Multiphysics benchmark simulations of an L band RF gun

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Outline

- Motivation
- Numerical simulations
  - ANSYS and CST simulations with empirical heat convection factor
  - ANSYS CFX simulations with dynamic heat convection factor
- Measurement
  - RF properties of gun 42 cavity
  - Frequency vs. average RF heating
- Conclusion

Motivation

- RF heating effect on a cavity
  - Deformation → frequency shift → online tuning range. For PITZ guns, no slide tuners, water is the only tool with limited tuning range (~22 kHz/°C).
  - Stress in steady state→ limitation on average power loss → limitation on RF duty factor, compromise between peak RF field and pulse length.
  - If stress exceeds material yield strength threshold permanent cavity deformation leaves. Surface damage such as micro cracks might occur due to cavity cyclic fatigue.

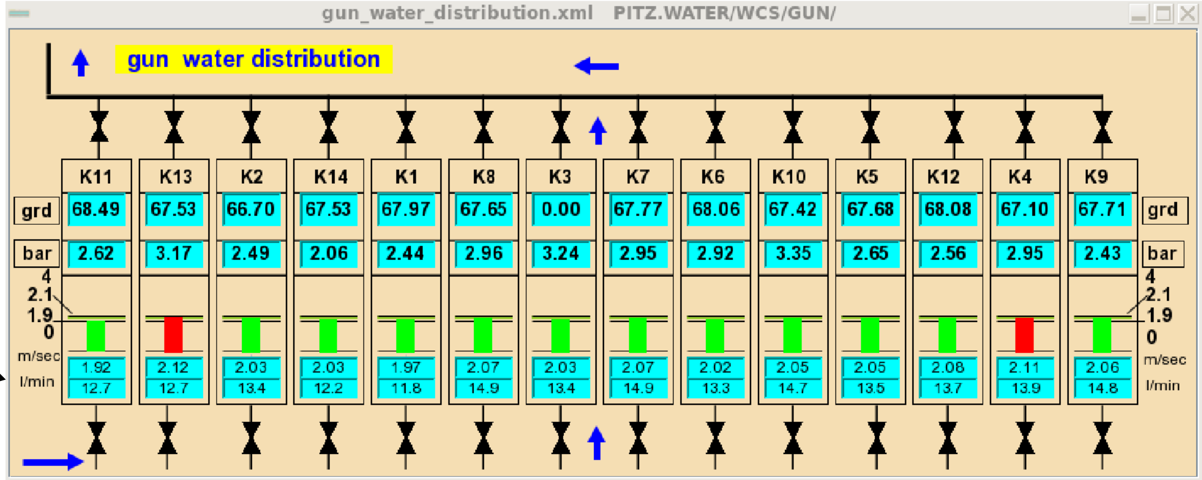
- How to estimate RF heating effect?
  - Cavity deformation is in sub-mm scale which is hard to be measured.
  - Cavity stress is impossible to measured as well.
  - Simulation seems the only way to estimate RF heating effect. Correct procedures and boundary conditions are important.
  - Relationship between RF heating and cavity frequency detuning is the only parameter which can be measured. This gives a chance to compare simulations with measurements → benchmark simulations are necessary for heavy heating load cavities, e.g. PITZ guns and NC CW guns.

RF-thermal-structure-RF coupled simulations

Multiphysics simulations

Heat exchange between water and cavity is the key point in thermal simulations

- Two options to calculate heat convection coefficient
  - Empirical equation
    - Water velocity and pipe → turbulent regime
    - Water temperature → physical properties
    - Uniform convection distribution, heat exchange of the interface between cavity and water surface is considered
    - CST and ANSYS is available for thermal simulations
    - Widely used in RF cavity design, e.g. APEX gun, RFQ etc.
  - Fluid dynamics simulation
    - Flow rate of each cooling channel can be applied as a boundary condition, much closer to real situation
    - Non-uniform convection distribution, heat exchange is considered not only at the metal-water surface but also in the internal water channel.
    - ANSYS CFX / Fluent is available for thermal simulations
    - Time consuming to reach convergence
    - Adopted in PITZ gun 5 and Daresbury CLARA gun mechanical design

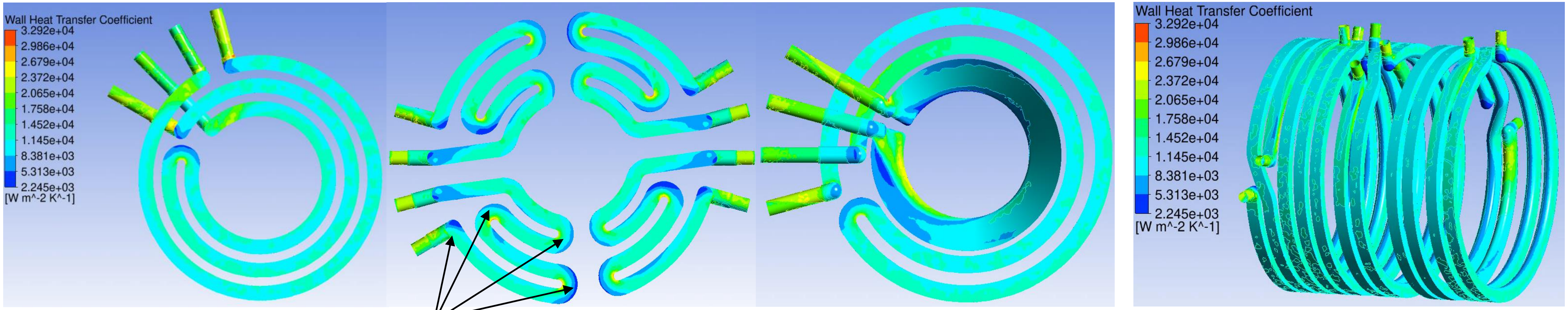


14 independent water input channels which allow a detailed control and monitoring of the water flow rate in the different parts of the cavity cooling.

Fluid dynamics simulations by ANSYS

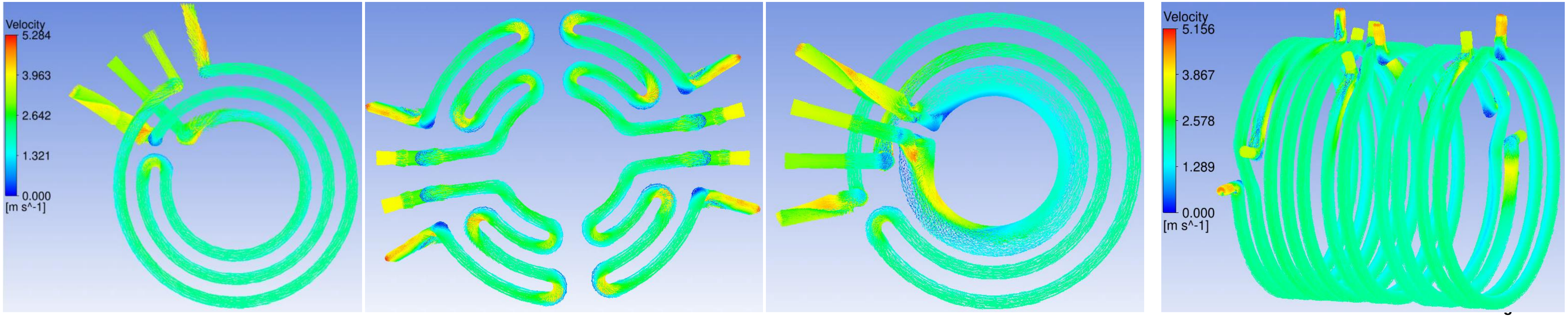
Adopt the same water flow with operation

Heat convection distribution



Cathode plate | **low velocity, low convection Optimized in gun 5** | Iris | Front plate | Cylindrical wall

Water velocity



Comparison between different convection calculation methods

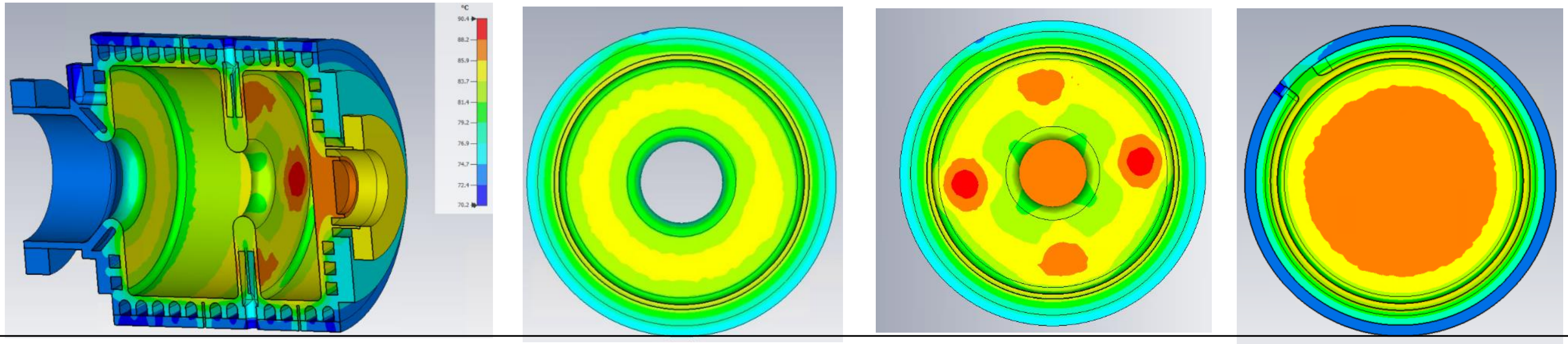
	Cooling channel	Water flow in operation (L/min)	Empirical convection (W/m2/°C)	Average of surface dynamic convection in ANSYS CFX (W/m2/°C)	Ratio (Empirical / average dynamic)
Front plate channel	K1	12.04	12676	11924	1.06
	K2	14.22	10806	11582	0.93
Full cell channel	K3	13.4	12391	11063	1.12
	K4	13.92	12775	11750	1.09
	K5	13.54	12495	11167	1.12
	K6	13.34	12347	11018	1.12
Iris channel	K7	14.96	13557	11589	1.17
	K8	14.96	13557	11530	1.18
	K9	14.86	13484	11523	1.17
	K10	14.76	13412	11394	1.18
Half cell channel	K11	12.7	11871	10558	1.12
	K12	13.76	12657	11358	1.11
Cathode plate channel	K13	12.72	13007	12544	1.04
	K14	12.26	12629	12143	1.04

Comparison between various codes, temperature distribution

40 kW heating load, 70°C cooling water

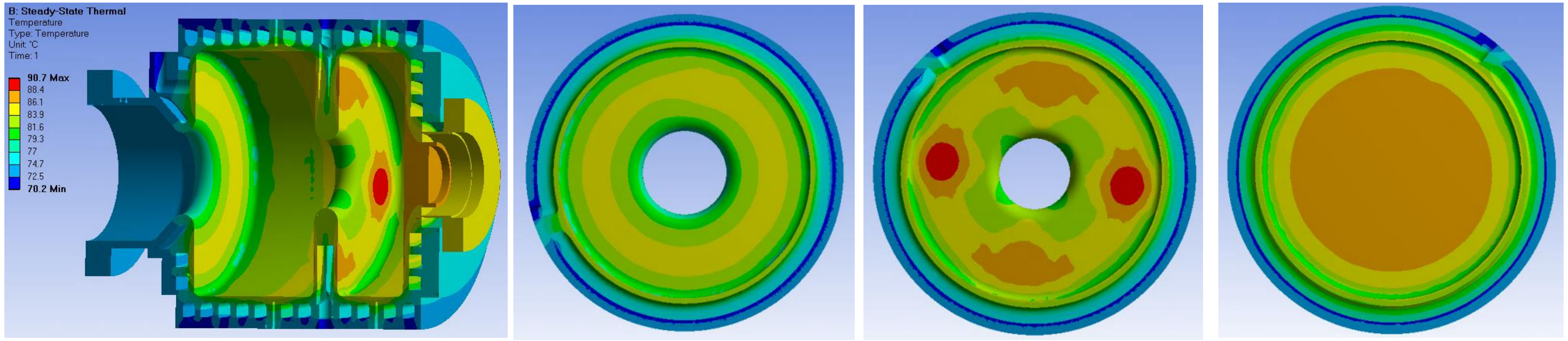
CST + empirical convection

T range : 70.2~90.4°C



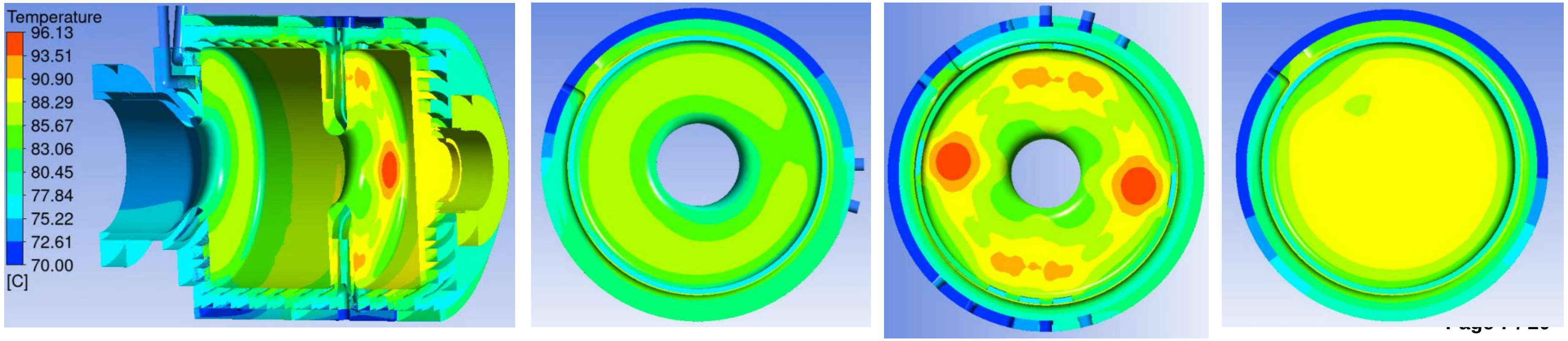
ANSYS + empirical convection

T range : 70.2~90.7°C



ANSYS + dynamic convection

T range : 70.0~96.1°C

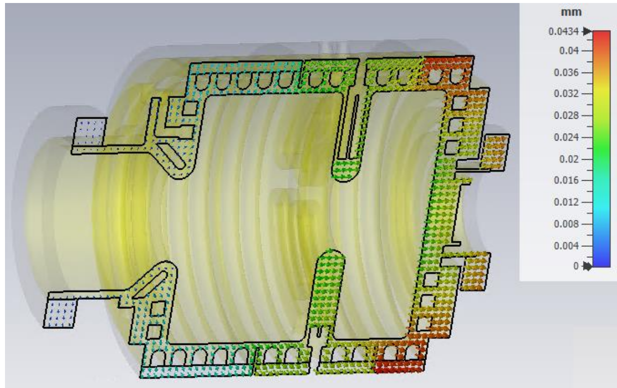


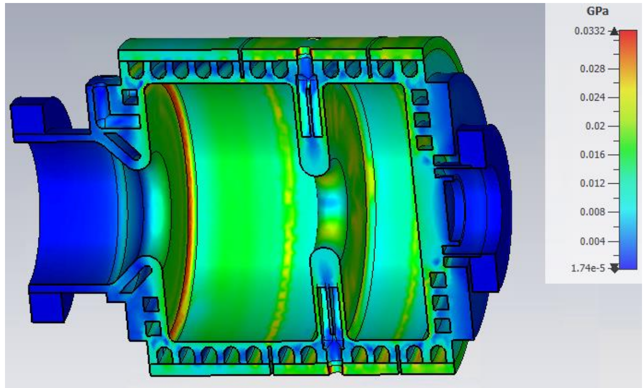
Comparison between various codes, deformation and stress distribution

40 kW heating load, 70°C cooling water

CST + empirical convection

- Max. deform = 38.1 um
- Max. von-Mises stress = 34.8 MPa



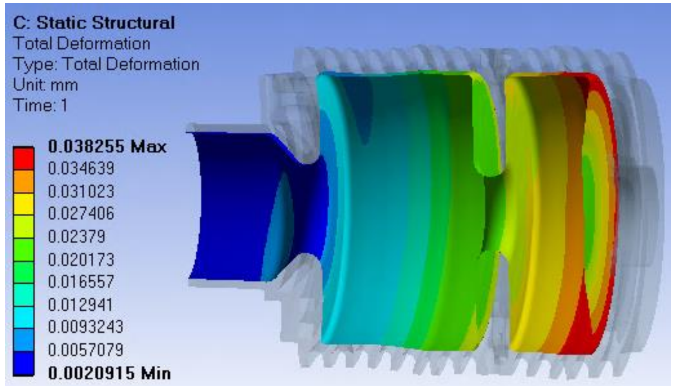


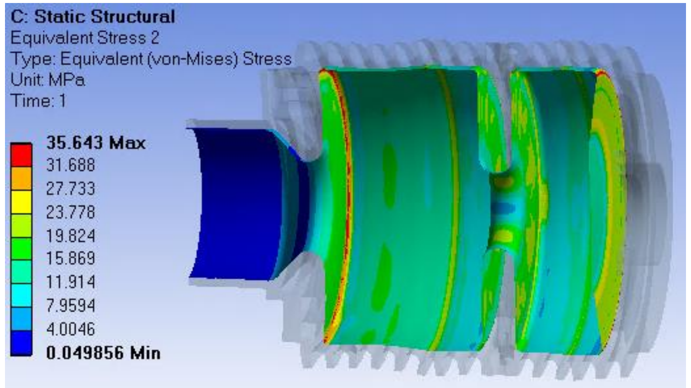
A fixed support locates at coupler WG, a bellow locates at right flange.

Boundary conditions: Longitudinally fixed at left flange. Rest part free.

ANSYS + empirical convection

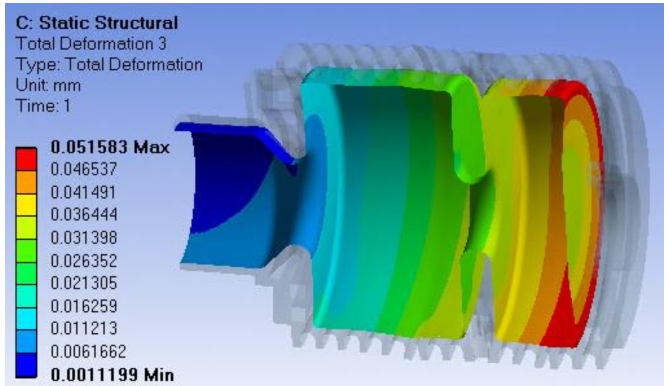
- Max. deform = 38.2 um
- Max. von-Mises stress = 35.6 MPa

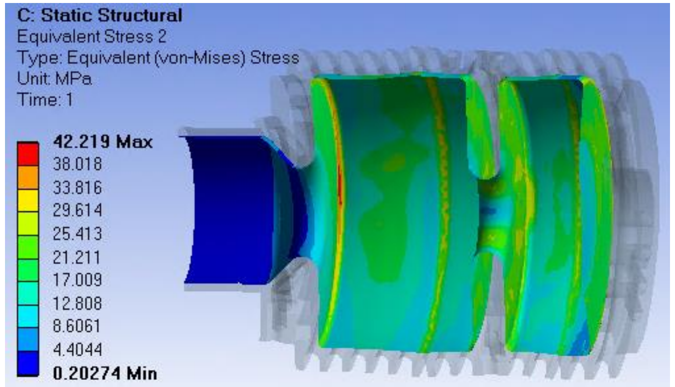




ANSYS + dynamic convection

- Max. deform = 51.6 um
- Max. von-Mises stress = 42.2 MPa

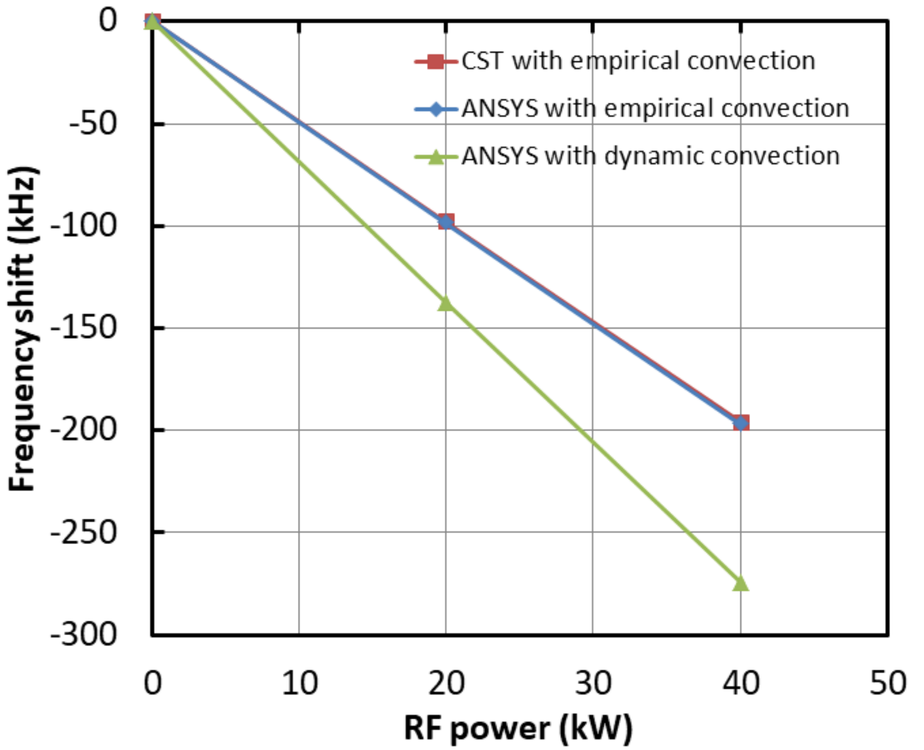




Comparison between various codes

40 kW heating load, 70°C cooling water

	CST with empirical convection	ANSYS with empirical convection	ANSYS with dynamic convection
T range (°C)	70.2-90.4	70.2-90.7	70.0-96.1
Ave. Cu body T(°C)	78.31	78.36	81.74
Ave. inner surface deform (um)	19.7	19.1	28.6
Ave. inner surface deform_z (um)	16.8	15.7	23.7
Ave. inner surface deform_r (um)	~	9.3	14.1
Peak von-Mises stress (MPa)	34.82	35.6	42.2
Freq. shift due to RF heating (kHz)	-196.0	-197.0	-274.5
Freq. sensitivity w.r.t RF heating (kHz/kW)	-4.9.	-4.9	-6.9



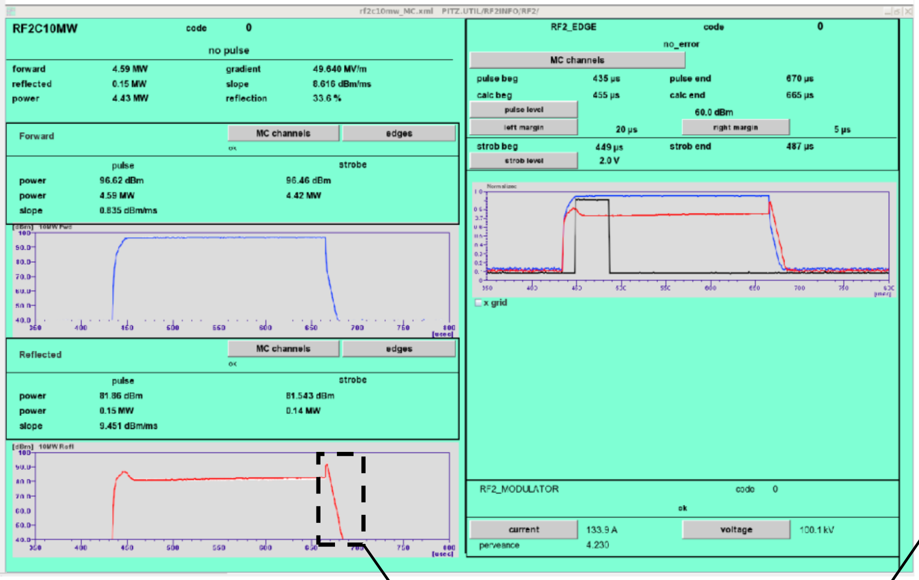
CST results are consistent with ANSYS with a same boundary conditions.

ANSYS with dynamics convection results in a 50% larger deformation and a 19% higher stress.

Measurements at PITZ

Online measurement on gun RF properties

RF signals are extracted from 10MW directional coupler



From CST simulations:
20°C Cu cavity Q0=23240
70°C Cu cavity Q0=21246

- Cavity filling time Tc

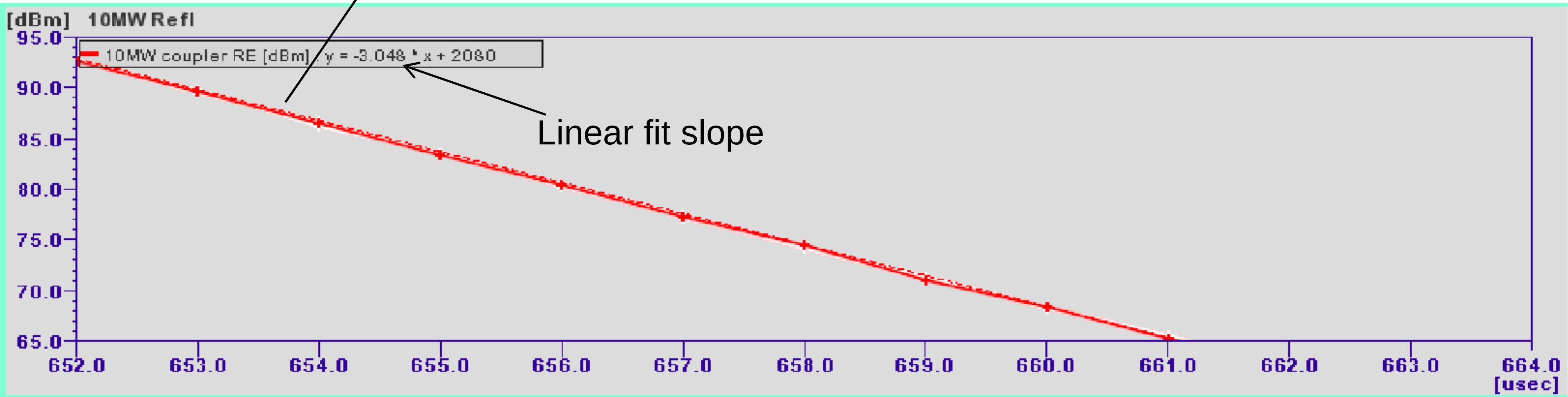
$$T_c = -\frac{20lg(e)}{slope} = 2.842\ \mu s$$

- Cavity unload Q0

$$Q_0 = \frac{T_c \times 2\pi f_0 \times (1+\beta)}{2}$$

Assume $\beta = 1 \rightarrow$ Q0 = 23214 (109% of simulation value), not reasonable.
β should smaller than 1

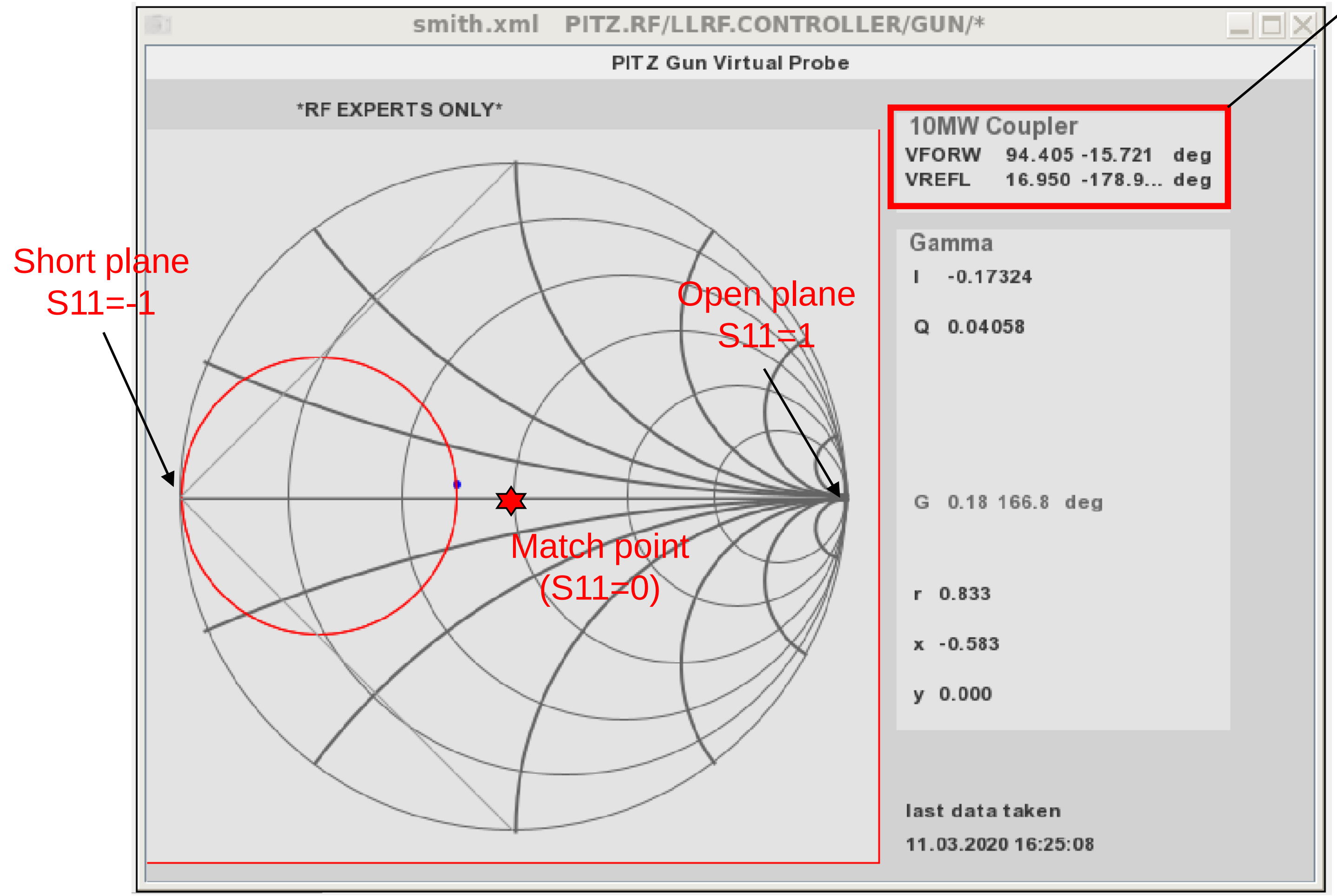
Zoom



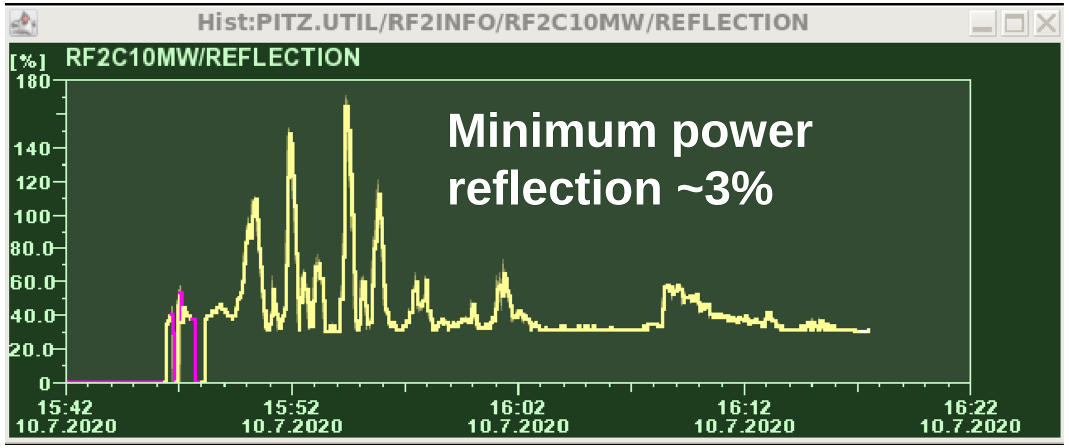
Linear fit slope

Online measurement on gun RF properties

RF signals are extracted from 10MW directional coupler



- At resonant point, $|S_{11}| = |V_{ref}|/|V_{for}| = 0.180$
- Coupling factor = 0.695
- Filling time Tc = 2.842 us, Q0=19674 (93% of simulation value, reasonable)
- Power reflection at resonance 3.2%, consistent with operation (~3%)
- Need conformation from our RF experts



Data taken at July 05,2020 Morning shift

Online measurement on gun RF properties

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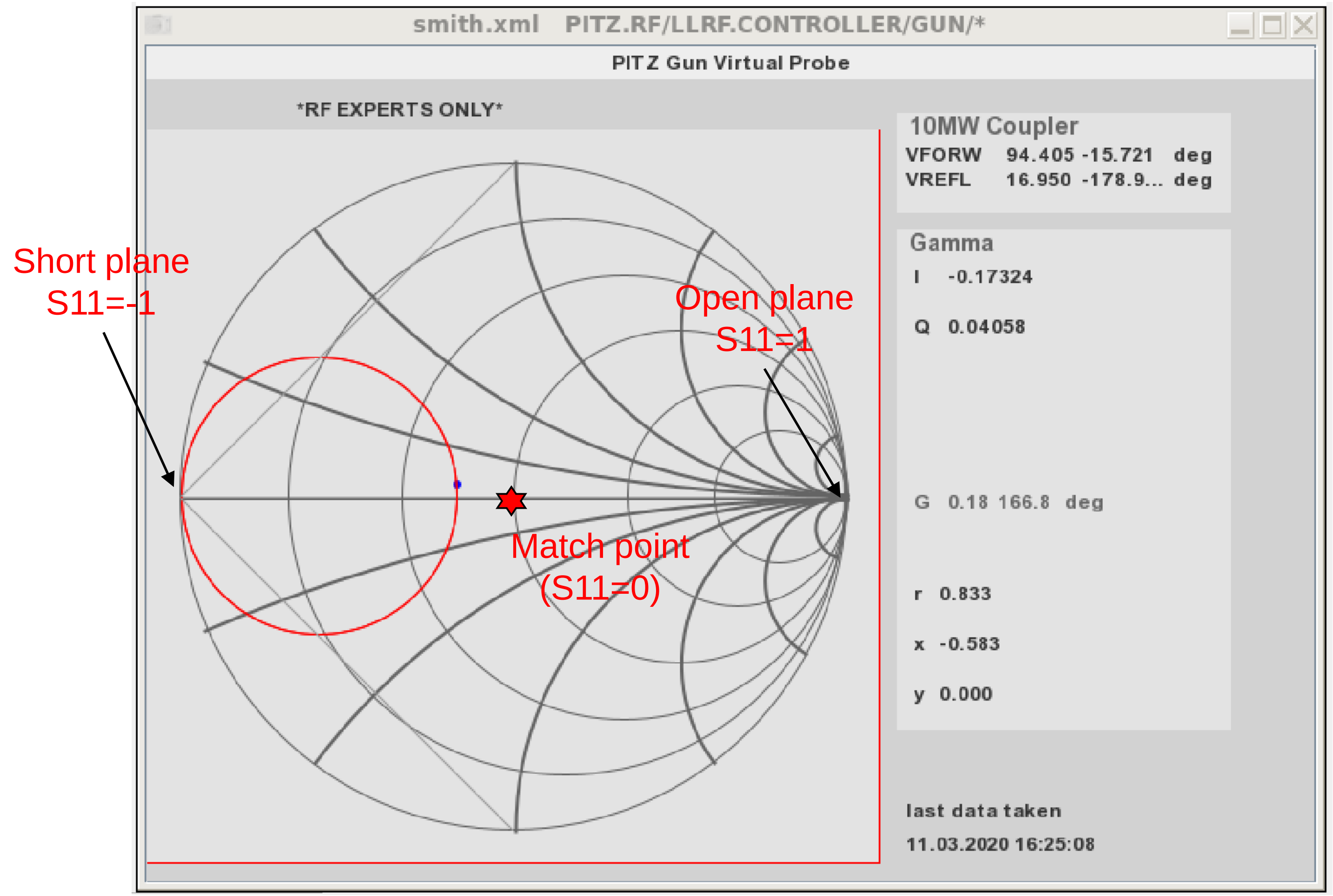
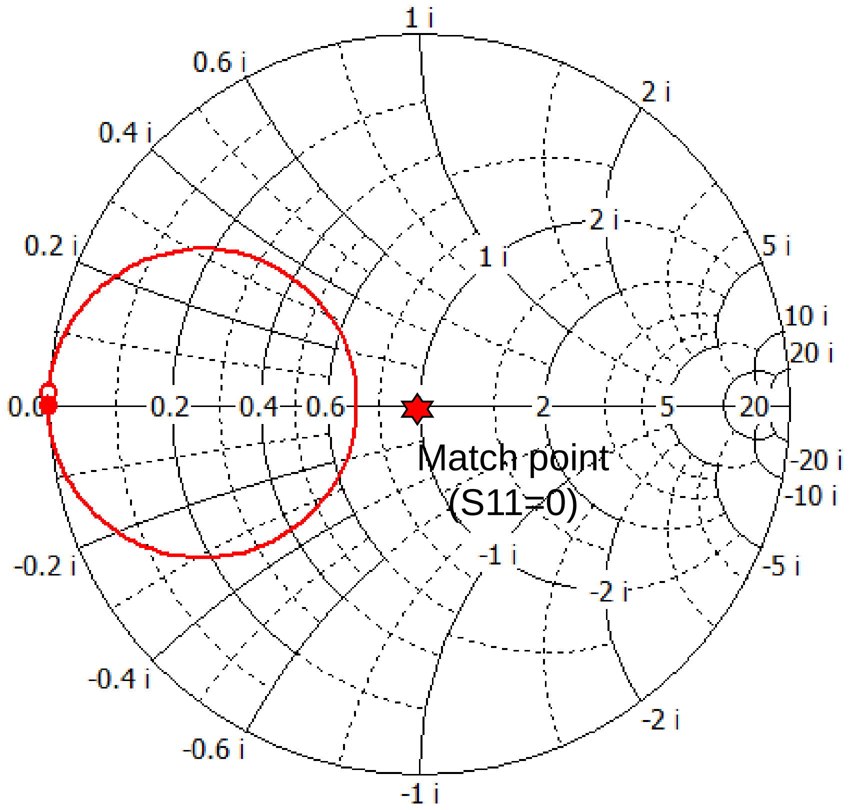


CST simulation by assuming coupling factor=0.695, Q0=19674



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Measurements on freq. vs average RF power

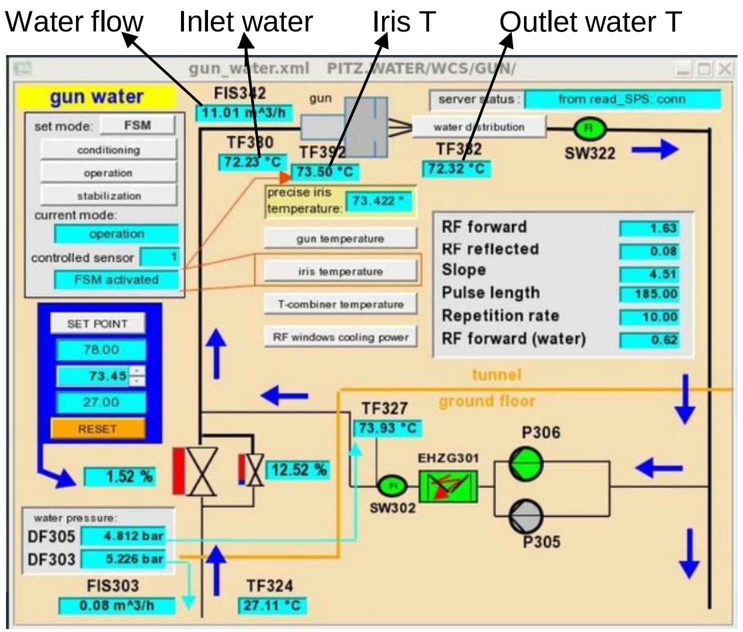
Average power loss calculated from two methods

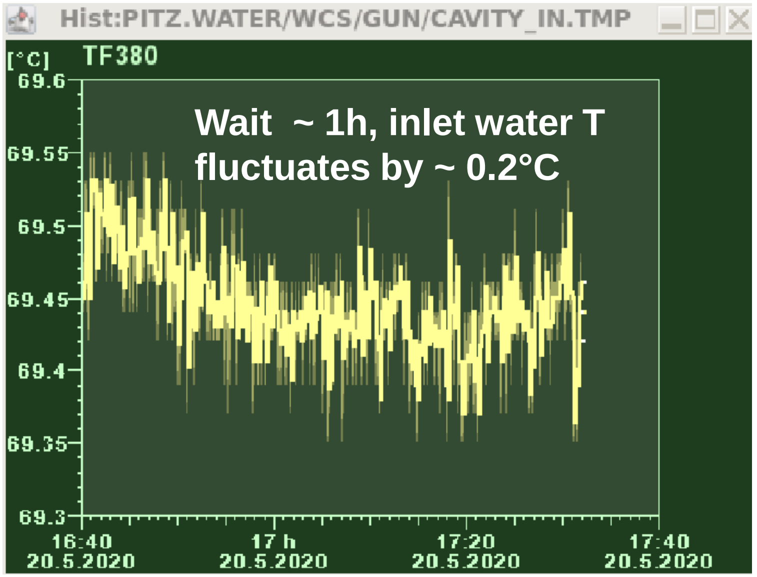
Gun SP=60, Pulse length 200-400us (step 50us)

Inlet water T
Outlet water T
Water flow

→ Average power loss

- T probe calibration is unknown
- Big T read back fluctuation is observed, e.g. 0.2°C results in a 2.7 kW power loss difference
- Can't be fully reliable, but can serve as a reference





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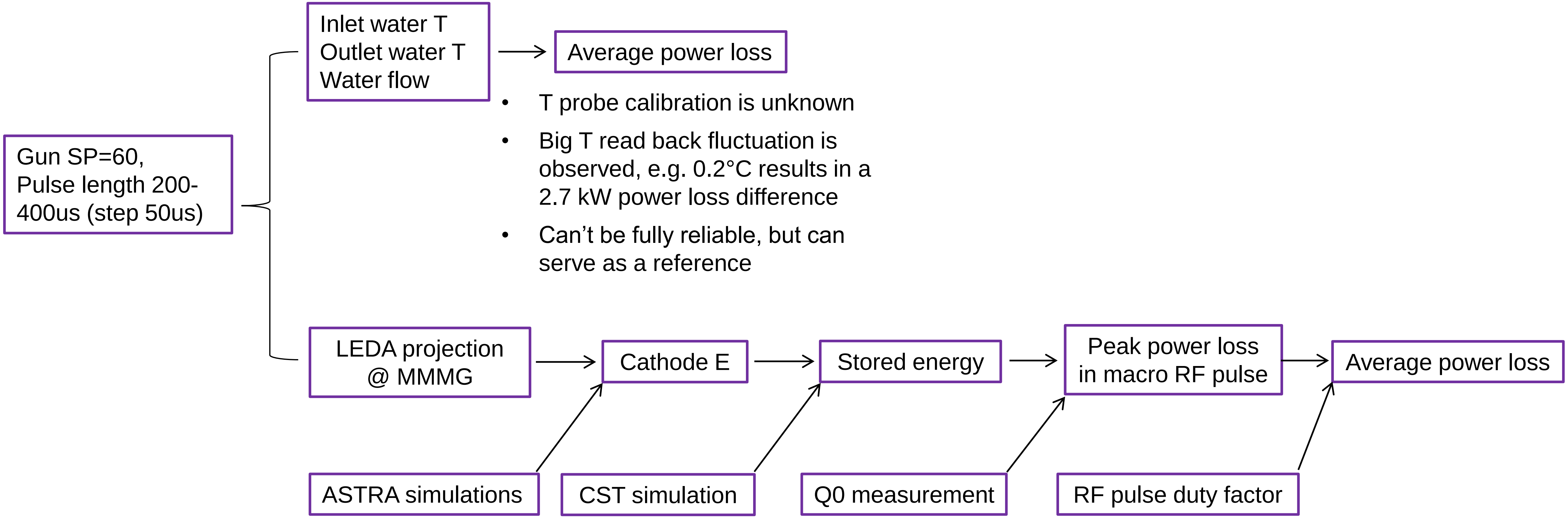
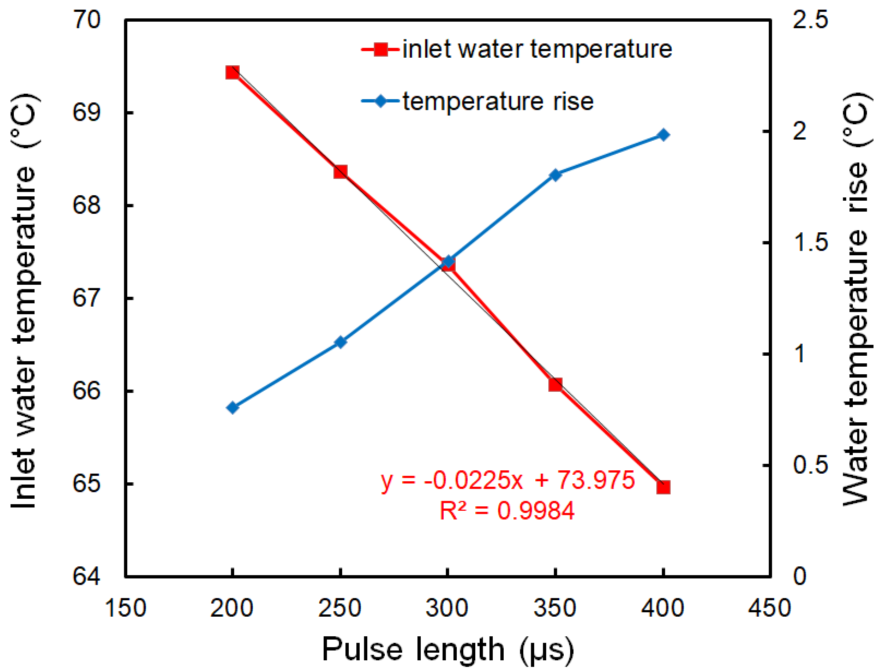


- T probe calibration is unknown
- Big T read back fluctuation is observed, e.g. 0.2°C results in a 2.7 kW power loss difference
- Can’t be fully reliable, but can serve as a reference

- The 2nd method is more reliable. Q0 measurement is the key point.

Inlet and outlet water T at various pulse length

Data taken at 20200520L, gun SP=60, mean Pz @ MMMG ~ 6.4MeV/c



- Inlet water temperature T (°C) vs. pulse length L (us)
  - T = -0.0225 * L+73.975. For L = 0 us (no RF power, vacuum condition), gun resonant at 73.975°C → predicted freq. in room temperature (20°C) and air is 1300.797 MHz.
  - Cold test of gun42 after dismount is proposed to check this.

Measurements on freq. vs average RF power

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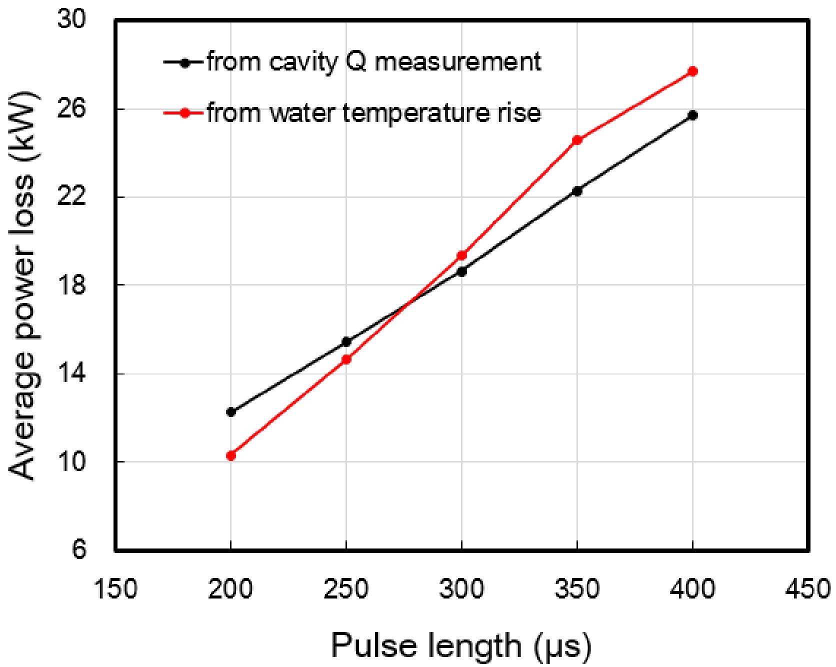
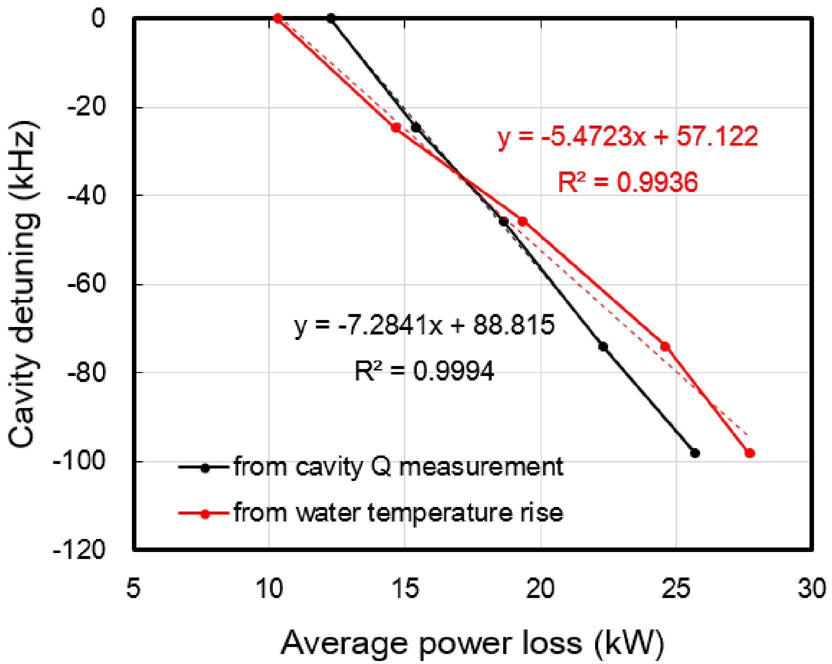


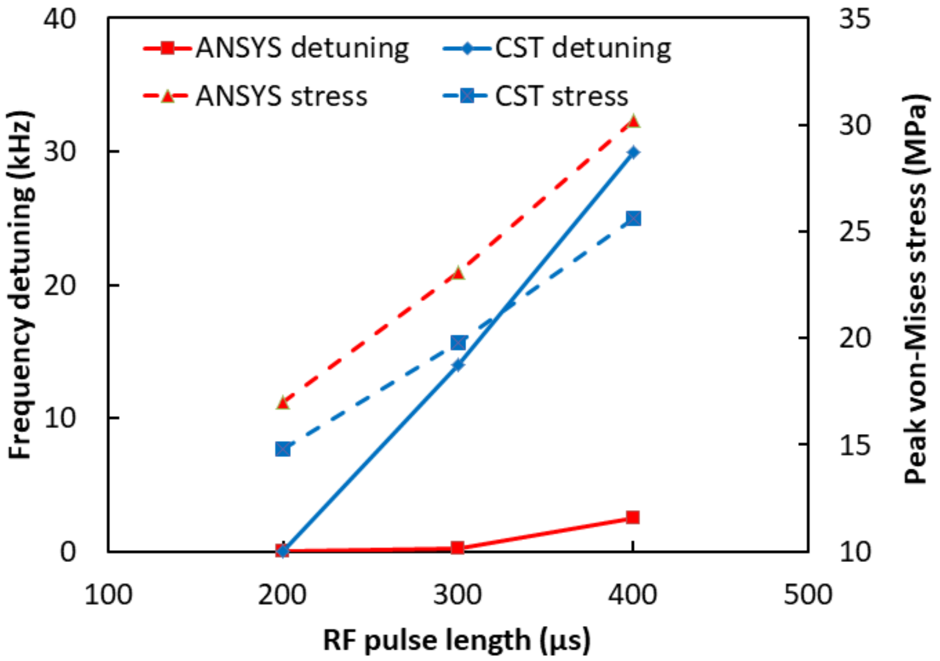


	Measurements		Simulations			
	Power calibrated by water T rise	Power calibrated by cavity Q0	CST with empirical convection	ANSYS with empirical convection	ANSYS with dynamics convection	Paramonov's ANSYS results
Freq. sensitivity (kHz/kW)	-5.5	-7.3	-4.9	-4.9	-6.9	-3.52
Max. surface T rise with 40 kW (°C)	~	~	20.4	20.7	26.1	21.7

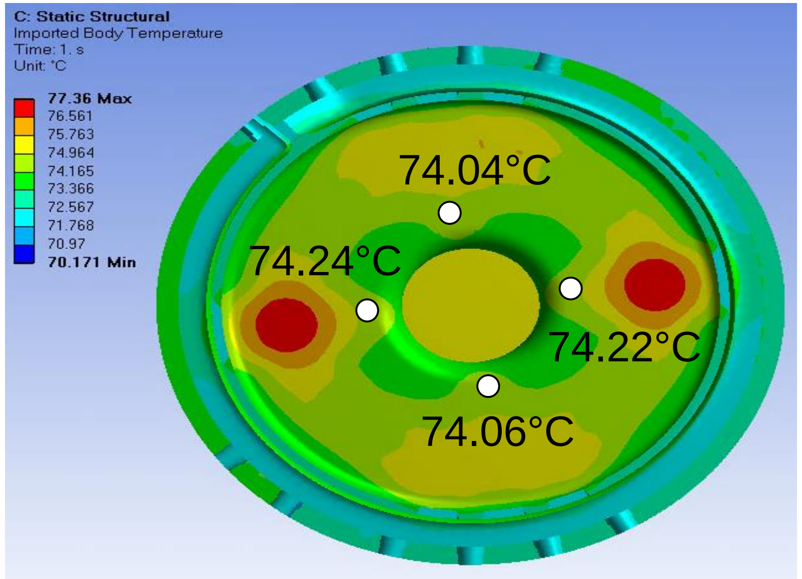
Benchmark simulation of measurements

Data taken at 20200520L, gun SP=60, mean Pz @ MMMG ~ 6.4MeV/c

	Pulse length (us)	200	300	400
Measurement conditions	Gun SP	60	60	60
	Average power (kW)	12.11	18.4	25.39
	Inlet water T (°C)	69.48	67.38	64.99
	Iris sensor (°C)	73.48	73.46	73.46
	Power reflection (%)	3.89	3.51	3.29



T distribution for 200 us case



Iris T for WCS feedback is 73.45°C in operation.

Benchmark simulation of measurements

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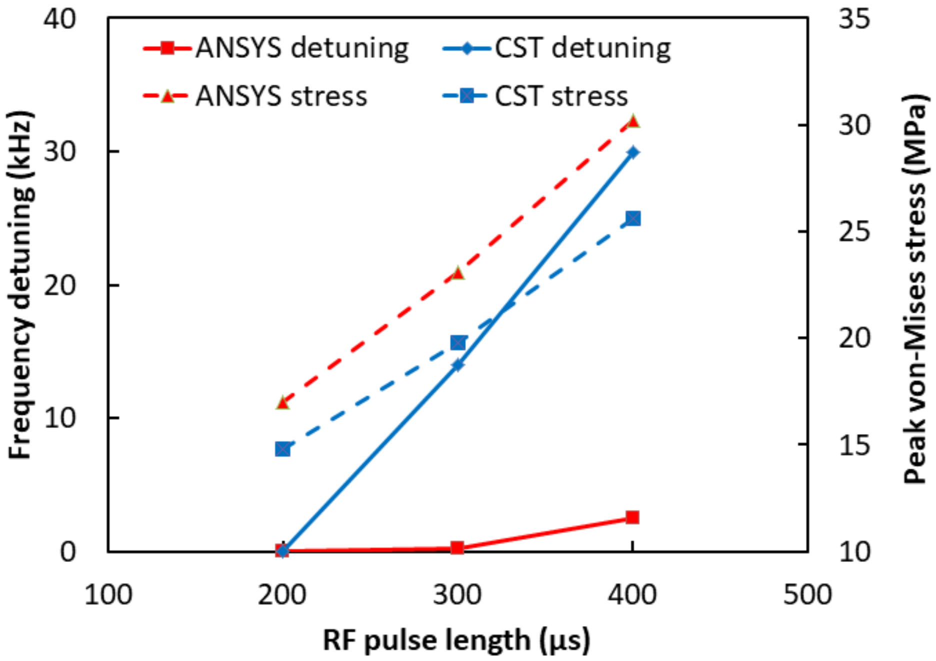

- With same cooling conditions of measurements, ANSYS simulations with dynamics convection fit better with measurements.
- With various RF pulse length, the average T of gun is almost constant to maintain the resonant frequency.
- The simulations indicate the maximum power of gun 42 can go up to ~ 50 kW (Ecath ~57 MV/m, 800 us / 10 Hz) within the soft copper yield strength threshold (62 MPa).

Conclusion

- Benchmark simulations were performed for gun 42
  - Multiphysics simulations with empirical convection underestimate RF heating induced frequency detuning and deformation. Empirical option is preferred for a quick simulation
  - Multiphysics simulations with dynamic convection fit very well with measurements
- What can be measured during gun 5 RF conditioning
  - Inlet water T vs. average power loss → cross check frequency tuning in cold test
  - Frequency detuning vs. average power loss → check simulation reliability
- Dynamic convection will be applied in the thermal simulations of CW VHF band gun
- Proposal
  - According to benchmark simulations gun 42 can goes up to ~50 kW.
  - Test gun 42 at a higher pulse length before gun 5 installation, test long pulse operation stability e.g. klystron status, MP around window and cavity, LLRF feedback etc., as a preparation for gun 5 conditioning.

Many thanks to Grygorii, Sebastian, Mikhail, Frank and Maxwell cluster team for the access to ANSYS software.