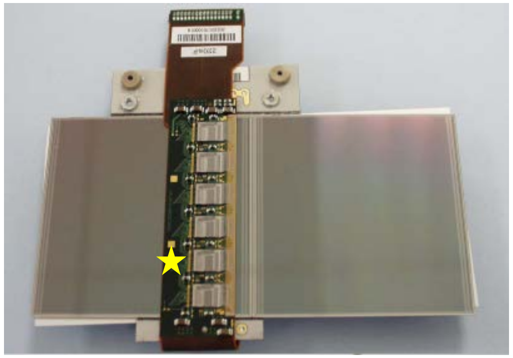
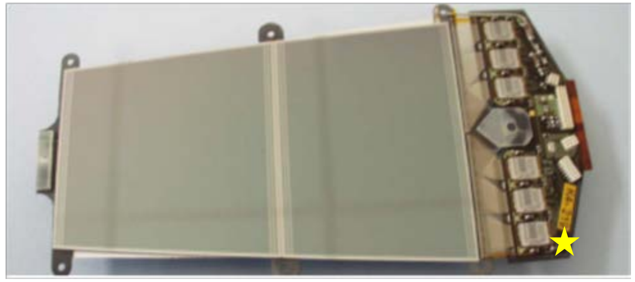
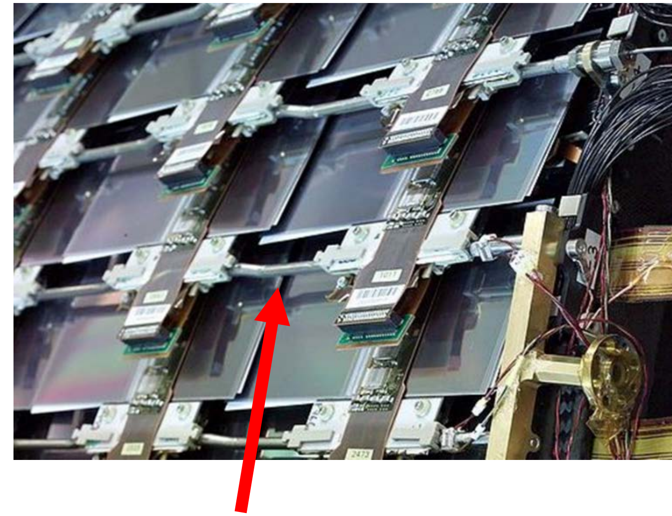
Measurements with the ATLAS strip detector (SCT)

Radiation Effects at the LHC Experiments and Impact on Operation and Performance
23-24 April 2018, CERN

Taka Kondo
High Energy Accelerator Research Organization (KEK), Japan
On behalf of the ATLAS SCT Collaboration







Barrel module (2112) **Endcap module (1976)** **C_3F_8 cooling pipe (4mmf)**

(☆Thermistors for temperature monitoring)

Brief summary of the ATLAS SCT

- Sensors : p-on-n type, 285μm thick, strips = 80μm×12cm, V_{FD}^0=70±10V
- Manufactured by Hamamatsu (88%) + CiS（12%）
- 4088 modules, ~6M strips, total Si area=60m^2
- Digital readout with 1 fC threshold and gate width of 25ns
- Cooled by C_3F_8 evaporative cooling to keep sensors at -10 ~ +5^{o}C

Status of ATLAS SCT operation

As of November 2017, 98.7 % of SCT are working properly.

Table 1: SCT Disabled Element Counts in May 2016.

Disabled Element Counts

	ECC	Barrel	ECA	Total
Modules	19	13	8	40
Chips	7	48	10	65
Strips	3953	4236	4063	12252
Active(%)	**97.76**	**99.06**	**98.84**	**98.69**

Table 2: Reason for disabled modules in May 2016

	LV	HV	Cooling	Readout	Total
ECC	1	2	13	3	19
ECA	1	4	0	3	8
Barrel	8	2	0	3	13
Total	10	8	13	9	40

Table 3: Use of optical redundancy in SCT in May 2016.

	ECC	Barrel	ECA	Total
TX Redundancy:	5	21	1	27
RX Redundancy:	33	50	64	147

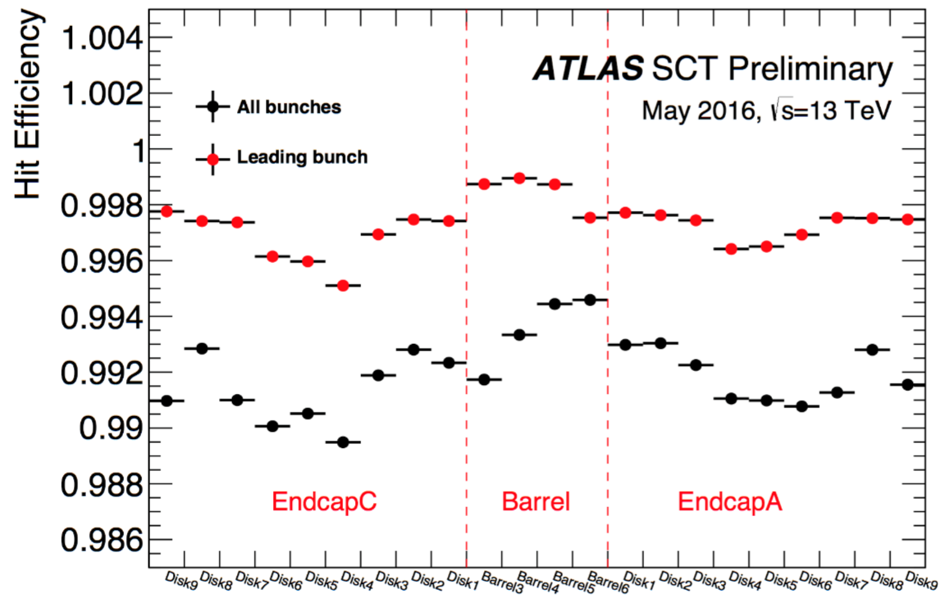
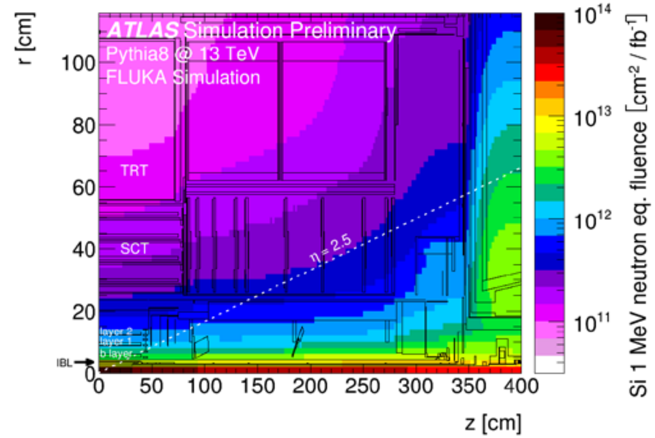


Table 1: Disabled element statistics.
Table 2: Reasons for disabled modules.
Table 3: Use of optical redundancy.

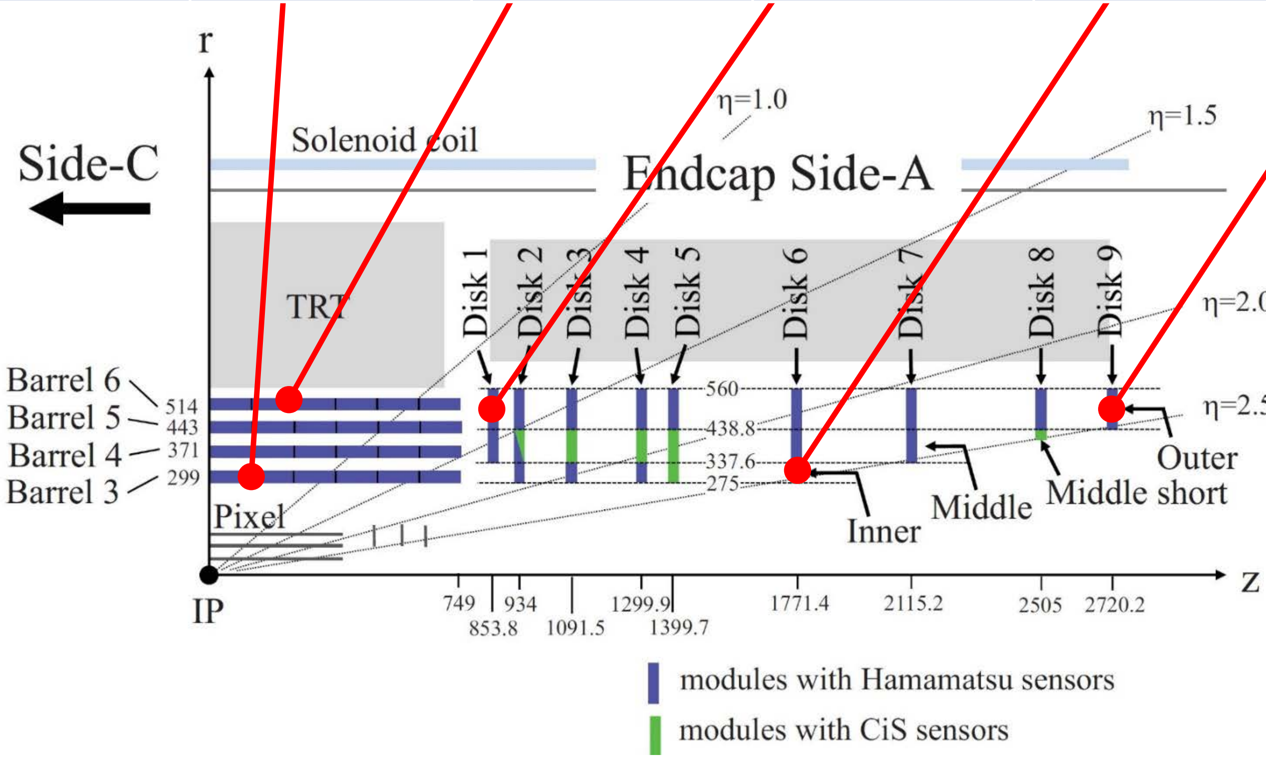
Hit efficiency of active strips
~99.7% for initial proton bunches
~99.2% with previous proton bunches

Estimate of NIEL fluence at the sensors



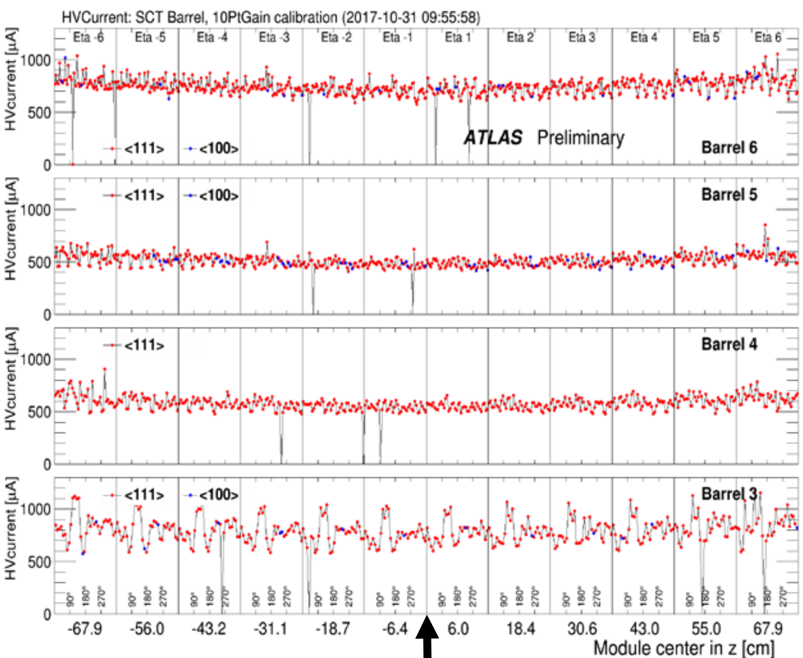
- Conversion factors from pp luminosity to NIEL fluences are given by the FLUKA simulation at 7, 8 and 13TeV.
- Total pp luminosities delivered up to Nov. 2017 are 5.62/23.2/93.0 fb^{-1} for 7/8/13 TeV runs respectively.

location	Barrel 3	Barrel 6	Disk 1 Outer	Disk 6 Inner	Disk 9 Outer
1 MeV n-eq Fluence [cm^{-2}]	3.0×10^{13}	1.7×10^{13}	2.0×10^{13}	3.7×10^{13}	3.5×10^{13}

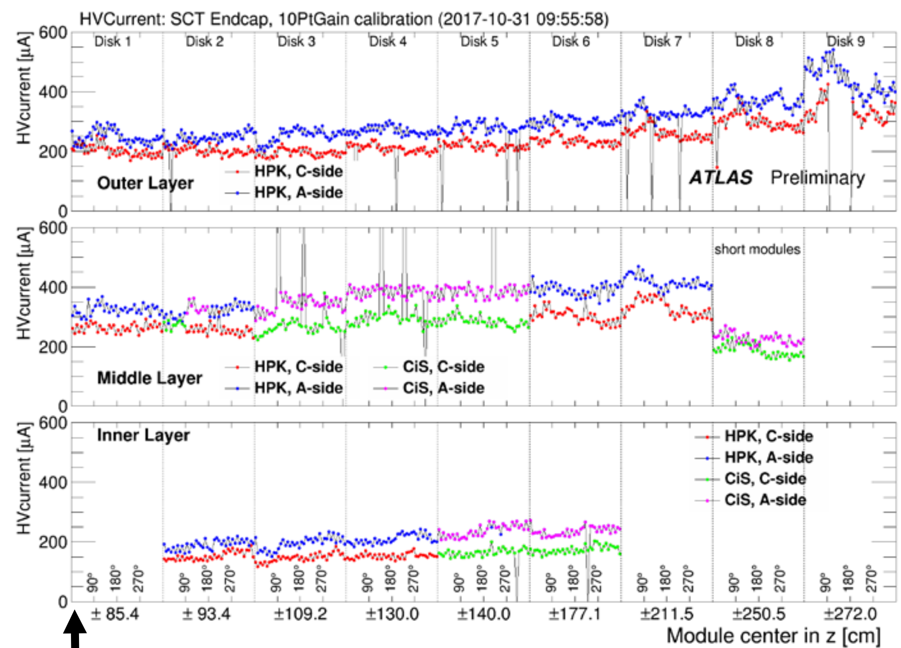


Module-by-module raw leakage current as of October 2017

Barrel modules



Endcap modules (C and A sides)



lower η ⟵ IP ⟶ higher η

IP ⟶ higher |η|

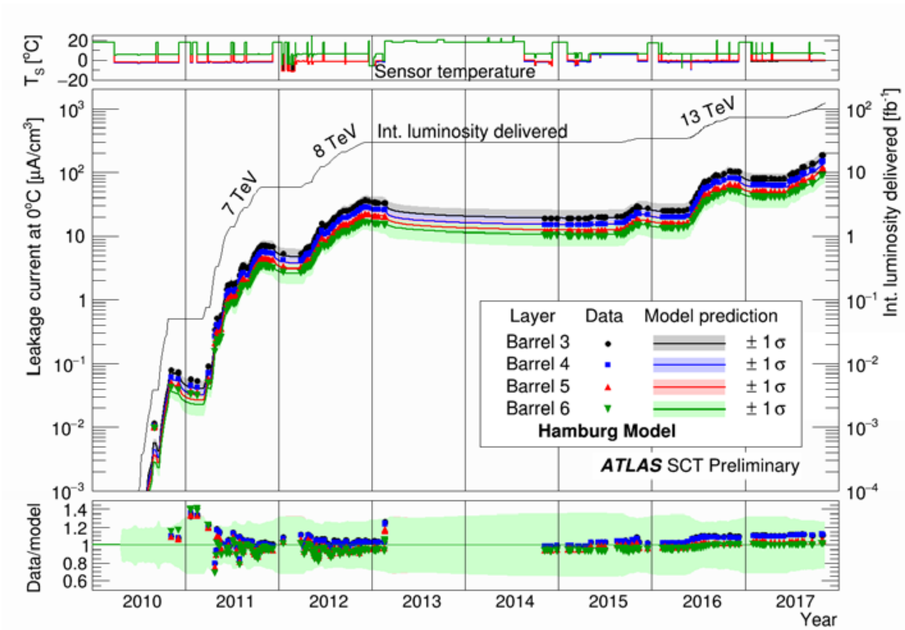
1. Quite uniform distribution of leakage current. Bumps in Barrel-3 are due to higher temperature in one of cooling loops.
2. Differences between C and A endcaps are due to different temperature settings.
3. Higher |η| modules draw higher leakage current both in Endcaps and Barrels.

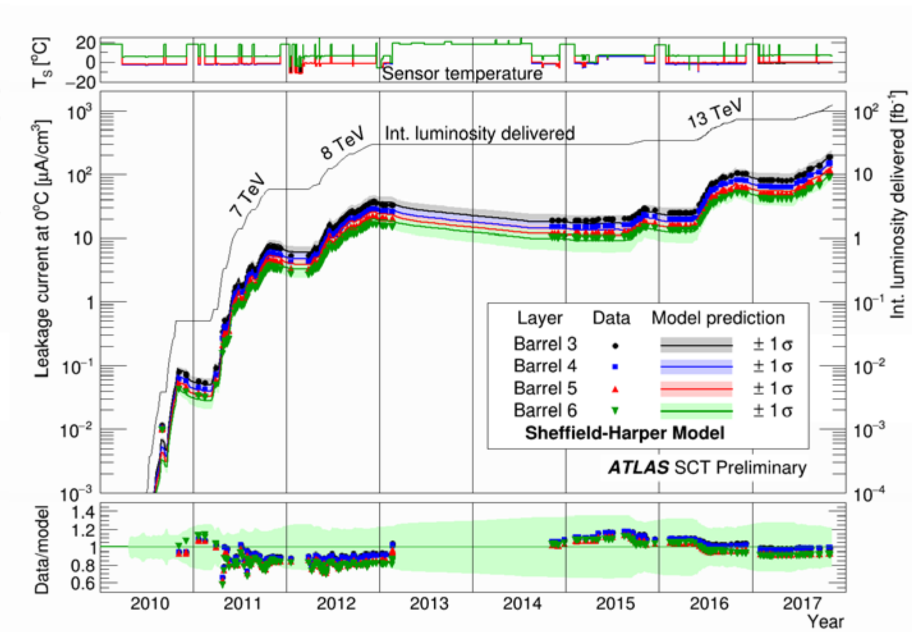
Evolution and Comparison with leakage current models

Leakage current of barrel module was normalized to 0°C using its hybrid temperature with δT of -3.7°C. Layer averages were taken. Endcaps are still under study (due to uncertainties in sensor temperature).

$$I_{leakage} = \alpha(T,t) \cdot V \cdot \phi_{n-eq}$$

$$\frac{I_0}{I_1} = \left(\frac{T_0}{T_1}\right)^2 \exp\left(-\frac{E_{gen}}{2k_B}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right), \quad E_{gen} = 1.21\text{eV}\ [1]$$





Hamburg model [2]

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

Sheffield-Harper model [3]

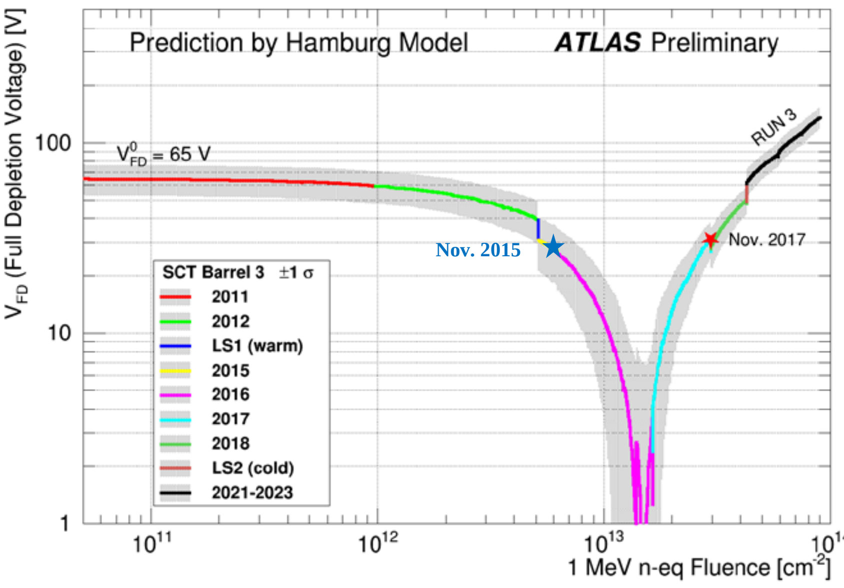
$$\alpha(t) = a_1 e^{-\frac{t}{\tau_1}} + a_2 e^{-\frac{t}{\tau_2}} + a_3 e^{-\frac{t}{\tau_3}} + a_4 e^{-\frac{t}{\tau_4}} + a_5 e^{-\frac{t}{\tau_5}}$$

Note : Uncertainties of conversion factors (luminosity to NIEL flux) are not included.
None of model parameters are adjusted. See backup for error details.

[1] A Chilingarov, 2013 JINST 8 P10003, [2] M. Moll, Thesis, Universität Hamburg (1999)
[3] R. Harper, Thesis, Sheffield University (2001)

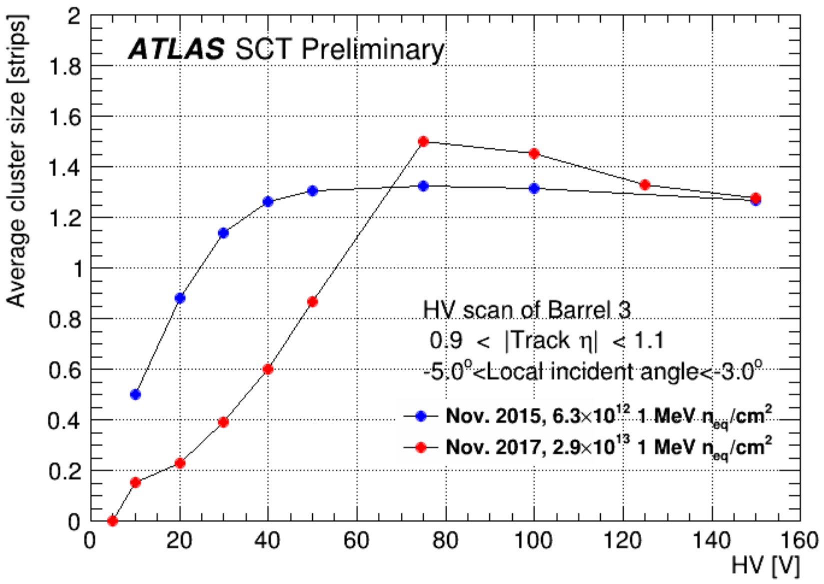
Evolution of Full Depletion Voltage V_{FD}

Prediction



Evolution of V_{FD} at the Barrel 3 layer as a function of 1 MeV n-eq. fluence, estimated by the Hamburg model using the FLUKA simulation, the pp luminosities at point-1 and the temperature history. The type inversion is expected to happen near 2016 end. V_{FD} will be close to 150V at the end of Run 3 if SCT remains cold during LS2.

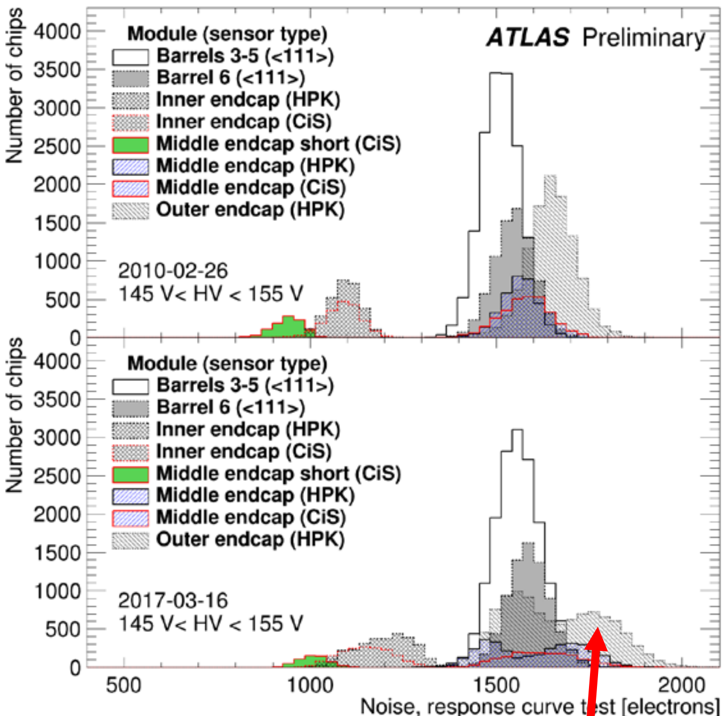
HV scan data



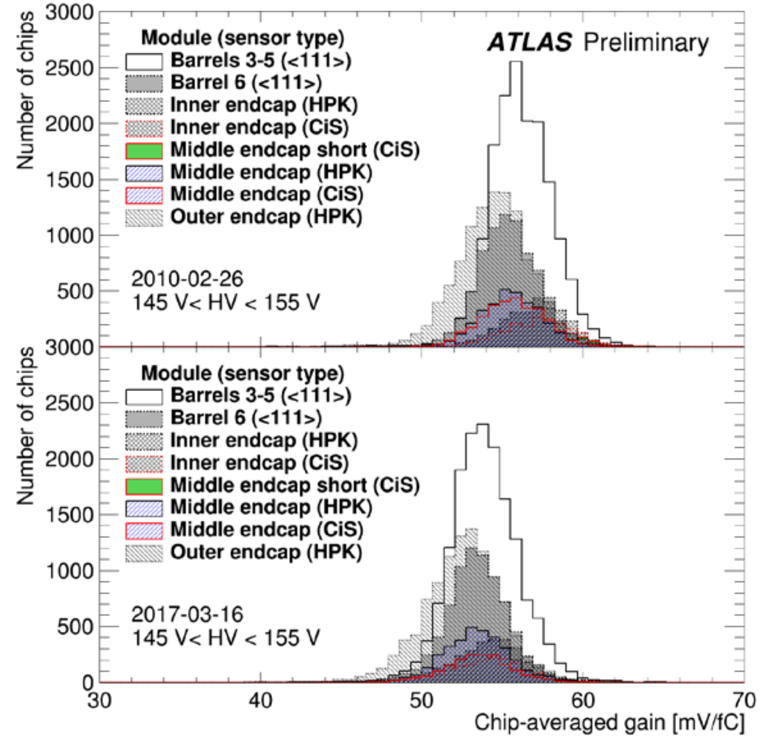
Average cluster sizes in Barrel 3 as a function of HV on Nov. 2015 and Nov. 2017. Expected V_{FD} based on the Hamburg model are 30V(n-type) and 30V (p-type) respectively. Red points indicate that depletion starts from the backplane side, a behavior expected after the n to p type inversion.

Evolutions of noise (ENC) and gain

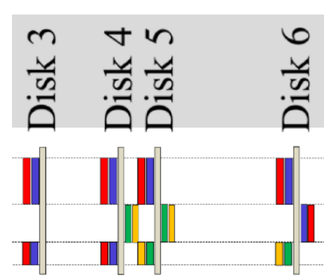
noise (ENC)



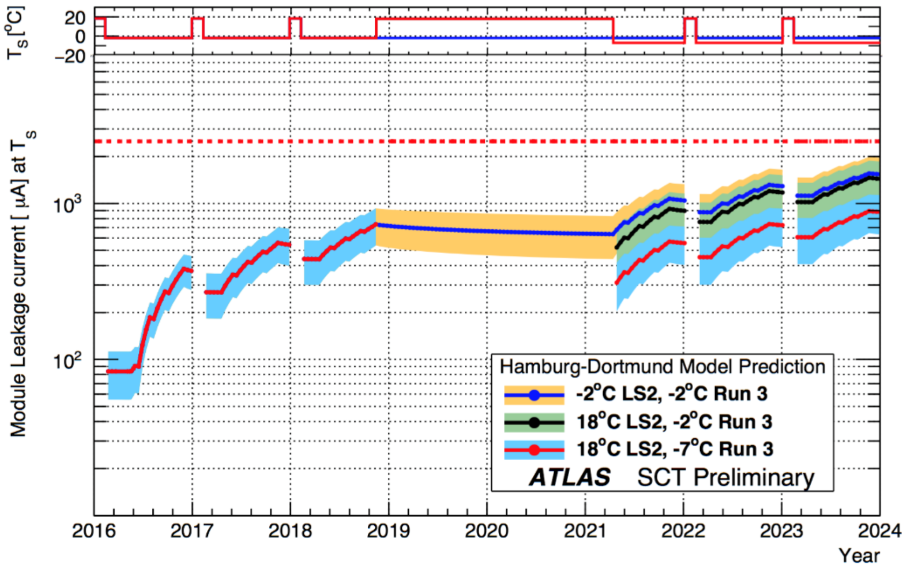
gain



~10% noise increases observed in the endcap strips facing to the N_2-gas gaps (red).



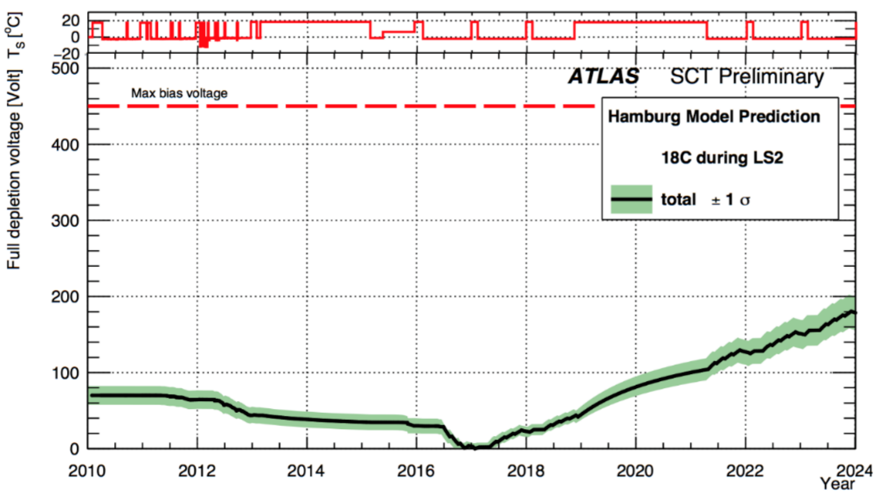
Expected SCT performance during Run 3



Leakage current per module in Barrel 3 under the Hamburg model for three temperature scenarios:

1) -2°C in LS2 and Run 3 (blue)
2) 18°C in LS2, -2°C in Run 3 (black)
3) 18°C in LS2, -7°C in Run 3 (red).

The dashed red line represents the upper limit for leakage current per module to ensure thermal runaway is suppressed.



Full depletion voltage of Barrel 3

2) 18°C in LS2, -2°C in Run 3

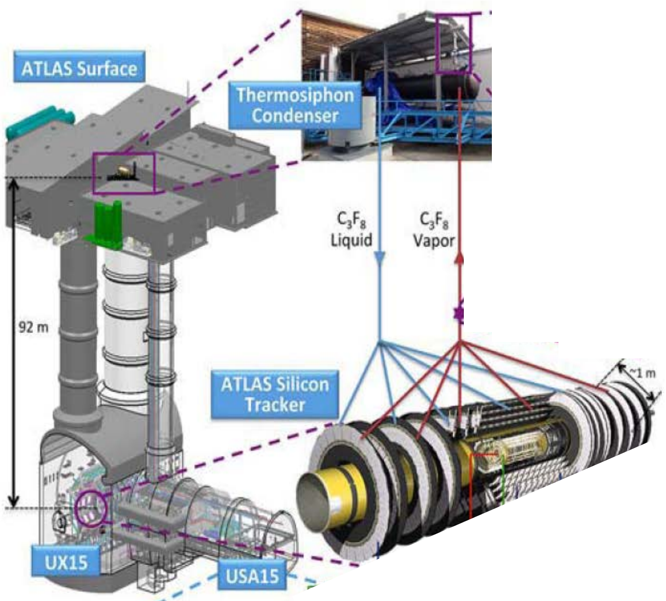
The dashed red line represents the upper limit for HV.

Recent developments in SCT/Pixel cooling technology

Two cooling technologies have been pursued to reduce the cooling temperature.

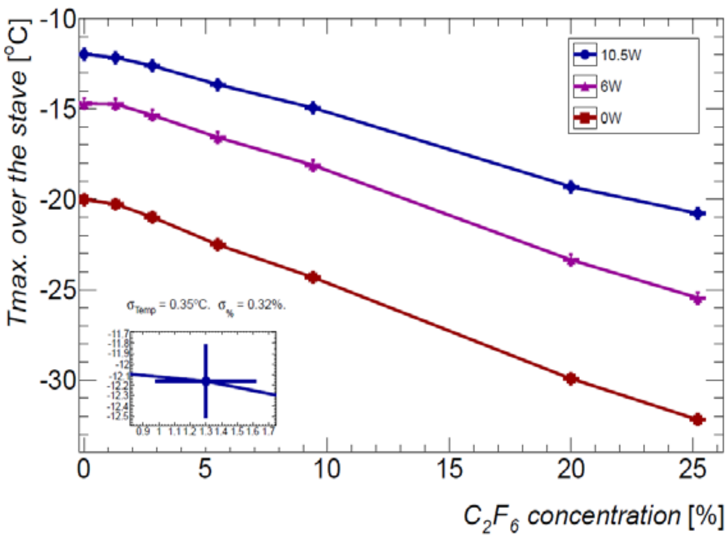
[1] 90m Thermosiphon system

- No active moving elements like pumps.
- Recover the design temperature of -25°C.
- Commissioned @ 60 kW with SCT and Pixel fully powered (April 2017).
- Will be available in 2018 replacing the current compressor system.



[2] C_2F_6/C_3F_8 blends

- The blends with molar admixtures up to 25% C_2F_6 was studied using 48 thermal emulator barrel modules.
- The superheated vapour phase was verified by an ultrasonic instrument.
- Suppression of 9°C is possible with blend.



Summary

- 98.7% of SCT elements are working well high efficiency.
- SCT received up to ~4×10^{13} 1MeV n-eq. paricles/cm^2.
- Leakage currents are higher in higher $|\eta|$ regions.
- Two leakage current models agree well with observations.
- Recent HV scan indicates a type inversion in Barrel 3.
- Noise and gain are stable over 7 years with a small exception.
- Safe operation is expected in Run 3.
- 90m thermosiphon scheme is ready to replace the compressor system. Bi-phase C_2F_6/C_3F_8 cooling is proven to lower the cooling temperature by another ~ 9^oC.

Backup slides

Leakage current models

[1] Hamburg model [1]

$$I_n(T_{\rm ref}) \equiv I_n^{\rm exp} + I_n^{\rm log} = \sum_{i=1}^{n} \delta\Phi_i^{\rm eq} \cdot \alpha_{\rm I} \cdot \exp\left(-\frac{t_{n,i}^{\rm I}}{\tau_{\rm I}(T_{\rm ref})}\right) + \sum_{i=1}^{n} \delta\Phi_i^{\rm eq}(\alpha_0^* - \beta \log(t_{n,i}^{\rm log}/t_0)) \quad \text{(A.1)}$$

$$t_{n,i}^{\rm I} = \sum_{j=i}^{n} \delta t_j \frac{\tau_{\rm I}(T_{\rm ref})}{\tau_{\rm I}(T_j)}, \qquad t_{n,i}^{\rm log} = \sum_{j=i}^{n} \delta t_j \Theta_{\rm A}(T_j) \quad \text{(A.2)}$$

$$\frac{1}{\tau_{\rm I}(T)} = k_{0\rm I} \cdot \exp(-\frac{E_{\rm I}}{k_{\rm B}T}), \qquad \Theta_{\rm A}(T) = \exp\left(-\frac{E_{\rm I}^*}{k_{\rm B}}\left[\frac{1}{T} - \frac{1}{T_{\rm ref}}\right]\right) \quad \text{(A.3)}$$

$\alpha_I = (1.23 \pm 0.06) \times 10^{-17}$ A/cm
$k_{0I} = 1.2^{+5.3}_{-1.0} \times 10^{13}$ s^{-1}
$E_I = 1.11 \pm 0.05$ eV
$\alpha_0^* = 7.07 \times 10^{-17}$ A/cm
$\beta = 3.29 \times 10^{-18}$ A/cm
$E_I^* = 1.30 \pm 0.14$ eV
$t_0 = 1$ min
$T_{ref} = 21$°C

[2] Sheffield-Harper model [2]

$$I_n(T_{\rm ref}) \equiv \sum_{i=1}^{n} g_{n,i} \cdot \alpha(T_{\rm ref}) \cdot \delta\Phi_i^{\rm eq} \quad \text{(A.4)}$$

$$g_{n,i} = \sum_{k=1}^{5} \left\{ A_k \frac{\tau_k}{\Theta_{\rm A}(T_i)\delta t_i} \left[1 - \exp\left(\frac{-\Theta_{\rm A}(T_i)\delta t_i}{\tau_k}\right)\right] \exp\left(-\frac{1}{\tau_k} \sum_{j=i+1}^{n} \Theta_{\rm A}(T_j)\delta t_j\right)\right\} \quad \text{(A.5)}$$

where $\alpha(T_{\rm ref} = 20°{\rm C}) = (4.81 \pm 0.13) \times 10^{-17}$ A/cm is the current-related damage constant.

$$\Theta_{\rm A}(T) = \exp\left(\frac{E_{\rm I}}{k_{\rm B}}\left[\frac{1}{T_{\rm ref}} - \frac{1}{T}\right]\right), \quad E_{\rm I} = 1.09 \pm 0.14\,{\rm eV}. \quad \text{(A.6)}$$

Parameters at T_{ref}=20°C

k	τ_k [min]	A_k
1	$(1.2 \pm 0.2) \times 10^6$	0.42 ± 0.11
2	$(4.1 \pm 0.6) \times 10^4$	0.10 ± 0.01
3	$(3.7 \pm 0.3) \times 10^3$	0.23 ± 0.02
4	124 ± 2.5	0.21 ± 0.02
5	8 ± 5	0.04 ± 0.03

[1] M. Moll, Thesis, Universität Hamburg (1999), O. Krasel, Thesis, Universität Dortmund (2004).
[2] R. Harper, Ph.D. Thesis, Sheffield University (2001).

Error analyses of the model predictions (case for Barrel 3)

[1] Hamburg model [1]

Par.	Value and Error	Dec. 2014	Nov. 2017
α_I	$(1.23 \pm 0.06)\times 10^{-17}$ A/cm	0%	0.5%
k_{0I}	$1.2^{+5.3}_{-1.0} \times 10^{13}$ s^{-1}	0.05%	5.7%
E_I	1.11 ± 0.05 eV	0.16%	6.9%
α_0^*	7.07×10^{-17} A/cm (±10%)	25.8%	16.3%
β	3.29×10^{-18} A/cm (±10%)	15.9%	7.3%
E_I^*	1.30 ± 0.14 eV	0.6%	1.9%
E_{gen}	$1.21^{+0.04}_{-0.09}$ eV	11.1%	11.1%
T_{sensor}	± 2°C	4.2%	3.7%
$Lum.$	± 3.7%	9.5%	6.4%
d_{sensor}	285 ± 15 μm	5.3%	5.3%
TOTAL		34.4%	24.7%

((±10%) means it is added by hand)

[2] Sheffield-Harper model [2]

Par.	Value and Error	Dec. 2014	Nov. 2017
α	$(7.00 \pm 0.20)\times 10^{-18}$ A/cm	2.9%	2.9%
A_1	0.42 ± 0.11	26.2%	17.0%
A_2	0.11 ± 0.01	1.1%	0.0%
A_3	0.23 ± 0.02	2.6%	1.4%
A_4	0.21 ± 0.02	2.5%	2.5%
A_5	0.04 ± 0.03	3.1%	3.1%
τ_1	833.3 ± 138.9 day	9.4%	1.4%
τ_2	28.47 ± 4.17 day	0.0%	0.4%
τ_3	2.57 ± 0.21 day	0.0%	0.5%
τ_4	0.086 ± 0.017 day	0.0%	0.1%
τ_5	0.0056 ± 0.0035 day	0.0%	0.0%
E_I	1.09 ± 0.14 eV	2.0%	3.9%
E_{gen}	$1.21^{+0.04}_{-0.09}$ eV	3.8%	3.8%
T_{sensor}	$\pm 2°C$	16.4%	5.5%
$Lum.$	$\pm 3.7\%$	3.7%	3.7%
d_{sensor}	285 ± 15 μm	5.3%	5.3%
TOTAL		33.7%	20.5%

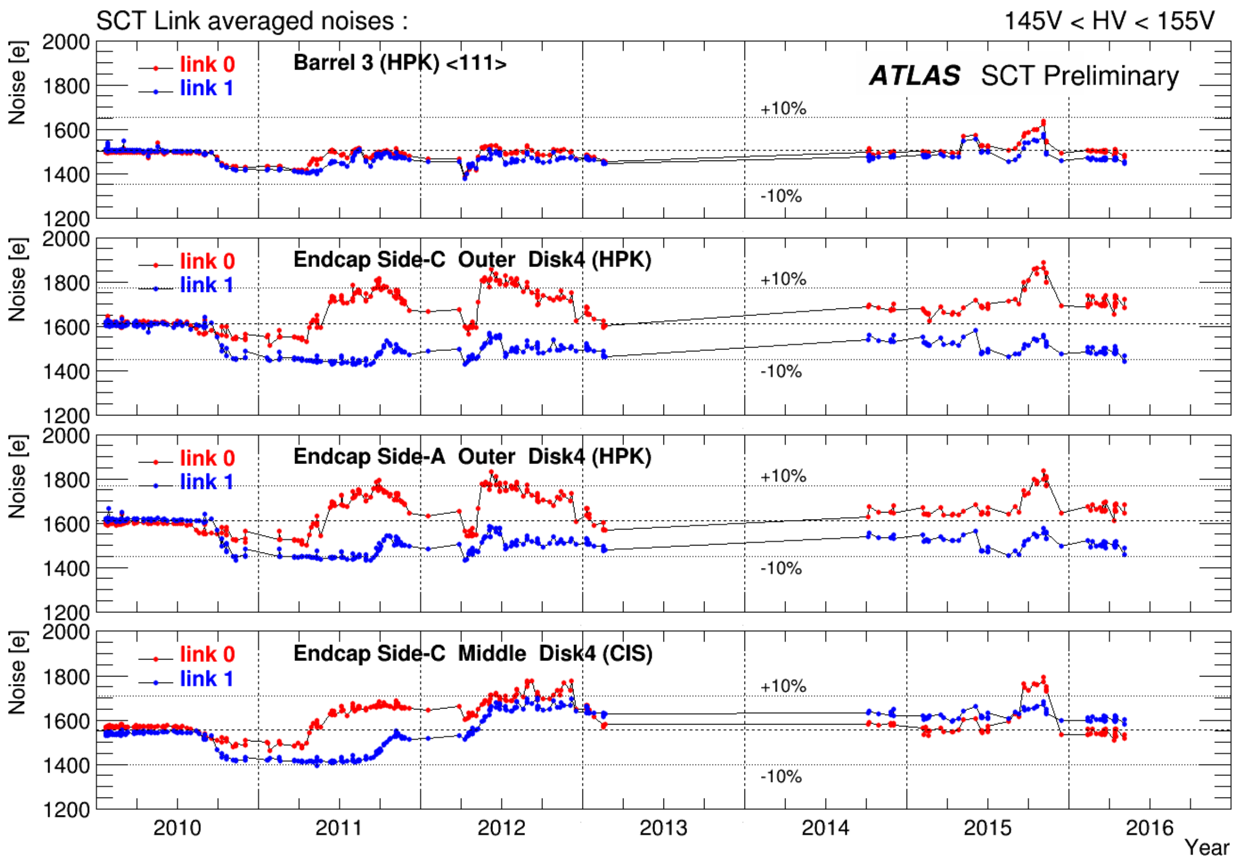
Hamburg model for effective dopant concentration [1]

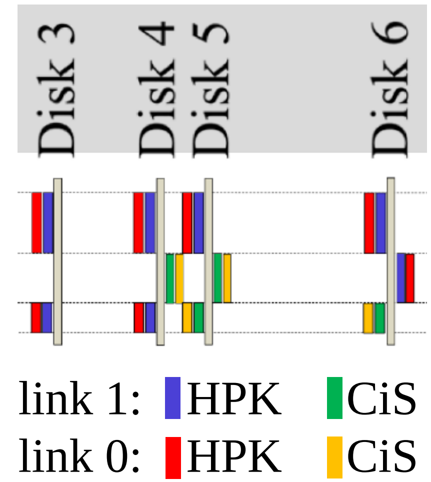
$$N_{eff}(\Phi,t,T) = N_{eff,0} - N_C(\Phi) - N_a(\Phi,t,T) - N_Y(\Phi,t,T)$$

Donor removal & Stable acceptor	$N_C(\Phi) = N_{C0}\left(1-e^{-c\Phi}\right) + g_C\Phi$
Unstable acceptor	$N_a(\Phi,t,T) = g_a\Phi\,\mathbf{exp}\left(-\Theta(T)_a t/\tau_a\right)$, $\Theta(T)_a = \mathbf{exp}\left(\frac{E_a}{k_B}\left[1/T_R - 1/T\right]\right)$
Reverse annealing	$N_Y(\Phi,t,T) = g_y\Phi\left(1-1/(1+\Theta(T)_y t/\tau_y)\right)$, $\Theta(T)_y = \mathbf{exp}\left(\frac{E_y}{k_B}\left[1/T_R - 1/T\right]\right)$
Parameters	$N_{C0} = 0.70\times N_{eff,0}$ (±10%) $c = 0.075\,\mathrm{cm}^{-1}/N_{C0}$ (±10%) $g_a = 0.018\pm0.0014\,\mathrm{cm}^{-1}$ $\tau_a = 2.29$ days (at 20°C ≡ T_R) (±10%) $E_a = 1.09\pm0.03\,\mathrm{eV}$ $g_C = 0.017\pm0.0005\,\mathrm{cm}^{-1}$ $g_y = 0.059\pm0.001\,\mathrm{cm}^{-1}$ $\tau_y = 480$ days (at 20°C) (±10%) $E_y = 1.33\pm0.03\,\mathrm{eV}$ $N_{eff,0} = 1.023\pm0.15\times10^{12}\,\mathrm{cm}^{-3}$ ($V_{FD} = 64.8\pm9.5$ V)

[1] G. Lindstrom et al., NIM A 466(2001) 308-326
M.Moll, Radiation Damage in Silicon Particle Detectors, Dissertation, Hamburg 1999.

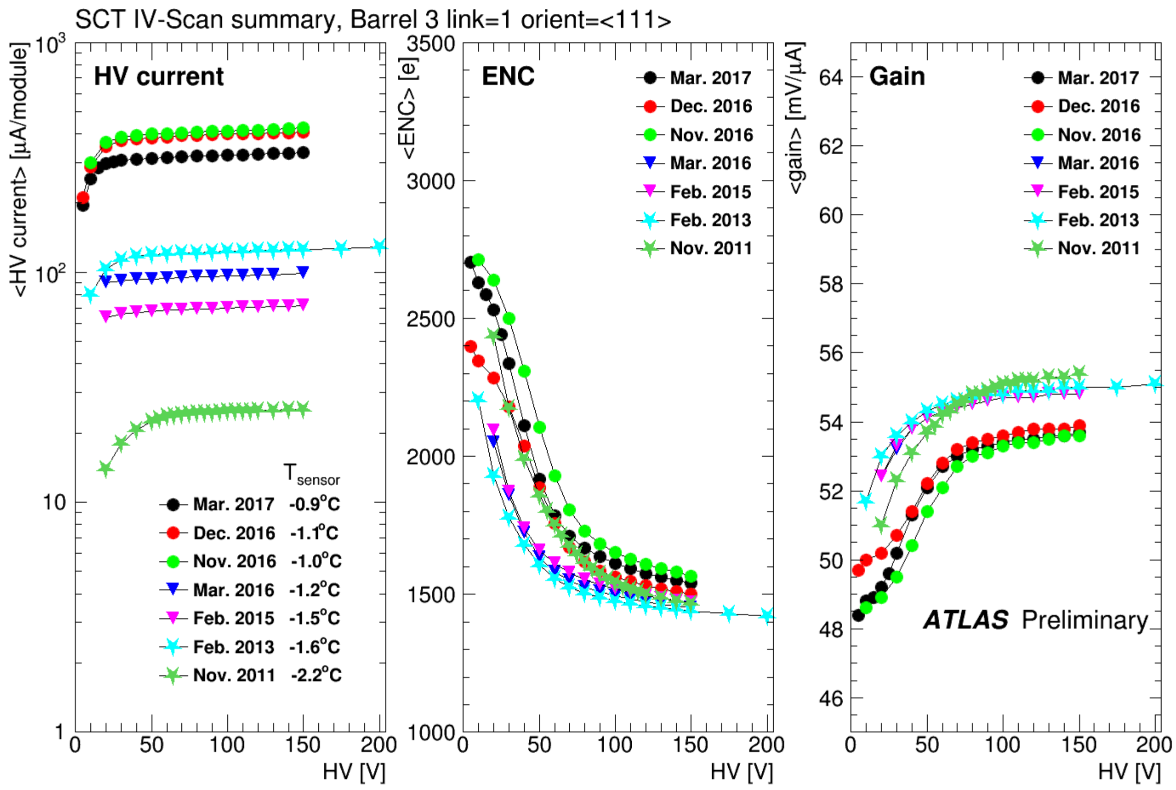
Evolution of link-averaged noise





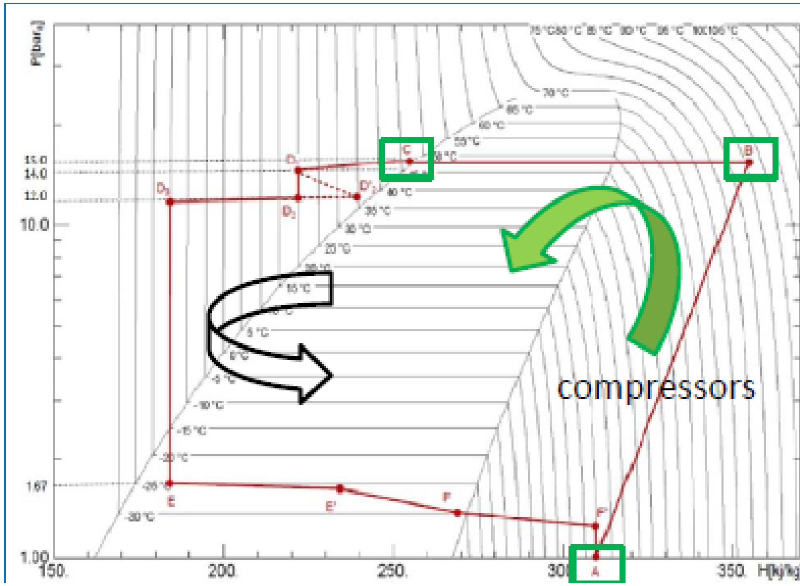
Evolution in noise (mean chip noise, in ENC) as a function of time, for four typical SCT layers: the inner most barrel layer (Barrel 3), two layers equipped with Hamamatsu (HPK) sensors from the outermost ring in disk 4, and one with CiS sensors in the middle ring in disk 4. The evolution is shown separately for the two data links of each module. For end-cap modules, link 1 is the side facing the disk supports, and link 0 faces away from the disk supports (facing the N_2 gas gaps).

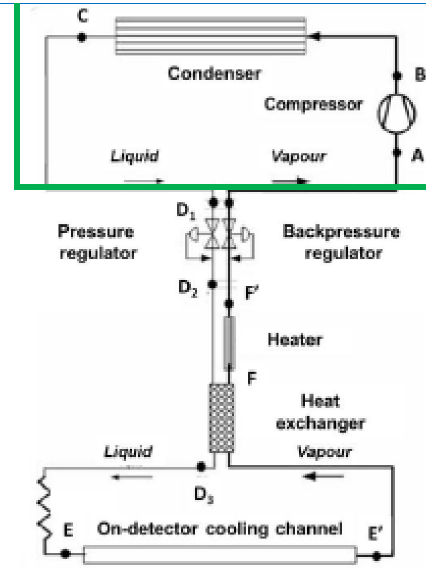
IV (Current Voltage) scan



The figure shows HV-currents, noises and gains averaged over Barrel 3 modules as a function of HV with N-point gain calibration runs. Sensor temperatures are estimated by the temperature sensors on the hybrids. The HV current data show moving “knee” points, a hint for changes in V_{FD} (full depletion voltage). Changes in noise and gain curves are probably due to changes in strip capacitance, but no reliable analyses are established yet.

Comparing the C_3F_8 compressor and thermosiphon systems

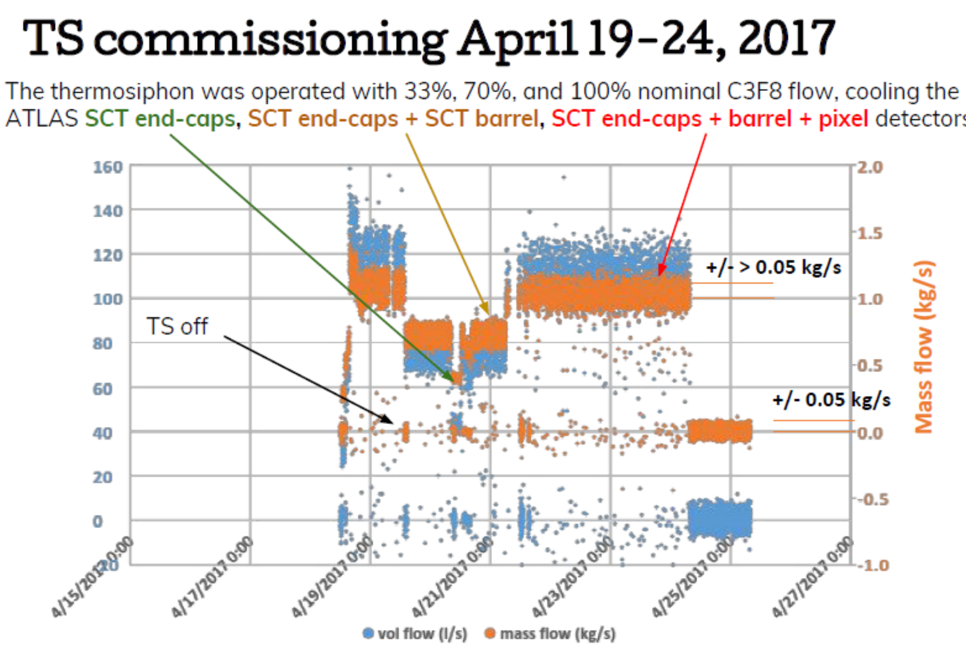




Compressor driven evaporative system (A-C)

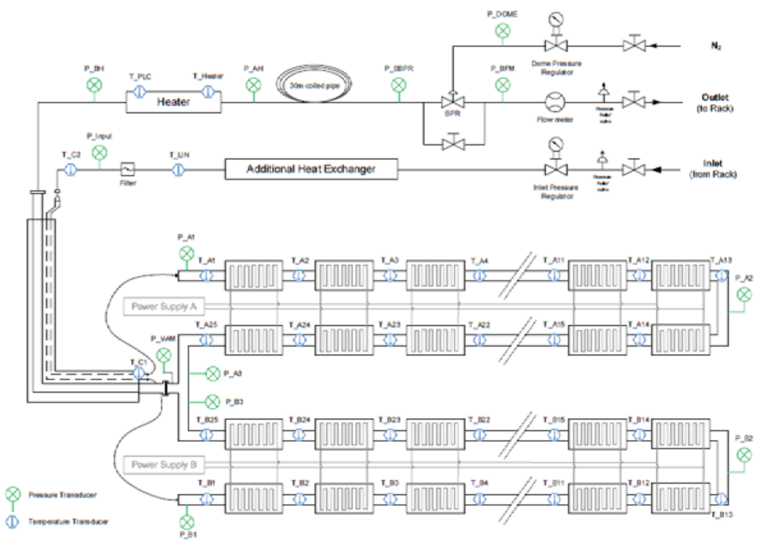
Internal circuit (D1 – F')

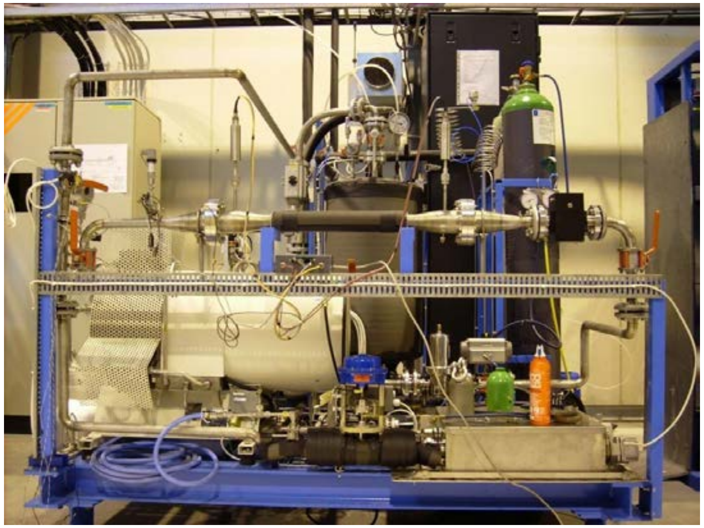
EDMS 1083852



Thermosiphon extensively tested with dummy load (2016):
also in April 2017 with SCT & pixel detectors
Including cold/power swaps between compressor and TS system.
(from sonar flowmeter measuring return C3F8 flow to condenser.
New condenser purchase approved for 2018 final commissioig

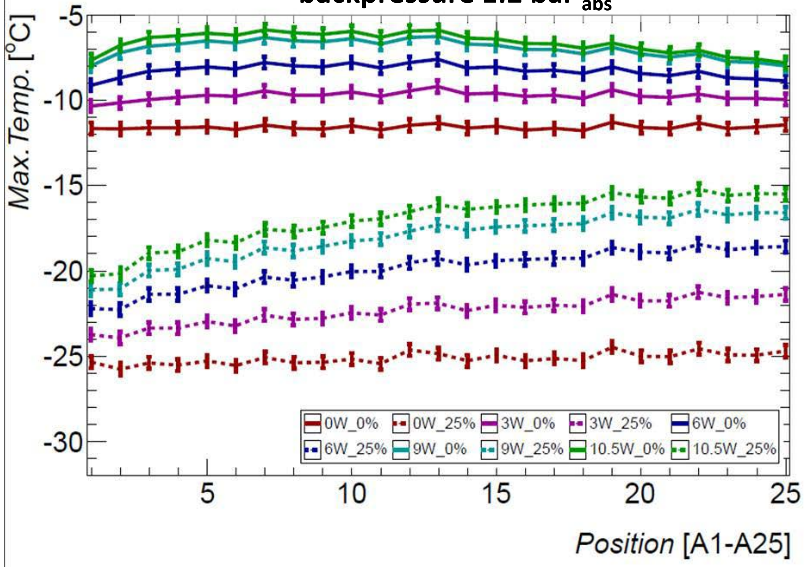
C_2F_6/C_3F_8 blends studies in thermal mockup of SCT bi-stave and external piping, using custom-made blend recirculator (SR1 2013-5)

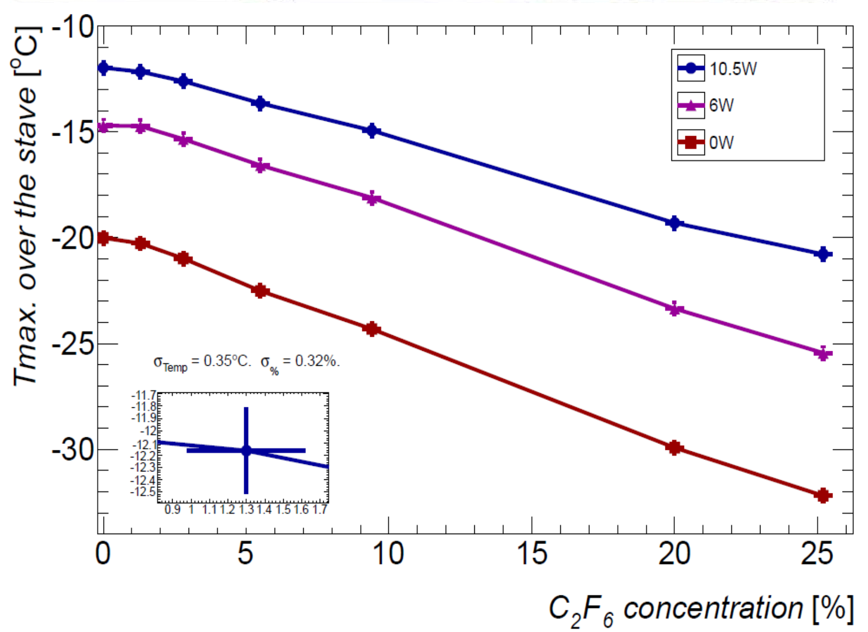




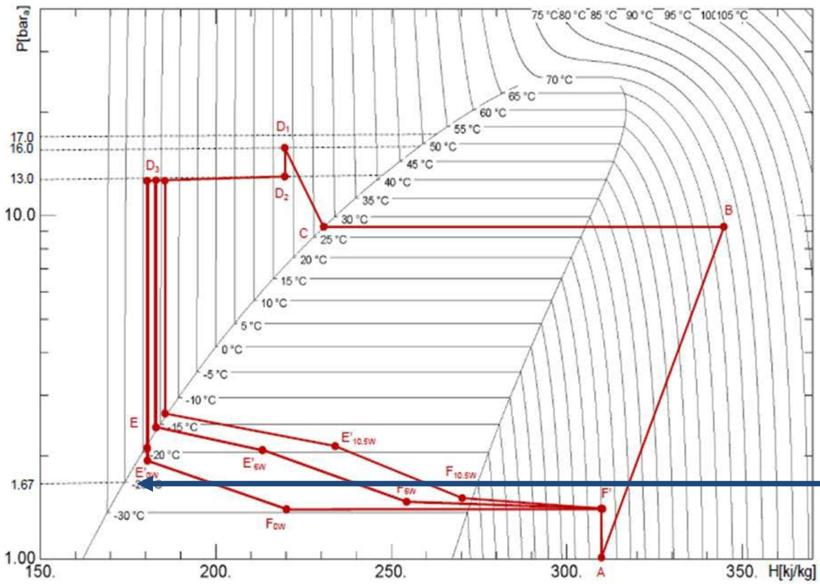
0% - 25%

Profile comparison C_3F_8 & 25%C_2F_6/75%C_3F_8, backpressure 1.2 bar $_{abs}$

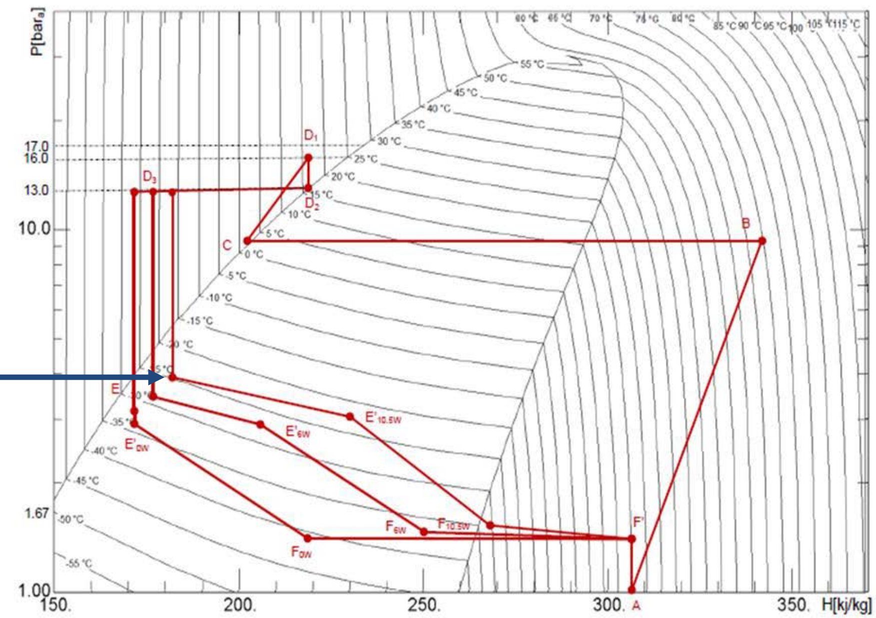




On-detector evaporation temperature reduction from C_3F_8 to 25% C_2F_8/75%C_3F_8



P-h diagram: C_3F_8



P-h diagram: 25% C_2F_8/75%C_3F_8