ATLAS at the Super-LHC

Phil Allport

Sixth International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors
Carmel Mission Inn, California
September 11-15, 2006

- Examples of Physics Gains
- SLHC Planning Status
- ATLAS Upgrade Requirements
- Short Strip Detector R&D Programme
- Conclusions

Examples of Physics Gain

(Physics case for **10 × luminosity** much better known after LHC start-up.)

See Eur. Phys. J. C39(2005)293

- **Precision Standard Model physics with 10 × data (sensitive to new physics)**
  - **Higgs couplings**
  - **Triple and quartic gauge couplings**
  - **Strongly coupled vector-boson scattering (if there is no Higgs)**
  - **Rare top decays through FCNC**

- **Extended mass reach for new particles (by ~0.5 to 1 TeV):**
  - **Heavy Higgs-bosons, extra gauge bosons, resonances in extra-dimension models, SuperSymmetry particles (if relatively heavy).**

- **SuperSymmetry (if relatively light, already discovered at LHC)**
  - **complete the particle spectrum**
  - **access rare decay channels and measure branching ratios**
  - **improve precision (e.g. to test against WMAP results)**

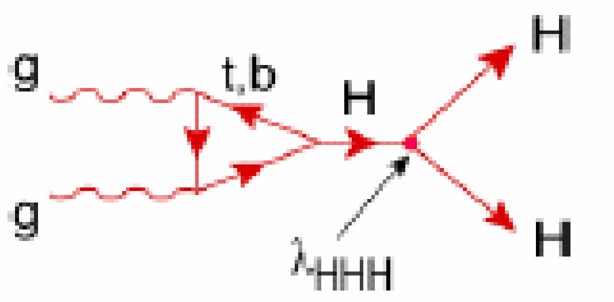
- **Because of statistics and mass reach, SLHC is to a large degree complementary to the ILC − only LHC/SLHC can pair produce particles with mass ≥ 0.5 TeV.**

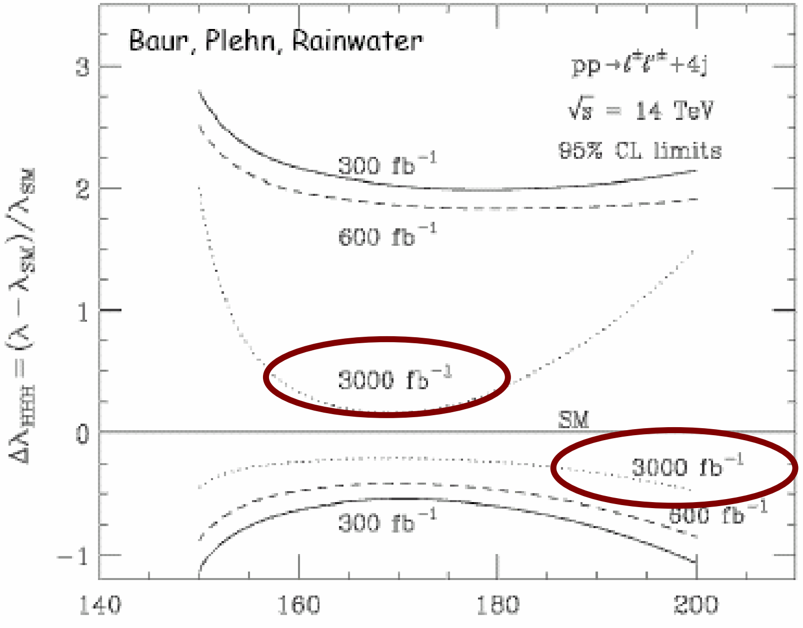
Examples of Physics Gain

Assumed SLHC Operating Parameters

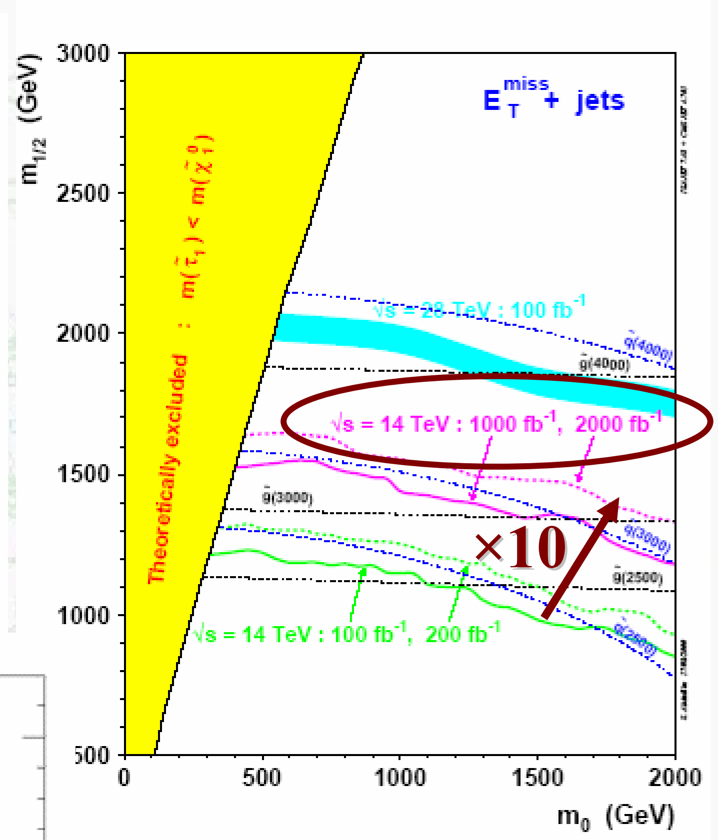
	LHC	SLHC	
$\sqrt{s}$	14 TeV	14 TeV	
Luminosity $\mathcal{L}$	10^{34} cm^{-2}s^{-1}	10^{35} cm^{-2}s^{-1}	
Bunch spacing Δt	25 ns	12.5 ns	assumed here (see below)
σ_{pp} inelastic	$\sim$ 80 mb	$\sim$ 80 mb	
Interactions/Xing N	$\sim$ 20	$\sim$ 100	
dN$_{ch}$/dη per X-ing	$\sim$ 150	$\sim$ 750	
$< E_T >$ charged particles	$\sim$ 450 MeV	$\sim$ 450 MeV	

Interactions/Xing: $N = \mathcal{L} \times \sigma_{pp} \times \Delta$





Sensitivity to variation from SM predictions for Higgs self-coupling



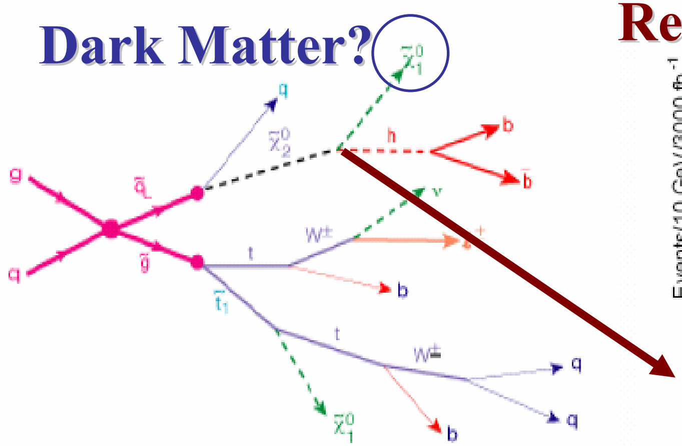
Improved mass reach for discovery of SuperSymmetry by ~500GeV (50%) with increased luminosity

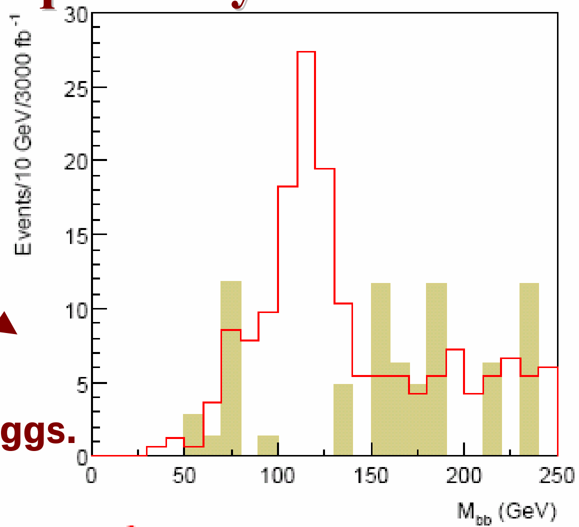
Examples of Physics Gain

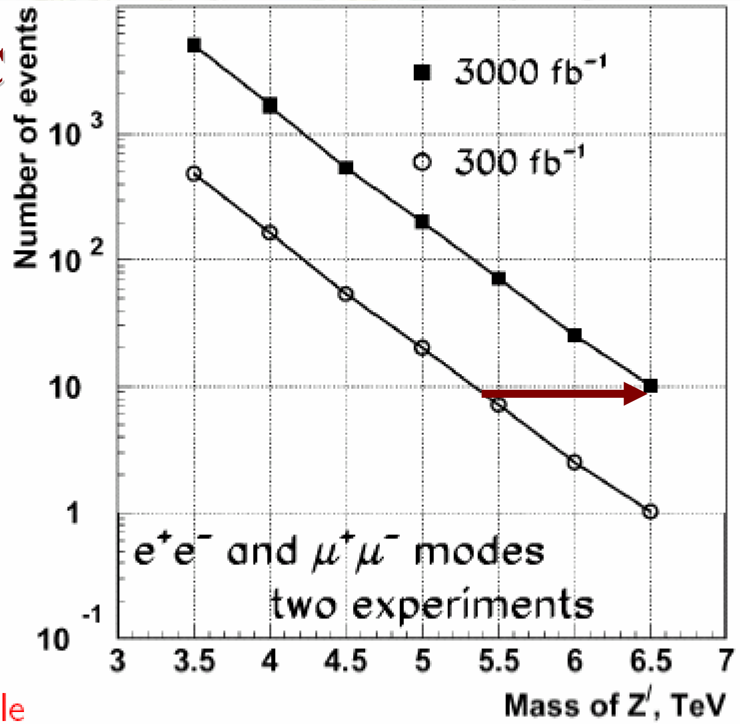
Require two b-tagged jets and reconstruct peak from $h \to bb$ decay

Dark Matter?

Requires 5 years of SLHC



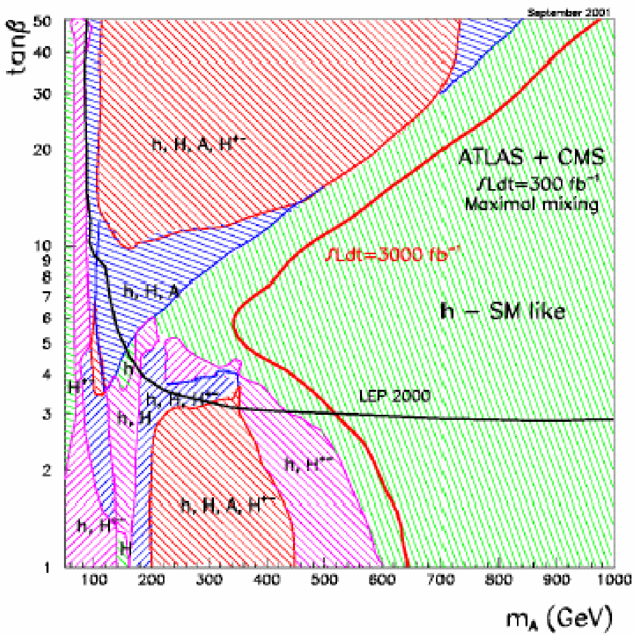




Measure coupling of neutralino to Higgs.
Determine its higgsino component.

Plot assumes $\epsilon_b = 60\%$ for light jet rejection of 100

In green region with 300 fb^{-1} per experiment only SM-like Higgs observable



If only one Higgs observed:

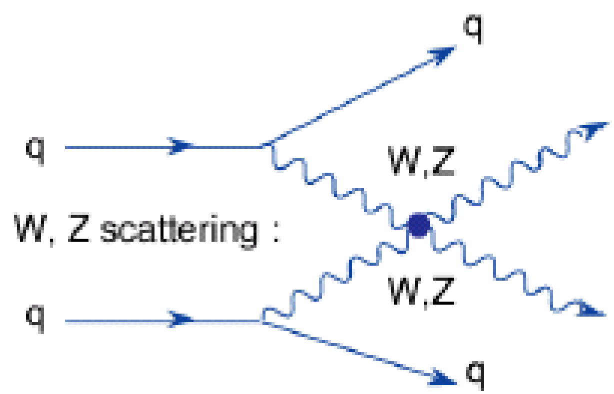
Difficult to distinguish MSSM from SM

Loose main handle on $\tan\beta$ measurement

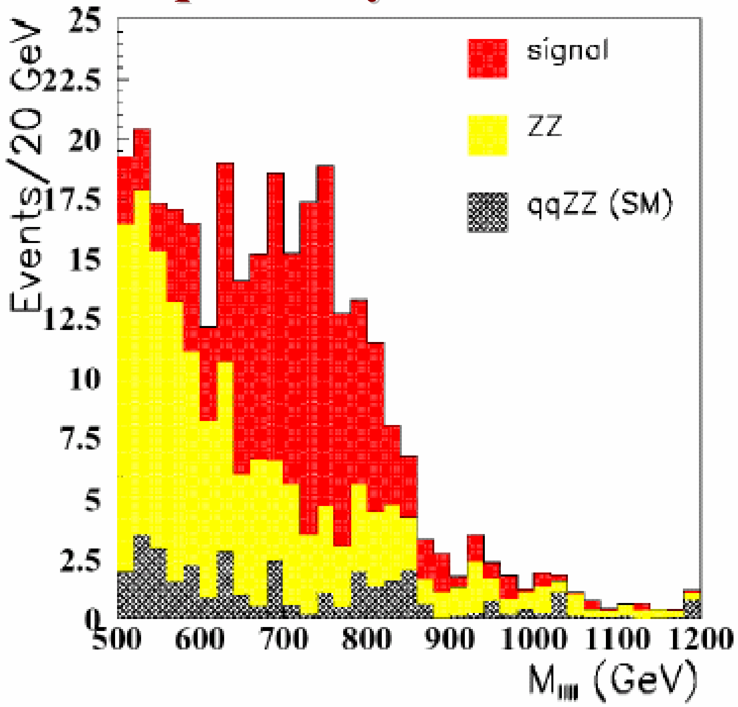
Red curve shows the 5σ discovery limit for an additional heavy higgs for an integrated luminosity of 3000 fb^{-1} per experiment

Improved exploration of SuperSymmetry parameter space and greater sensitivity to any new resonant state *eg* heavier version of Z^0

Examples of Physics Gain



Requires 5 years of SLHC



In absence of clear Higgs at LHC, SLHC statistics could be needed to probe the W, Z scattering process which has diverging cross-section in SM without Higgs.
It is therefore particularly sensitive to whatever new physics must exist to keep this process finite.

Scalar resonance $Z_L Z_L \rightarrow 4\ell$

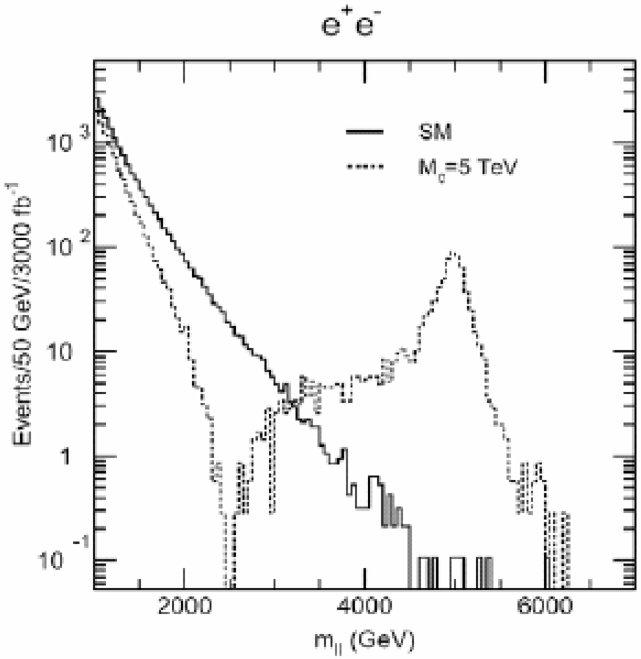
Not accessible at the LHC

Study of several channels my be accessible at SLHC $\Rightarrow$ insight into the underlying dynamics

Examples of Physics Gain

Theories with compactified extra space-time dimensions (ED): signatures are

Kaluza-Klein (KK) resonances of SM fields in "bulk"



Example:

ED with compactification scale $R = 1/M_c \sim$ TeV^{-1}

SM gauge fields can propagate in "bulk" $\Rightarrow$

KK resonances of γ, Z, W with masses M_c, $2M_c$, ..

In figure γ/Z resonance for 3000 fb^{-1} and $M_c = 5$ TeV

Note also negative interference with Z/γ for $m_{\ell\ell} < M_c$

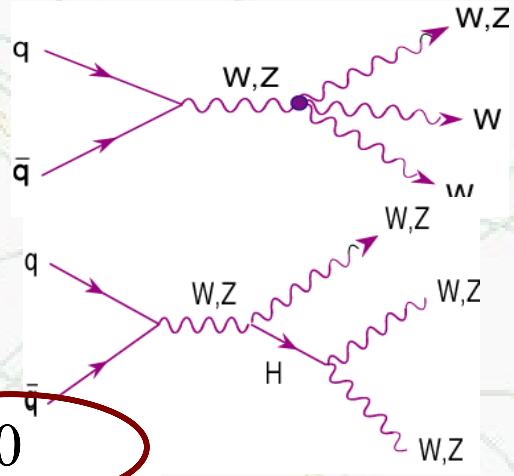
Reach ~6 TeV for 300 fb^{-1}, 7.7 TeV for 3000 fb^{-1} for peak observation

Improved sensitivity to signature for "large" (not Planck scale) extra dimensions and anomalous couplings of top quark.

Expected 99% CL confidence limits in units of 10^{-5}

Channel	LHC (600 fb^{-1})	SLHC (6000 fb^{-1})
$t \to q\gamma$	0.9	0.25
$t \to qg$	61	19
$t \to qZ$	1.1	0.1

Examples of Physics Gain



Test non-Abelian structure SM / Sensitive to new physics
Mostly still statistics limited after 5 years LHC

example: quartic gauge coupling rates with 6000

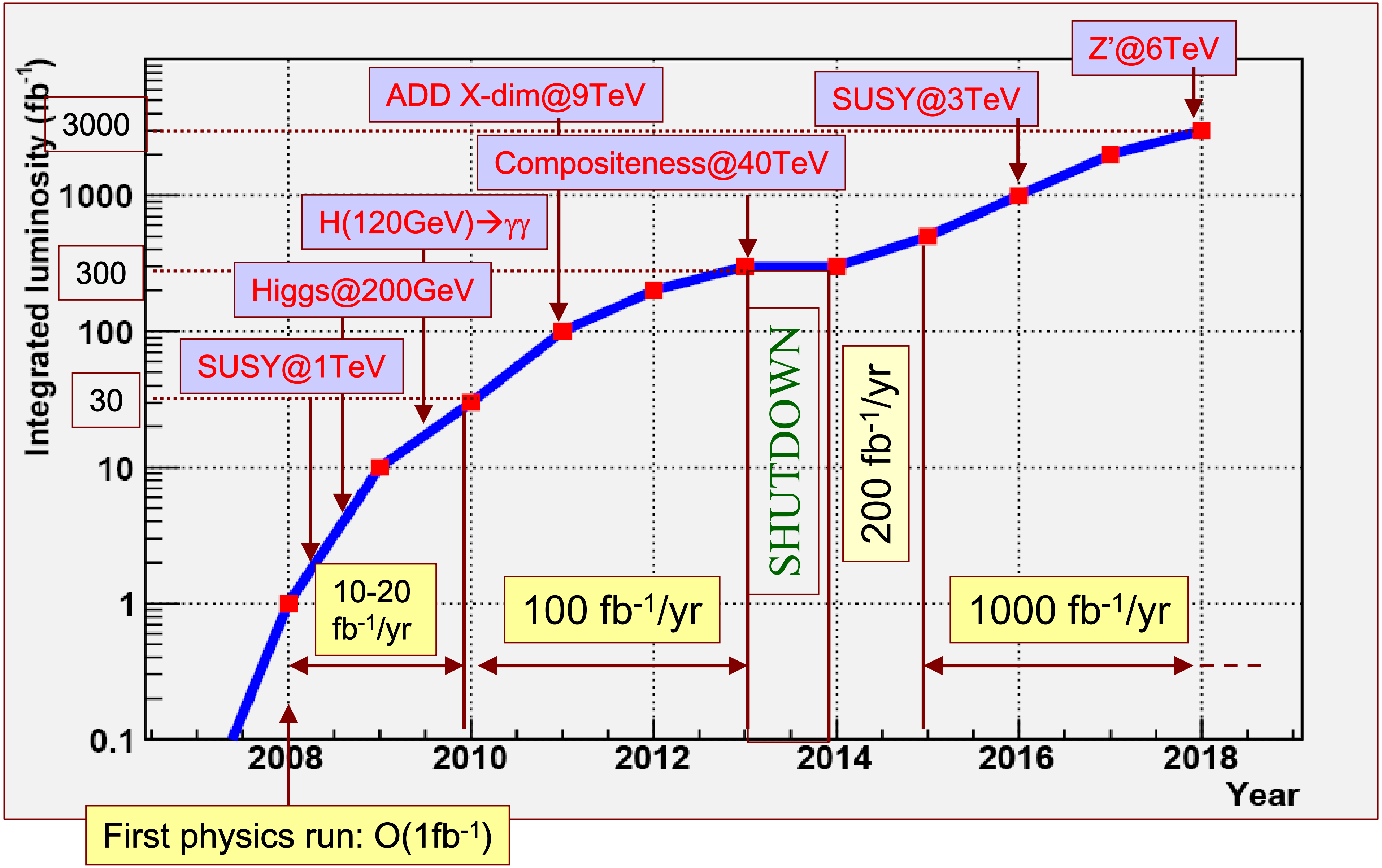
Process	WWW	WWZ	ZZW	ZZZ	$WWWW$	$WWWZ$
N(m_H=120 GeV)	2600	1100	36	7	5	0.8
N(m_H=200 GeV)	7100	2000	130	33	20	1.6

TGC parameter sensitivity LHC/SLHC/ILC

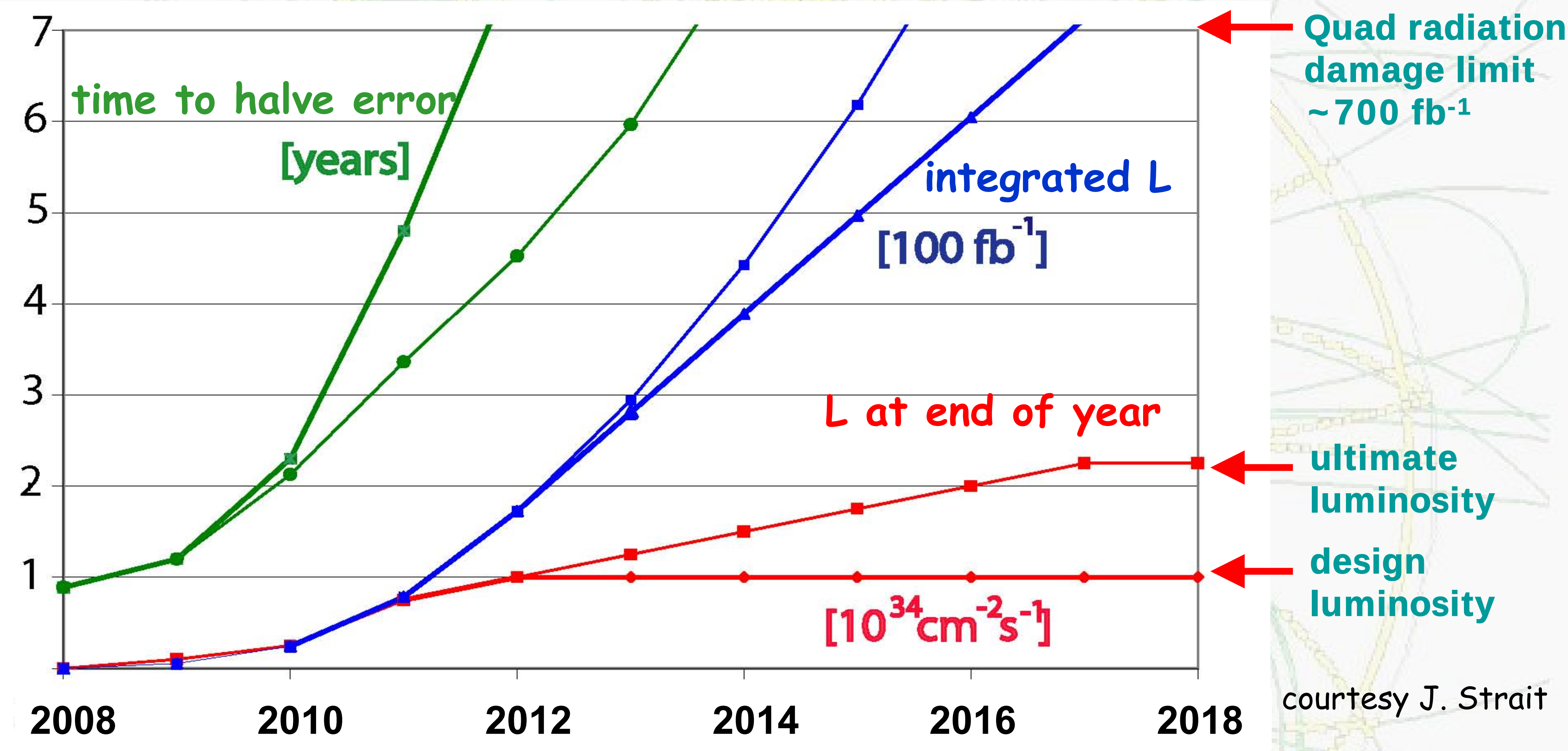
Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g_1^Z	0.0038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

λ parameters better at SLHC, κ parameters at ILC

LHC Luminosity Profile



Timescale of LHC upgrade



- The **life expectancy of LHC IR quadrupole magnets** is estimated to be **<10 years** owing to high radiation doses
- The **statistical error halving time** will exceed 5 years by 2011-2012
- Therefore, it is reasonable to plan a **machine luminosity upgrade based on new low-ß IR magnets before ~2015**

LHC/SLHC Operation

Rober Aymar

Zeuthen Workshop (2/5/06)

- **Phase 0:** without hardware changes in the LHC
  - Improve injectors to increase brightness N_b/e up to ultimate
    $\rightarrow$ $L_0 = 2.3 \times 10^{34}$ cm^{-2} s^{-1} & $\int Ldt \sim 1.5 \times$ nominal
  - increase the dipole field from 8.33 to 9 T: $\rightarrow$ $E_{max} = 7.54$ TeV
- **Phase 1:** with major hardware changes in the LHC
  - modify the insertion quadrupoles and/or layout: $\beta^* = 0.25$ m
    $\rightarrow$ more R&D needed in higher field magnets
  - increase crossing angle θ_c by $\sqrt{2}$: - $\theta_c = 445$ µrad
  - halve bunch length with new high harmonic RF system in the LHC:
    $\rightarrow$ $L_0 = 4.6 \times 10^{34}$ cm^{-2}s^{-1} & $\int Ldt \sim 3 \times$ nominal
  - double the number of bunches [new RF systems in the injectors (including SPS if 12.5 ns bunch spacing)] & increase θ_c:
    $\rightarrow$ $L_0 = 9.2 \times 10^{34}$ cm^{-2}s^{-1} & $\int Ldt \sim 6 \times$ nominal

Reference LHC Luminosity Upgrade: Workpackages and Tentative Milestones

accelerator	WorkPackage	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	after 2015
LHC Main Ring	Accelerator Physics	red	red	yellow	yellow	green	green	green	green	green		
	High Field Superconductors	red	red	yellow	yellow	yellow	green	green	green			
	High Field Magnets		red	red	red	yellow	yellow	green	green	green	blue	
	Magnetic Measurements			red	red	yellow	yellow	green	green	green	blue	
	Cryostats					red	yellow	yellow	green	green	blue	
	Cryogenics: IR magnets & RF		red	red	red	yellow	yellow	green	green	green	blue	
	RF and feedback	red	yellow	red	red	yellow	yellow	green	green	green	blue	
	Collimation&Machine Protection	red	yellow	yellow	green	blue	red	red	red	red		
	Beam Instrumentation	red	red	red	red	red	yellow	yellow	green	green	blue	
	Power converters					red	yellow	yellow	green	green	blue	
SPS	SPS kickers			red	red	red	yellow	yellow	green	blue		
	Tentative Milestones	Beam-beam compensation test at RHIC	SPS crystal collimation test	LHC collimation tests	LHC collimation tests	Install phase 2 collimation	LHC tests: collimation & beam-beam			Install new SPS kickers	new IR magnets and RF system	
	Other Tentative Milestones	Crab cavity test at KEKB	Low-noise crab cavity test at RHIC	**LHC Upgrade Conceptual Design Report**		LHC Upgrade Technical Design Report	Nominal LHC luminosity 10^34			Ultimate LHC luminosity 2.3x10^34	beam-beam compensation	Double ultimate LHC luminosity 4.6x10^34

LHC Upgrade Reference Design Report

R&D - scenarios & models	red
specifications & prototypes	yellow
construction & testing	green
installation & commissioning	blue

Reference LHC Upgrade scenario: peak luminosity 4.6x10^34/(cm^2 sec)
Integrated luminosity 3 x nominal ~ 200/(fb*year) assuming 10 h turnaround time
new superconducting IR magnets for beta*=0.25 m
phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A
beam-beam compensation may be necessary to attain or exceed ultimate performance
new superconducting RF system: for bunch shortening or Crab cavities
hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade
R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade

ATLAS Sub-system Upgrade Requirements

Inner Detector:

- Need finer granularity to cope with occupancy ×10 ($dN_{ch}/d\eta$ ~1500 per beam crossing)
- Need factor of ~6 greater radiation tolerance

⟶ Replace Entire Inner Detector

Trigger Electronics:

- "Front-end electronics can probably stay" (clock speed? deeper pipelines?)
- Extensions to trigger capability needed
- Need to maintain L1 output rate (more data per event)
  - Must upgrade detector backend electronics
    - adapt clock speed to bunch-crossing rate
    - increase bandwidth to deal with more data per event
  - Modify trigger algorithms to deal with high occupancy (and increase thresholds)

L-Ar:

- Some performance degradation due to high rates. (e.g. electron isolation suffers from 200 min. bias events.) Concern of space charge effect especially in FCAL.

TileCal:

- Some radiation damage scintillators
- Challenging calibration with strong increase in pile-up

Muon systems:

- MDT's some degradation in performance due to high rates, in particular in the forward regions:
  - May need additional shielding forward region
  - Aging/radiation damage needs confirmation for SLHC operation
- RPC's, TGC's: Need an upgrade? (Replacement poses serious services problems)

ATLAS ID Upgrade Requirements

To keep ATLAS running more than 10 years the inner tracker will need to be replaced.
Current tracker designed to survive 3 years of 10fb^{-1}/year and 7 of 100 fb^{-1}/year ie 730fb^{-1} plus a further 50% margin for dose estimation uncertainty

For the luminosity-upgrade the new tracker will have to cope with:

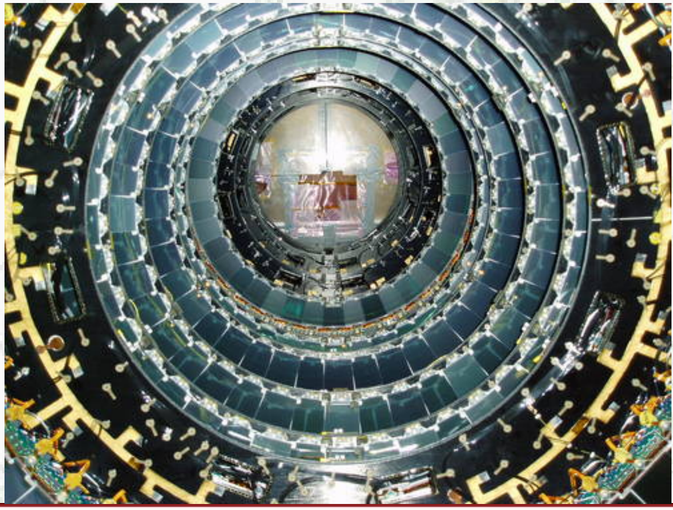
- **5-10×higher occupancy levels (12.5ns – 25ns BCO)**
- **much higher dose rates**

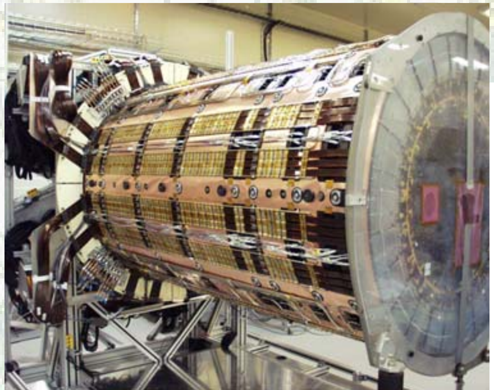
To build a new tracker for 2015, work needs to start now.

Timescales: (See Genova July 2005 AUHL Workshop Introduction: Abe Seiden)

- **ATLAS High Luminosity Steering Group established June 2005**
- **R&D until 2009 leading into a full tracker proposal (TDR) in 2009/2010**
- **Construction phase to start in 2010**
- **Installation and Commissioning 2014**

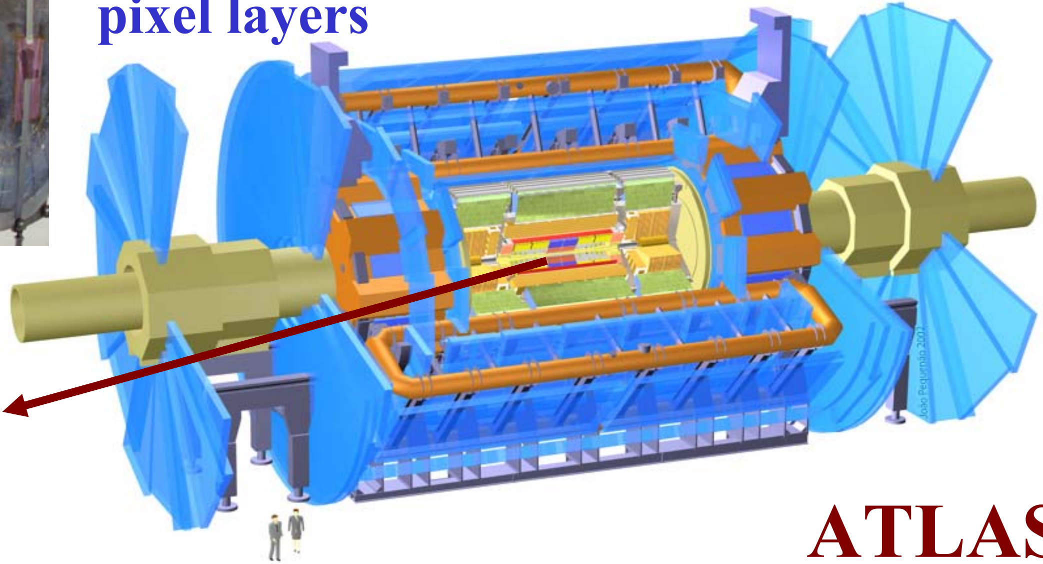
The ATLAS Silicon Central Tracker



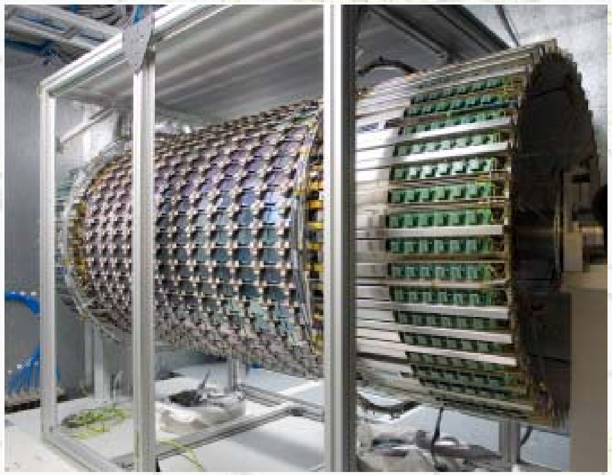


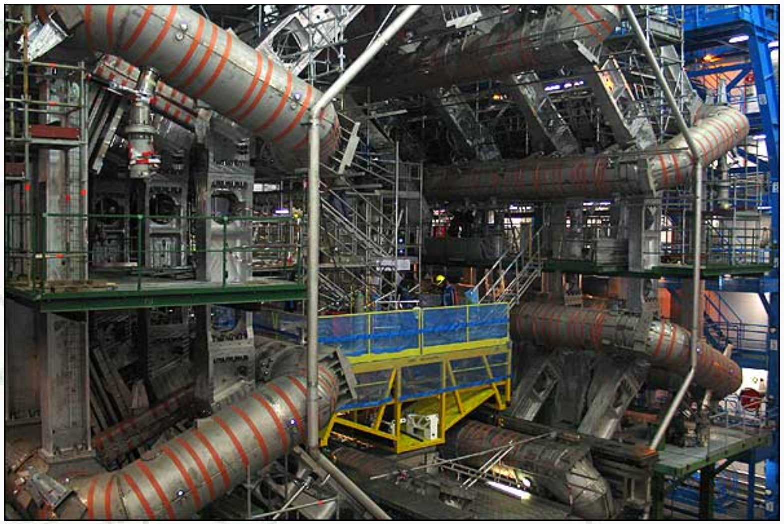
4 barrels and 2 sets of 9 disk end-caps

61m² of silicon at intermediate radii between straw layers (TRT) and 3 pixel layers



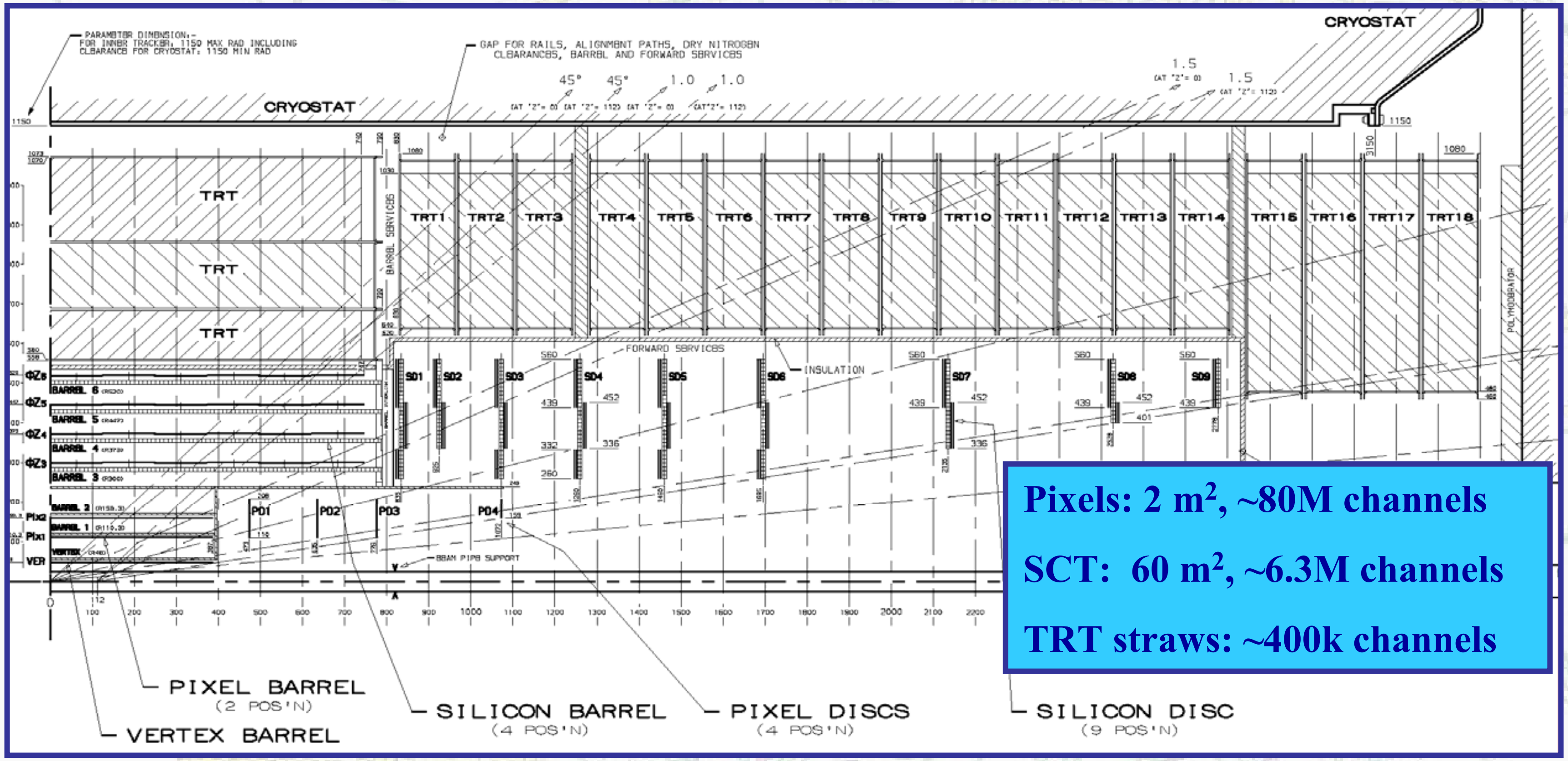
ATLAS





(*cf* presentations by Mike Tyndel, Uli Parzefall and Allan Clark)

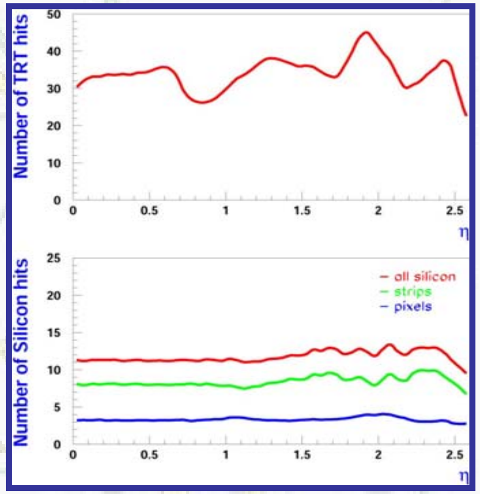
Inner Tracker TDR Layout

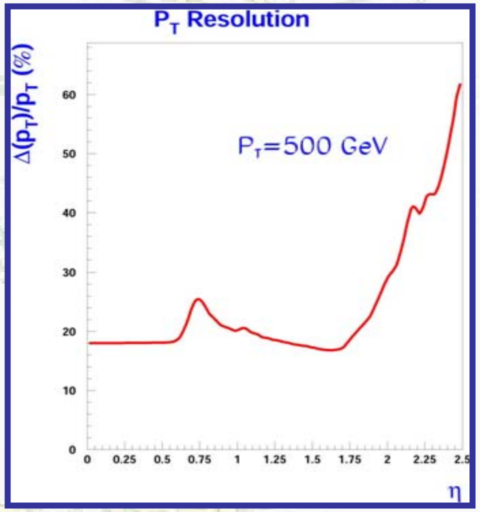


Pixels: 2 m^2, ~80M channels

SCT: 60 m^2, ~6.3M channels

TRT straws: ~400k channels





Pixels (50 μm × 400 μm): 3 barrels, 2×3 disks **4.7cm < r < 20cm**

- **Pattern recognition in high occupancy region**
- **Impact parameter resolution (in 3D)**

Radiation hard technology: n$^+$-in-n Silicon technology, operated at -6°C

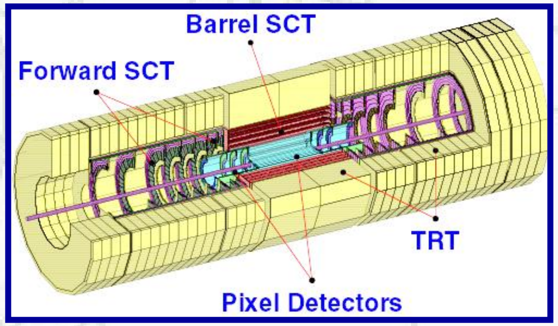
Strips (80 μm × 12 cm) (small stereo angle): SCT 4 barrels, 2×9 disks

- **pattern recognition** **30cm < r < 51cm**
- **momentum resolution**

p-strips in n-type silicon, operated at -7°C

TRT 4mm diameter straw drift tubes: barrel + wheels **55cm < r < 105cm**

- **Additional pattern recognition by having many hits (~36)**
- **Standalone electron id. from transition radiation**



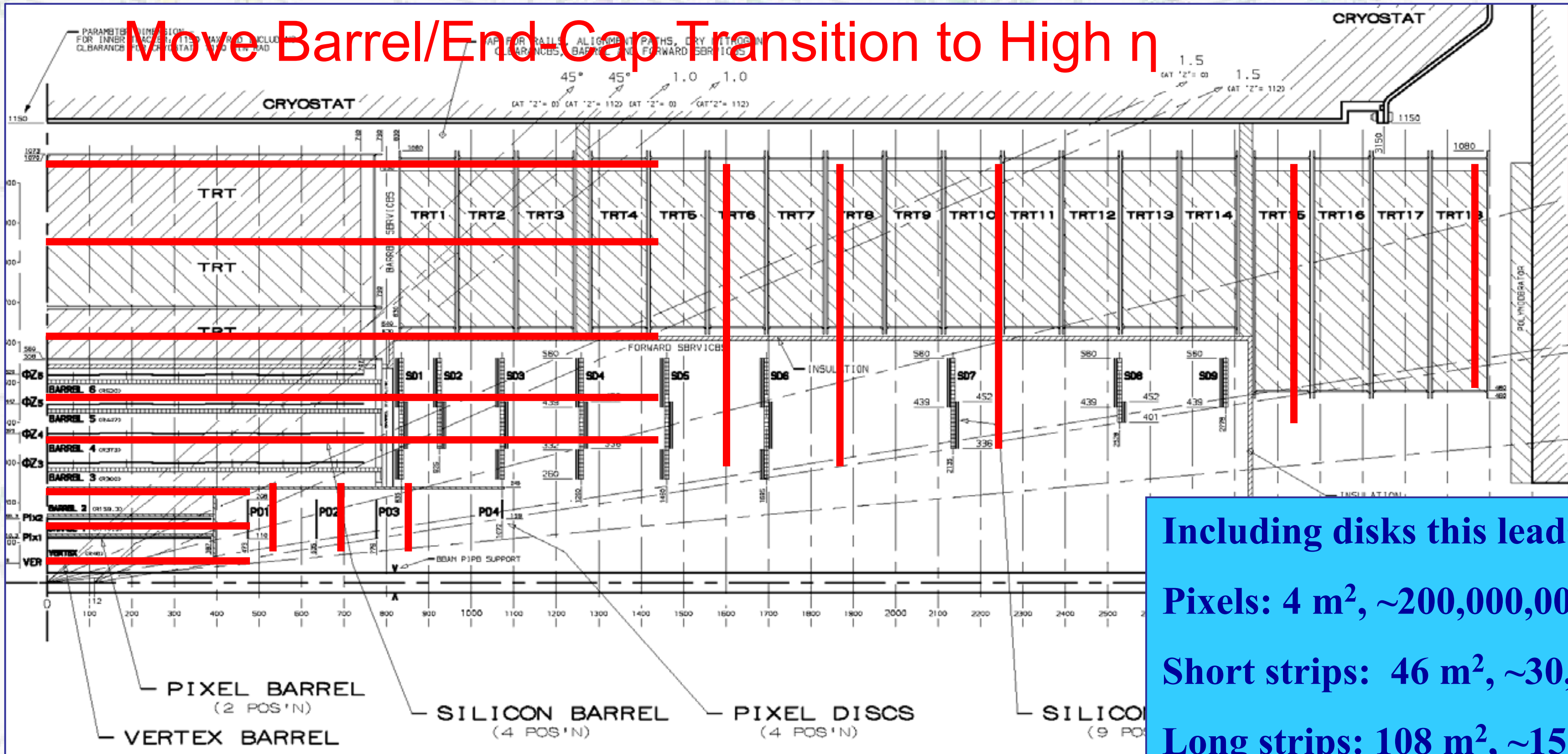
Example SLHC Tracker Layout

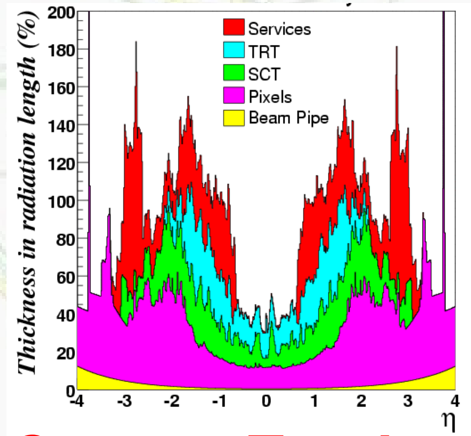
Some all silicon layout proposals have been made.

<u>Long Barrel Proposal</u> (Genova July 2005)

(*see* conceptual layout by Abe Seiden:
Strip Detector Issues, Both Mid and Large Radius
13/2/05 AUHL Workshop CERN)

Pixels:	**r=6cm, 15cm, 24cm**	**z=±50cm**
Short (3cm) μ-strips (single layer):	**r=35cm, 48cm, 62cm**	**z=±144cm**
Long (12 cm) μ-strips (stereo layers):	**r=84cm, 105cm**	**z=±144cm**





Current Tracker Material

Including disks this leads to:

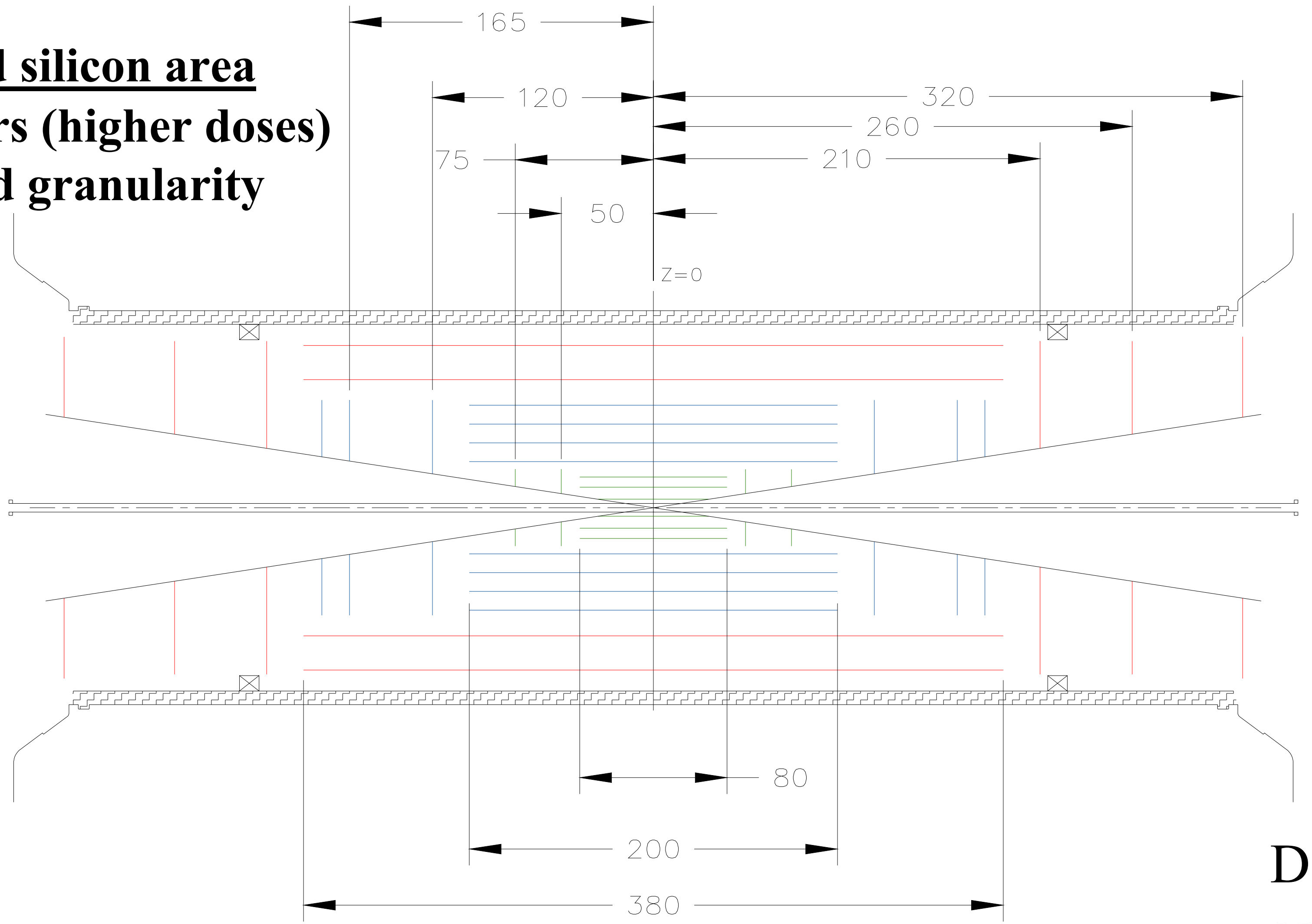
Pixels: 4 m², ~200,000,000 channels

Short strips: 46 m², ~30,000,000 channels

Long strips: 108 m², ~15,000,000 channels

ID “Straw-man” Layout
(3/4 SS layers)

→ **Reduced silicon area**
Closer layers (higher doses) and reduced granularity



David Lissauer

BROOKHAVEN NATIONAL LABORATORY

* = C4NP (IBM)

Costing Speculations [CHF/cm²]

R. Horisberger PSI

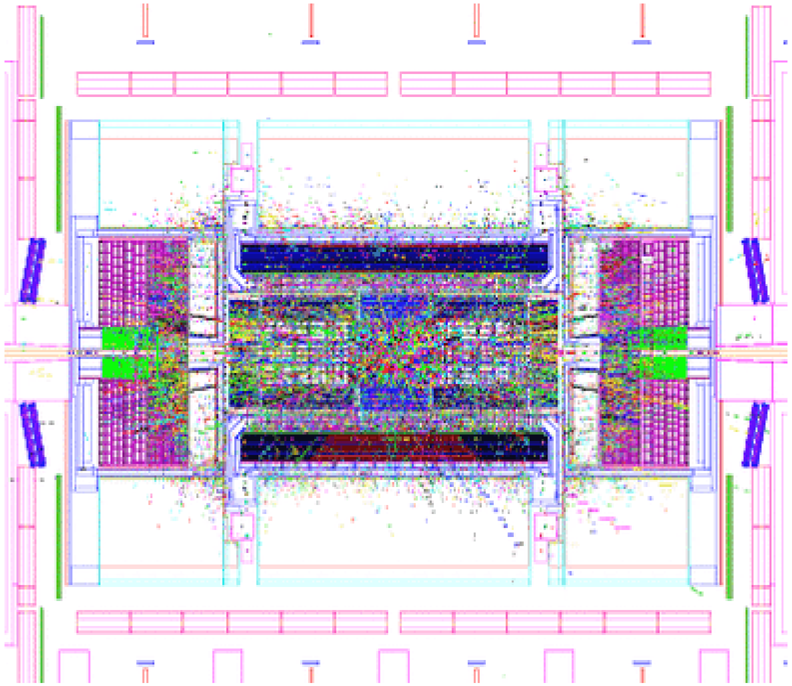
	Pixel (now)	Large pixels	Macropixels	MAPS	CMOS+Sensor
Pixel Area	0.015 mm^2	0.15 mm^2	1.5 mm^2		
Sensor/ROC	1 / 1	1 / 1	10 / 1	0 / 1	1 / 1
Tiling unit	10 cm^2	40 cm^2	100 cm^2	4 cm^2	4 cm^2
Bumping	320	20*	2*	0	0
Sensors	80	10	10	0	10+10?(4)
ROC	25	50	2	50	200?(3)
HDI	30	30	3	30	30
Cables	8	8	0.8	8	8
Baseplate	5	5	0.5	5	5
Pitchadjust	0	0	15(2)	0	0
Optical Link (1)	32	6	0.6	6	32
pxFED	25	4	0.4	4	25
Total	**525**	**~130**	**~35**	**~105**	**~320?**

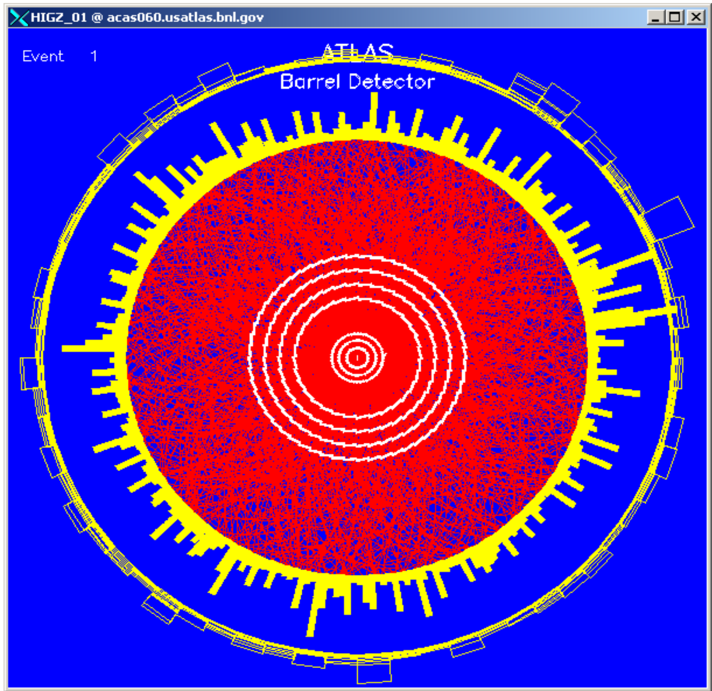
(1) ~ 320 CHF/channel
(2) ~ 0.02 CHF/cm fine pitch trace
(3) Yield speculations based on experience with DMILL SOI-wafers
(4) Extra cost for anodic wafer bonding or SOI wafer growth

(Current CMS micro-strips ~40CHF/cm^2)

Single Beam-Crossing Occupancy

Expected Pile-up at Super LHC





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

- 230 min.bias collisions in bunch
- ~ 10000 particles in $|\eta| \leq 3.2$
- mostly low p_T tracks

Pavel Nevski

Note: numbers based on factor 10 increase in luminosity but still 25 ns bunch crossing. May be better for shorter bunch crossing time, depending on whether detectors can run at 80MHz

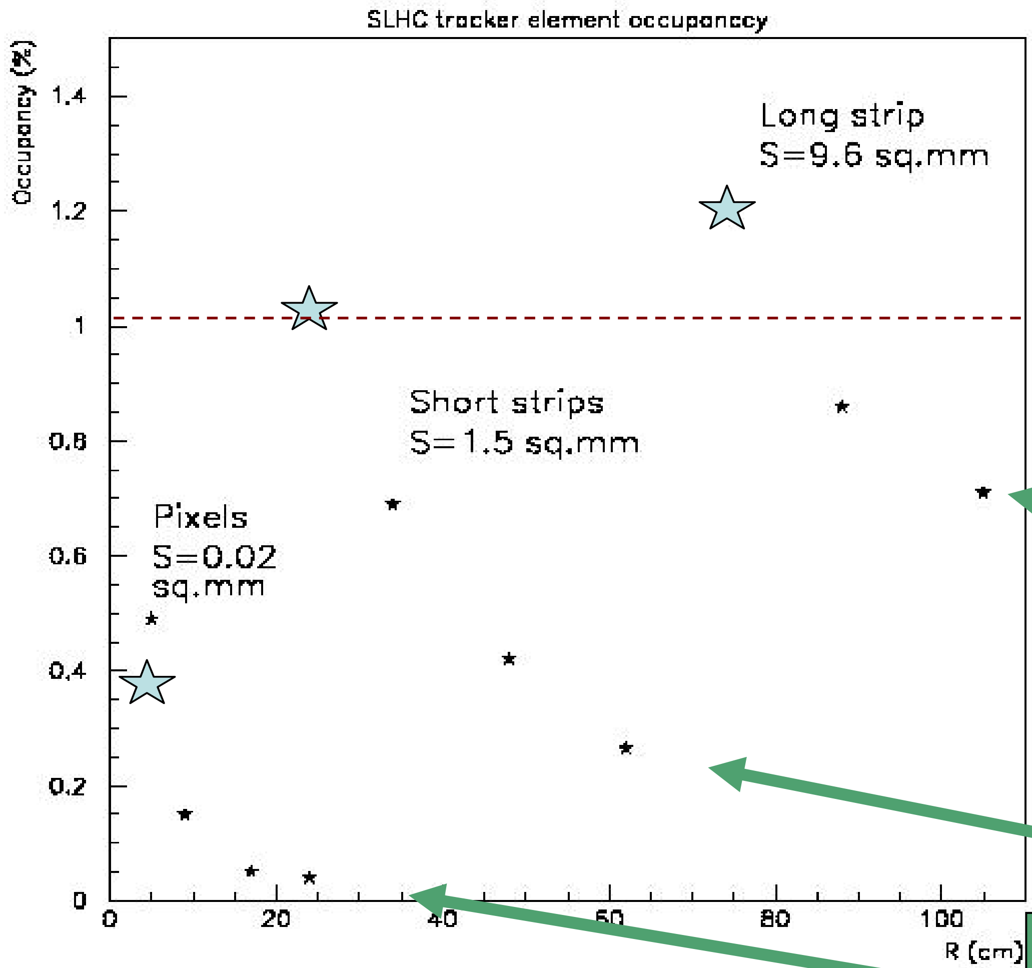
Occupancy Constraints on Upgrade Tracker

SLHC predicted occupancy

Simulation studies looking at occupancy levels to determine appropriate design (segmentation) at different radii for the SLHC tracker.

Radii used here are for the long barrel layout.

Studies underway for ID Straw-man



Long strips:
12cm×80μm

Short strips:
3cm×50μm

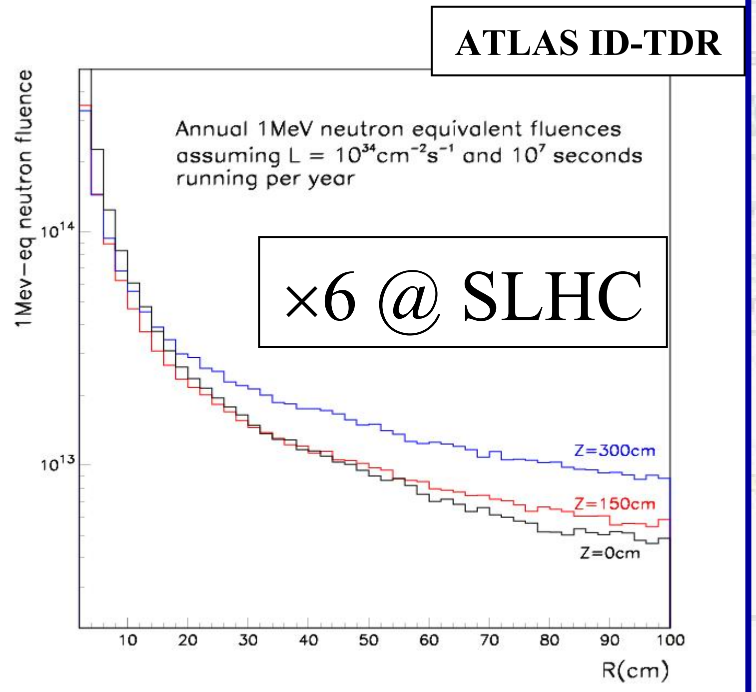
Pixels:
400 μ m×50μm

Long Barrel Layout Dose Estimates
(1 MeV neutron equivalent fluence)

Flux scales with luminosity.

(Thermal neutron flux depends on added moderator material to compensate for loss of neutron moderating effects of TRT.)

Assume overall factor 6 increase in annual doses.



Assuming 10 years of SLHC running (~6000fb^{-1}).

Pixels	Max. annual dose	10 years (~6000 fb^{-1})
Disks, r=9-25 cm, z=50-85 cm	~6×10^{14} n_{eq}/cm^2	~6×10^{15} n_{eq}/cm^2
barrel, r=6 cm	~1.1×10^{15} n_{eq}/cm^2	~1.1×10^{16} n_{eq}/cm^2
barrel, r= 15 cm	~2.4×10^{14} n_{eq}/cm^2	~2.4×10^{15} n_{eq}/cm^2
barrel, r= 24 cm	~1.3×10^{14} n_{eq}/cm^2	~1.3×10^{15} n_{eq}/cm^2
Short strips	**Max. annual dose**	**10 years (~6000 fb^{-1})**
disks, r=35-80 cm, z=150-300 cm	~8.4×10^{13} n_{eq}/cm^2	~8.4×10^{14} n_{eq}/cm^2
barrel, r= 35 cm	~8.4×10^{13} n_{eq}/cm^2	~8.4×10^{14} n_{eq}/cm^2
barrel, r= 48 cm	~6.6×10^{13} n_{eq}/cm^2	~6.6×10^{14} n_{eq}/cm^2
barrel, r= 62 cm	~4.4×10^{13} n_{eq}/cm^2	~4.4×10^{14} n_{eq}/cm^2
Long strips	**Max. annual dose**	**10 years (~6000 fb^{-1})**
disks, r= 80-100 cm, z= 150-300 cm	~6×10^{13} n_{eq}/cm^2	~6×10^{14} n_{eq}/cm^2
barrel, r= 84 cm	~3.1×10^{13} n_{eq}/cm^2	~3.1×10^{14} n_{eq}/cm^2
barrel, r= 105 cm	~2.8×10^{13} n_{eq}/cm^2	~2.8×10^{14} n_{eq}/cm^2

Unlike for LHC no further 50% safety margin included

Ian Dawson

Operating Silicon Sensors at SLHC doses

For LHC doses:

• Main failure mode is when full depletion voltage grows beyond breakdown voltage. *Undepleted region low field → poor charge collection*.

For the SLHC doses:

• Will not be able to operate (conventional) silicon fully depleted (V_{DEP} >> 1000V) However, *p-type* silicon with n-strips (collecting electrons) *can work* as the *undepleted region is semi-insulating after heavy irradiation*.

• Trapping is dominant radiation effect on sensor performance.

Optimize for charge collection efficiency CCE not for V_{DEP}

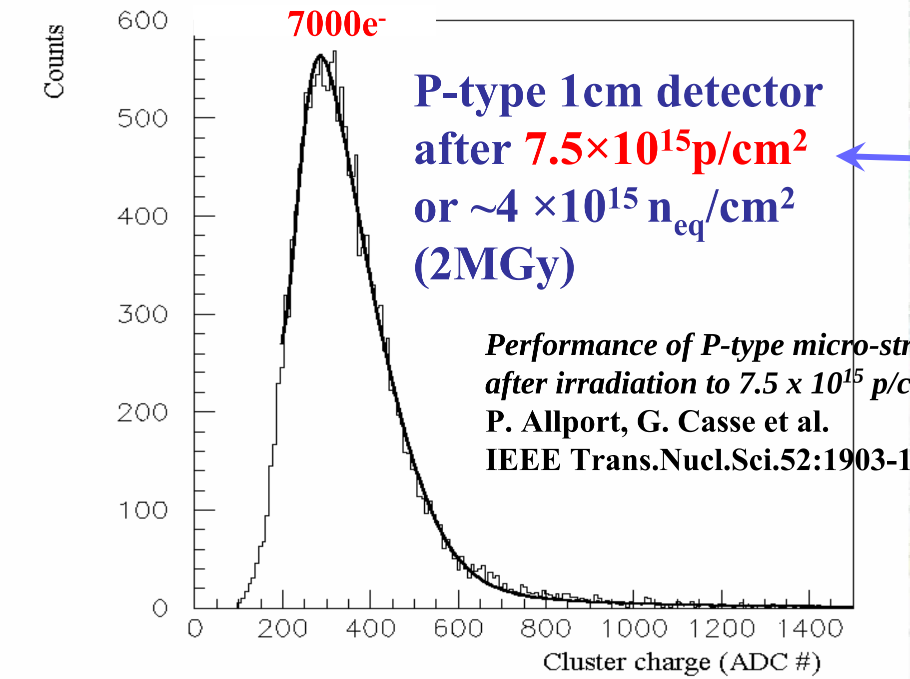
• High currents threaten stable operation (thermal runaway)

Require robust cooling to reduce currents and remove heat

Silicon R&D Towards Super-LHC

RD50 leads the programme to develop silicon sensors able to withstand up to ten times the LHC radiation doses required for the luminosity upgrade (Super-LHC) Layers from r ~ 12cm, require survival to $\leq 4 \times 10^{15}\ n_{eq}/cm^2$ ($7.3\times10^{15} p/cm^2$) with Signal/Noise > 10.

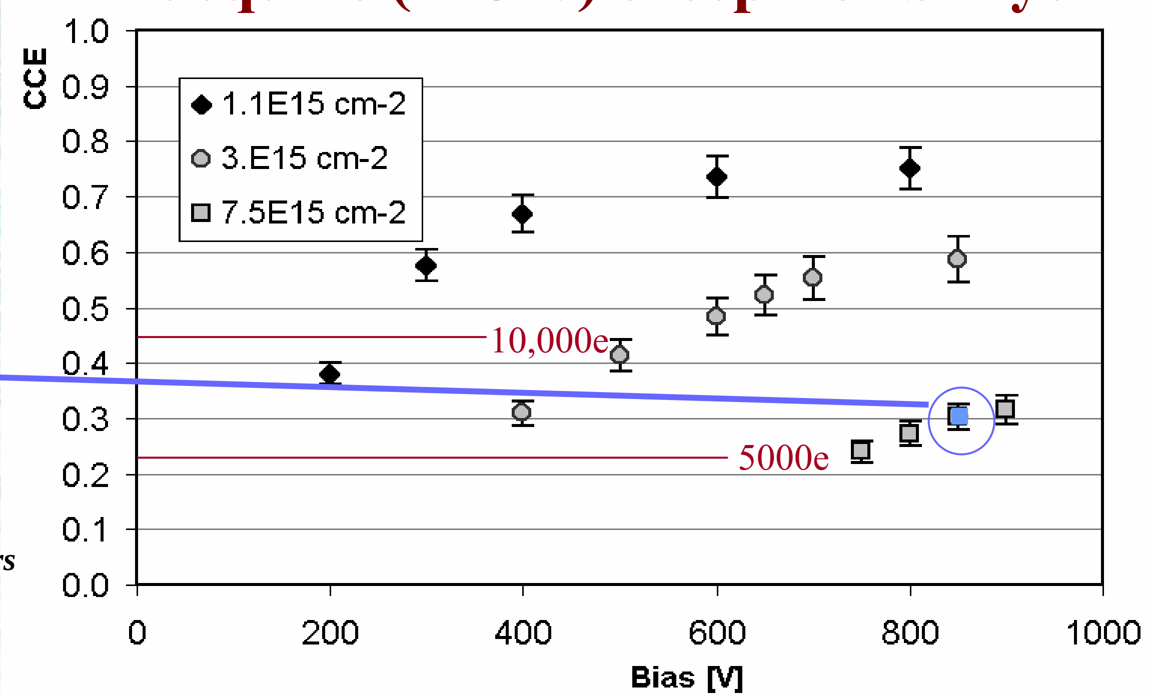
Depending on the achievable noise, p-type planar silicon (or n-on-n as currently used) could just about be adequate (MCz?) except for b-layer



P-type 1cm detector after $7.5\times10^{15} p/cm^2$ or $\sim 4 \times 10^{15}\ n_{eq}/cm^2$ (2MGy)

Performance of P-type micro-strip detectors after irradiation to 7.5 x 10^{15} p/cm².
P. Allport, G. Casse et al.
IEEE Trans.Nucl.Sci.52:1903-1906,2005

Pulse height distribution of a miniature n+-in-p detectors with ^{106}Ru β-source, after exposure at the CERN-PS to $7.5\times10^{15} p\ cm^{-2}$ with LHC speed electronics.



P-type prototypes manufactured by Centro Nacionale Microelectronica, CNM, Barcelona.

Full scale detectors also now manufactured with good characteristics by a number of leading vendors. (*cf* Gianluigi Casse and Yoshinobu Unno presentations).

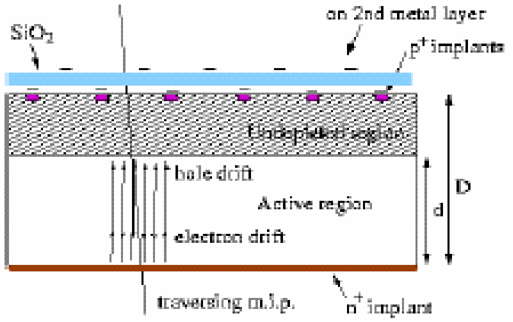
RD50

Device engineering

p-in-n versus n-in-n detectors

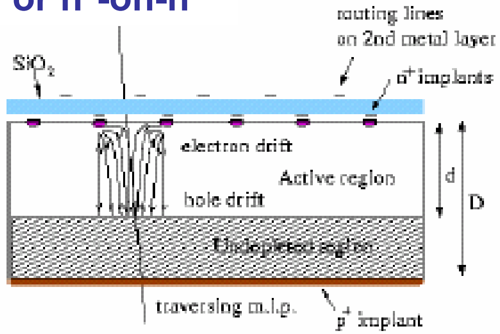
n-type silicon after type inversion:

p^+-on-n^-



n^+-on-p^- or n^+-on-n^-

(*cf* Mara Bruzzi presentation)



p-on-n silicon, under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced CCE

n-on-n silicon, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (fast)

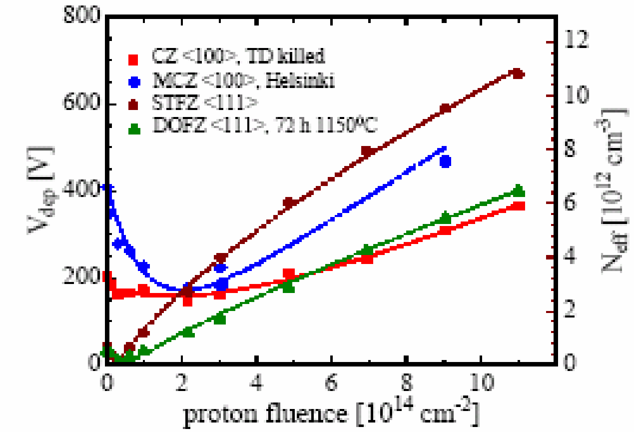
(simplified, see talk of Gianluigi and Vincenzo for more details)

RD50

Standard FZ, DOFZ, Cz and MCz Silicon

24 GeV/c proton irradiation

- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm²
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm²
  - reduced N_{eff} increase at high fluence



- **CZ silicon and MCZ silicon**
  - no type inversion in the overall fluence range (verified by TCT measurements) (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
  - ⇒ donor generation overcompensates acceptor generation in high fluence range

- **Common to all materials (after hadron irradiation):**
  - reverse current increase
  - increase of trapping (electrons and holes) within ~ 20%

MCz: Reduced Operating Voltages

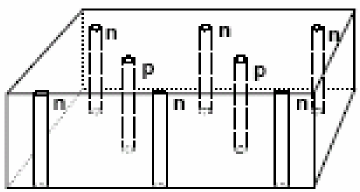
RD50

Device Engineering: 3D detectors

(Introduced by S.I. Parker et al., NIMA 395 (1997) 328)

- **Electrodes:**
  - narrow columns along detector thickness-"3D"
  - diameter: 10µm distance: 50 - 100µm
- **Lateral depletion:**
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
- **Hole processing :**
  - Dry etching, Laser drilling, Photo Electro Chemical
  - Present aspect ratio (RD50) 30:1

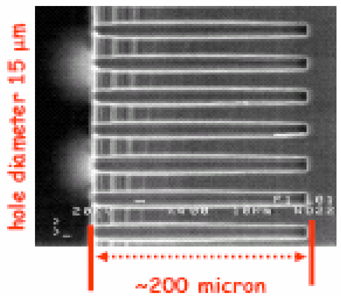
(*cf* Cinzia DaVie presentation)



3D detector developments within RD50:

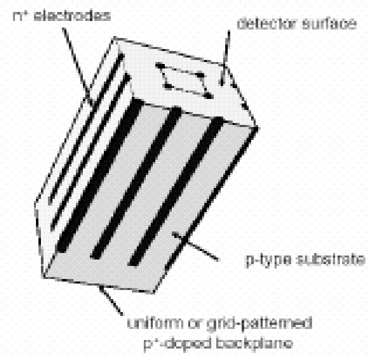
1) Glasgow University – pn junction & Schottky contacts
   Irradiation tests up to 5×10^{14} p/cm² and 5×10^{14} π/cm²:
   V_{fd} = 19V (inverted); CCE drop by 25% (α-particles)

2) IRST-Trento and CNM Barcelona (since 2003)
   CNM: Hole etching (DRIE); IRST: all further processing
   diffused contacts or doped polysilicon deposition

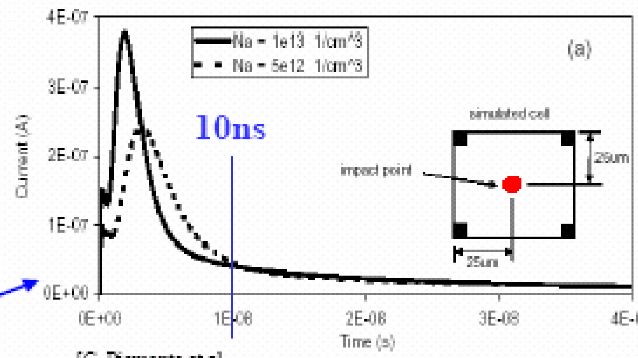


RD50

3D Detectors: New Architecture



- **Simplified 3D architecture**
  - n^+ columns in p-type substrate, p^+ backplane
  - operation similar to standard 3D detector
- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed
- **Fabrication planned for end 2005**
  - INFN/Trento funded project: collaboration between IRST, Trento and CNM Barcelona
- **Simulation**
  - CCE within < 10 ns
  - worst case shown (hit in middle of cell)



[C. Piemonte et al., NIM A541 (2005) 441]

Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC

The RD42 Collaboration

CERN/LHCC 2006-010
LHCC-RD-010
Status Report/RD42
March 1, 2006

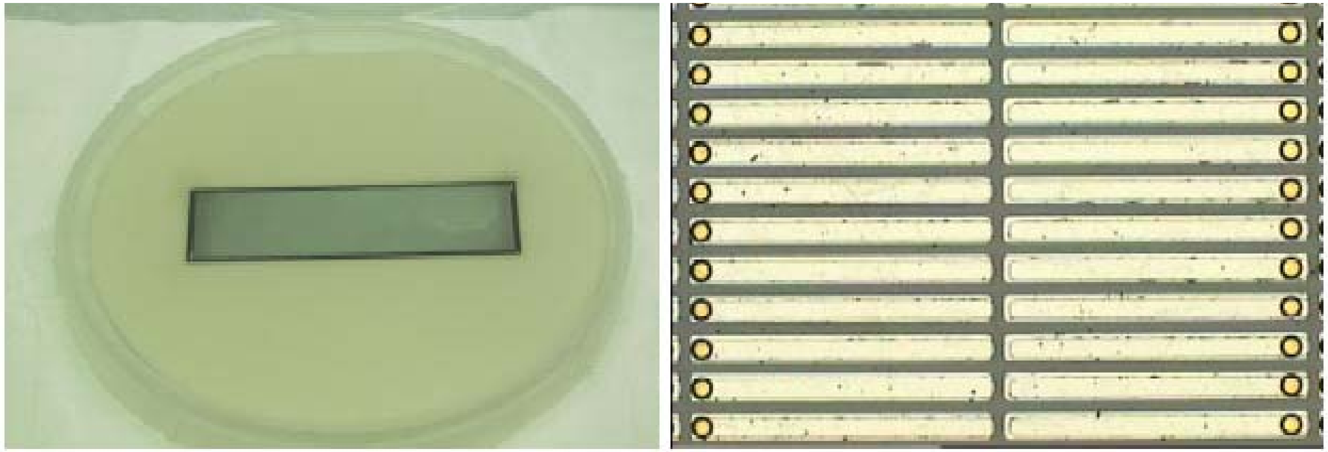


Figure 10: (a)Photograph of the ATLAS pixel diamond mounted in the carrier ready for bump bonding. (b)Zoom view of the pixel pattern after the under-bump metal is deposited.

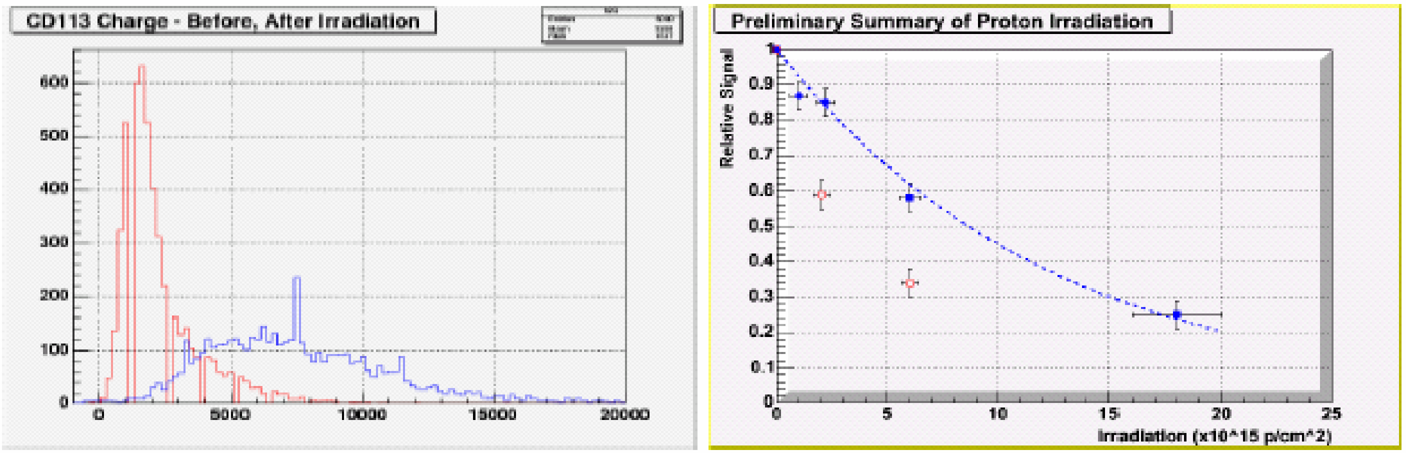


Figure 17: (a)Pulse height distributions before (blue curve) and after (red curve) the irradiation to 18×10^{15} p/cm^2. (b)Summary of proton irradiation results for pCVD material up to a fluence of 20×10^{15} p/cm^2 (filled data points). The blue curve is an exponential with exponent -0.08×fluence. Also shown are the results of the irradiation of the first scCVD diamond (open data points).

(*cf* Harris Kagan presentation)

Increase in Leakage Current with Dose

Flux dependence leakage current:

$$I = \alpha \Phi_{eq} V$$

- **Independent of bulk type**
- **Temperature dependent. Common to use $\alpha_{20°C}$ and calculate temperature dependence using:**

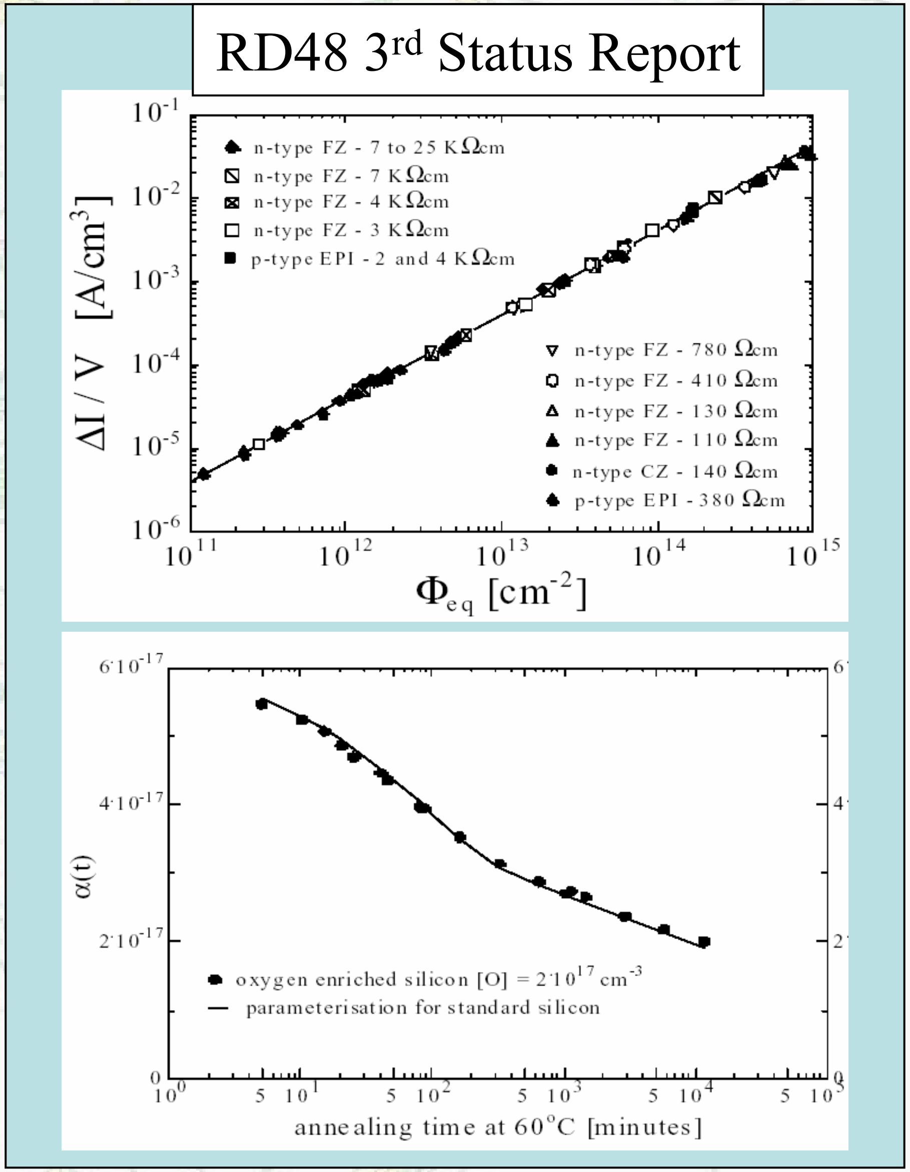
$$I(T) = I_{20^\circ C}\left(\frac{T}{293}\right)^2 \exp\left[-\frac{E_{gap}}{2k_B}\left(\frac{293-T}{293T}\right)\right]$$

- **Annealing time dependent. $\alpha_{20°C}$ is:**

4E-17A/cm $\Rightarrow$ **~400 days**

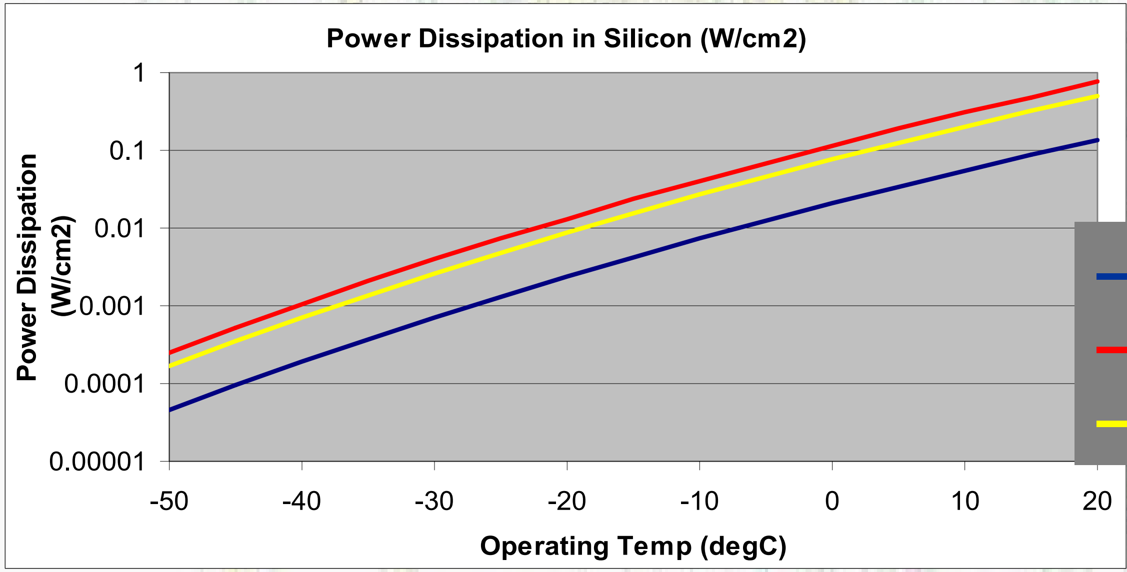
5E-17A/cm $\Rightarrow$ **~100 days** $\Leftarrow$ **used here**

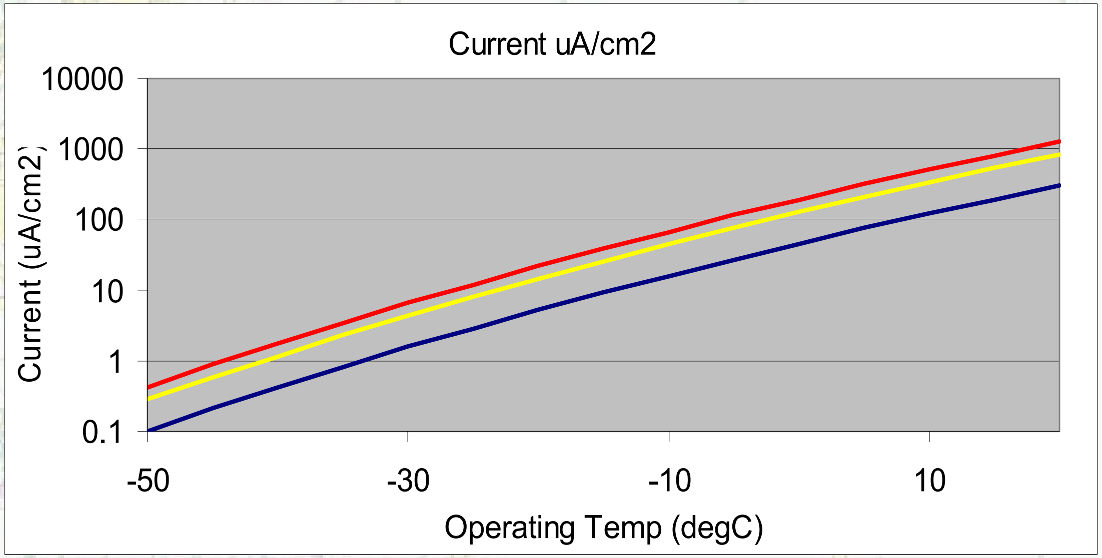
5.5E-17A/cm $\Rightarrow$ **~25 days**



Current & Power Dissipation

Short strips at 35cm radius: 3cm×50µm





- LHC: flux = 2×10^{14} n_{eq}/cm^2, bias = 450V, 300µm
- SLHC: flux = 8.4×10^{14} n_{eq}/cm^2, bias = 600V, 300µm
- SLHC: flux = 8.4×10^{14} n_{eq}/cm^2, bias = 600V, 200µm

Temperature	-40°C	-30°C	-20°C	-10°C	0°C	10°C	20°C
LHC (mW/cm^2)	0.19	0.70	2.4	7.2	21	54	135
SLHC (mW/cm^2)	1.1	3.9	13	41	115	305	756

Currents: × 4
Power: × 6

SLHC: to keep power dissipation same as LHC would need to run ~15°C colder.

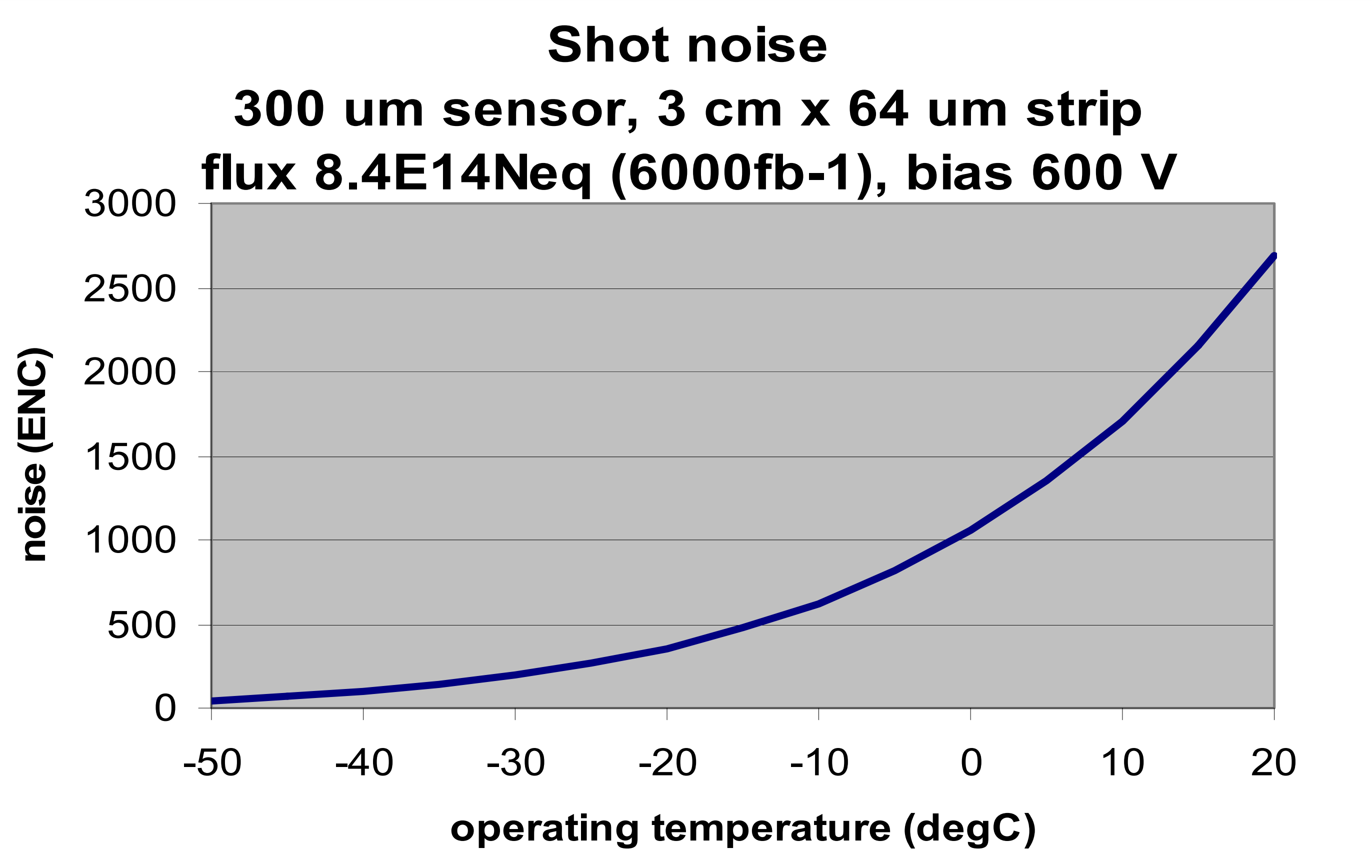
Note only LHC includes 50% safety factor.

Joost Vossebeld

Shot Noise

High leakage current also adds to the noise.

$$\text{shot noise (ENC)} \approx \sqrt{12\, I_{\text{detector}}\ (\text{nA})\ t_{\text{shaping}}\ (\text{ns})}$$ **(Spieler, PDG 2004)**



This gets added in quadrature to other noise contributions.

In short strip region probably need to keep total noise below ~1000ENC (for 25 ns shaping time).

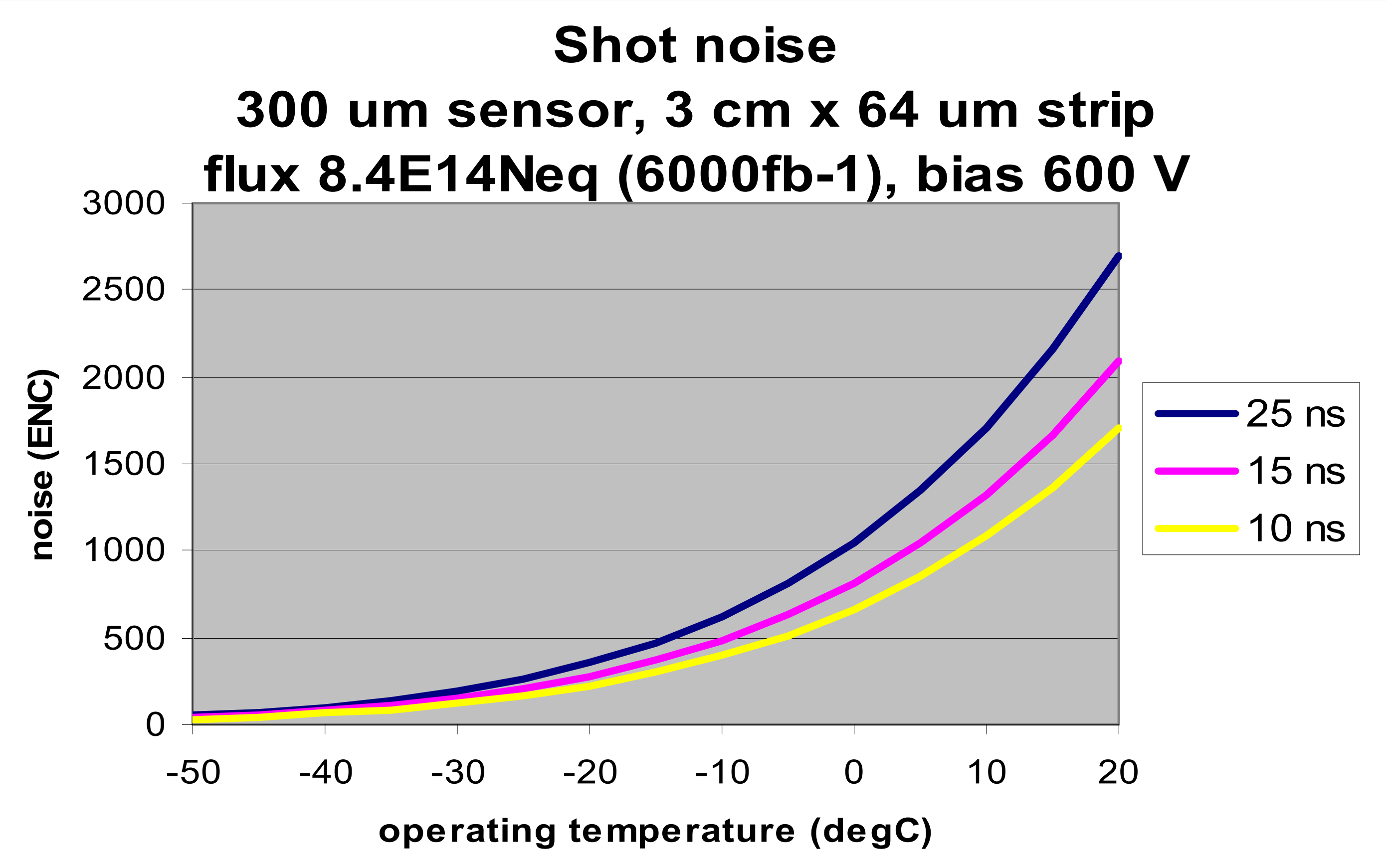
To keep shot noise contribution below ~400enc, need to keep the sensor operating temperature below -15°C.
(Shot noise reduced by 20% for 200µm thick sensor.)

Joost Vossebeld

Shot Noise

High leakage current also adds to the noise.

$$\text{shot noise (ENC)} \approx \sqrt{12\, I_{\text{detector}}\,(\text{nA})\; t_{\text{shaping}}\,(\text{ns})}$$ **(Spieler, PDG 2004)**



This gets added in quadrature to other noise contributions.

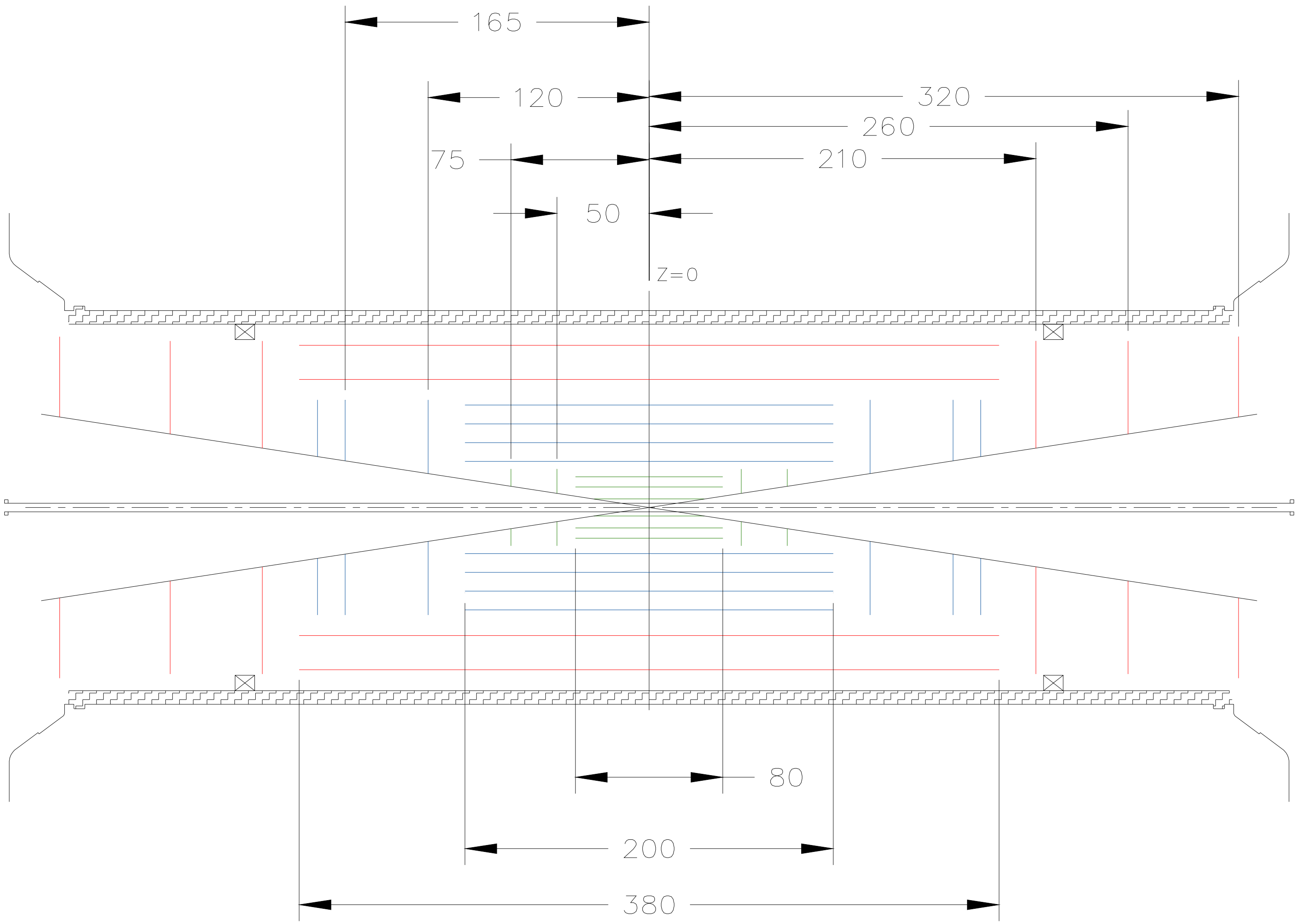
In short strip region probably need to keep total noise below ~1000ENC (for 25 ns shaping time).

To keep shot noise contribution below ~400enc, need to keep the sensor operating temperature below -10°C (10-15ns).
(Shot noise reduced by 20% for 200μm sensor.)

Joost Vossebeld

ID “Straw-man” Layout

(3/4 SS layers)



David Lissauer

BROOKHAVEN NATIONAL LABORATORY

Straw-man Barrel Layouts

- b-layer integrated to the beam pipe.
  - 1 layer at — R= 5 cm — **new technologies required**
  - Granularity — 300μ x 50 μ
  - Z — 2x40 cm
- Inner Layers - Pixels
  - 2 additional layers at — R=12, 18 cm
  - Granularity — 400μ x 50 μ — ($1.9m^2$)
  - Z length — 2x 40 cm
- Middle Layers
  - 3 layers at — R=27,38,50 cm — 4 Layers (27,38,49,60)
  - Granularity — 3.5 cm x 80 μ
  - Z length — 2x100 cm — ($30m^2$)
- Outer Layers
  - 2 Layers — R= 70,95 cm — 2 Layers (75,95)
  - Granularity — 9 cm x 80 μ
  - Z length — 2x190 cm — ($112m^2$)

David Lissauer

Straw-man End-cap Layouts

- Discs
  - 7 discs
  - Pixel: Z= 50, 75 ($1.9m^2$)
  - SS: Z= 120,165 ($6m^2$) 4 layers 120,165,180
  - LS: Z= 210,260,320 ($14m^2$)
- Coverage in η
  - Assume coverage up to 2.5
- Moderator
  - Need to optimize the amount of moderator on the EC face.

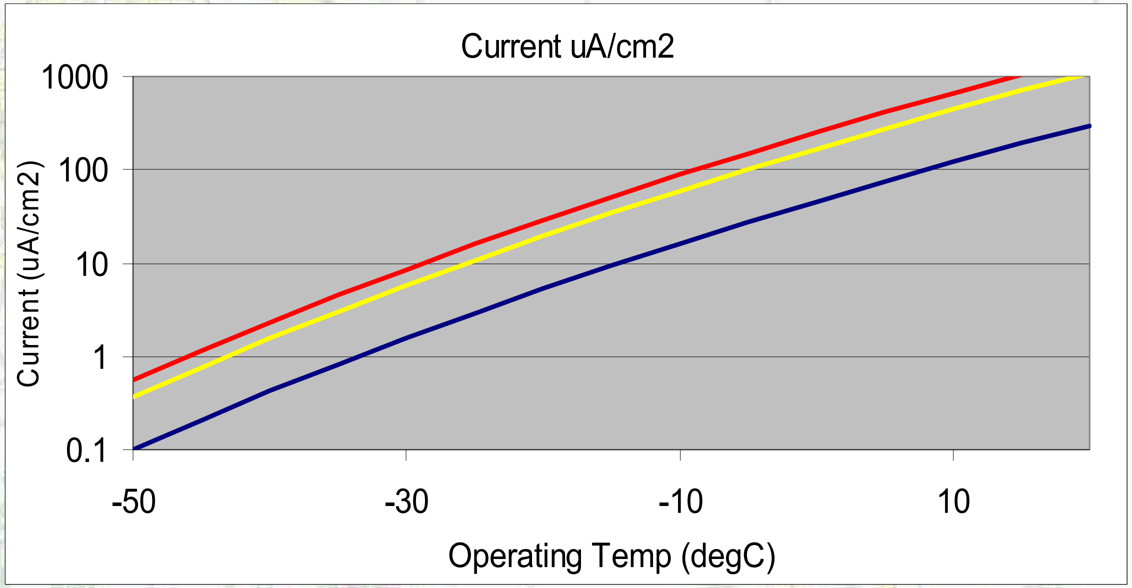
ID Straw-man could be 3 or 4 SS layers and 6 or 7 Discs.

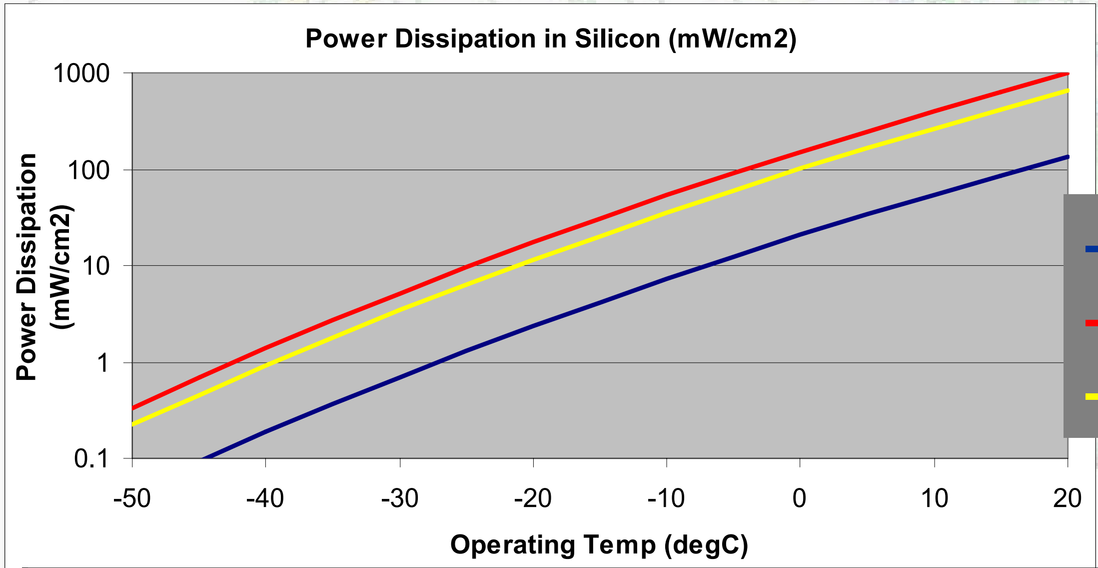
This will depend at the end on the optimization of the overall detector.

David Lissauer

Current & Power Dissipation

SLHC: Straw-man Layout
Innermost short strip radius 27cm





— LHC: flux = 2×10^{14} n_{eq}/cm^2, bias = 450V, 300μm
— SLHC: flux = 1.1×10^{15} n_{eq}/cm^2, bias = 600V, 300μm
— SLHC: flux = 1.1×10^{15} n_{eq}/cm^2, bias = 600V, 200μm

Temperature	-40°C	-30°C	-20°C	-10°C	0°C	10°C	20°C
LHC (mW/cm^2)	0.19	0.70	2.4	7.2	21	54	135
SLHC (mW/cm^2)	1.4	5.1	17	53	151	399	990

Currents: $\times$ 5.5
Power: $\times$ 7

SLHC: to keep power dissipation same as LHC would need to be nearly 20°C colder.

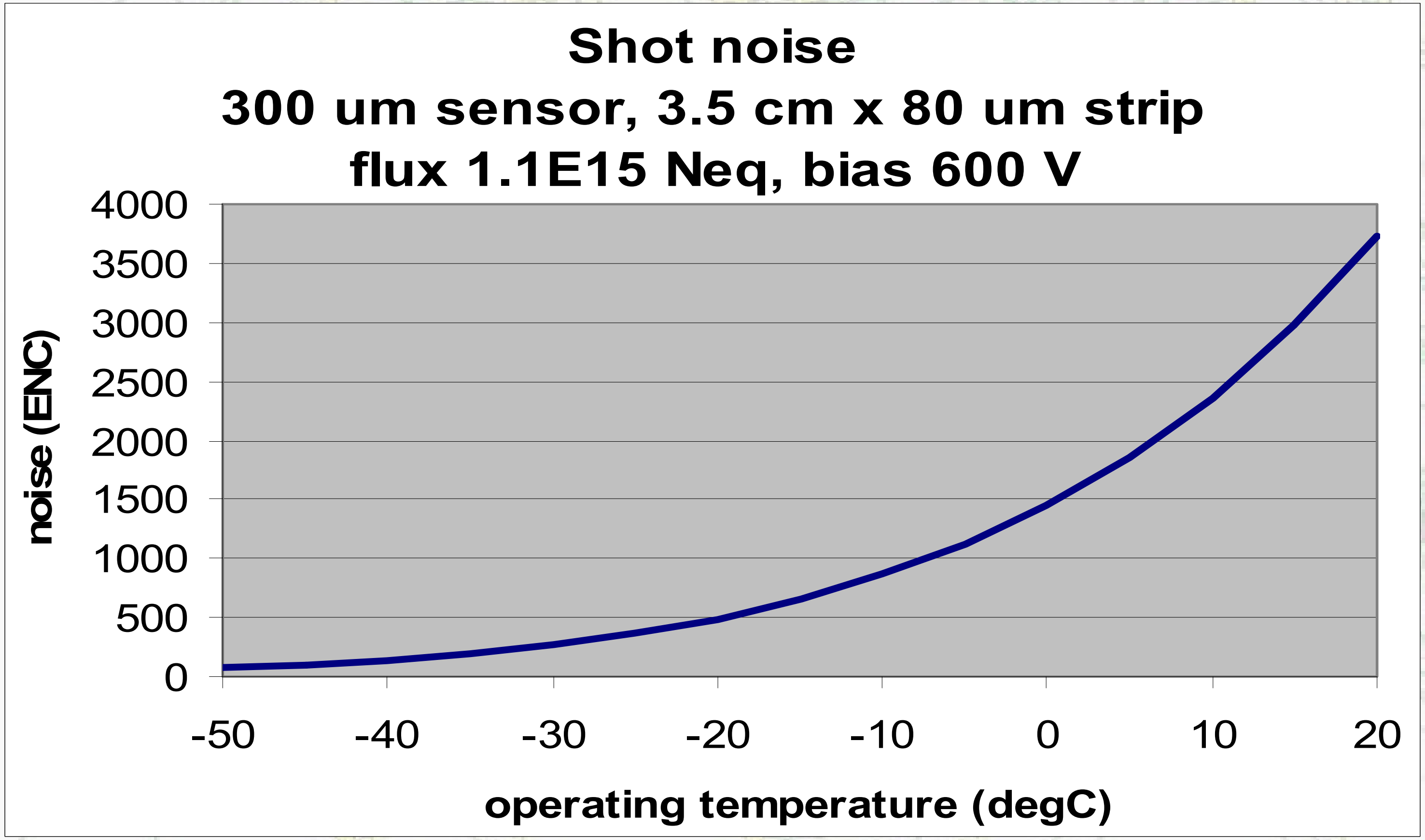
Note only LHC includes 50% safety factor.

Joost Vossebeld

Shot Noise

High leakage current also adds to the noise.

$$\text{shot noise (ENC)} \approx \sqrt{12\ I_{\text{detector}}\ (\text{nA})\ t_{\text{shaping}}\ (\text{ns})}$$ **(Spieler, PDG 2004)**



This gets added in quadrature to other noise contributions.

In short strip region probably need to keep total noise below ~1000ENC (for 25 ns shaping time).

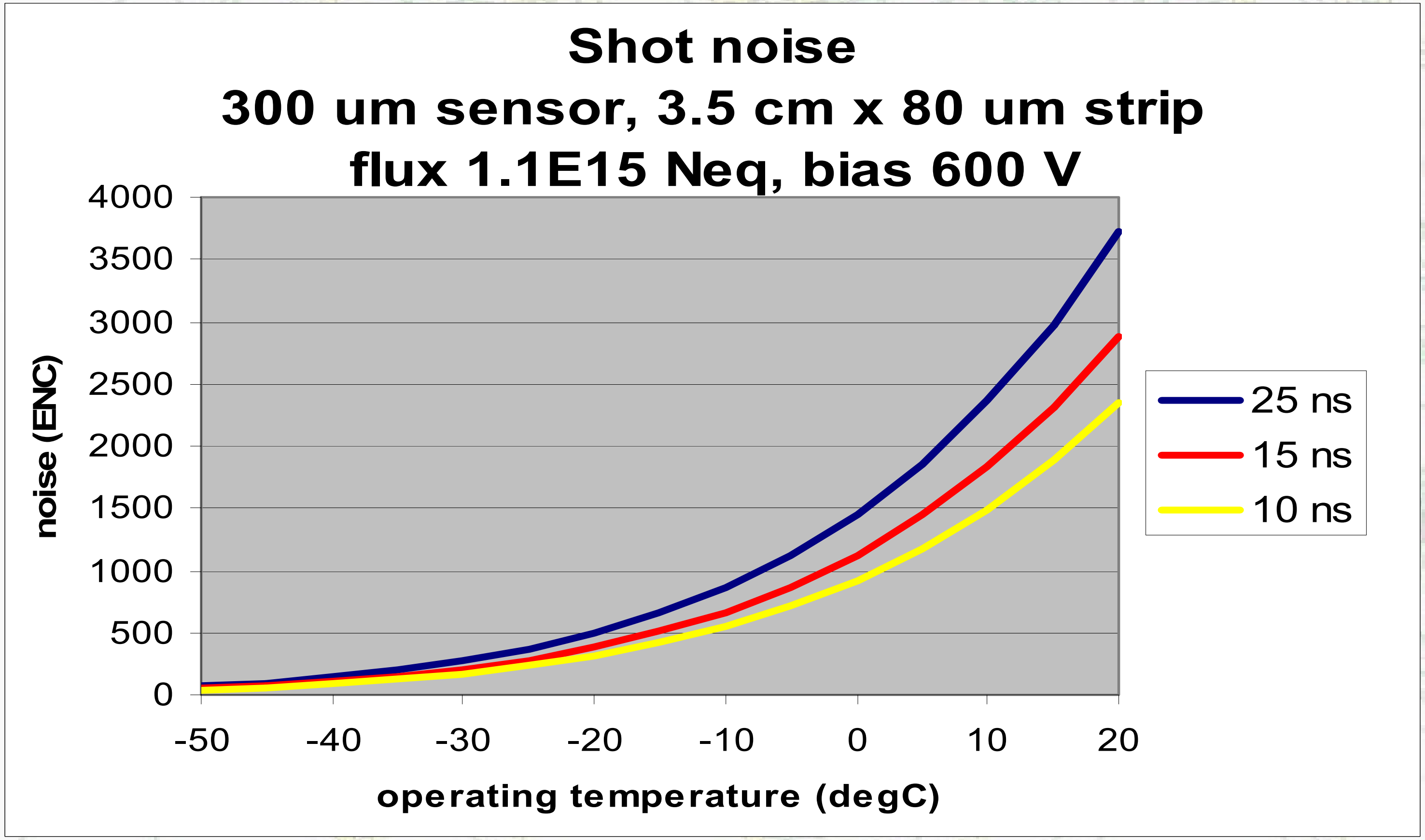
To keep shot noise contribution below ~500enc, need to keep the sensor operating temperature below -20°C.
(Shot noise reduced by 20% for 200µm sensor.)

Joost Vossebeld

Shot Noise

High leakage current also adds to the noise.

$$\text{shot noise (ENC)} \approx \sqrt{12\, I_{detector}\,(\text{nA})\; t_{shaping}\,(\text{ns})}$$ **(Spieler, PDG 2004)**



This gets added in quadrature to other noise contributions.

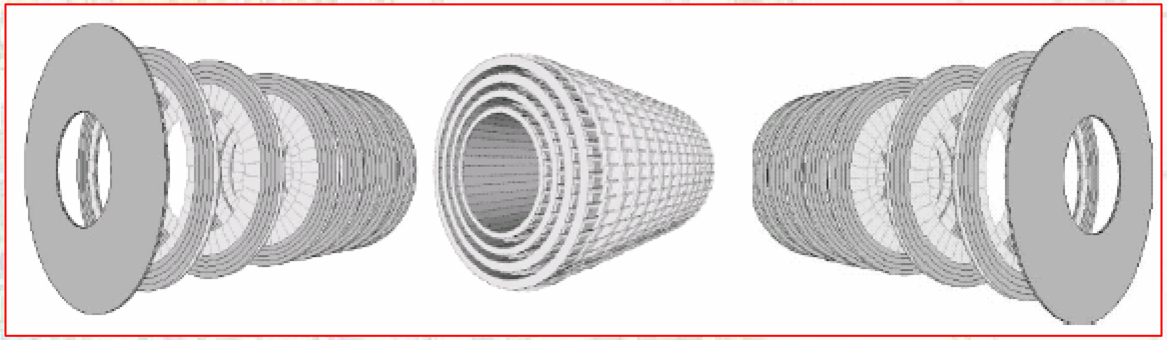
In short strip region probably need to keep total noise below ~1000ENC (for 25 ns shaping time).

To keep shot noise contribution below ~500enc, need to keep the sensor operating temperature below -15°C (10-15ns).
(Shot noise reduced by 20% for 200μm sensor.)

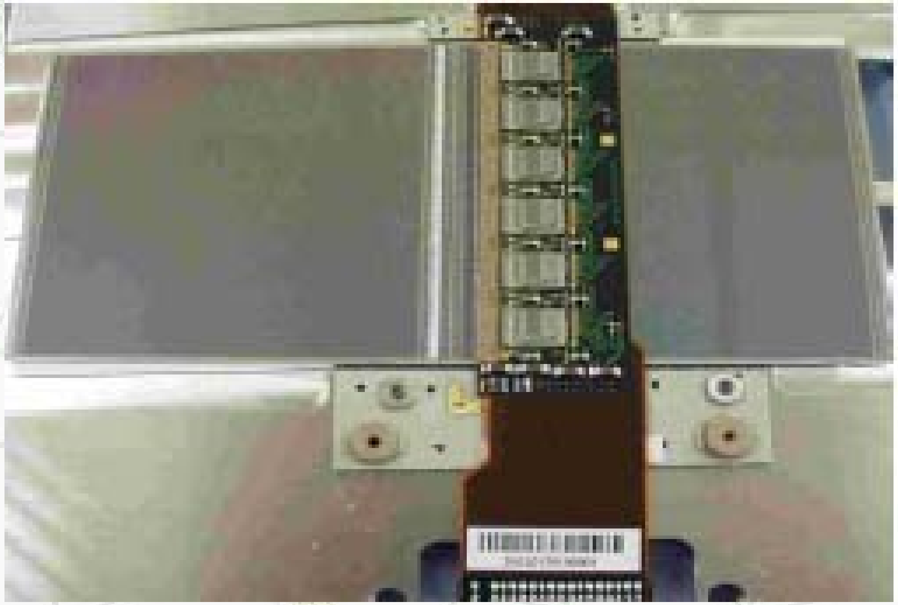
Joost Vossebeld

Possible Super-LHC Module Design

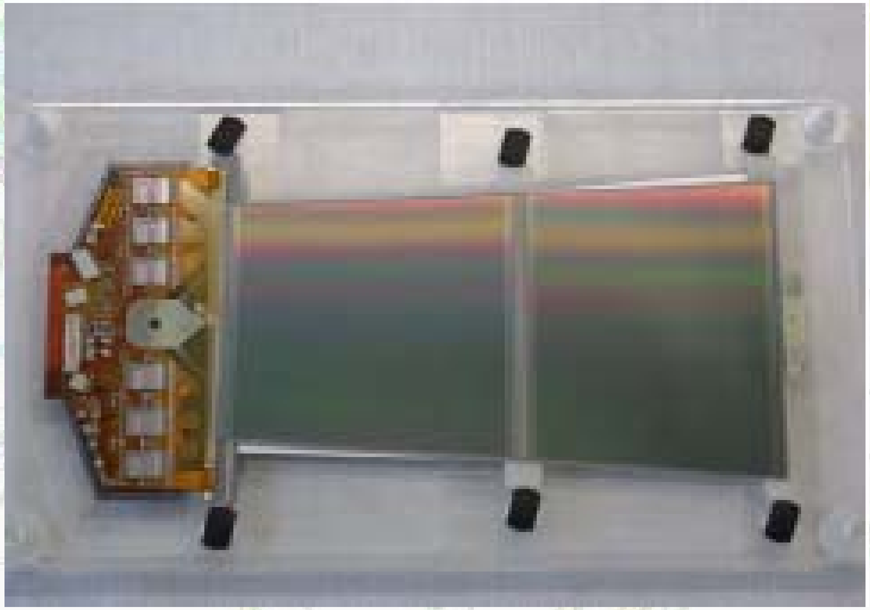
ATLAS Tracker Based on Barrel and Disc Supports



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



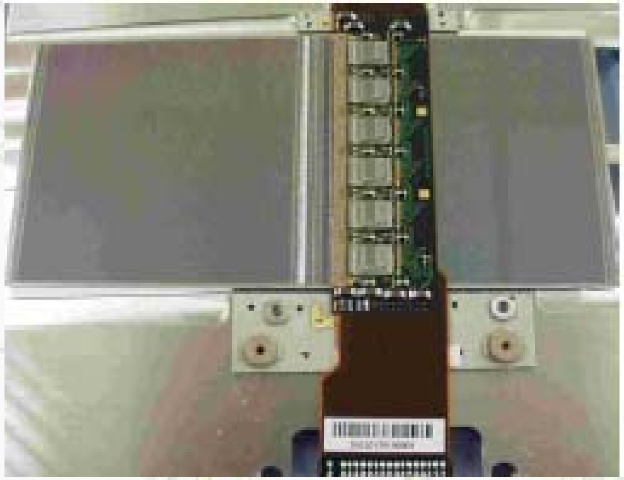
Barrel Modules



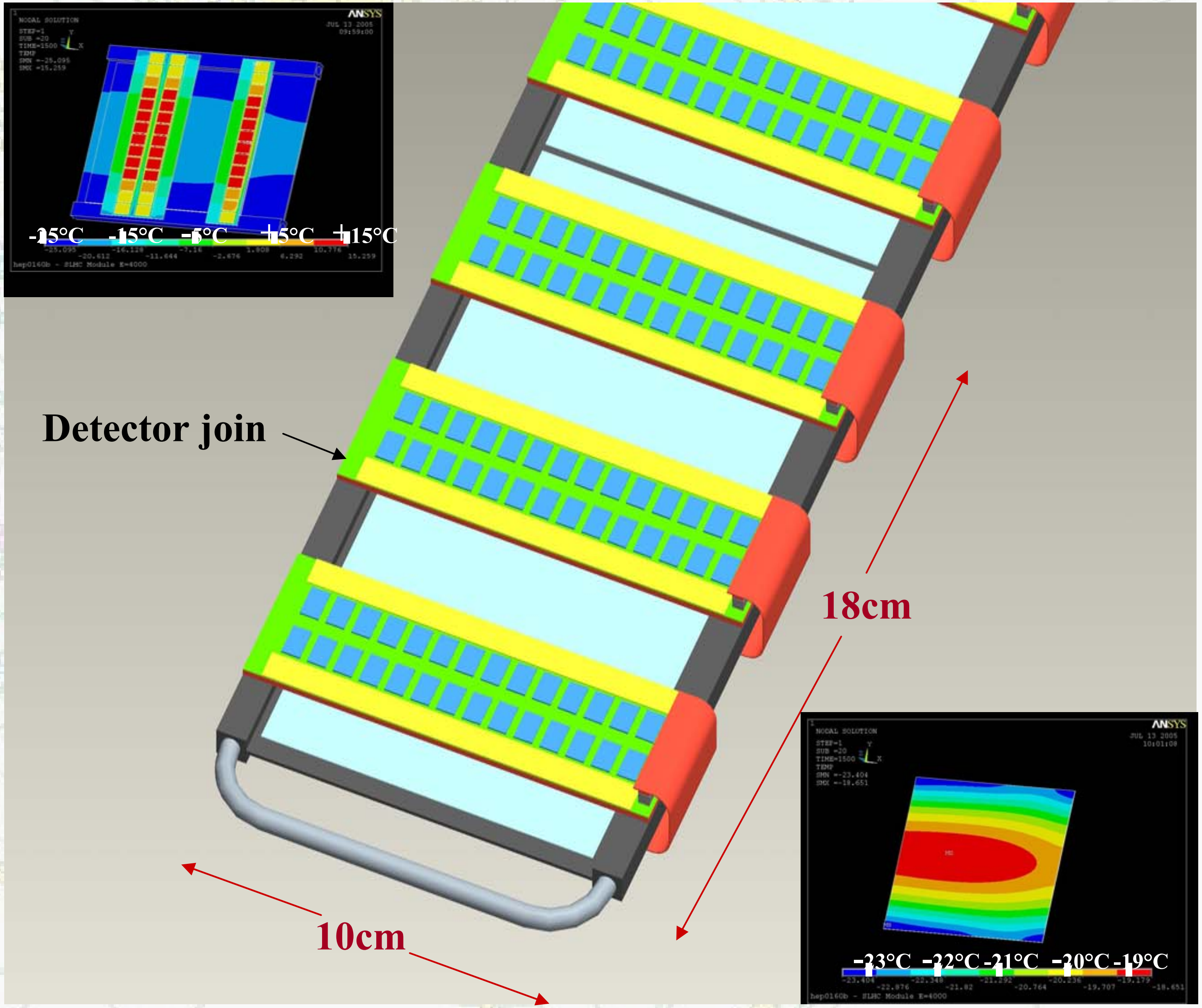
Forward Modules

Possible Short Strip Super-Module Design

SLHC 'Stave' concept based on current ATLAS barrel module with bridging structure for hybrid and TPG baseboard

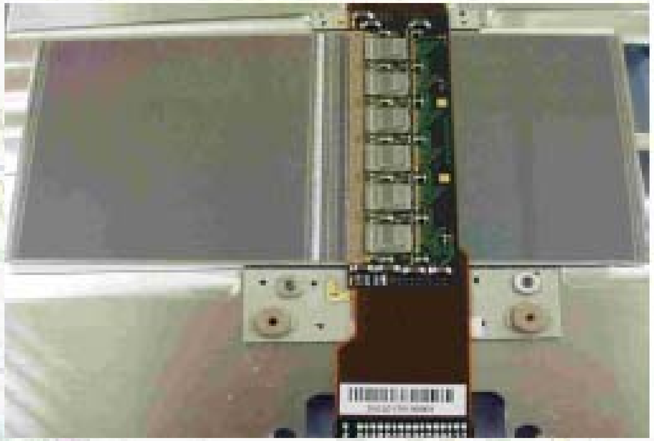


Other "Stave" designs developed from the CDF Run-IIb prototype modules (*cf* Carl Haber Presentation)

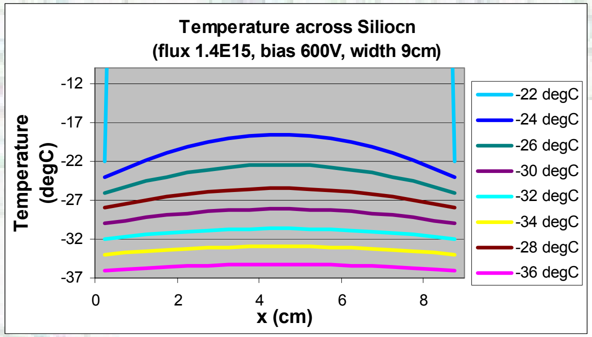


Z=0 End of 144cm Length Stave with 9cm Sensor Width

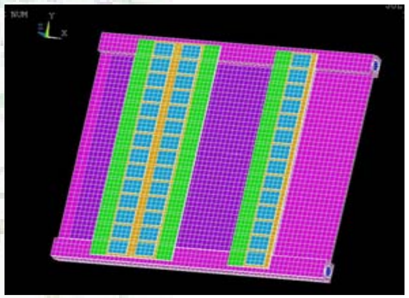
Possible Short Strip Super-Module Design

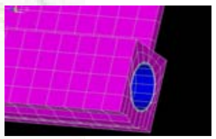


Ideas based on current ATLAS barrel design with bridging structure for electronics hybrid and TPG baseboard using
48μm/64μm pitch (φ)
3cm short strips
giving ~9×10cm
single-sided sensors.

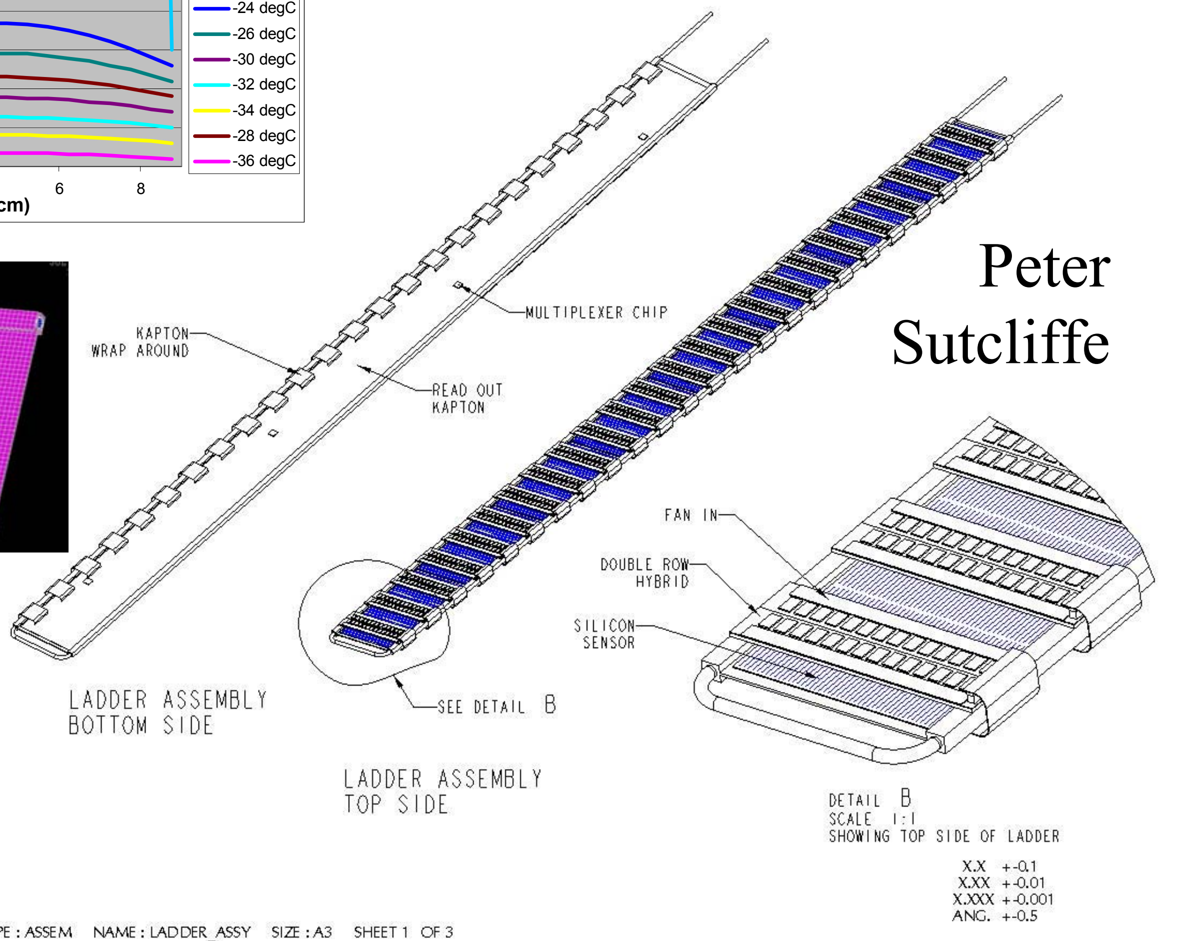


Each sensor has 3 sets of 3cm strips which could be DC coupled electronics.





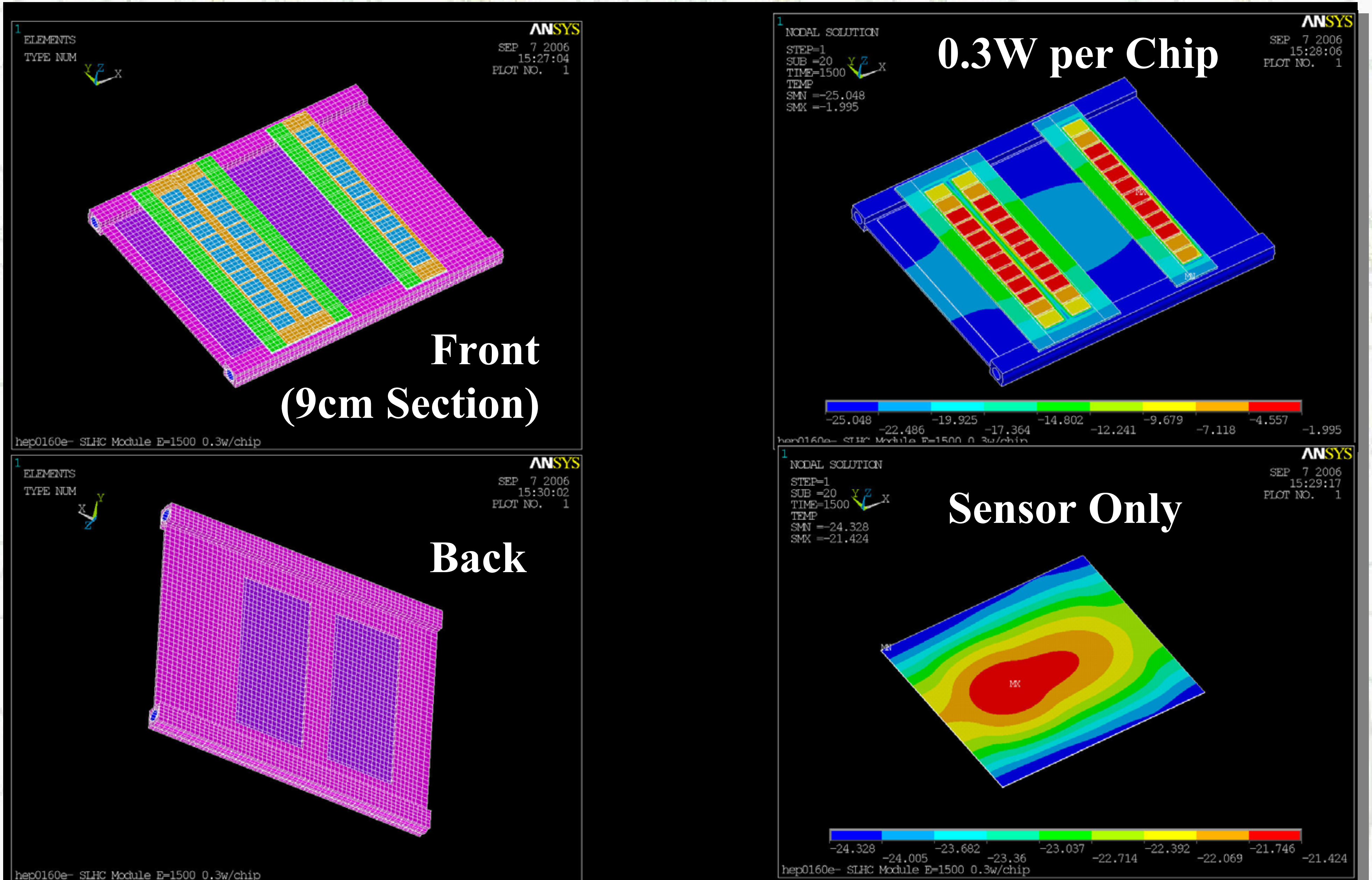
Indications from initial simulation are that thermal runaway can be avoided with -25^{o}C coolant. (27 cm radius)



Peter Sutcliffe

Short Strip Super-Module Simulation

Thermal simulation including effects of thermal runaway with 12 chip wide (64μm pitch) modules on carbon-carbon substrate with cut-away 3cm short strips



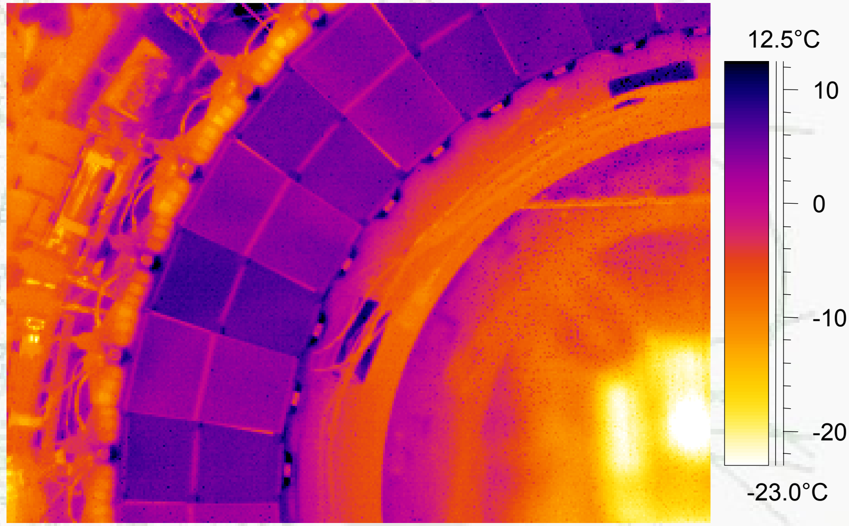
Cooling Challenges

SCT experience C_3F_8 evaporative cooling system

- constant temperature throughout cooling lines
- high cooling capacity (limited flow)

Also

- successful thermal separation hybrid and sensors.



Challenges for the SLHC:

- more modules / more power dissipation
- need to keep silicon temperature at -20°C.
    - **strong constraint on thermal separation hybrid and sensor**

Proposals for study:

- sensors on high thermal conductivity spine/base (TPC,CC)
- Use two-phase cooling again. Limited number of coolants available
    - C_3F_8 (start to hit problems for very low temperatures)
    - CO_2 (high cooling capacity with very thin pipes but high pressure)

Front-end Electronics, Power, Readout

<u>Front-end electronics</u>

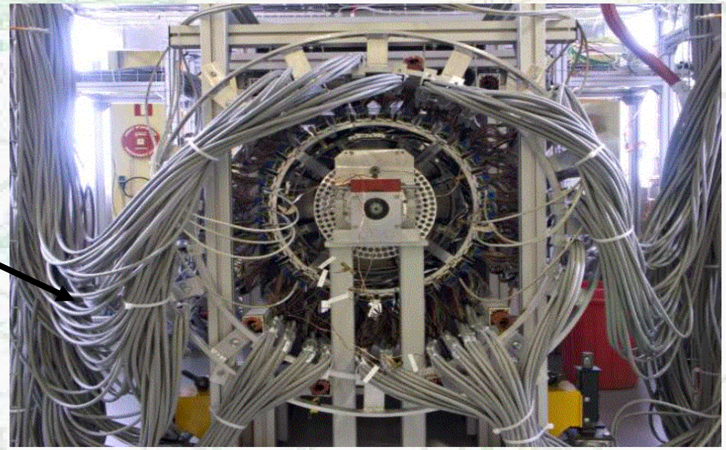
- **ABCD-next: port ABCD to 0.25 μm and then to 0.13 μm CMOS**
- **SiGe-biCMOS: also 0.25 or 0.13 μm**

In both cases deep sub-micron: (*cf* Wladek Dabrowski)

- **Radiation hard**
- **Reduced power dissipation per chip (but more chips, still ×2 power increase)**
- **Low driving voltages (large voltage drop, or thick cables)**

<u>Power distribution:</u>

Cannot afford to have thousands more of these



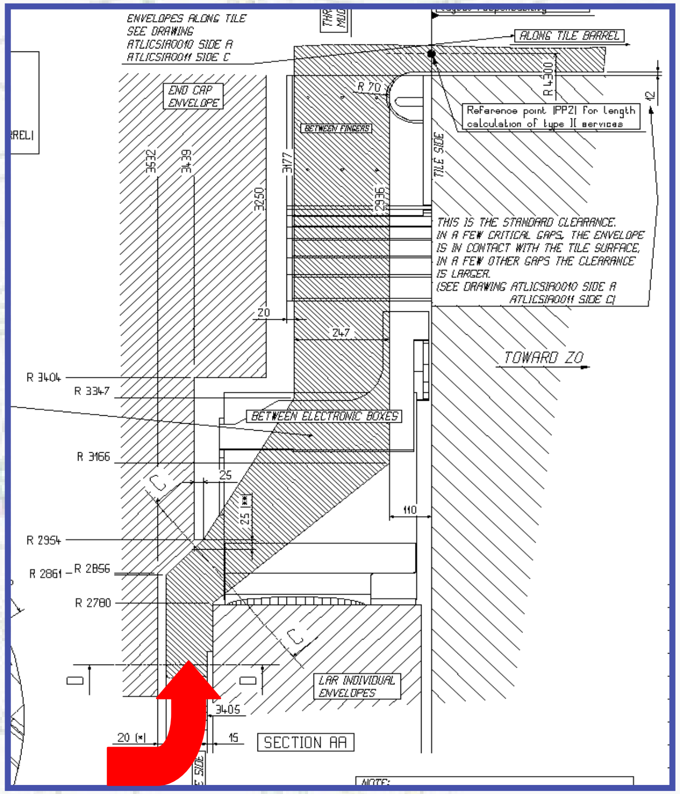
- **shared power to modules:**
  - **DC-DC conversion near the modules?**
  - **Serial powering? (*cf* Marc Weber presentation)**

<u>Data output:</u>

Similar problem, more channels limited space.

Use shared high speed optical links. (SLHC requires customised solutions)

Other Tracker Challenges (mainly for middle and outer radii)



Replacement inner tracker will need to <u>fit in the same space</u> as the current one.

The same goes for the <u>services</u>. (Almost factor 10 more channels in SCT/TRT region)

<u>Limited time for building</u> system with many modules

Should make something that's easy to build.

Where possible use experience of the current build.

- Build something similar or completely different?

ATLAS Tracker Upgrade Summary

Likely date for SLHC luminosity upgrade to 10^{35} $cm^{-2}s^{-1}$ is around 2015.
Preparations for required inner tracker replacement already urgent.

Sensor technology:

- Sensor solutions may exist but urgently require commercial prototyping:
  n-side readout silicon pixels/strips could provide 10 years operation.
- b-layer at 5/6cm radius would require 3D or other advanced technologies.

Need to operate sensors much colder than at the LHC (around -20°C?).

Front-end electronics: deep sub-micron rad-hard technologies needed

Engineering issues may be the biggest challenge:

- require integrated design of module/stave with full services incorporated
- need to work on cooling, electrical power distribution and optical read-out
- limited time to build large tracker requiring many innovative technologies

Back-up Slides

The LHC programme

The results are impossible to predict
(no Higgs (yet); a light Higgs; a heavy Higgs;
SUSY – Higgses, sleptons, squarks (light, heavy);
extra dimensions; ...)

but

the LHC is likely to reveal new fundamental mass scales in the region 0.114 - >~ 1 TeV

Its findings will highlight the next physics opportunities at the energy frontier

The LHC programme upgrade

1. **Efficient running of the LHC complex** requires consolidation of the injectors, in particular of the Proton Synchrotron (1959), but also of the SPS

2. **The next step at the energy frontier** could be a very high luminosity hadron collider at LHC energy (SLHC)
   - higher statistics
   - higher mass reach

   This requires major modifications of the injector complex and the LHC hardware and new R&D on detectors (higher irradiation on trackers)

Maximization of LHC Luminosity

(L1) - Minimize turn-around time by improving reliability / minimizing duration of stops

(L2) - Remove bottle-necks towards ultimate luminosity

(SL) - Refine / select scenario for SLHC (start in ~ 2015)

LHC: “Maximize integrated luminosity” (2007- 2015)

– Phase 0: without hardware changes in the LHC
  - Improve injectors (⇒ actions L1 and L2) to increase brightness N_b/ε up to ultimate:

    → $L_0 = 2.3 \times 10^{34}$ cm^{-2} s^{-1} & $\int Ldt \sim 1.5 \times$ nominal (= 100 fb^{-1} / year)
  - increase the dipole field from 8.33 to 9 T: ↑ E_{max} = 7.54 TeV

– Phase 1: with major hardware changes in the LHC (IR, RF, collimation, dump, …)
  - modify the insertion quadrupoles and/or layout: ↓ β^* = 0.25 m → more R&D needed in higher field magnets
  - increase crossing angle θ_c by $\sqrt{2}$: ↑ θ_c = 445 μrad
  - halve bunch length with new high harmonic RF system in the LHC:

    → $L_0 = 4.6 \times 10^{34}$ cm^{-2}s^{-1} & $\int Ldt \sim 3 \times$ nominal (= 200 fb^{-1} / year)
  - double the number of bunches [⇒ new RF systems in the injectors (including SPS if 12.5 ns bunch spacing)] & increase θ_c:

    → $L_0 = 9.2 \times 10^{34}$ cm^{-2}s^{-1} & $\int Ldt \sim 6 \times$ nominal (= 400 fb^{-1} / year)

Luminosity and Luminosity Lifetime

$$L = \frac{N_b^2 \, n \, f_r \, \gamma}{4\pi \ \varepsilon_n \, \beta^*} F$$

	N_b (10^{11})	n	L (10^{34})	τ_L (h)
Nominal	1.15	2808	1.0	15
Ultimate	1.7	2808	2.3	12
β-squeeze / 2	1.7	2808	4.6	6.5
Double bunches	1.7	5616	9.2	6.5

Motivations for Stave Designs

Advantages

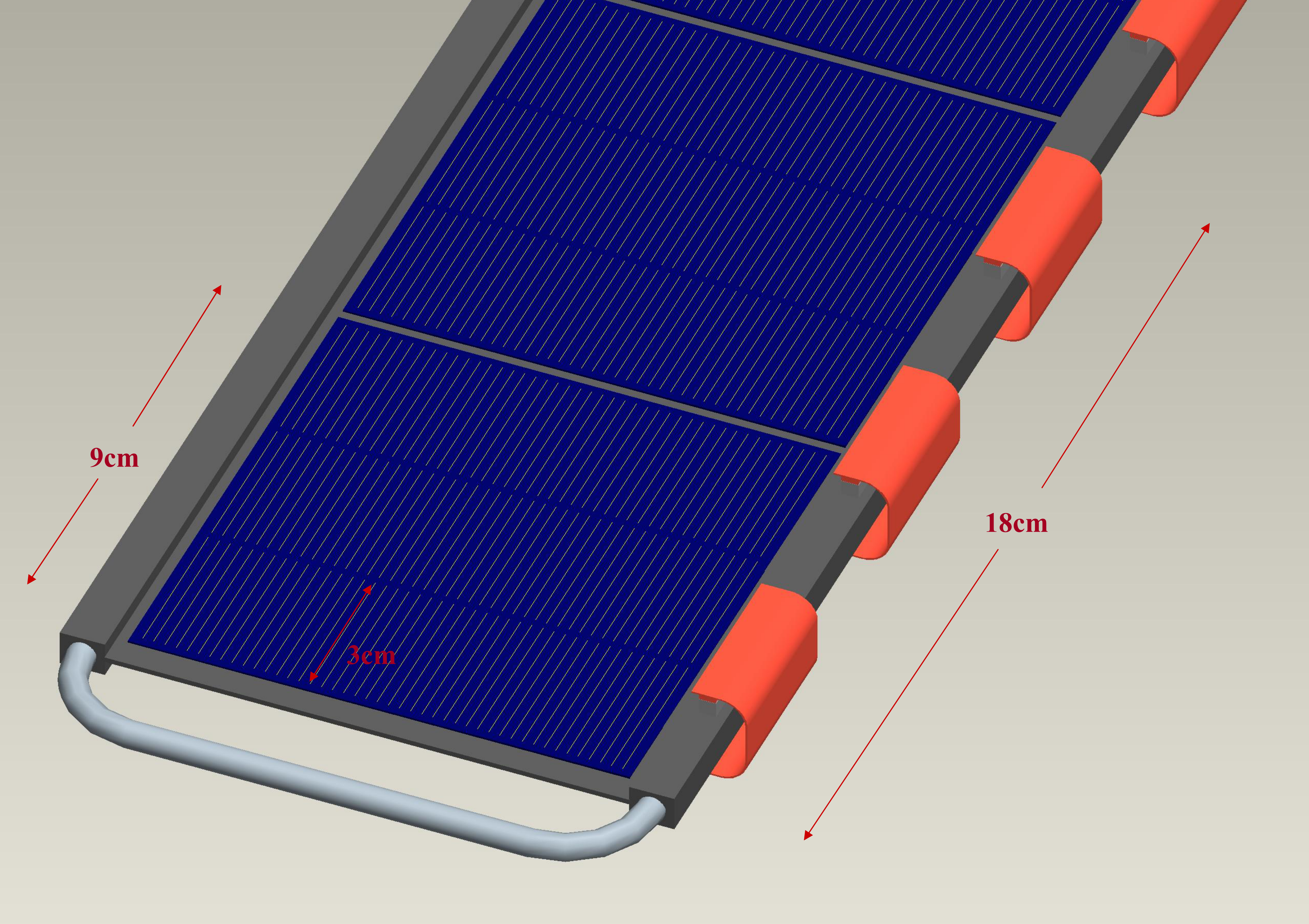
- Single unit with all services (included cooling) integrated.
- All performance aspects can be tested prior to assembly.
- Lends itself naturally to distributed production.
- Ease of assembly, removal, repair and replacement.
- Less thermal and electrical connections.
- Tapered staves for forward region naturally offer lower width (better cooling) at low radii.
- Forward staves could be inclined to reduce scattering material and optimise coverage.

Disadvantages

- Danger of more scattering material when including support space-frame/cylinder.
- Harder to ensure minimal distance between overlapping modules in a given layer.
- Different services are forced to address the same set of sensors/hybrids.
- Need to ensure space-frame structure is highly stable and rigid.
- Metrology of final object less straightforward.

Forward region assumed to require radial sensors, so 7 different types of 10cm long objects needed in all designs. With the tapered stave concept, these would go from 10cm width at 100cm radius down to 3cm at 30cm radius, subtending 5.7^{o} so that 64 such units would be needed to give 2π coverage at each z position.

Outer radii assumed to have extra small angle stereo layers to give space-point for both other barrels and high radius on forward tapered staves.


9cm
18cm
3cm

Results from n-in-p Irradiation Studies

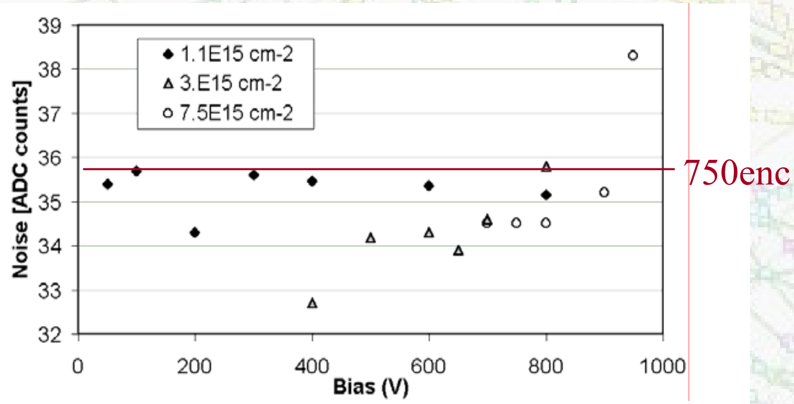
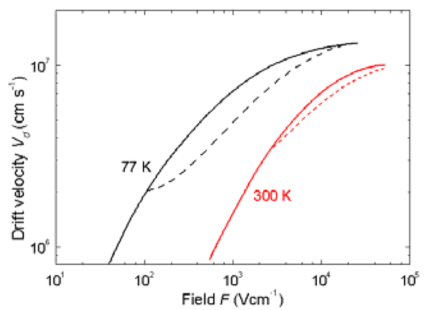


Fig. 1 Noise as a function of the applied voltage for the three different irradiation doses. The pre-irradiation value is about 35 ADC counts, similar to the value found after irradiation.



- Signals (>7000e) independent of annealing over many years (trapping dominates) and noise does not vary with voltage or dose for SCT128a read-out.
- Charge Collection no longer a function of depletion voltage, since material is semi-insulating when undepleted and field region extends throughout.
- CCE depends primarily on trapping time (remember drift velocity saturates much above 1V/μm) so raising V_{det} does not keep increasing signal.

- **S/N of >10 expected for 3cm ministrips at doses corresponding to 25 cm radius ($1.5\times10^{15} n_{eq} cm^{-2}$) with voltages ~600V.**

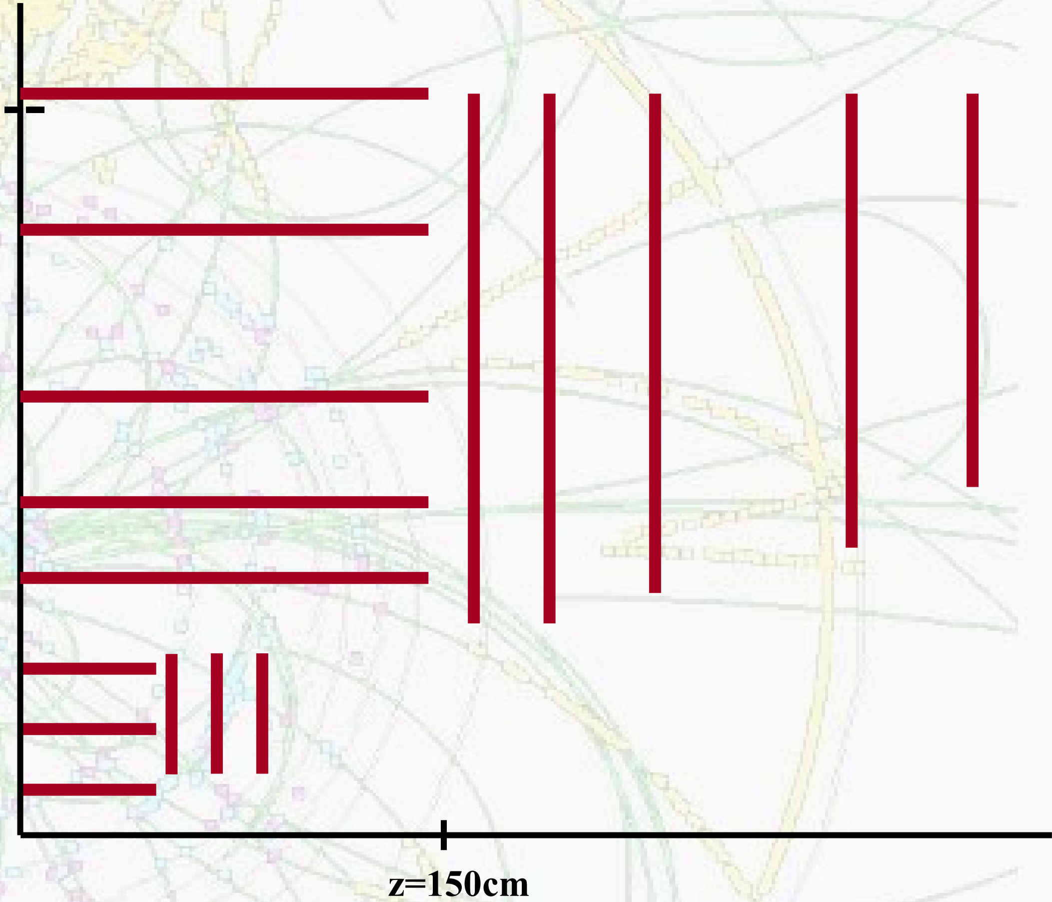
Pixel region (other than b-layer) should see 6000e signals even after $4\times10^{15} n_{eq} cm^{-2}$ which, with improved uniformity electronics, might prove manageable.

Outer tracking layers could see doses 2 times current SCT (depends on neutron absorber) and may also need to be p-type with signals of order 16,000e at 500V.

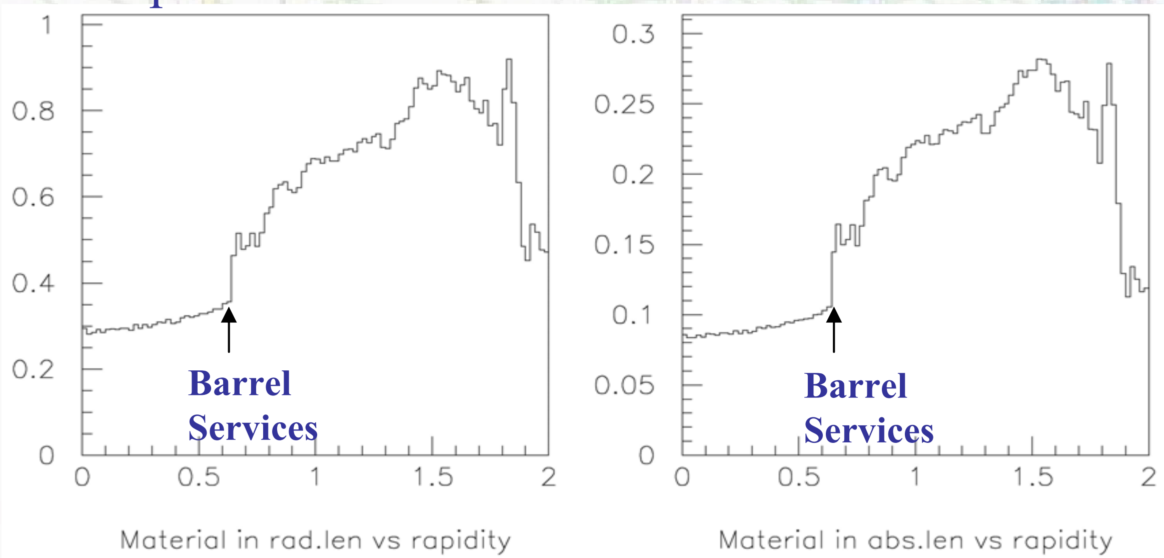
Tracker Layout Motivation

Long Barrel design motivated by material and pattern recognition considerations.

Pixels: r=6cm, 15cm, 24cm z=±50cm
Ministrips: r=35cm, 48cm, 62cm z=±144cm
Microstrips: r=84cm, 105cm z=±144cm



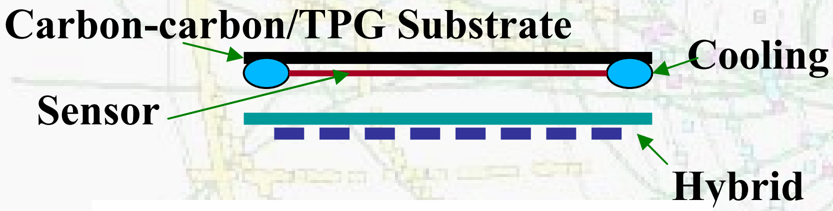
Updated Material for Current ATLAS Tracker



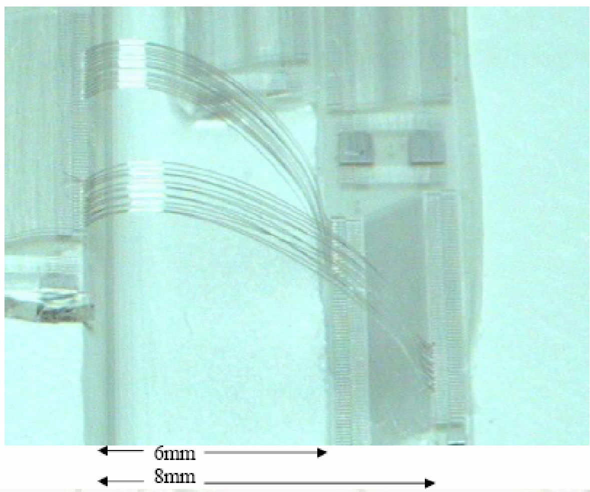
- Proposed new design pushes transition from barrel to end-cap geometries out to $\eta = \pm 1.5$
- Crossing angles get larger (up to 75° so 4× orthogonal thickness for inner ministrip layer)
- Correspondingly wasteful of silicon, so coverage eventually needs disc geometries
- Have not exploited stave possibilities to incline in forward directions (but then still need to keep to reasonable numbers of wafer geometries).

How to Reduce Gaps

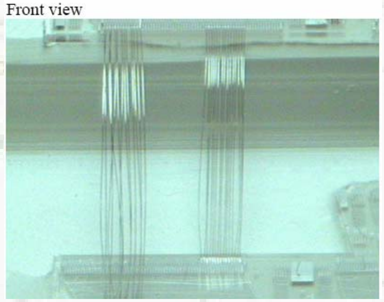
However you achieve the mechanical design, the issue of gaps remains.
Use of DC coupled sense elements removes needs for bias resistors, but gaps every 9cm remain.
Overlaps in φ need to take account of cooling pipe locations.
Detectors can be castellated along the z-direction to avoid gaps at the cost of complicating the wire bonding.
Stave design could be adapted to reduce distances for overlaps but, again, this makes wire bonding harder (longer).



Side view 6mm platform with 30um loop hieghts

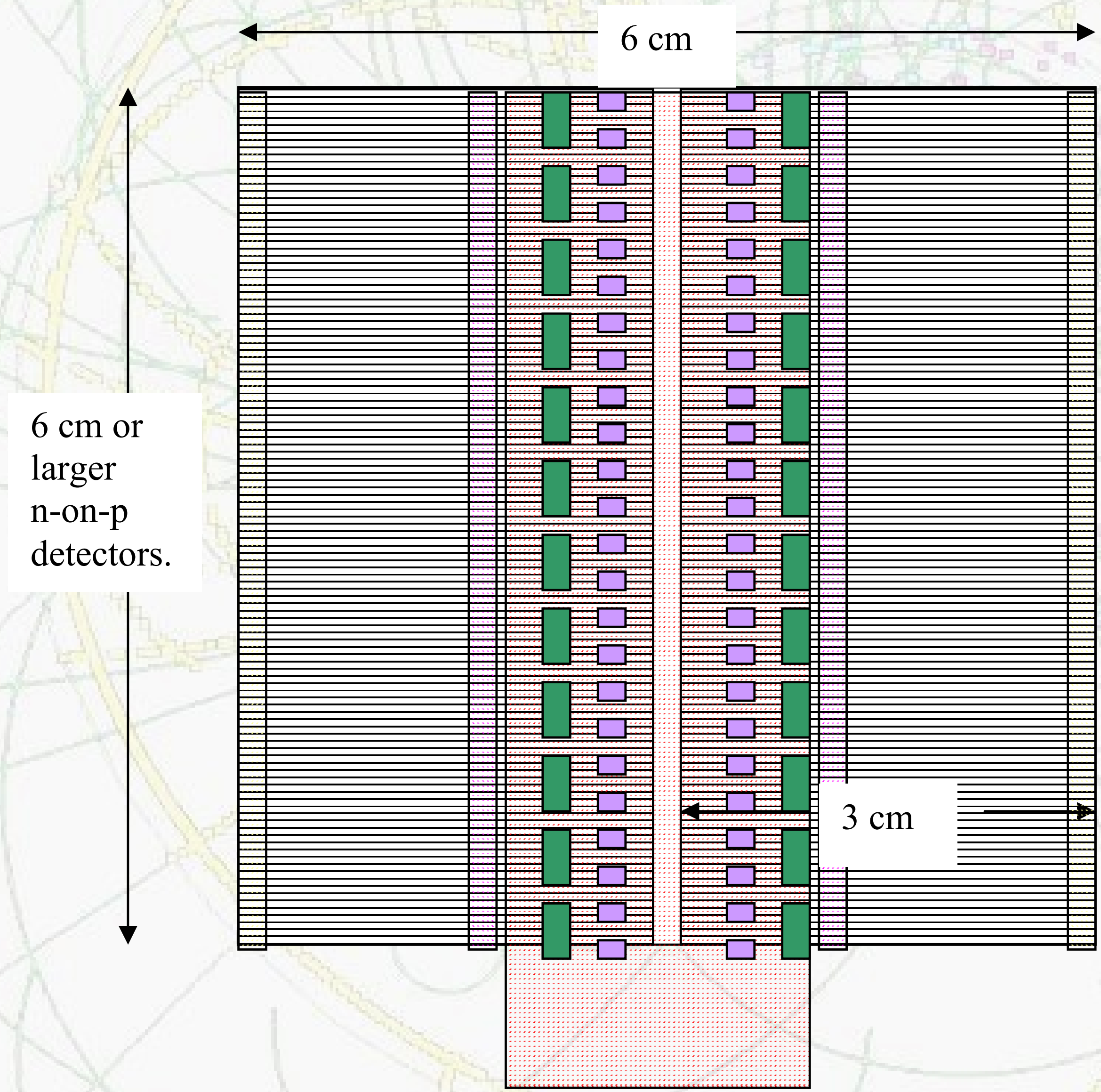


Front view



First look at bonding down 6mm to bond-pads at 50μm pitch

Alternative Mid-Radius 'Stripsel' Detector

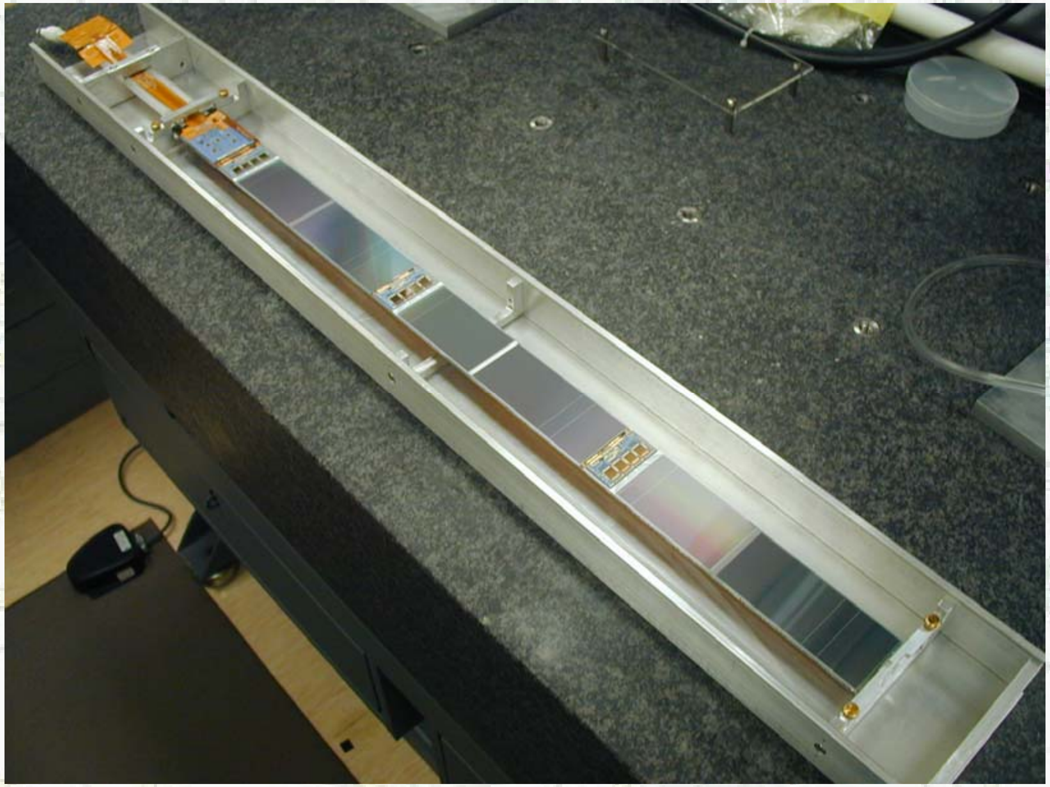


Abe Seiden

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

Cooling Integrated Beneath Sensor

Carl Haber



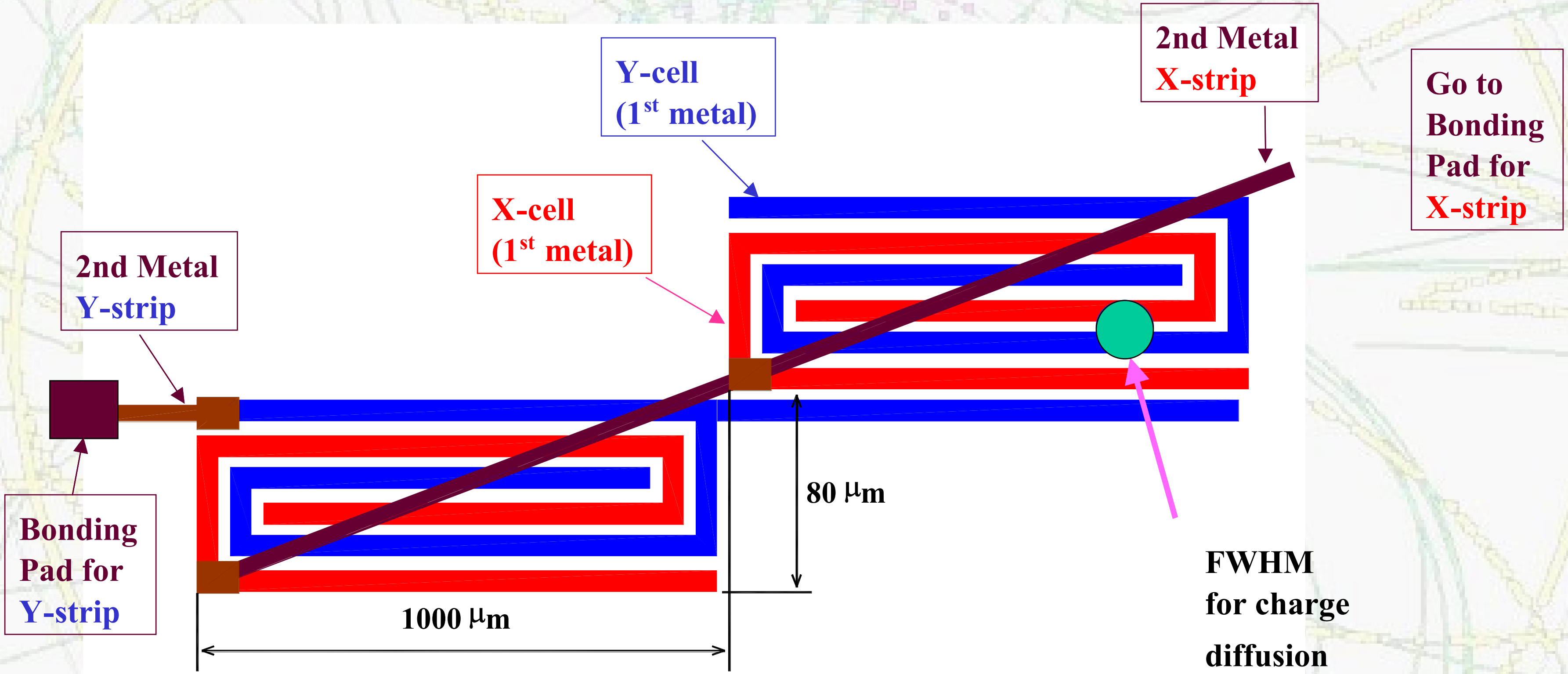
CDF Stave

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

But thermal issues much more severe at SLHC doses

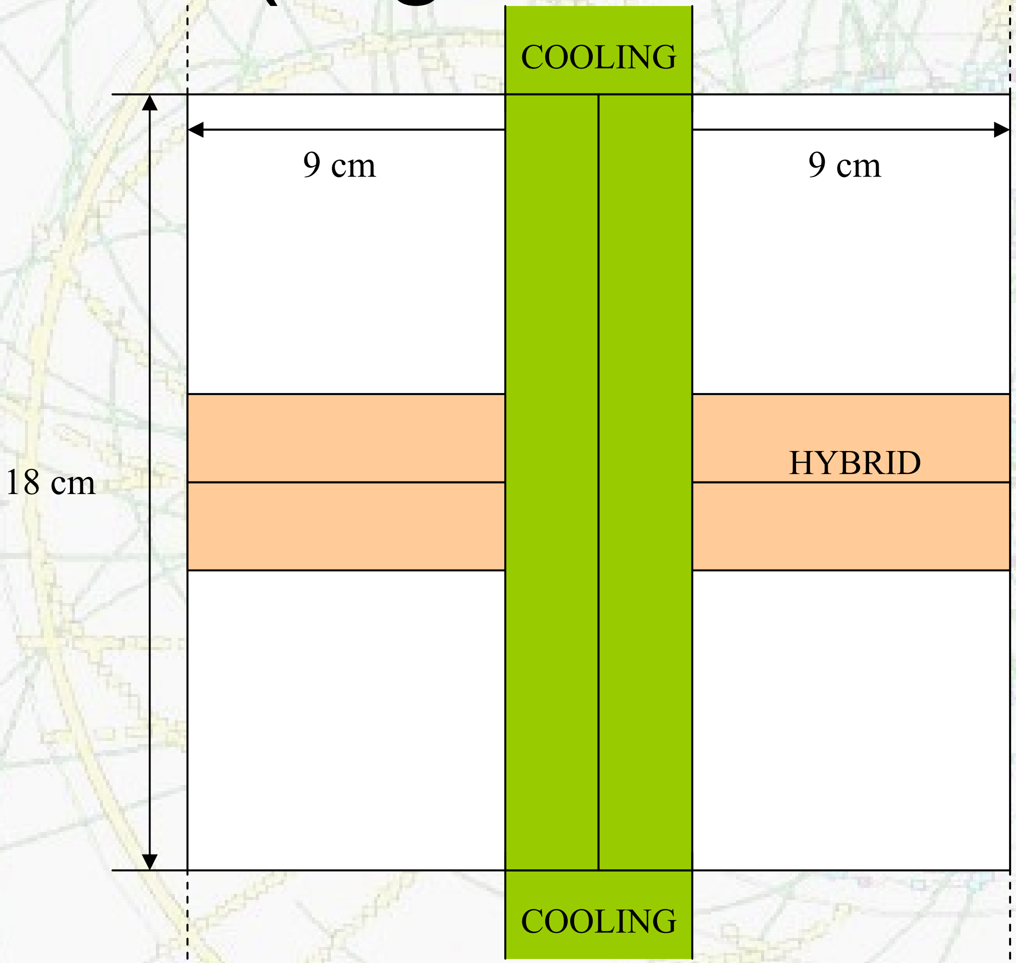
Options for Higher Radii: 2D Detector

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 halving of signal due to two readouts.

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.

Power Management and Serial Powering

- Features of ATLAS SCT

  - 6 M channels
  - 50 kW of power
  - 50% of power loss in cables
  - separate analogue and digital power lines for each module
  - material of power and cooling services dominates detector material

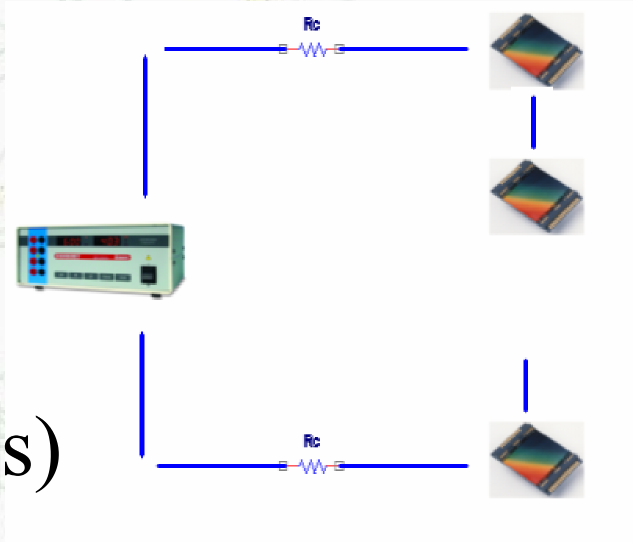
- Challenge for SLHC tracker

  - 60 M channels
  - cannot bring in 10-fold number of cables
  - ~80% power loss in cables for SLHC electronics
  - material of power cables ruins tracking resolution/reconstruction

- **Serial powering possible solution to this problem**

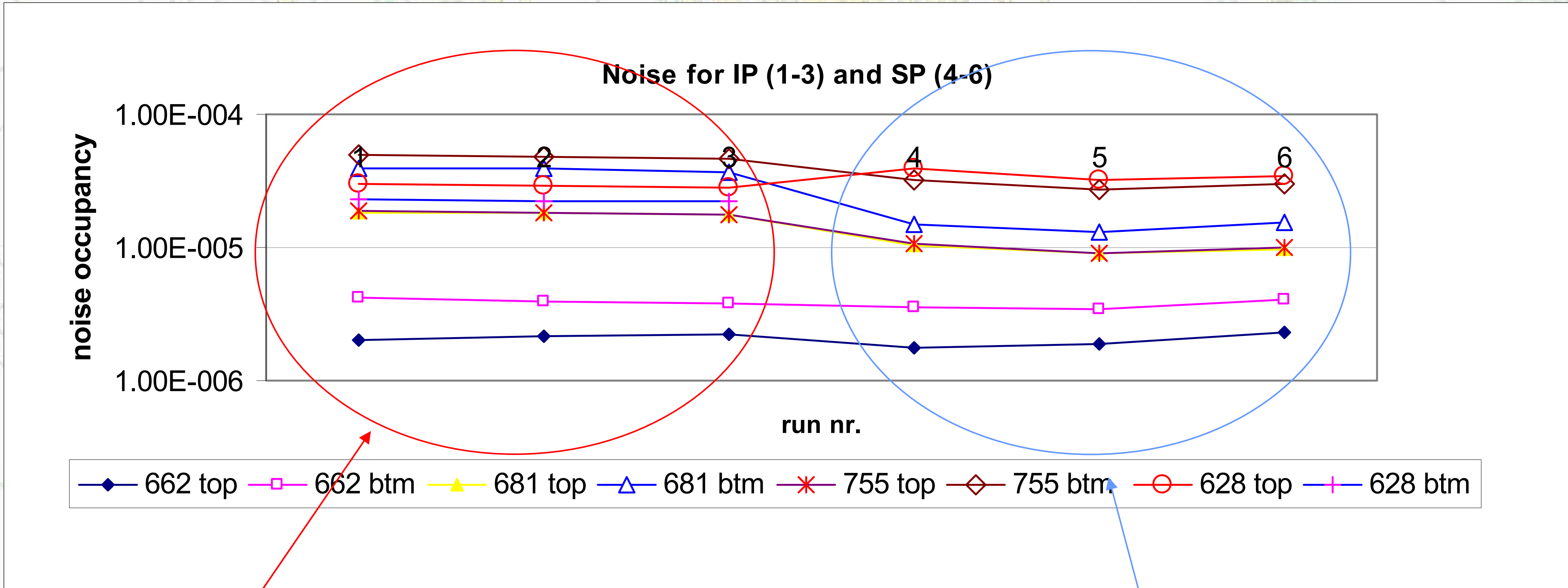
Serial Powering

- Power n modules from a single current source
  - number of cables reduced by factor 2n
  - much reduced power losses in cables
  - much reduced material
  - reduced costs   (power supplies, power bills)



- RAL initiated R&D programme
  - first results very promising (no extra noise with serial power)
  - goal is proof of principle for a large scale application
  (crucial for SLHC tracker and elsewhere)

First Published Serial Powering Results



- First 3 runs with independent powering and last 3 runs with serial powering for 8 ATLAS barrel modules
- For this bench-test (studies on prototype stave structures required) serial powering works well with no difference in noise performance