CLIC Module
Heat load calculations, modelling and experimental program

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On behalf of A. Vamvakas, A. Moilainen and E. Lam

CLIC workshop 2018

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Outline

- A bit of history
- Experiment
- Numerical approaches
- Conclusion and Outlook

In the frame of the CLIC implementation process we had to provide heat to air/water numbers for all three machines

-> work based on CDR effort with updates and some revisions

Drive Beam Machine 3 TeV

Description	total water	unit	total air	unit	local air	unit
Alignment systems:						
Main beam	0	W	22,259	W	1.0	W/m
Drive beam	0	W	18,666	W	0.9	W/m
MBQs	0	W	0	W	0.0	W/m
Sum:	**0**	**W**	**40,925**	**W**	**1.9**	**W/m**
BPM@Quads:						
Main Beam	0	W	25,948	W	1.2	W/m
Drive Beam	0	W	269,620	W	12.6	W/m
Sum:	**0**	**W**	**295,568**	**W**	**13.9**	**W/m**
Vacuum:						
Main Beam	0	W	751,825	W	35.3	W/m
Drive Beam	0	W	337,025	W	15.8	W/m
Sum:	**0**	**W**	**1,088,850**	**W**	**51.1**	**W/m**
Magnets:						
MBQs	5,040,929	W	265,312	W	12.4	W/m
MBQ cables	0	W	132,000	W	6.2	W/m
DBQs	3,369,213	W	177,327	W	8.3	W/m
DBQ cables	0	W	408,000	W	19.1	W/m
Sum:	**8,410,142**	**W**	**982,639**	**W**	**46.1**	**W/m**
MBQ stabilisation systems:						
Controller	0	W	159,680	W	7.5	W/m
Seismometer & powersupply	0	W	13,695	W	0.6	W/m
Piezo actuators	0	W	11,668	W	0.5	W/m
Sum:	**0**	**W**	**185,043**	**W**	**8.7**	**W/m**
RF systems (unloaded case!):						
AS	27,334,217	W	3,727,393	W	174.8	W/m
RF loads	18,394,186	W	[illegible]		[illegible]	
AS WFM	0	W	[illegible]		[illegible]	
PETS	2,764,840	W	[illegible]		[illegible]	
RF distribution	355,031	W	[illegible]		[illegible]	
Sum:	**48,848,273**	**W**	**8,876,684**	**W**	**416.3**	**W/m**
RF systems (loaded case!):						
AS	21,955,346	W	2,993,911	W	140.4	W/m
RF loads	10,962,249	W	2,740,562	W	128.5	W/m
AS WFM	0	W	125,307	W	5.9	W/m
PETS	2,764,840	W	377,024	W	17.7	W/m
RF distribution	355,031	W	48,413	W	2.3	W/m
Sum:	**36,037,466**	**W**	**6,285,217**	**W**	**294.8**	**W/m**
Total per linac **ZERO** beams:	**8,410,142**	**W**	[illegible]		[illegible]	
Total per linac **ONE** beam:	**57,258,415**	**W**	[illegible]		[illegible]	
Total per linac **TWO** beams:	**44,447,608**	**W**	**8,878,242**	**W**	[illegible]	

416 W/m

537 W/m

Drive Beam Machine 380 GeV

Description	total water	unit	total air	unit	local air	unit
Alignment systems:						
Main beam	0	W	3,701	W	1.0	W/m
Drive beam	0	W	2,671	W	0.8	W/m
MBQs	0	W	0	W	0.0	W/m
Sum:	**0**	**W**	**6,372**	**W**	**1.8**	**W/m**
BPM@Quads:						
Main Beam	0	W	7,436	W	2.1	W/m
Drive Beam	0	W	38,584	W	10.9	W/m
Sum:	**0**	**W**	**46,020**	**W**	**13.0**	**W/m**
Vacuum:						
Main Beam	0	W	107,590	W	30.3	W/m
Drive Beam	0	W	48,230	W	13.6	W/m
Sum:	**0**	**W**	**155,820**	**W**	**43.9**	**W/m**
Magnets:						
MBQs	895,379	W	47,125	W	13.3	W/m
MBQ cables	0	W	22,000	W	6.2	W/m
DBQs	482,152	W	25,376	W	7.1	W/m
DBQ cables	0	W	68,000	W	19.1	W/m
Sum:	**1,377,530**	**W**	**162,502**	**W**	**45.7**	**W/m**
MBQ stabilisation systems:						
Controller	0	W	45,760	W	12.9	W/m
Seismometer & powersupply	0	W	2,258	W	0.6	W/m
Piezo actuators	0	W	2,720	W	0.8	W/m
Sum:	**0**	**W**	**50,738**	**W**	**14.3**	**W/m**
RF systems (unloaded case!):						
AS	3,548,084	W	483,830	W	136.2	W/m
RF loads	2,773,331	W	693,333	W	195.2	W/m
AS WFM	0	W	19,292	W	5.4	W/m
[illegible]	398,661	W	54,363	W	15.3	W/m
RF distribution	51,192	W	6,981	W	2.0	W/m
Sum:	**6,771,267**	**W**	**1,257,798**	**W**	**354.1**	**W/m**
RF systems (loaded case!):						
AS	2,623,009	W	357,683	W	100.7	W/m
RF loads	1,227,283	W	306,821	W	86.4	W/m
AS WFM	0	W	19,292	W	5.4	W/m
PETS	398,661	W	54,363	W	15.3	W/m
RF distribution	51,192	W	6,981	W	2.0	W/m
Sum:	**4,300,145**	**W**	**745,139**	**W**	**209.7**	**W/m**
Total per linac **ZERO** beams:	**1,377,530**	**W**	**421,451**	**W**	**118.6**	**W/m**
Total per linac **ONE** beam:	**8,148,798**	**W**	**1,679,249**	**W**	**472.7**	**W/m**
Total per linac **TWO** beams:	**5,677,675**	**W**	**1,166,591**	**W**	**328.4**	**W/m**

Klystron machine 380 GeV

Description	total water	unit	total air	unit	local air	unit
Alignment systems:						
Main beam	0	W	2,621	W	0.8	W/m
Drive beam	0	W	0	W	0.0	W/m
MBQs	0	W	0	W	0.0	W/m
Sum:	**0**	**W**	**2,621**	**W**	**0.8**	**W/m**
BPM@Quads:						
Main Beam	0	W	7,644	W	2.3	W/m
Drive Beam	0	W	0	W	0.0	W/m
Sum:	**0**	**W**	**7,644**	**W**	**2.3**	**W/m**
Vacuum:						
Main Beam	0	W	105,560	W	31.7	W/m
Drive Beam	0	W	0	W	0.0	W/m
Sum:	**0**	**W**	**105,560**	**W**	**31.7**	**W/m**
Magnets:						
MBQs	688,237	W	36,223	W	10.9	W/m
MBQ cables	0	W	22,000	W	6.6	W/m
DBQs	0	W	0	W	0.0	W/m
DBQ cables	0	W	0	W	0.0	W/m
Sum:	**688,237**	**W**	**58,223**	**W**	**17.5**	**W/m**
MBQ stabilisation systems:						
Controller	0	W	47,040	W	14.1	W/m
Seismometer & powersupply	0	W	2,327	W	0.7	W/m
Piezo actuators	0	W	2,804	W	0.8	W/m
Sum:	**0**	**W**	**52,171**	**W**	**15.7**	**W/m**
RF systems (unloaded case!):						
AS	3,963,768	W	540,514	W	162.1	W/m
RF loads	2,710,723	W	677,681	W	203.3	W/m
AS WFM	0	W	18,928	W	5.7	W/m
Pulse compression & distribution	5,094,787	W	268,147	W	80.4	W/m
Klystron	8,541,260	W	449,540	W	134.9	W/m
Modulator	3,768,203	W	198,326	W	59.5	W/m
Sum:	**11,769,277**	**W**	**1,505,269**	**W**	**451.6**	**W/m**
RF systems (loaded case!):						
AS	2,938,744	W	400,738	W	120.2	W/m
RF loads	1,199,278	W	299,820	W	89.9	W/m
AS WFM	0	W	18,928	W	5.7	W/m
Pulse compression & distribution	5,094,787	W	268,147	W	80.4	W/m
Klystron	8,541,260	W	449,540	W	134.9	W/m
Modulator	3,768,203	W	198,326	W	59.5	W/m
Sum:	**9,232,809**	**W**	**987,632**	**W**	**296.3**	**W/m**
Total per linac **RF OFF**:	**688,237**	**W**	**226,219**	**W**	**67.9**	**W/m**
Total per linac **RF ON & NO** beam:	**12,457,514**	**W**	**1,731,488**	**W**	**519.4**	**W/m**
Total per linac **RF ON &** beam:	**9,921,046**	**W**	**1,213,851**	**W**	**364.1**	**W/m**

Situation as of July 2017

Looking closer on the accelerating structures and their loads

Main Beam:			
Thermal dissipation of AS	435	W	**unloaded!**
Thermal dissipation of RF loads	322	W	**unloaded!**
Thermal dissipation of AS	349	W	**loaded!**
Thermal dissipation of RF loads	192	W	**loaded!**
total # AS	71,406	---	
total power AS	31,061,610	W	**unloaded!**
total power AS	24,949,256	W	**loaded!**
Power to water AS	0.88	---	
total power RF loads	22,992,732	W	**unloaded!**
total power RF loads	13,702,811	W	**loaded!**
Power to water RF loads	0.80		

These numbers varied historically from 1 to 0.8

-> we had to understand those numbers better and get them as high as we can

Two beam module test lab:

Heat to air 'measured'

Assume all heat from heater goes to water or air

$$P_{air} = P_{tot} - P_{water}$$

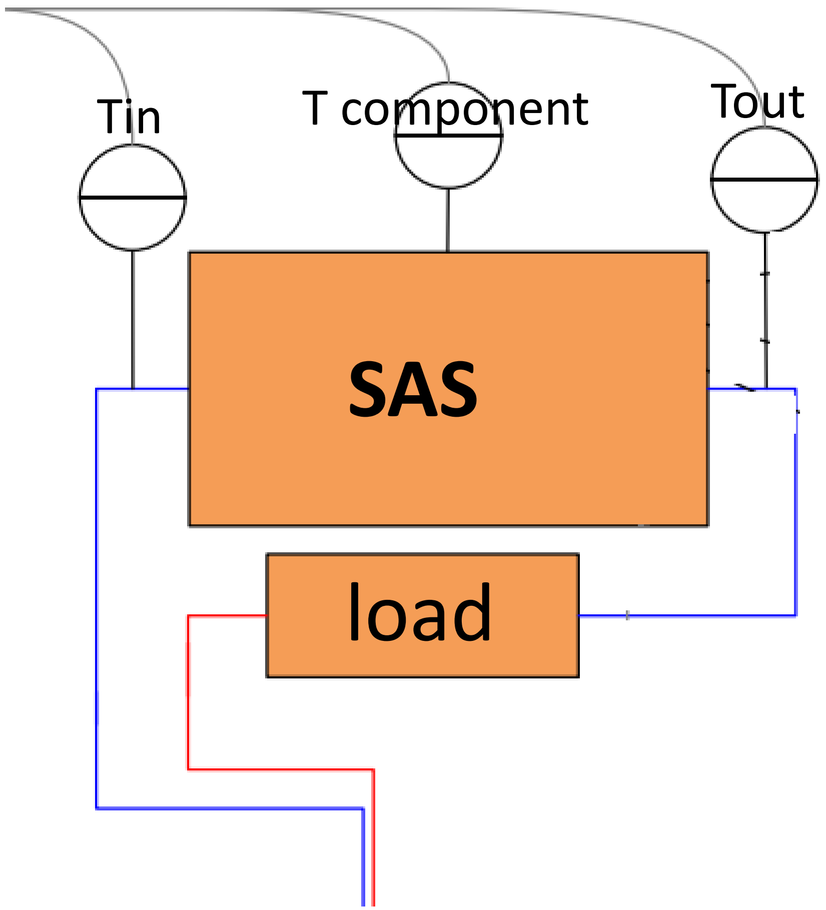
$$P_{water} = \dot{m}_w C_p [T_{out} - T_{in}]$$

$$P_{tot} = V * I$$

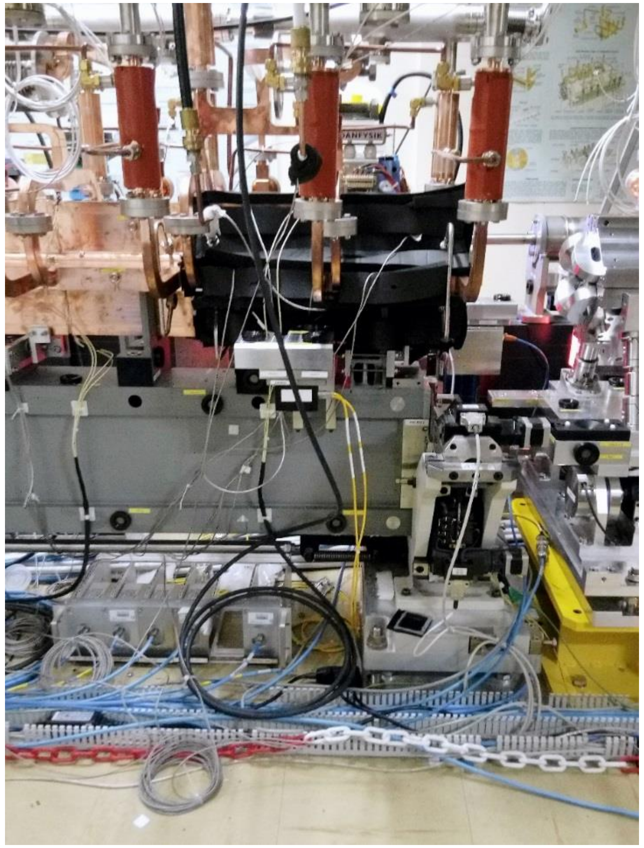
Heat to air theory

$$P_{air} = hA[T_{comp} - T_{ambient}]$$

Cp	4184	J/kg/K
h	11~20	W/m2/K
A	0.7273	M2
m'	0.026~0.039	kg/sec



Naked and insulated SAS



Problem:

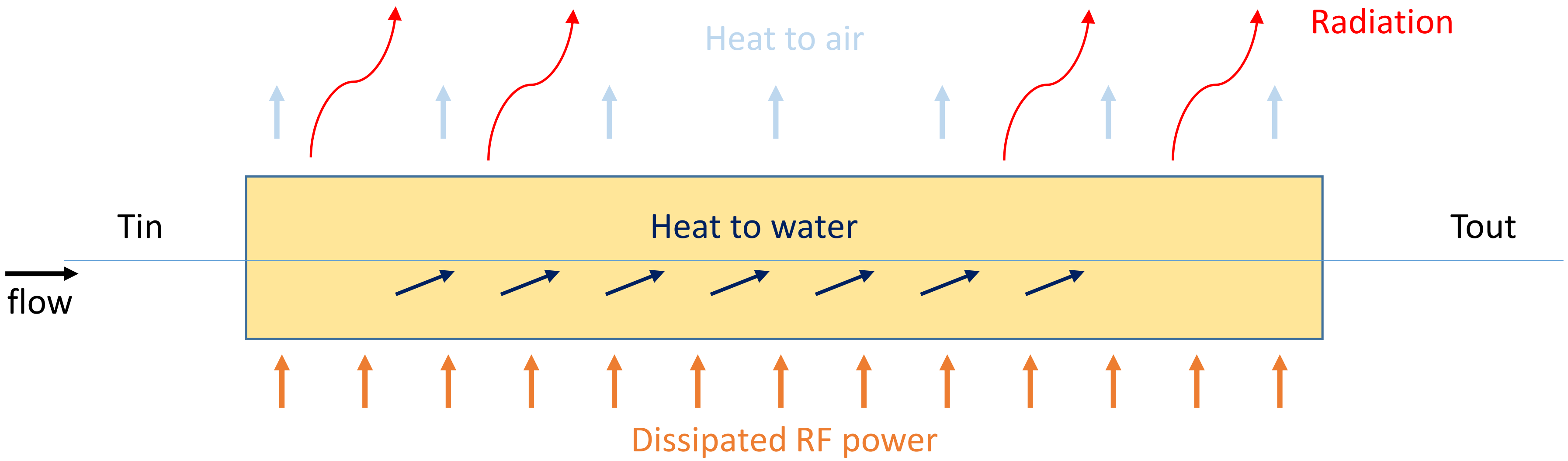
- heat conducted away through girder/waveguides/vacuum system
- Minor errors in temperature accuracy huge errors in power

Analytical Model

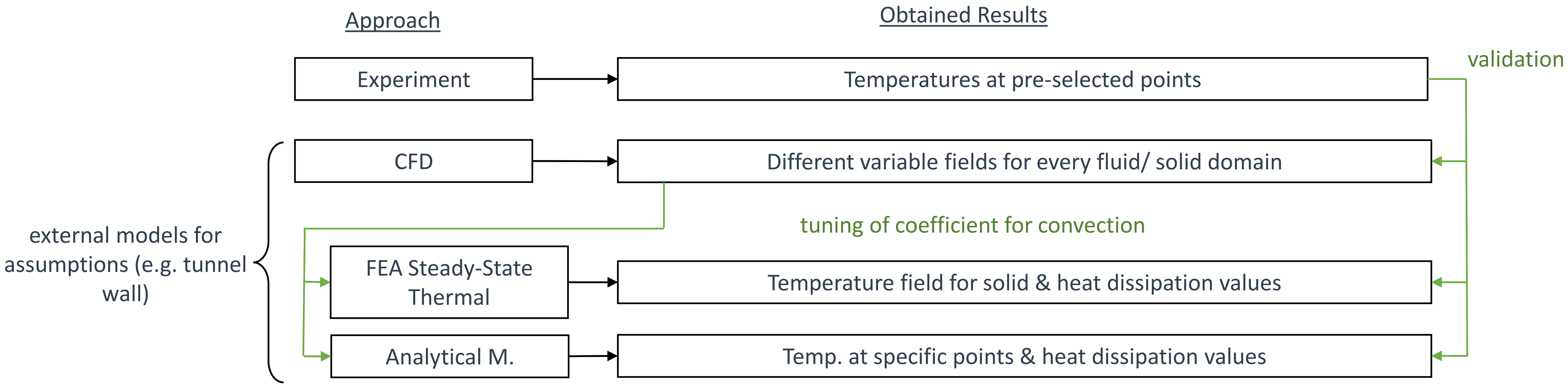
- Simple pipe, heated and cooled all along
- Excludes folding of piping
- Run time for SAS: 1 sec
- Run time for TBM: 3 sec
- Can be used to run many different combinations,

Downsides:

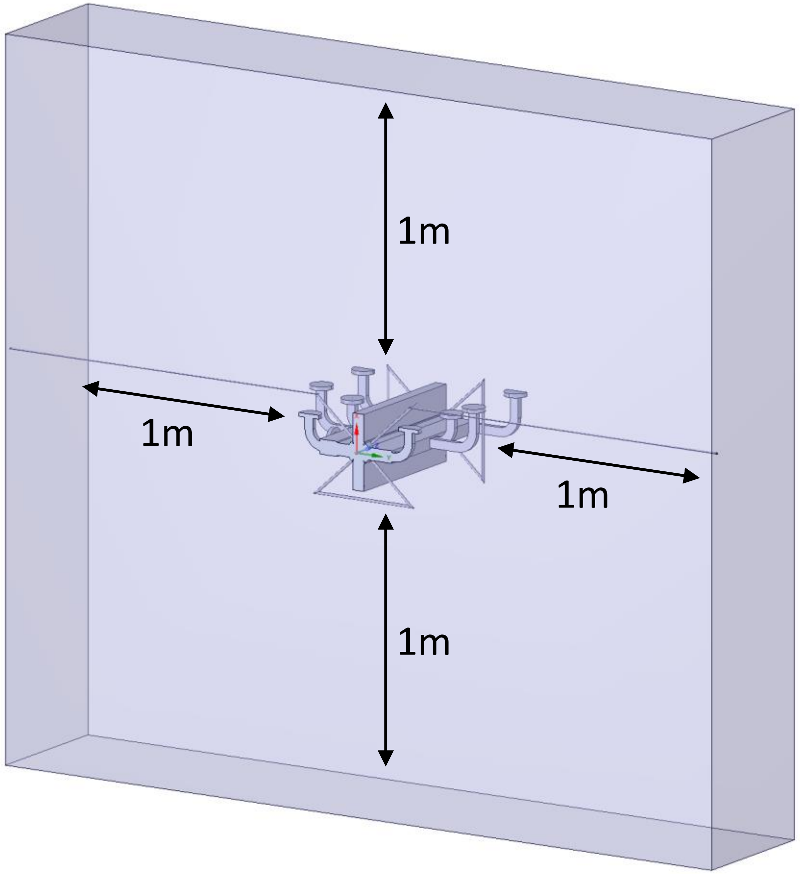
- Heavy assumptions for heat transfer coefficient
- No possibility to simulate real heat channel routing in SAS



Combined approach



Problem Definition

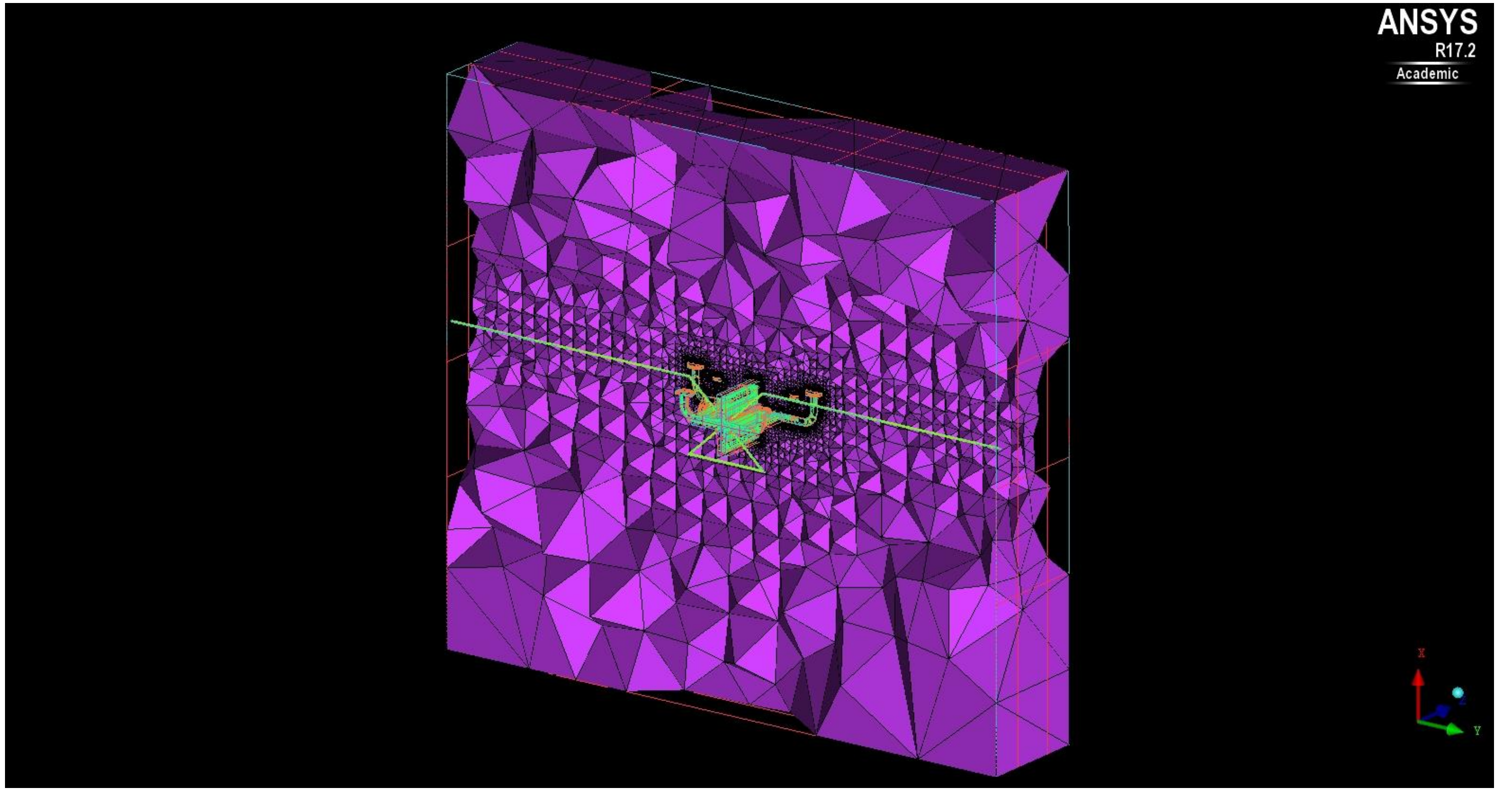


- Only one super-accelerating structure
- In “free” space
- Domain boundary 1 m from the structure
- Artificial pipes

Materials:

- Copper for the structure and pipes
- Air (variable ρ, incompressible ideal gas law)
- Water (constant ρ)

Meshing



a cross section of the mesh

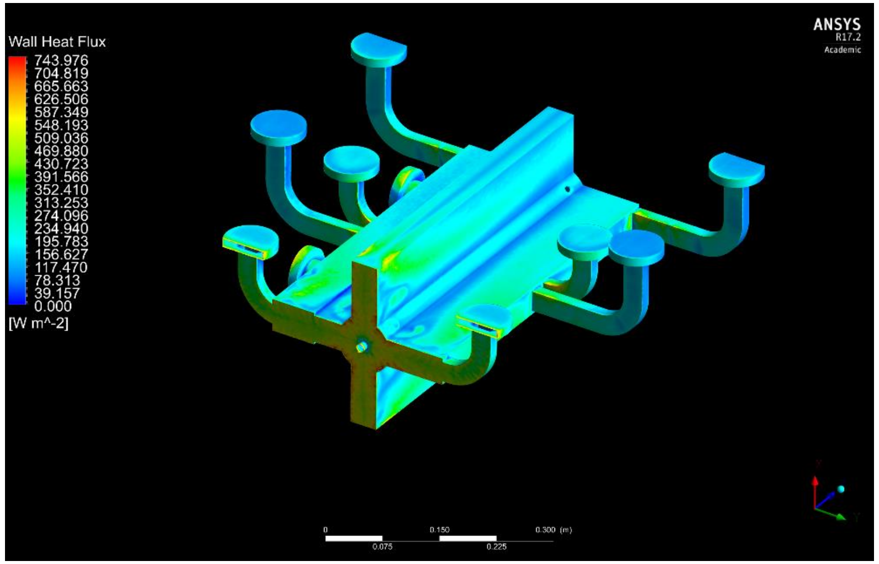
Mesher: ANSYS ICEM CFD v17.2

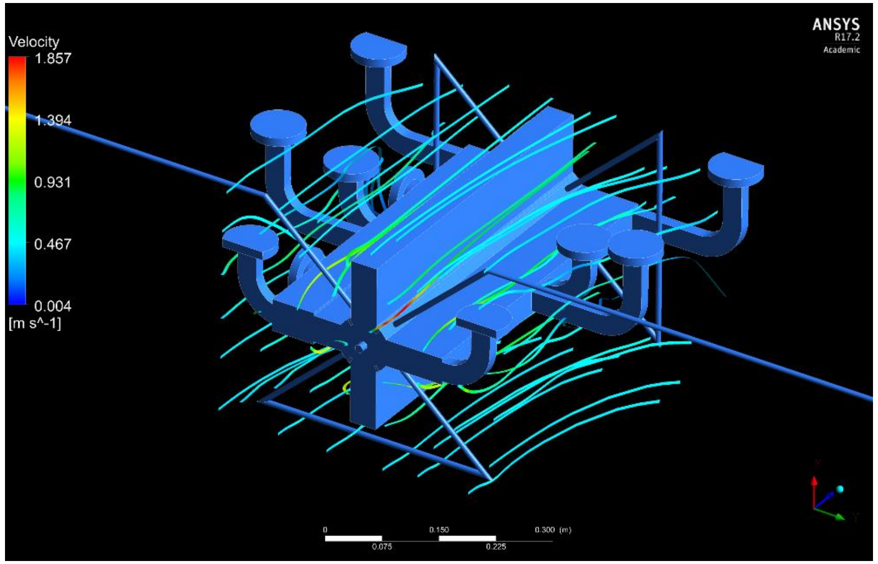
Type of elements: tetrahedron

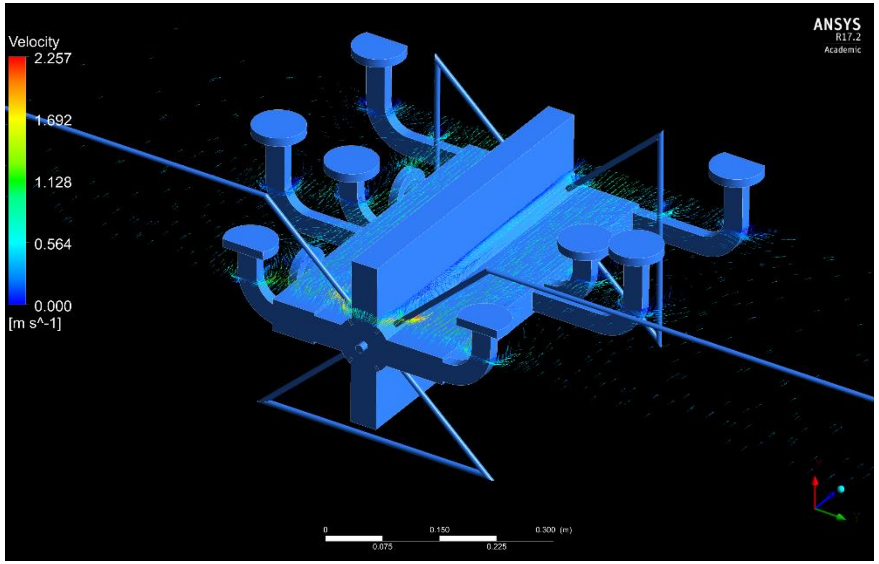
Number of elements:
43 million for the finest mesh
Coarser meshes were generated to determine mesh independence

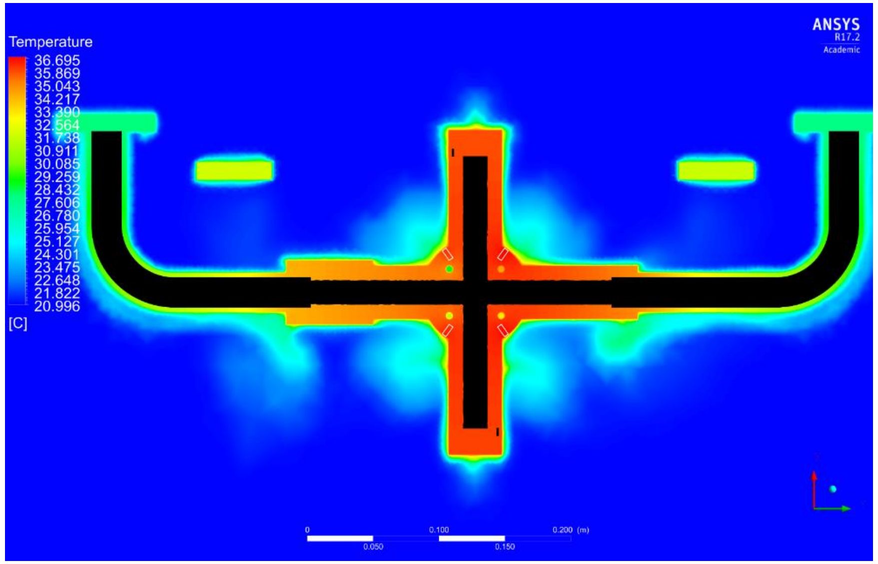
Minimum size of elements: 1 mm

Output


Wall Heat Flux
743.976
704.819
665.663
626.506
587.349
548.193
509.036
469.880
430.723
391.566
352.410
313.253
274.096
234.940
195.783
156.627
117.470
78.313
39.157
0.000
[W m^-2]
ANSYS
R17.2
Academic


Velocity
1.857
1.394
0.931
0.467
0.004
[m s^-1]
ANSYS
R17.2
Academic


Velocity
2.257
1.692
1.128
0.564
0.000
[m s^-1]
ANSYS
R17.2
Academic


Temperature
36.695
35.869
35.043
34.217
33.390
32.564
31.738
30.911
30.085
29.259
28.432
27.606
26.780
25.954
25.127
24.301
23.475
22.648
21.822
20.996
[C]
ANSYS
R17.2
Academic

SAS (no compact loads)

SST simulation

CFD simulation (E. Lam)

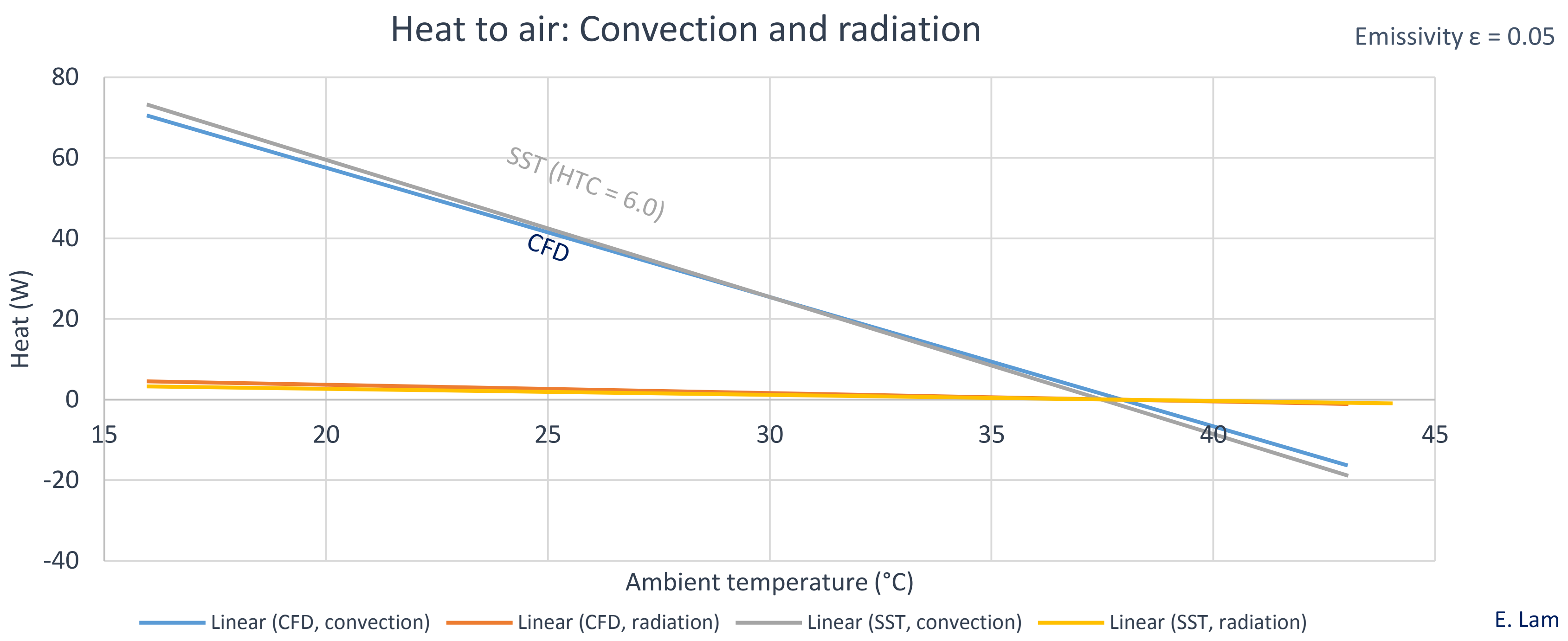
- horizontal air flow 0.4 m/s

SAS:

Heat 780 W

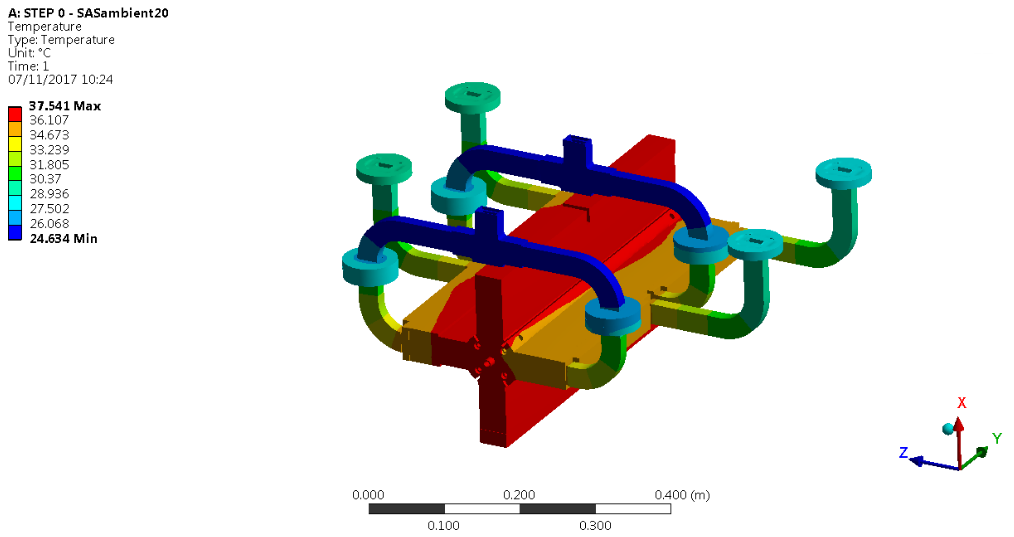
Water 27 °C

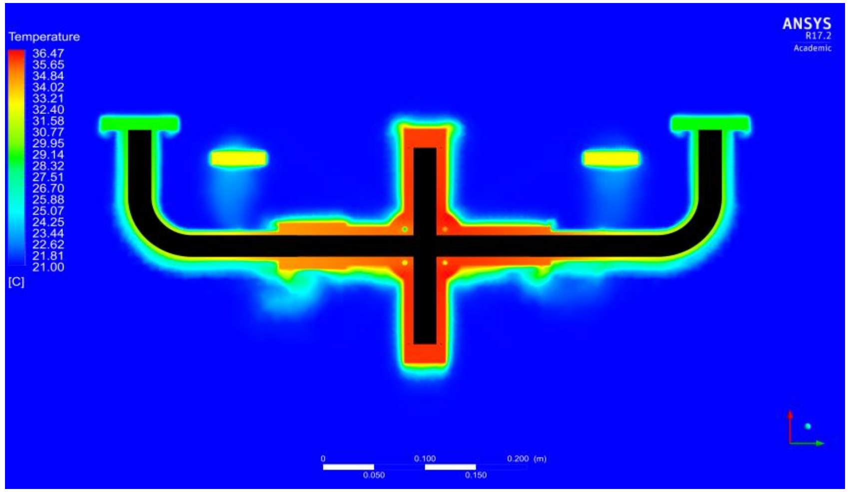
Flow 1.3 l/min



A. J. Moilanen

E. Lam





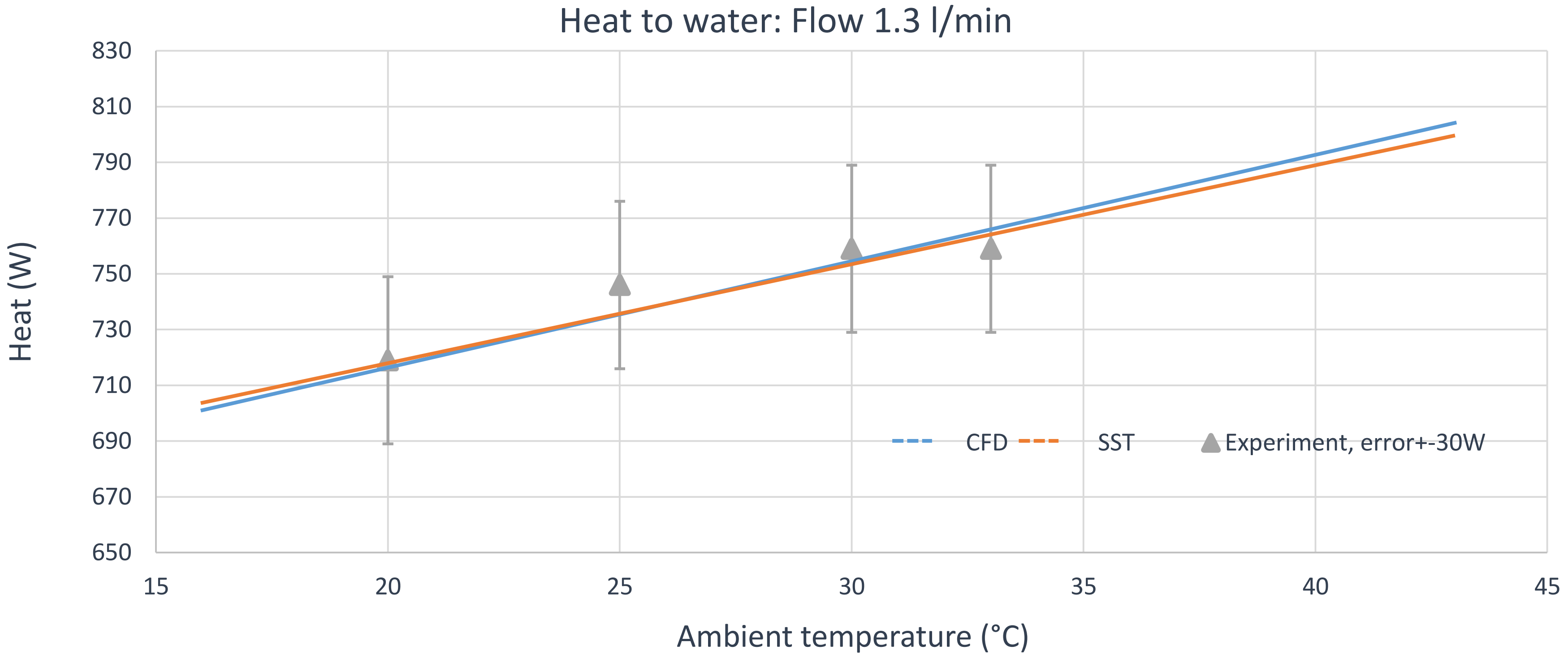
SAS (no compact loads)

SST simulation

CFD simulation (E. Lam)

Measurement (V. Andavan, A. Vamvakas)

- horizontal air flow 0.4 m/s



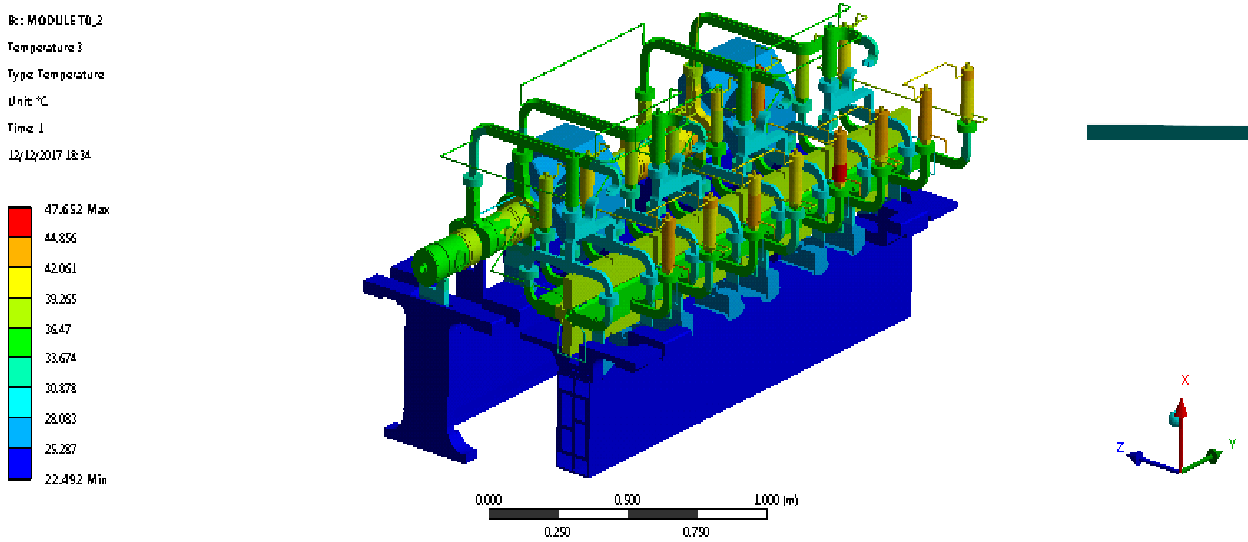
FEM Thermal analysis of the entire CLIC module

Aim of the Finite Element Method (FEM) simulation is to study heat distribution and dissipation in CLIC module T0#2.

Thermal gradients originate from several sources: RF structures produce heat, components are cooled by water and air flow, ambient temperature varies

The modelling is done using ANSYS 17.2 Workbench. The FEM simulation of includes:

- 3D CAD geometry
- Steady-state thermal analysis (followed by Static structural analysis)
- Isotropic materials: OFE copper, aluminium, stainless steel, SiC
- Thermal loads
- Ambient temperature
- Thermal fluid (water)
- Convection, radiation, conduction



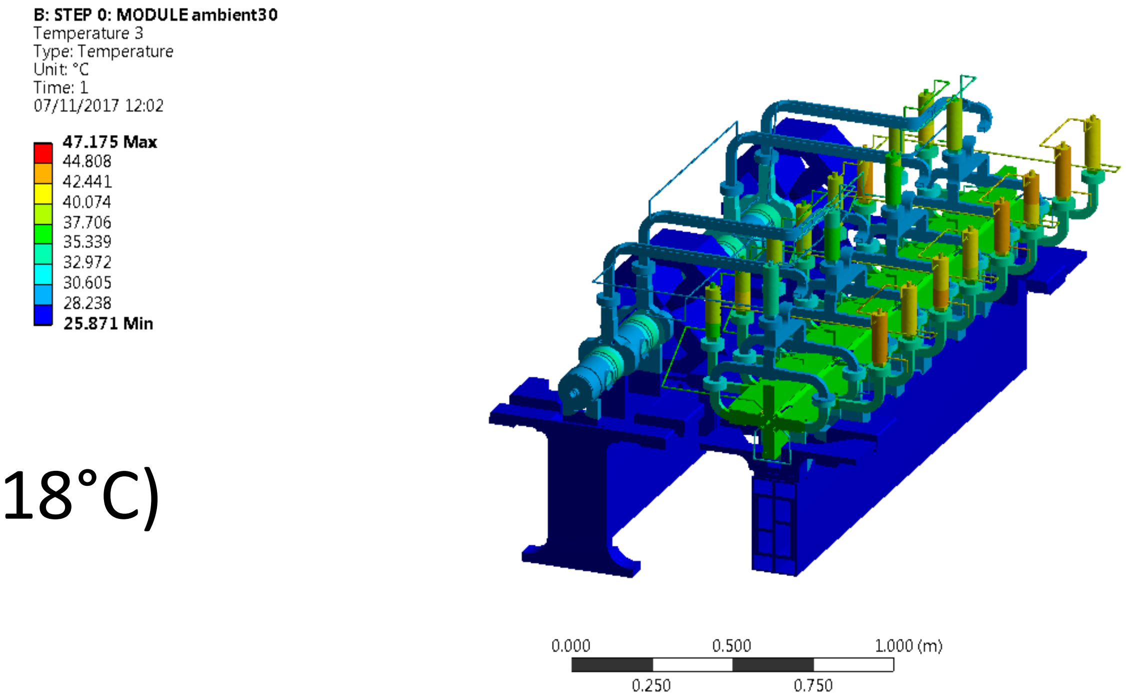
FEA thermal simulations for TBM

- ANSYS Thermal steady-state analysis
- T0#2 Module
- Run time: ~1hr

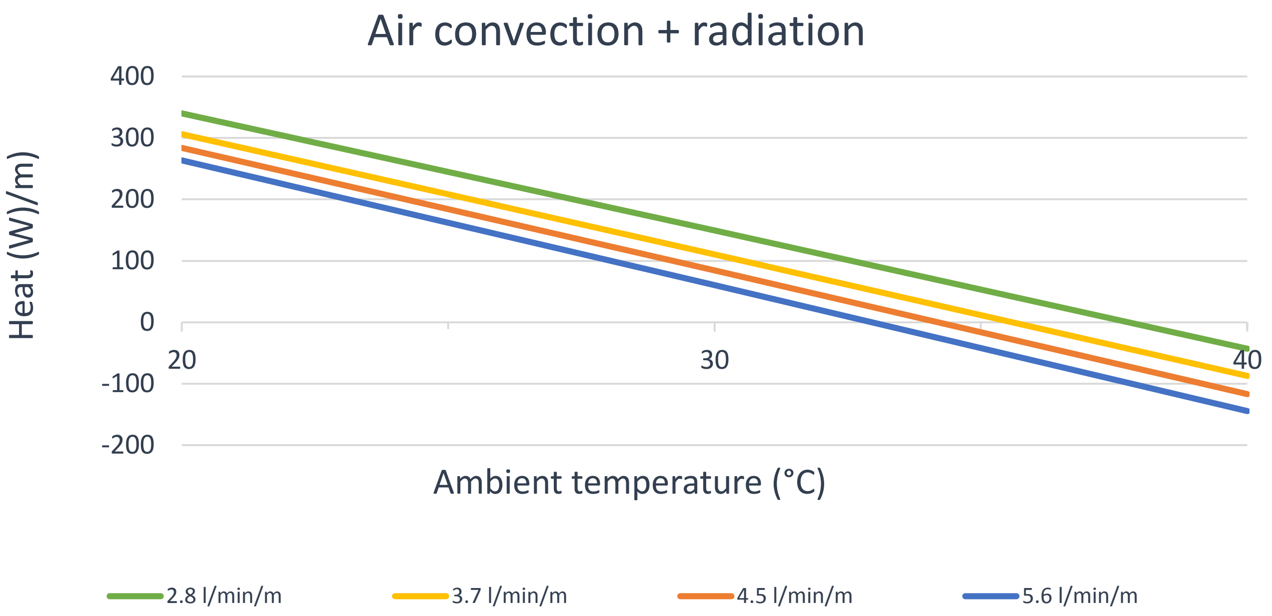
		Heating power (W)		
CL	20x	161	3220	
PETS	4x	88	352	
SAS	4x	860	3440	
DBQs	2x	171	342	
Total			**7354**	**W**

- Total heating power 7354 W
- Cooling water 27 °C, 1.3 l/min
- Ambient T = 20...40 °C
- Convection HTC_air = 7.5 W/m^2K
- Radiation to surrounding ”space” (T = 18°C)

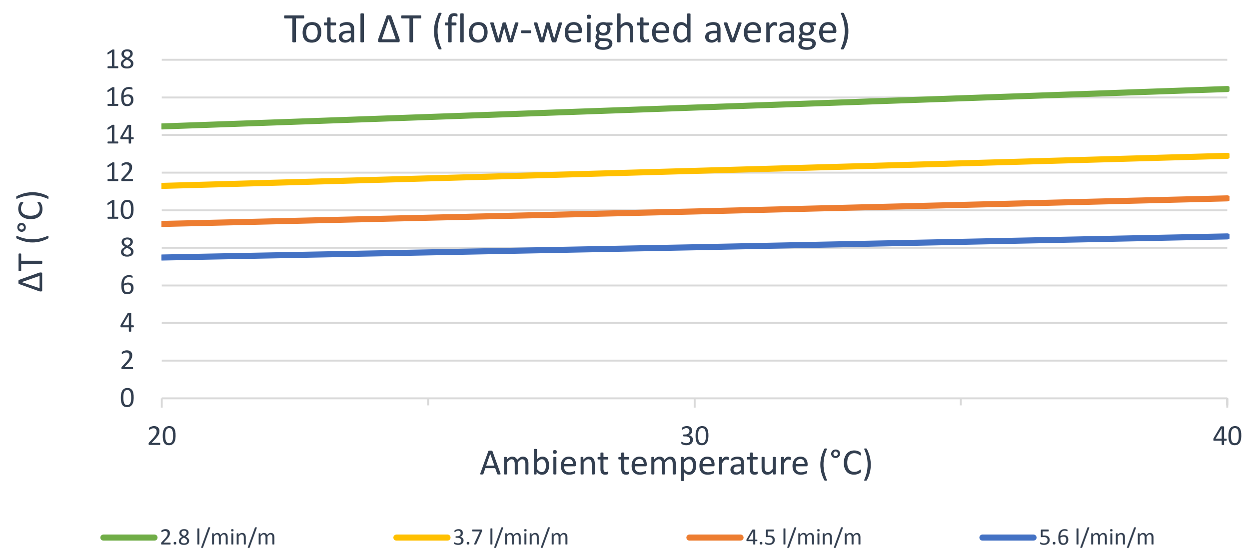
(no surface-to-surface effect)



Module: Results for different flows: Unloaded case



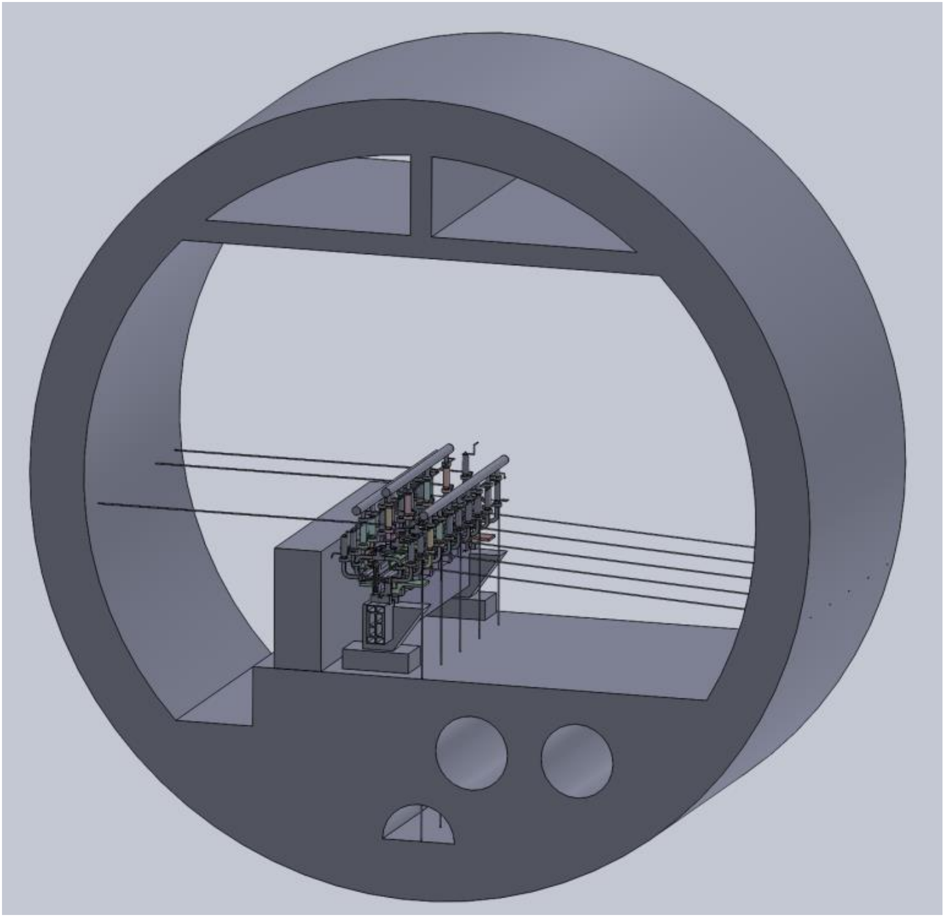
- Higher flow lowers component T (but not below 27°C)
- Higher flow lowers heat to air
- Higher ambient T lowers heat to air
- Zero emission point



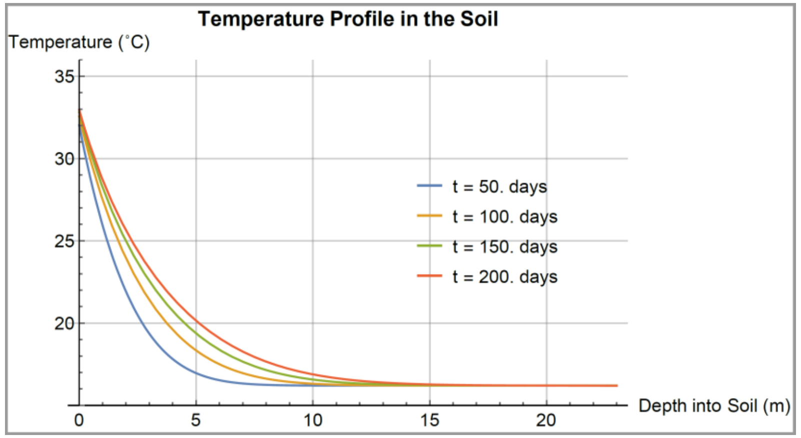
- Higher flow lowers ΔT of water!
- Higher ambient T increases ΔT of water!

-> to our colleagues from Cooling&Ventilation

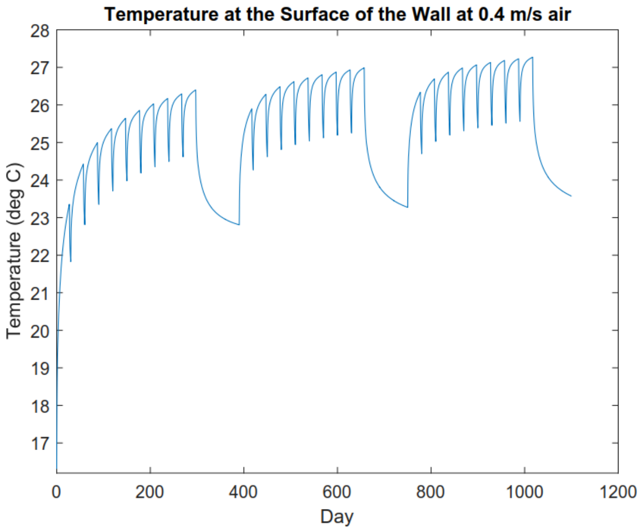
In the mean time...



- Entire main beam part of the module into CFD for getting a glimpse of longitudinal effects
- Modeling of tunnel wall and soil for evaluation of feasibility of temperature stability requirements
- Machine operation transitioning states



Analytical model in development for assumptions that can be made for the tunnel wall in steady-state CFD or FEA simulations



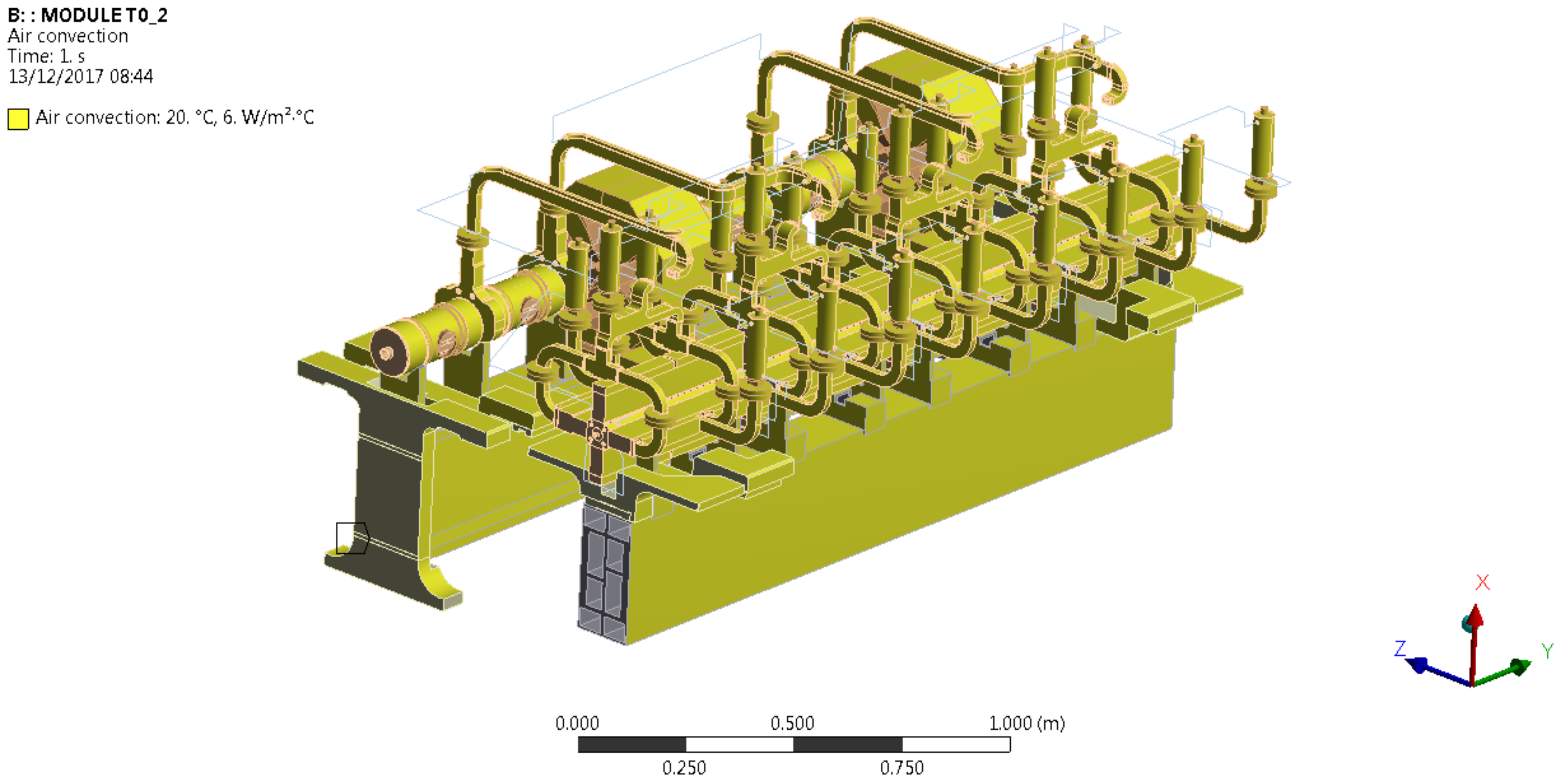
3 days off per month
3 months off per year
Off means 25 °C
On means 32 °C
Initial 16.2°C
Always 0.4 m/s

CERN

Module: Air convection

Convection to air

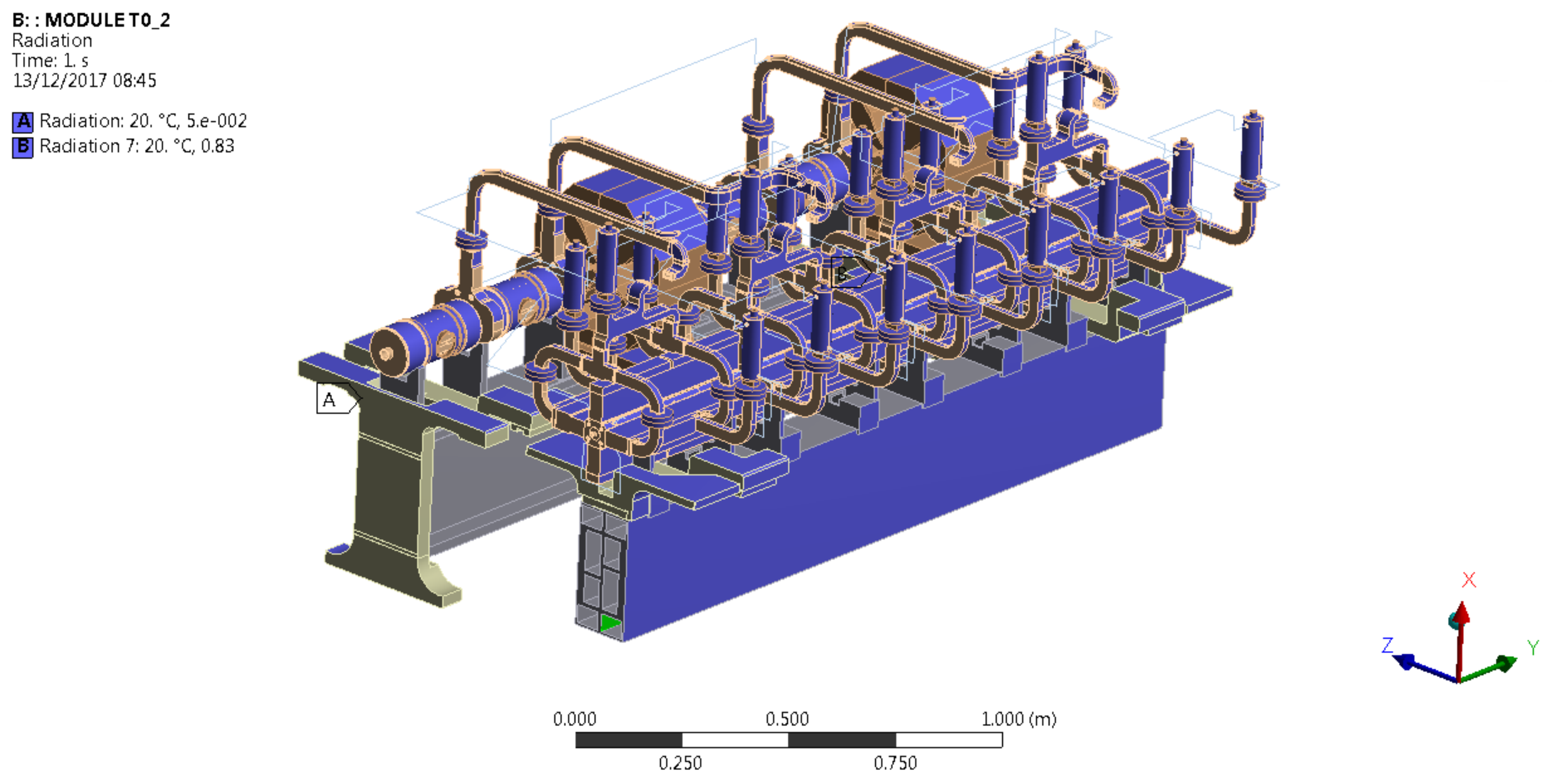
- Constant heat transfer coefficient 6 W/(m² °C)



Module: Thermal radiation

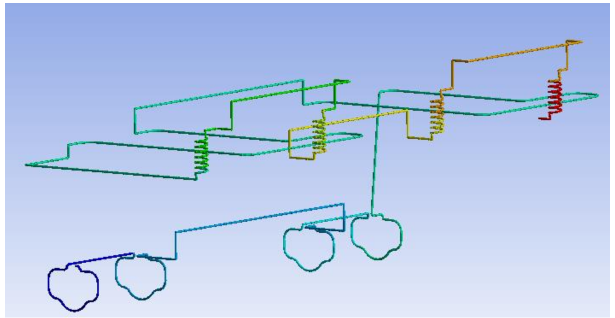
Radiation to surrounding space (ambient temperature):

- Emissivity for copper, aluminium and stainless steel (0.05) and SiC (0.83)
- No surface-to-surface effects

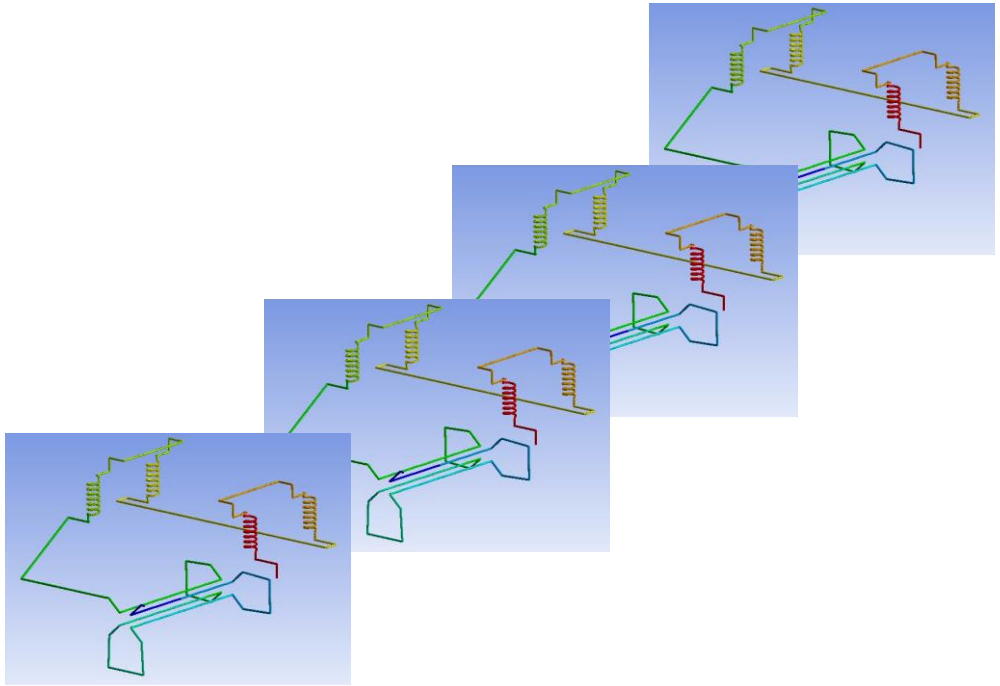


Module: Water cooling

5 separate cooling circuits
- Water heat transfer coefficient is calculated similarly as in Refs. [1-4]
- Flow can be varied
- Inlet temperature can be varied



2 double PETS and 4 RF loads on series



SAS and 4CLs on series