Silicon Pixel Tracker (SPT)

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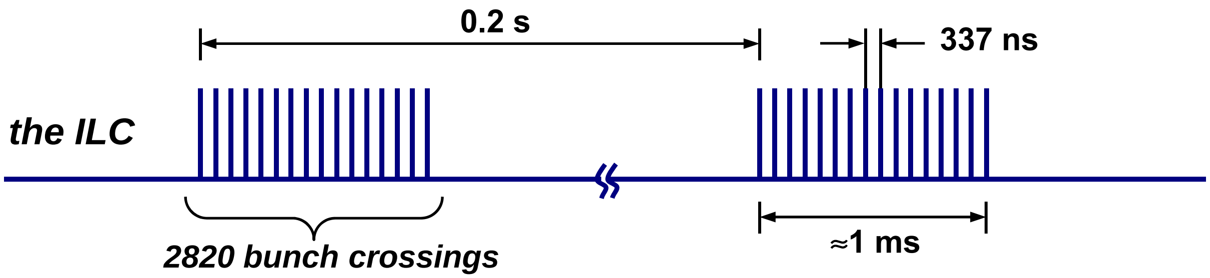
Update from Sendai talk by Konstantin Stefanov

Motivation – why a new tracker concept?

- Are 5 layers of single-sided strip detectors (rϕ only) sufficient for standalone track finding in dense jets?
- There are concerns over material budget, given unprecedented need for uniformly excellent PFA performance down to 7 degrees θ_P
- Declared goal of a tracking system with ~10% X_0 total thickness at all angles remains to be established
- Thin monolithic pixel or microstrip sensors are a 'solved problem', with 0.1-0.3% X_0 per layer
- But, what additional material will be needed to assemble these into mechanically ultra-stable metre-radius barrels and endcaps, supplying the necessary peak power and cooling?
- The ILC bunch structure and pulsed power permits gaseous cooling for appropriate choice of sensors, but does NOT reduce the cabling needed to deliver the peak power, and pulsed power may create other problems (mechanical impulses from the Lorentz forces on the structure)



Bunch structure at the ILC

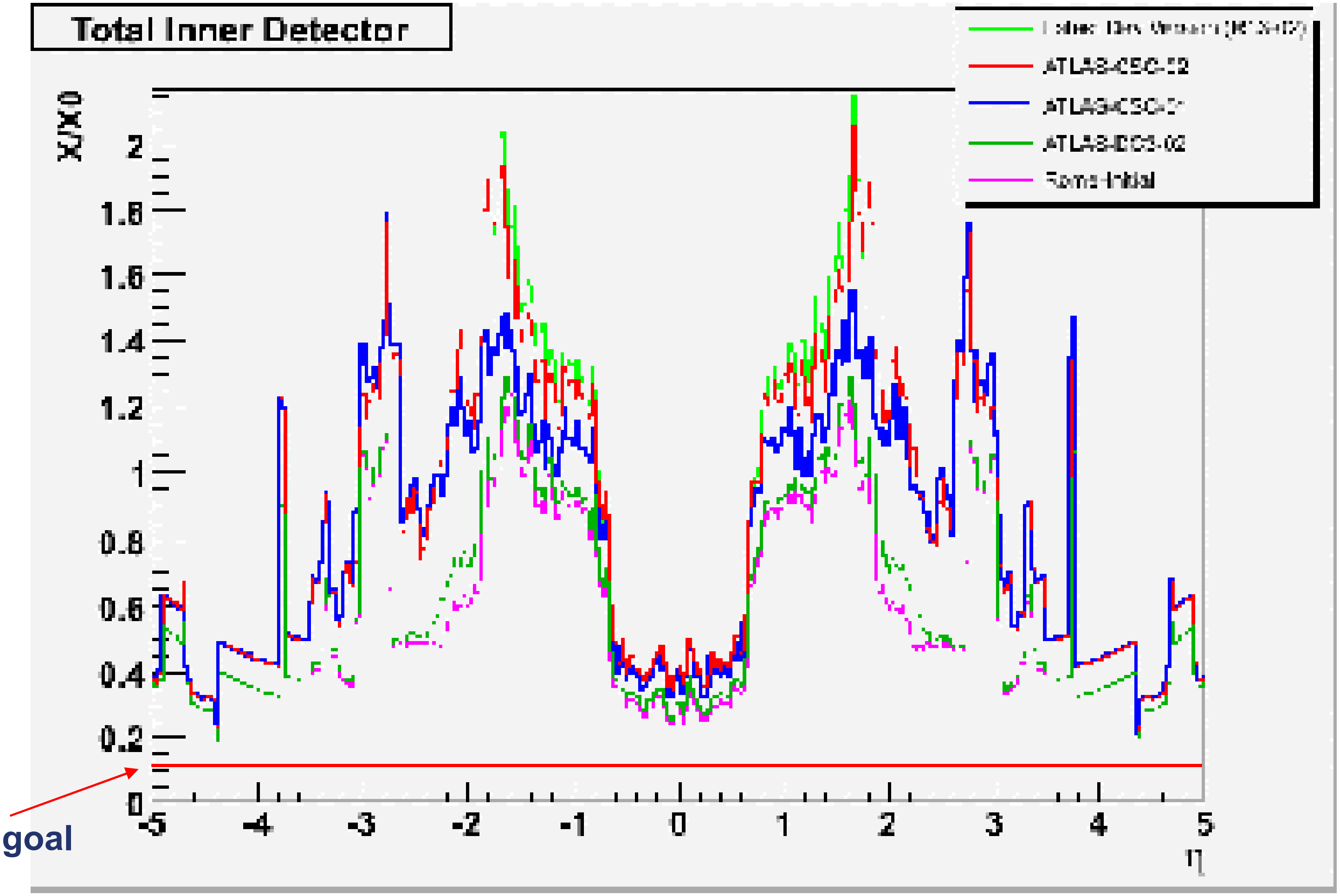
- Detector options:
  - Single bunch timing
  - Time-slicing of train (eg at 50 μs intervals, 20 slices)
  - Integrate signals through train, with relaxed readout during the inter-train period

- No ‘right answer’. There’s an advantage in time integration, namely *reduced power* Fine sensor granularity may compensate for pileup of background from multiple bunch crossings

- Lower peak power permits reduced cable plant, hence reduced material budget. Avoiding pulsed power has further mechanical advantages

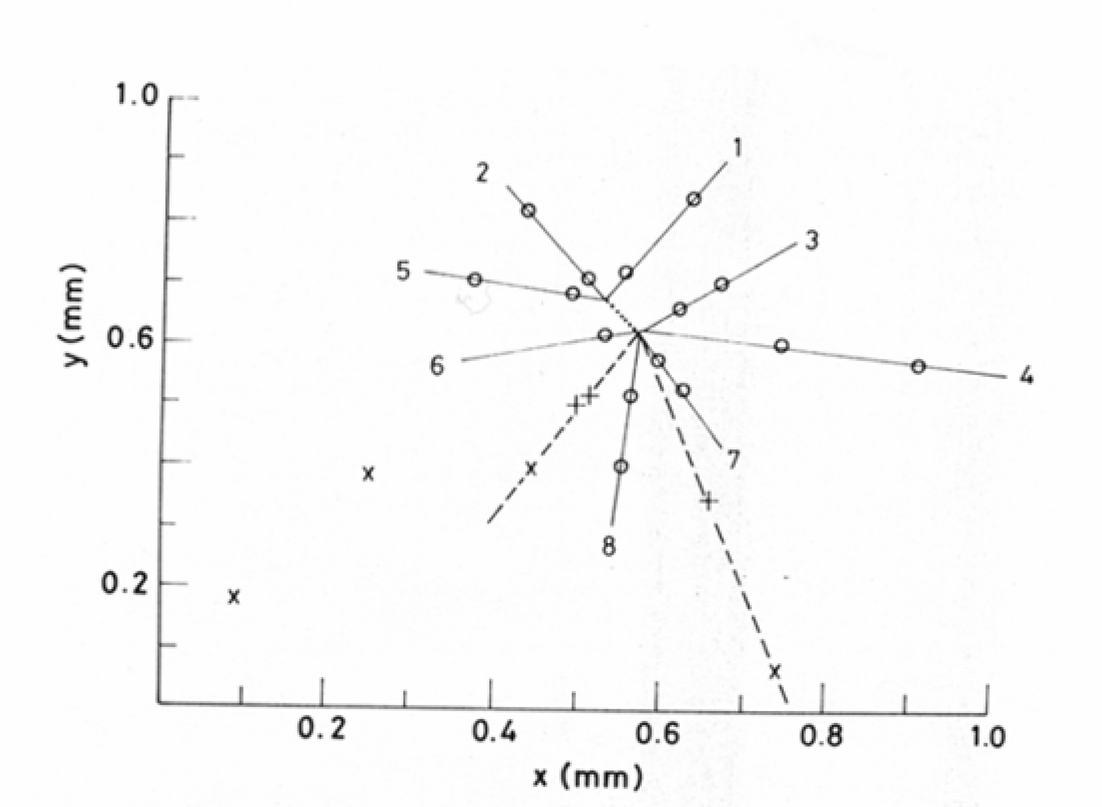
- There has been a successful history of exploiting tradeoffs between granularity and time resolution in ACCMOR and SLD vertex detectors

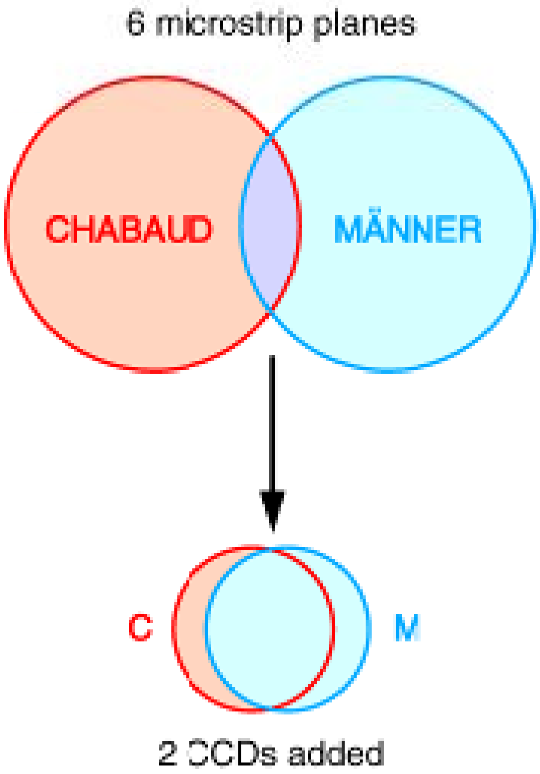
- Contrast LHC, where single bunch timing is mandatory, but one pays a heavy price in material …


Total Inner Detector
X/X0
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
Latest Dev Version
ATLAS-CSC-02
ATLAS-CSC-01
ATLAS-DC3-02
Rome-Initial

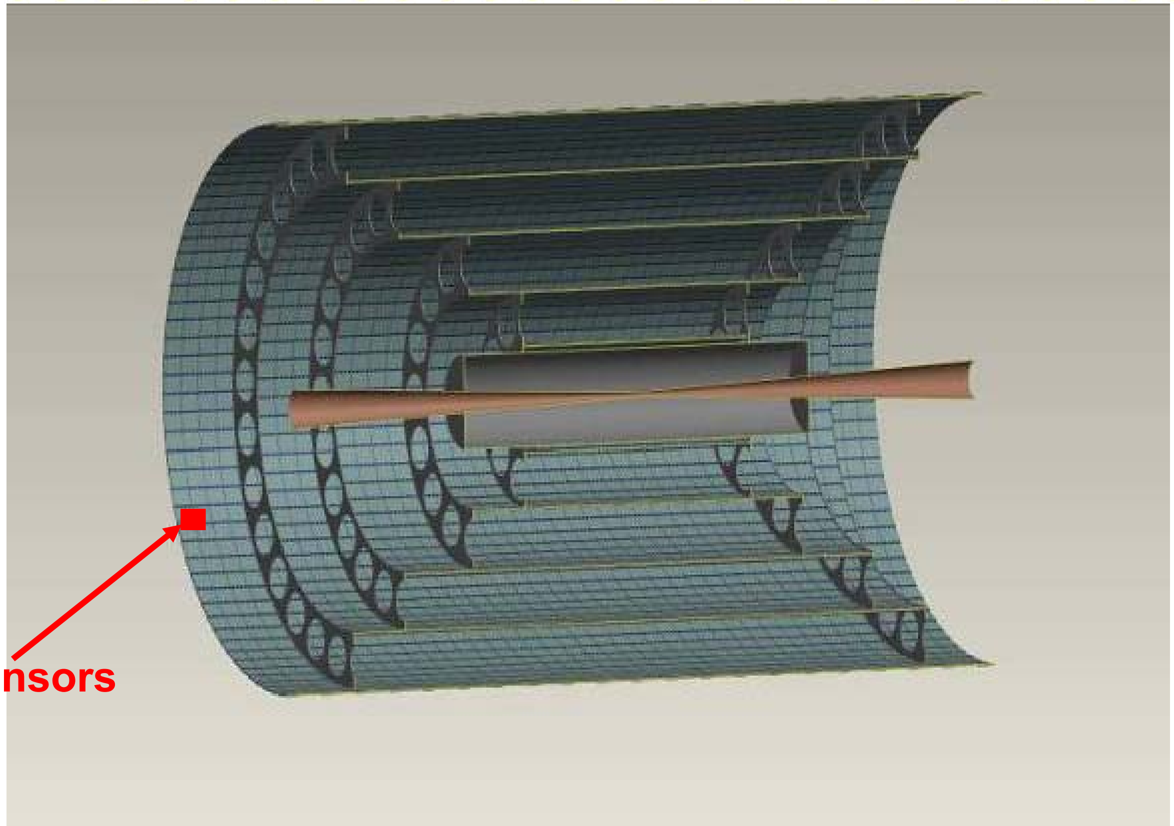
ILC goal

- A pixel tracker, being free of ghost hits, has a proven record for extremely high pattern recognition efficiency compared to microstrips, in high multiplicity jet-like events (ACCMOR Collaboration, mid-1980s)
- Total thickness of this standalone tracking system was 0.2% X_0





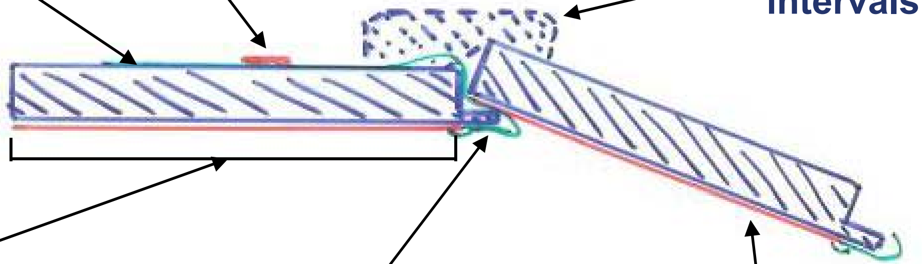
- We suggest that 5 layers of 50 μm pixels would have excellent track reconstruction efficiency in the core of high energy jets, where 5 layers of single-sided unidirectional microstrips may be struggling
- However, ‘standard’ MAPS devices would consume far too much power, so material budget would be blown away by the required cooling system
- If one can afford to integrate the background through the bunch train, one can adopt relaxed readout between trains, so exchanging high pulsed power for low continuous power, with consequential benefit to material budget (cabling and mechanics)
- Integrating through a train causes no problems to the ‘real’ track finding: density of extra hits within a jet is negligible
- What is less clear is the impact on track finding of the salt-and-pepper background that populates the detector. Risk of an unacceptable load of fake tracks. Thanks to Marcel Vos for eloquently alerting us to this in Sendai



one of 11,000 sensors
8x8 cm^2

- SiC foam support ladders, linked mechanically to one another along their length
- 5 closed cylinders (incl endcaps, not shown) will have excellent mechanical stability
- ~0.6% X_0 per layer, 3.0% X_0 total, over full polar angle range
- 30 Gpixels, in line with trends in astronomical wide-field focal plane systems by 2020

End view of 2 barrel ladders ('spiral' geometry)



1 readout chip/sensor

SiC foam, 4-8%

**

wedge links at ~40 cm intervals

devices will be 2-side buttable, so inactive regions in z will be ~ .2 mm (~ 0.2%)

Sensor active width 8 cm, with ~2 mm overlaps in rϕ

thin Cu/kapton tab (flexible for stress relief), wire bonds to sensor

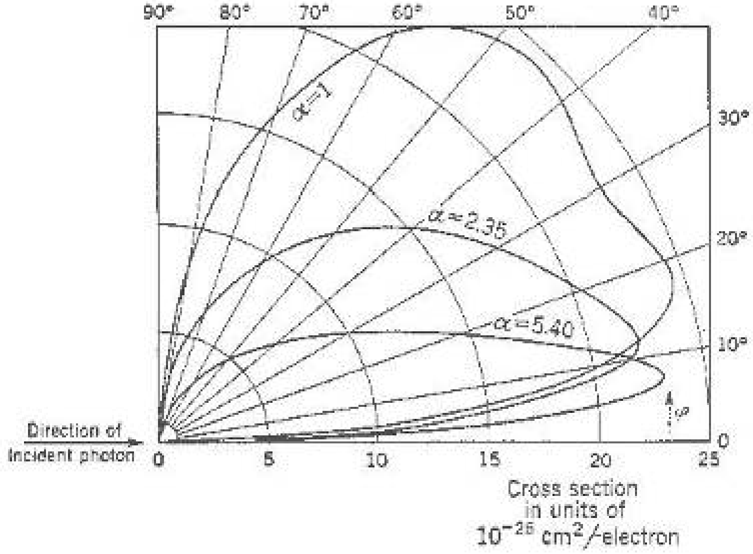
Sensor thickness ~100 μm, inner 30 μm active

** single layer Cu/kapton stripline runs length of ladder, double layer in region of tabs (~5 mm wide) which contact each sensor. Single Cu/kapton stripline runs round the end of each barrel, servicing all ladders of that barrel

Bottom line: potential material budget ~0.6% X_0 per layer, but much design and R&D needed to establish mechanical stability, including shape stability wrt push-pull operations (taking advantage of stress-free 3-point kinematic mount)

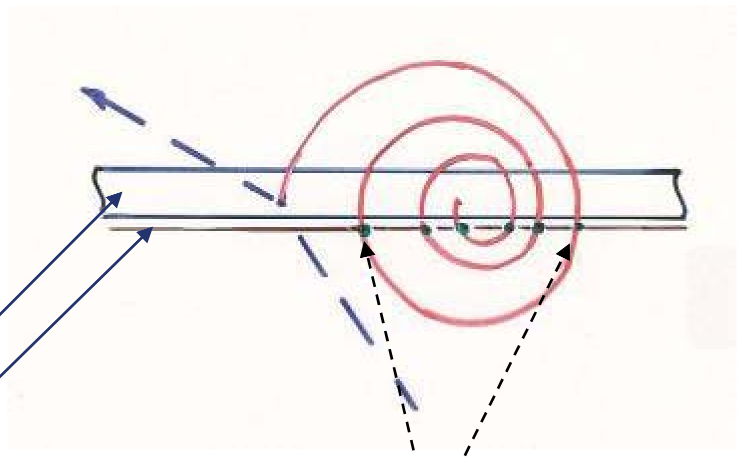
Backgrounds in silicon tracker

- Thanks to Takashi Maruyama, Norm Graf and John Jaros for help with this
- Takashi has calculated beamstrahlung-related and 2-photon backgrounds, both charged tracks and photon conversions
- 80% of hits are due to photons emitted from the BEAMCAL region, converting in the material of the tracker
- These photons are mostly of energy 0.1-1 MeV, with a peak at 0.51 MeV from positron annihilation in the BEAMCAL
- Using EGS, Takashi studied the conversion process in the detector, mostly Compton scattered electrons which generate typically 1-10 hits in a tracker layer, which he idealised as 300 μm Si. In our case, this probably over-estimates the effect, but not by much



Evans, p 691: photon energies 0.51, 1.2 and 2.76 MeV; electron angular distns

barrel ladder, rφ view

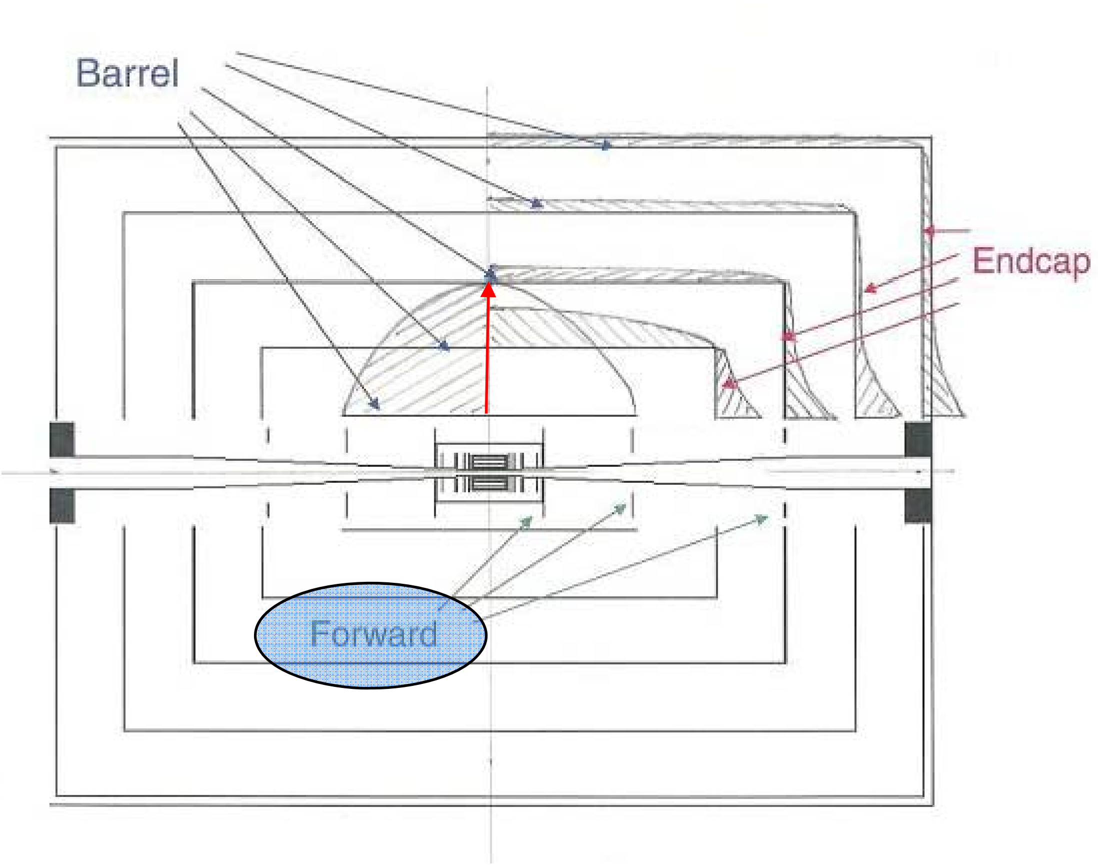


~0.5% X_0 support foam and Cu-kapton

~0.1% X_0 silicon, 30 μm active on inner surface

6 hits, stepped in z, each hit indistinguishable from min-I

- Total hit density ranges from 2.5/cm^2/train (layer 1 barrel) to 1/10 of that (layer 5 barrel) – occupancies in SPT are everywhere < 10^{-4} ‘negligible’, or so we thought
- For the forward disks, densities exceed 600/cm^2/train, so pixels with short sensitive windows will be needed. Fortunately, area to be covered is small



Possible track-finding strategy

- First deal with tracks having approximate IP constraint – prompt tracks and B and D decay products

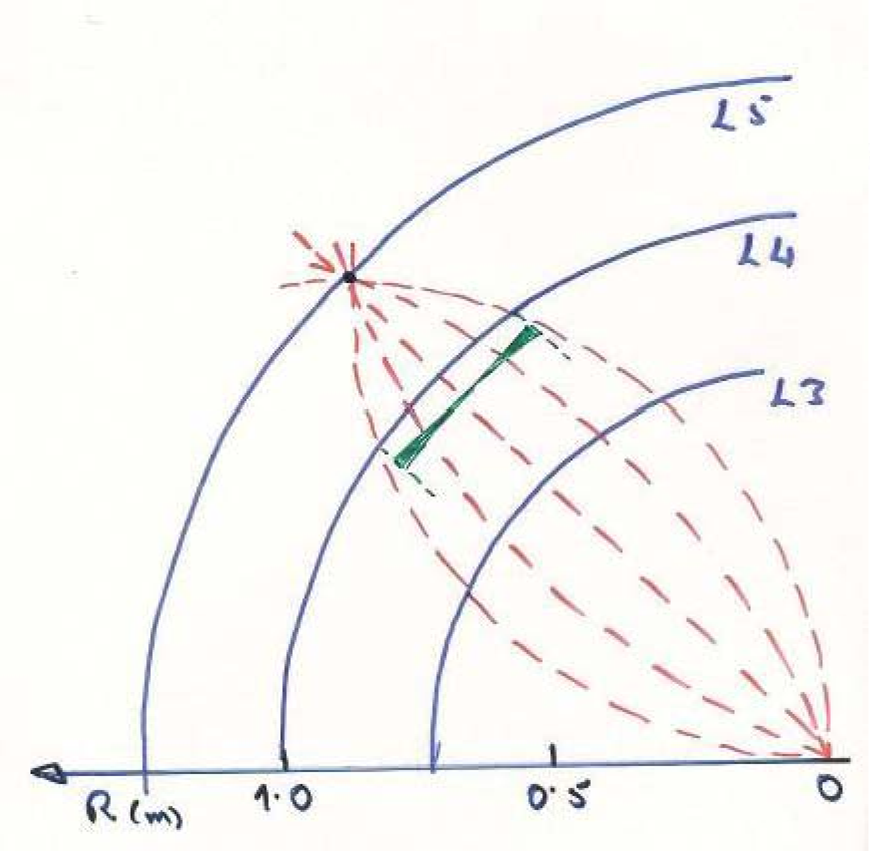
- [Use Garfield approach for K-shorts and lambdas, as well as photon conversions and secondary interactions. A key point is that the latter will be considerably suppressed by the reduced material budget]

- Work from 'outside' in, where outside means seed layer 5, 4, 3, 2, 1, down to a p_T limit p_T(crit) for which track in r-ϕ view is at 45 degrees to the layer surface

-

Layer	p_T(crit) (GeV/c)
5	1.33
4	1.05
3	0.77
2	0.49
1	0.21

- Particles with p_T below 200 MeV/c are to be found as curlers in the forward tracking detectors. This should be OK for those which originate within the VXD volume – but challenging for the small number born beyond (from late B and D decays)



- Start with seed layer 5, and extrapolate each hit as a track candidate to layer 4, respecting the IP constraint and the p_T(crit) limit
- Multiple scattering implies a bow-tie profile for acceptable layer-4 links; +- 3 σ limit delivers on average 0.9 candidate tracks (looks pretty bad at this stage!)
- However, we can now extrapolate tracks of increasingly well-defined momentum to layer 3, 2, 1 with precision limited mainly by multiple scattering, and end up with well below 1 fake track per event, from 52000 seeds in layer 5

- Extrapolation outwards to ECAL cleans up the fake tracks, plus the out-of-time background charged particles, which mostly come from 2-photon background
- This step won't be perfect – a fake track may point to a genuine ECAL cluster, but we appear to be talking about cleanup of a small number of fakes, and the cluster does need to be charged and compatible both in position and direction
- Procedure becomes less beautiful as seed layer is stepped inwards to pick up lower-p_T tracks, but even the lowest momentum particles end up in the forward ECAL for validation, so this approach probably remains robust
- Same procedure works for the endcap disks, with p_T(crit) defined by the radial position of the seed hit. Multiple scattering effects are generally reduced (fewer cases of extreme obliquity)

Technology options

- Conventional CCDs can be used wherever full train integration is permissible. Availability of 30 Gpixel system with 8x8 cm^2 devices on timescale of 2020 is assured – driven by dark energy and other wide-field camera systems in astronomy

- Cost is expected to be ~$30M, far higher than microstrips, so a serious performance comparison (particularly of PFA) will be needed before carrying this forward

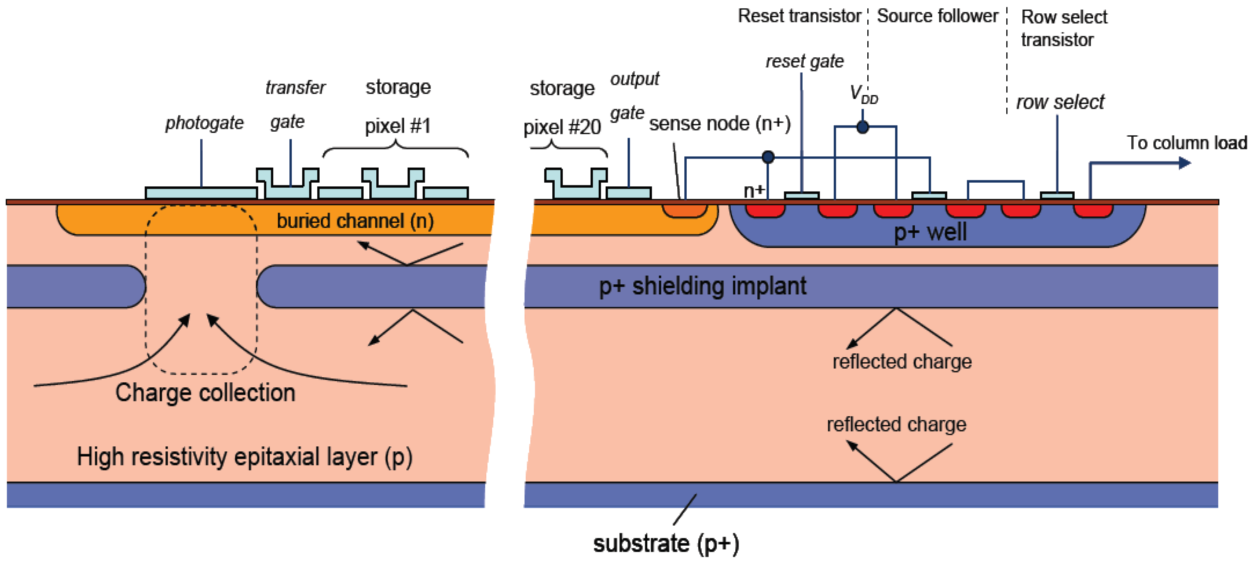
- If finer time slicing is required (10 to 100 sensitive windows per train) the ISIS technology looks promising. Availability and yield of 8x8 cm^2 devices is not yet established, but there is time enough for that

- With either option, slowly step through all 11000 devices ladder by ladder for relaxed readout of undisturbed signal charge from up to 100 time slices during the 200 ms, with low and constant power dissipation. Estimate for the CCD option is 600 W total power, dissipated steadily while running – well within the capability of gentle gas cooling

Conclusions

- Silicon pixel tracker with signal integration through the bunch train looks promising
- If it works, it should deliver a tracking system with extremely high performance and very little material in front of the calorimeter
- The technology is being developed anyway, for multi-Gigapixel focal plane arrays in astronomy
- Low level of fake tracks and background charged tracks can be efficiently suppressed by demanding position/direction match to an on-time charged ECAL cluster
- Needs a serious simulation of track reconstruction, not just back-of-envelope
- If integration through the train is inadequate, one can switch to 10-100 time slices while retaining the principle of steady low power, with no increase needed during the bunch train. ISIS approach is established for optical imaging, and under development for charged particle detection
- Still need Garfield (or equivalent) to handle non-IP tracks, viz. K-shorts, lambdas, and the greatly reduced incidence of photon conversions and secondary interactions

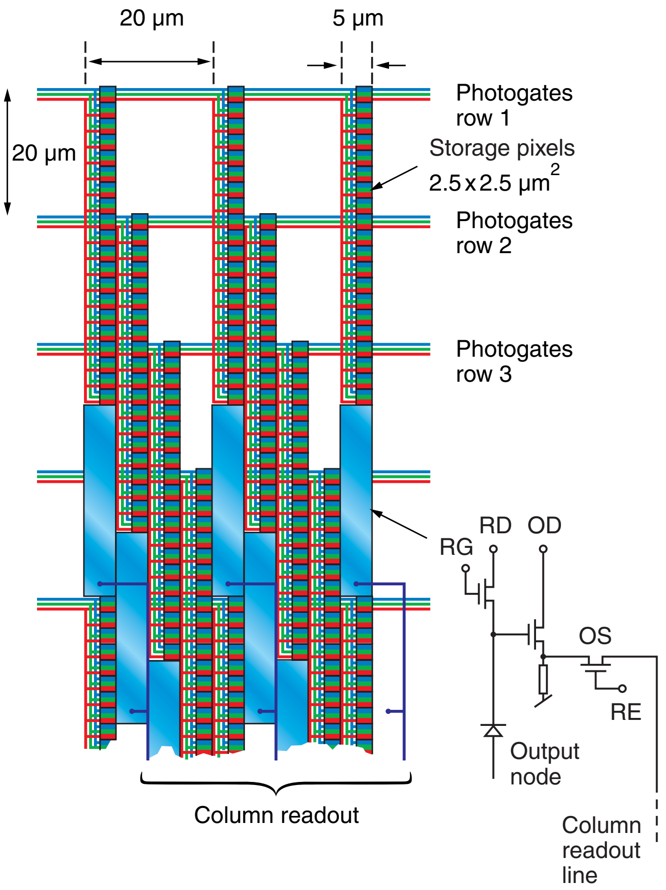
Backup

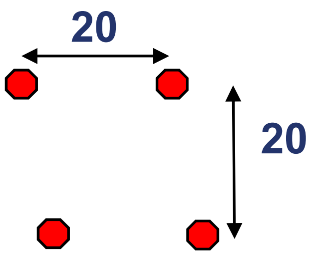


Operating principles of the ISIS:

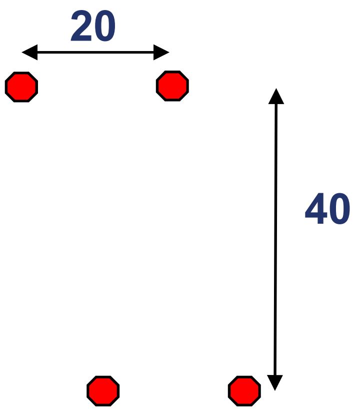
- Charge collected under a photogate
- Charge is transferred to N-cell storage CCD in situ, N times during the 1 ms-long train
- Converted to voltage and read out in the 200 ms-long quiet period after the train (insensitive to beam-related RF pickup)
- For SPT, 50 µm pixels with binary readout will suffice
- Proof-of-principle ISIS-1 (e2V) demonstrated effective punch-through operation with x-rays; small-pixel version ISIS-2 is now in production with Jazz Semiconductors
- 20 storage cells the goal with 20 µm square pixels for vertexing; 100 cells would easily be accommodated in a 50 µm square pixel

Dimensions of ISIS pixels: (storage and imaging)



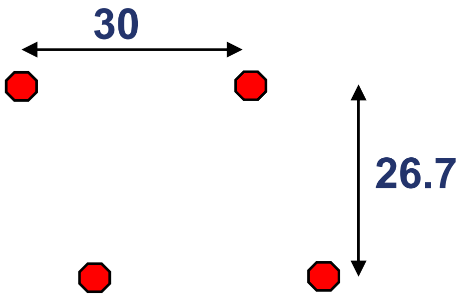


80 x 5 µm with 4-column repeat



80 x 10 µm with 2-column repeat

(ISIS2)

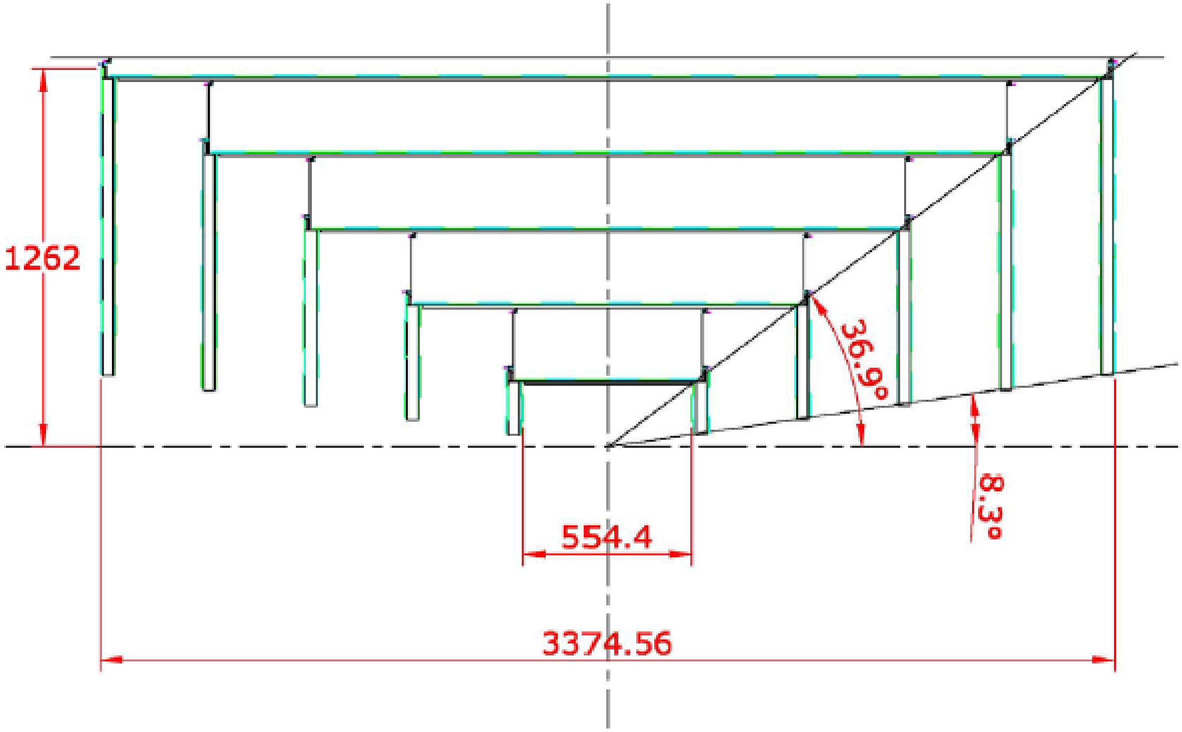


80 x 10 µm with 3-column repeat

(ISIS3?)

imaging pixel = storage pixel = 150x40 µm

(ISIS1)



- Barrel and Forward trackers, total area = 70.3 m^2
- With 50 µm × 50 µm pixels – 28.1 Gpix system
- If each chip is 8 cm × 8 cm (2.6 Mpix): 11,000 sensors is total

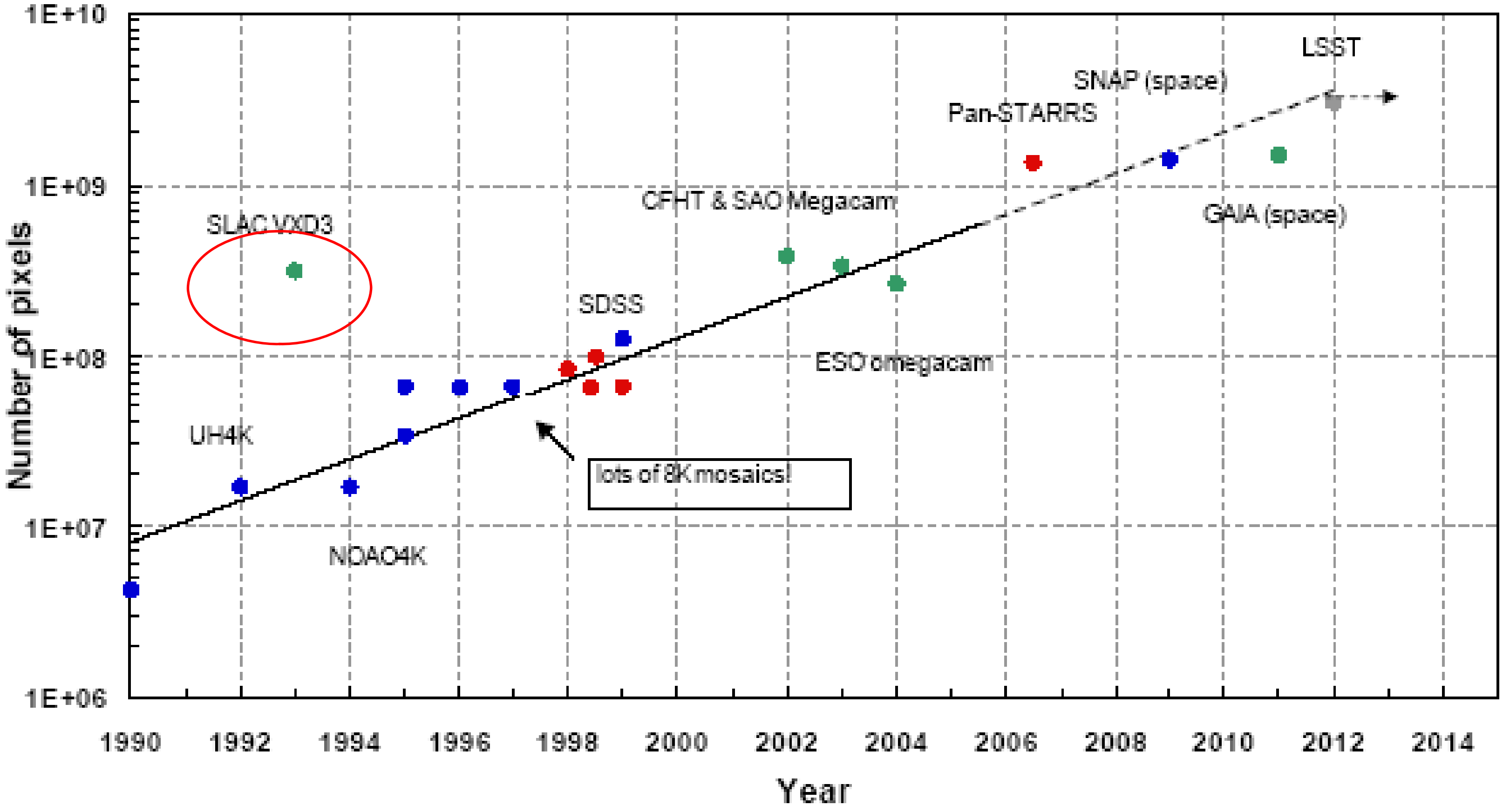
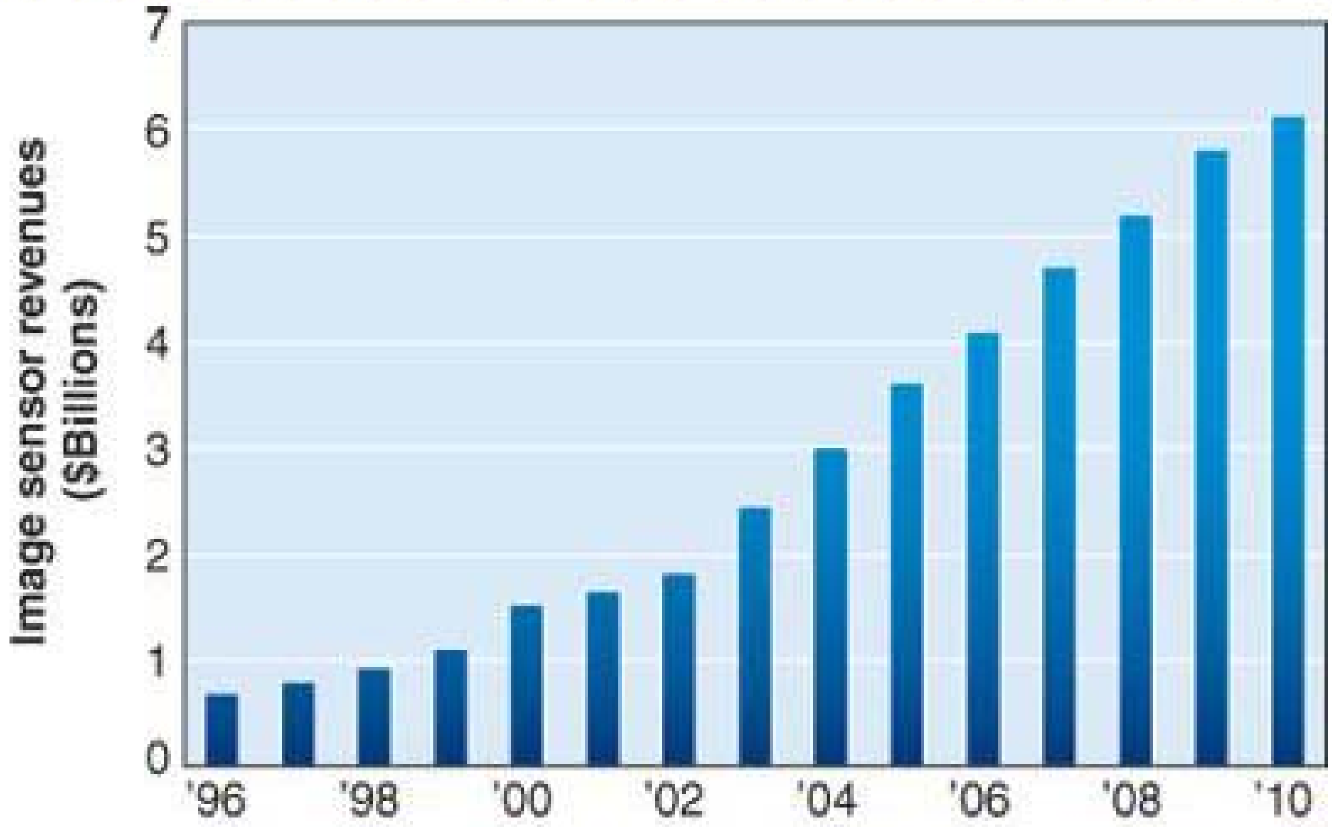


Illustration of focal plane sizes, from Luppino/Burke 'Moores' law

Focal plane size doubles every 2.5 years

From: Burke, Jorden, Vu, SDW Taormina 2005



As with developments in microelectronics, we (the particle physics community) are now small fish in a very large pond.

In the '50s and 60s, fast electronics was synonymous with 'nuclear electronics'

These days, progress driven by consumer markets is much faster.

We scientists can be very grateful for that …