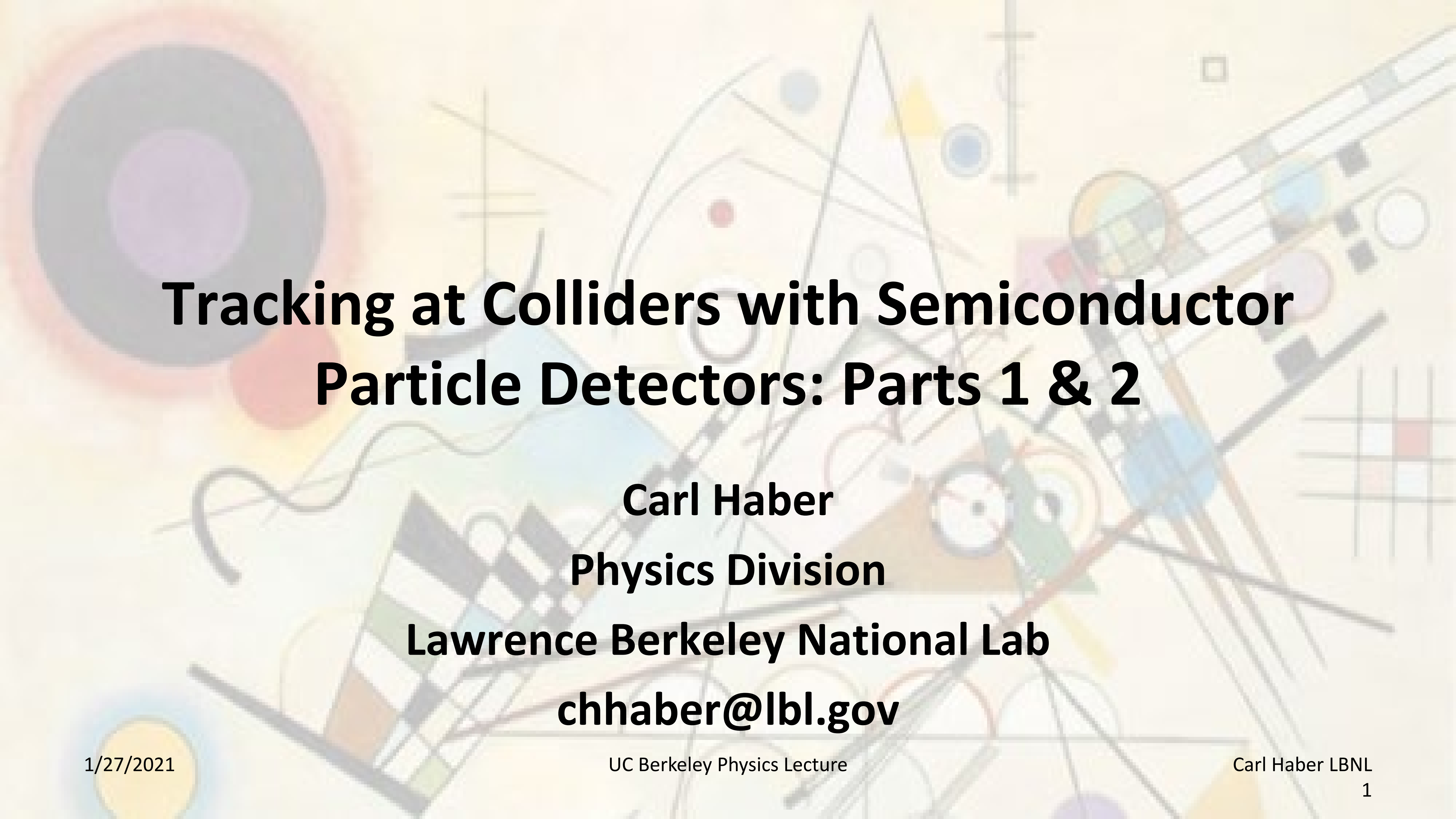

Tracking at Colliders with Semiconductor Particle Detectors: Parts 1 & 2

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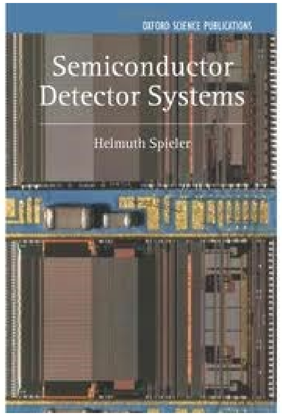
Suggestions for further reading

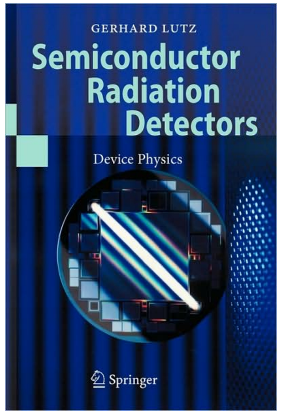
- H. Spieler, Semiconductor Detector Systems, Oxford Science Publications, 2005

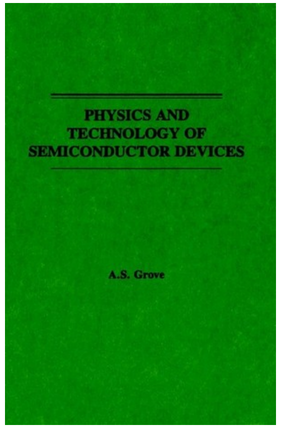
See also: http://www-physics.lbl.gov/~spieler/

- G. Lutz, Semiconductor Radiation Detectors: Device Physics , Springer (July 11, 2007)
- G. Knoll, Radiation Detection and Measurement Wiley; 4 edition (August 16, 2010)
- A.S. Grove, Physics and Technology of Semiconductor Devices, (1967) John Wiley & Sons; ISBN: 0471329983
- S.Sze, Physics of Semiconductor Devices, J.Wiley, 1981
- T. Ferbel, Experimental Techniques in High Energy Nuclear and Particle Physics, World Scientific, 1992
- W.Blum, W.Reigler, L.Rolandi, Particle Detection with Drift Chambers, 2nd edition, Springer, 2008
- https://pdg.lbl.gov/2020/reviews/contents_sports.html
- https://pdg.lbl.gov/2020/reviews/rpp2020-rev-particle-detectors-accel.pdf
- P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).

…and references therein

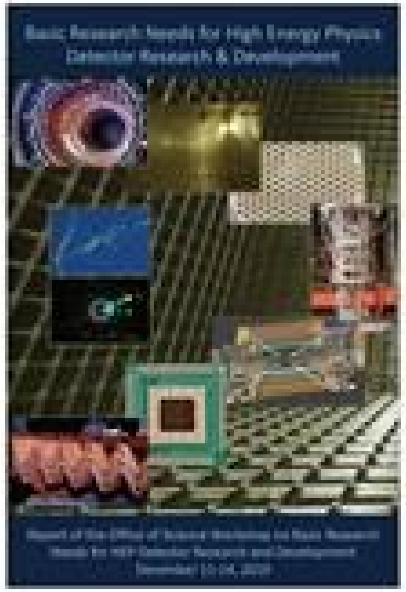






Basic Research Needs

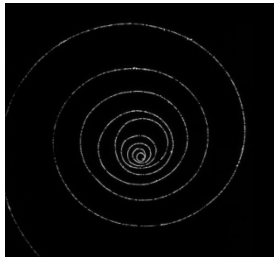
- In 2019-20 the Dept of Energy Office of High Energy Physics requested a community study of needs for transformational instrumentation R&D for future HEP experiments. Report released Aug 2020
- https://science.osti.gov/hep/Community-Resources/Reports
- Input to the HEP Snowmass process for summer 2022
- Tracking recommendations
  - High resolution per pixel fast (ps) timing
  - Scalable irreducible mass trackers
  - New materials and processes
  - Sustain/expand/create infrastructure including test beams, irradiation facilities, ASIC and mechanical engineering, silicon fabrication capabilities…



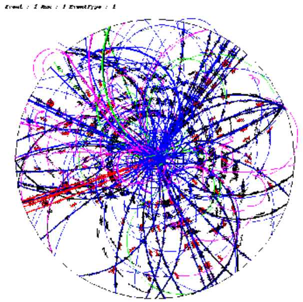
Basic Research Needs for High Energy Physics Detector Research & Development

Outline

- Introduction to tracking
- Semiconductor detectors
- Signal processing
- Sensors and architectures
- Radiation effects
- System issues – mechanics, power, metrology
- Conclusions



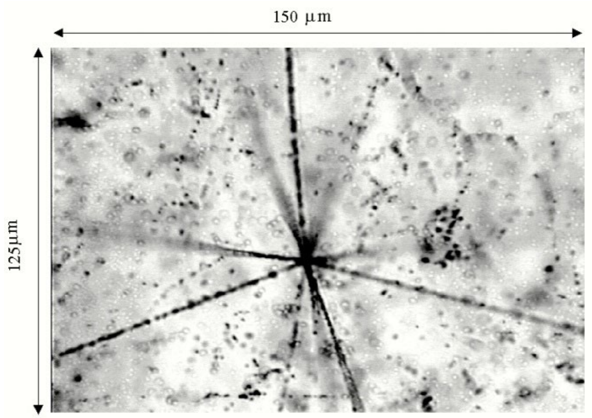
Tracking



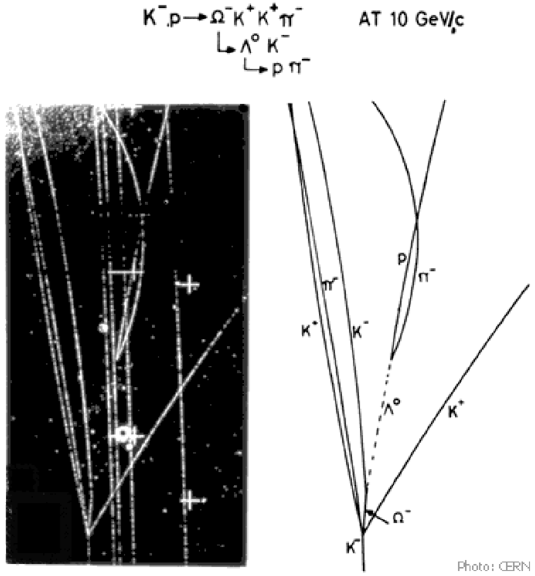
- The process of sampling a particle's trajectory and determining its parameters.
  - Momentum, Direction, Decay points (kinks)
- High energy
  - Small fraction of energy deposited in instrument
- Trajectory is disturbed minimally by the process.
- Charged particles ionize matter along their path.
- Tracking is based upon detecting ionization trails.
- An “image” of the charged particles in the event.

Technology

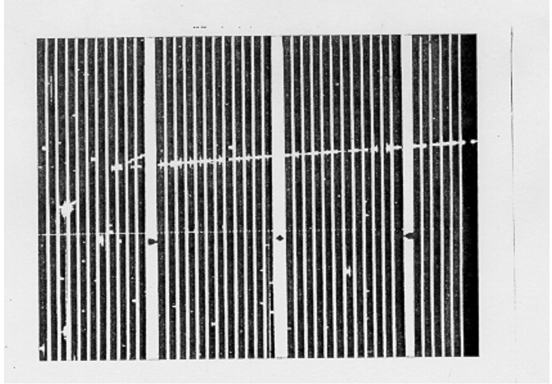
- “Old”: Emulsions, cloud, and bubble chambers
  - Continuous media
  - Typically gave very detailed information but were slow to respond and awkward to read out
- “New”: Electronic detectors, wire chambers, scintillators, solid state detectors
  - Segmented
  - Fast, can be read out digitally, information content is now approaching the “old” technology



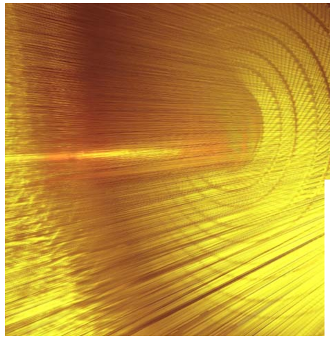
Pre-WWII

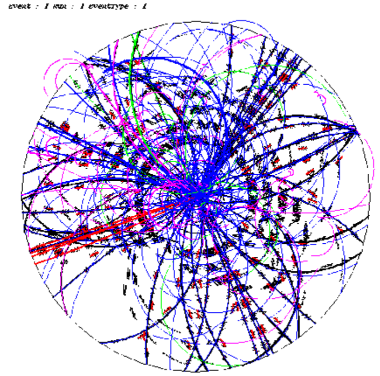


1950's-70's

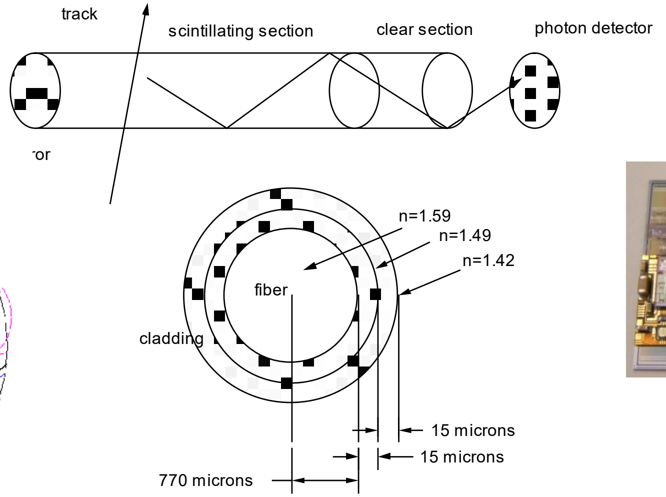


1960's-70's

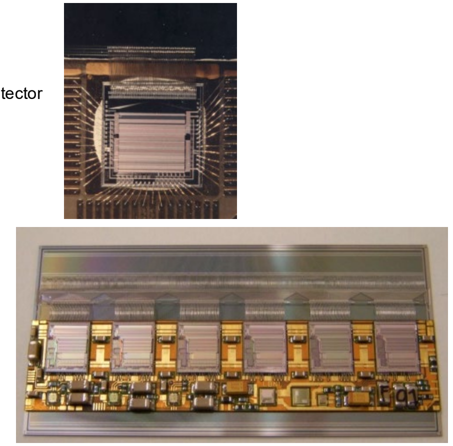




1970's-present

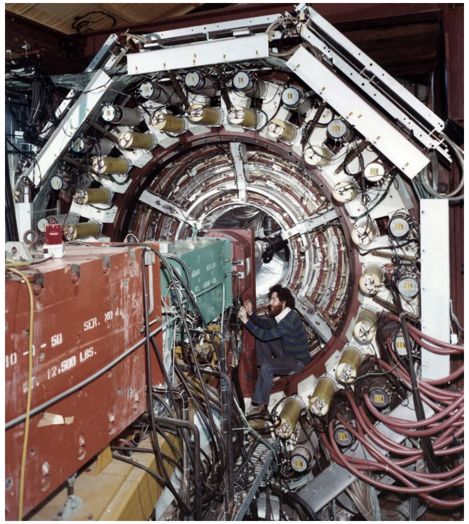


1990's

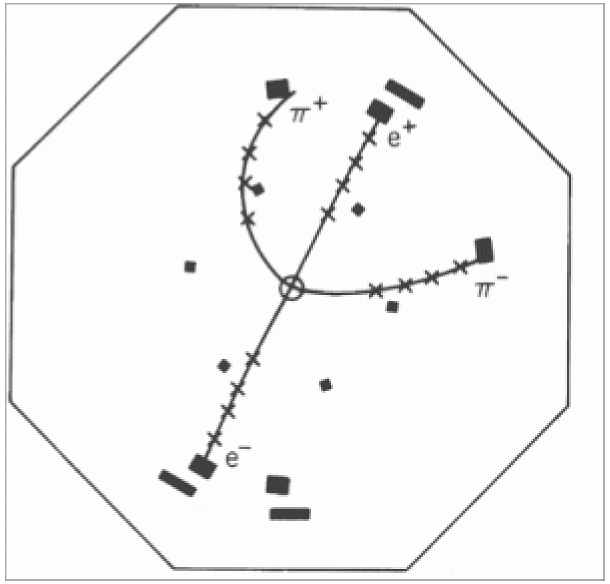


1990's-present

Track Parameters



- Basic idea is a track curving in a magnetic field
- 3D track described by 5 parameters
- p=momentum (or curvature in B field)
- d=distance of closest approach to the origin
- ϕ=azimuthal angle at the origin
- z_0= vertex along the beamline
- $\theta =$ polar angle



Tracker Characteristics

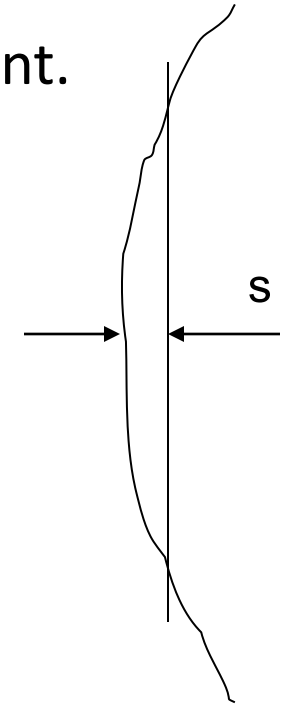
- Performance on reconstruction of track parameters defined in terms of:
  - parameters of the system (geometry, layout, material, magnetic field, etc)
  - performance of position sensing elements.
- Performance of position sensing elements
  - hit resolution, timing resolution, effects of data transmission, 1D/2D/3D
  - Radiation damage effects
  - defined by physics of detecting medium/process and general considerations such as segmentation and geometry.
- Evaluation
  - Initially evaluate with simple parametric analyses.
  - Fast simulation
  - Full simulation
  - Bench, CR, and beam tests

Momentum Resolution

Simple case: Measure sagitta *s* of track with radius *R,* over projected arc length *L* (cm, KGauss, MeV/c), assuming R>>L

$$p = \frac{0.3BR}{\cos\theta} = \frac{0.3BL^2}{8s\cos\theta} \quad \text{using } R = \frac{L^2}{8s} \Rightarrow \left(\frac{\Delta p}{p}\right)_{sagitta} = \frac{8p\Delta s}{0.3BL^2\cos\theta}$$

where Δs is the error on the sagitta measurement.



Effect of material: multiple scattering

$$(\Delta s)^2 = \frac{\sigma^2{}_{MCS}}{16}\frac{L^2}{3\cos^2\theta} \Rightarrow \left(\frac{\Delta p}{p}\right)_{MCS} = \frac{52.8}{B\sqrt{LX_0\cos\theta}}$$

$$\frac{\Delta p}{p}_{TOTAL} = \left(\left(\frac{\Delta p}{p}\right)^2_{saggita} + \left(\frac{\Delta p}{p}\right)^2_{MCS}\right)^{\frac{1}{2}}$$

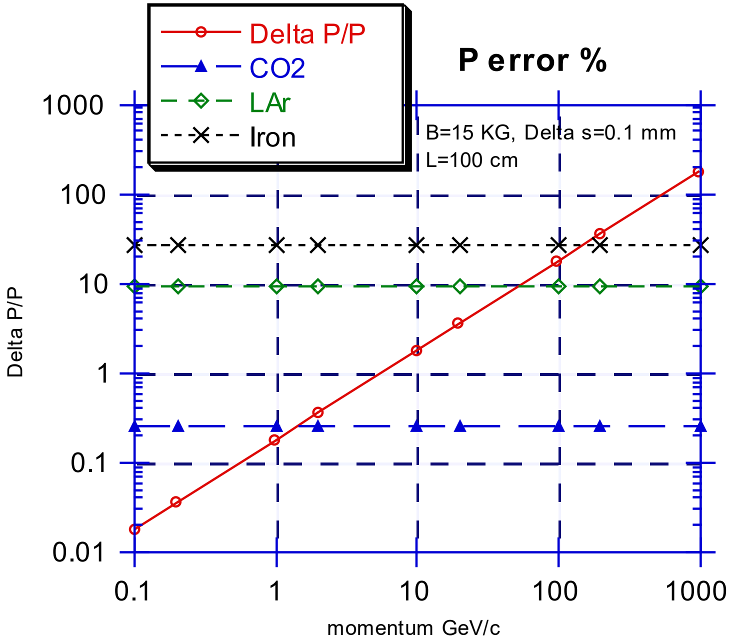
Effect of Material

$$\left(\frac{\Delta p}{p}\right)_{sagitta} = \frac{8p\Delta s}{0.3BL^2\cos\theta}$$

$$\left(\frac{\Delta p}{p}\right)_{MCS} = \frac{52.8}{B\sqrt{LX_0}\cos\theta}$$

$$\frac{\Delta p}{p}_{TOTAL} = \left(\left(\frac{\Delta p}{p}\right)^2_{saggita} + \left(\frac{\Delta p}{p}\right)^2_{MCS}\right)^{\frac{1}{2}}$$

- Minimize sagitta error
- Maximize B,L
- Minimize material



Vertex Resolution

$x1, x2 =$ measurement planes

$y1\ , y2 =$ measured points, with errors δy

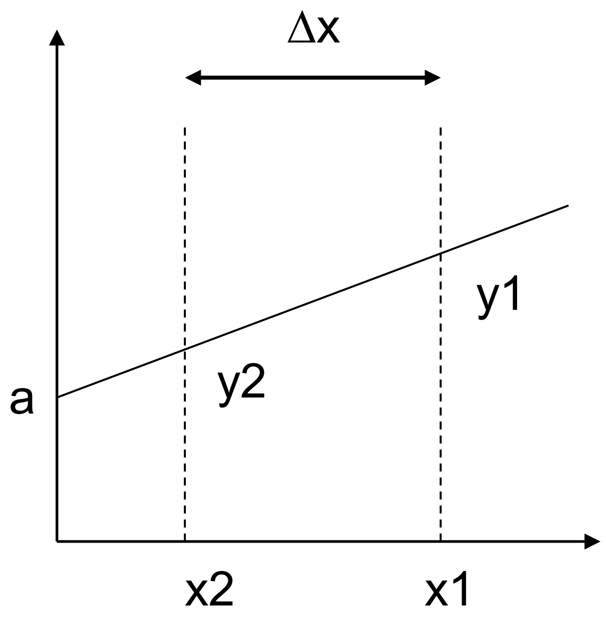
$y = a + bx$

$$b = \text{slope} = \frac{y1 - y2}{x1 - x2} = \frac{y1 - y2}{\Delta x}$$

$$a = \text{intercept} = \frac{1}{2}(y1 + y2) - \frac{1}{2}(y1 - y2)\left(\frac{x1 + x2}{\Delta x}\right) = \bar{y} - b\bar{x}$$

$$(\delta b)^2 = \left(\frac{\partial b}{\partial y1}\right)^2 (\delta y)^2 + \left(\frac{\partial b}{\partial y2}\right)^2 (\delta y)^2 \Rightarrow \delta b = \frac{\sqrt{2}\delta y}{\Delta x}$$

$$\delta a = \frac{\delta y}{2}\sqrt{1 + \frac{8\bar{x}}{\Delta x}}$$



for good resolution on angles (ϕ and θ) and intercepts (d, z_0)

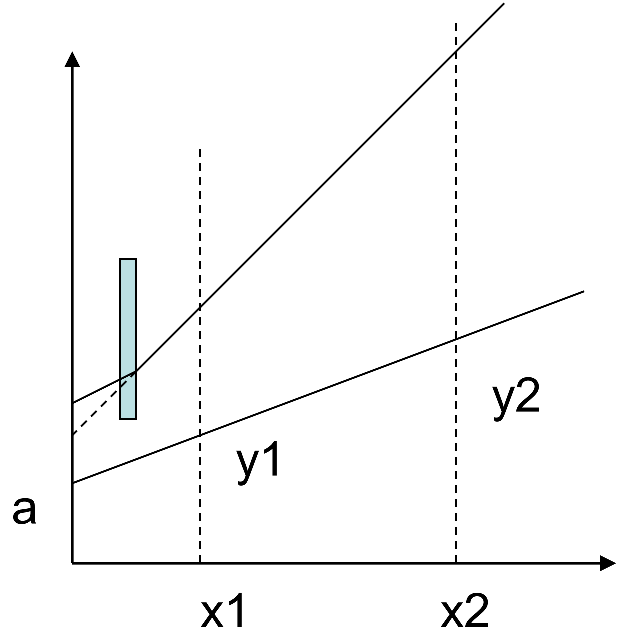
- Precision track point measurements
- Maximize separation between planes for good resolution on intercepts
- Minimize extrapolation - first point close to interaction

Effect of Material

$x1, x2 =$ measurement planes

$y1\ , y2 =$ measured points, with errors δy

$$\delta a = \frac{\delta y}{2}\sqrt{1+\frac{8\overline{x}}{\Delta x}}$$

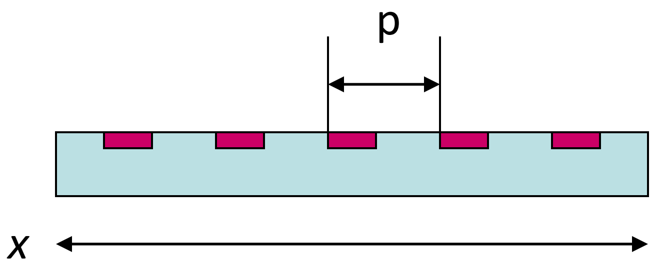


for good resolution on angles (f and q) and intercepts (d, z_0)

- Precision track point measurements
- Maximize separation between planes for good resolution on intercepts
- Minimize extrapolation - first point close to interaction
- Material inside 1st layer should be at minimum radius (multiple scattering)

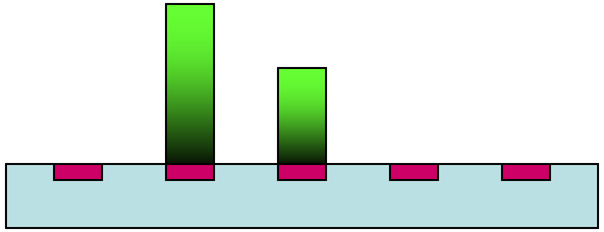
Point Resolution: Segmentation

- Discrete sensing elements (binary response, hit or no hit), on a pitch *p,* measuring a coordinate *x*



$$\sigma_x = \frac{p}{\sqrt{12}}$$

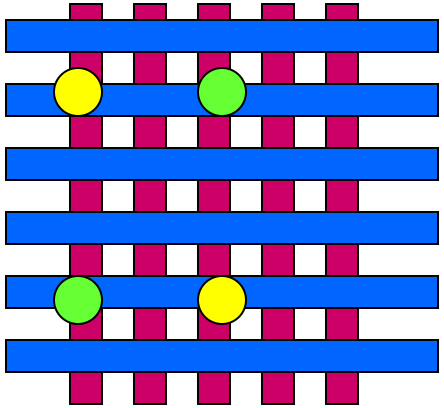
- Discrete sensing elements (analog response with signal to noise ratio S/N) on a pitch *p,* where f is a factor depending on pitch, threshold, cluster width

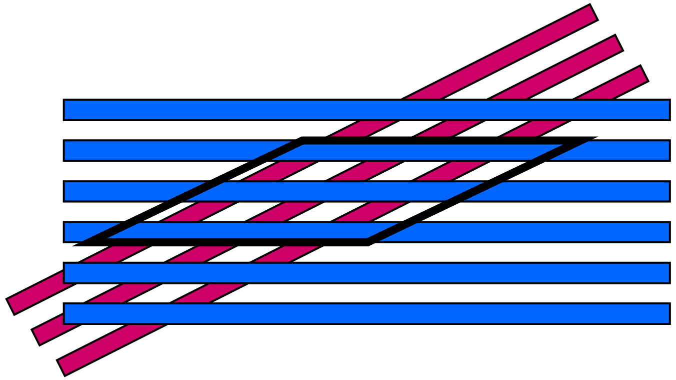


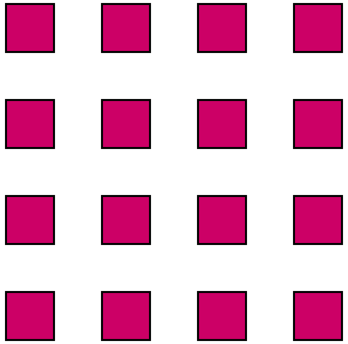
$$\sigma_x \sim fp(\frac{N}{S}) < \frac{p}{\sqrt{12}}$$

2D

- The problem of 2 dimensions:
  - 90^o array of *n* elements on pitch *p:* equal resolution on both coordinates.
    - m hits -> m^2 combinations with $m^2 - m$ false combinations
  - Small angle stereo geometry, angle α
    - False combinations are limited to the overlap region but resolution on second coordinate is worse by $1/\sin(\alpha)$
- Pixel structure: *n* x *m* channels
  - Ultimate in readout structure
  - Expensive in material, system issues, technology, cost
- Pixels and strips can also be thought of as 2 extremes of a continuum (super-pixels, short-strips,…..)
  - Some potential for optimizations of performance vs. complexity but needs to be analyzed on a case by case basis





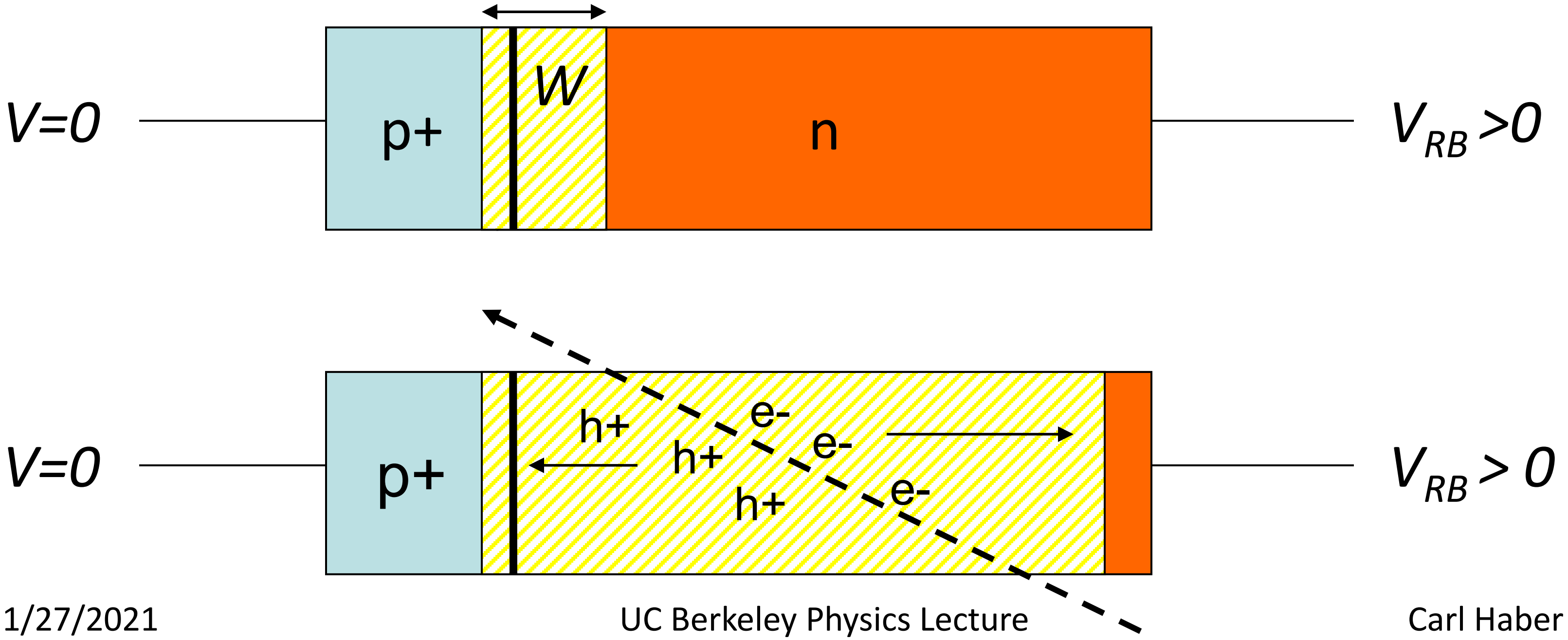


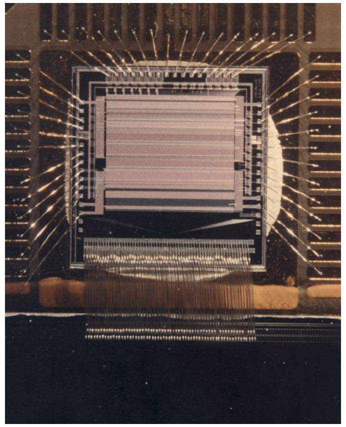
Semiconductor Detectors

- Since mid-80’s use of position sensitive “silicon detectors” became widespread
- Can resolve track positions to ~10 microns
- Used to measure momentum and identify secondary vertices due to decays of primary particles
- Handle high particle rates and radiation dose
- Substantial commercial basis for technology

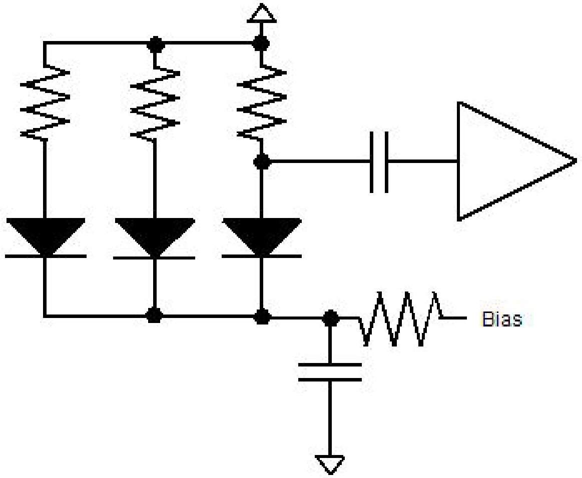
Silicon Detectors

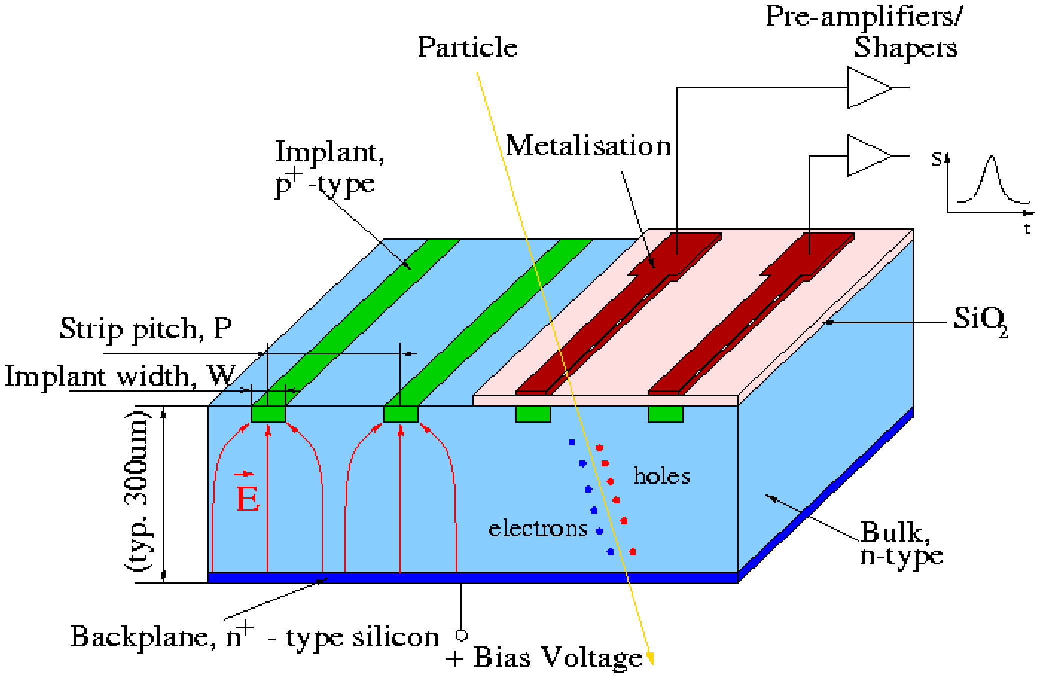
- Asymmetric diode junction: p(+) into contact with n, ($N_A >> N_D$) (can also have n+ in p)
- Space charge region formed by diffusion of free charges, increased with "reverse bias“
- Electron-hole pairs formed in the depletion zone drift under the influence of the electric field
- Signal depends on width of depletion zone
- Drift time determined by mobility and field
  - ~7 ns to cross 300 microns
- Drifting charge is a current which can be measured

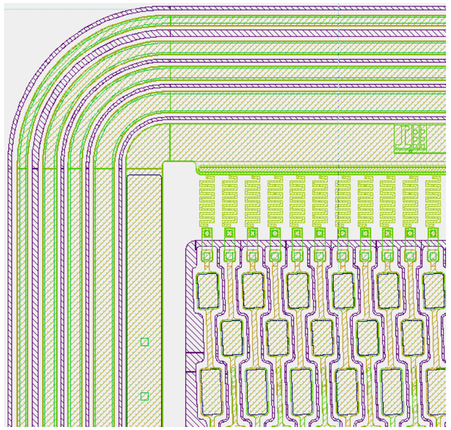




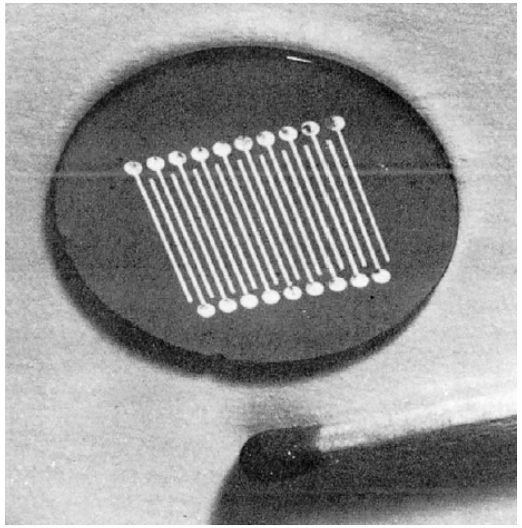
Basic Strip Sensor Details



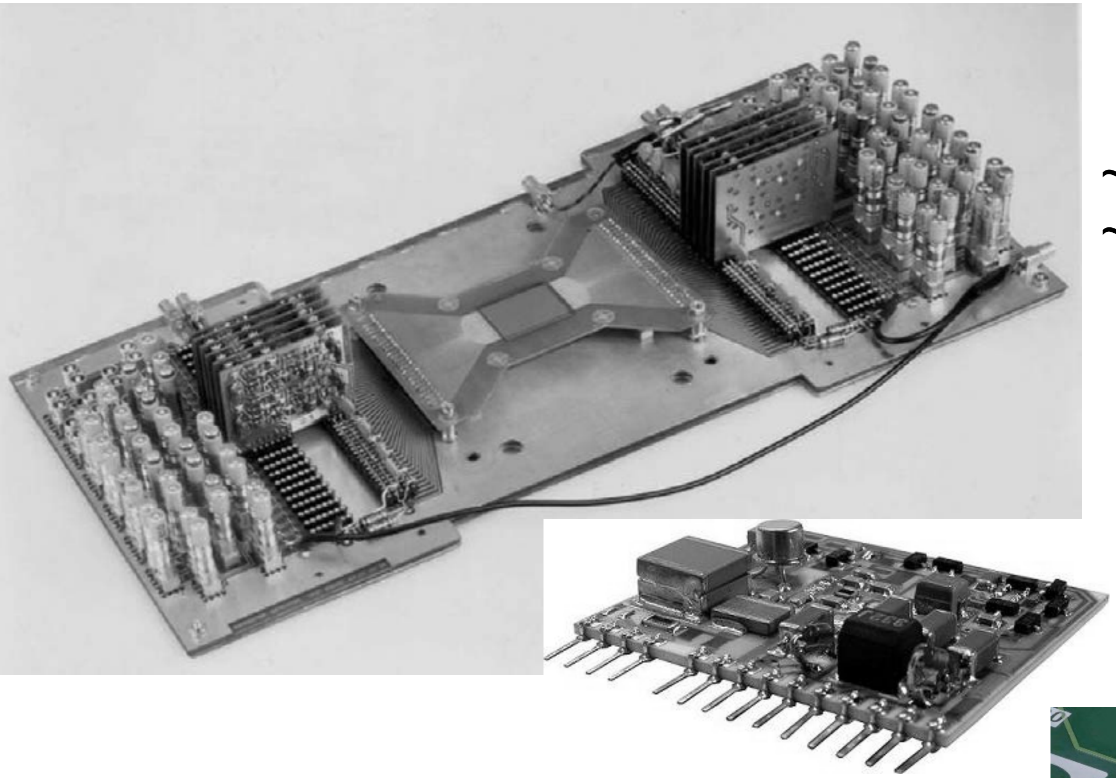




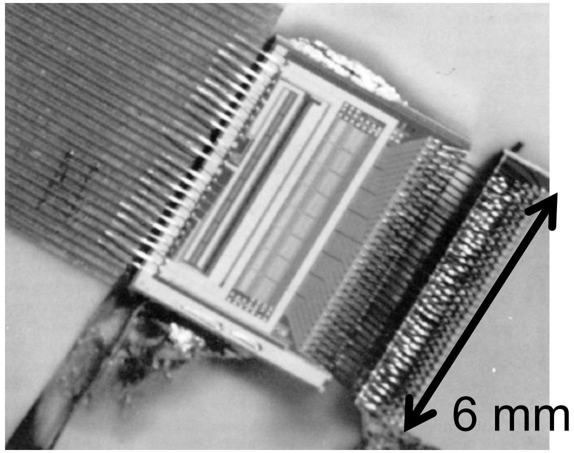
Looking for charm in fixed target hadronic interactions…..b's at lepton colliders….Higgs/BSM @LHC



Late 1970's surface barrier strip detector (Pisa)

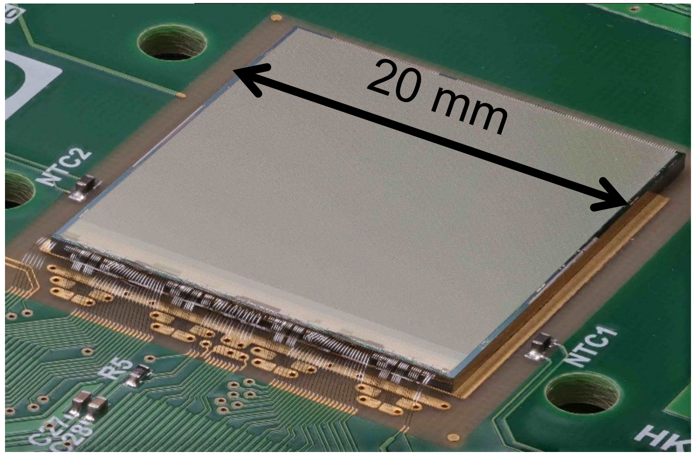


~1980, 128 discrete channels
~14 mW/channel (CERN)

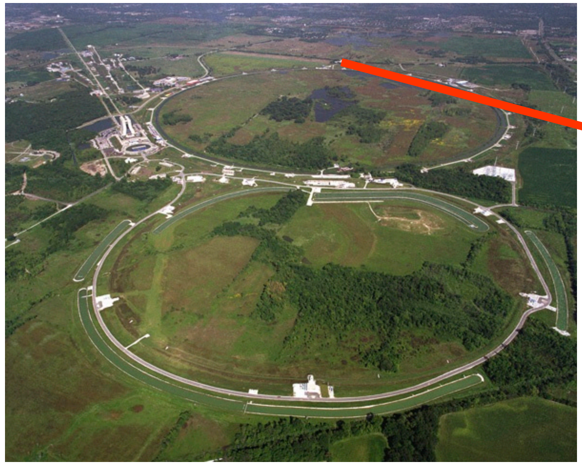


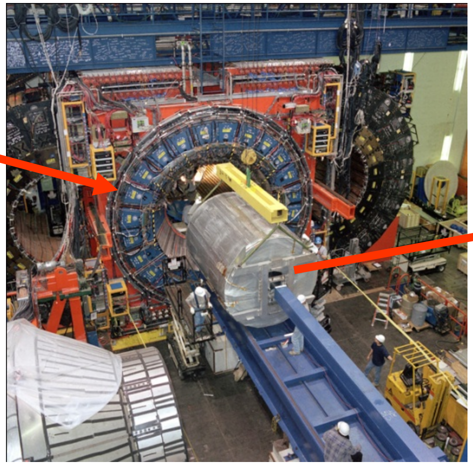
~1985, "Microplex", 3 mW/ch
1st 128 readout ASIC,
1st application to colliding beams
(SLAC Mark II)
(Parker,Hyams,Walker)

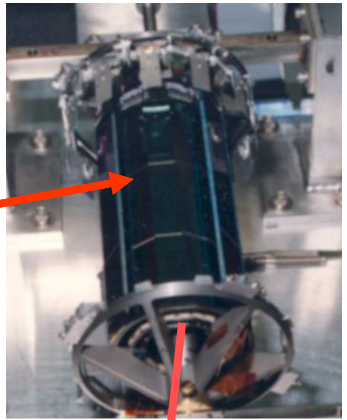
2020 RD53B
ATLAS
153,600 pixels
8 μA /pixel

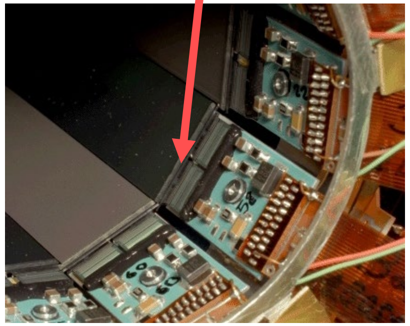


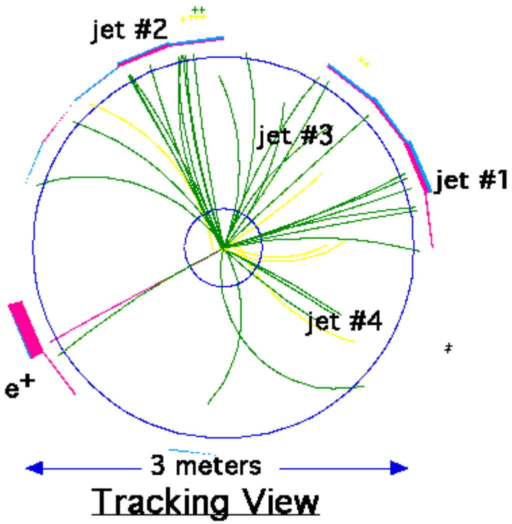
Finding top and bottom at the Tevatron ~1995…..

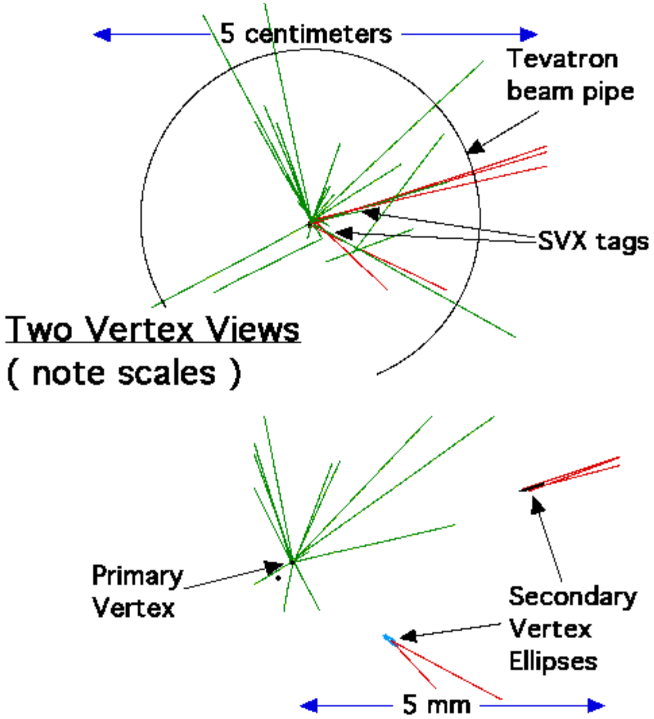


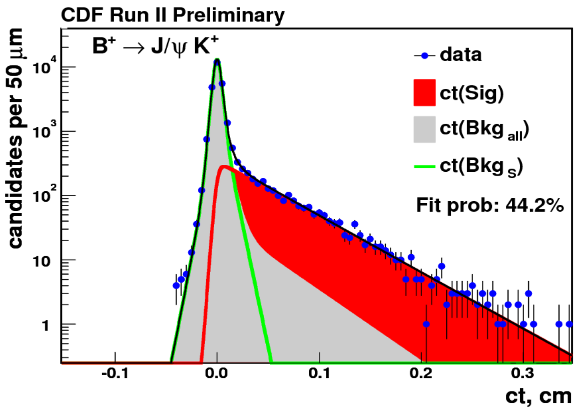




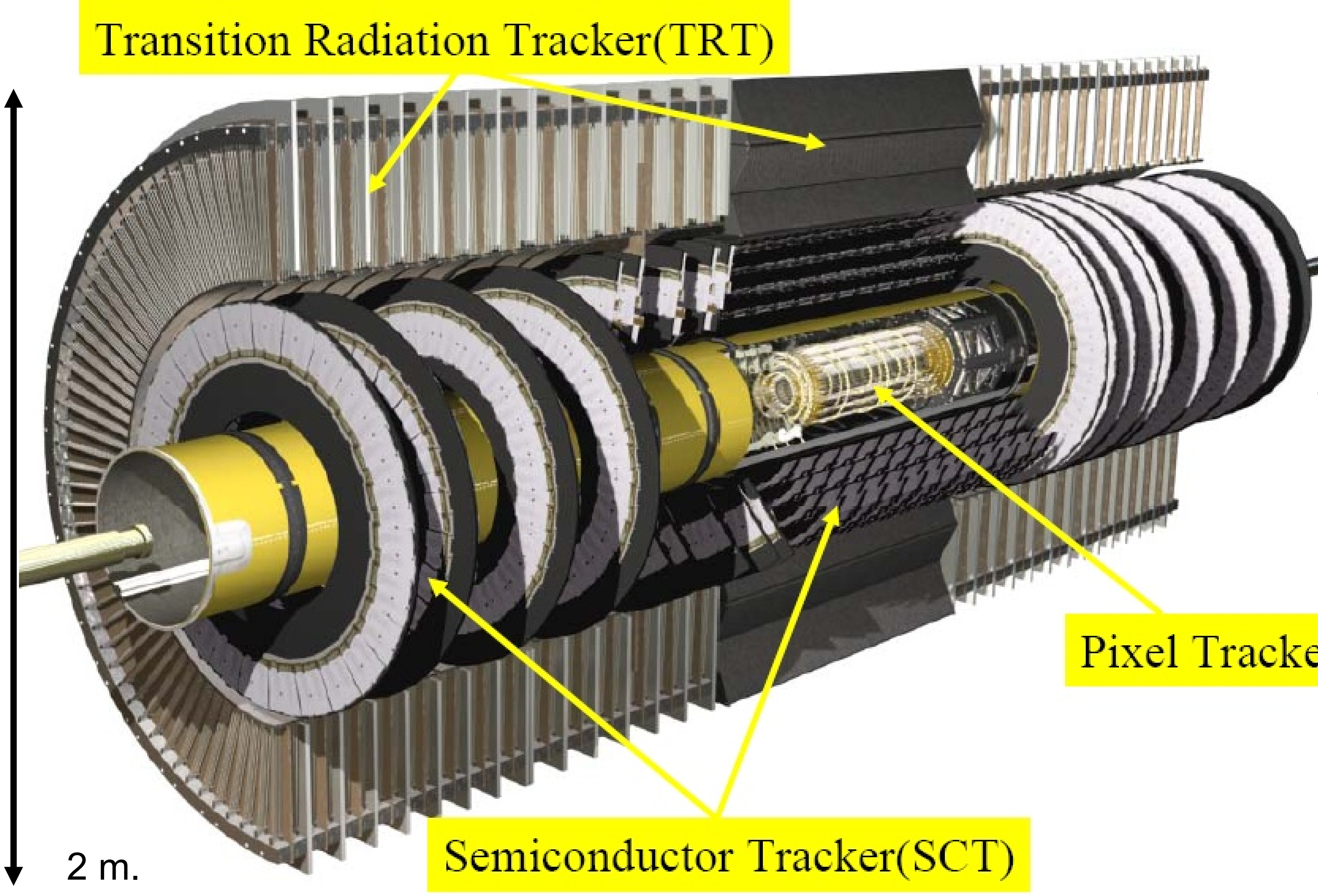








CERN ATLAS tracker (4th generation, beam in 2008)



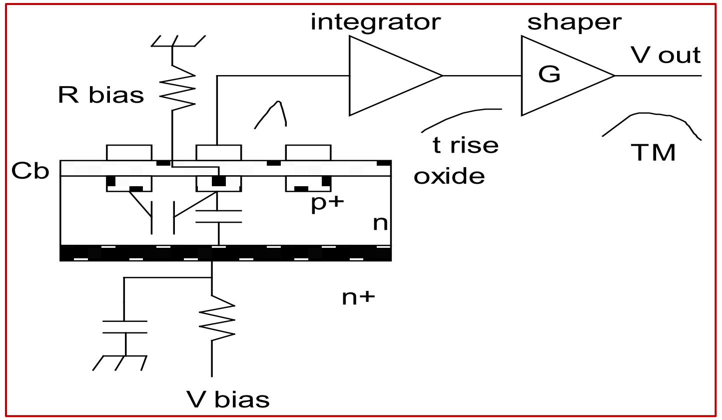
CDF
1992

Hadron Collider View

generation	year	luminosity	ΔT	chan/area	dose	readout
1 CDF SVX	1990	10^{29}	3.5 μs	50K/ 0.68 m^2	25 Krad	3 μm CMOS
2 CDF SVX*	1995	10^{30}	3.5 μs	50K	100 Krad	1.2 μm RHCMOS
3 Run 2	2000	10^{32}	128 ns	600K / 5 m^2	1 Mrad, $10^{13}/cm^2$	0.8 μm RHCMOS
4 LHC	2009	10^{34}	25 ns	5 x10^6 / 68 m^2 10^8 pixels	10 Mrad 10^{15}	0.25 μm CMOS RH Bi-CMOS
5 HL-LHC	2025	5 x 10^{34}	25 ns	10^8 / 200 m^2 10^9 pixels	100 Mrad 10^{16}	65 – 130 nm CMOS SiGe, Commercial
6 HE-LHC/FCC	>2035	3 x 10^{35}	25 ns (5 ps)	5 x 10^8 / 400 m^2 5 x 10^9 pixels	1-10 Grad 10^{18}	Unknown features Monolithic CMOS?

Signal Processing Issues

- Signal
  - Energy loss by particle in Si
  - Proportional to thickness (volume)
  - Radiation can effect efficiency
- Leakage current
  - If DC coupled then must be compensated by filter, feedback, or injection
  - Before (after) LHC radiation damage ~ 1 nA (1 μa)
  - AC component is seen by pre-amp: noise source
- Input Noise
  - Preamp "input noise charge", white noise, decreases with pre-amp current, increases with faster risetime
  - Bias resistor: source of thermal noise
  - Radiation activated



$$\sigma_N \propto \sqrt{I_{LEAK} T_M}$$

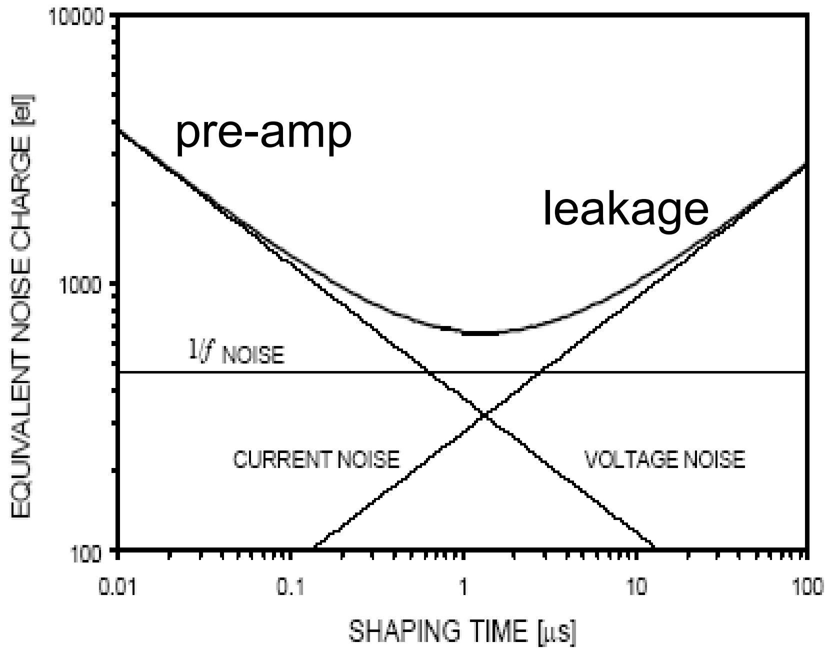
$$\sigma_N \propto a + bC_D$$

$$\sigma_N \propto \frac{1}{R_{BIAS}}$$

Signal Processing Optimizations

- Signal increases with volume
- Leakage current
  - Decreases with lower temp and volume
  - Increases with radiation and integration time
- Noise
  - Decreases with capacitance, leakage, power
  - Increases with faster risetime

Generic no-name amplifier



Combination of rise and integration time

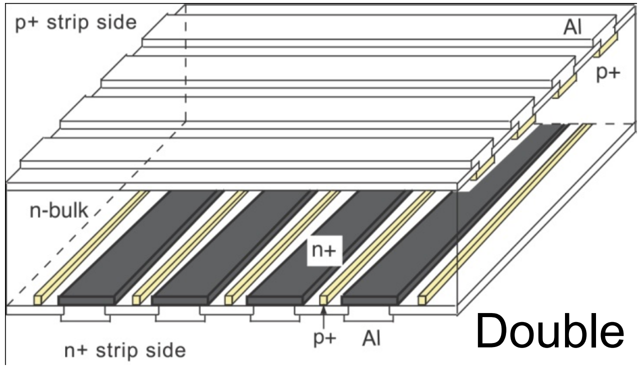
1st Order Correlations Between Sensor and Readout Electronics Characteristics

Dep\Indep	Volume	Radiation	Temp	Power	Leakage	Capacitance	Integrat. time	Risetime*
Signal	↑	↓						↑
Leakage	↑	↑	↑					
Input noise		↑		↓		↑		↑
Shot noise	↑	↑	↑		↑		↑	
Risetime*				↑		↑		
Power		↑			↑			↑
Required bias	↑	↑	↑					

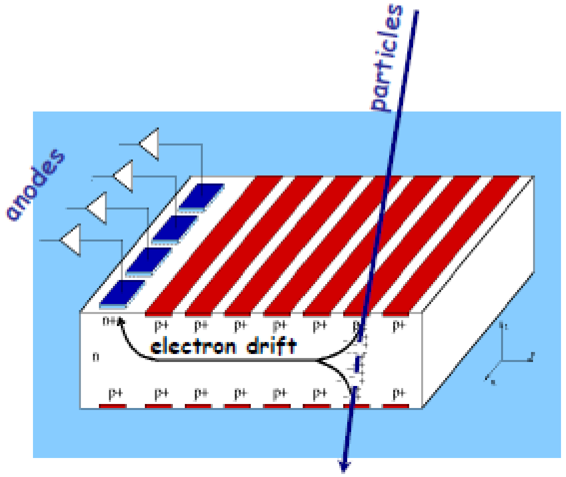
* Up means faster

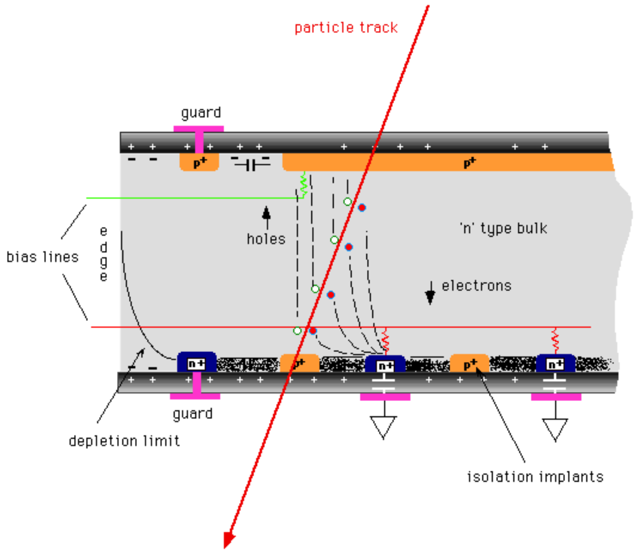
Consider this as representative. The point is that a signal processing optimization should always be performed

Variations on the Strip Detector

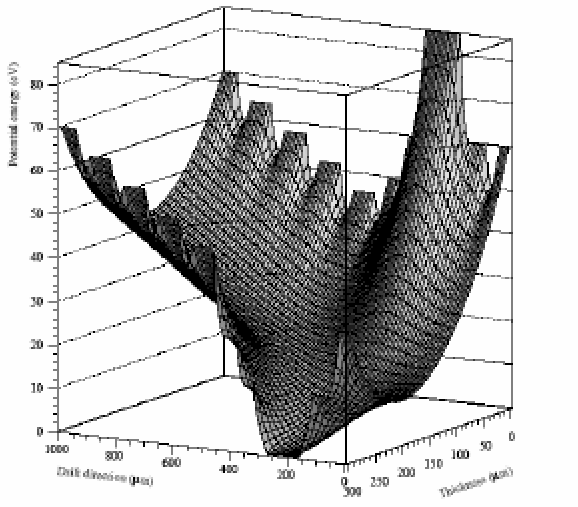


Double sided detector





p+ in n
n+ in p
n+ in n



Silicon drift detector

Pixel Detectors

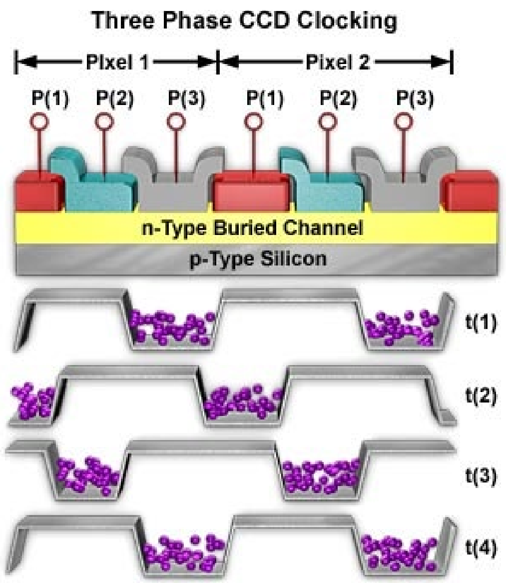
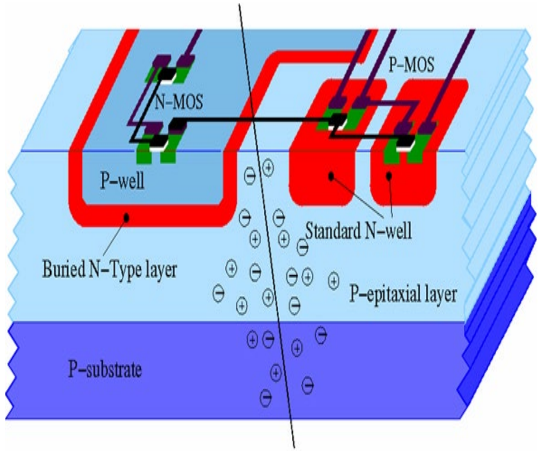
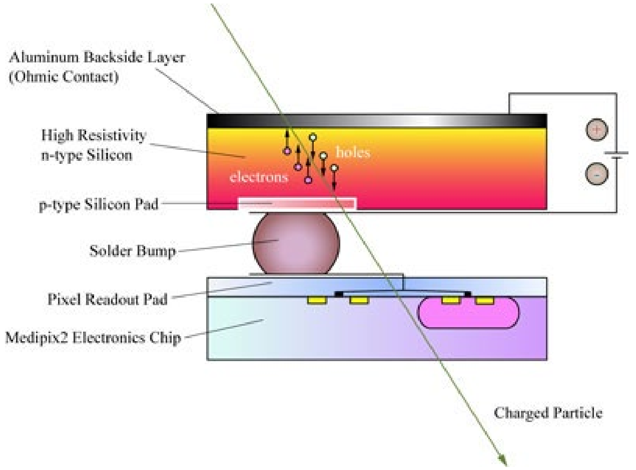


Figure 1

CCD
Charge Coupled Device
Relatively slow
Low noise, Low mass

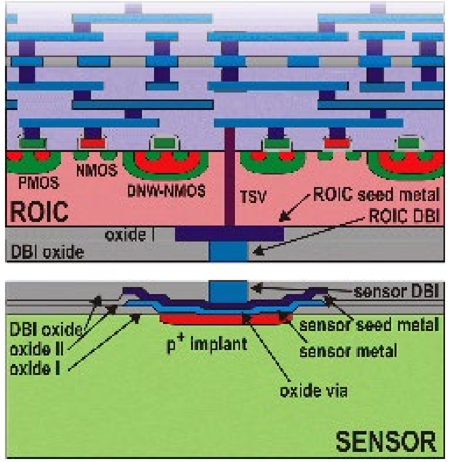


Monolithic Active Pixel
electronics and charge
formation/collection in a
thin epitaxial layer, diffusion
Moderate speed
Low noise, Low mass



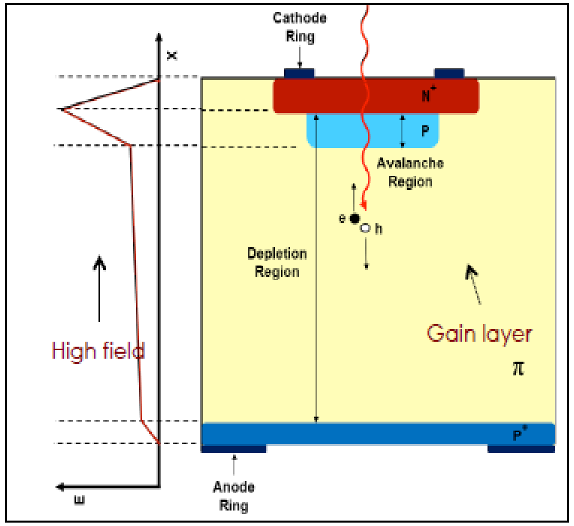
Hybrid pixel
FE IC and sensor joined
by a bump bond
Fast,Radiation Hard
Most widely used now

Extended Structures



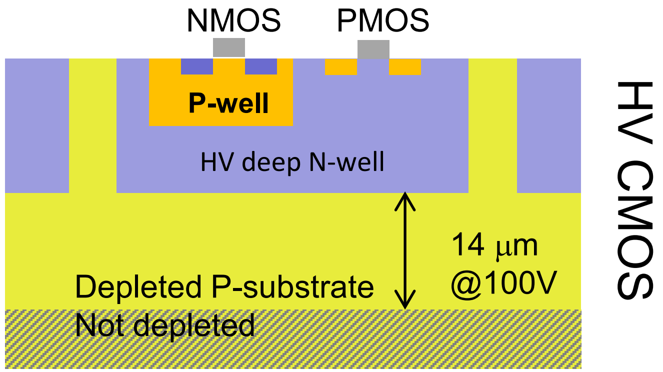
Vertical Integration
Sensor die and electronics die are directly bonded
Advanced packaging Process

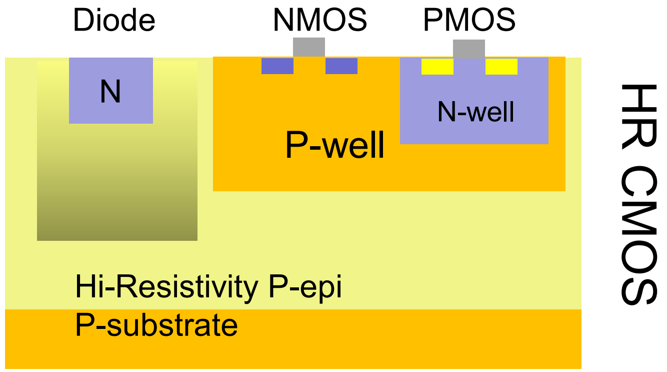
R.Lipton FNAL



Ultra Fast Silicon Detector
Uses n-in-p sensor, add p+ implant below n+ to small charge gain, increase signal so that rising current edge can be used for timing with resolutions of ~20 ps

H.Sadrozinski UCSC

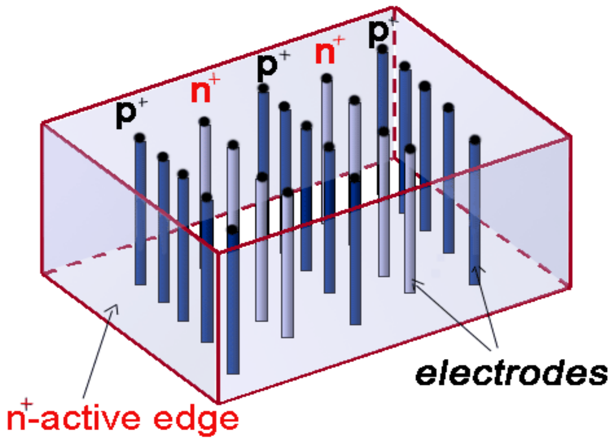


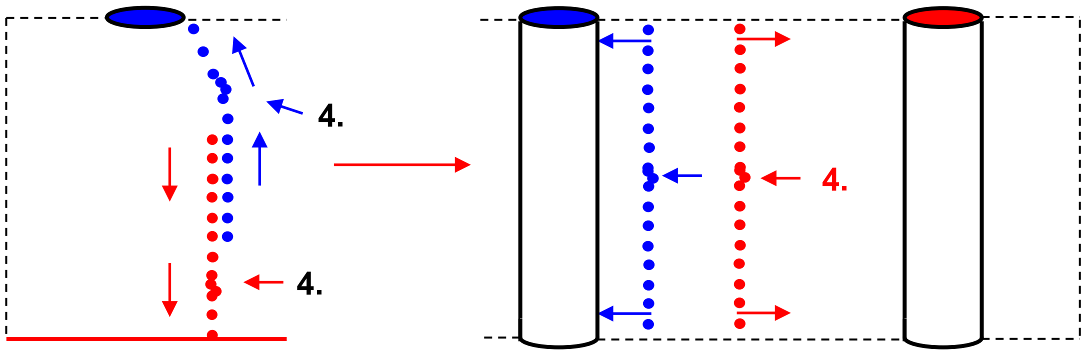


HV/HR CMOS – MAPS concept made compatible with LHC like operating conditions using drift from depleted zones, cheap?

3D Sensors (S.Parker)

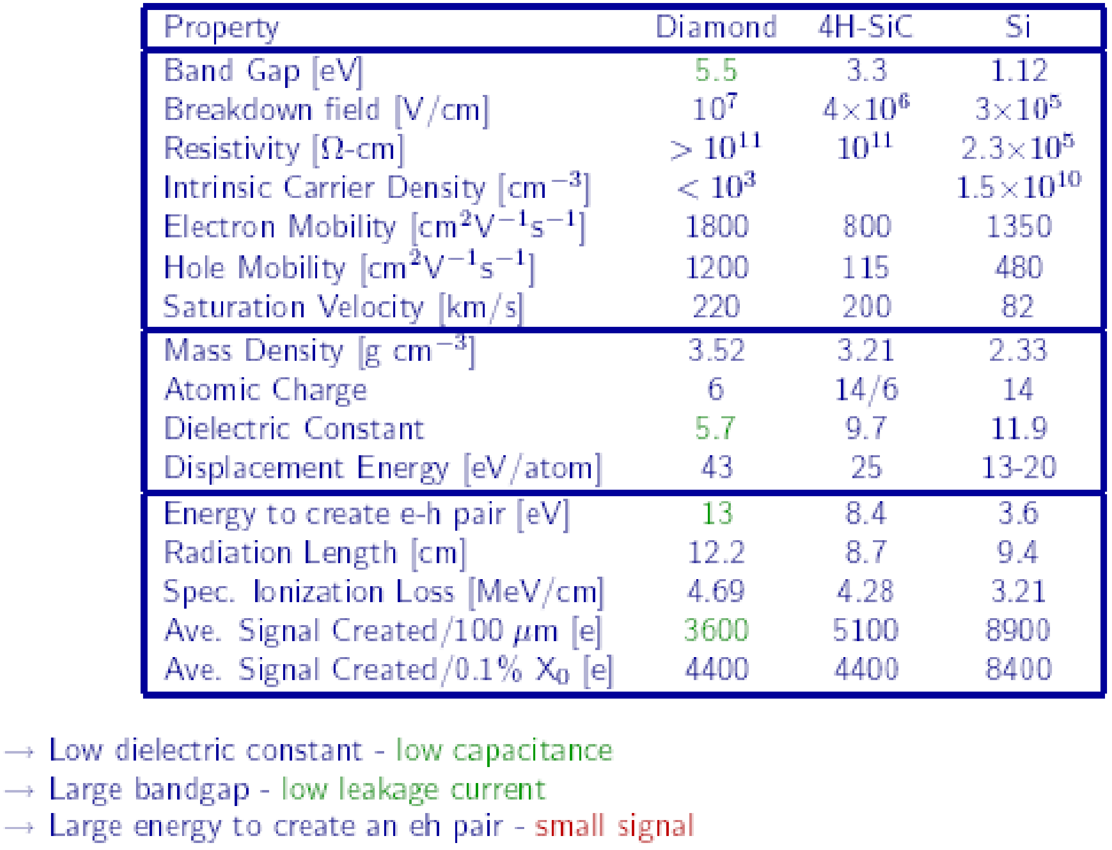
- Implants are vertical
  - Larger capacitance/pixel
  - Requires special processing including MEMS technology
- Collection distance is reduced
  - Faster signal
  - More rad-hard for CCE
- Current applications to inner layers, beam monitors, timing





Alternate Materials

- Very active R&D effort for >20 years
  - http://rd48.web.cern.ch/RD48/
- Most work has been on pCVD diamond material
  - Significant improvement in charge collection
- New results on single crystal materials – but small samples
- Issue of industrial capacity vs silicon
- New interest in energy technologies (batteries, electric transportation) has grown industrial focus on the large bandgap materials



Property	Diamond	4H-SiC	Si
Band Gap [eV]	5.5	3.3	1.12
Breakdown field [V/cm]	10^7	4×10^6	3×10^5
Resistivity [Ω-cm]	$> 10^{11}$	10^{11}	2.3×10^5
Intrinsic Carrier Density [cm^{-3}]	$< 10^3$		1.5×10^{10}
Electron Mobility [$cm^2V^{-1}s^{-1}$]	1800	800	1350
Hole Mobility [$cm^2V^{-1}s^{-1}$]	1200	115	480
Saturation Velocity [km/s]	220	200	82
Mass Density [g cm^{-3}]	3.52	3.21	2.33
Atomic Charge	6	14/6	14
Dielectric Constant	5.7	9.7	11.9
Displacement Energy [eV/atom]	43	25	13-20
Energy to create e-h pair [eV]	13	8.4	3.6
Radiation Length [cm]	12.2	8.7	9.4
Spec. Ionization Loss [MeV/cm]	4.69	4.28	3.21
Ave. Signal Created/100 μm [e]	3600	5100	8900
Ave. Signal Created/0.1% X_0 [e]	4400	4400	8400

→ Low dielectric constant - low capacitance

→ Large bandgap - low leakage current

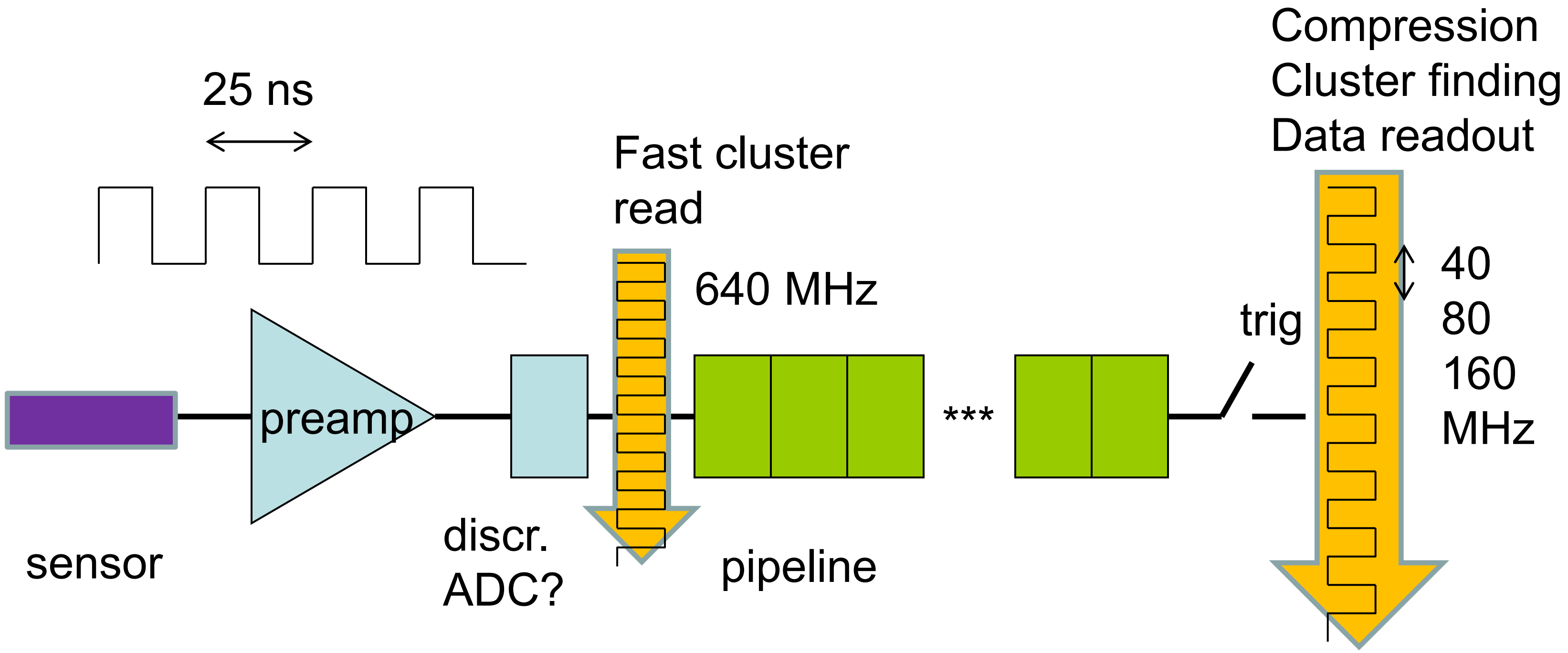
→ Large energy to create an eh pair - small signal

Type	D	Timing	Fab	Cost	Application/Limitations/Comments
Silicon Strip p in n	1	ns	standard	$	Basic, rad hard, outer tracking layers
n in p	1	ns	standard	$	More rad hard, outer tracking layers
n in n	1	ns	double side	$$	Partial depletion
Double sided	2	ns	double side	$$	Radiation hardness issues with biasing
Silicon drift	2	Drift time	special	$$$	Niche application to high multiplicity
CCD	2	Readout	boutique	$$$	Slow, linear collider vertex
Monolithic Active Pixel	2	ns	commercial	$	Large area, low cost, low mass
Hybrid Pixel	2	ns	combined	$$	Hadron collider inner layers, bump bonded
Vertical Integration	2	ns	Sp. commercial	$$	Advanced comm IC process, low mass
LGAD	2*	~20 ps	special	$$	Fast timing by not yet high spatial resolution
3D Sensor	2	~100 ps	very special	$$	Fast, very rad hard, inner layers
HVCMOS	2	ns	commercial	$	Fast, large area, in development, rad hard
High Resistivity CMOS	2	ns	commercial	$	Fast, large area, in development, rad hard
Non- silicon		ns	boutique	$$	Diamond, SiC, etc, see DOE BRN report

Readout Architectures

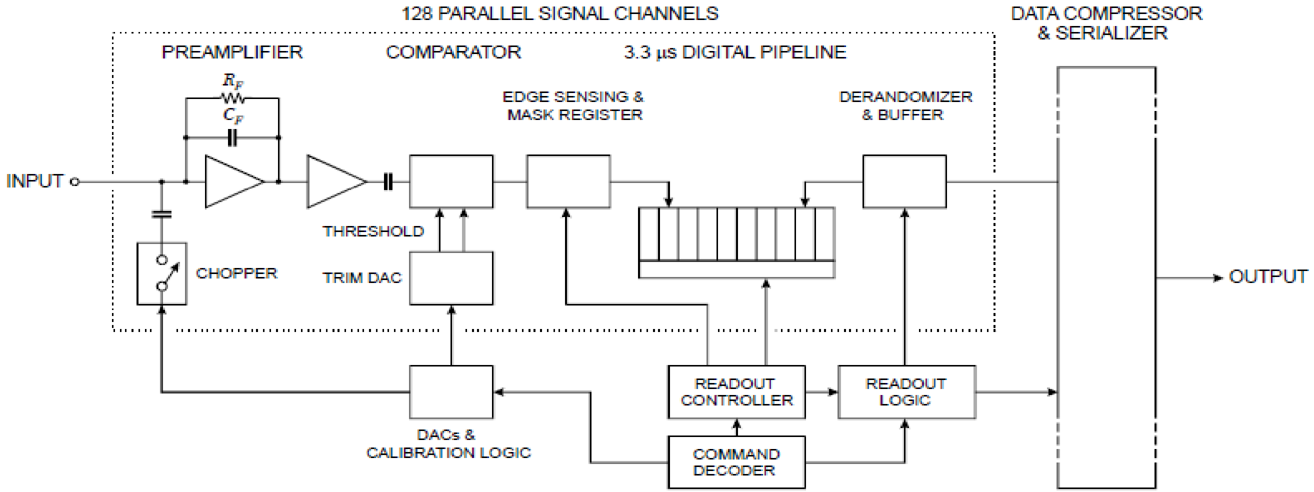
- Experimental conditions, have, to some extent driven the development of a variety of readout architectures (see also backup slides)
- Accommodate properties and limitations of available IC processes, a moving target
- Subjective aspects have entered as well
- Analog: process analog pulse heights off detector, full resolution, diagnostics, example is CMS APV25 series
- Digital: digitize on detector, full resolution, examples are CDF SVX2-4 series, ATLAS pixel TOT system
- Binary: on detector threshold, simplify readout, example is ATLAS ABC
- Fast Timing is an emerging capability (few 10's of ps)

A Basic Collider Readout Architecture



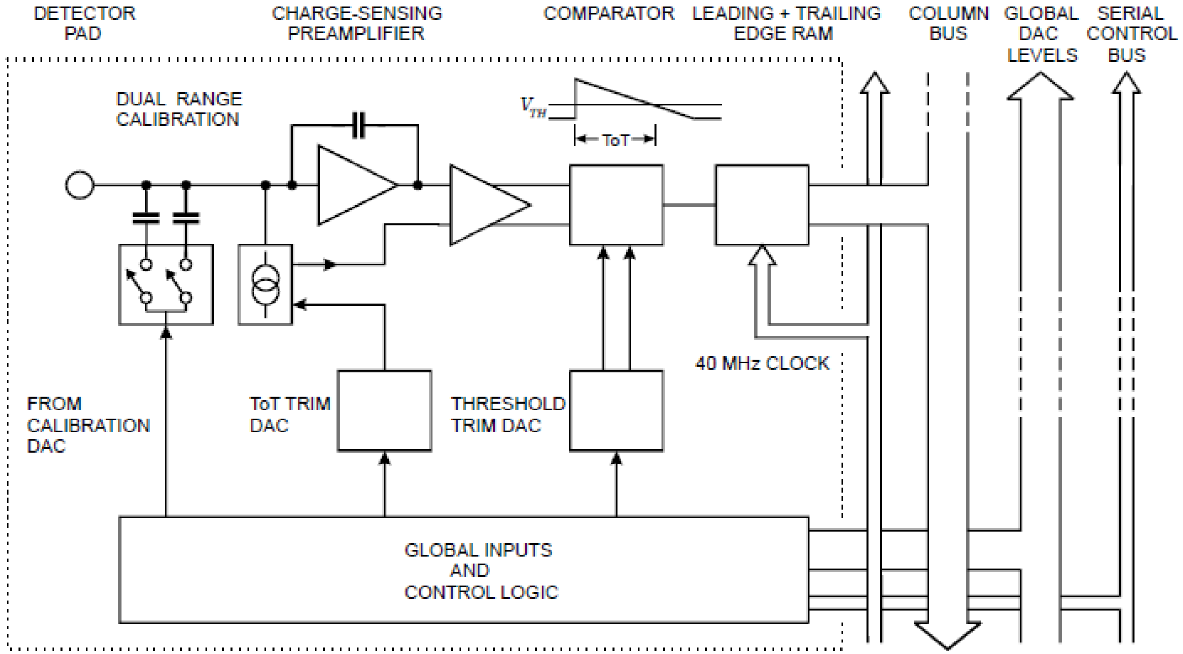
- Beam clock (BC) runs at collision rate, advances pipeline
- Pipeline length determined by required latency
- Trigger determines whether last cell will be read
- Fast cluster read enables access to prompt data

Binary

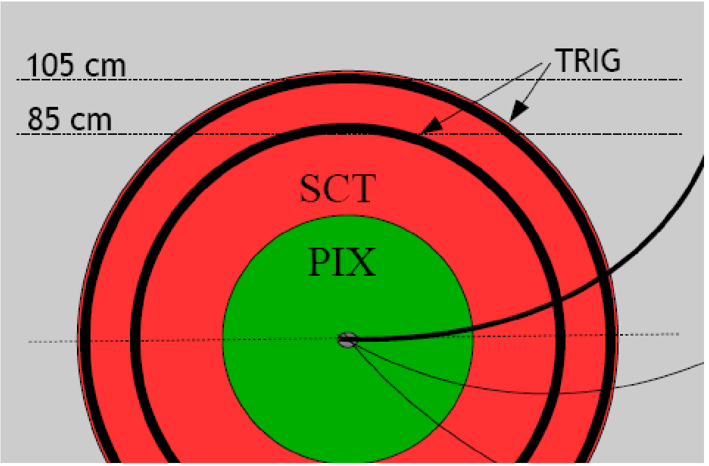


- Example is the ABC chip developed for ATLAS, BiCMOS
- AC coupled pre-amplifier shaper for 25 ns collisions
- Comparator + trim DAC per channel
- 1 bit pipeline clocked at 40 MHz, L1 buffer
- Data compression
- Control and configuration protocol
- DSM CMOS version exists as well, 130 nm underway

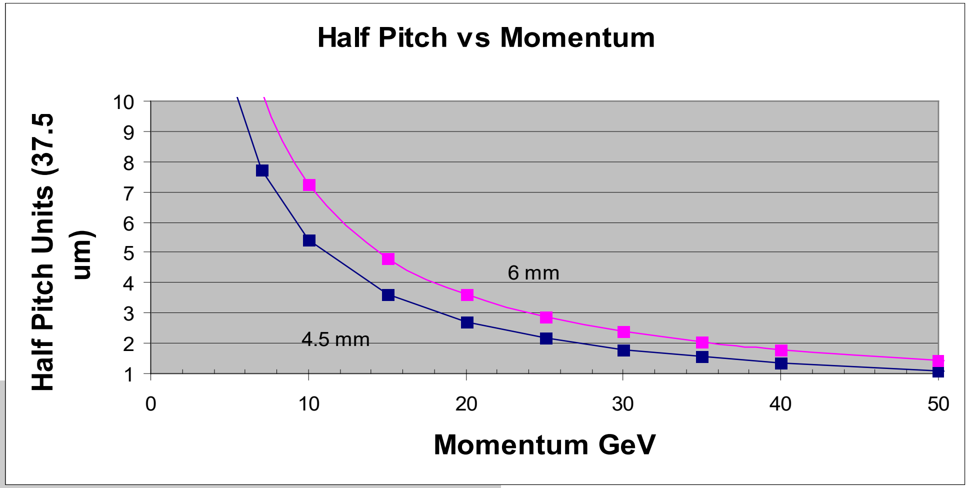
ATLAS Pixel

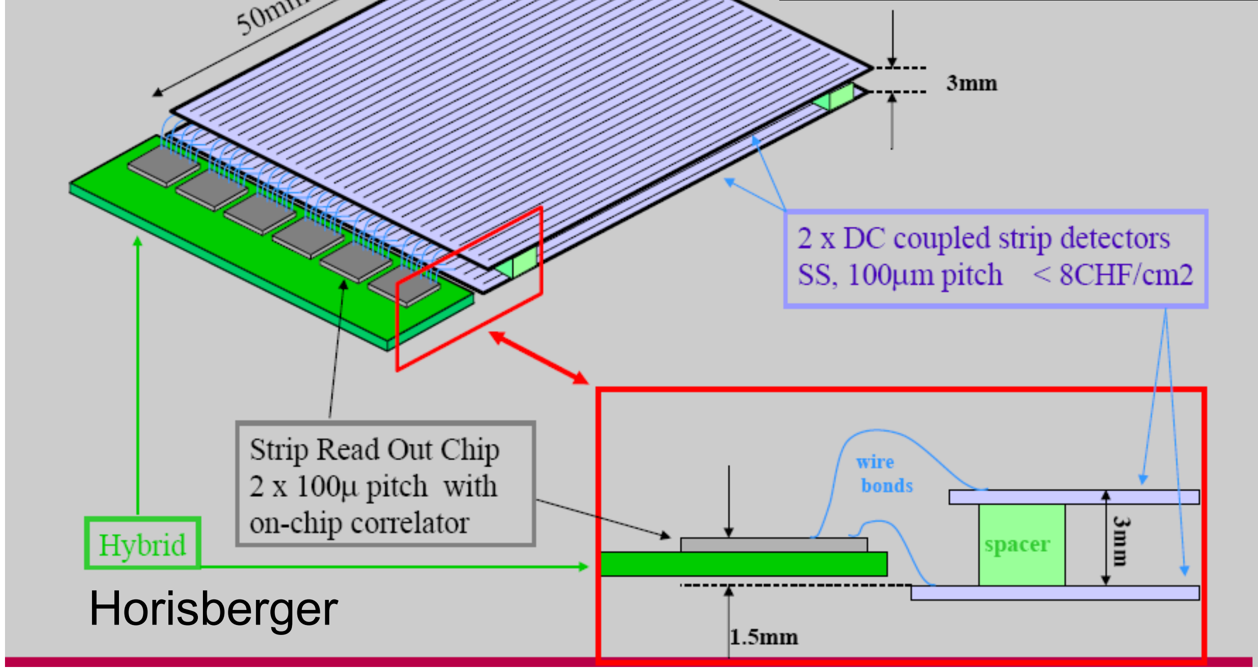


- Example is ATLAS FEI3 pixel cell
- DC couple preamp with leakage current compensation
- Pulse height is measured by "Time over Threshold"
- Additional architecture organizes the data in columns for readout



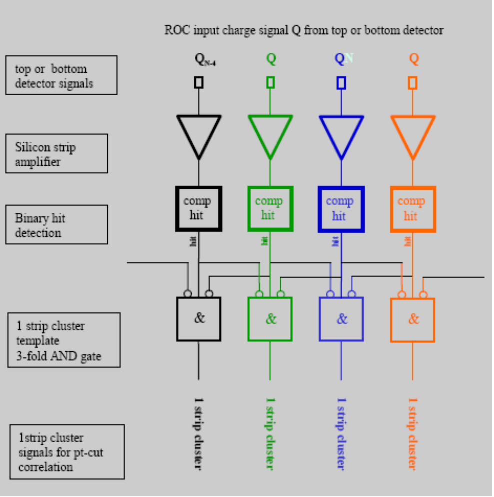
Real time momentum trigger





Horisberger

See WIT2010,12,14 pub in JINST



This concept has been developed into a full scale tracker architecture by the CMS collaboration for the HL-LHC. See their TDR

https://cds.cern.ch/record/2272264/files/CMS-TDR-014.pdf

The ATLAS collaboration has studied, but will not use, a more limited version of this

Radiation Environment

- Primary source are collision products
  - High energy charged particles + neutrals
- Additional component due to “accidents”
- Primary field falls with radius as ~r $^{-(1-2)}$
- Each interaction yields ~7 particles/angular unit: sum crossings and interactions
- Fluence and dose have increased $>10^4$ since mid-80’s
  - Near future expect unprecedented dose due to increased luminosity and energy
    - 100 Mrad absorbed energy (units)
    - 10^{15}-10^{16} particles/cm^2
    - Compare to: space (~1 MRad), nuclear weapons (~10^{13})

Radiation Effects: Ionizing

- Incident particle interacts with atomic electrons
- Measure in energy absorbed (rads (Si))
- e/h pairs created, recombine or trap
- Transient effect
  - Actual signal formation
  - Single event upset condition in circuits
- Electronics: charge trapping at Si/SiO2 interface (largely controlled by rad-hard circuit designs or thinner oxides)
- Detectors: surface effects, oxides

Electronics

- For presently operating systems commercial rad-hard CMOS has provided sufficient resistance.
- New chips use commercial deep submicron CMOS
  - Thin oxides provide automatic hardness, verified in test
  - Augment design rules with enclosed gate geometries to block radiation induced leakage paths
- Certain bipolar technologies are also rad-hard (analog)

Radiation Effects: Non-ionizing

- Incident particle interacts with nucleus
  - Displacement damage – permanent or slow to reverse
  - 2nd order effects as defects interact over time
- Depends upon particle type and energy
- Measure in particles/cm^2

Radiation Effects: Detectors

- Damage to the periodic lattice creates mid-gap states
- Increased leakage
  - Shot noise
  - Power
  - Heat

$$I_L = \frac{en_i(\sigma v_{thermal} N_T)WA}{2}$$

n_i = intrinsic carrier concentration

σ = recombination cross section

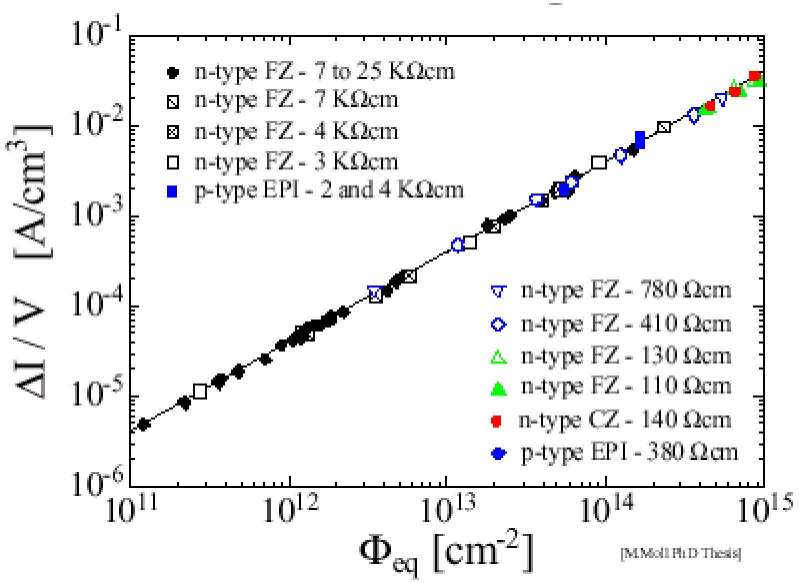
$v_{thermal}$ = carrier thermal velocity

N_T = trap density

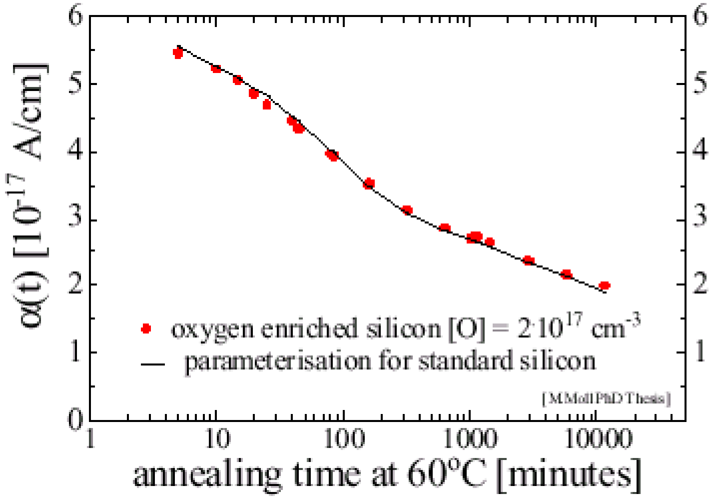
A = junction area

$$I_L(T) \propto T^2 e^{-E_a/2kT}$$

Reverse current with fluence and time



[M.Moll PhD Thesis]



[M.Moll PhD Thesis]

$$\Delta I = \alpha V \Phi$$

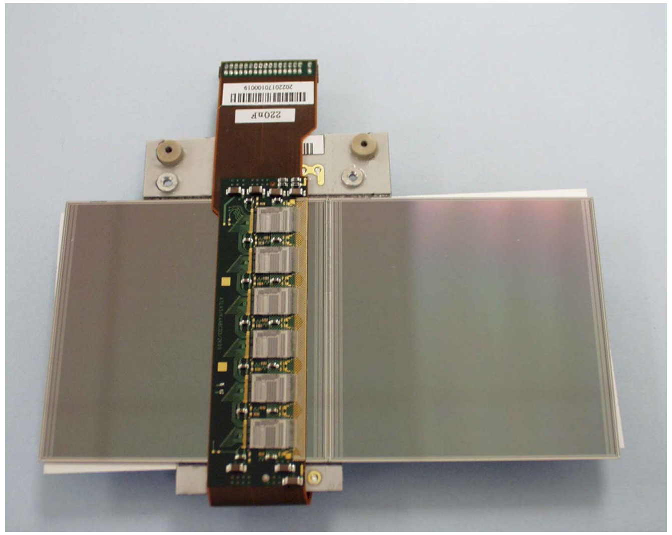
Damage constant $\alpha \approx 2-3\times10^{-17}\,\dfrac{Amp}{cm}$

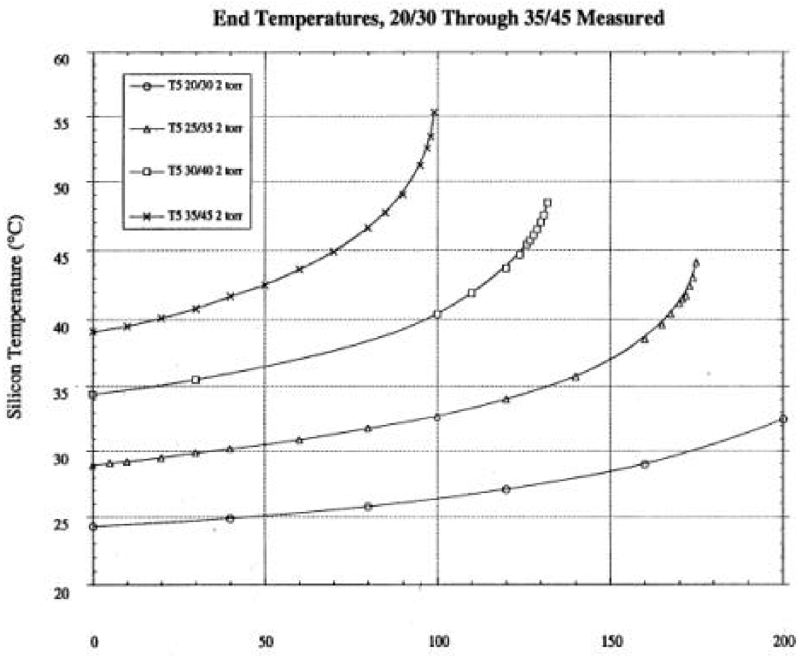
Volume $V \approx 2\times10^{-3}\,cm^3$

Incident Flux $\Phi \approx 10^{14} - 10^{15}\,particles/cm^2$ @ LHC

$\Rightarrow \Delta I \approx 2\mu A @ 0^o C$ (current doubles every 7 degrees)

Thermal Run-away



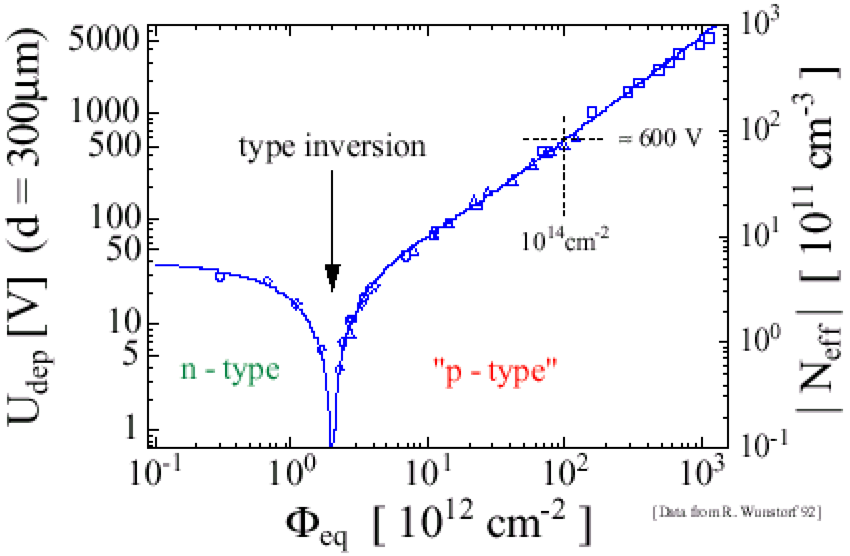


Power density μw/mm^2

Increased current → Power dissapation →Increased temperature →Increased current

Change in effective acceptor concentration

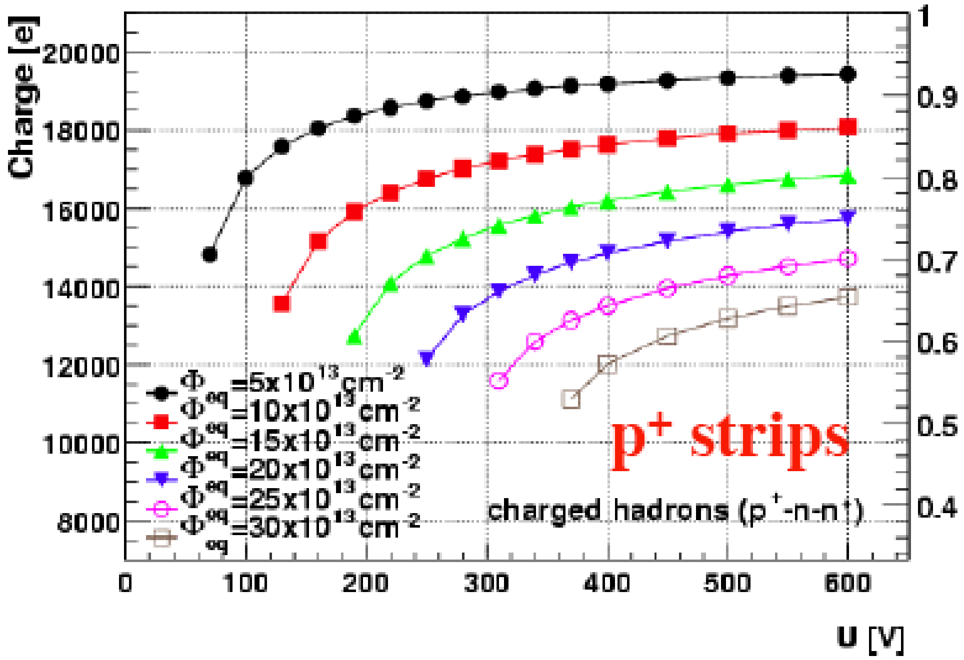
Effective space charge ($N_{eff} \Rightarrow V_{fd}$) with fluence and time



- Creation of acceptor states or removal of donor states
  - Effective change of resistivity
  - Type inversion: *n* → *p*
  - Depletion voltage changes in proportion to $|N_{eff}|$ ’higher voltage operation required
  - Dramatic time and temperature dependence

Charge Collection

- Reduction in charge collection efficiency (CCE)
  - $N_{e,h}(t) = N_0\, exp\,(-t/\tau_{trap})$
  - Ratio of collection and charge trapping time constants evolves with fluence



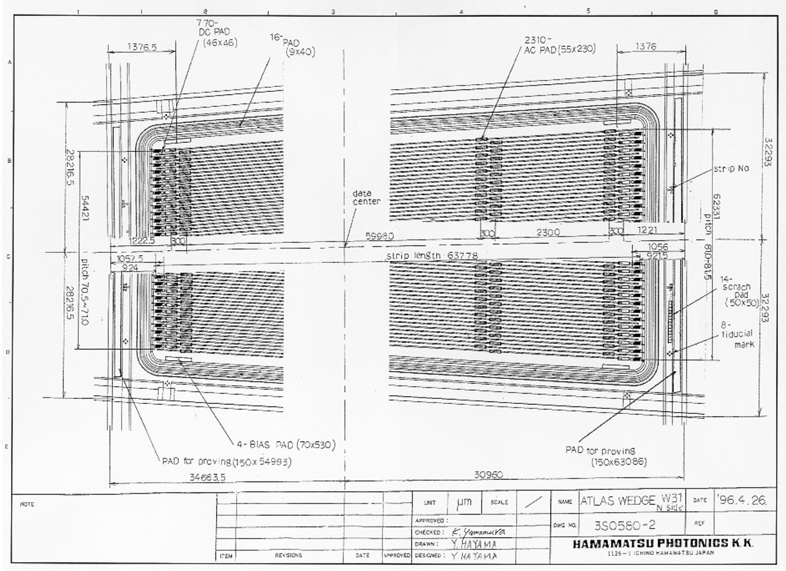
Gregor
Kramberger,
Ljubljana

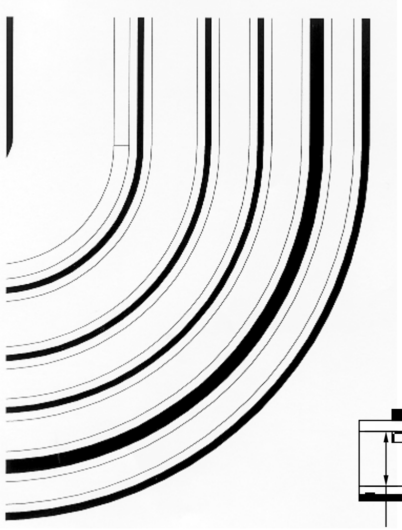
Methods to Control Radiation Effects

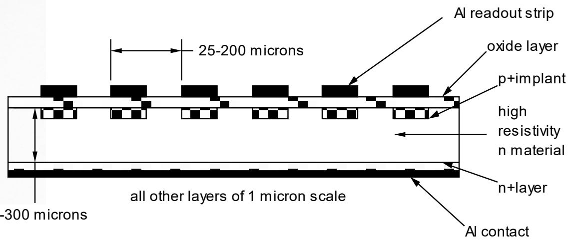
- Most represent some tradeoff
- Size matters
  - Smaller volumes generate less leakage current (but require more channels, power, heat…)
  - Thinner detectors deplete at lower voltage (usually means less signal)
- Temperature
  - Low temperature (-10 C) operation can “stabilize” reverse annealing for $< 10^{14}$
  - Reduce leakage current effects
- Integration time
  - Current noise is reduced for short shaping times at the expense of increased pre-amp noise, power.

- Biasing schemes
  - Reduce value of parallel biasing resistor to reduce voltage drop due to $I_{Leak}R_{bias}$ at the expense of increased thermal noise
- HV operation
  - Configure detectors to withstand higher voltage operation
  - Tolerate increased depletion voltage
  - Operate in partial depletion (collection issues)
- Low noise electronics
  - Tolerate reduced signal due to CCE and partial depletion
- Configuration
  - p in n substrate – simple, type inverts
  - n in n substrate – 2 sided process, can be operated in partial depletion after inversion
  - n in p – non-traditional process, does not invert

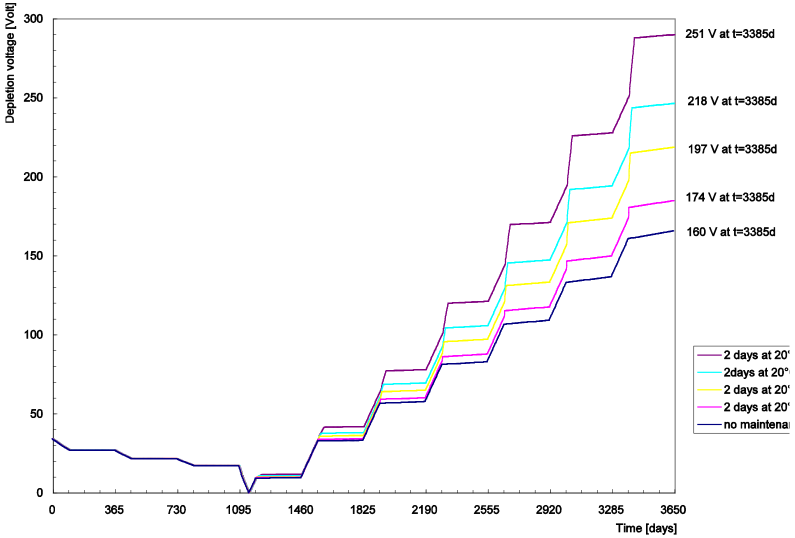
Strip detectors with multiple guard ringstructures to tolerate HV=500 V operation







Simulation of 10 year operating scenarios for silicon tracking at the LHC
L= 10^{33}-10^{34}

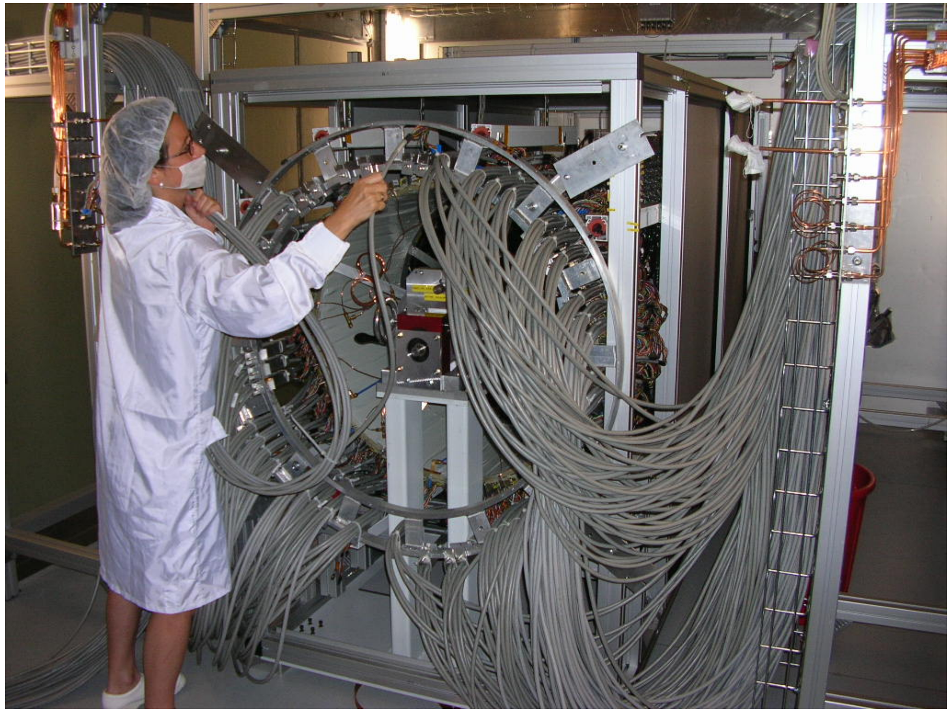


Issues for Large Systems

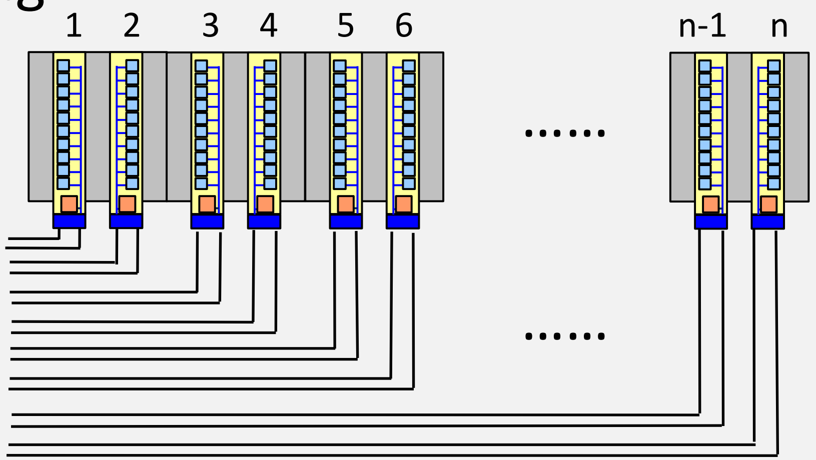
- Grounding and Shielding
- Powering
- Bias
- Control and Data Transmission
  - Cables
  - AC Coupling
- Monitoring and fast/slow control
  - Interlocks, safety

Power Distribution

- Conventional wisdom stated that each “module” of tracker should be serviced independently
  - isolate single point failures
  - Avoid electrical interference and ensure low noise
- For large trackers this has led to a cabling (mass and access) limitation
- Future trackers are larger by x5 or more
- An active R&D effort in alternative powering approaches resulted in a major revision of this orthodoxy
- Now alternative powering schemes are in wide use with significant material and cabling reductions as a result
- Also HV multiplexing with rad hard switches
- Sophisticated monitoring and control ASICs – ATLAS AMAC, PSPP



- Independent powering

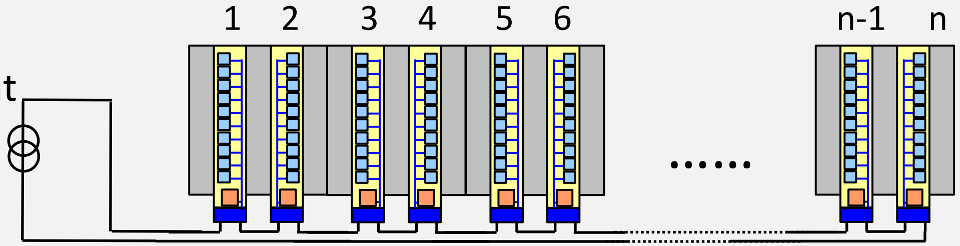


Hybrid current = I
Number of hybrids =n
Total current = nI
Power lines = n

- Serial powering

Hybrid current = I
Number of hybrids =n
Total current = I
Power lines = 1

Constant
current
source

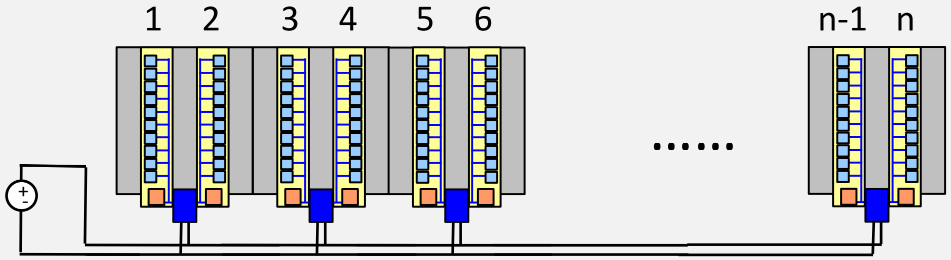


Requires AC coupling
Vtot = N*Vmod
Shunt regulation
Equal I per module

- DC-DC powering

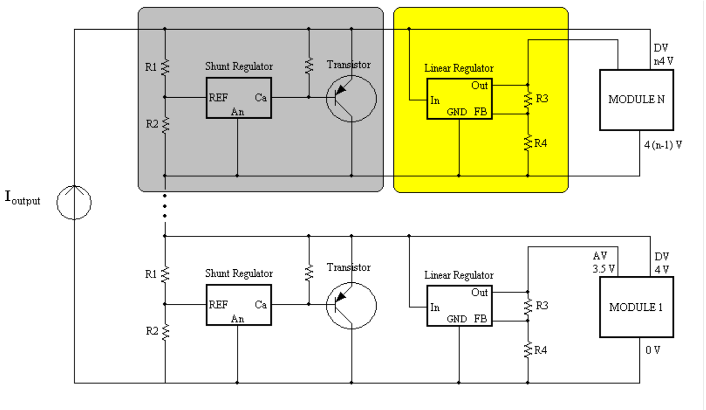
Hybrid current = I
Number of hybrids =n
Total current = n(I/R)
Power lines = 1

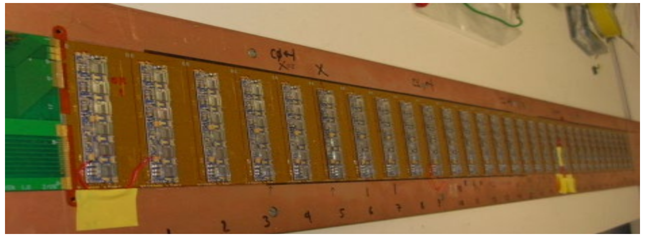
Constant
(high)
voltage
source

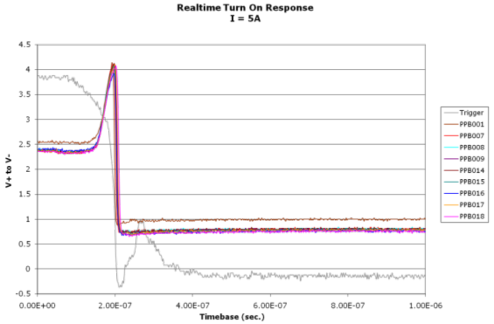


Requires clocked
stepdown converter
per module
Inductor
Vin=Vmod*R

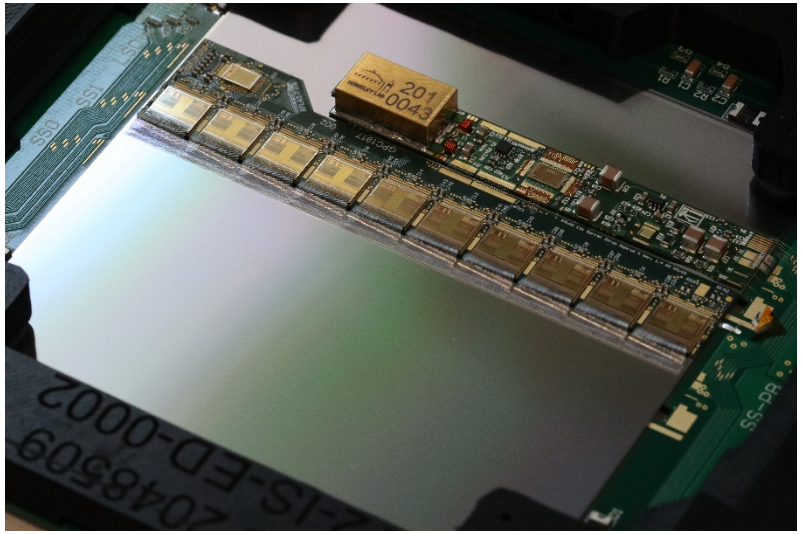
Implementations





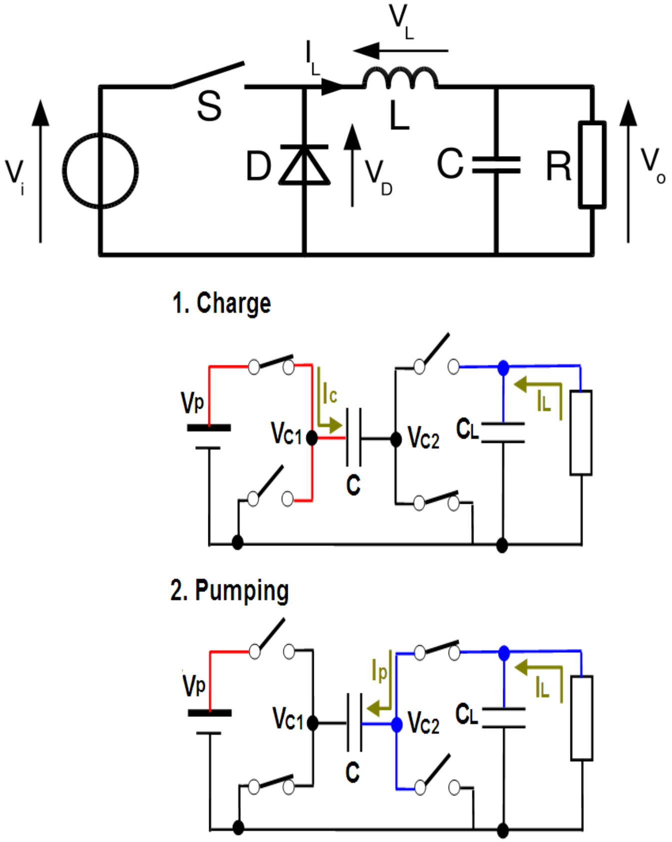


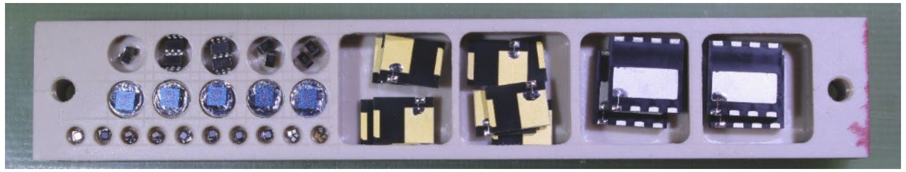
30 drop
Serial powered
Stave



ATLAS HL-LHC Module with DCDC,
HV-mux, monitoring and control ASIC

DCDC Converters





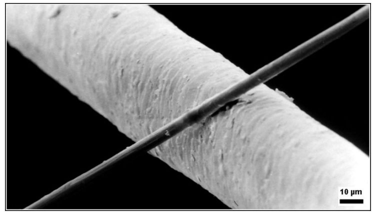
HV multiplexers

Mechanical and Thermal Aspects

- Precision tracker requires support structure which is stable, can be efficiently cooled, and is low in mass (Xo).
- There are two key materials/classes which come into consideration here
  - Beryllium: structural grade metal, low Z, metallic CTE, expensive, and hazardous to machine, probably impractical for very large structures
  - Carbon composites: tremendously flexible class of materials, reasonable Xo, good thermal properties, variable CTE
- Many advanced implementations now favor integrated carbon composite structures ie: staves, I-beams, tubes…
- Flow of liquid coolants – initially fluorocarbons, now CO2, air cooling for very low mass systems - MAPs

Mechanical Grade Materials

material	Density (gr/cc)	Xo (cm)	Young's Mod (GPa)	CTE (ppm/°K)	TC: W/m°K
Silicon	2.33	9.37	130-185	2.8-7.3	149
Beryllium	1.85	35.27	255	12.4	201
Aluminum	2.70	8.9	69	23.9	237
Stainless Steel	7.9	1.76	193	11.7	95
Titanium	4.54	3.56	116	8.5	
Carbon	2.21	19.32		0.6-4.3	
Carbon fiber frac 70-40%	~1.7-2	23-27	180-125 along fibre	Varies with layup	10's – several 100's
CF: K13D2U	2.2		135 Msi		800
POCO Graphite foam	0.5	~100	low	0.7	45/135 in/out
Boron Nitride	2.25	20.8		<1	250-300



Carbon Composites

- Carbon fiber “sheets” consist of filaments or woven layers impregnated with epoxy.
- By arranging layers in various “lay-ups” and configurations, a great variety of components can be created with enhanced mechanical and thermal properties.
- Importance of symmetry and stress balance
- Other advanced carbon based materials can be combined in structure as well
- Multiple shapes and materials can be simultaneously co-cured

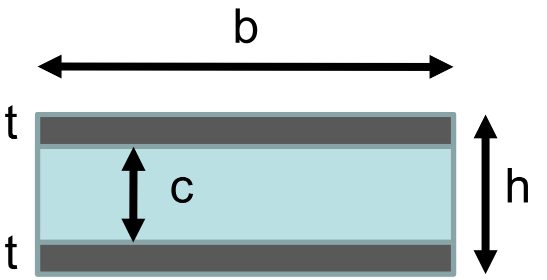
Basic Issues

- Sag in a uniform composite beam

$$\delta(bending) = \frac{wL^4}{384EI}$$

$$I = 2\frac{bt^3}{12} + 2bt\left(\frac{c+t}{2}\right)^2 = \frac{bt^3}{6} + \frac{btc^2 + 2bct^2 + bt^3}{2} \approx btc\left(\frac{c}{2} + t\right)$$

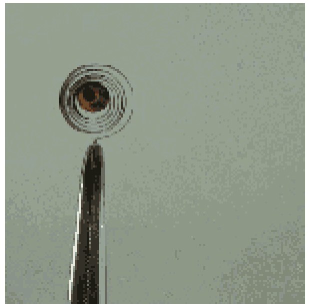
$$\delta = \frac{wL^4}{384Ebtc\left(\frac{c}{2} + t\right)}$$



- Stress in the “bi-material” strip

$$\kappa = \frac{6E_1E_2(h_1+h_2)h_1h_2\epsilon}{E_1^2h_1^4 + 4E_1E_2h_1^3h_2 + 6E_1E_2h_1^2h_2^2 + 4E_1E_2h_2^3h_1 + E_2^2h_2^4}$$

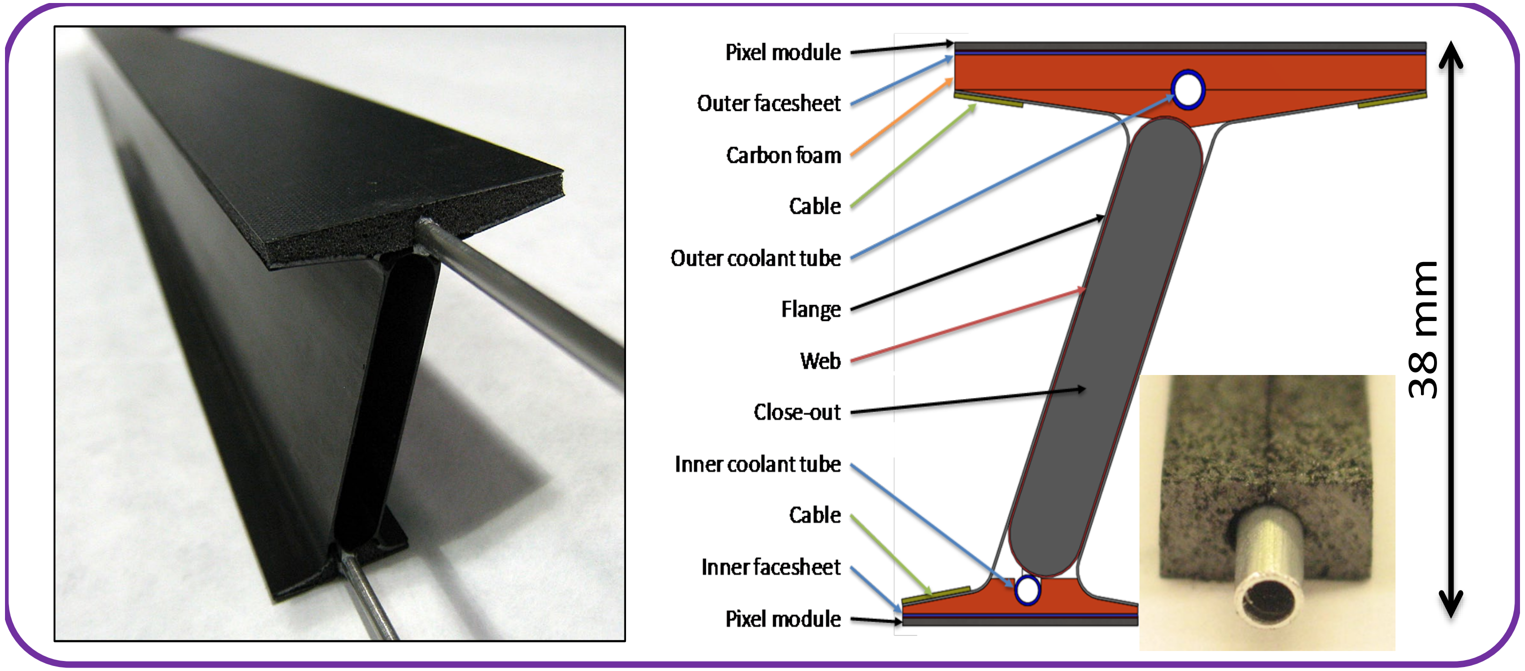
$$\epsilon = (\alpha_1 - \alpha_2)\Delta T$$



Example: Carbon Fiber Beam

- Structure consists of 2 CF facings laminated on either side of a “soft” core w. embedded metal cooling lines: sandwich beam
- Symmetry keeps the structure flat
- Facing contains multiple sheets in order to tune mechanical and/or thermal properties
- Core may have enhanced thermal properties to improve cooling efficiency
- Subsequent (or co-)lamination of electrical circuitry and sensors
- Issue of stress between carbon and other unlike materials as composite is cooled from lamination temperature to RT and to operating temperature

ATLAS I-beam Structures

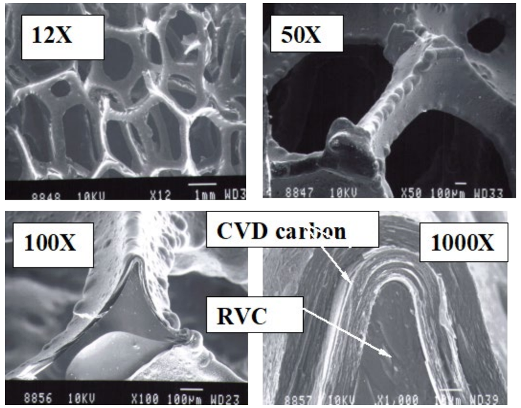


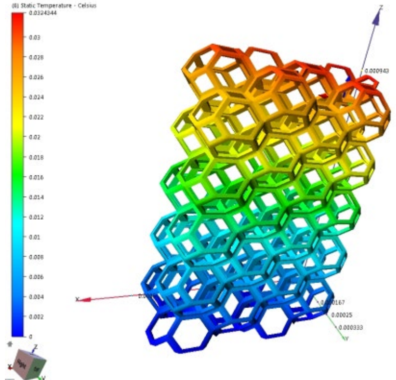
- Typically a cured (or co-cured) structure composed of fibers, a polymer matrix, additional elements such as foam, honeycomb, embedded cooling channels, electrical interconnects
- Low mass CF structure/specialized materials
- Embedded thermal aspect, thin walled pipes, engineered interfaces
- Embedded electrical functions

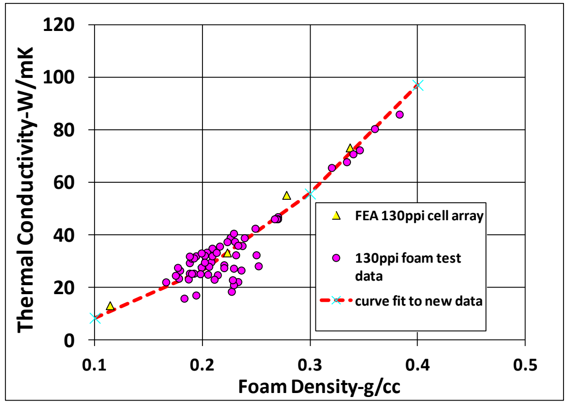
Materials: Carbon Foams: Low density, hi conductivity

- Developed in collaboration with industry through SBIR
- Qualified for radiation tolerance and thermal/mechanical performance, in use.
- FEA modeling of thermal and mechanical properties.

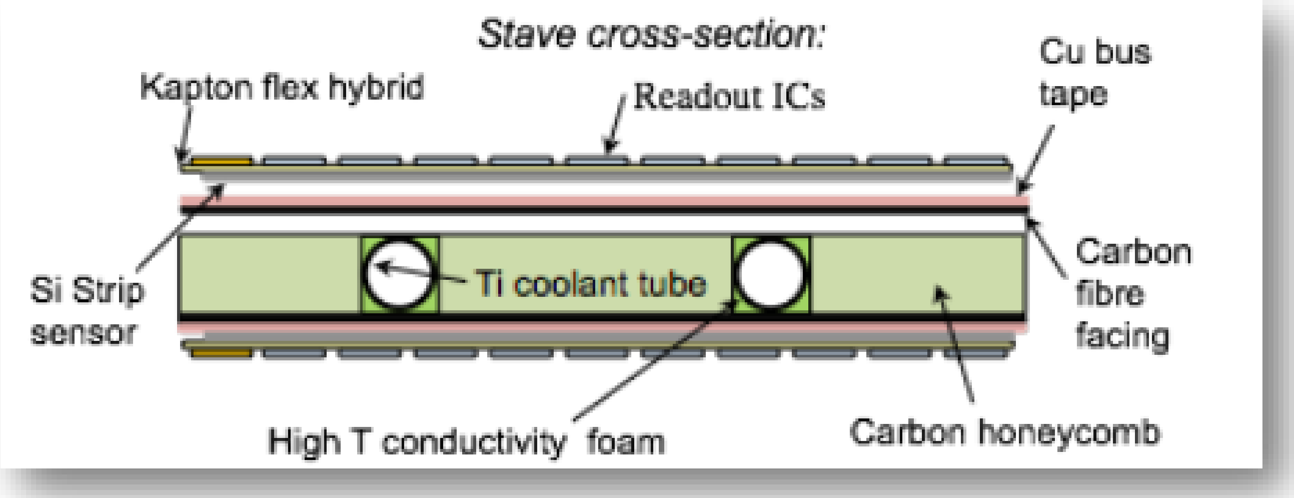
Property	Value(Unit)
Density	~ 0.23 g/cc
Initial porosity	130 pores/inch
Thermal conductivity	30-40 W/m-K
CTE	<2 ppm/°C
Tensile modulus	35ksi
Tensile strength	515psi
Compressive modulus	50ksi
Compressive strength	280psi

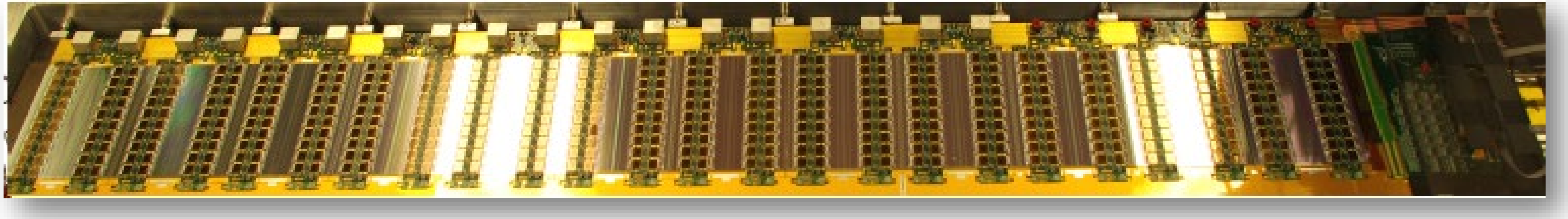






ATLAS ITk Strip Tracker Stave Structure





400 staves, 1.4 meter, 28 10x10cm silicon modules, DCDC power

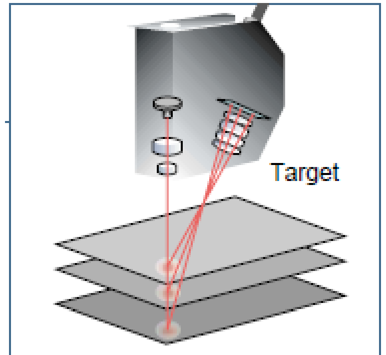
Metrology Tools for Survey

Technology	Application	Resolution	Interface	Ease/Speed
CMM-touch	Large objects	x/y/z ~ µm's	commercial	Teach mode
CMM-optical	In plane location Small heights	x/y/z ~ µm's	commercial	same
ESPI	Dynamics	x/y/z ~ µm's	commercial	R&D tool
FSI	In-situ alignment Stability	One axis	custom	System design
Laser Displacement	Flexible heights R&D tests	z ~ µm's	User defined	User defined, 1 KHz
Structured Illumination	Fast large area 3D	x/y ~ mm z ~ 0.2 mm	Video or still camera	Typical frame rates
Confocal	Precision heights Small area	10-100 nm	User or commercial	User defined, 100 Hz–2 KHz

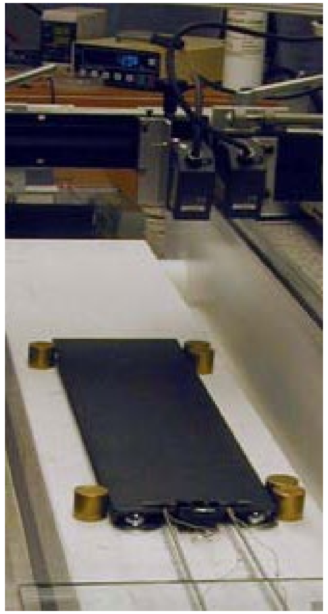
Examples

Touch/Optical Coordinate Measuring Machines Image analysis

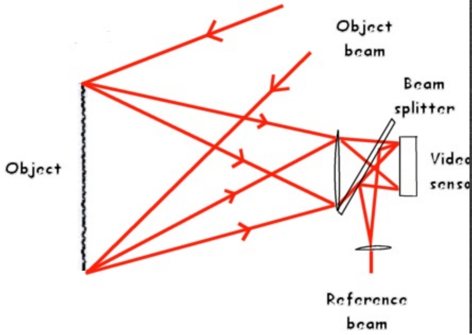
Scanning Laser Rangefinding Triangulation

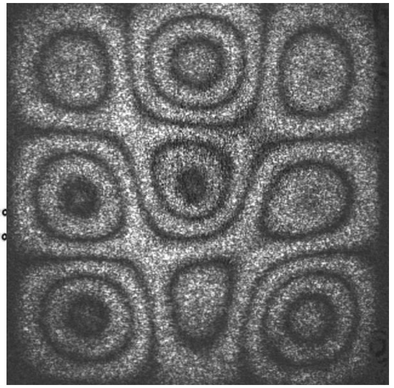


The measurement principle uses triangulation. The position of the reflected light on the Li-CCD moves as the position of the target changes. The displacement amount of the target is measured by detecting this change.

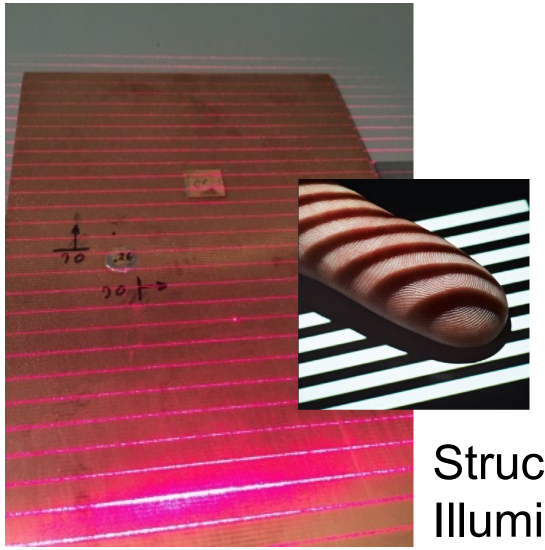


Electronic Speckle Pattern Interferometry

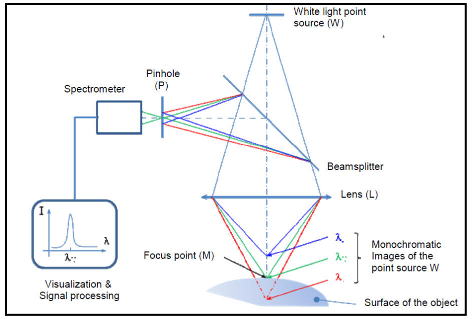


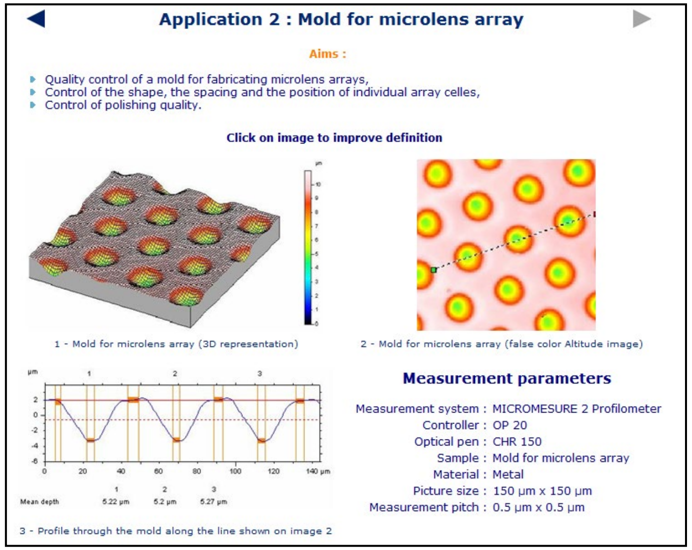


Structured Illumination



Color Coded or Laser Confocal Microscopy





Application 2 : Mold for microlens array

Aims :

- Quality control of a mold for fabricating microlens arrays,
- Control of the shape, the spacing and the position of individual array celles,
- Control of polishing quality.

Click on image to improve definition

1 - Mold for microlens array (3D representation)

2 - Mold for microlens array (false color Altitude image)

Mean depth	1	2	3
	5.22 µm	5.2 µm	5.27 µm

3 - Profile through the mold along the line shown on image 2

Measurement parameters

Measurement system : MICROMESURE 2 Profilometer
Controller : OP 20
Optical pen : CHR 150
Sample : Mold for microlens array
Material : Metal
Picture size : 150 µm x 150 µm
Measurement pitch : 0.5 µm x 0.5 µm

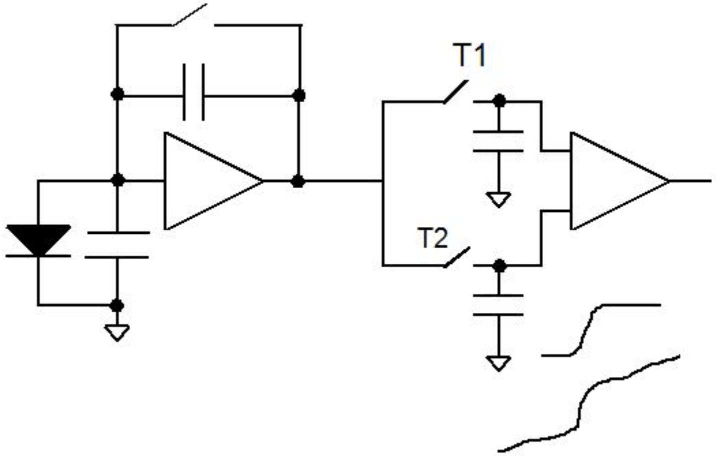
Conclusions

- Huge progress ~30 years to build silicon trackers using a broad suite of advanced technologies
- Much significant science done, and to be done, with these devices
- R&D underway for the next generation

Back Up Slides

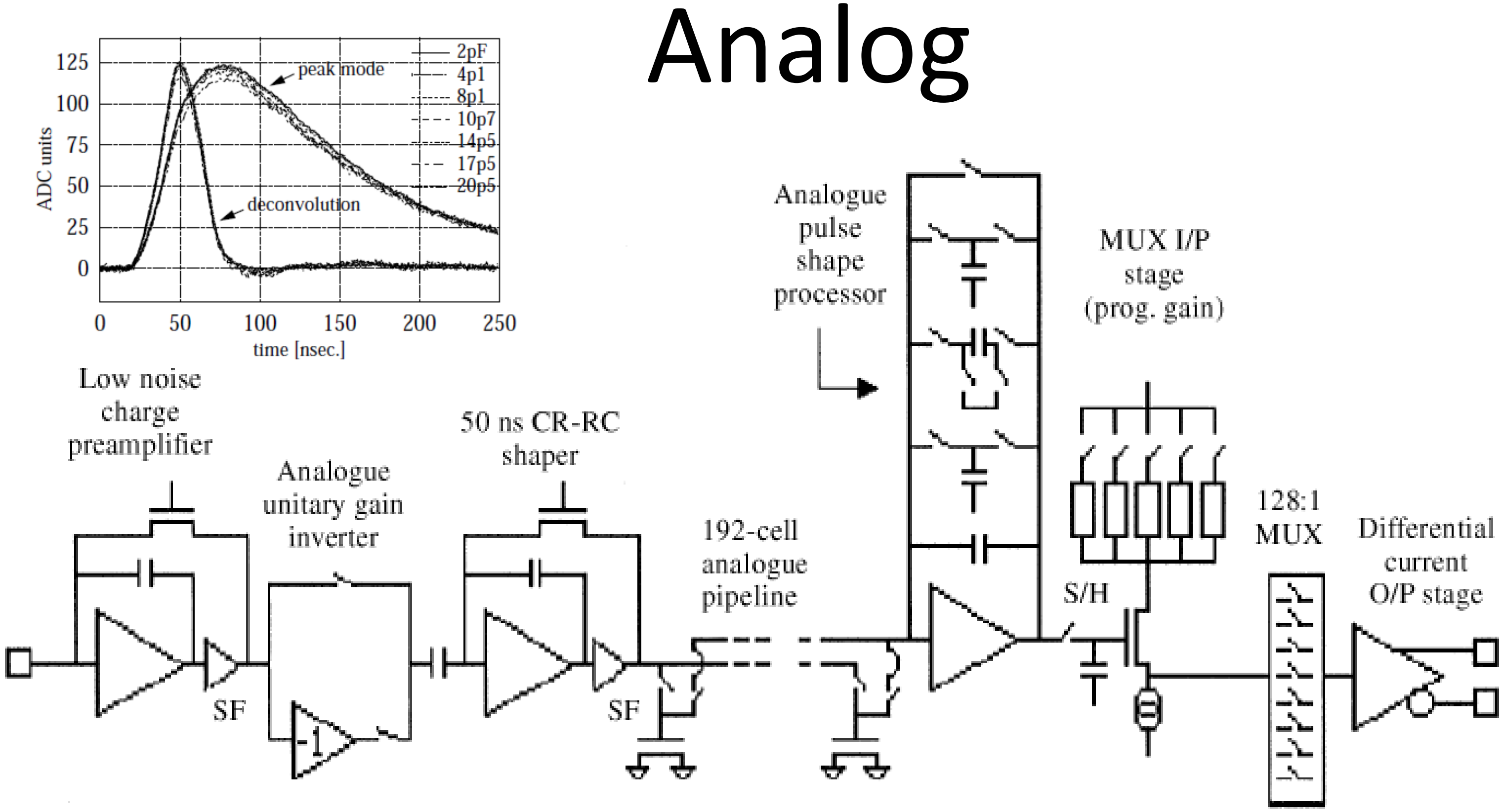
- Front End Architectures
- Fast Cluster Finding Architecture
- Thermally enhanced materials
- Newer processes
- Electronic Packaging
- Production Lines

Double Correlated Sample and Hold



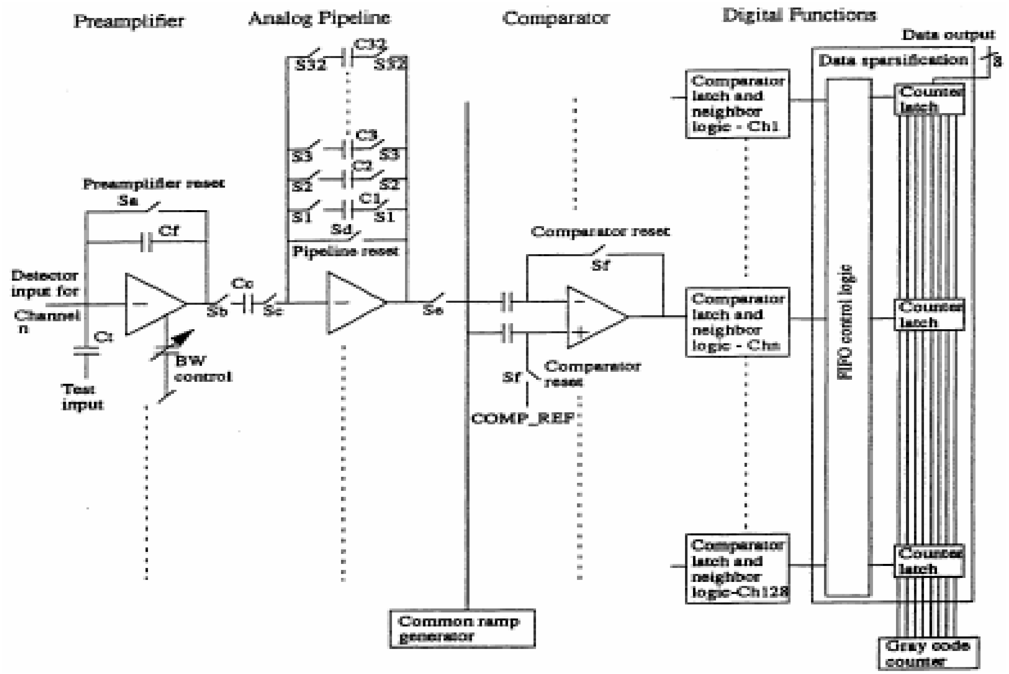
- Original MOS monolithic architecture, no resistors
- High frequency bandwidth limited by pre-amp
- Low frequency limited by ∆T=T2-T1
- Can be generalized to N samples but incurs a noise penalty factor of √2 for each pair

Analog



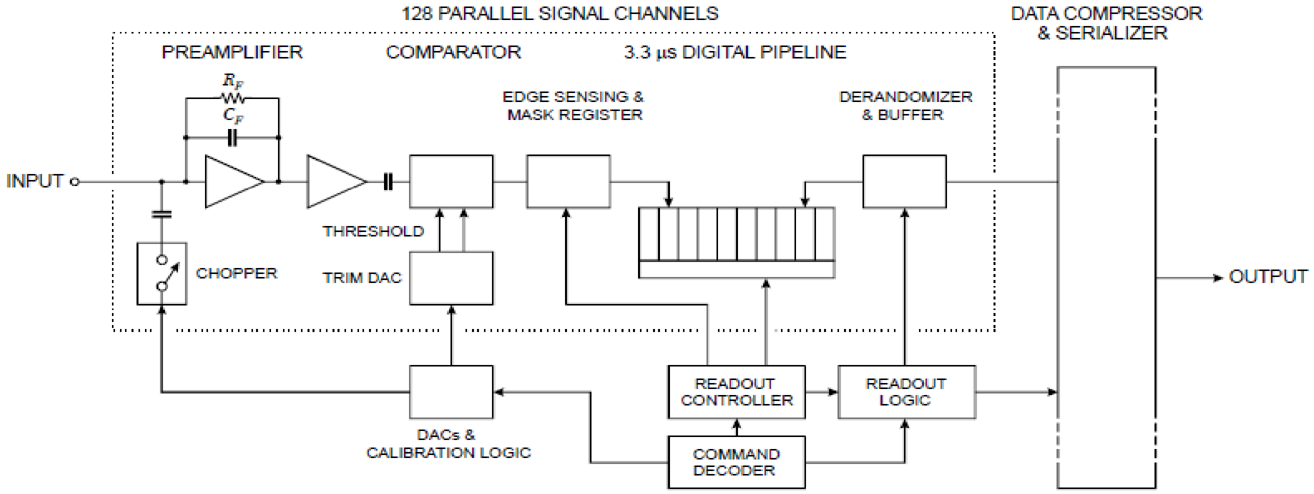
- Example is the APV25 chip developed for CMS
- Readout all analog pulse heights, no sparsification
- Dual function: fast time mode, slow low noise mode
- Utilize analog signal processing on-chip to measure pulse time

Digital



- Example is the SVX4 chip developed for CDF
- Switched capacitor analog pipeline
- Combined analog threshold + 8 bit digitization
- Sparse readout

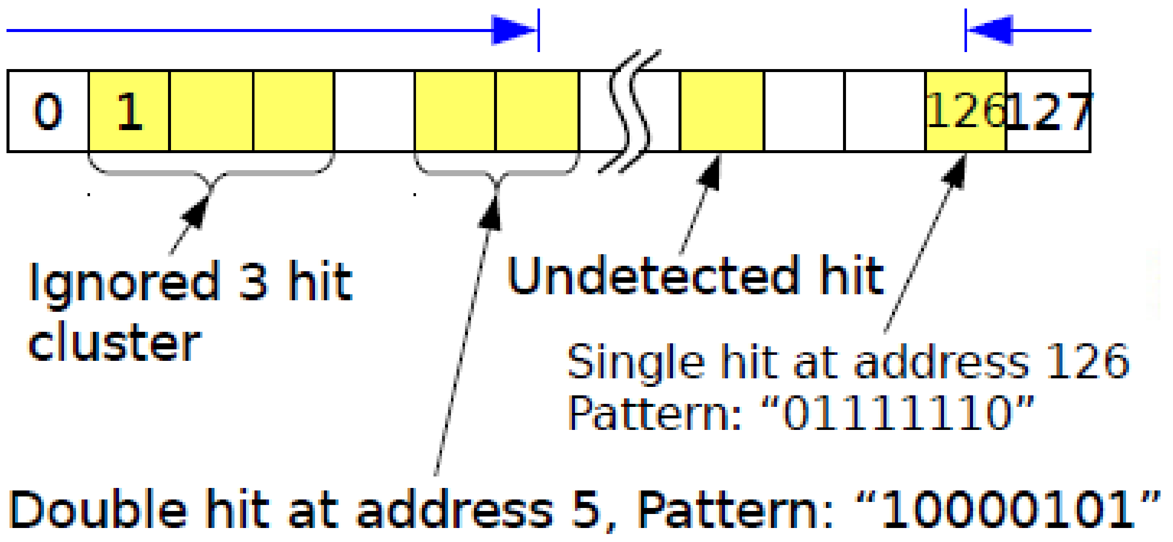
Binary



- Example is the ABC chip developed for ATLAS, BiCMOS
- AC coupled pre-amplifier shaper for 25 ns collisions
- Comparator + trim DAC per channel
- 1 bit pipeline clocked at 40 MHz, L1 buffer
- Data compression
- Control and configuration protocol
- DSM CMOS version exists as well, 130 nm underway

Fast Cluster Finder

- Normal operation
  - Beam clock advances FE pipeline
  - Readout clock at beam clock rate or more pushes data out for full readout
- Possible to do a fast internal search for a limited number of clusters (hits)
- Read these out on dedicated lines at hundreds of MHz
- Sufficient to supply 2x16 bit addresses per BC which is OK for <1% occupancy, more for

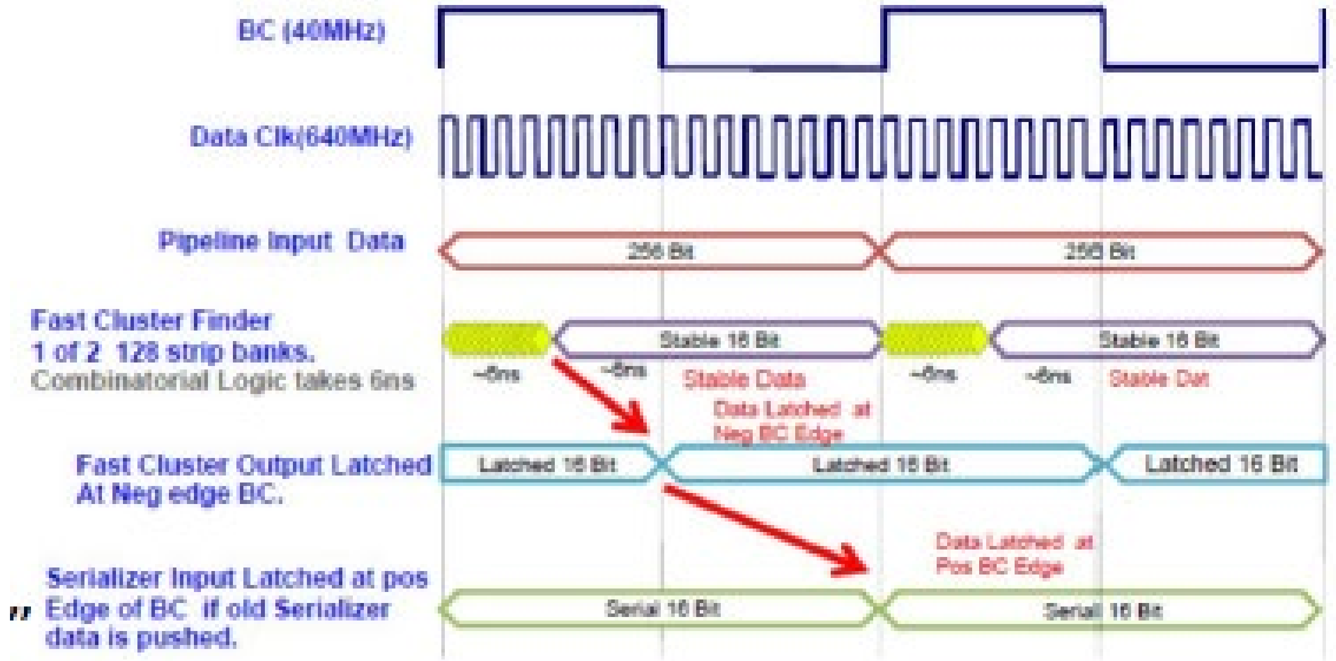


Ignored 3 hit cluster

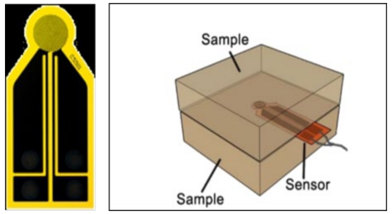
Undetected hit

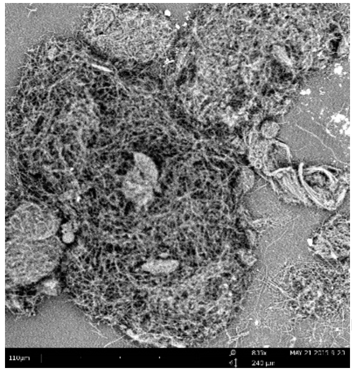
Single hit at address 126
Pattern: “01111110”

Double hit at address 5, Pattern: “10000101”

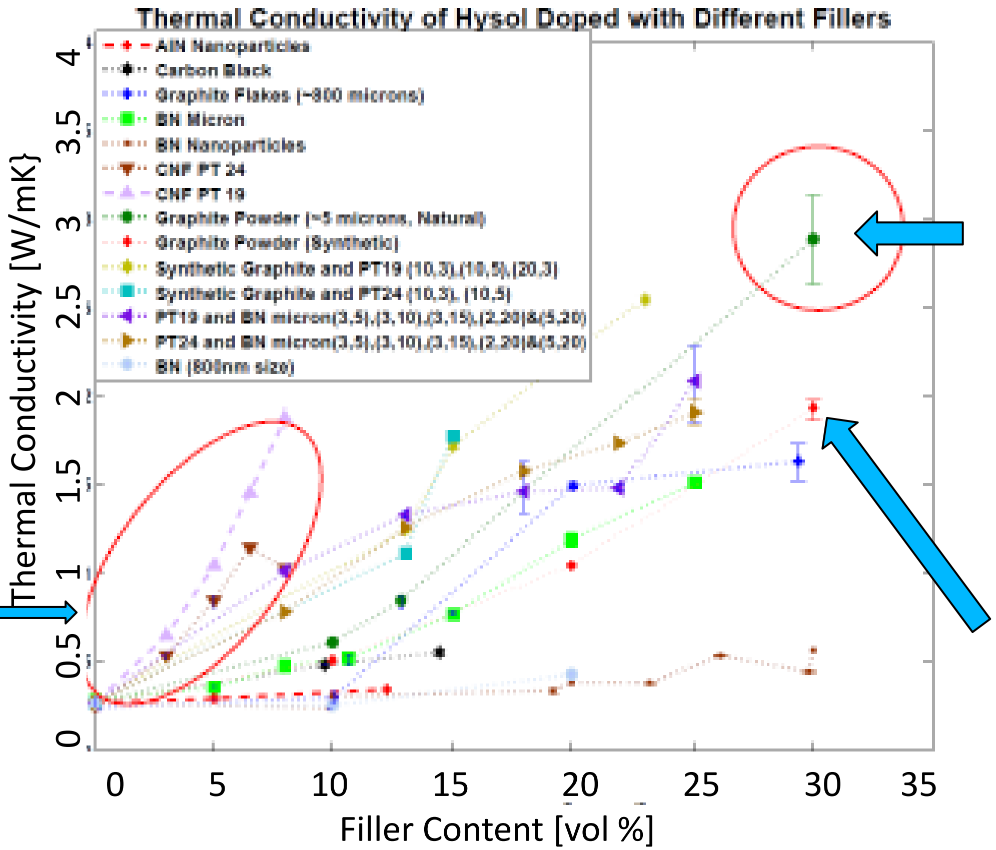


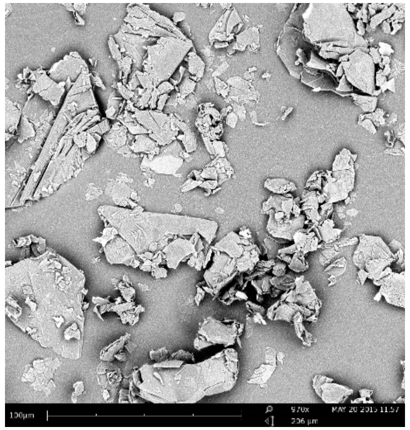
Example: Thermally Enhanced Materials Survey



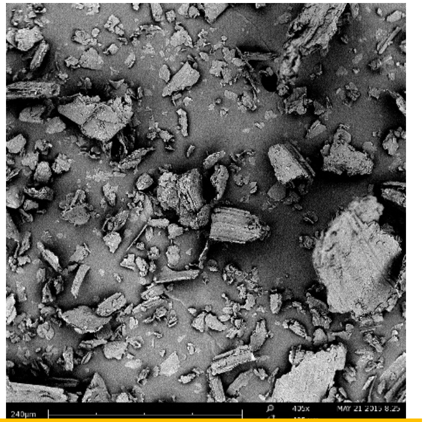


Carbon NanoFiber





Natural graphite



Synthetic graphite

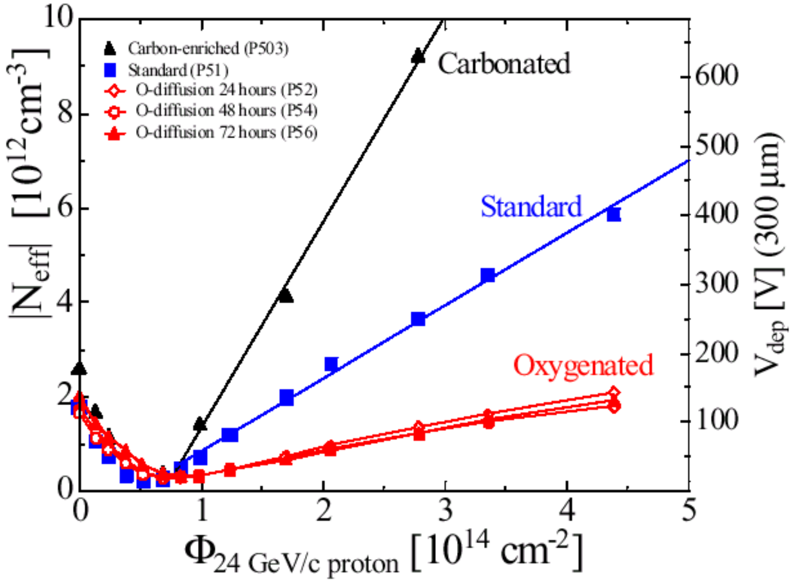
Loading of epoxy or other adhesives
Typical materials in present use for HEP: 1-1.25 W/mK
Can improve by x >2…

New developments

- Engineered materials
- New configurations, 3D electrodes, interleaved strips
- Cryogenics
- Alternate materials: Diamond, SiC,…
- RD efforts organized at CERN
  - RD42: development of diamond as detector
  - RD48: radiation damage to silicon
  - RD50: development of radiation resistant detectors
  - RD39: cryogenic detectors and systems
  - http://rdXY.web.cern.ch/rdXY

Engineered Silicon

- Microscopic understanding of damage mechanisms, defects, and kinetics
  - Modeling
  - Measurements
  - Time and temperature dependence
- Engineer the silicon for greater radiation resistance



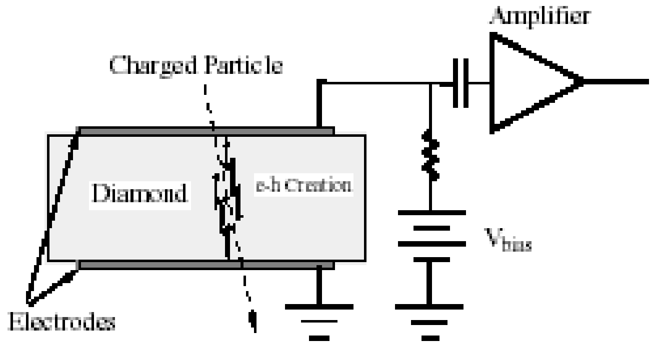
[RD48-NIMA 465(2001) 60]

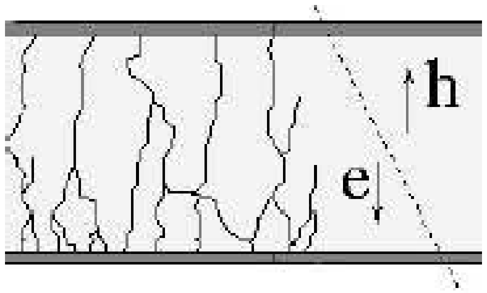
Harris Kagan

http://rd42.web.cern.ch/RD42/

Characterization of Diamond:

Signal formation

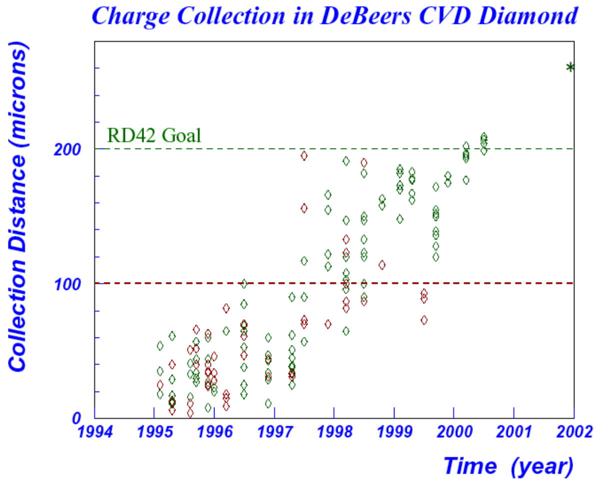




- $Q = \frac{d}{t} Q_0$ where d = collection distance = distance e-h pair move apart
- $d = (\mu_e \tau_e + \mu_h \tau_h) E$
- $d = \mu E \tau$

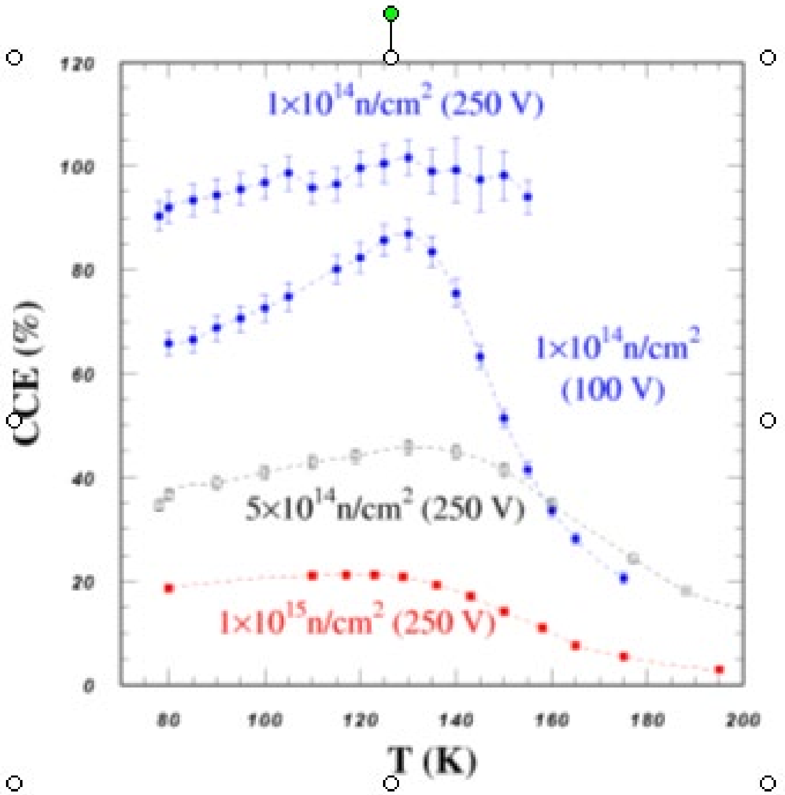
  with $\mu = \mu_e + \mu_h$

  and $\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$



Cryogenic operation

- Palmieri et al (1998) recovery of lost CCE at cryogenic temperatures
- “Lazarus Effect” due to freeze-out of traps
- R&D activity centered at CERN (RD39
- Practical difficulty for “low mass” tracker if substantial cryogenic engineering and infrastructure is required.



High Density Packaging

- Electronic packaging is often the only “reducible” part of the detector mass
- Advances in packaging have allowed us to integrate increasing complexity into denser footprints
- Maintain necessary thermal performance with minimized mass and high reliability
- Key technologies are based upon commercial processes
- Avoid the homemade syndrome

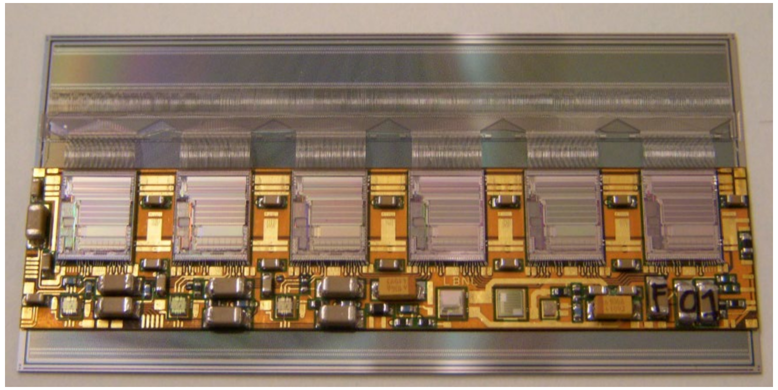
Key Technologies

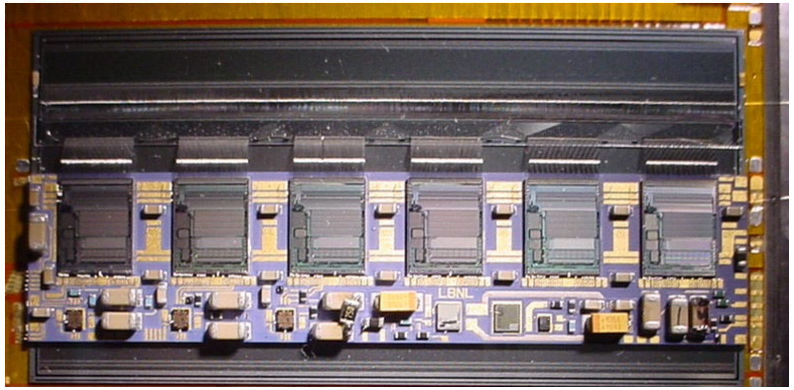
- Surface mount technology (SMT), pick & place
- Flexible circuits
- High density multilayer PCB and flex
  - Trace widths/space approaching 25 μm
- Large area flexible circuits > 1 meter length
- Chip on Board (COB) and Chip on Flex
- Thin film on ceramic, glass, and polyimide
- Thick film on ceramic, BeO and AlN substrates
- Lamination onto high-TC carbon substrates

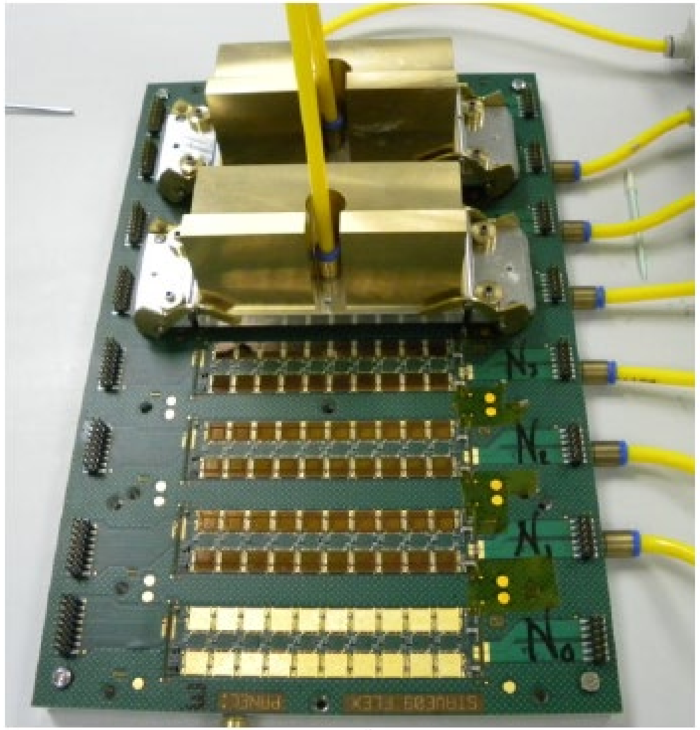
Electrical Materials

material	Resistivity ($\mu\Omega$cm)	dielectric constant	Xo(cm)	Thermal C. (W/m°K)	CTE (ppm)
Silicon		11.9	9.37	149	2.6
Aluminum	2.65		8.9	237	23.9
Copper	1.67		1.43	398	16.6
Gold	2.44		0.335	297	14.2
Carbon	1375		19.32	varies	
Kapton		3.4	28.4	0.2	~20
SiO_2		3.9	10	1.1	
BeO	10^{21}	6.6	14.4	230	8.3
AlN	$>10^{20}$	9	8.4	170	4.3
Al_2O_3	$>10^{20}$	9.0	7.55	24	7.2
G-10		4.7	19.4	0.2	

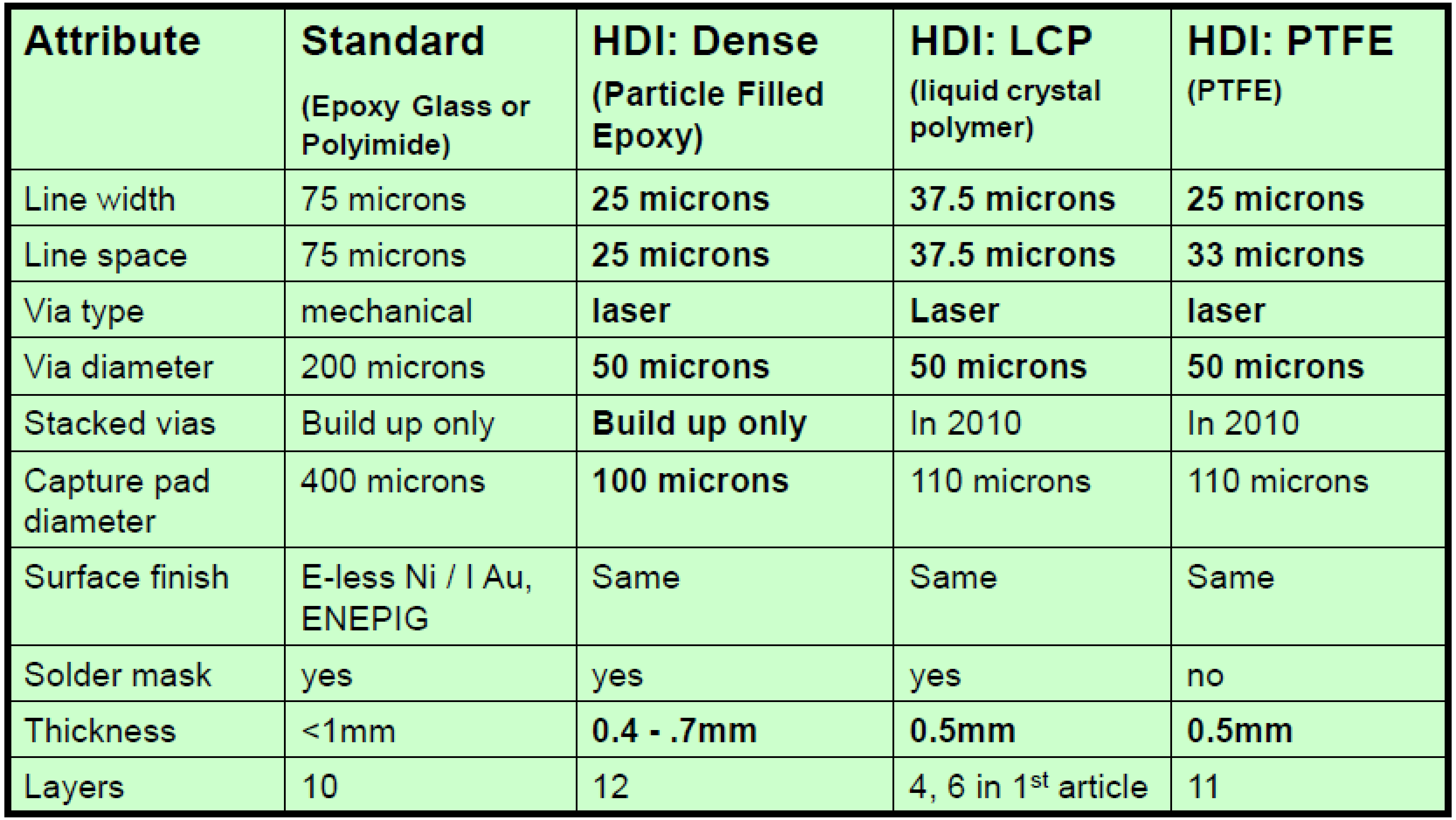
Technology examples





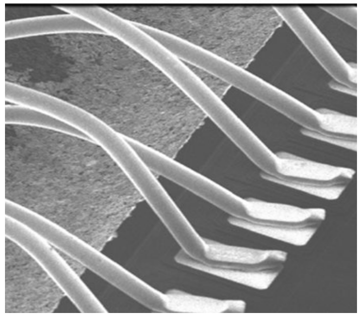


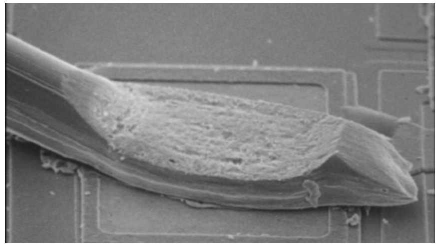
Emerging Interconnects

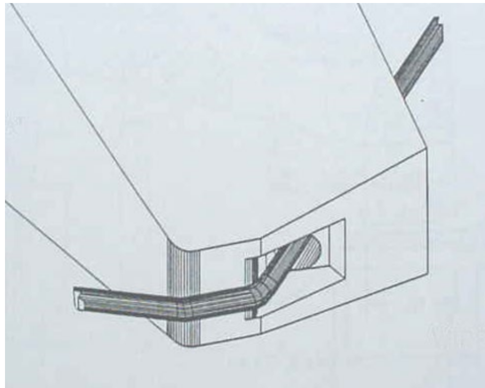


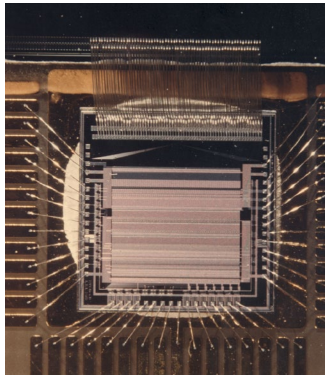
Attribute	**Standard** **(Epoxy Glass or Polyimide)**	**HDI: Dense** **(Particle Filled Epoxy)**	**HDI: LCP** **(liquid crystal polymer)**	**HDI: PTFE** **(PTFE)**
Line width	75 microns	**25 microns**	**37.5 microns**	**25 microns**
Line space	75 microns	**25 microns**	**37.5 microns**	**33 microns**
Via type	mechanical	**laser**	**Laser**	**laser**
Via diameter	200 microns	**50 microns**	**50 microns**	**50 microns**
Stacked vias	Build up only	**Build up only**	In 2010	In 2010
Capture pad diameter	400 microns	**100 microns**	110 microns	110 microns
Surface finish	E-less Ni / I Au, ENEPIG	Same	Same	Same
Solder mask	yes	yes	yes	no
Thickness	<1mm	**0.4 - .7mm**	**0.5mm**	**0.5mm**
Layers	10	12	4, 6 in 1st article	11

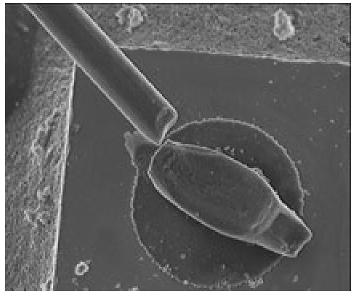
Wirebonding

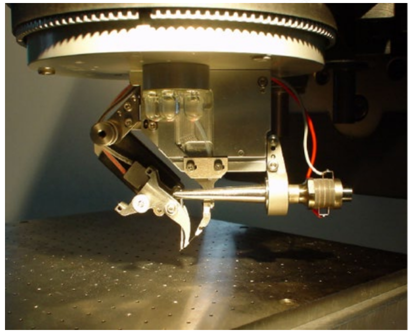






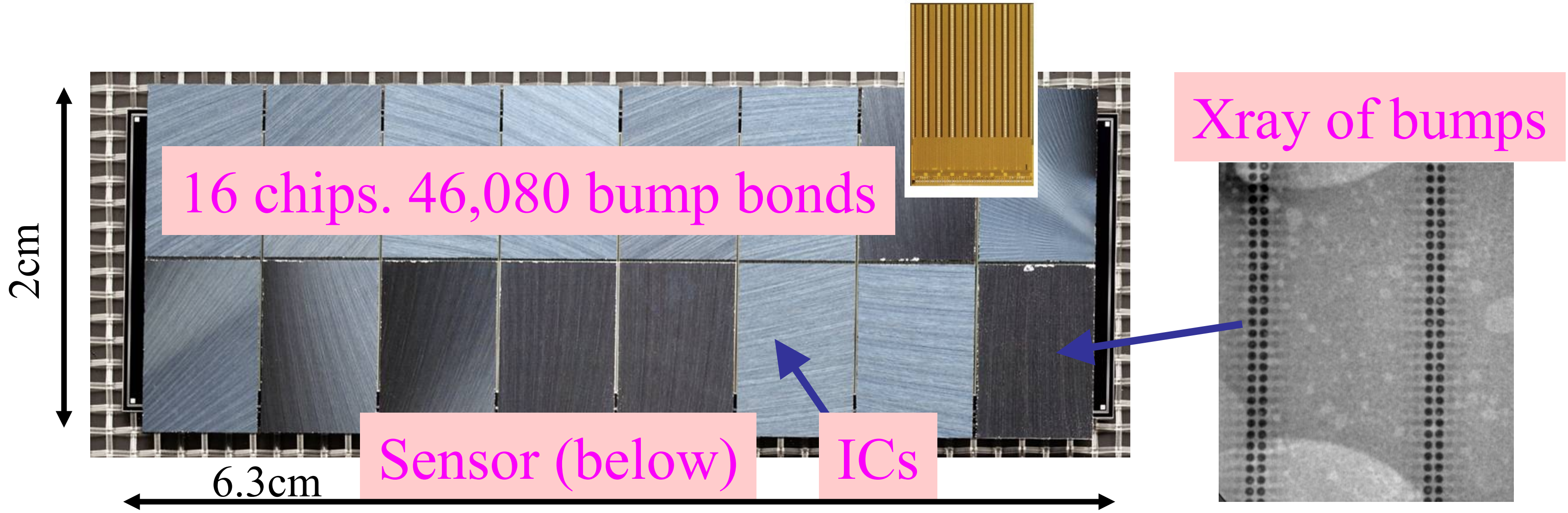






- Mainstay of microelectronic interconnection
- Typically uses 25 μm Al or Au wire, ultrasonic welding process
- Requires particular control of materials, cleanliness, and process
- Automated (5 bonds/sec) machines are commercially available and in widespread use in the HEP and related communities
- 75 μm pitch is achievable with good process control, a typical HEP “module” might contain ~5000 bonds

Bump or Flip Chip Bonding

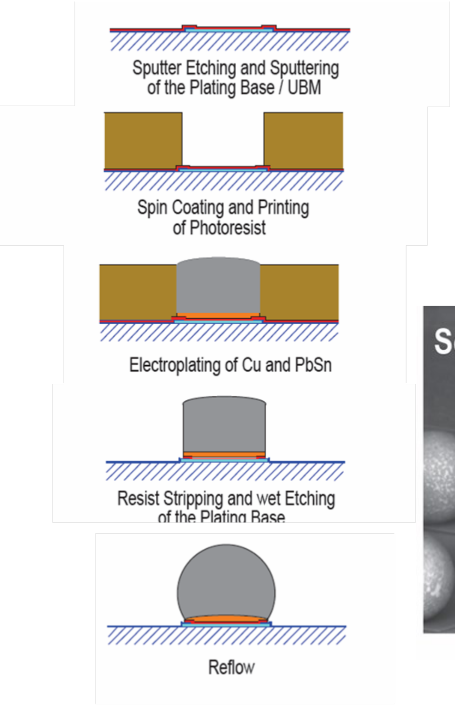


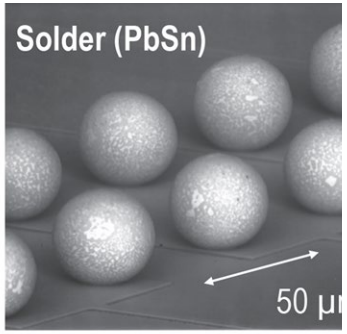
- Wirebonding is impractical for large 2D arrays
- ATLAS pixel cell is 50 x 250 μm
- At this density FE interconnect is made with a conductive “bump”
- This is an industrial process and requires expensive technology, therefore has not become “in-house”

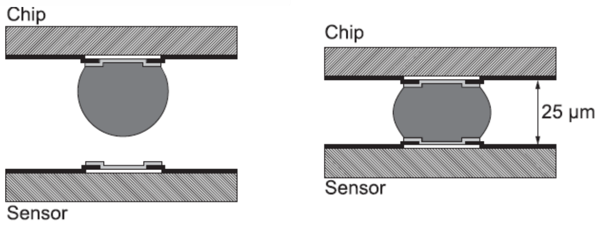
Bump Bonding Processes

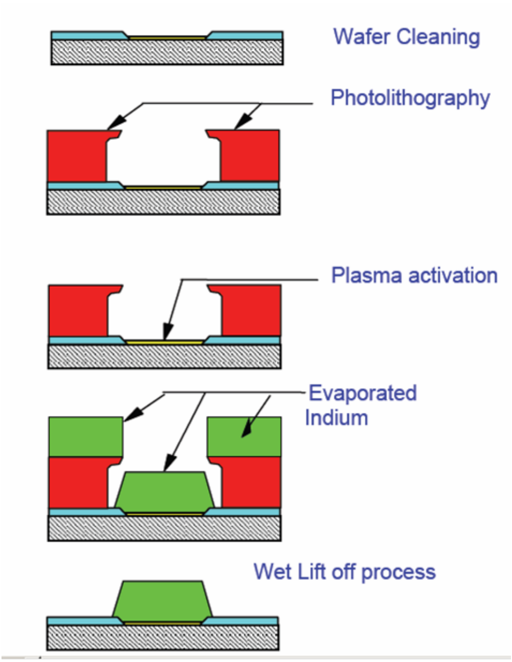
SOLDER BUMPING

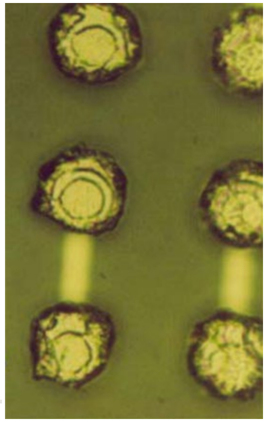
INDIUM BUMPING

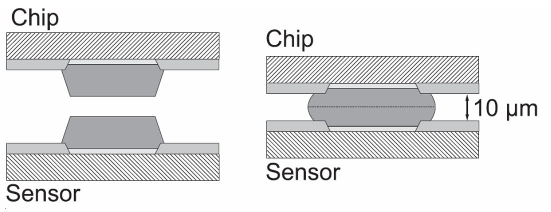


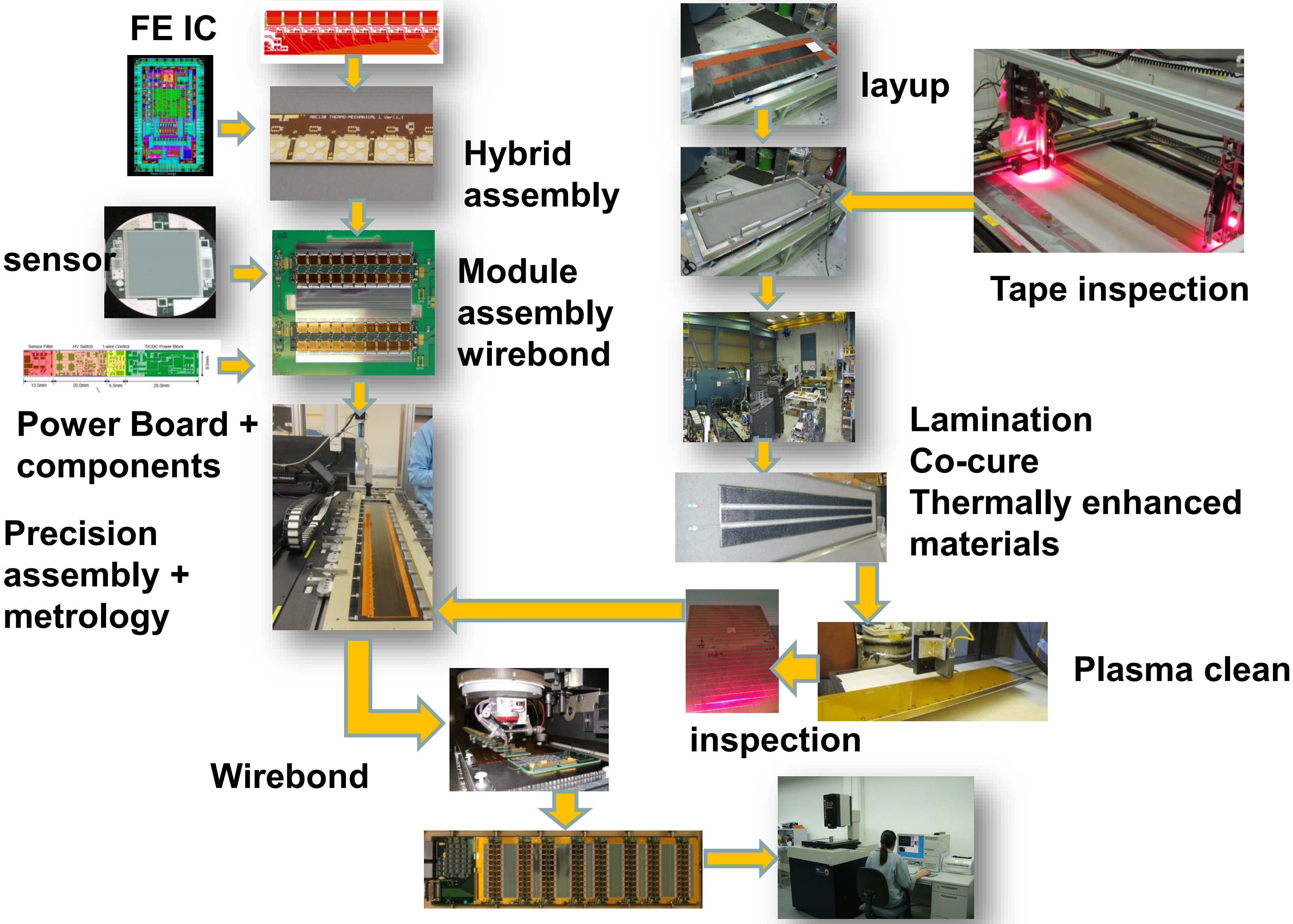












FE IC

Hybrid assembly

sensor

Module assembly wirebond

Power Board + components

Precision assembly + metrology

Wirebond

layup

Tape inspection

Lamination
Co-cure
Thermally enhanced materials

Plasma clean

inspection