CMS Tracker Module Design

Andreas Mussgiller

9th Detector Workshop of the
Terascale Alliance

University of Freiburg

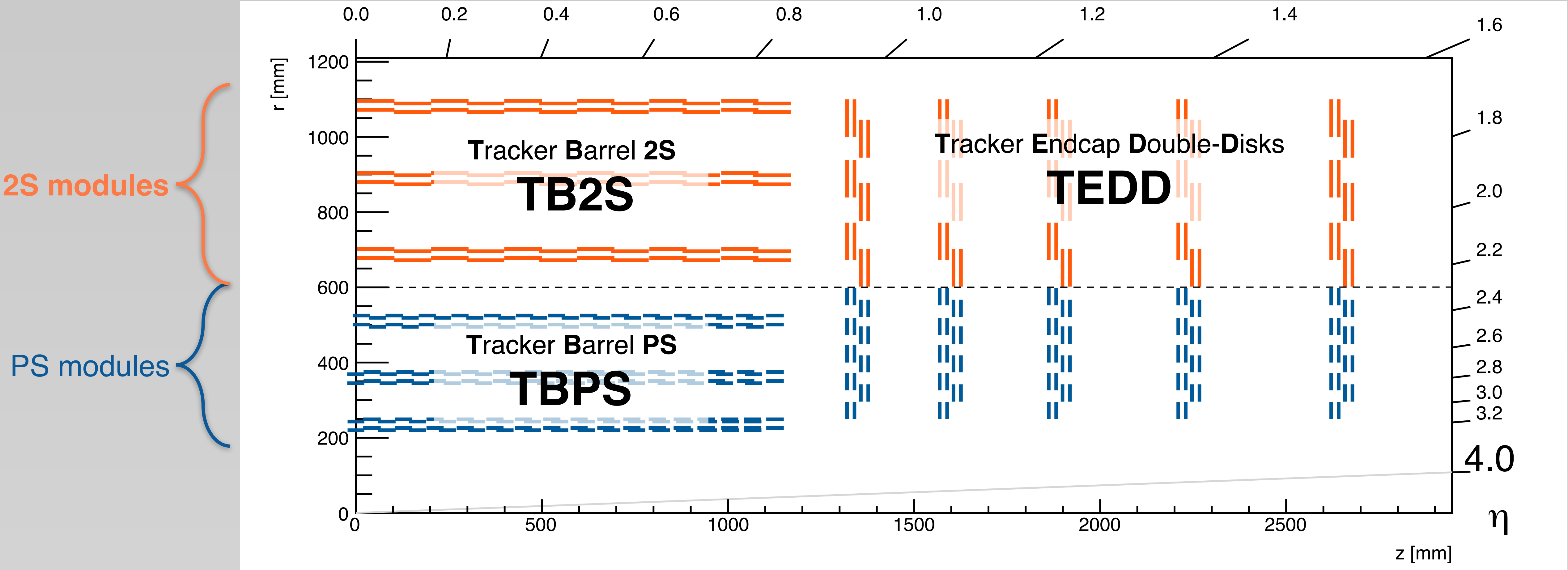
06/04/2016

Outline

- introduction
- module design and performance
    - 2S module
    - PS module
- prototyping
- module assembly
- module production logistics
- detector assembly facility

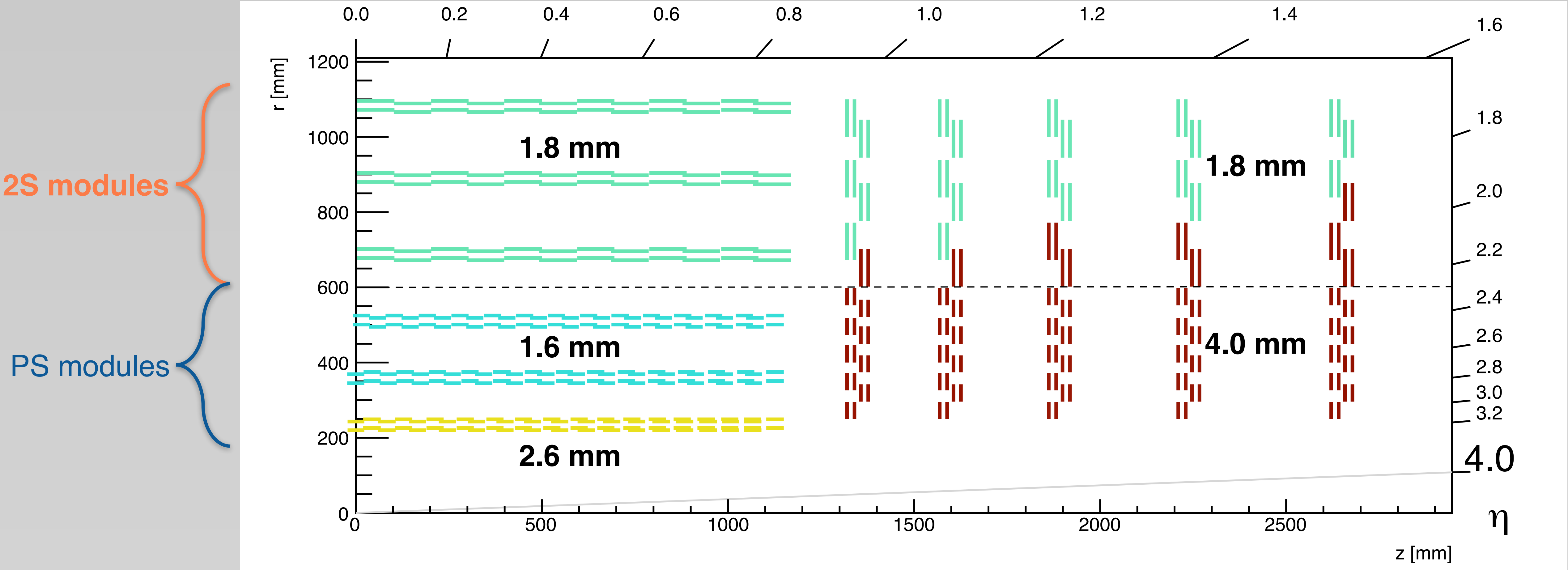
Introduction - Tracker Layout

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



Introduction - Module Configuration

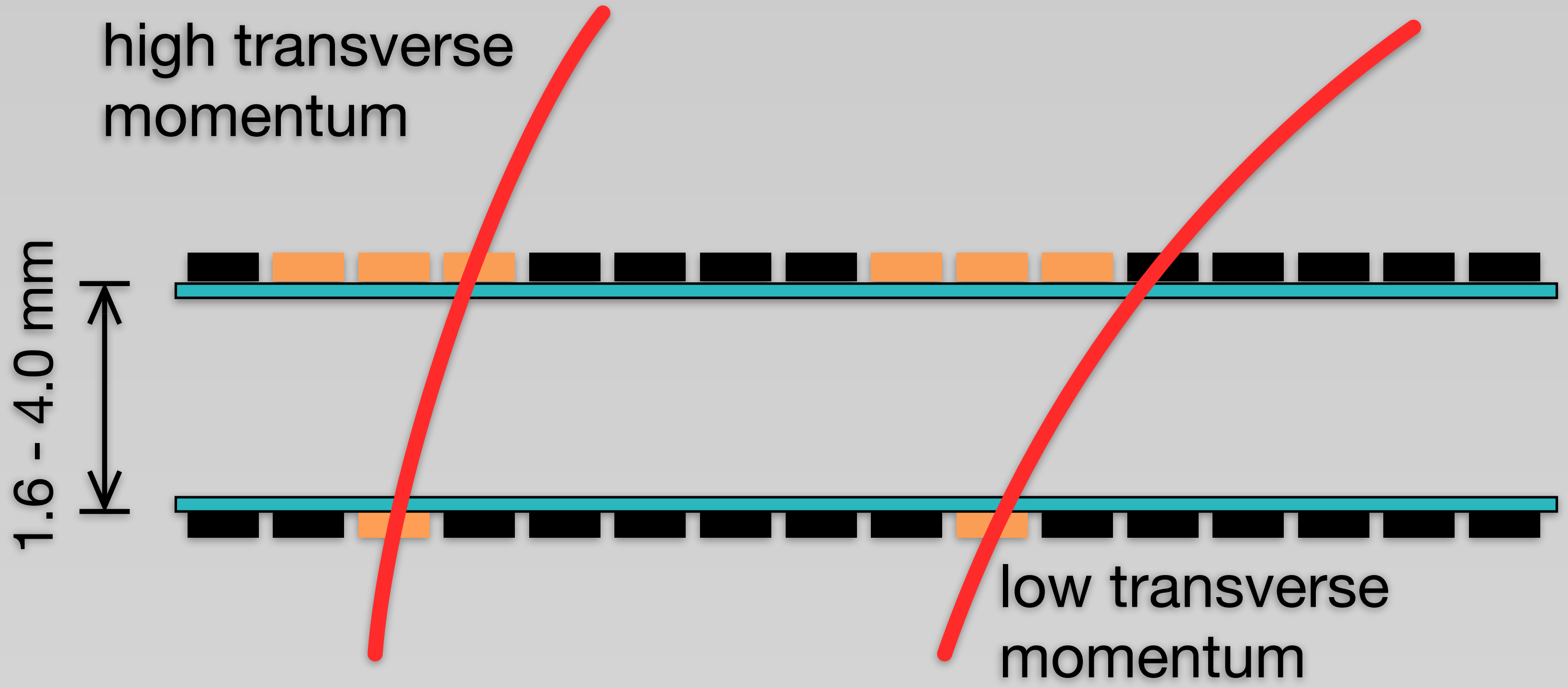
- layout with 6 barrel layers and 5 end cap double-disks
  - pixelated modules at r < 60 cm - stack of pixel and strip sensor (PS)
  - stack of two strip sensors at r > 60 cm (2S)
- PS modules
  - sensor spacings: 1.6 mm, 2.6 mm and 4 mm
- 2S modules
  - sensor spacings: 1.8 mm and 4 mm



Introduction - 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 minimise 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 CO2
  - sensors at ~ -20 °C
- integrated at module level:
  - low power giga-bit transceiver (LP-GBT) as data link
  - powering via DC-DC conversion
- two different module types
  - different sensor spacings are treated as ‚variants‘
  - requires optimisation of only two designs



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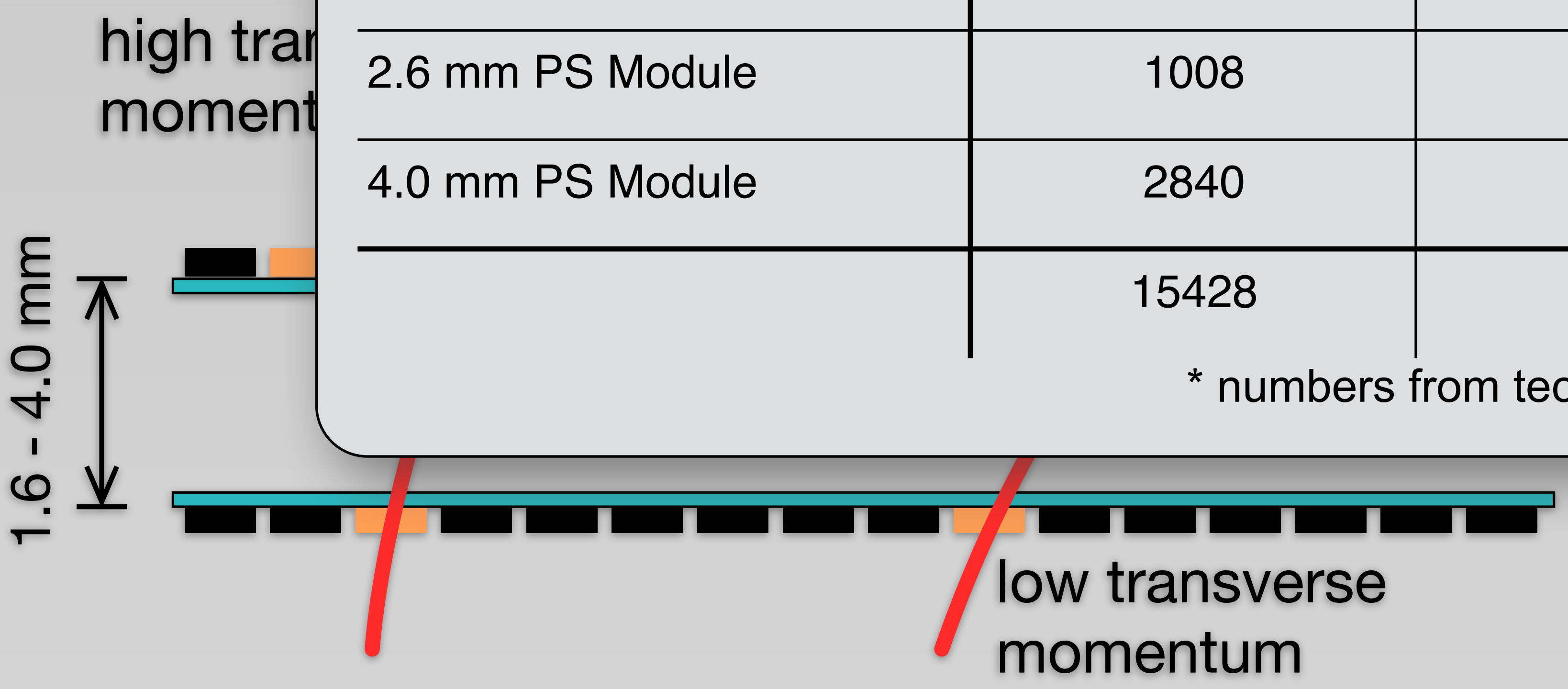
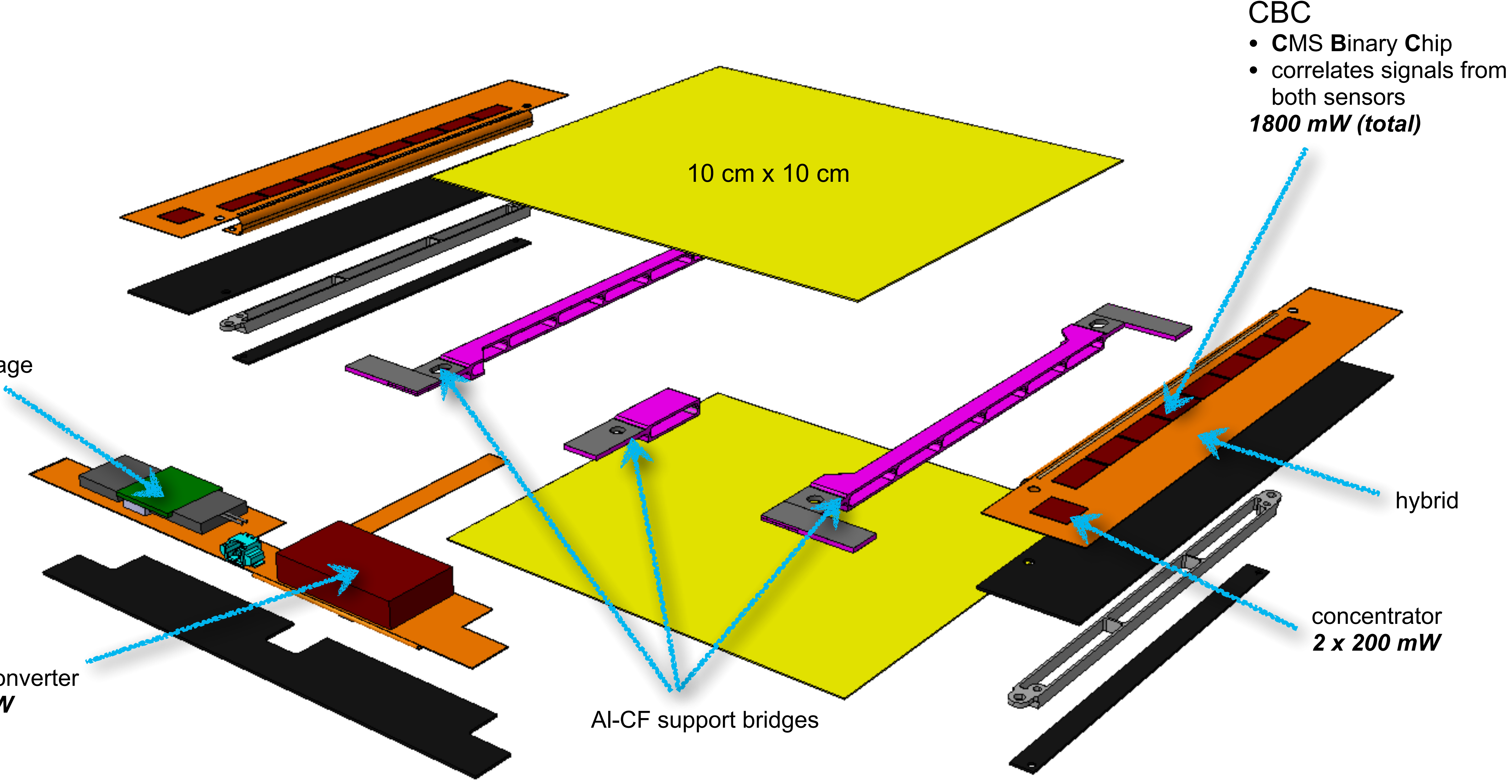
	full tracker	per end cap
1.8 mm 2S Module	7440	1488
4.0 mm 2S Module	984	492
1.6 mm PS Module	3156	
2.6 mm PS Module	1008	
4.0 mm PS Module	2840	1420
	15428	3400

* numbers from technical proposal



Design of the 2S Module

4.0 mm variant is shown



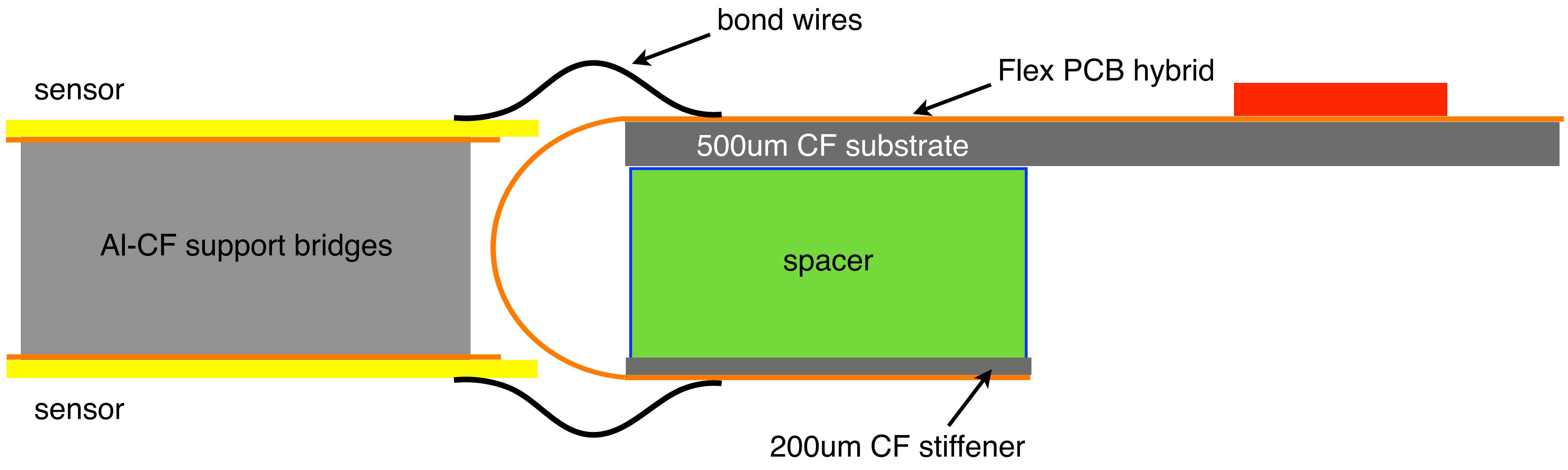
CBC

- **C**MS **B**inary **C**hip
- correlates signals from both sensors

1800 mW (total)

- sensors are supported by AlCF bridges
  - AlCF = carbon fibre reenforced aluminum
  - good CTE match to silicon: 3.6 ppm/K vs. 4 ppm/K
  - coated with parylene for HV insulation
- five cooling contacts per module
  - extra AlCF stumped bridge introduced for thermal management
  - heat load from service hybrid (~2W)
- recently focused on streamlining the designs w.r.t. integration aspects

2S Module Read-Out Hybrid



- flexible hybrid is glued on CFRP stiffeners and folded around a spacer
- bond pads on hybrid are on the same level as the bond pads on the sensor
- requires different spacer thicknesses and hybrid variants

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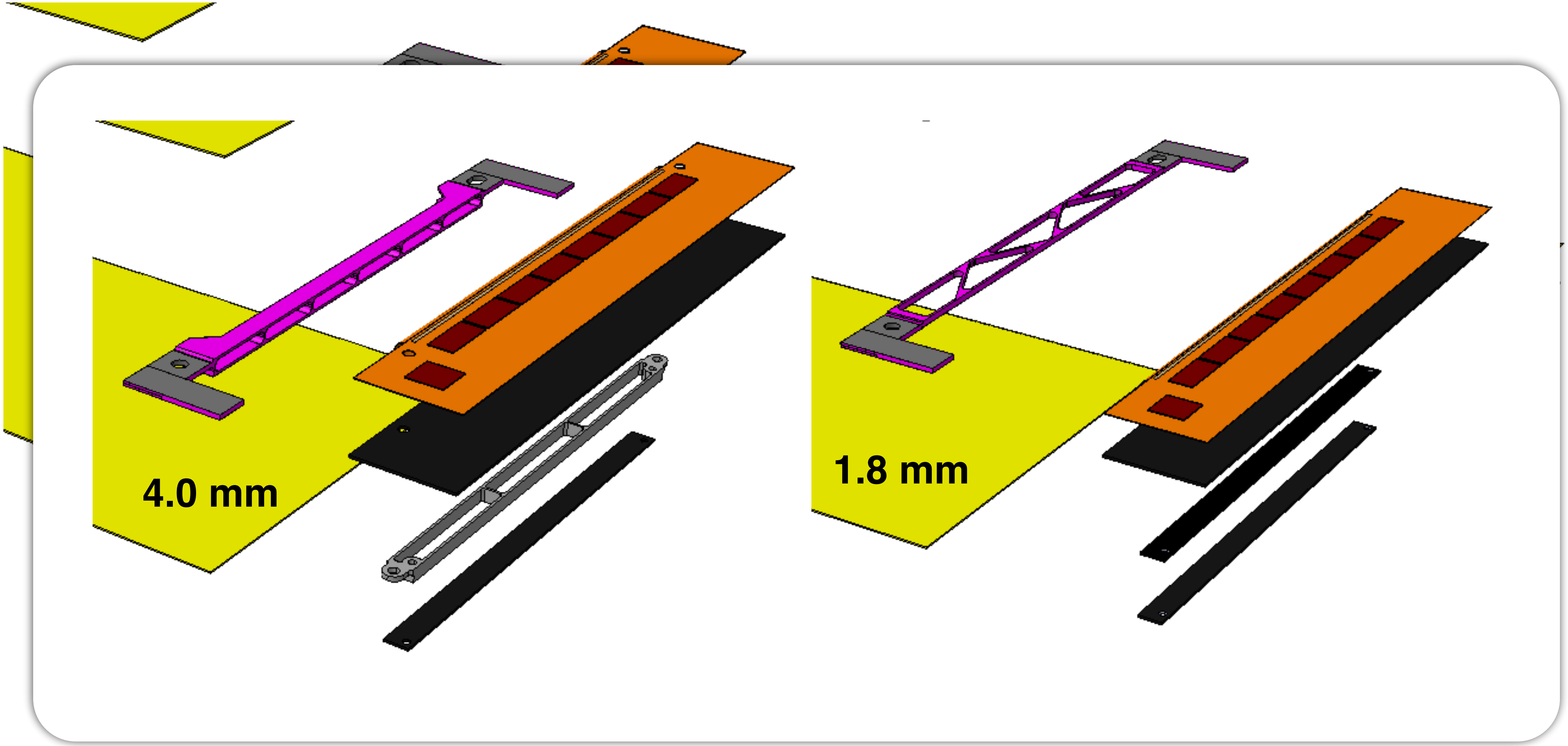
2S Module 4.0 mm vs 1.8 mm



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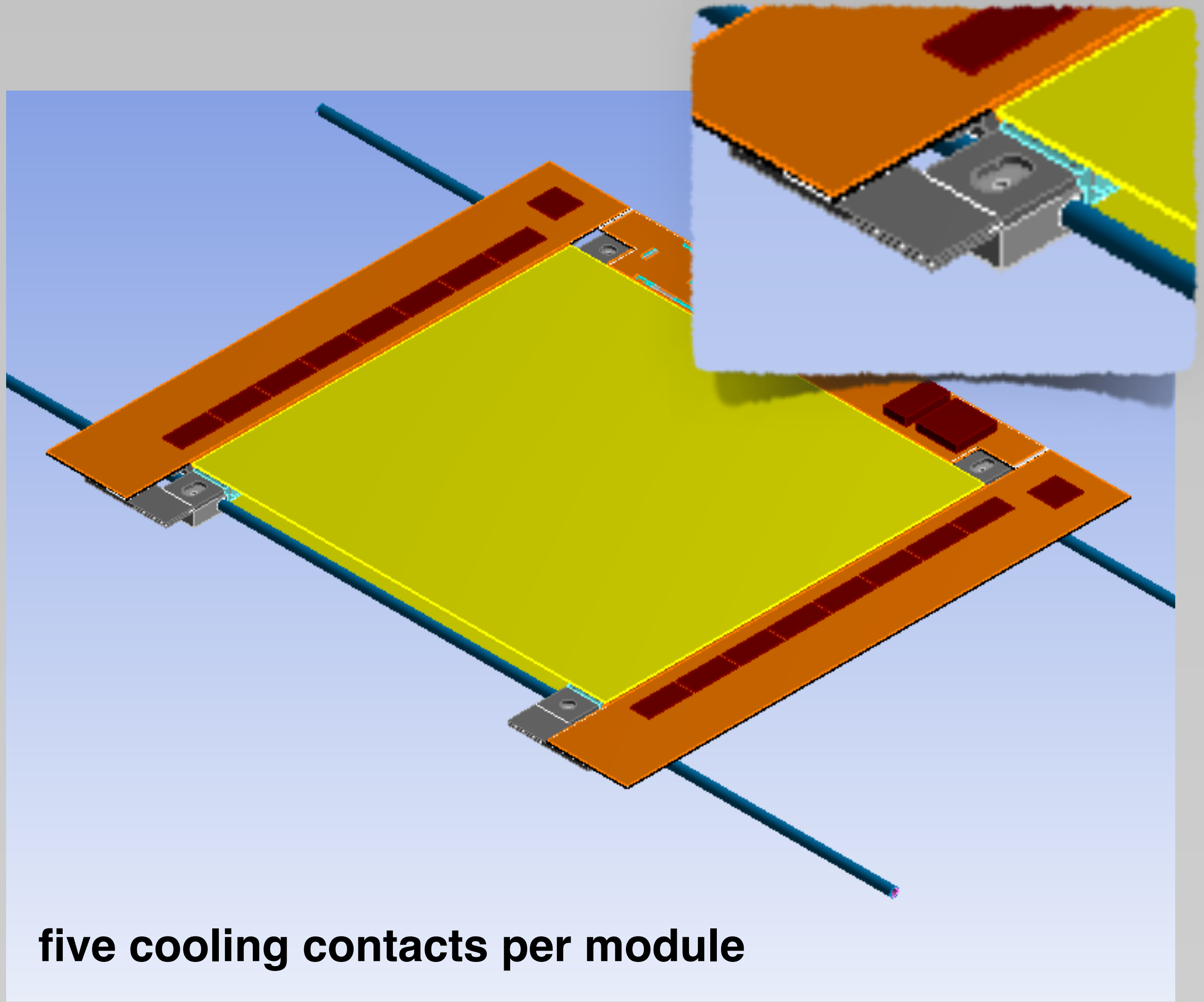
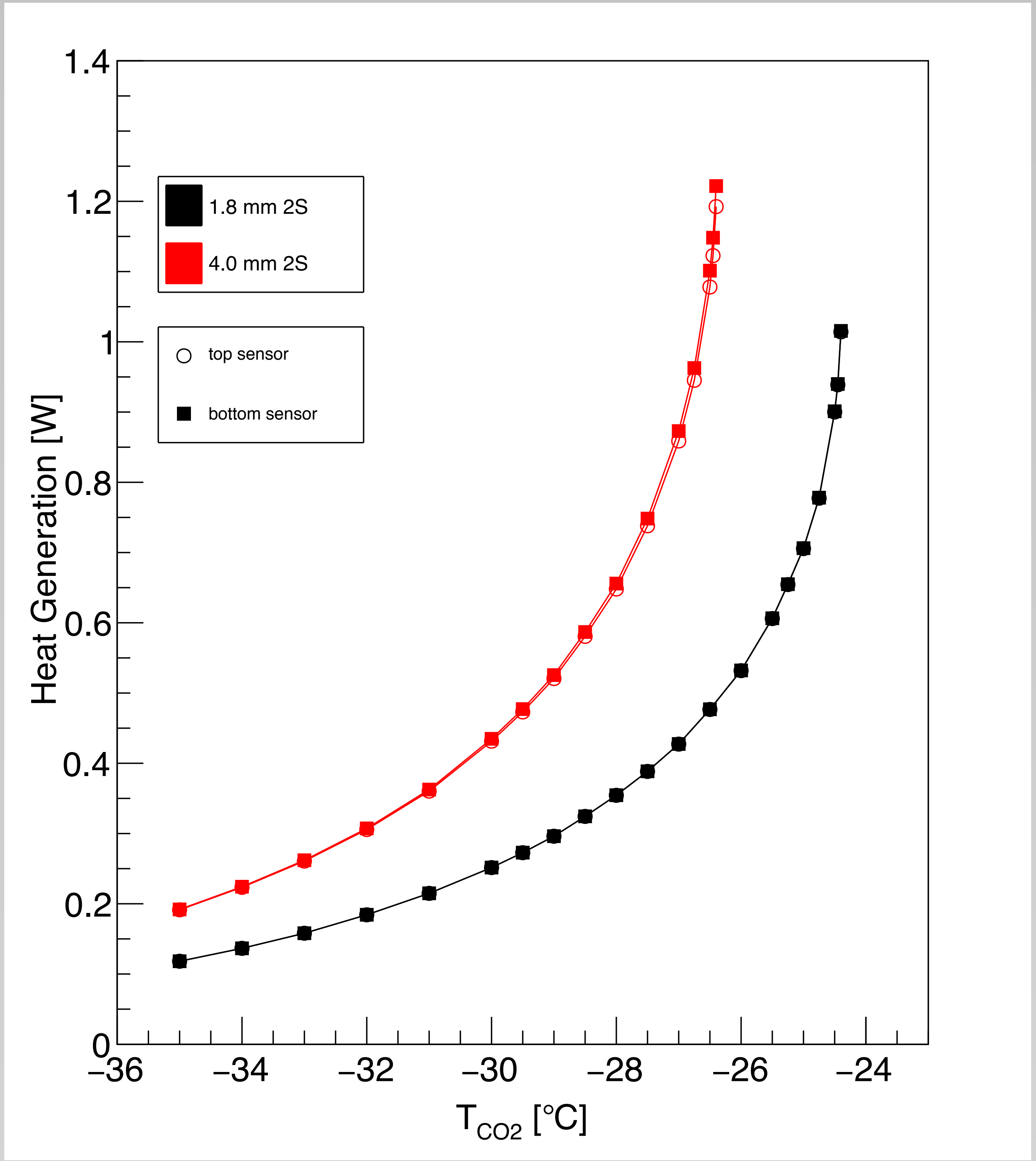
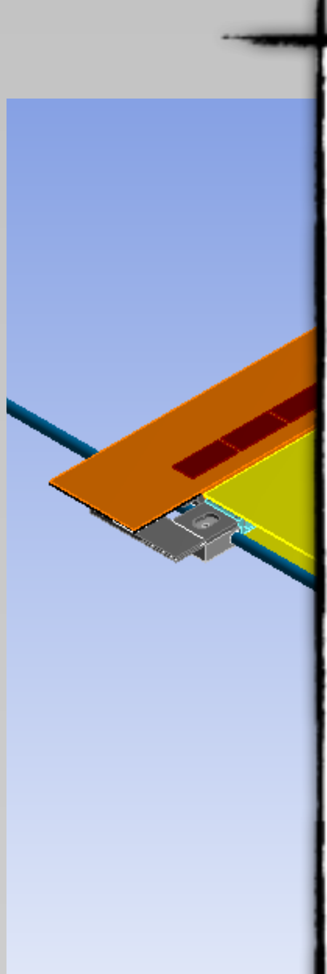


five cooling contacts per module

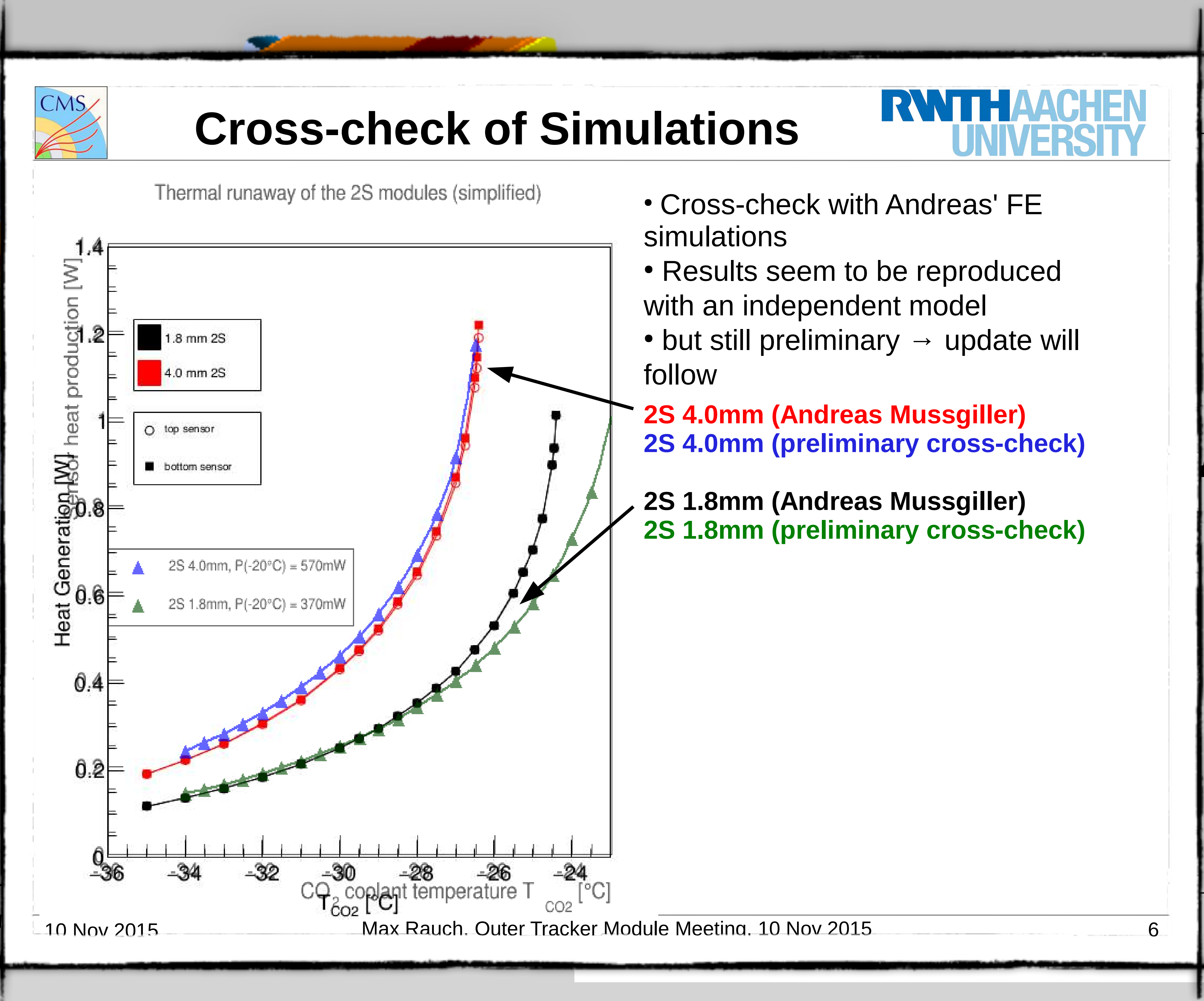


- sensors after 3000 fb^{-1}: 572 mW each (@ -20°C)
- total power: 5444 mW
- 320 µm physical sensor thickness
- 200 µm active sensor thickness
- thermal runaway at
  - 1.8 mm: -24.5 °C
  - 4.0 mm: -26.5 °C

2S Module 4.0 mm vs 1.8 mm



five cooling



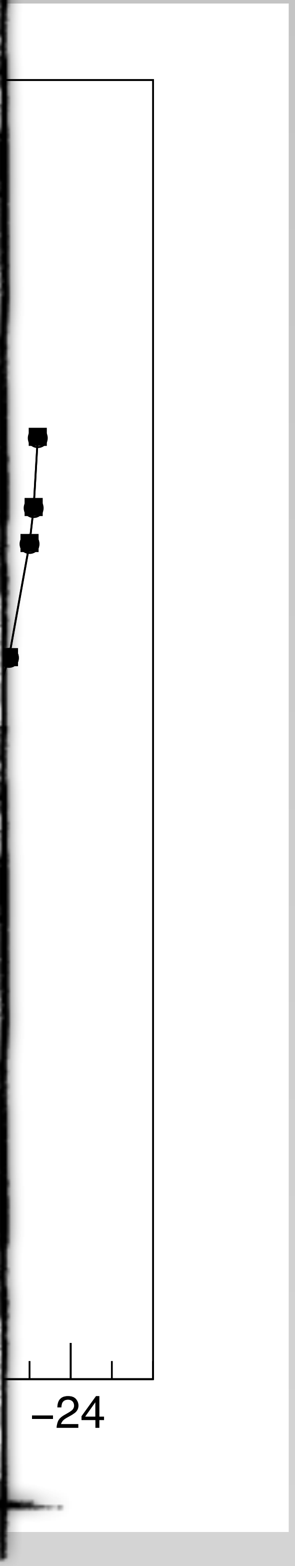
Cross-check of Simulations

- Cross-check with Andreas' FE simulations
- Results seem to be reproduced with an independent model
- but still preliminary → update will follow

2S 4.0mm (Andreas Mussgiller)
2S 4.0mm (preliminary cross-check)

2S 1.8mm (Andreas Mussgiller)
2S 1.8mm (preliminary cross-check)

10 Nov 2015 Max Rauch, Outer Tracker Module Meeting, 10 Nov 2015 6



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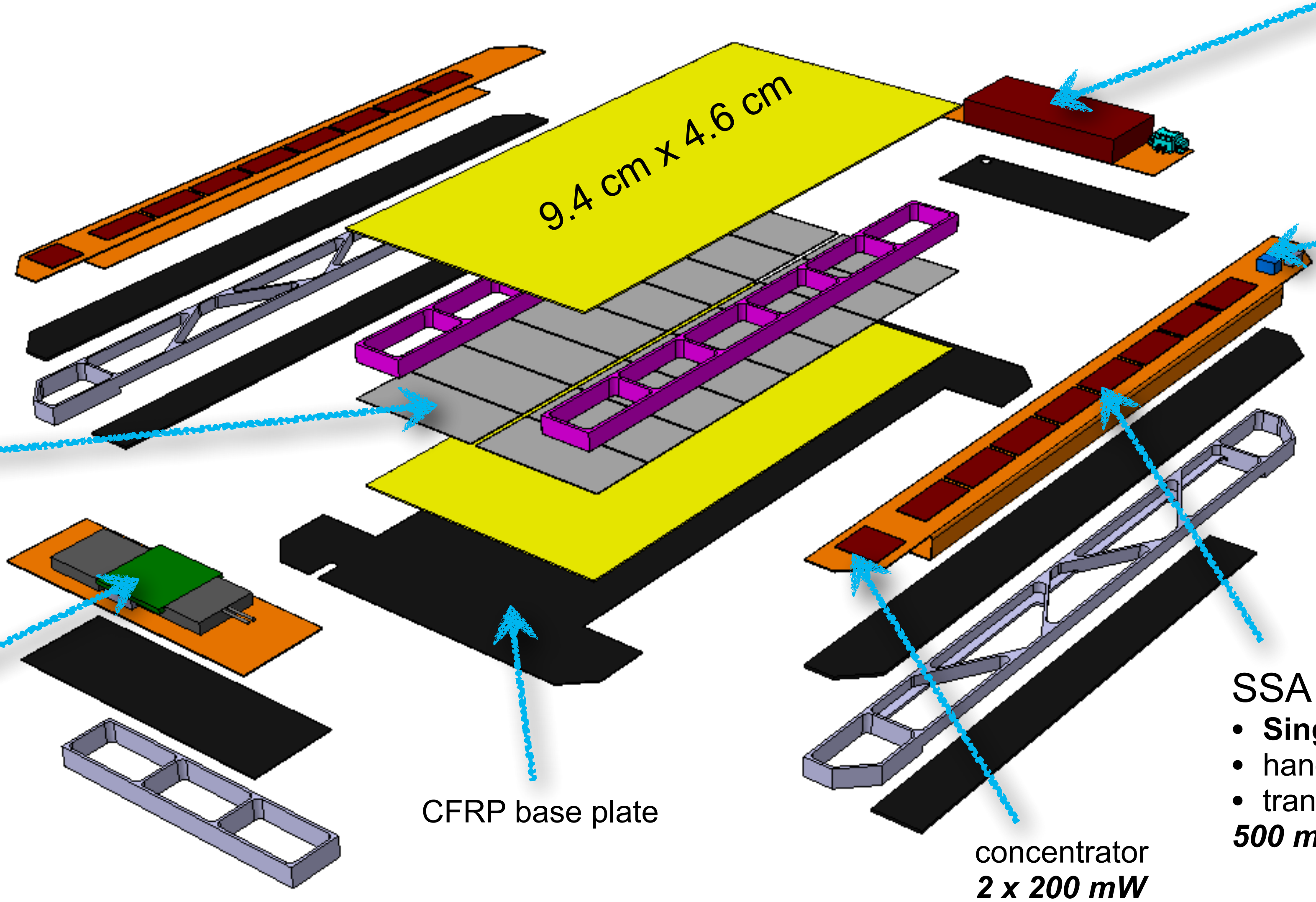
  - 4.0 mm

Design of the PS Module

4.0 mm variant is shown



power converter
~2000 mW

hybrid

MPA
- **Macro Pixel Asic**
- pixel size: 1400 x 100 µm
- correlates signals from both sensors

3000 mW (total)

opto package
800 mW

CFRP base plate

concentrator
2 x 200 mW

SSA
- **Single Strip Asic**
- handles signals from strip sensor
- transfers data to pixel chip

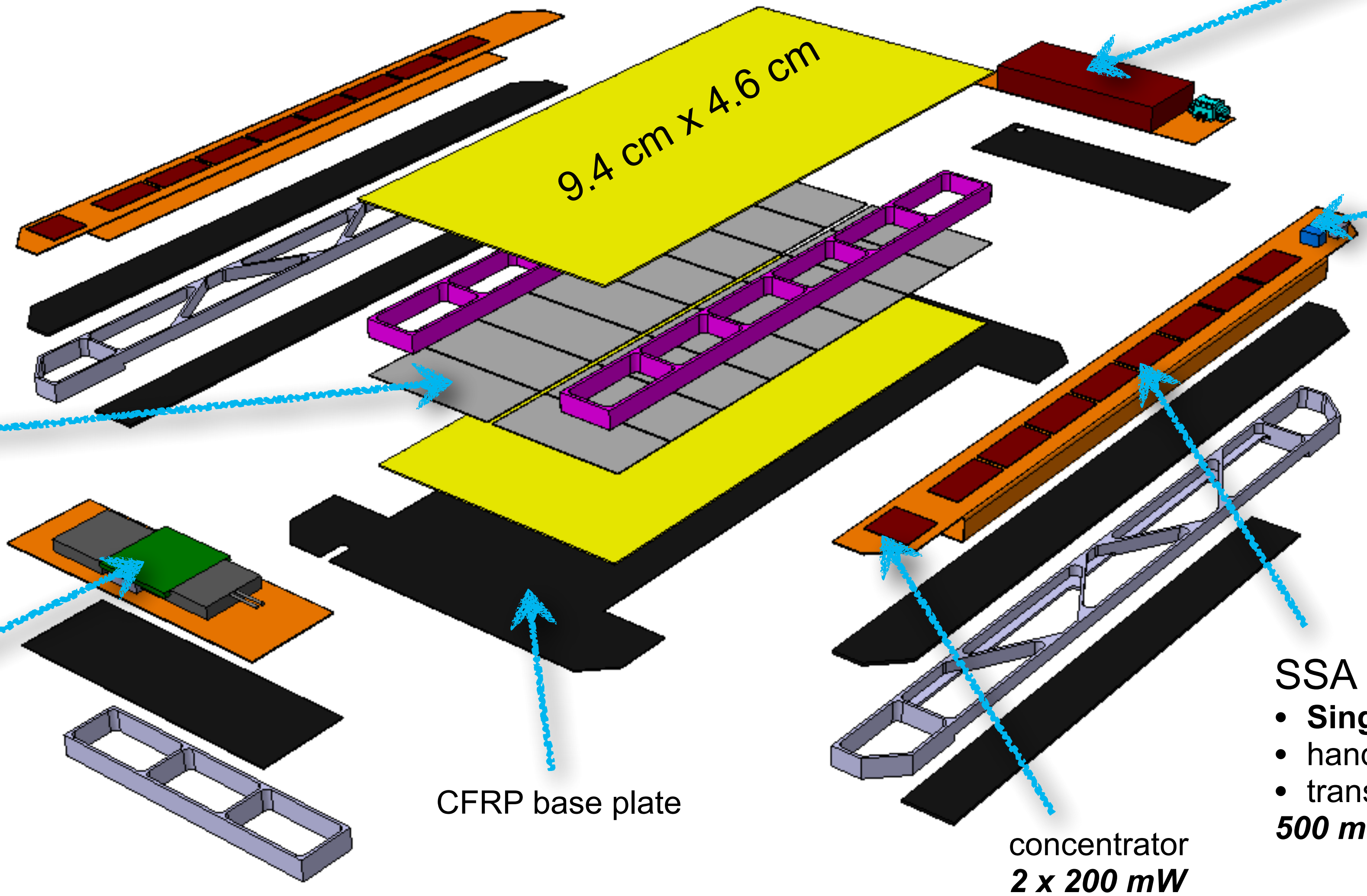
500 mW (total)

- sensors are supported by AlCF bridges
- initially same cooling concept as in 2S module
  - four cooling contacts at end of bridges
  - power density of PS module is too high
- PS module needs large-area thermal contact

- module is built on top of a CFRP base plate
- MPAs and sensors are cooled through base plate
  - requires a large-area glue joint between pixel sensor and base plate

Design of the PS Module

4.0 mm variant is shown



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opto package
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concentrator
2 x 200 mW

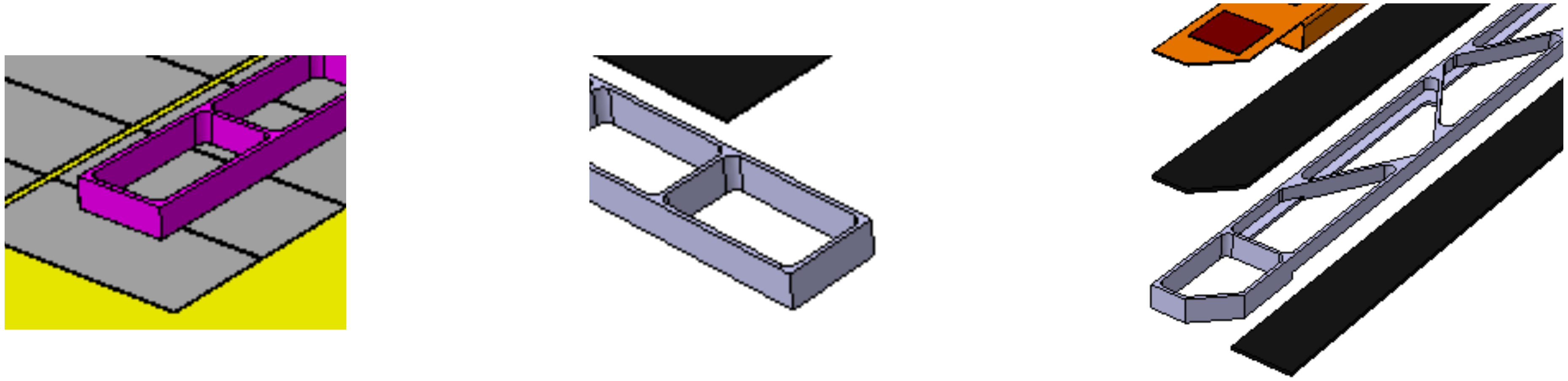
SSA
- **Single Strip Asic**
- handles signals from strip sensor
- transfers data to pixel chip

500 mW (total)

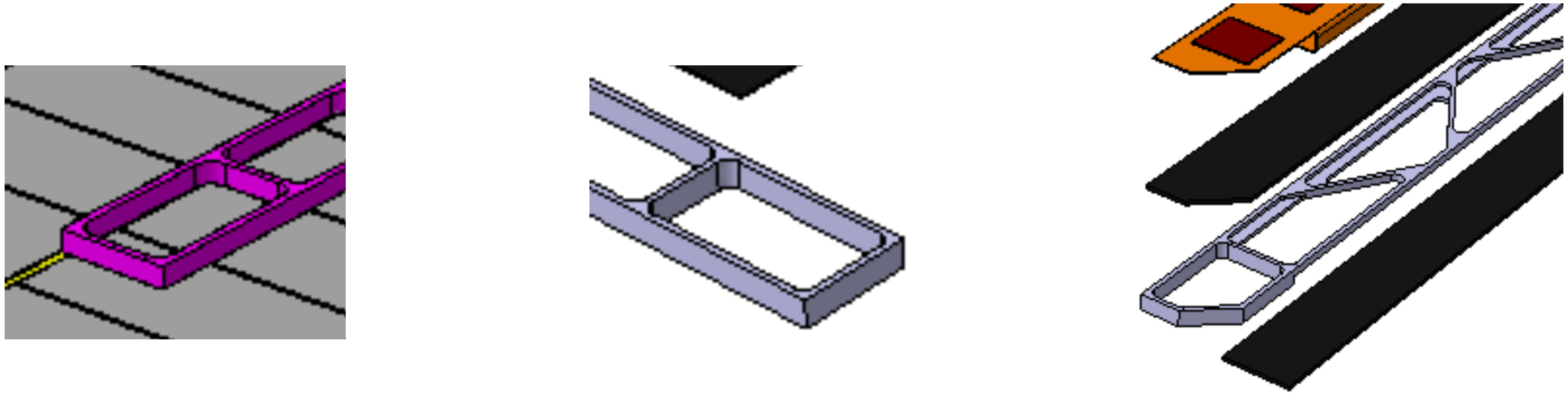
- large number of bond wires between read-out hybrid and opto hybrid requires opto hybrid to be at the same level as read-out hybrid
- heat load from power converter and size of package requires power converter to be at level of base plate

PS Module 4.0 mm vs 2.6 mm vs. 1.6 mm

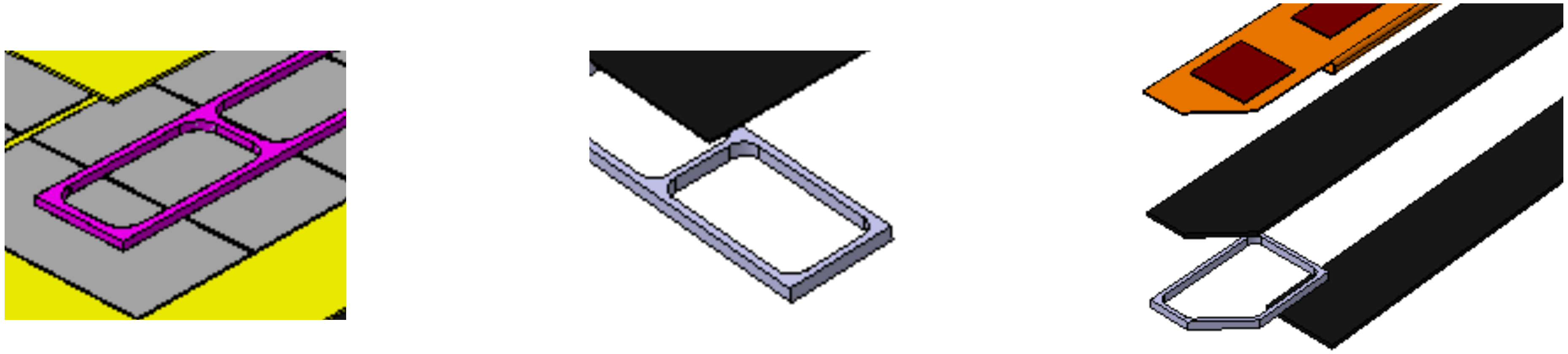
4.0 mm



2.6 mm

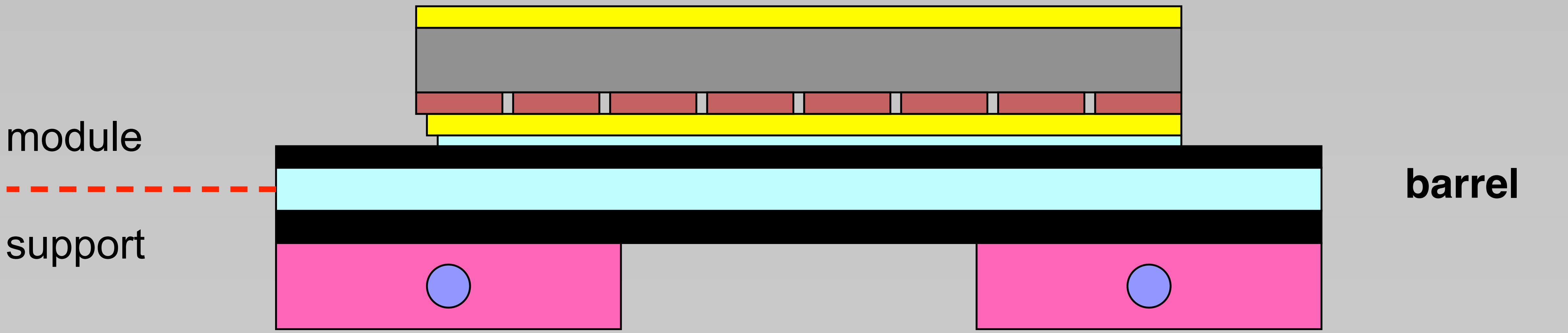


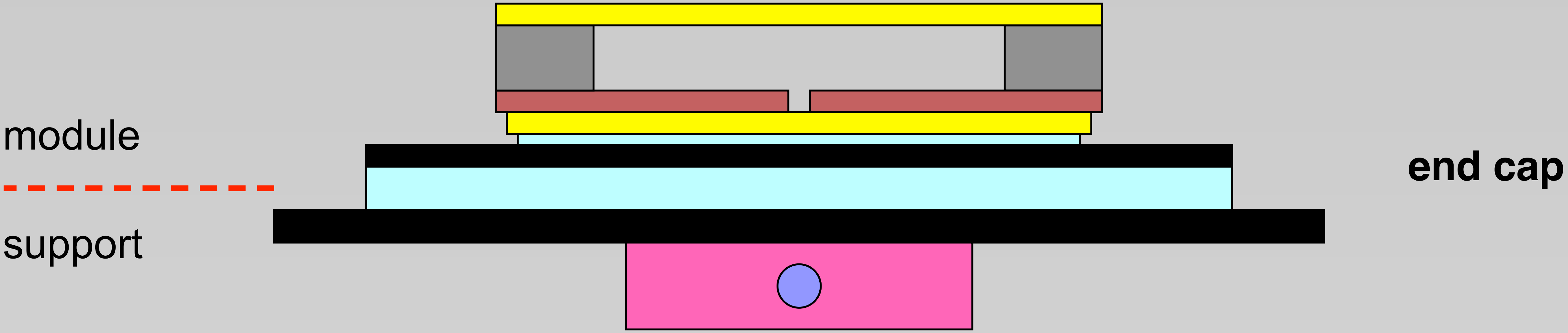
1.6 mm



- flexible hybrid is folded on the outside
- four parts change between 1.6 mm, 2.6 mm and 4.0 mm variant
  - AlCF sensor spacers
  - opto spacer
  - hybrid spacer
  - length of hybrid fold-over region
- 1.6 mm spacing is a handling challenge
  - spacing between middle of sensor active thickness

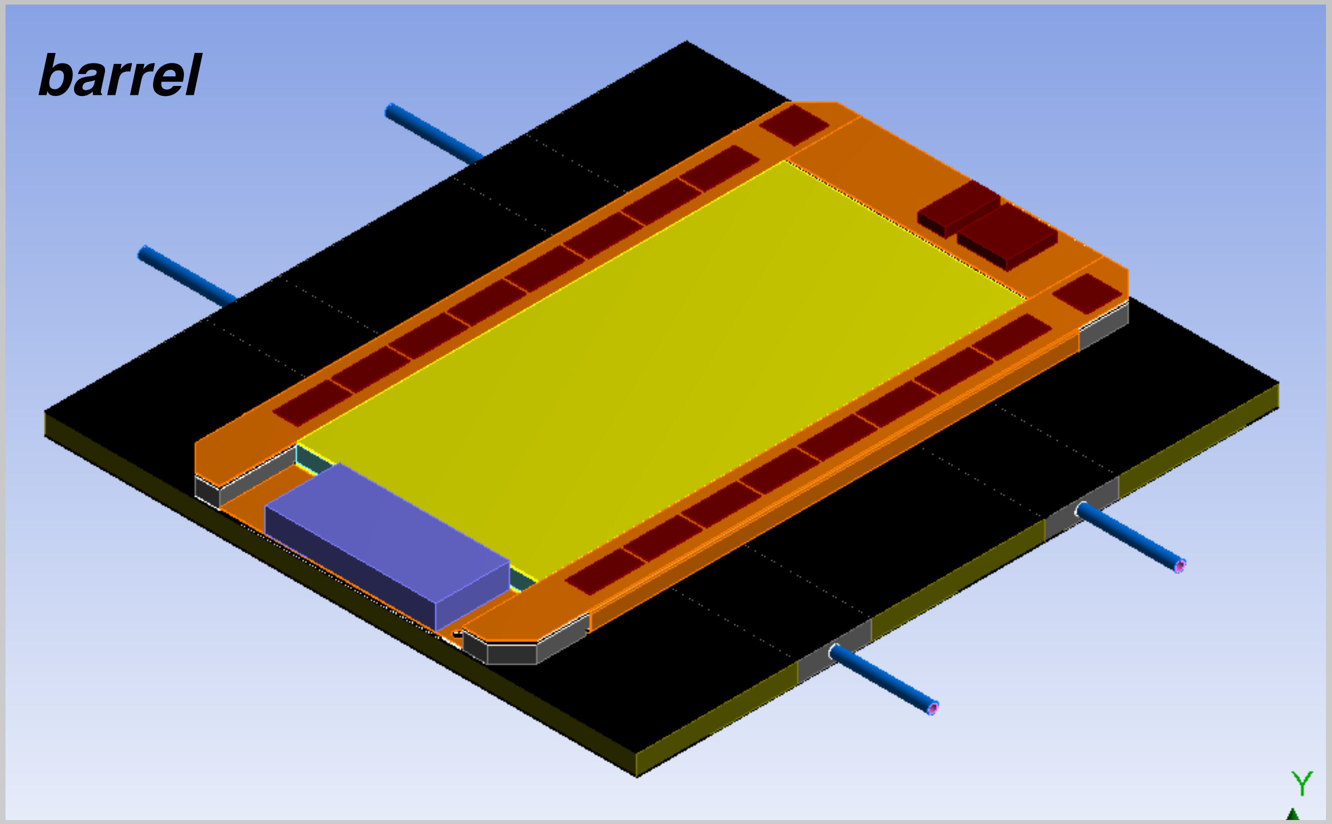
PS Module on Support Structure

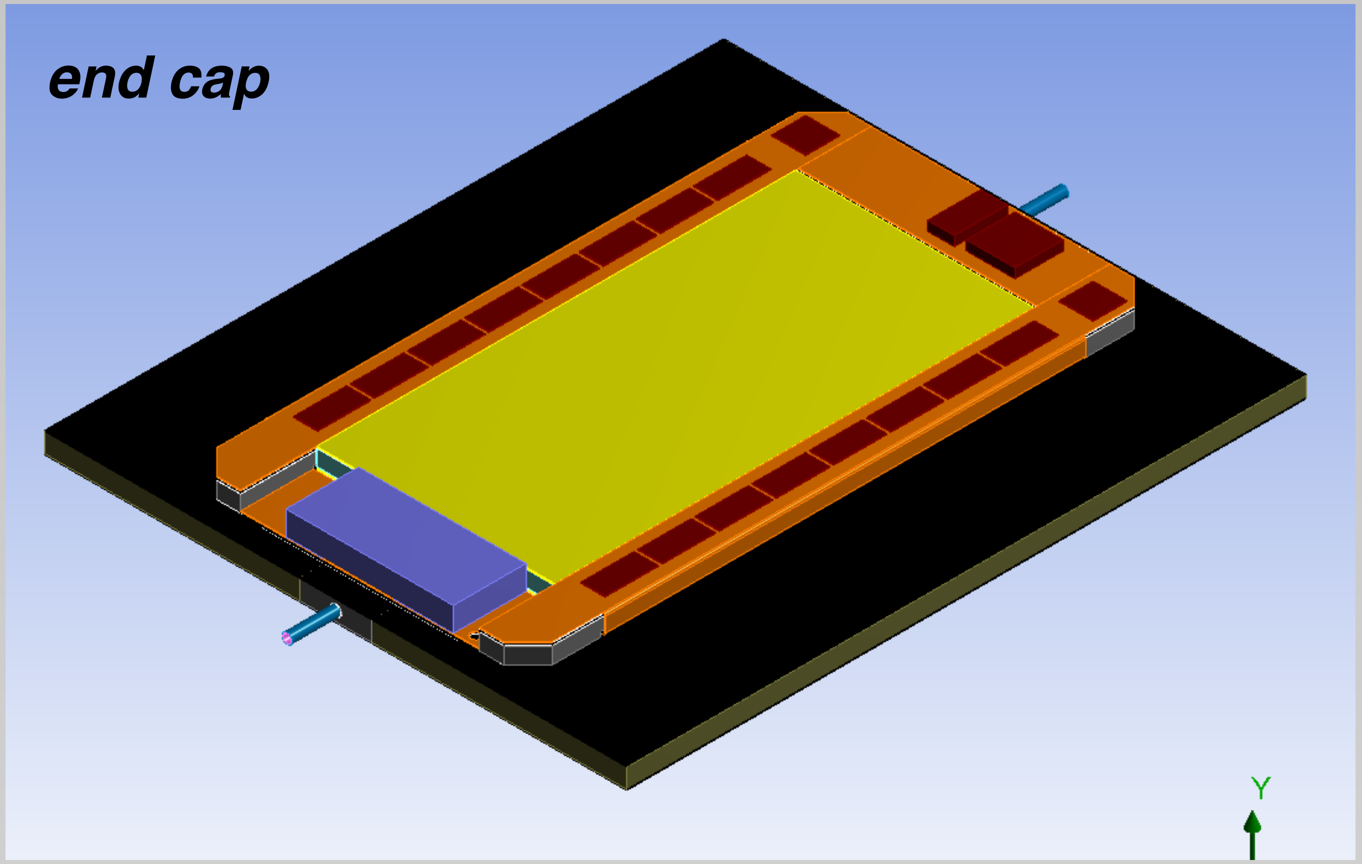




- module is built on top of a CFRP base plate
- base plate serves as a large-area thermal interface between module and support structure

4.0 mm PS Module - FEA Geometry

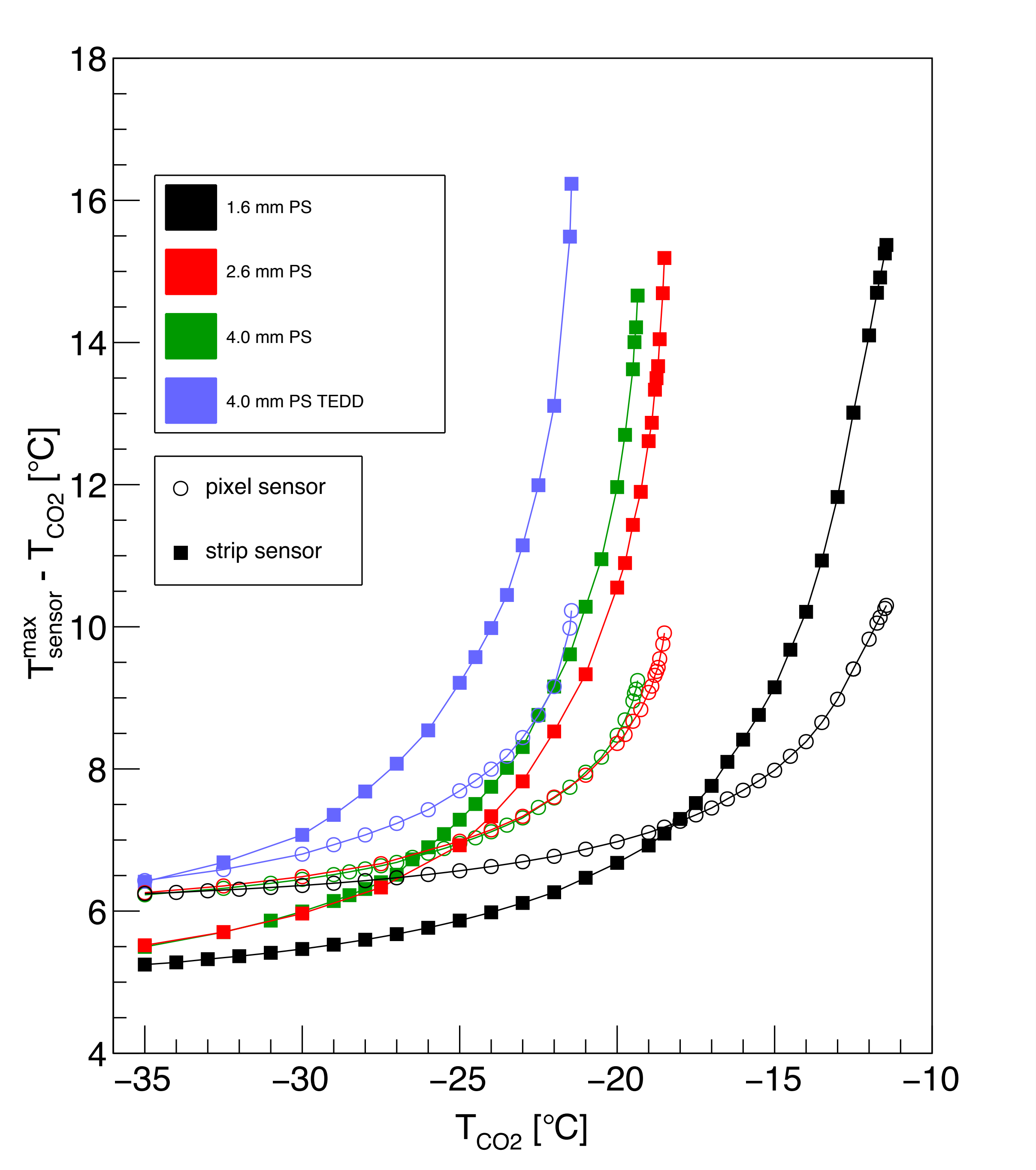


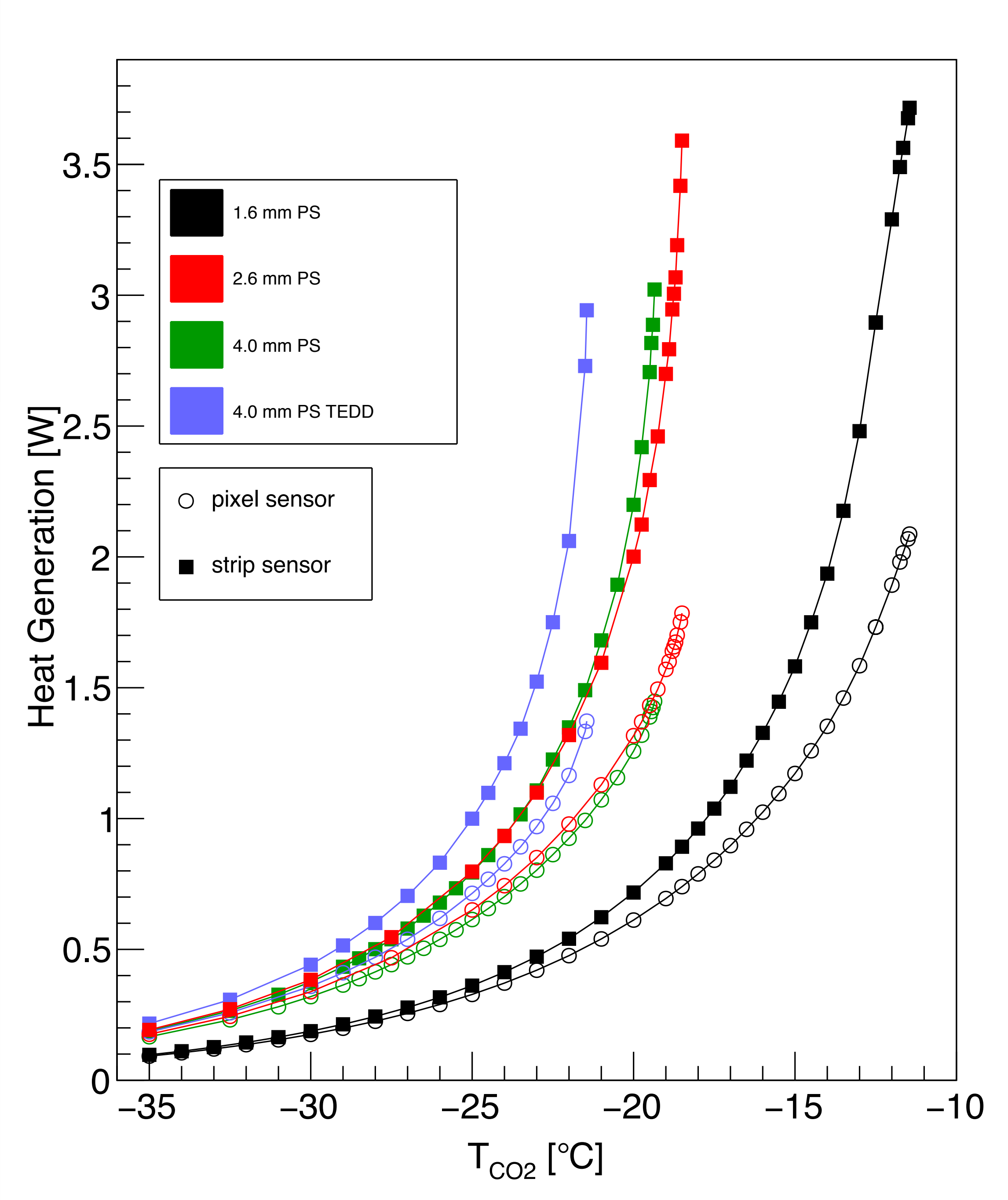


- 2 x 8 MPA: 3000 mW
- 2 x 8 SSA: 500 mW
- 2 CIC: 400 mW
- LP-GBT: 500 mW
- opto package: 300 mW
- power converter: 2000 mW
- 320 µm physical sensor thickness
- 200 µm active sensor thickness

- sensors after 3000 fb^{-1}: 646 mW each (@ -20°C)
- total power: 7994 mW
- heat transfer coefficient into CO2: 5000 W/m^2/K
- geometry of tilted barrel option is similar to end cap geometry

PS Module Thermal Runaway

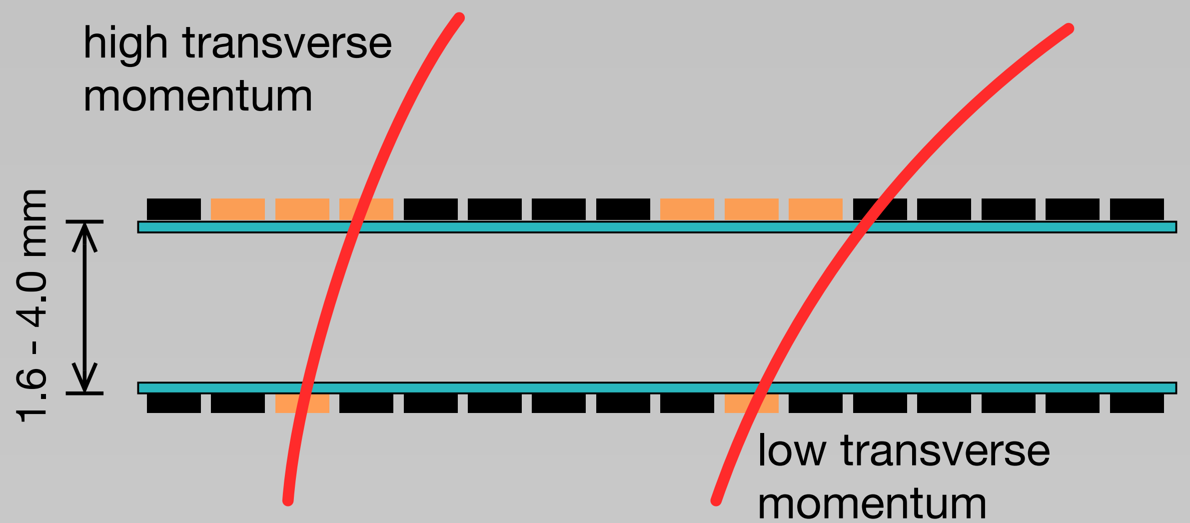


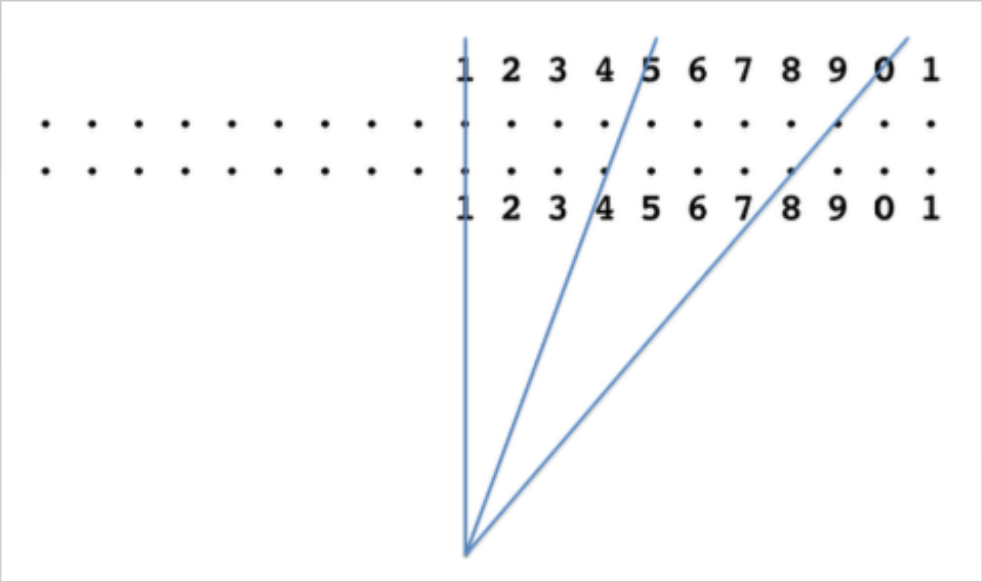


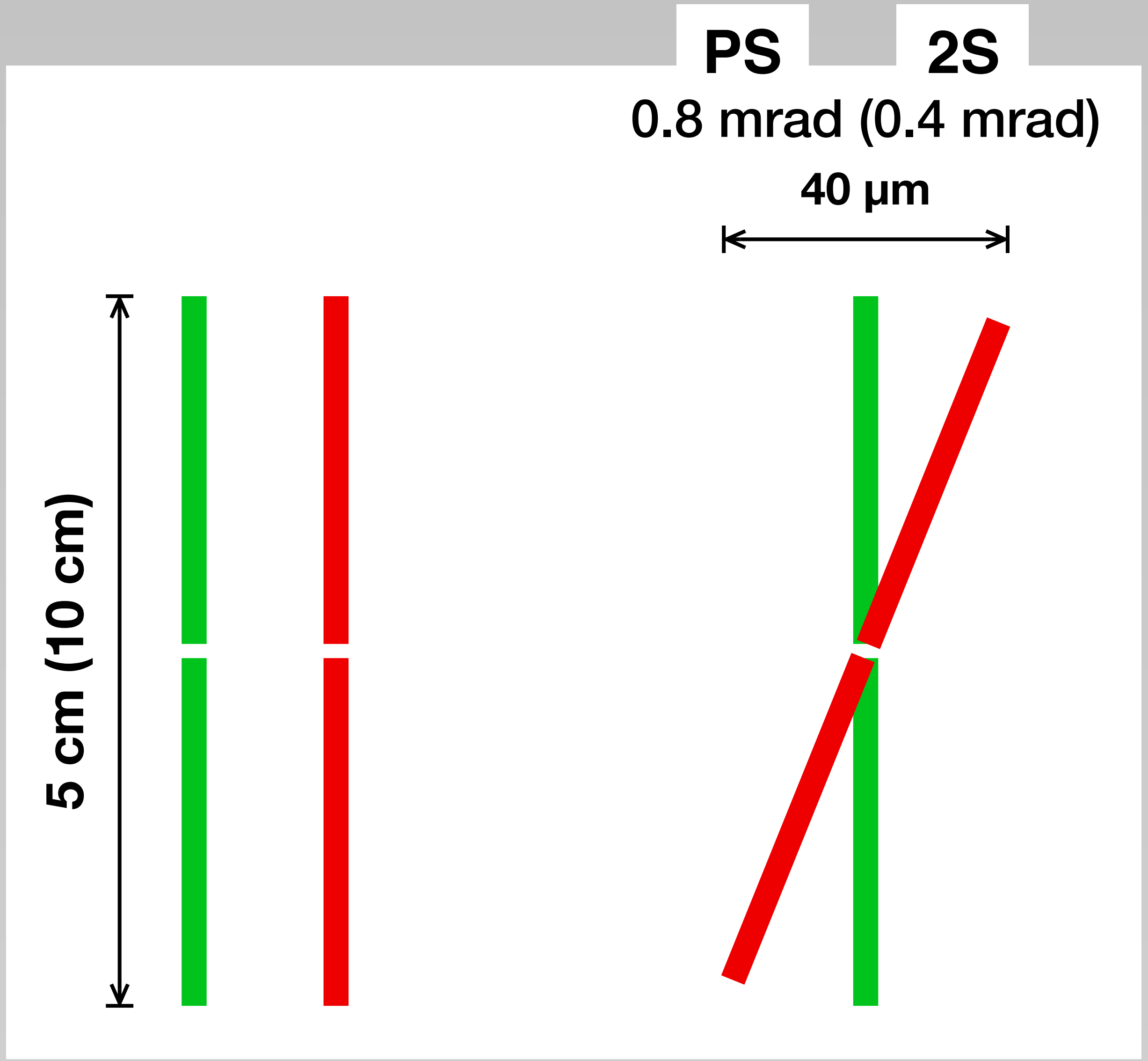
- thermal runaway at
  - 1.6 mm: -12 °C
  - 2.6 mm: -20 °C
  - 4.0 mm: -22 °C

- thermal runaway temperature is defined by strip sensor

Module Assembly Requirements

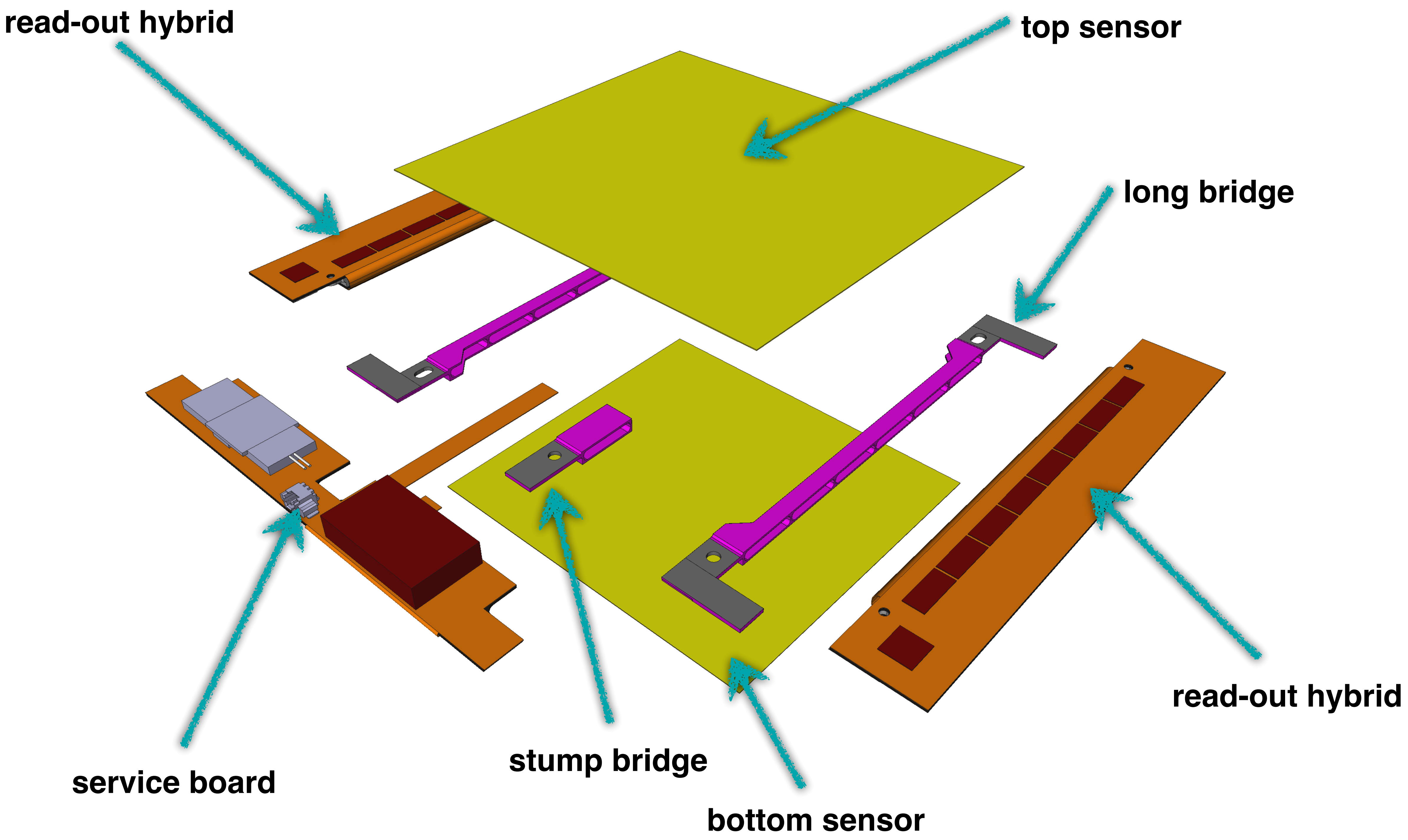






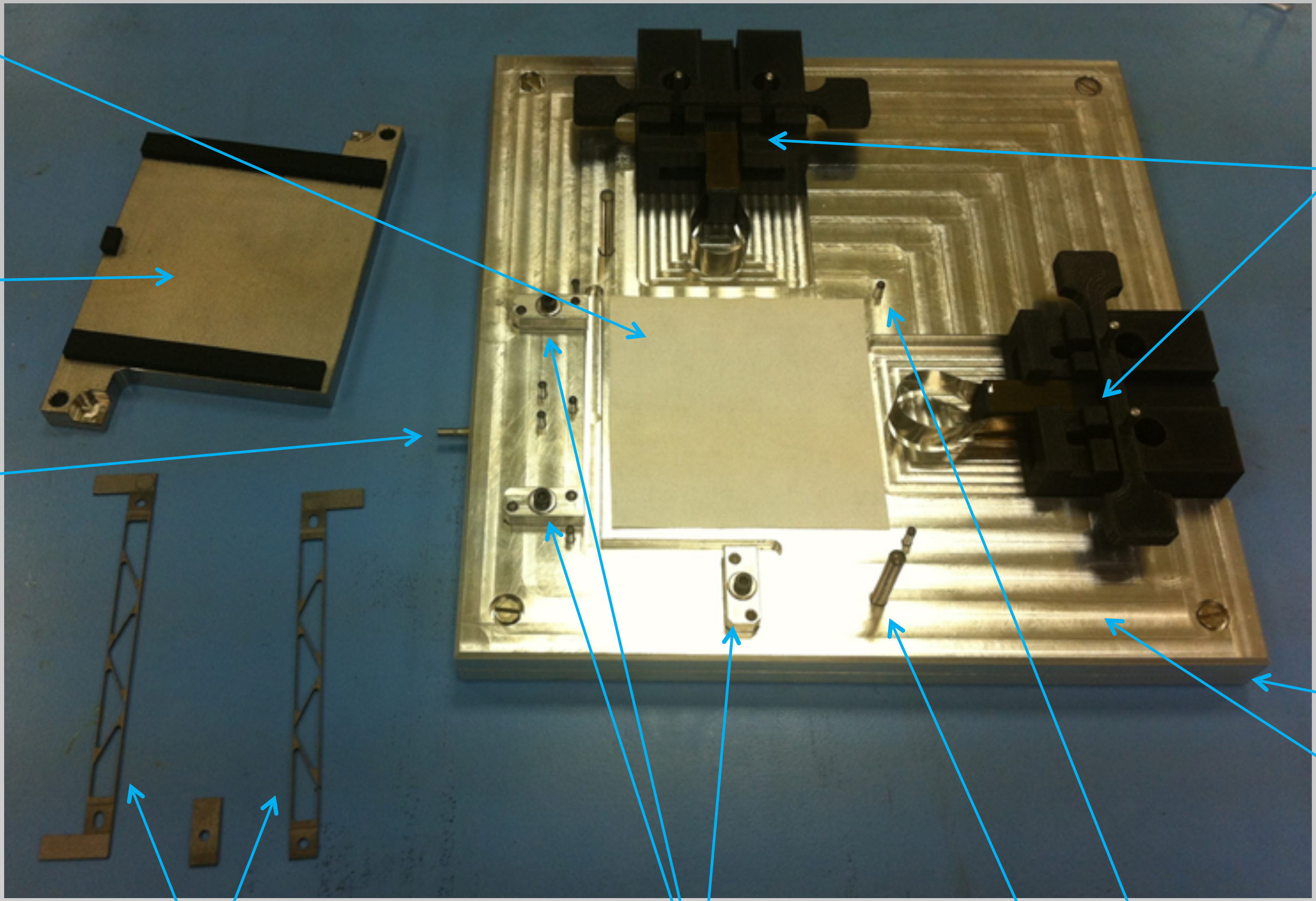
- straight trajectories do not cross the same strip on the sensors of a module
  - offset can be corrected for in the stub finding logic of the chip
  - programmable in steps of 0.5 strips
- a tilt of one sensor with respect to the other introduces a variation of the offset along the strip that cannot be corrected for
- to minimise the effect on the resolution the requirement on the assembly precision is t < 40 µm

2S Module Assembly



- assembly-friendly view
- read-out hybrids are already folded around their spacers
    - done in industry

Manual Module Assembly Jig



Clean room tissue to protect the sensors (250um thick)

Weight plate with foam to push on the bridges

Vacuum hose fitting

2 spring pushing devices, 3D printed, using metal foil bands as springs

Vacuum plate

Base plate

Long bridges with hybrid supports already glued (one support was broken in handling)

3 toes, very precisely machined

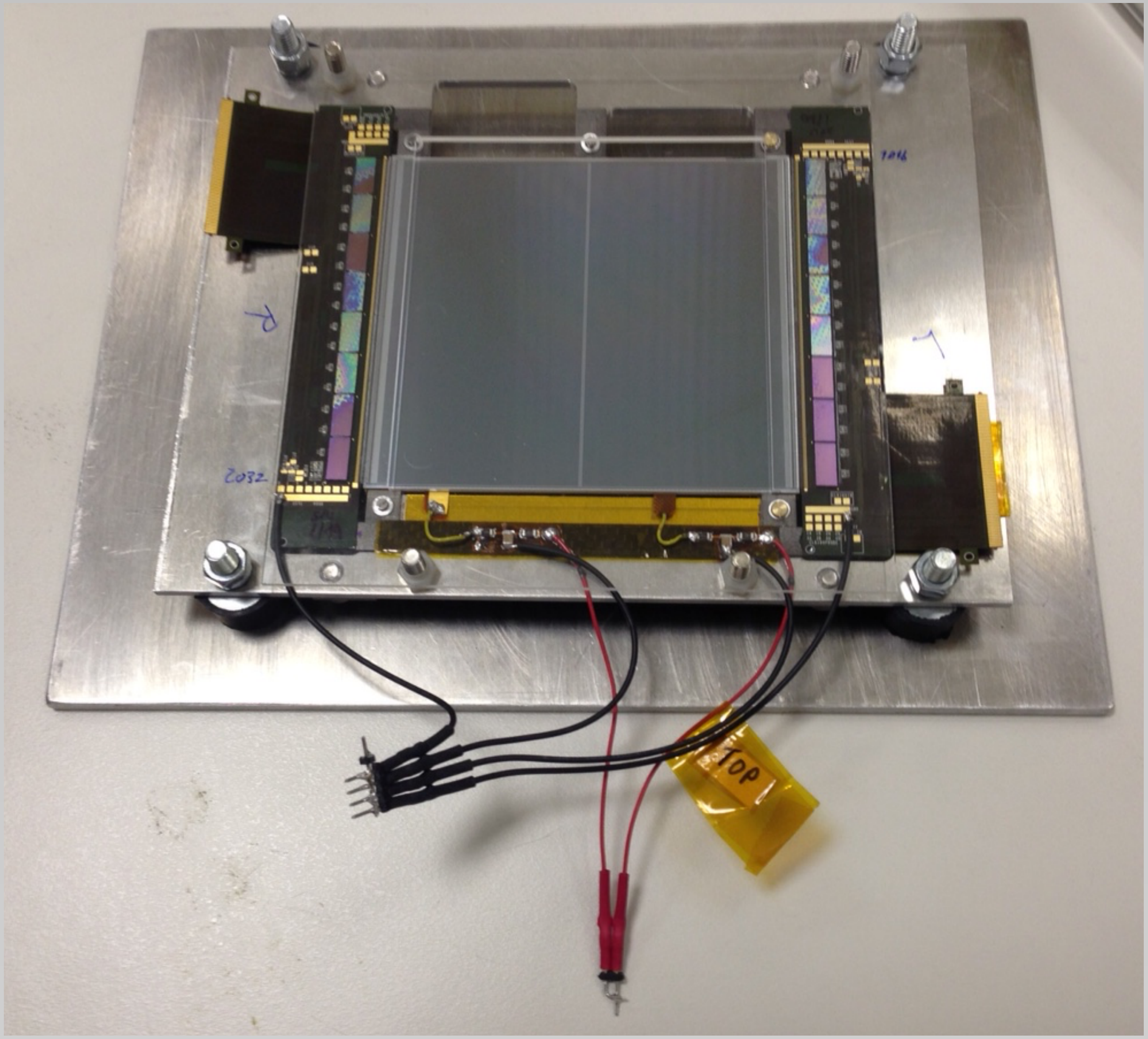
Pins for positioning the bridges

Pins for guiding the weight plate

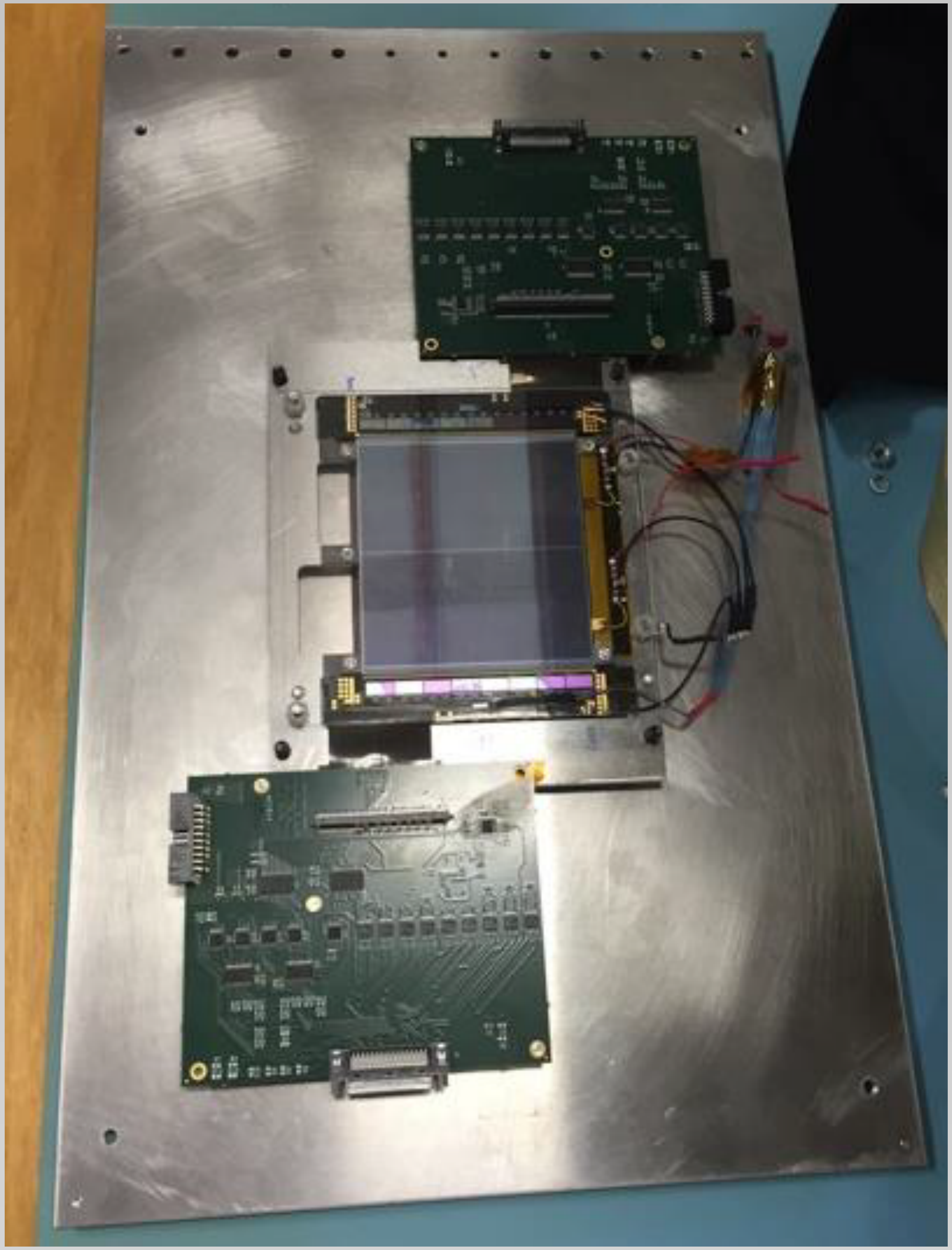
basic steps:

1. gluing of bridges to top sensor
2. gluing of bottom sensor to top sensor package
3. gluing of hybrids to module
4. wire-bonding of top and bottom sides

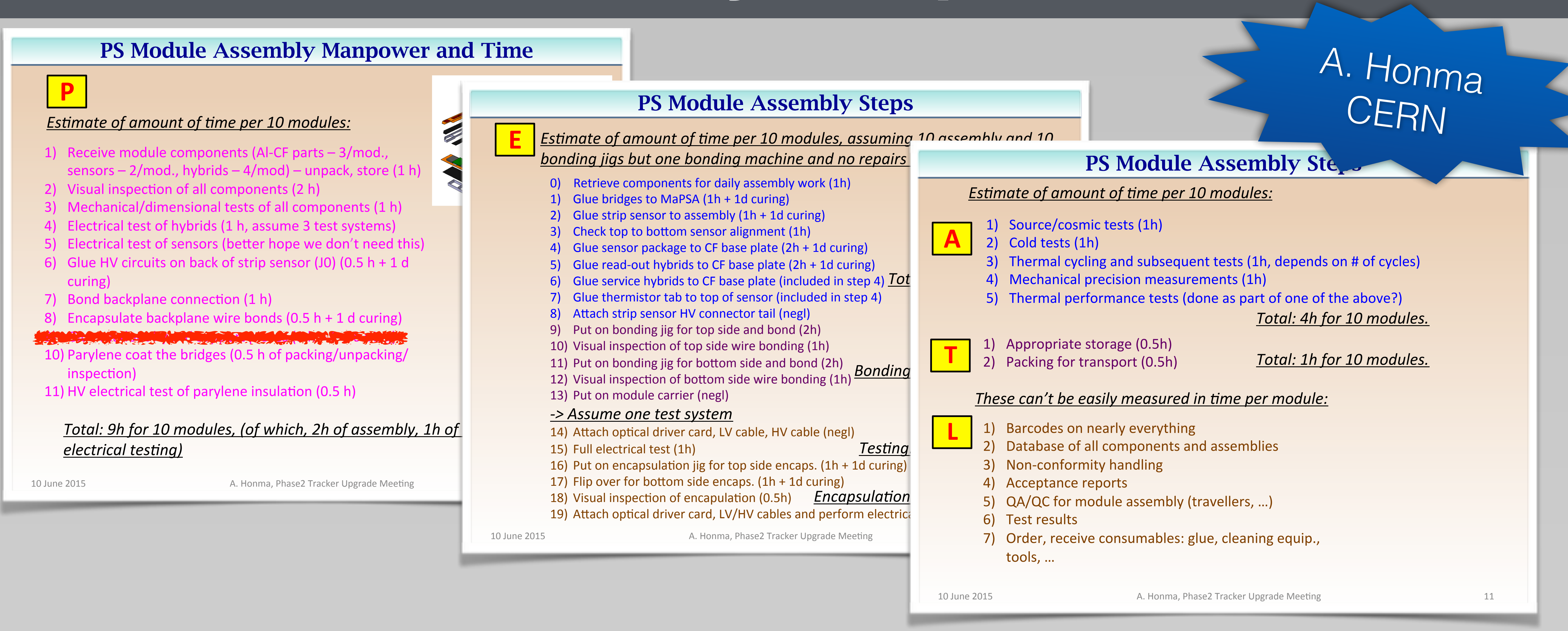
1st Working 2S Module



- module successfully tested in test beam
- sensor to sensor alignment measured in Aachen on two dummy modules
  - 14 / 1 µrad (27 / 13 µrad rms)
  - goal is < 400 µrad



PS Module Assembly Manpower and Time



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PS Module Assembly Manpower and Time

P

Estimate of amount of time per 10 modules:

1) Receive module components (Al-CF parts – 3/mod., sensors – 2/mod., hybrids – 4/mod) – unpack, store (1 h)
2) Visual inspection of all components (2 h)
3) Mechanical/dimensional tests of all components (1 h)
4) Electrical test of hybrids (1 h, assume 3 test systems)
5) Electrical test of sensors (better hope we don't need this)
6) Glue HV circuits on back of strip sensor (J0) (0.5 h + 1 d curing)
7) Bond backplane connection (1 h)
8) Encapsulate backplane wire bonds (0.5 h + 1 d curing)

[redacted]

10) Parylene coat the bridges (0.5 h of packing/unpacking/ inspection)
11) HV electrical test of parylene insulation (0.5 h)

Total: 9h for 10 modules, (of which, 2h of assembly, 1h of electrical testing)

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PS Module Assembly Steps

E

Estimate of amount of time per 10 modules, assuming 10 assembly and 10 bonding jigs but one bonding machine and no repairs

0) Retrieve components for daily assembly work (1h)
1) Glue bridges to MaPSA (1h + 1d curing)
2) Glue strip sensor to assembly (1h + 1d curing)
3) Check top to bottom sensor alignment (1h)
4) Glue sensor package to CF base plate (2h + 1d curing)
5) Glue read-out hybrids to CF base plate (2h + 1d curing)
6) Glue service hybrids to CF base plate (included in step 4) *Tot*
7) Glue thermistor tab to top of sensor (included in step 4)
8) Attach strip sensor HV connector tail (negl)
9) Put on bonding jig for top side and bond (2h)
10) Visual inspection of top side wire bonding (1h)
11) Put on bonding jig for bottom side and bond (2h) *Bonding*
12) Visual inspection of bottom side wire bonding (1h)
13) Put on module carrier (negl)

-> Assume one test system

14) Attach optical driver card, LV cable, HV cable (negl)
15) Full electrical test (1h) *Testing*
16) Put on encapsulation jig for top side encaps. (1h + 1d curing)
17) Flip over for bottom side encaps. (1h + 1d curing)
18) Visual inspection of encapsulation (0.5h) *Encapsulation*
19) Attach optical driver card, LV/HV cables and perform electrica

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PS Module Assembly Steps

Estimate of amount of time per 10 modules:

A

1) Source/cosmic tests (1h)
2) Cold tests (1h)
3) Thermal cycling and subsequent tests (1h, depends on # of cycles)
4) Mechanical precision measurements (1h)
5) Thermal performance tests (done as part of one of the above?)

Total: 4h for 10 modules.

T

1) Appropriate storage (0.5h)
2) Packing for transport (0.5h)

Total: 1h for 10 modules.

These can't be easily measured in time per module:

L

1) Barcodes on nearly everything
2) Database of all components and assemblies
3) Non-conformity handling
4) Acceptance reports
5) QA/QC for module assembly (travellers, …)
6) Test results
7) Order, receive consumables: glue, cleaning equip., tools, …

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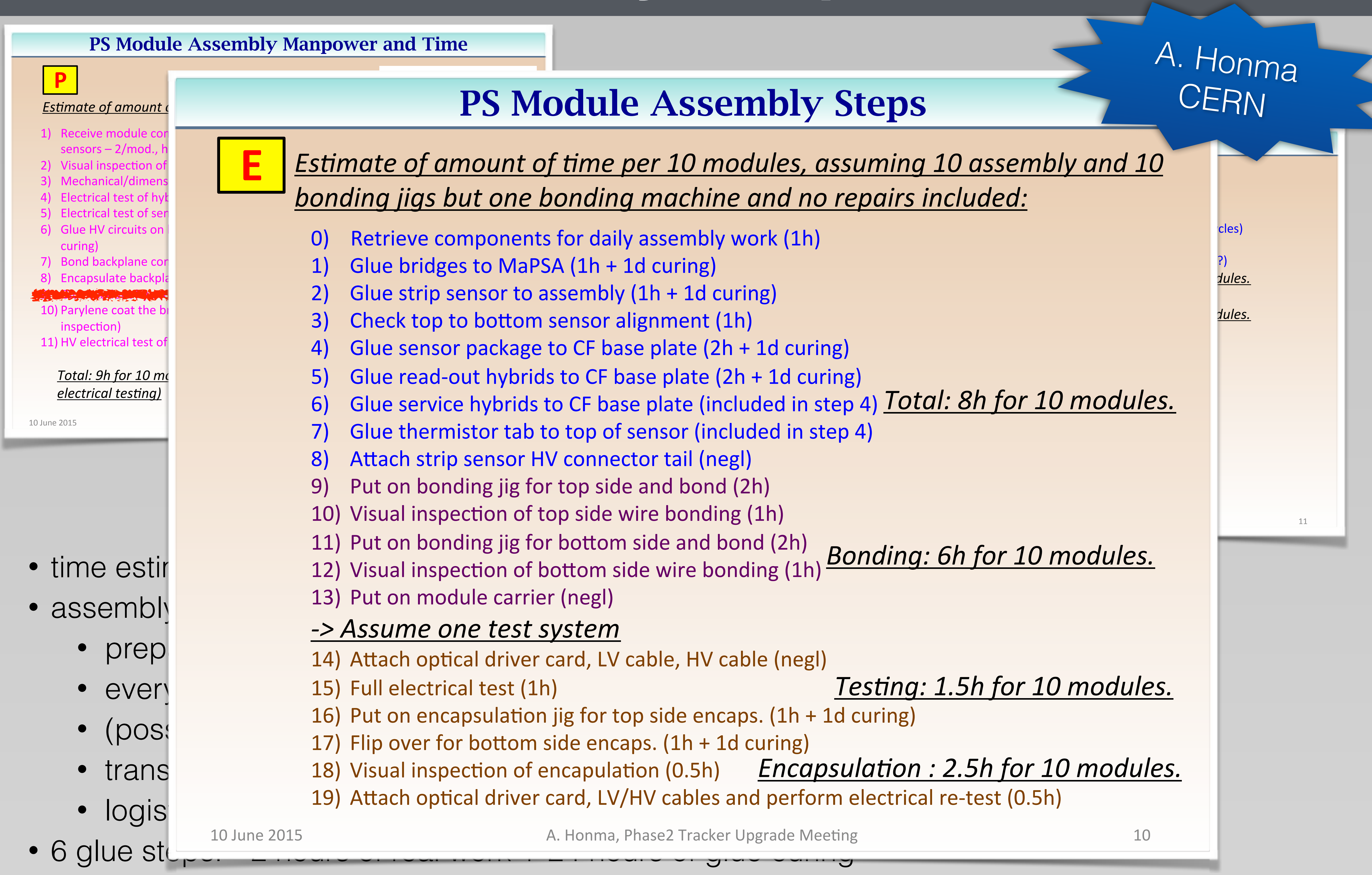
- time estimates are for production of 10 modules in parallel
- assembly steps in different categories
  - preparatory steps: **P**
  - everyday steps: **E**
  - (possible) additional steps: **A**
  - transport: **T**
  - logistics: **L**
- 6 glue steps: ~2 hours of real work + 24 hours of glue curing

PS Module Assembly Manpower and Time



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Total: 9h for 10 mo electrical testing)

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PS Module Assembly Steps

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Estimate of amount of time per 10 modules, assuming 10 assembly and 10 bonding jigs but one bonding machine and no repairs included:

0) Retrieve components for daily assembly work (1h)
1) Glue bridges to MaPSA (1h + 1d curing)
2) Glue strip sensor to assembly (1h + 1d curing)
3) Check top to bottom sensor alignment (1h)
4) Glue sensor package to CF base plate (2h + 1d curing)
5) Glue read-out hybrids to CF base plate (2h + 1d curing)
6) Glue service hybrids to CF base plate (included in step 4)
7) Glue thermistor tab to top of sensor (included in step 4)
8) Attach strip sensor HV connector tail (negl)

Total: 8h for 10 modules.

9) Put on bonding jig for top side and bond (2h)
10) Visual inspection of top side wire bonding (1h)
11) Put on bonding jig for bottom side and bond (2h)
12) Visual inspection of bottom side wire bonding (1h)
13) Put on module carrier (negl)

Bonding: 6h for 10 modules.

-> Assume one test system

14) Attach optical driver card, LV cable, HV cable (negl)
15) Full electrical test (1h)

Testing: 1.5h for 10 modules.

16) Put on encapsulation jig for top side encaps. (1h + 1d curing)
17) Flip over for bottom side encaps. (1h + 1d curing)
18) Visual inspection of encapulation (0.5h)

Encapsulation : 2.5h for 10 modules.

19) Attach optical driver card, LV/HV cables and perform electrical re-test (0.5h)

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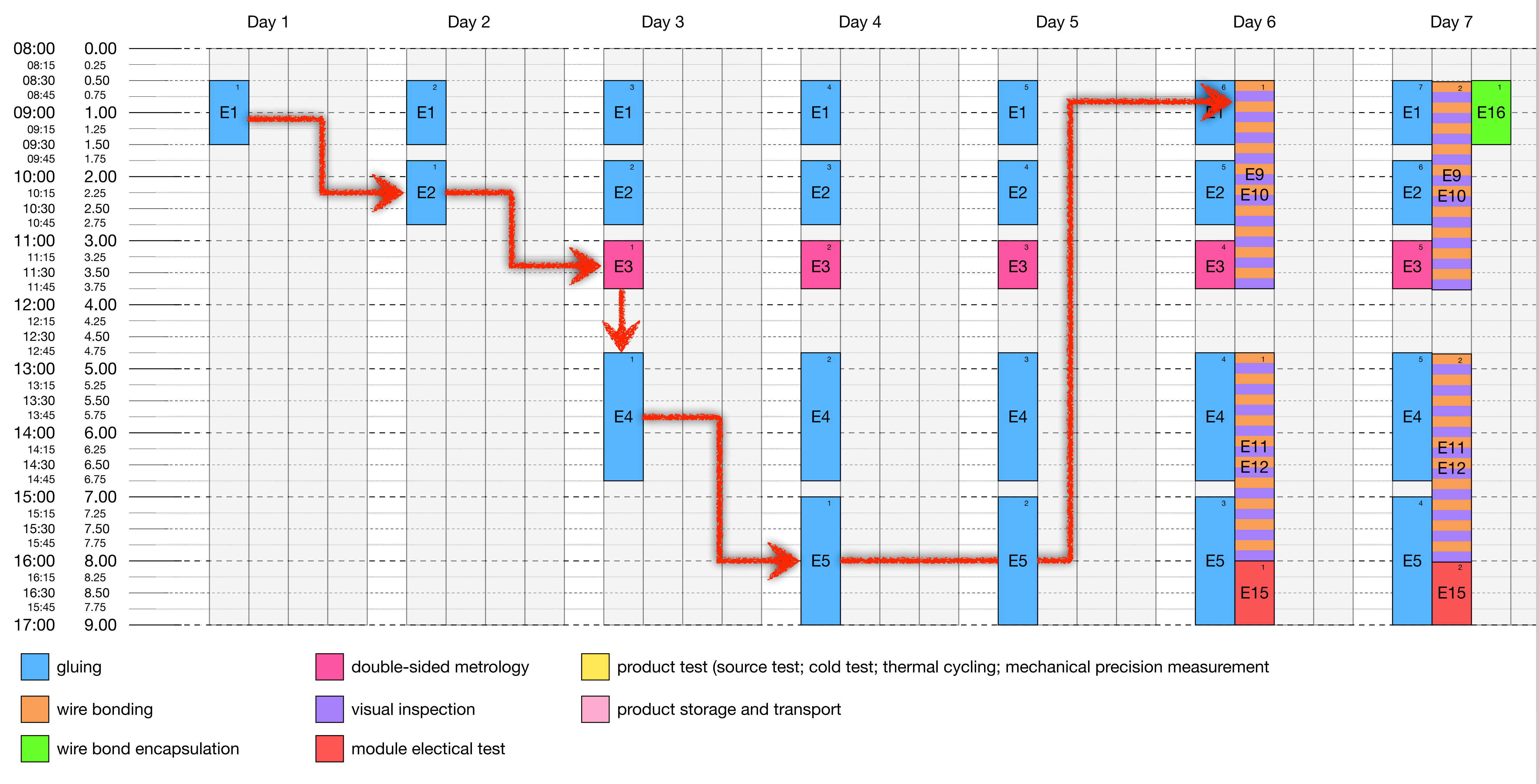
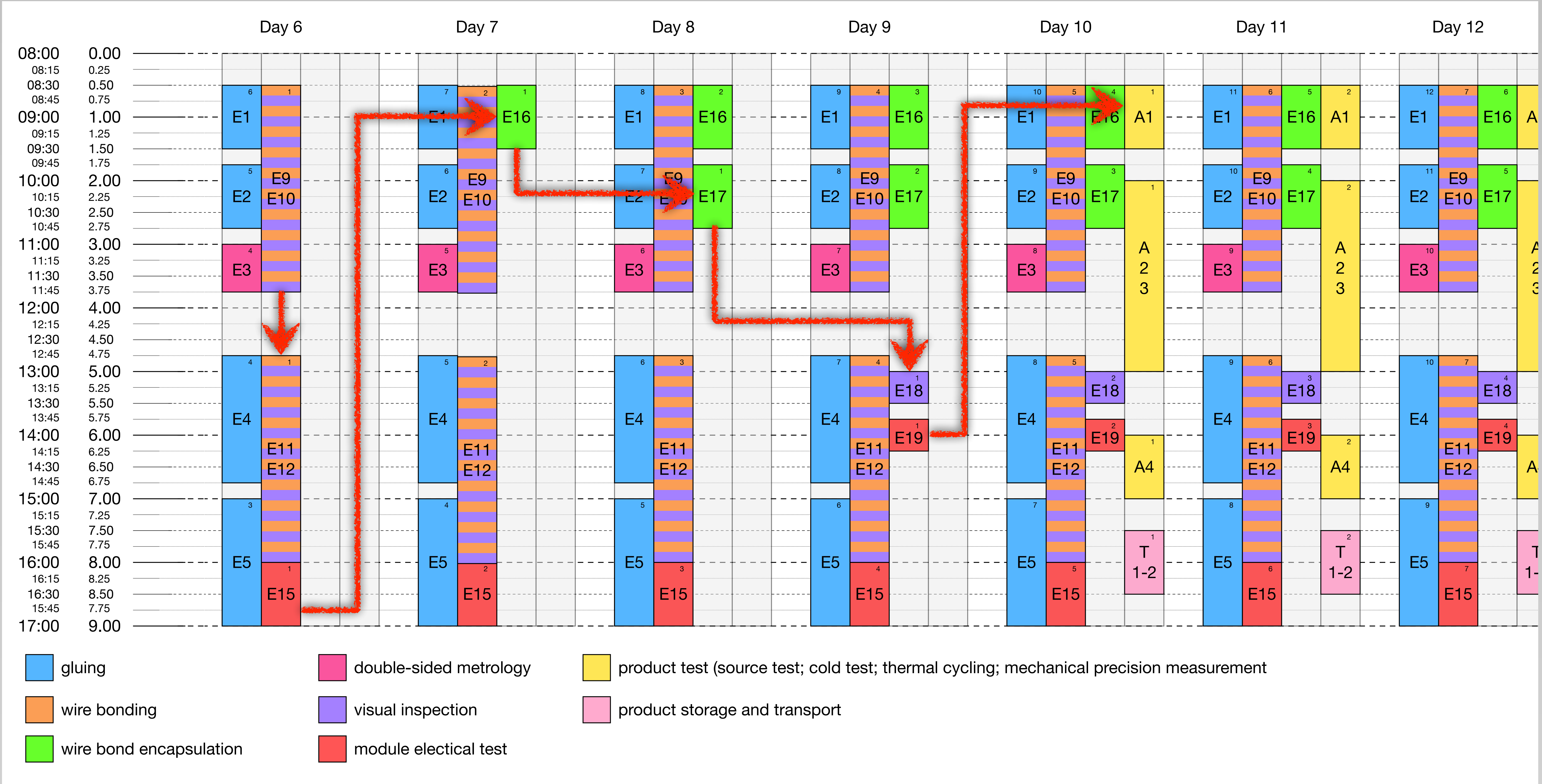
Every Day Assembly Steps - Day 1 - 5



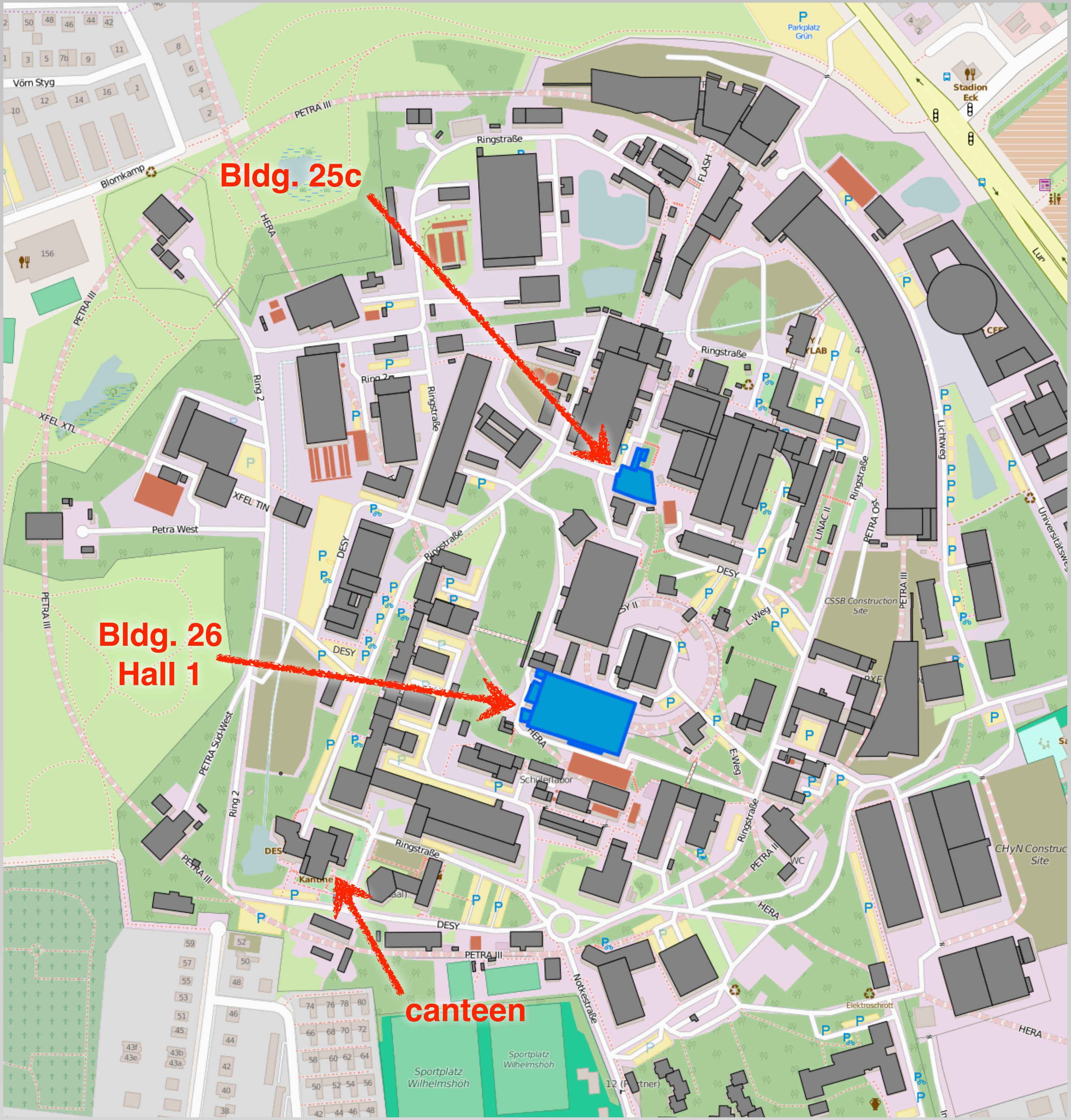
- every gluing step requires curing for 24 hours
  - two sets of jigs (set A and B) with ten jigs in each set are needed for each type of jig in order to minimise number of module handling steps
  - storage for every gluing step is needed
- gluing station is occupied most of the day

Every Day Assembly Steps - Day 6 - 12



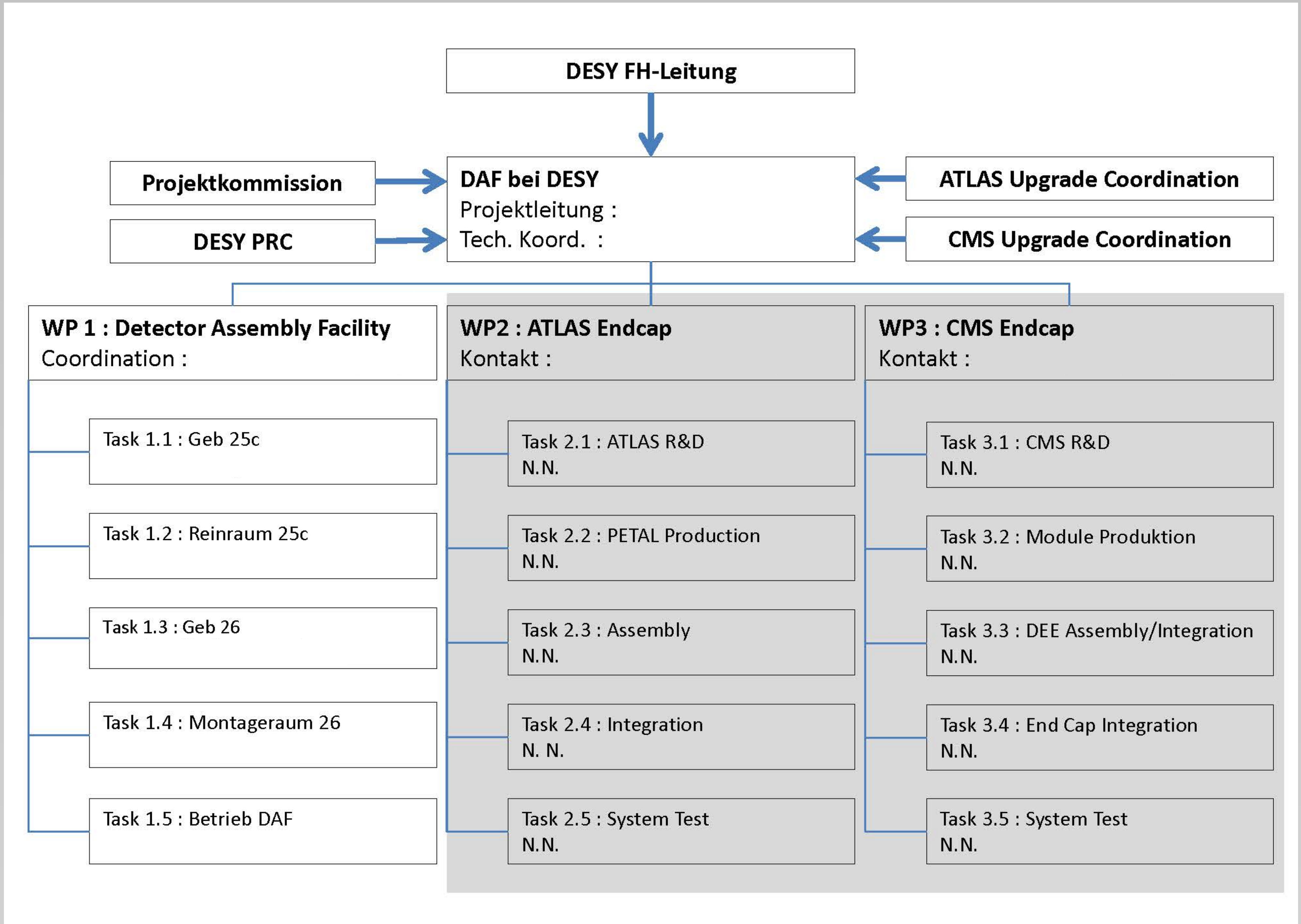
- wire bonding for one batch of modules is done on the same day
- tests, packaging and storage for one batch of modules are done on the same day
- full production mode established after 10 working days

Detector Assembly Facility - DAF



- German community plans to build one tracker end cap for both ATLAS and CMS
- dedicated ***D**etector **A**ssembly **F**acility* at DESY
  - partial module production
  - (partial) integration of sub-structures
  - integration of end caps
- approved by DESY directorate in December 2015
- facility split into two sites
  - building 25c: clean room (ISO 6)
  - building 26 (Hall 1): assembly lab and integration hall (ISO 7)
- organised as a DESY project
  - project proposal almost final
- planning office (TGA, technical building equipment) has been contacted

DAF Project Structure



DESY FH-Leitung

DAF bei DESY
Projektleitung :
Tech. Koord. :

Projektkommission

DESY PRC

ATLAS Upgrade Coordination

CMS Upgrade Coordination

WP 1 : Detector Assembly Facility
Coordination :

- Task 1.1 : Geb 25c
- Task 1.2 : Reinraum 25c
- Task 1.3 : Geb 26
- Task 1.4 : Montageraum 26
- Task 1.5 : Betrieb DAF

WP2 : ATLAS Endcap
Kontakt :

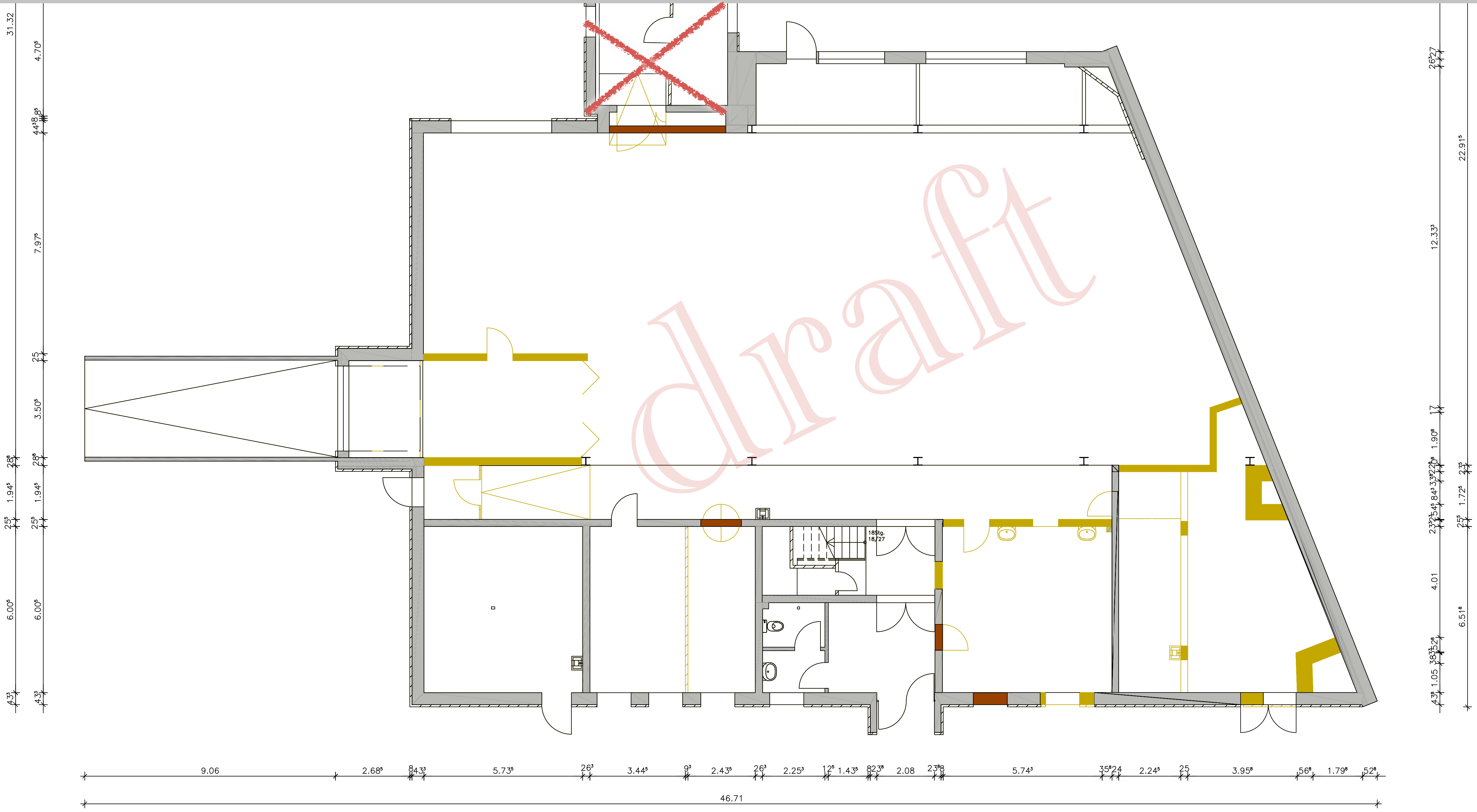
- Task 2.1 : ATLAS R&D
  N.N.
- Task 2.2 : PETAL Production
  N.N.
- Task 2.3 : Assembly
  N.N.
- Task 2.4 : Integration
  N. N.
- Task 2.5 : System Test
  N.N.

WP3 : CMS Endcap
Kontakt :

- Task 3.1 : CMS R&D
  N.N.
- Task 3.2 : Module Produktion
  N.N.
- Task 3.3 : DEE Assembly/Integration
  N.N.
- Task 3.4 : End Cap Integration
  N.N.
- Task 3.5 : System Test
  N.N.

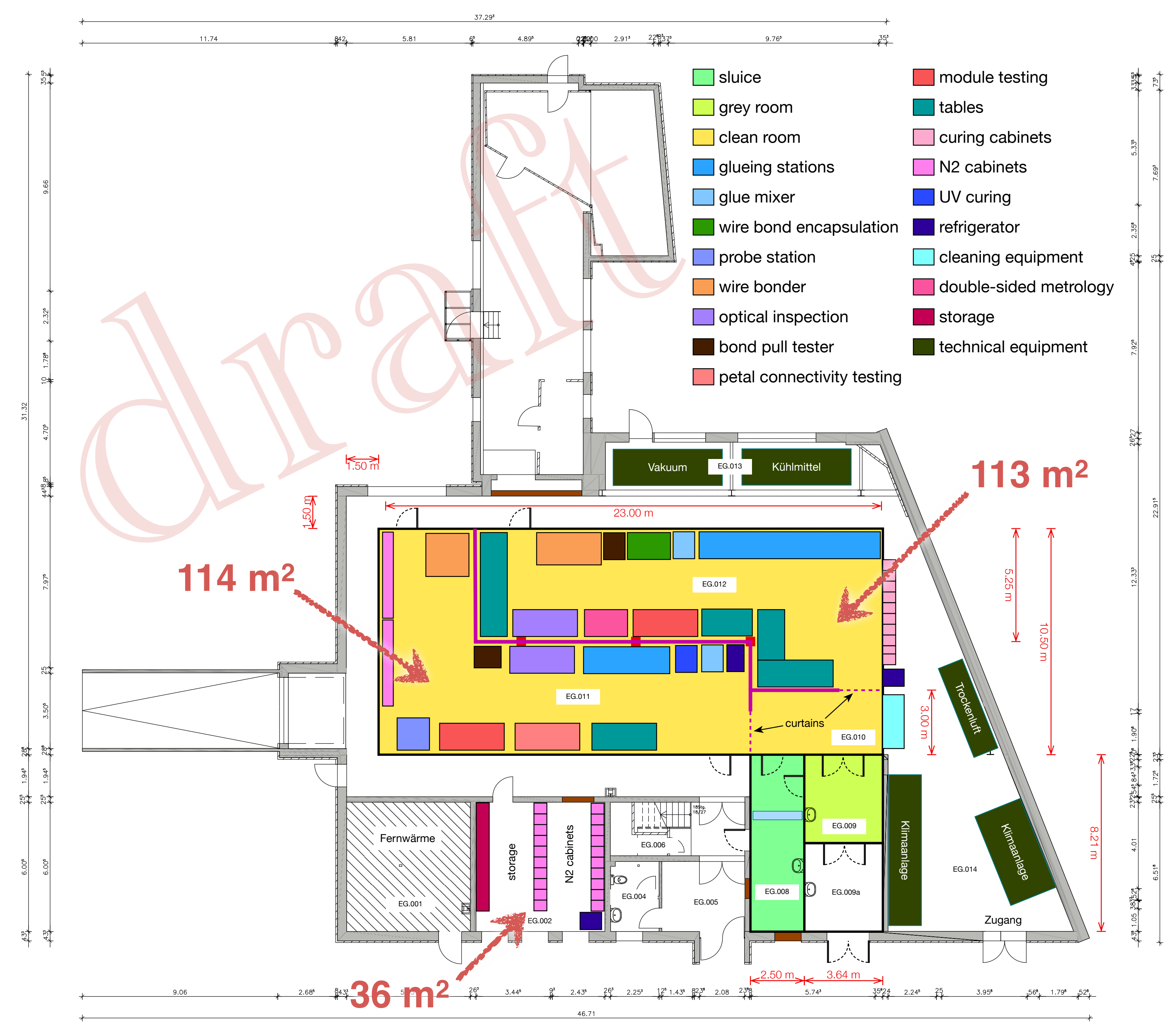
- greyish parts - the actual detectors - are pending funding by Helmholtz
  - hopes are high…
- WPs 2 and 3 are yet too be defined in detail (not part of project proposal)

Bldg. 25c EG - Floor Plan



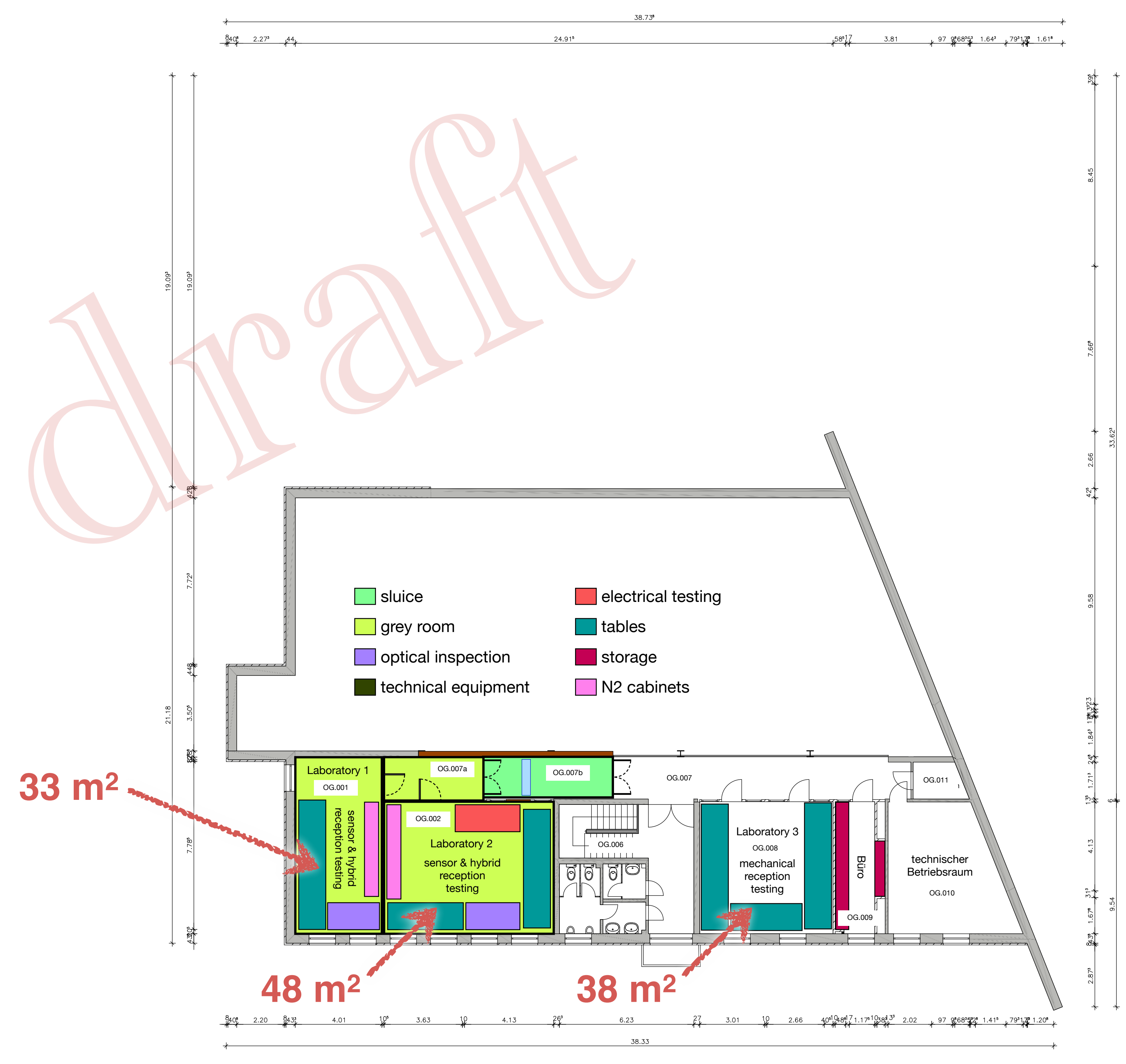
- complete area is available to the DAF

Bldg. 25c EG - ISO 6 Clean Room



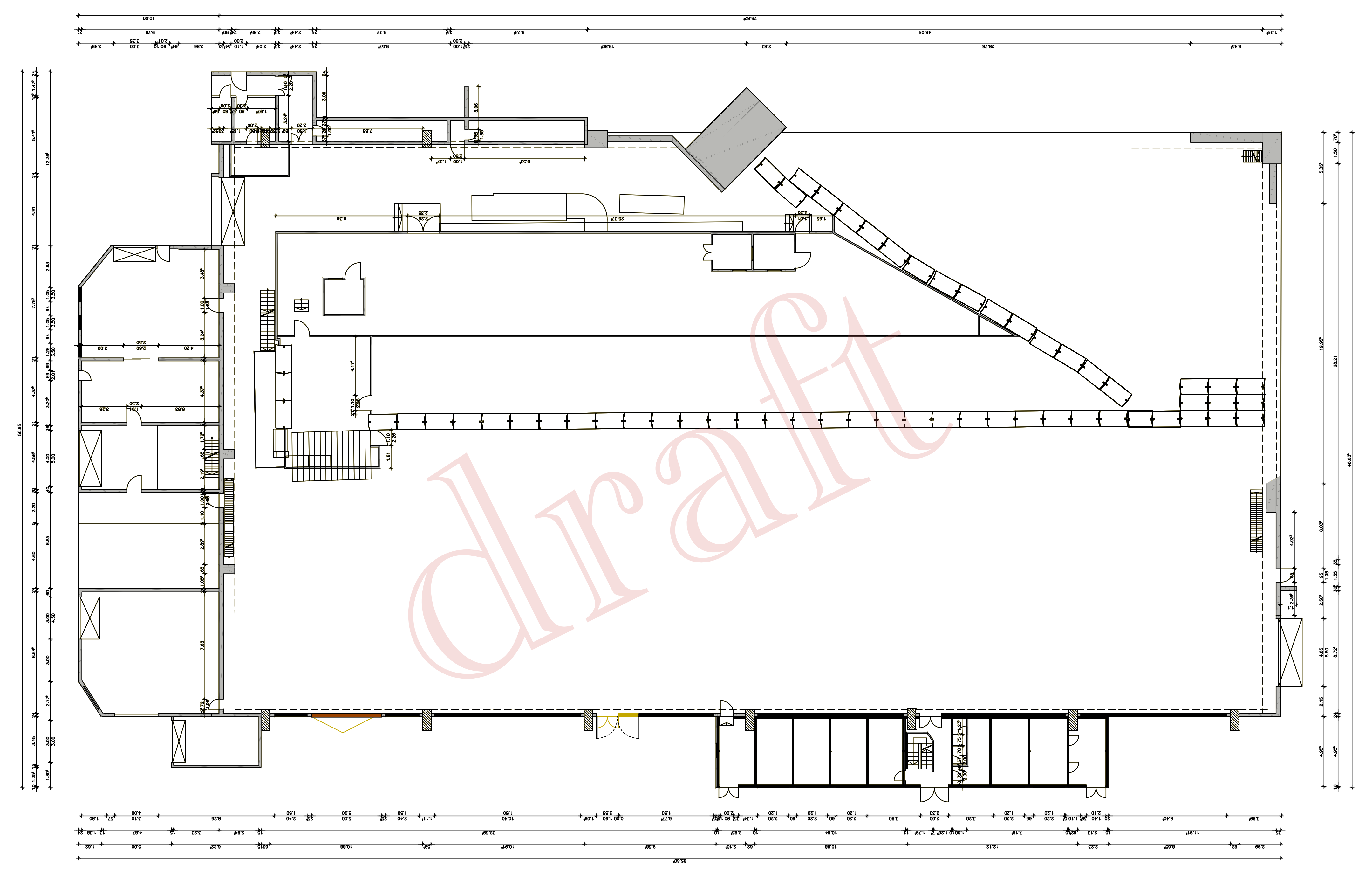
- a physicists view of a
  - clean room incl. infrastructure and
  - possible usage of the available space (2 x ~110 m²)
- details concerning building and clean room have to be iterated with planning office
  - this will define the final number for the space available
- usage has to be iterated with involved university groups

Bldg. 25c OG



- details concerning building and clean room have to be iterated with planning office
  - this will define the final number for the space available
- usage has to be iterated with involved university groups

Bldg. 26 - Assembly and Integration



- will be covered in next presentation…

Forum on Tracking Detector Mechanics 2016

A meeting to discuss issues of engineering and integration for present and future tracking systems

- 23 - 25 May 2016
- University of Bonn
- http://indico.cern.ch/event/469996
- registration still open…

- Topics:
  - Detector cooling
  - Deflection, stability and precision of the structures
  - Thermal expansion differences inside the detector
  - Mass and therefore radiation length of mechanics, cables and pipes
  - Humidity control
  - Structural issues concerning humidity or outgassing
  - Choices of construction materials
  - Alignment systems, requirements and "weak modes" of the system
  - Pipe materials, pipe connection techniques and fittings
  - Shock and vibration issues
  - Effects on mechanics during fast discharge of magnet coils
  - Tracker to beam-pipe interfaces
  - Radiation and mechanics: impacts on design, materials and access constraints
  - Maintenance scenarios and the required special tooling
  - FEA and its comparison to real objects

Forum on Tracking Detector Mechanics 2016

23-25 May 2016, Bonn (Germany)

A meeting to discuss issues of engineering and integration for present and future tracking systems.

TOPICAL INTEREST

- Mechanical design
- Quality control
- FEA Simulations
- Thermal management
- System integration
- Lessons learned

ORGANISING COMMITTEE

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Summary

- CMS will use two different module types throughout the LH-LHC tracker
    - 2S and PS module
    - different variants
- only two designs need to be optimised
- PS module shows good thermal performance
- some room for improvements in case of the 2S module

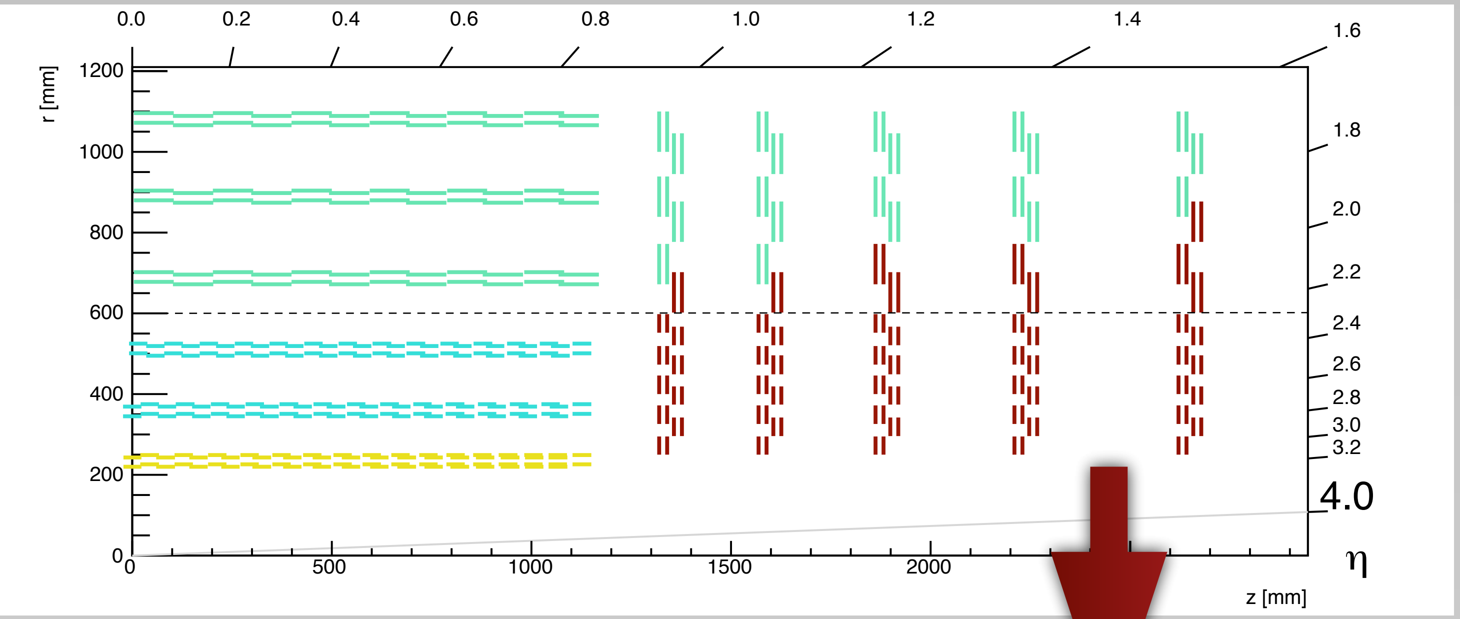
- p_T-discrimination on module level requires precise sensor to sensor alignment
- manual assembly scheme shows excellent results for 2S modules
- concept seems also be possible in case of the PS module

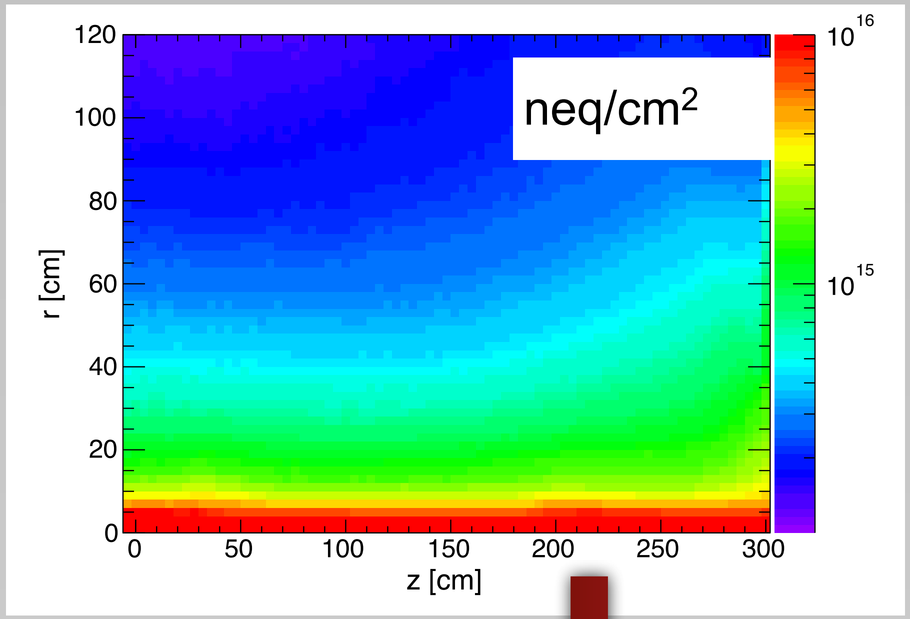
- large scale module production is challenging but appears manageable

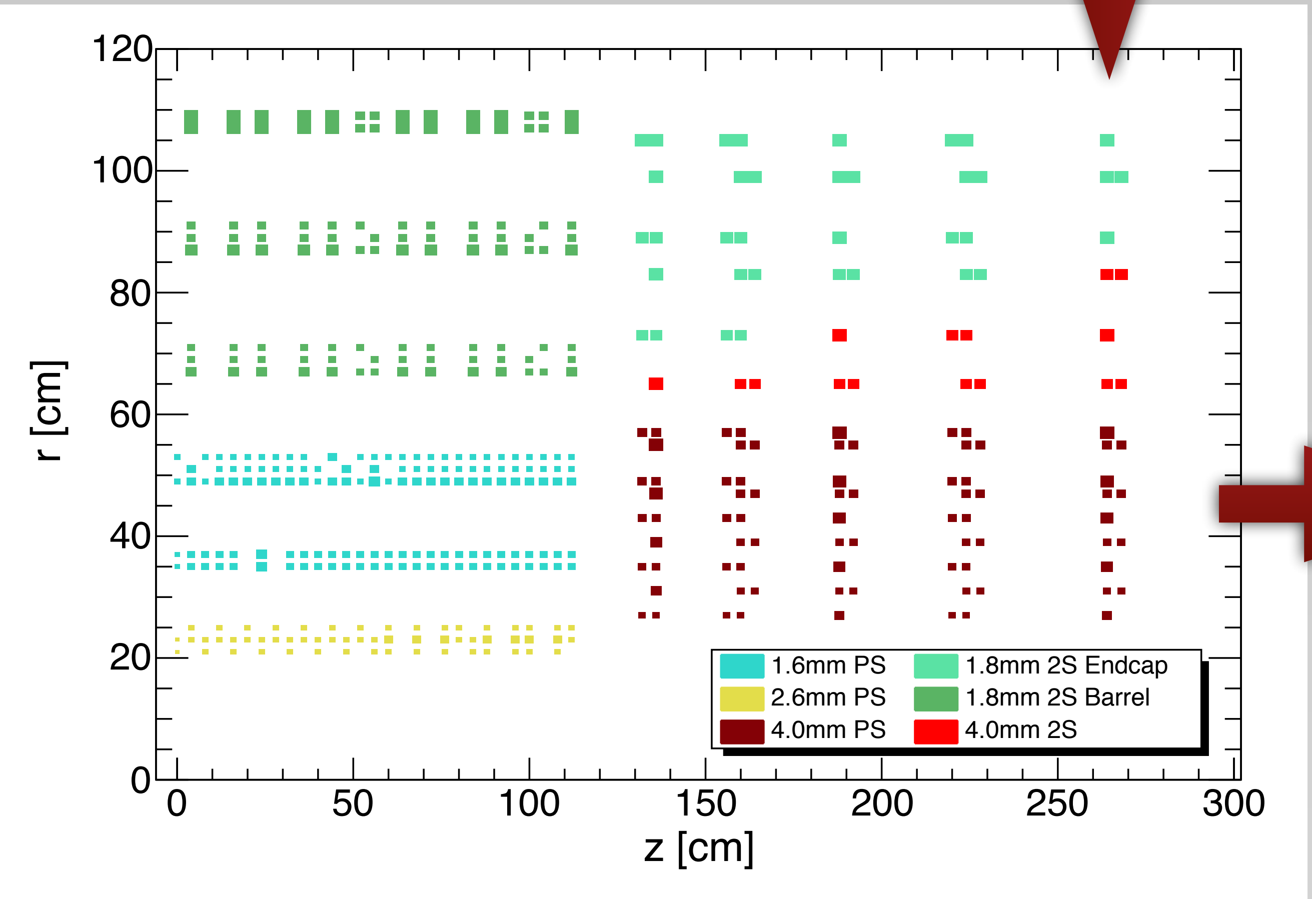
- detector assembly facility will become reality

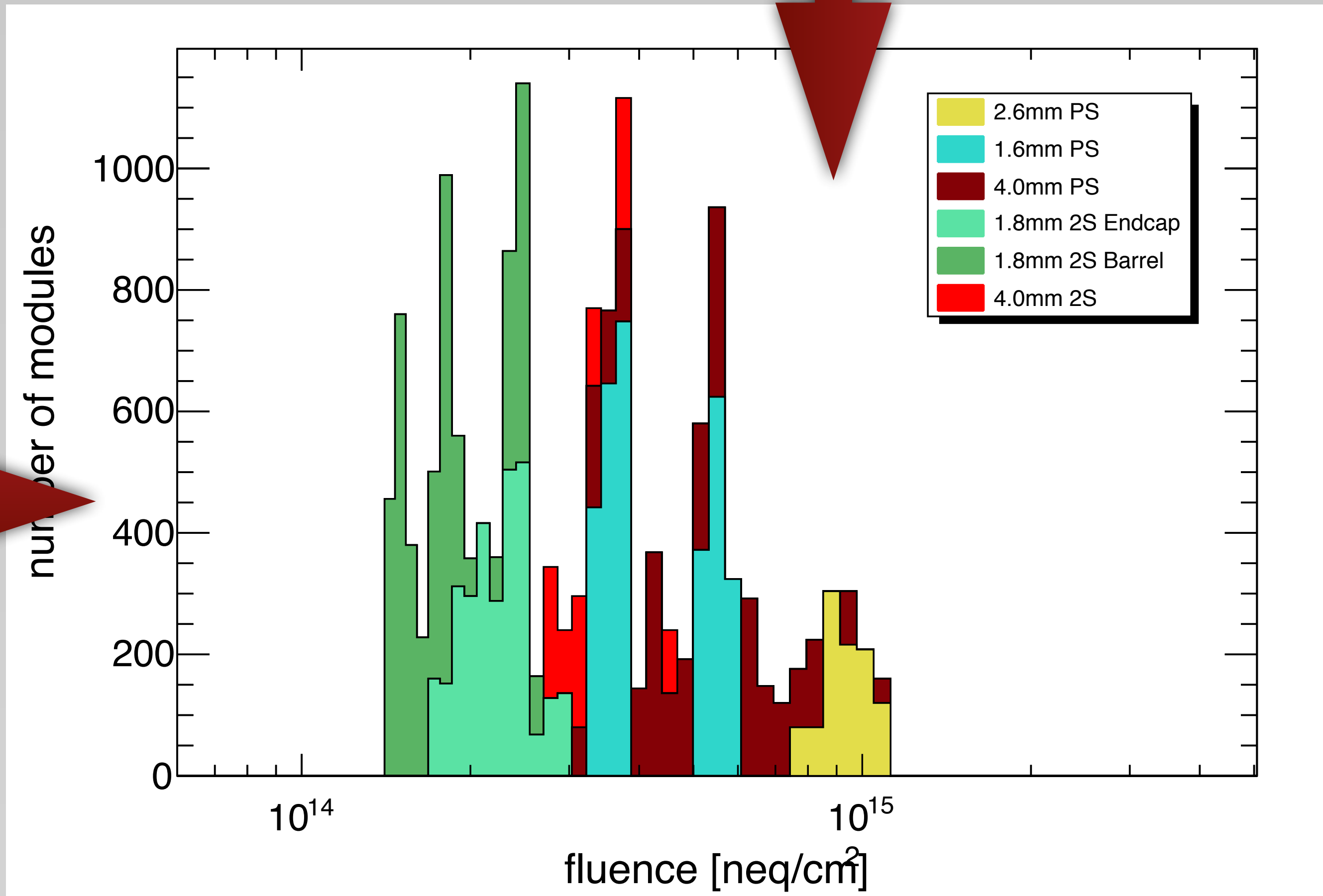
Backup

Sensor Power Generation

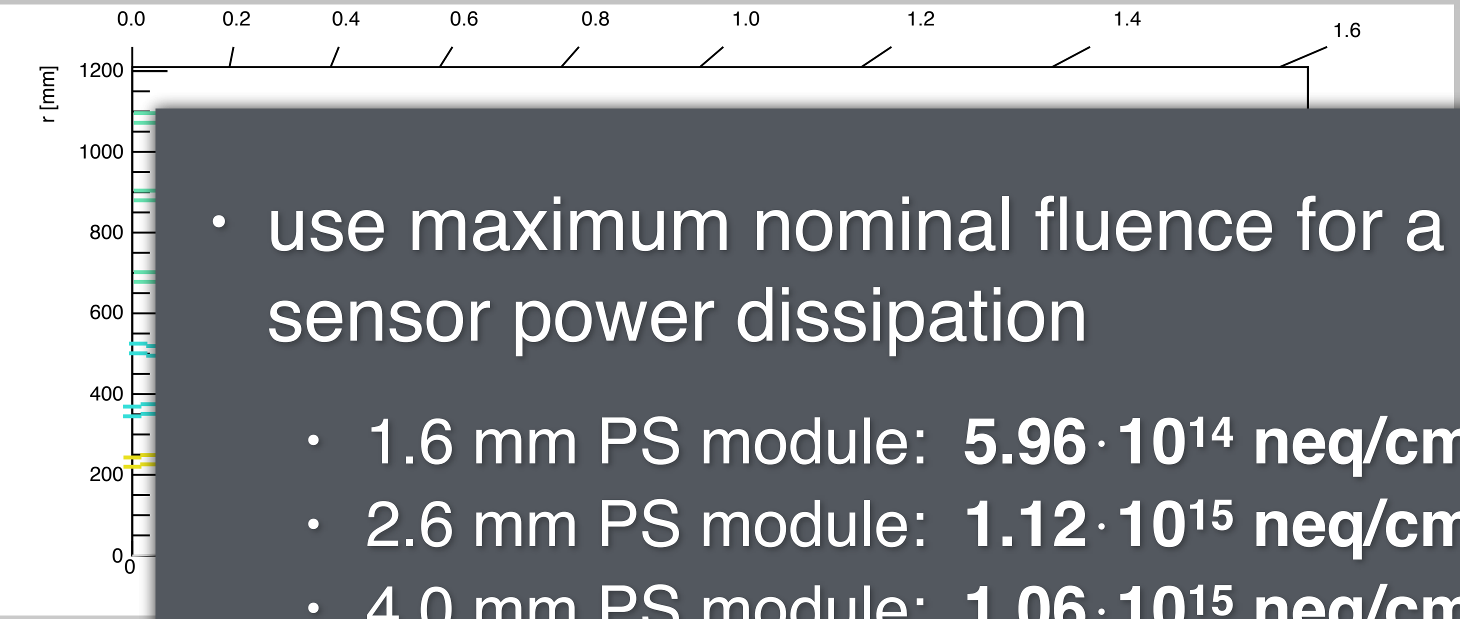


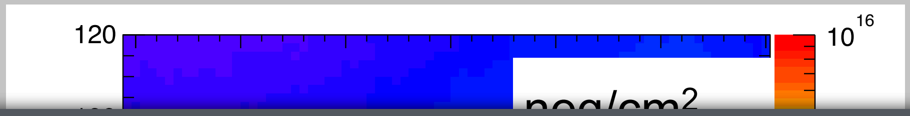




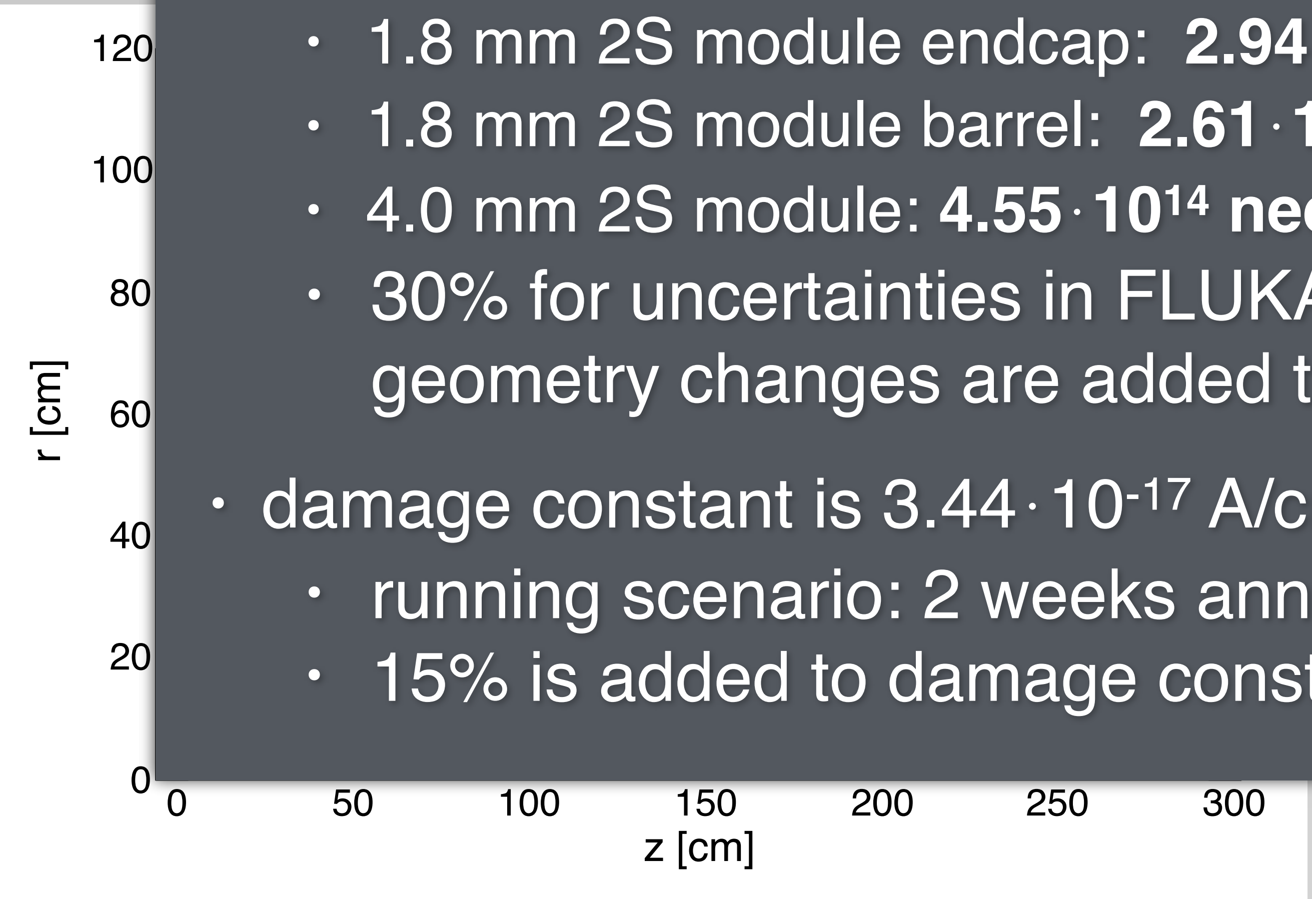


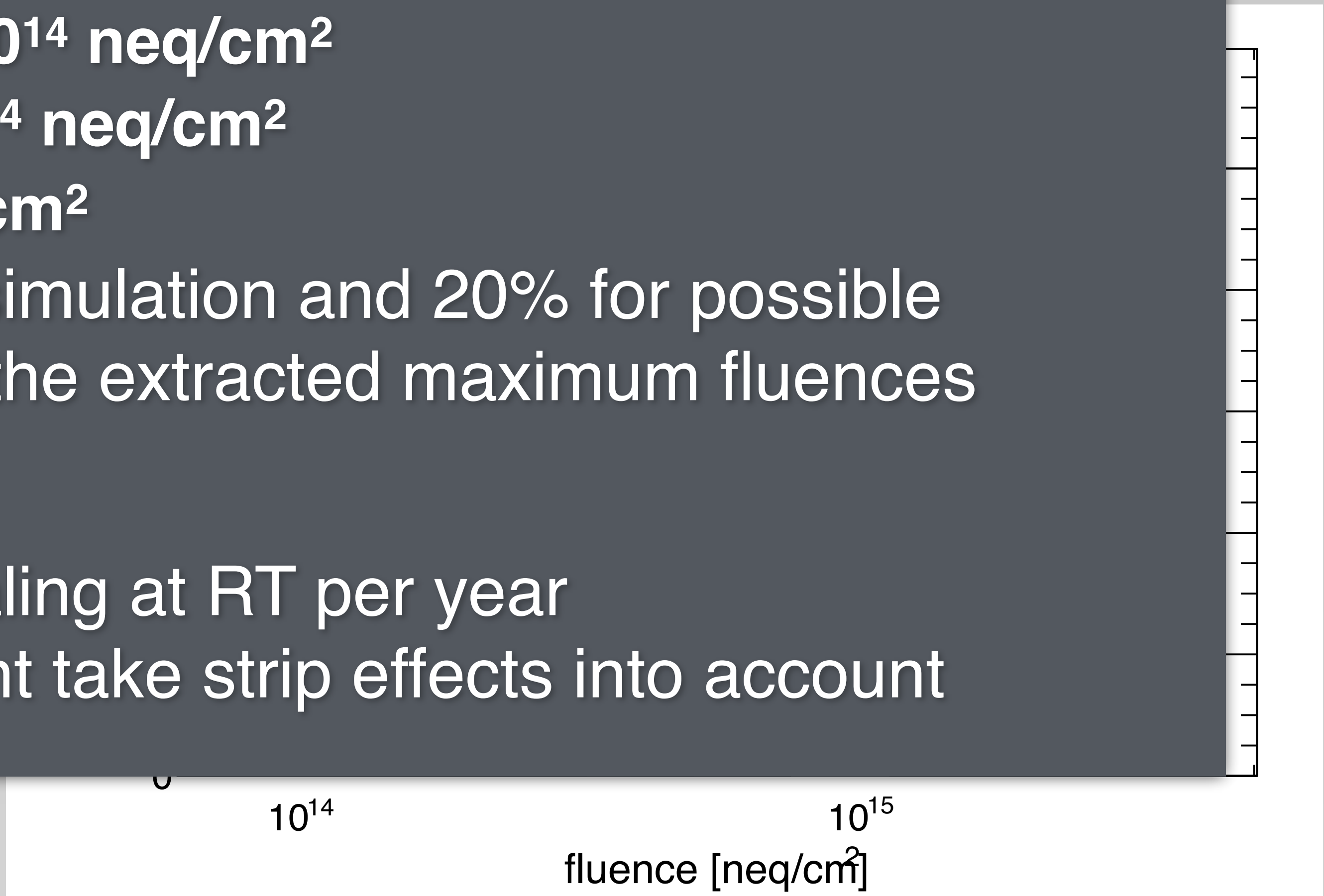
Sensor Power Generation



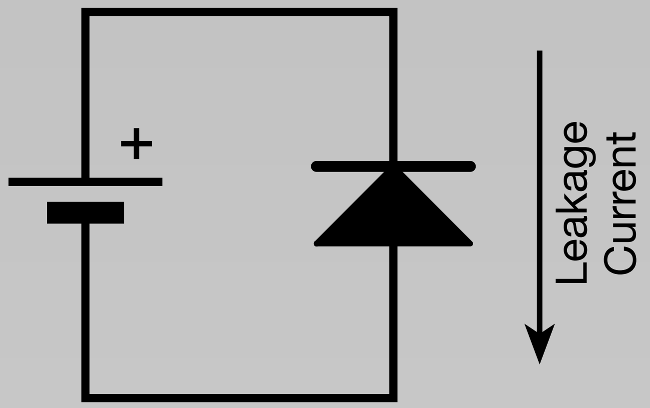


- use maximum nominal fluence for a given module type to estimate sensor power dissipation
  - 1.6 mm PS module: **$5.96 \cdot 10^{14}$ neq/cm²**
  - 2.6 mm PS module: **$1.12 \cdot 10^{15}$ neq/cm²**
  - 4.0 mm PS module: **$1.06 \cdot 10^{15}$ neq/cm²**
  - 1.8 mm 2S module endcap: **$2.94 \cdot 10^{14}$ neq/cm²**
  - 1.8 mm 2S module barrel: **$2.61 \cdot 10^{14}$ neq/cm²**
  - 4.0 mm 2S module: **$4.55 \cdot 10^{14}$ neq/cm²**
  - 30% for uncertainties in FLUKA simulation and 20% for possible geometry changes are added to the extracted maximum fluences
- damage constant is $3.44 \cdot 10^{-17}$ A/cm
  - running scenario: 2 weeks annealing at RT per year
  - 15% is added to damage constant take strip effects into account





Sensor Power Generation



- a silicon sensor is essentially a reverse biased diode
- leakage current produces heat

$$P = U_{bias} \cdot I_{leakage}$$

- leakage current at room temperature is a function of
  - sensor volume $V = 200\ \mu\mathrm{m} \cdot 9.87\ \mathrm{cm} \cdot 4.92\ \mathrm{cm} = 0.9712\ \mathrm{cm}^3$
  - fluence $\Phi_{\mathrm{eq}} = 1.5 \cdot 10^{15}\ \mathrm{n_{eq}/cm^2}$
  - damage constant $\alpha = 4.0 \cdot 10^{-17}\ \mathrm{A/cm}$

$$I_{leakage}^{RT} = V \cdot \phi \cdot \alpha = 0.9712\ \mathrm{cm}^3 \cdot 1.5 \cdot 10^{15}\ \mathrm{n_{eq}/cm^2} \cdot 4.0 \cdot 10^{-17}\ \mathrm{A/cm} = 58\ \mathrm{mA}$$

- leakage current is a function of temperature $I \propto (kT)^2 \exp\left(-\frac{1.21\ \mathrm{eV}}{kT}\right)$

- in this example I = 0.99 mA at -20 °C
- for a bias voltage of 600 V the heat produced by the sensor is 593 mW

- need a temperature dependent heat source in FEA