Thermal Simulation with OpenModelica of the X-IFU Focal Plane in the Athena X-ray Space Observatory

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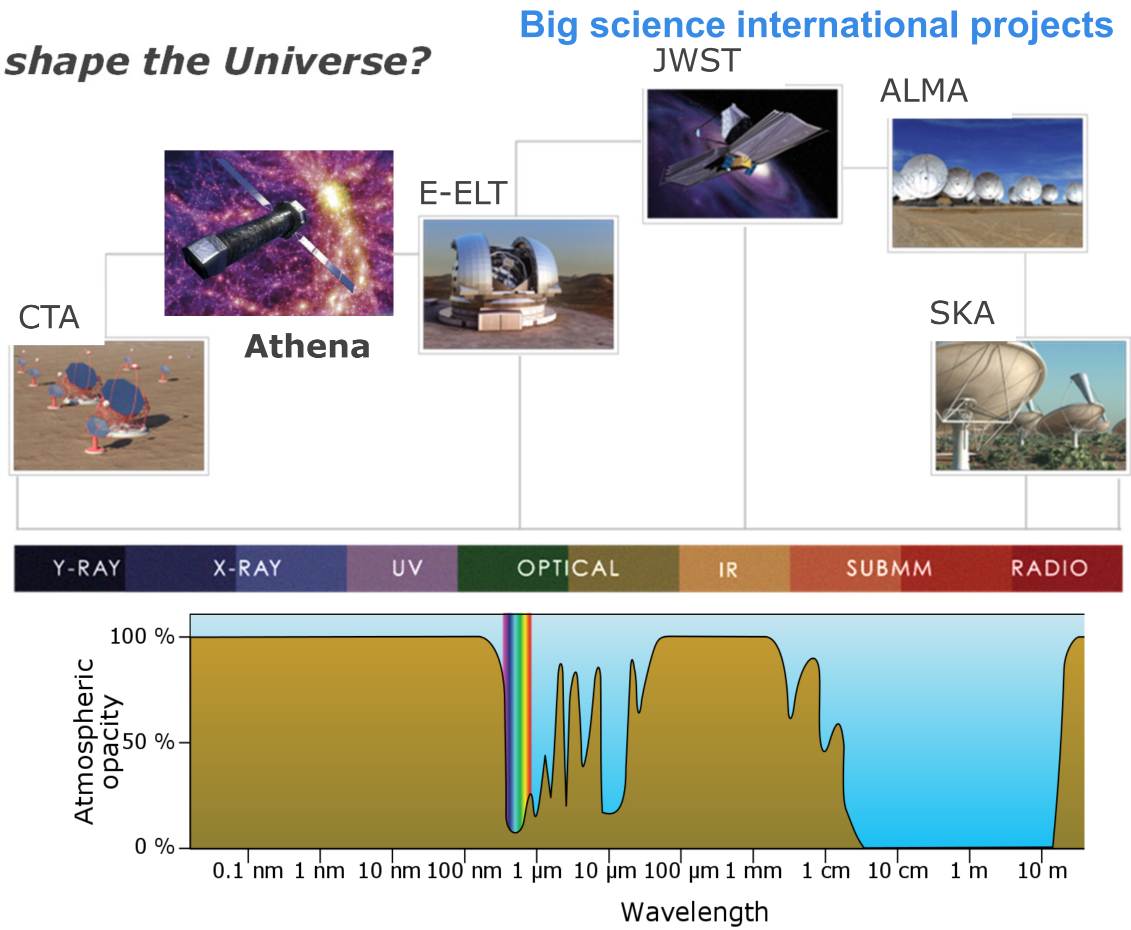
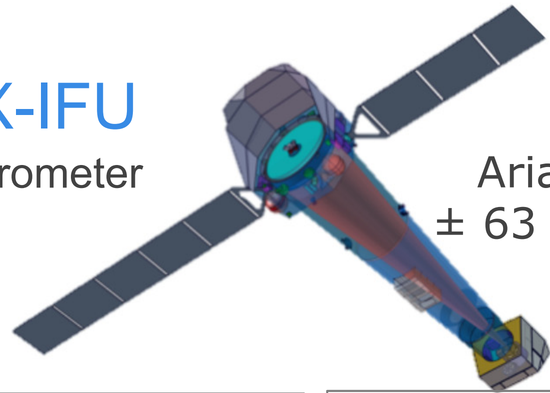
Athena: ESA's next X-ray Space Observatory

- Athena science case is selected by ESA after strong international competition (Cosmic vision)
- Athena is an "L-class" observatory mission addressing key scientific challenges:
  - ***How does ordinary matter assemble into large scale structures that we see today?***
  - ***How do black holes grow and shape the Universe?***
- Mission Adoption is expected by 2021 (moment when all critical technologies should be demonstrated)
- About half of the baryonic mass is best observed by X-rays and requires space missions

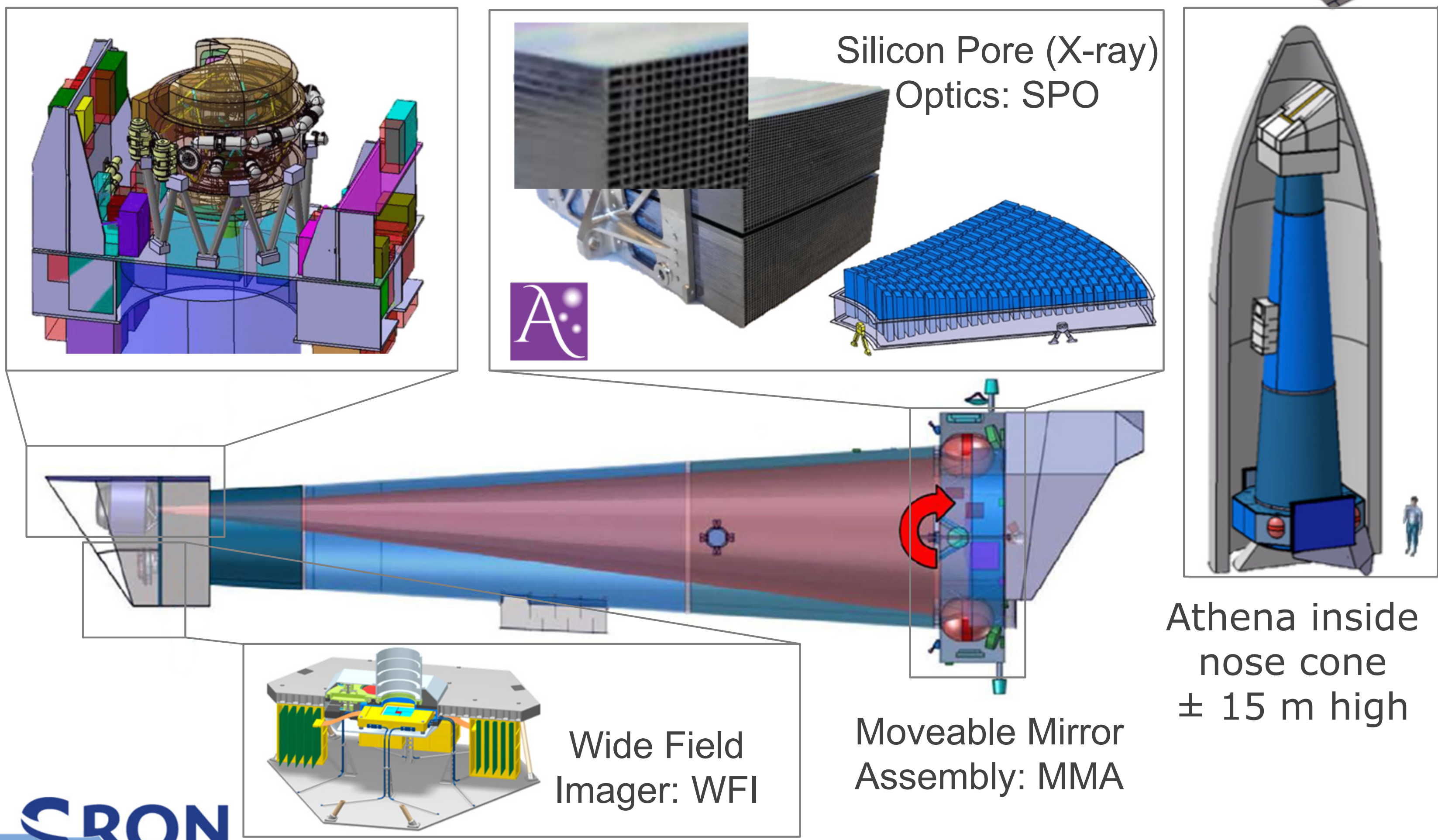


Athena & its instruments WFI and X-IFU

- X-IFU (X-ray Integral Field unit) is an imaging spectrometer with an energy resolution of 2.5 eV in the range of 400eV-12KeV



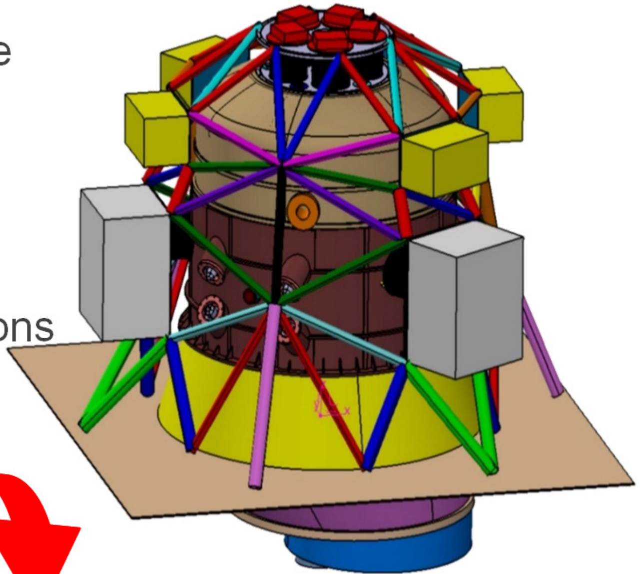
X-IFU instrument



The X-IFU instrument and its Focal Plane Assembly (FPA)

Big Science, small numbers:

- The 3840 pixels need to be operated at **0.05 K** to achieve the required energy resolution. Detector operating principle is based on superconducting transition sensing.
- Less than **1 μW** of cooling power is available at this temperature stage.
- The sensors are extremely sensitive to magnetic field variations as well: An attenuation factor of **$2 \cdot 10^{-6}$** is required during operation, **10^{-2}** during cool down.
- To achieve the performance extreme temperature stability is required: **< 0.9 μK rms** during observations.



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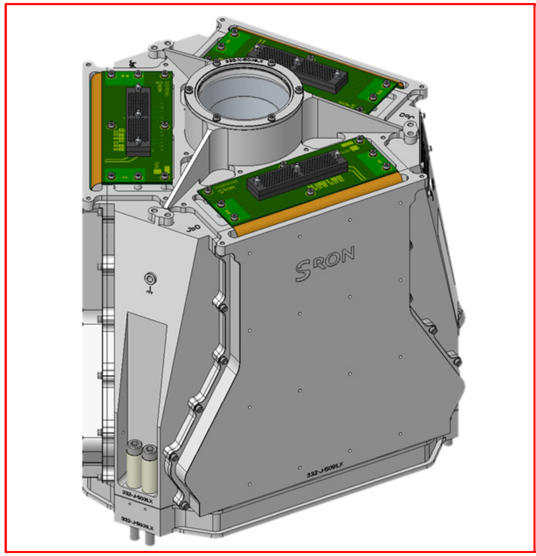
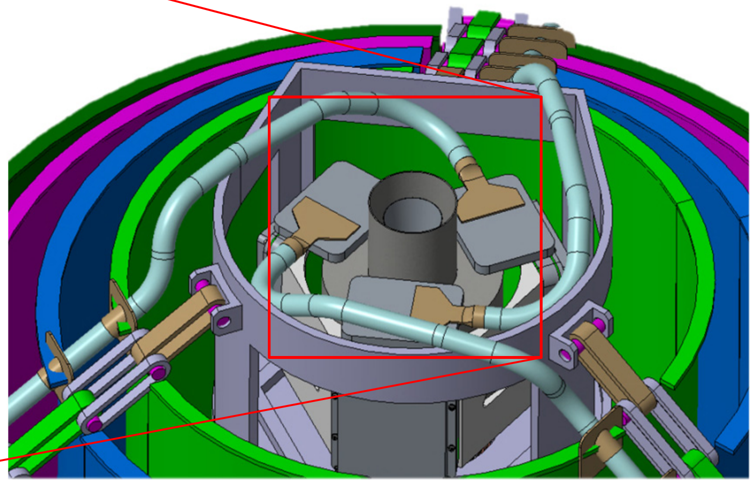
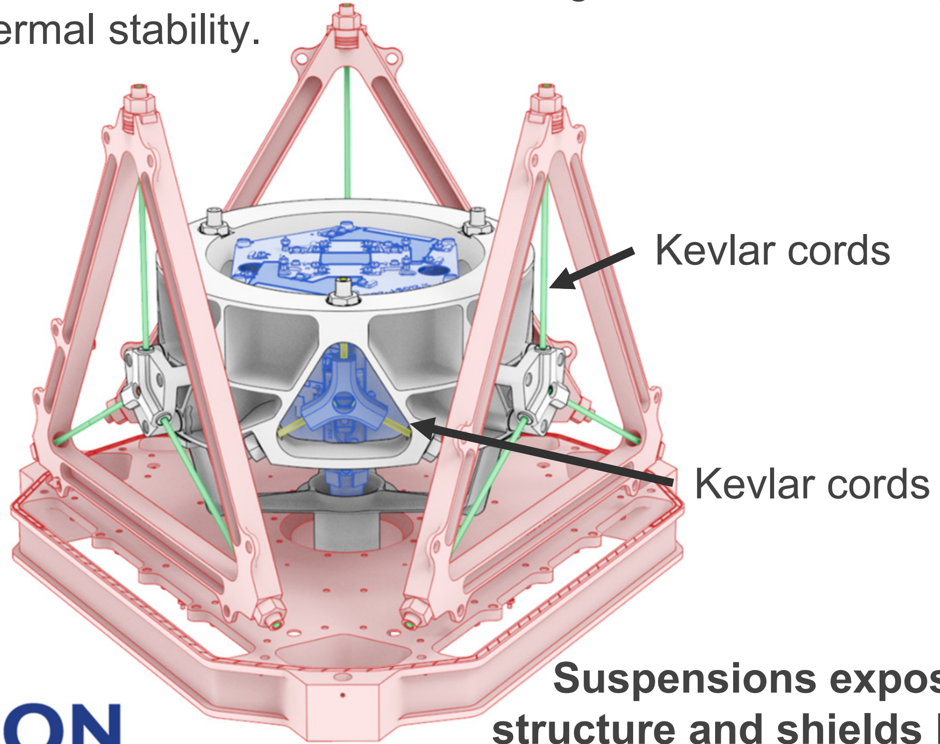


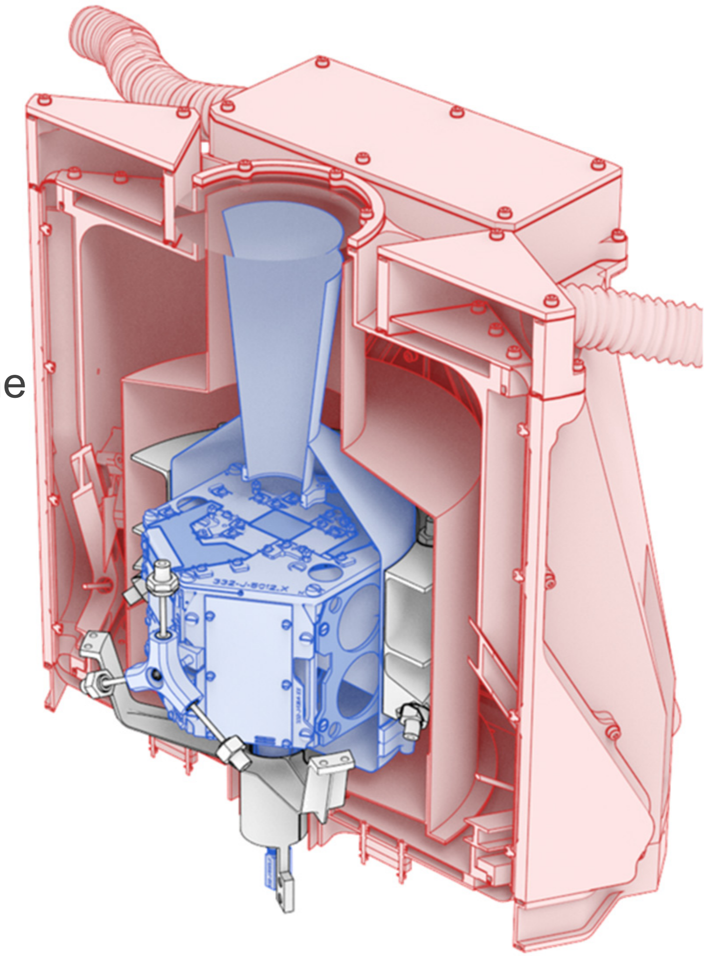


FPA thermal- mechanical design

- Outer structure at 2 K, ± 4.5 Kg: Red
- Thermal heatsink at 0.3 K, ± 0.7 Kg: White
- Detector unit at 0.05 K, ± 1.2 Kg : Blue
- The detector unit is suspended from 0.3 K, which is suspended from 2 K structure.
- Suspensions are Kevlar cords (yellow, green) to minimize heat leak and optimize stiffness & strength.
- Micro-vibration can cause heating, which can endanger the thermal stability.



Suspensions exposed, structure and shields hidden

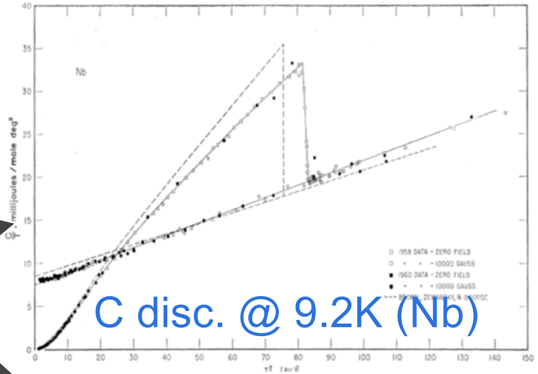


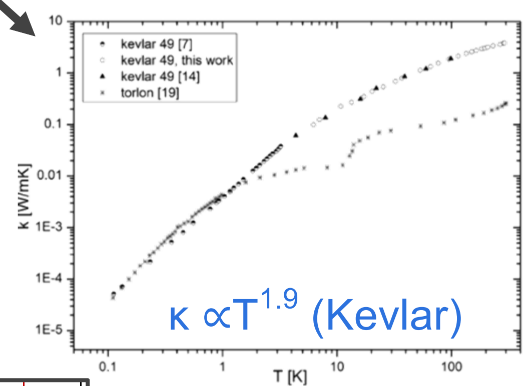
FPA cross section

FPA thermal modelling needs and approach

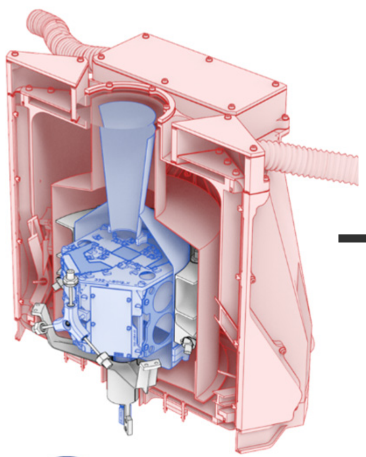
Why do we use OpenModelica for thermal modelling?

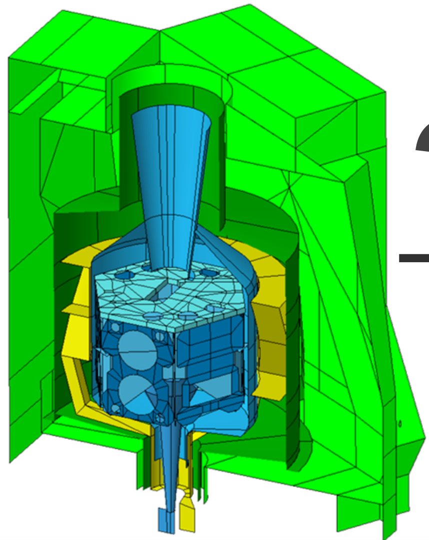
- Thermal Mathematical Model (ESA ECSS: TMM = *concentrated thermal capacitance nodes or elements, coupled by a network made of thermal conductors*) is common in spacecraft thermal modelling.
- At FPA temperature levels material properties are highly temperature dependent, radiative coupling is less dominant
- Desire to couple thermal model to mechanical model to assess mech. induced thermal fluctuations. (see slides 11, 12)
- Commercial thermal packages contain unneeded functionality, provide no additional material data at ultra low temperatures and licensing/support is costly.





How to implement a TMM in OpenModelica?





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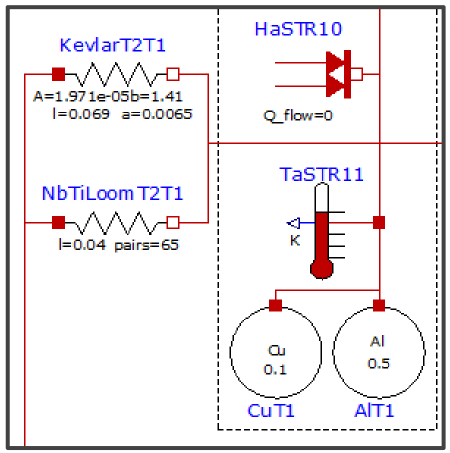
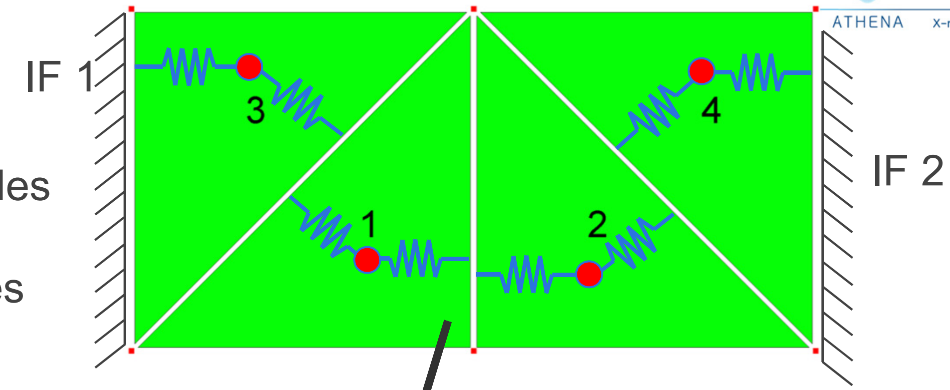


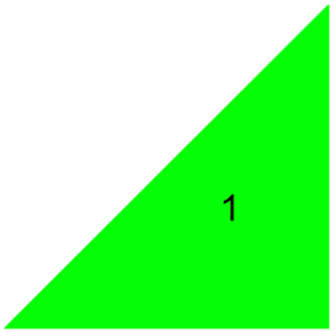
Far field example

- Combined several existing Python packages to create script which provides automated conversion of meshes consisting of Quadrilaterals & Triangles to nodal parameters



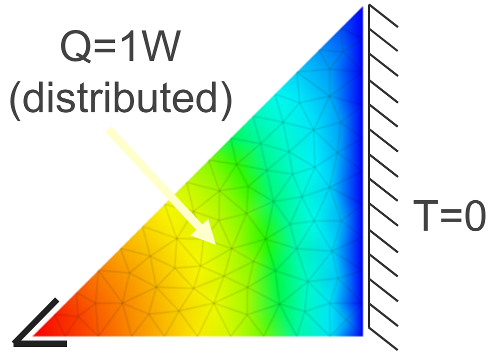
Steps taken (in Python script) for each element edge with an IF:

Import step (once per element)



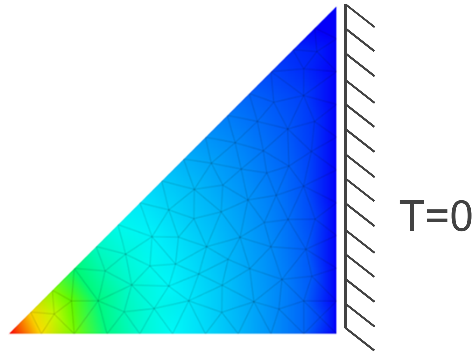
- Import in Python (PyNastran)
- Determine volume V
- Transf. faces to XY plane

1st FEM step



- Generate mesh (pyGMSH)
- Setup FEM problem (Sfepy)
- Determine Far Field boundary by solving FEM problem

2nd FEM step

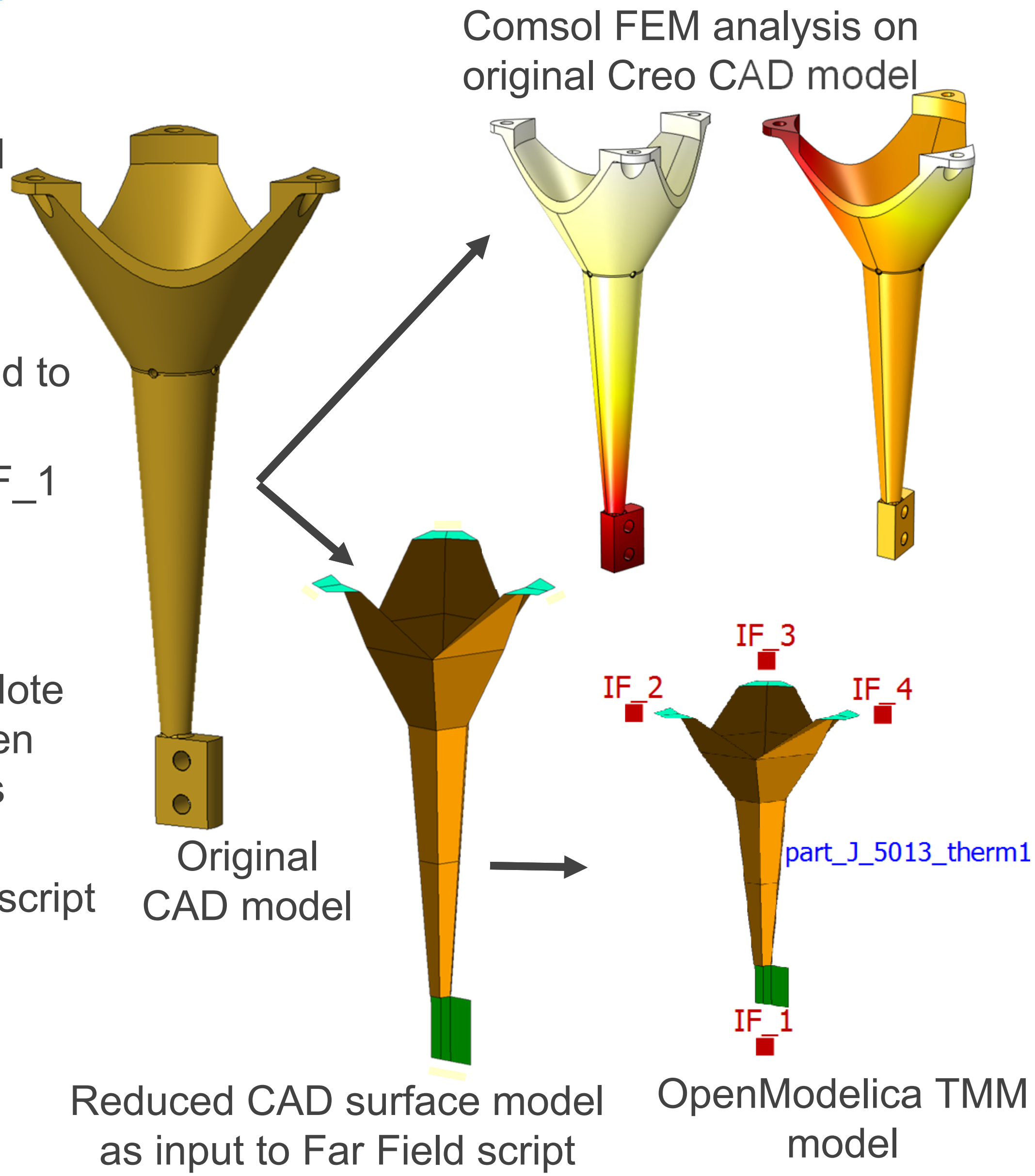


- Apply unitary heat flux on Far field boundary (Sfepy)
- Determine T_{avg}
- Calculate G (A/l)

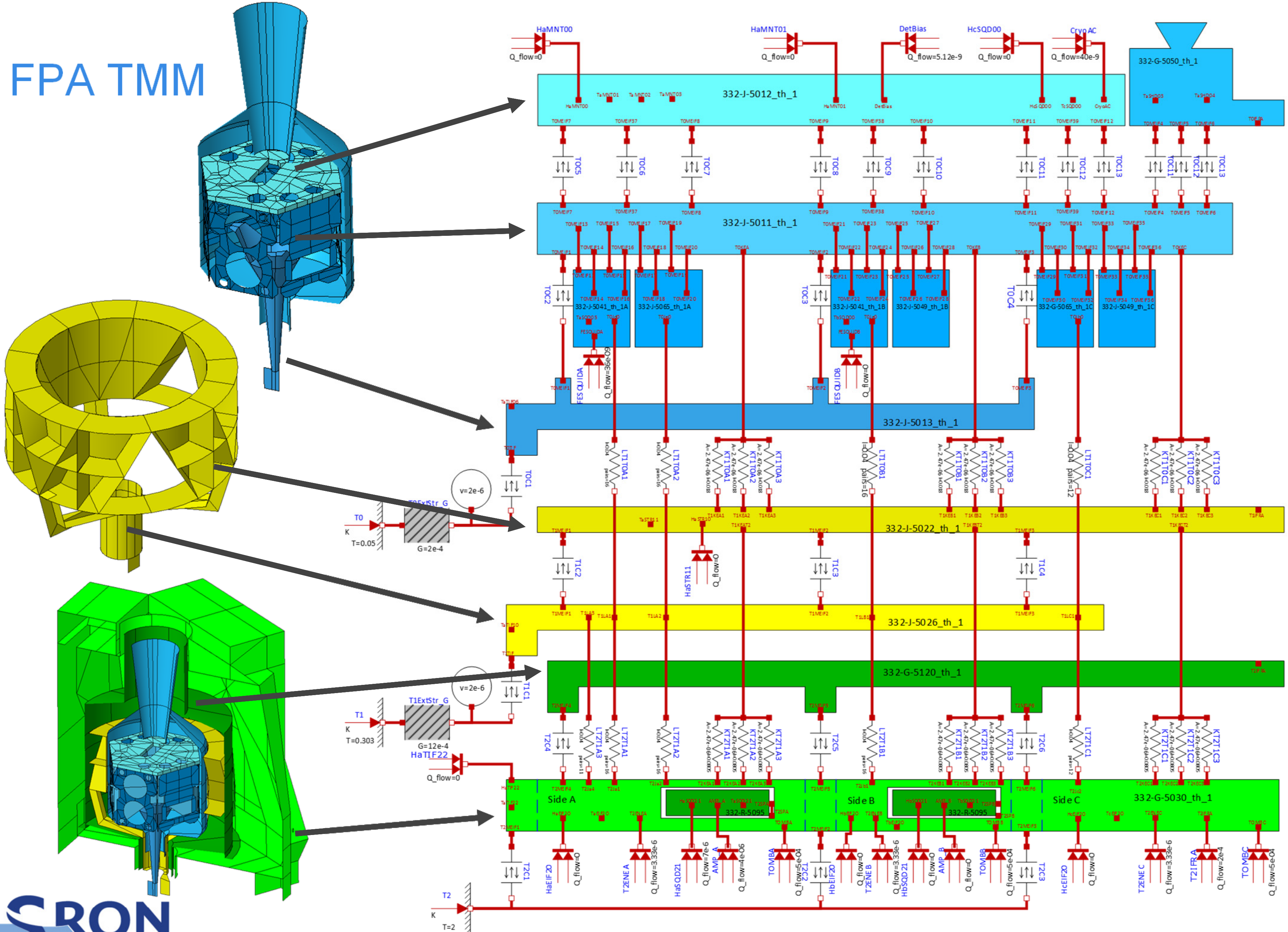
- Far Field Method developed by ESA around 2004: ICES 2004-01-2397

Example: 50 mK strap compared to FEM model

- Compared Comsol FEM model to OpenModelica Thermal Mathematical Model (TMM, ESA acronyms…).
- Nastran surface model consisted of 33 elements
- Surface model volume error compared to original CAD: 5.1%
- Error in Conductance (A/l) between IF_1 and
  {IF_2, IF_3, IF_4} : 4.6%
  Seems acceptable
- Error between IF_2 and IF_4: 31%. Note that there are only 6 elements between these IF's and heat-flow is not always normal to element boundaries.
- Multiple models converted by SRON script give identical results compared to conversion in ESATAN-TMS.



FPA TMM



HaMNT00
HaMNT01
DetBias
HcSQD00
Cryo AC
Q_flow=0
Q_flow=5.12e-9
Q_flow=40e-9
332-J-5012_th_1
332-G-5050_th_1
332-J-5011_th_1
332-J-5041_th_1A
332-J-5065_th_1A
332-J-5041_th_1B
332-J-5049_th_1B
332-G-5065_th_1C
332-J-5049_th_1C
332-J-5013_th_1
332-J-5022_th_1
332-J-5026_th_1
332-G-5120_th_1
332-G-5030_th_1
Side A
Side B
Side C
332-R-5095
T0
T=0.05
G=2e-4
v=2e-6
T1
T=0.303
G=12e-4
HaTIF22
T2
T=2

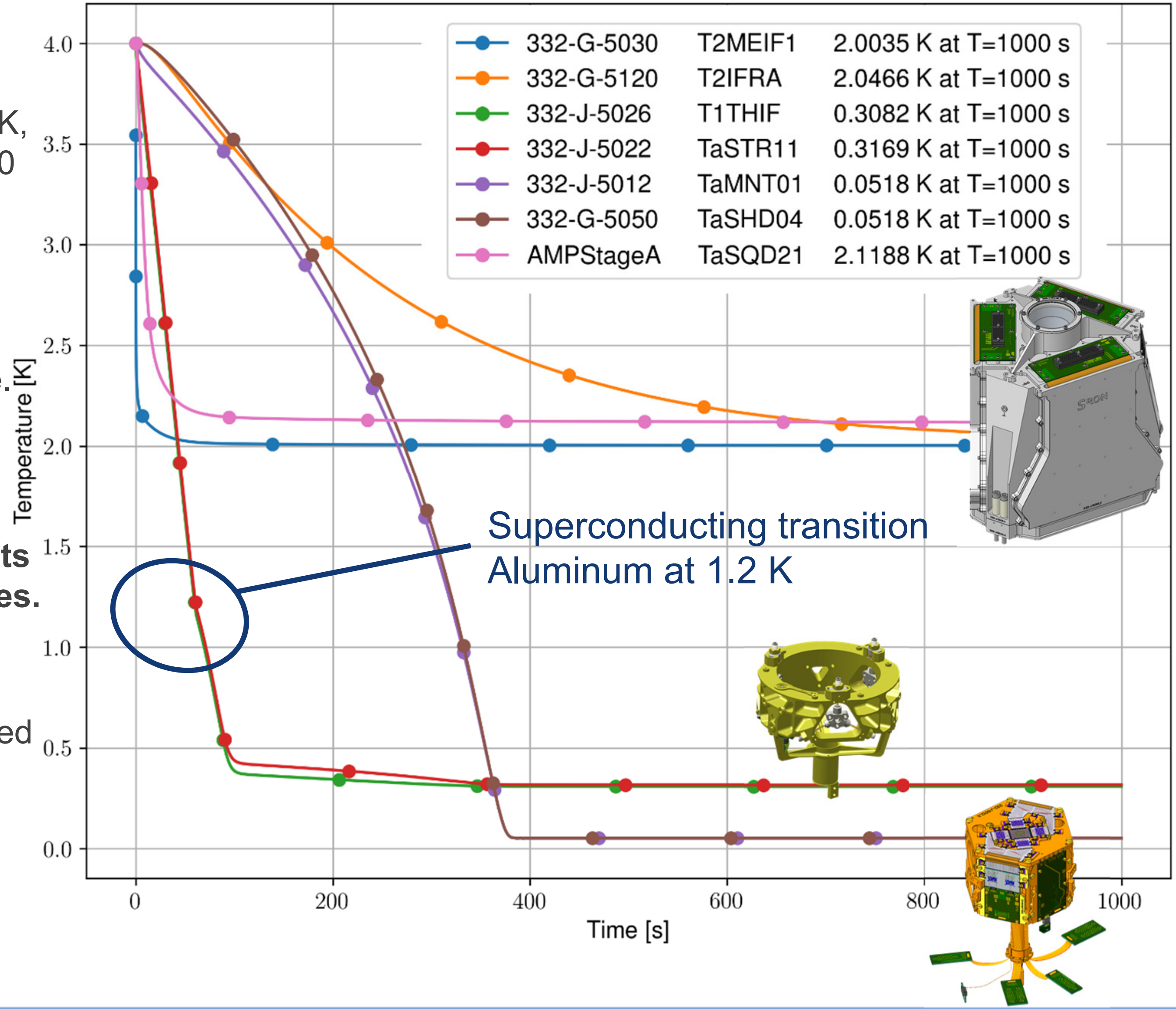
OpenModelica thermal result example

"Large signal" model:

- **Initial condition:** T2 =T1=T0=4K at t=0. T2=2K, T1=0.303K, T0=50mK for t>0
- **Total cool down time to reach equilibrium:** estimated to ≈ 2Ksec.
- **Kink in T1 curve** due to Sc. Transition of AL T1 structure.

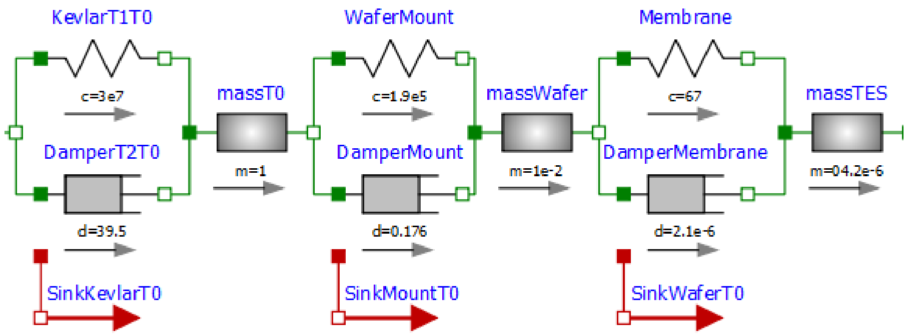
Linearized State Space results used for small signal analyses.

- Linearize command in OpenModelica
- Python-control library used for transfer functions

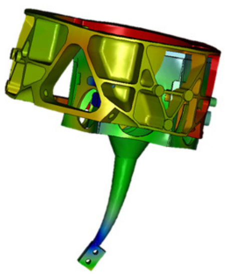


Assessing micro-vibration induced heating impact I

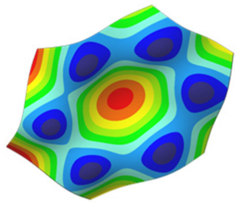
- Mechanical vibrations inside FPA are a source for mechanical dissipation
- Mechanical modes include Kevlar suspensions & thermal straps (≈ 300 Hz) , detector wafer (≈ 700 Hz) and pixels (≈ 3 KHz).
- Depending on location of dissipation the heat is damped by the FPA thermal system before reaching the detector



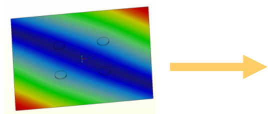
Mech. Modes with dissipation at different locations in detector stage:



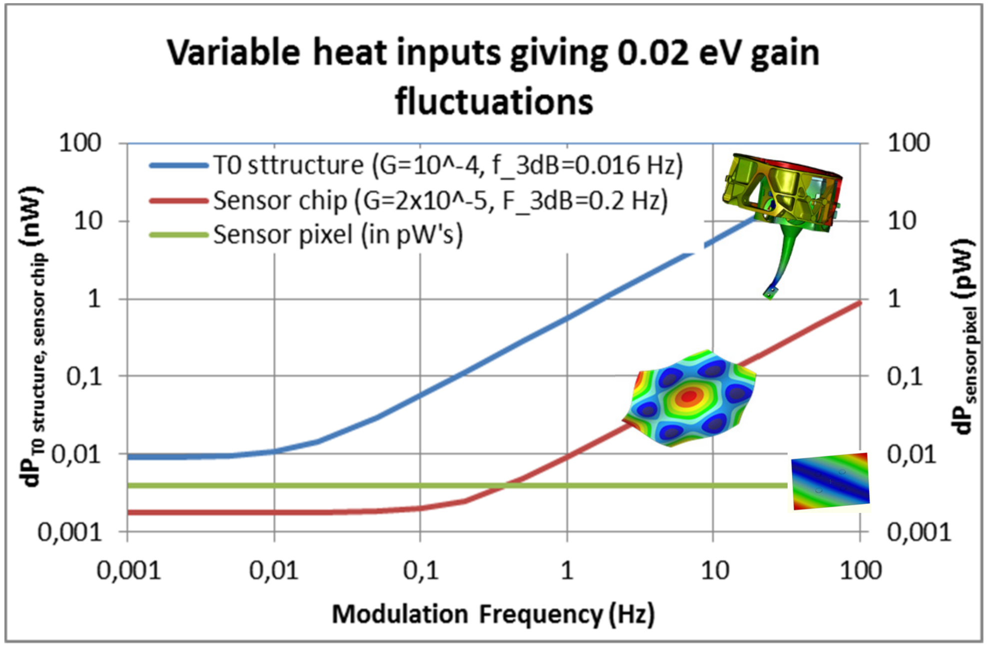
T0 structure $f_1 \approx$ 300 Hz



Sensor chip $f_1 \approx$ 700 Hz



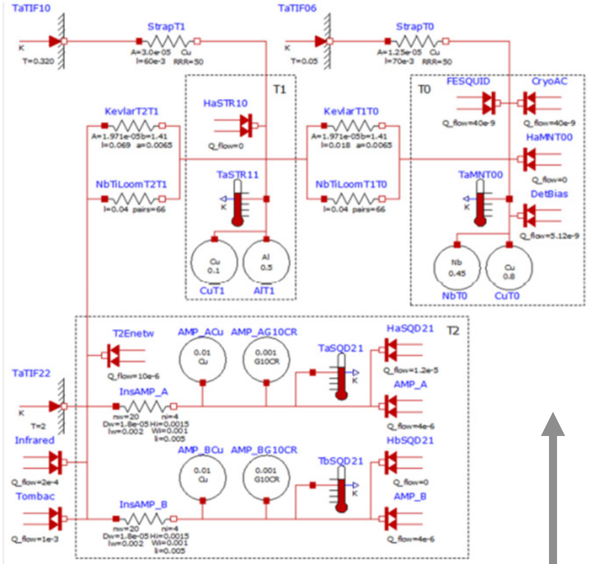
Sensor pixel $f_1 \approx$ 30 KHz



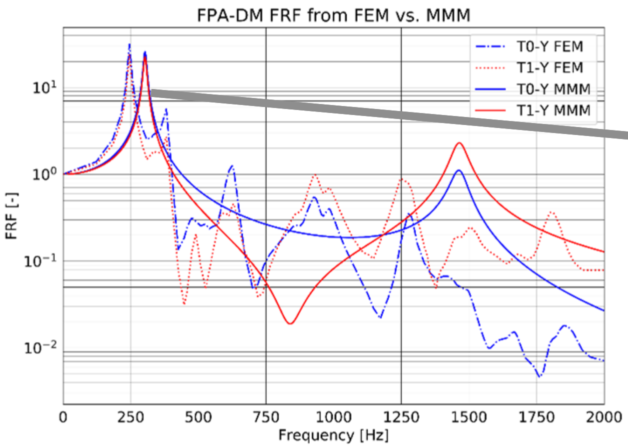
Assessing micro-vibration induced heating impact II

Vibration induced dissipation:

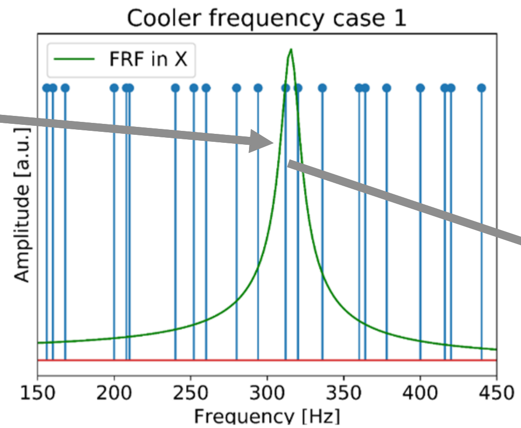
- All instrument moving parts (compressors, pulse-tubes) Generate mechanical vibrations that can be transmitted to the FPA. Impact of coolers is currently under study
- Coupling mechanism is assessed by a combination of:
  - Thermal model
  - Mechanical model
- Experimental verification of models is essential for reliable results in coupled analysis
- Iteration of this loop is required for a reliable micro-vibration IF specification



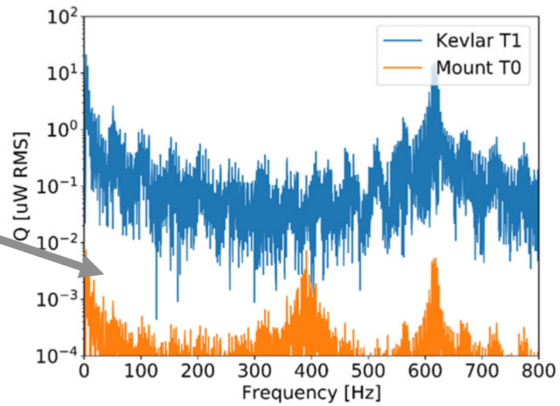
Assess impact of dissipation source (variations) in thermal model



Mechanical Frequency Response function



Cooler harmonics around FPA f_1 act as a mechanical vibration source



Calculated dissipation spectrum, Intermodulation at low freq.

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OpenModelica related points of interest
(from an unexperienced user…)

- SRON created a Modelica "ThermalCryogenics" material properties library for use within thermal-models. Any suggestions on how to implement libraries in an efficient manner are welcome.

- We are interested in experiences from Mechanical Multi-Body modelling users: This could potentially be interesting to assess micro-vibration induced heating.

- Our intention is to include a simplified radiative coupling between the 2K, 0.3K and 0.05 K stages by using the "inner" and "outer" definitions in the FPA model. However practical experience in how to implement this efficiently is lacking. Any suggestions related to information on this subject is welcome.

- We would like to include the (cryogenic) material which is assigned to a model in its graphical annotation. Any suggestions how this can be implemented in OMEdit?

- Are there any others interested in the use of OpenModelica for cryogenic thermal modelling? If so: maybe we can collaborate.

References:

Athena and X-IFU related web pages:

- ESA website with Athena Observatory related information: http://sci.esa.int/athena/59896-mission-summary/
- X-ray Integral Field Unit (X-IFU) public portal: http://x-ifu.irap.omp.eu/
- SRON (Netherlands Institute for Space Research) webpage related to Dutch contribution: https://www.sron.nl/missions-astrophysics/athena

Far Field Python scripts developed by SRON and available under GNU license:

- The scripts described on slide 7 are available at: https://github.com/sron-opensource

Open source Python software packages used within the SRON scripts above:

- Sfepy: "Simple Finite Elements in Python" a Python module: http://sfepy.org/doc-devel/index.html
- pyNastran a package to handle Nastran mesh files from within Python: http://pynastran-git.readthedocs.io/en/latest/quick_start/index.html
- GMSH "A three-dimensional finite element mesh generator with built-in pre- and post-processing facilities": http://gmsh.info/