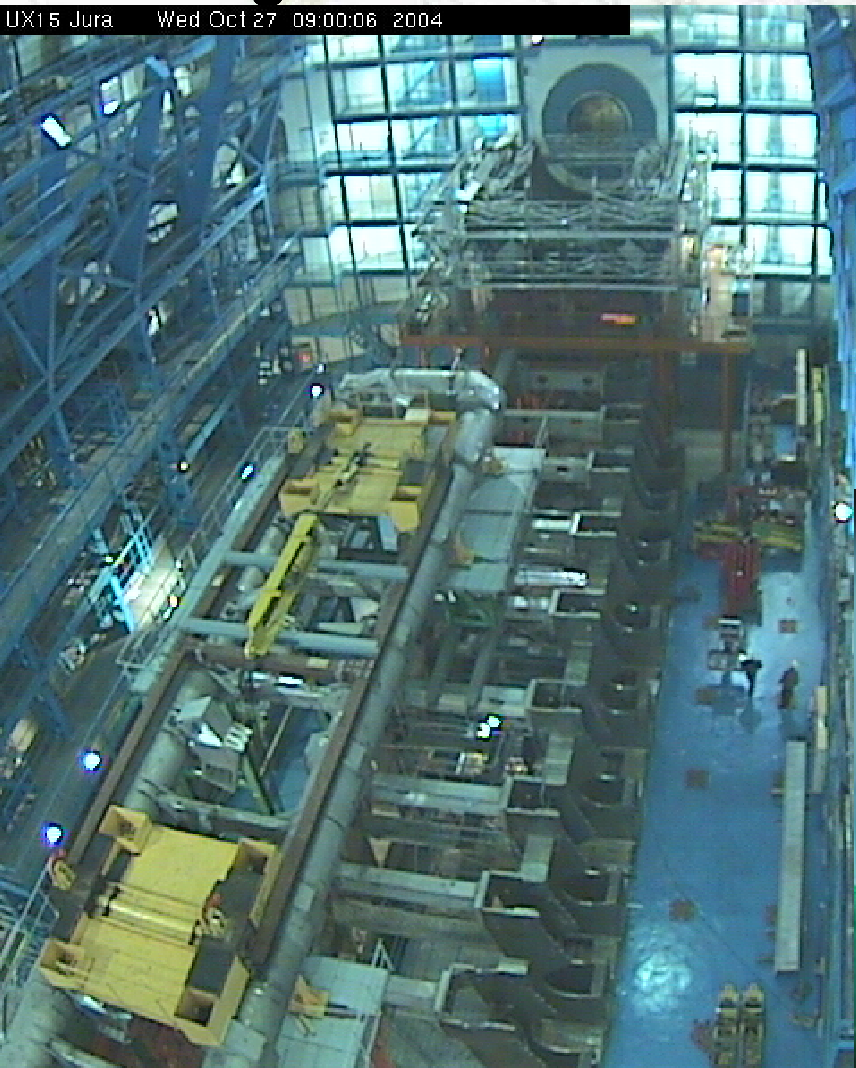
ATLAS Plans for Operation at an Upgraded LHC (Super-LHC)

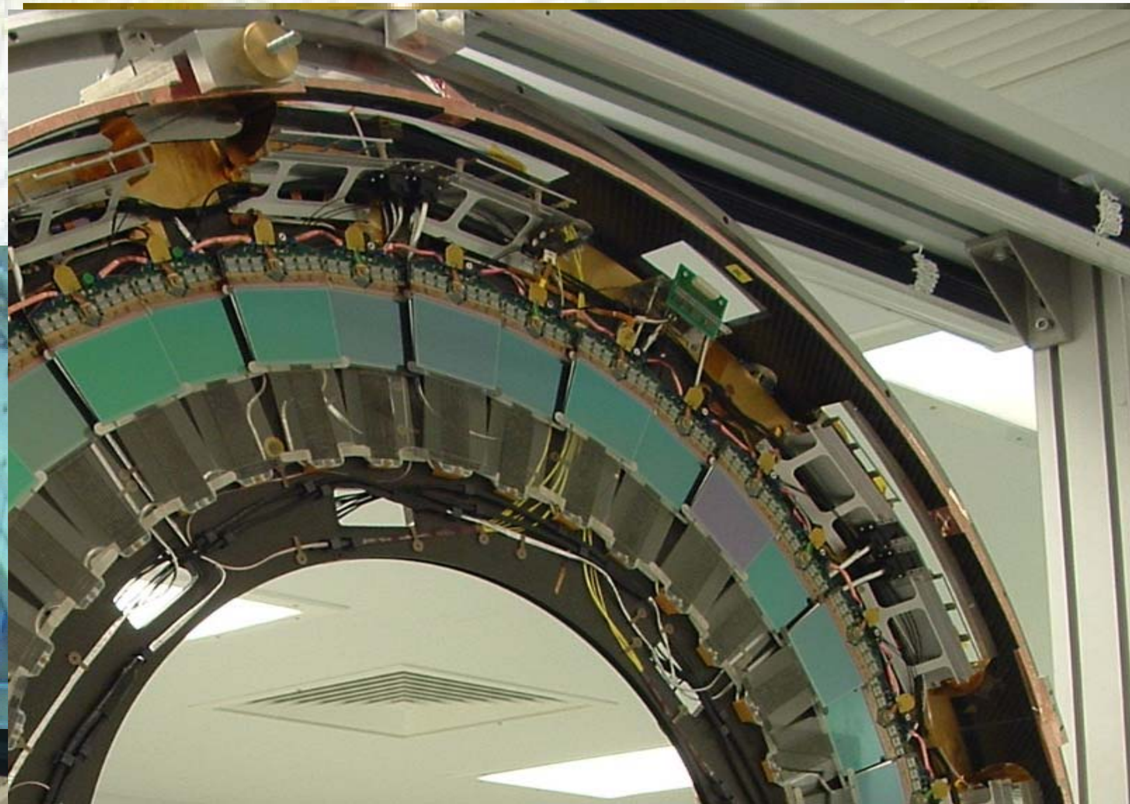
Phil Allport

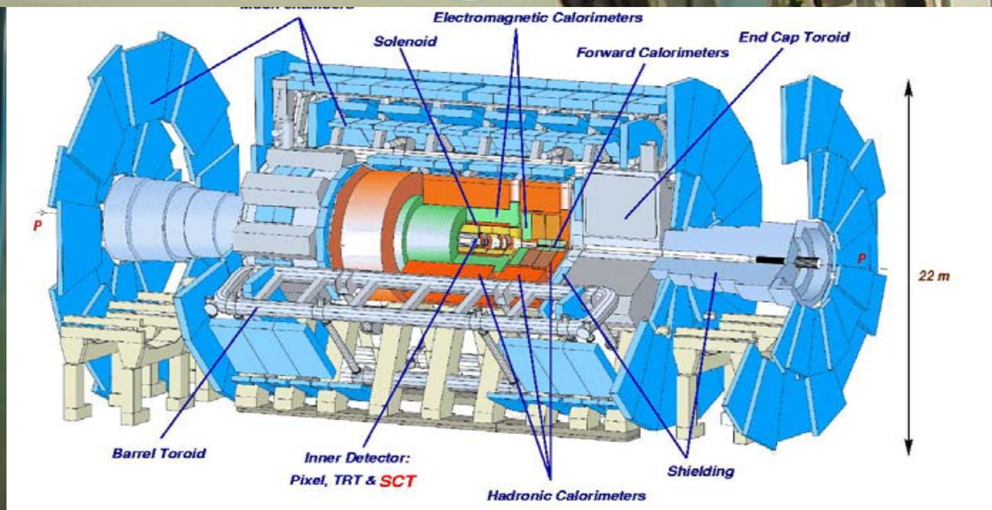
- **Introduction to ATLAS SCT**
- **Principal Issues at the SLHC**
- **Layout Options**
- **P-type Sensors for the SLHC**
- **Possible Microstrip Module/Stave Concepts**
- **Lessons from ATLAS SCT (M. Gilcriese)**
- **Conclusions**

The Semiconductor Central Tracker (SCT) of the ATLAS Experiment

- **The 61m^2 ATLAS SCT will be delivered to CERN for installation into the full ATLAS experiment during 2006.**

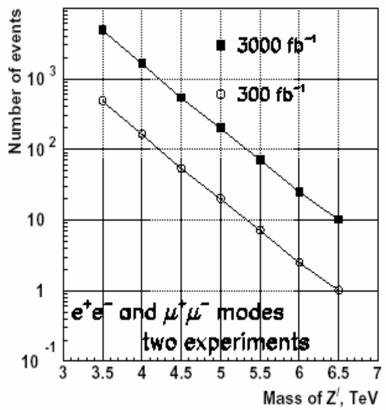




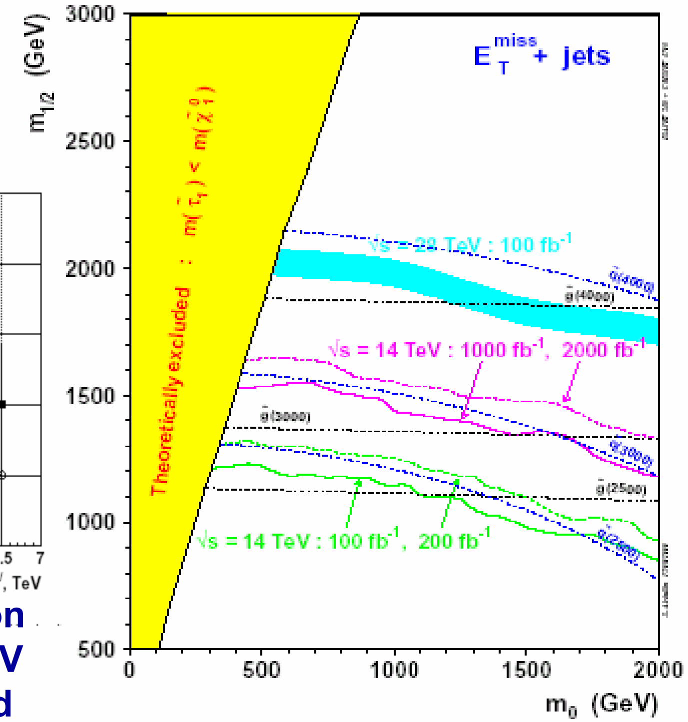


SLHC Requirements

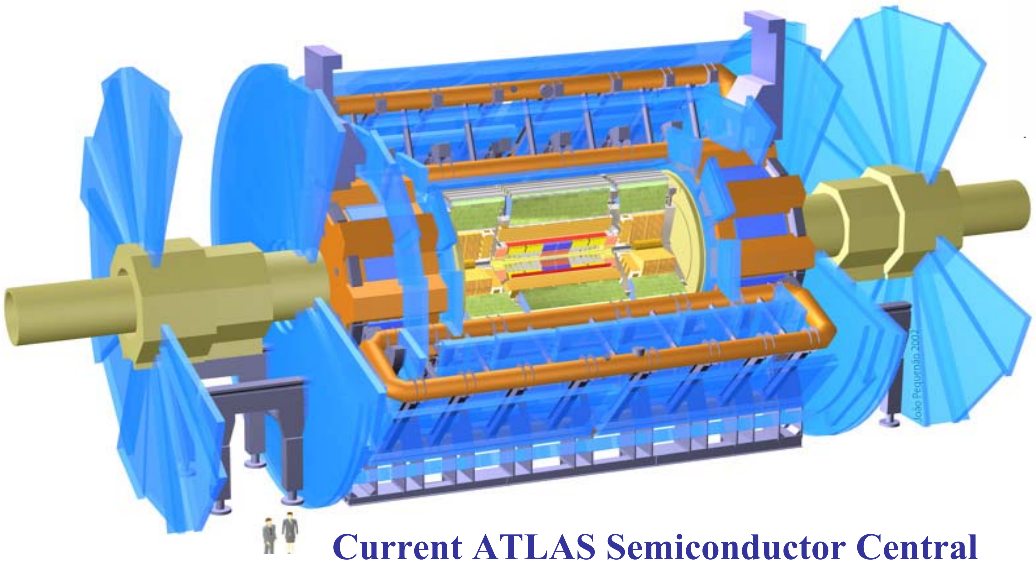
A factor of 10 upgrade in luminosity of the LHC looks both practical and highly desirable for physics on a timescale of year 2015.
However, several 100m^2 of silicon needed, which can affordably withstand about 10× the dose.



Compactification scales to 7.7 TeV could be probed



g. 13: Expected 5σ discovery contours in the mSUGRA plane m_0 versus $m_{1/2}$ for $A_0 = 0$, $\tan\beta$=10 and $\mu < 0$. The various ırves show the potential of the CMS experiment at the standard LHC (for luminosities of 100 fb^{-1} and 200 fb^{-1}), at the SLHC ɔr 1000 fb^{-1} and 2000 fb^{-1}), and (for comparison) at a machine with a centre-of-mass energy of 28 TeV.



Current ATLAS Semiconductor Central Tracker

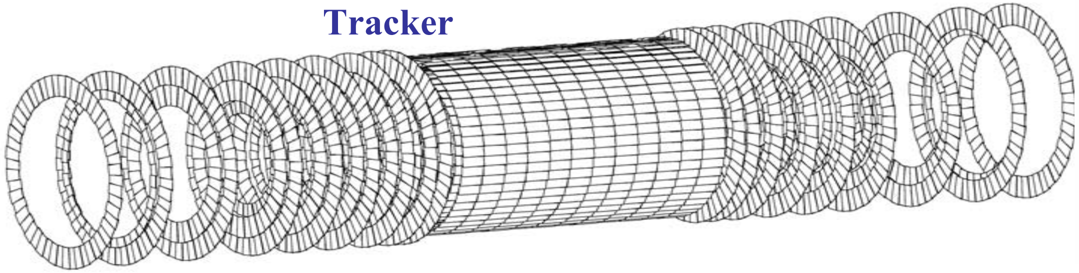
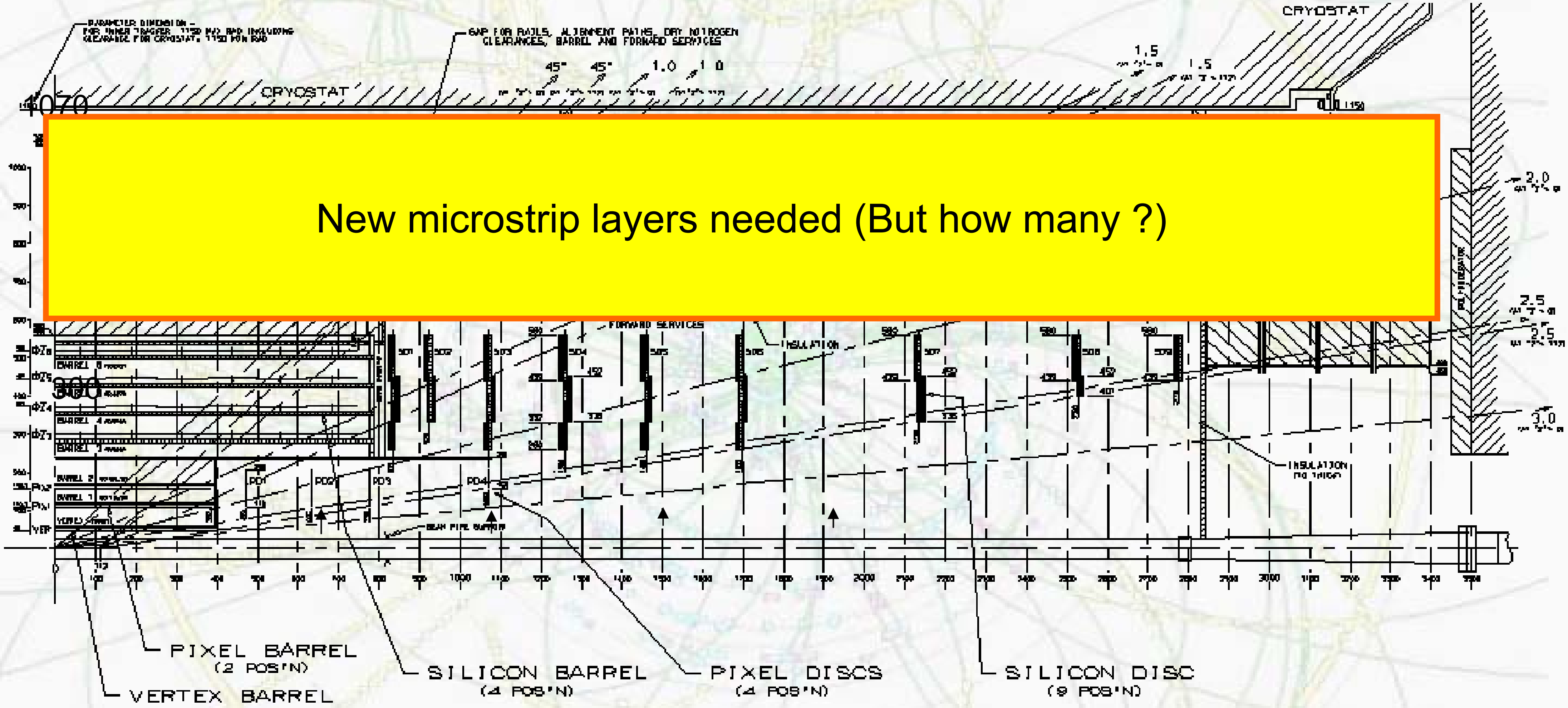


Table 4: Expected 95% C.L. constraints on Triple Gauge Couplings in ATLAS for various luminosity/energy scenarios (Λ =10 TeV). Only one coupling is allowed to vary at the time, while the others are fixed at their SM values. The last column shows the expectation for a Linear Collider with $\sqrt{s}$=500 GeV and 500 fb^{-1} [10].

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g_1^Z	0.0038	0.0024	0.0023	0.0007	0.0050

ATLAS Straw Tracker (TRT) will not Operate at SLHC



New microstrip layers needed (But how many ?)

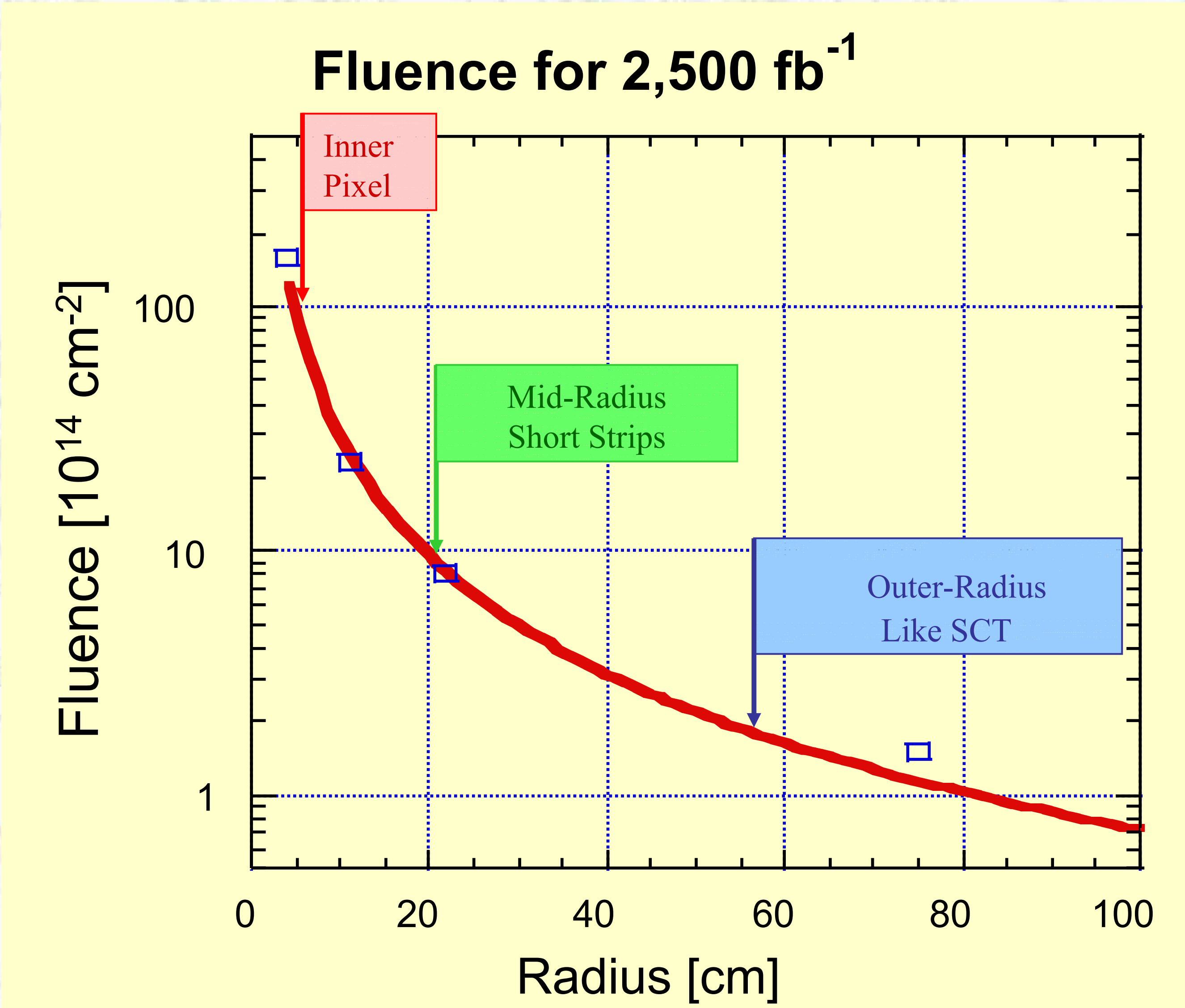
Current ATLAS Silicon Tracking

Pixels 50x300 μ at R=5 cm, 50x400 μ at R=9,12 cm

Strips 80μ*12cm at R=30,37,44,51 cm

Pavel Nevski

Tracker Region Charge Hadron Irradiation

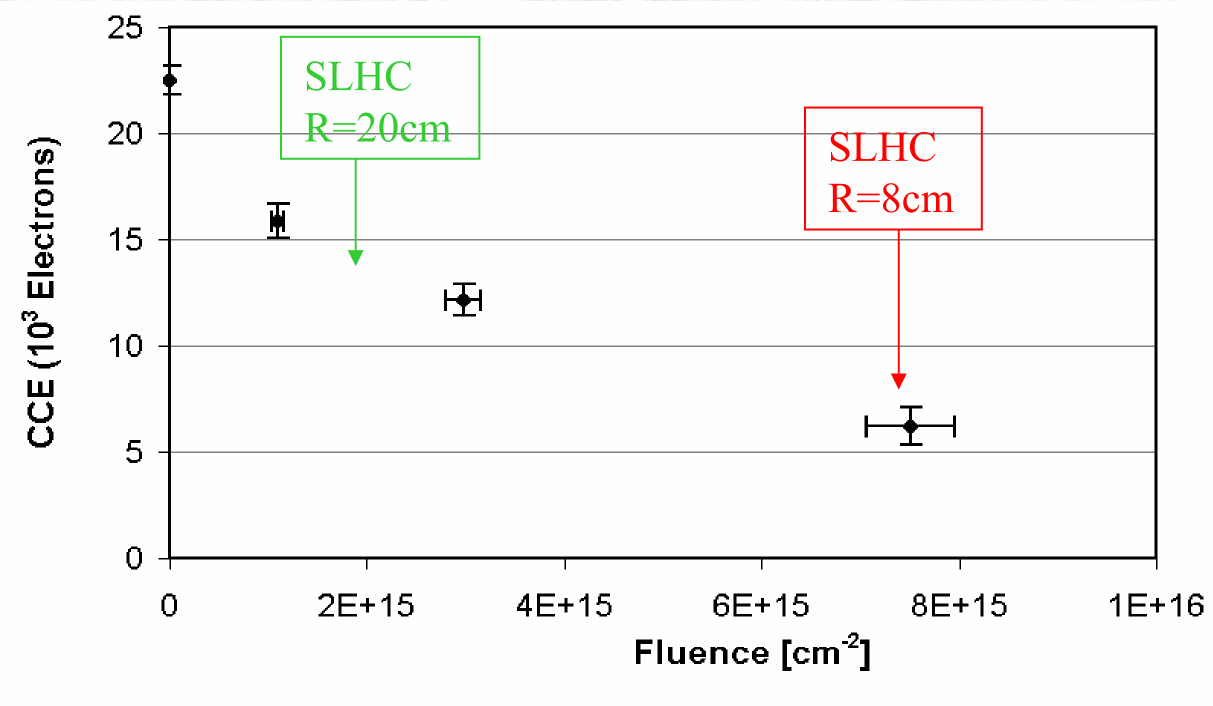


Note: Will require improved neutron absorber to avoid factor of 10 increase in neutrons at all radii.

Abe Seiden

Charged Trapping in Silicon

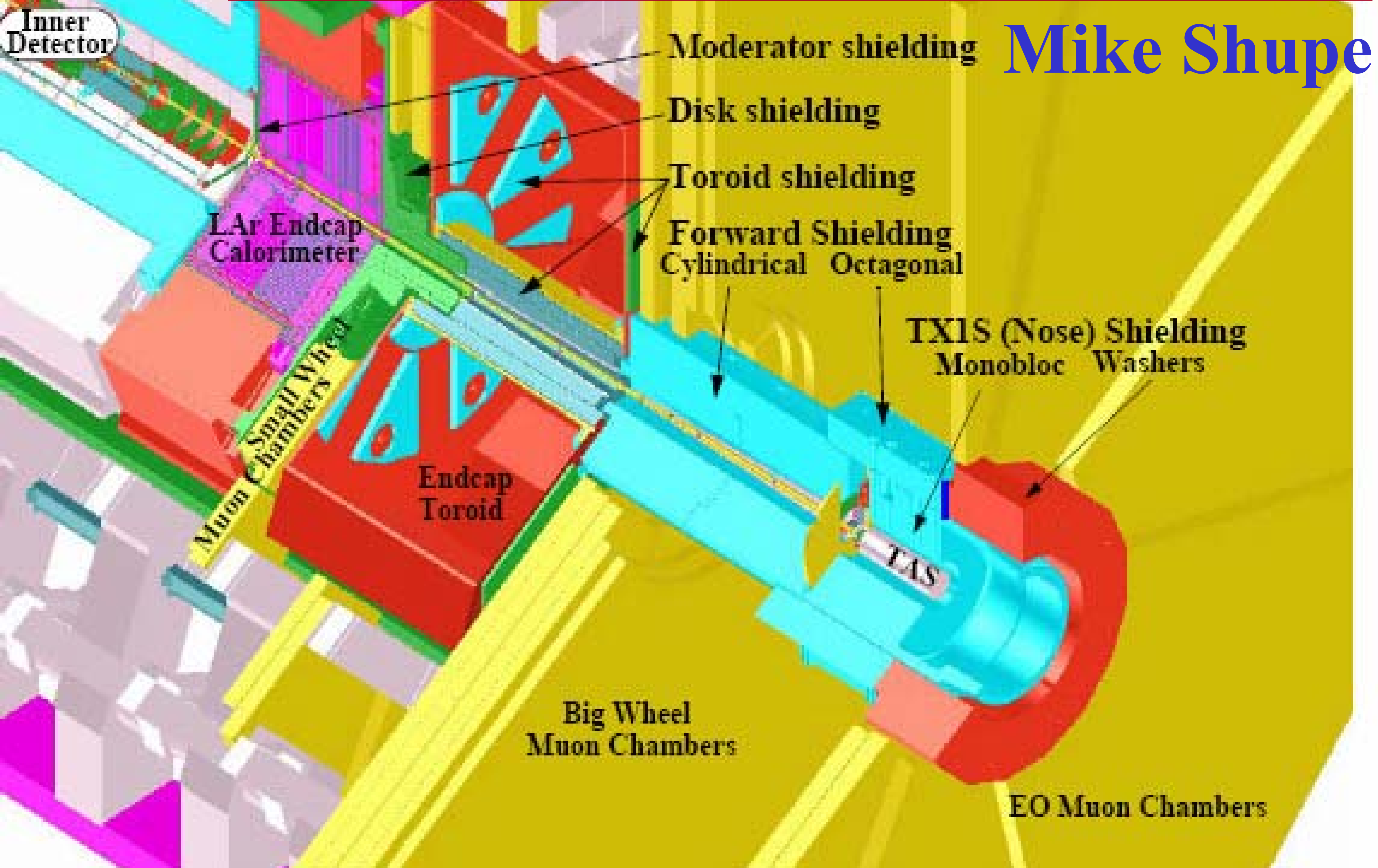
Efficiency of Charge Collection in 280 um thick p-type SSD
G. Casse et al., (RD50): After 7.5 $*10^{15}$ p/cm^2, charge collected is > 7000 e^-



Abe Seiden

Not Just Radiation But Activation

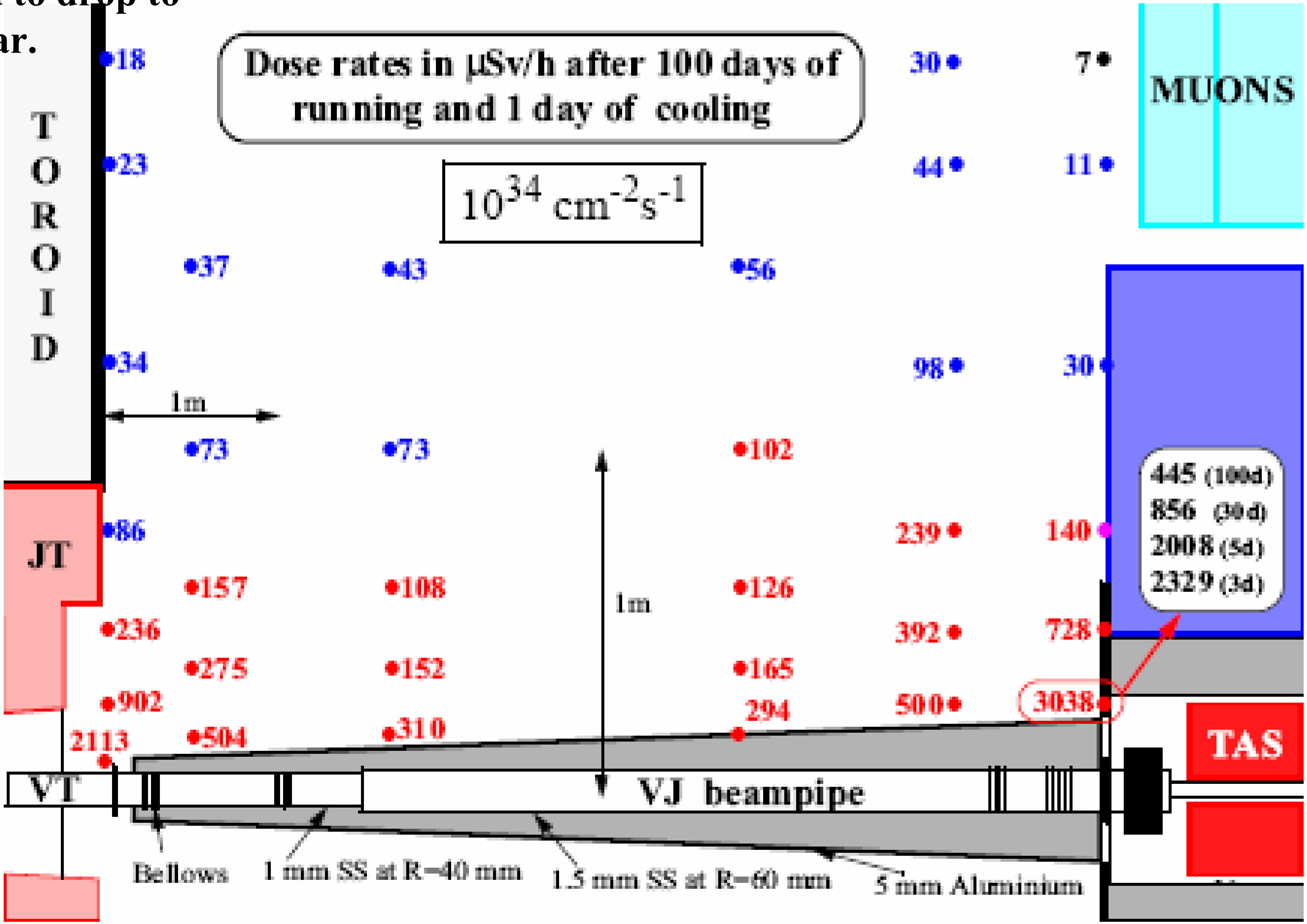
Mike Shupe



50 mSv/year maximum in “controlled area”. Expected to drop to 6mSv/year.

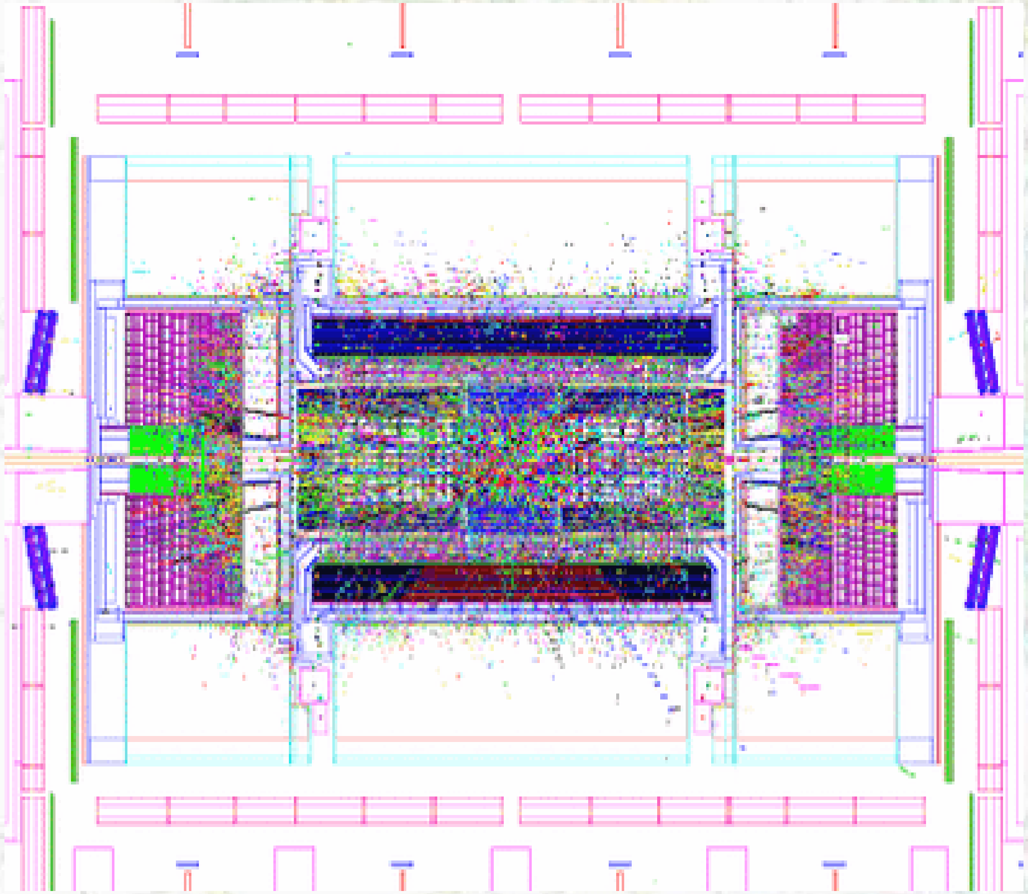
Current stainless steel beampipe: High doses !

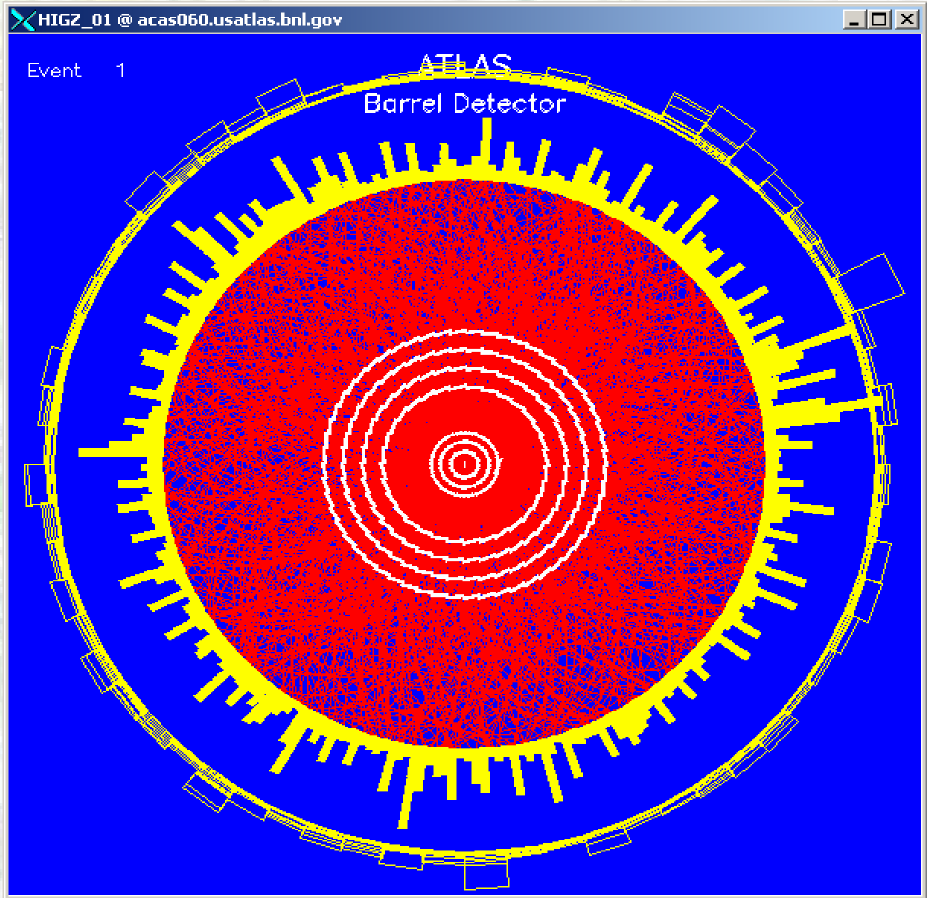
Accesses challenging even at 10^{34}.



… and Hit Density

Pavel Nevski

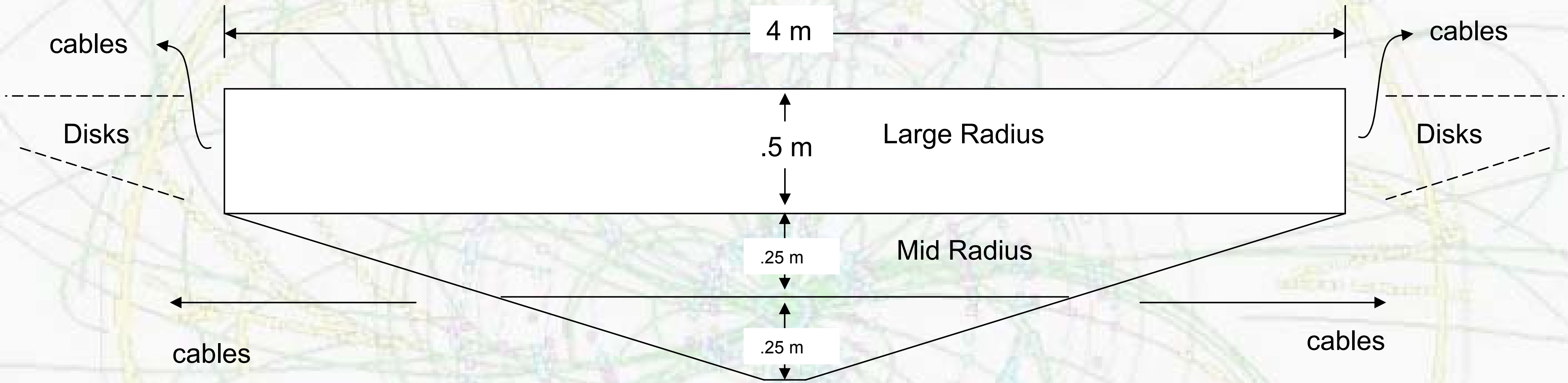




$N_{ch}(|y| \leq 0.5)$

- ~ 10000 particles in $|\eta| \leq 3.2$
- mostly low p_T tracks

Global Organization



Mid Region barrel covers $|y| \leq 2$. Might be sufficient coverage, depends on physics.

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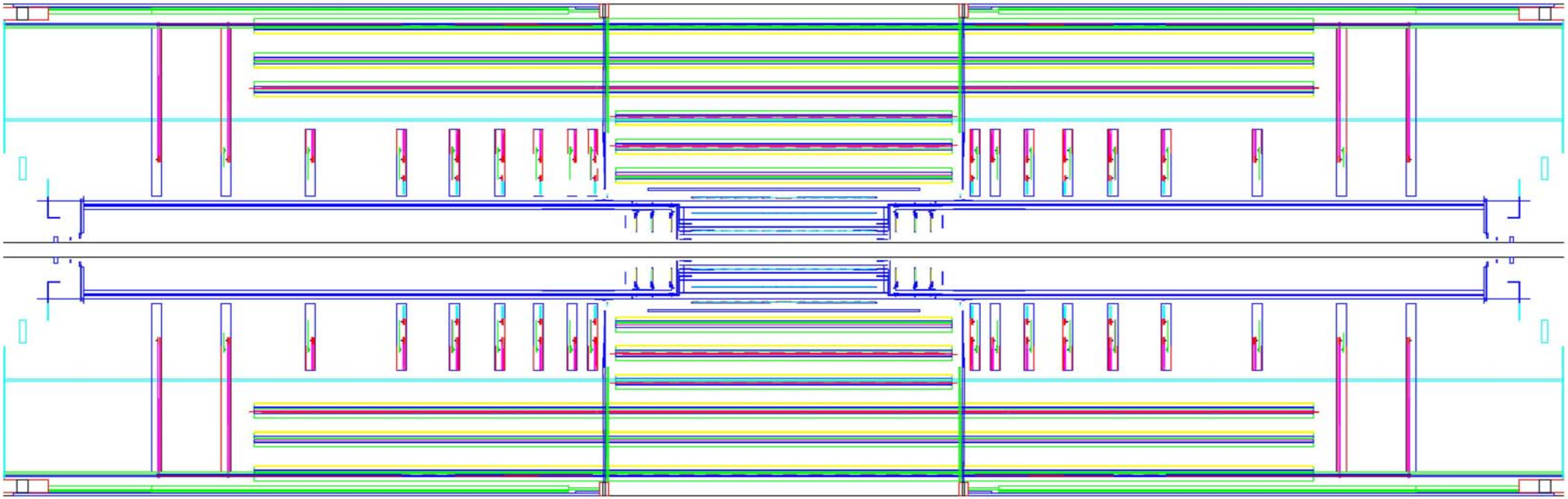
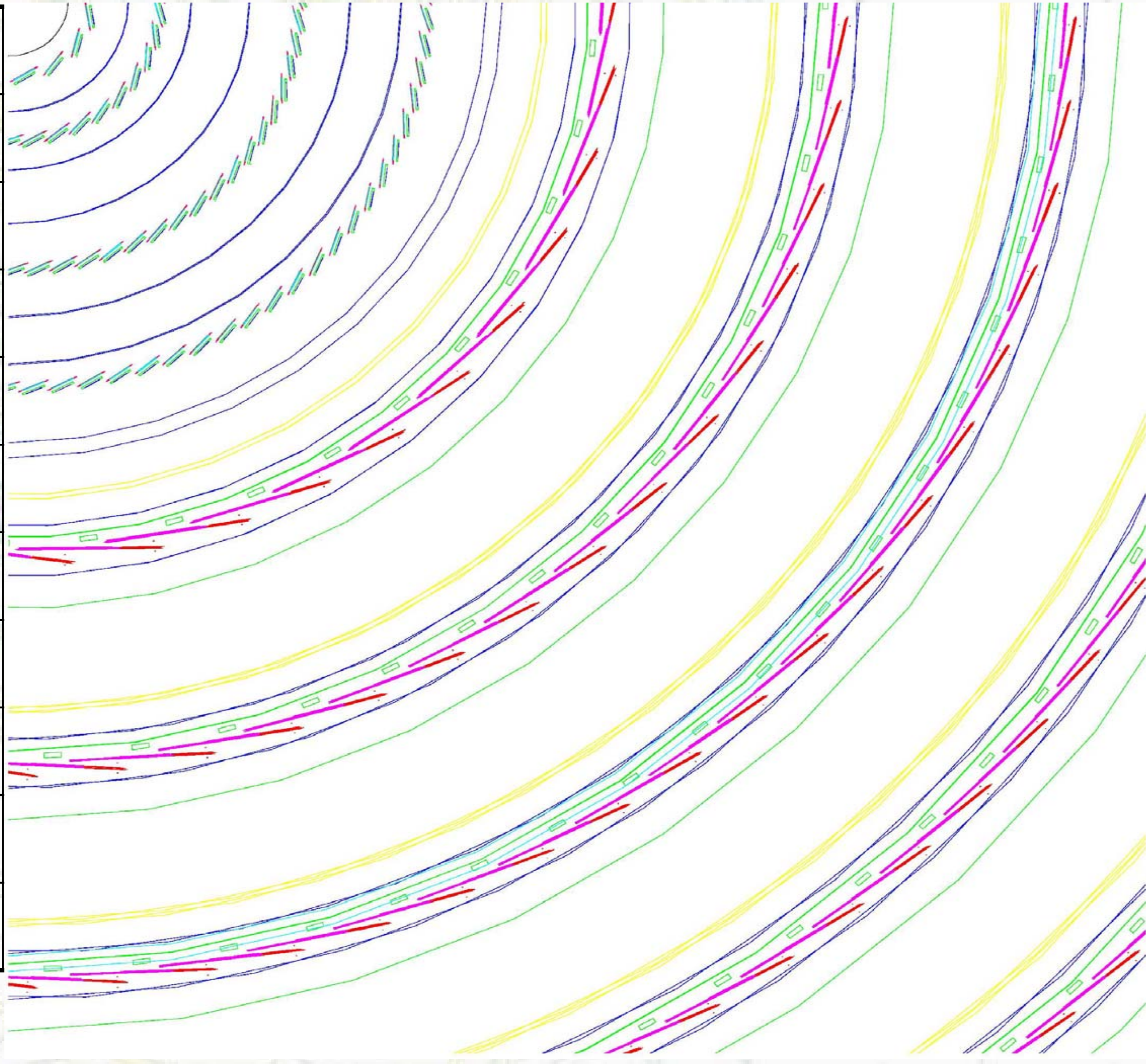
Model for Simulations



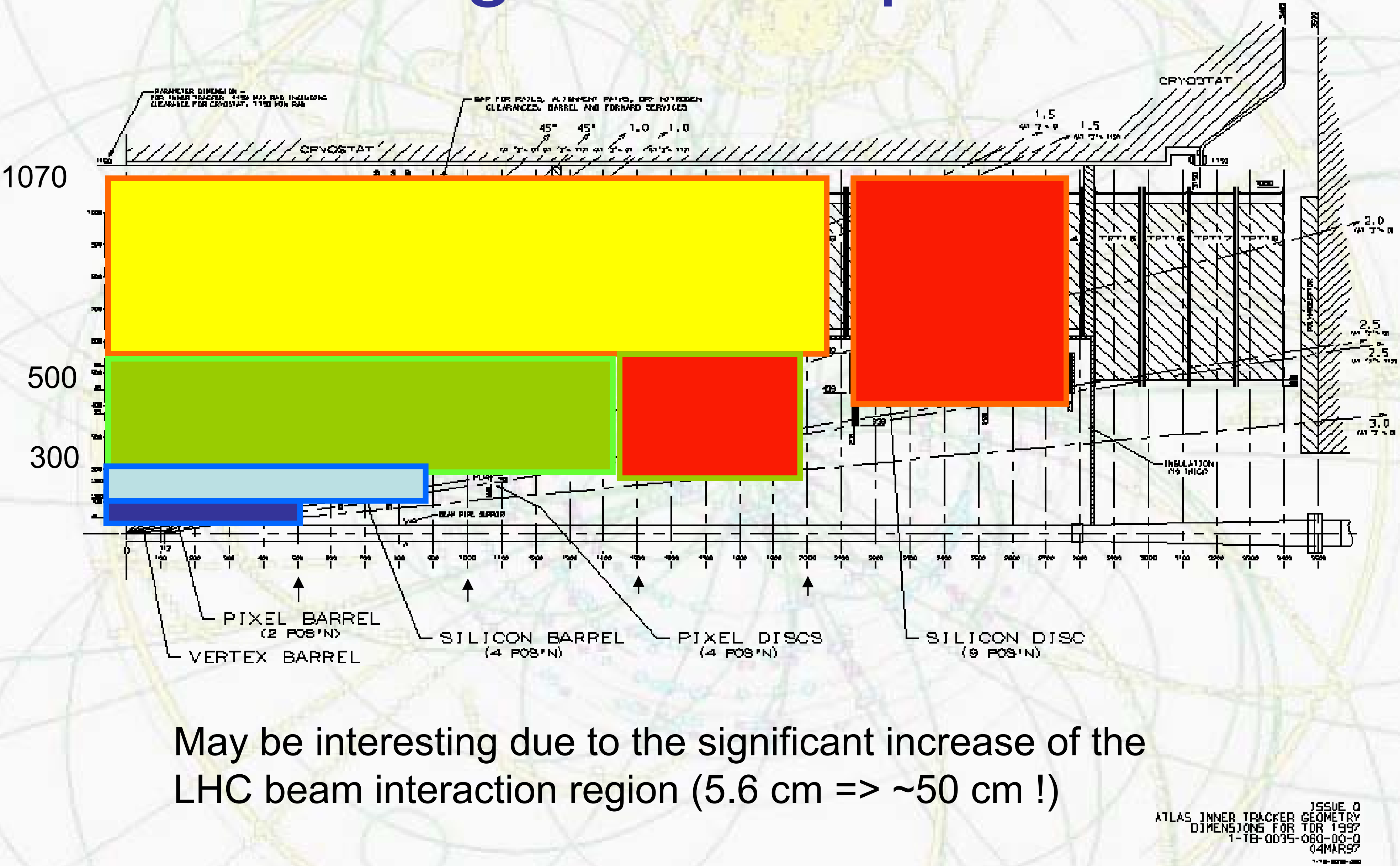
- Used to estimate occupancies only

Pavel Nevski

Technology
Pixels
Strips
TRT

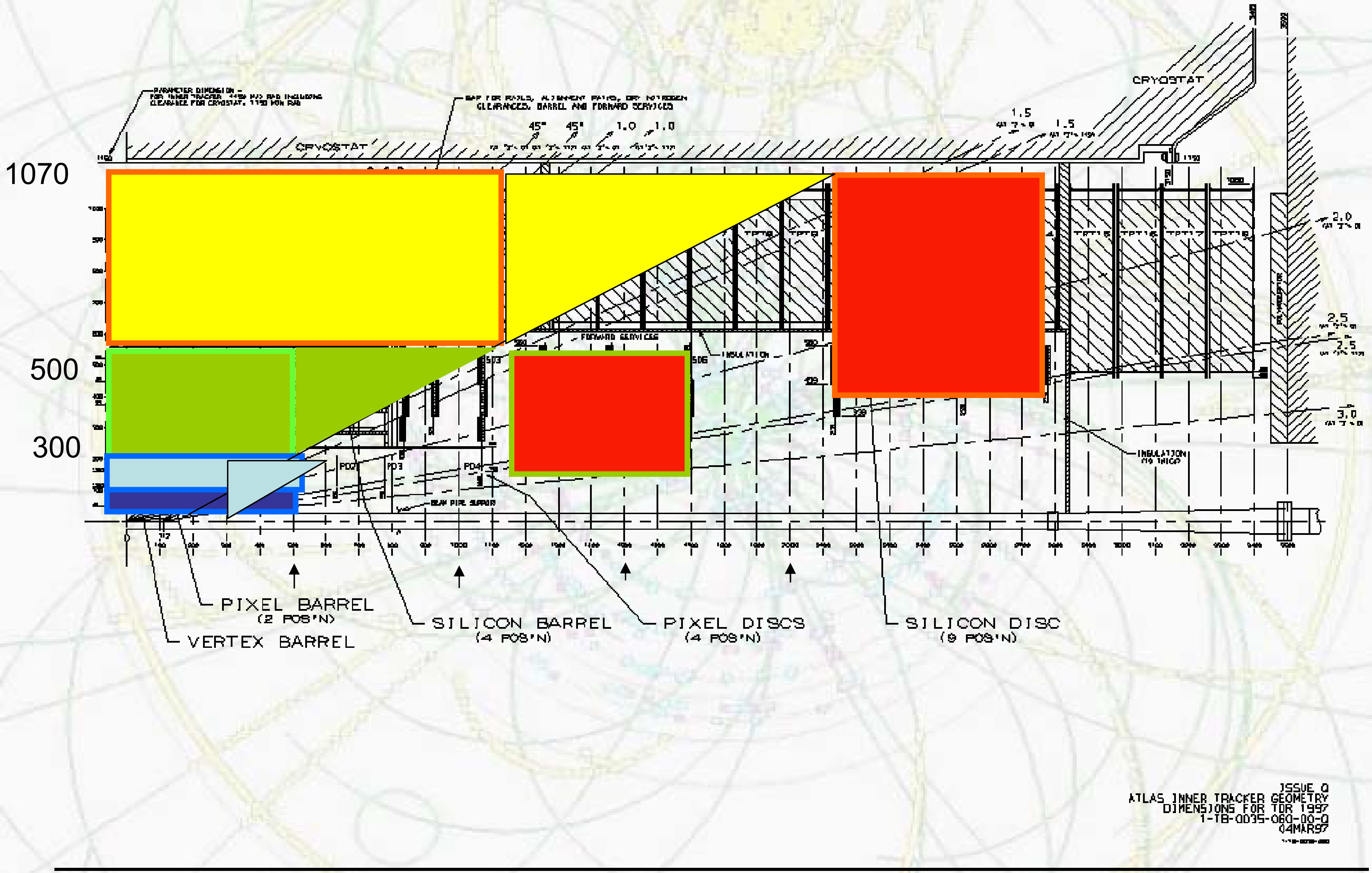


Long barrels option

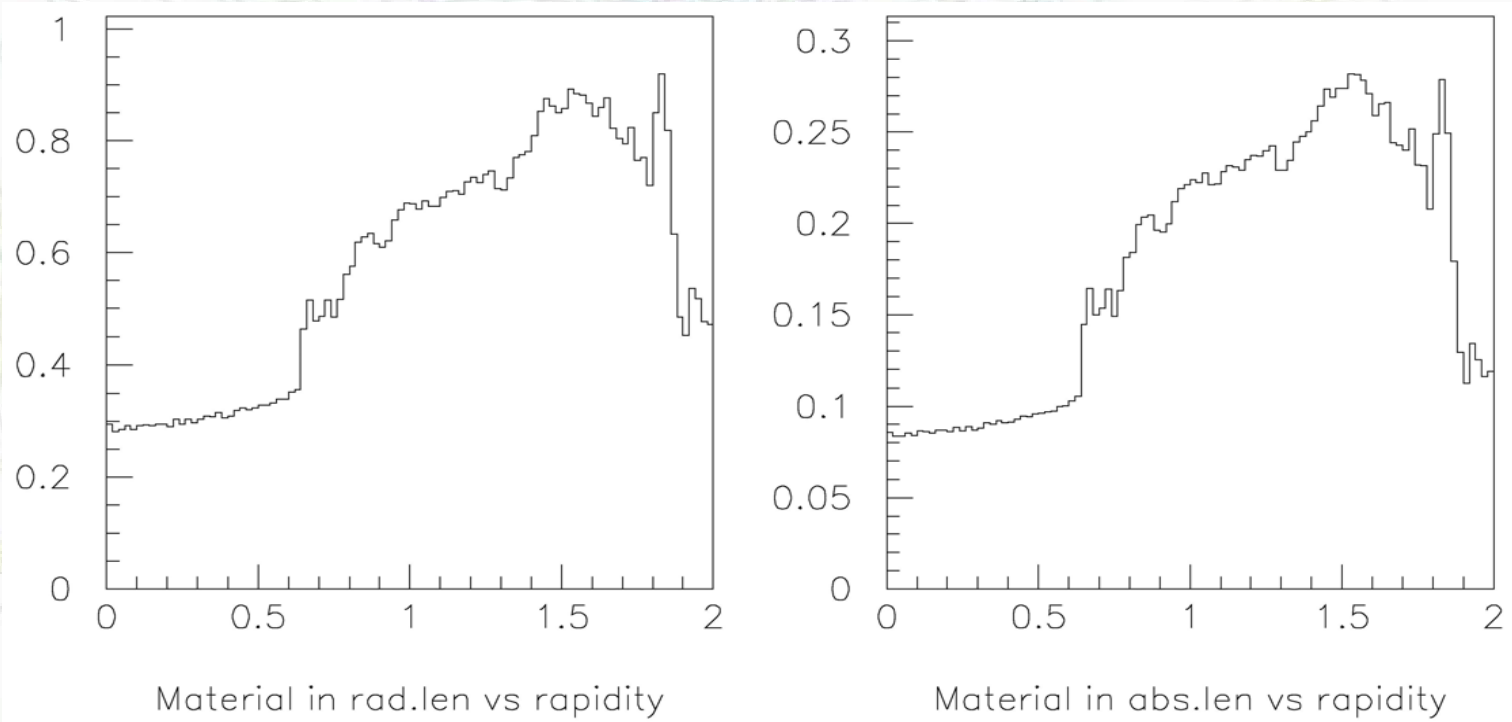


May be interesting due to the significant increase of the LHC beam interaction region (5.6 cm => ~50 cm !)

tapered barrels option



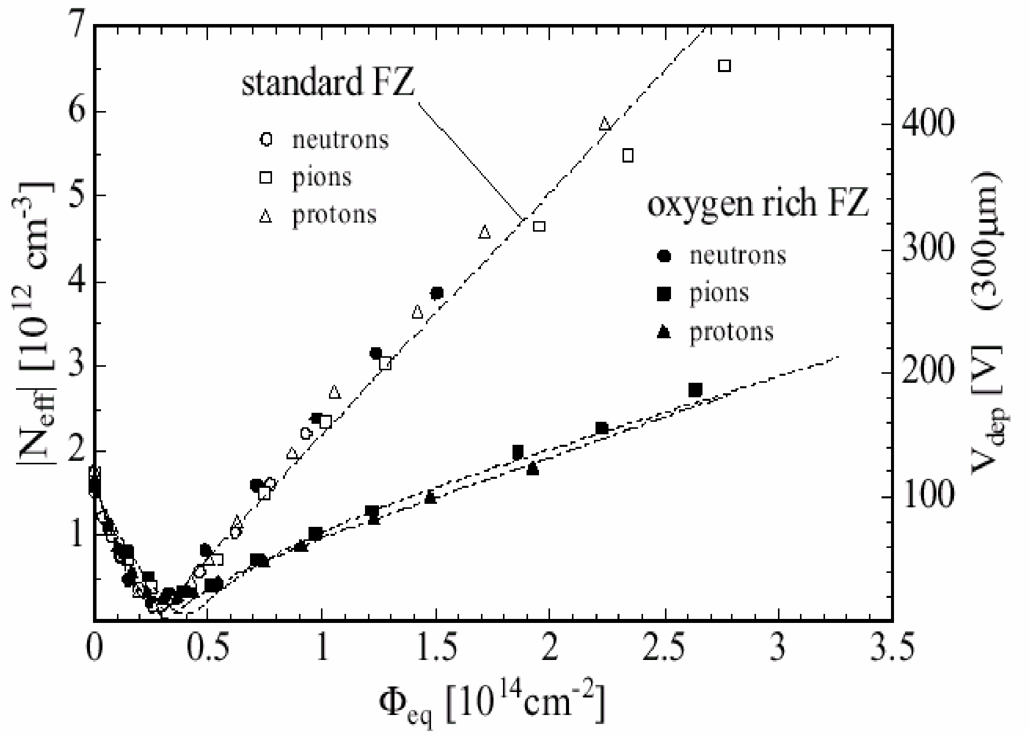
Updated Inner Detector Material



Radiation Hardness Issues at Very High Dose

For standard microstrips:

- Reverse currents rise.
- Trapping increases.
- Bulk type inverts to effectively p^--type.



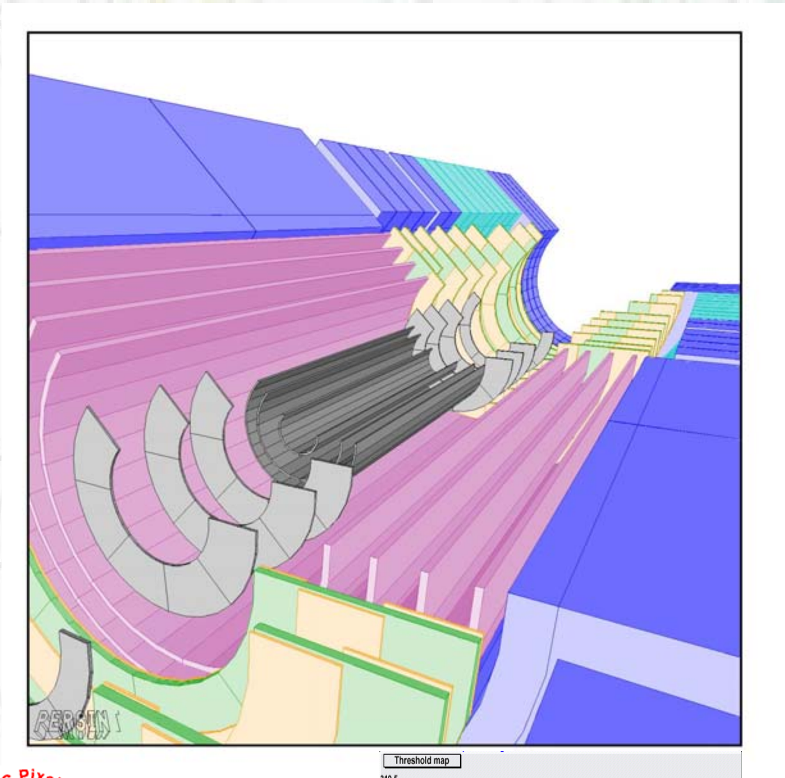
→ n^--type detectors with p^+-strip read-out continue to function but, with dose, become increasingly difficult to operate significantly under-depleted with good efficiency.

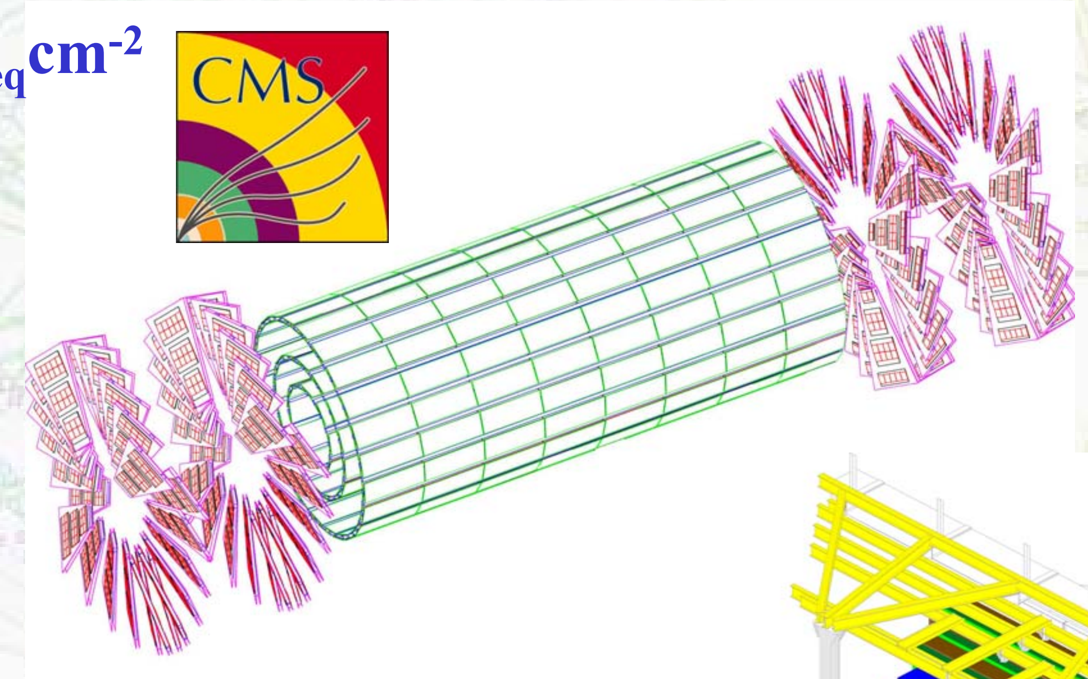
n^--bulk detectors with n^+-strip read-out perform better at higher doses due in part to the high field side now being at the n+-implanted contacts, *but due mostly to collecting electrons rather than holes* (3×faster collection so ~3×less trapping).

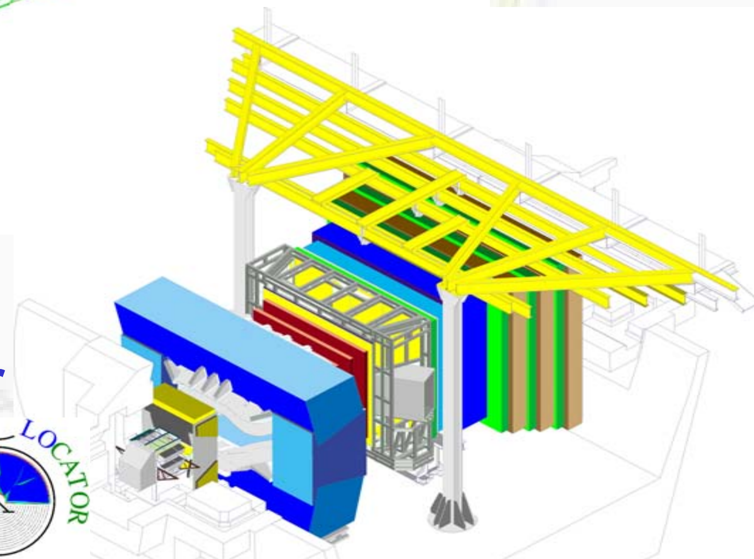
N-Side Read-out Detectors

Examples of n^+ in n^- Readout at the LHC:

- **Because of these advantages, the highest dose detectors at the LHC (ATLAS and CMS Pixels and LHCb Vertex Locator) have all adopted n^+ in n^- and the pixel layers could probably do so again (or n^+ in p^-) for doses up to at least $5\times10^{15}\ n_{eq}cm^{-2}$**

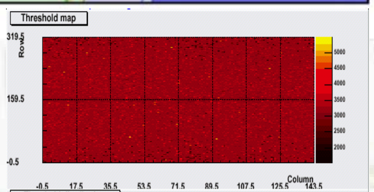




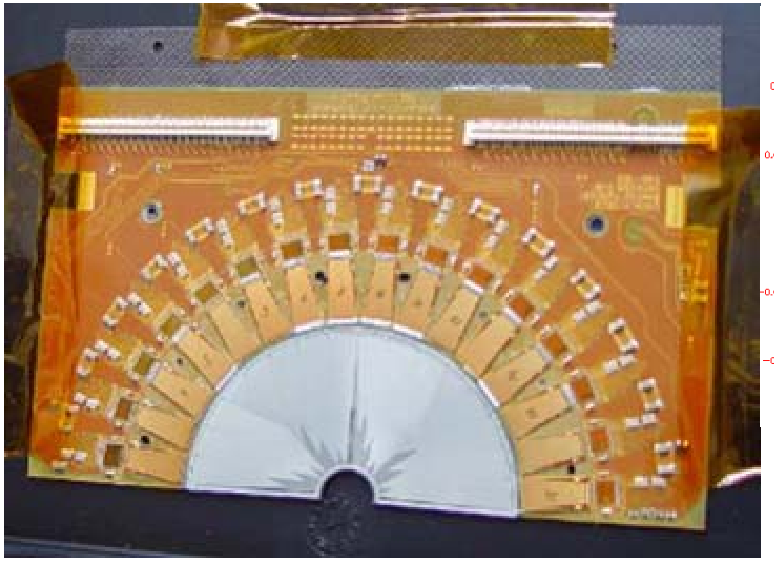


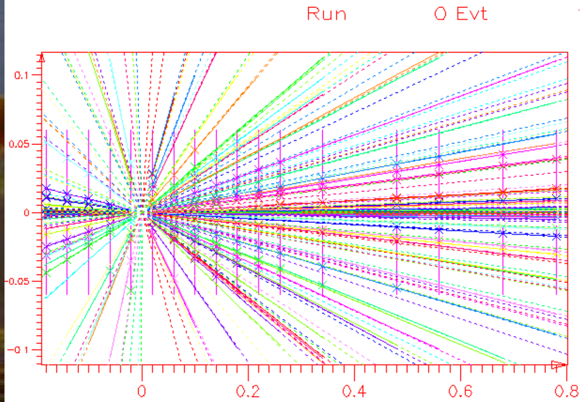
LHCb
Vertex Locator
Z(mm)=0-990

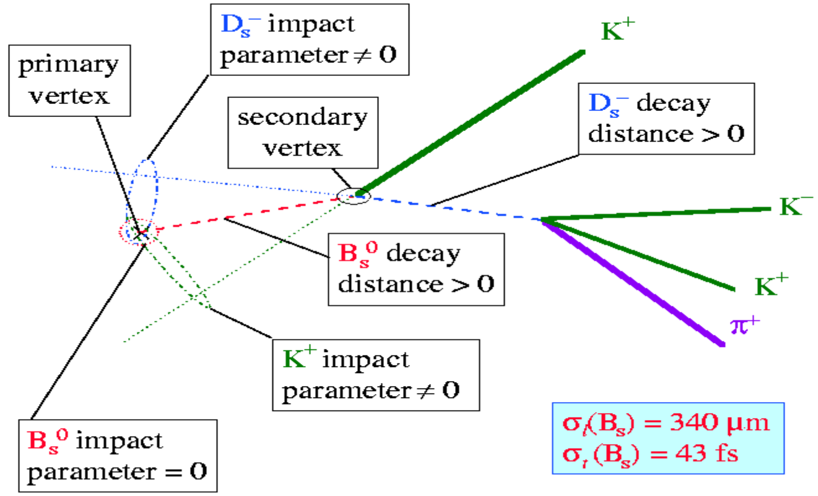
ATLAS 100 million Pixels

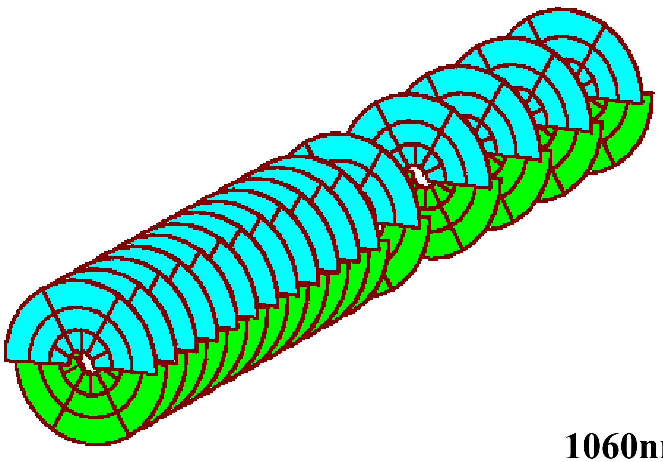


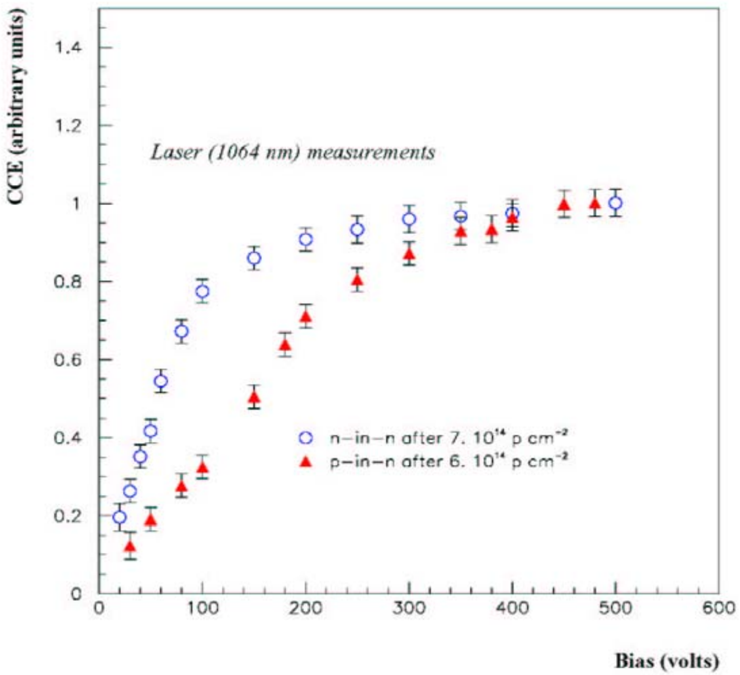
LHCb n-in-n Vertex Locator



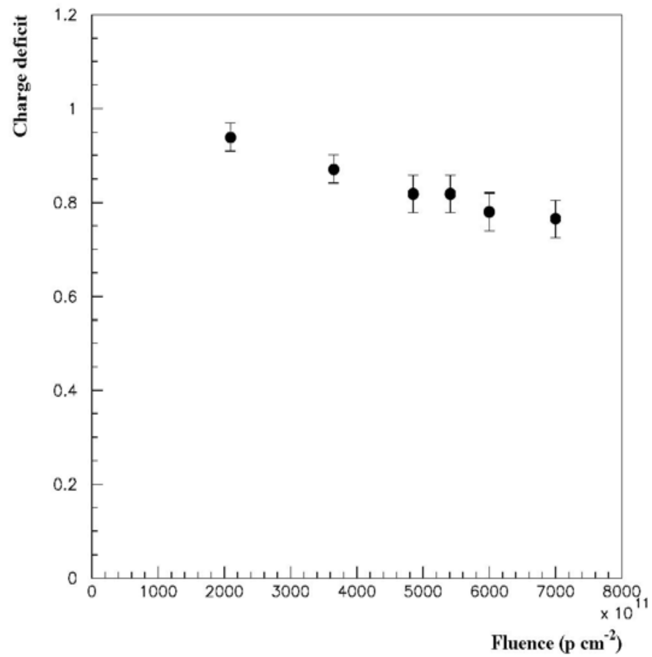








1060nm laser relative CCE(V) for the highest dose regions of irradiated oxygenated n-in-n (7×10^{14}p/cm^2) and oxygenated p-in-n (6×10^{14}p/cm^2). LHC-b full-size prototype detectors.



^{106}Ru β-source CCE at high voltage *vs* dose for the LHC-b n-in-n prototype

Motivations for P-type

Starting with a p^--type substrate offers the advantages of single-sided processing while keeping n^+-side read-out:

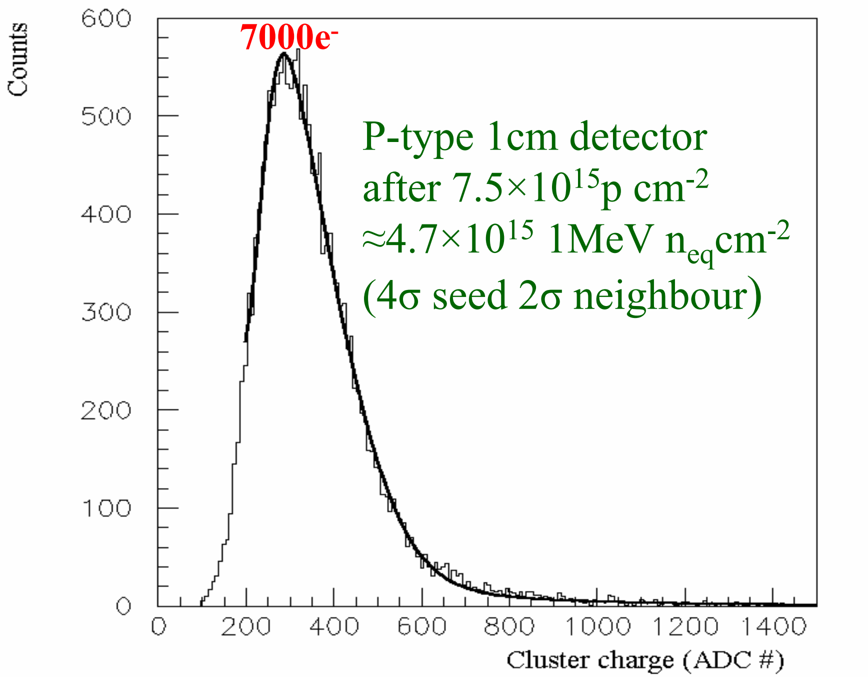
- **Processing Costs (~50% cheaper).**
- **Greater potential choice of suppliers.**
- **High fields always on the same side.**
- **Easy of handling during testing.**
- **No delicate back-side implanted structures to be considered in module design or mechanical assembly.**

So far, capacitively coupled, polysilicon biased devices fabricated to ATLAS mask designs with Micron Semiconductor Ltd (full size: 6cm×6cm) and Centro Nacional de Microelectronica, CNM (miniature: 1cm×1cm)

Recent n-in-p Results

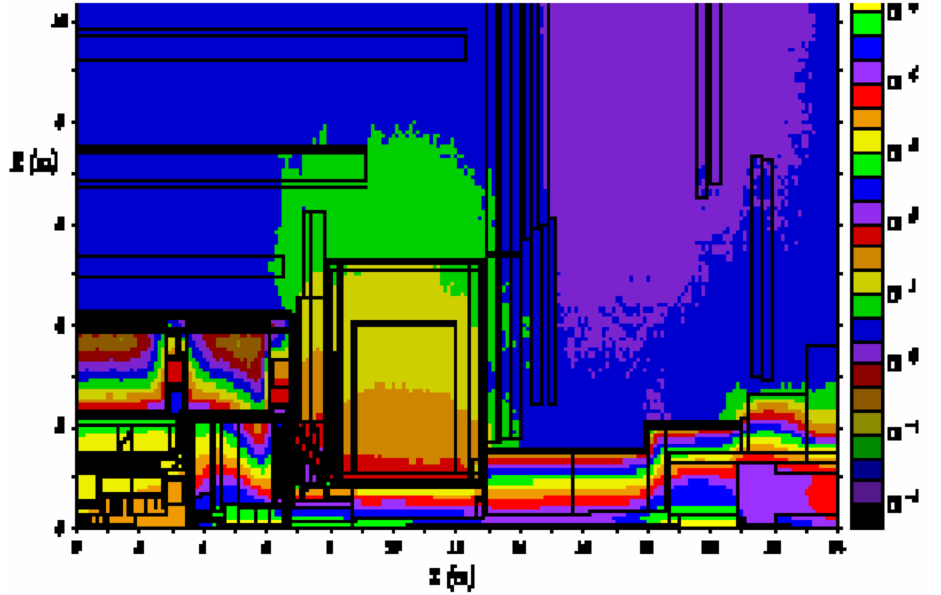
At 30cm, the expected annual 1MeV neutron equivalent dose at ten times LHC in ATLAS is expected to be ~1.6×10^{14} cm^{-2}.

A conservative target for SLHC operation would be survival of 3×10^{15}p cm^{-2} (2×10^{15} cm^{-2} 1MeV neutron equivalent), with S/N > 10 at 500V operation.

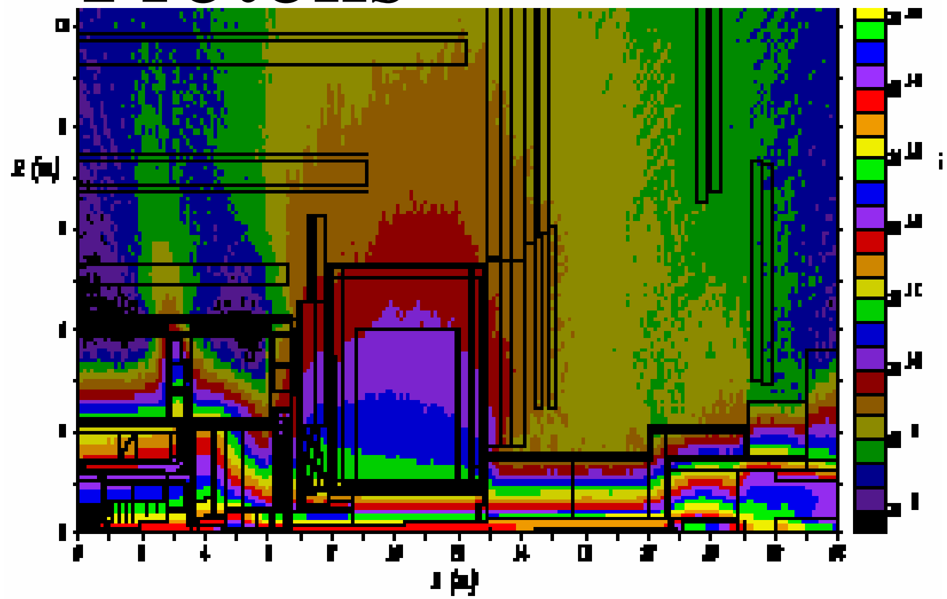


Pulse height distribution of a miniature n+-in-p detectors with ^{106}Ru β-source, after exposure at the CERN-PS to 7.5×10^{15}p cm^{-2} *i.e.* 20 times the dose at the end of currently anticipated LHC running.
The peak corresponds to a signal at 850V of 7000e- with LHC speed electronics.

Neutrons

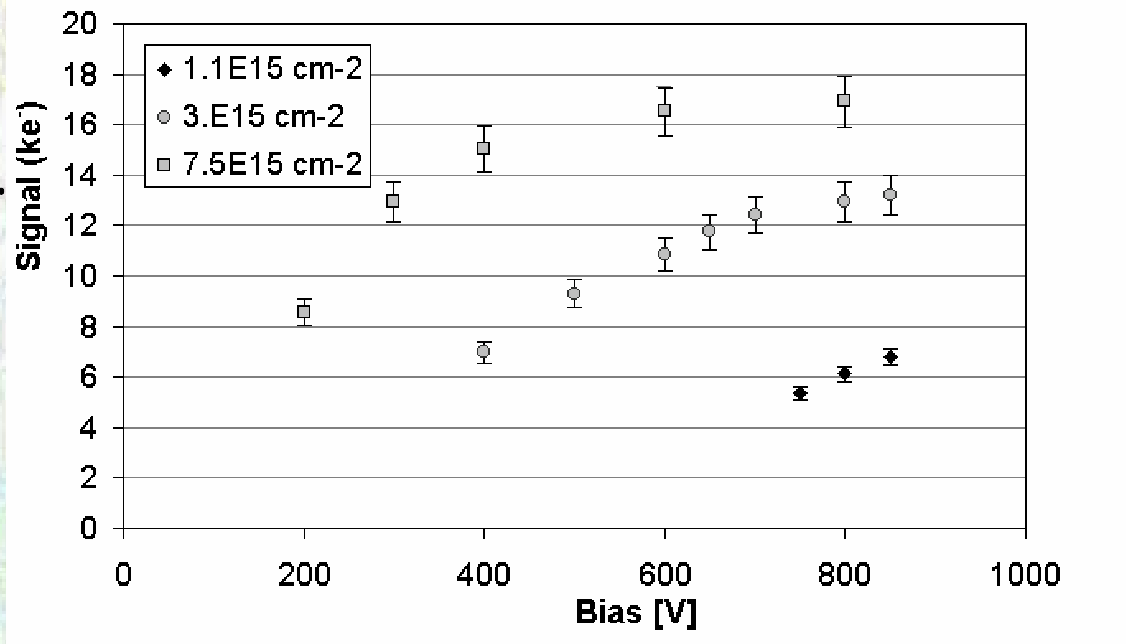


Protons



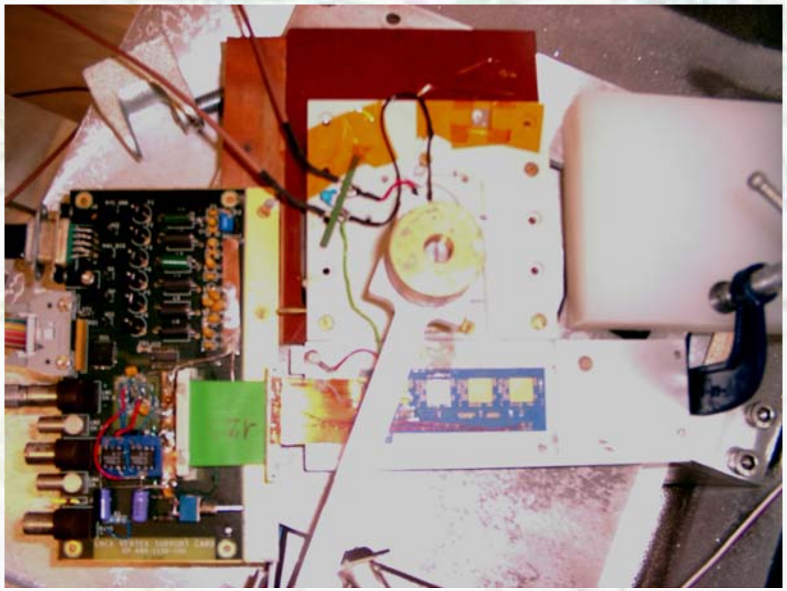
Recent n-in-p Results

Even if the noise is considered not to improve with future electronics, the data at 3 ×10^{15}p cm^{-2} (2 ×10^{15} cm^{-2} 1MeV neutron equivalent), shows an S/N for 3cm strip length (20% more noise for SCT128a → 930enc) of >10 could be achieved with 500V operation at 30cm radius even after 10 years of high luminosity running by using n-in-p technology.

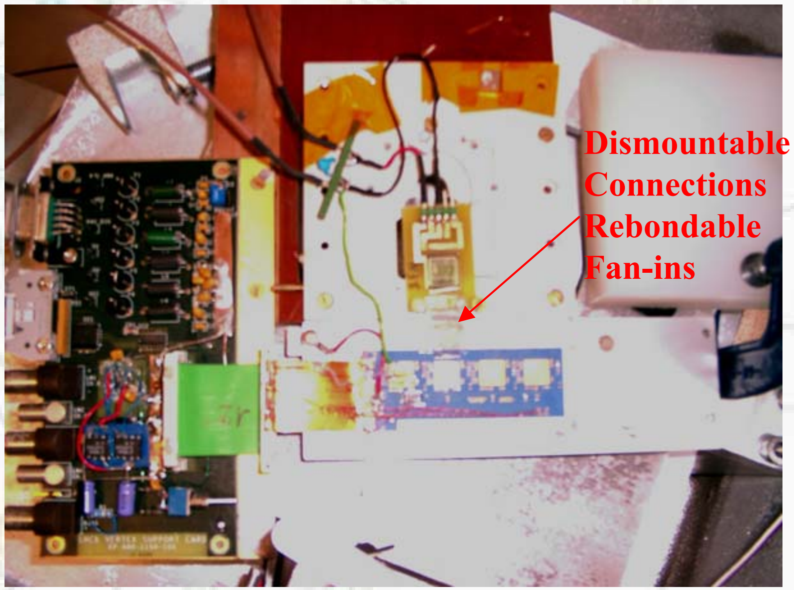


Measurements using mip from ^{106}Ru β-source, triggered with scintillator.

Highest dose detector operated at -25°C to control thermal runaway.



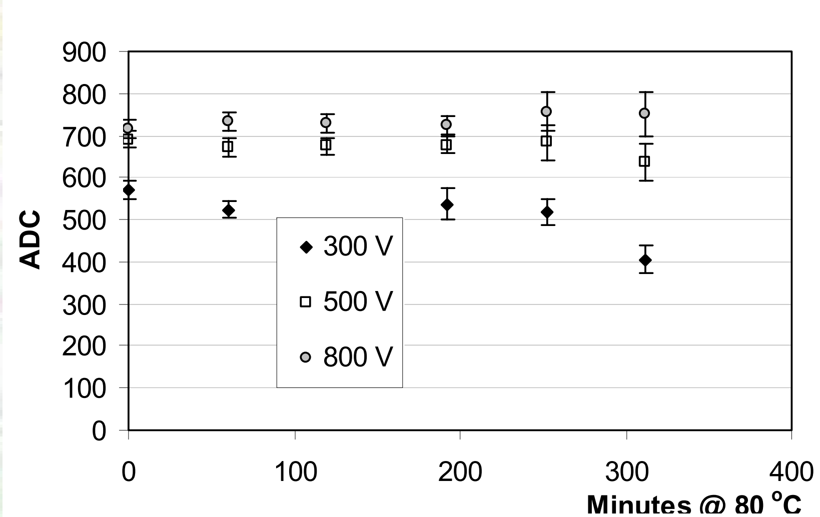
SCT 128a Test Stand at Liverpool

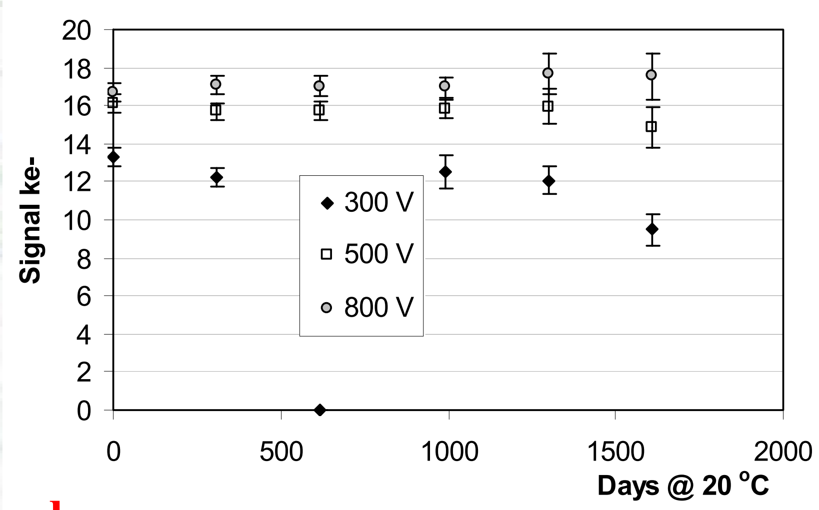


Test Stand without ^{106}Ru β-Source

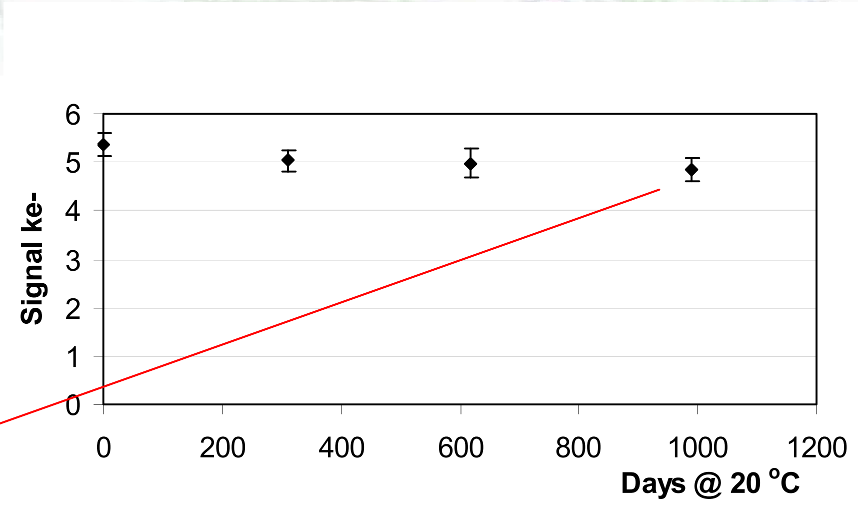
Recent n-in-p Results

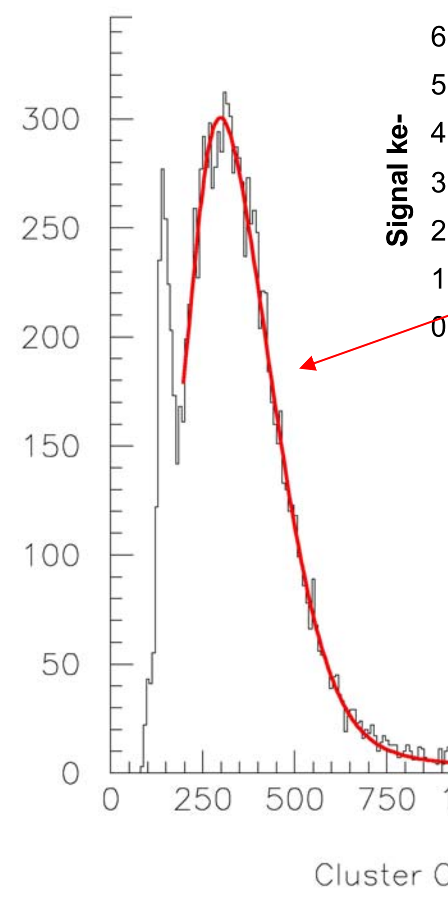
Important to check that no unpleasant surprises during annealing.
Minutes at 80°C converted to days at 20°C using acceleration factor of 7430 (M. Moll).





Detector with 1.1× 10^{15} p/cm²

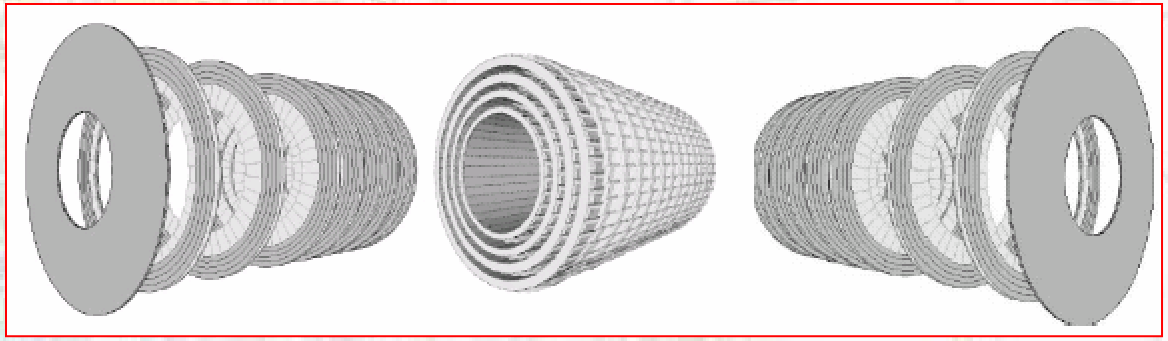




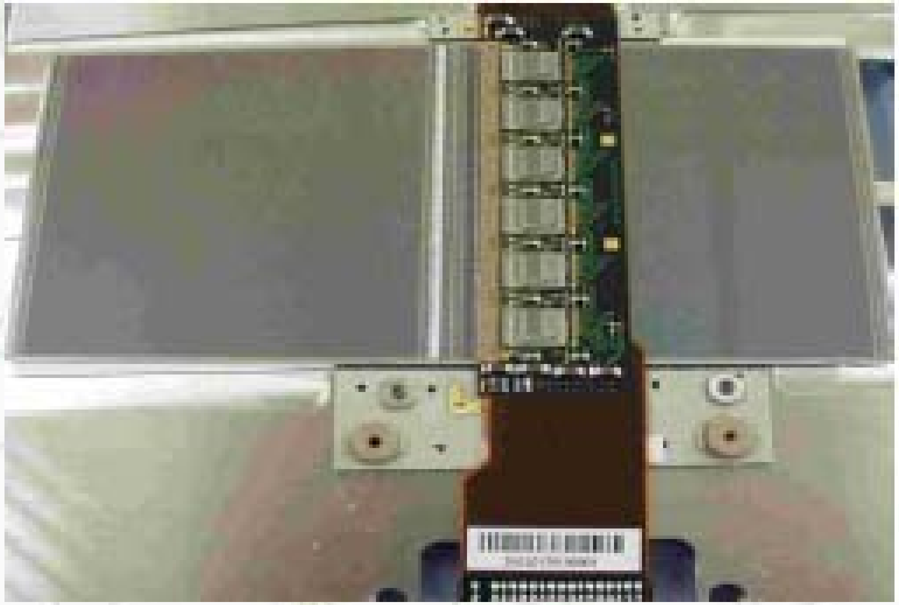
Detector after 7.5× 10^{15} p/cm² showing pulse height distribution at 750V after annealing. Here the seed cut was dropped to 3σ with 2σ for neighbours. (Landau + Gaussian fit)

Possible Super-LHC Module Design

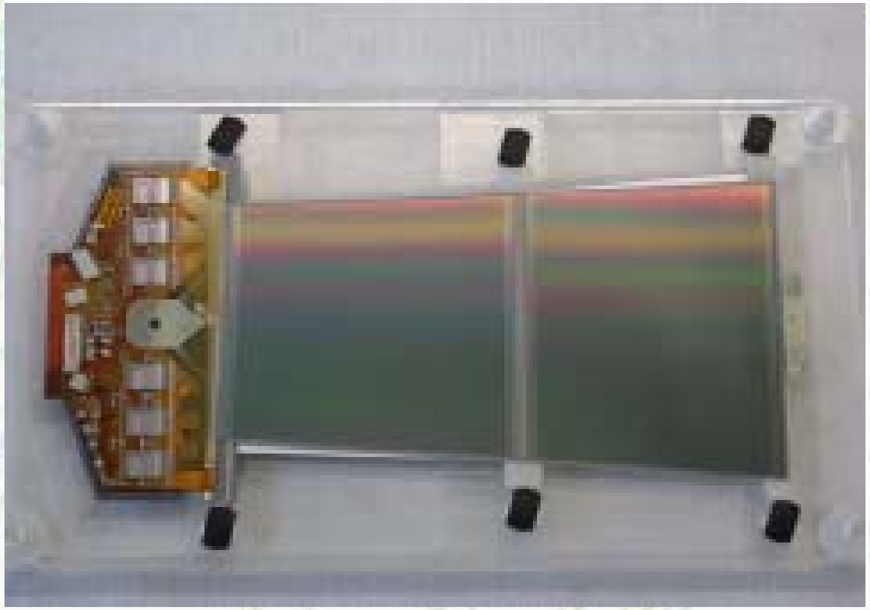
ATLAS Tracker Based on Barrel and Disc Supports



Effectively two styles of modules (with 12cm long strips)

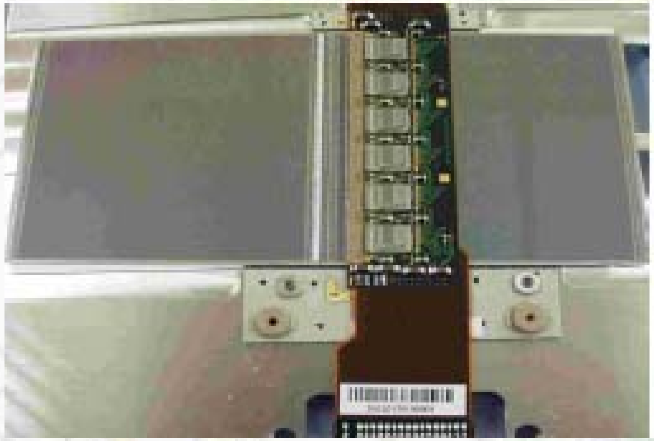


Barrel Modules



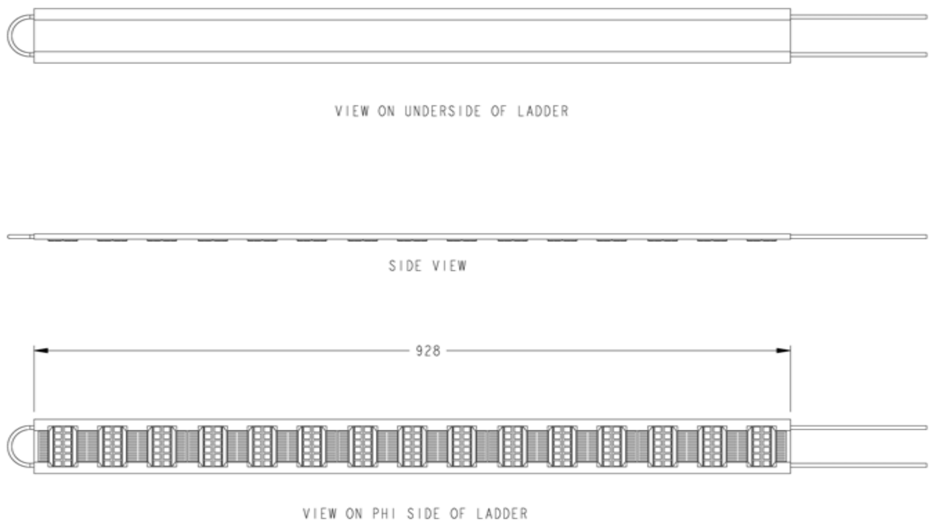
Forward Modules

Possible SLHC Module Design

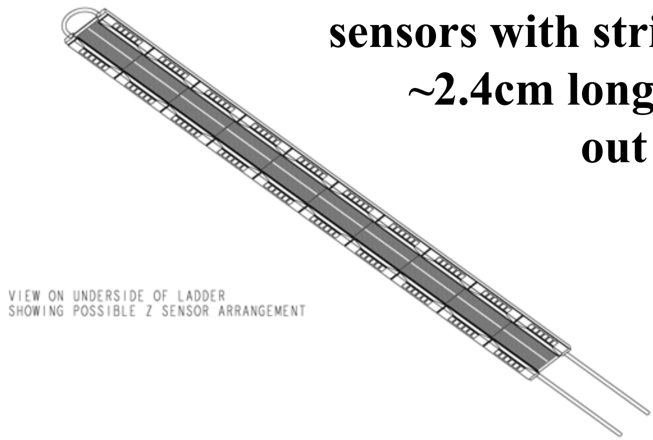


Barrel design with bridging structure for hybrid and TPG baseboard lends itself to a possible SLHC 'Stave' concept based on 62µm pitch (φ) and 114µm (z) 9×5cm single-sided detectors (2 per 6" wafer).

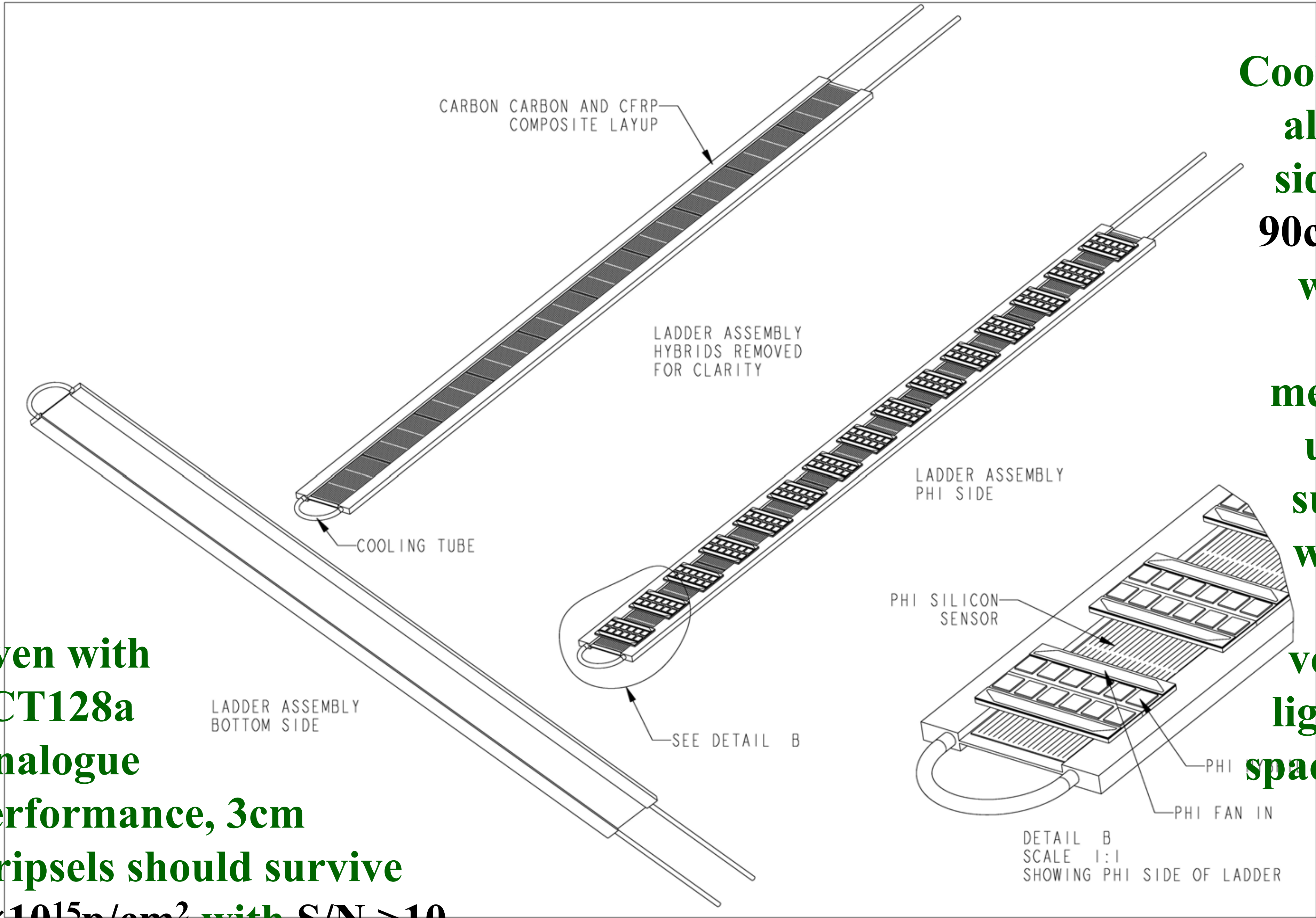
Φ-side of proposed 1m stave with ten 9cm long sensors each divided into 3 rows of 768 stripsels



Possible z-side of proposed 1m stave with ten 9cm long sensors with stripsels ~2.4cm long read out from each side



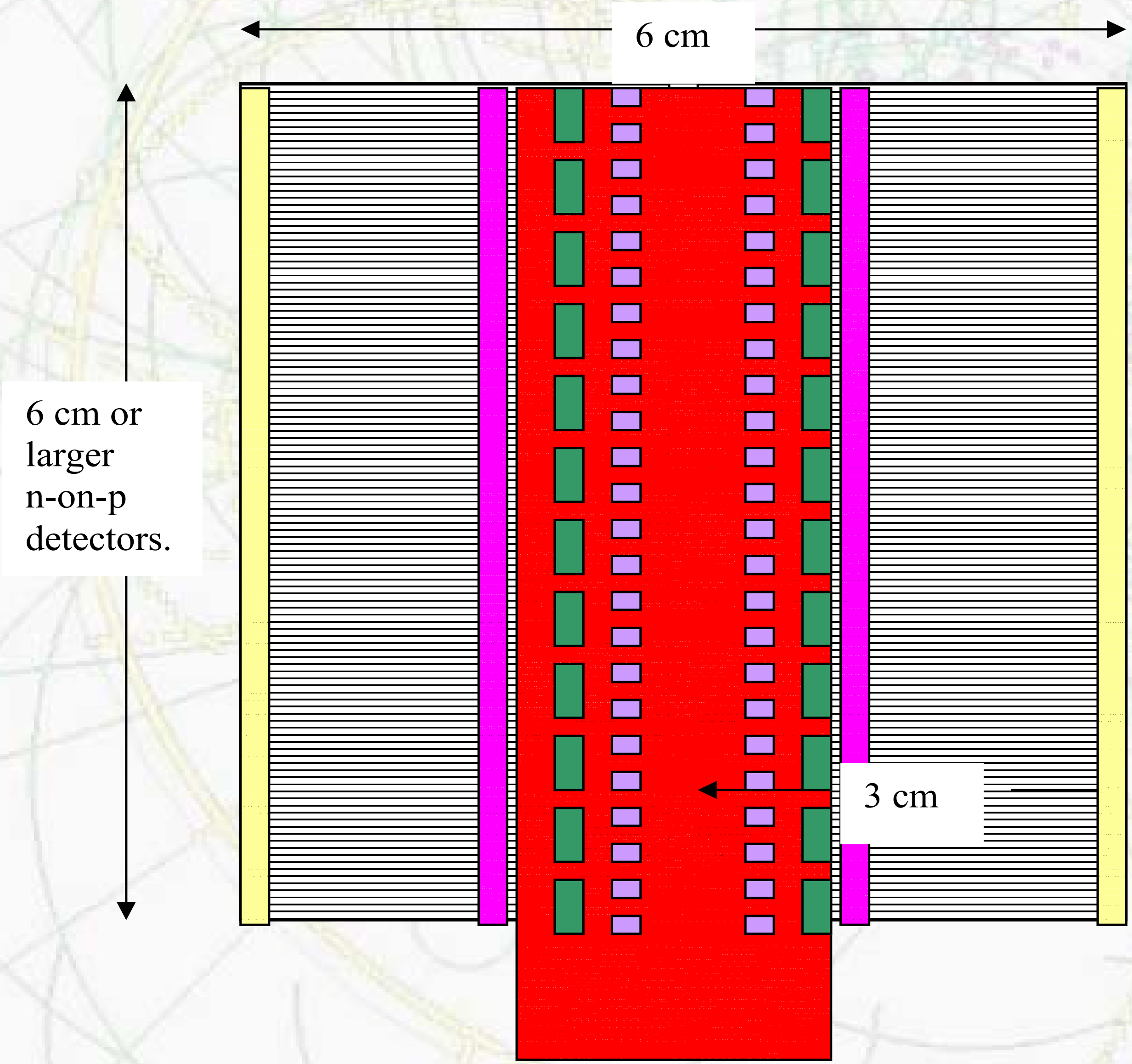
Possible SLHC Module Design



Cooling runs along both sides of the 90cm staves which are the basic mechanical unit to be supported within the tracking volume on lightweight space frame.

Even with SCT128a Analogue performance, 3cm stripsels should survive 3×10^{15}p/cm^2 with S/N >10

Alternative Mid-Radius Stripsel Detector

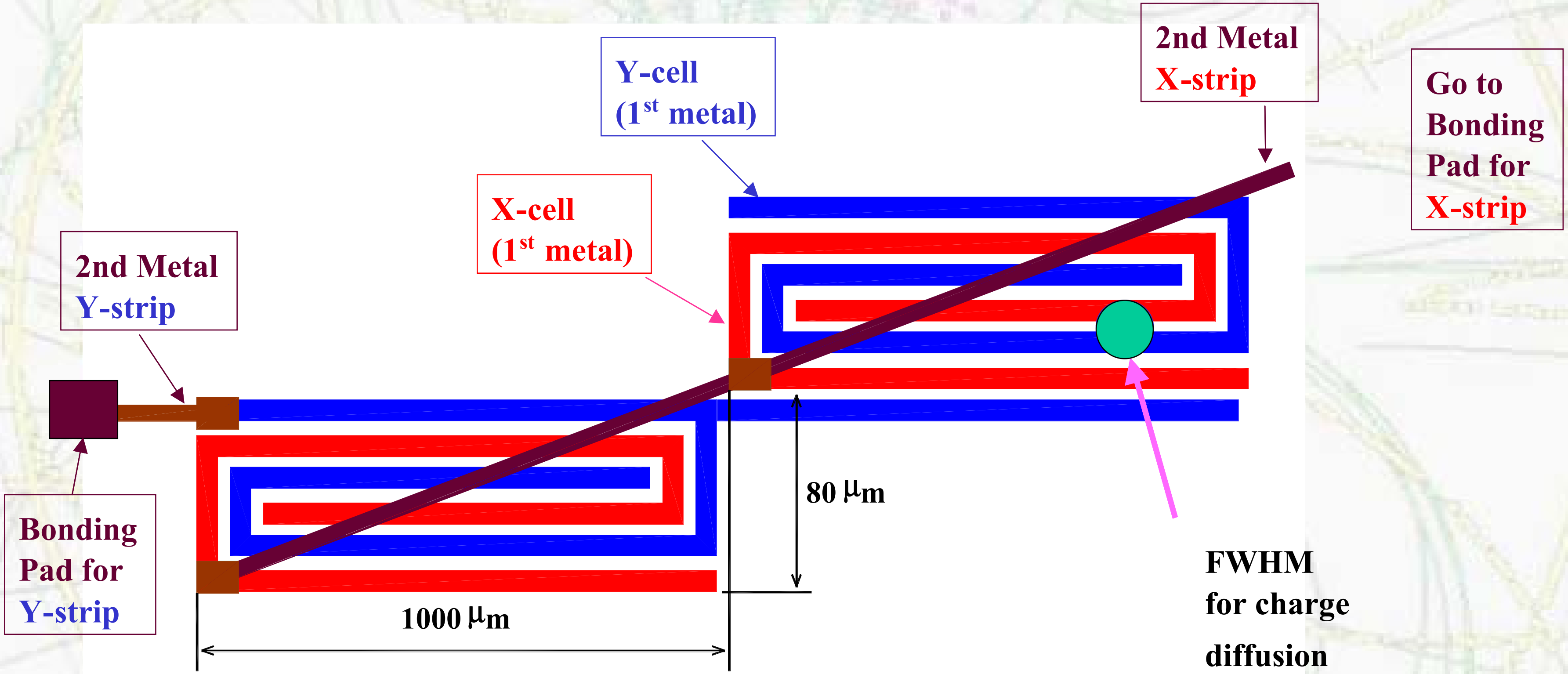


Abe Seiden

Requires stereo layers to measure z-coordinate. For 100 μm x 3 cm strips, results in 1.3 x 10^7 channels for global layout. If hybrid picks up stereo detectors (supermodule), results in about 5,400 modules, 30% more than present SCT.

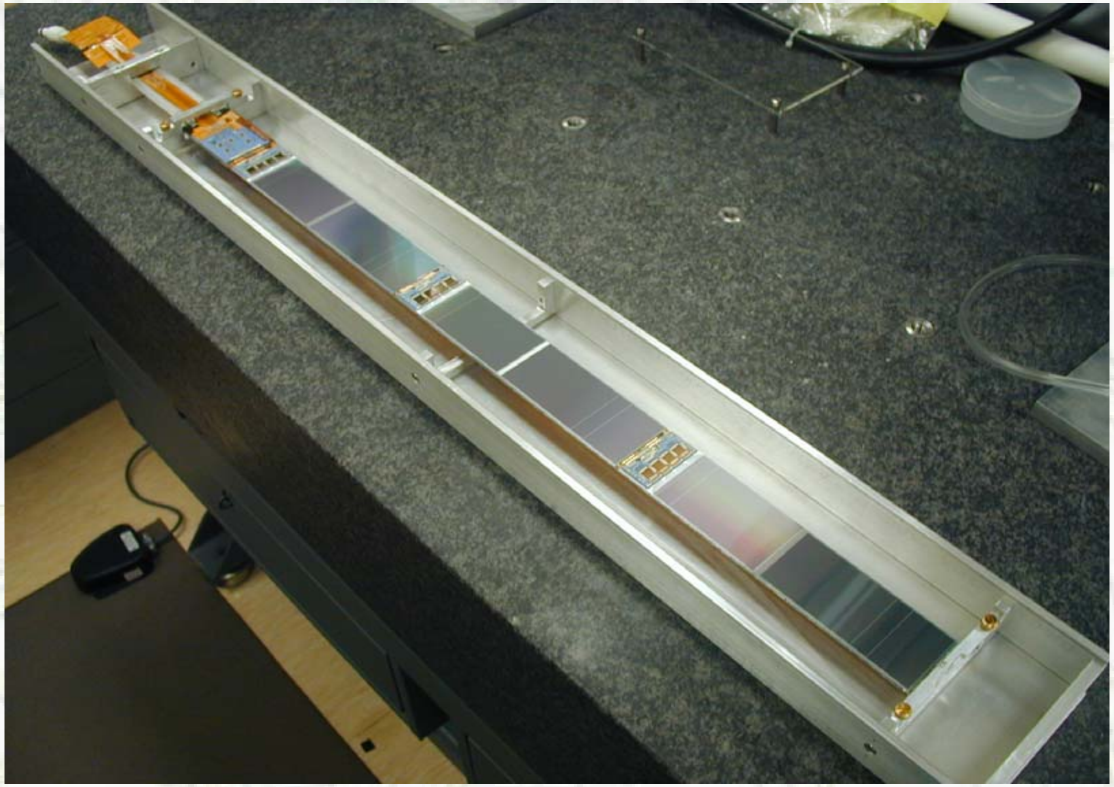
Options for Mid Radius: Stripixel Detector

Z. Li, D. Lissauer, D. Lynn, P. O'Connor, V. Radeka



Smaller signal would require shorter detector to have adequate signal-to-noise. Assuming a 100 µm x 2 cm strip length, global layout has 10^7 channels. Challenge: signal-to-noise due to additional capacitance of detector and splitting of signal between two readouts.

Global Integration



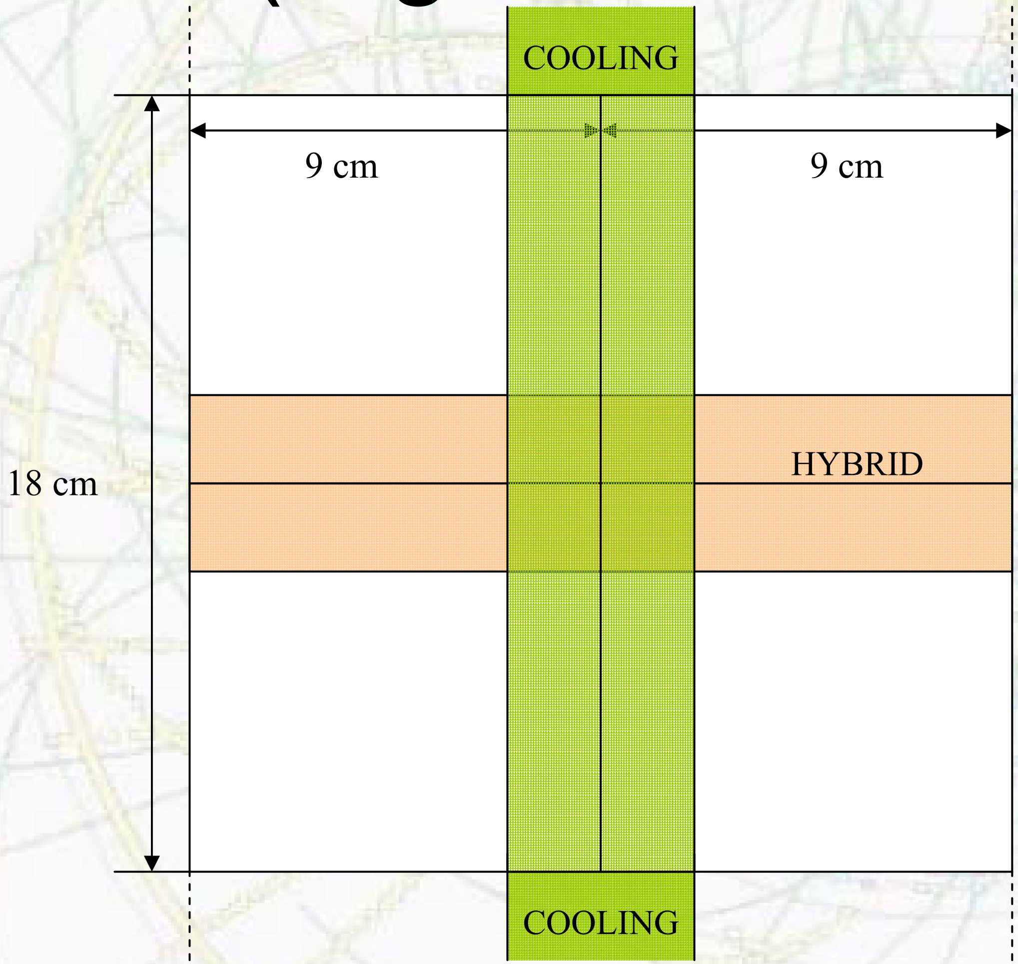
CDF Stave

Can we make use of large amount of work already done?

But thermal issues much more severe at SLHC doses

Module Level Integration

(High Radius Supermodule)



Units matched to 6 inch wafer to minimize costs.

Abe Seiden

Number of supermodules for global layout ≈ 2400, similar to present SCT barrel.

Lesson Learned
Inner Detector

ATLAS Upgrade R&D Meeting

February 13,2005

M. Gilchriese

Goals and Flexibility

- Nominal goal of upgrade R&D and later production is complete replacement of Inner Detector for the SLHC by roughly a decade from now.
- Earlier replacement of B-layer is likely to be necessary and could be a step to part of the SLHC upgrade.
- However, the path from our current situation to 10^{35} may not be so straightforward
  - C wheel region?
  - TRT performance sensitive to peak luminosity (limit?) not just integrated luminosity
  - Can easily imagine circumstances (mistakes, unforeseen beam-loss accidents) that reduce lifetime of pixels, for example
- Can't plan for all possibilities but….
- *Lesson: need some flexibility in the R&D planning and regular updating of R&D goals. Full replacement of the ID may not be the only goal. May occur in stages.*

Timescale(I)

- You all know that R&D for ATLAS started 15+ years ago eg.

  TASK FORCE ON DETECTOR R & D FOR THE SSC: **PRELIMINARY REPORT.**(SSCL), SSC-SR-1009, May 1985. 24pp.

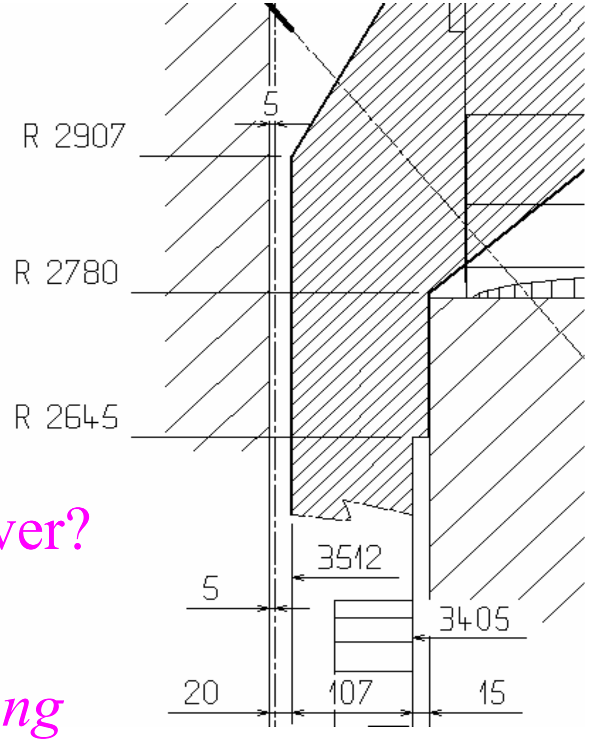
- We wont really know until how well this all worked until some data are accumulated – a few years from now.
- Although we surely know more than circa 1990, our experience suggests fundamental R&D takes a very long time.
- If ~ 2015 is taken seriously, then time is really short!
- *Lessons*
  - *Minimize fundamental R&D. Only where really needed*
  - *Minimize shootouts, make decisions early whenever possible*
  - *In my opinion, implies a much more directed structure than was the case in the very early days of ATLAS*

Timescale(II)

- For the SLHC, the outer region (roughly the current TRT region) requires mostly D and, in principle, not much R.
- The construction time, not including R&D and much of the engineering design, is likely to be >5 years. > much more probable than 5 under the likely practical constraints (people, funding,….)
- *Lesson: Actually opinion. Start early on this region. Most of the silicon. Nucleus of overall engineering and systems design. Minimize research, emphasize construction feasibility, cost and schedule.*

Technical Constraints(I)

- Cryostat
  - Current ID with services is a very tight fit. In retrospect, too tight.
  - *Lesson: Increase clearances. Leave more room or don't commit to active layout unless services are very well understood*
- The Gap
  - A pain. Let's hope it works.
  - *Lesson: More clearance. Boundary condition on design from earliest stage. Increase gap?*



- Services replacement
  - Can we really afford to replace everything and start over?
  - How to tell?
  - *Lesson: services constraints must be integral and strong part of design effort from earliest stages*

Technical Constraints(II)

- Insertable part
  - Currently we have support tube for pixels so that, in principle, it can be removed and (re)inserted.
  - Do we want to do this again? Probably. Conservative solution, since technology may not be found to survive many years at 10^{35}. But at some considerable cost in complexity of services routing and mechanics.
  - *Lesson: Original ID design did not have this option and much time and money lost moving to insertable system. Decide early. Default?*
- Integrated beampipe
  - Do we want to do this again? Connected with above point.
  - Activation implications (for access)?
  - Most conservative would be both insertable system near beam pipe but not integrated beampipe. But may have performance implications.
  - *Lesson: Early constraint in layout – radius of innermost layer, which determines (largely) impact parameter resolution. Work on this early.*

Technical Constraints(III)

- Reliability
  - We have a very complex system and don't know much at all about it's reliability.
  - Maintenance is nearly impossible. Repair is very difficult.
  - This wont get better for the SLHC
  - *Lesson: We may get lucky and reliability will be OK but for now would plan on much more systematic approach to reliability issues, particularly for services.*
- Services modularity
  - Not just one PS per module or similar, but many pieces in the chain for each module.
  - Has major impact on ID material budget and many practical complications
  - Interesting ideas (serial power, DC-DC converters) being explored to reduce modularity. However, see point above about reliability.
  - *Lesson: Be much more aggressive about development, including reliability, of concepts to reduce modularity. For now this should be the default goal. Of course, we may change our mind when have operational experience, but easier to drop something than wait to do R&D.*

Technical Constraints(IV)

- Cooling
  - Choice of cooling technique (liquid or evaporative) has major impact on mechanical support design and connections to silicon modules (of any type). A some point cannot proceed until cooling medium is known.
  - Ideally, we would wait until we have real operational experience with evaporative cooling. Maybe we will have this by 2006 certainly by 2007. One could argue that since evaporative has to work for current ID, just go with it in the future.
  - *Lesson: Make this choice as early as possible. Uniform system default.*
- Operating environment
  - Since all silicon, perhaps will take care of itself.
  - *Lesson: Common design for operating environment (gas, humidity, etc)*

Engineering Design and Organization

- We have built up a very significant engineering (mechanical and electrical) organization. It took a decade.
- My impression is that it's just enough and just in time in almost all cases but wont know for sure for a few years. For sure manpower too tight, not enough flexibility to move from subsystem to subsystem as problems develop.
- Coordinating (some systems) engineering came late to the project.
- Replacement ID would greatly benefit from starting off with a coherent, integrated design, including systems and reliability aspects, rather than as a loose collection of engineers connected to parts of the new ID. In short start with an <u>ID</u> organization and not pixels, short strips, long strips…….
- There needs to be a balance between new ideas and concepts and the need to address systematically many interrelated issues.
- *Lesson: Start with coherent ID engineering organization tasked (eventually) to look at all aspects of engineering for replacing the ID. Then break down into deliverables.*
- Note: This will be very difficult to organize soon. Experienced ID engineers still busy. What about engineering outside the ID community (are there any)? Fresh look, not biased….don't know what they are getting into…

Construction Organization(I)

- First we should acknowledge that the ATLAS ID construction organization is working.
- So why consider changes?
- One, we have a lot of experience and should benefit from it
- Two, the scale of the silicon project for the ID replacement is about 4 times (maybe more) larger than what we have done => current techniques don't work fast enough. ATLAS module assembly/test average rate will end up to be about 2K/year(adding SCT+pixels)
- Three, the availability of personnel (physicists) is likely to be less than we have had in building ATLAS.
- Four, the timescale may be shorter (we don't really know)

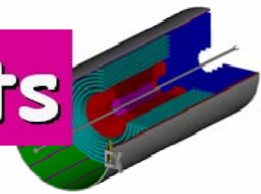
Construction Organization(II)

- The CMS silicon strip tracker is roughly the same scale as the ID upgrade. What can we learn from their experience?
- Overall organizational scale (working centers) similar to ATLAS but
  - Started off with more centralized organization of techniques for module assembly/test.
  - More commonality
  - Rate is 5or more times ATLAS via robotic assembly. Average rate planned is expected to end up at about 10K/year
  - Tolerances (I believe) are looser.

distributed module production

4 Si sensors quality assurance centers
2 Si sensors irradiation facilities
2 centers for FE hybrid assembly/bonding (40/day)
7 module assembly centers (Gantry) (>90/day)
13 bonding centers and QA&C (>130000/day)

43 major working points



10 centers where module are installed into mechanical supporting structures
4 centers where sub-detectors are assembled
1 Tracker assembly center

M. Gilchriese

Cattai at Hiroshima Symposium 2004

Construction Organization(III)

- Both ATLAS and CMS have imposed some degree of industrial order on the collaborating institutions (or have used industry eg. in Japan).
- Is it time to go the next step and actually mostly use industry for module assembly, wire bonding etc?
- Will we be forced in this direction because not enough institutions are interested in building another giant silicon tracker soon? Rate too high for institutions? (CMS experience would suggest not).
- In any event, I believe we will likely follow a technical path similar to CMS: uniform robotic assembly, more distributed mechanical assembly,…..at least for most of the silicon. Will be different for smaller radius.
- *Lesson: Have construction organizational concept early in project*

Construction Organization(IV)

- Software (database and testing) has been an integral part of the construction. Uniformity, flexibility and maintainability of database essential.
- *Lesson: Don't forget this software aspect in the construction organization and again needs to start early.*
- It should also be emphasized that fabrication of the silicon sensors can only be done in a few companies.
- *Lesson: It's imperative to maintain a relationship with these companies and this means, I think, buying significant amounts of silicon as part of the development process.*

Finances and Organization

- Our current mode of operation has a minimal common fund element and a maximum institutional element.
- The three ID subdetectors started as largely separate projects in their financial organizations.
- The PLs are, I believe, in agreement that the common fund element needs to be increased for the next ID.
- It would also be beneficial if the common fund element contained some aspects of contingency.
- *Lesson: Agree on the financial structure and definition of deliverables early in the project and in a uniform way across the different ID subdetectors.*

Conclusions

Phil Allport

- Need to confirm FZ p-type results and test with neutrons
- Need to cross-check results with CCE models
- Need to encourage Hamamatsu to prototype on p-type
- Desirable to reduce voltage (power) so p-type Cz or epitaxial of interest, if might be adopted commercially
- For module designs, need to know required z-resolution
- Need detailed thermal simulations of module options
- Need prototype readout and enc(C_{in}) to optimise sensors
- More work on layout and pattern recognition required
- Management structure and decision process to be defined
- Project needs to start now if 2015 to be achieved