Update on thermal analysis of gun 4.2 for green cathode operation

Outline

- Multiphysics simulations of PITZ gun 4.2 (new model)
- Simulations for gun 4.2 operation with green cathode
- Conclusion

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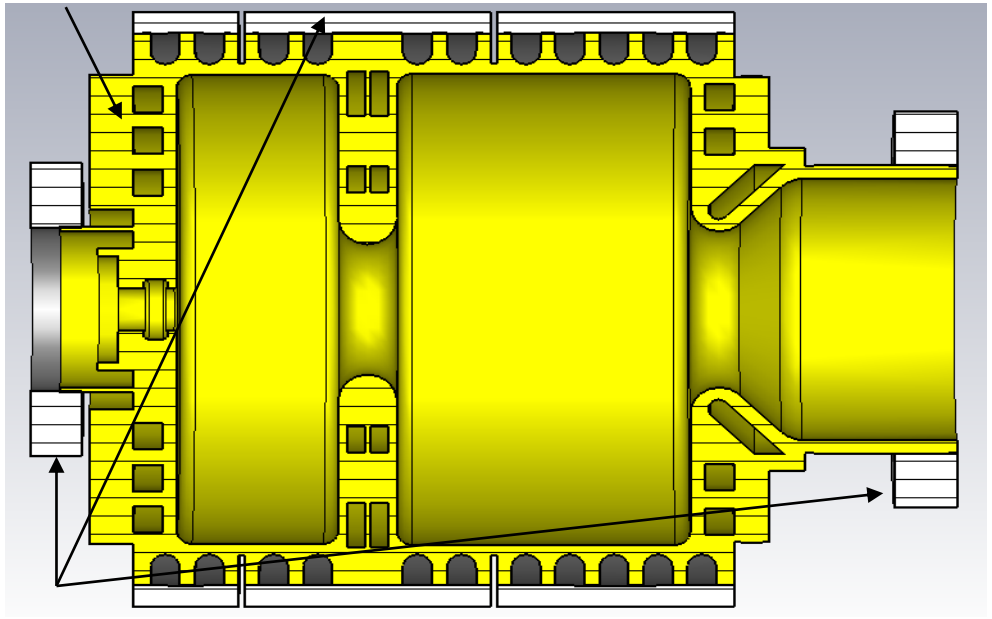
May. 7, 2020

Multiphysics simulations of PITZ gun 4.2 (new model)

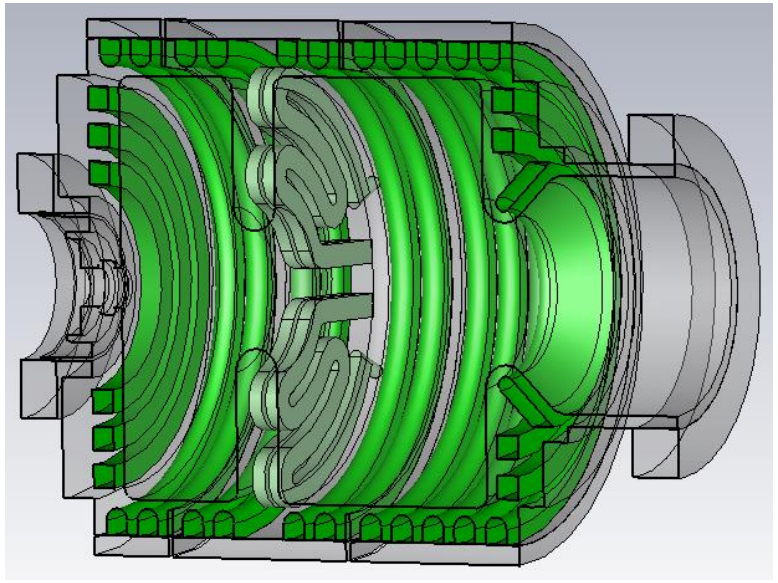
New model in simulation

Gun 4.2

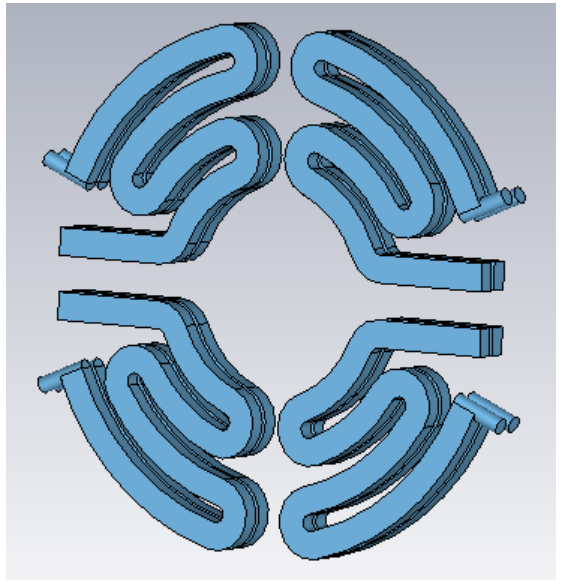
Copper cavity



Stainless steel



Cavity wall cooling channels



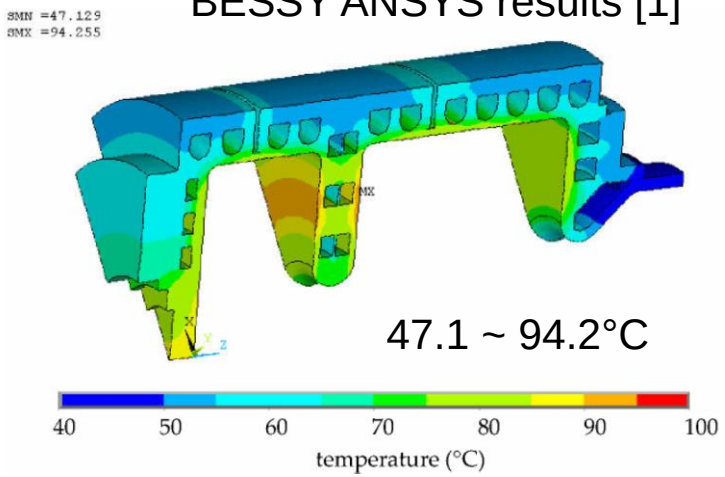
Iris cooling channels

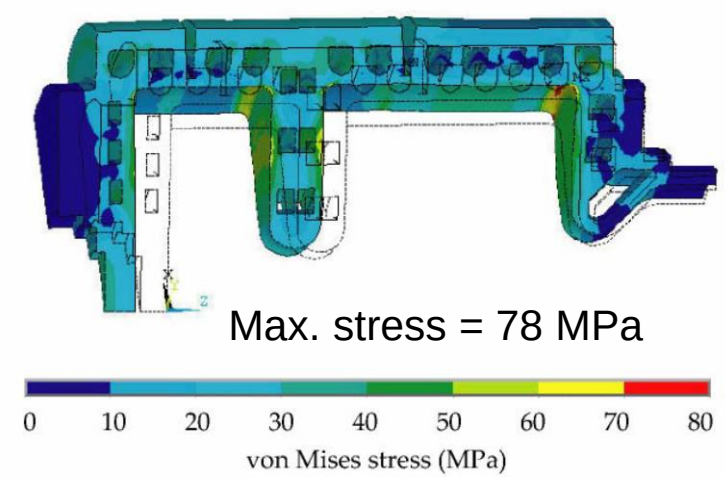
Water velocity 2 m/s

Comparison with BESSY simulations

100 kW, 40°C water

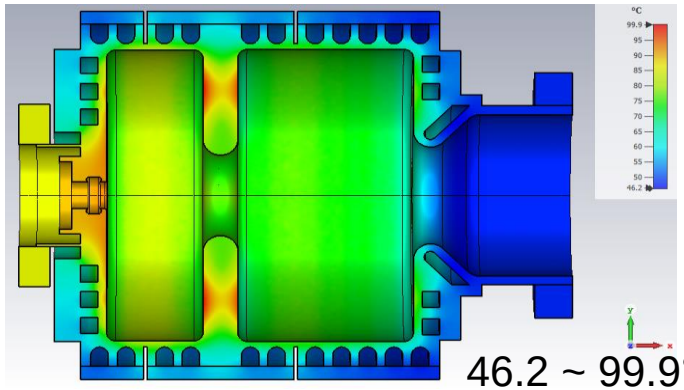
BESSY ANSYS results [1]

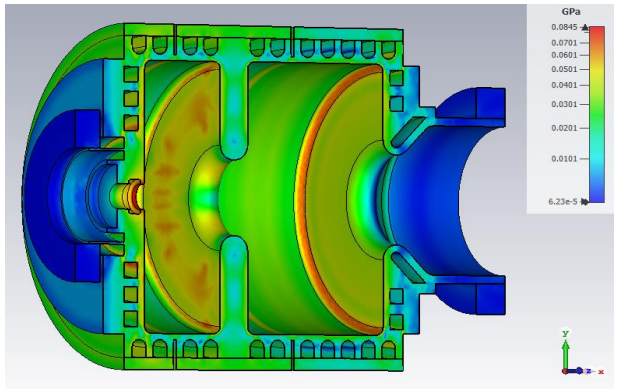




RF induced frequency shift: ~6 kHz/kW

PITZ CST results





Max. stress = 84.5 MPa

CST results are roughly consistent with ANSYS results. The deviation might result from the model simplification in ANSYS.

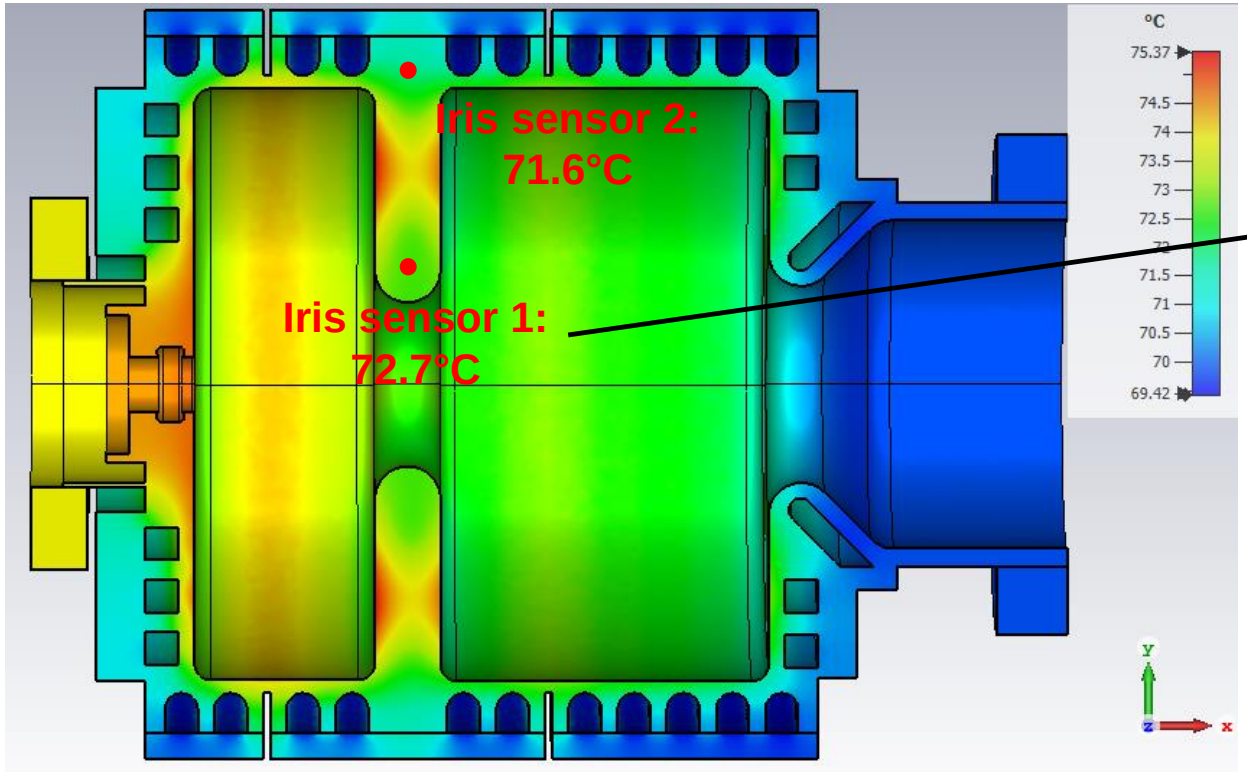
RF induced frequency shift: 6.5 kHz/kW

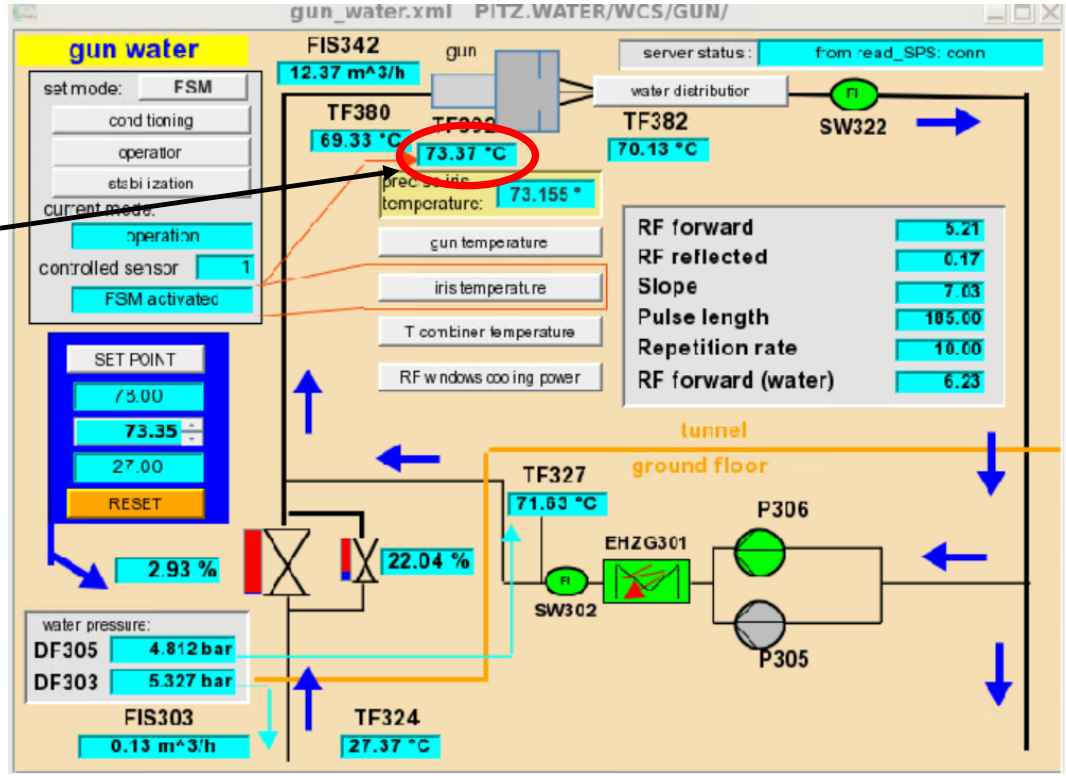
[1]. Marhauser, Frank. *Finite element analyses for RF photoinjector gun cavities*. No. TESLA-FEL--2006-02.

Temperature distribution for PITZ nominal operation

200 us / 10Hz / 60MV/m cathode E

- 11 kW average power loss in cavity
- Inlet water T : 69.3°C





Measurement at 20200427L

Average power loss calculated from three methods

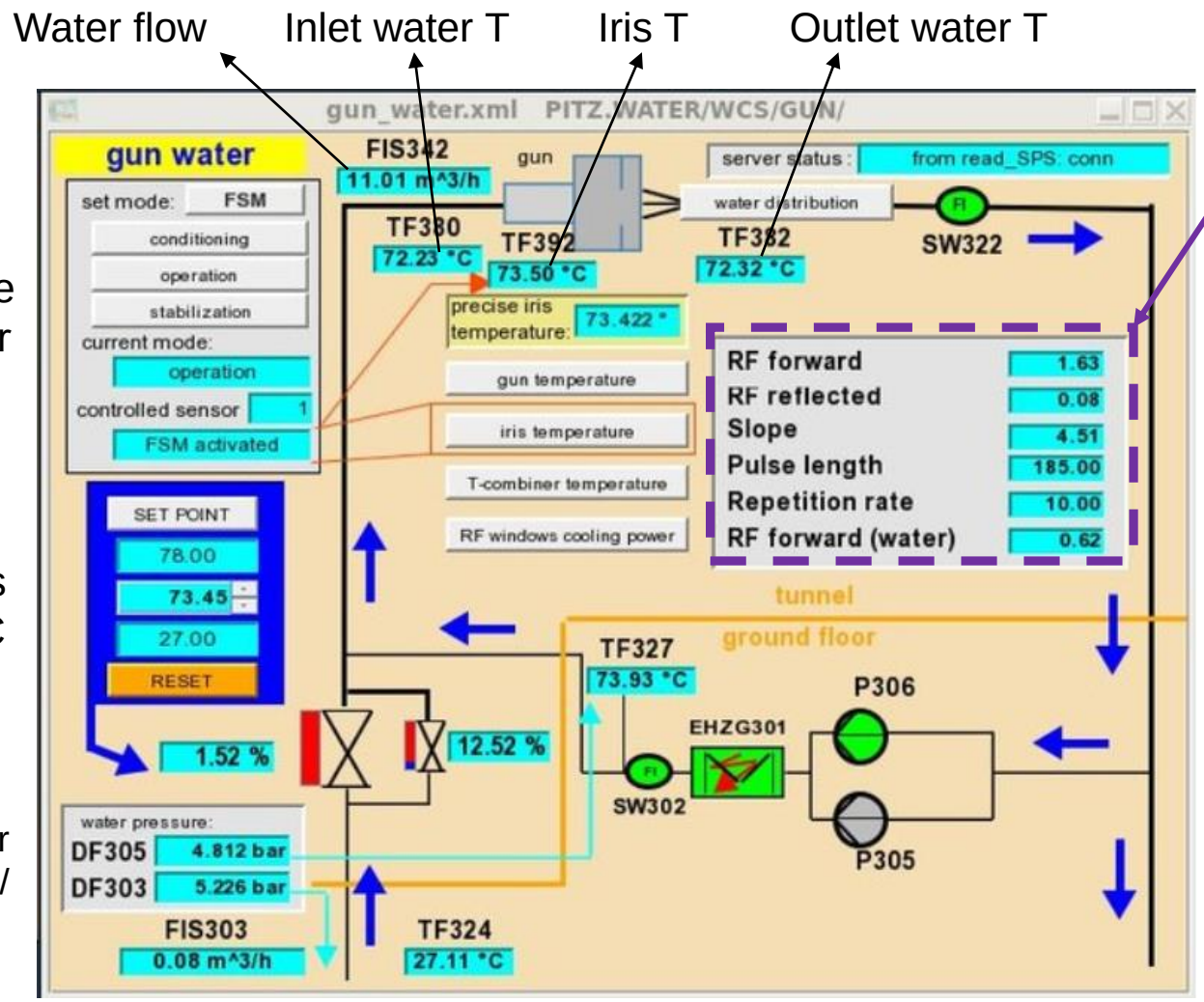
Method 1:

- Inlet and outlet water temperature rise, water flow → average power loss in cavity

Uncertainty:

- Temperature sensor calibration is unknown. New calibration ±0.4°C @ 80°C can be achieved.

Cooling power will be monitored under doocs address: 'PITZ.WATER / WCS / GUN / cooling_power' (from Jörg)



Method 2:

- Forward and reflected power, pulse length and rep-rate → average power loss in cavity

Uncertainty:

- RF power meter calibration

Method 3:

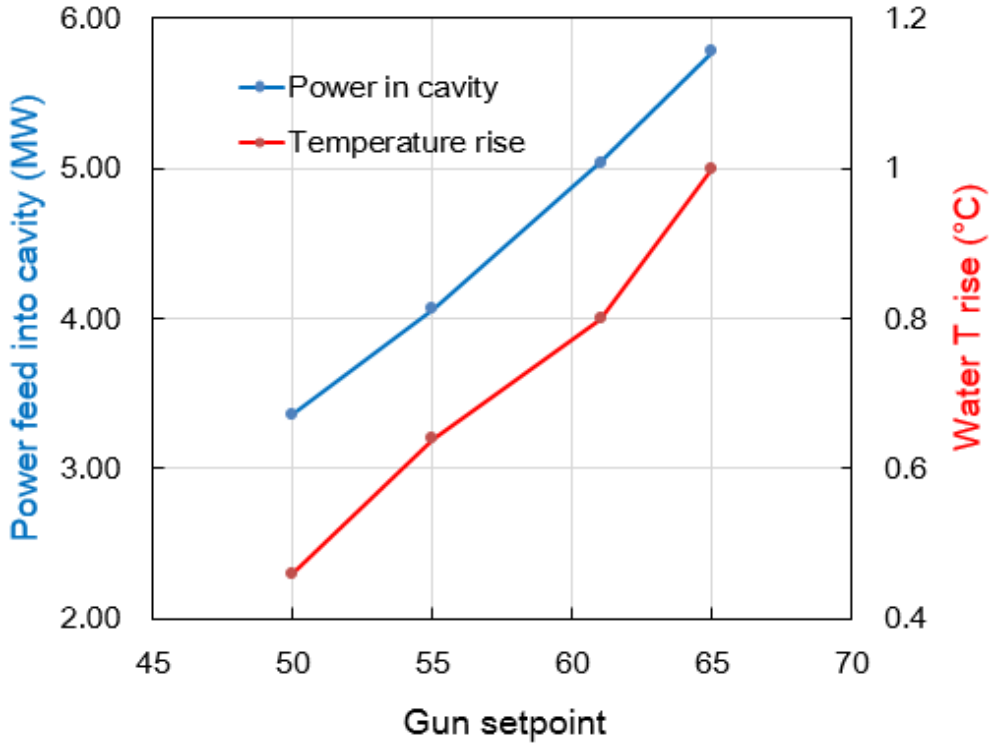
- Beam momentum, stored energy in cavity, unload Q0, pulse length and rep-rate → average power loss in cavity

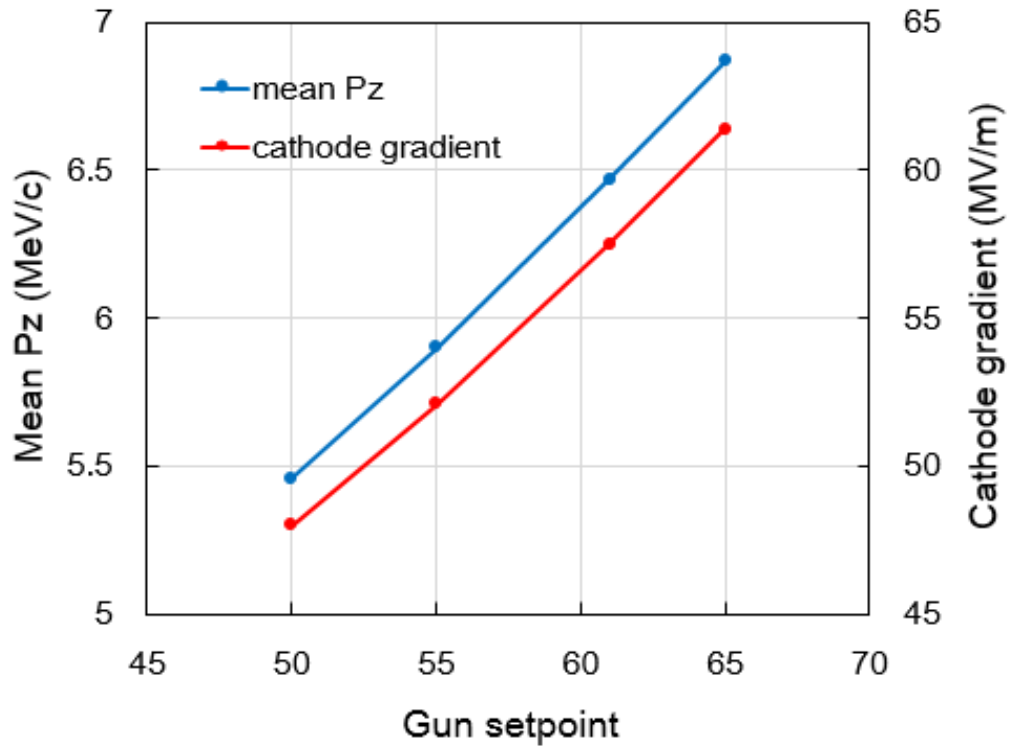
Uncertainty:

- Cavity unload Q0 is unknown

Measurement at 20200427L

Pulse length 200us, rep-rate 10Hz

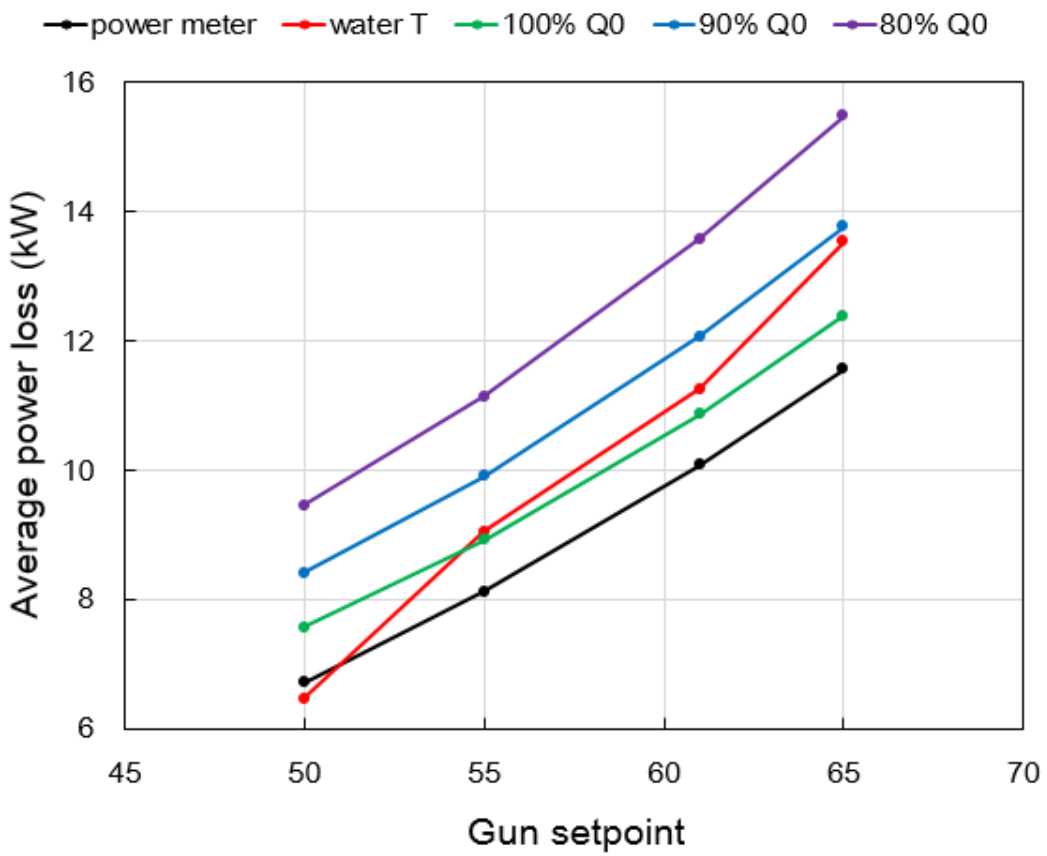


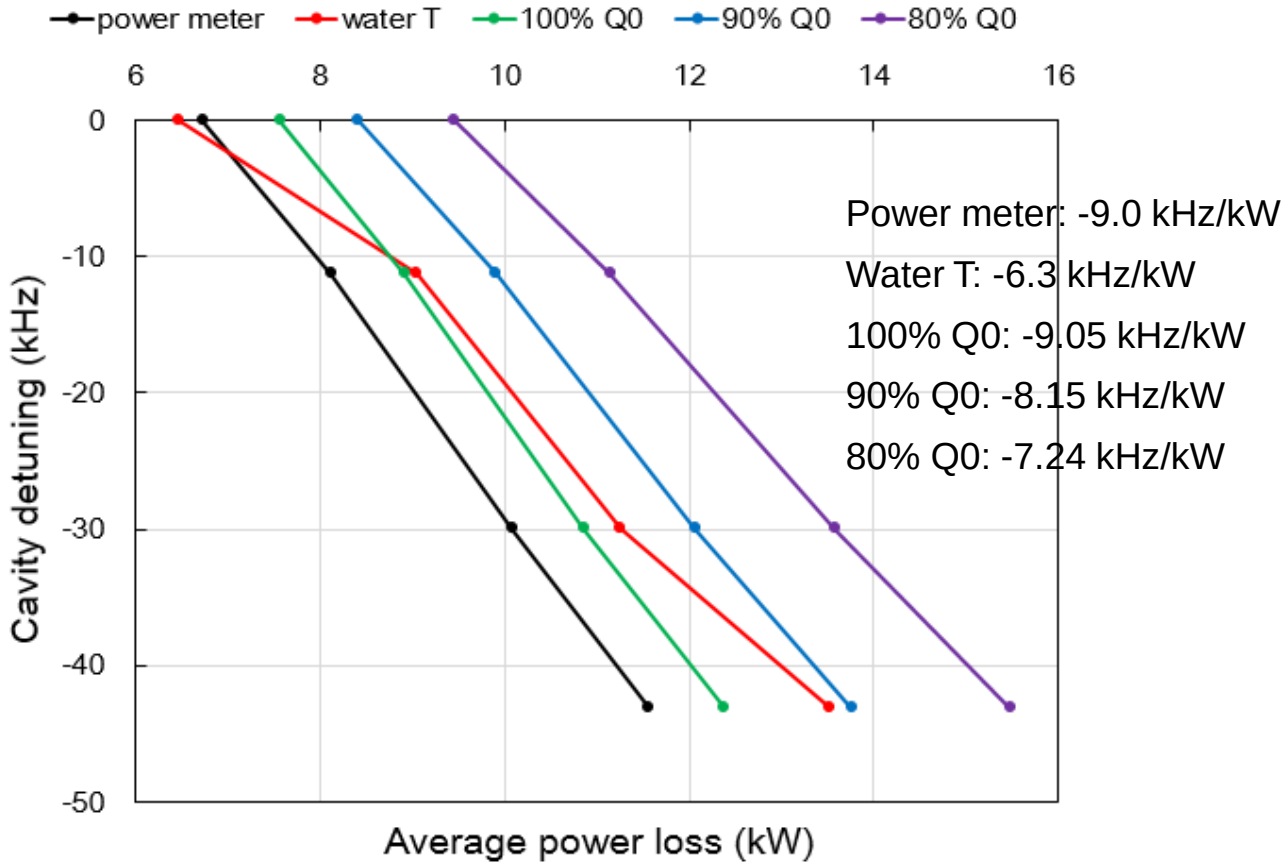


Power in cavity (MW) = $P_{forward} - P_{reflected} = 0.0017\ E_{cath}(MV/m)^2$

Measurement at 20200427L

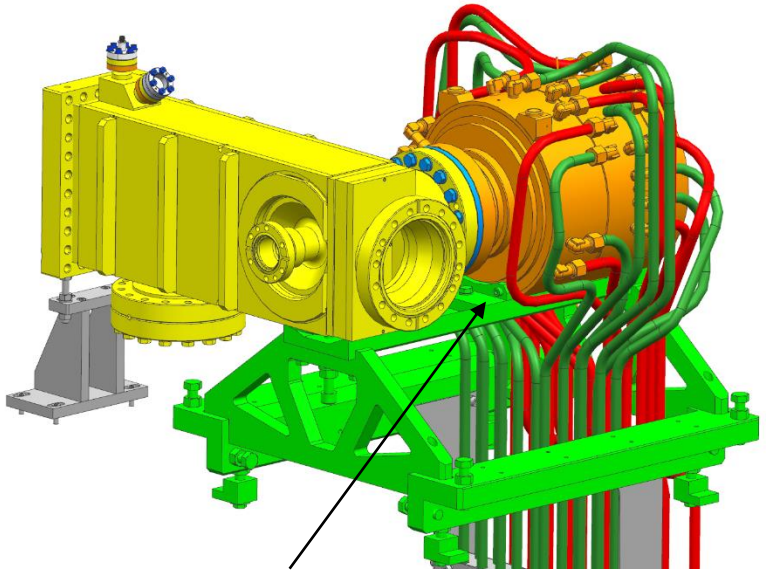
Pulse length 200us, rep-rate 10Hz



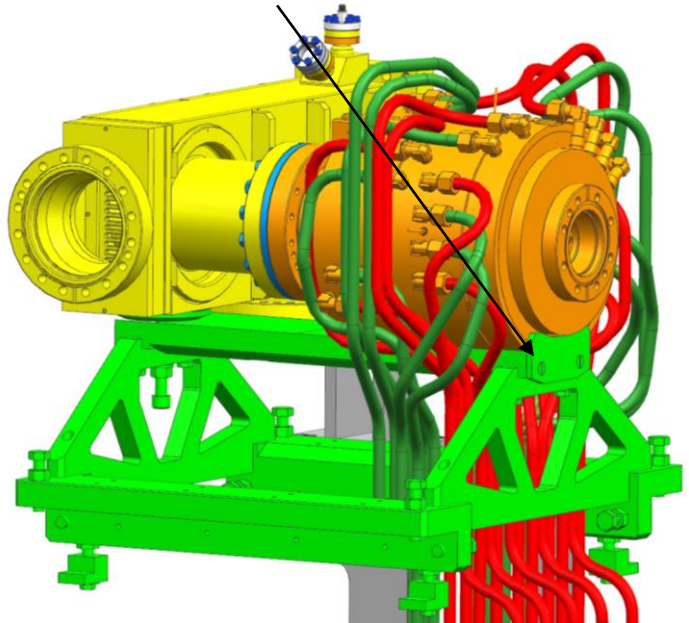


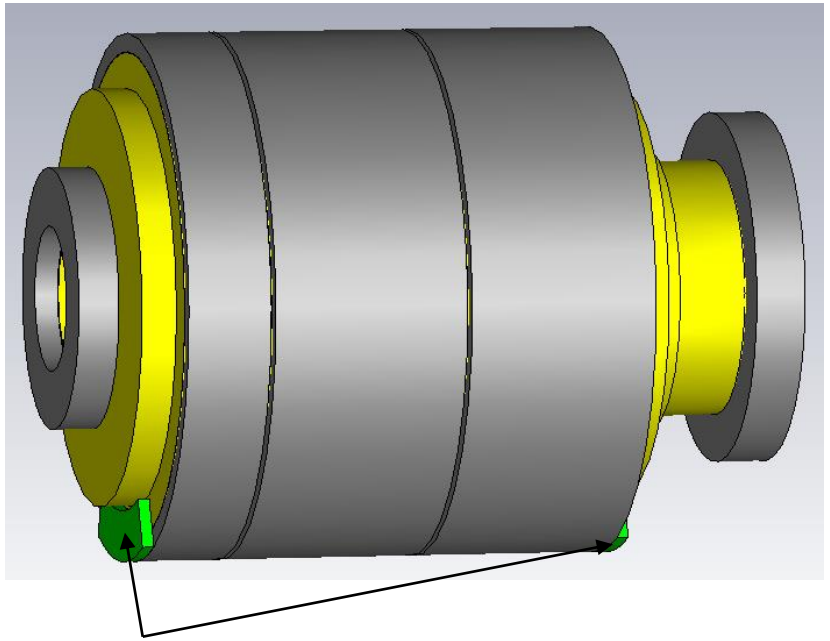
- With various power calculation methods, the frequency detuning due to RF heating is 6.3~9.1 kHz/kW.
- Simulation value is 5.1 kHz/kW (free expansion boundary condition), underestimate w.r.t measurement. The deviation might result from the inaccurate boundary conditions in structure expansion simulation.

Boundary conditions discussion

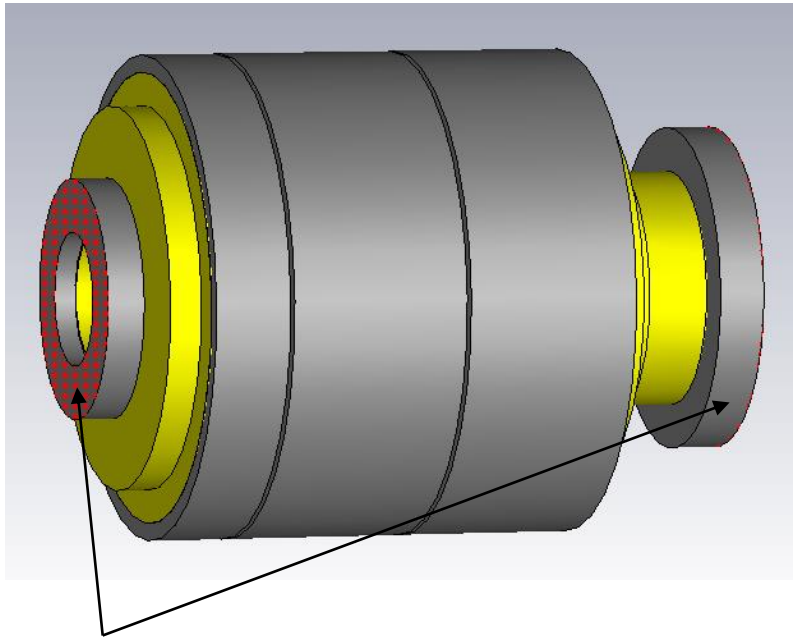


Fixed plane





Longitudinally fixed #1



Longitudinally fixed #2

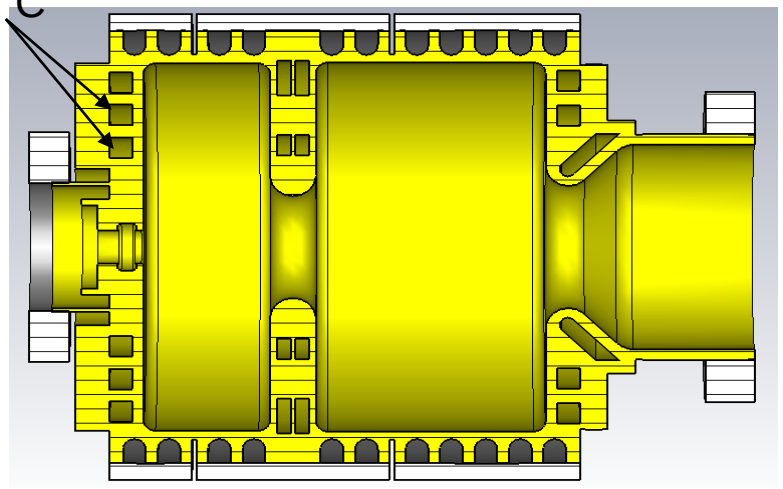
Boundary condition	Freq. sensitivity (kHz/kW)
Free expansion	-5.1
Longi. Fixed #1	-5.6
Longi. Fixed #2	-6.4
Experiment	-6.3~-9.1

Simulations for gun 4.2 operation with green cathode

27°C cooling for rear plate

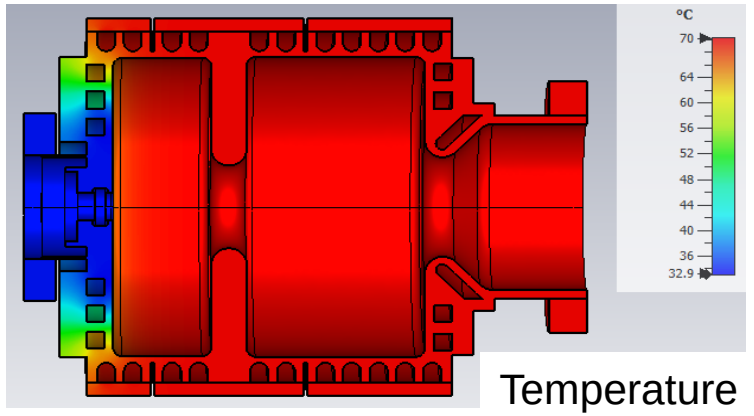
70°C cooling for the other channels

27°C

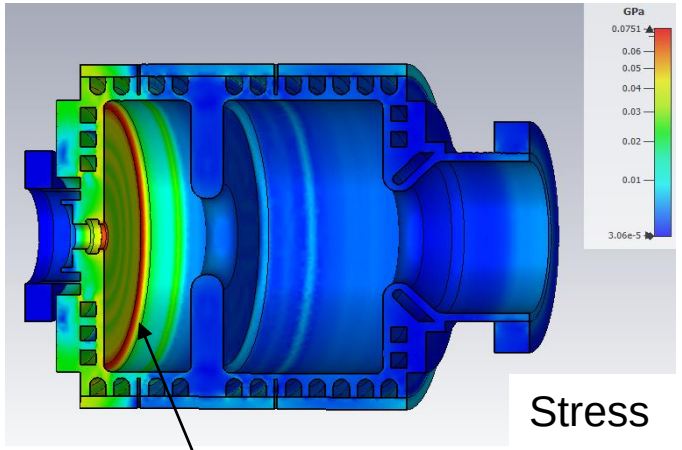


27°C water temperature fluctuates 26.1°C ~ 27.8°C (from Jörgs).

0 kW



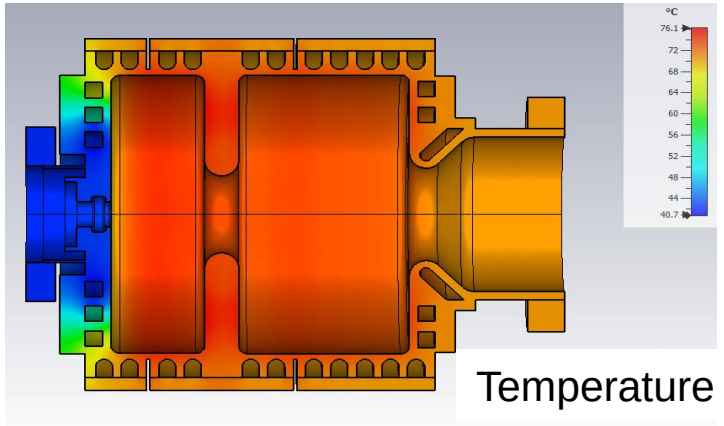
Temperature



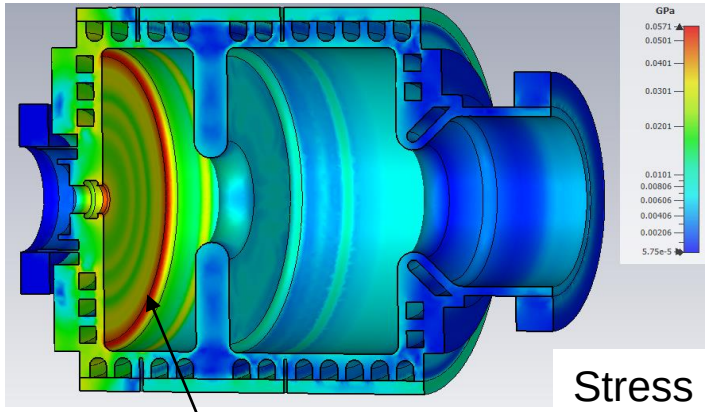
Stress

Peak stress 75.1 MPa

11 kW (200us / 10Hz / 60MV/m)



Temperature



Stress

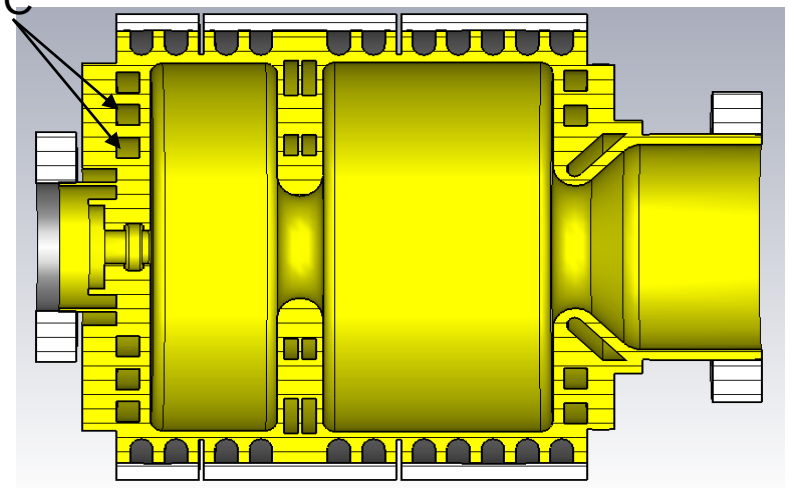
Peak stress 57.1 MPa

Yield strength limit for annealed Cu is 62 MPa. For 0 kW RF heating, cavity might be damaged!!!

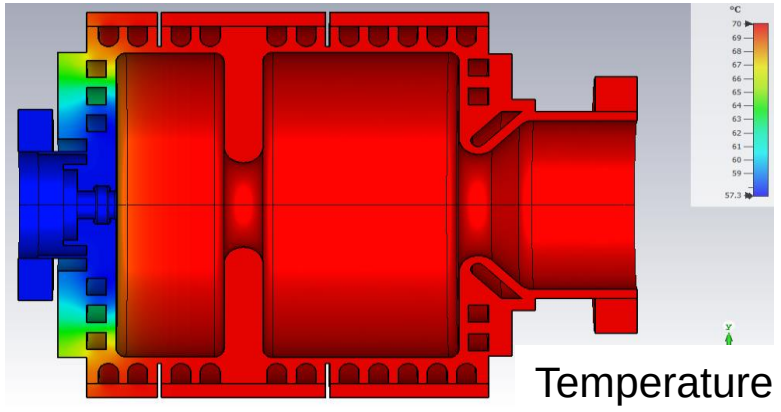
55°C cooling for rear plate

70°C cooling for the other channels

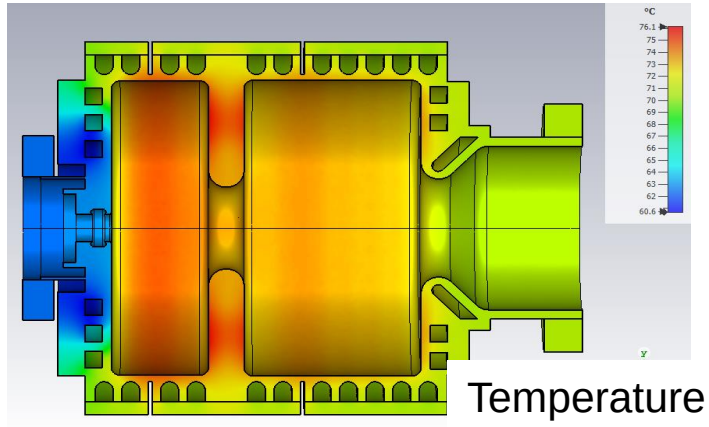
55°C

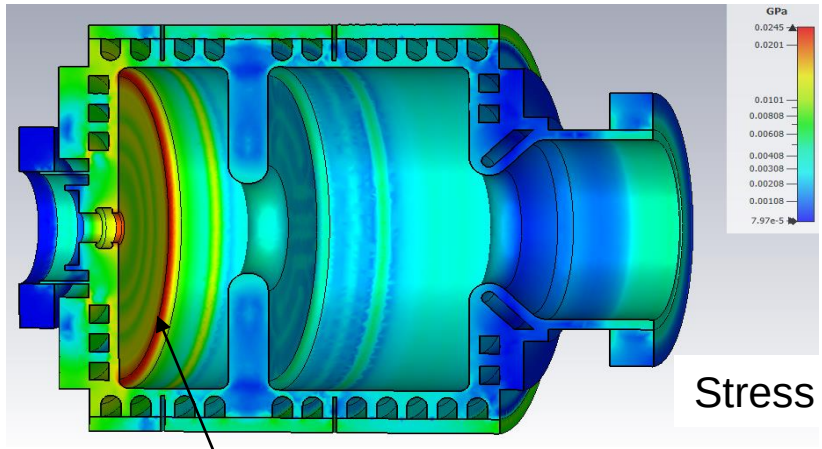


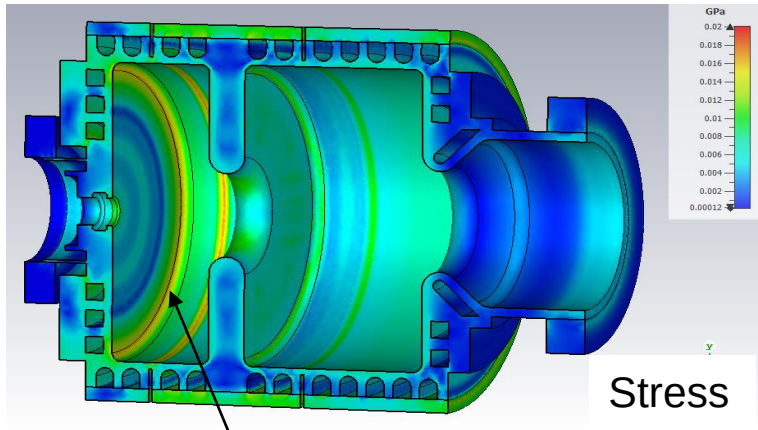
0 kW



11 kW (200us / 10Hz / 60MV/m)







Frequency sensitivity due to backplane water T : -0.67 kHz/°C

Stress is within the safe limit of the material.

Lower cooling temperature for backplane

27°C and 55°C water cooling for backplane, 70°C for rest cooling channels, heat load 11kW

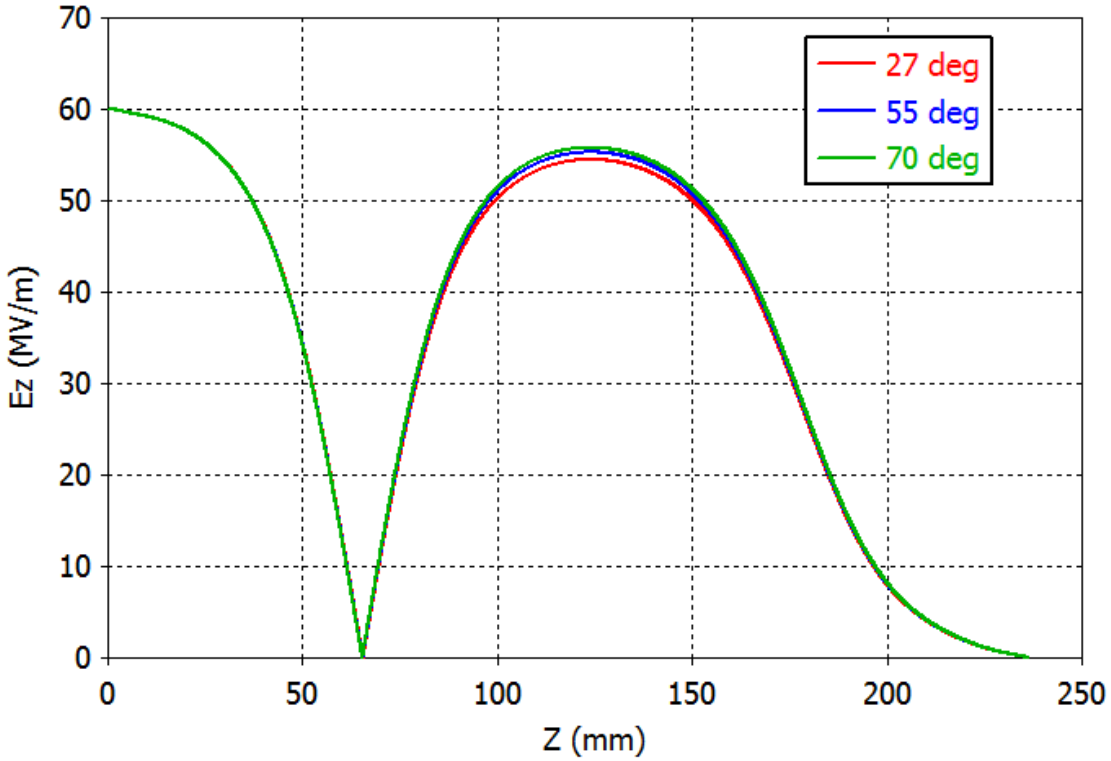
	All channels 70°C, 11kW	Backplane 27°C, 11 kW	Backplane 27°C, 0 kW	Backplane 55°C, 11 kW	Backplane 55°C, 0 kW
Max. T (°C)	76.1	76.1	70.0	76.1	70.0
Plug T(°C)	70.1	40.1	32.9	60.6	57.3
Max. defor. (mm)	0.284	0.252	0.237	0.271	0.261
Max. stress (MPa)	14.6	57.1	**75.1**	20.0	24.5
Freq. deviation from 1.3GHz (kHz)	0	+29	~	+12	~

- Lower water T is effective to reduce copper backplane T and plug T
- Backplane T ↓, temperature gradient ↑, stress ↑.
  - 27°C, peak stress = 75.1 MPa @ 0 RF power (yield limit for annealed Cu is **62** MPa)
  - 40°C, peak stress = 50 MPa @ 0 RF power, 40~50°C can be a safe working point
- With water T changing from 70°C to 27°C (55°C), cavity frequency increases by 29 kHz (12 kHz). The wall T for rest part must be increased to tune frequency back.

Field balance and coupling factor

- CST MPhysics Studio can not give the RF field map of the deformed cavity.
- 27°C backplane cooling
  - Half cell volume ↓, freq ↑ 29 kHz
  - Full cell volume ↑ to tune freq back to 1.3 GHz
  - In the RF simulations, the half cell radius is reduced by 5 um to introduce a + 29 kHz detuning and the full cell radius is increased by 3 um to compensate it.

	27°C	55°C	70°C
Field balance	1.102	1.086	1.075
Coupling factor	0.98	0.99	1



Conclusion

- RF heating effect on gun 4.2 frequency detuning was studied
  - CST vs. ANSYS, consistent
  - Simulation: -6.4 ~ -5.1 kHz/kW due to different constraint conditions
  - Measurement: -9.1~-6.3 kHz/kW due to various power calibration methods

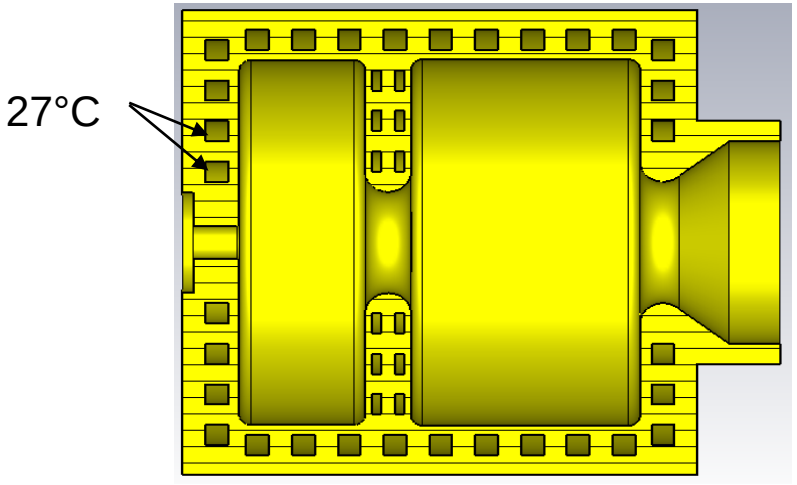
- Operation for green cathode in gun 4.2 was simulated
  - 27°C cooling, harmful for cavity with RF off, stress > yield strength limit.
  - 55°C cooling, everything is fine, hardware implementation might be an issue.
  - Water T around 40°C~50°C is suggested (plug T < 55°C and stress is safe).
  - Freq. sensitivity of backplane cooling is -0.67 kHz/°C.
  - Field balance and coupling factor are not significantly influenced by 27°C or 55°C water.

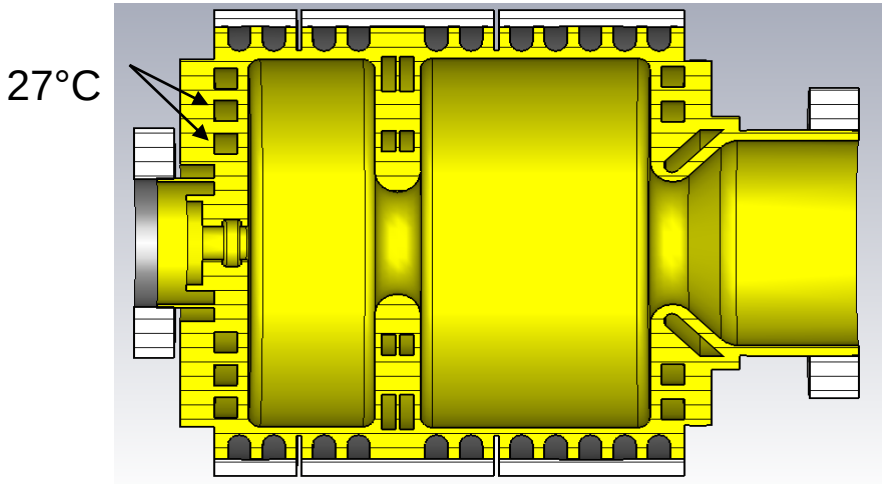
Outlook

- Higher power region might be helpful to reduce water sensor error effect (keep SP=60, increase pulse from 200us to 400us).

Backup slide

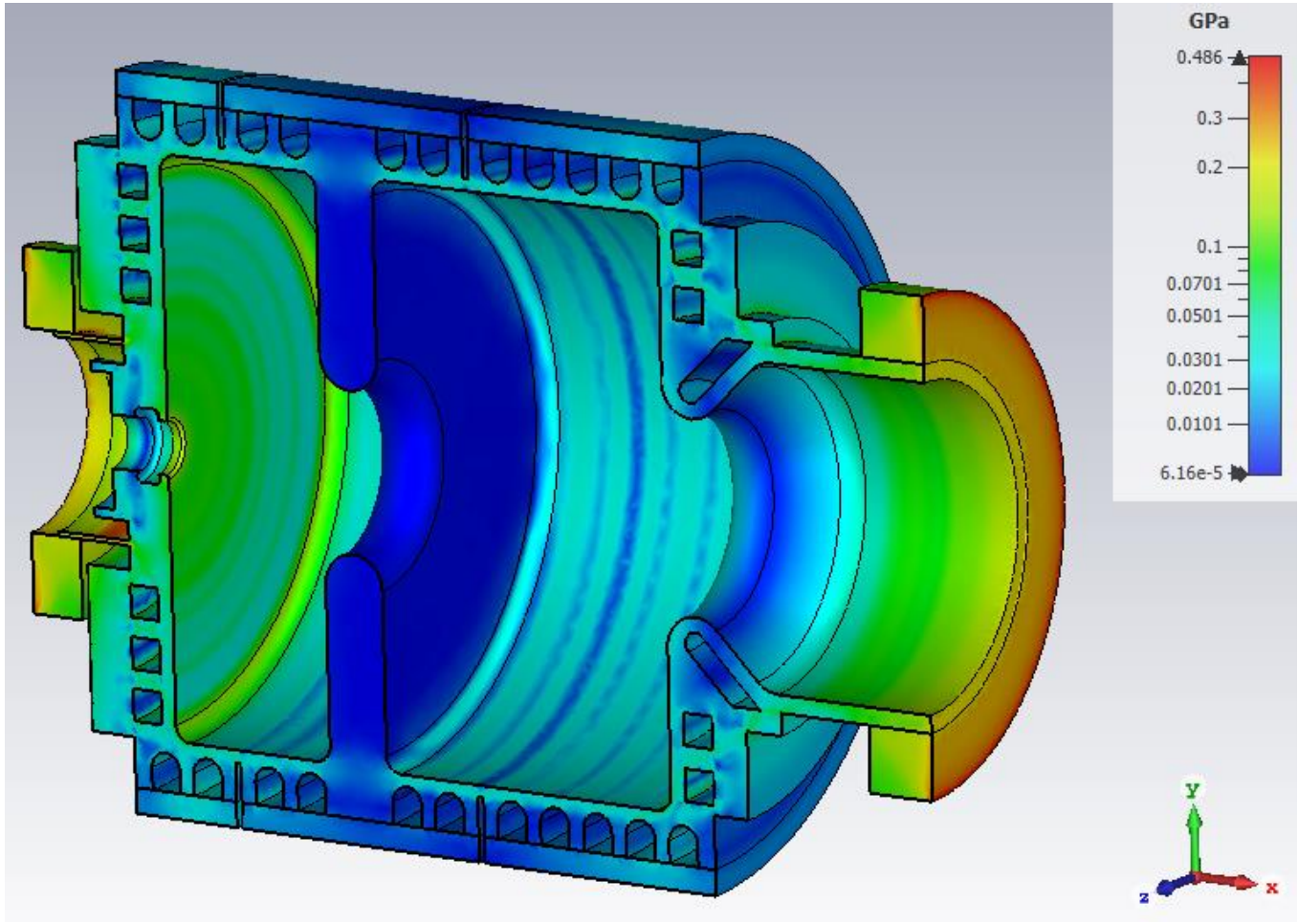
Previous model vs. current model





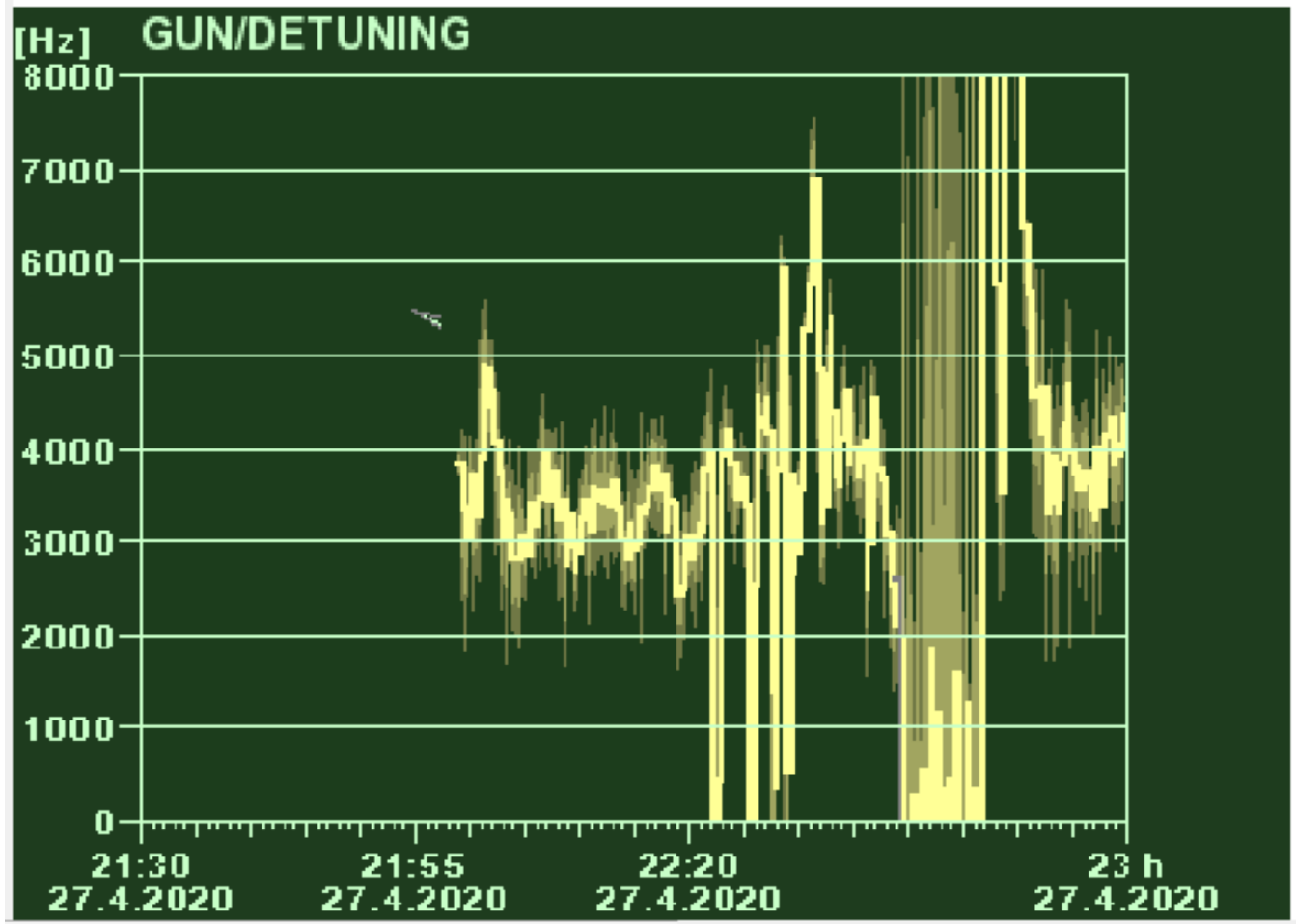
	Previous model		Current model	
	Backplane 27°C, 11 kW	Backplane 27°C, 0 kW	Backplane 27°C, 11 kW	Backplane 27°C, 0 kW
Max. T (°C)	76.7	70.0	76.1	70.0
Plug T(°C)	38.6	34.9	40.1	32.9
Max. defor. (mm)	0.218	0.205	0.252	0.237
Max. stress (MPa)	50.0	53.2	57.1	**75.1**

Longitudinally fixed, stress distribution



- Extremely large stress exists at the fixed area due to the strong boundary condition.
- The gun can not be longitudinal fixed in reality. A proper boundary which is closer to reality should be found in simulation.

Frequency vibration during test



Frequency vibration is ~2kHz (~0.1 °C water detuning). It may has an influence on sensor measurement