Design and cooling of the tracking detector for the P2 experiment

Michail Kravchenko

PhD student, AG Berger
PRISMA+ Cluster of Excellence/
Institute for Nuclear Physics,
Johannes Gutenberg University Mainz

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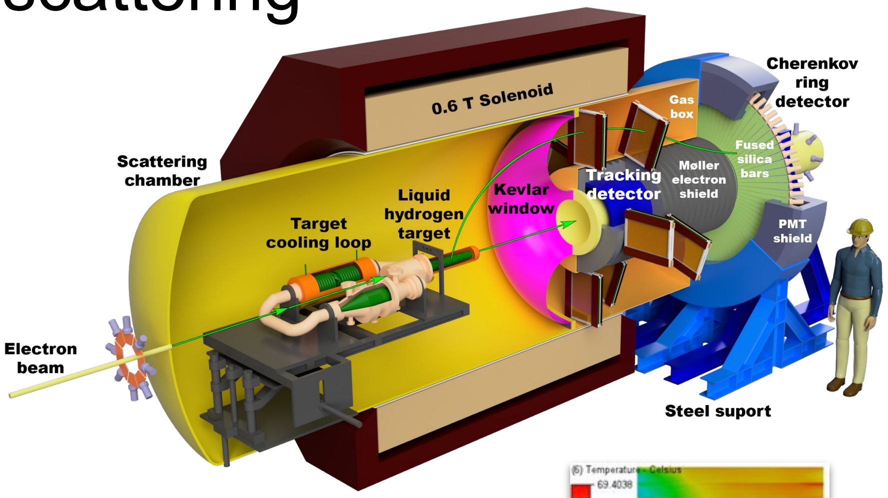
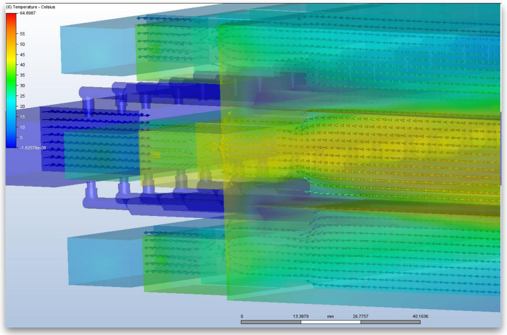
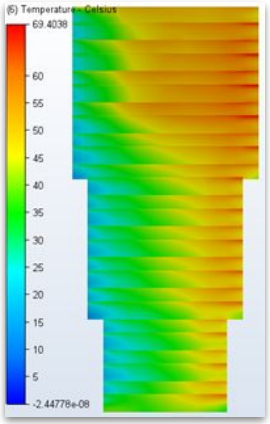


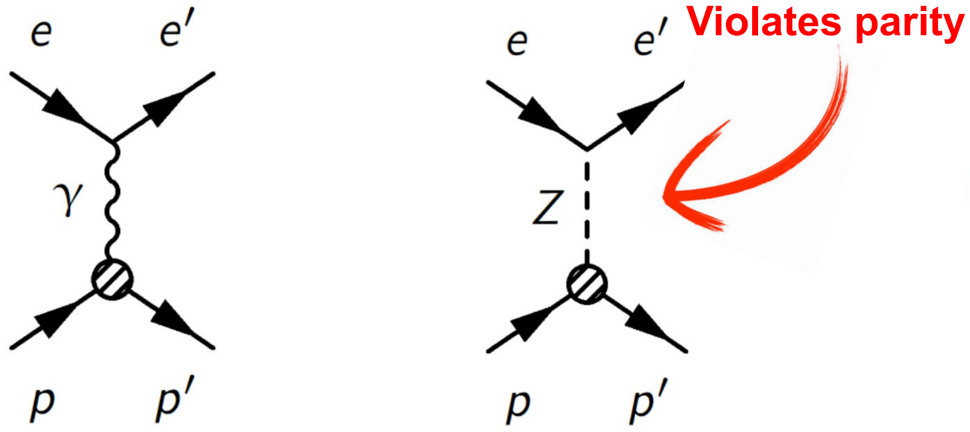




The P2 experiment: overview and theory

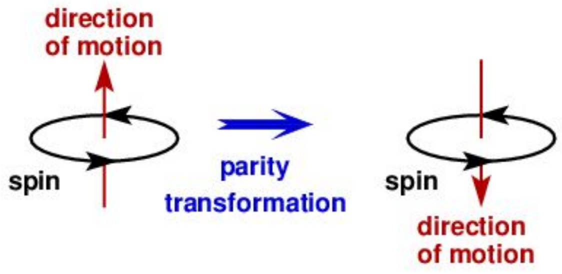
The weak mixing angle
(Weinberg-angle)

$$\boxed{\sin^2\theta_W = \frac{g'^2}{g^2+g'^2}}$$

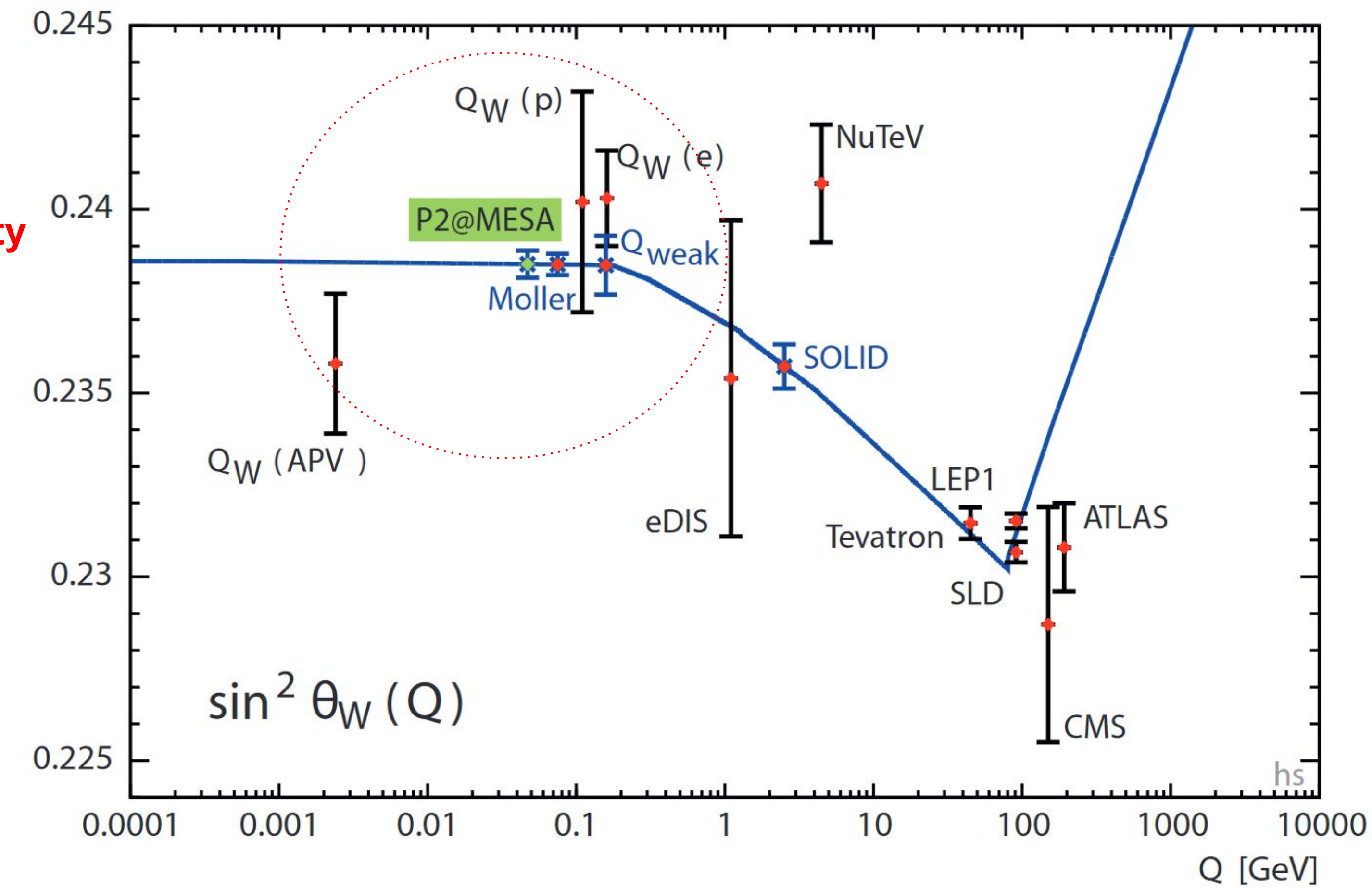


Proton electric charge
$+1$

Proton weak charge
$1 - 4\sin^2\theta_W$



Scale dependence (running) of $\sin^2\theta_W(Q^2)$



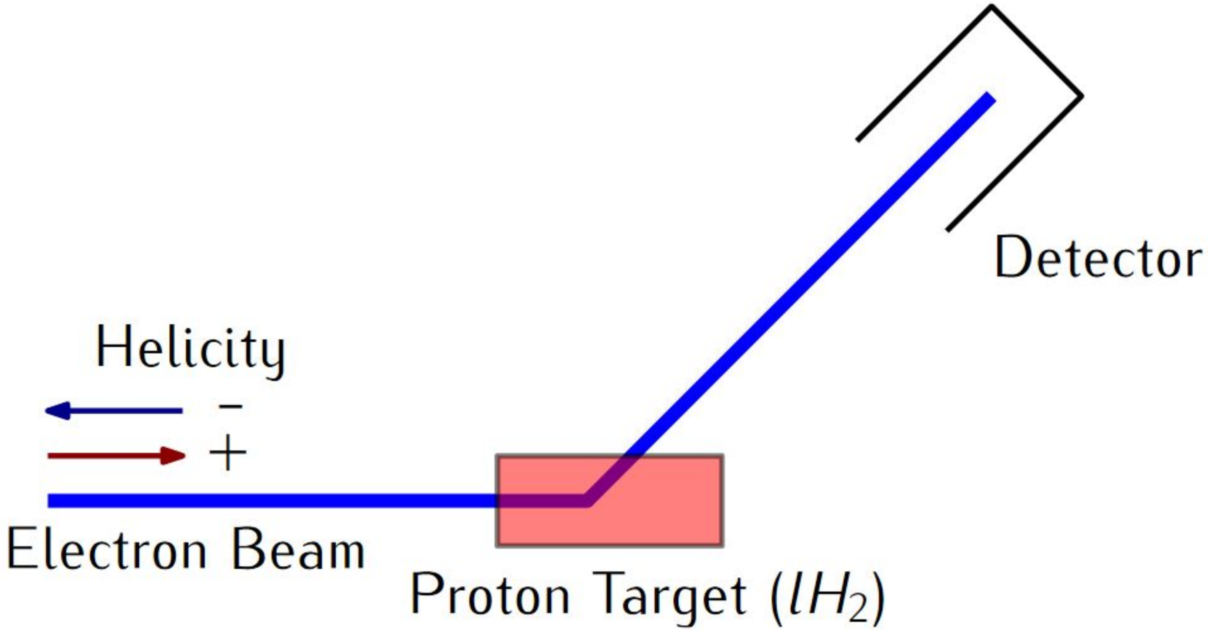
*Previous measurements are in **black**, possible future results are in **blue***

Measuring the parity violating asymmetry in e^-p-scattering

momentum transfer

Asymmetry: $\boxed{A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(1 - 4\sin^2\theta_W - F(Q^2)\right)}$ ~ **<u>40 ppb</u>**

proton form factor
(small @ low Q^2)



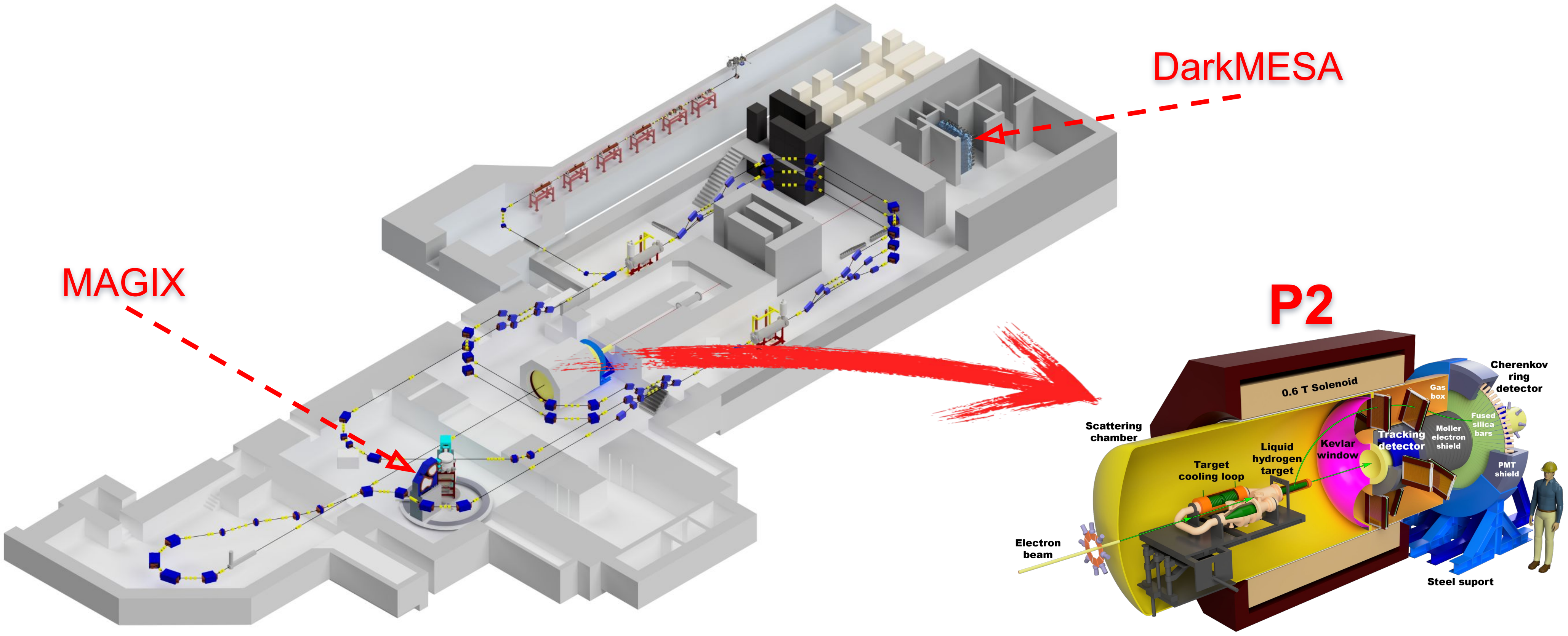
<u>Goal:</u>

- measure $\sin^2\theta_W$ @ ~0.14%
- Need Q_W @ 1.5%, 1.5% on A_{PV}
- $\delta(A_{PV})$ is 0.6 parts per billion

Measuring the parity violating asymmetry in $e^- p$-scattering

Challenge: needs approx. **10 000 hours** of measuring with ~**100 GHz electrons beam**!

Mainz Energy-Recovery Superconducting Accelerator (MESA)



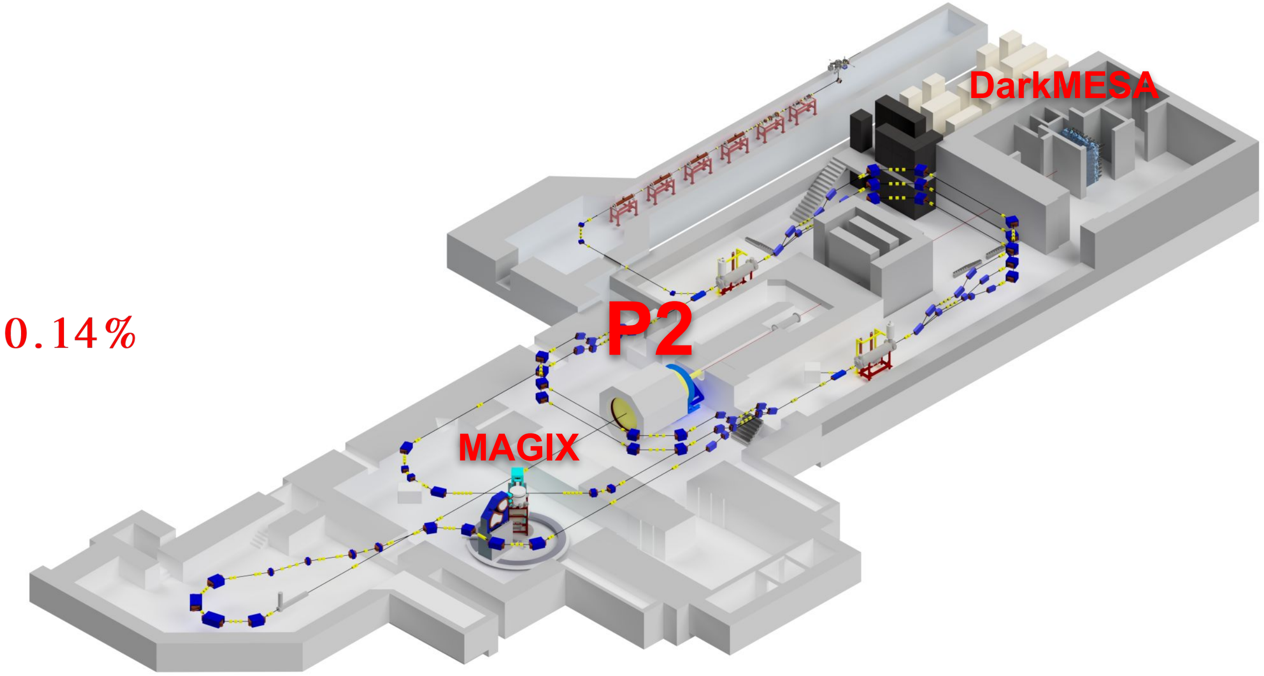
Measuring the parity violating asymmetry in $e^- p$-scattering

Beam:

- Current: 150 µA = 10^{15} e^-/s
- $L \approx 2.4 \cdot 10^{39}\ cm^{-2}s^{-1}$
- Energy: 155 MeV
- Highly polarized (≳85%)
- Flip helicity @ 1 kHz
- Extremely stable
- High runtime (>4k h/year)

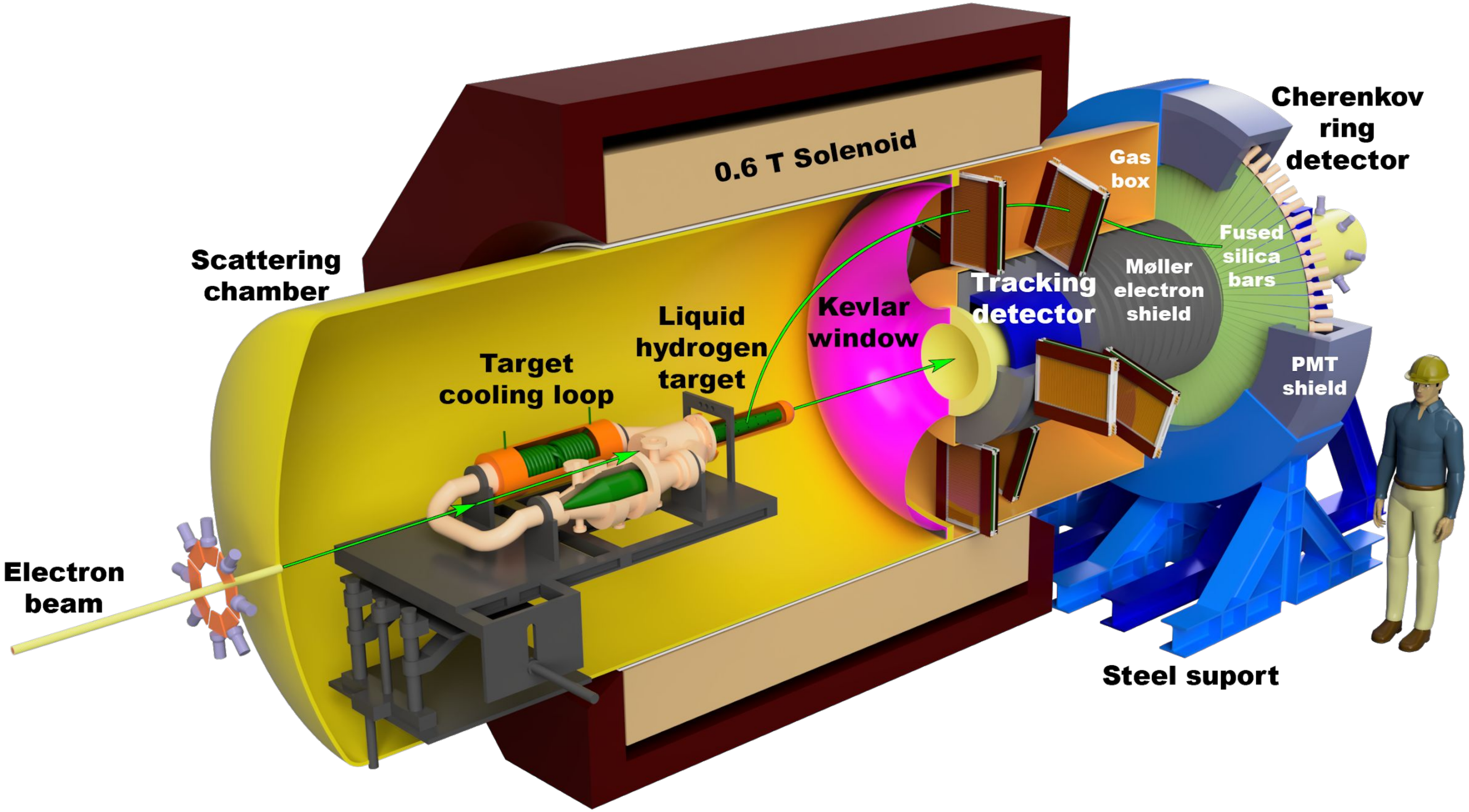
$$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W} \sim 0.14\%$$

Mainz Energy-Recovery Superconducting Accelerator (MESA)



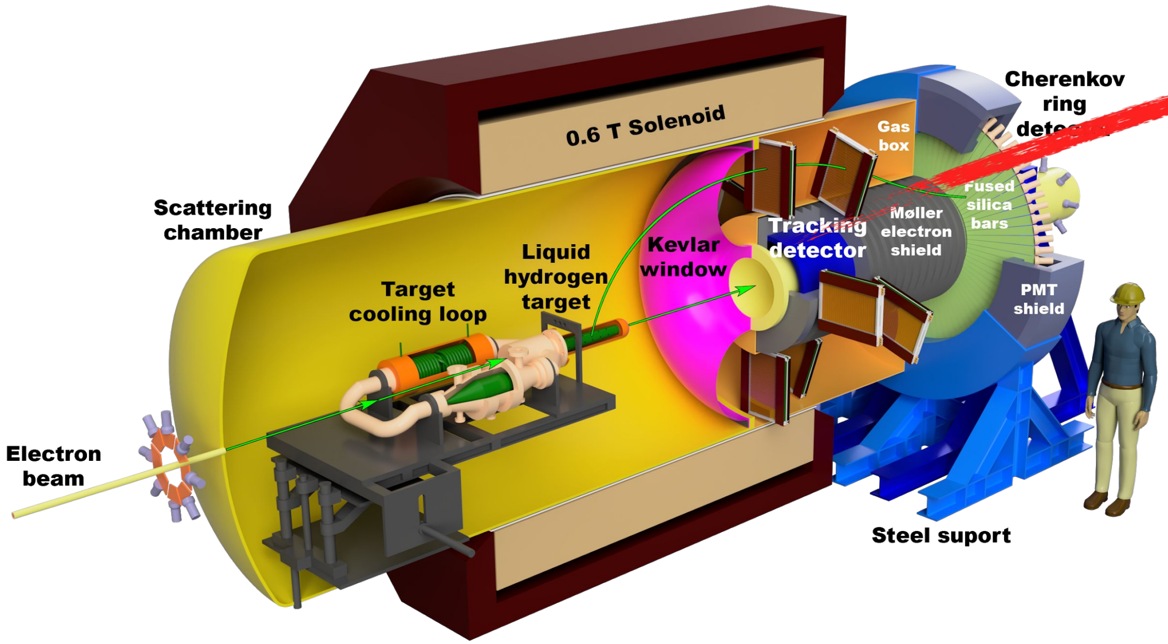
First beam run is planned for 2024

P2 setup



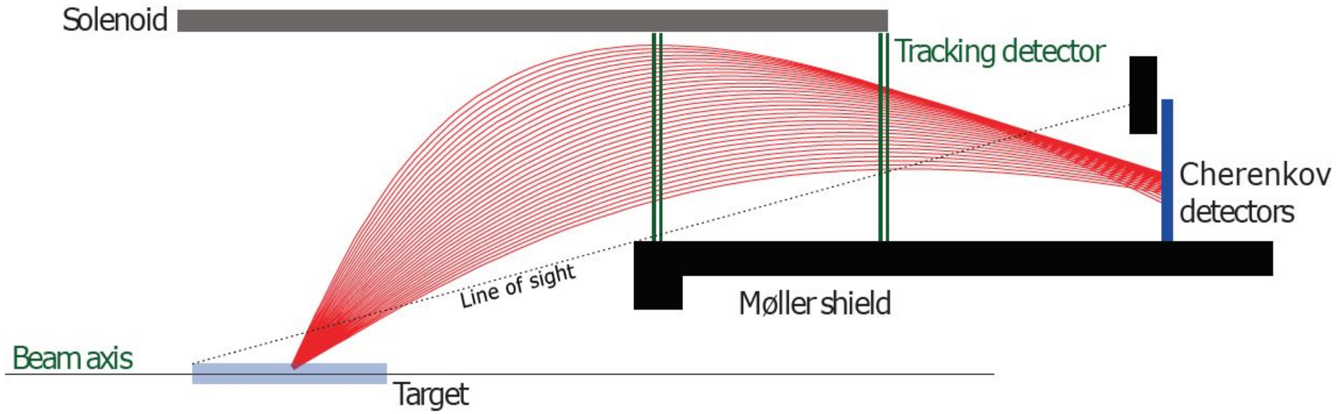
- 60 cm LH_2 target
- Magnetic field along the beam axis
- Tracking detector will determine Q^2
- Integrating Cherenkov detector will measure the asymmetry

P2 setup

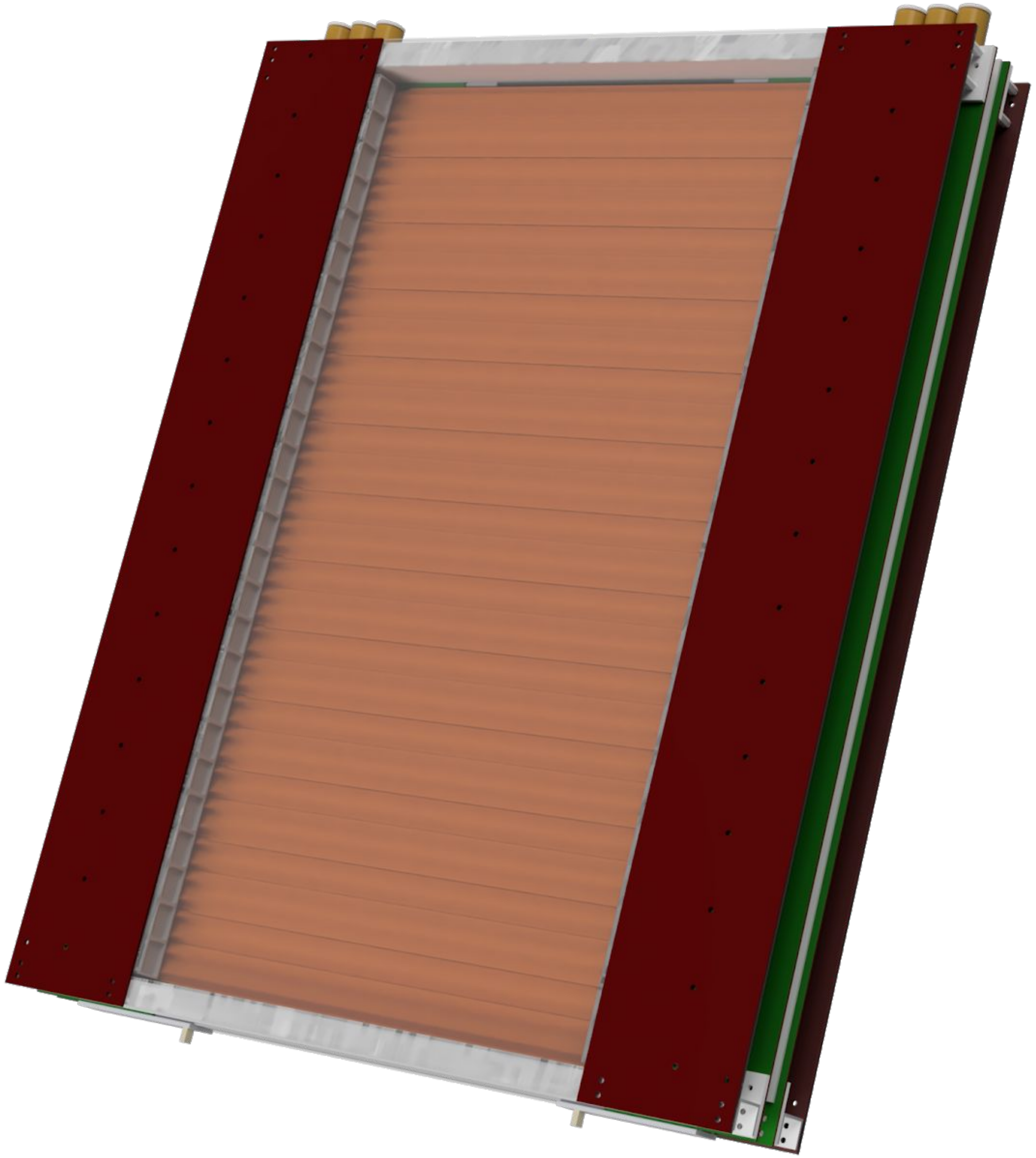


Tracking detector:

- 2 planes with 4 modules/plane;
- Helium inside gas box;
- ~15° azimuthal coverage per module;
- measure average Q^2;
- reconstruct individual electron tracks;
- 4 hits per track.



Tracking detector module



AUTODESK® INVENTOR®

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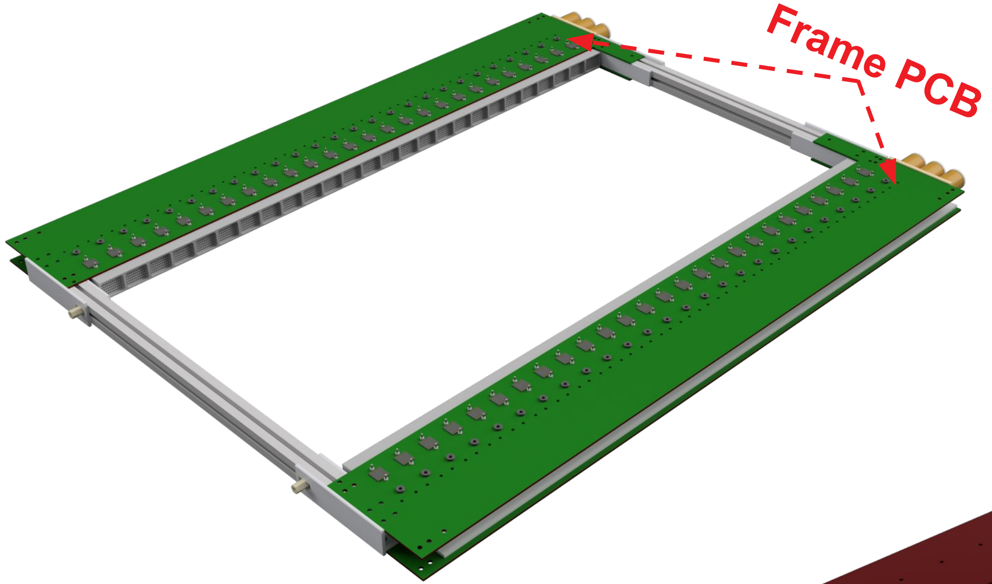
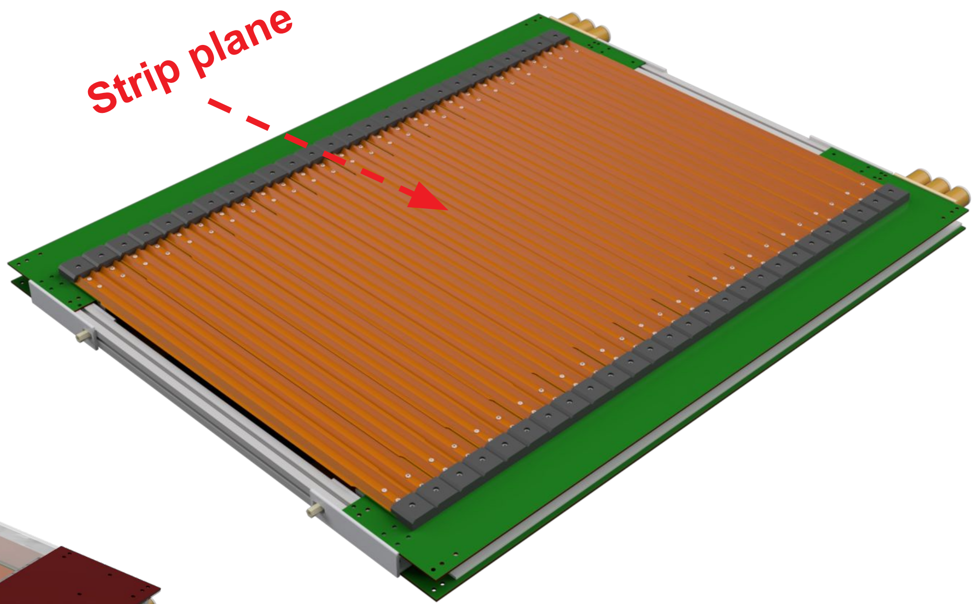
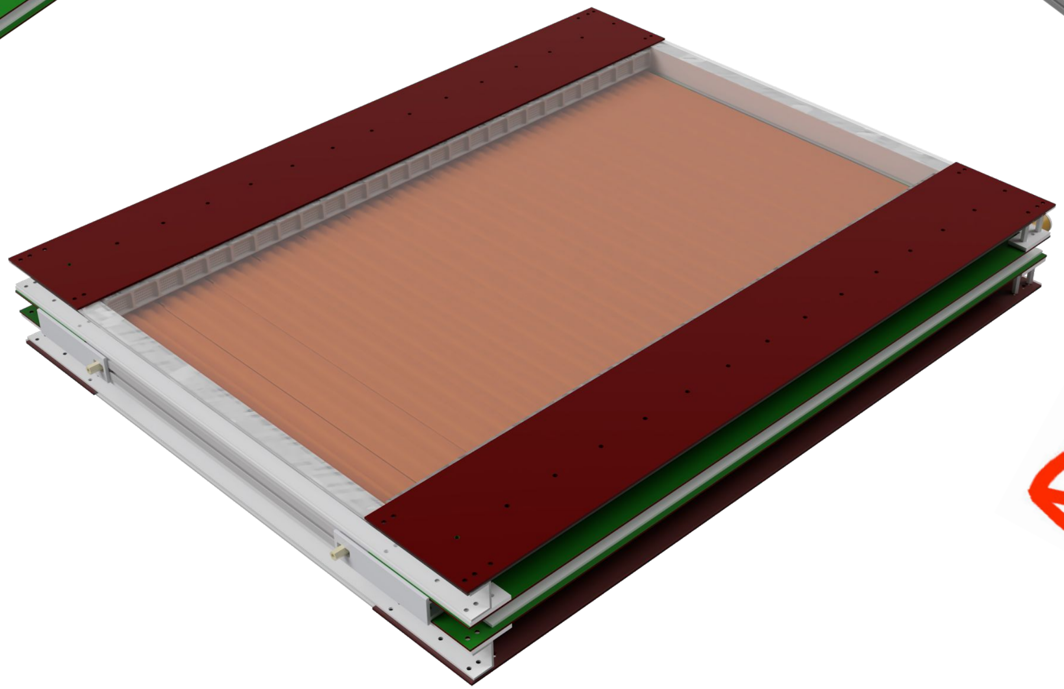
Tracking detector module



Inner frame

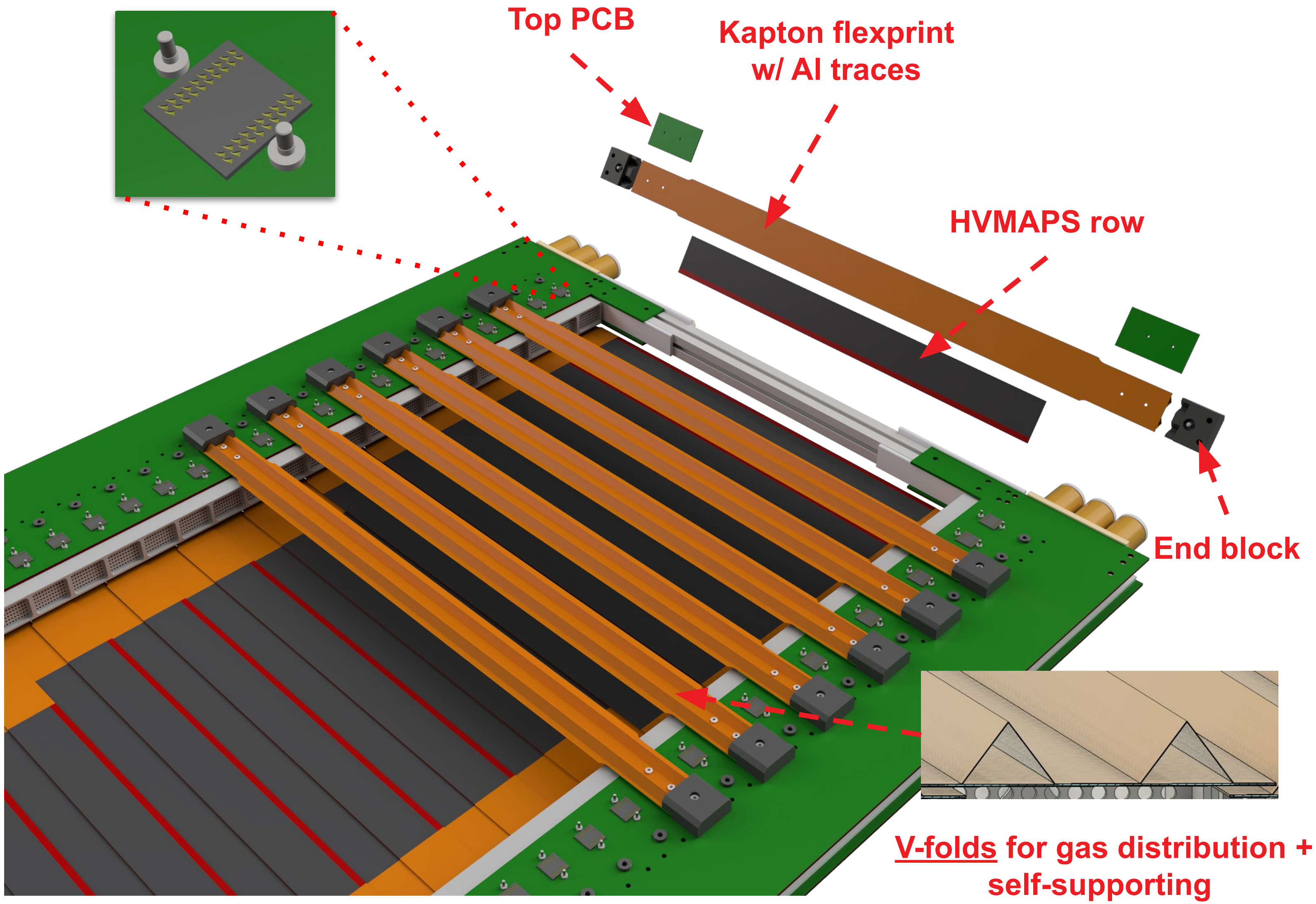


Module (inner part)

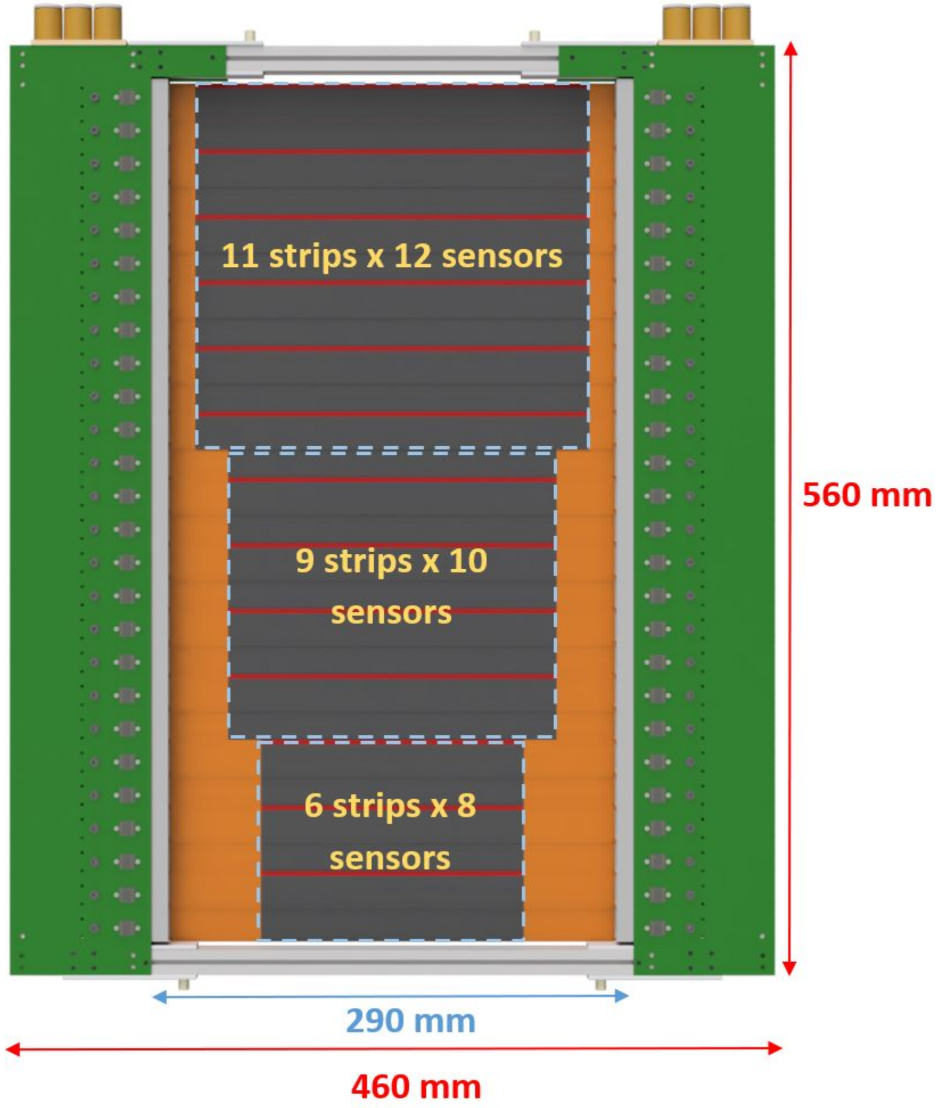


Module (w/ outer support frame)

Tracking detector module

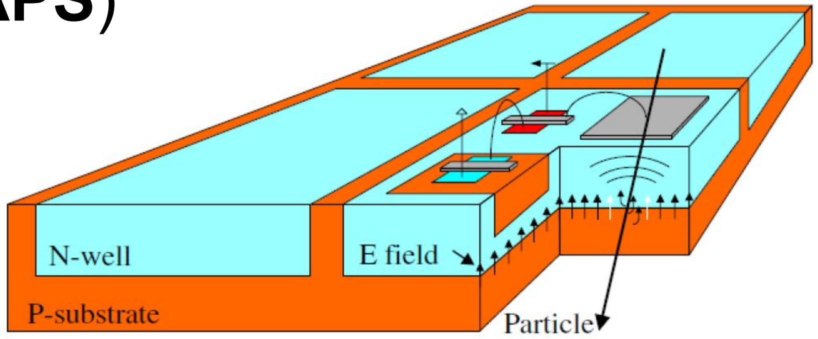


26 strips, 270 sensors (per plane)

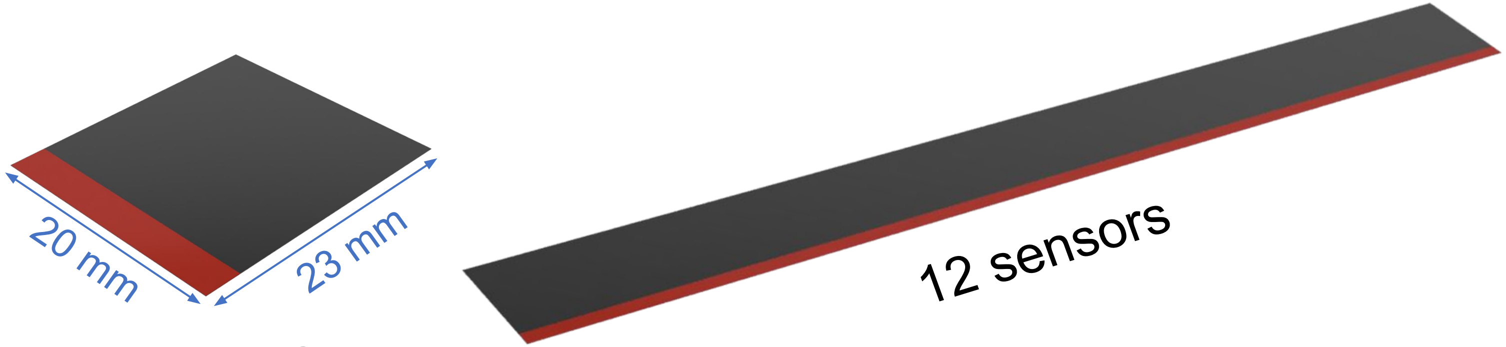


Tracking detector module: Silicon pixel chips

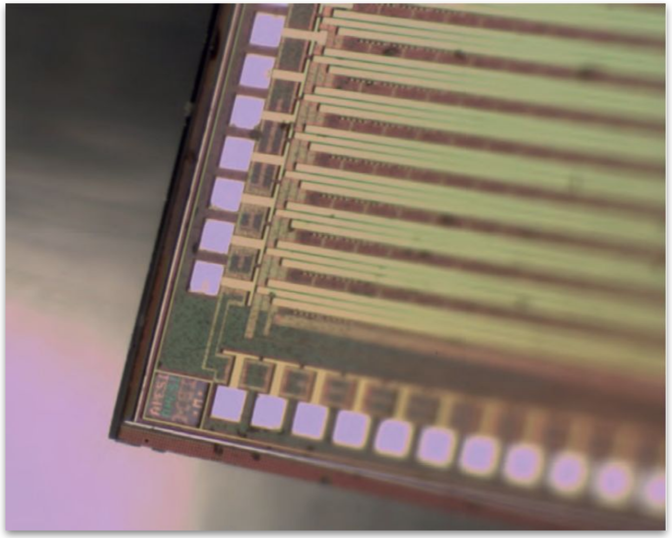
- High voltage Monolithic Active Pixel Sensors (**HV-MAPS**)
- 20 x 23 mm^2 sensors with 80 x 80 µm^2 pixels
- 50 µm thickness
- Detection efficiency > 99%
- Streaming digital readout of up to 7.8 Mhits/s/cm^2
- Power consumption: 0.96 - 1.7 W/chip



Schematic drawing of an HV-MAPS



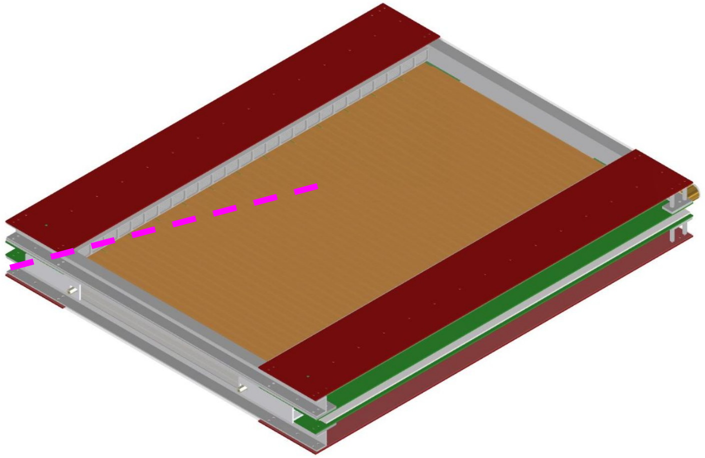
HV-MAPS

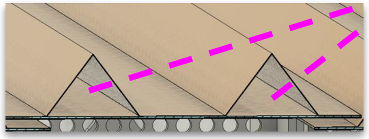


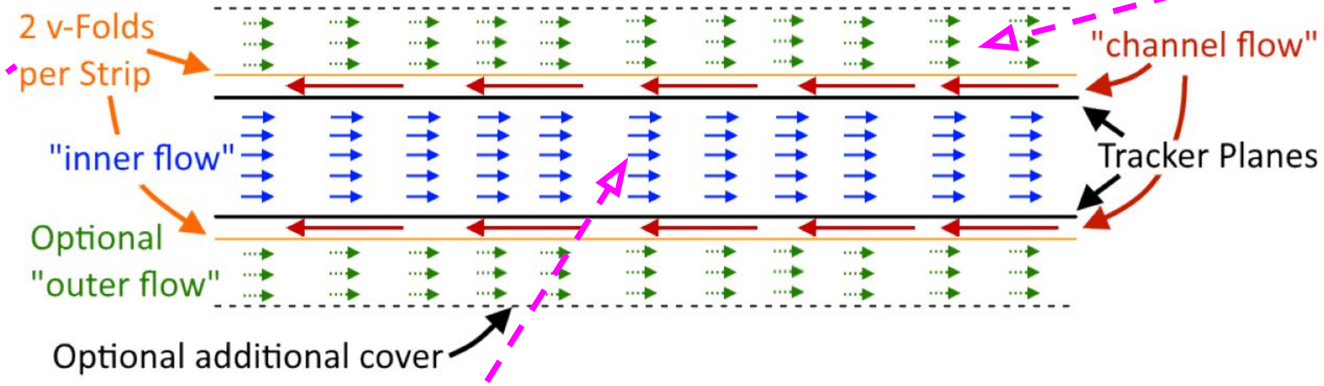
Tracking detector module: cooling

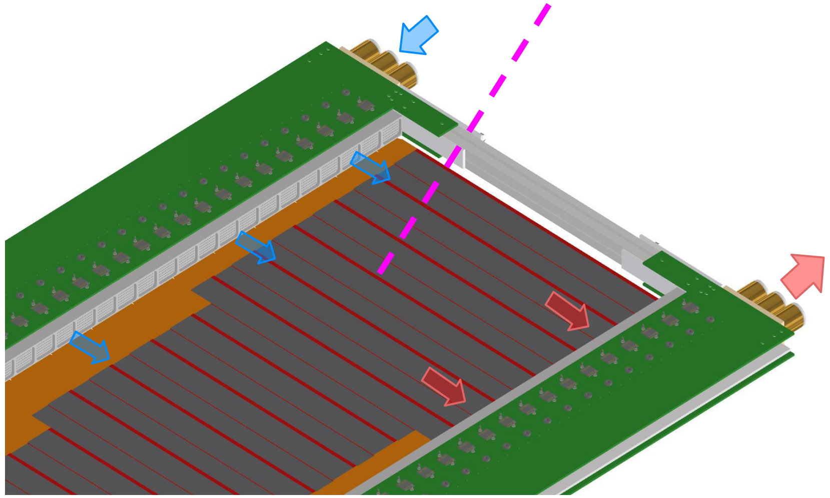
- **Power dissipation**: between 200 mW/cm^2 and 300 mW/cm^2
- **Low material budget** in the detector area
- **Prevent secondary scattering** on coolant shells

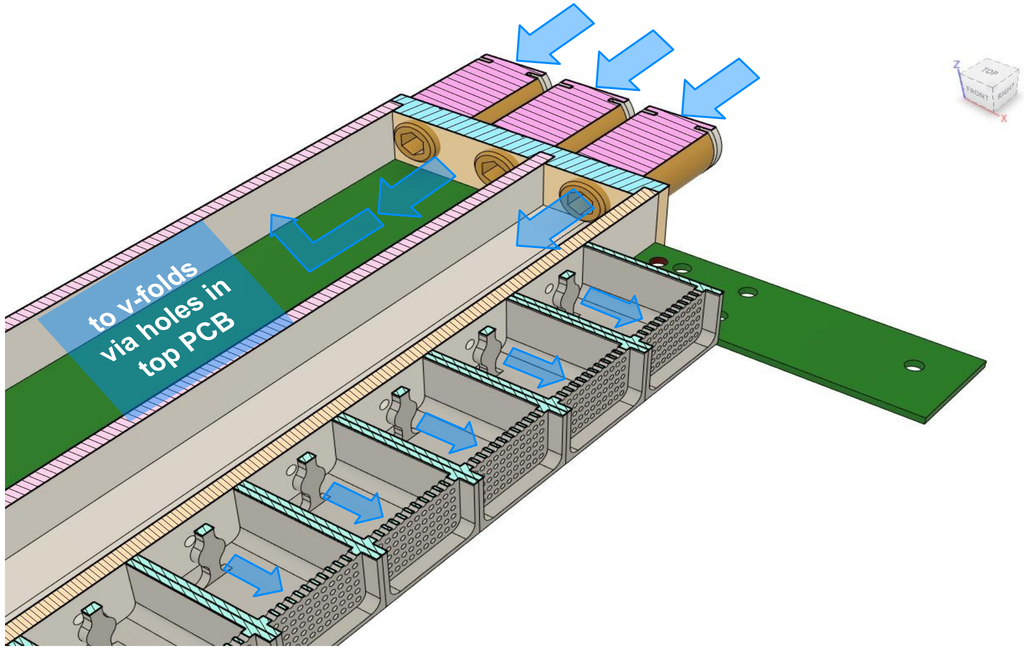
} gaseous He



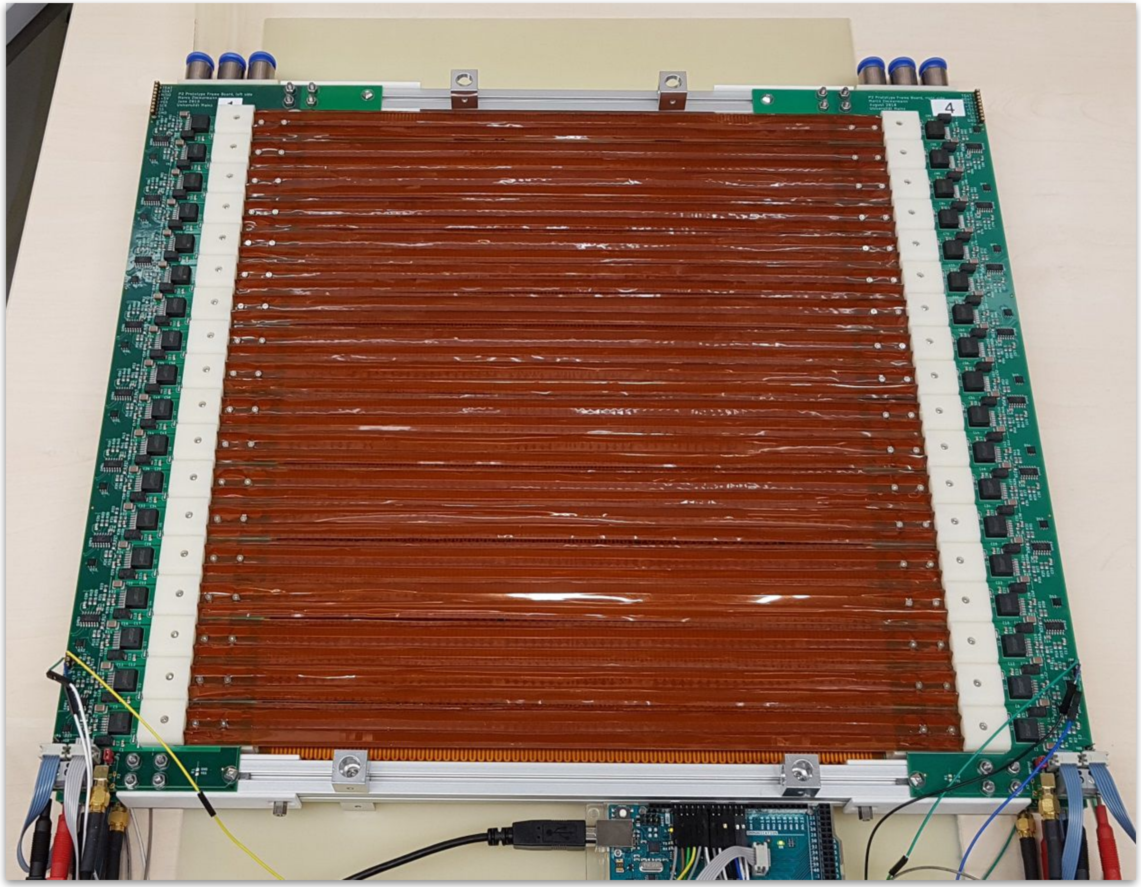


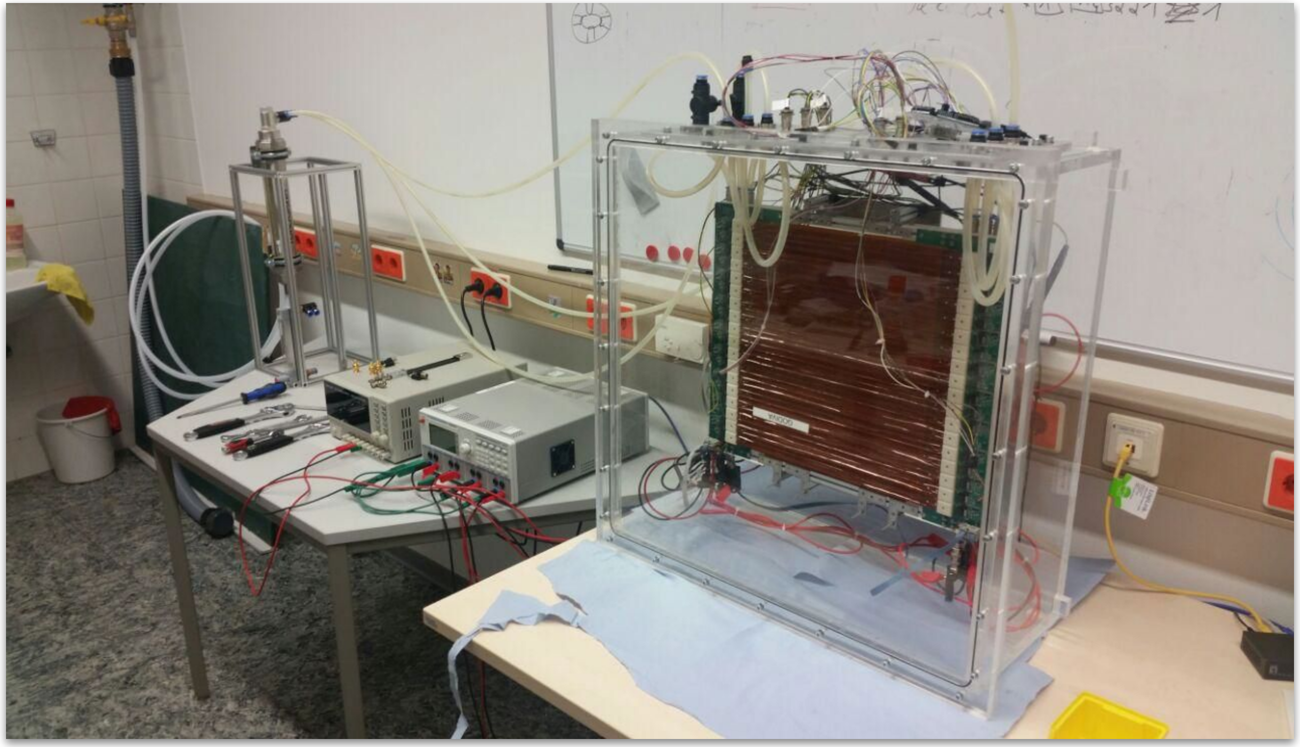






Tracking detector module: prototype





Initially developed by M. Zimmermann

CFD simulation

Computational fluid dynamics (CFD)

- Full equation for fluid dynamics:
  - Navier Stokes equations:

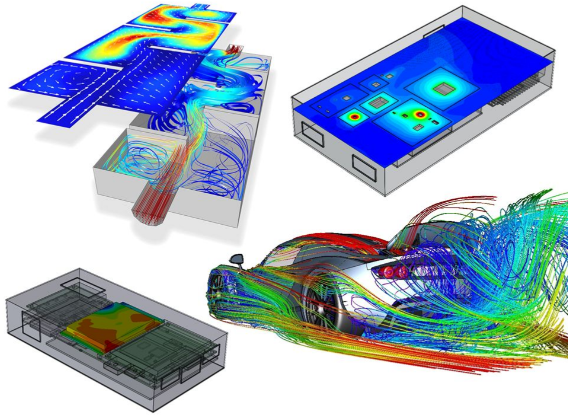
$$\rho \frac{D\vec{q}}{Dt} = -\nabla p + \mu \nabla^{2}\vec{q} + \frac{1}{3}\mu \nabla (\nabla \vec{q}) + \rho \vec{g}$$

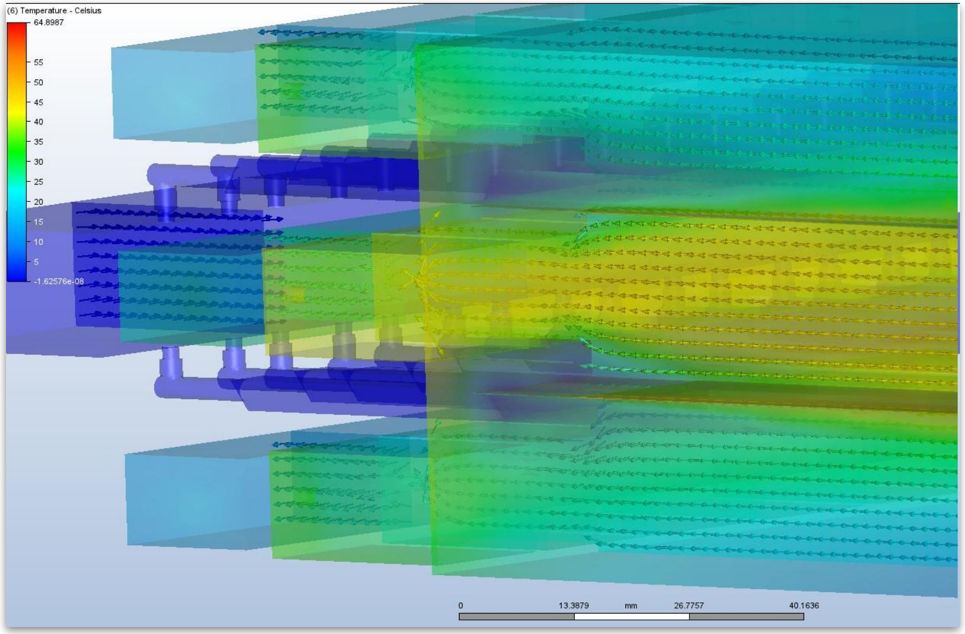
  - Extremely complicated mathematics without general analytical solution

- Allows predict how liquids and gases will perform, heat transfer is also possible

- Minimization of the need for physical prototypes => saving in time & budget

- Possible cons: over- or underestimating of some physical parameters (e.g. temperature, pressure)



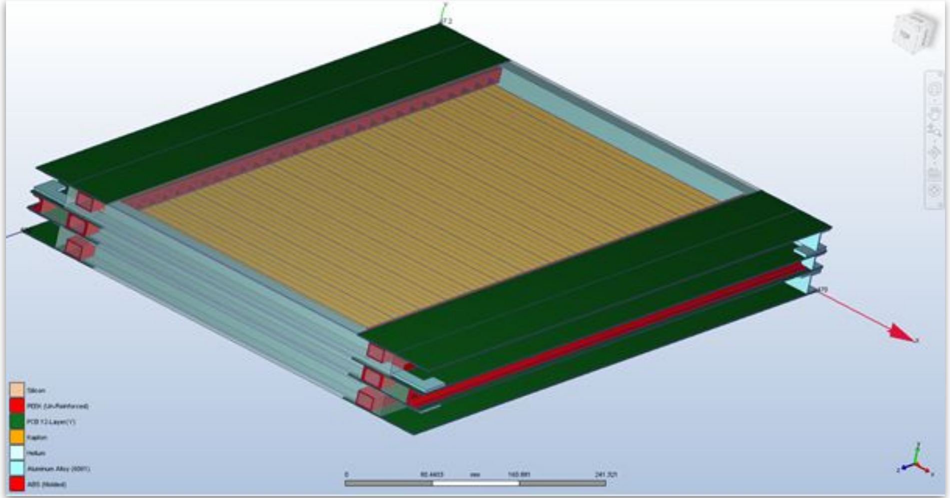


CFD simulation: model

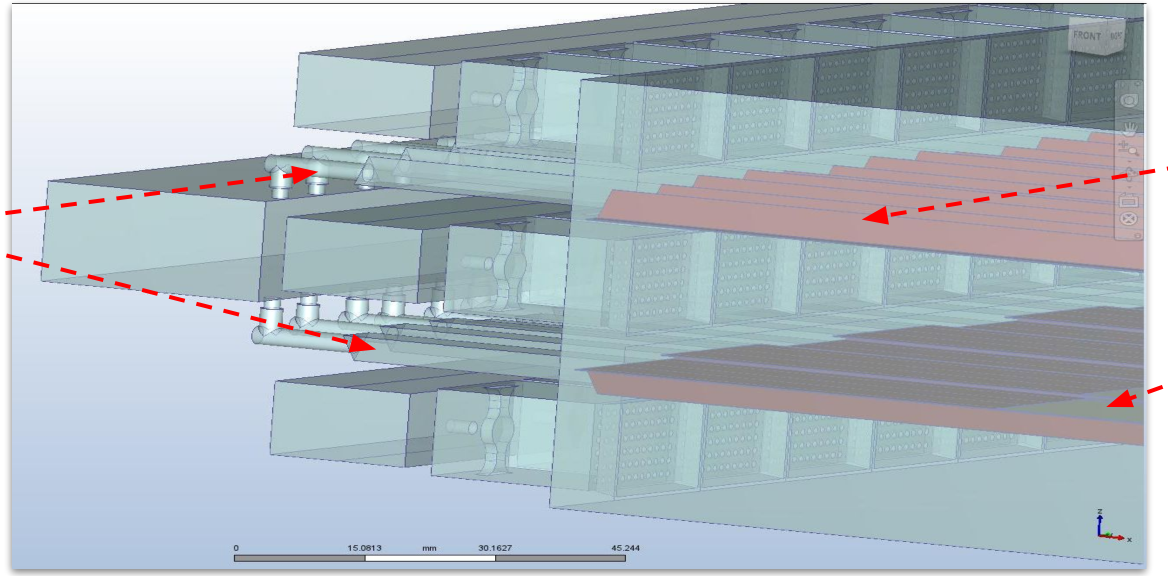
➔ Simplified model in order to save computational time:

- Only the most necessary parts (no unused holes, corners, etc.)

➔ Gas volume as a common 3D-body + essential heat generating and thermal conducting parts (HVMAPS and flexprint with v-folds in this case)



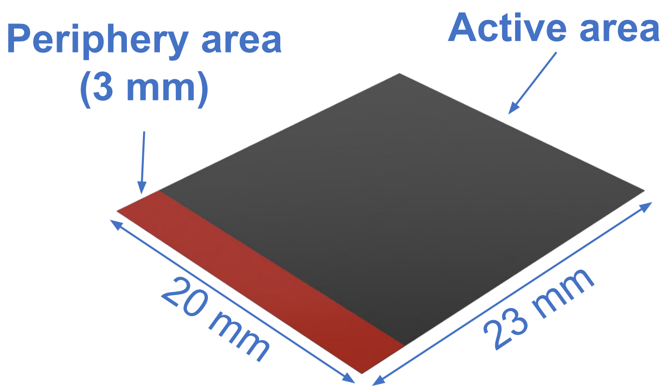
He inside pipes and v-folds



Kapton v-folds and flexprint

HVMAPS

CFD simulation: unequal heat dissipation



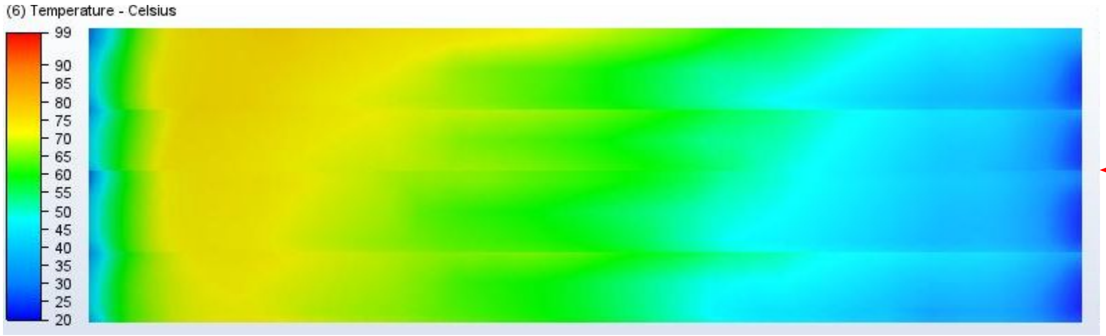
HV-MAPS

periphery area could produce up to 50% of total heat

8 strips simplified model
(4 top and 4 bottom)

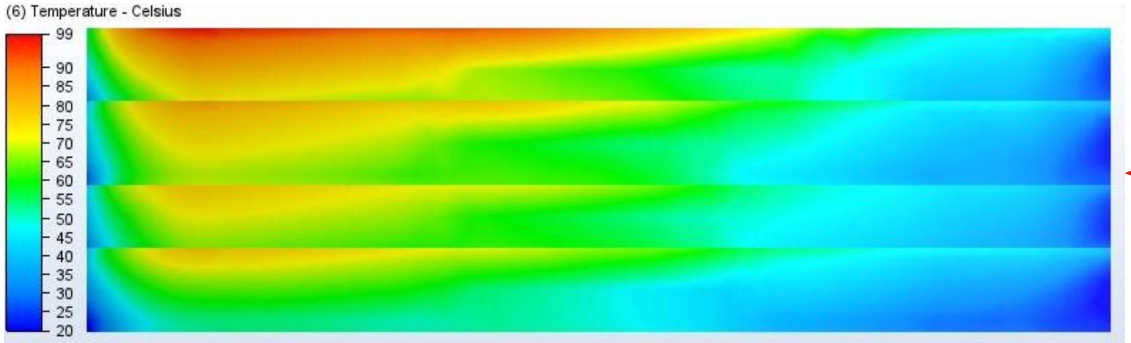
Max sensor temperature

Equal



76.9 °C

Unequal

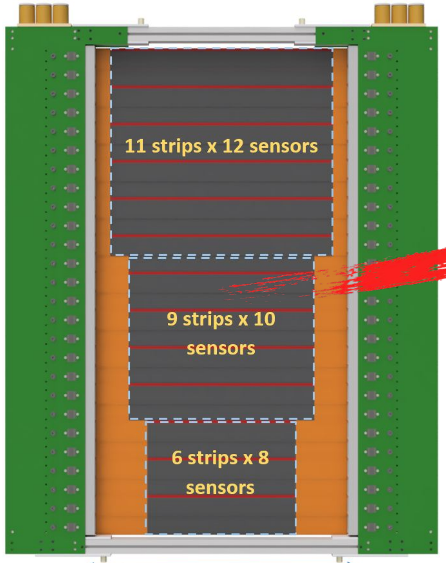


99.0 °C

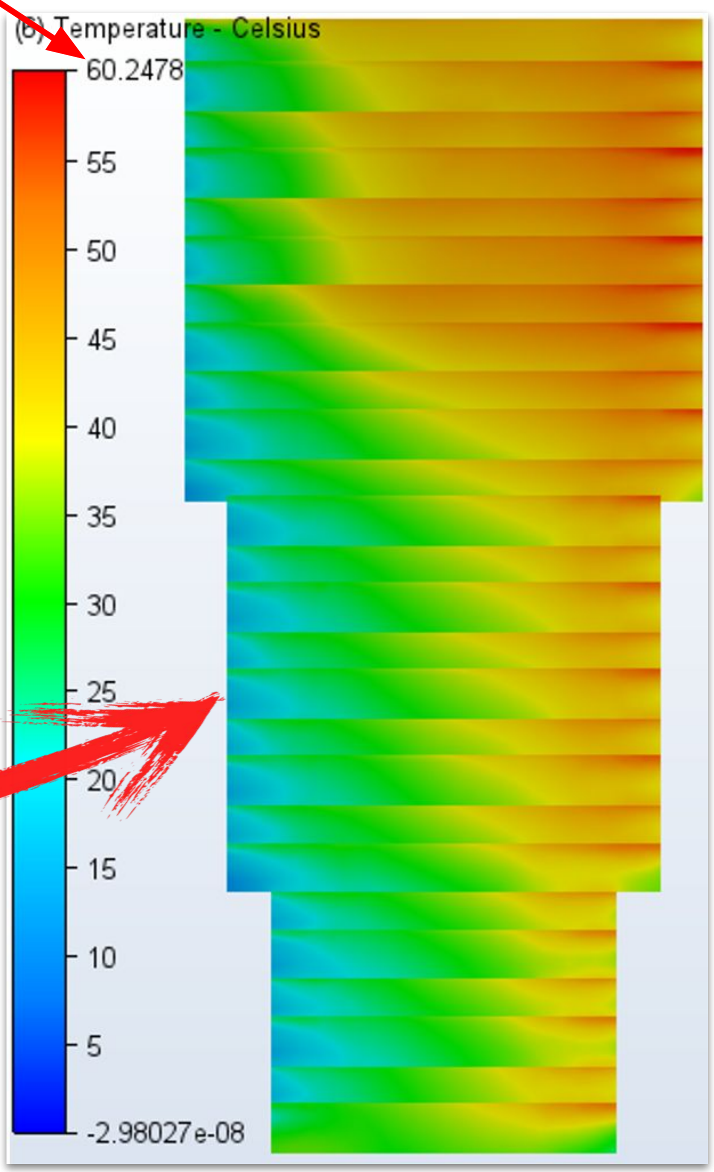
CFD simulation: current results

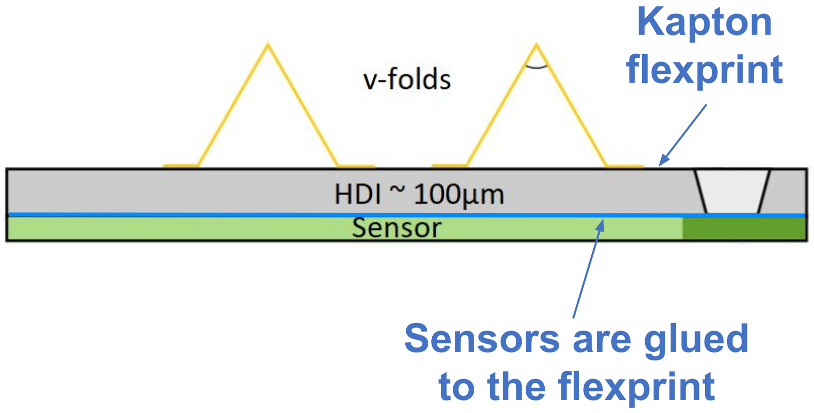
<u>High power scenario</u>:

- **300 mW/cm^2** unequal heat production by sensors;
- **0 °C** He
- **15 l\s** – channel flow
- **8.5 l\s** – all others;

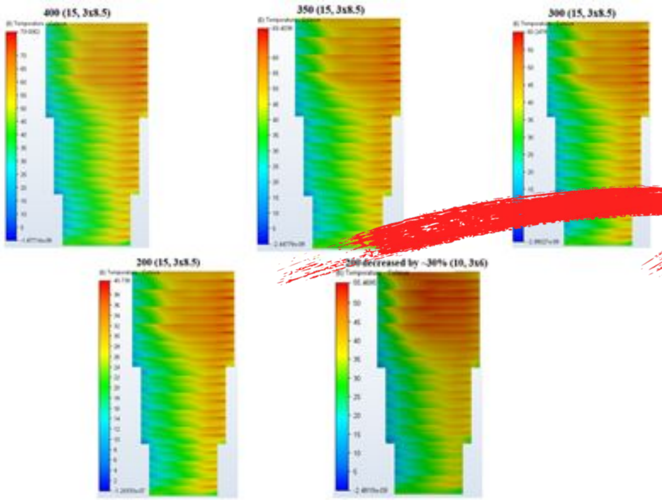


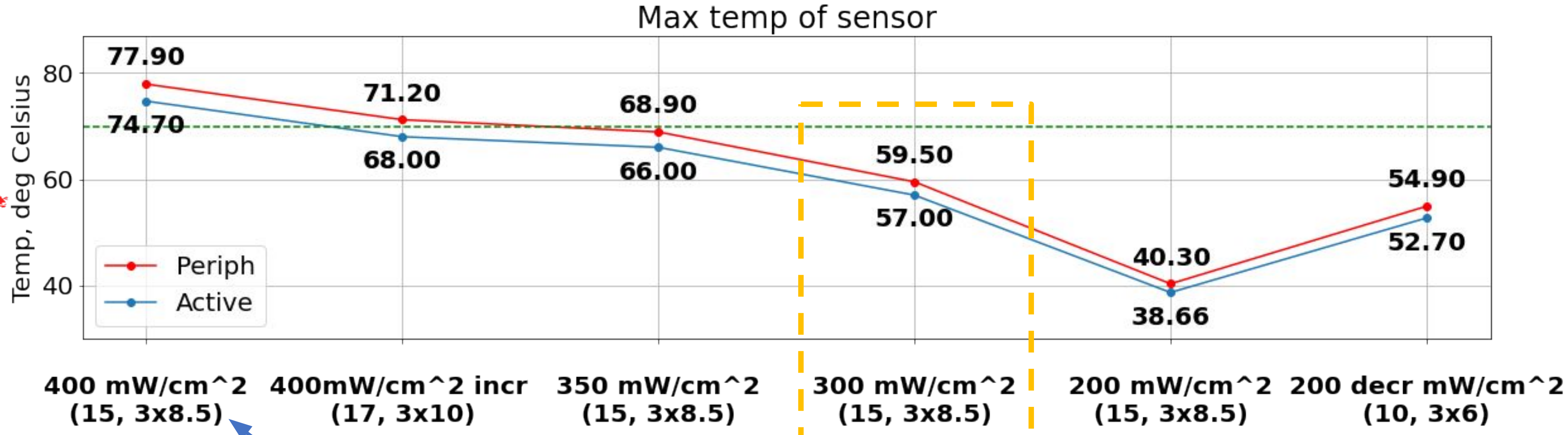
<70 °C





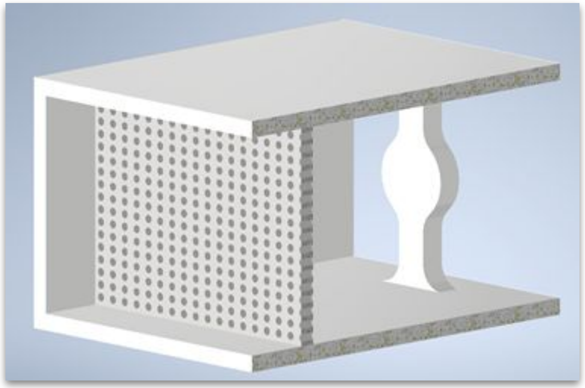
CFD simulation: Comparison of different scenarios

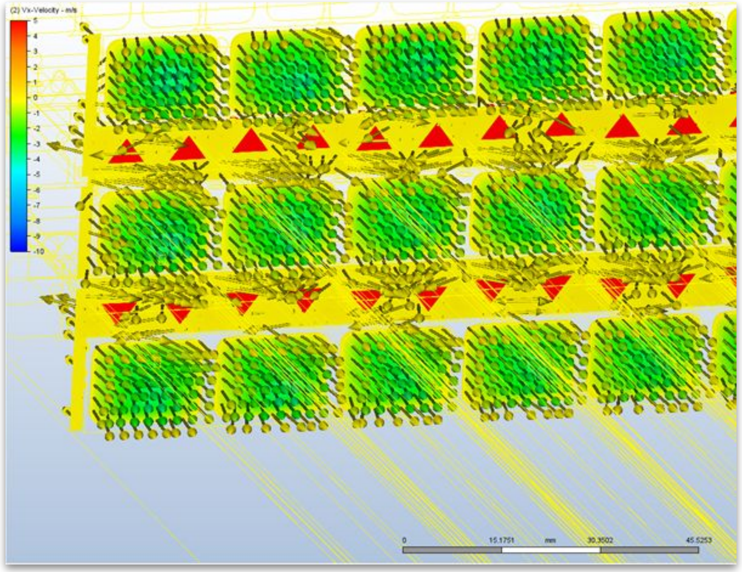




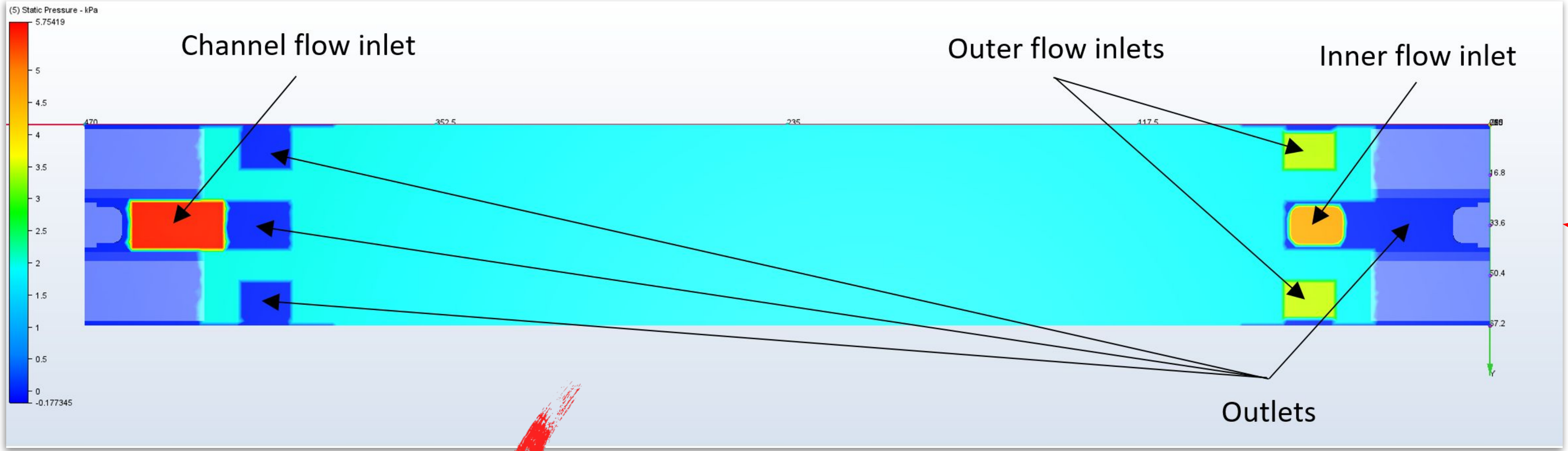
(`channel flow`, 3x`inner&outer flows` [l/s])

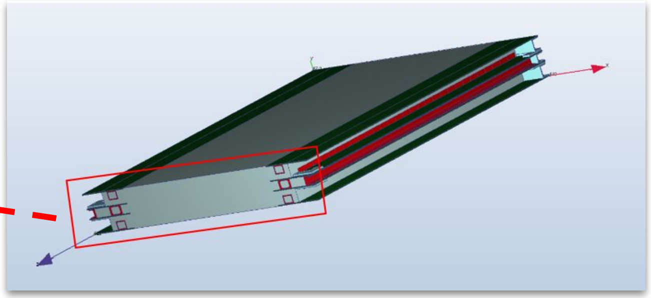
Gas diffuser





CFD simulation: current results



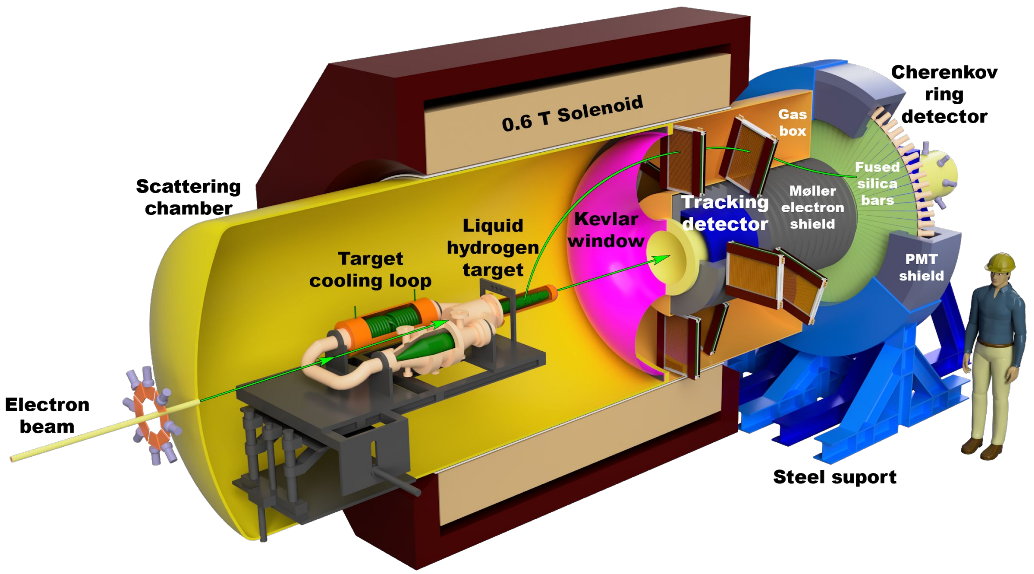


High power scenario (300 mW/cm^2):

- Total He mass flow (per module): ~7 g/s
- Pressure drop (per flow): <30-60 mbar

Summary

- Measurement of the weak mixing angle in the P2 experiment can precisely test the SM or provide a sign of the new physics;
- Detector development with silicon sensors => efficient cooling system;
- CFD simulation is an powerful tool for fluid cooling simulations.



Thank you for your attention!

Questions/comments?

DPG Spring Meeting 2021, Dortmund

Michail Kravchenko

PRISMA+ Cluster of Excellence/
Institute for Nuclear Physics,
University of Mainz

Stay healthy and keep on doing physics!

Michail Kravchenko

PRISMA+ Cluster of Excellence/ Institute for Nuclear Physics, University of Mainz

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Backup

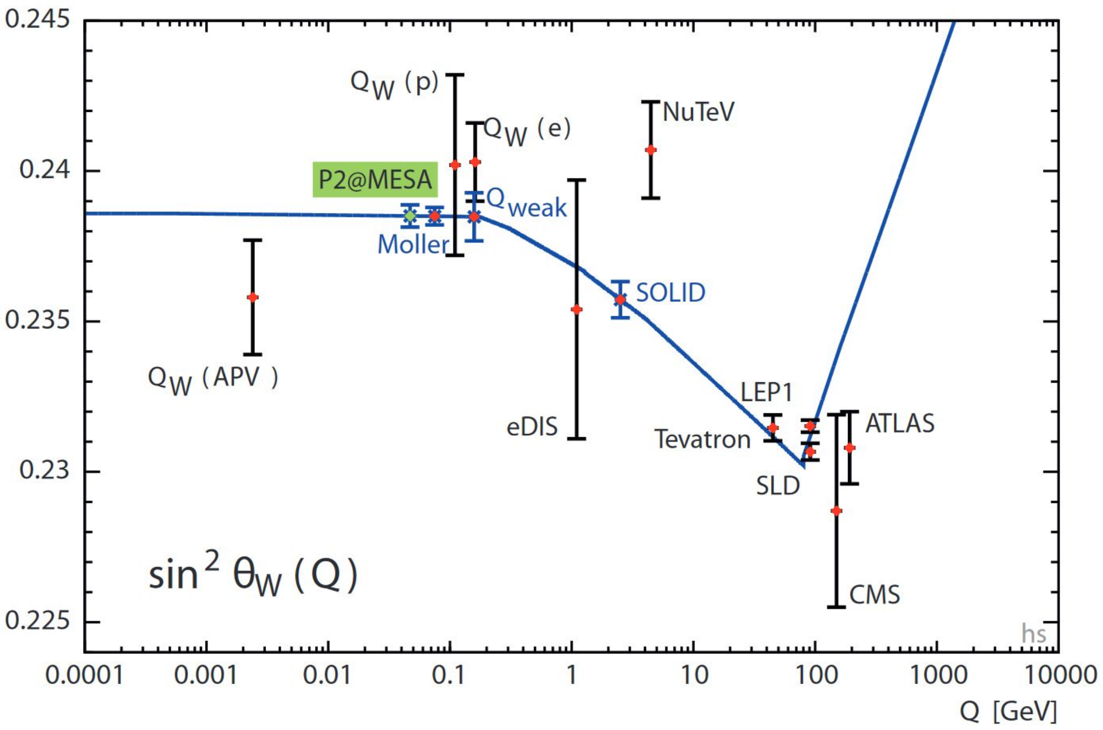
The P2 experiment

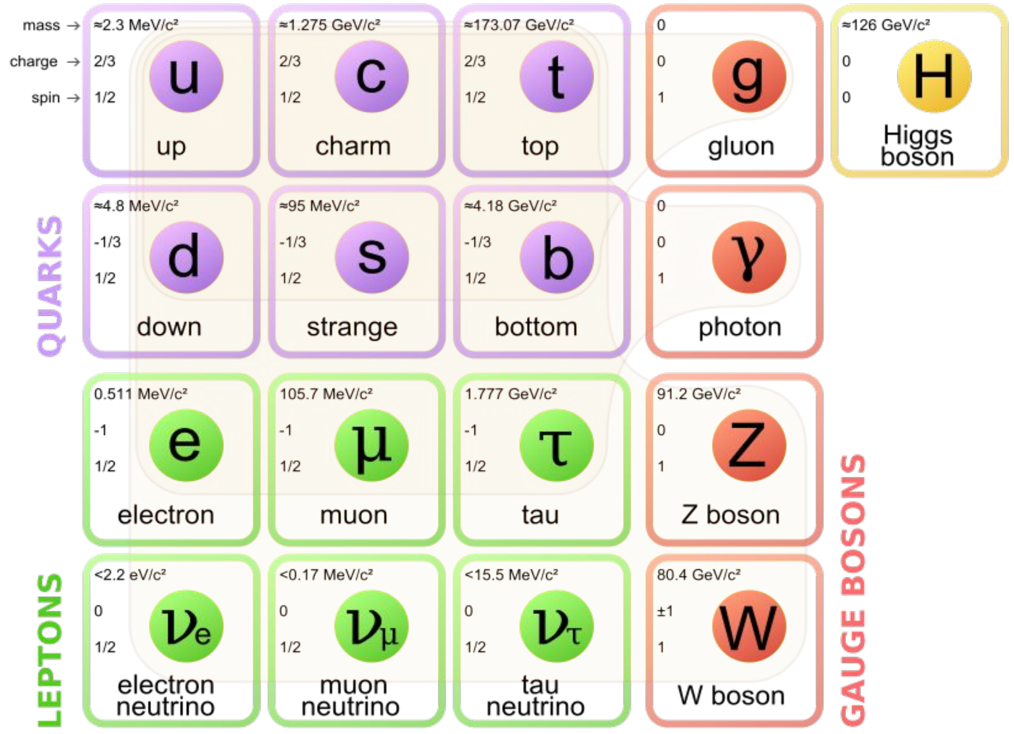
The idea

Precise measurement of the weak mixing angle $\sin^2\theta_W$ at low Q^2

Motivation

- $\sin^2\theta_W$ is a fundamental quantity of the SM and a parameter in the electroweak unification theory;
- accurate testing the SM or providing the new physics;



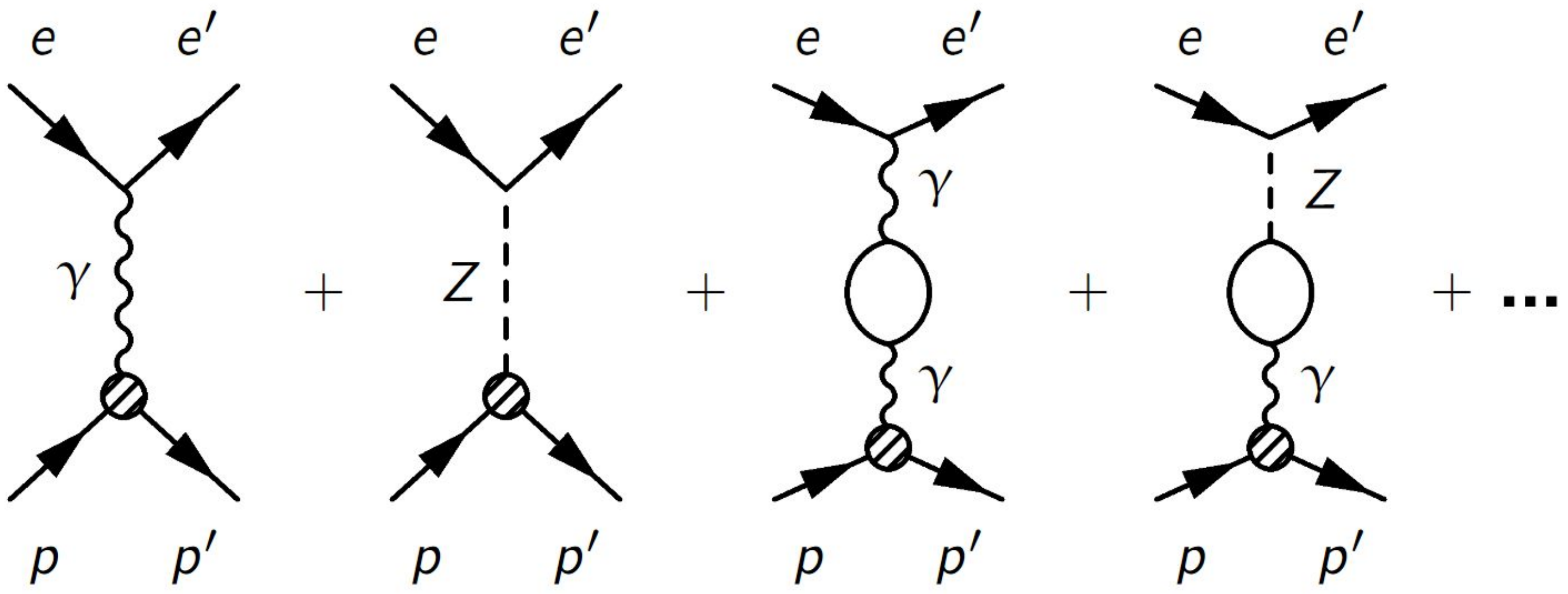


The P2 experiment: overview and theory

- Angle shows up both in masses and couplings (charges)

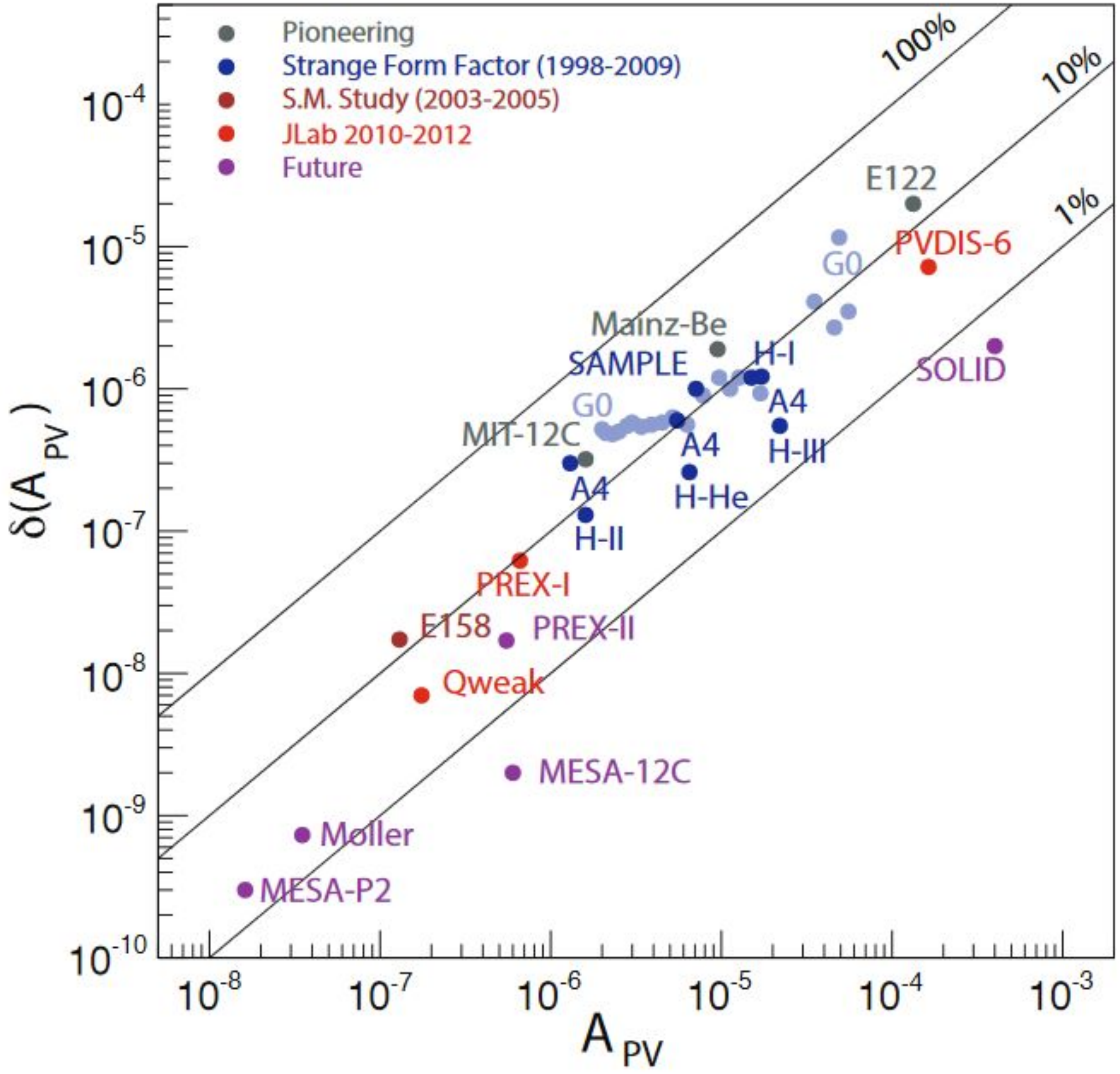
- The second options is used here (depends on energy): $$\boxed{\sin^2\theta_W = \frac{g'^2}{g^2+g'^2}}$$

"$\overline{\mathrm{MS}}$ − scheme"



- Absorb radiative corrections into effective, scale-dependent (“running”) $\sin^2\theta_W(Q^2)$

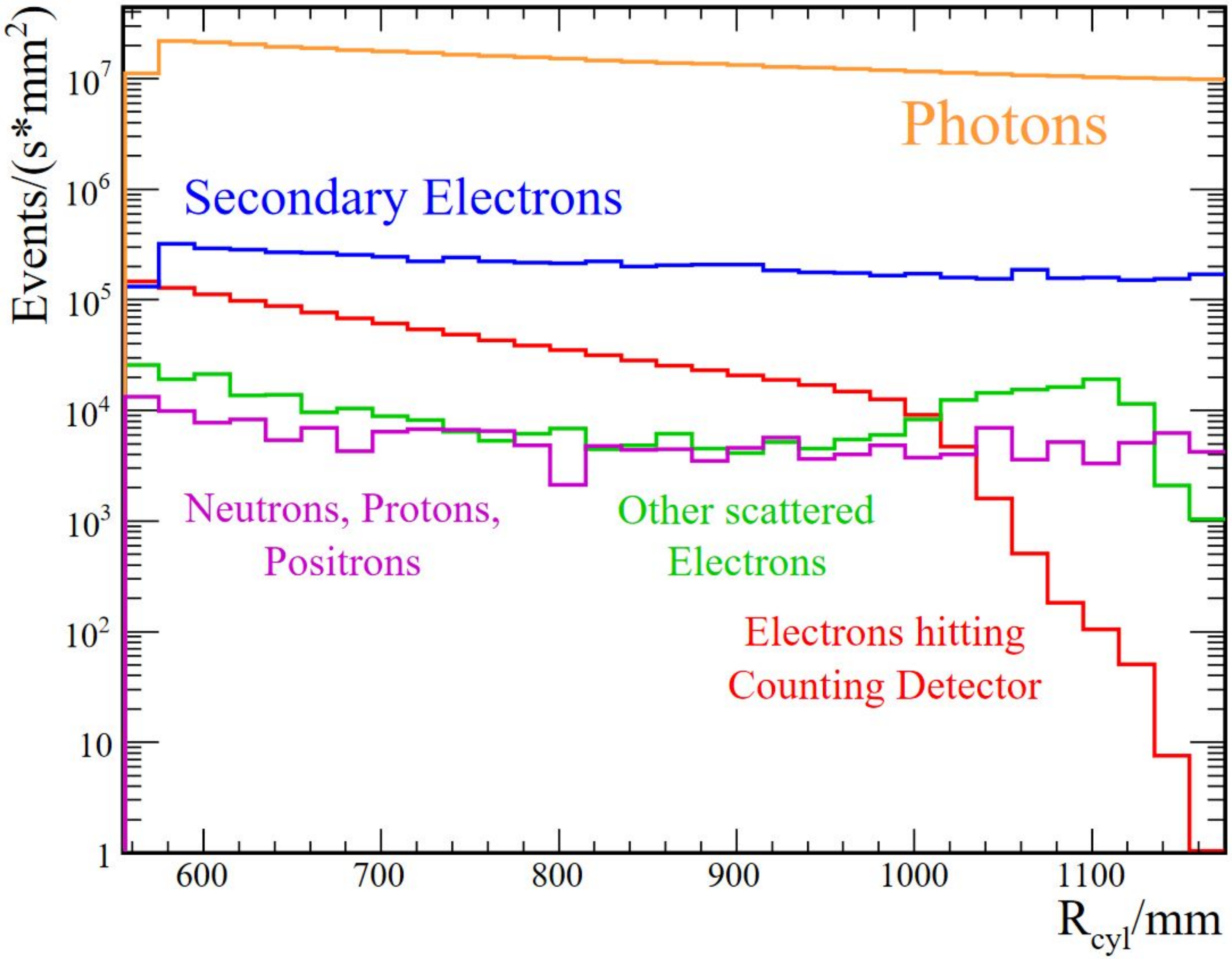
PVeS experiment summary



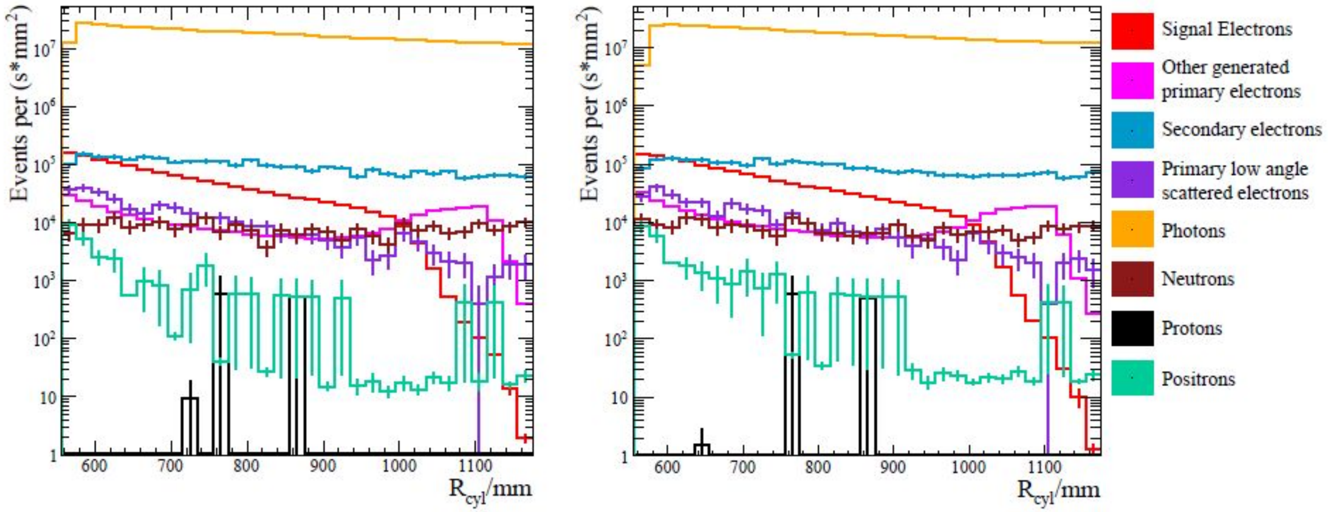
MC particle rates on 1st tracker plane

Photon Background:

- Continuous bremsstrahlung energy distribution
- Secondary electrons mainly produced by photo-effect
- Low detection rate of higher energetic photons

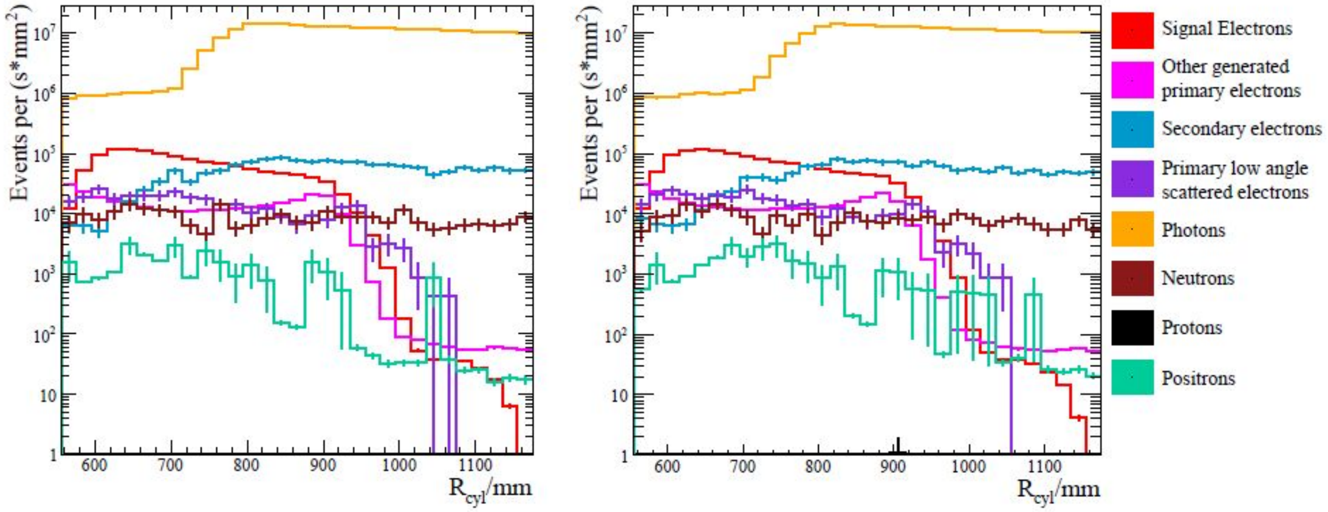


Particle rates on different planes



(a) *First plane*, z = 1080 mm.

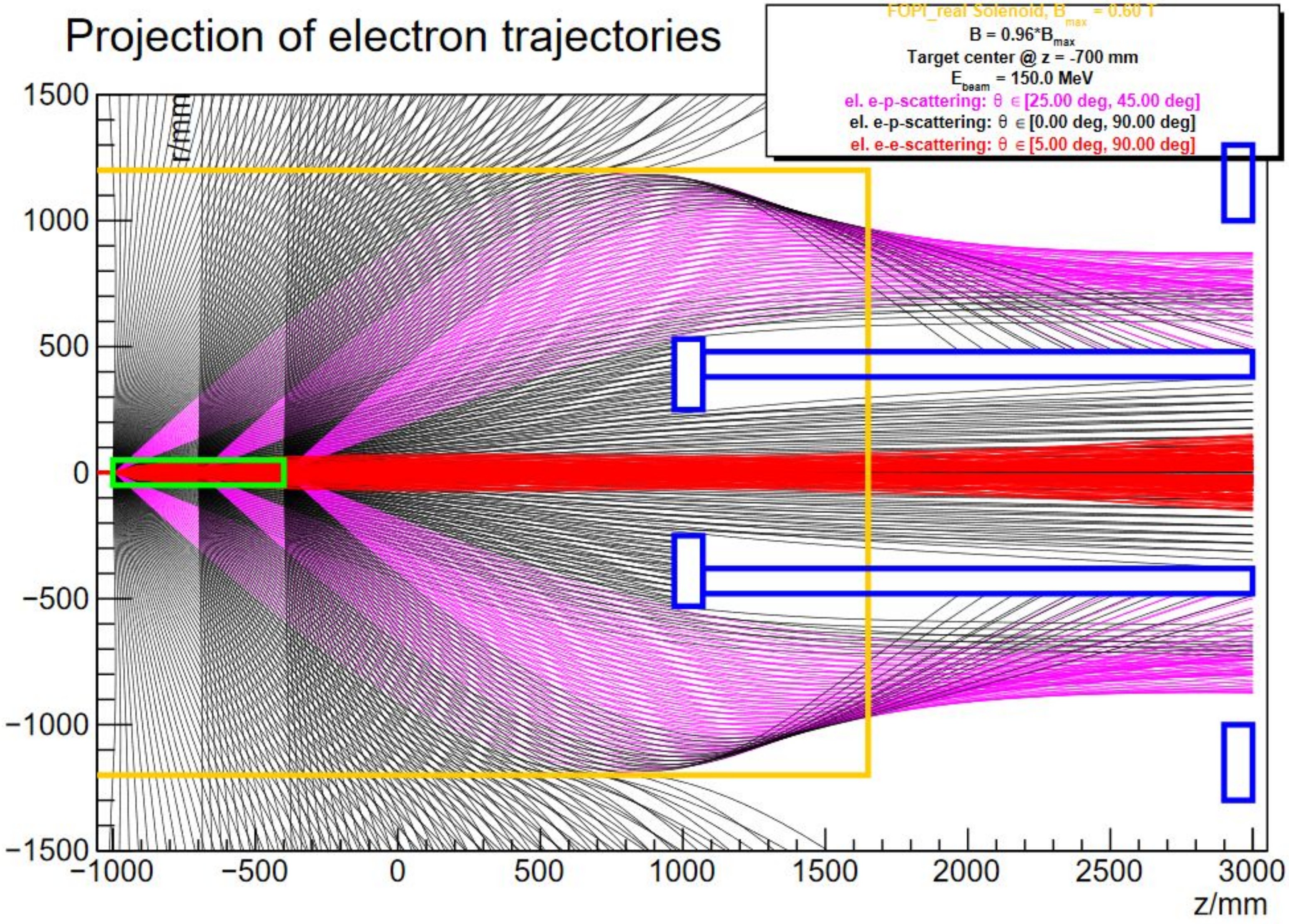
(b) *Second plane*, z = 1103 mm.



(c) *Third plane*, z = 1640 mm.

(d) *Fourth plane*, z = 1663 mm.

Projection of expected electron trajectories

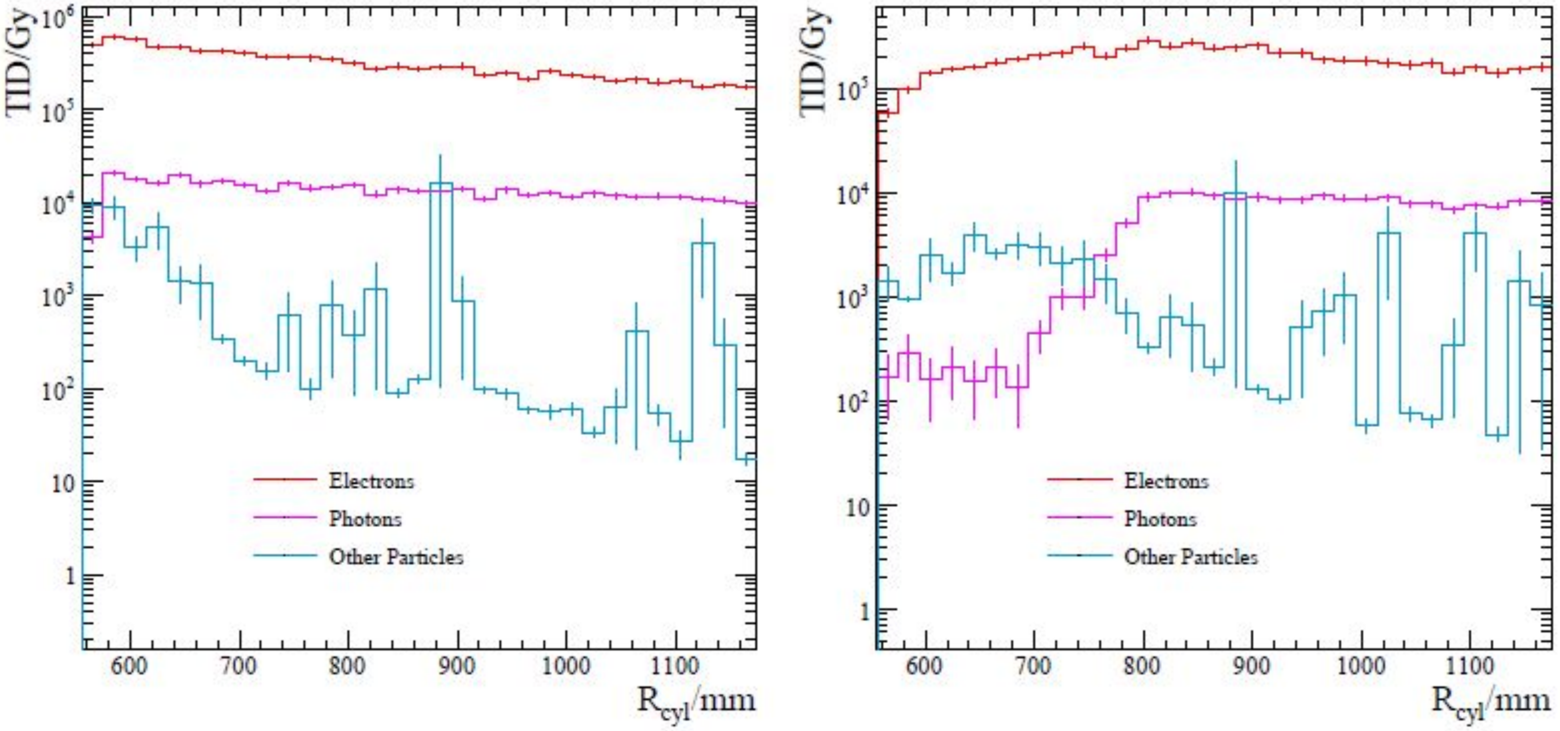


P2 error budget

E_{beam}	155 MeV
$\bar{\theta}_{\text{f}}$	$35°$
$\delta\theta_{\text{f}}$	$20°$
$\langle Q^2 \rangle_{L=600\,\text{mm},\ \delta\theta_{\text{f}}=20°}$	$6 \times 10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle$	-39.94 ppb
$(\Delta A^{\text{exp}})_{\text{Total}}$	0.56 ppb (1.40 %)
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	0.51 ppb (1.28 %)
$(\Delta A^{\text{exp}})_{\text{Polarization}}$	0.21 ppb (0.53 %)
$(\Delta A^{\text{exp}})_{\text{Apparative}}$	0.10 ppb (0.25 %)

$\langle s^2_{\text{W}} \rangle$	0.231 16
$(\Delta s^2_{\text{W}})_{\text{Total}}$	3.3×10^{-4} (0.14 %)
$(\Delta s^2_{\text{W}})_{\text{Statistics}}$	2.7×10^{-4} (0.12 %)
$(\Delta s^2_{\text{W}})_{\text{Polarization}}$	1.0×10^{-4} (0.04 %)
$(\Delta s^2_{\text{W}})_{\text{Apparative}}$	0.5×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\Box_{\gamma Z}}$	0.4×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\text{nucl. FF}}$	1.2×10^{-4} (0.05 %)
$\langle Q^2 \rangle_{\text{Cherenkov}}$	$4.57 \times 10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle_{\text{Cherenkov}}$	-28.77 ppb

TID



(a) *First plane* (b) *Third plane*

Figure 5.12.: *Total ionizing dose on the first and third tracker plane, evaluated with the detector simulation and normalized to* 1×10^4 h *run time at full beam current.*

TID varies between 10 Mrad to 60 Mrad @ different planes

Tracking detector module: coolant

- **Low material budget** in the detector area
- **Prevent secondary scattering** on coolant shells

gaseous He

	Atomic number	Density [kg/m^3]	Specific heat capacity c_p [kJ/(kg K)]	Volumetric heat capacity c_v [kJ/(kg K)]	Thermal conductivity k [W/(m K)]
H_2	1	0.09	14.32	10.16	0.18
He	**2**	**0.18**	**5.19**	**3.12**	**0.15**
N_2	7	1.23	1.04	0.73	0.02
Air	7.6 (eff.)	1.27	1.01	0.72	0.03

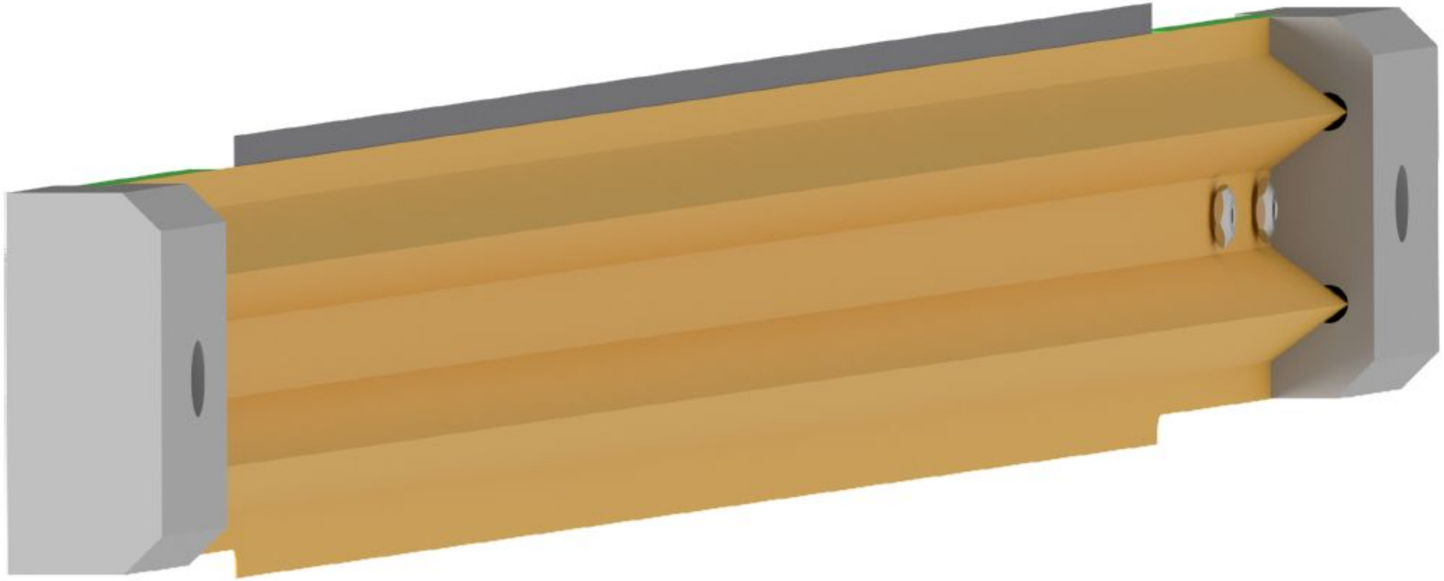
@ T = 300 K and p = 101 325 Pa

Hydrogen gas forms explosive mixtures with air in concentrations from 4–74%

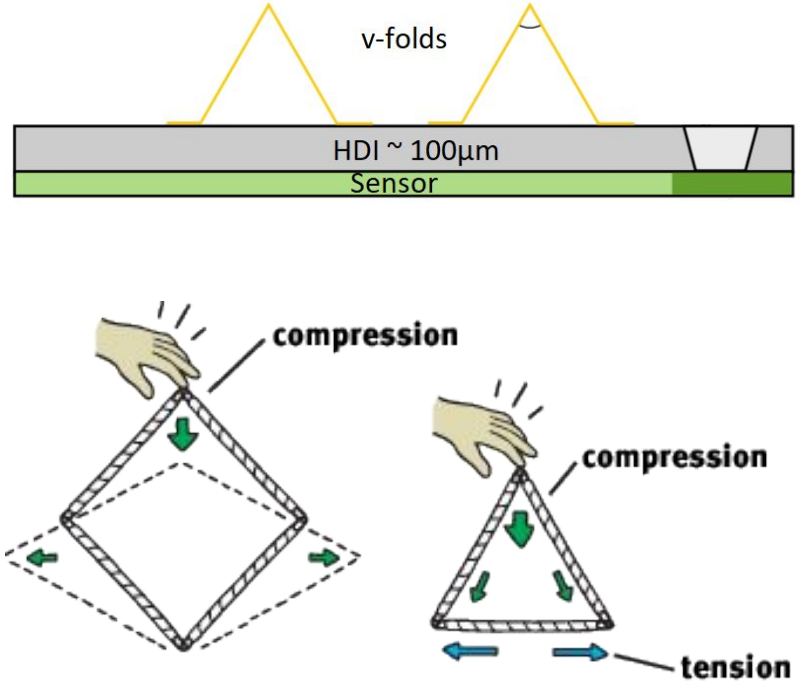
Strip submodule

(a) *Front side of the strip submodule*

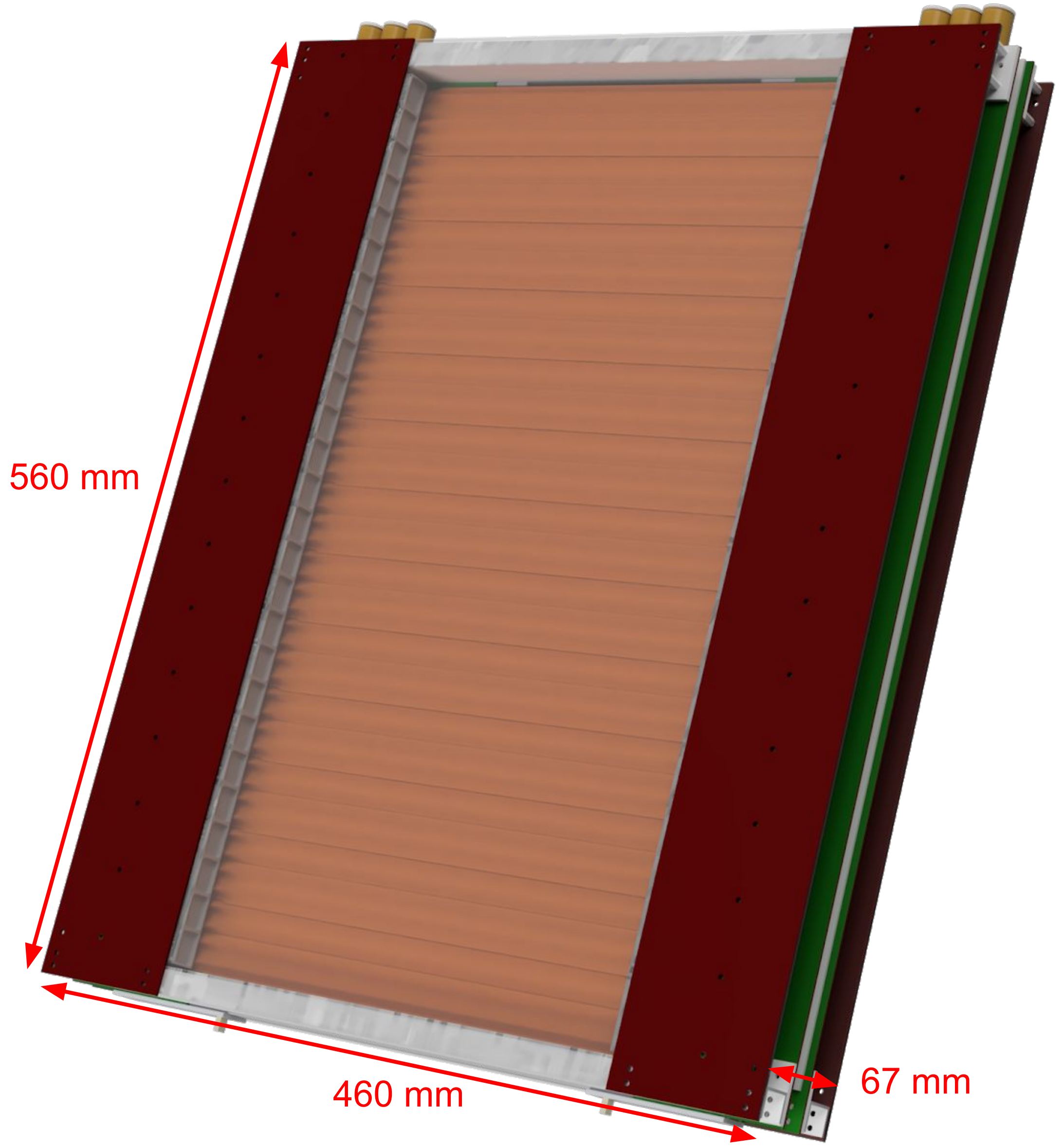
(b) *Back side of the strip submodule*



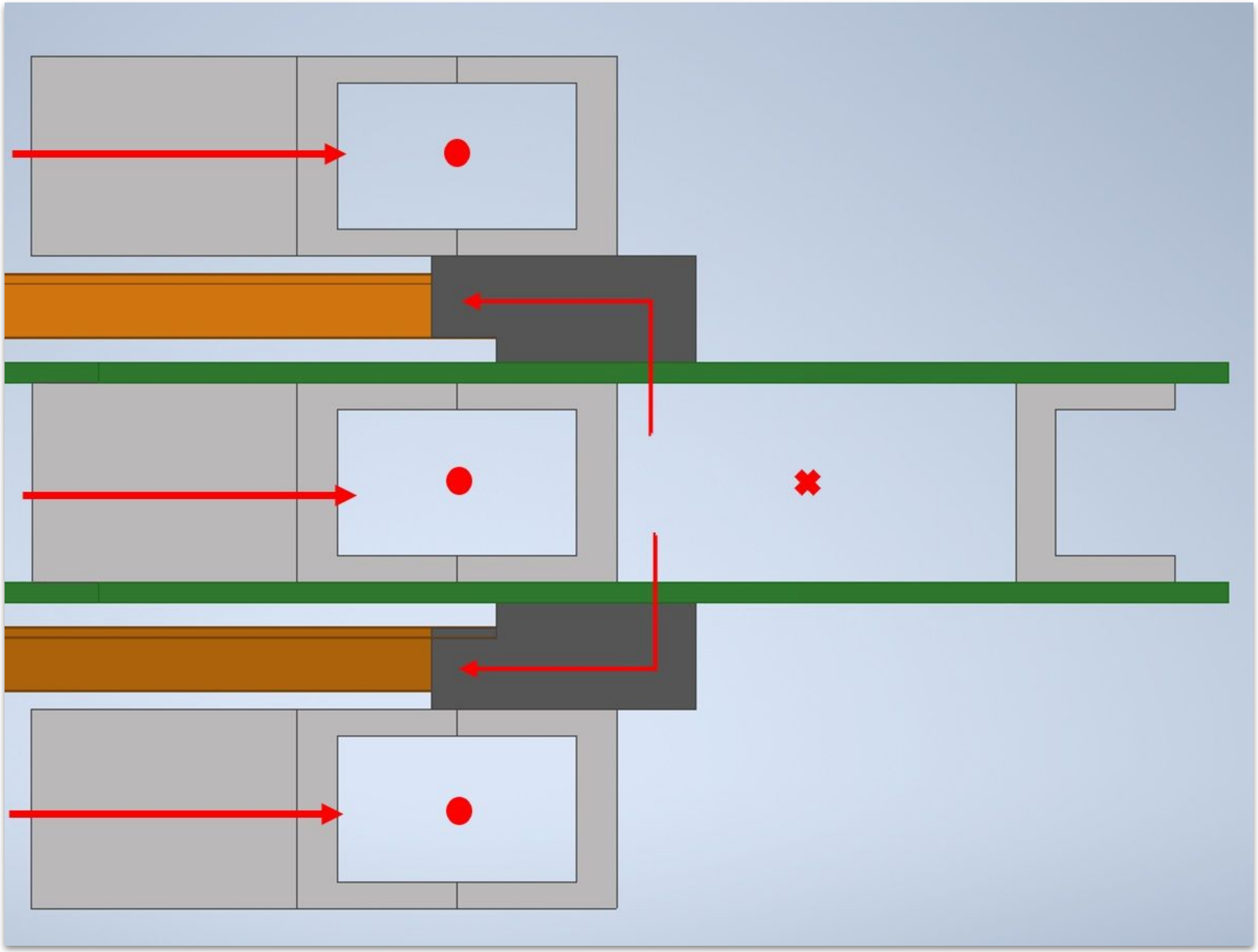
(c) *Side view on the back side of the strip submodule*



Tracking detector module: dimensions

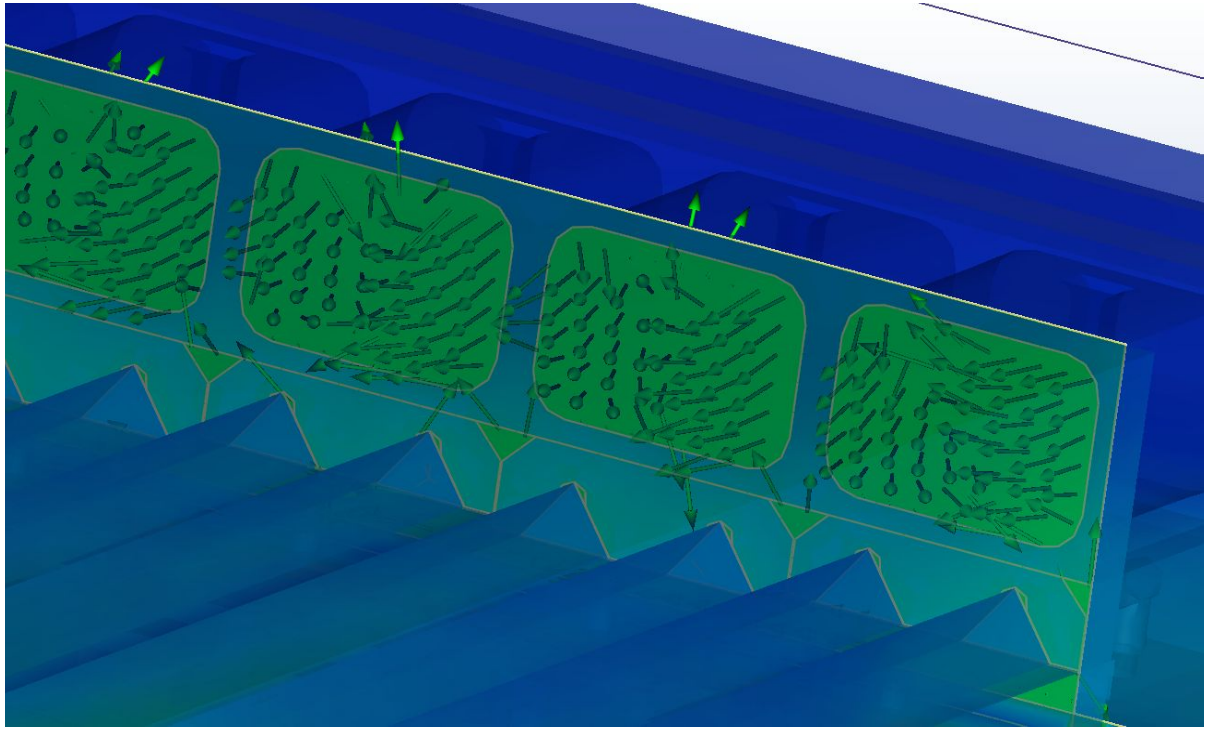


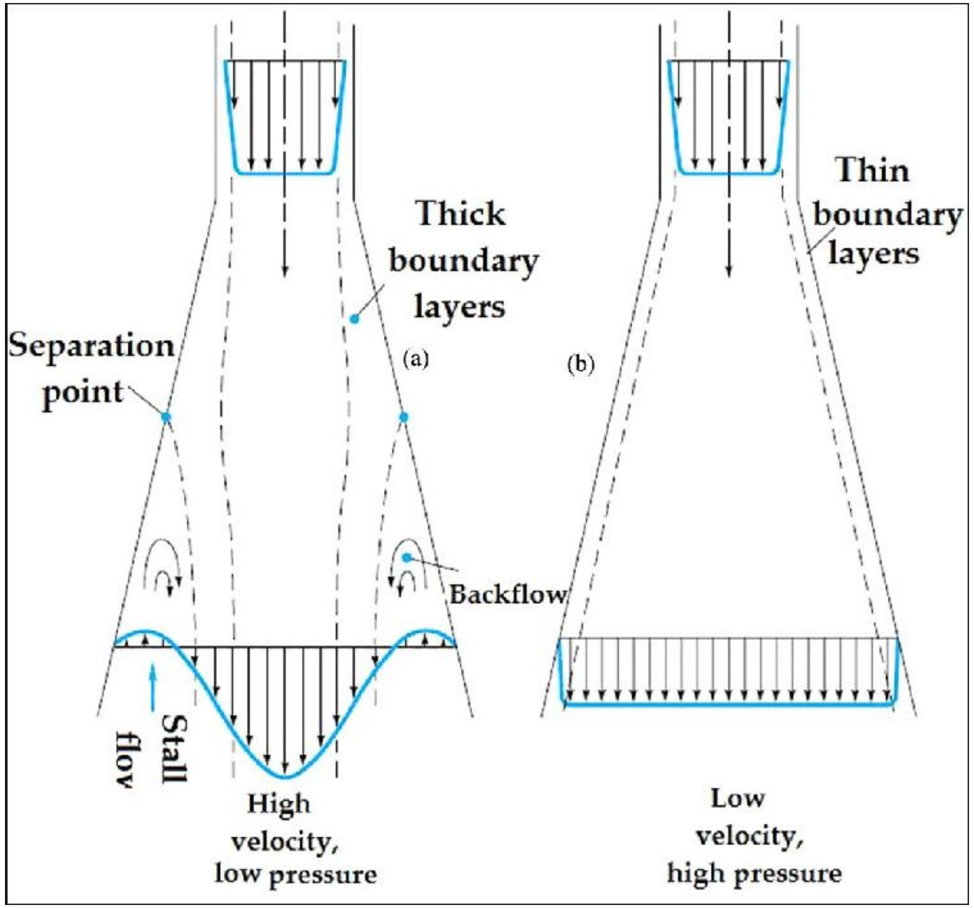
Increased gas flows: problem



Increased gas flows: problem

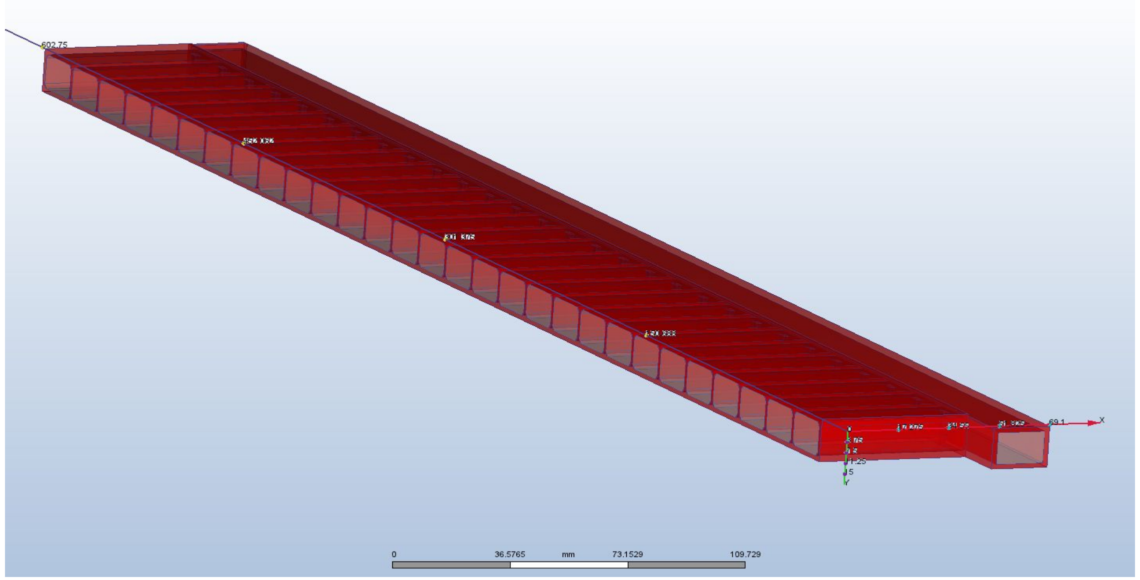
Random orientation of velocity vectors at the outlet of the diffuser part

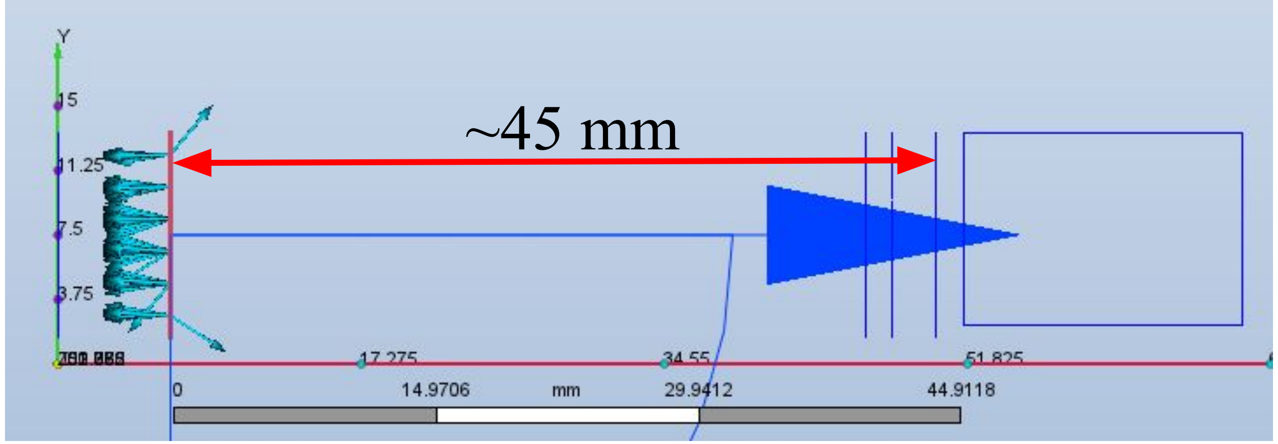


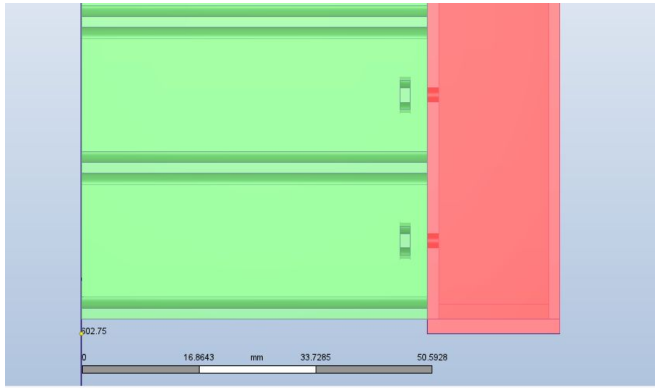


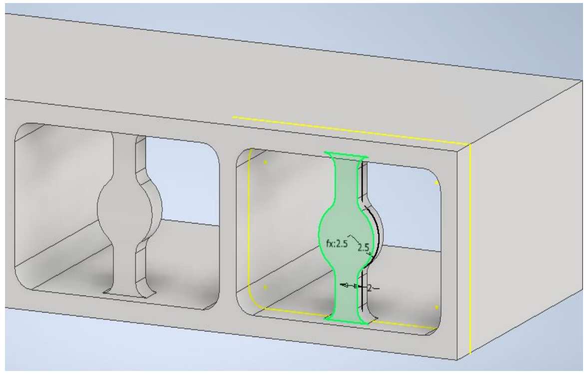
Uneven flow front with backflows

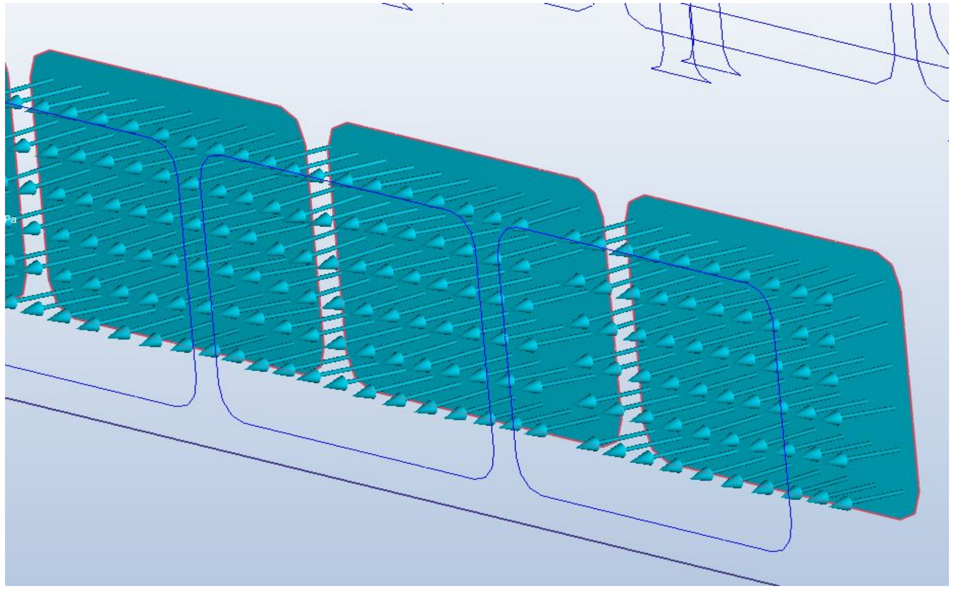
Increased gas flows: problem



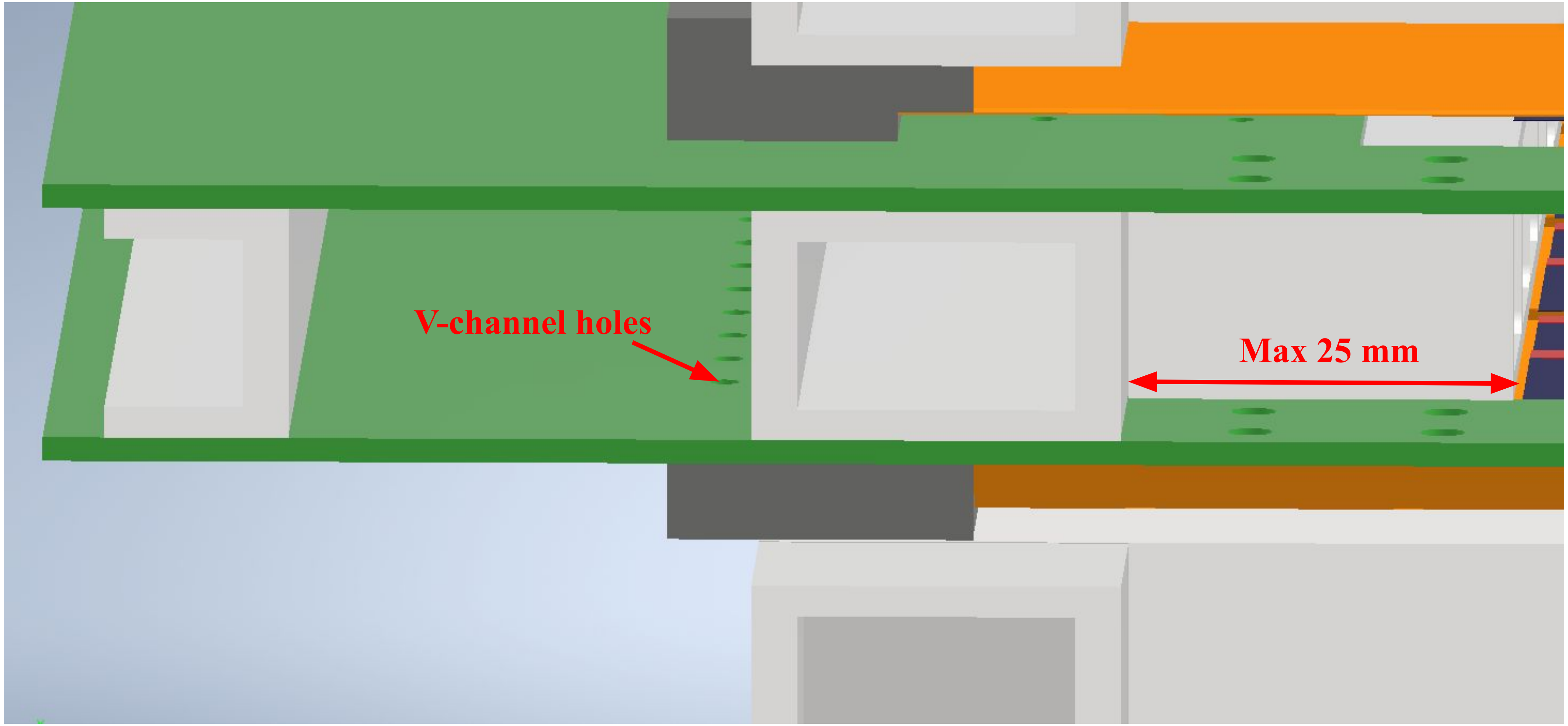




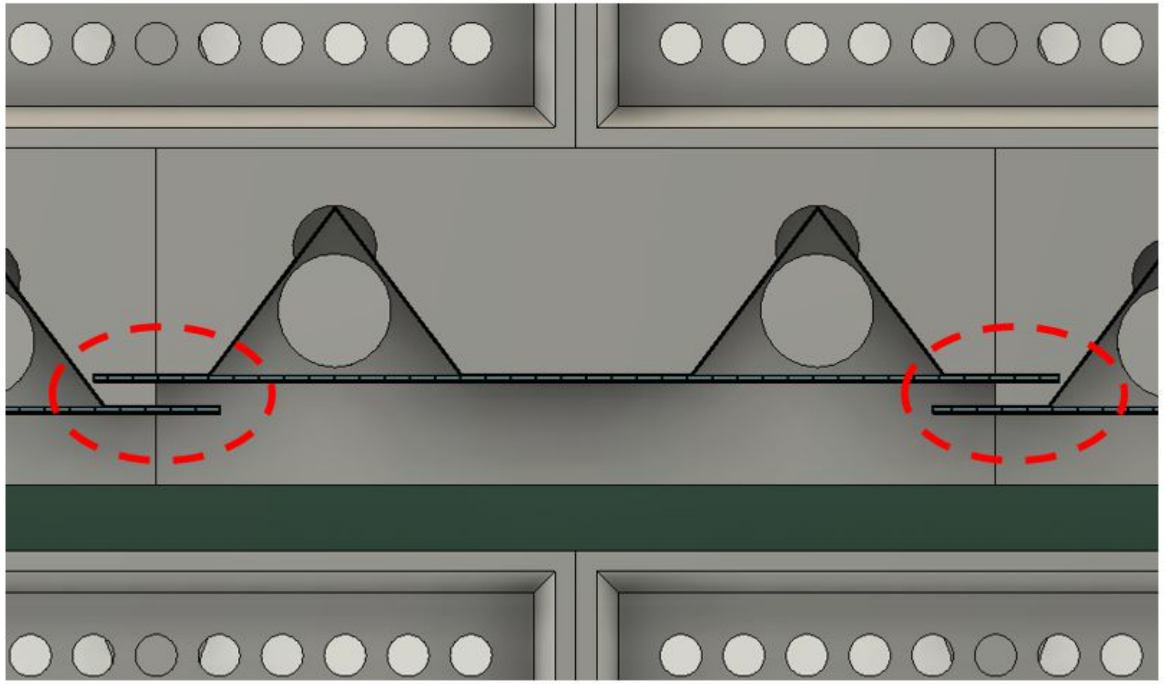


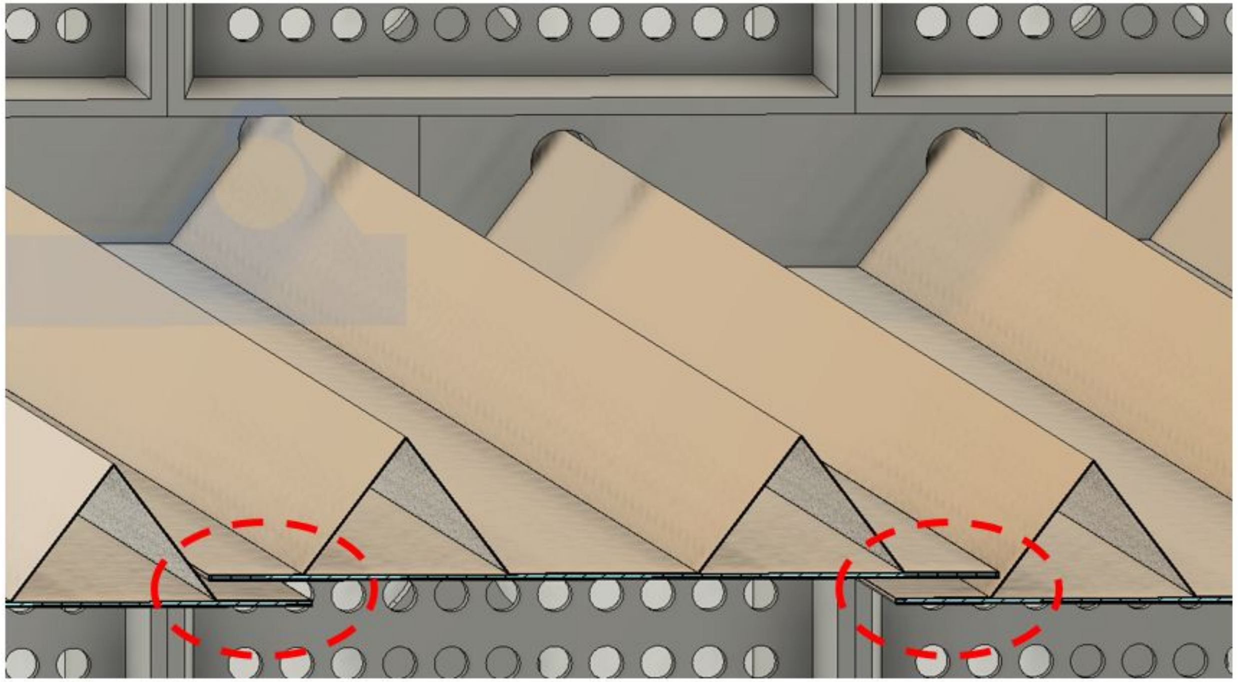


Increased gas flows: problem

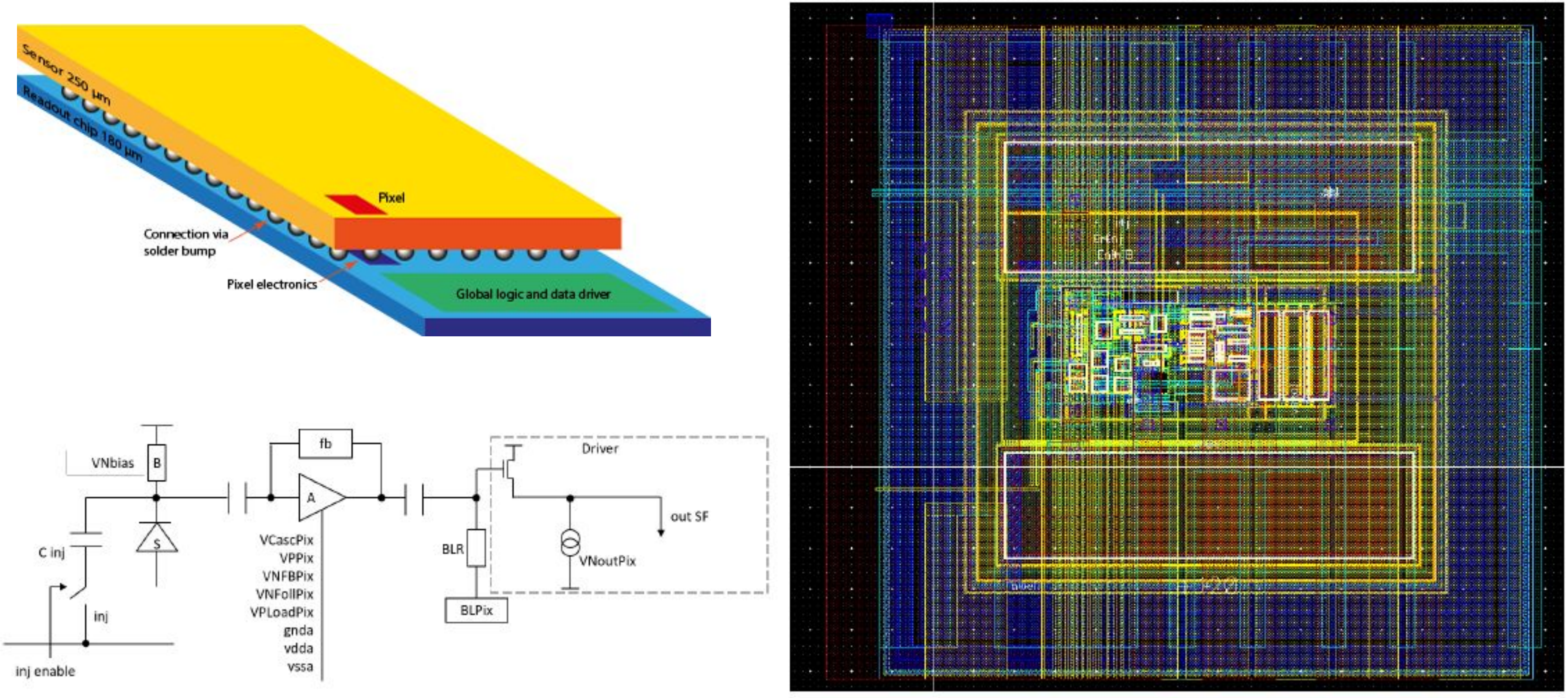


Overlapping of sensors





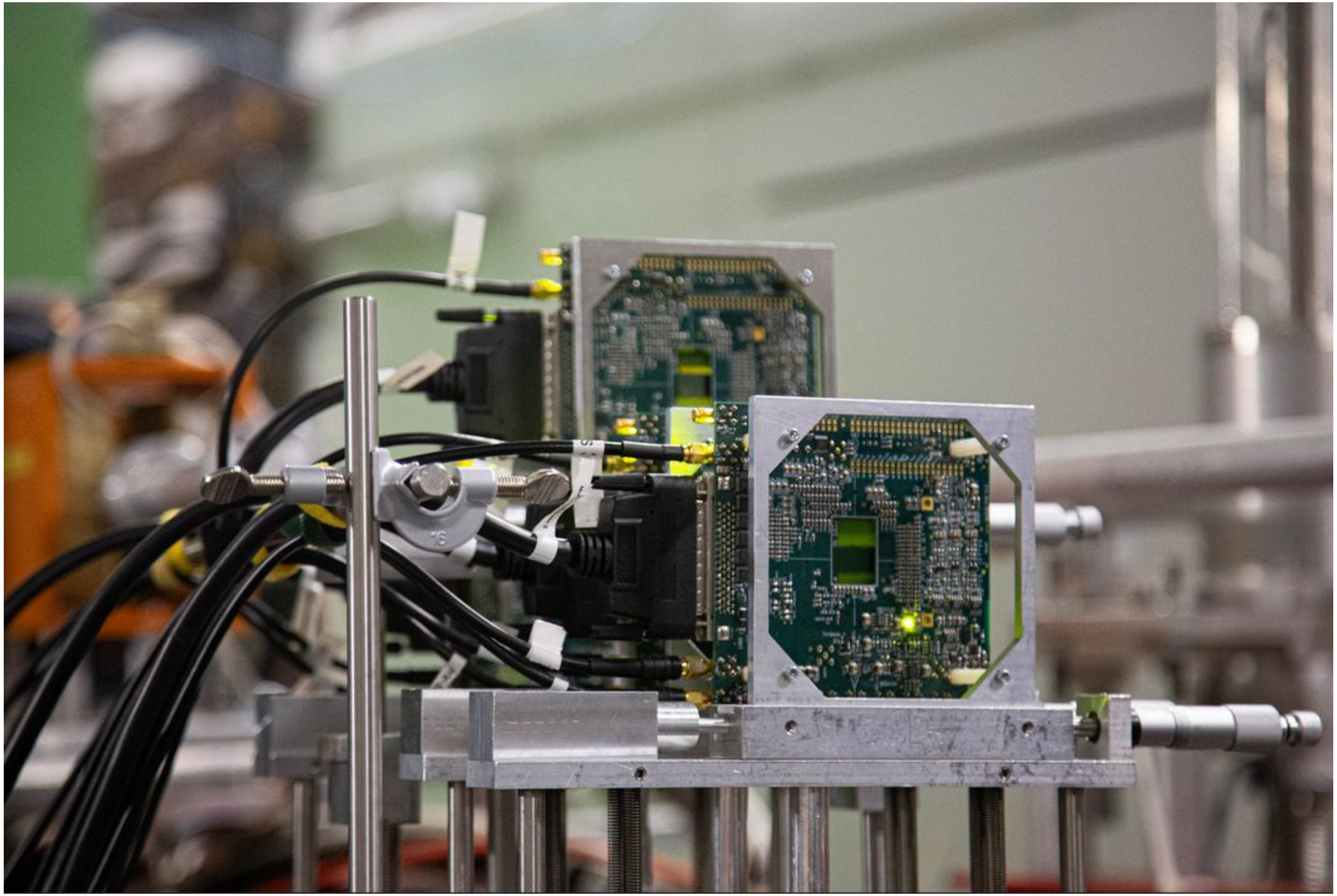
MuPix10



(a) Pixel schematic.

(b) Pixel layout.

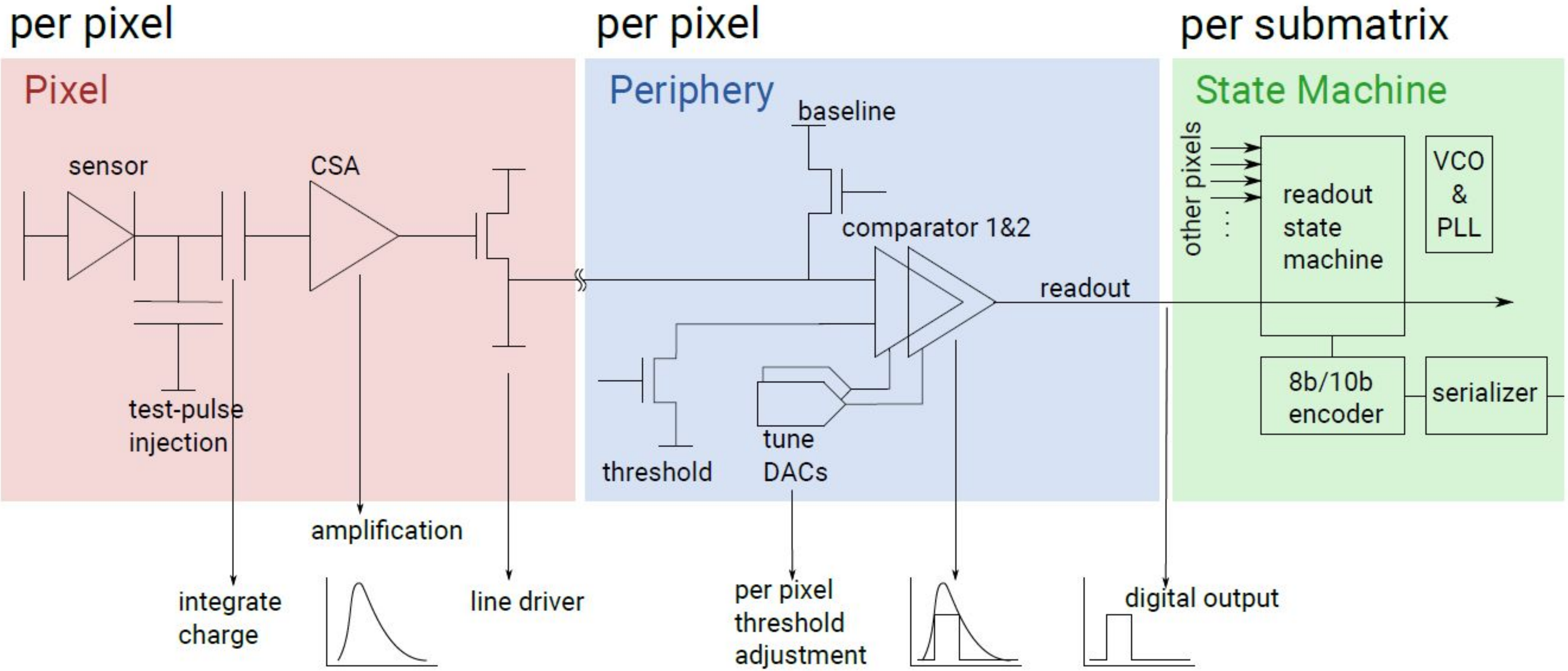
MuPix: telescope during the testbeam



MuPix specs

	MuPix8	MuPix10	ATLASPix1_Simple	ATLASPix3
Process	AH18 (AMS) [3]	H18 (TSI) [4]	AH18 (AMS) [3]	H18 (TSI) [4]
Sensor size [mm^2]	10.7×19.5	20.2×23.0	3.4×18.4	20.2×21.0
Pixel matrix	128×200	250×256	25×400	132×372
Pixel size [μm^2]	81×80	80×80	130×40	150×50
Active area [mm^2]	10.3×16.0	20.1×20.0	3.25×16.0	19.8×18.6
#Bits timestamp & ToT	10+6	11+5	10+6	10+7
Pixel tune DACs [bits]	3	3	3	3
Bandwidth [Gbit/s]	$\leq 1.6\ (3\times)$	$\leq 1.6\ (3\times)$	≤ 1.6	1.28
Readout architecture	continuous	continuous	continuous	trigger (cont.)
Status (December 2019)	tested	in production	tested	under test

MuPix: readout schematics

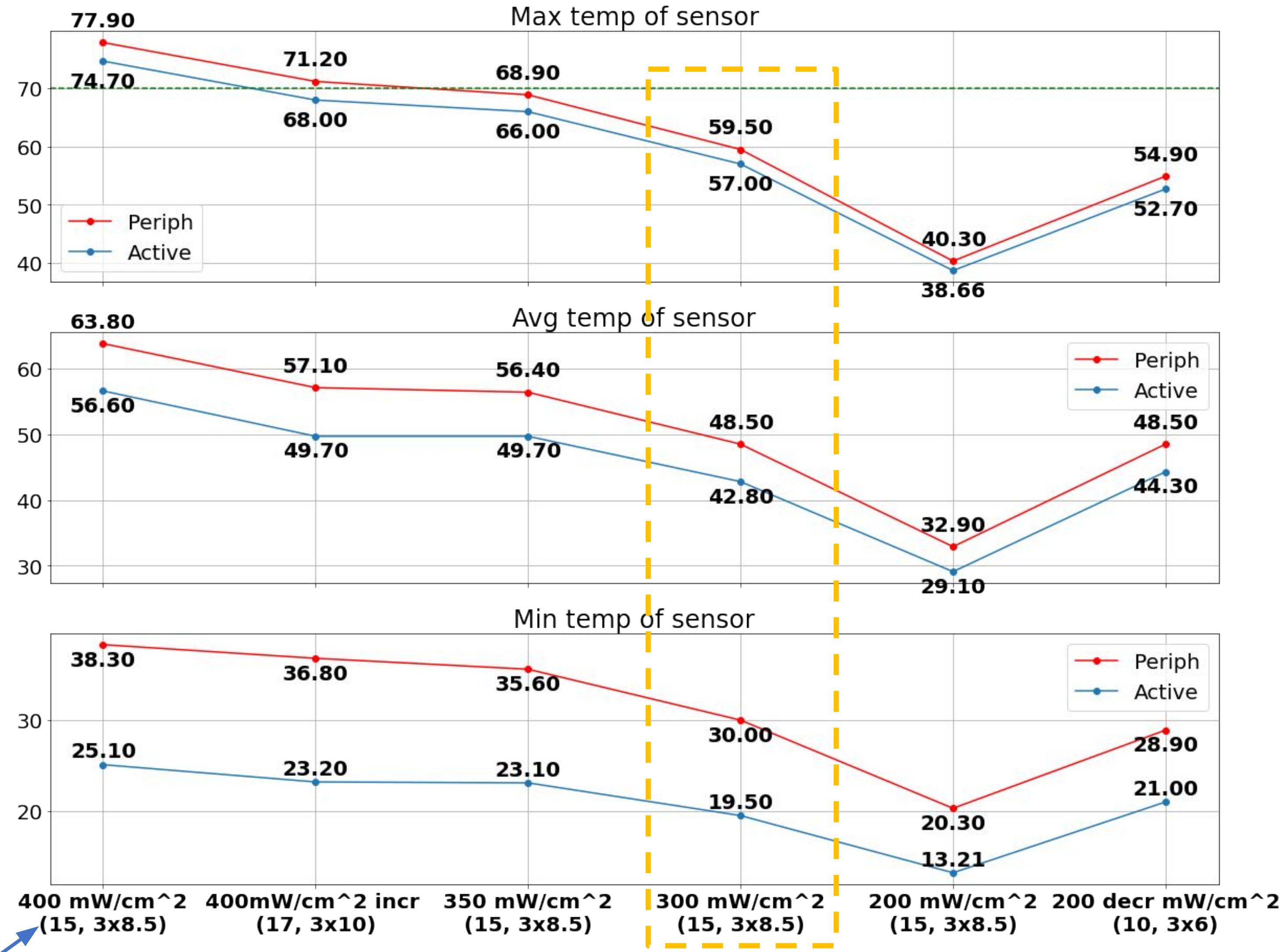


CFD simulation: Comparison of different scenarios

Total heat production of one MuPix, mW/cm^2	**Volumetric analogue** (used in CFD for dissipation in all directions), W/cm^3		
	Total*	**Active area** (87%)	**Periphery area** (13 %)
400	80	40	346
350	70	35	304
300	**60**	**30**	**260**
250	50	25	217
200	40	20	174

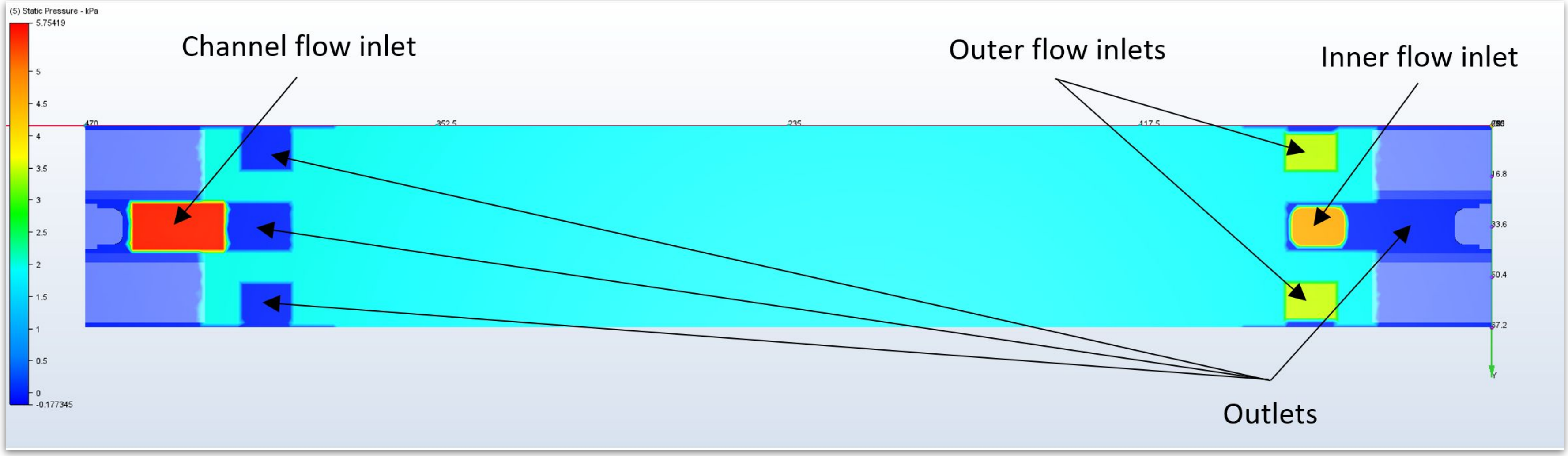
*periphery area will (can) produce up to 50% of the total heat

CFD simulation: Comparison of different scenarios



(`channel flow`, 3x`inner&outer flows` [l/s])

CFD simulation: pressure drop & mass flow



High power scenario (300 mW/cm^2):

	Channel flow	Inner and outer flows (per flow)
Mass flow, g/s	~ 2.6	~ 1.5
Total mass flow, g/s	~ 7	
Pressure drop, mbar*	<30	<60
Max velocity, m/s	~22 (locally)	≈2

* Pressure at the inlet, outlet pressure is 0 Pa

Helium cooling system

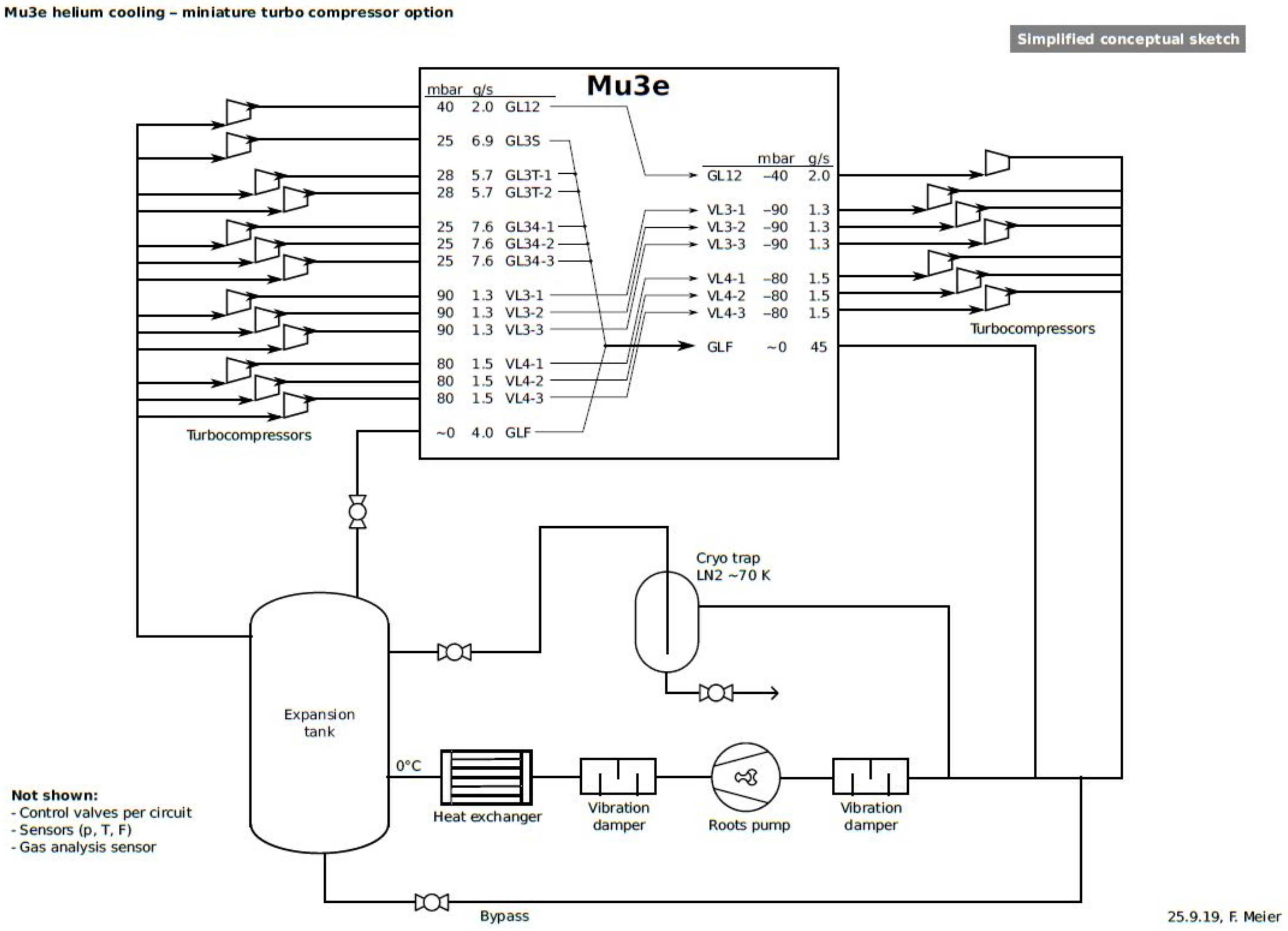


Figure 2: PFD of helium cooling plant in a version with a number of small compressors (see text).

Backup