Large-Scale Comprehensive Thermal Simulation of the CBM Silicon Tracking System (STS) on the Virgo Cluster at GSI

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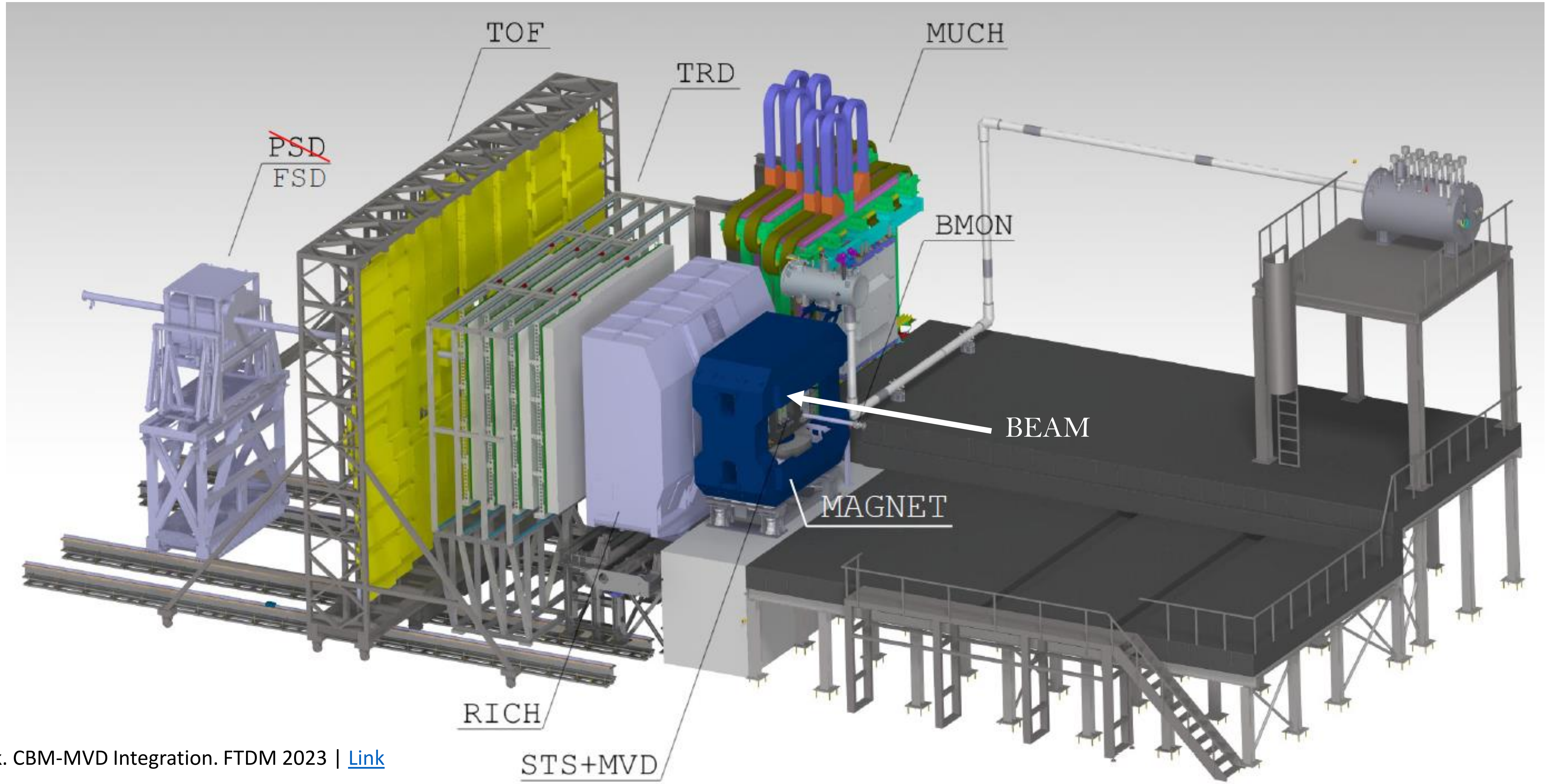
on behalf of the CBM Collaboration

GSI Helmholtzzentrum für Schwerionenforschung GmbH

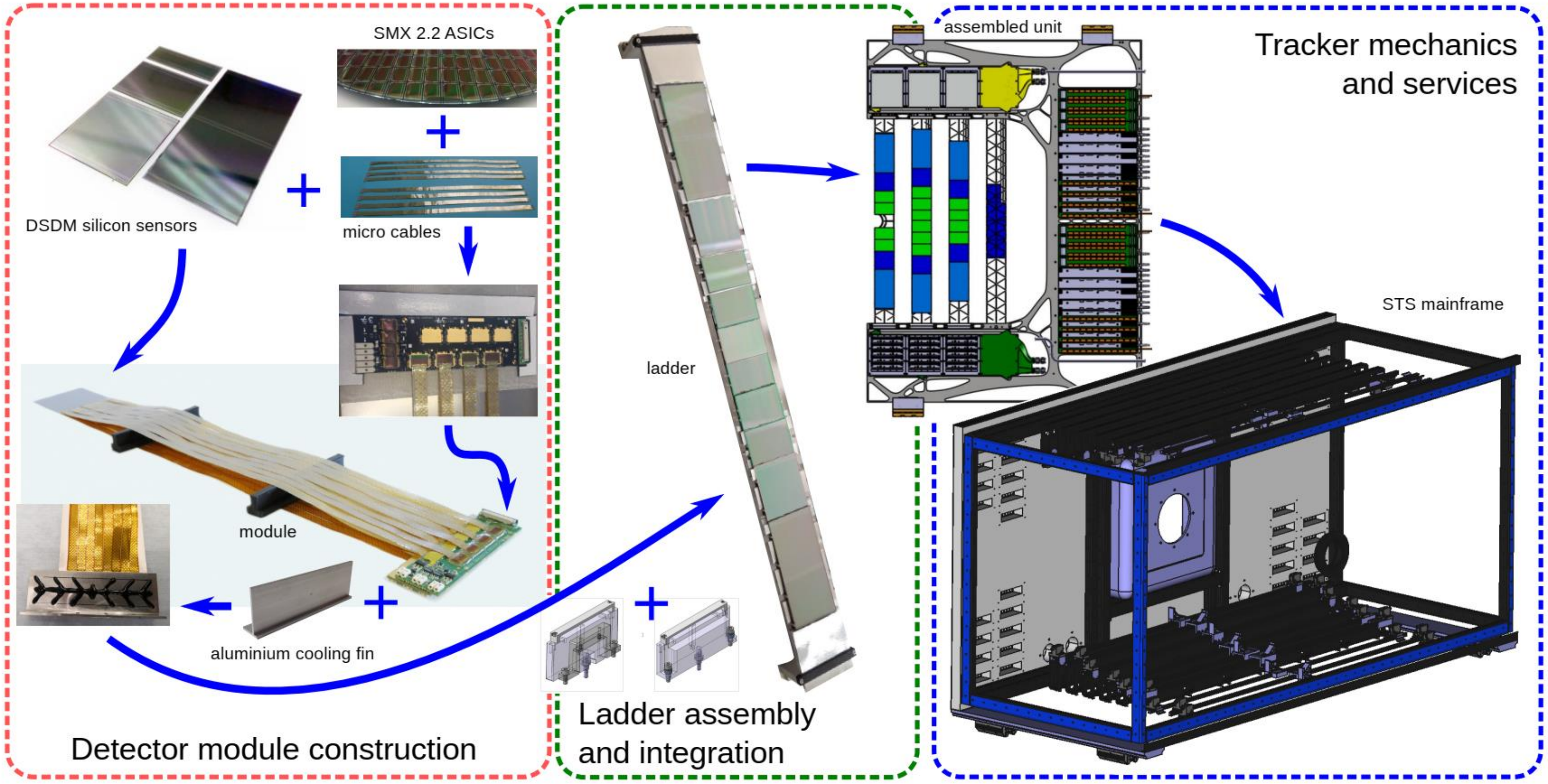
29.05.2024

Compressed Baryonic Matter (CBM) Experiment



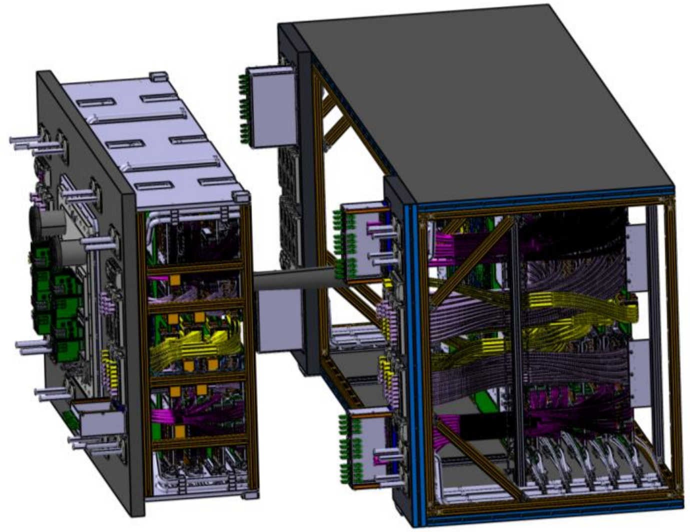
F. Matejcek. CBM-MVD Integration. FTDM 2023 | [Link]

Silicon Tracking System (STS) Detector Structure

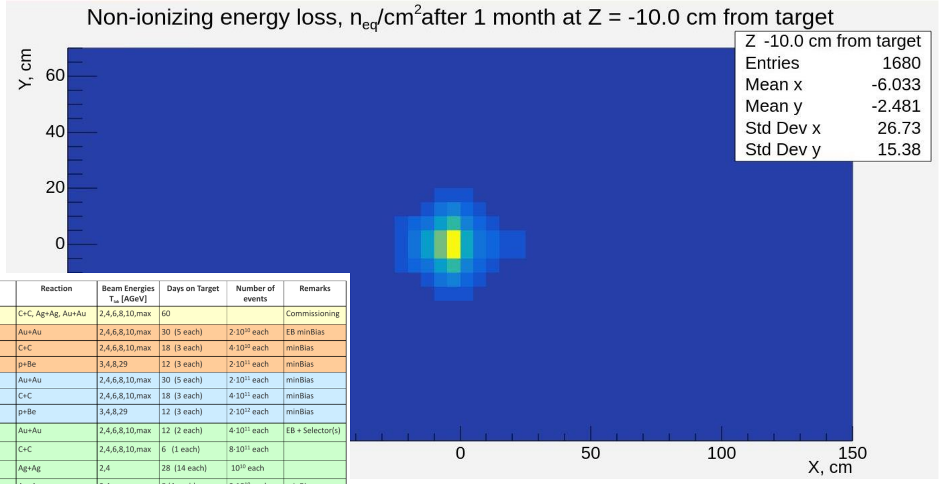


M. Teklishyn. CBM-STS Integration. FTDM 2022 | [Link]

Challenges for the Thermal Simulations



How does every silicon sensor perform
in complex 3D geometry?



Year	Setup	Reaction	Beam Energies T_{lab} [AGeV]	Days on Target	Number of events	Remarks
0	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10,max	60		Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{10}$ each	EB minBias
1	ELEHAD	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{10}$ each	minBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{11}$ each	minBias
2	MUON	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{11}$ each	minBias
2	MUON	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{11}$ each	minBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{12}$ each	minBias
3	HADR	Au+Au	2,4,6,8,10,max	12 (2 each)	$4\cdot10^{11}$ each	EB + Selector(s)
3	HADR	C+C	2,4,6,8,10,max	6 (1 each)	$8\cdot10^{11}$ each	
3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	$2\cdot10^{10}$ each	minBias

How does irradiation scenarios affect
the sensors thermal performance?

$$\Delta I(T) = I(\Phi) - I_{Vol}(\Phi = 0) = \alpha \Phi V$$

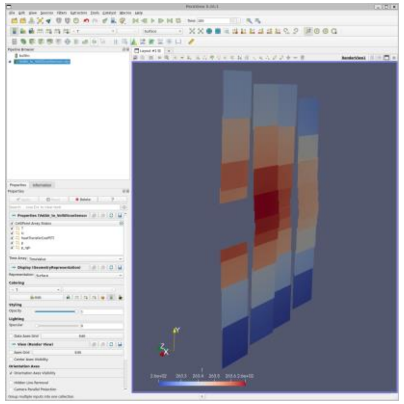
$$i_n^2 = \frac{4k_BT}{R_{bias}} + \frac{4k_BT}{R_{fb}} + 2eI_{det}$$

$$I(T_0) = I(T_1) \times \left(\frac{T_0}{T_1}\right)^2 e^{-\frac{E_g}{2k_B}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)}$$

$$ENC^2 = \underbrace{i_n^2 F_i T_s}_{\text{current noise}} + \underbrace{e_n^2 F_v \frac{C_T^2}{T_s}}_{\text{voltage noise}} + \underbrace{F_{vf} A_f C_T^2}_{\text{1/f noise}}$$

Can particles physics related effects
be integrated in the thermal performance?

```
alpha_d             4.81e-16;
I_0Ref              0.1875;
T_ref               263;
intensity           1;
irradiationTime     2;
E_g                 1.12;
K_b                 8.6173303e-5;
```



Can a broad group of scientists, students and
engineers be involved?

Open Source Computational Software

- OpenFOAM (Open Field Operation And Manipulation) is the free, open source computational software that utilizes finite volume method for thermofluidic simulations
- **Allows parallel computations, as a result, suitable for high performance computing in computer clusters**
- **Can be easily customized for specific tasks**

- The Salome platform is an open-source software for pre-processing
- Allows for simplifying geometry for simulations and initial meshing

- Power open source visualization engine
- Allows for results analysis

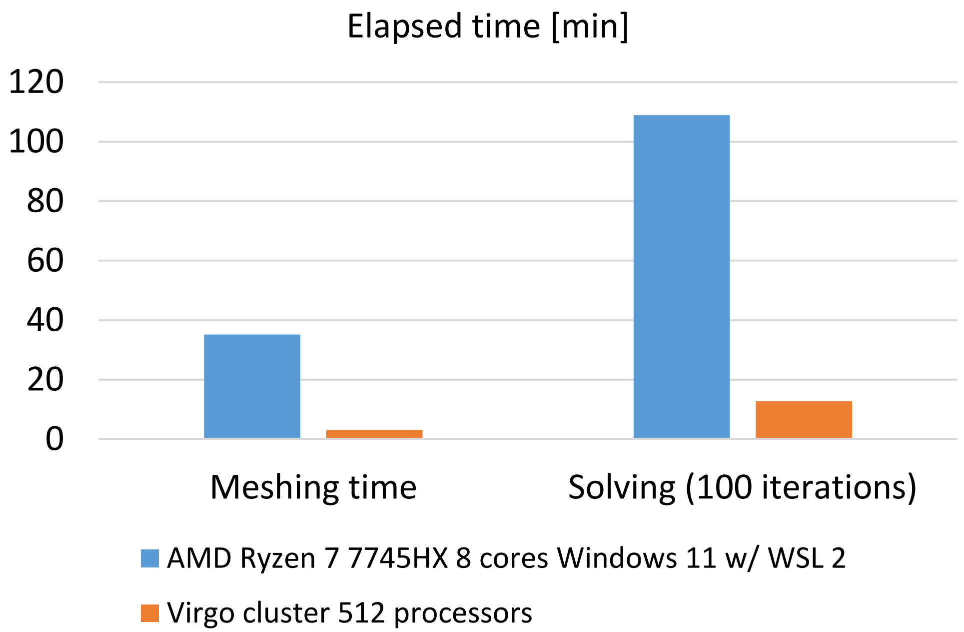
High Performance Computing at GSI – Green IT Cube

The Green IT Cube is one of the largest high-performance data centers in the world

Partition	CPUs max	RAM max [TB]	Time limit
debug	2048	8	30 minutes
main	2048	8	8 hours
high_mem	2048	16	7 days

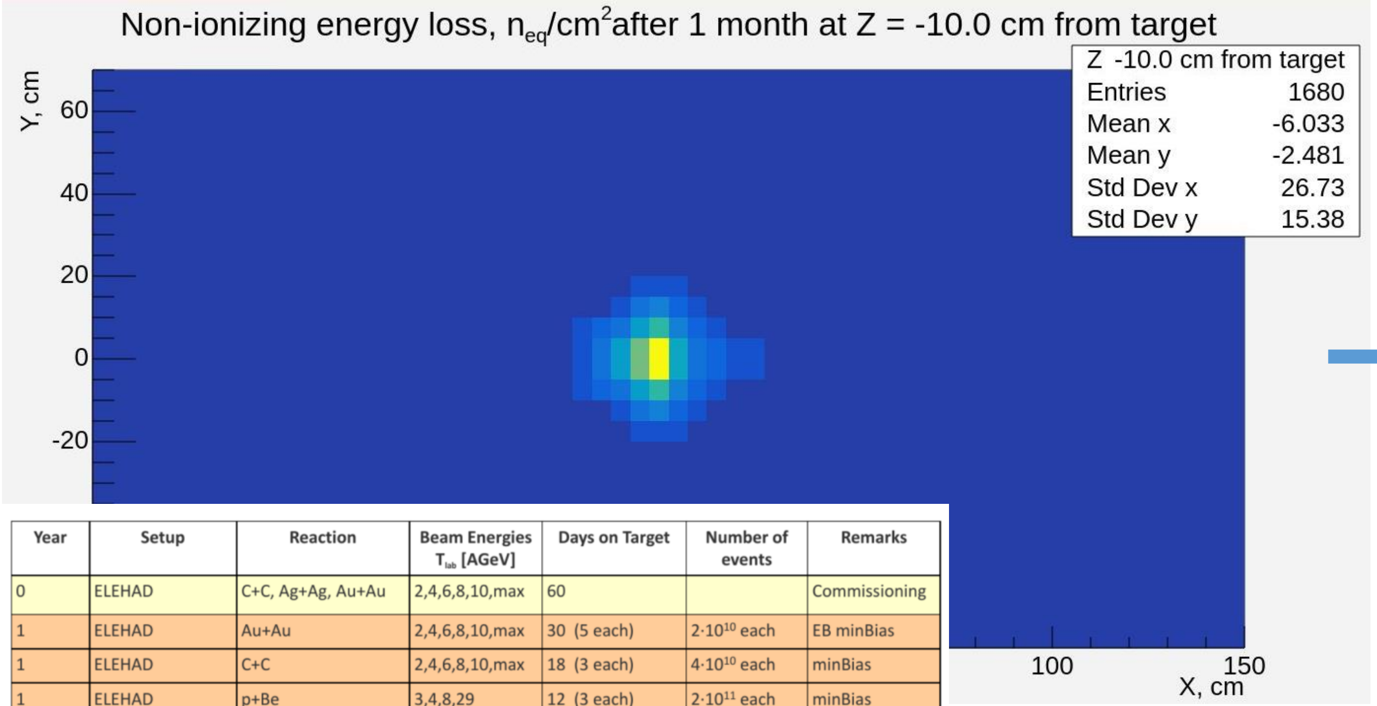
Two regions (conjugate heat transfer)

- Region VolAir 20,4 million cells
- Region VolSiliconSensors: 1 million cells



Customization for STS: Non-Ionizing Energy Loss (NIEL)

FLUKA diagrams in Root-format can be converted into OpenFOAM directly



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3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	
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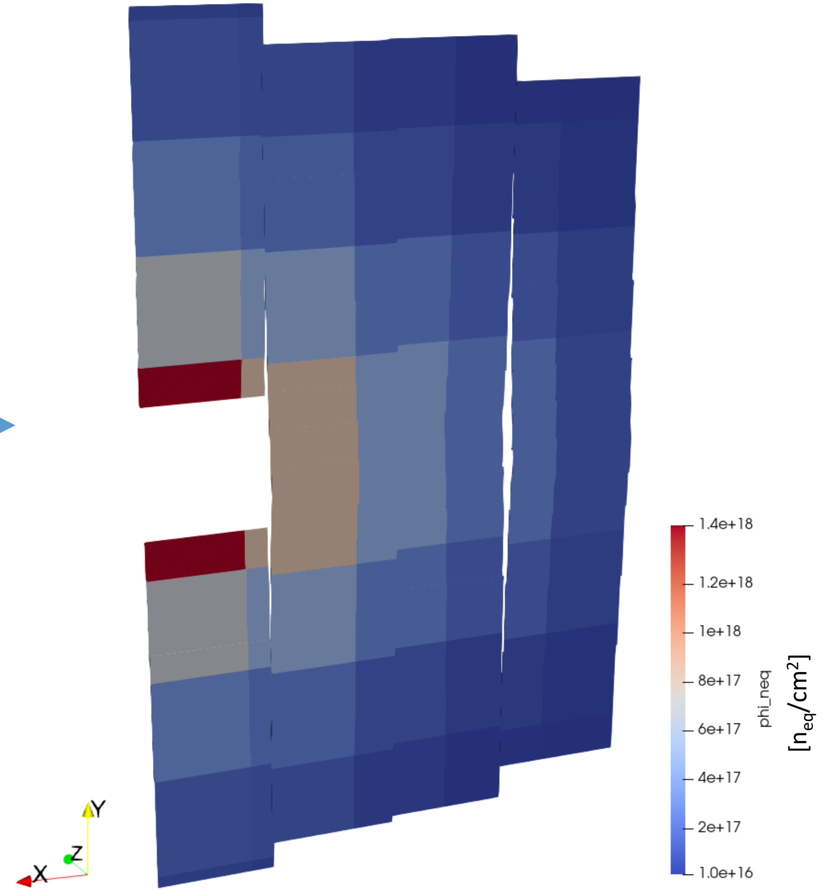



```
root -q rootDir/ConvertToOpenFoam.C'("rootDir/MagnetGap.root","rootDir/root_out.txt","rootDir/map.txt")'
```

Customization for STS: Thermal Model for Sensors

Conjugate heat transfer solver was modified to account power dissipation caused by radiation damage

```
forAll(solidRegions, i)
{
    fvMesh& mesh = solidRegions[i];

    #include "readSolidMultiRegionSIMPLEControls.H"
    #include "setRegionSolidFields.H"

    /* --- Customization --- */

    // Calculate fluence from gold ion normalized flux, intensity and time exposure
    phi_neq[i] = phiGoldIonNorm[i] * intensity[i] * irradiationTime[i];

    // Calculate irradiated leakage current at reference temperature [A/m^3], formula (2.8) Momot
    I_irrRef[i] = alpha_d[i] * phi_neq[i]+ I_0Ref[i];

    // Calculate irradiated leakage current at actual temperature [A/m^3]
    const volScalarField& T = solidRegions[i].lookupObject<volScalarField>("T");
    I_irr[i] = I_irrRef[i] * pow(T/T_ref[i], 2) * exp(-E_g[i]/(2*K_b[i])*(1/T - 1/T_ref[i]));

    // Calculate heat disspation [W/m^3]
    Q_irr[i] = I_irr[i] * U_bias[i];

    #include "solveSolid.H"
}
```

$$\Delta I(T) = I(\Phi) - I_{Vol}(\Phi = 0) = \alpha \Phi V$$

$$I(T_0) = I(T_1) \times \left(\frac{T_0}{T_1}\right)^2 e^{-\frac{E_g}{2k_B}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)}$$

$Q = I \; x \; U$

```
elizarov@lxbk1133:/lustre/cbm/users/elizarov/OpenFOAM/elizarov-v2206/run/siliconSensors_turbulence/constant > cat radiationDamageProperties
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  v2206                                 |
|   \\  /    A nd           | Website:  www.openfoam.com                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    object      radiationDamageProperties;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

alpha_d         4.81e-16; // radiation damage coefficient [A/m],
I_0Ref          0.1875; // 1.875e-3; // non-irradiated leakage current at reference temperature [A/m^3]
T_ref           263; // Reference temperature at which leakage current is given [K]
intensity       1; // Not relevant
irradiationTime 2; // [months]
E_g             1.12; // Band-gap, 1.12 eV [-]
K_b             8.6173303e-5; // The Boltzmann constant, 8.617e-5 eV/K [1/T]
```

Radiation damage properties are combined in one file

```
Solving for solid region VolSiliconSensors
Additional heat dissipation due to the radiation damage of the sensors is taken into account
GAMG:  Solving for h, Initial residual = 0.630116, Final residual = 0.0285421, No Iterations 3
Total heat dissipation due to the leakage current [W]: 0.181431
Min/max T:263.002 263.023
ExecutionTime = 1294.83 s  ClockTime = 1411 s
```

The solver prints power dissipation every time step for controlling computation

Analytical Noise Estimation Model

Sensor

Electronics

From sensors thermal model

- parallel current noise (i_n^2)

$$i_n^2 = \frac{4k_BT}{R_{bias}} + \frac{4k_BT}{R_{fb}} + 2eI_{det} + \cancel{2eI_{ESD_n}} + \cancel{2eI_{ESD_p}}$$

- series voltage noise (e_n^2)

Electronics

$$e_n^2 = 4k_BT\boxed{R_{Al}} + 4k_BT\boxed{R_{cable}} + 4k_BTR_{inter} + e_{na}^2$$

Sensor

Cable

$$ENC^2 = \underbrace{i_n^2F_iT_s}_{\text{current noise}} + \underbrace{e_n^2F_v\frac{\boxed{C_T^2}}{T_s}}_{\text{voltage noise}} + \underbrace{F_{vf}A_f\boxed{C_T^2}}_{\text{1/f noise}}$$

$$ENC^2 = ENC_i^2 + ENC_e^2 + ENC_{1/f}^2$$

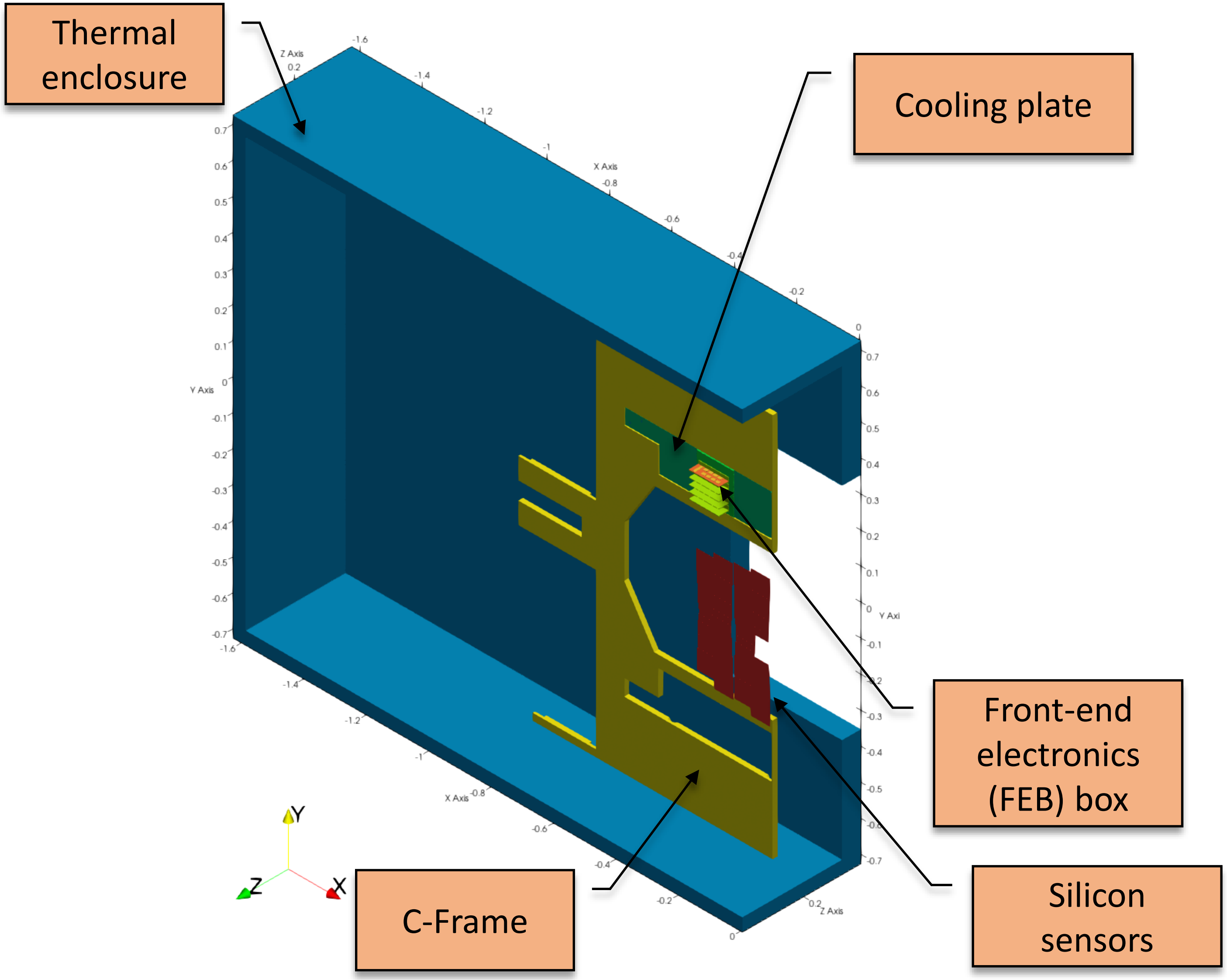
$C_T = C_{sensor} + C_{cable}$

Need to know heights of sensors and lengths of cables

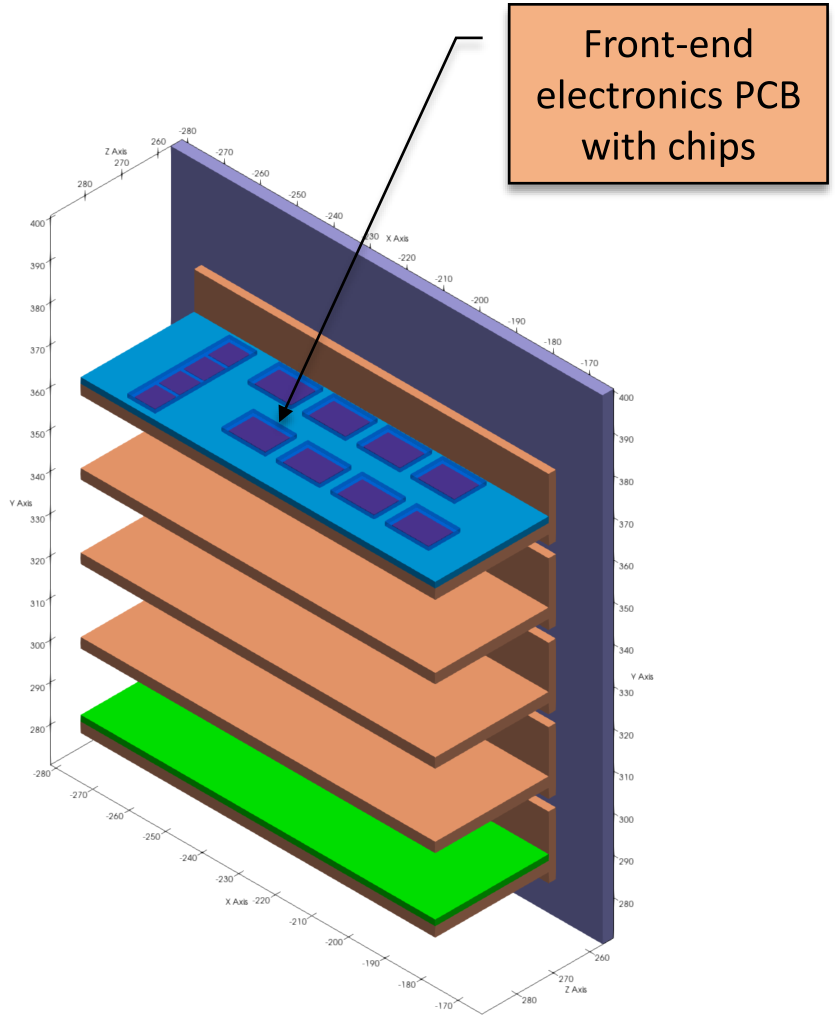
```
K_bn          1.380649e-23; // Boltmann constant [J/K]
e             1.60217663e-19; // electron charge [C]

R_bias        1e6; // [Ohm]
R_fback       12e6; // [Ohm]
R_inter       12.7; // [Ohm]
R_al_m        10.5e2; // R_al per meter [Ohm/m]
R_cable_m     0.6e2; // R_cable per meter [Ohm/m]

C_sensor_m    1.02e-10; // C_sensor per meter [F/m]
C_cable_m     0.382e-10; // C_cable per meter [F/m]
C_FEBc        8e-12; // FEB-C fanout lines capacitance [F]

alpha         0.5;      // [-]
gamma         1;        // [-]
g_m           0.044;    // [A/V]

T_s           90e-9;    // integration constant [s]

F_i           0.64; // [-]
F_v           0.85; // [-]
F_vf          3.41; // [-]

A_f           9.5e-12; // [C^2/F^2]
```

Source: Rodriguez Rodriguez, Adrian “STS FRONT-END ELECTRONICS ENC measurements & estimation”

Work on the STS Detector's Model: Geometry

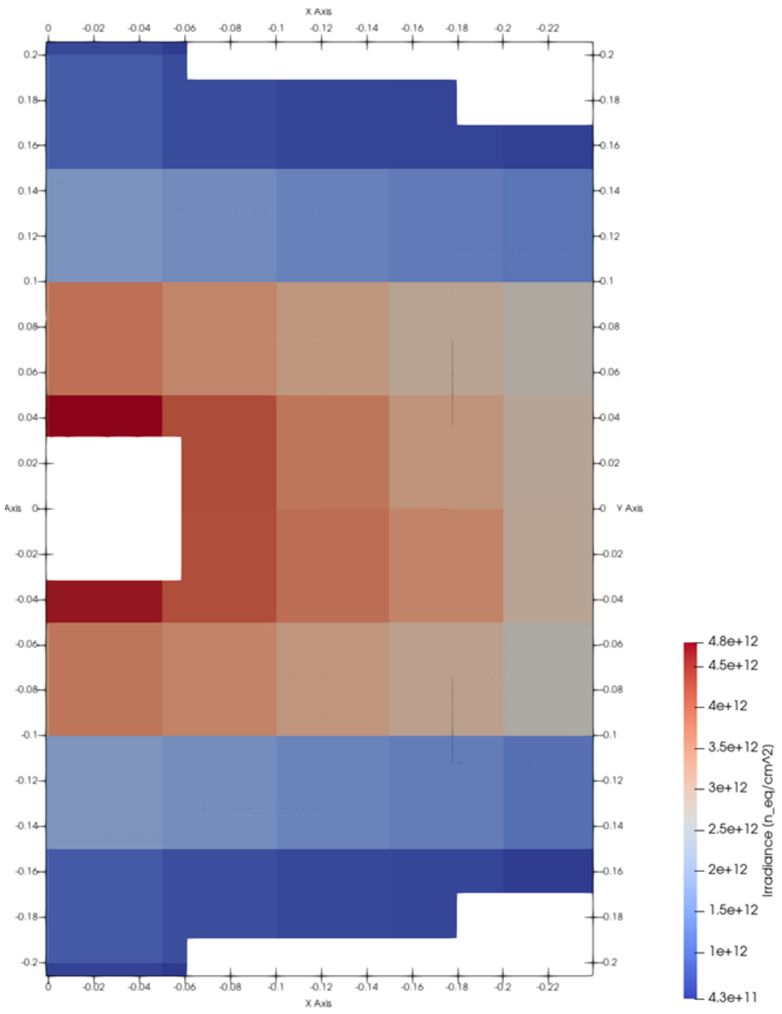


STS detector simplified geometry

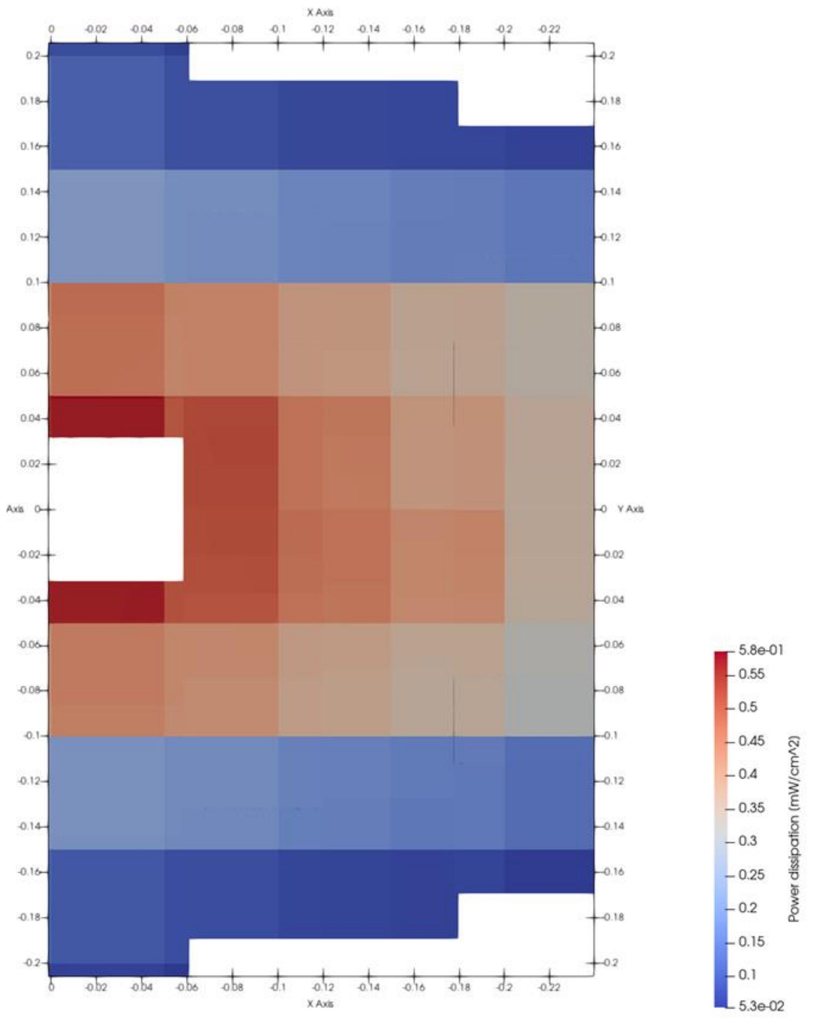


Front-end electronics Box

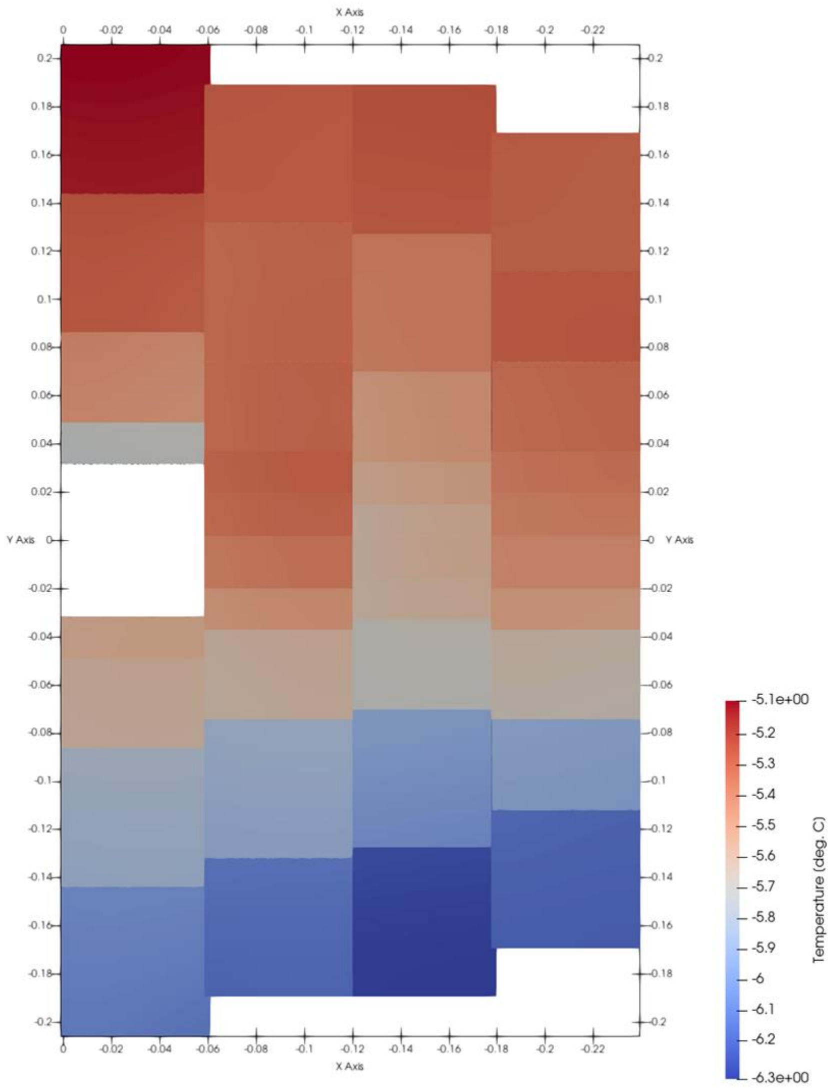
First Results from the Detector Thermal Simulation: Sensors



Non-ionizing energy loss

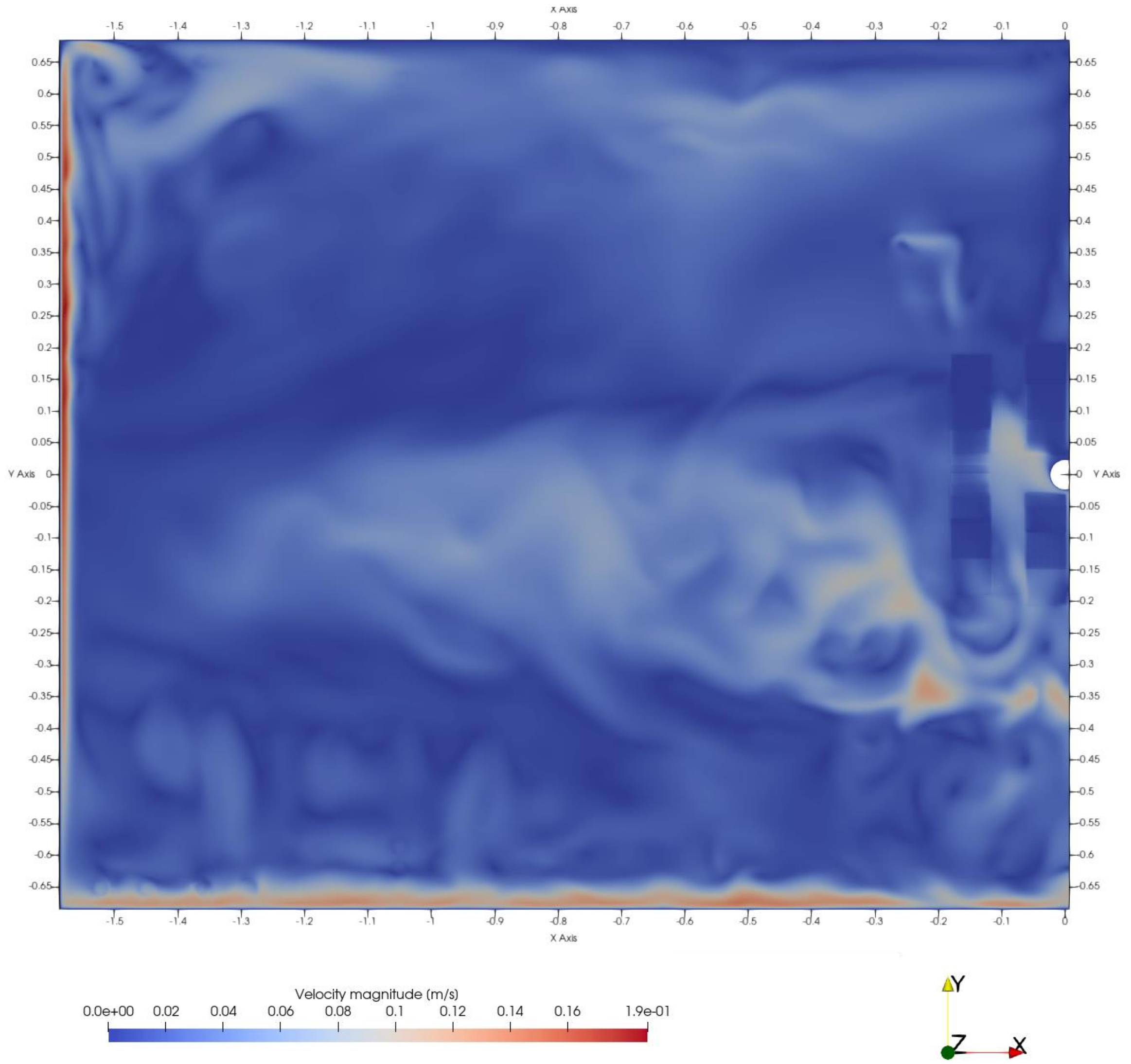


Power dissipation

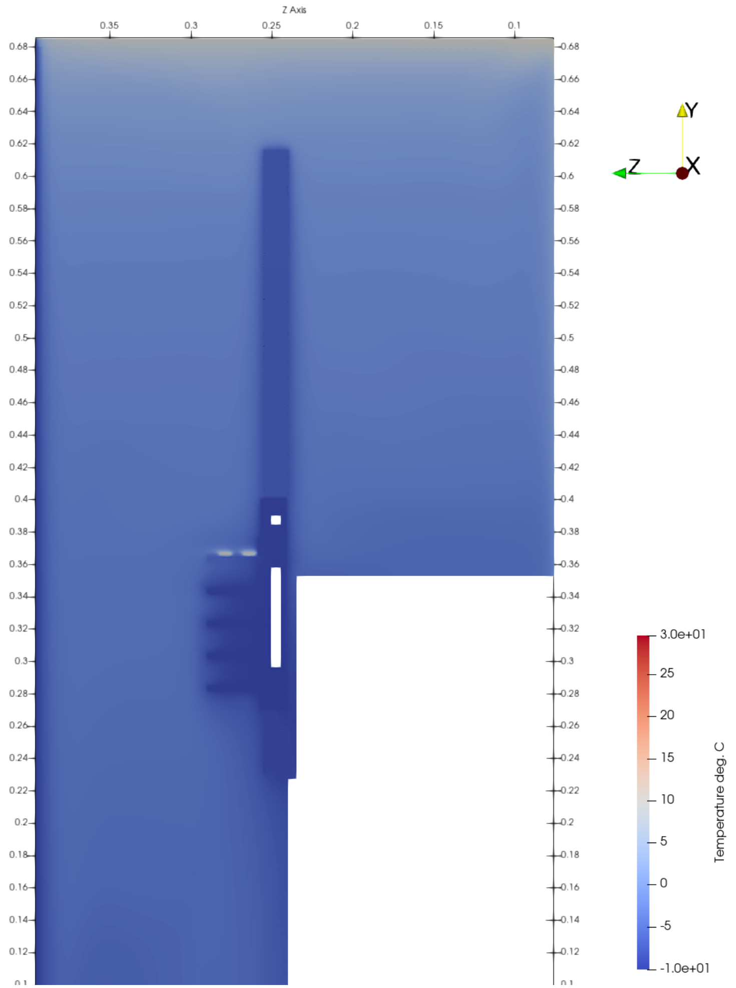


Temperature field

First Results from the Detector Thermal Simulation: Air Convection

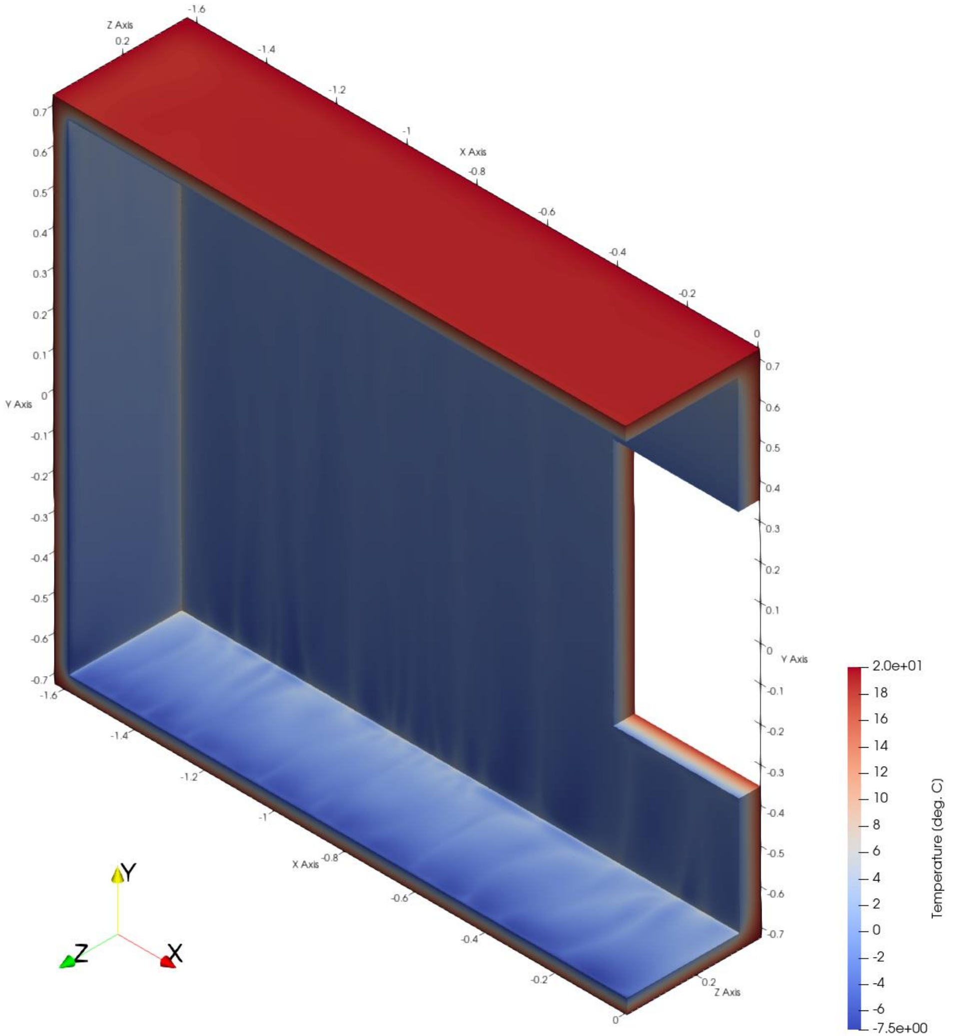


Air velocity field inside the thermal enclosure

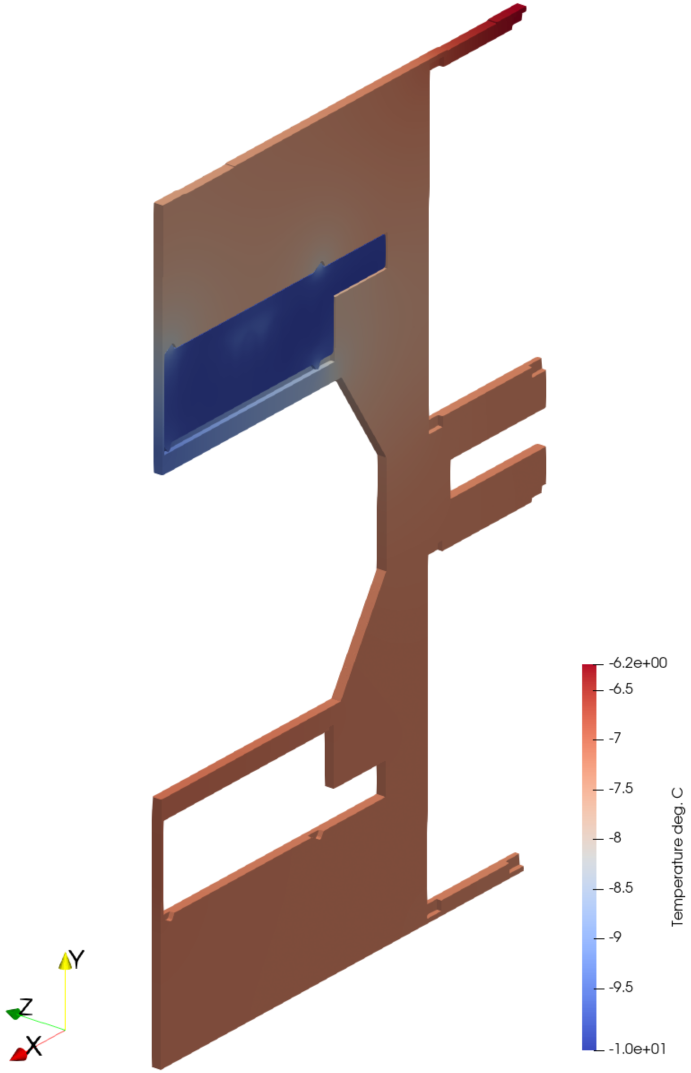


Air temperature around the cooling plate

First Results from the Detector Thermal Simulation: Supplementary Results



Temperature field:
Thermal enclosure walls



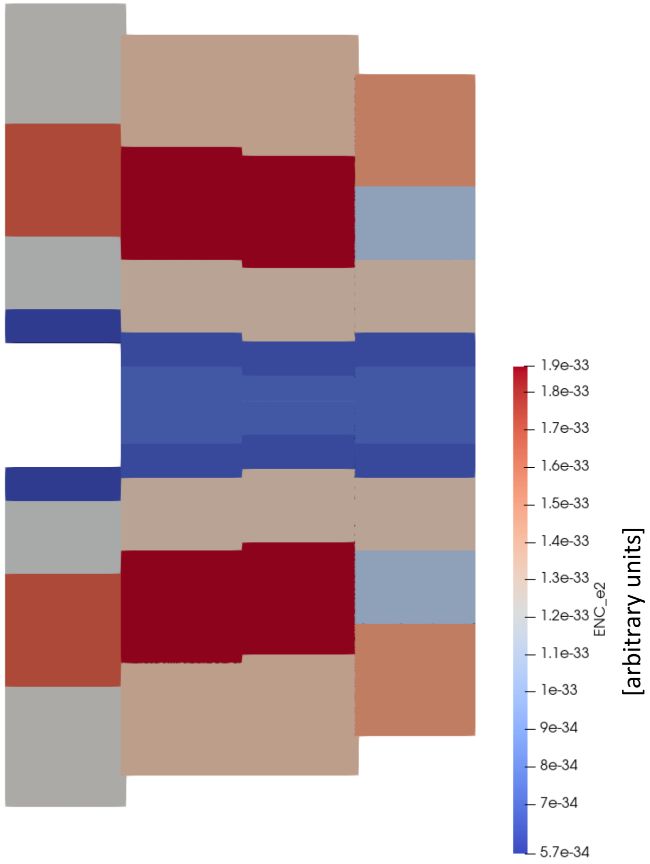
Temperature field:
C-Frame

First Results from the Detector Thermal Simulation: Noise analytical model

- series voltage noise (e_n^2)

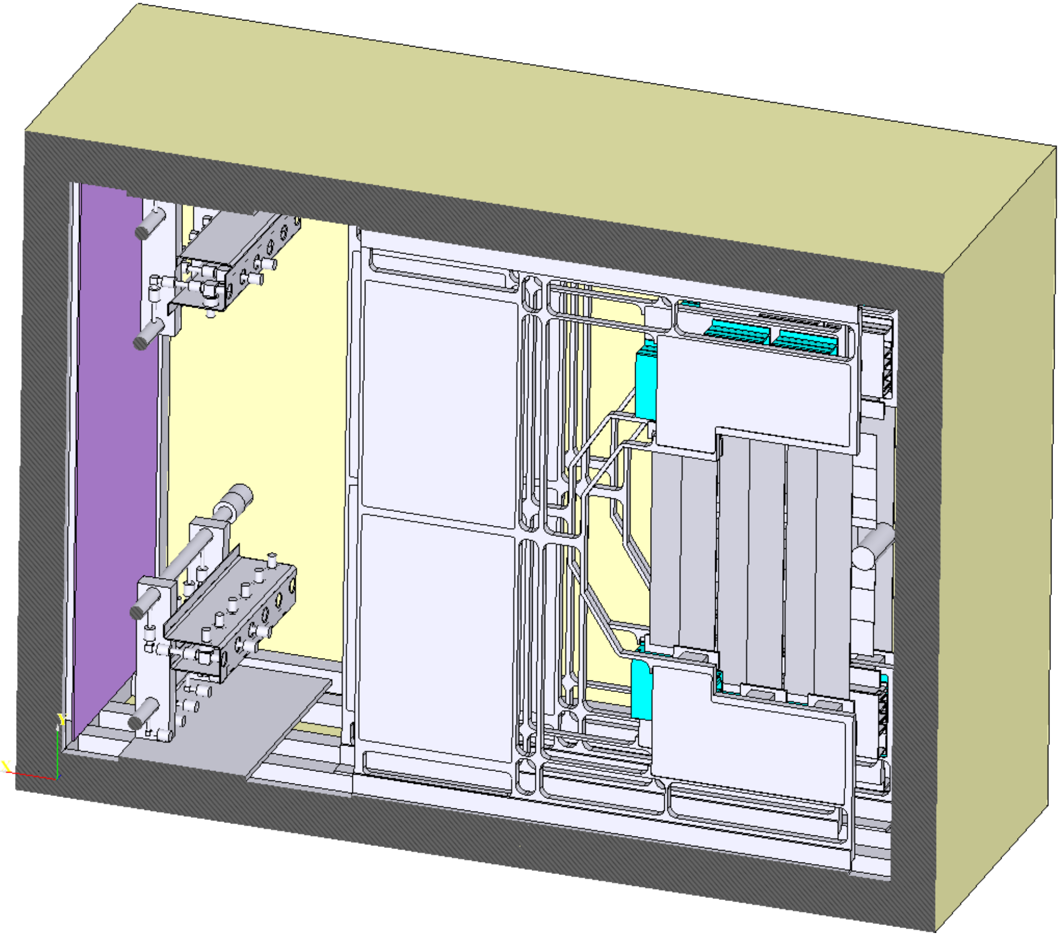
$$e_n^2 = 4k_BT\boxed{R_{Al}} + 4k_BT\boxed{R_{cable}} + 4k_BTR_{inter} + e_{na}^2$$

Silicon sensor module

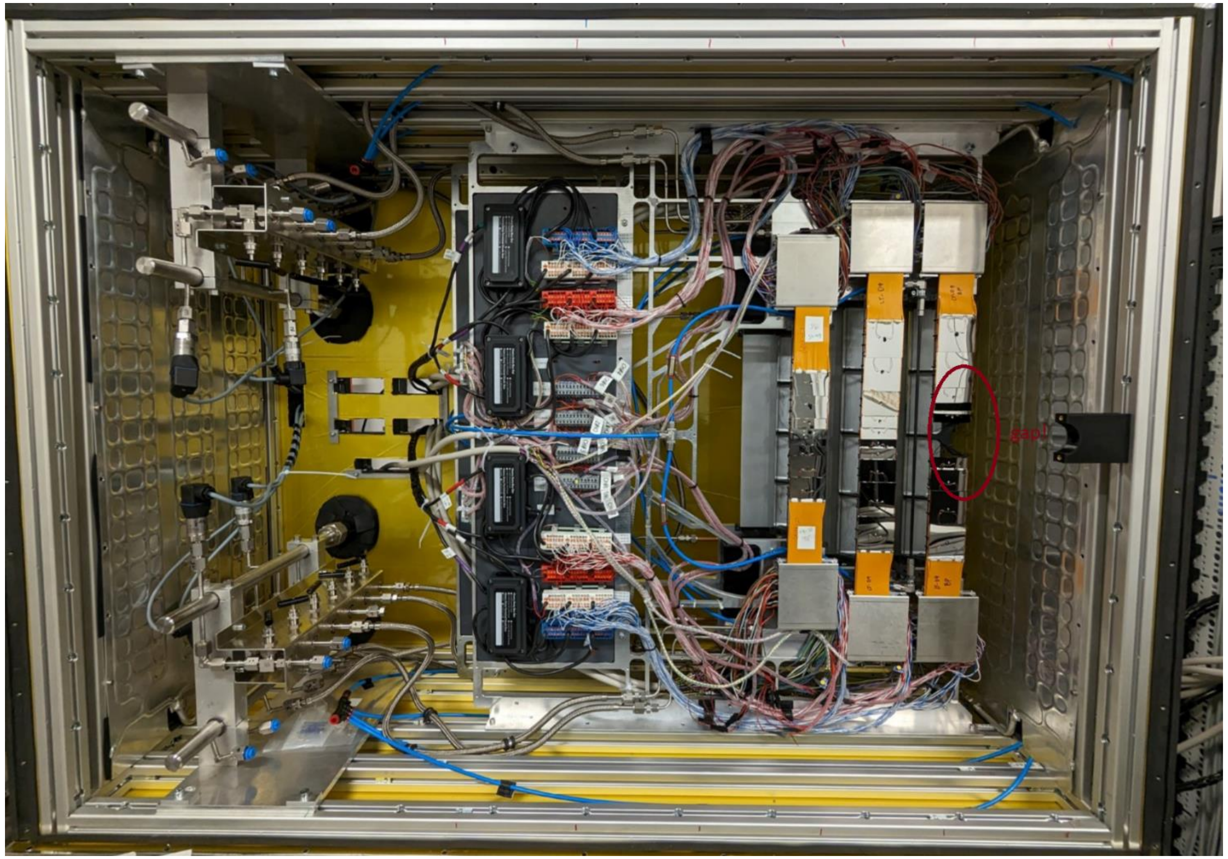


Series voltage noise

Experimental Verification of the Model

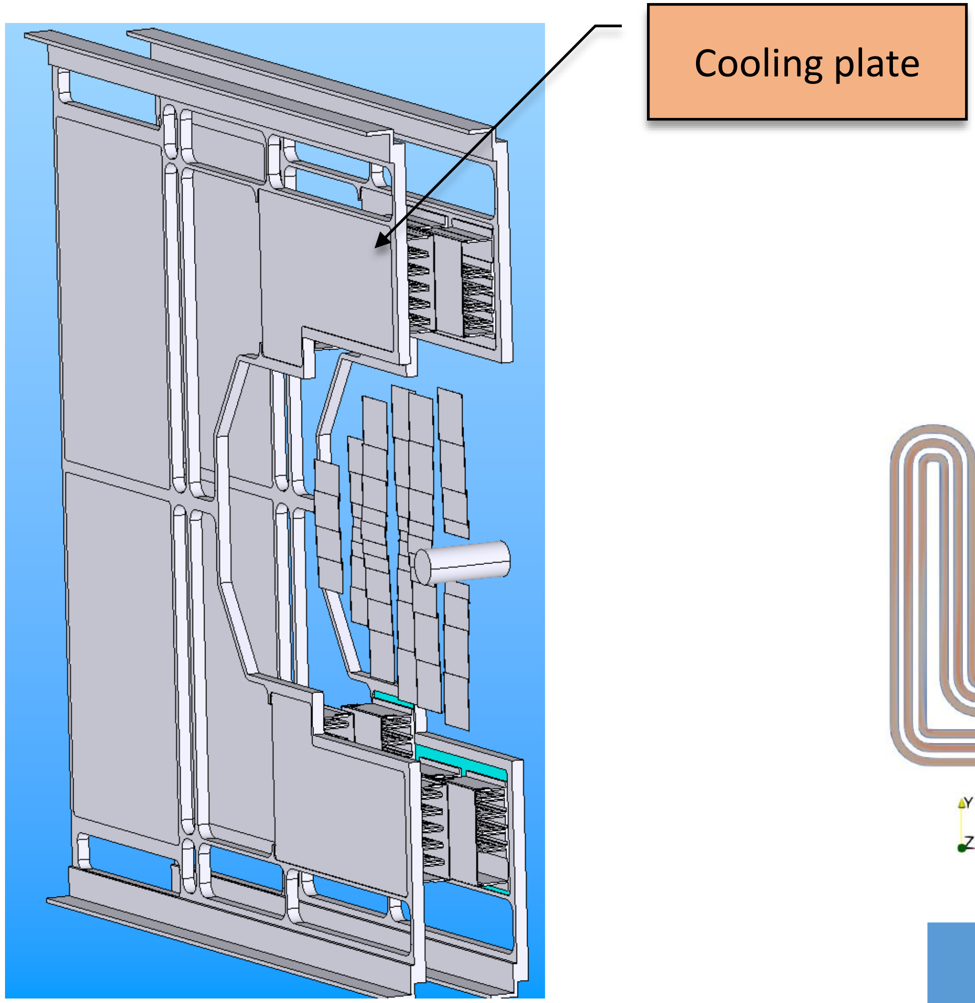


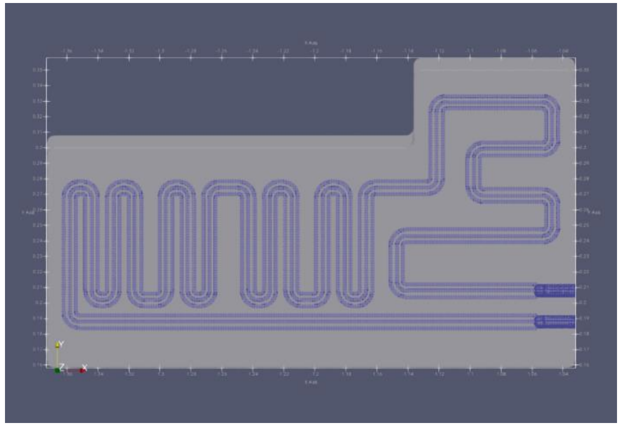
Geometry
of the thermal demonstrator
prepared for the simulation

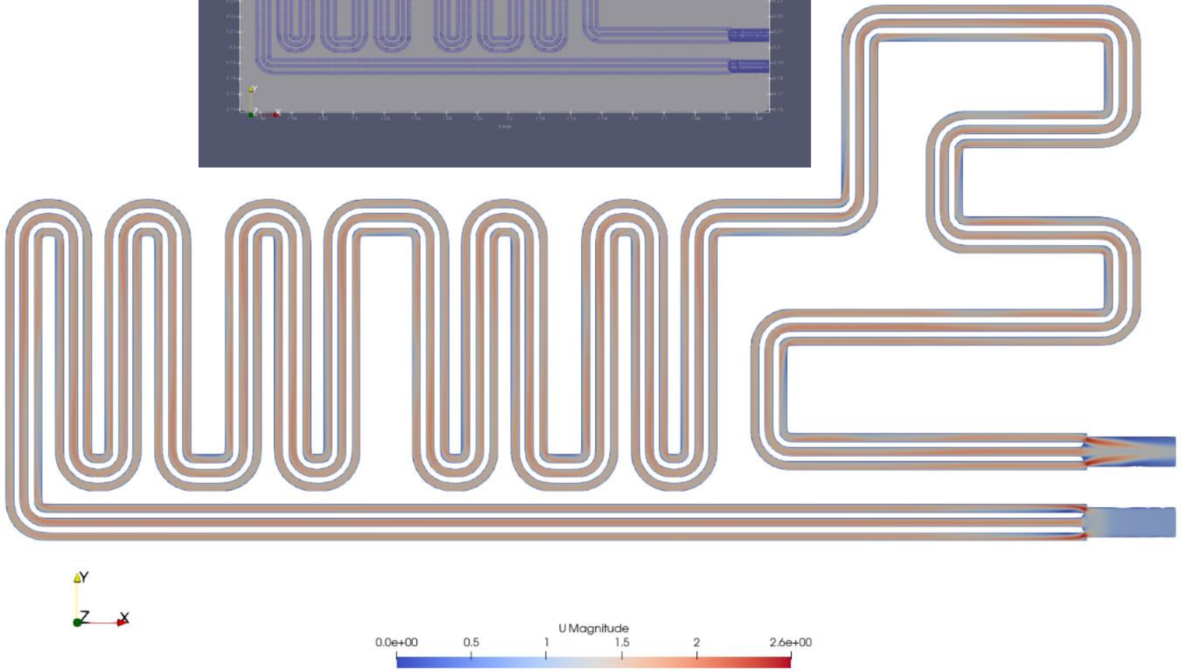


Actual assembly
of the thermal demonstrator

First Simulation Results of the Thermal Demonstrator: Pressure Loss

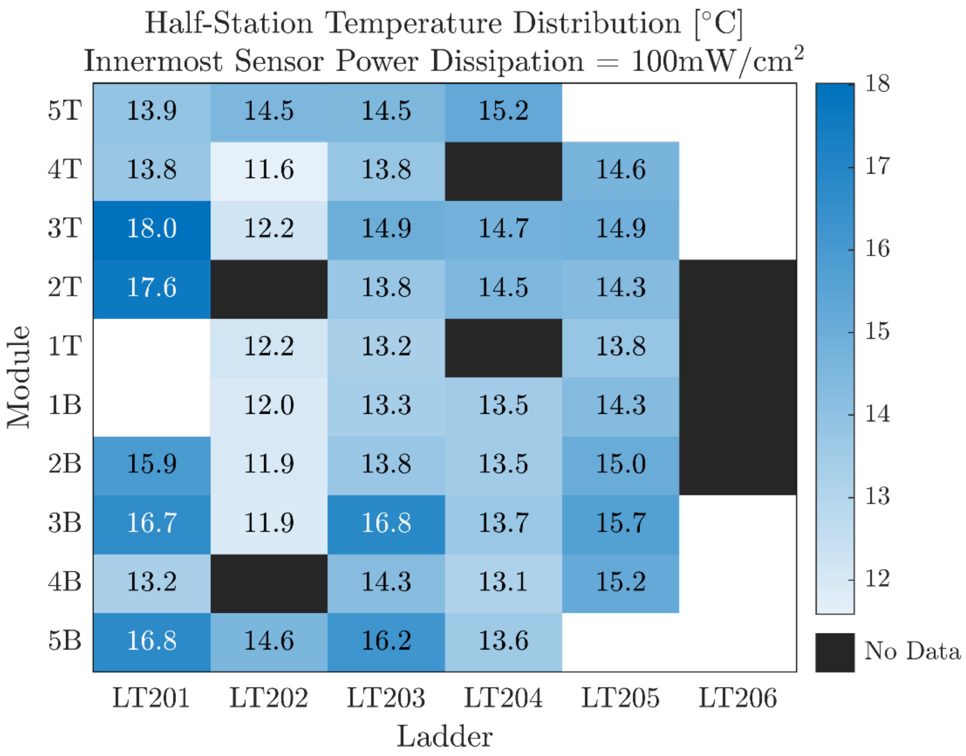






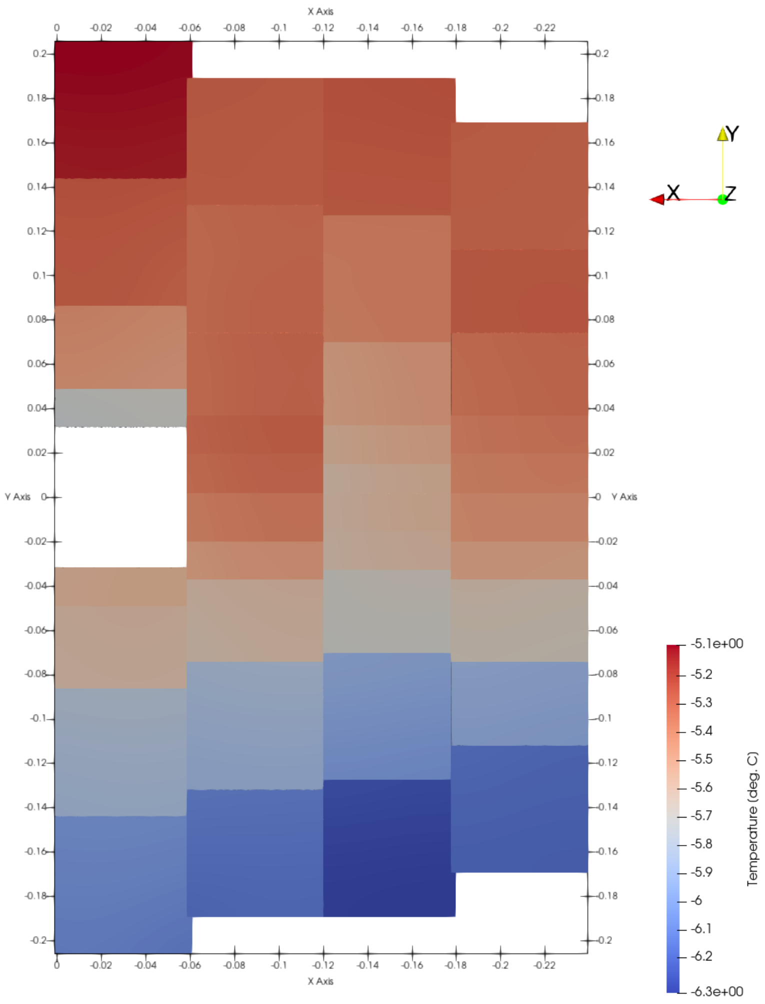
	Pressure difference, Pa
Mesh w/o inflation layers	47462
Mesh w/ inflation layers	54403,7

Results from thermal demonstrator



Thermal demonstrator measurements
of the sensors dummies temperatures

Courtesy of K. Agarwal



Preliminary simulation
of the STS sensors temperatures

Summary

- A comprehensive thermal model of the STS detector is being prepared
- OpenFOAM® allows for implementation of the specific features for the detector
- Power dissipation of the silicon sensors with respect to irradiation and signal-to-noise model is implemented
- This model is suitable for high performance computing on the Virgo cluster at GSI
- Utilizing open-source software allows for the broad usage of the model and results analysis

Outlook and future work

- Experimental results have been acquired from the thermal demonstrator
- These results will be used for cross-validation of our detector model
- Geometry of the thermal demonstrator was prepared for the simulation
- Simulated results has been acquired for the pressure loss in the cooling plates

The results of this work (know-how) is foreseen as a contribution for DRD8