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Thermal modeling for next upgrade DAMIC100

4th. International workshop for the design of the ANDES Underground laboratory
30 to 31 of January 2014, UNAM

DAMIC: cryogenic system

- DAMIC is a dark matter experiment based on Charge-Coupled Devices (CCD) whose maximum sensitivity is achieved between 100 K and 150 K.

- To determine and to achieve the required temperature to maximize the sensitivity with the lowest possible noise as well as to operate the CCDs, a cryogenic experiment using a commercial cryo-refrigerator is needed.

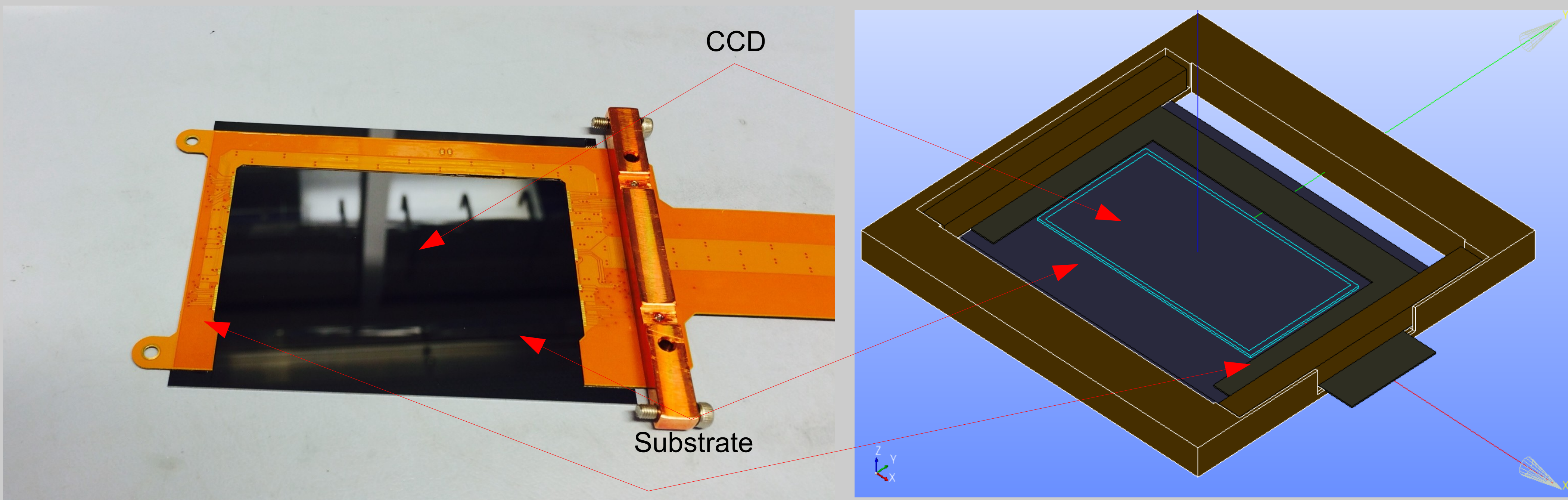
- The elected cryo-refrigerator is a single stage pulse tube cryocooler (low vibration) with enough power cooling to give enough temperature range to regulate and explore the CCDs sensitivity at the lowest achievable fluctuations (typical PID system can achieve ± 0.1 K)

- To predict the temperature distribution of the detector, a thermal modeling is proposed which includes the thermal contacts between parts.

- The thermal model is based on the mechanical structure proposed by Greg Derylo from FermiLab. It is still a work in progress and a first analysis based on a preliminary design is presented hereby.

CCD package: geometric model

- A certain number of simplifications are considered to take into account only relevant geometries for thermal analysis and thermal contact modeling. 15 CCDs of 8 gr each are considered giving 120 gr assuming a fiducial volume of the sensor equal to 80% (100 gr).
- The present model has been based on the preliminary designed by Greg Derylo in mid 2013. It has been slightly modified keeping the same layout.
- A new mechanical structure is on its way. Once sufficiently advanced, the latest geometric models will be implemented to determine the expected operating temperature of the CCDs.

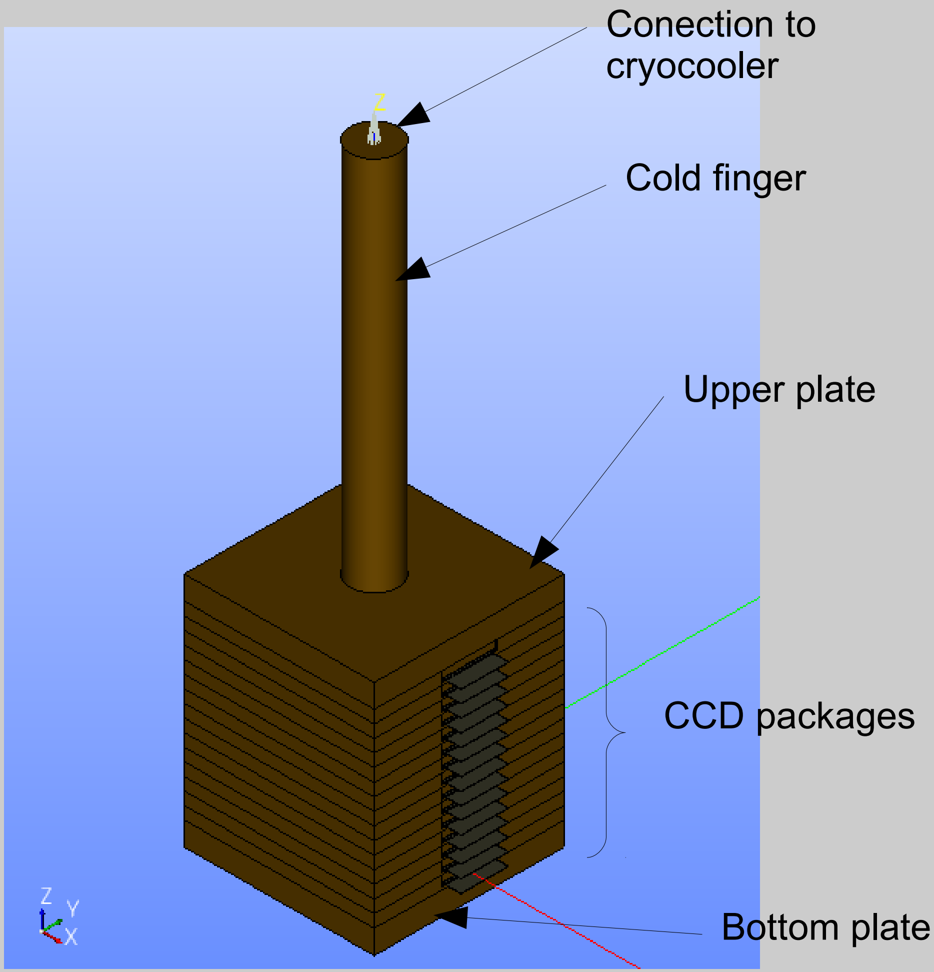


Actual CCD (FermiLab)

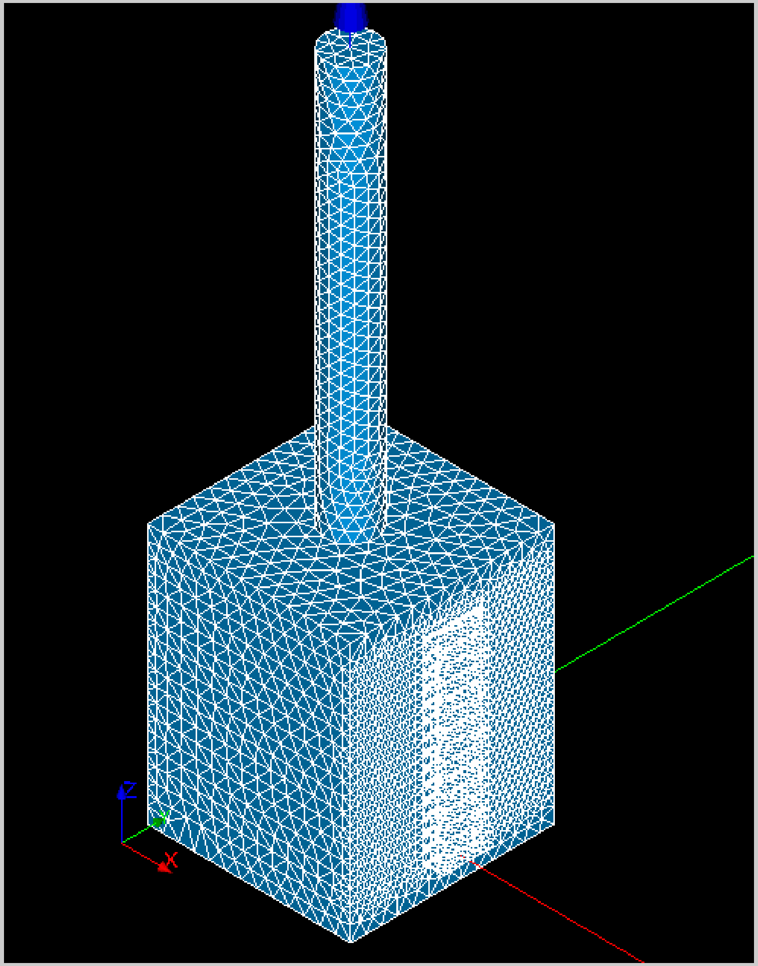
Model of a CCD package based on drawings 9213.750-MD-493961, 64, 62 and 489136, 34 (FermiLab)

Detector: geometric model

- The DAMIC 100 gr detector is constituted of 15 CCDs of 8 gr.



Geometric model



Corresponding mesh

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Thermal contact modeling

- Objective: obtaining an idea of the expected temperature at the CCDs before assembly and operation including the different thermal contacts that are present in the detector

- Means:
  - Mechanical design (Greg Derylo)
  - Finite Element Analysis using thermal contact modelling
  - Values of material properties at cryogenic temperatures from literature
  - Modelization of the thermal contact between solids on the basis of a heat convection approach
  - Steady state computations including the behavior of the cryocooler
  - Fitting the model to experimental data

- The thermal contact is implemented through a convection heat model. The interface is characterized by a constant heat transfer coefficient *h* in W/m^2K which lumps all the characteristics of the contact interface.

Thermal contact modeling: some details

- The convection model assumes that the contact elements are acting as a medium transferring heat "from one solid to another".
- The contact elements are meshes created between solids (required by Cast3M solver, see next slide).
- The mathematical model to simulate the interface between solid 1 and 2 is applied to the contact elements and can be described as follows:

$$\phi_1 = h\left(T_1 - T_{\text{ref}}\right), \quad (1)$$

$$\phi_2 = h\left(T_2 - T_{\text{ref}}\right), \quad (2)$$

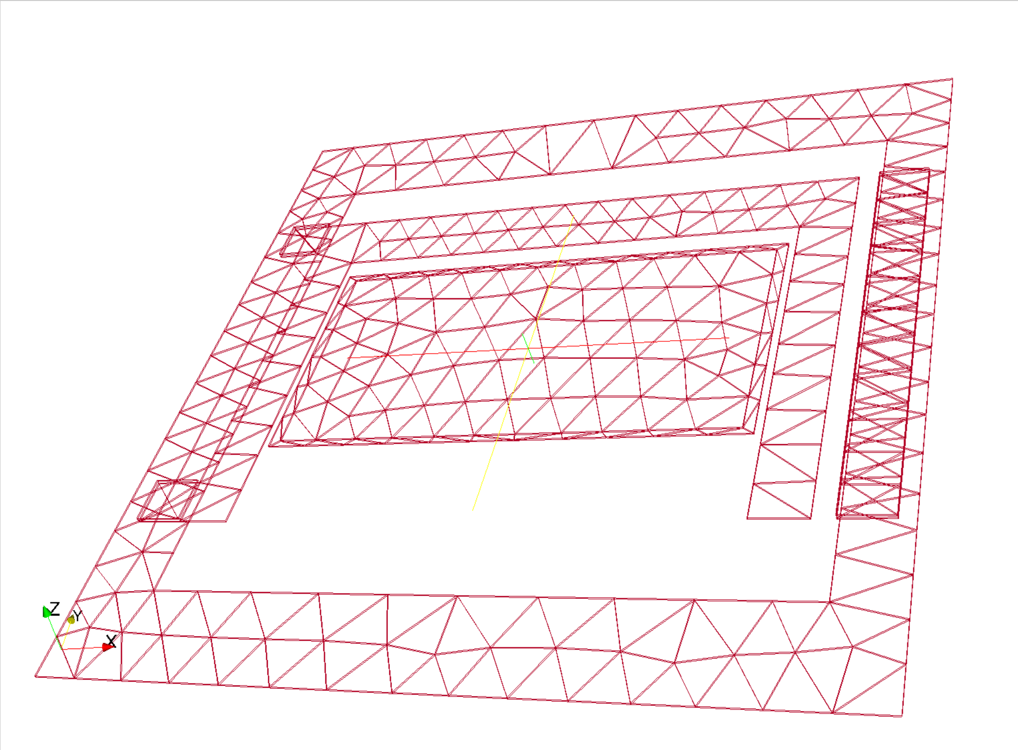
$$\Delta\phi = h\left(T_1 - T_2\right). \quad (3)$$

- Where the couples (T_1, φ_1) and (T_2, φ_2) are the temperatures of solid 1 and 2 and the heat fluxes leaving the solids, respectively. The contact elements hold the convection model acting as a fake medium sharing nodes with the conductive solids.
- The solver assumes a reference temperature T_{ref} which is presently irrelevant since only the net flux matters (specific to Cast3M solver).

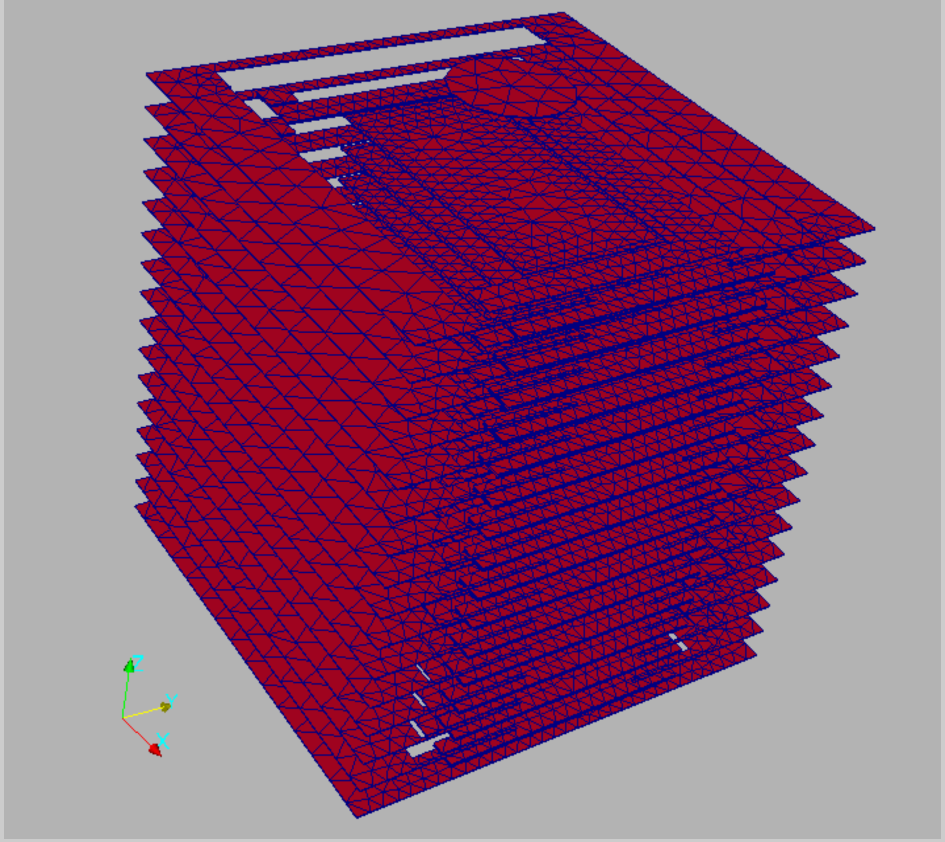
Contact elements

- Contact elements automatically generated between meshes (more than 78 contacts).

Contact elements between one CCD and its support



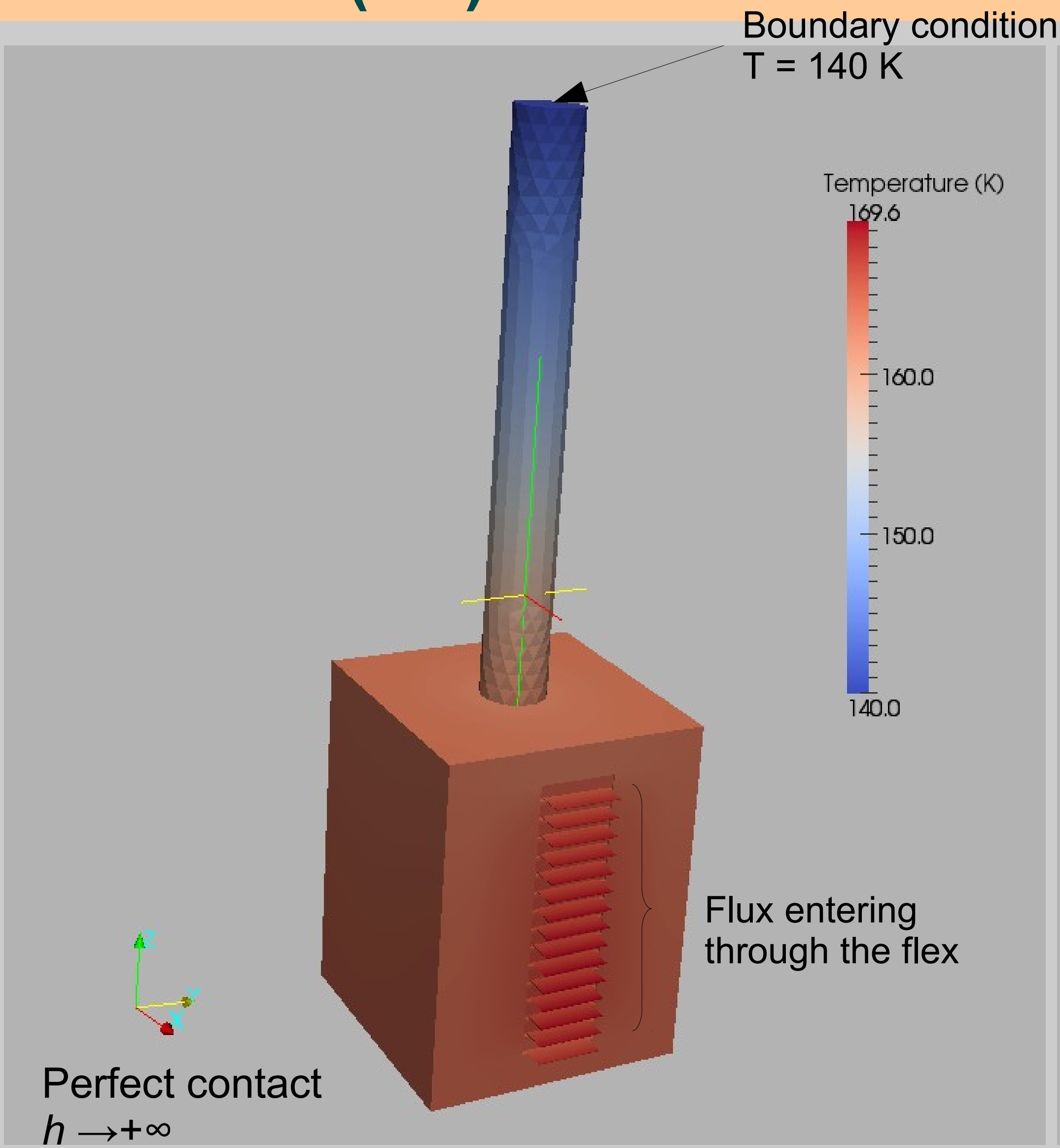
Contact elements between all geometries

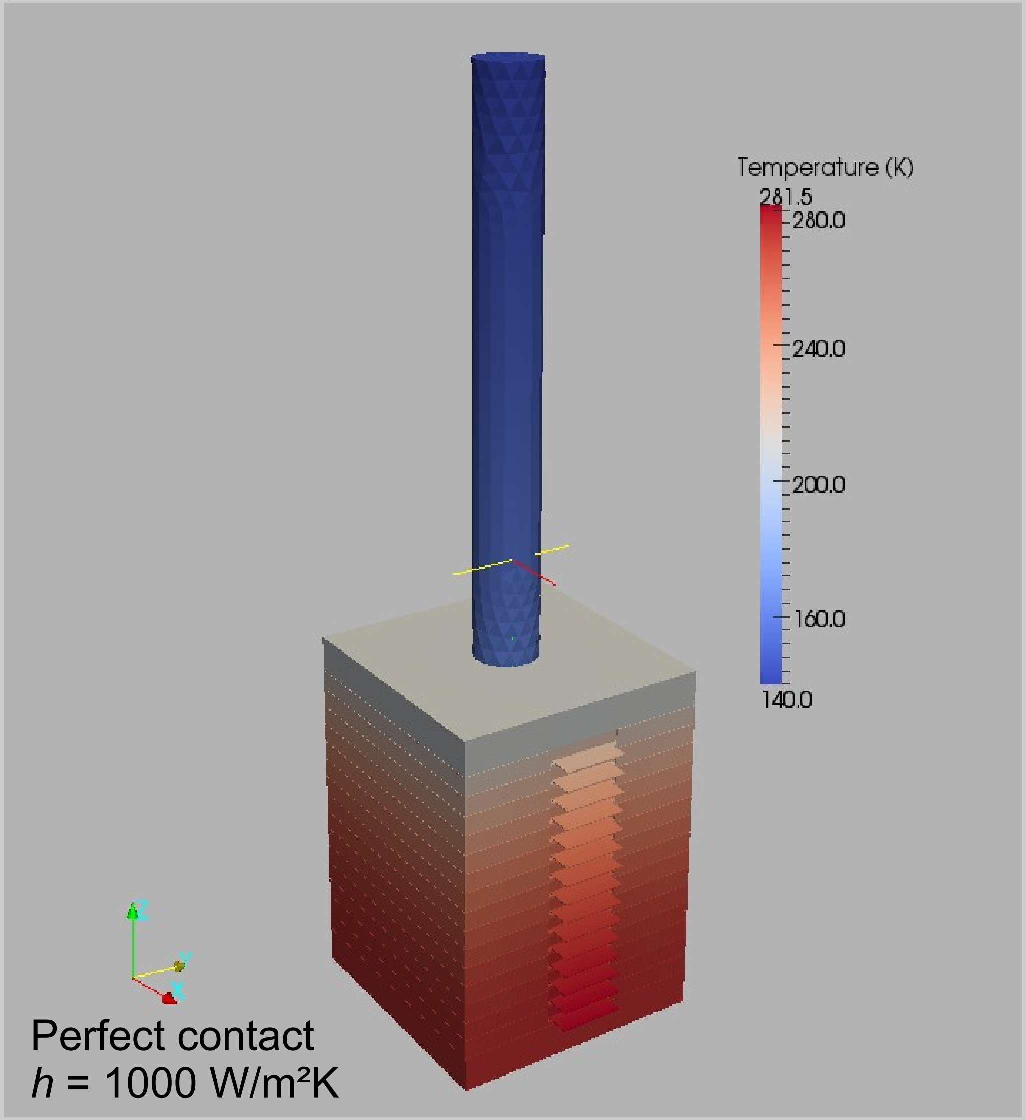


Details of the simulations

- Steady state computation
- Boundary conditions: upper face of the CCD package at fixed temperature equal to 140 K (regulated temperature)
- Loading:
  - Heat flux coming from flex cable equal to 1 W over the cross-section of the cable (conduction heat load, 15 W)
  - Dissipation per CCD equal to 0.5 W distributed over its volume (7.5 W)
  - Heat radiation transfer with total hemispherical emissivity equal to 0.015 (Cu at low temperature), temperature of reference equal to 293 K (0.5 W)
  - Cartridge heater for temperature regulation (? W to reach 140 K)
- Heat transfer coefficient equals for all the interfaces (for now, to be adjusted upon availability of experimental data)
- Material properties at 140 K:
  - Silicon: k = 240 W/m-K
  - Flex (copper and Kapton): k_x = k_y = 430 W/m-K, k_z = 0.2 W/m-K (orthotropic material)
  - Copper: k = 430 W/m-K
  - *h,* typical values between 500 W/m²-K and 5000 W/m²-K for bare contacts. It may be very different between different codes or solvers (to be scaled to the experimental data)

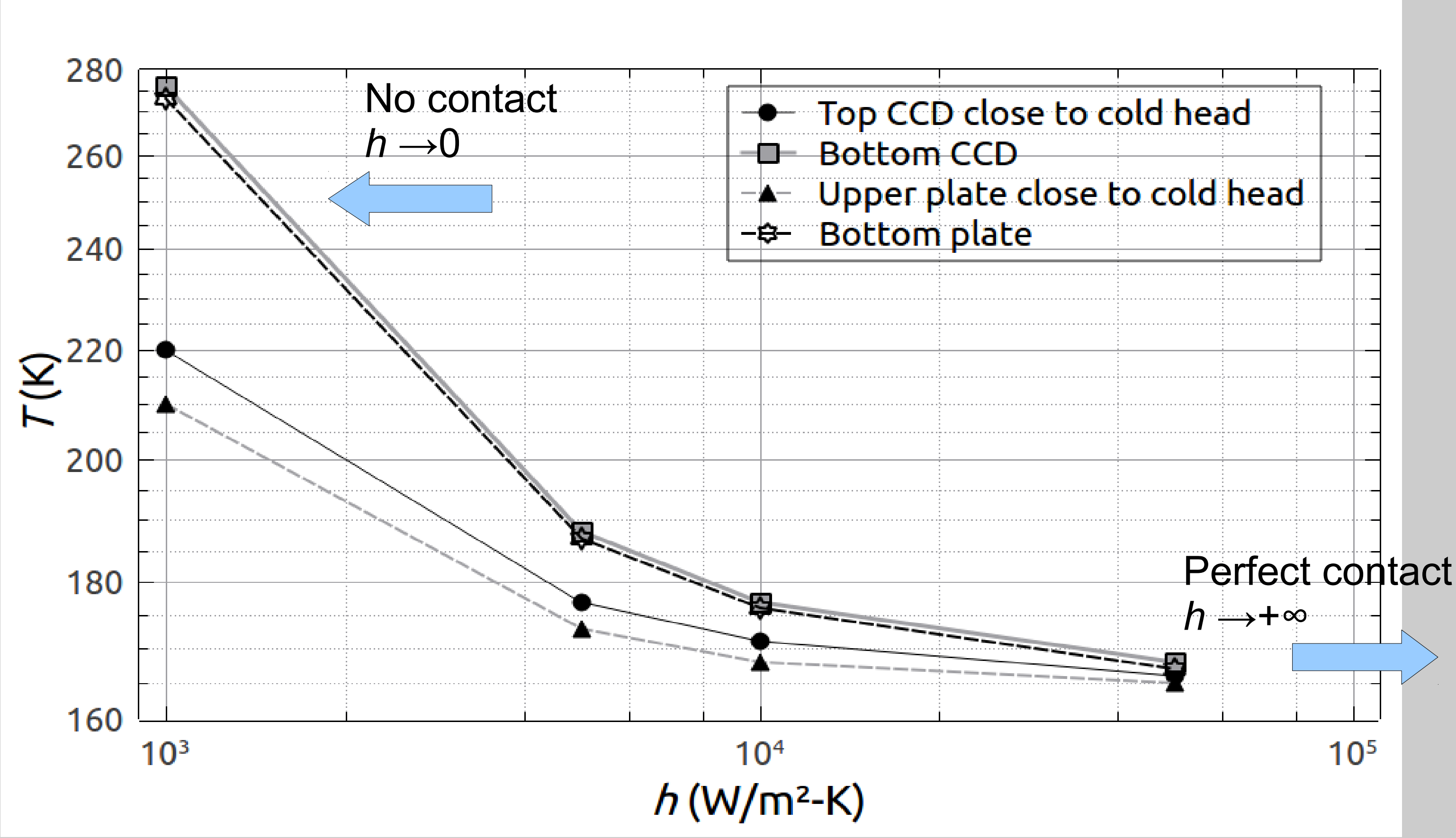
Results (1/3)


Boundary condition,
T = 140 K
Temperature (K)
169.6
160.0
150.0
140.0
Flux entering
through the flex
Perfect contact
h →+∞


Temperature (K)
281.5
280.0
240.0
200.0
160.0
140.0
Perfect contact
h = 1000 W/m²K

Results (2/3)

- The following results show that a good thermal contact should be achieved (bonding agent between parts may be considered, mostly relevant between the CCD and the Cu package and between the CCD packages)
- Under a poor thermal contact, the copper packages barely transfer the heat to the cryocooler cold head



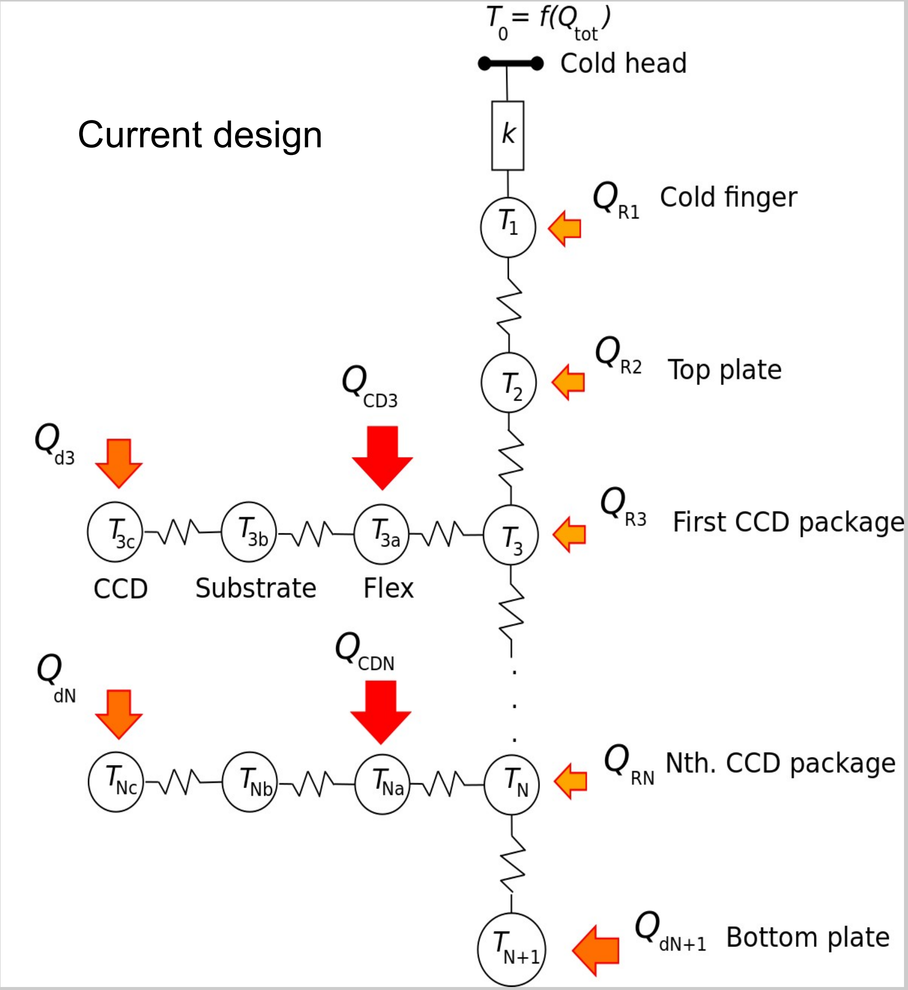
Results (3/3)

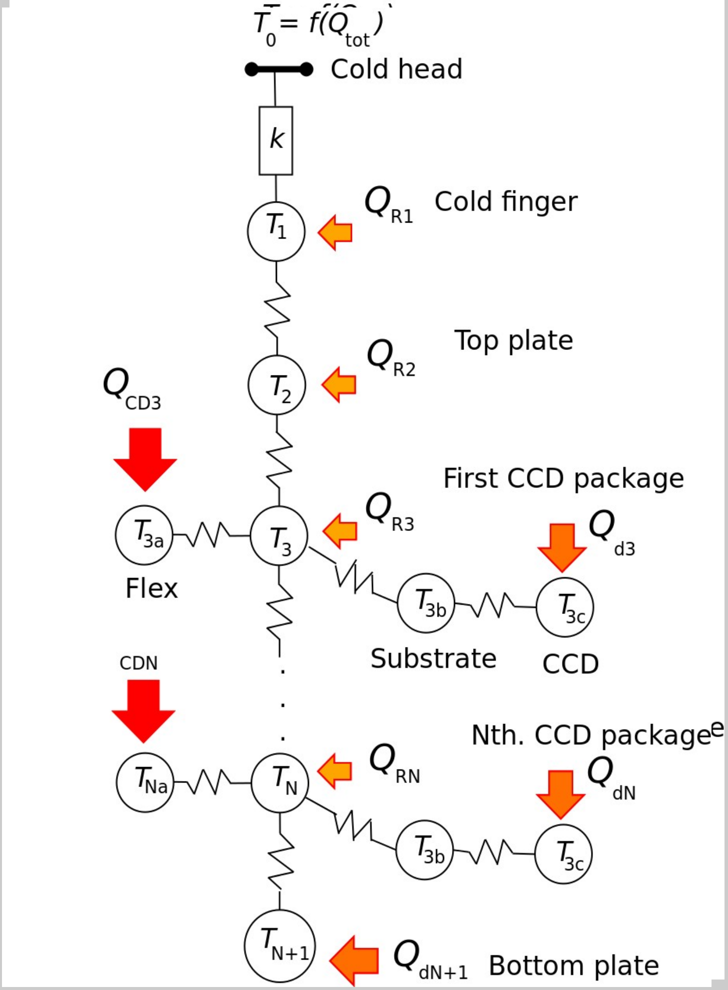
- Results compiled in the following table.
- It should be mentioned that the temperature drop across the cold finger is independent of the heat coefficient and depends on the quality of the copper and its dimensions. The temperature drop is equal to 21 K.

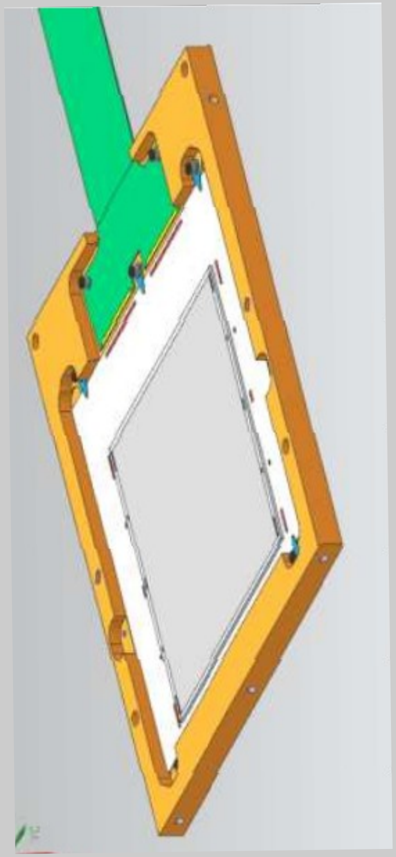
h (W/m²K)	+∞	1,000	5,000	10,000	50,000
Top CCD (K)	165	220	177	171	166
Bottom CCD (K)	165	276	188	177	168
Top plate (K)	164	210	173	168	165
Bottom plate (K)	165	273	187	176	167

Qualitative comparison: first model and next model

- The next mechanical structure is uundergoing. However, there is some qualitative considerations to be drawn.
- The thermal connection to between the substrate and the CCD package will facilitate the homogeneization of the ccd temperature and reduce the thermal gradient.



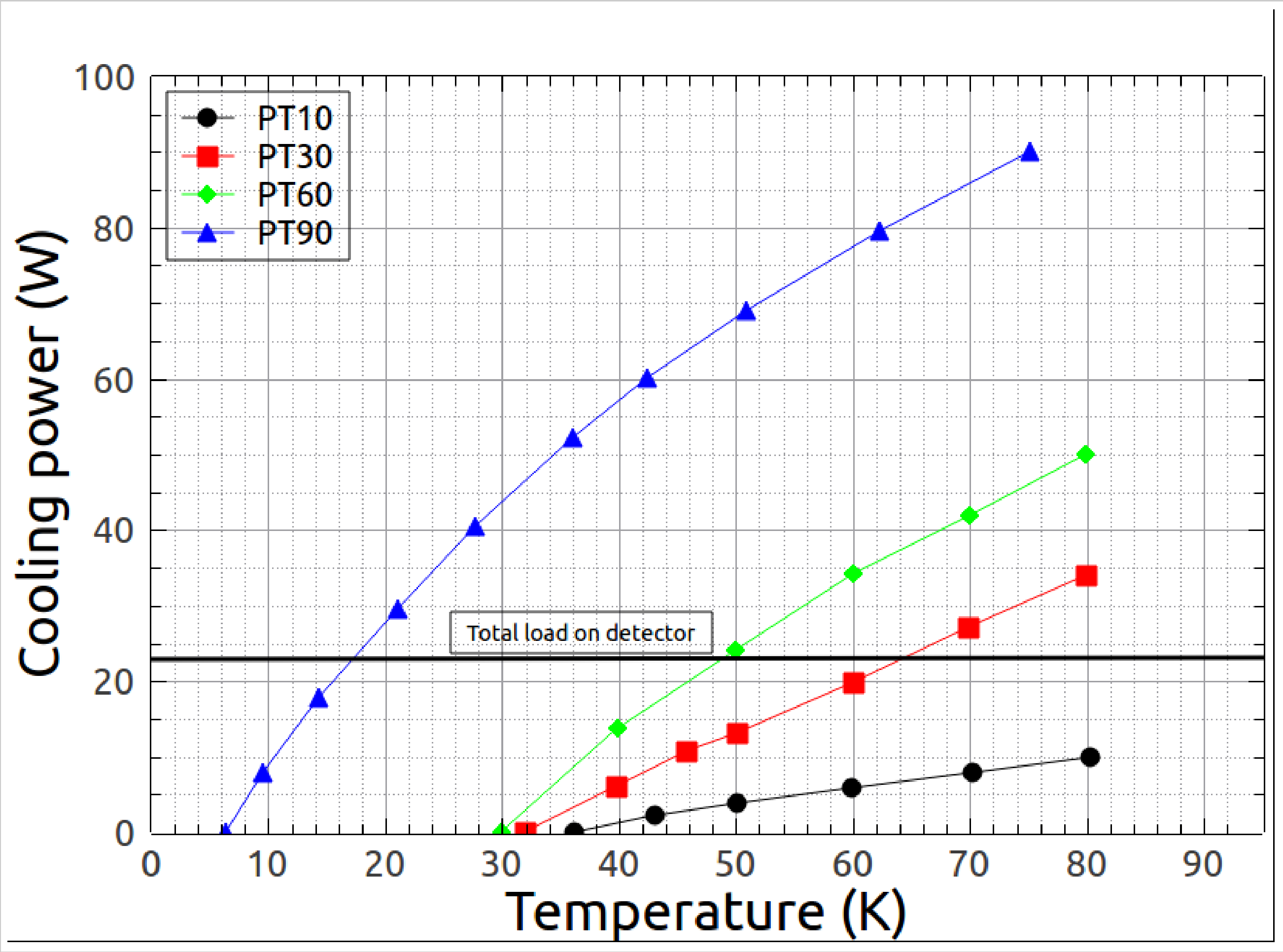


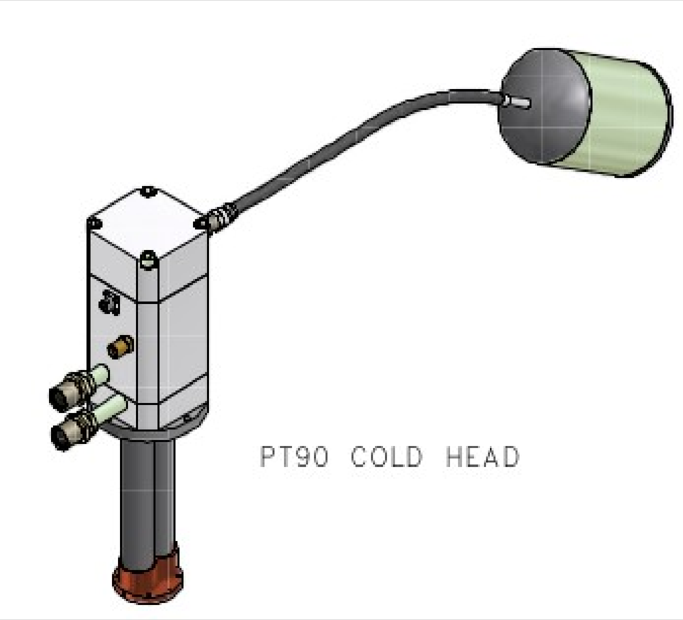


New concept, subsrate on a solid Cu plate (Greg Derylo)

Design of cartridge heater to load th cryocooler

- The total heat load for 15 CCDs is not large enough to load the cryocooler to reach 100 K-150 K.
- A cartridge heater (>100 W, not simple to come by) should be added. It allows to load the cryocooler to the desired temperature.





Conclusion

- The model of the CCDs and their thermal connections to the cryocooler cold head and the corresponding steady-state computation have been completed based on Greg Derylo's preliminary mechanical structure.

- The solver has been implemented and can be used to explore the thermal response of new mechanical structures. It should be mentioned that the thermal results can be converted in thermal mechanical stress to study the thermo-mechanical behavior of the detector.

- The dynamic solver, that was not considered at first (see presentation to DAMIC meeting on 16/12/2013), has been implemented. It does not add any value to the thermal analysis, it is useful only to determine the cooling time from room temperature to the operating temperature.

- The heat transfer coefficient *h* should depend on contact pressure, temperature and “quality” of the interface. It is a complex problem which is not considered relevant at that point.

- Experimental measurements should be considered to determine the heat transfer coefficient between different thermal contacts so as to feedback the model with realistic values (“numerical” *h* scaled to experimental values).

- Modification of the geometric model is a slow process. If a full reimplementation is necessary, a month of work (one person, 25%) should be considered to obtain new results.