Detector Module R&D for the future CMS Tracker

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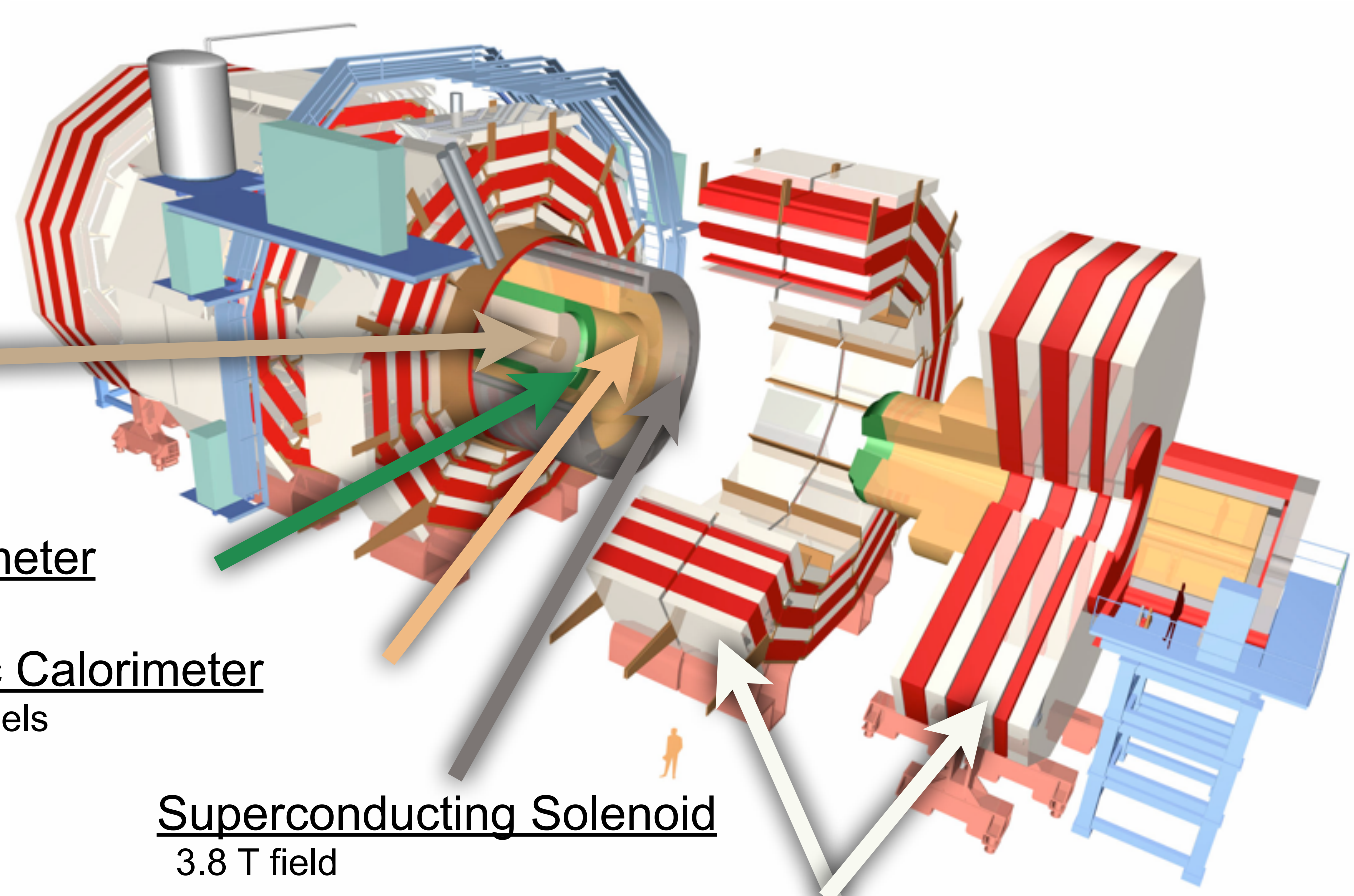
HELMHOLTZ | ASSOCIATION

DESY

Outline

- introduction
  - requirements
  - general concepts
  - module concepts
- strip-strip module
  - evolution of the design
  - thermal FEA results
  - prototyping
- pixel-strip module
  - evolution of the design
  - thermal FEA results
- module assembly
- summary

The CMS Experiment the LHC



Tracker
76M channels
16588 modules

Electromagnetic Calorimeter
76k channels

Hadronic Calorimeter
10k channels

Superconducting Solenoid
3.8 T field

Muonspectrometer
840k channels
1400 chambers

Weight	12500 t
Length	21,5 m
Diameter	15 m

Requirements to the Future CMS Tracker

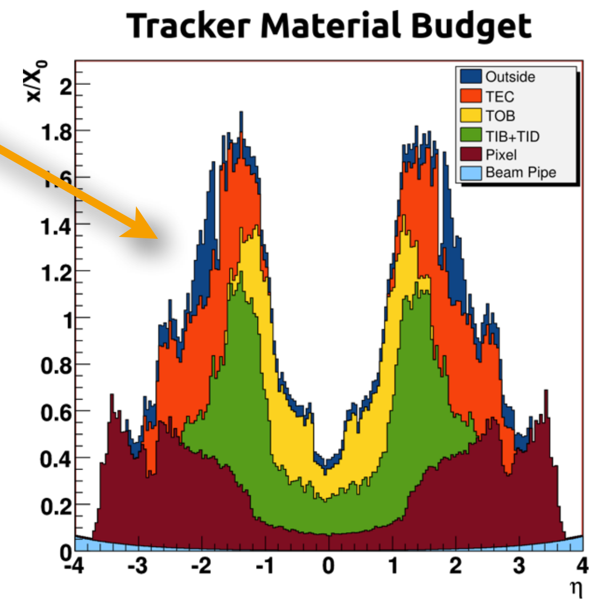
> granularity

- expect up to 200 collisions per bunch crossing
- occupancy must stay at the few % level
- modules will have much shorter strips

> improve tracking performance

- reduce the strip pitch
  improves the resolution for high pT tracks
- reduce the amount of material in the tracker volume
  improves resolution for low pT tracks

number of channels increases substantially



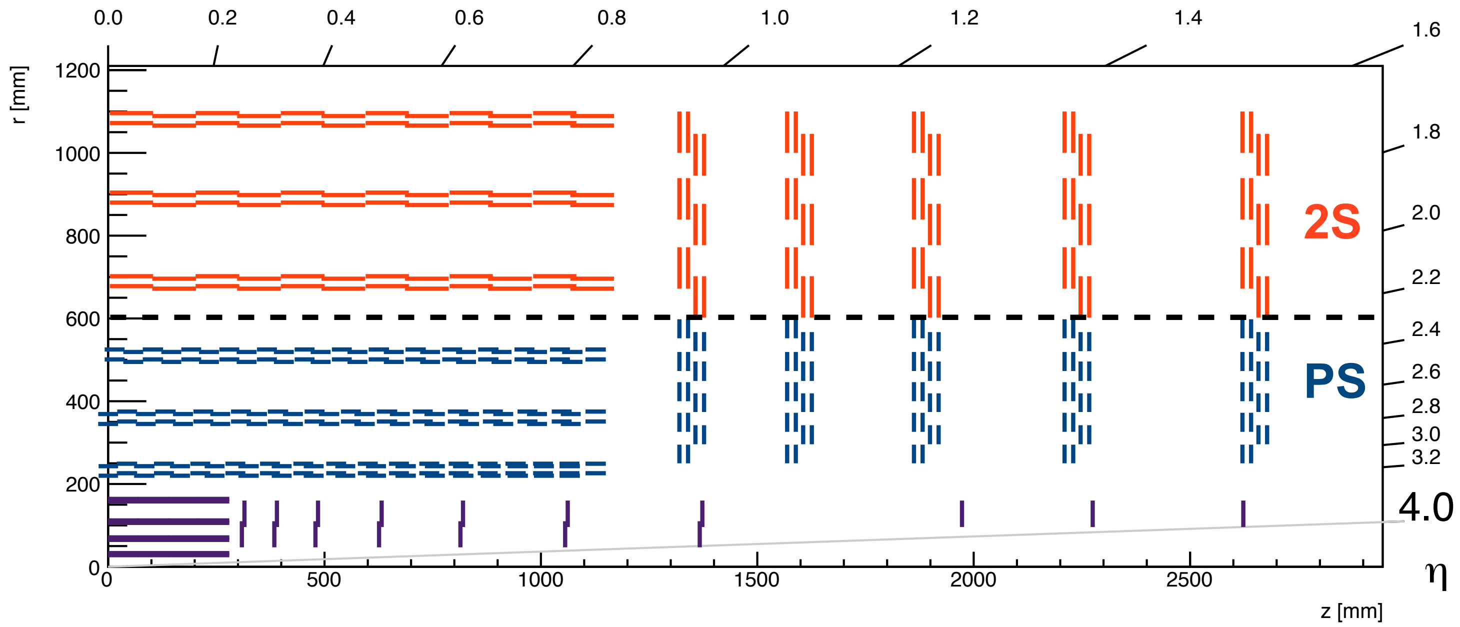
> radiation hardness

- tracker has to tolerate 3000 fb^{-1}
- use radiation hard sensor material
- sensors have to be cooled to -20 °C

> tracker input to Level-1 trigger

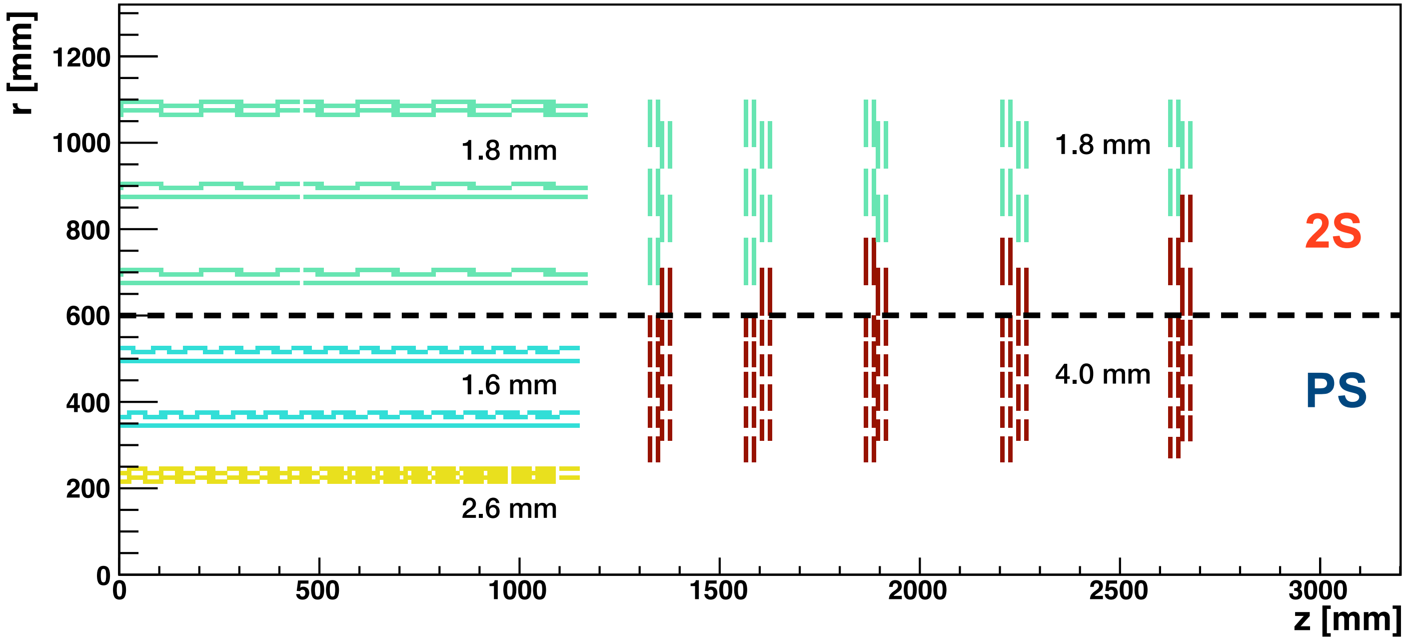
- single μ, e and jet rates would exceed 100 kHz at HL-LHC
- increasing thresholds would reduce physics performance
- need tracker information already in the Level-1 trigger decision

Baseline Layout



- baseline layout with 6 barrel layers and 5 endcap disks
  - pixelated modules at r < 60 cm - stack of pixel and strip sensor (PS)
  - stack of two strip sensors at r > 60 cm (2S)

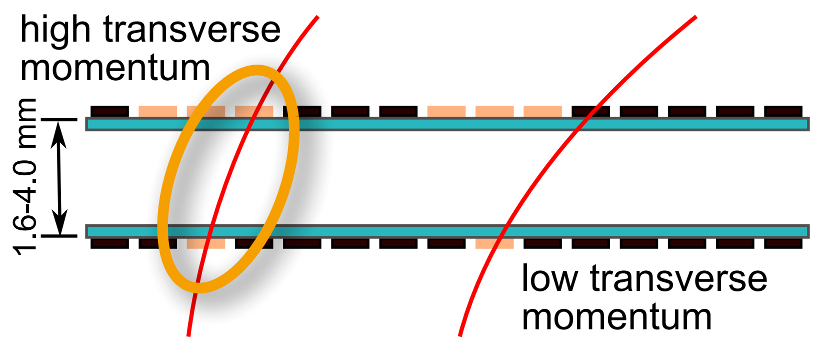
Baseline Layout - Module Configuration



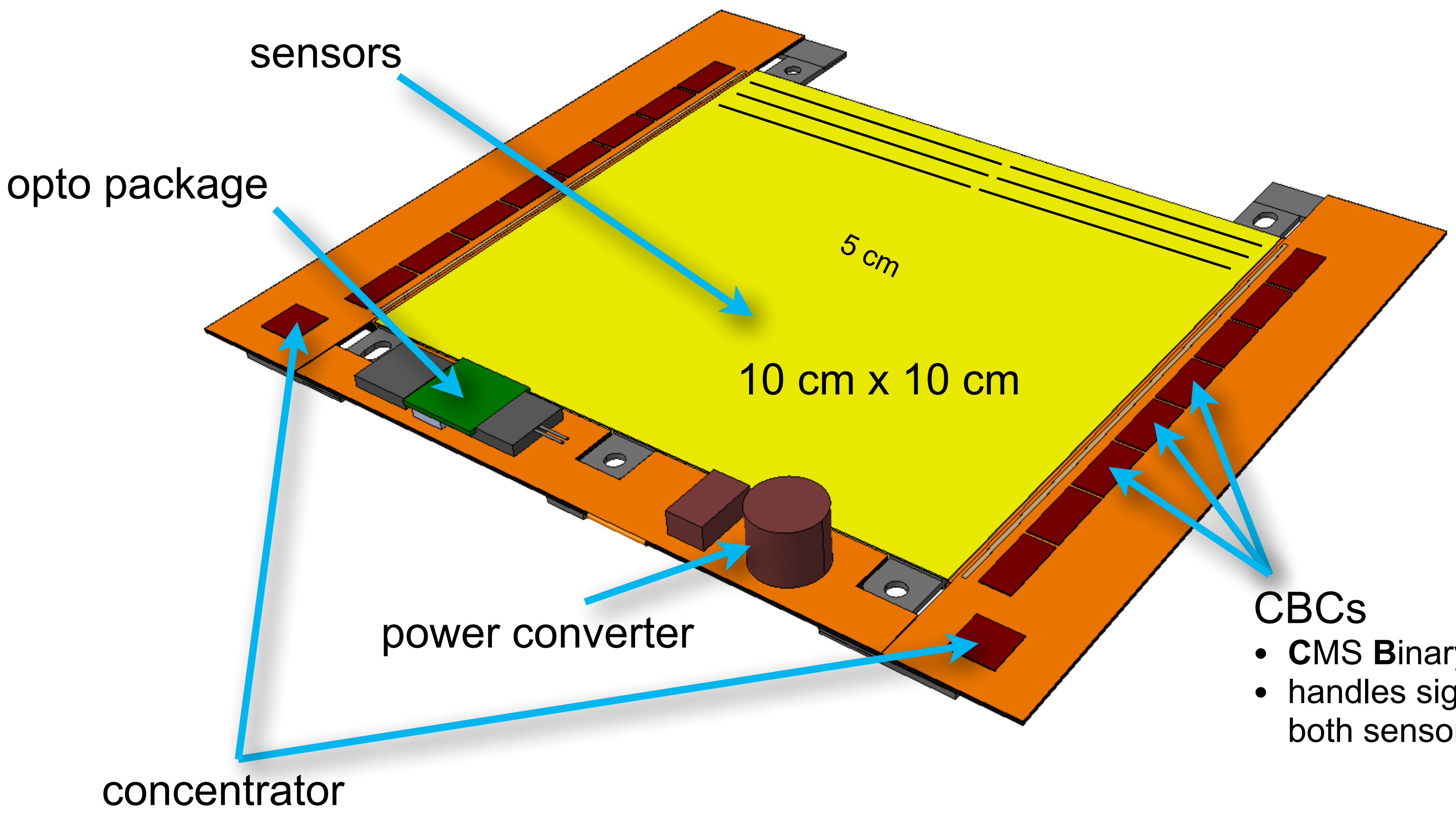
- baseline layout with 6 barrel layers and 5 endcap disks
  - pixelated modules at r < 60 cm - stack of pixel and strip sensor (PS)
  - stack of two strip sensors at r > 60 cm (2S)
- PS modules
  - sensor spacings: 1.6 mm, 2.6 mm and 4 mm
- 2S modules
  - sensor spacings: 1.8 mm and 4 mm

Module Concept

- modules will have on-board pT discrimination
  - signals from two closely spaced sensors are correlated
  - exploit strong magnetic field for local pT measurement
  - local rejection of low-pT tracks to minimize data volume
- detector modules provide Level-1 and readout data at the same time
  - the whole tracker sends trigger data („stubs“) at each bunch crossing (40 MHz)
  - readout data at 100 kHz
- „stubs“ are used to form Level-1 tracks
- cooling via evaporative CO_2
- low power giga-bit transceiver (LP-GBT) as data link
  - integrated at module level
- powering via DC-DC conversion
  - integrated at module level
- two different module types
  - different sensor spacings are treated as ‚variants‘ of one module type with only minimum changes
  - requires optimization of only two design

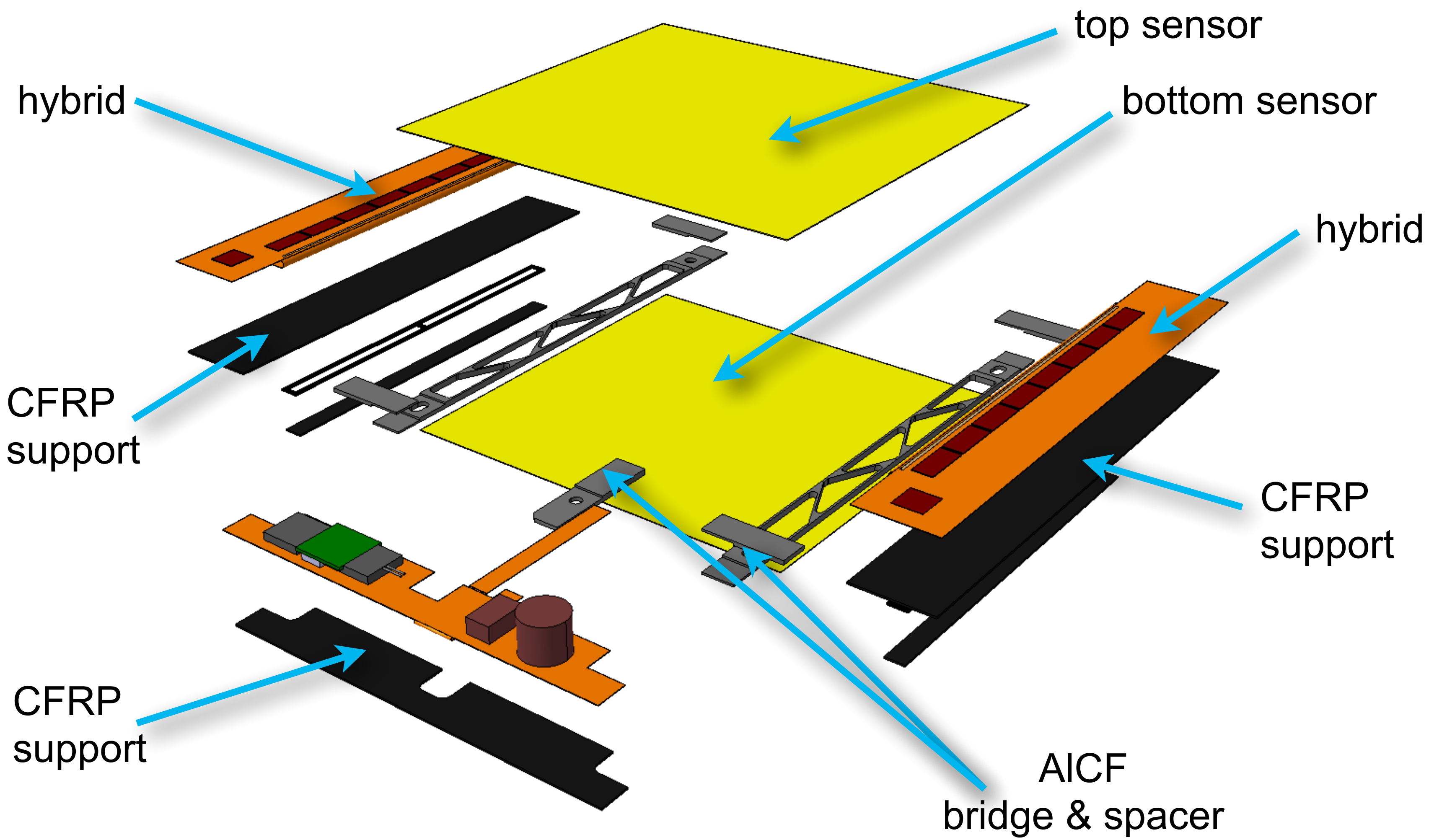


2S Module

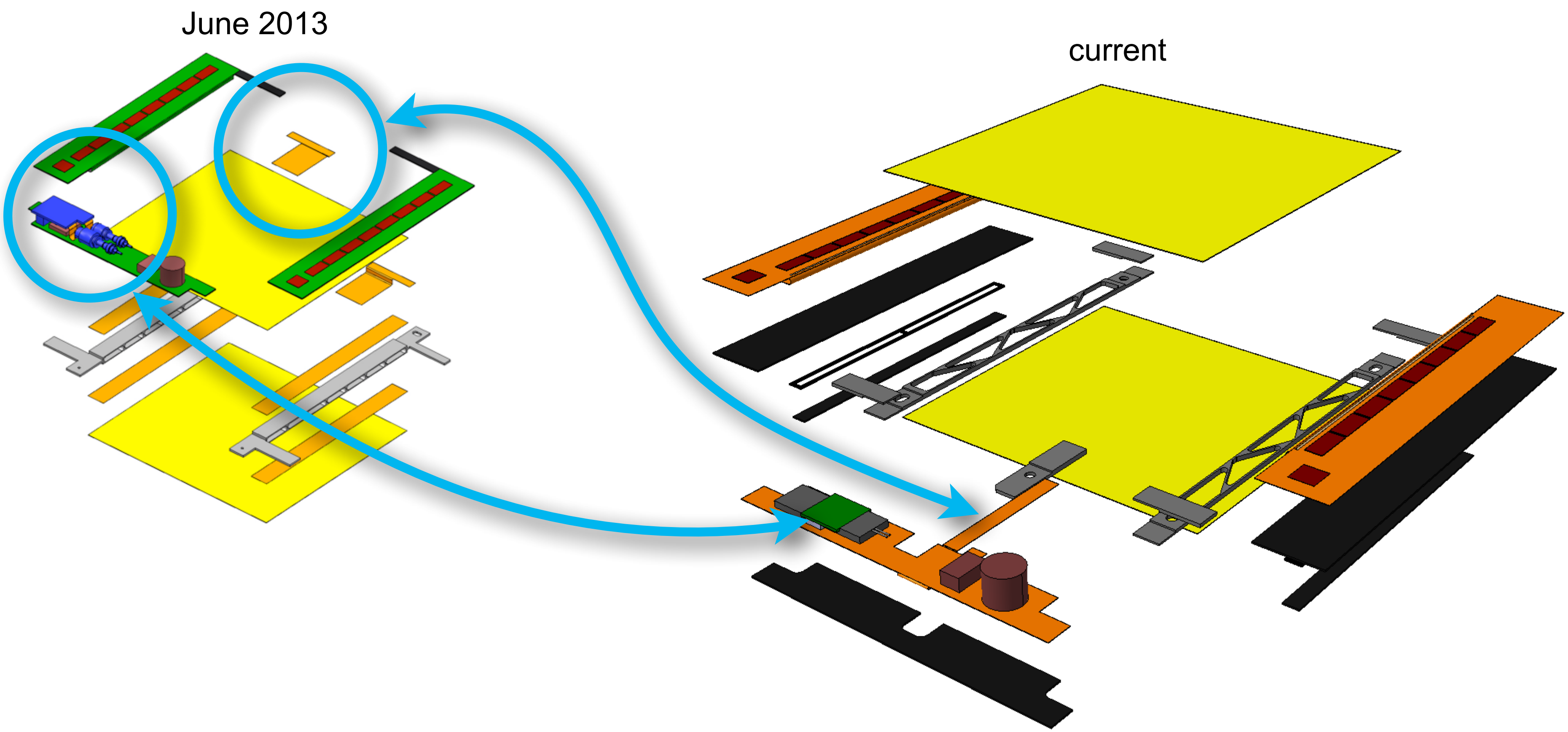


- **C**MS **B**inary **C**hip
- handles signals from both sensor

2S Module - Exploded View



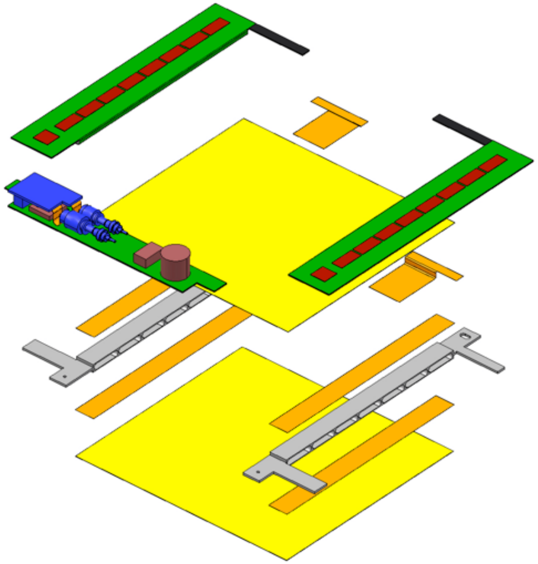
2S Module - Evolution of the Design



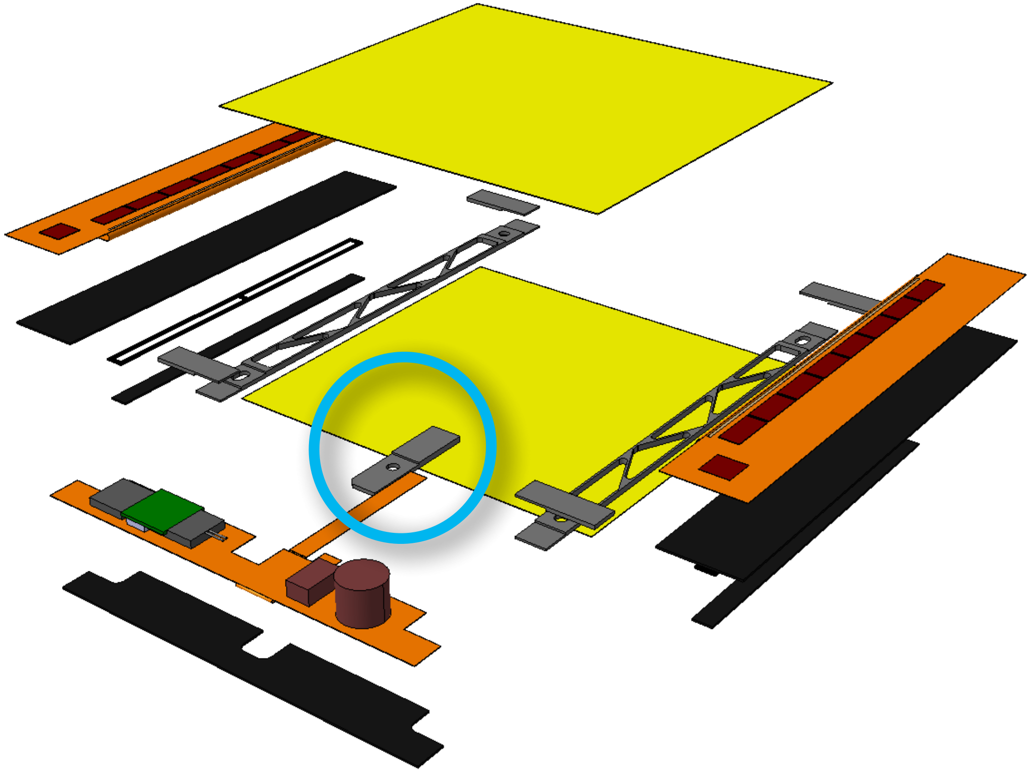
- sensor bias voltage supply was moved to service board side of module
- a smaller opto package was integrated

2S Module - Evolution of the Design

June 2013

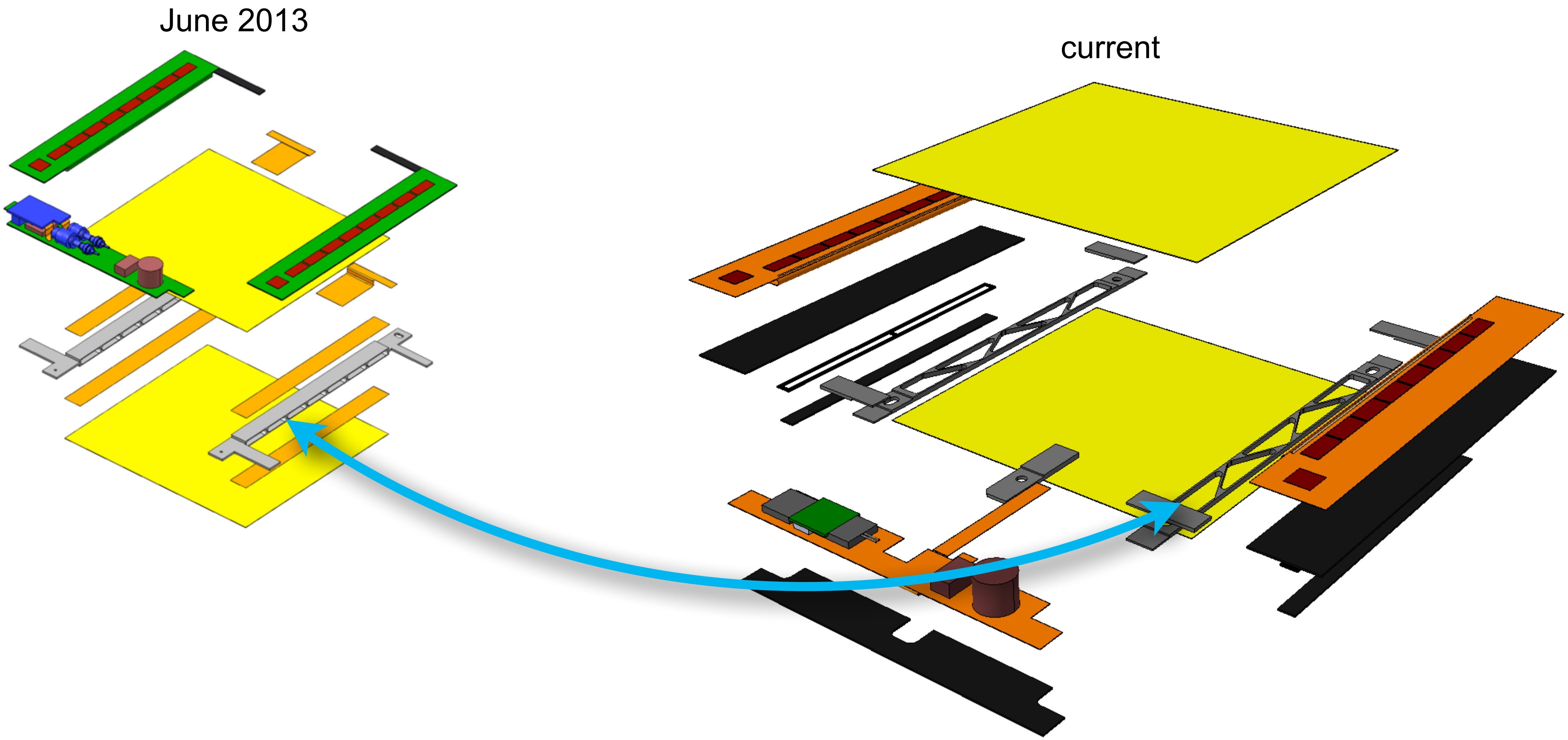


current



- a fifth cooling contact was introduced
  - heat load from power converter and opto package makes temperature distribution on sensors asymmetric

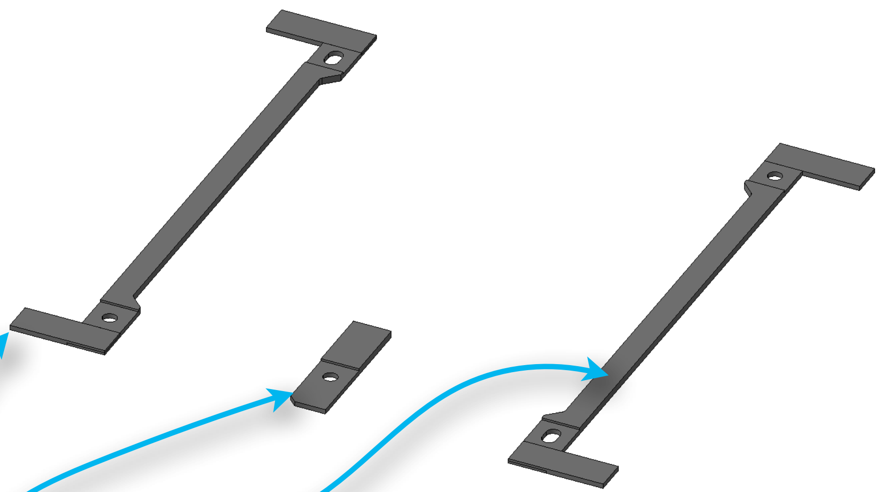
2S Module - Evolution of the Design



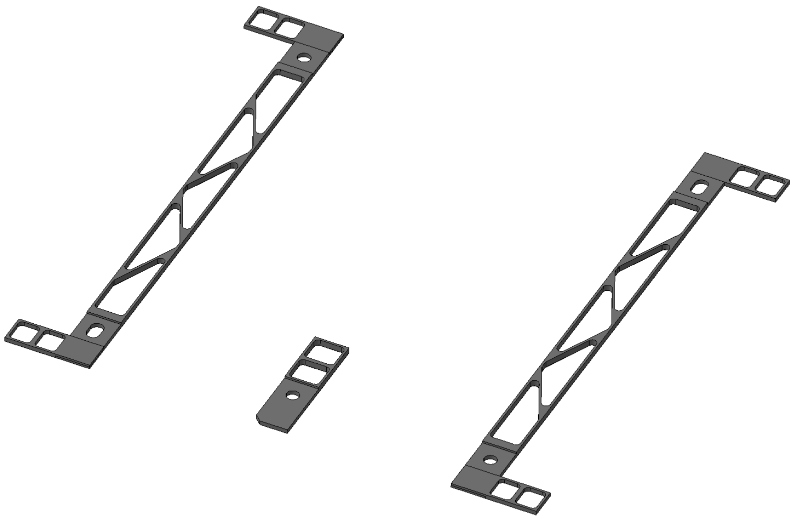
> AlCF bridges and supports were / are being optimized for mass

2S Module - Optimization of 1.8 mm Variant

original design



optimized design



	Weight [g]	Number/Module	Total Weight [g]
Bridge	2.11	2	4.22
Stump	0.69	1	0.69
Readout	0.27	4	1.08
		Total	**5.99**

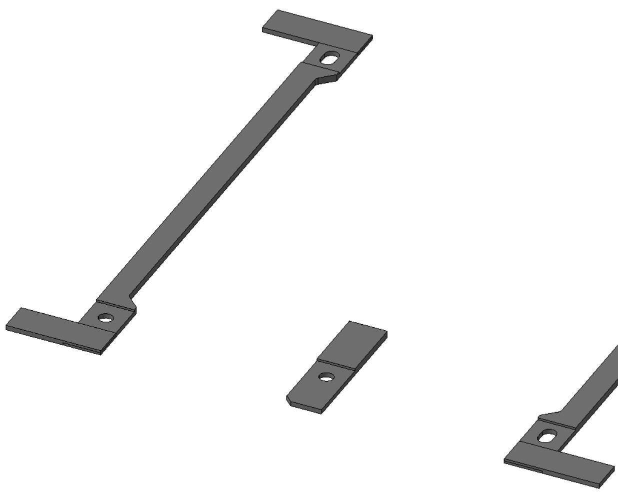
	Weight [g]	Number/Module	Total Weight [g]
Bridge	1.04	2	2.08
Stump	0.38	1	0.38
Readout	0.13	4	0.52
		Total	**2.98**

total mass of module: ~30 g

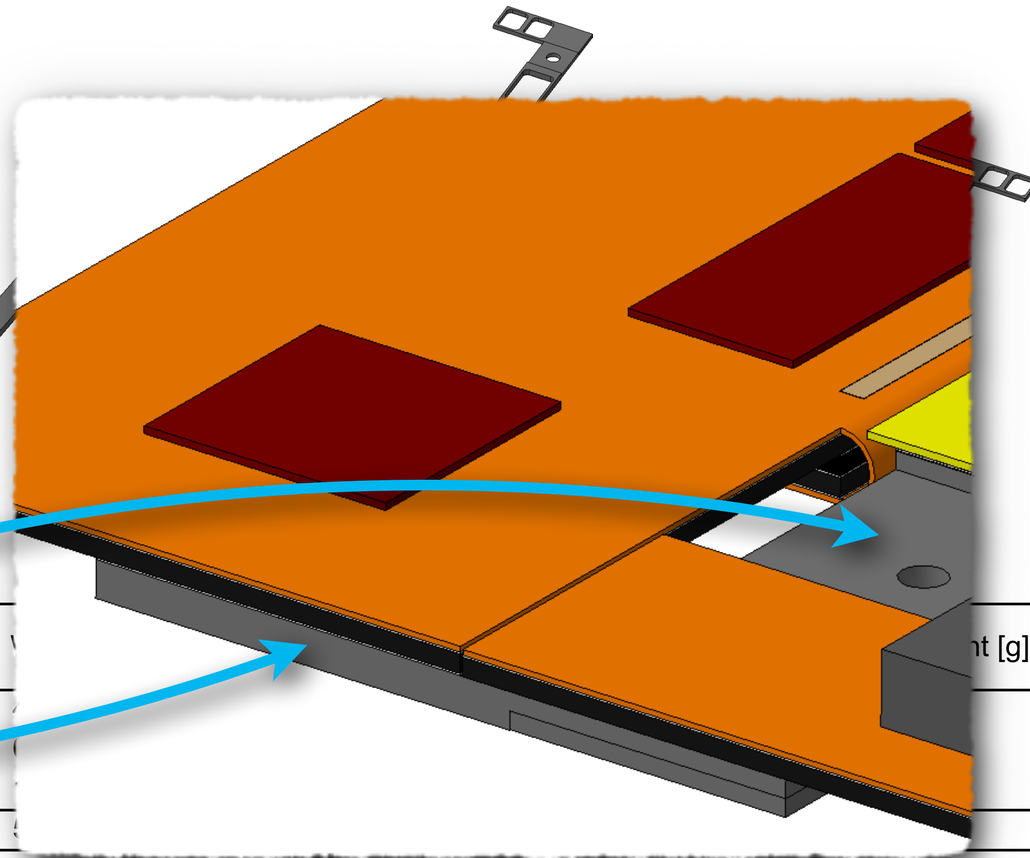
- optimized for low mass, mechanical and thermal performance
- thermal FEA results will be shown on later slides

2S Module - Optimization of 1.8 mm Variant

original design



optimized design



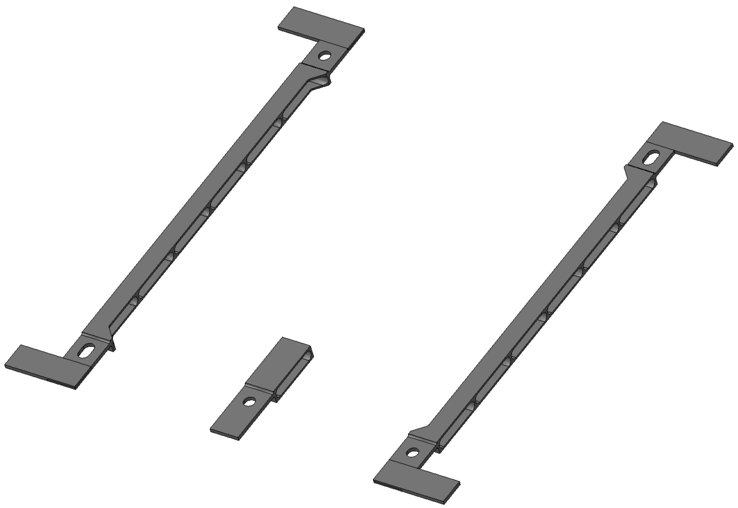
	Weight [g]	Number/Module	Total \	...nt [g]
Bridge	2.11	2	[illegible]	[illegible]
Stump	0.69	1	[illegible]	[illegible]
Readout	0.27	4	[illegible]	[illegible]
		Total	[illegible]	[illegible]

total mass of module: ~30 g

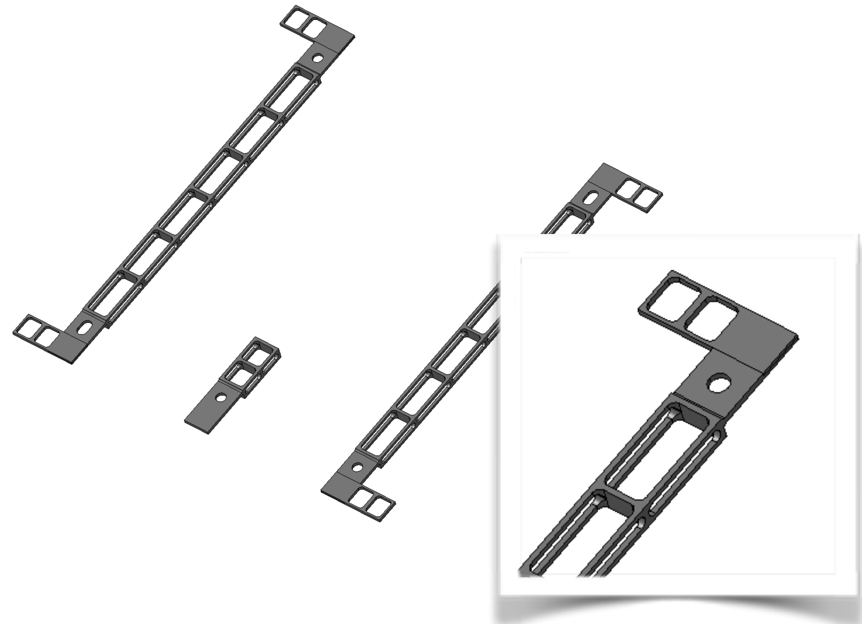
- optimized for low mass, mechanical and thermal performance
- thermal FEA results will be shown on later slides

2S Module - Optimization of 4.0 mm Variant

original design



optimized design



	Weight [g]	Number/Module	Total Weight [g]
Bridge	1.84	2	3.68
Stump	0.67	1	0.67
Readout	0.27	4	1.08
		Total	**5.43**

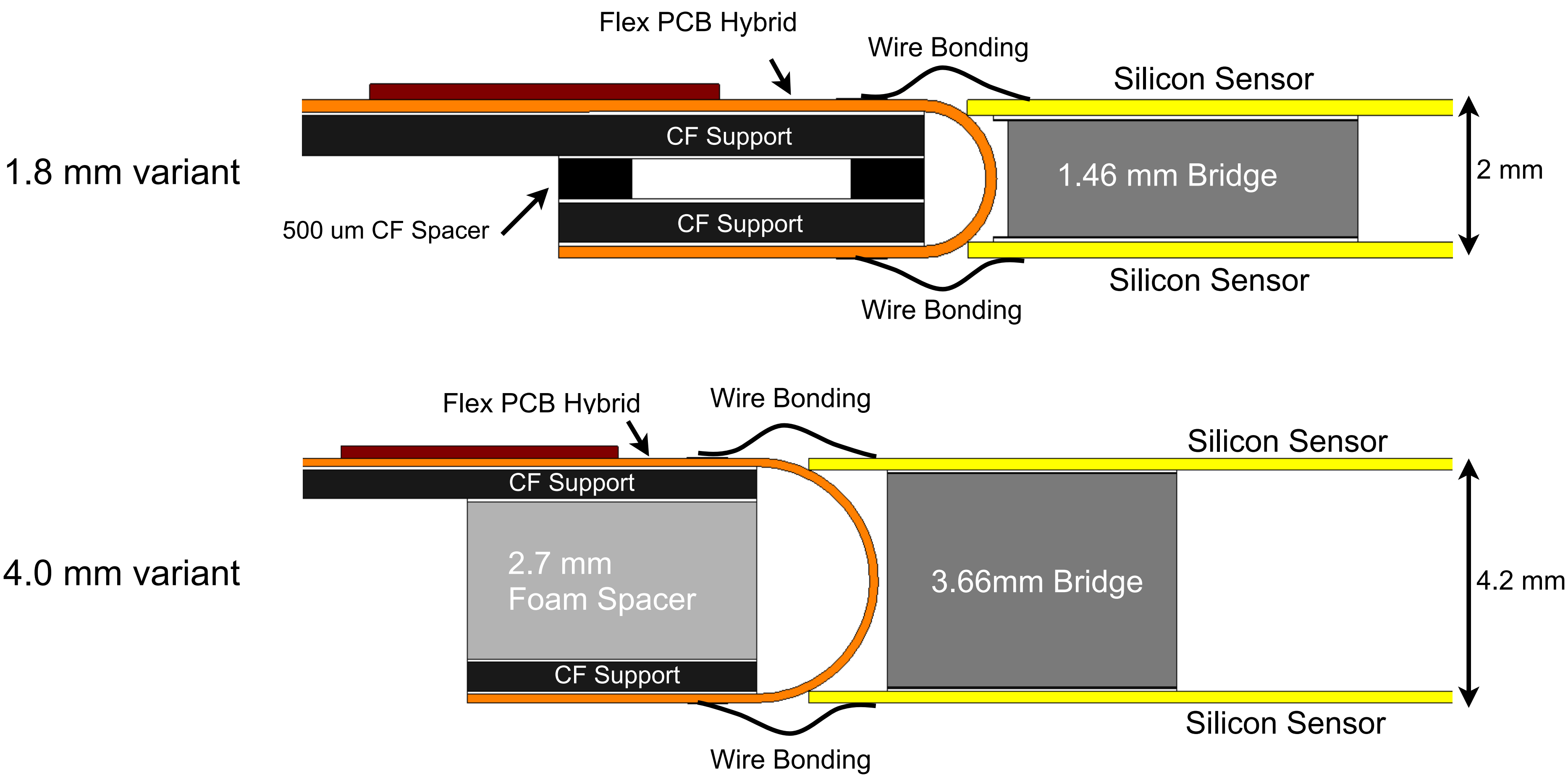
	Weight [g]	Number/Module	Total Weight [g]
Bridge	1.40	2	2.81
Stump	0.55	1	0.55
Readout	0.13	4	0.52
		Total	**3.88**

total mass of module: ~30 g

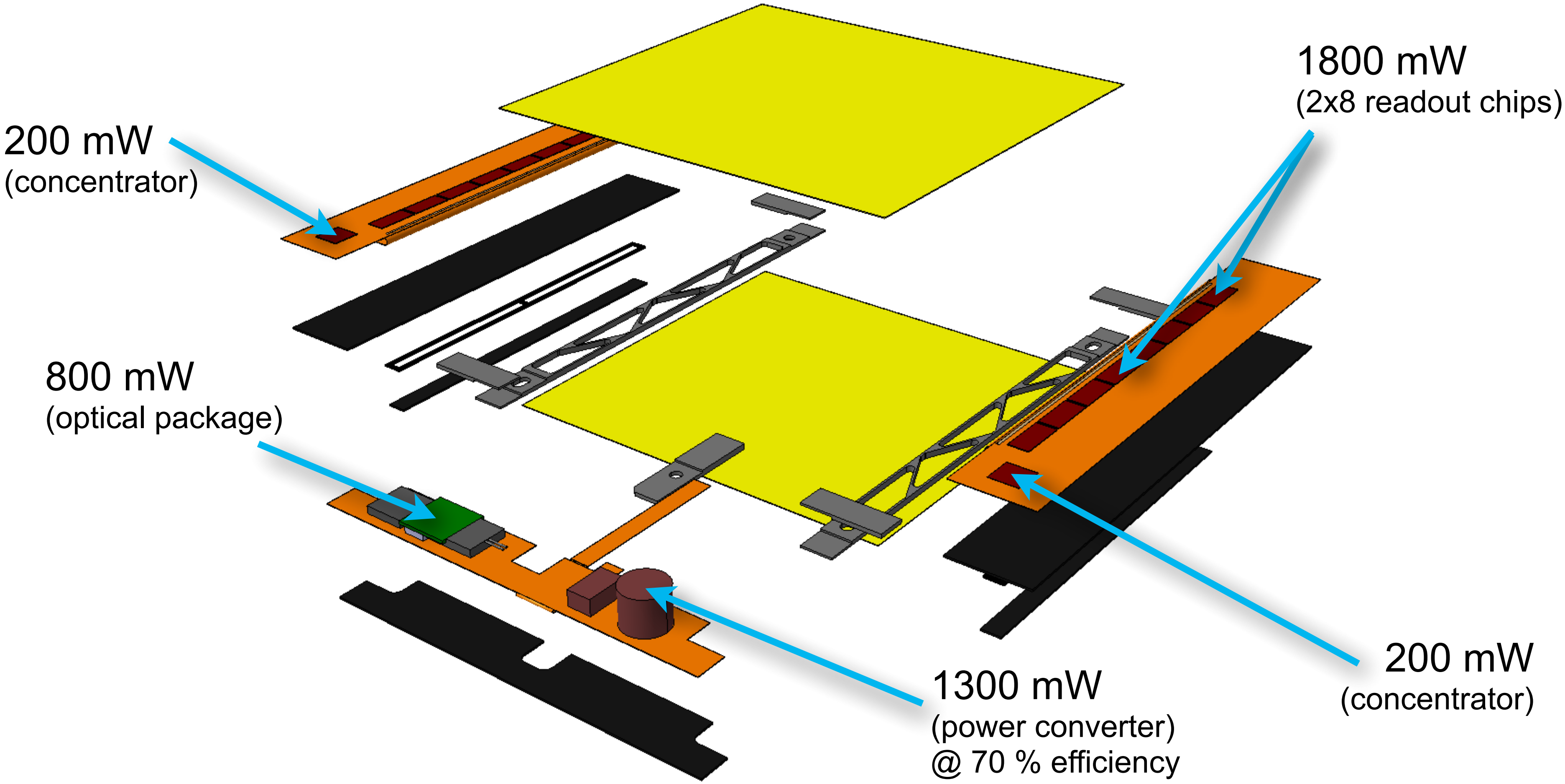
- optimized for low mass, mechanical and thermal performance
- thermal FEA results will be shown on later slides

2S Module - Evolution of the Design

- flexible hybrid has become the baseline solution



2S Module - Power Consumption Estimates



- total power of 1.8 mm module: 4.3 W (FE) + 2 · 0.4 W = 5.3 W
- total power of 4.0 mm module: 4.3 W (FE) + 2 · 0.6 W = 5.5 W

@ -20°C

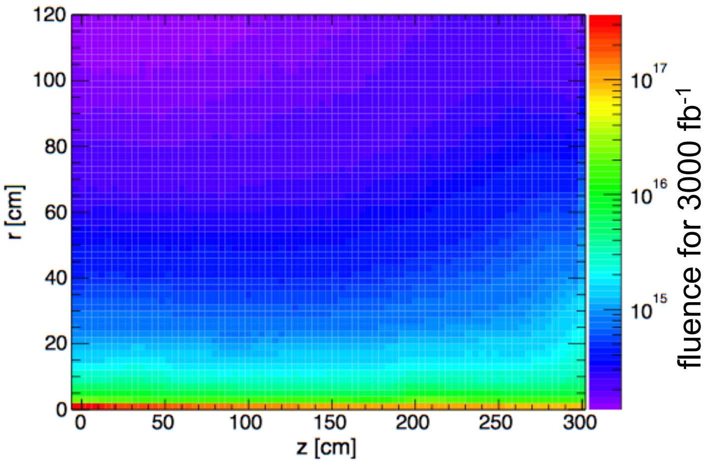
Intermezzo - Sensor Power Consumption

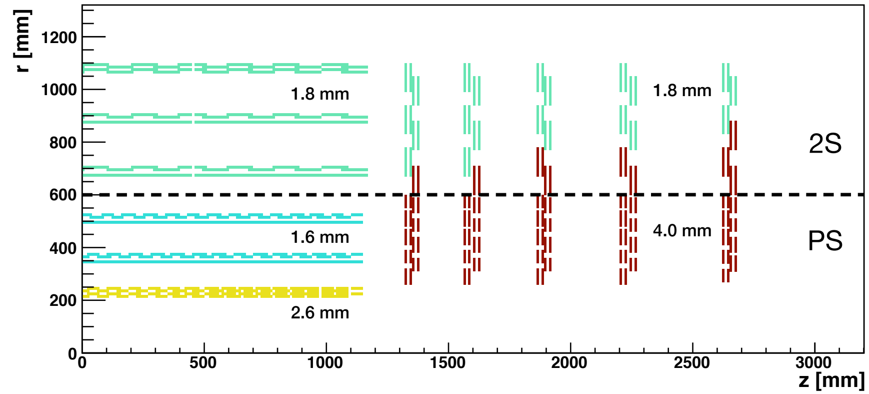
- power consumption is a function of temperature
- in an FEA one can treat the sensor like a resistor
  - temperature dependence of power consumption is modeled via temp. dependence of resistivity
  - one ‚silicon' material definition per
    - running scenario (damage constant α)
    - fluence
    - sensor thickness

- assumptions for damage constant α
  - 12 years of running at 250 fb^{-1}/year for integrated lumi of 3000 fb^{-1}
  - no annealing during operation (< -10 °C)
  - annealing during year end technical stops at room temperature
- $\alpha = 3.44 \cdot 10^{-17}$ A/cm
- plus 15 % safety

Intermezzo - Sensor Power Consumption

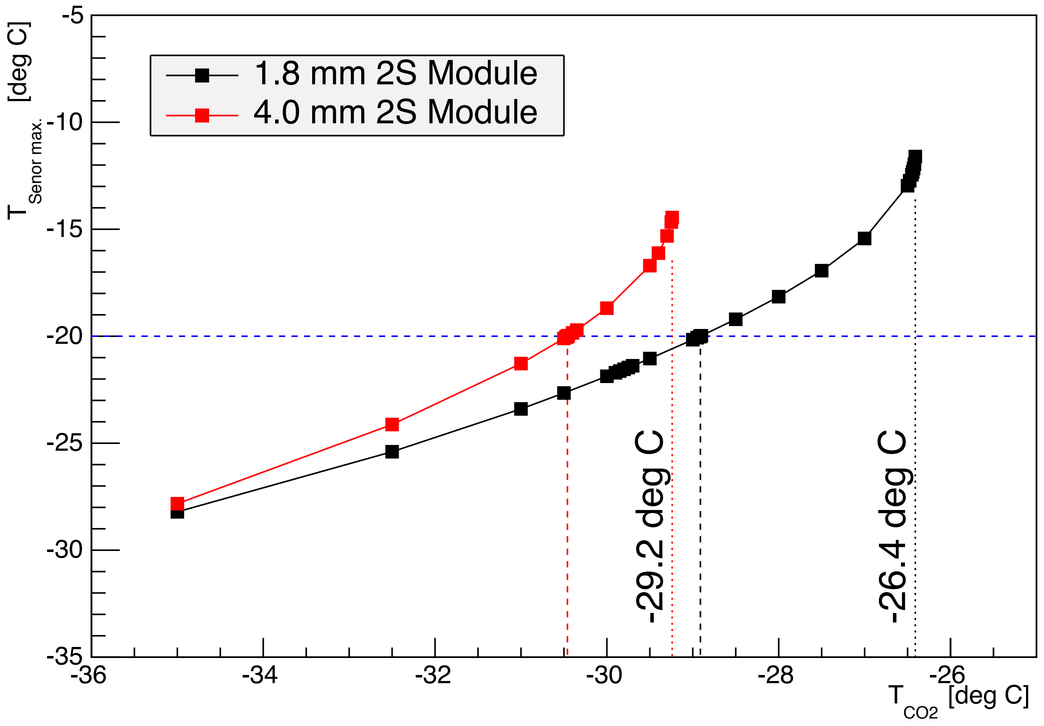
- power consumption is a function of temperature
- in an FEA one can treat the sensor like a resistor
  - temperature dependence of power consumption is modeled via temp. dependence of resistivity
  - one ‚silicon' material definition per
    - running scenario (damage constant α)
    - fluence
    - sensor thickness

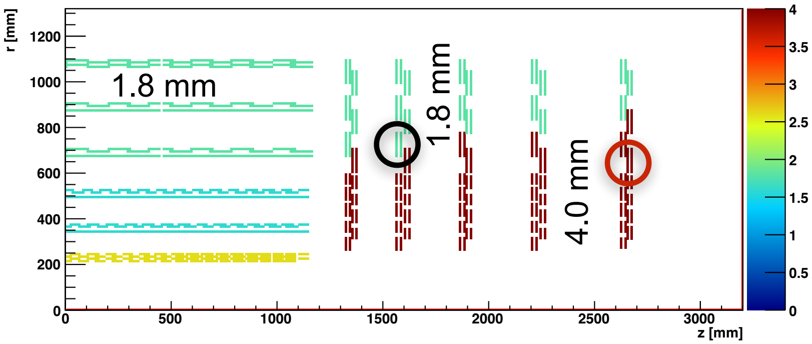




- use maximum nominal fluence for a given module type to estimate sensor power dissipation
  - 1.6 mm PS module: $5.96 \cdot 10^{14}$ neq/cm^2
  - 2.6 mm PS module: $1.12 \cdot 10^{15}$ neq/cm^2
  - 4.0 mm PS module: $7.93 \cdot 10^{14}$ neq/cm^2
  - 1.8 mm 2S module endcap: $3.44 \cdot 10^{14}$ neq/cm^2
  - 1.8 mm 2S module barrel: $2.61 \cdot 10^{14}$ neq/cm^2
  - 4.0 mm 2S module: $4.71 \cdot 10^{14}$ neq/cm^2
- plus 50 % safety

2S Module - Thermal Runaway



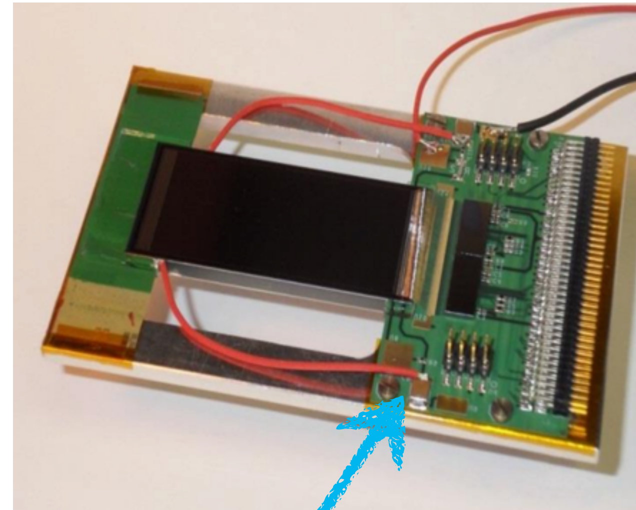


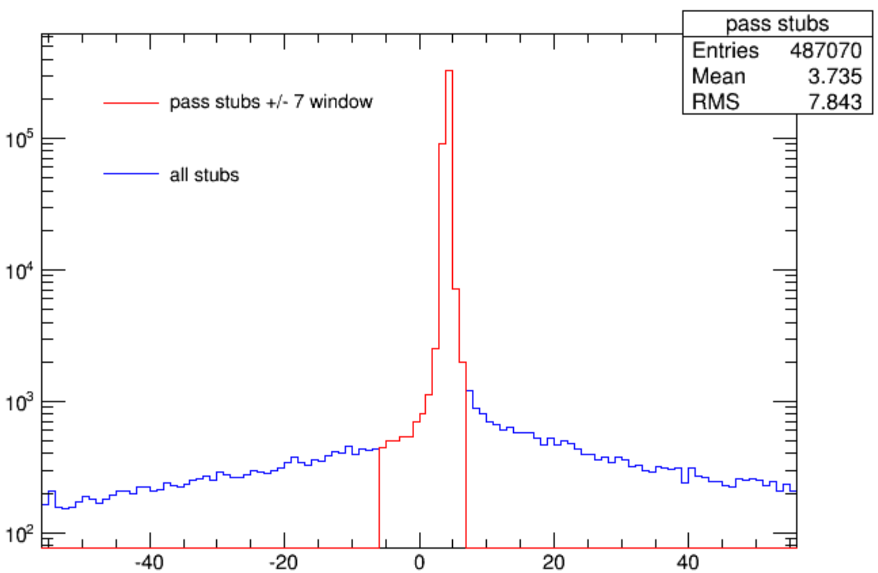
2S module	CO2 temperature @ working point [°C]	thermal runaway [°C]
1.8 mm	-28.9	-26.4
4.0 mm	-30.5	-29.2

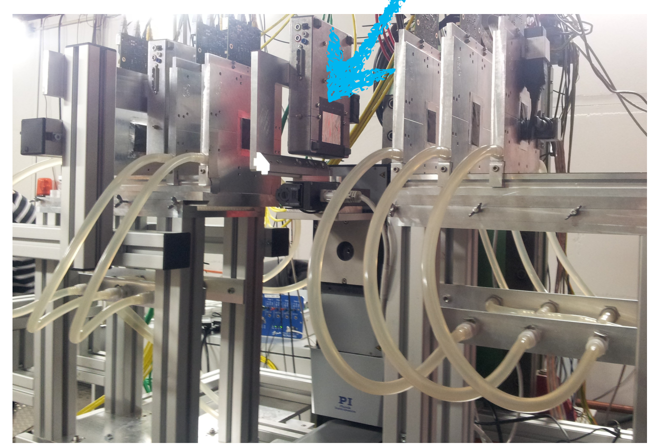
- sensor power consumption is calculated from absolute temperature of sensors
- working point is CO2 temperature for which sensor temperature is below -20°C
- current 4.0 mm design is too close to thermal runaway
  - design aimed at maximum possible reduction of material from mechanical and machinability point of view
  - adding back material (e.g. larger contact surface between sensor and bridge) will make performance similar to that of the 1.8 mm design

Two CBC2 Prototype Module

- equipped with two CBCs
- 25 x 54 mm2 active area
- successful test beam at DESY in November 2013
- modules were integrated into DATURA telescope
- successful commissioning of DAQ
- test of CBC functionality and trigger capability







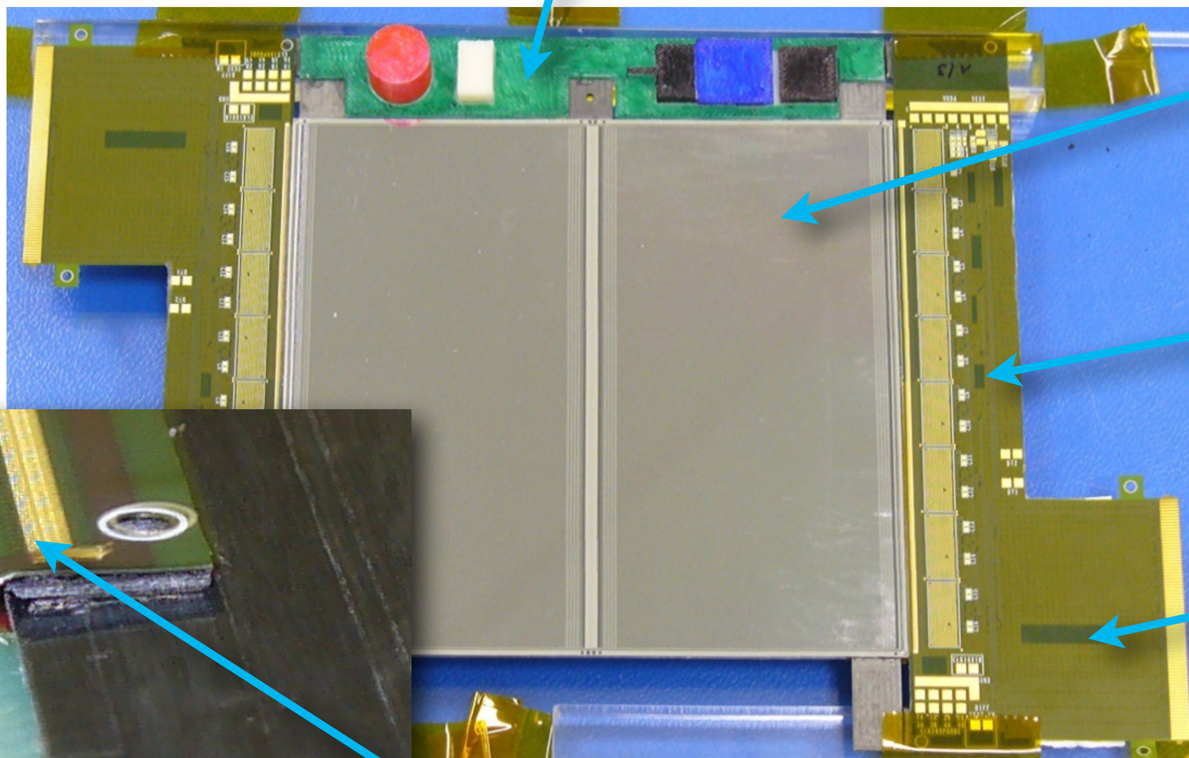
1.8 mm 2S Module Prototype

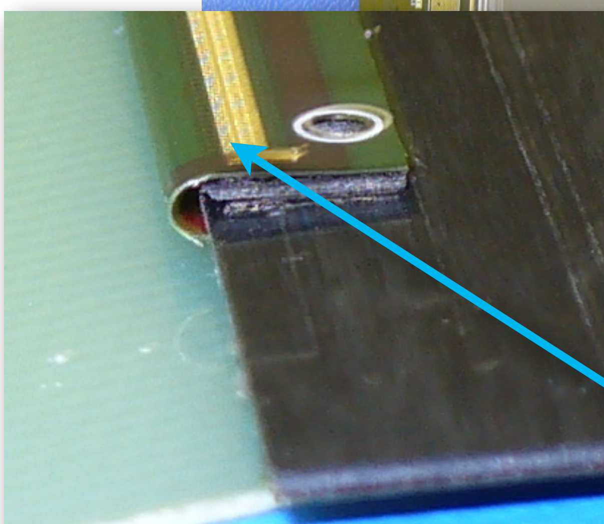
3D Printed Service Board

2S module dummy sensor

eight CBC flex prototype hybrid

flex tail for testing and connectivity





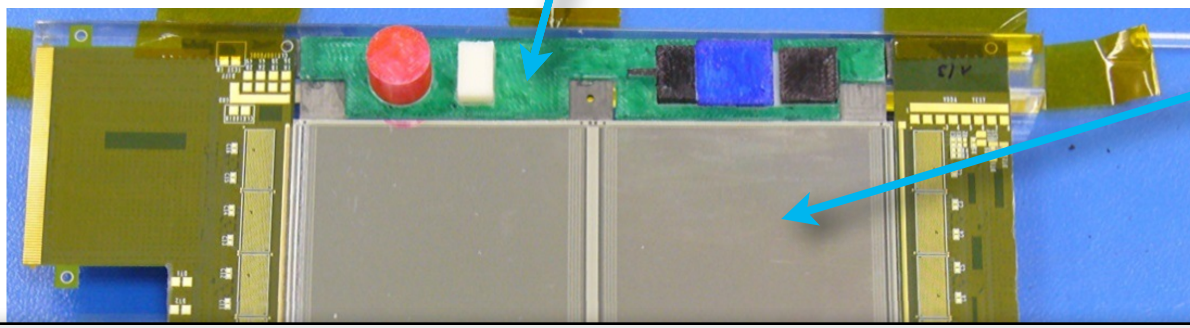
folded flex hybrid

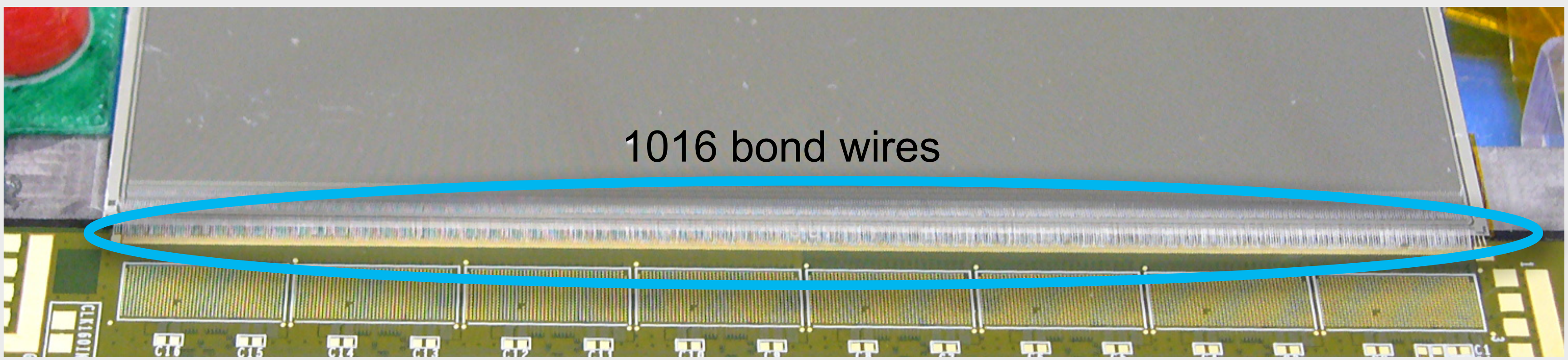
1.8 mm 2S Module Prototype

3D Printed Service Board

2S module dummy sensor

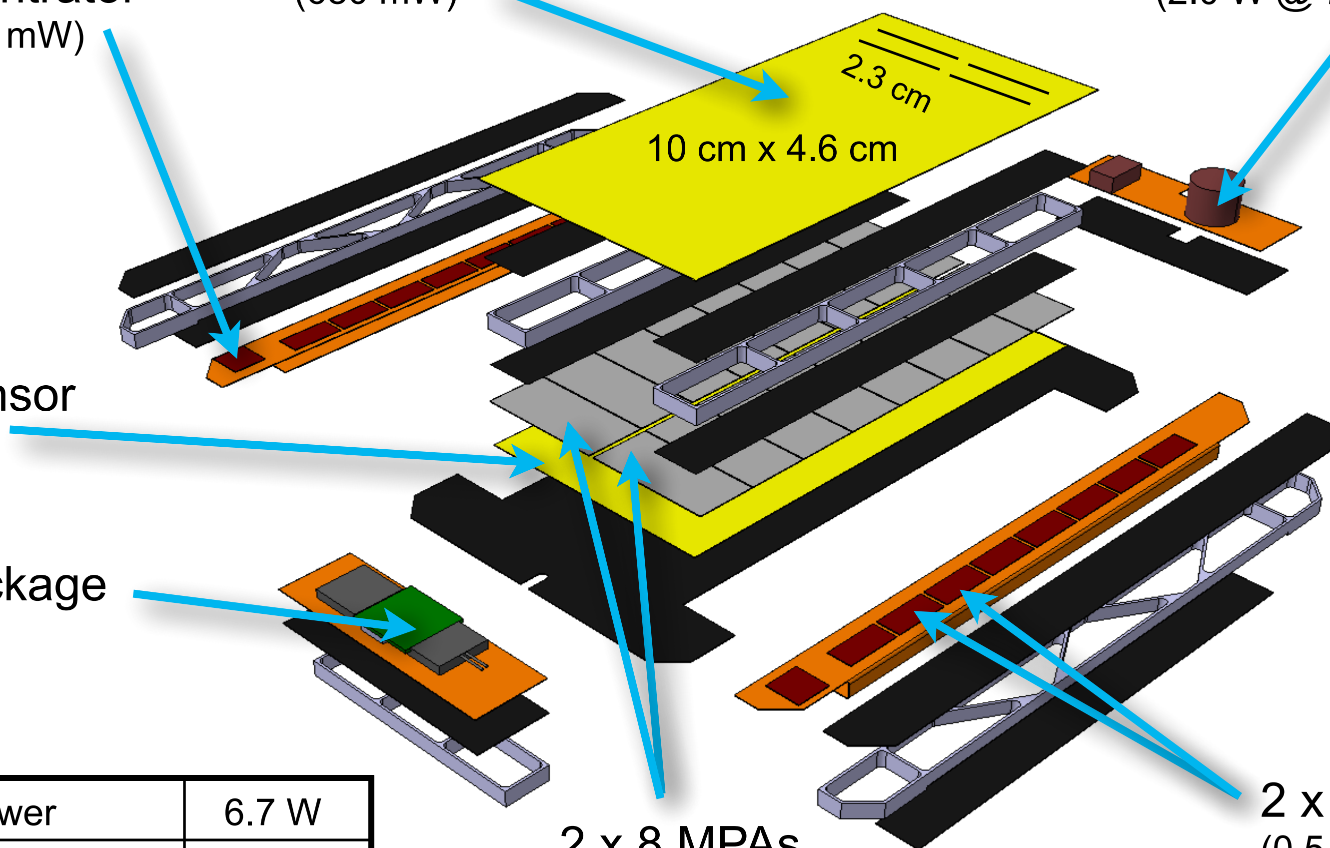
eight CBC flex prototype





wire bonds from sensors to hybrids placed on all four sides (left/right, top/bottom) without significant problems

PS Module

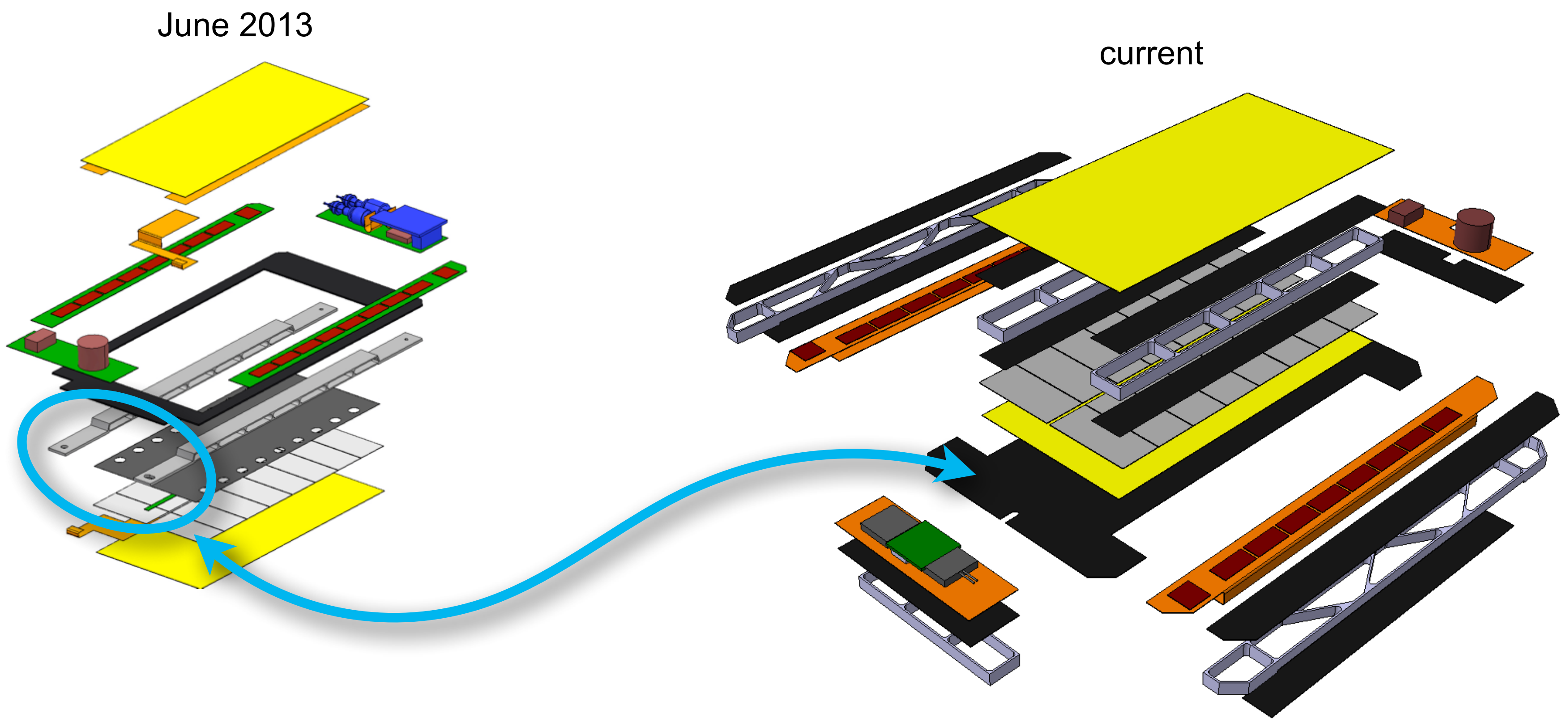


total FE power	6.7 W
1.6 mm module	7.4 W
2.6 mm module	8.1 W
4.0 mm module	7.7 W

2 x 8 MPAs

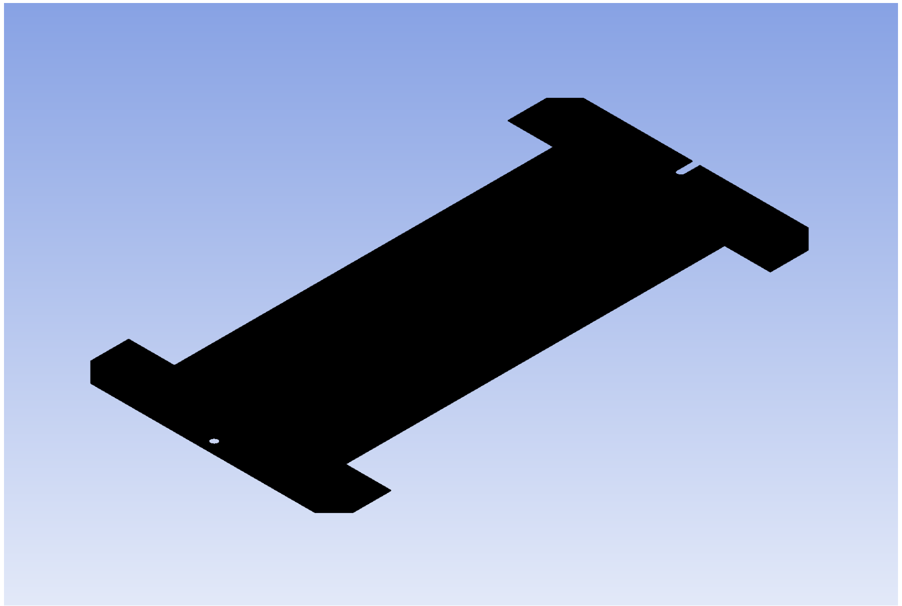
- **M**acro **P**ixel **A**sic
- performs correlation and produces stubs
- 3.0 W

PS Module - Evolution of the Design



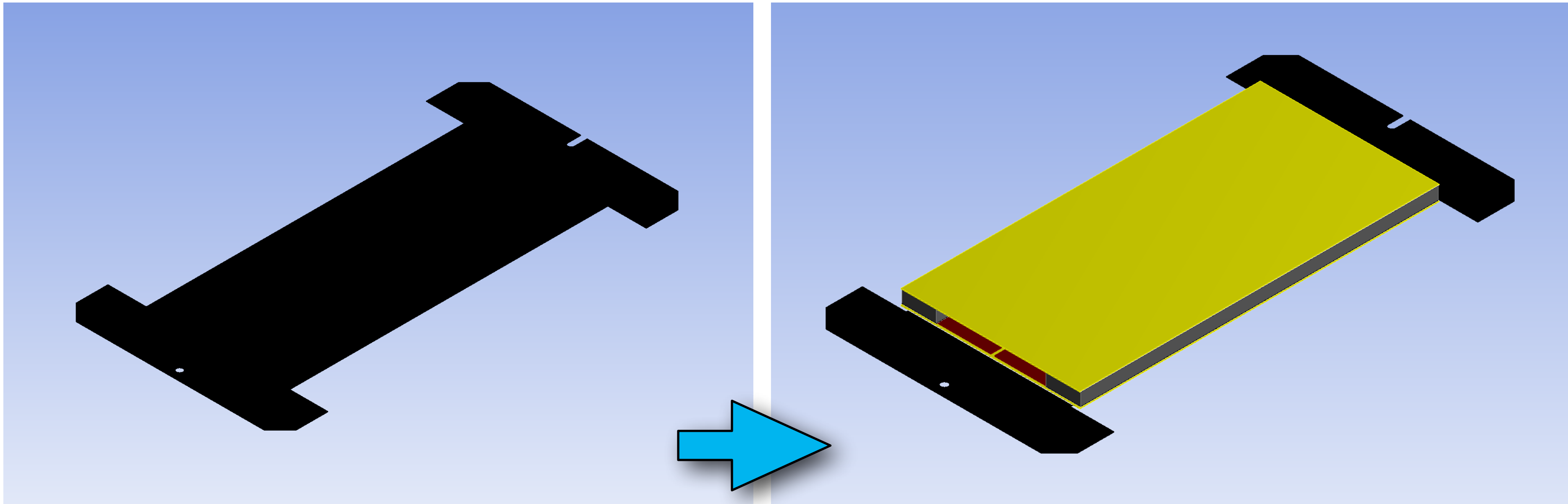
- AlCF bridges with cooling contacts at the end (2S module concept) yielded a too high temperature gradient
- module is now built on top of a CFRP base plate
- base plate has a large area thermal connection to the cooling structure
- AlCF bridges are only used as spacers

Current PS Module Design



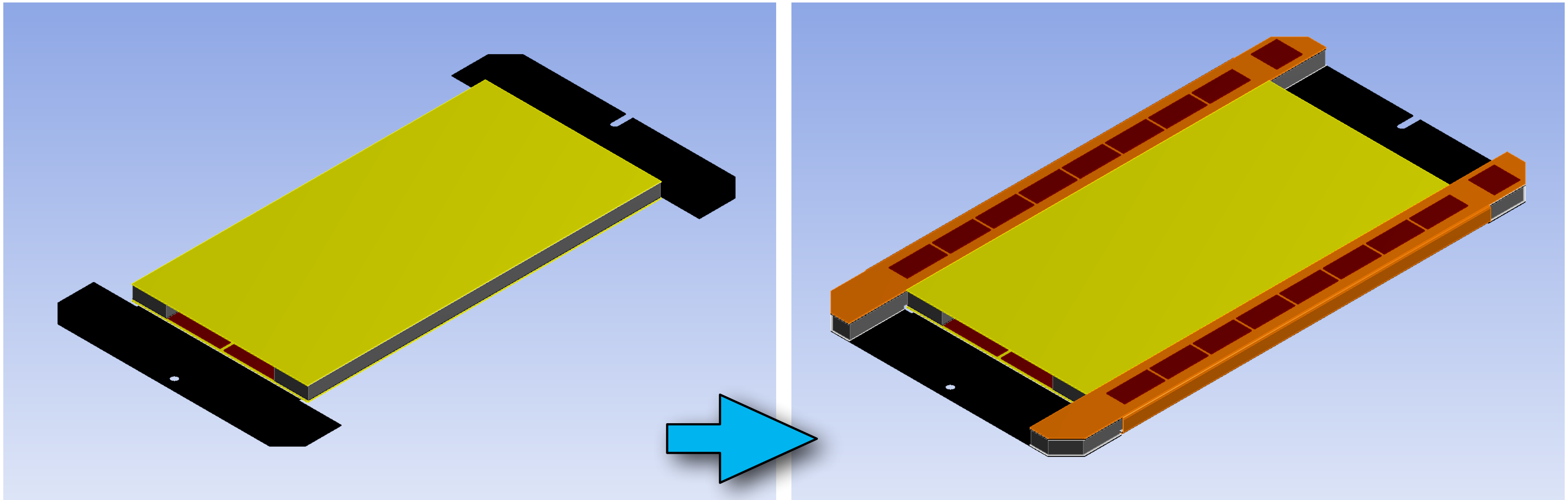
> module is built on top of CFRP base plate

Current PS Module Design



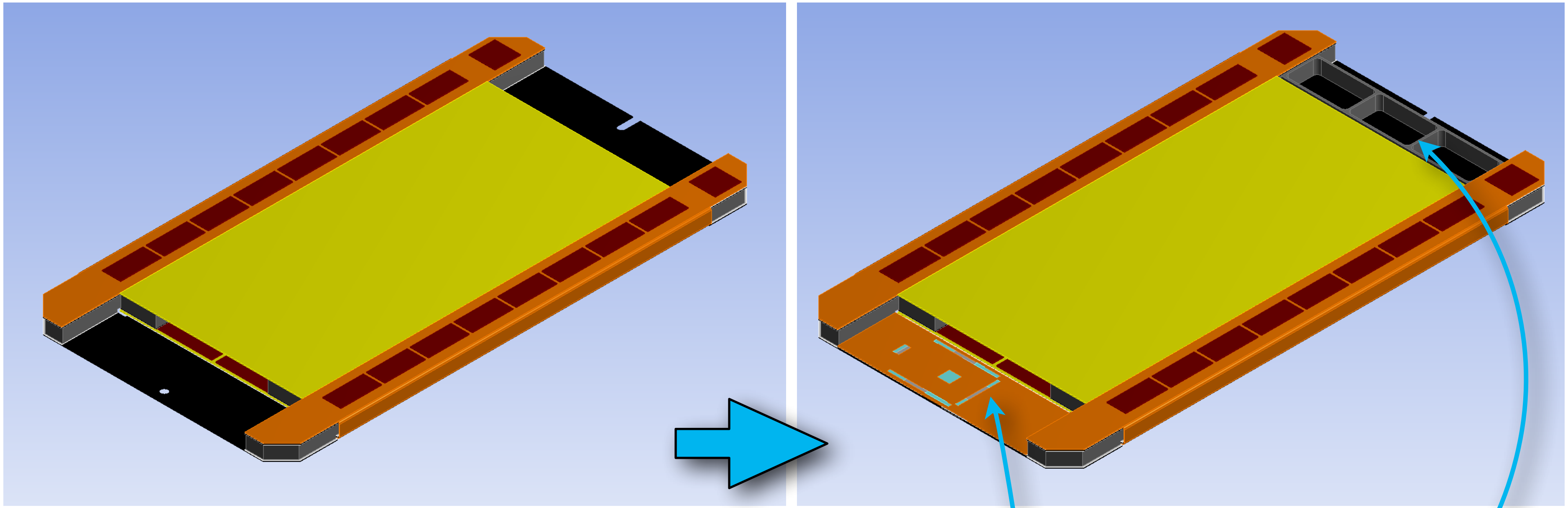
- sensor sub-assembly consists of
  - pixel sensor with pixel chips
  - strip sensor
  - AlCF sensor spacers
- sensor sub-assembly is glued to base plate

Current PS Module Design



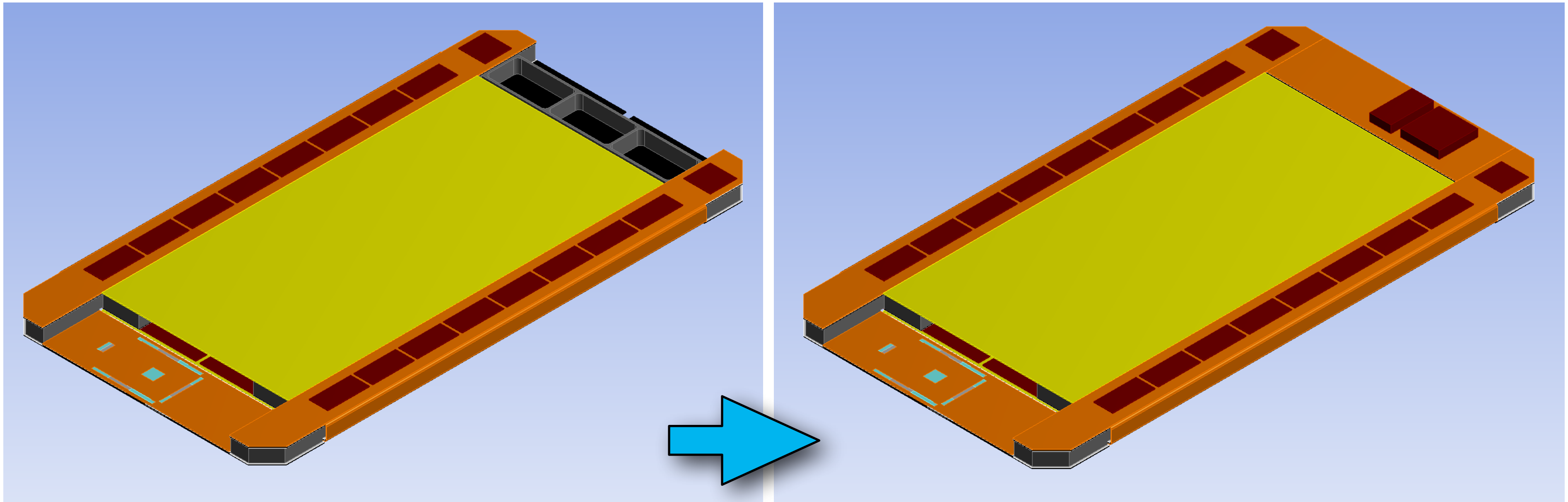
- hybrids are folded around AlCF spacers
- AlCF spacers with hybrids are glued to base plate

Current PS Module Design



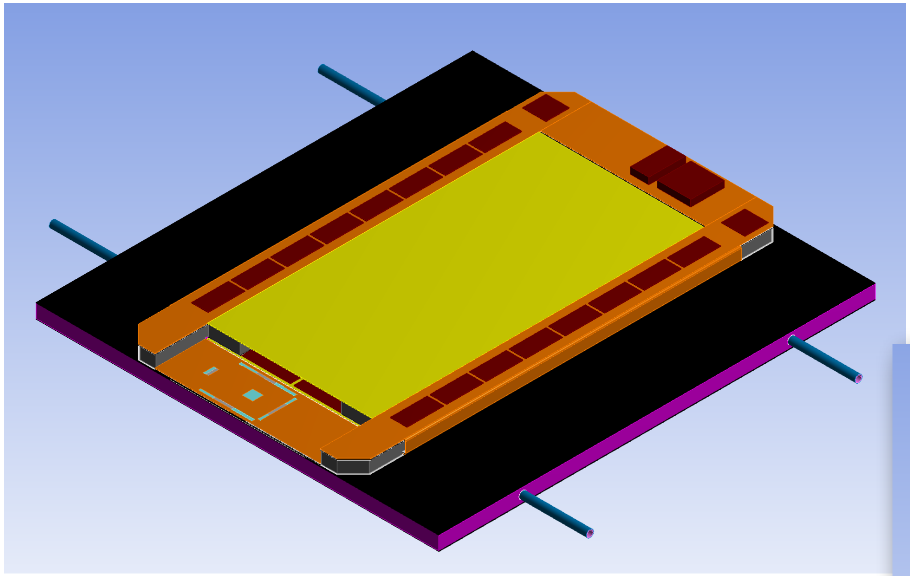
- service board with power converter is glued to base plate
- AlCF spacer for opto hybrid is glued to base plate

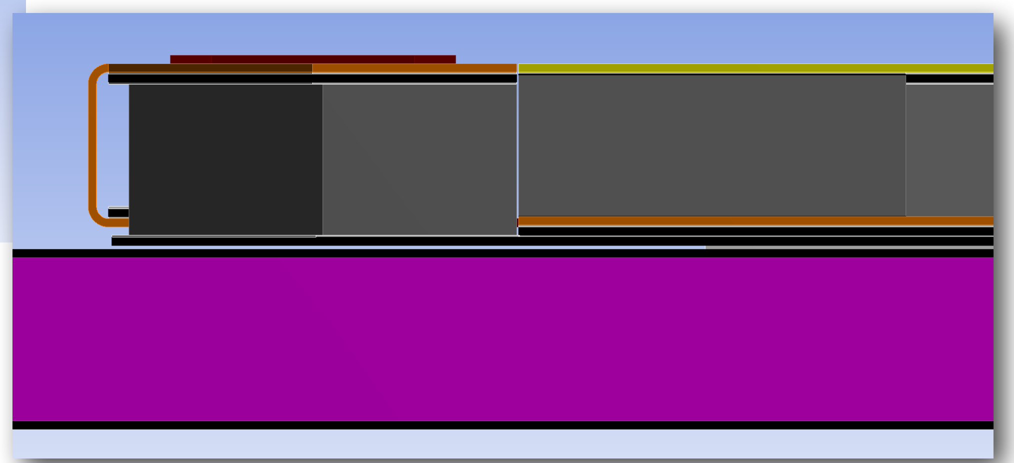
Current PS Module Design



> opto hybrid is glued to AlCF spacer

PS Module on Cooling Structure





- module will be attached to cooling structure by a layer of phase change thermal interface material
- phase change material allows to remove modules from support structure
- work has started on the design and optimization of the cooling / support structures
  - orientation of pipes in barrel and end caps are different (barrel configuration is shown on this slide)

PS Module Masses

1.6 mm

AL-C V2-4	2.70
CFRP	4.41
Glue	2.17
Hybrid	1.76
Parylene	0.10
Sensors	4.54
Chips	2.70
GBT/DCDC	0.75
	19.13

→ + 1.75 g

2.6 mm

AL-C V2-4	4.39
CFRP	4.41
Glue	2.19
Hybrid	1.82
Parylene	0.10
Sensors	4.54
Chips	2.70
GBT/DCDC	0.75
	20.90

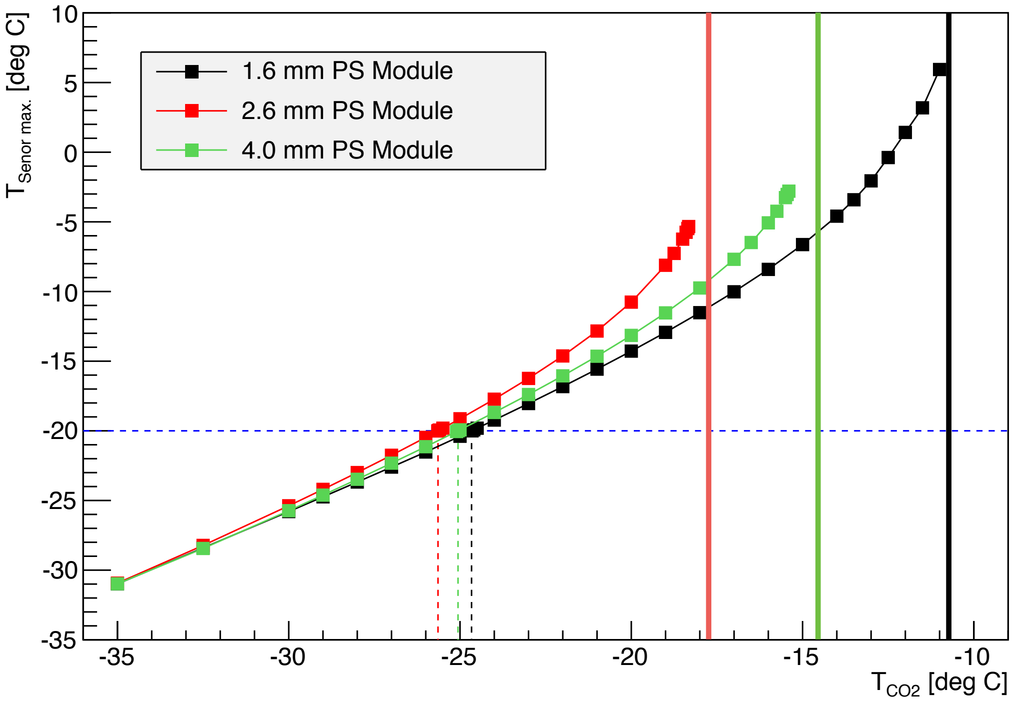
→ + 1.95 g

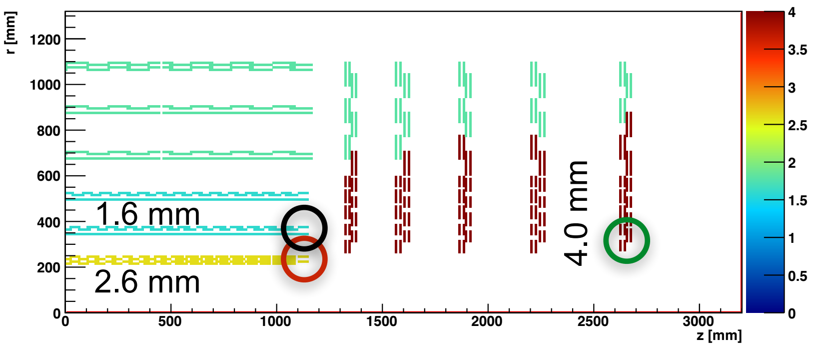
4.0 mm

AL-C V2-4	6.26
CFRP	4.41
Glue	2.18
Hybrid	1.90
Parylene	0.10
Sensors	4.54
Chips	2.70
GBT/DCDC	0.75
	22.84

all masses are in grams

PS Module - Thermal Runaway





PS module	CO2 temperature @ working point [°C]	thermal runaway [°C]
1.6 mm	-24.7	-10.8
2.6 mm	-25.6	-17.5
4.0 mm	-25.1	-14.5

- sensor power consumption is calculated from absolute temperature of sensors
- working point is CO2 temperature for which sensor temperature is below -20°C
- all three variants are robust with respect to thermal runaway
- potential to reduce mass in module and support / cooling structure

PS Module - New Power Consumption Estimates

- power estimates for MPA and SSA are higher than currently assumed
  - MPA: 3 W ➟ 4 W
  - SSA: 0.5 W ➟ 1 W
  - power converter: 2 W ➟ 2.7 W
  - total FE power: 6.7 W ➟ 8.9 W

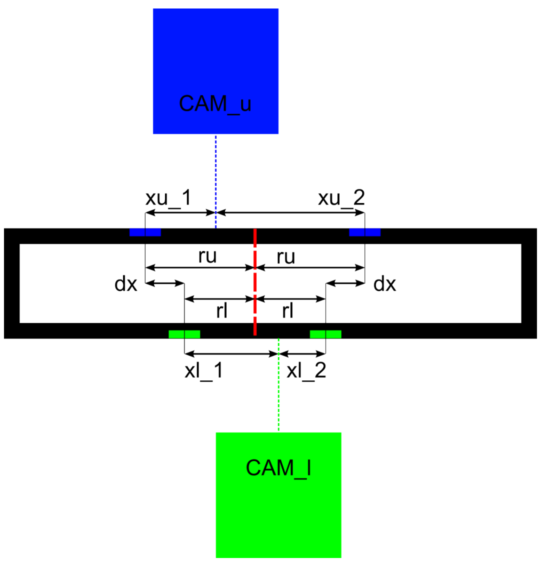
total FE power	6.7 W
1.6 mm module	7.4 W
2.6 mm module	8.1 W
4.0 mm module	7.7 W

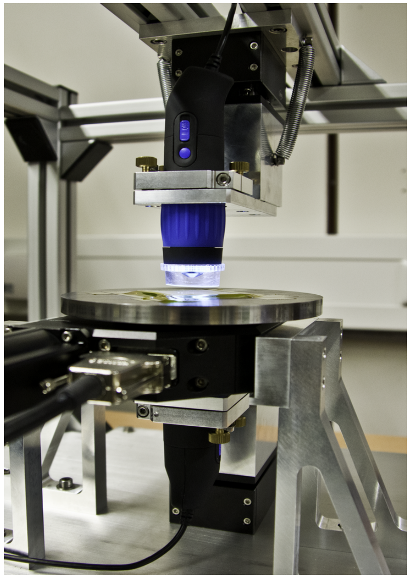
total FE power	8.9 W
1.6 mm module	9.6 W
2.6 mm module	10.3 W
4.0 mm module	9.9 W

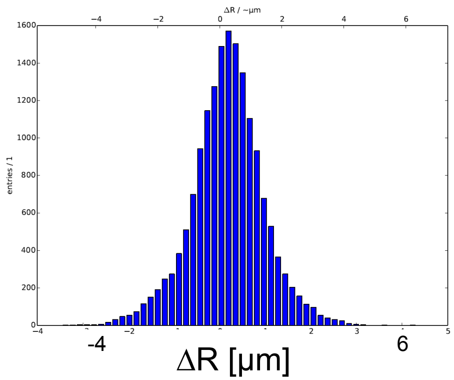
- total temperature gradient increases by 1.3 °C
  - based on preliminary study for 4.0 mm module variant
- this also shifts the thermal runaway curve and reduces the safety margin

Double-Sided Metrology

- misalignment of sensors within a module results in an additional error in the on-module pT-measurement
- cannot be corrected on the module or offline using software alignment
- goal is to limit the displacement to 20 μm (3σ) already during module production
  - resulting error smaller than the intrinsic strip-resolution
- verify the modules after production using a “double-sided metrology” setup
  - look from bottom and top onto markers on each sensor
  - offset between both cameras/pictures directly results in measurement errors (μm precision)
  - generate a reference point (during each measurement) using a rotation axis





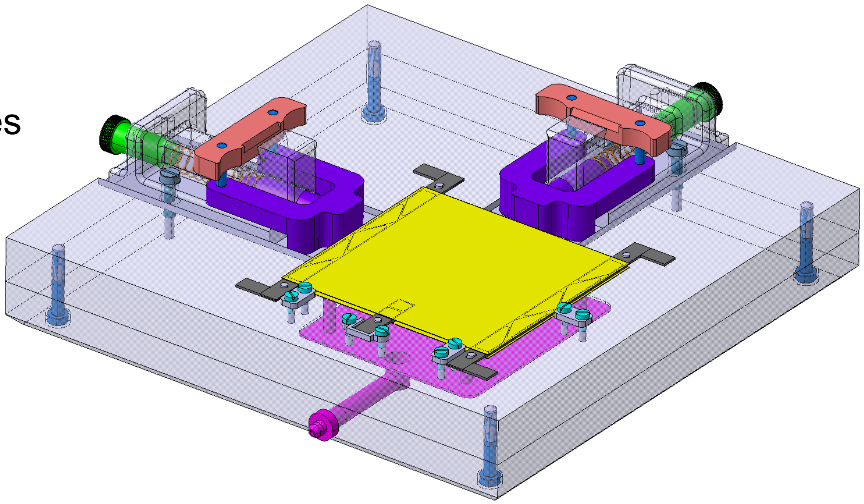


First results suggest a measurement-error of σ = 1.5 μm using off-the-shelf components

Module Assembly

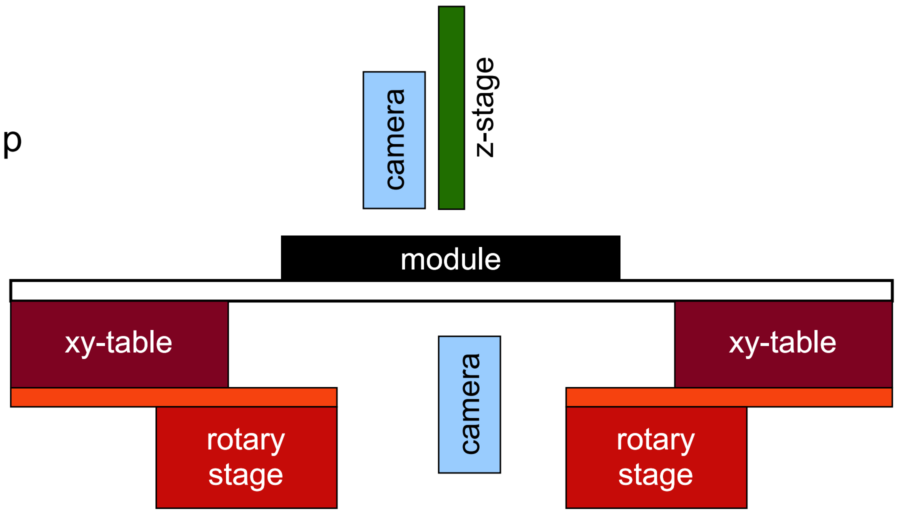
manual assembly

- bottom sensor is placed on jig and pushed against latches
- sensor is held by vacuum
- AlCF bridges are glued to bottom sensor
- top sensor is glued to AlCF bridges and positioned by latches
- requires precision cutting of sensors



semi-automated assembly

- double-sided metrology setup could be extended by a z-stage and used as an assembly setup
- AlCF bridges are fixed on an assembly frame
- first sensor is held by a vacuum jig and placed on setup
- position of sensor is measured
- frame with AlCF bridges is placed over sensor and measured
- frame is lifted by z-stage and first sensor is moved to correct position
- AlCF bridges are glued to first sensor
- procedure is repeated for second sensor

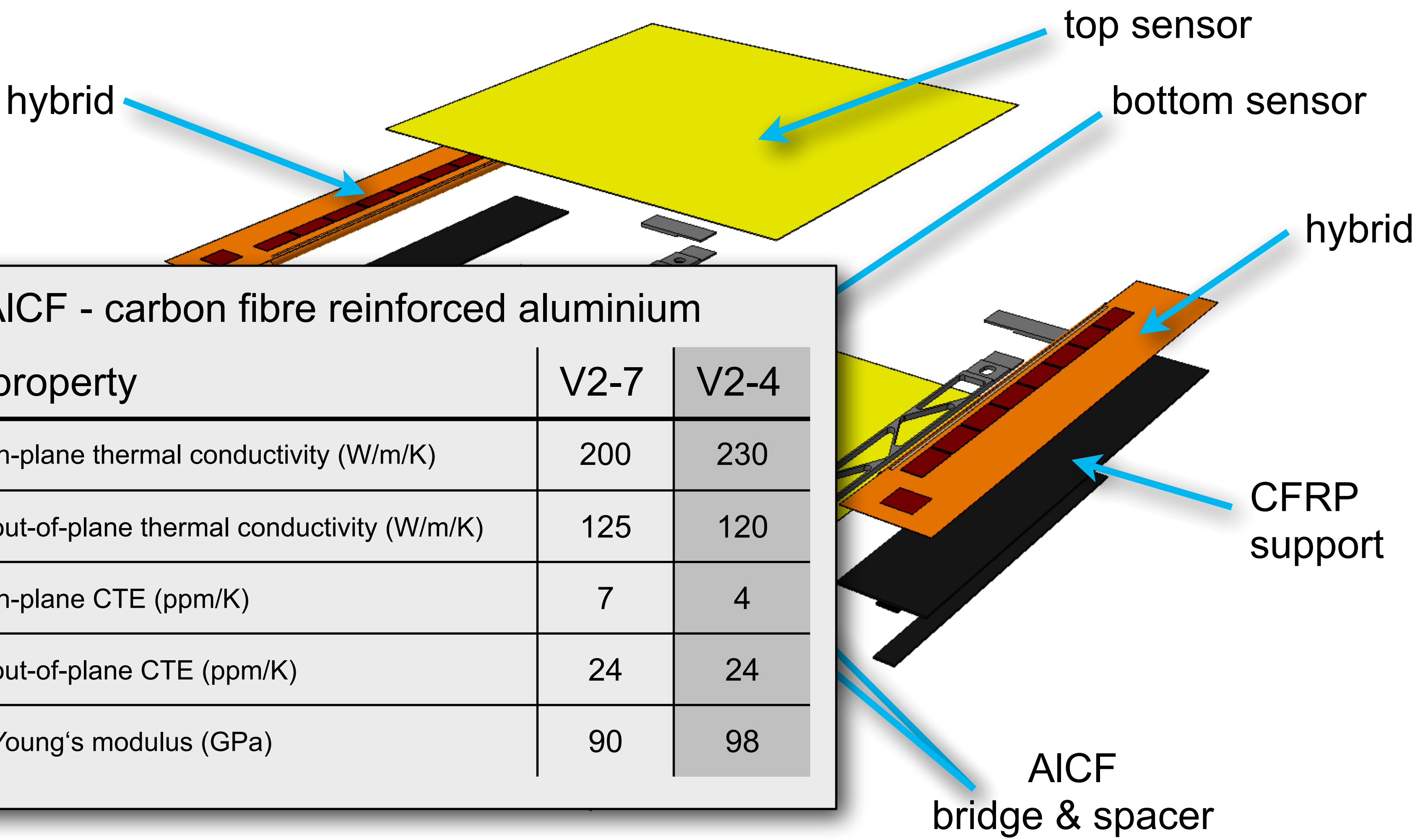


Summary

- design of 2S module is in an advanced stage
  - functionality of a two CBC2 test module was successfully tested in beam
  - a full scale mechanical prototype was built and will be tested for thermal and mechanical performance
  - we have a clear idea of the design parameters that are most relevant in order to improve the performance while maintaining low mass
- PS module has made a large step forward
  - a copy of the 2S module concept turned out to be not feasible
  - module thermal performance now relies on a large area contact between module and support
  - performance is well within what is required (based on FEA)
  - optimization of the cooling structure has started with the potential of a significant mass reduction
  - details have to be understood - e.g. reworkability of the module to support glue joint
- first concepts of module assembly schemes were developed
  - both manual and semi-automated

Backup

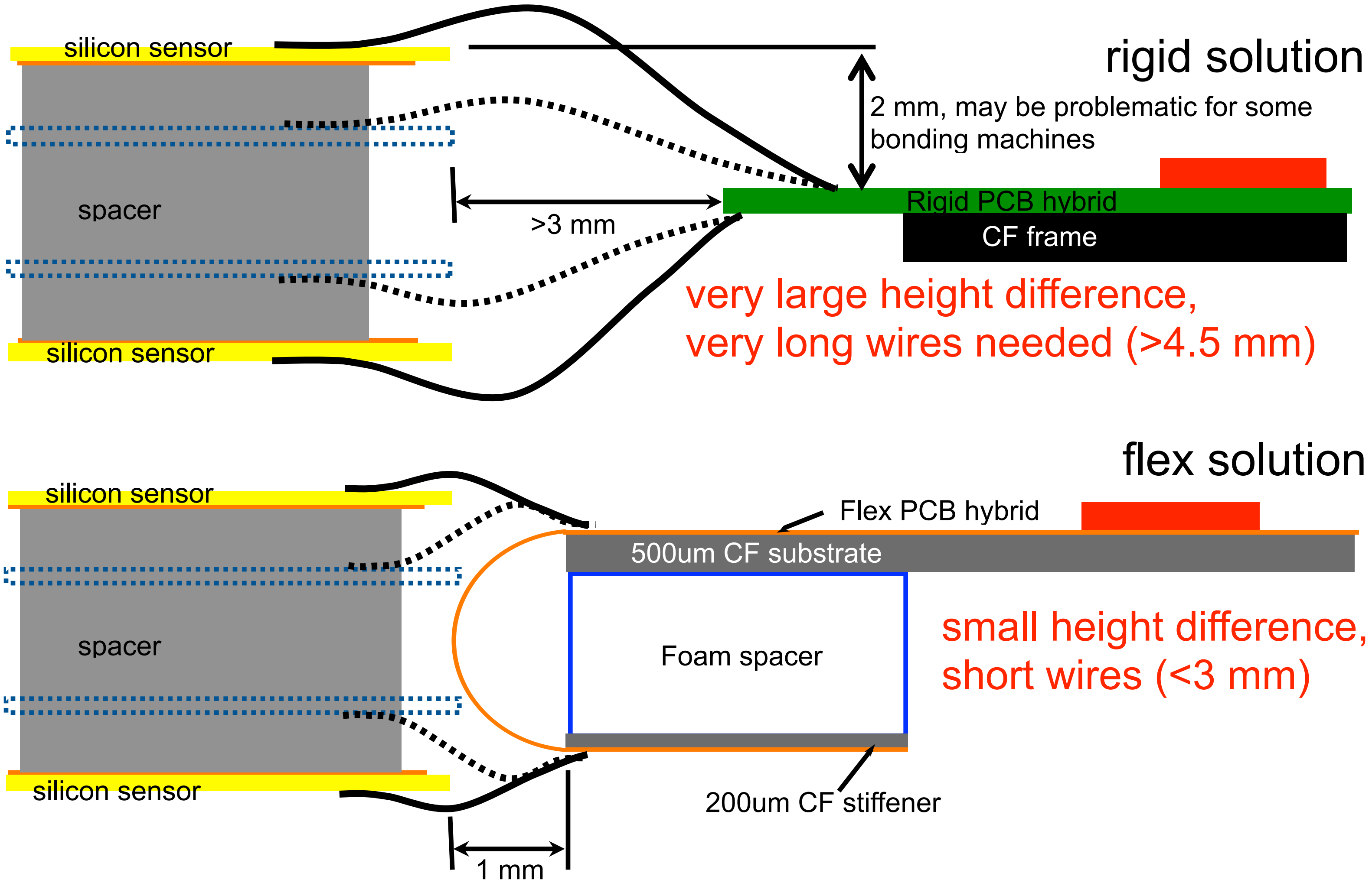
2S Module - Exploded View



AlCF - carbon fibre reinforced aluminium

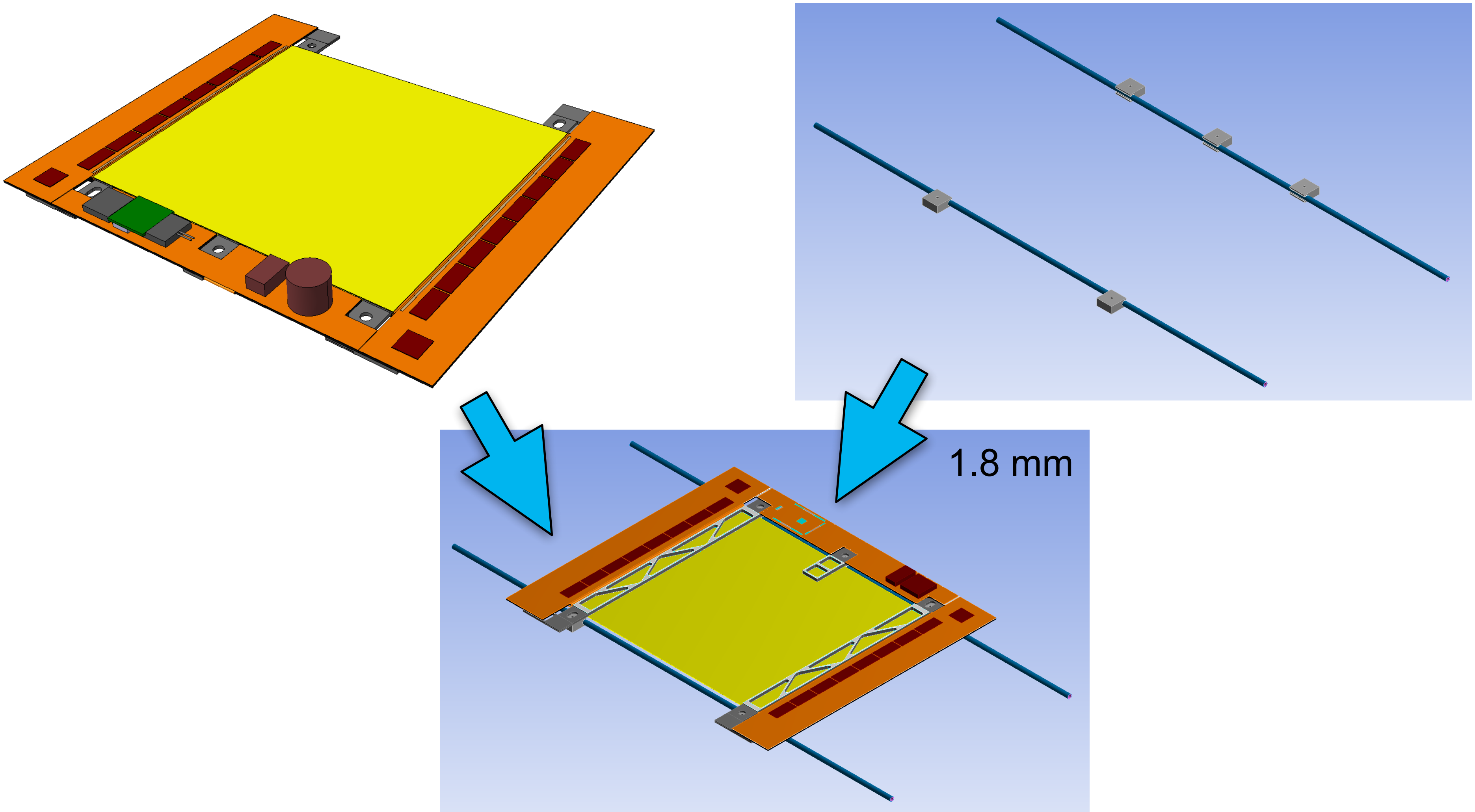
property	V2-7	V2-4
in-plane thermal conductivity (W/m/K)	200	230
out-of-plane thermal conductivity (W/m/K)	125	120
in-plane CTE (ppm/K)	7	4
out-of-plane CTE (ppm/K)	24	24
Young's modulus (GPa)	90	98

2S Module - Hybrid Options



- flexible hybrid has become the baseline solution

2S Module - FEA Model



> cooling pipes in barrel configuration

Collection of Phase Change Thermal Interface Materials (TIM)

Manufacturer	Glue	Thickness [mm]	Thermal conductivity [W/m/K]	phase change / burn in	Density [g/cc]	Operation range	Comment
Laird Technologies	Tpcm 905C	0.130	0.70	5 min @ 70C	1.31	-25C to +70C	film
Laird Technologies	Tpcm 910	0.250	2.23	5 min @ 70C	1.39	-25C to +70C	film
Laird Technologies	Tpcm 920	0.510	2.23	5 min @ 70C	1.39	-25C to +70C	film
Laird Technologies	Tpcm 780SP		5.40	45C to 70C	2.48		printable paste
Laird Technologies	Tpcm 780	0.203 / 0.254 / 0.406 / 0.635	5.40	45C to 70C	2.48		film
Loctite	Isostrate 2000	???	0.45	60C			on substrate
Honeywell	PCM45F	0.254	2.35	45C			pad or tape
Parker Chomerics	Thermflow T725	0.125	1.41	55C	1.1	-55C to +125C	film
Parker Chomerics	Thermflow T557	0.125	7.7	45C / 62C	2.4	-55C to +125C	film
Parker Chomerics	Thermflow T777	0.115	7.7	45C / 62C	1.95	-55C to +125C	film

- data on radiation tolerance might be available but is not part of this collection
- could be used as large-area thermal interface between module and support
  - mechanically mount all modules onto support with TIM film as interface
  - burn in takes place once everything is tested and working
  - heating up would allow to remove module without destroying support and other modules
- re-workabilty has to be tested