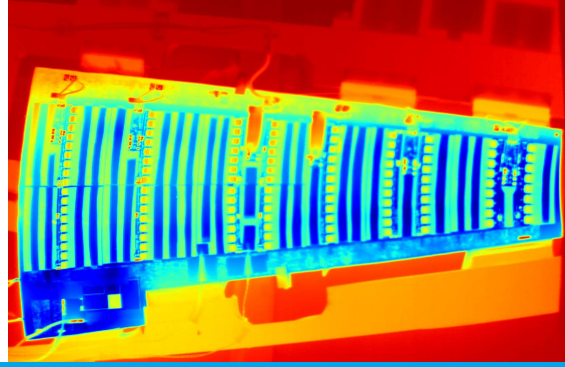


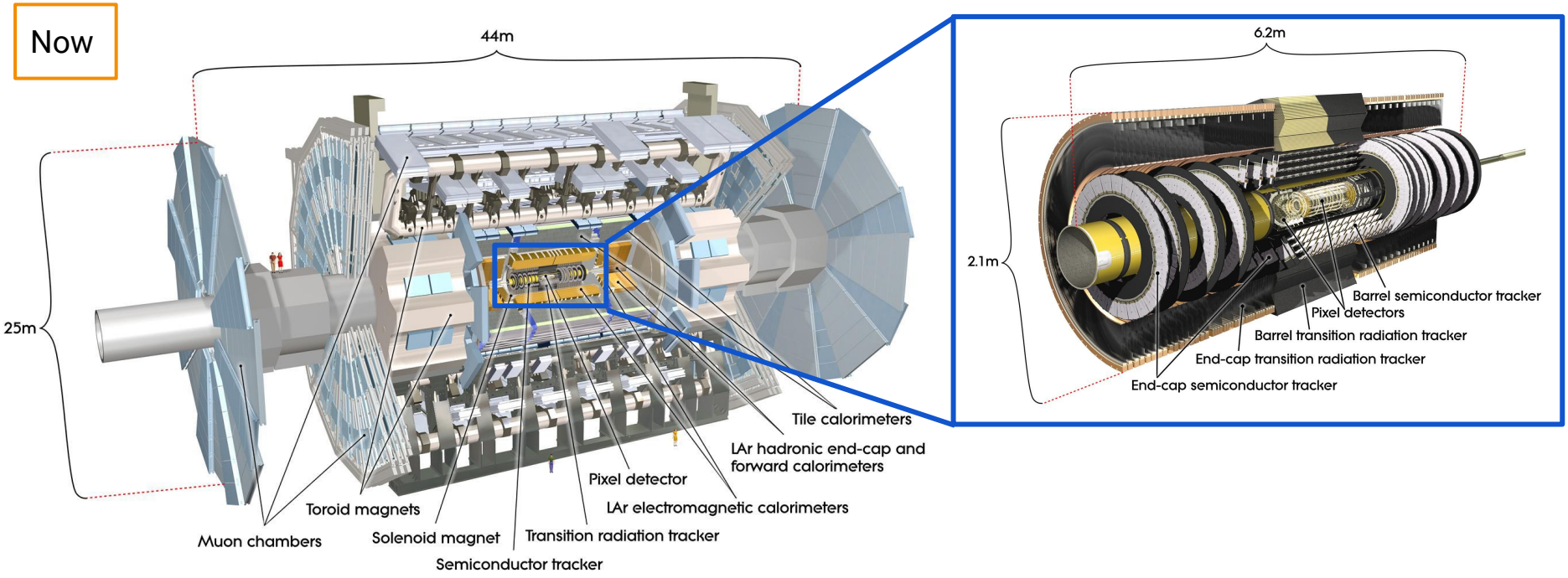
Infrared Thermal Imaging of the ATLAS future inner strip tracker

Maximilian Caspar, University of Wuppertal, ATLAS summer student at DESY

The inner tracker of the ATLAS detector

The Inner Tracker of the ATLAS detector

Now



For HL-LHC

Current inner tracker to be fully replaced by all-silicon tracker (**ITk)**

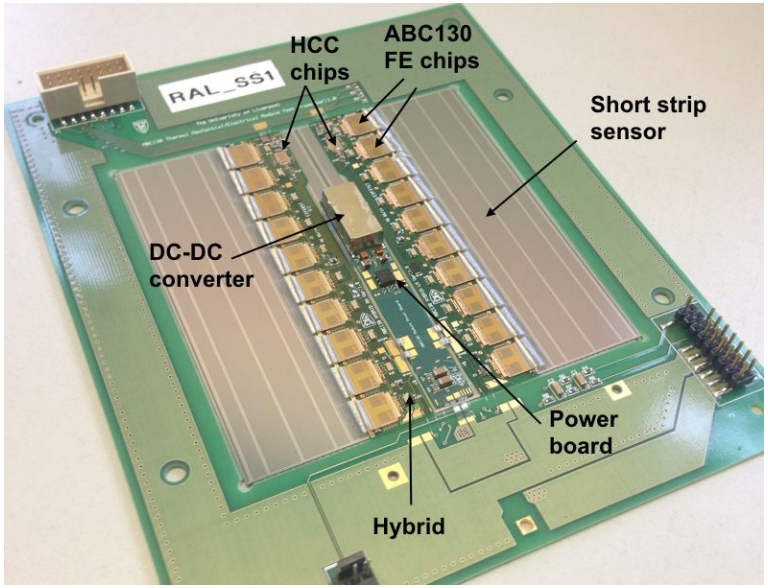
⇒ **ATLAS Upgrade (Phase II)**

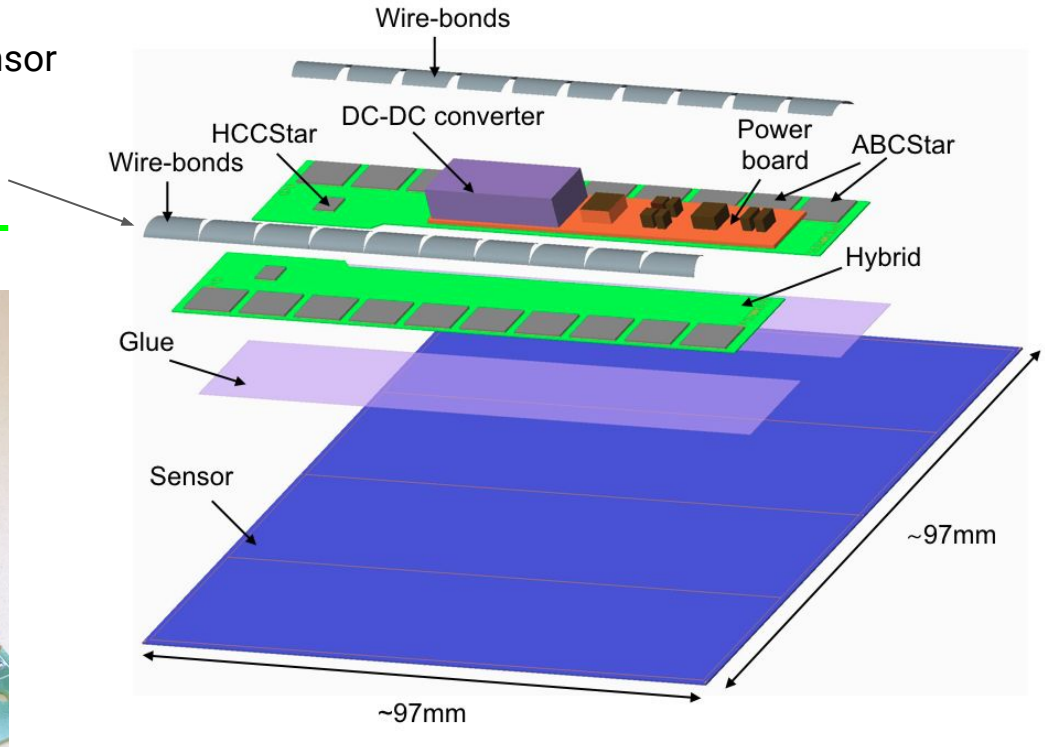
Goals: **Sustain** and **improve** the excellent performance of ATLAS Run 2 in denser environment

Strip Module

= Silicon sensor + hybrid + power board

- Low mass PCB's directly glued on sensor
- Hosting readout electronics
- Connection to strips by wire-bonds



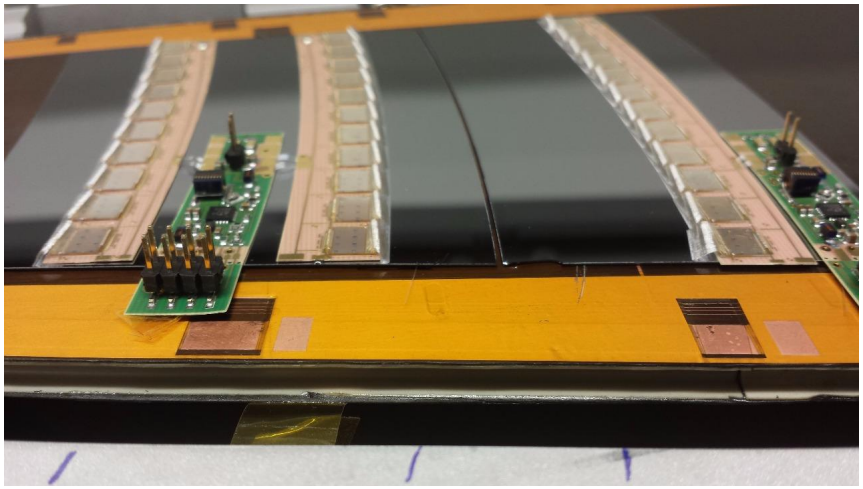


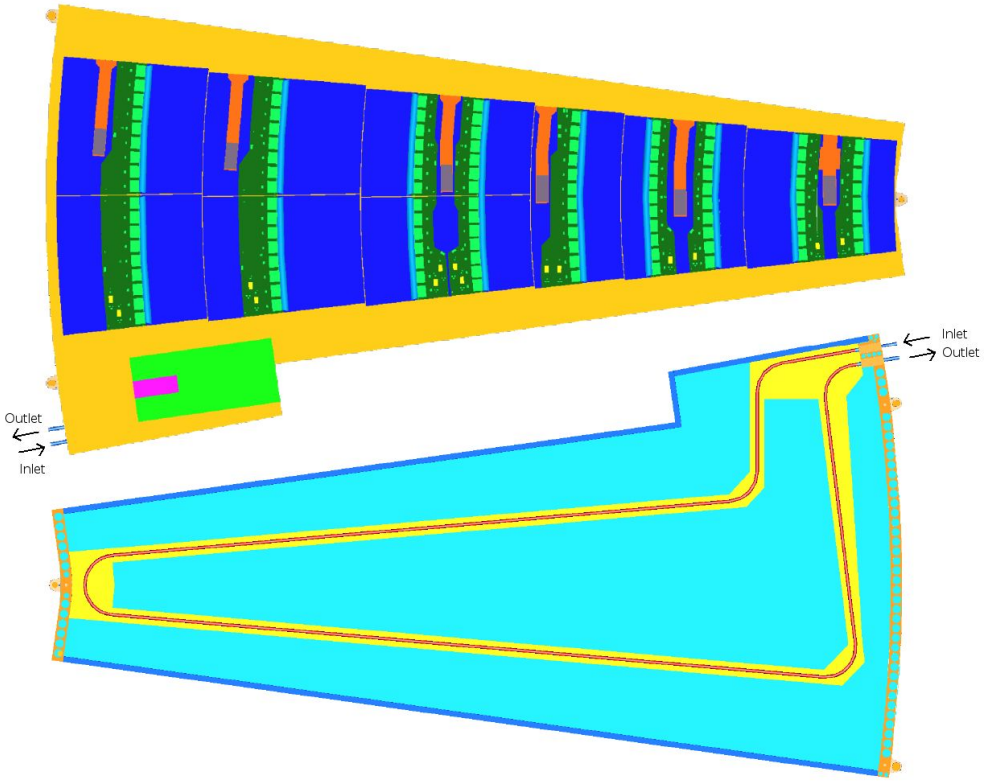
Total number of modules = 17888

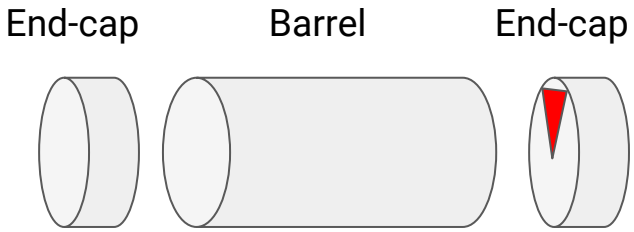
⇒ designed for mass production

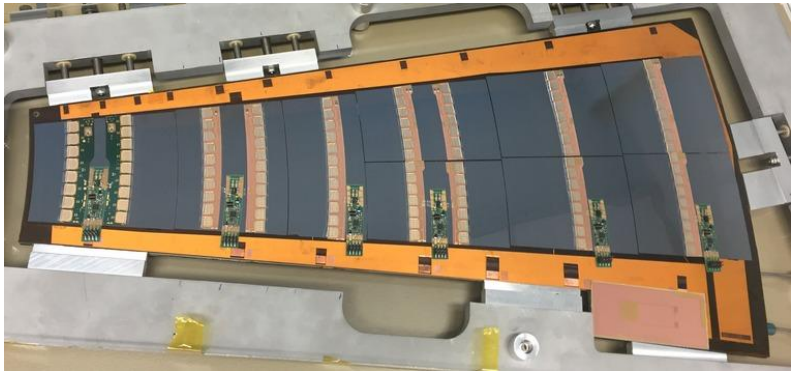
The Petal

- The endcap modules and the electronics are held by the petal
- A prototype petal with dummy sensors and electronics was built at DESY
- The petal has an internal titanium cooling pipe





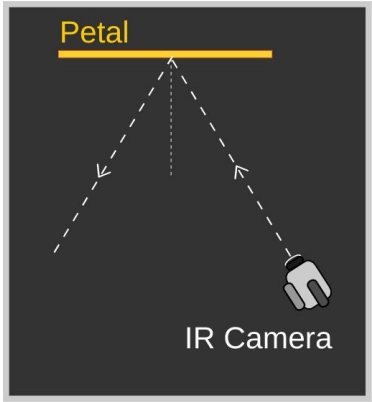




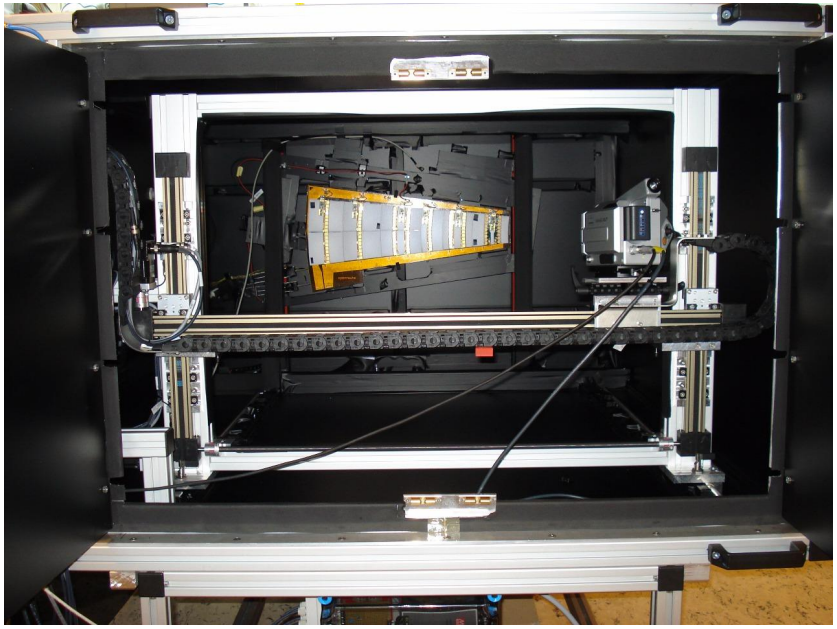
Setup and Automation

Thermal chamber

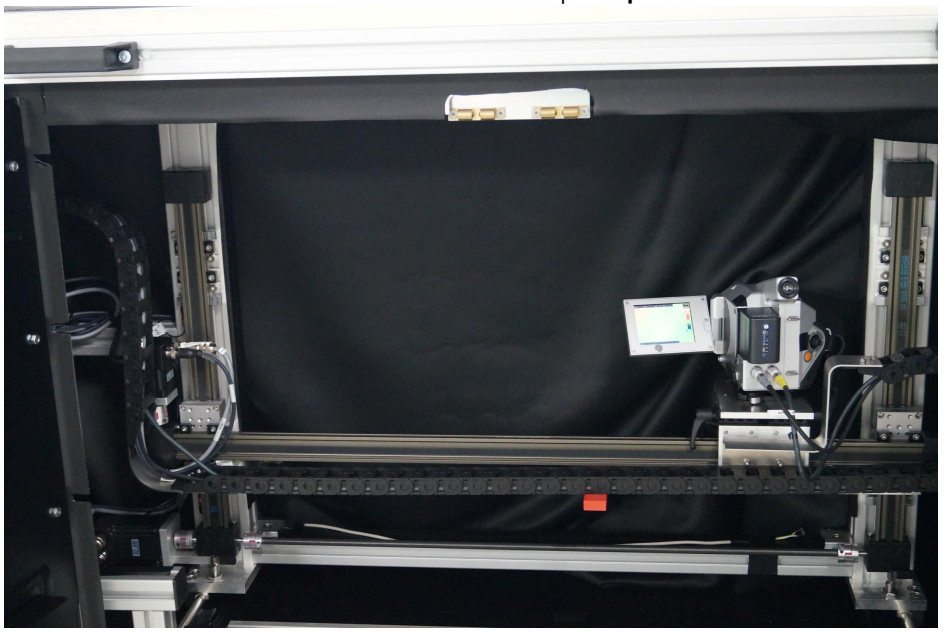
- Insulated thermal chamber with inner separation by black curtains
- Infrared camera mounted on gantry behind curtain
- Petal mounted in the chamber and supplied with cooling and power from the outside



↑ Top view



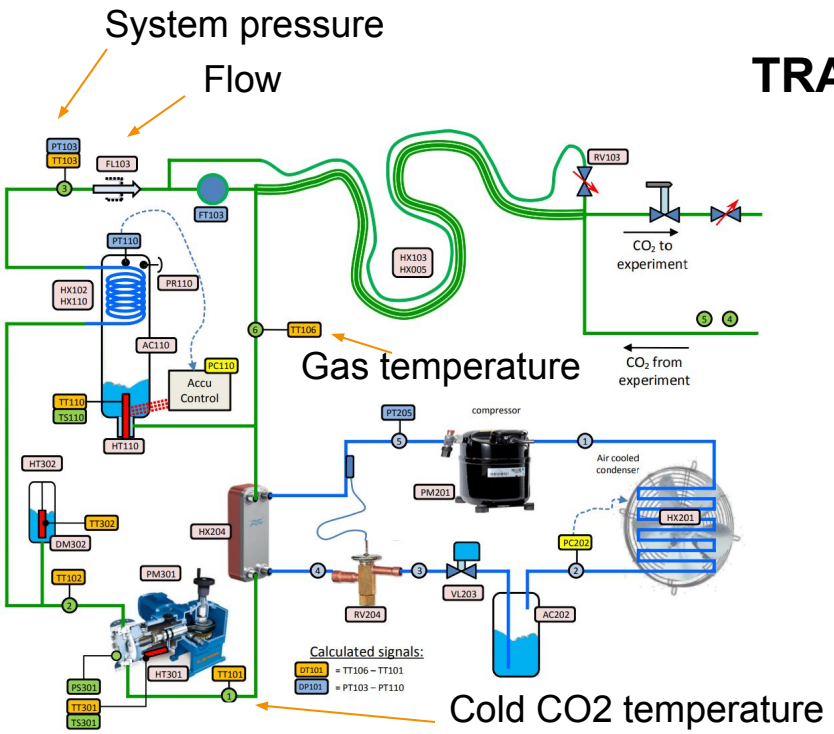
Petal inside of the chamber



Camera behind the curtain

Cooling system

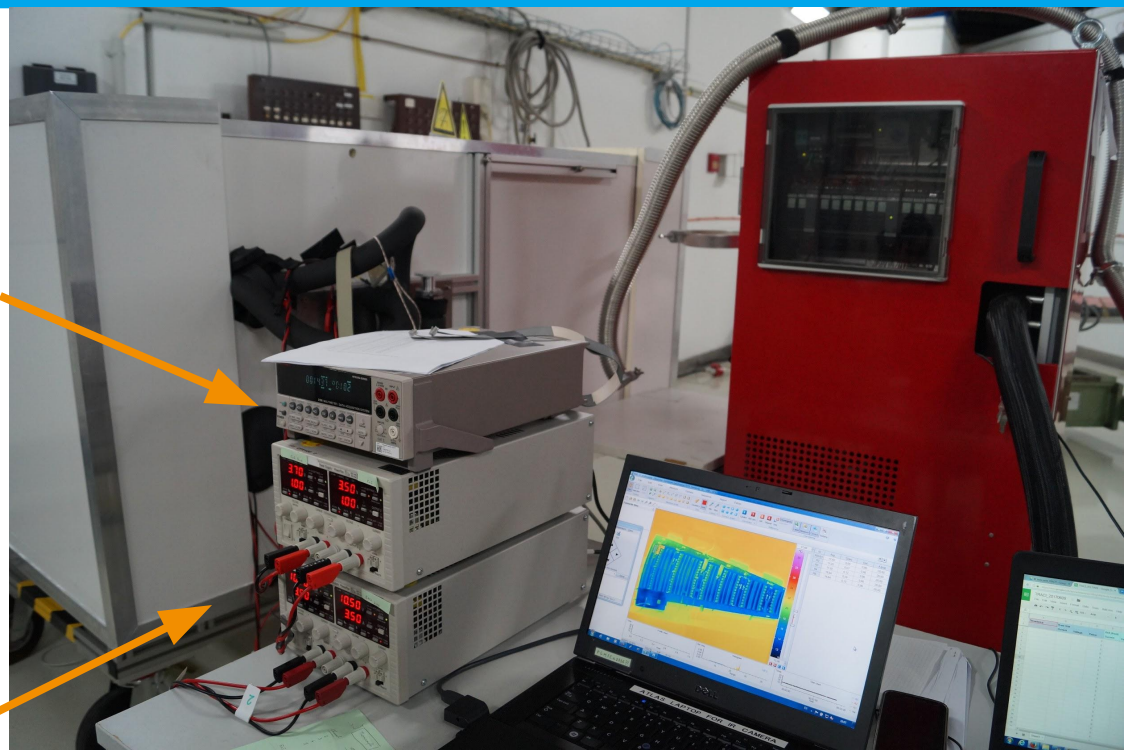
- Petal cooled down with evaporative dual phase CO2 cooling
- Prototype cooling system from CERN (TRACI)
- Connection to thermal chamber via adapted connectors
- Vacuum pump to remove air in petal's cooling loop before CO2 filling



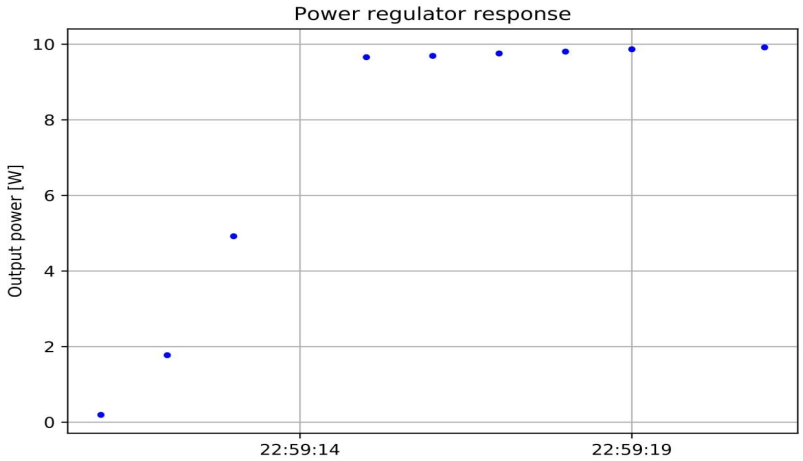
- Certain parameters inside TRACI need to be monitored
- A combination of voltages and temperatures is measured by the multimeter
- The cooling setpoint is represented as a pressure, conversion to temperature using CO2 properties

Setup instrumentation and automation

- TRACI DAQ using NI card + Labview
- NI Card not working, replaced by:
  - Multimeter via RS-232
  - custom python script
- Additional thermocouples inside of the chamber connected to the multimeter



- Four power supply channels for petal powering (ASICs)
- Created a program that controls the power supplies and regulates the output power to a reference value



- Additional humidity and temperature probes connected to a Raspberry Pi for monitoring chamber environment
- The readout of the camera is handled by IRBIS (camera software)
- Instrumentation readout is done using a linux machine

Automation at work: tests and validation

TIME	Inlet	Outlet	R0	R1	R3b	R3m	R4	R5	TT103	TT106	PT103	PT110	FLOW	DP101	TT102	TT101	TT110	TT301	TT302
2017-08-09_15:51:11	24.416	24.263	24.323	24.331	24.387	24.43	24.457	24.423	16.164	13.254	61.382	51.109	0.034	10.227	-18.856	-32.435	38.48	7.734	35.926
2017-08-09_15:51:22	24.406	24.288	24.312	24.318	24.38	24.42	24.449	24.413	16.168	13.287	61.35	51.125	0.04	10.222	-18.858	-32.445	38.428	7.736	35.057
2017-08-09_15:51:34	24.39	24.282	24.306	24.311	24.371	24.412	24.44	24.401	16.167	13.323	61.354	51.112	0.011	10.196	-18.849	-32.449	38.369	7.736	42.496
2017-08-09_15:51:46	24.394	24.307	24.301	24.3	24.353	24.402	24.425	24.389	16.167	13.357	61.382	51.129	0.041	10.223	-18.855	-32.454	38.318	7.736	41.178
2017-08-09_15:51:58	24.364	24.232	24.293	24.295	24.338	24.387	24.408	24.373	16.171	13.397	61.392	51.116	0.04	10.227	-18.855	-32.457	38.346	7.734	39.302
2017-08-09_15:52:10	24.349	24.245	24.285	24.285	24.324	24.374	24.396	24.359	16.169	13.43	61.432	51.128	0.032	10.247	-18.852	-32.453	38.332	7.735	37.577
2017-08-09_15:52:22	24.364	24.311	24.28	24.28	24.318	24.365	24.384	24.343	16.166	13.505	61.36	51.114	0.036	10.221	-18.841	-32.449	38.391	7.736	36.209
2017-08-09_15:52:34	24.364	24.31	24.277	24.275	24.31	24.352	24.377	24.335	16.168	13.524	61.378	51.135	0.024	10.214	-18.841	-32.445	38.402	7.736	35.278
2017-08-09_15:52:46	24.366	24.318	24.274	24.27	24.295	24.339	24.366	24.328	16.172	13.551	61.357	51.127	0.03	10.218	-18.84	-32.445	38.408	7.737	41.035
2017-08-09_15:52:58	24.365	24.318	24.267	24.257	24.287	24.332	24.356	24.315	16.175	13.58	61.378	51.123	0.045	10.222	-18.844	-32.445	38.316	7.739	41.898
2017-08-09_15:53:10	24.362	24.326	24.256	24.259	24.276	24.324	24.35	24.31	16.172	13.612	61.44	51.125	0.041	10.263	-18.85	-32.441	38.325	7.739	40.059
2017-08-09_15:53:22	24.362	24.333	24.25	24.246	24.271	24.315	24.343	24.313	16.175	13.635	61.385	51.115	0.036	10.221	-18.834	-32.441	38.335	7.74	38.225
2017-08-09_15:53:34	24.359	24.331	24.25	24.242	24.262	24.307	24.337	24.305	16.174	13.664	61.414	51.132	0.041	10.244	-18.842	-32.436	38.351	7.741	36.823
2017-08-09_15:53:46	24.357	24.332	24.243	24.235	24.257	24.3	24.33	24.3	16.173	13.69	61.391	51.114	0.042	10.244	-18.829	-32.436	38.479	7.742	35.664
2017-08-09_15:53:58	24.357	24.336	24.241	24.232	24.25	24.293	24.325	24.291	16.182	13.719	61.391	51.128	0.038	10.247	-18.836	-32.434	38.421	7.743	35.073
2017-08-09_15:54:10	24.35	24.3	24.233	24.227	24.244	24.285	24.313	24.277	16.179	13.747	61.375	51.123	0.036	10.224	-18.83	-32.435	38.357	7.744	42.702
2017-08-09_15:54:22	24.337	24.271	24.234	24.224	24.239	24.284	24.315	24.271	16.178	13.774	61.403	51.131	0.041	10.233	-18.824	-32.432	38.368	7.744	40.852
2017-08-09_15:54:34	24.336	24.282	24.242	24.235	24.257	24.297	24.328	24.287	16.18	13.8	61.439	51.126	0.058	10.247	-18.825	-32.436	38.379	7.745	39.093
2017-08-09_15:54:46	24.356	24.348	24.243	24.233	24.28	24.314	24.359	24.336	16.183	13.832	61.426	51.115	0.038	10.254	-18.825	-32.435	38.482	7.746	37.594
2017-08-09_15:54:58	24.387	24.332	24.25	24.248	24.314	24.34	24.388	24.368	16.182	13.854	61.399	51.128	0.034	10.237	-18.816	-32.441	38.46	7.746	36.29
2017-08-09_15:55:10	24.418	24.451	24.261	24.262	24.334	24.365	24.415	24.396	16.184	13.883	61.398	51.124	0.035	10.222	-18.811	-32.441	38.402	7.746	35.303
2017-08-09_15:55:22	24.436	24.431	24.279	24.281	24.385	24.4	24.463	24.433	16.188	13.91	61.36	51.133	0.031	10.22	-18.793	-32.427	38.391	7.747	39.846
2017-08-09_15:55:34	24.42	24.373	24.296	24.302	24.403	24.431	24.485	24.455	16.185	13.943	61.377	51.119	0.033	10.22	-18.788	-32.42	38.449	7.747	41.946
2017-08-09_15:55:46	24.43	24.428	24.301	24.313	24.42	24.447	24.5	24.469	16.189	13.976	61.41	51.132	0.03	10.221	-18.777	-32.407	38.454	7.748	40.418
2017-08-09_15:55:58	24.463	24.456	24.316	24.327	24.43	24.457	24.511	24.486	16.191	14.008	61.413	51.119	0.041	10.243	-18.773	-32.398	38.496	7.749	38.925
2017-08-09_15:56:10	24.494	24.487	24.329	24.34	24.447	24.482	24.521	24.496	16.193	14.037	61.434	51.141	0.035	10.226	-18.767	-32.388	38.496	7.75	37.701
2017-08-09_15:56:22	24.484	24.448	24.336	24.349	24.454	24.484	24.526	24.487	16.192	14.062	61.388	51.14	0.045	10.216	-18.763	-32.384	38.489	7.75	36.687
2017-08-09_15:56:34	24.499	24.471	24.335	24.352	24.457	24.488	24.528	24.489	16.196	14.087	61.385	51.13	0.034	10.228	-18.743	-32.384	38.086	7.75	35.643
2017-08-09_15:56:46	24.497	24.452	24.332	24.348	24.447	24.486	24.521	24.48	16.192	14.111	61.384	51.115	0.037	10.236	-18.754	-32.388	38.084	7.751	37.097
2017-08-09_15:56:58	24.488	24.434	24.323	24.343	24.436	24.473	24.508	24.475	16.19	14.138	61.35	51.097	0.034	10.223	-18.74	-32.384	38.161	7.751	42.334
2017-08-09_15:57:10	24.479	24.432	24.318	24.331	24.427	24.46	24.503	24.457	16.19	14.155	61.371	51.104	0.039	10.222	-18.726	-32.384	38.229	7.753	40.789
2017-08-09_15:57:22	24.468	24.425	24.309	24.324	24.411	24.445	24.485	24.449	16.186	14.184	61.359	51.09	0.047	10.227	-18.71	-32.384	38.311	7.753	39.09

TRACI and petal data

- Collection of all parameters of the test automatically written to text file:
  - Chamber: ambient temperature, moisture at multiple positions
  - TRACI: input / output CO2 pressure, flow
  - Petal: inlet / outlet temperature, additional thermocouples taped to sensors

Thermal Imaging and Analysis

Basics of Thermal Imaging

- The radiation power inside of the spectral range 7.5 µm to 14 µm is measured for each camera pixel
- For each Pixel, the temperature is calculated using the Stefan-Boltzmann law for non-black bodies

$$P = \varepsilon(T) \cdot \sigma \cdot A \cdot T^4$$

Ratio of emitted power w.r.t. black body radiation (emissivity)

Stefan-Boltzmann constant

Pixel Area

- Kirchhoff's law of thermal radiation:

Emissivity + Transmissivity + Reflectivity = 1

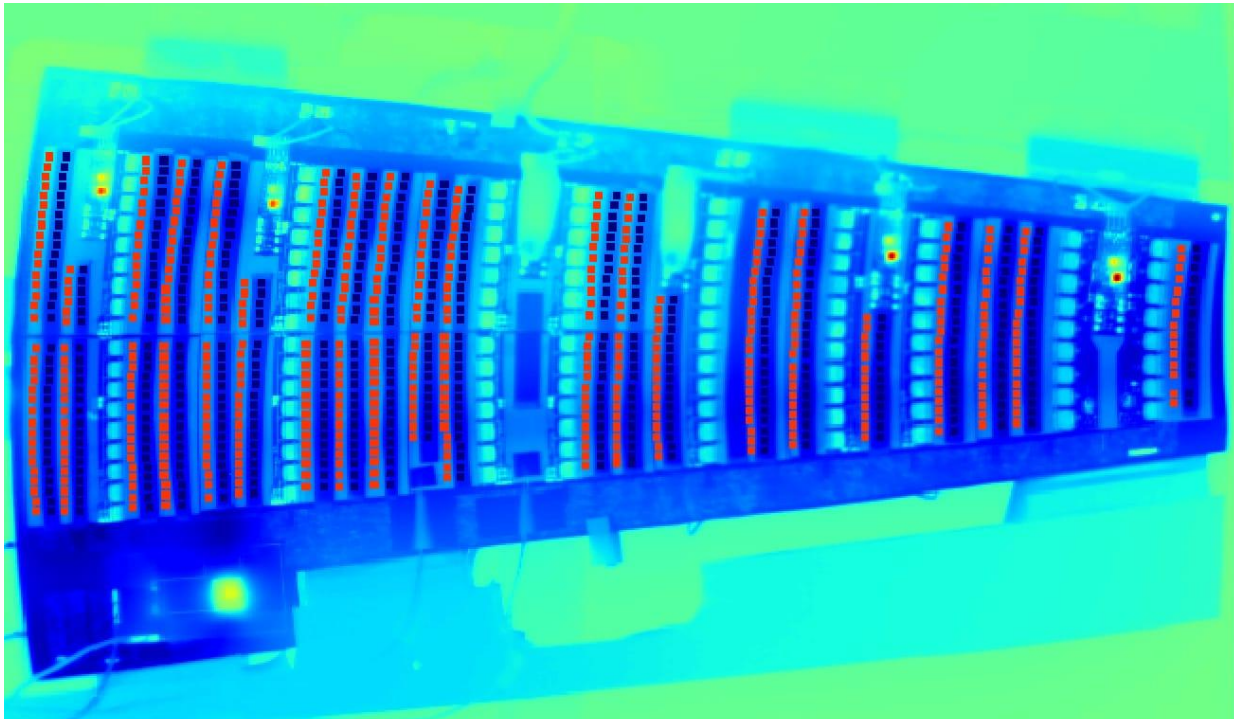
- Silicon is very difficult to handle since the emissivity can with different properties (angle, surface coating, ...)
- Ongoing study: Transmissivity of the silicon sensors

Basics of Thermal Imaging

Markers

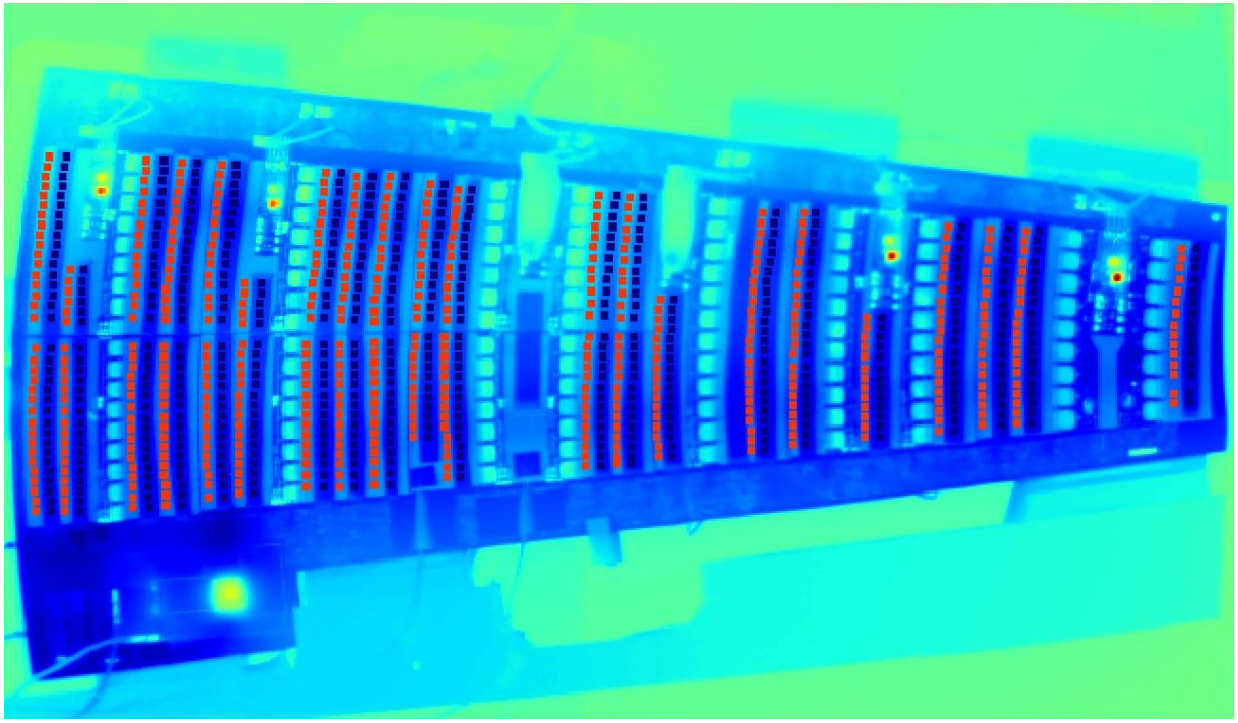
- We want to measure the temperature on different location of the petal's sensors

  ⟹ Use of the marker concept provided by the infrared software
- Marker: Area of pixels with average / standard deviation
- Parsing of thermograms and marker files in python for automated analysis of the IR data



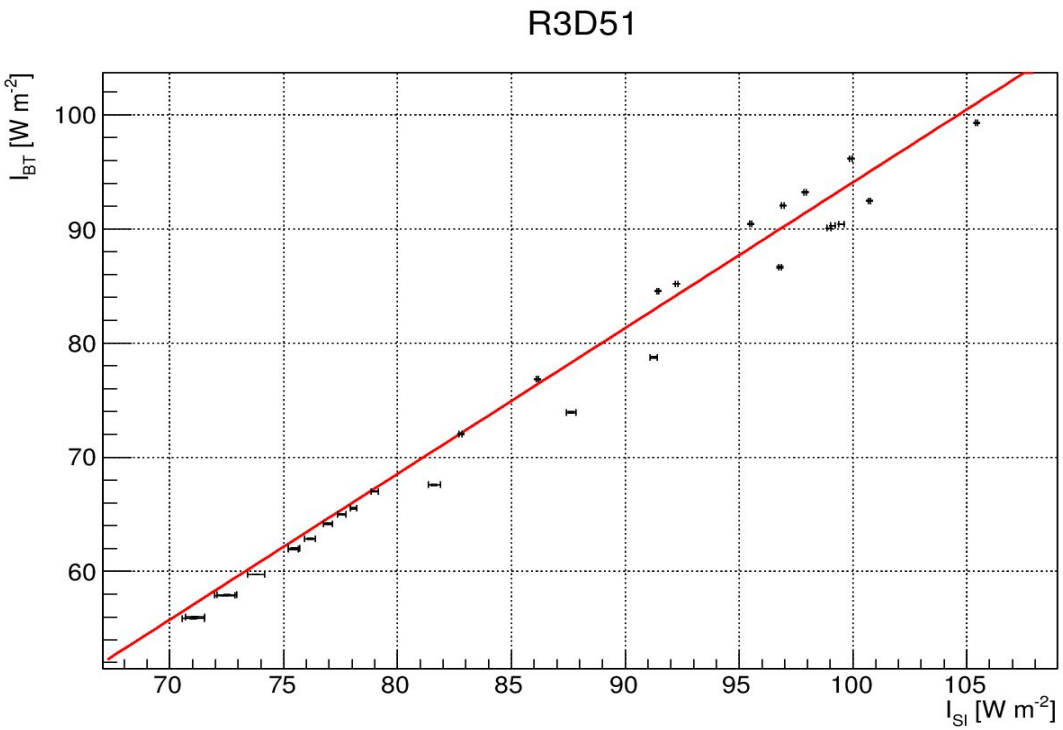
Black Tape Calibration

- Since the emissivity of the silicon is unknown, we want to use black tape ($\varepsilon = 0.95$) as a reference (assume $T_{Si} = T_{BT}$)
- Marker pairs are compared against each other to calibrate the temperature read on the silicon offline



Data Analysis

- First I created a script to transfer all reference points for silicon and black tape into a .root file
- Goal: Relating intensity on black tape to intensity on silicon for each position on the petal
- Applying linear fits and plotting the results gives clues about two different overlaying effects in the same image



- Idea: Compare different quantities (cycle direction, heating power, nitrogen flushing, etc)
- This will hopefully deliver a separation between both lines

Conclusion & Outlook

- <u>The physics</u>
  - Took part in future ATLAS endeavours through R&D work on ITk project
  - Understand thermography and the challenges of silicon emissivity

- <u>The instrumentation</u>
  - Successfully instrumented & automated all devices for thermal cycling / measurements
  - All scripts + framework on CERN gitlab & fully documented

- <u>The analysis</u>
  - Converting data to the root format for more versatile handling + storage
  - Investigating the relation $T_{Si} = f(T_{BT})$ is still ongoing

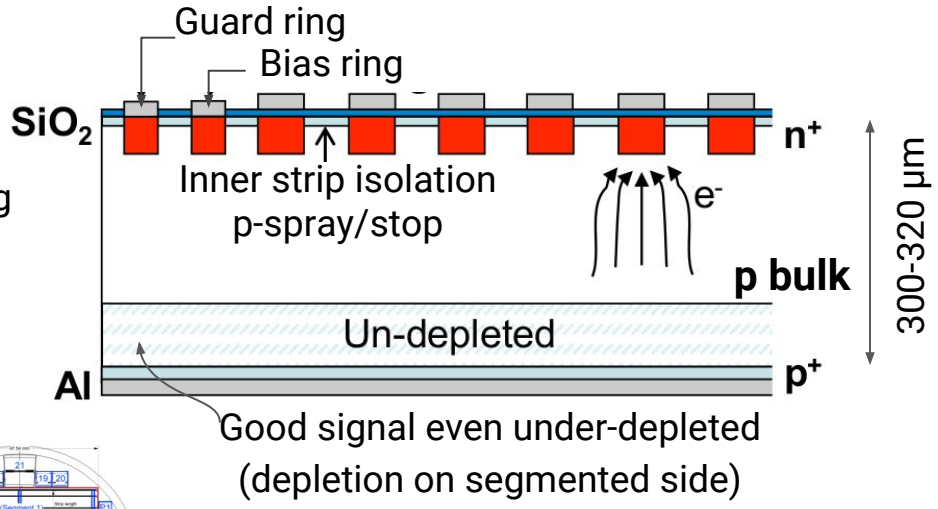
Backups

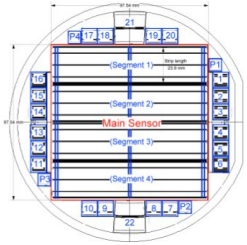
Silicon sensors

Technology

Silicon sensors → n^+-in-p float-zone (FZ)

- collects electrons: more & faster signal, less trapping
- no radiation-induced type inversion
- single-sided process
  - ⇒ cheap & easy
  - ⇒ more available foundries worldwide
- sensor edges at bias potential (~700 V)

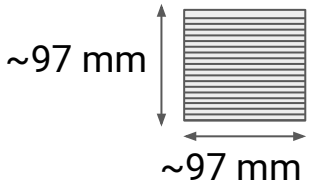


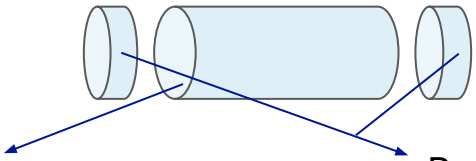


← design based on 6-inch wafer technology

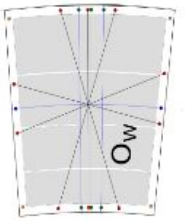
Sensor shapes & pitch

Barrel → rectangular





End-caps → trapezoidal shape for r-Φ coverage



Radial strips pointing to beam axis

⇒ wedge-shaped sensors with curved edges

75.5 µm	**Strip pitch**	60 - 80 µm