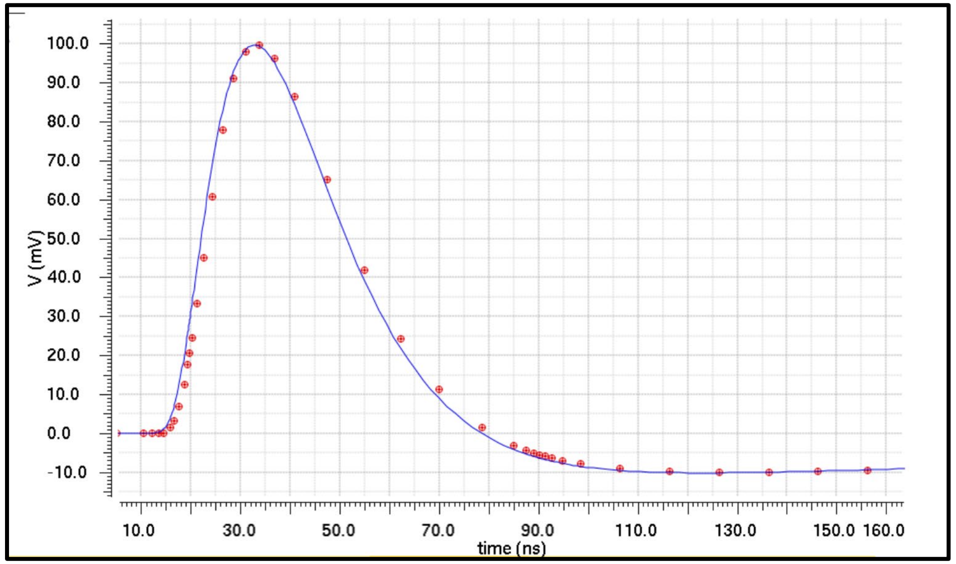


25 micron diameter aluminum wires



Silicon Strip Detector: Each strip is a reverse biased diode

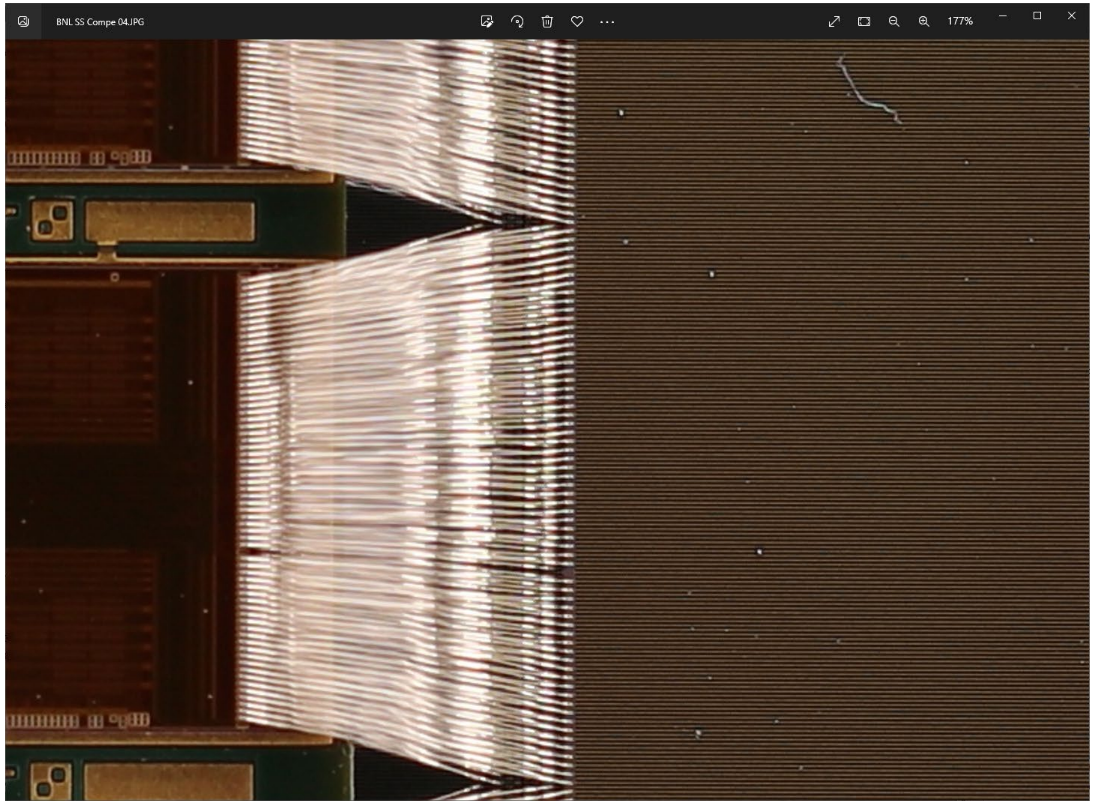




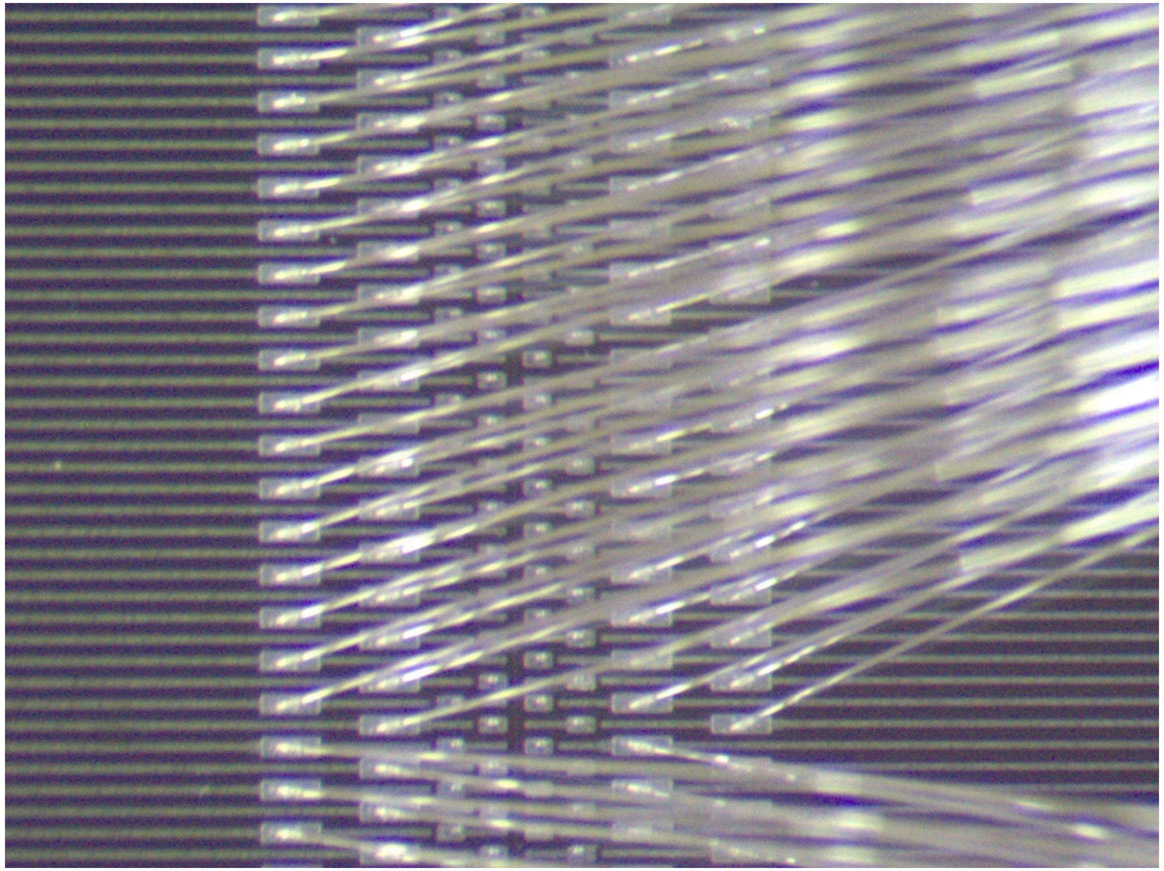
Charge to voltage converter in ASIC
(Application Specific Integrated Circuit)

Silicon Strip Detector Closer View

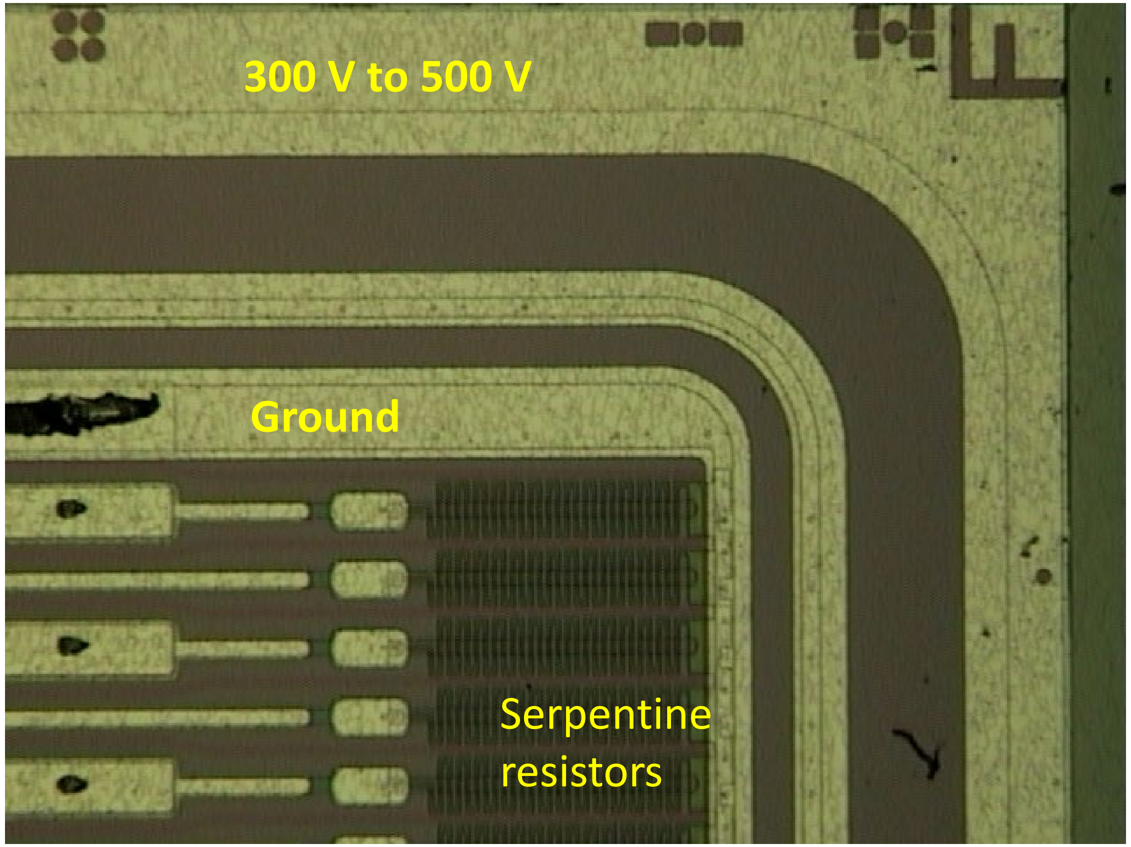
ASIC (contains 256 amplifiers)

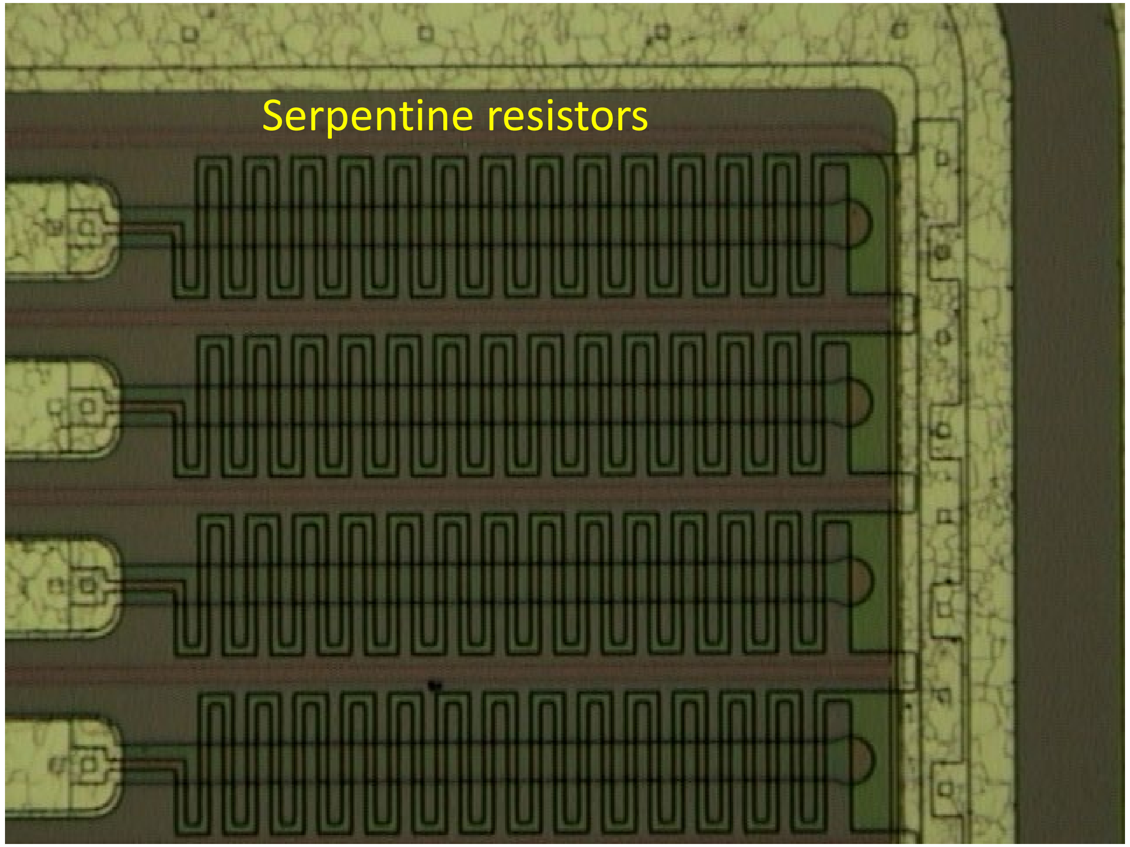


25 um (1/1000th inch)diameter aluminum wires



Silicon Strip Detector Closer View

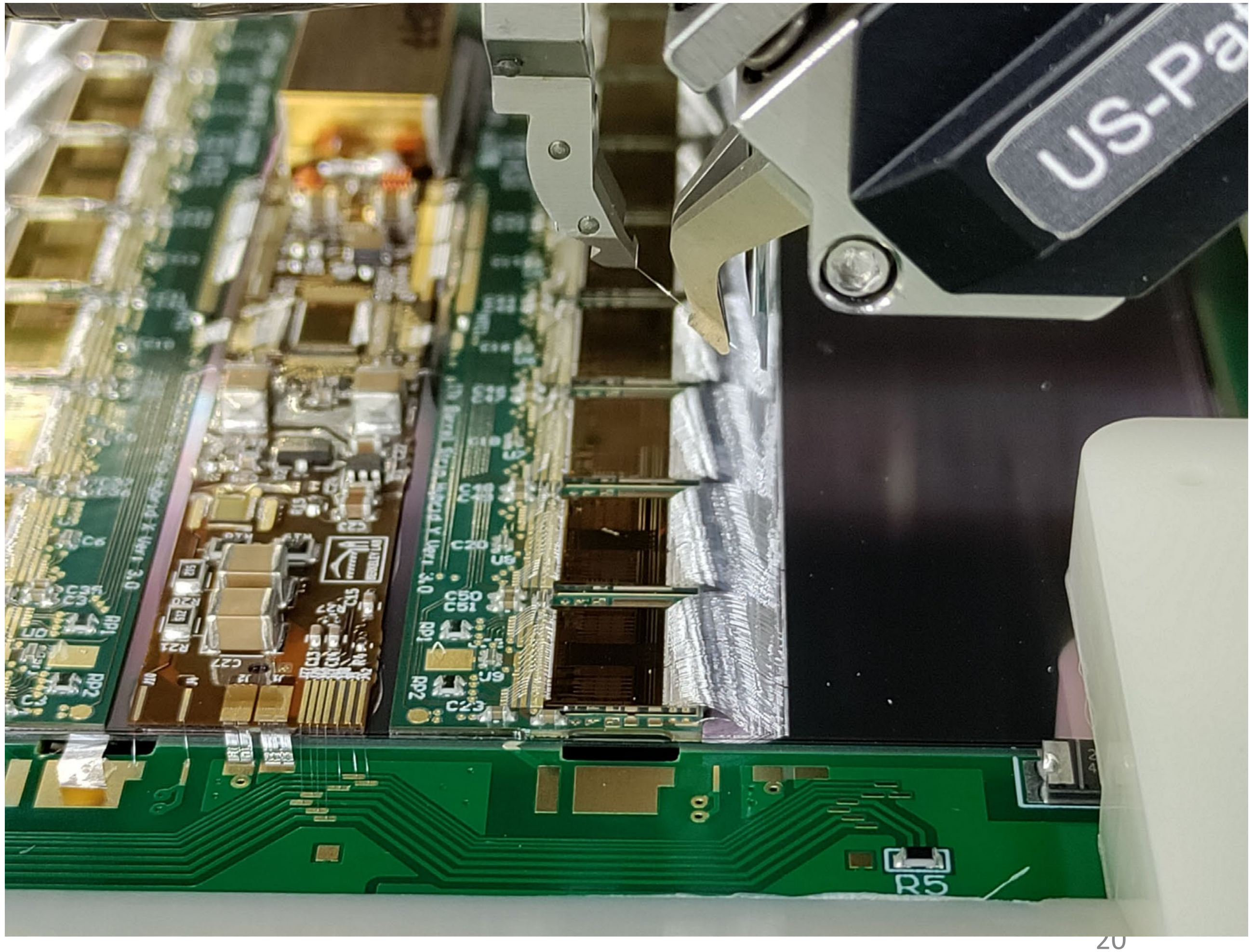




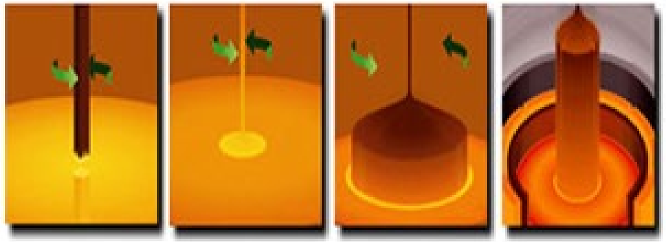
Want > 1 MΩ resistors for thermal noise reasons. *Why do resistors have “serpentine shape”?*

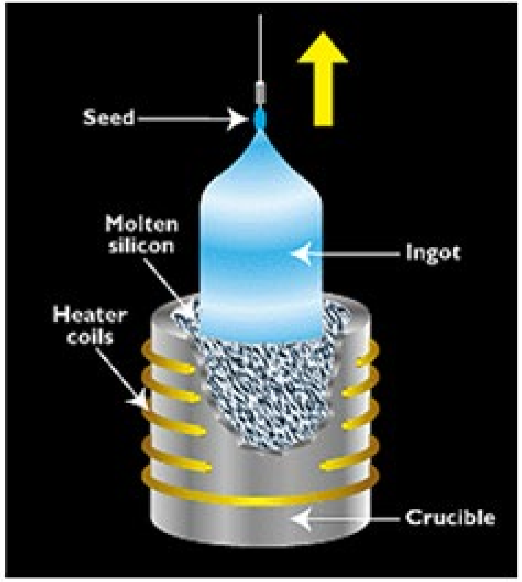
Aluminum Ultrasonic Wedge Bonding

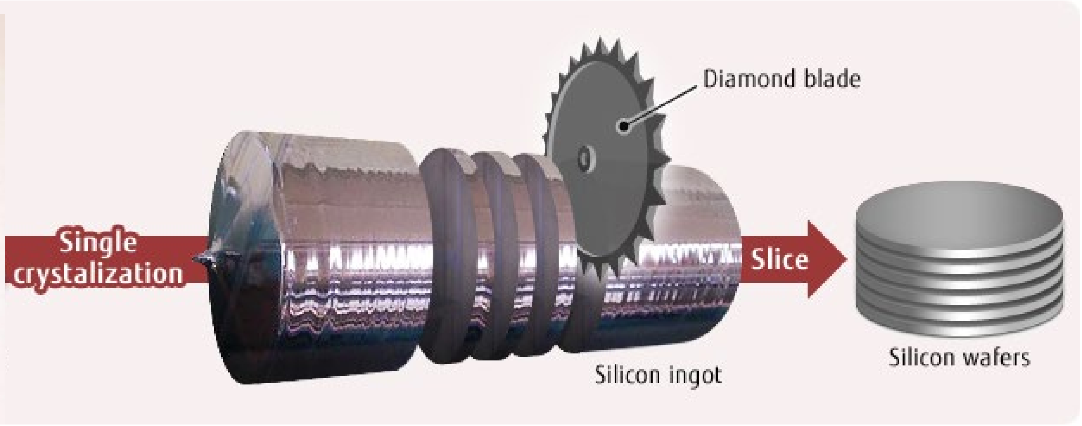
- H&K Bondjet 820 wirebonding machine.
- Cost about $250k, but owner gave us a discount to support science. Cost about $150k.
- Makes several wirebonds per second! Wires weld ultrasonically.
- Photo is from our assembly cleanroom in the back of the physics department.



How Silicon Wafers are Grown



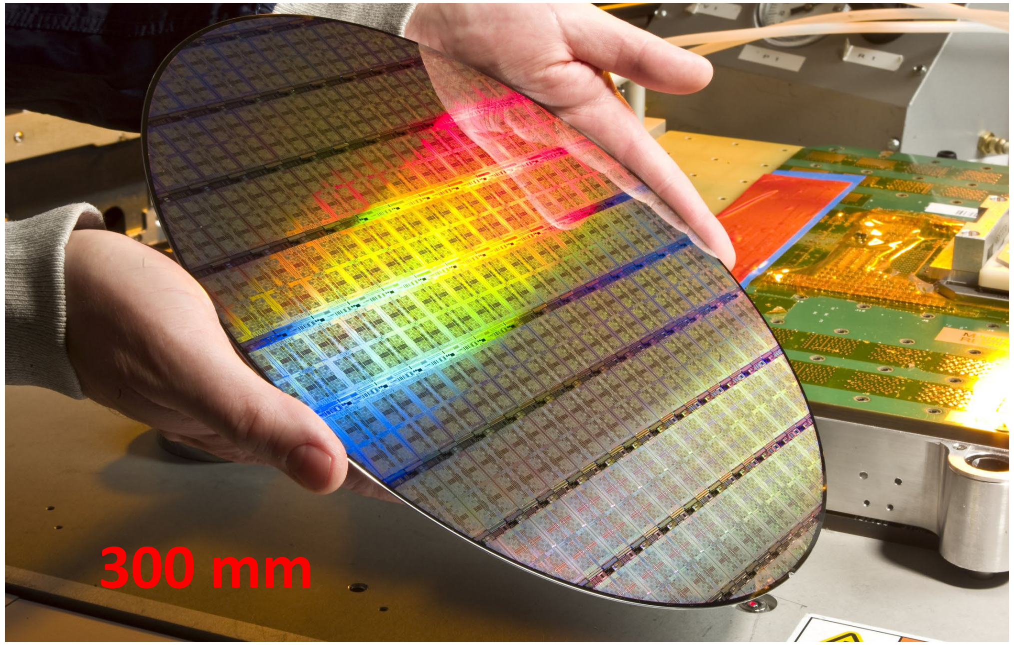




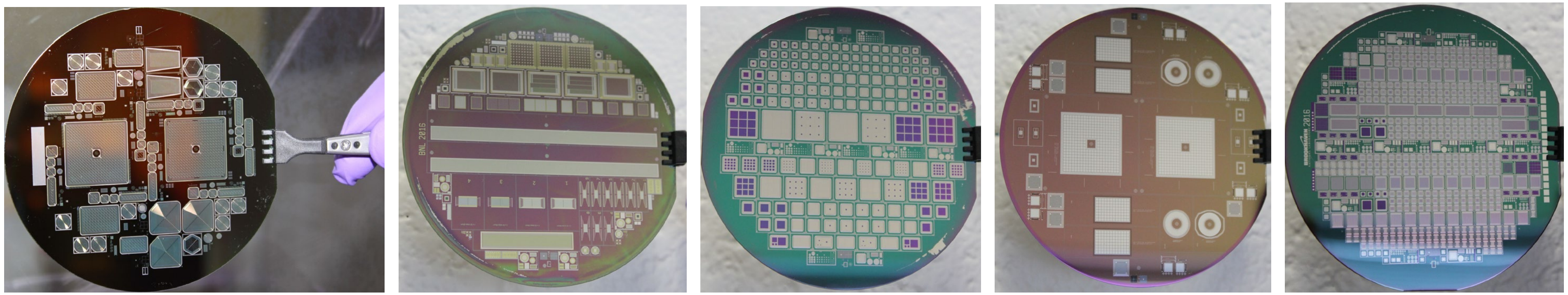
Fabrication of silicon sensor similar to that of integrated circuits like those found in your computer

Silicon wafers as you can buy

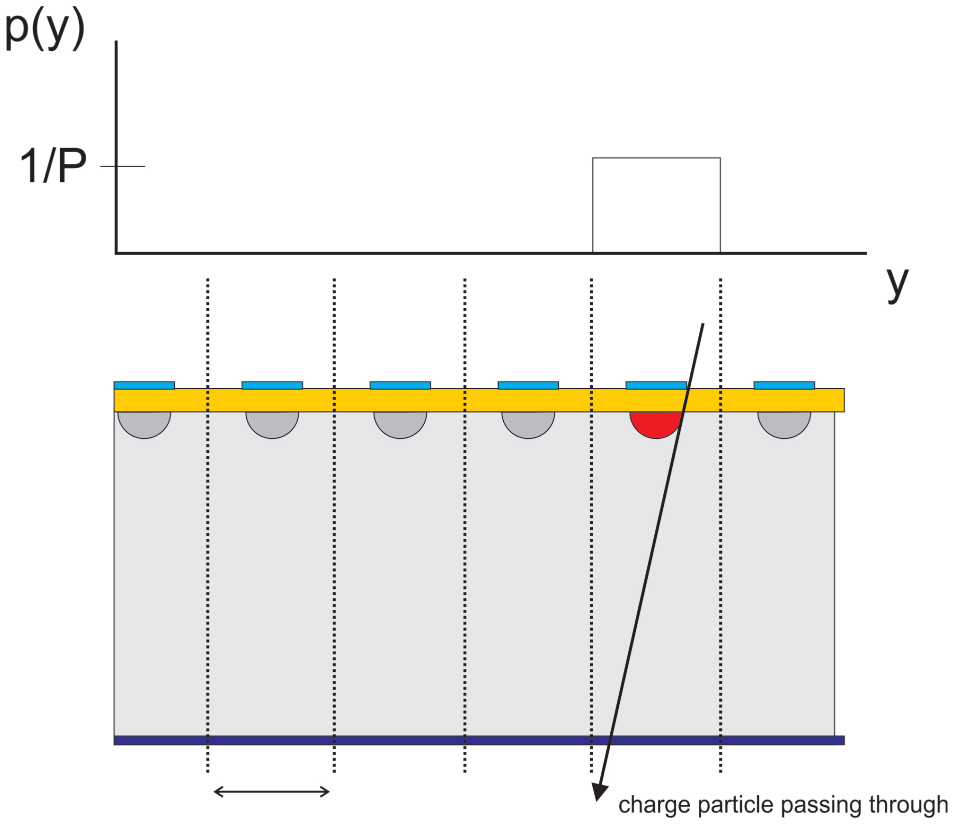
Integrated Circuits (ICs like computer chips) on a Silicon wafer



4” (10-cm) silicon wafer processed at BNL

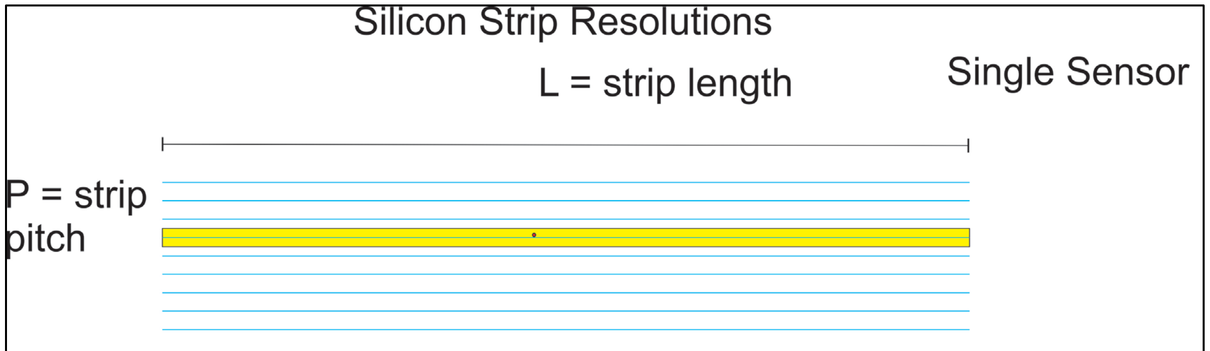


Silicon Strip Resolutions: $P/\sqrt{12}$ rule



P = pitch
= distance between strips

σ_x^2 = variance
σ_x = standard deviation

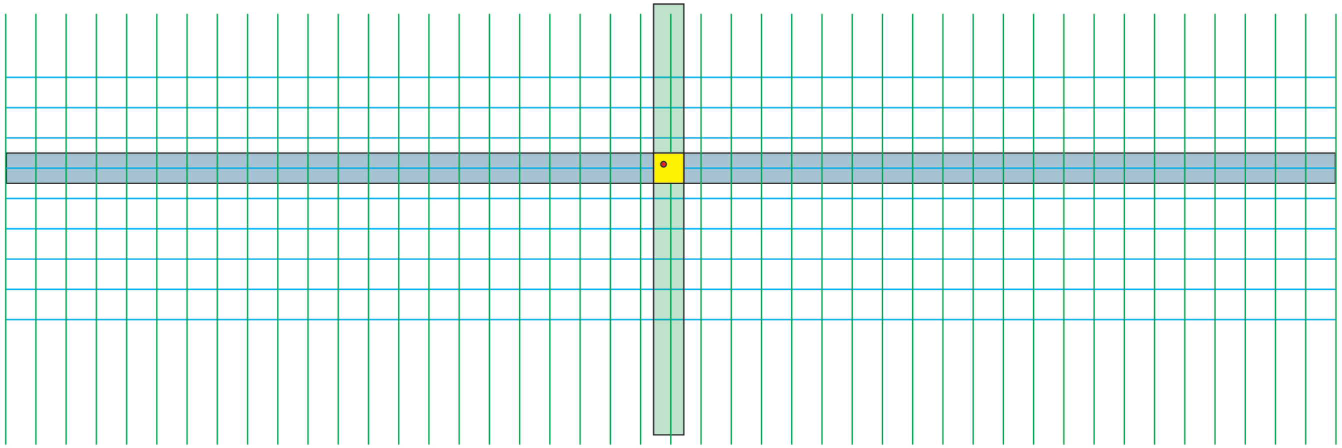


$\sigma_x^2 = \int_{-L/2}^{L/2} x^2\, p(x)\, dx \,/ \int_{-L/2}^{L/2} p(x)\, dx$, where p(x) = 1/L for $-L/2 < x < L/2$, p(x) = 0 otherwise. This gives $\sigma_x = L/\sqrt{12}$, and similarly $\sigma_y = P/\sqrt{12}$

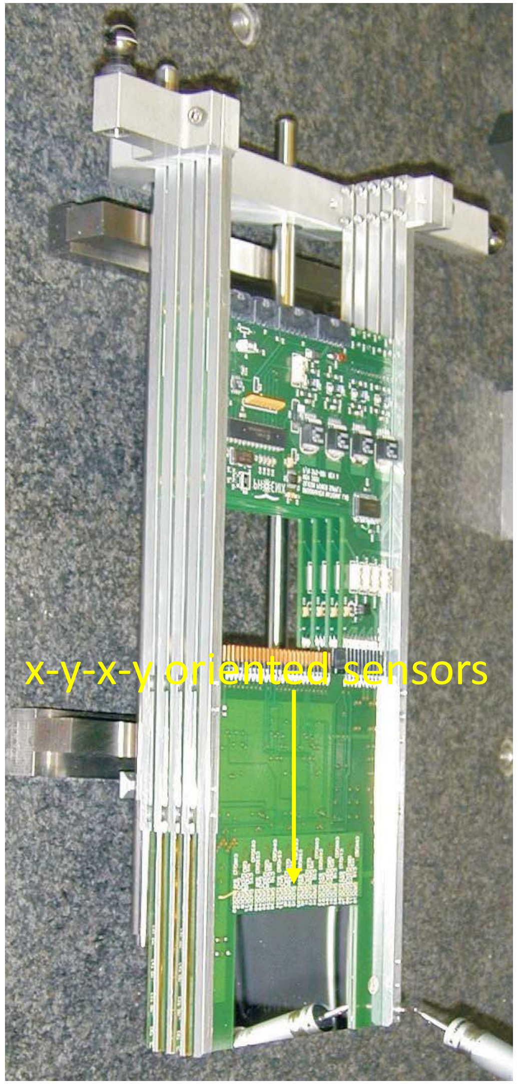
σ (x) = 5m/sqrt(12) = 2.2 cm (not so good)
σ(y) = 75 um/sqrt(12) = 22 um (less than 1/1000th of an inch)

Improved resolution with sensors rotated at 90 degree angle (PP2PP experiment)

90 degree rotated sensors



$$\sigma_x = P/\sqrt{12}, \quad \sigma_y = P/\sqrt{12}$$



Measuring particle momentum by measuring track radius of curvature

Lorentz force $F = q(\mathbf{E} + \mathbf{v_T} \times \mathbf{B})$, where $\mathbf{v_T}$ is the velocity in the transverse (non axial) direction.

Magnetic field is along center of axis of barrels (i.e. axial direction)

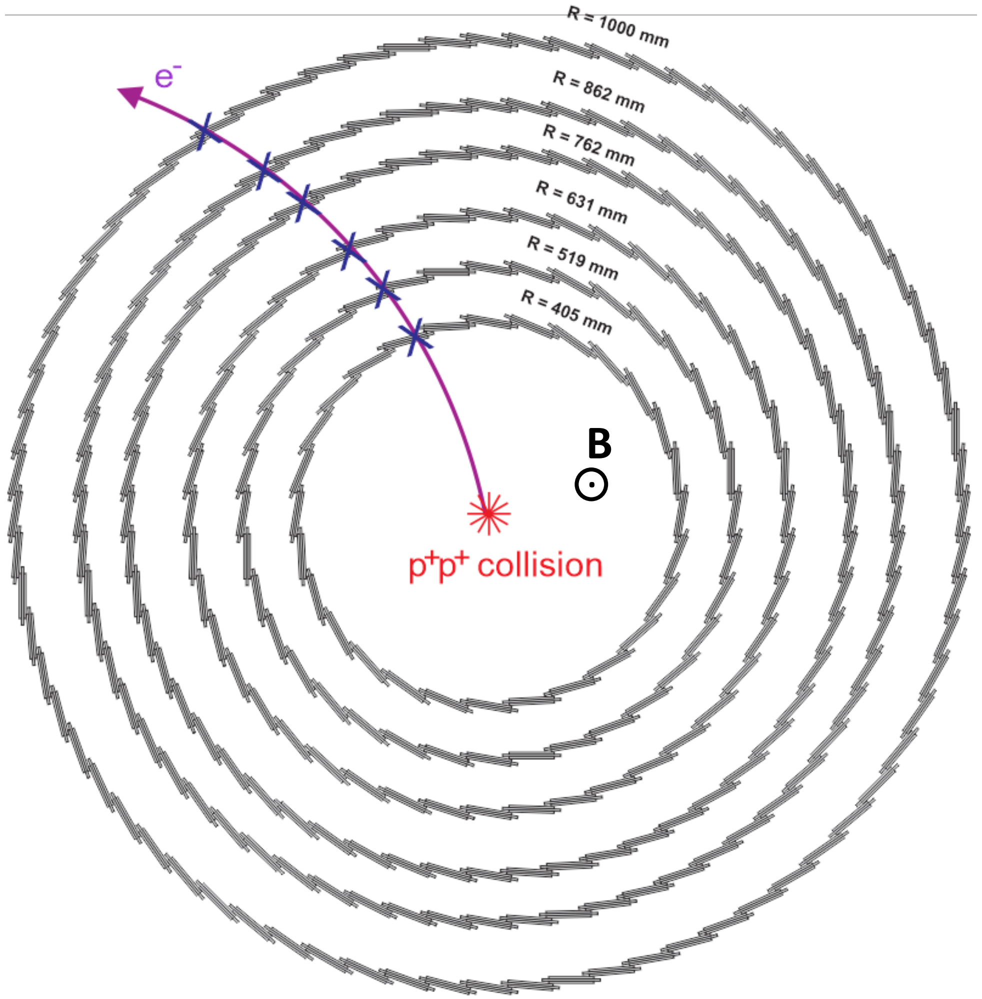
$F = qv_T B = mv_T^2/r$

$p_T = mv_T = qBr$, where P_T is transverse (non axial) direction.

When one knows p_T, one knows overall momentum p by measuring axial track angle.

Finally, if one measures the energy E in the calorimeter then by following equation one knows the mass of the particle.

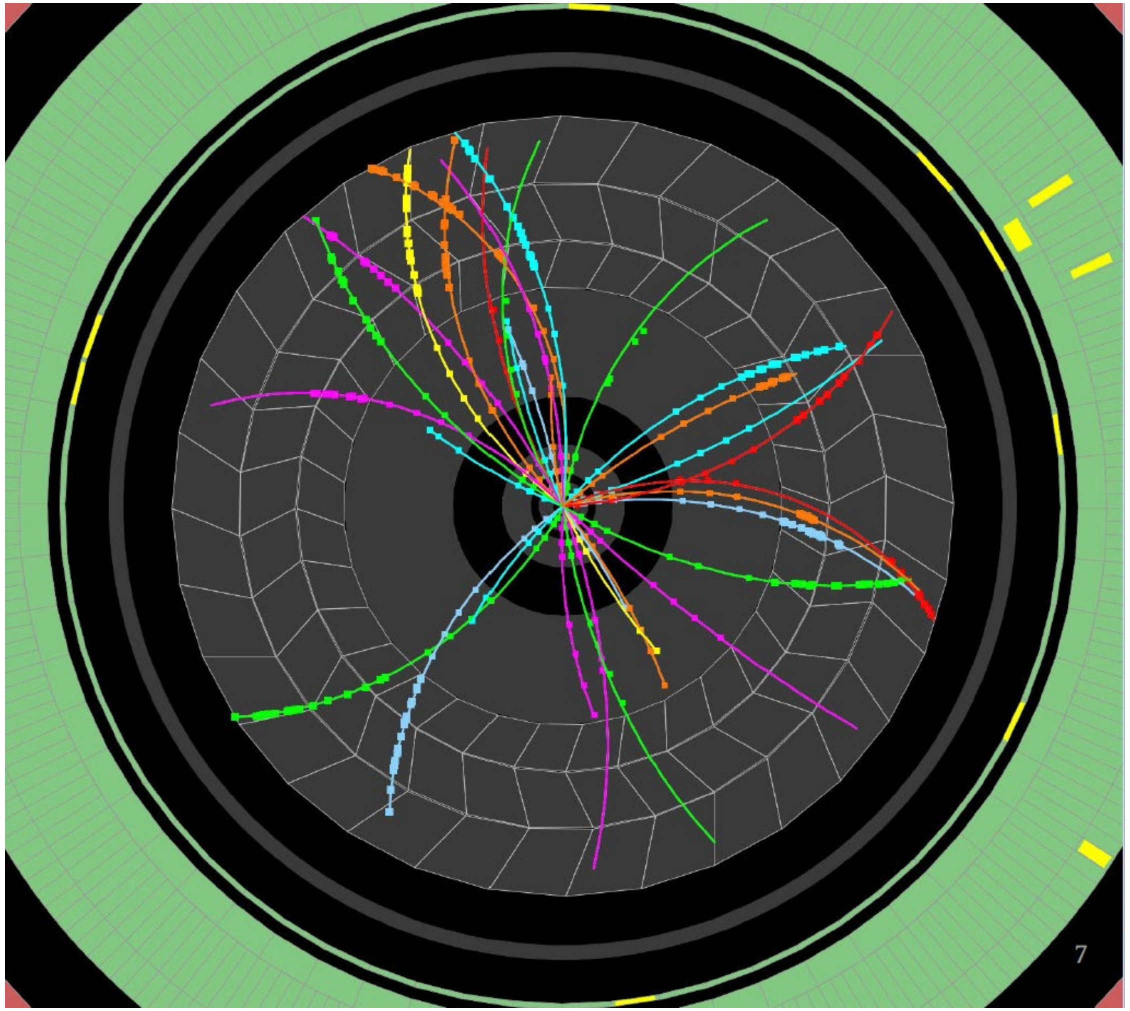
$E^2 = p^2c^2 + m^2c^4$



(Paul Dirac derived this equation: I had thought it was Einstein. I learned something new!)

Axial view of a reconstructed proton-proton collision.

Why do some tracks bend one way and others the opposite?



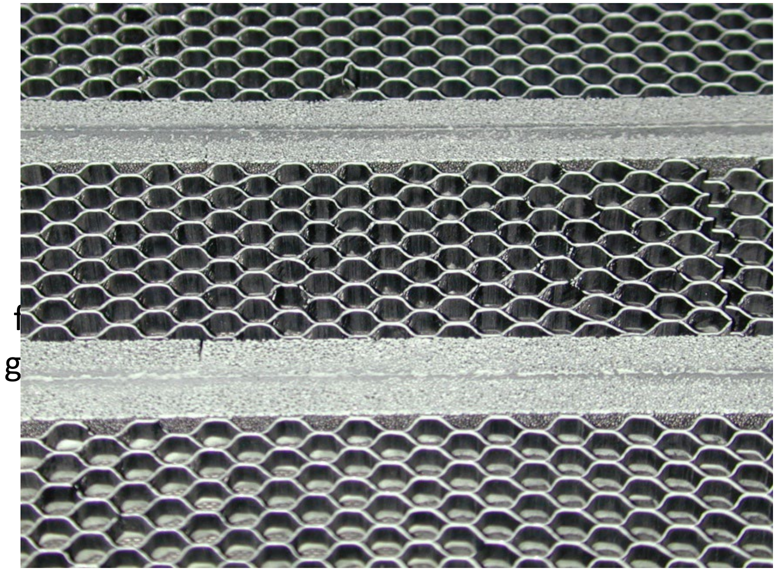
Silicon Detectors/modules need to be mounted on a support that also provides cooling

Carbon fiber is used extensively; low weight and strong (e.g. Boeing Dreamliner)

Honeycomb and carbon foam

Copper ground strip in End-of-Stave region

Co-cured facing (Kapton bus tape cured into carbon fiber facesheet)



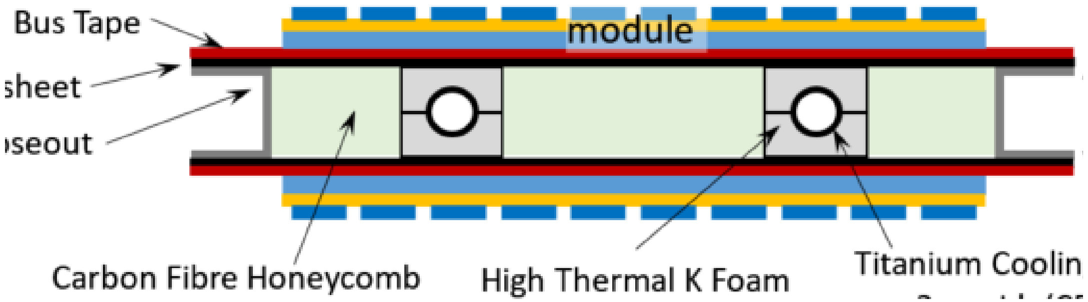
Locking point insert

Carbon honeycomb

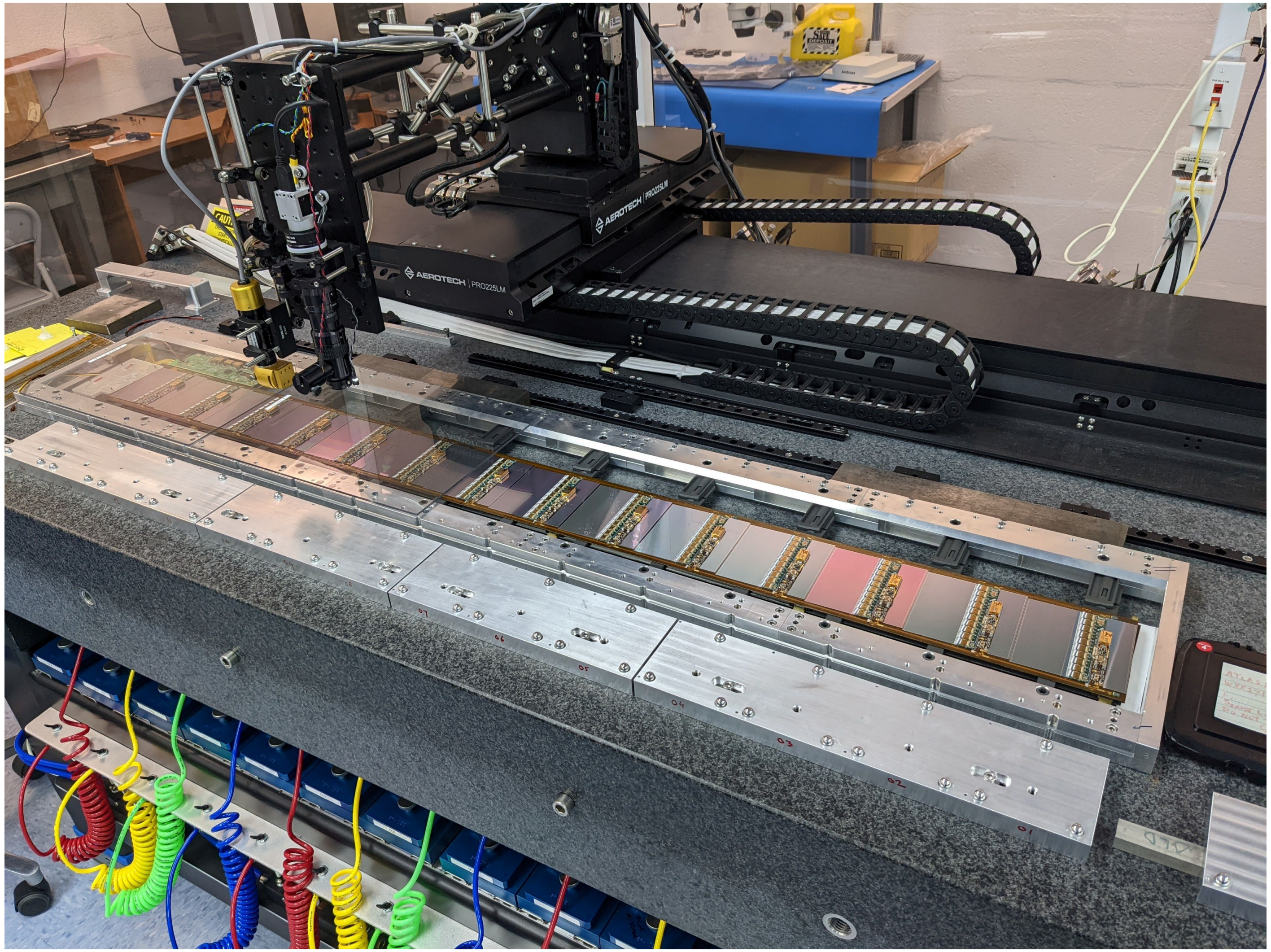
Carbon foam enclosing titanium pipe

C-channel

End closeout

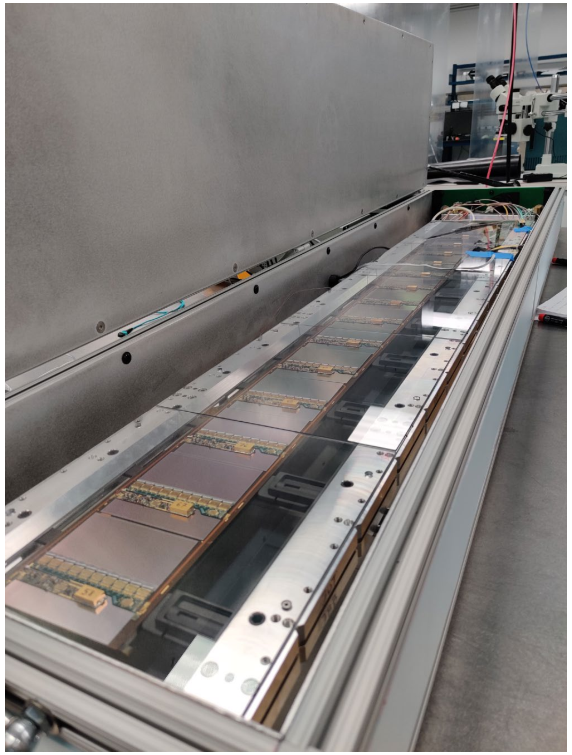


Gluing module to carbon support structure. Modules must be placed to within 50 microns



Testing of final stave is done at cold temperature (~ -40 °C) Inside a “coldbox”

- Detectors will run cold in experiment to reduce current in sensor that is due to radiation damage
- BNL is responsible for building 200 of these staves (1/2 the barrel) and sending them to CERN to be installed in ATLAS

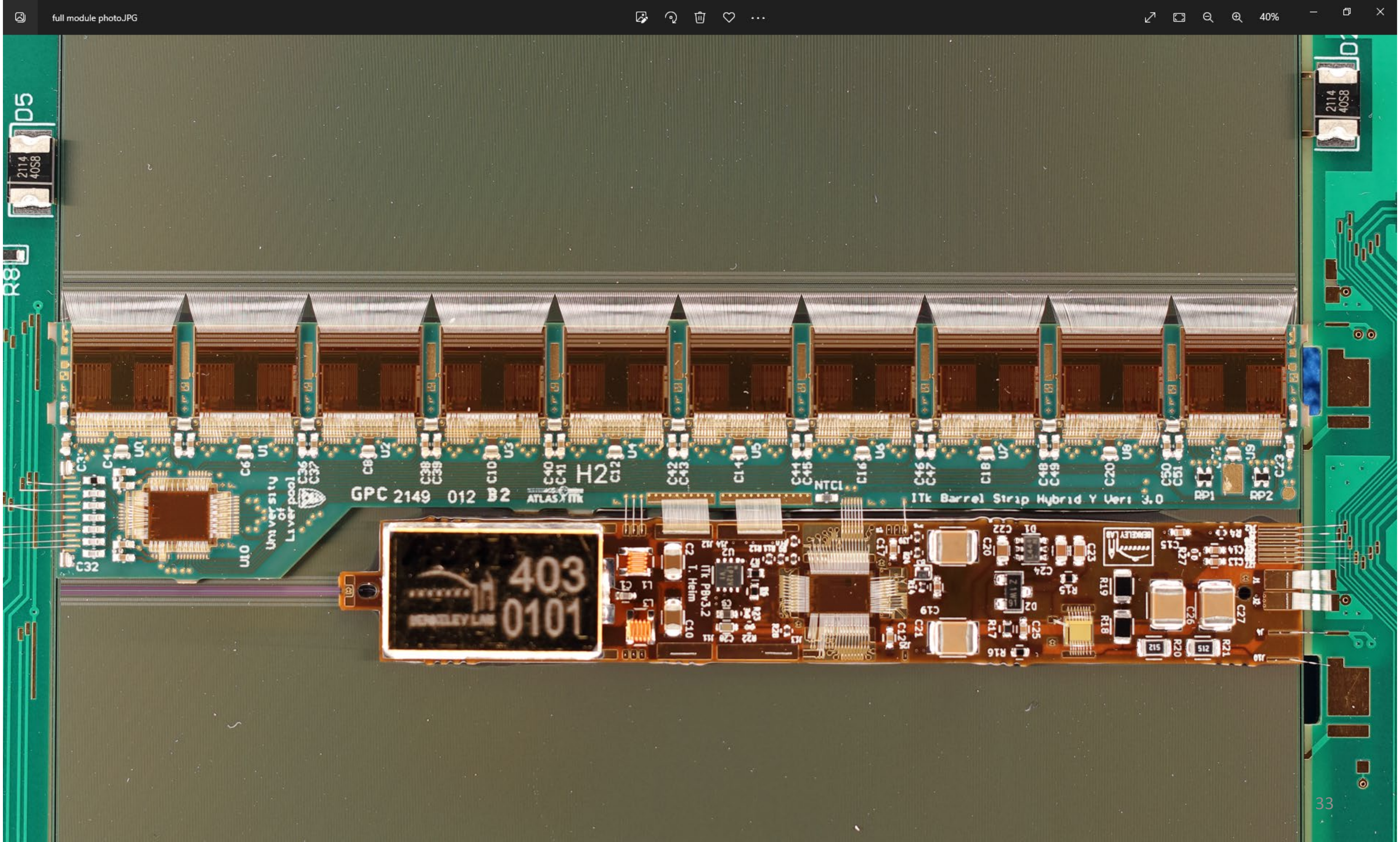


Summary

- Silicon detector systems are used in a variety experiments in high energy and nuclear physics experiments.
- There are many different types of silicon sensors, with silicon strips being a very common type.
- Physicists as well as engineers and students work to design build such detectors.
- In my group we have had ~ 20 graduate students with our team over the last 6 years.
- Silicon detectors provide measurements of tracks and their momentum. Together with an energy measuring detector such as a calorimeter they assist in identifying a track's mass and thus the type of particle.

End

Backup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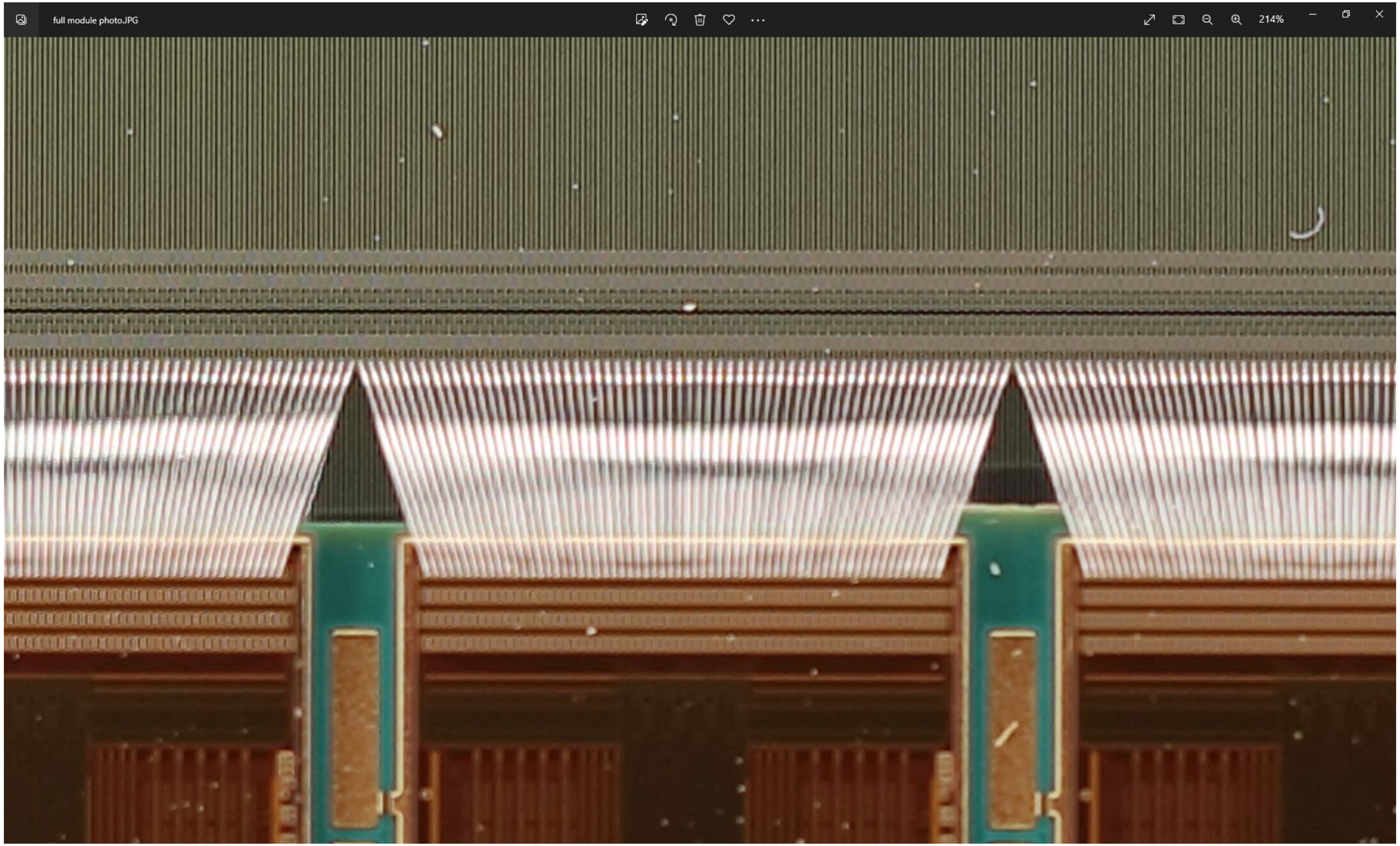
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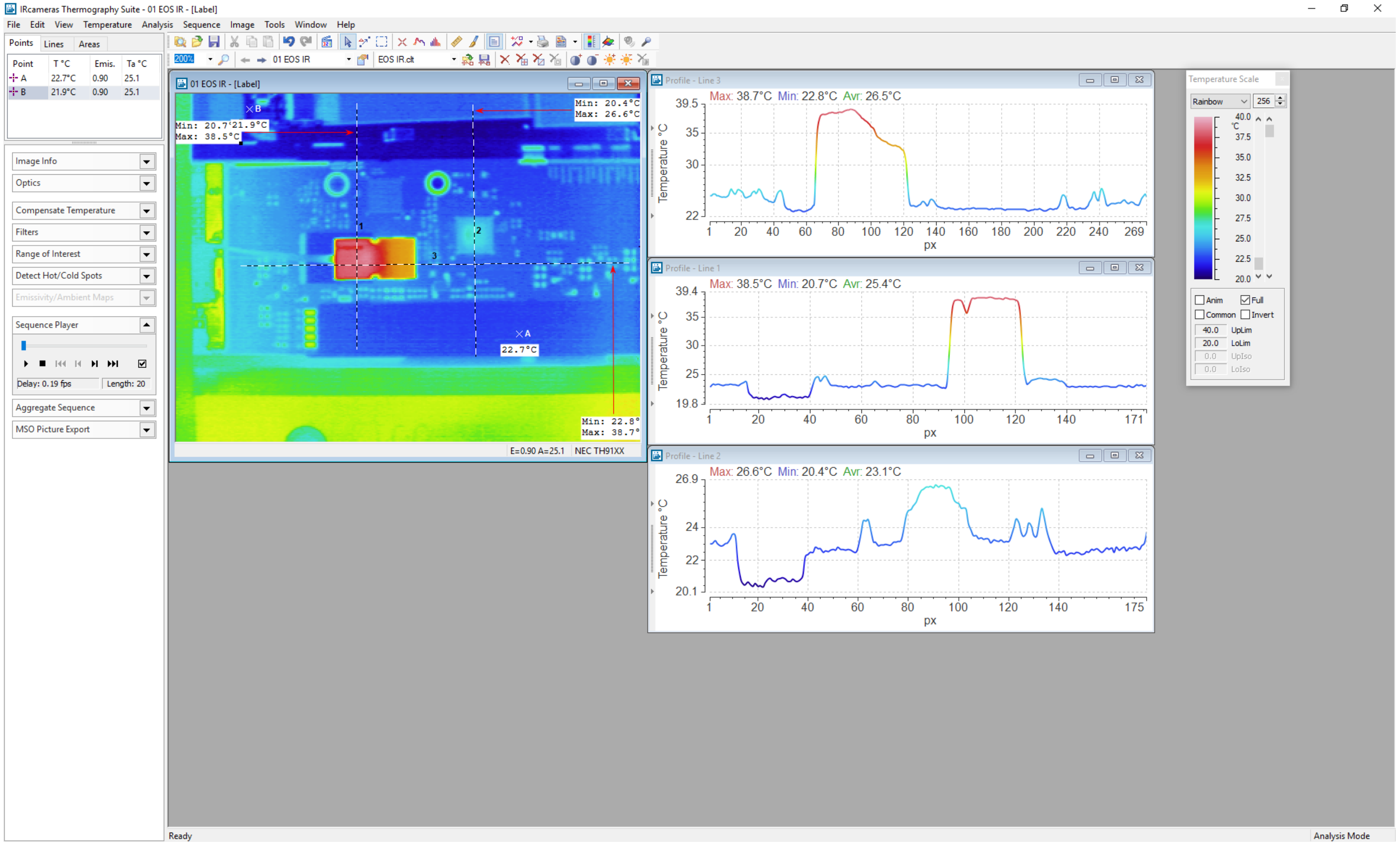
IR Imaging US Long Strip Stave Master EOS



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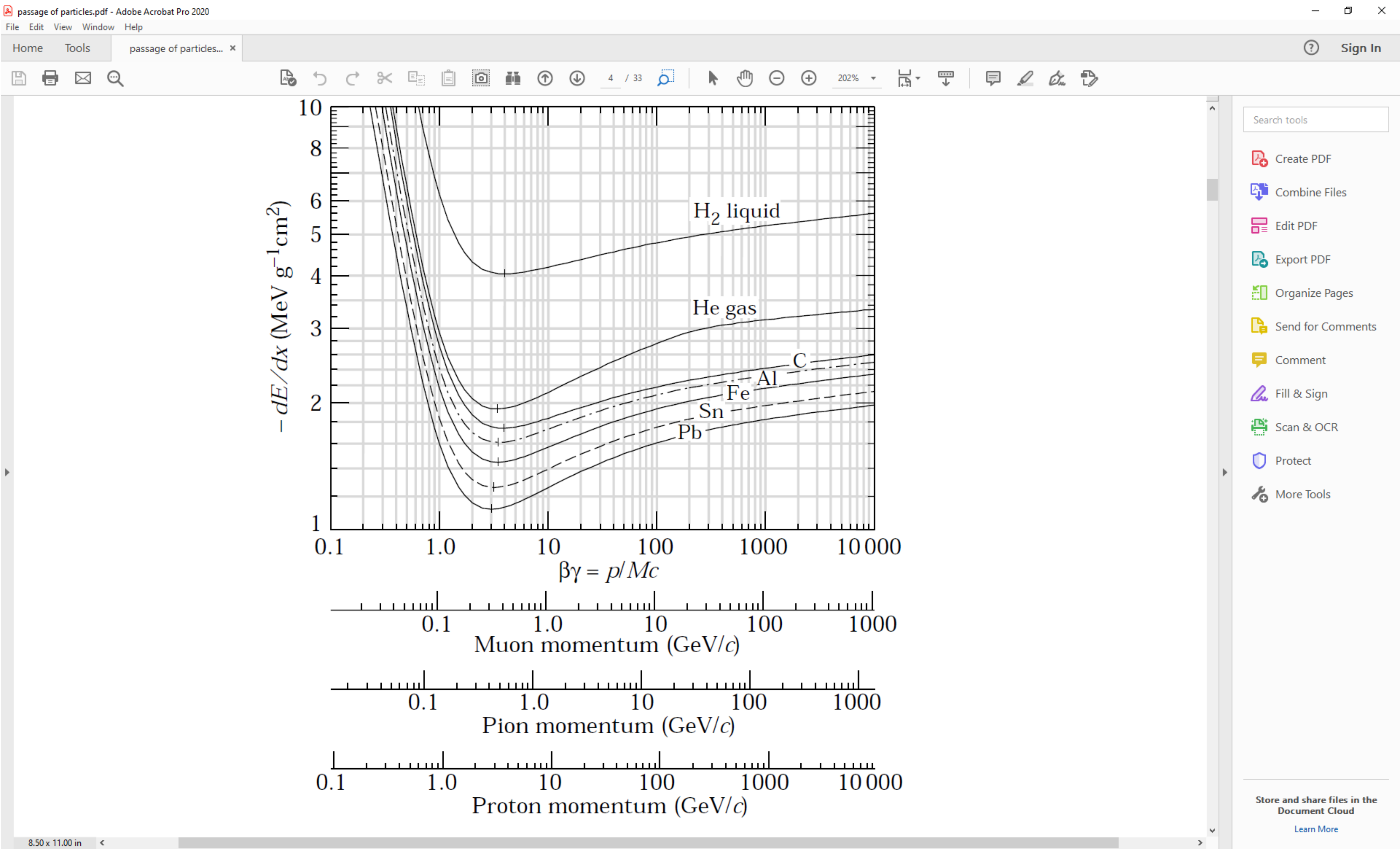
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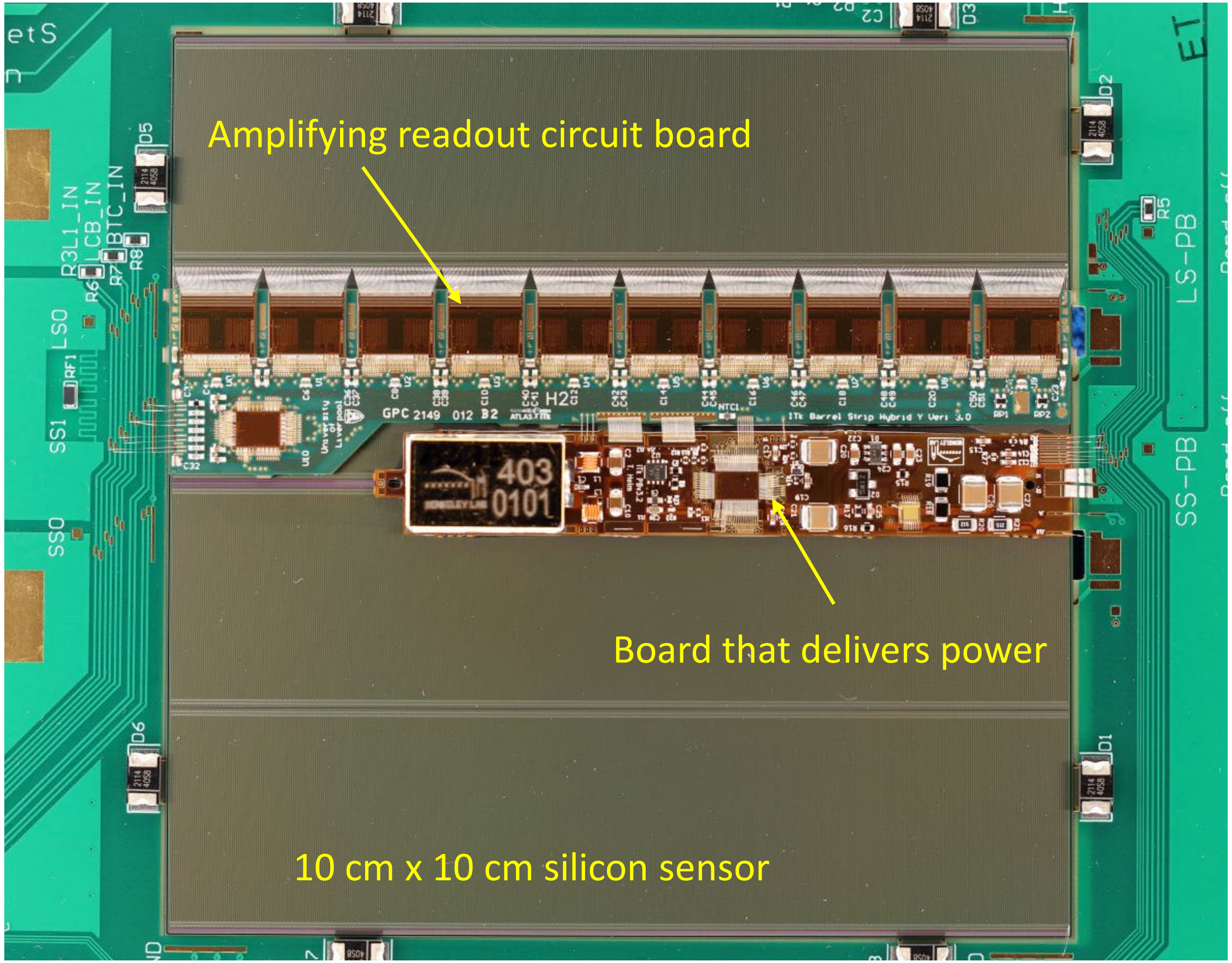
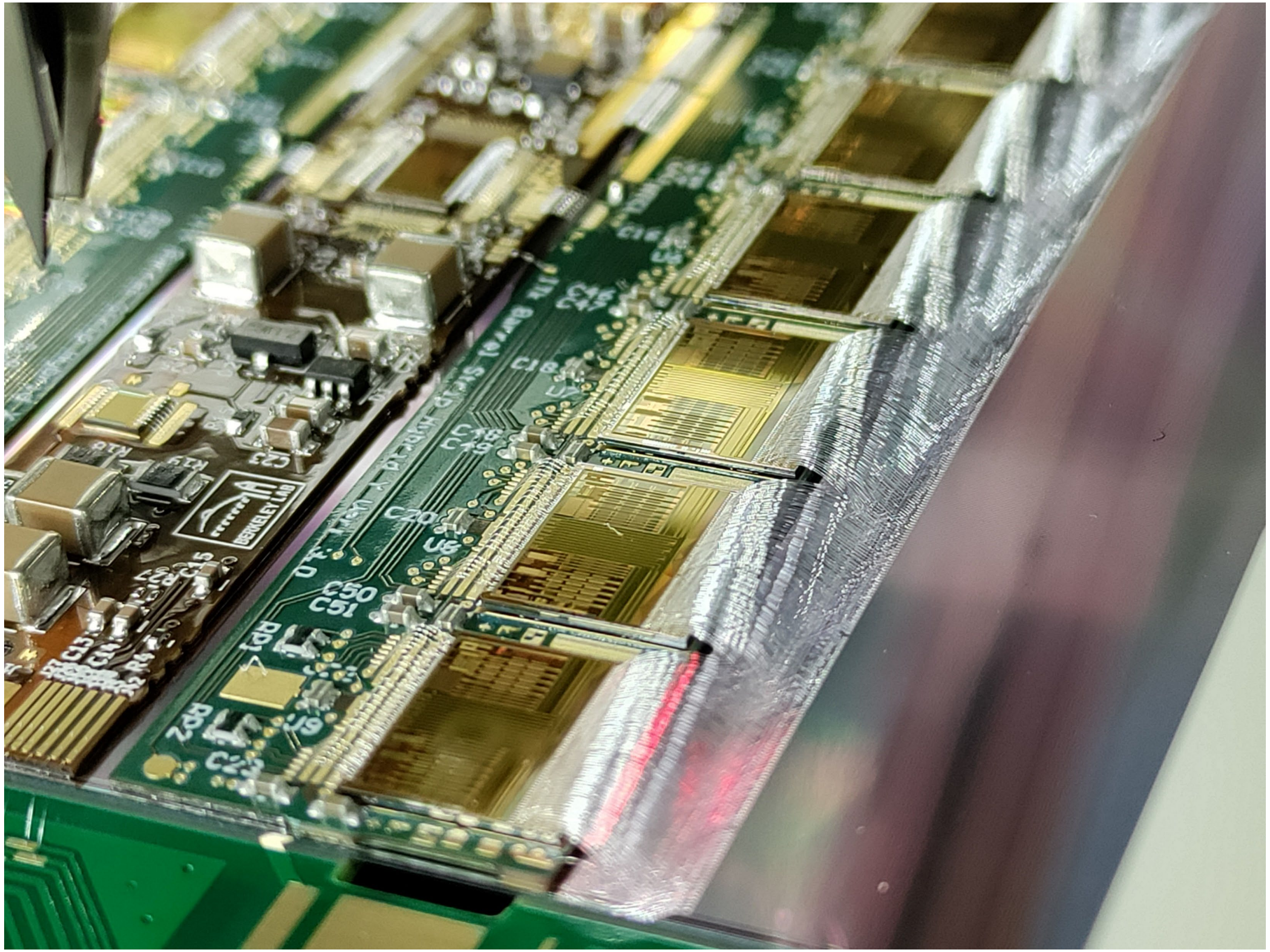
Silicon Strip Module

Module = silicon strip sensor + readout circuit board + power board

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Basic Strip Detector Front-end Modeling and Noise Analysis

1. Basic Model

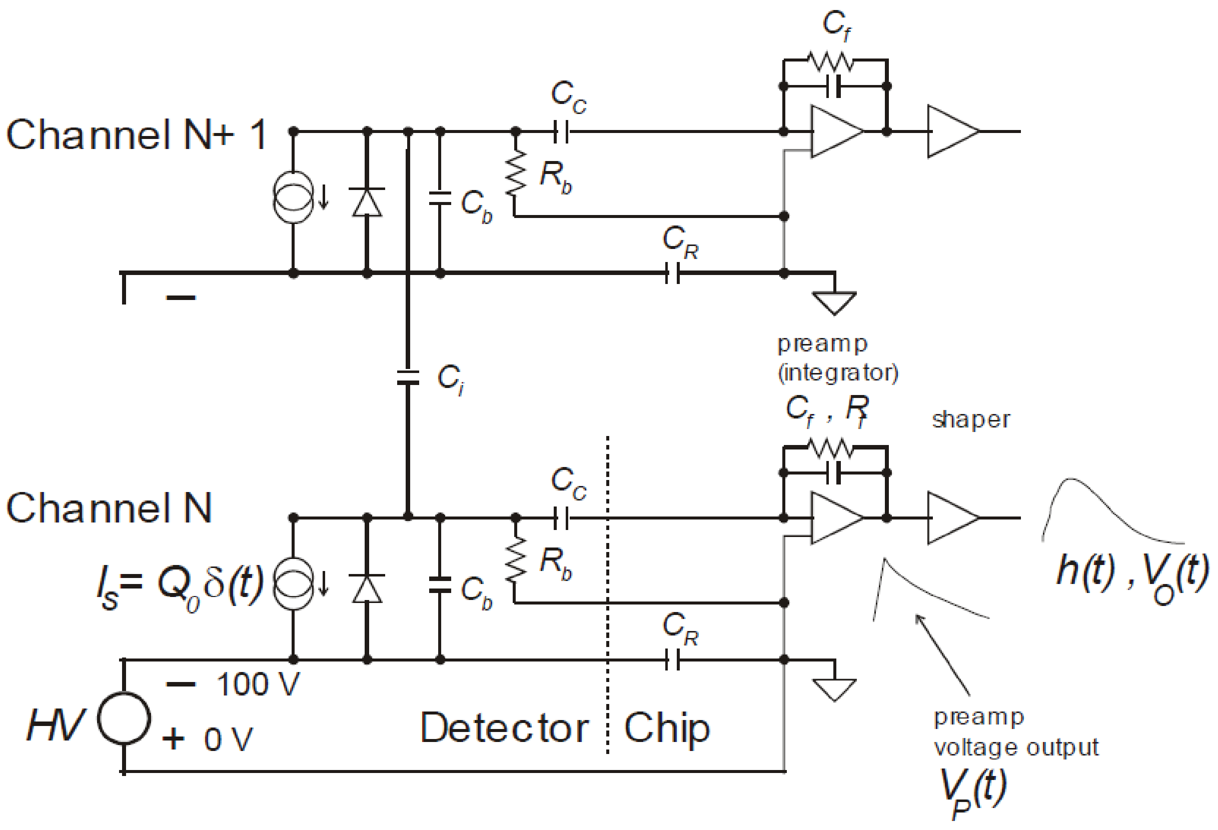

Figure 1. Model of one channel of a silicon strip detector and frontend interface.

Strip Detector Cross-Section