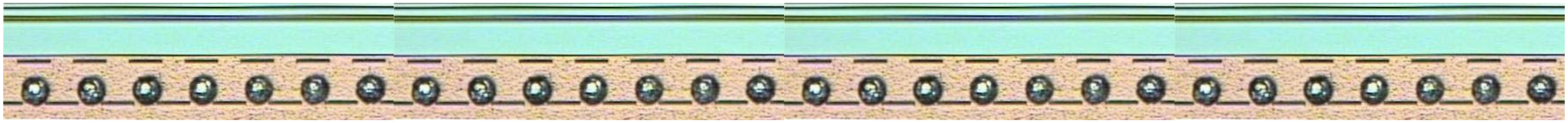
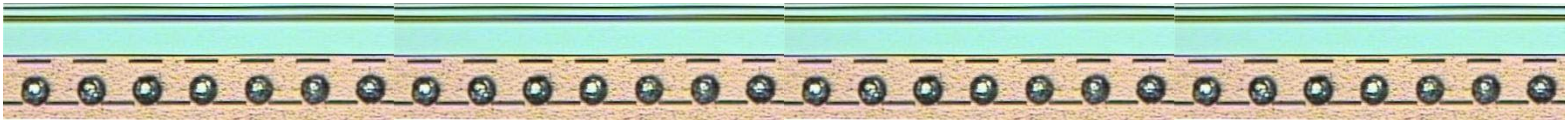


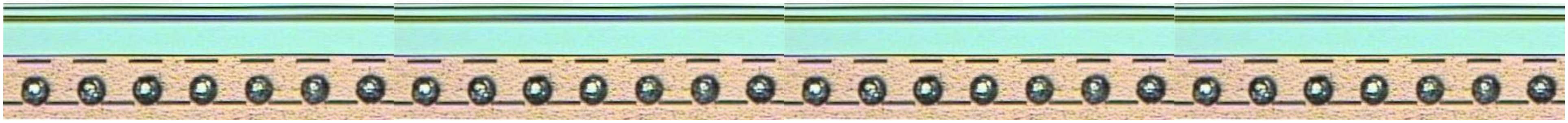
The ATLAS Pixel Detector

Maurice Garcia-Sciveres
Lawrence Berkeley National Laboratory

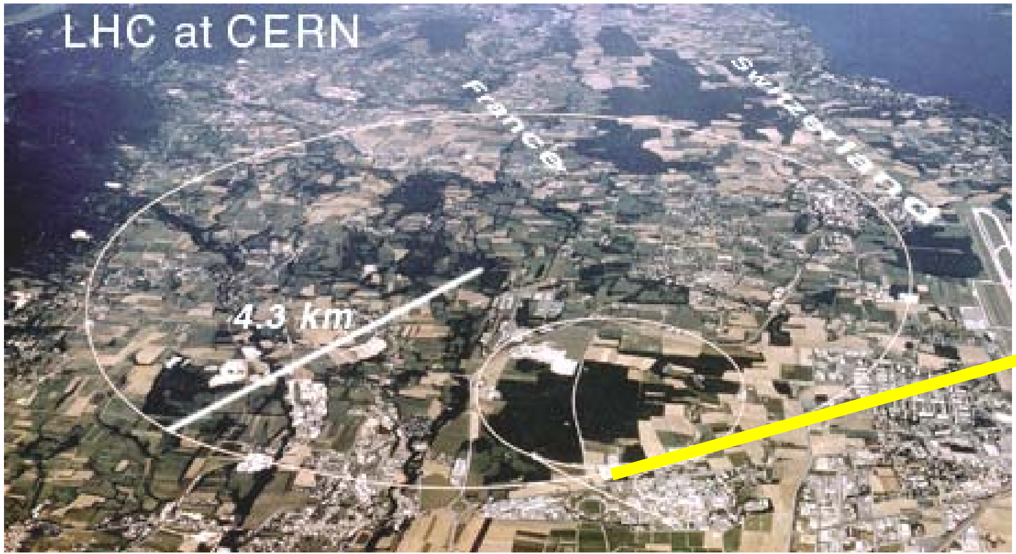


ATLAS Pixel Collaboration

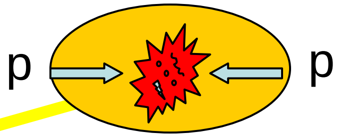
- ~100 collaborators
- 17 institutions
- 8 countries



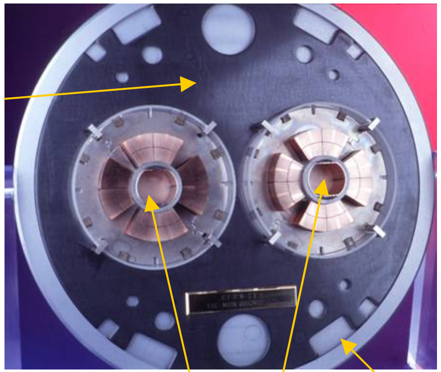
The **L**arge **H**adron **C**olloder will be the world's most powerful microscope



Camera goes here

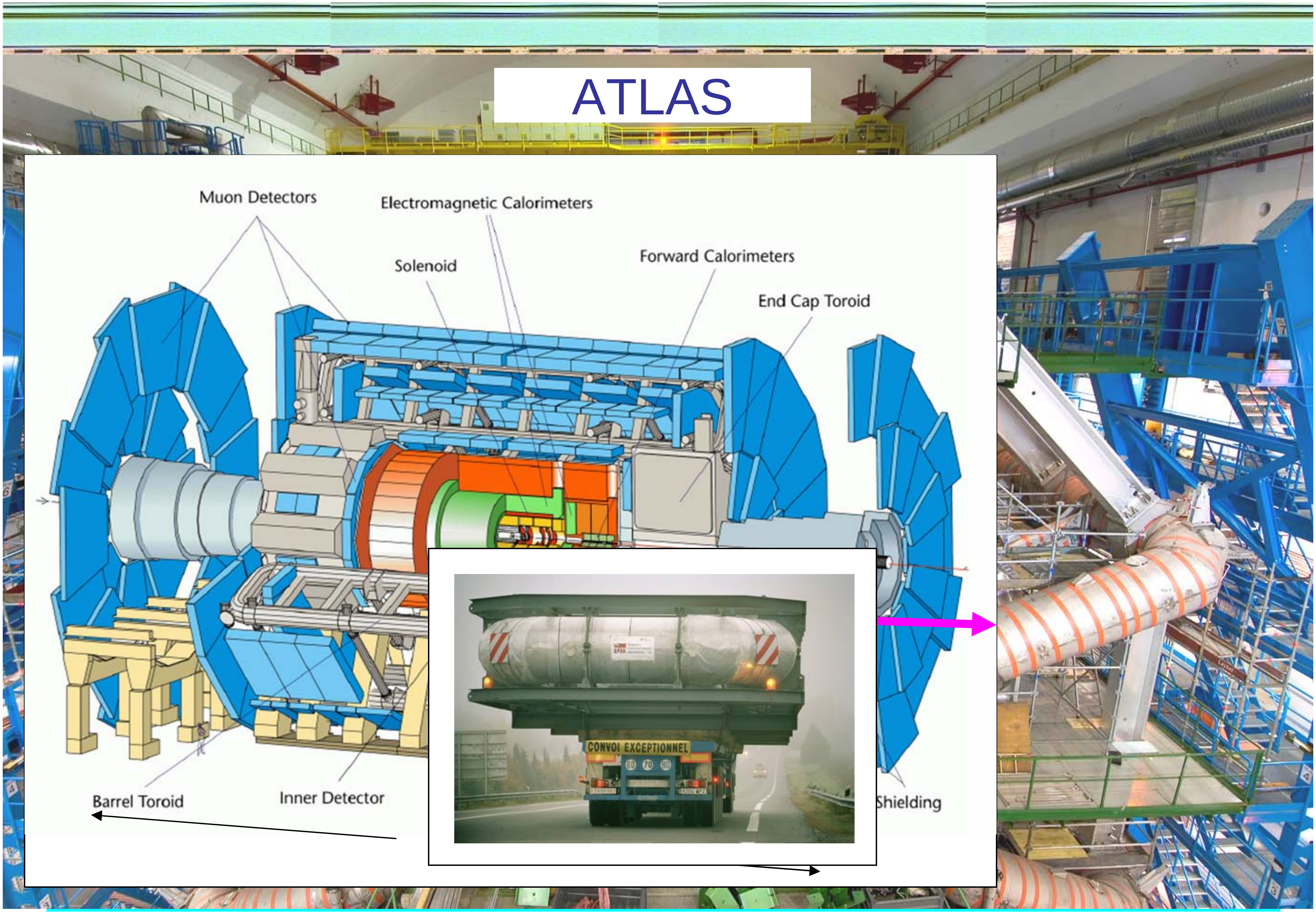


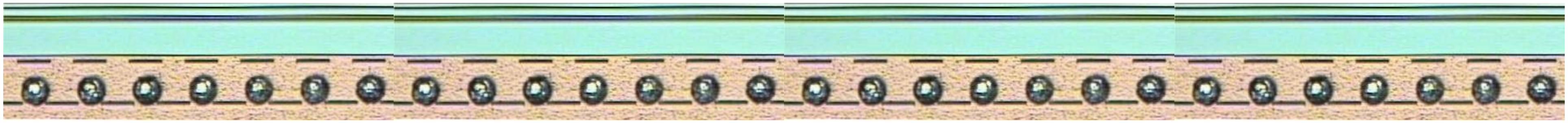
14TeV
~10^{-19}m resolution
but…



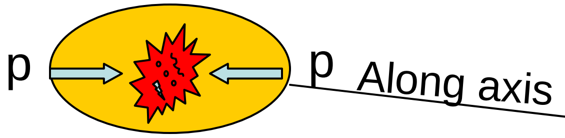
- **Need high intensity**
- **At design intensity LHC beam has 330MJ stored energy**
- **1% will blow up dipole**
- **Driving factor in vertex detector design**

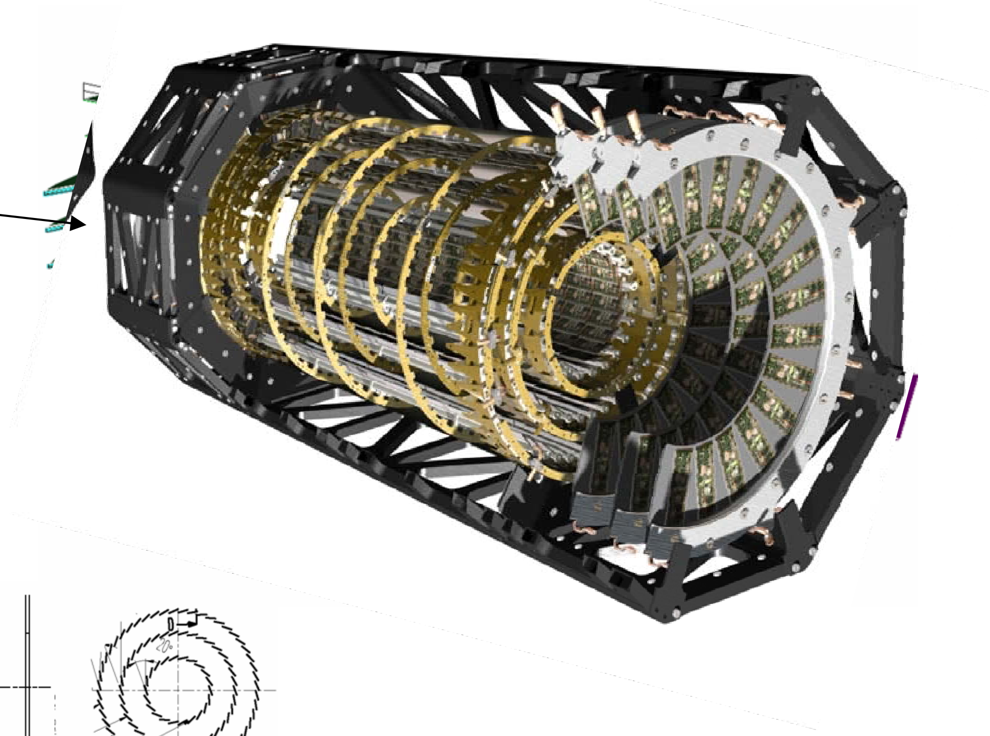
ATLAS


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Shielding
CONVOI EXCEPTIONNEL

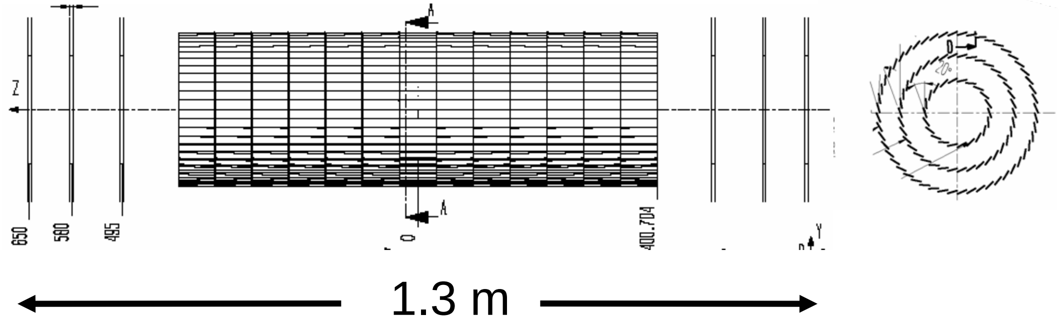


ATLAS Pixel Detector

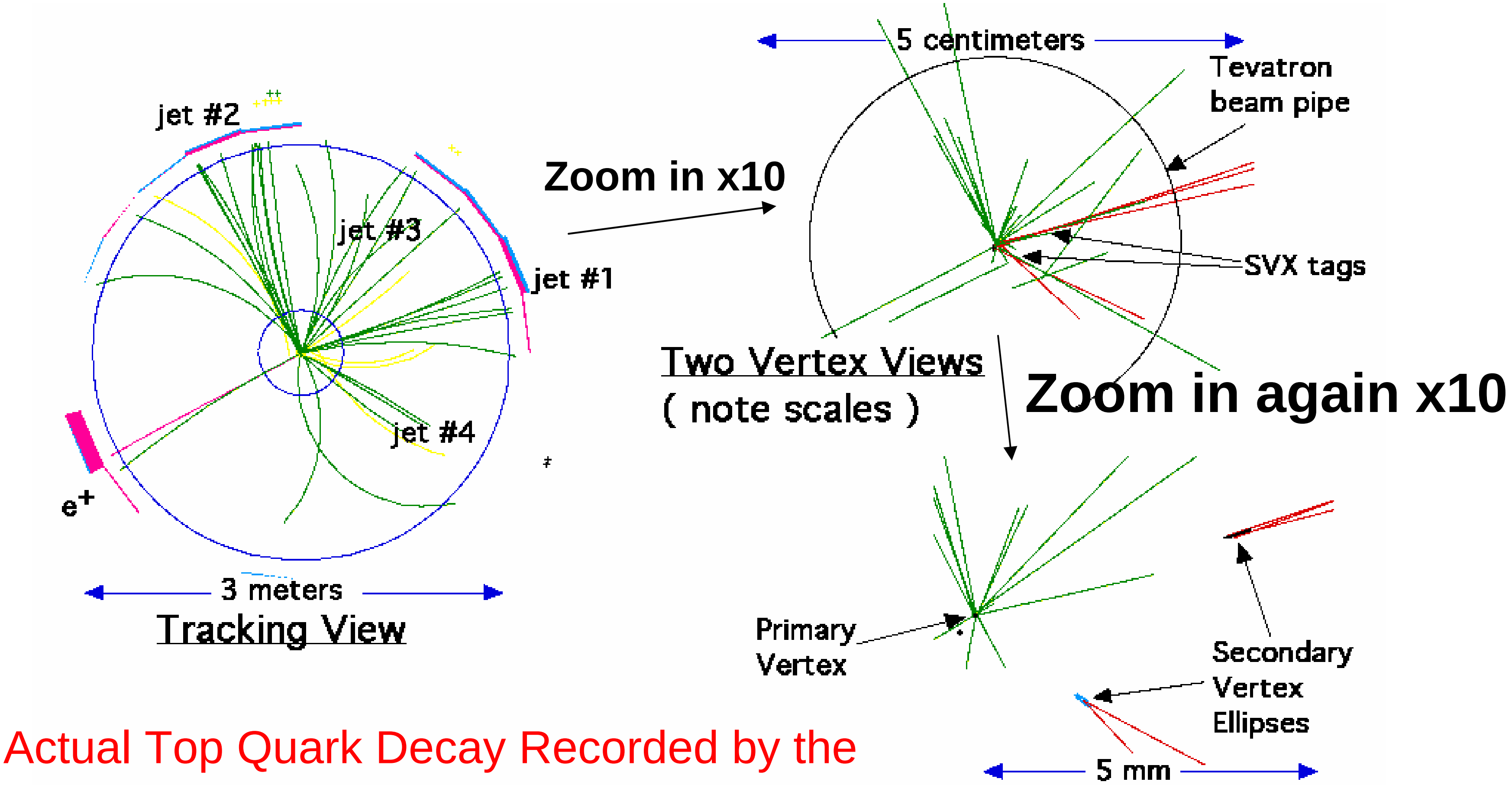




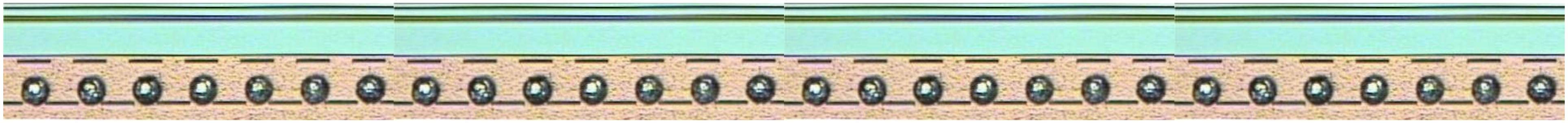
80M pixels (2m^2 active area)
1744 parallel modules covering
3 barrels + 6 disks



Top Quark Photo

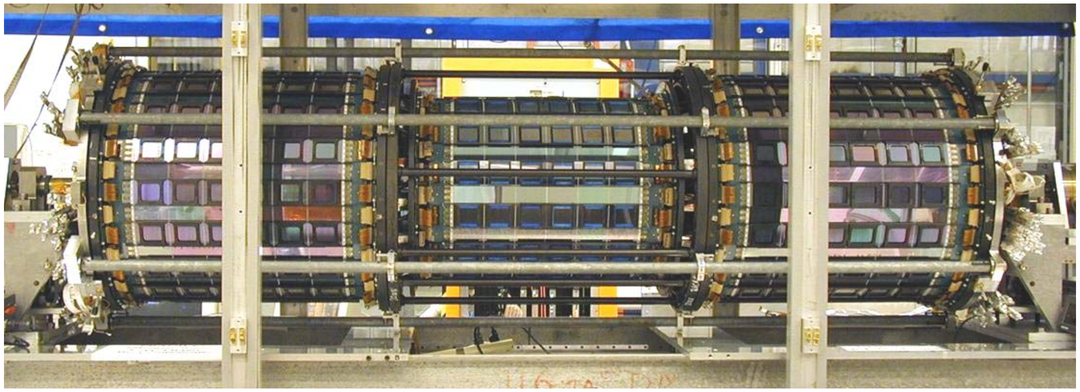


Actual Top Quark Decay Recorded by the CDF experiment with a silicon strip detector



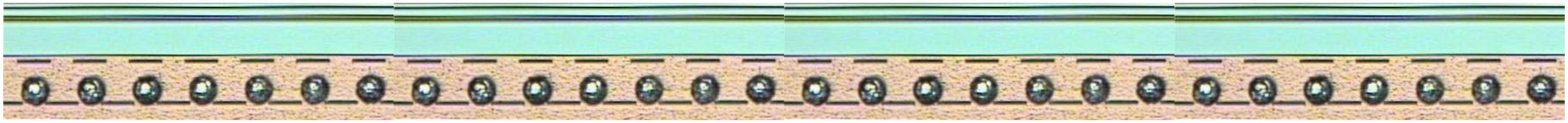
Hybrid pixel detectors in particle physics

- Silicon strip detectors have been used in particle physics for some 20 years (and are here to stay). This is a type of hybrid imager with resolution in only 1 dimension.

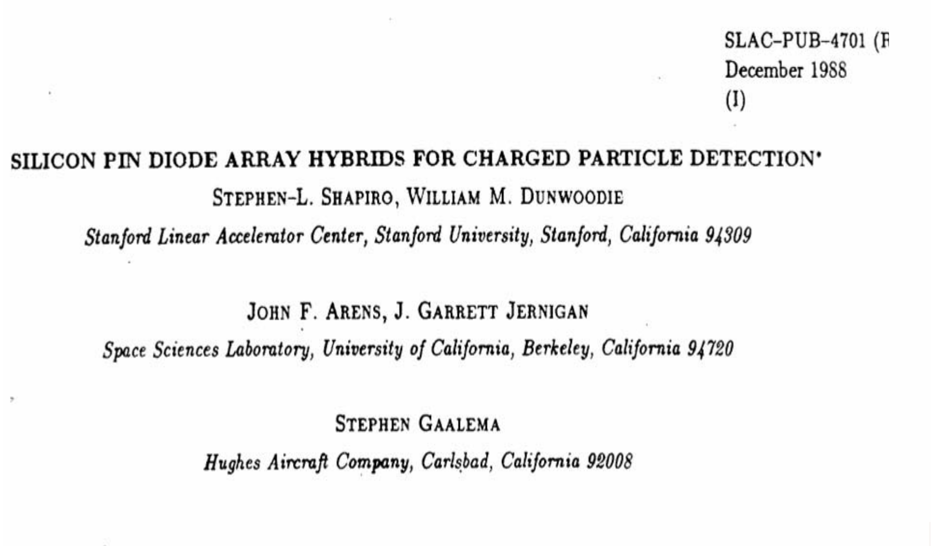


ISL detector of CDF experiment

- A hybrid pixel detector is a conceptually trivial (but technically difficult) generalization of a strip detector to 2 dimensions.
- Potential ways to practically make hybrid pixel detectors were first proposed in 1988-1990 (see next slide)
- The first hybrid pixel detectors to function in physics experiments came in 1997-1998. Modest scope.
- The first "full strength" hybrid pixel detectors are now being built and will come on-line at the Large Hadron Collider (LHC) in 2007-2008.



Particle Physics Examples



SLAC–PUB–4701 (F
December 1988
(I)

SILICON PIN DIODE ARRAY HYBRIDS FOR CHARGED PARTICLE DETECTION*

STEPHEN-L. SHAPIRO, WILLIAM M. DUNWOODIE

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

JOHN F. ARENS, J. GARRETT JERNIGAN

Space Sciences Laboratory, University of California, Berkeley, California 94720

STEPHEN GAALEMA

Hughes Aircraft Company, Carlsbad, California 92008

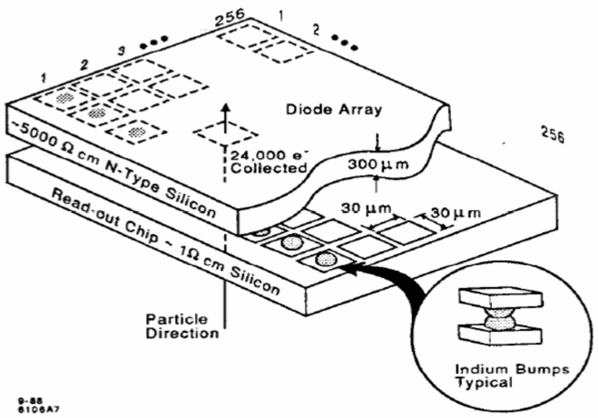
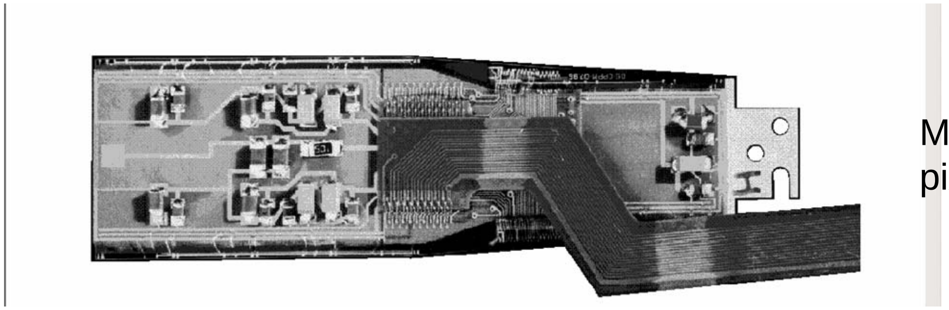
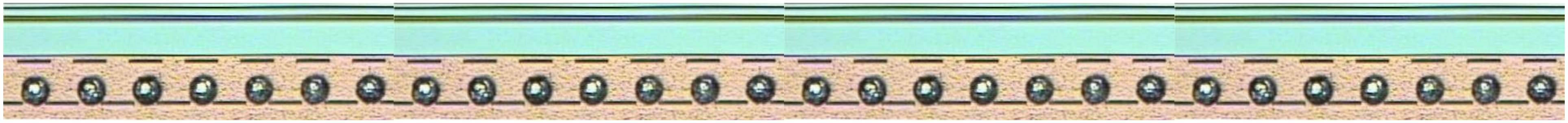


Fig. 1. Schematic representation of a hybrid de-



Module of DELPHI experiment pixel endcaps. CERN, 1999



ATLAS Pixel Challenges

- **Technological Challenges**
  - **Radiation resistance**
  - **Speed**
  - Remote operation
  - Channel density

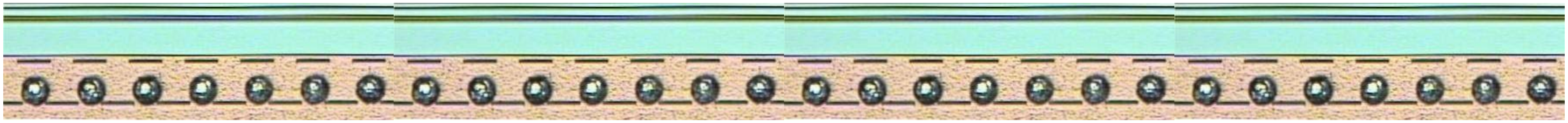
Hybrid pixel is the only technology that even comes close to requirements

Addressed mainly at the single module level

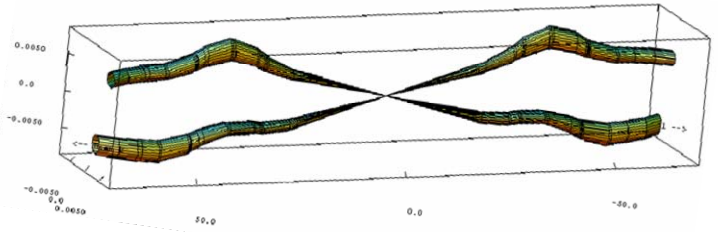
- **Engineering Challenges**
  - Size and manufacturability
  - Low mass mechanical stability
  - Power density and distribution
  - Cold operation
  - Inaccessible operation and reliability

These are especially difficult for hybrid pixels, compared to other pixel imagers

Addressed mainly in the mechanical integration of the 1744 modules (array must work as a single instrument of 10μm precision)



A few numbers

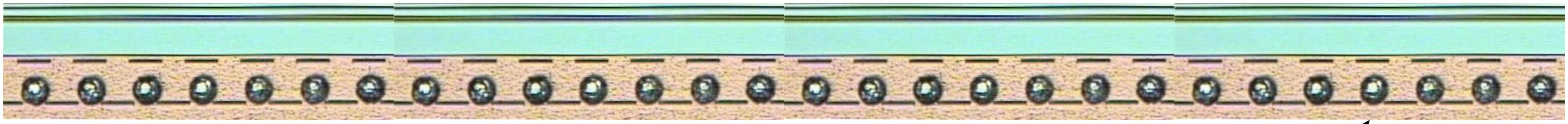


- Recall LHC beam has 330MJ stored energy

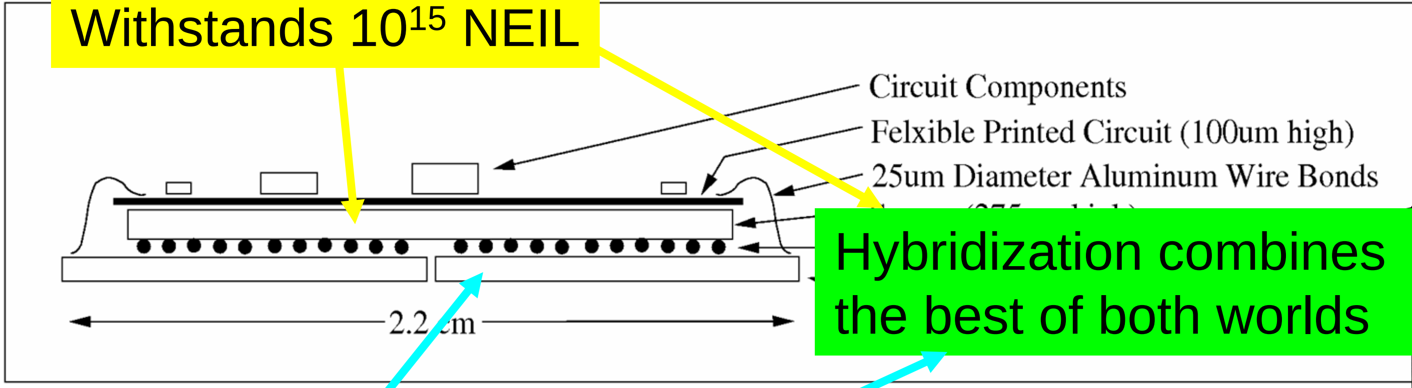
- Each inner pixel must measure 5x10^{11} particles in ~4 year lifetime
- = Every atom will be traversed by a charged particle
- = 10^{15} NEIL sensor bulk damage

- 40MHz “frame rate”
- Data driven “sparsified” readout
  (reading out 80Mpixels every 25ns would fill 10^8 Terabytes/day !)
- Local data buffering with triggered readout
  (reading out every nonzero pixel would still fill 10^5 TB/day)

- Typically ~1000 charged particles in interesting events
- Need ~10μm position resolution with >97% single hit efficiency.

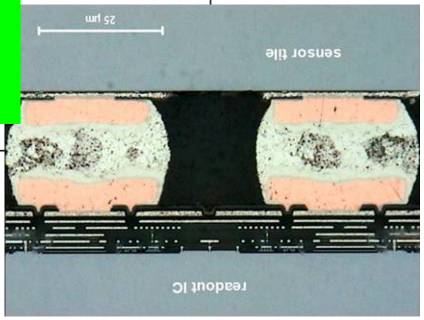


The ATLAS Hybrid Pixel Module



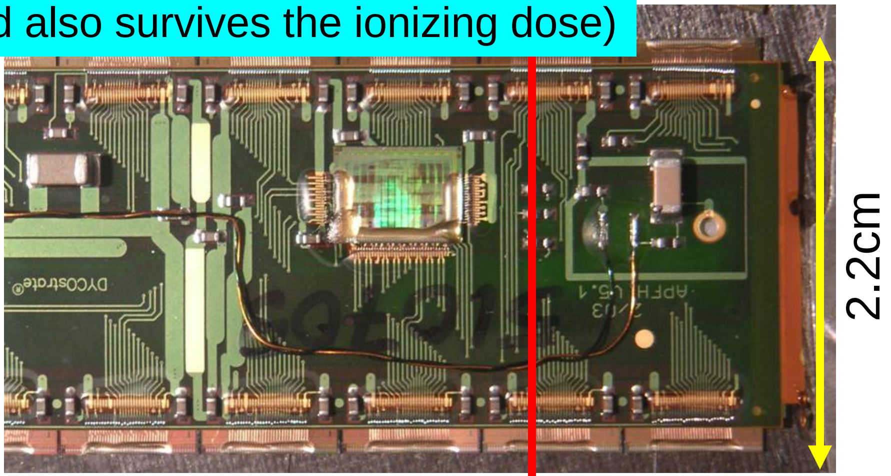
Withstands 10^{15} NEIL

Hybridization combines the best of both worlds



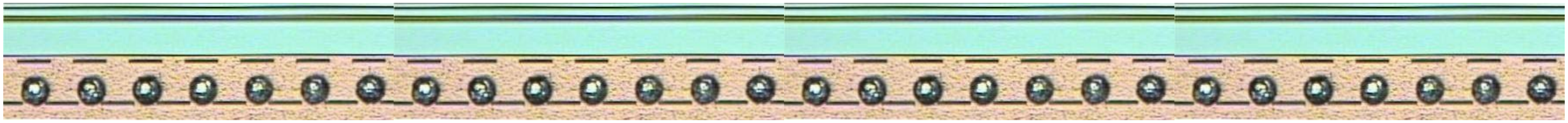
Cross section through here →

Manages the high data rate
(and also survives the ionizing dose)

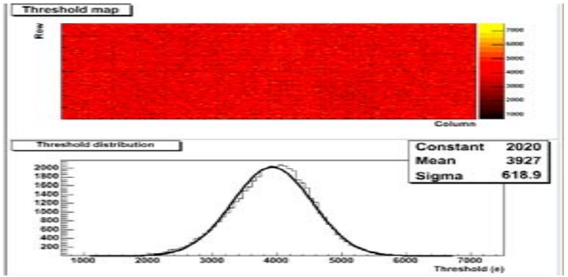


All 1744 modules are identical (cables vary)

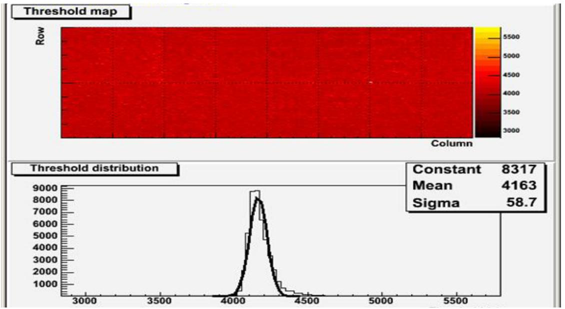
Each module is a fully functional detector



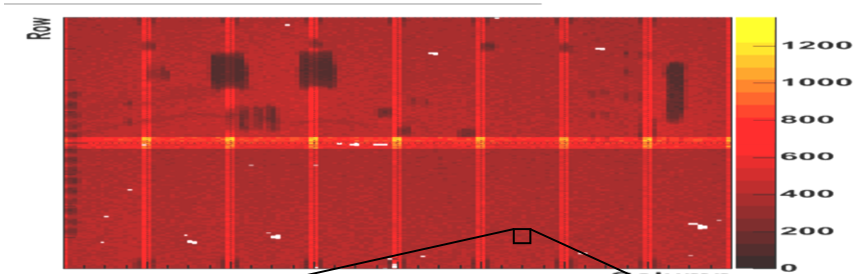
Module Functionality



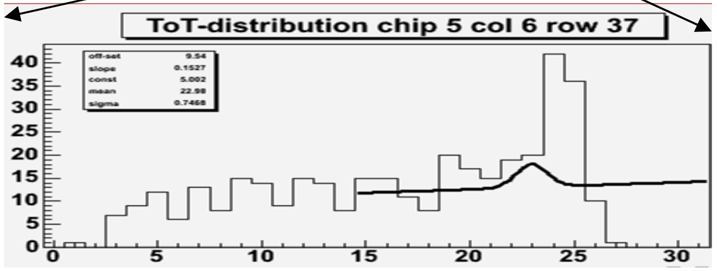
Raw threshold uniformity



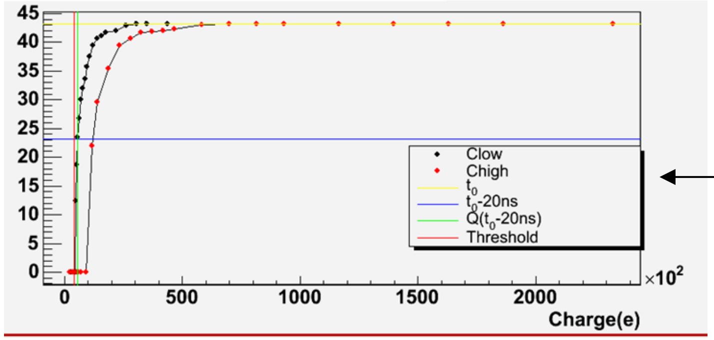
After each pixel level individually adjusted (tuning) (can be done internally- “auto-tuning”)



Module response to Am-241 source

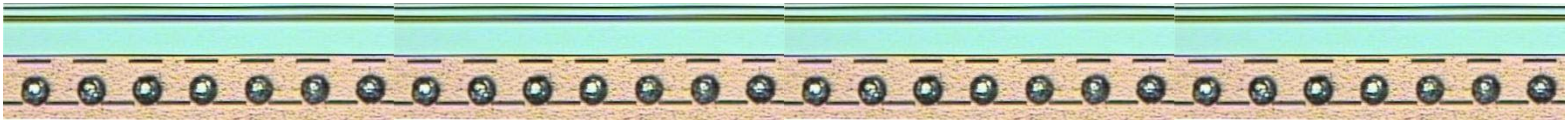


Source spectrum measured by single pixel. Peak is 60KeV line



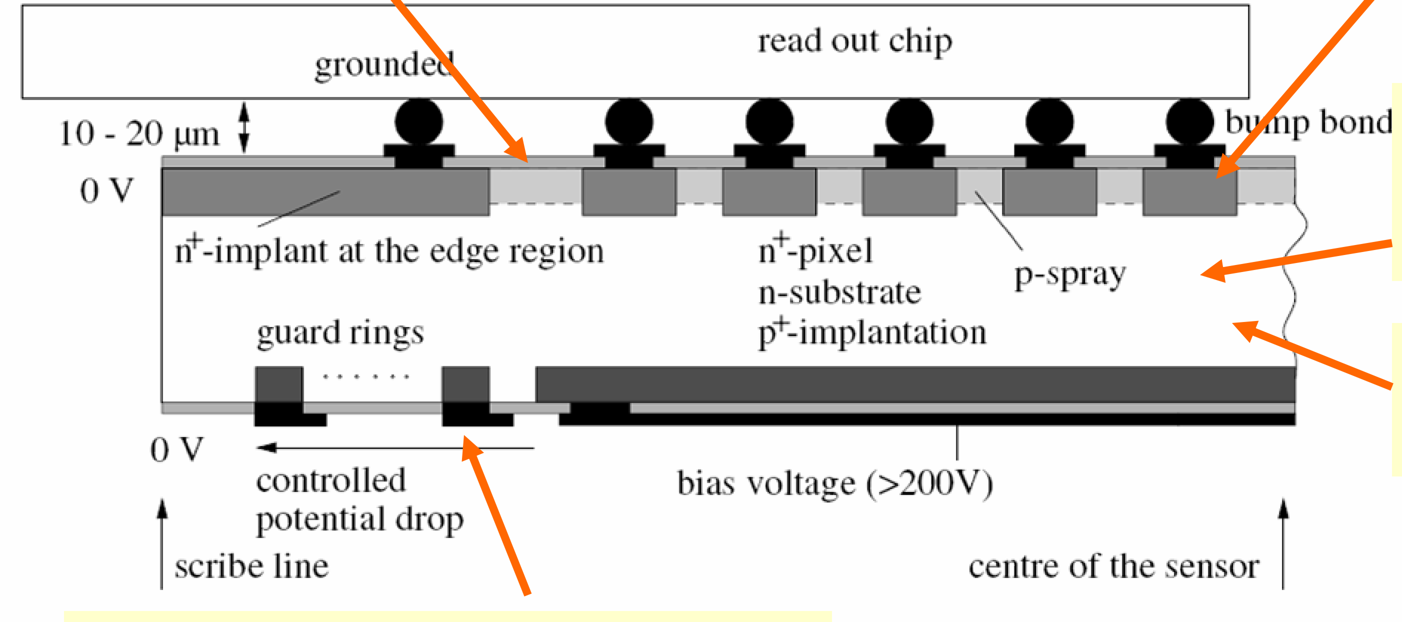
Time stamping of each pixel hit

Plot of time stamp relative delay vs. charge



Sensor Design

- **Basic Requirements:**
  - **Leakage current after 10^{15} neq/cm^2: <50nA / pixel (-7C operation)**
  - **Total input capacitance: <400fF**
  - **Charge collection time <10ns**
  - **Signal after irradiation: >10Ke$^-$**



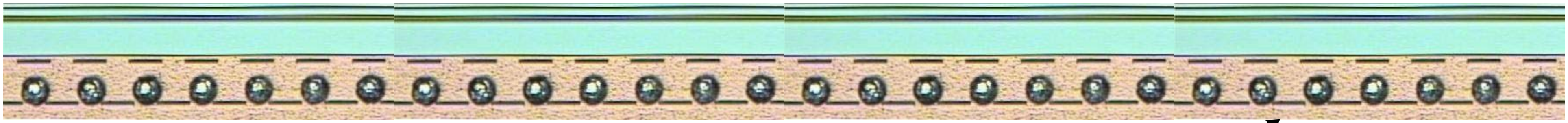
Built in bias "grid" allows full testing without readout chip

n-implants to collect e- (needed for 10ns collection)

n-bulk. Type inverts after few months. (Turns out could have been p)

Oxygenated to keep depletion voltage low (700V at end of life).

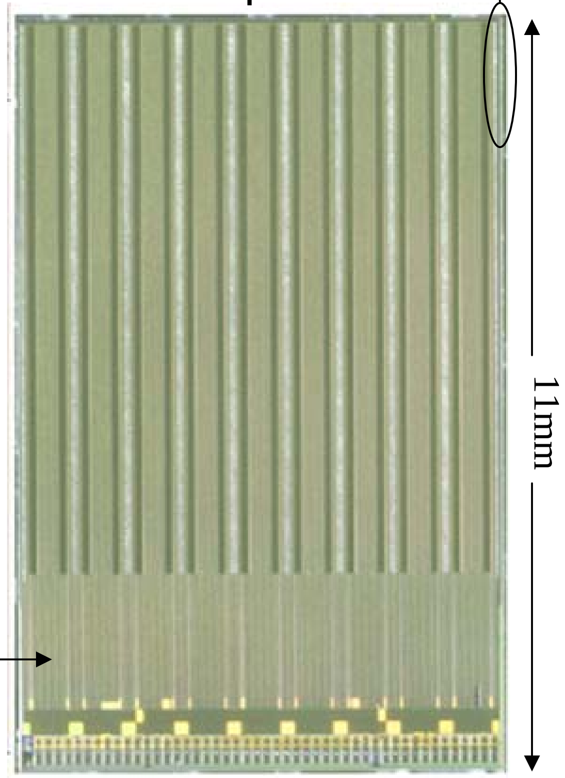
Multi guard ring design critical for 700V



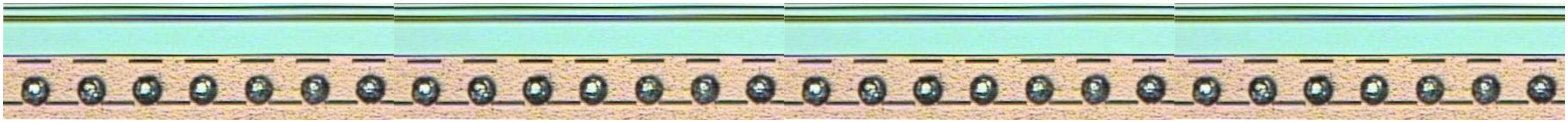
Readout Integrated Circuit

- 3.5M Transistor 0.25μm CMOS
- Custom layout for radiation tolerance (tested to 100MRad)
- 43Kb programmable configuration in SEU-hard (varying levels) registers
- Free-running amplifier, ADC with 8-bit time-stamp and TOT for each pixel (150e ENC)
- 15Kb data buffering and time-stamp select trigger logic

FE-I3 chip



Singe IC with 2880 bumps

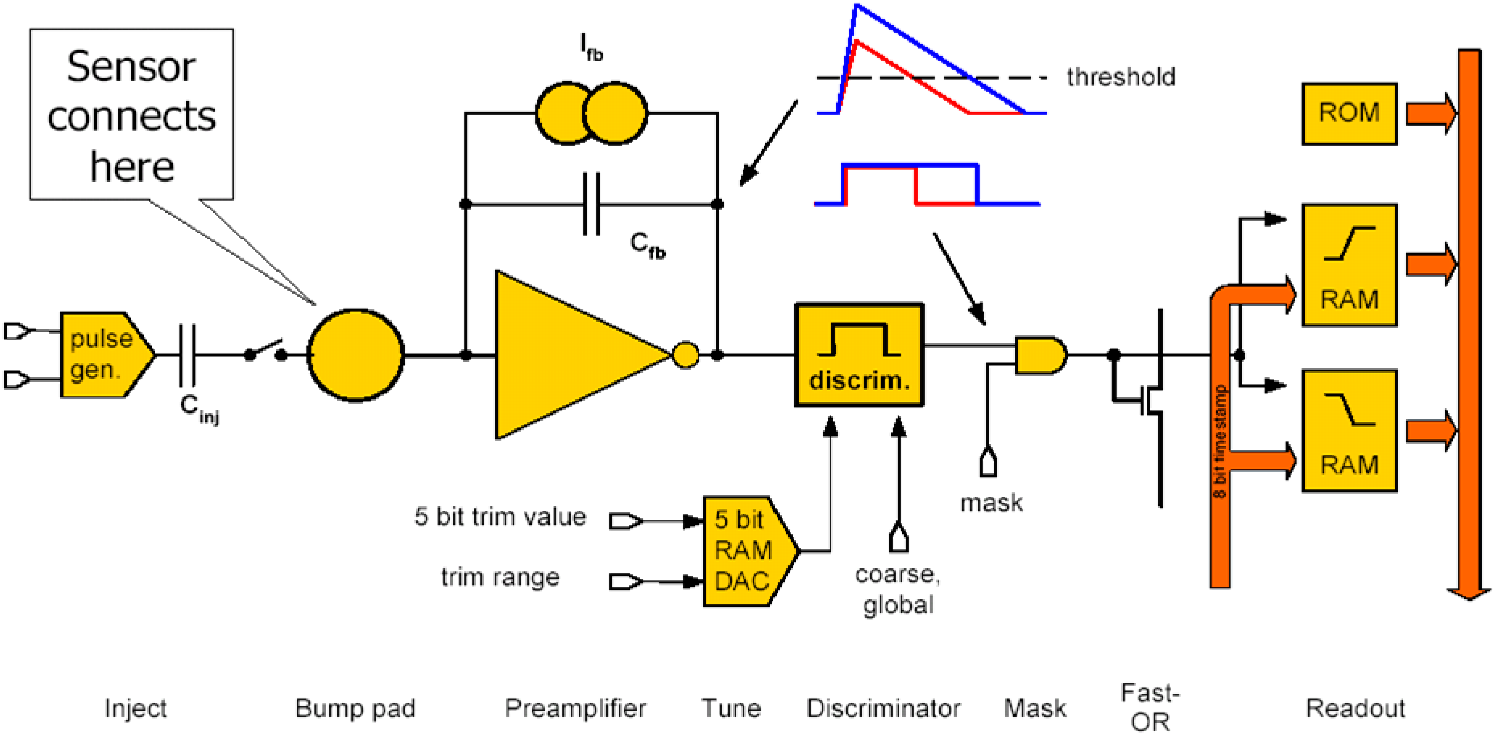


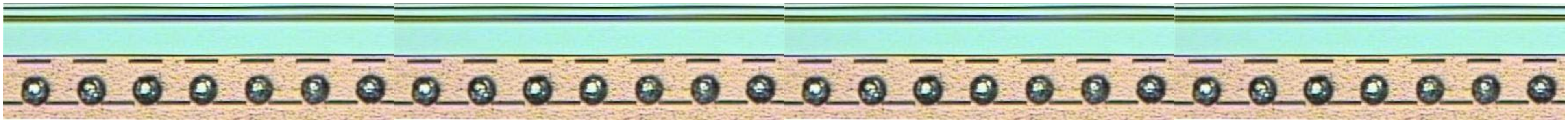
Single Channel Functional Schematic

Constant current feedback
- Leakage tolerance > 100 nA
- Linear decay

Charge information
- Measure hit width

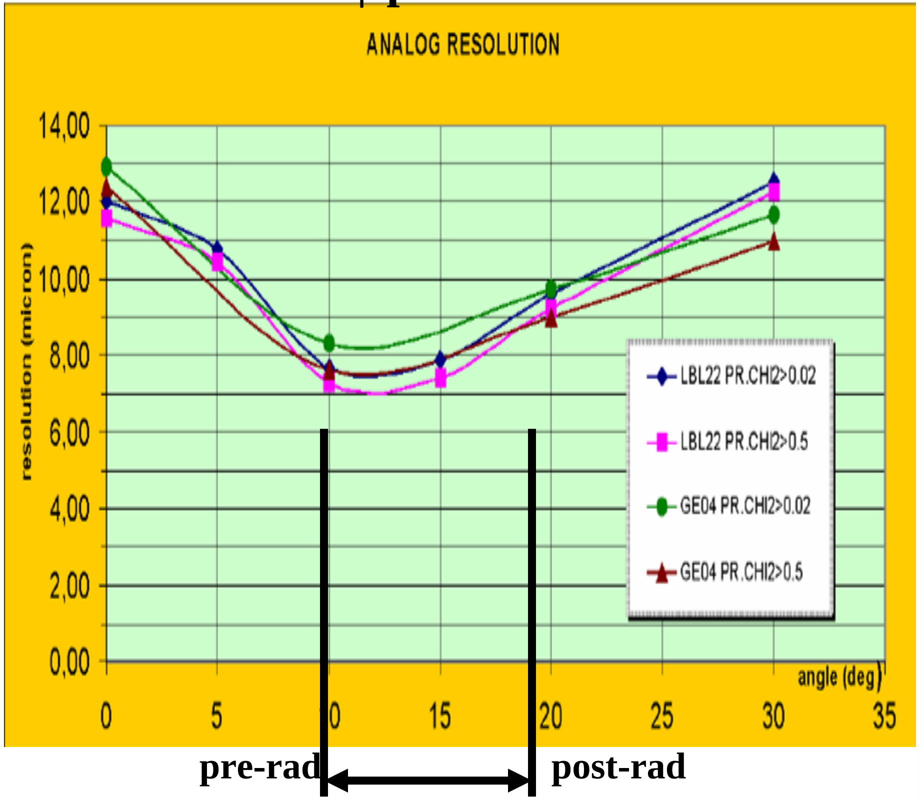
Individual Adjustment of
- Threshold
- Feedback current
- Adjust ranges





Module Performance in 20GeV π test-beam

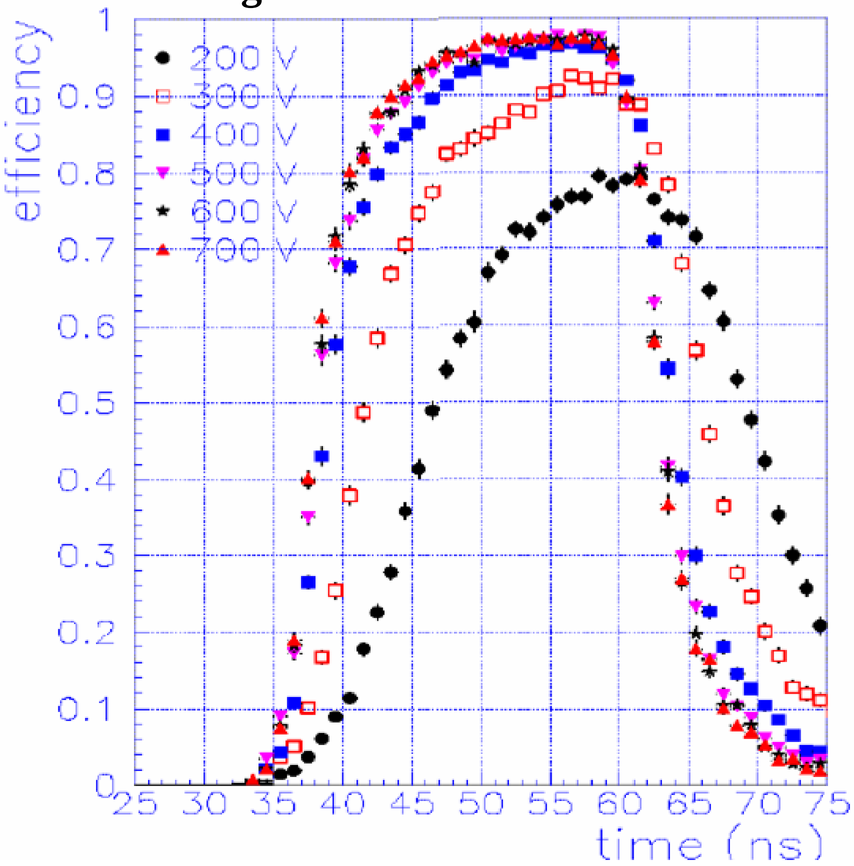
Cluster r-φ position resolution

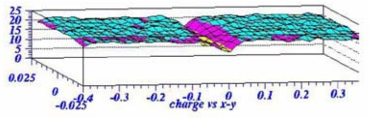


pre-rad **post-rad**

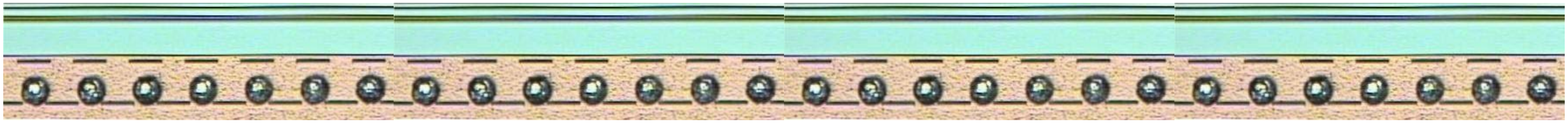
Effective incidence angle range

In-time signal eff. vs. bias after lifetime dose



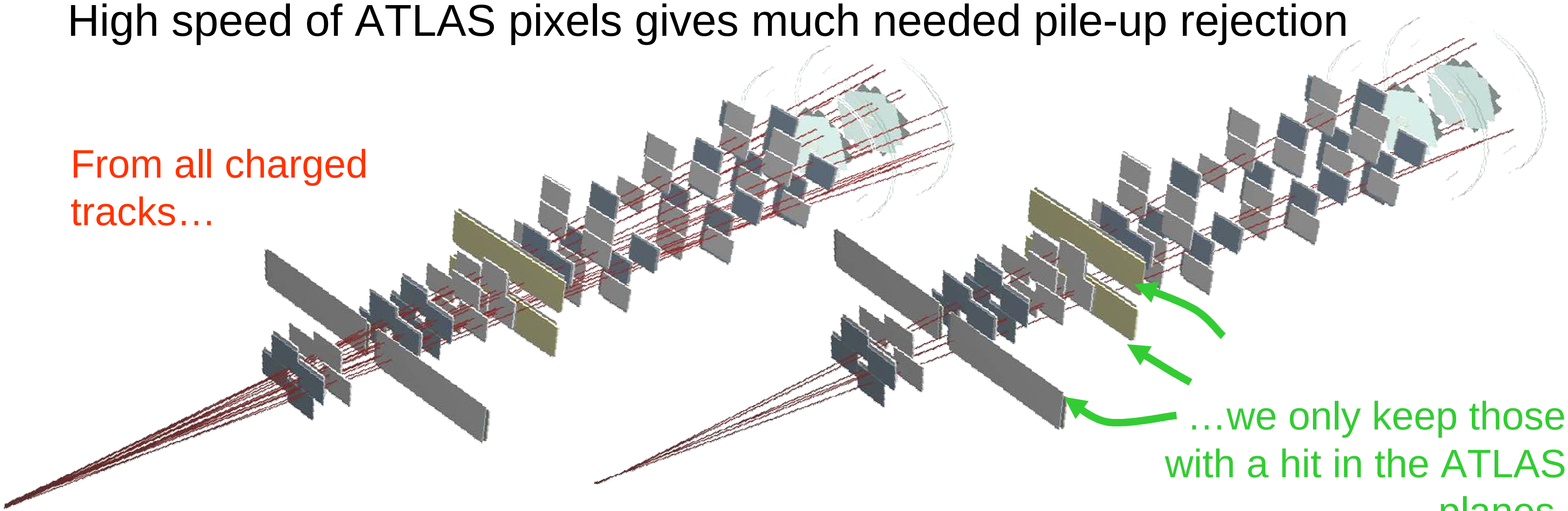


Plateau at 98% (2% loss is in bias grid)



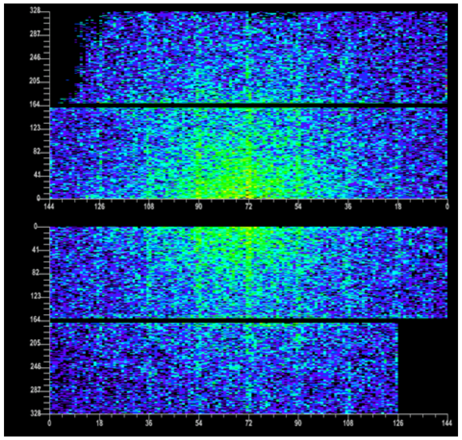
Modules already used in NA60 experiment

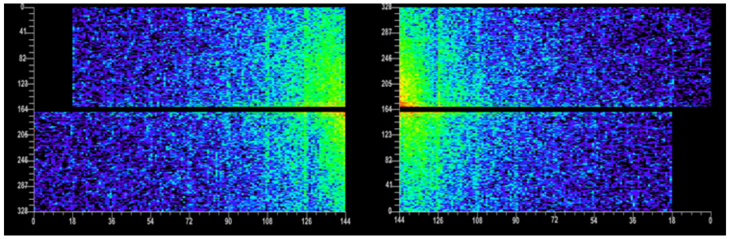
High speed of ATLAS pixels gives much needed pile-up rejection

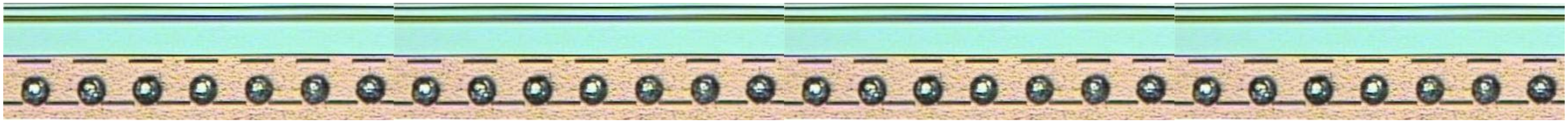


From all charged tracks…

…we only keep those with a hit in the ATLAS planes.

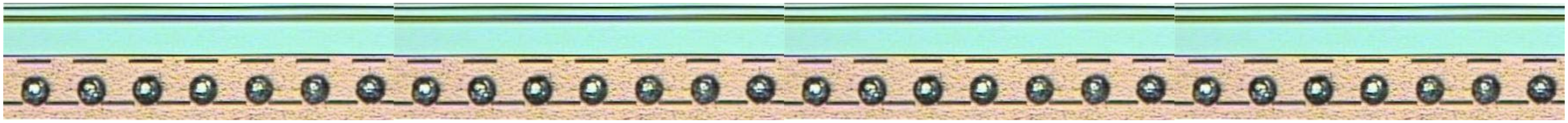






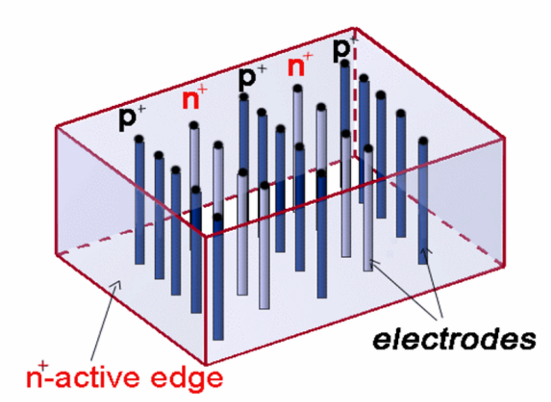
After 10^{15}

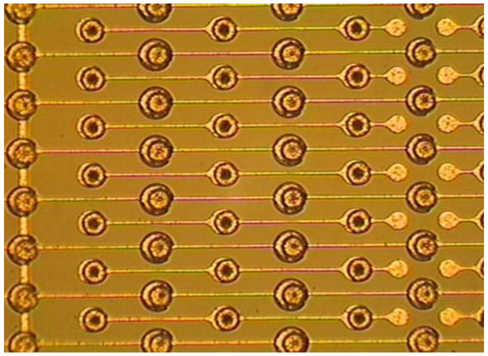
- Collider will be upgraded to increase intensity on a time scale of 2015
- 10x intensity demands:
  - Faster charge collection time
  - Faster readout
  - More radiation tolerance (must withstand 10 particles through every atom)
  - Higher granularity
- R&D already started to produce a new pixel detector on a 2015 timescale (already later than R&D history for present device)

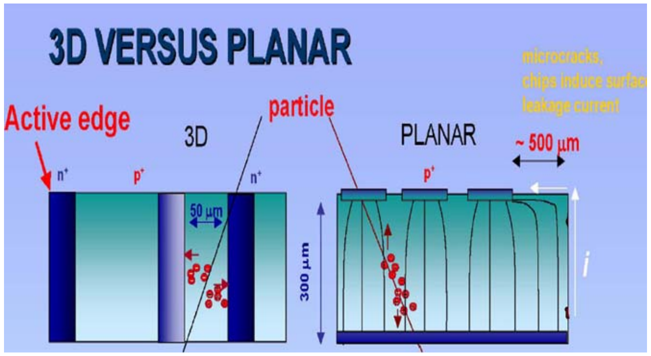


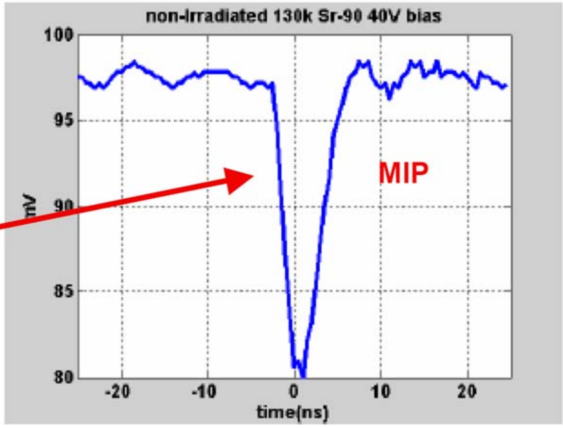
A New sensor candidate

3-D sensor: S. Parker & C. Kenney

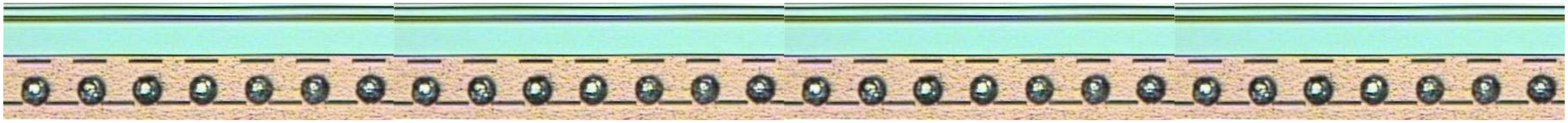






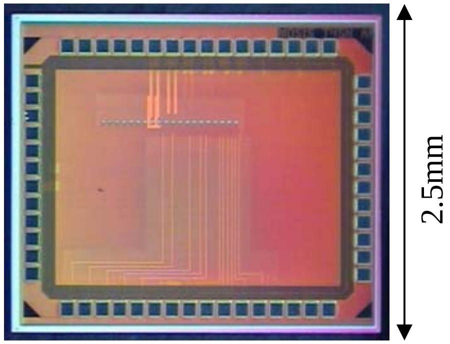


- ➢Fast signal pulse
(1.5ns present data limited by electronics)
    - ➢Good for high rate
    - ➢Good also for radiation damage
        - ➢Only known way to beat the charge trapping “wall” in silicon



Future readout chips

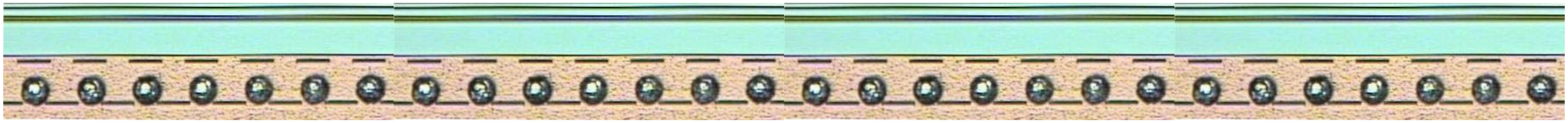
- Electronics must also become faster
  - Denser
  - More buffering & faster I/O
  - 1GRad tolerant
- Favored R&D direction is towards 0.13μm CMOS
- Design effort needed is very large
- Prototyping is much more expensive than 0.25μm
- Even thinner gate oxide is good for radiation tolerance, but resulting “leaky” transistors maybe not so good for analog design



Initial 0.13um test chip now under irradiation at LBNL

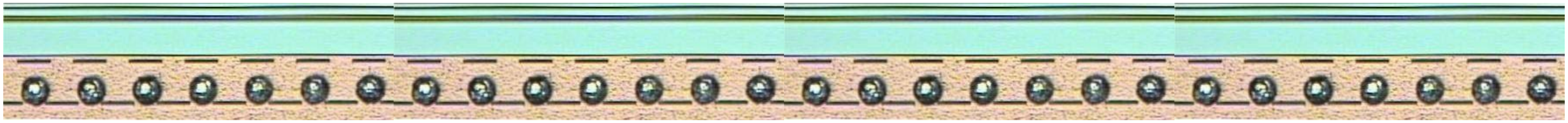
Many system issued such as power distribution

- Less relevant to SR- not covered



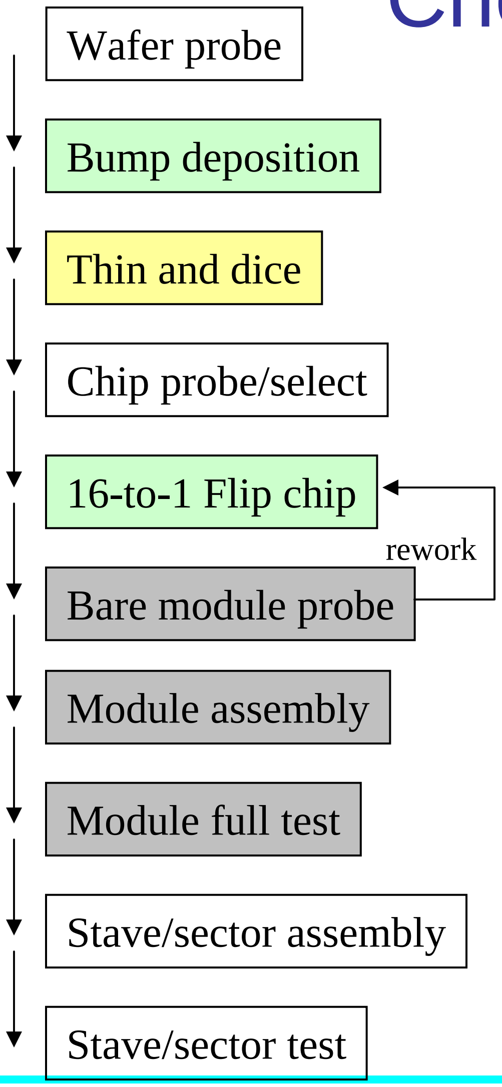
Cost

- Present fabrication cost (given design)
  - – Sensor ~ $1K each
  - – Flip chip bump bonding ~ $1.5K each
    - (boutique fab. Unlikely to become mainstream)
  - – IC's ~ $100K + ~$250 each (module)
    - Yield-dependent
  - – Testing and integration- priceless



Cheaper construction?

NOW



Wafer probe

Bump deposition

Thin and dice

Chip probe/select

16-to-1 Flip chip

rework

Bare module probe

Module assembly

Module full test

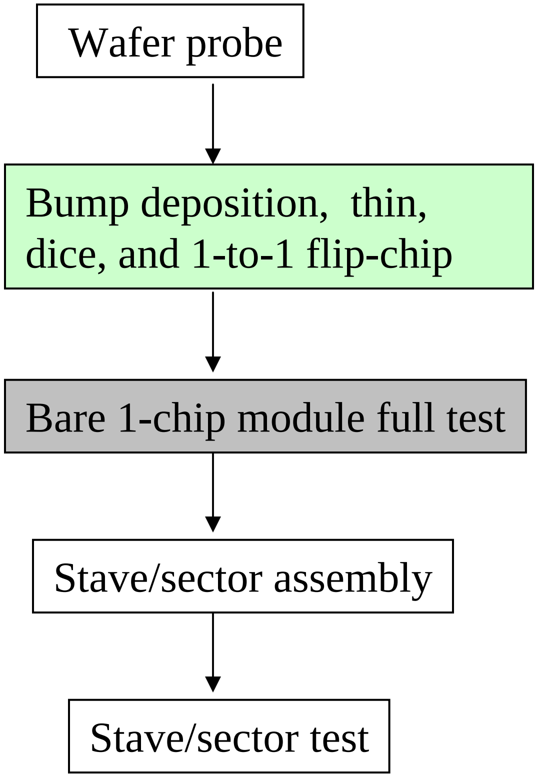
Stave/sector assembly

Stave/sector test

More standard and reliable 1 chip to 1 sensor bump bonding: no need for ultra high KGD yield. EXPLOIT ACTIVE EDGES

Higher level of integration at IC stage: no separate “module control chip”

FASTER, CHEAPER, BETTER?



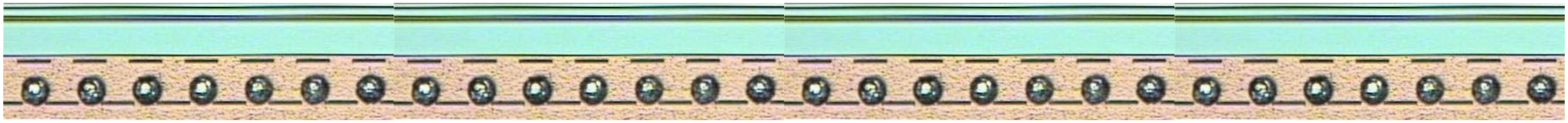
Wafer probe

Bump deposition, thin, dice, and 1-to-1 flip-chip

Bare 1-chip module full test

Stave/sector assembly

Stave/sector test



Conclusion

- The colliding beam experiments at the Large Hadron Collider will all install hybrid pixel detectors immediately outside the collision point
- No other known technology can operate in this environment
- The construction (in progress) of large scale, high performance hybrid pixel detectors required a massive R&D and engineering effort over the past 10 years
- The exploration of new territory in fundamental physics using these devices will begin in 2007 and will go on for many years