Status of radiation damage of the ATLAS SCT detector

20th RD50 Workshop on Radiation hard semiconductor devices
for high luminosity colliders, Bari, Italy

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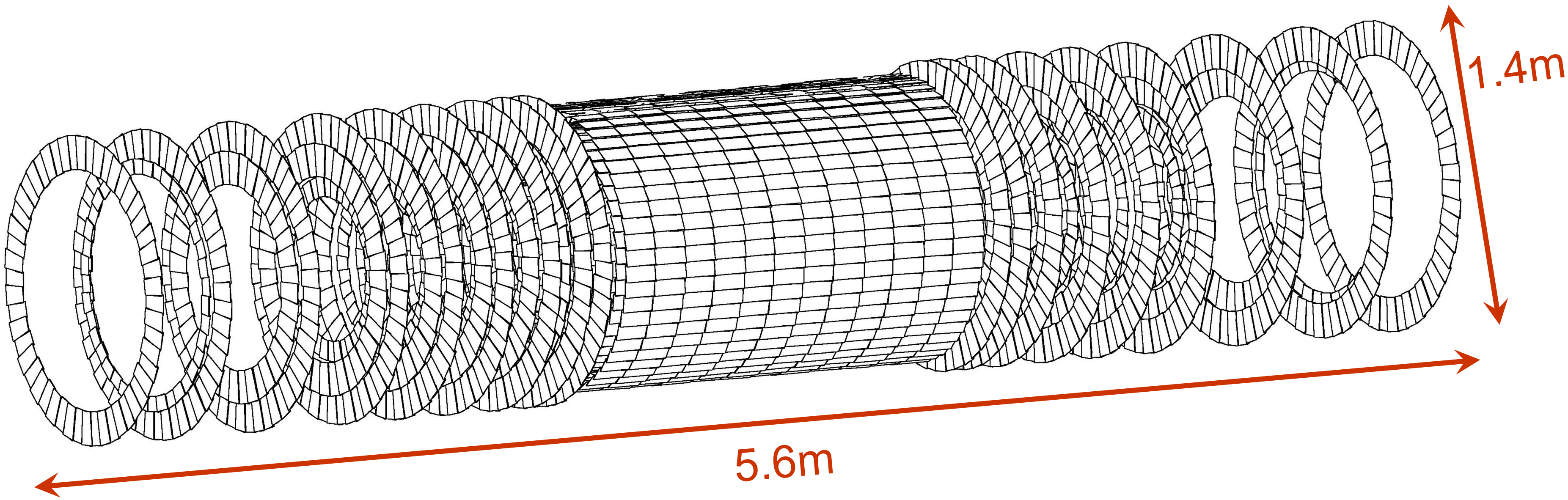
on behalf of the ATLAS SCT Collaboration

The Semi Conductor Tracker (SCT)



- 61 m^2 of silicon with 6.3 million readout channels
- 4088 silicon modules in 4 Barrels and 18 EC Disks
- C_3F_8 Cooling (-7^{o}C to +6^{o}C silicon)

Sensors

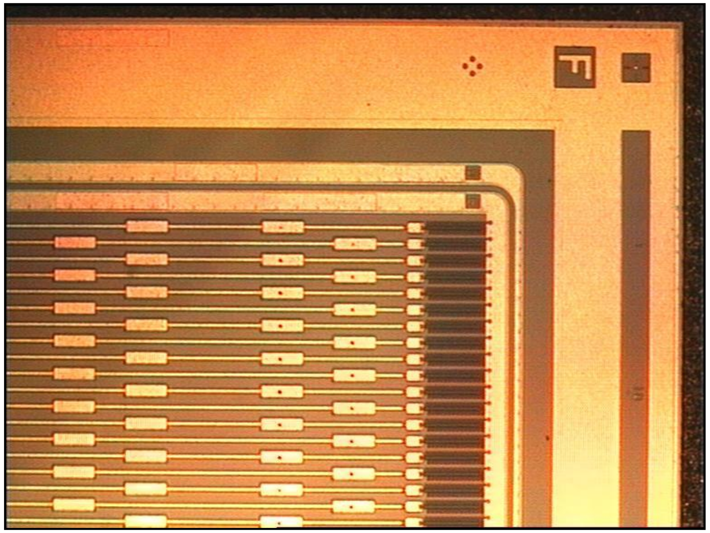
- Single sided p-on-n
- 285μm thick
- 768+2 AC-coupled strips

Barrel

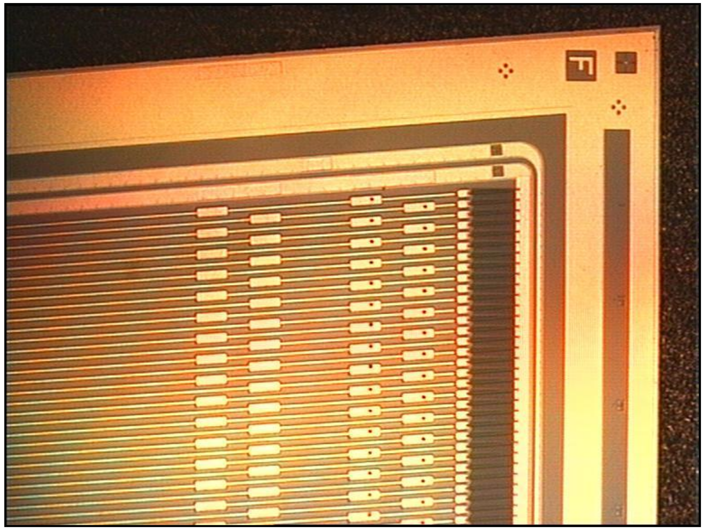
- 8448 barrel sensors
- 8081 sensors with **<111>**
- 367 (4.4%) sensors with **<100>** mounted on B3, B5 and B6
- 64.0 x 63.6mm
- 80μm strip pitch
- 100% Hamamatsu Photonics

Endcap

- 6944 wedge sensors
- 56.9-90.4μm strip pitch
- 5 flavours
- 82.8% Hamamatsu Photonics
  17.2% CiS (some oxygenated)



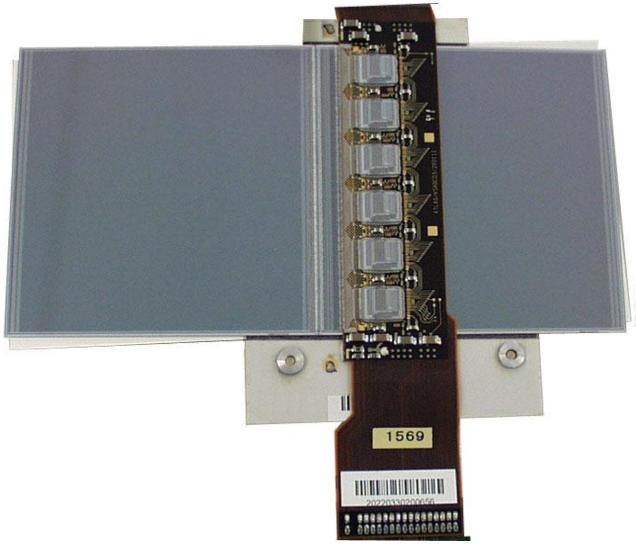
Barrel sensors

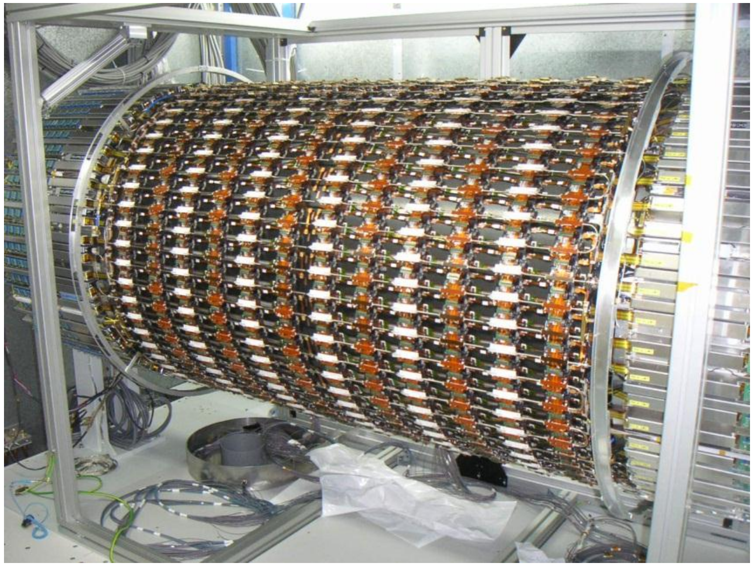


Endcap sensors

Barrel Modules and Layout

- 2112 barrel modules, 4 sensors/module
- back-to-back with 40 mrad stereo angle
- 12 chips (6 each side) with binary readout
- bridge-shape hybrids of flex circuit
- 5.6W/module (rising up to ~9W)



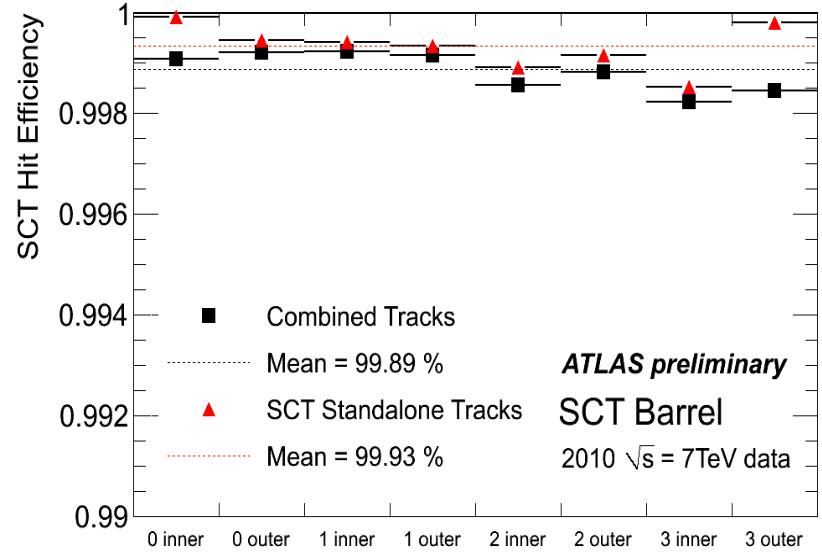


- 4 barrel layers
- 12 eta modules |Z|<80.5cm

Layer	radius	modules	T(sensor)
B3	29.9 cm	384	~ -2^{o}C
B4	37.1 cm	480	~ -2^{o}C
B5	44.3 cm	576	~ -1.3^{o}C
B6	51.4 cm	672	~ +6^{o}C

SCT performance

- 99.9 % efficiency for charged particles in Barrel

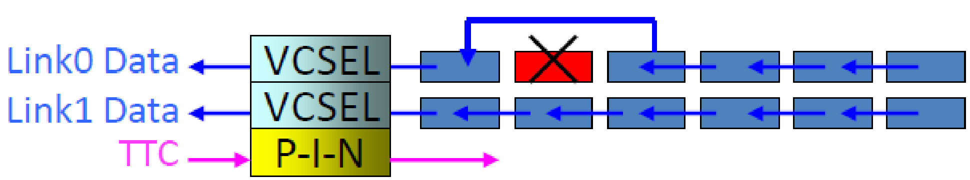


- Keeping low percentage of defect chips/modules

Table 2: Numbers of Disabled SCT Detector Elements.

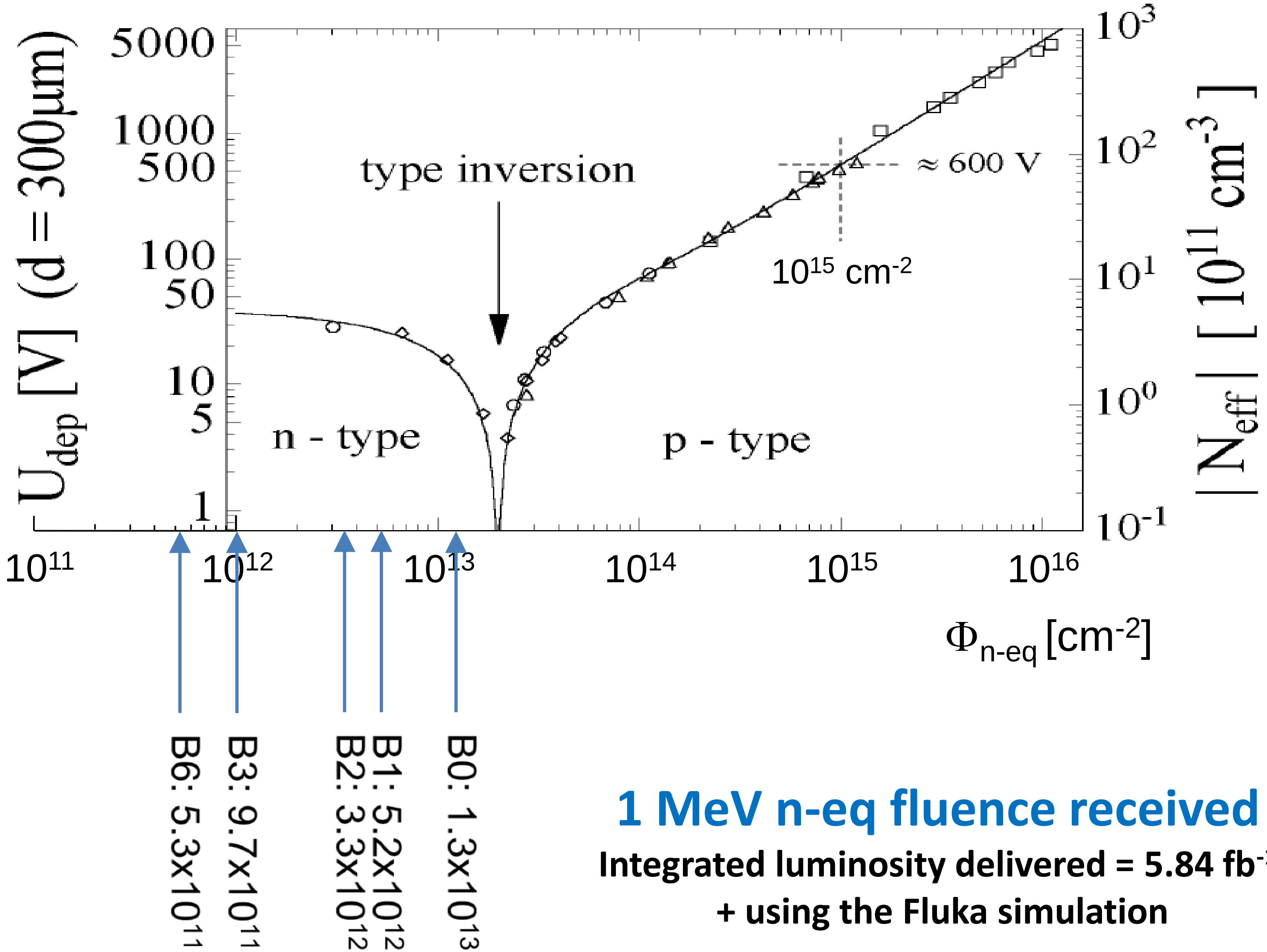
Component	Endcaps	Barrel	SCT	Fraction (%)
Modules	20	10	30	0.73
Strips	6992	3681	10673	0.07
Chips	40	16	56	0.17

mainly thanks to the built-in redundancy.



Dead chip bypassed
All fibres ok

Radiation level by the end of 2011 @ Point-1



SCT **Pixel**

1 MeV n-eq fluence received

Integrated luminosity delivered = 5.84 fb^{-1}
+ using the Fluka simulation

Leakage current

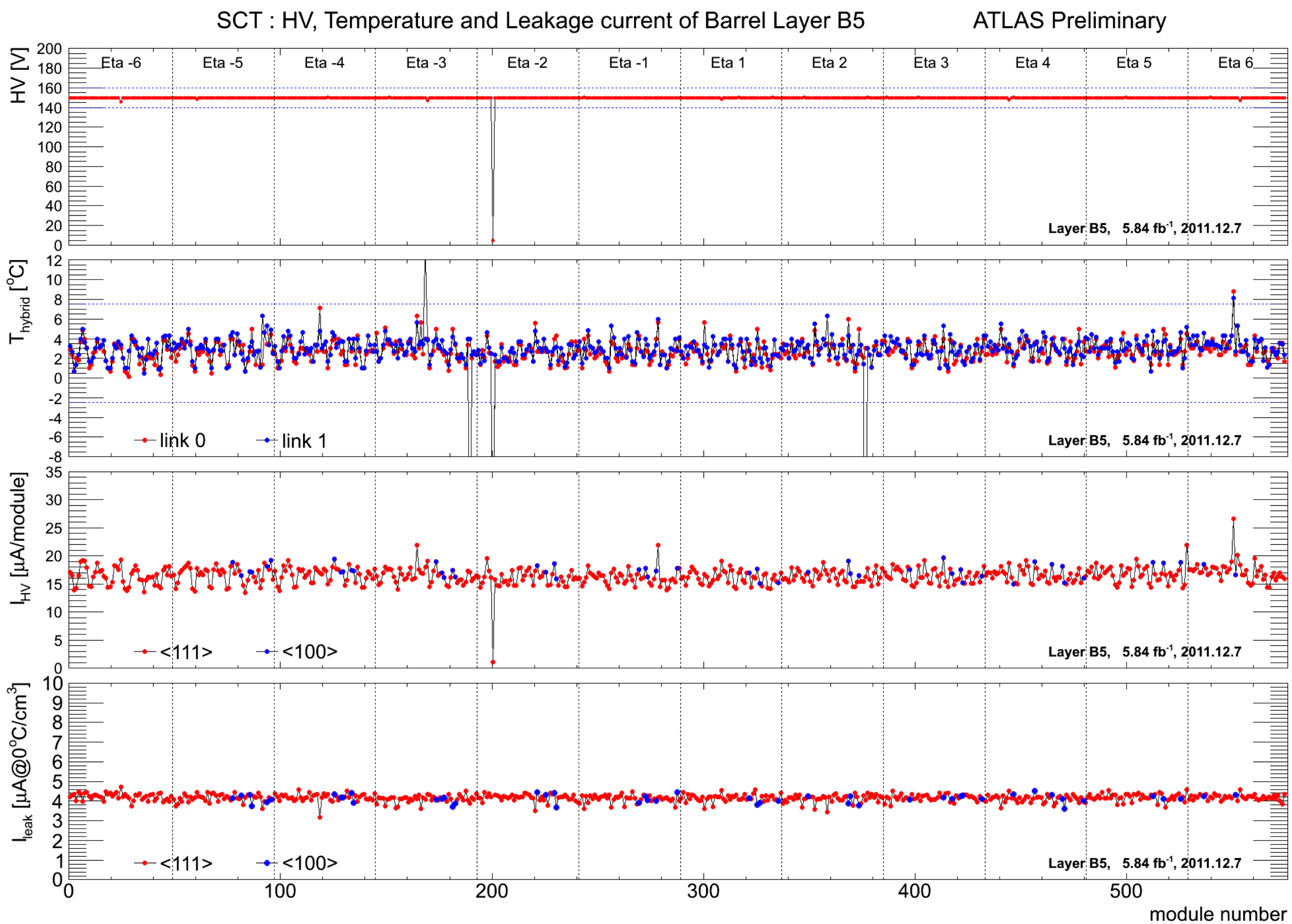
Status of Layer B5 as of Dec. 7, 2011

High Voltage

two hybrid Temperatures

HV current

Leakage current scaled to 0ºC



Note (1) two hybrid temperatures agree well.

(2) no difference between <111> and <100> modules.

Leakage current and Sensor temperature

- All the current measured in the HV power supply at 150V are assumed to be due to generation current in the silicon bulk.

- They are converted to the value at the temperature of 0°C using the temperature scaling formula [1]

$$\frac{I(T_{0^\circ C})}{I(T_{sensor})} = \left(\frac{T_{0^\circ C}}{T_{sensor}}\right)^2 \exp\left(-\frac{E_{gen}}{2k_B}\left[\frac{1}{T_{0^\circ C}} - \frac{1}{T_{sensor}}\right]\right)$$

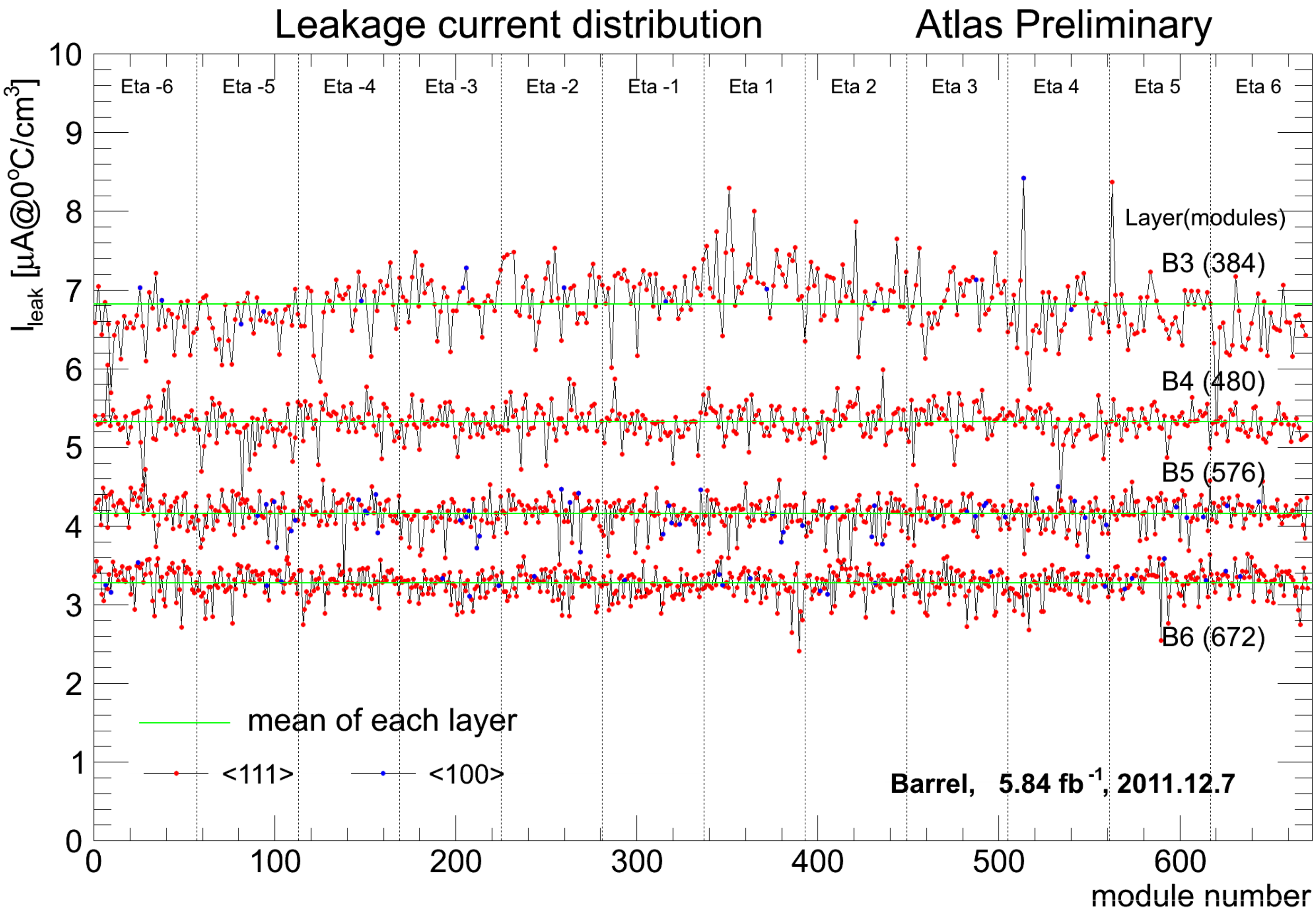
  with E_{gen} = 1.21 eV following the RD50 recommendation [2].

- Sensor temperature
  - When cooled:

$$T_{sensor} = \frac{T_{hybrid}(link\text{-}0) + T_{hybrid}(link\text{-}1)}{2} - 3.7^\circ\mathrm{C}$$

    where 3.7°C is a difference estimated via FEA for barrel modules.
  - When the cooling is off, T the environmental temperature (17.5°C during 2010-2011 winter shutdown) is used.

[1] S. Sze, Physics of semiconductor devices, 1981.
[2] RD50 Note: A.Chilingarov, RD50-2011-01.



All layers (except B3) showed quite uniform leakage current distributions. No phi dependences are seen.

Prediction of the SCT leakage current

- Two models of bulk leakage currents are used for comparison:
  1. Hamburg/Dortmund model [1][2]

     Summary of small sample tests mostly at or above room temperature.
  2. Harper model [3]

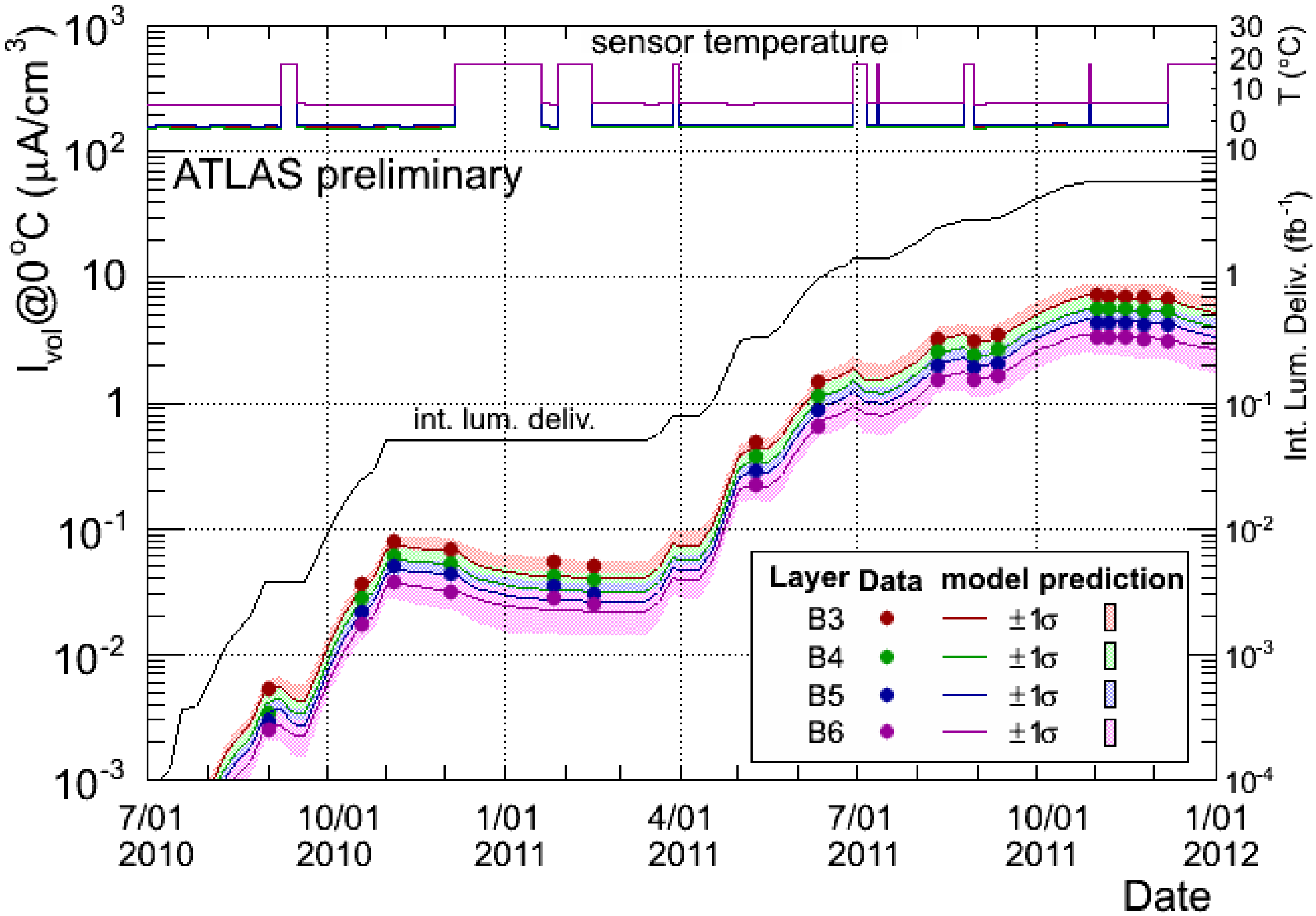
     The damage constants were obtained from four 24 GeV proton beam tests using ATLAS SCT sensors cooled at -10°C ~ -8°C.

- Radiation fluences at sensors are estimated using the results of FLUKA simulation of 7 TeV pp collision by Ian Dawson et al.

- Integrated Luminosity is the total “delivered” 7TeV collisions at Point-1 including non-Stable beam collisions.

- Uncertainties of predictions are estimated assuming the errors of model parameters and measurements are independent. Errors of the FLUKA simulation are not included (not known).

[1] M. Moll, DESY-THESIS-1999-040 (Dec 1999).
[2] Oraf Krasel, Dortmund Dissertation, July 2004.
[3] R. Harper, Thesis of University of Sheffield, Oct. 2001.



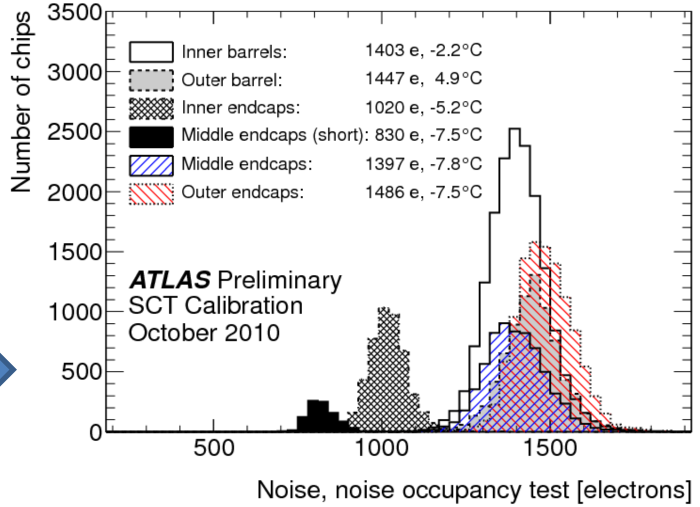
Good agreements between data and model predictions.
The Harper model predicts ~10% less but within uncertainties.
Note that there are no parameter re-adjustments.

Noise

Two ways of measuring ENC:

(1) Response Curve at 2 fC:

Fitting the threshold S-curves by complementary error function in 3 point gain calibration runs. ENC is obtained by dividing with the gain.



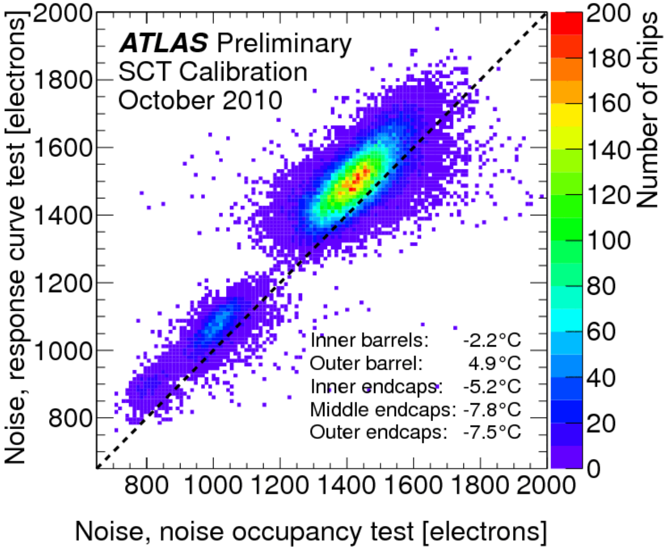
(2) Noise Occupancy (NO) fit:

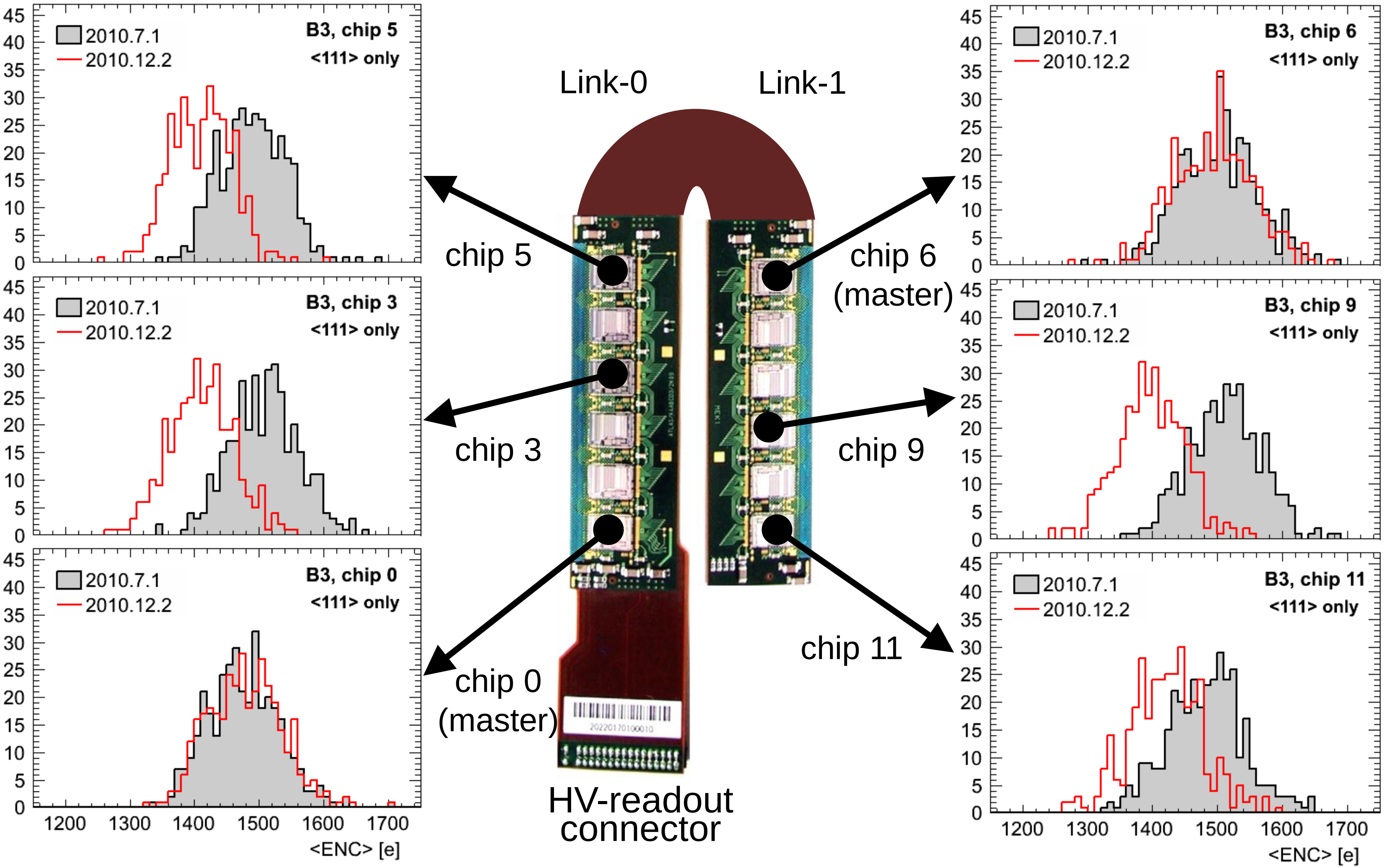
NO is related to the threshold charge q_{th}

$$NO \propto \exp\left(-\frac{(q_{th})^2}{2\langle ENC\rangle^2}\right)$$

A linear fit of the distribution of ln(*NO*) vs q_{th}^2 gives an ENC for each channel.

Fairly good chip-by-chip correlations have been observed in 2008 and 2010.



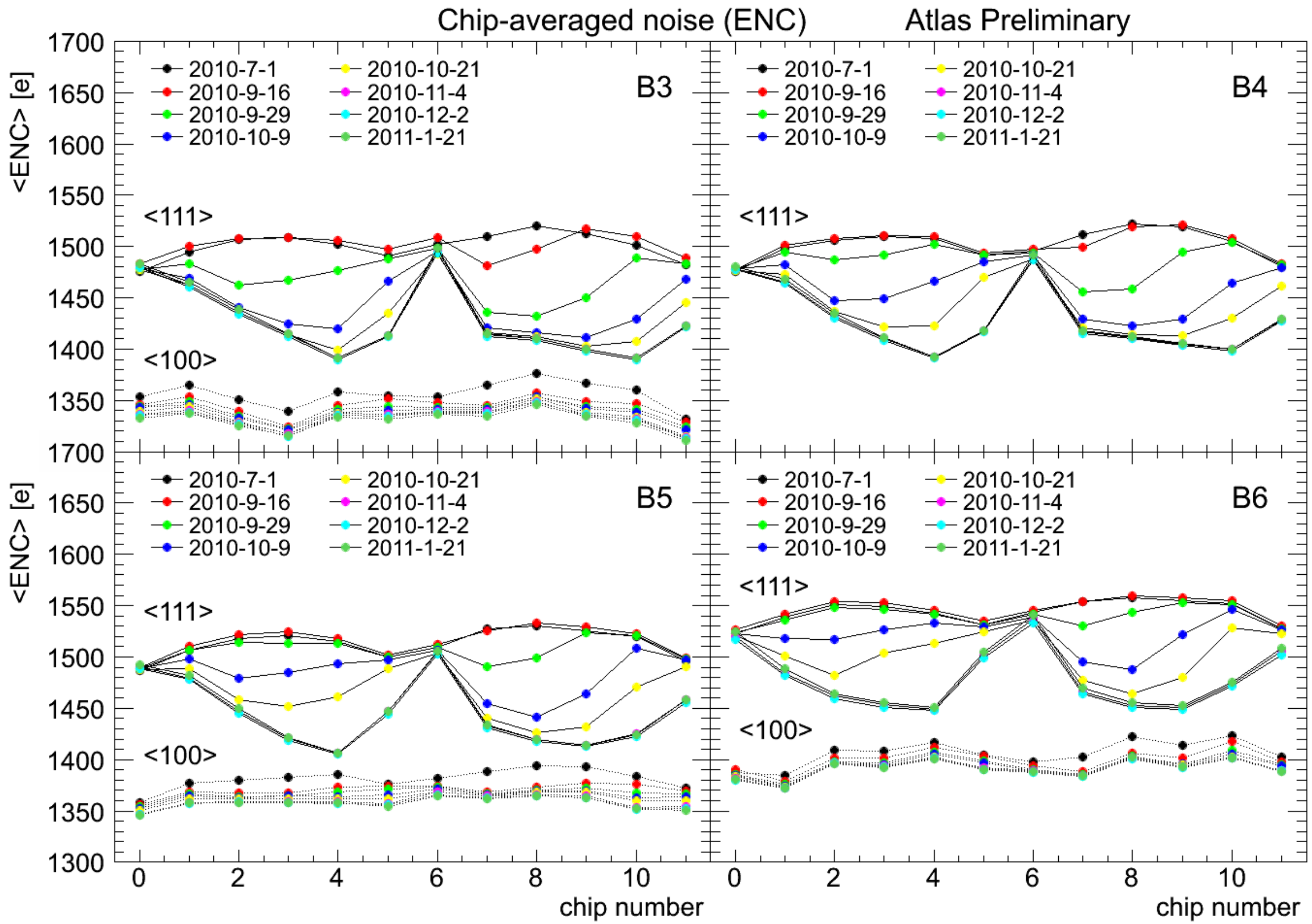


Systematic decrease of <ENC> was observed in fall 2010.
The amount of decrease depends on the chip location !!

“Eye-glass” plots for July 2010 to Jan. 2011

B3

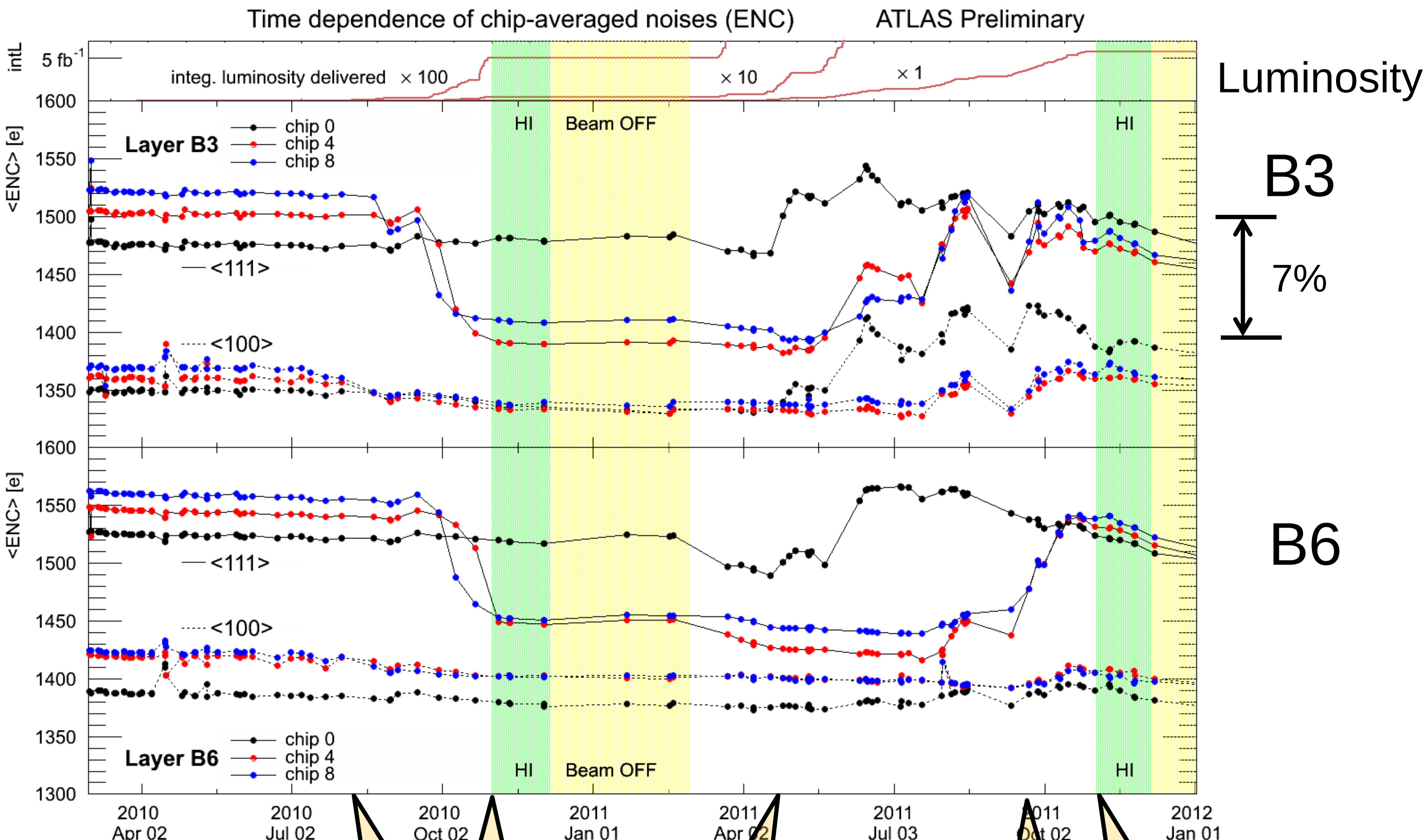
B4



B5

B6

Note: initial bow-shape may be due to chip temperature profile along the hybrid length. Chips 0, 5, 6 and 11 are close to cooling anchors.



n-eq Fluence	B3:	3.3×10^{8}	8.4×10^{9}	5.4×10^{10}	5.0×10^{11}	9.7×10^{11}	cm^{-2}
	B6:	2.8×10^{8}	4.6×10^{9}	3.0×10^{10}	2.7×10^{11}	5.3×10^{11}	cm^{-2}
TID	B3:	0.14	3.5	22.6	206	403	Gy
	B6:	0.05	1.4	8.9	81	158	Gy

Some points of the “SCT noise mystery”

(1) ~ 7% decrease in <ENC> was observed in Sep-Oct. 2010 runs at the fluence level of $10^{10}cm^{-2}$ (a few Gy).

(2) Its time profile indicates a radiation induced phenomenon.

(3) It occurred systematically on all chips of the Barrel and EC modules. More complex in EC case (not mentioned here).

(4) It depends strongly on the chip location on the flex hybrid.

(5) The <ENC> of <100> modules, however, stayed constant. They are ~10% lower from the beginning.

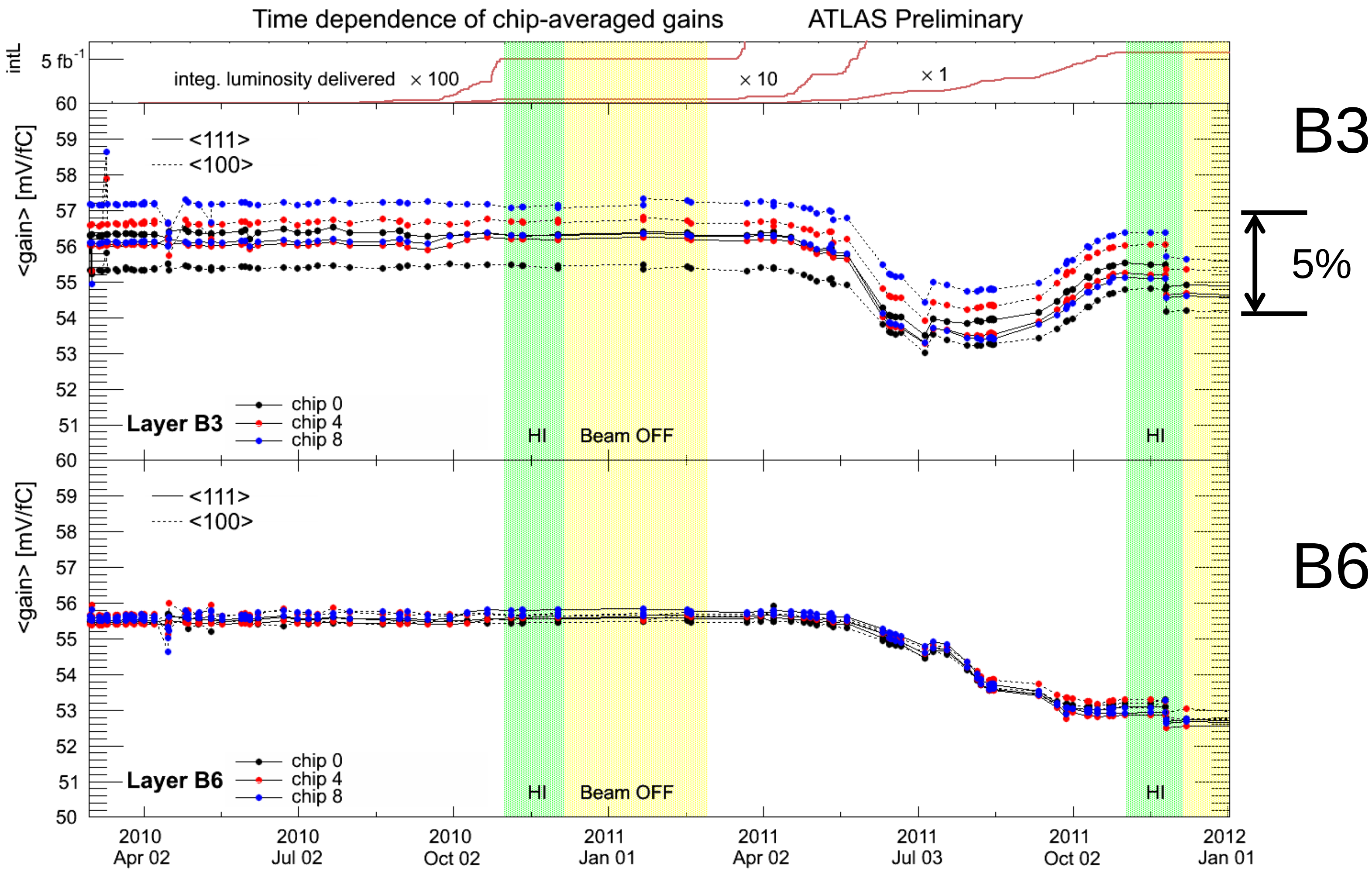
(6) No further decrease was observed in 2011. Some increase. Most of <ENC>s are now back closed to original values.

(7) Noise Occupancy (NO) exibited similar drops.

(8) Disconnected strip channels showed no such drops.

(9) A PS beam test with low rate done in 2011 fall reproduced the effects at similar dose level.

Gain



The gain has been very stable till mid 2011. Then gradually decreased. All chips simultaneously changed. Checked no effects on performance such as hit efficiency for tracks.

Summary

- The Barrel layer B3 received ~$10^{12}/cm^2$ 1MeV n-eq fluence by the end of 2011.

- Leakage current at 150V steadily increased. Barrel layers show very flat distribution in eta (except B3).

- Model predictions with annealing effects reproduce the Barrel leakage current within 1σ (~20%) with no parameter re-adjustments.

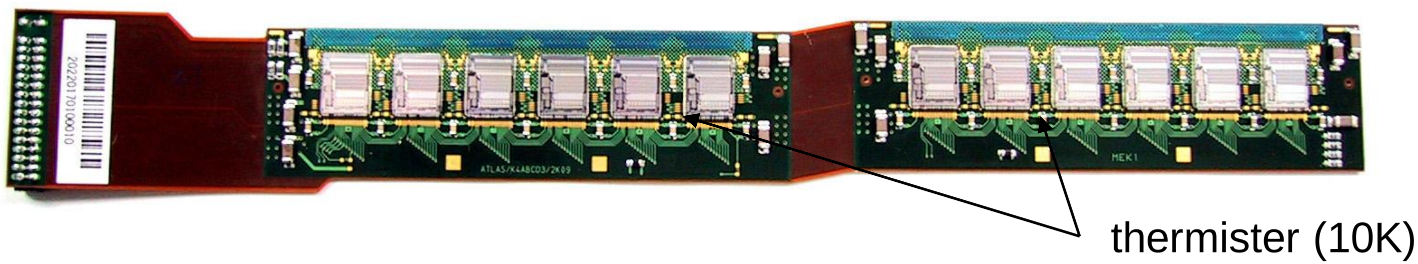
- The noise(ENC) and gain have been monitored frequently. The noises initially decreased by up to 7% with strong dependence on chip location and crystal orientation. Their behaviors in 2011 are different and rather complex.

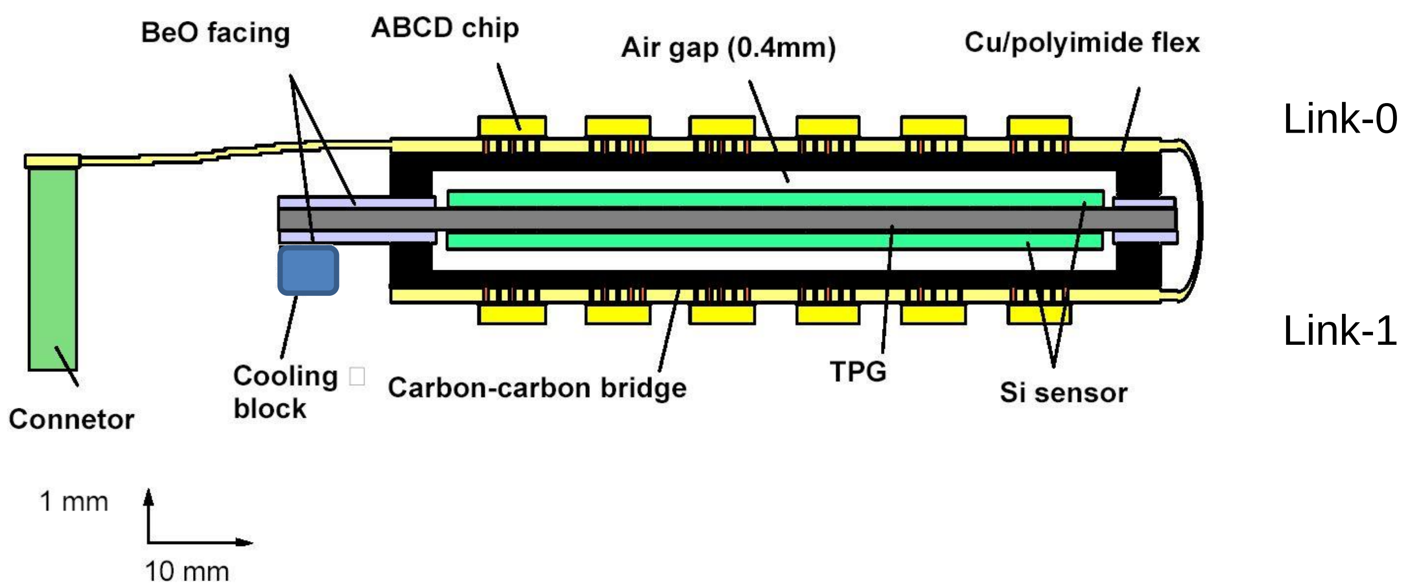
Backup slides

Barrel hybrid

Link-0 Link-1

chip-0 ……………......chip-5 chip-6……………...…..chip-11





Hamburg/Dortmund Model

Based on Moll's thesis [1], the leakage current coefficient α is given by Krasel [2] is

$$\alpha(t) = \alpha_I \cdot \exp(-\frac{t}{\tau_I}) + \alpha_0^* - \beta \cdot \ln(\Theta(T_a)t/t_0)$$

$$\alpha_I = (1.23 \pm 0.06) \cdot 10^{-17}\,\mathrm{A/cm}$$

$$\frac{1}{\tau_I} = k_{0I} \cdot \exp(-\frac{E_I}{k_B T_a}), \qquad t_0 = 1\,\mathrm{min.}$$

$$k_{0I} = 1.2^{+5.3}_{-1.0} \cdot 10^{13}\,\mathrm{s}^{-1}, \quad E_I = (1.11 \pm 0.05)\mathrm{eV}$$

$$\Theta(T_a) = \exp\left[-\frac{E_I^*}{k_B}(\frac{1}{T_a} - \frac{1}{T_{ref}})\right]$$

$$\alpha_0^* = 7.07 \cdot 10^{-17}\,\mathrm{A/cm}$$

$$\beta = 3.29 \cdot 10^{-18}\,\mathrm{A/cm}$$

$$E_I^* = (1.30 \pm 0.14)\,\mathrm{eV}$$

$$T_{ref} = 21\,^\circ\mathrm{C}$$

$$G_i = G_i^{\exp} + G_i^{\log}$$

$$G_i^{\exp} = \sum_{j=1}^{i} \Phi_{eq,j} \alpha_I \exp\left(-t_{i,j}^I / \tau_I(20^\circ\mathrm{C})\right)$$

$$t_{i,j}^I = \sum_{j=1}^{i} \Delta t_j \cdot \frac{\tau_I(20^\circ\mathrm{C})}{\tau_I(T_j)}$$

$$G_i^{\log} = \sum_{j=1}^{i} \Phi_{eq,j}\left(\alpha_0^* - \beta \cdot \ln\left(t_{i,j}^{\log}/t_0\right)\right)$$

$$t_{i,j}^{\log} = \sum_{k=j}^{i} \Delta t_k \cdot \Theta(T_k)$$

These two equations in [2] are corrected here.

[1] M. Moll, DESY-THESIS-1999-040 (Dec 1999)
[2] Oraf Krasel, Dortmund Dissertation, July 2004

Harper Model

Leak current formula by R. Haper [1] is used for prediction.
F : n_{eq} fluence, *V*: volume

$$I = g(\Theta(T_A)t_{ir}, \Theta(T_A)t') \cdot \alpha \cdot \Phi \cdot V$$

$$g(\Theta(T_A)t_{ir}, \Theta(T_A)t') = \sum_{i=1}^{n} \left\{ A_i \frac{\tau_i}{\Theta(T_A)t_{ir}} \left[1 - \exp\left(-\frac{\Theta(T_A)t_{ir}}{\tau_i} \right) \right] \exp\left(-\frac{\Theta(T_A)t'}{\tau_i} \right) \right\}$$

$$\Theta(T_A) = \exp\left(\frac{E_I}{k_B} \left[\frac{1}{T_R} - \frac{1}{T_A} \right] \right),$$

$$T_R = 20°\mathrm{C}$$

$$E_I = 1.09 \pm 0.14\,\mathrm{eV}$$ [2]

$$\alpha_{eq}(-7°C) = (7.00 \pm 0.20) \times 10^{-18}\ \mathrm{A \cdot cm^{-1}}$$

	(min)	
τ_1	$(1.2 \pm 0.2) \times 10^6$	$A_1 : 0.42 \pm 0.11$
τ_2	$(4.1 \pm 0.6) \times 10^4$	$A_2 : 0.10 \pm 0.01$
τ_3	$(3.7 \pm 0.3) \times 10^3$	$A_3 : 0.23 \pm 0.02$
τ_4	124 ± 25	$A_4 : 0.21 \pm 0.02$
τ_5	8 ± 5	$A_5 : 0.04 \pm 0.03$

Changed from original value of 6.90+-0.20 due to E_g= 1.12 -> 1.21eV change.

[1] R. Harper, Thesis of University of Sheffield, Oct. 2001, p.35
[2] A Chilingarov et al., NIM A360 (1995) 432-437, Table 2.

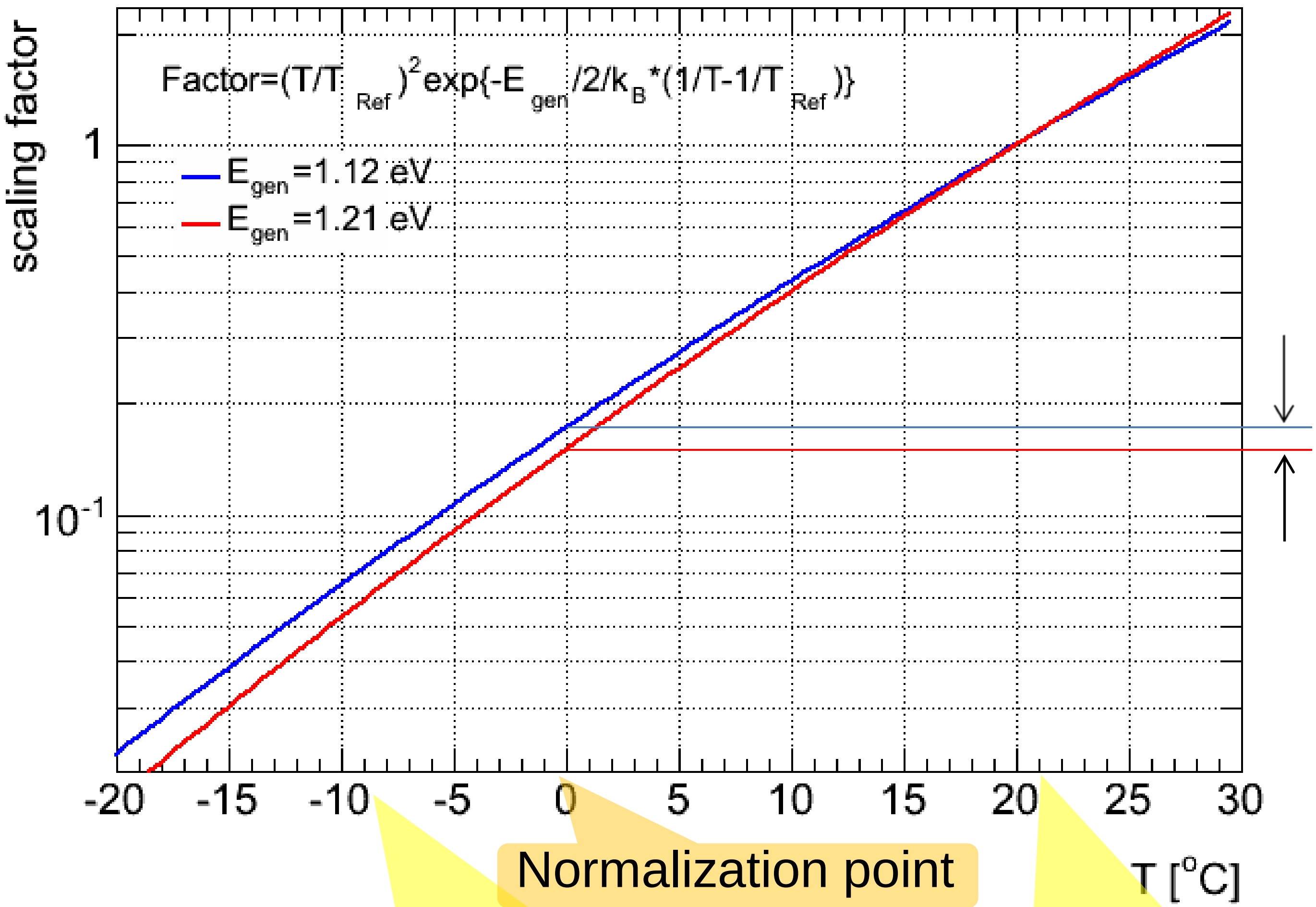
Estimate of uncertainties of Hamburg/Dortmund model prediction

$$\alpha(t) = \alpha_I \cdot \exp(-\frac{t}{\tau_I}) + \alpha_0^* - \beta \cdot \ln(\Theta(T_a)t/t_0), \qquad \frac{1}{\tau_I} = k_{0I} \cdot \exp(-\frac{E_I}{k_B T_a})$$

No.	parameter	value	1σ	I@0°C with -1σ	I@0°C with +1σ
0	center value			5.177 μA/cm³ (for B3 at 2011.12.31)	
1	α_I	1.23×10^{-17}A/cm	0.06×10^{-17}A/cm	5.166 (-0.21%)	5.188(+0.21%)
2	k_{0I}	1.2×10^{13} s^{-1}	$(+5.3,-1.0)\times10^{13}$s^{-1}	6.108(-17.98%)	4.951(-4.37%)
3	E_I	1.11 eV	0.05 eV	4.951 (-4.37%)	6.188 (+19.53%)
4	α_0*	7.07×10^{-17}A/cm	Set to 5% error	4.708 (-9.06%)	5.646 (+9.06%)
5	β	3.29×10^{-18}A/cm	Set to 5% error	5.398 (+4.28%)	4.956 (-4.28%)
6	E_I*	1.30 eV	0.14 eV	5.134 (-0.84%)	5.216 (+0.75%)
7	E_g	1.21 eV	+0.04, -0.09 eV	5.934(14.62%)	4.872 (-5.89%)
8	T_{sensor}	T_{hybrid} – 3.7°C	1°C or 2°C	5.469 (+5.63%)	4.921 (-4.94%)
9	fluence	Lum*Fluka simul.	3.7%	4.986 (-3.70%)	5.369 (+3.70%)
	Adding percent deviations quadraticaly			**25.27 %** (for B3 at 2011.12.31)	

Note: Uncertainties of parameters 4, 5, 7 and 8 are unknown. These values are set by hand here.

Temperature scaling issue



14 % difference at 0°C with T_{ref} = 20°C.

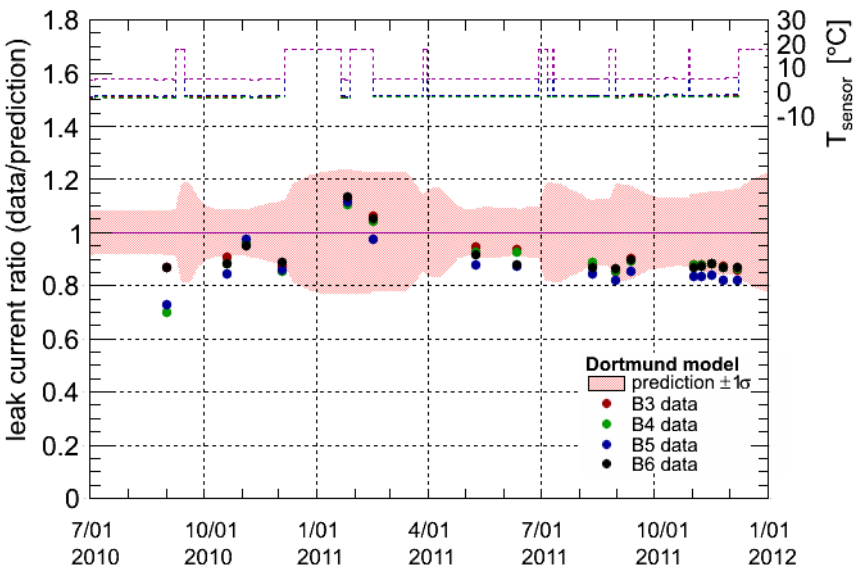
Normalization point

Harper model is based on experiments at -10°C ~ -8°C.

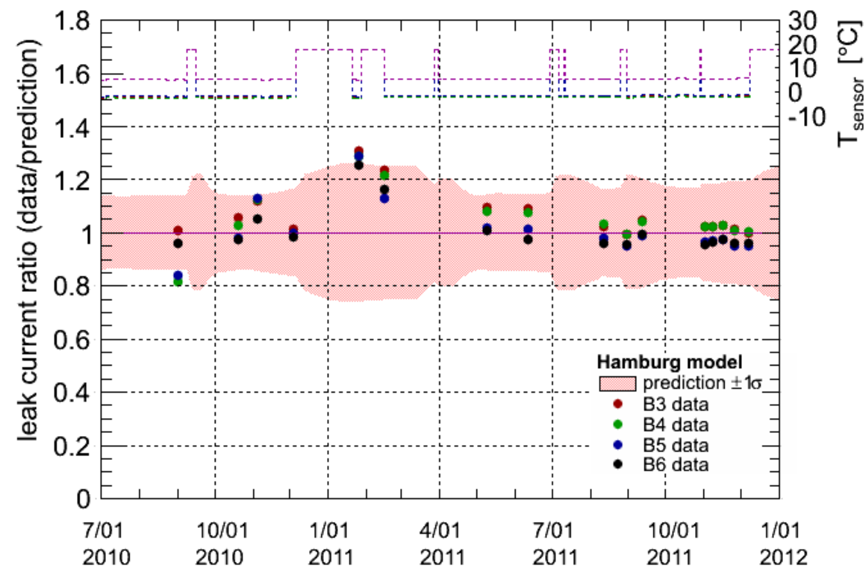
Hamburg/Dortmund model is given with T_{ref}= 21°C

Comparison of data and models: ratios

Hamburg/Dortmund model



Hamburg/Dortmund model



E_{gen} = 1.12 eV

E_{gen} = 1.21 eV

Chip dependence of ENC distribution : ATLAS Preliminary