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Simulation of Convection in Water Phantom Induced by Periodic Radiation Heating

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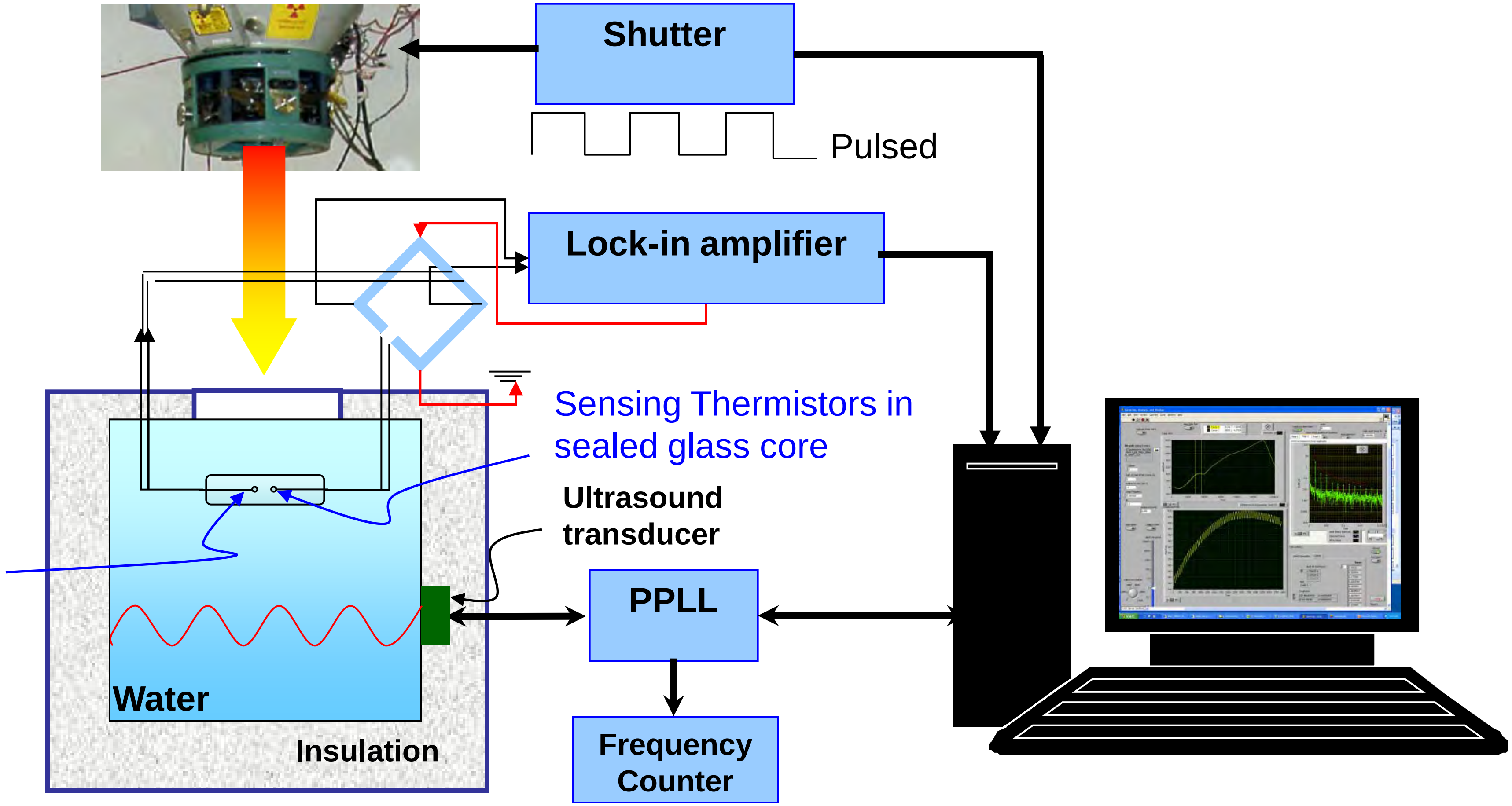
Radiation dosimetry

- Cancer therapy – MeV photons produced from clinical linear accelerator or Co-60
- Ionizing radiation breaks DNA bonds of tumor cells
- Radiation absorbed dose – 1 Gy = 1 J/kg
- Q (W/m^3) = ρ (kg/m^3) D(Gy/s)
- 1 Gy/min = 17 mGy/s → Q = 17 W/m^3
- Dose: Water calorimetry: in water, 1 Gy causes temperature rise ~0.24 mK, yielding a dosimetry primary reference standard
- Dose rate:

  1 Gy/min → $\Delta T/\Delta t = Q/(\rho C_p) = 17/(1000 x 4180) = 4\ \mu K/s$
- Precise instrument for measuring small temperature changes – sensitive thermistors wired in a Wheatstone bridge with a lock-in amplifier
- Alternative technique – ultrasonic pulsed phase lock loop (PPLL), same sensitivity, non-invasive
- Problem – convection in large phantom caused by temperature gradient due to non-uniform radiation heating

Experimental set up



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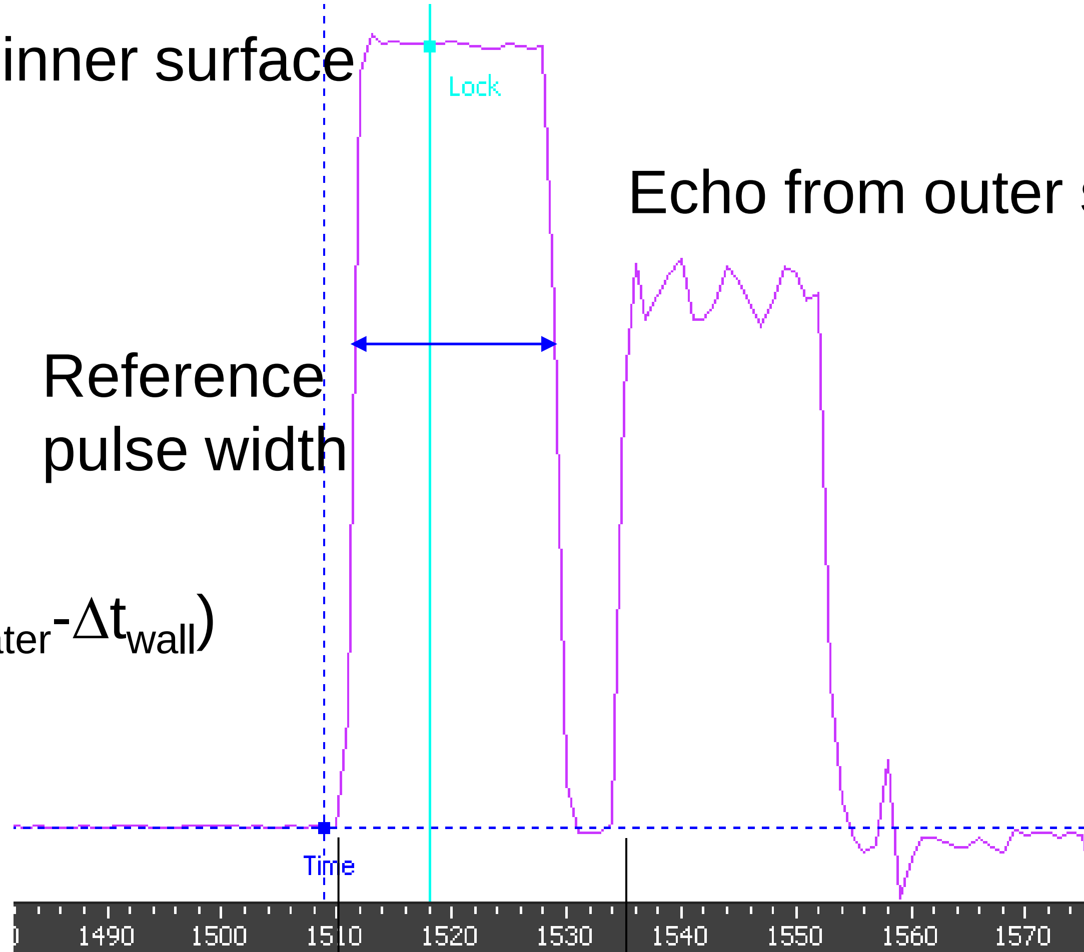
Ultrasound Thermometer Operation principles

Echo from inner surface

Echo from outer surface

Reference pulse width



$v = 2L/(\Delta t_{water} - \Delta t_{wall})$

Δt_{water}

Δt_{wall}

t (in units of $T_0 = 1/f_0$, 5 MHz → 0.2 us)

Calibration and noise issues

- Δf, deviation from f_0, linearly proportional to Δv
- $v = v_0 + a(T-T_0) + b(T-T_0)^2$
- $\Delta T = \alpha(f,T)\Delta f$
- α -- experimentally calibrated ~ 95.5 μK/Hz
- f_0 = 5 MHz at 20 ˚C
- v = 1482 m/s
- f can be resolved to 0.01 Hz or better, ΔT ~ μK.
- A root-mean-square (RMS) noise of 3.2 μK 30x30x30 cm^3 water tank
- averaging over 400 s
- sampling rate of ~ 1 per second

Typical operation parameters

f_0 Ultrasound detection frequency	5×10^6	Hz
T_0 Ultrasound period	0.2	μs
L Nominal length of ultrasound path	30	cm
Δt Time delay for a round trip in the water tank	240	μs
Reference pulse rate	6000	Hz
Reference pulse width (number of cycles at T_0 period)	18	
Number of “sample and hold” cycles	13	

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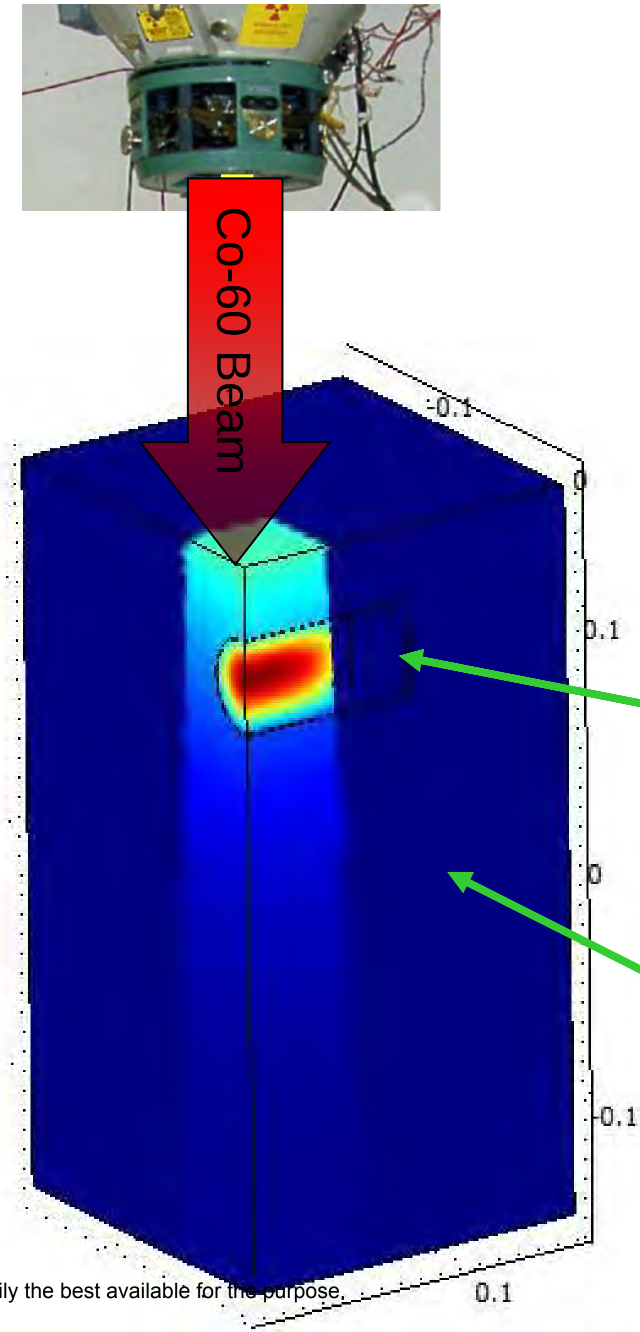
“standard” thermistor-based water calorimetry



Convection less of a problem in thermistor-vessel based water calorimeters, though other labs have gone to 4 C operation to shut off convection altogether.

Glass vessel
Containing high purity water
Convection barrier

Outside water stirred

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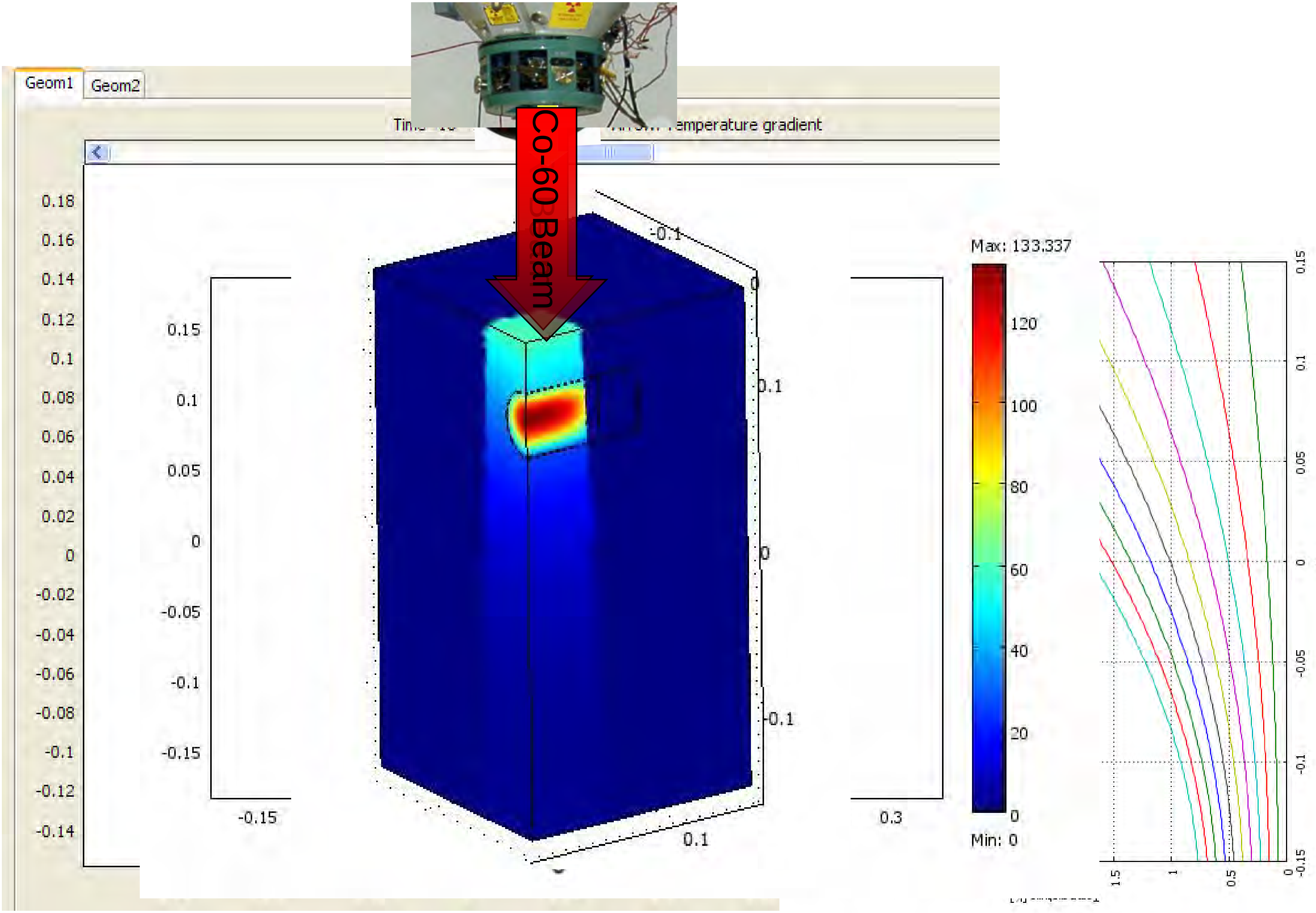

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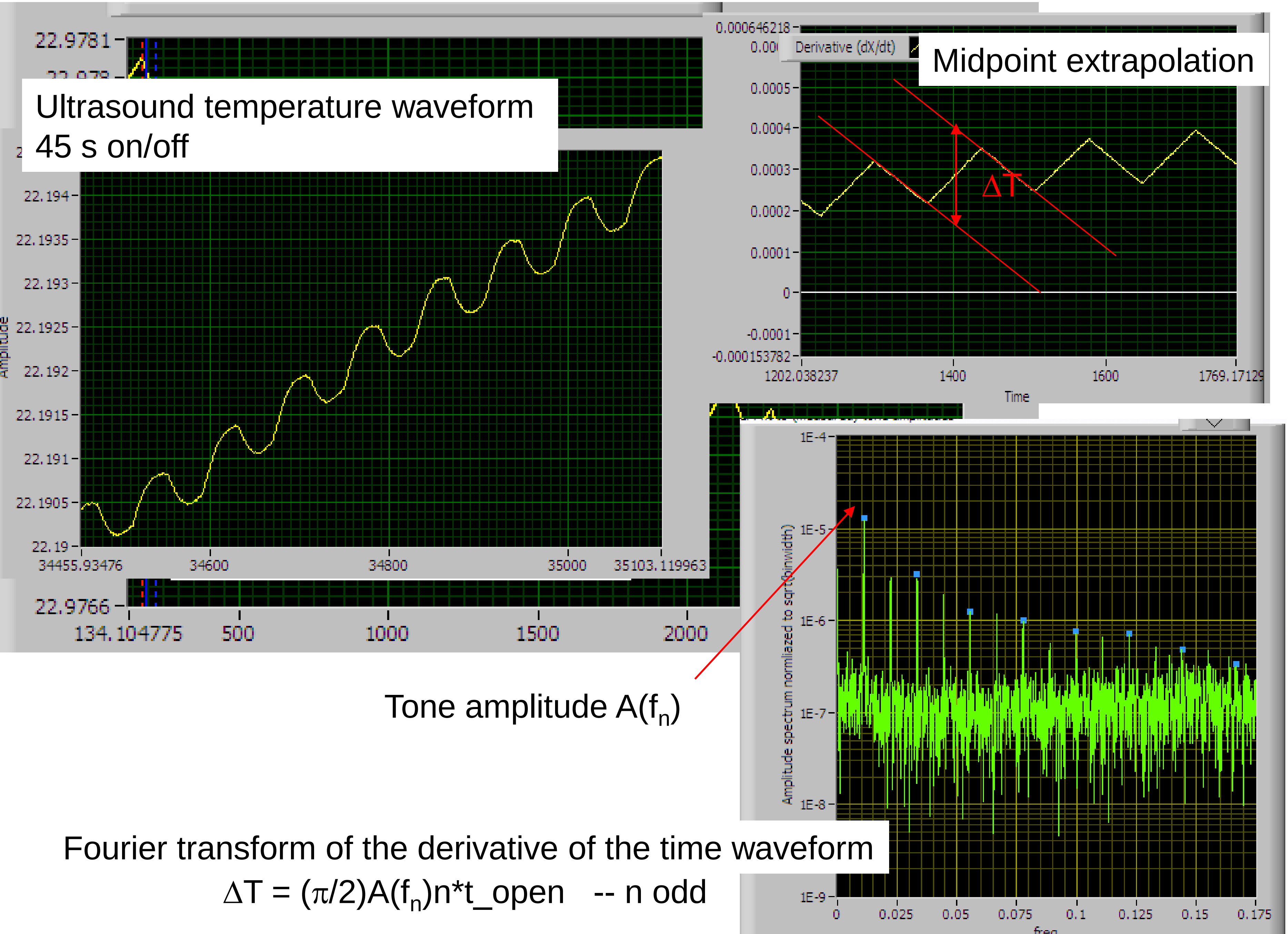
Ultrasound temperature waveform
45 s on/off

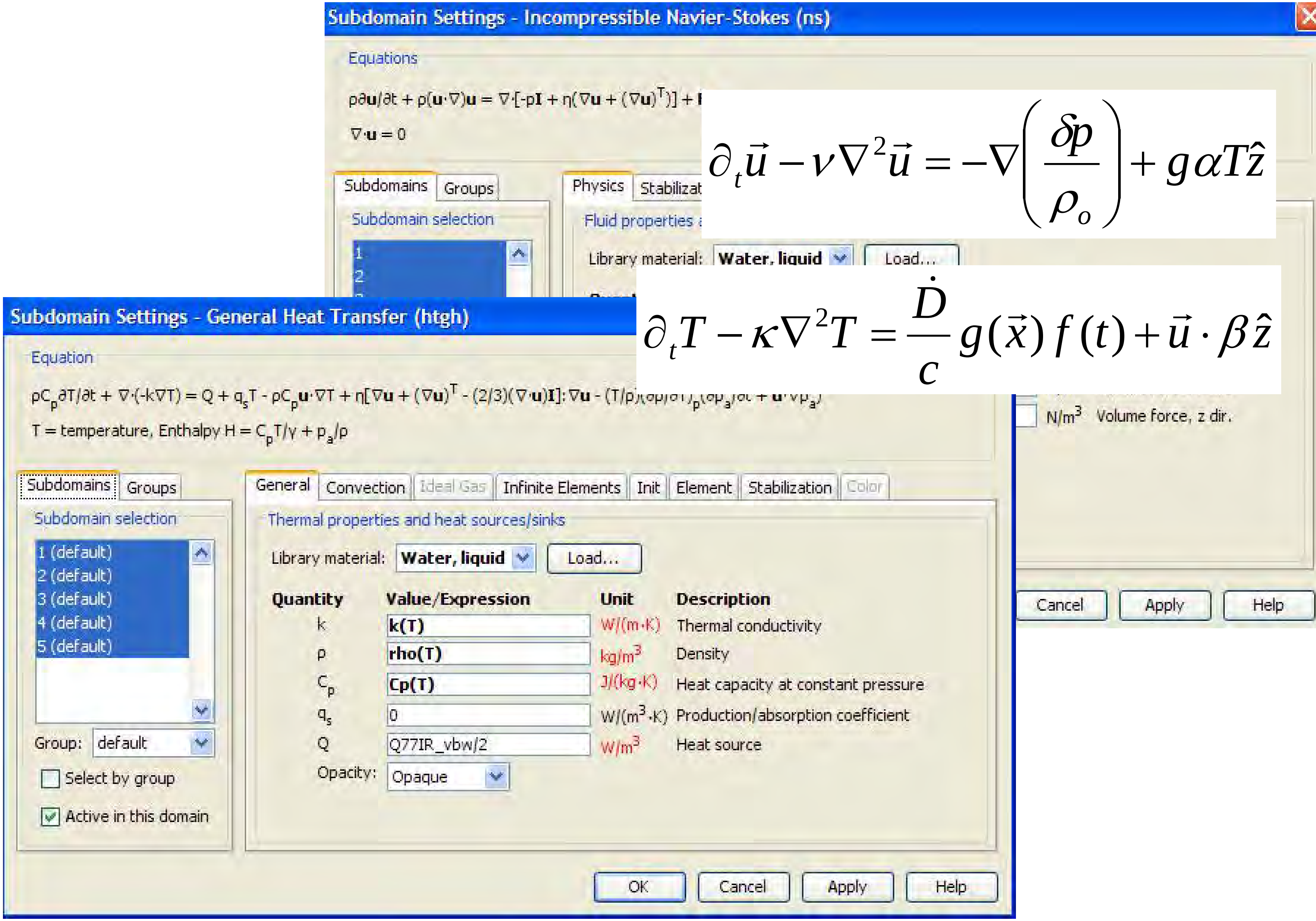
Midpoint extrapolation



Tone amplitude $A(f_n)$

Fourier transform of the derivative of the time waveform

$\Delta T = (\pi/2)A(f_n)n^*t\_open$ -- n odd



$$\partial_t \vec{u} - \nu \nabla^2 \vec{u} = -\nabla\left(\frac{\delta p}{\rho_o}\right) + g\alpha T\hat{z}$$

$$\partial_t T - \kappa \nabla^2 T = \frac{\dot{D}}{c} g(\vec{x}) f(t) + \vec{u}\cdot\beta\hat{z}$$

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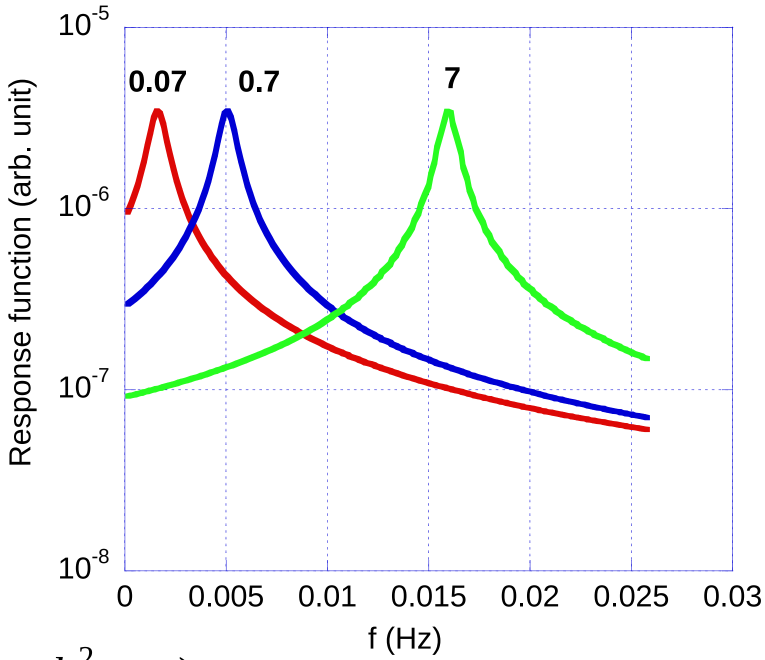
Response function of a system with a natural oscillation frequency f0

Lorentzian function

$$f(x;x_0,\gamma) = \frac{1}{\pi\gamma\left[1+\left(\frac{x-x_0}{\gamma}\right)^2\right]}$$

$$= \frac{1}{\pi}\left[\frac{\gamma}{(x-x_0)^2+\gamma^2}\right]$$

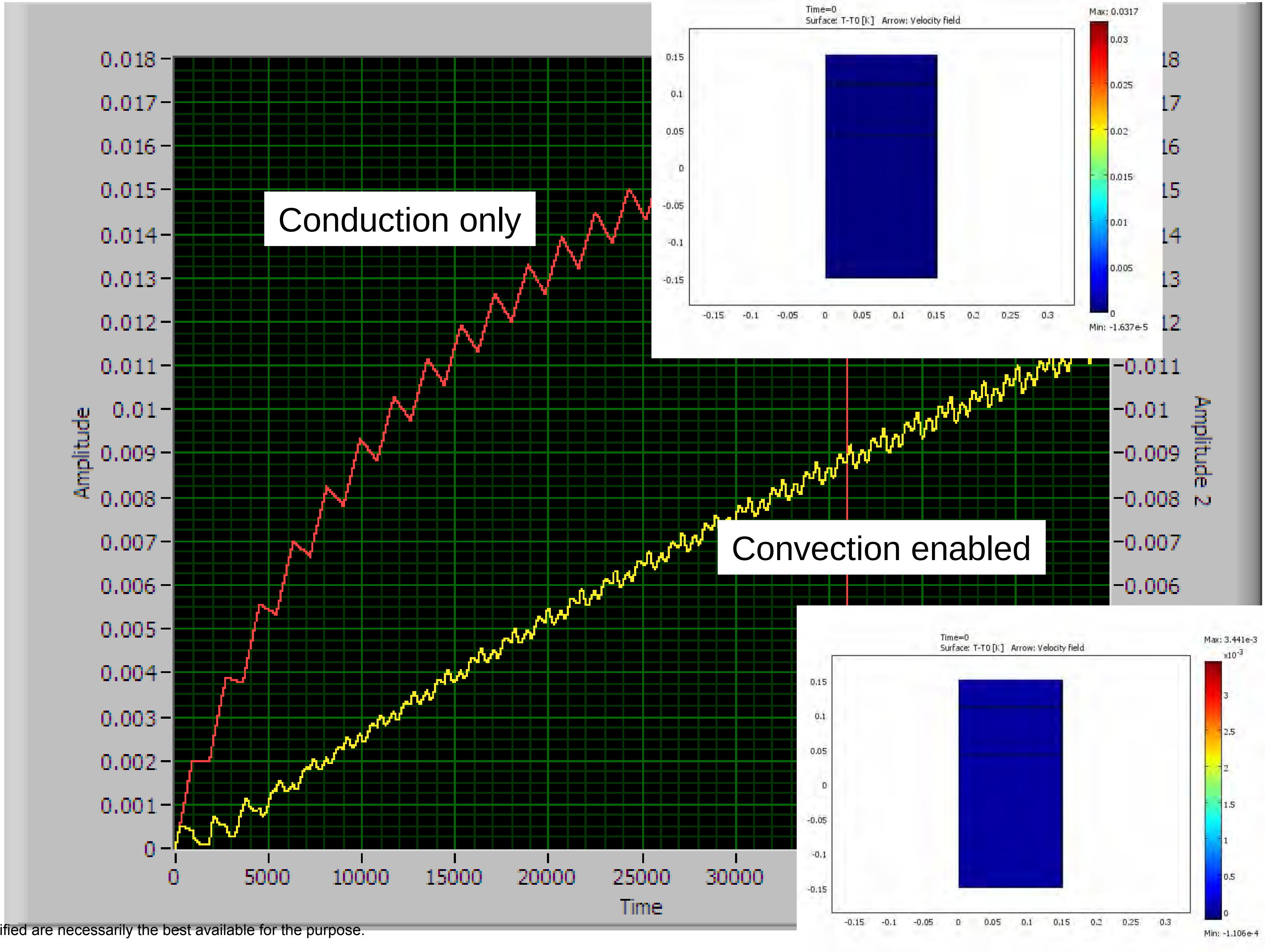


Temperature gradient (K/m)

$$H_{cc}(\vec{x},\omega) = \sum_{l,m,n=-\infty}^{\infty} \frac{(i\omega + \nu k_u^2 \sigma_{lmn})}{\left(\left[\frac{\beta\alpha g}{\sigma_{lmn}}(l^2+m^2)+\kappa\nu k_u^2 k_\theta^2 \sigma_{lmn}^2\right]-\omega^2\right)+i\omega(\kappa k_\theta^2+\nu k_u^2)\sigma_{lmn}} g_{lmn}(\vec{x})$$

α volume expansion coefficient
ν kinematic viscosity
K_θ, k_υ, spatial modes of *temperature and velocity*

R. E. Tosh and H. H. Chen-Mayer, "A Transfer-function Approach to Characterizing Heat Transport in Water Calorimeters Used in Radiation Dosimetry," Proceedings International Thermal Conductivity Conference (ITCC29) U. of Alabama, June 24-27, 2007 DEStech Publications, Lancaster PA.



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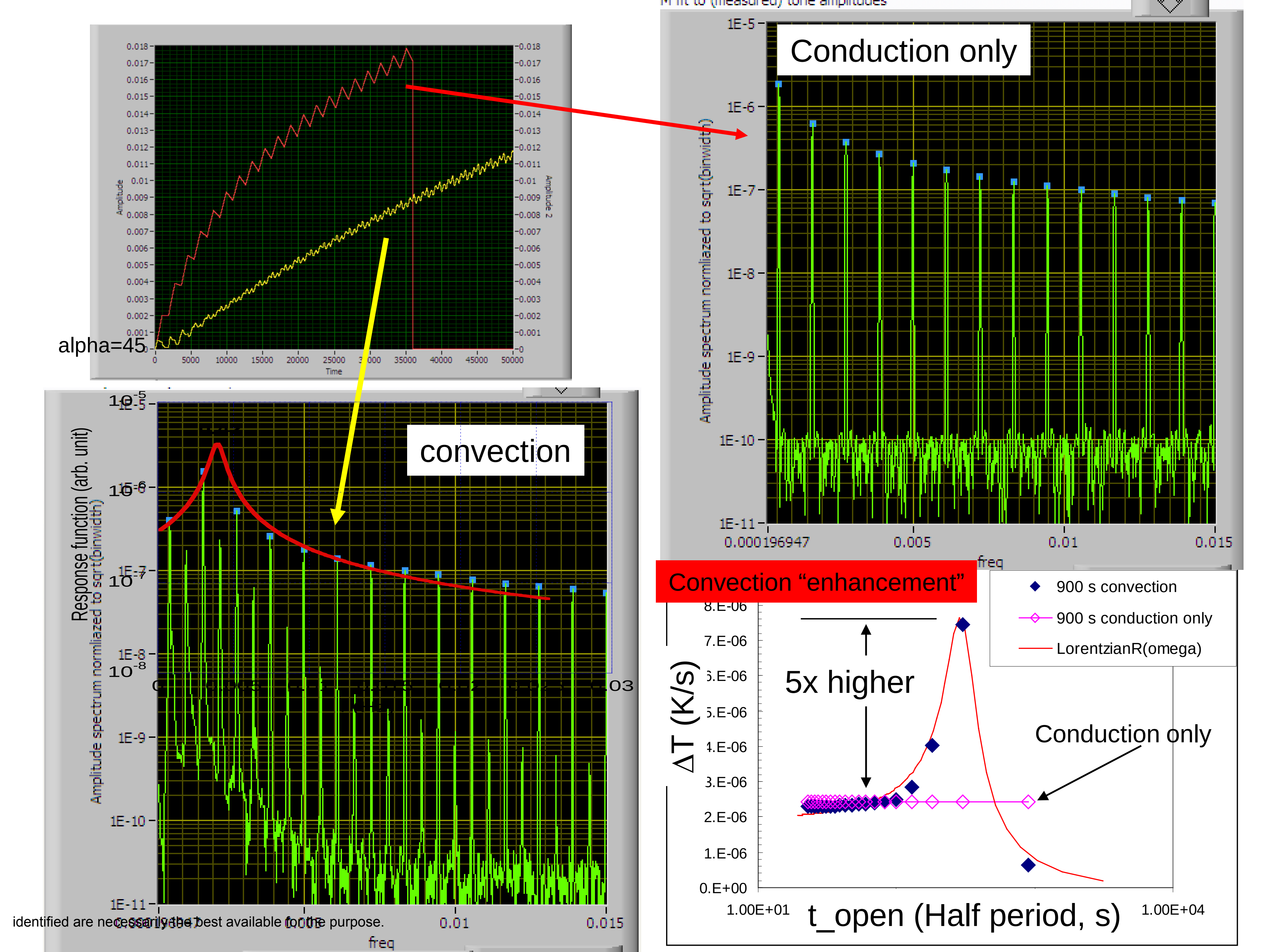

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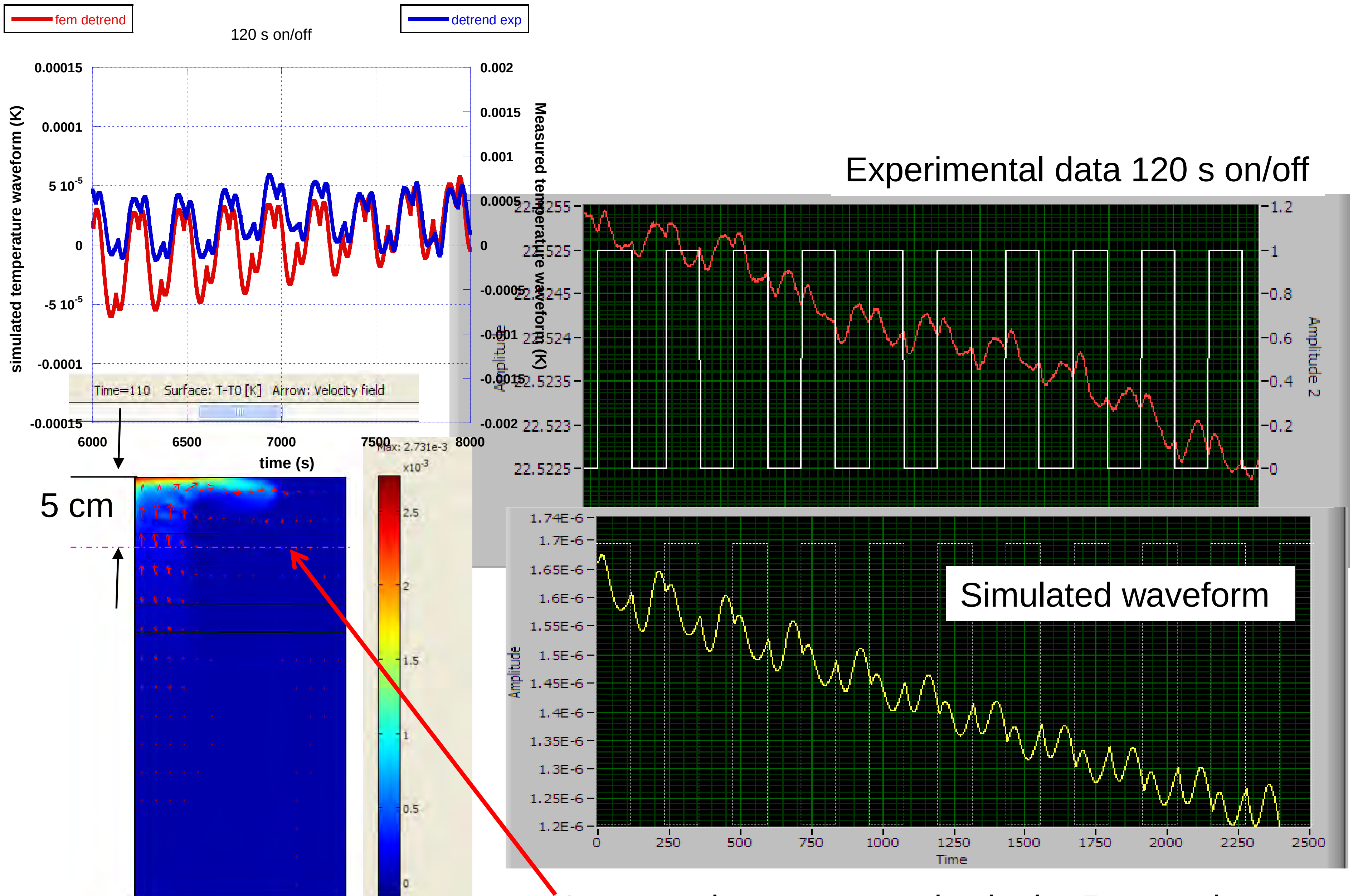

Integrated temperature rise in the 5 cm path

2D simulations with convection

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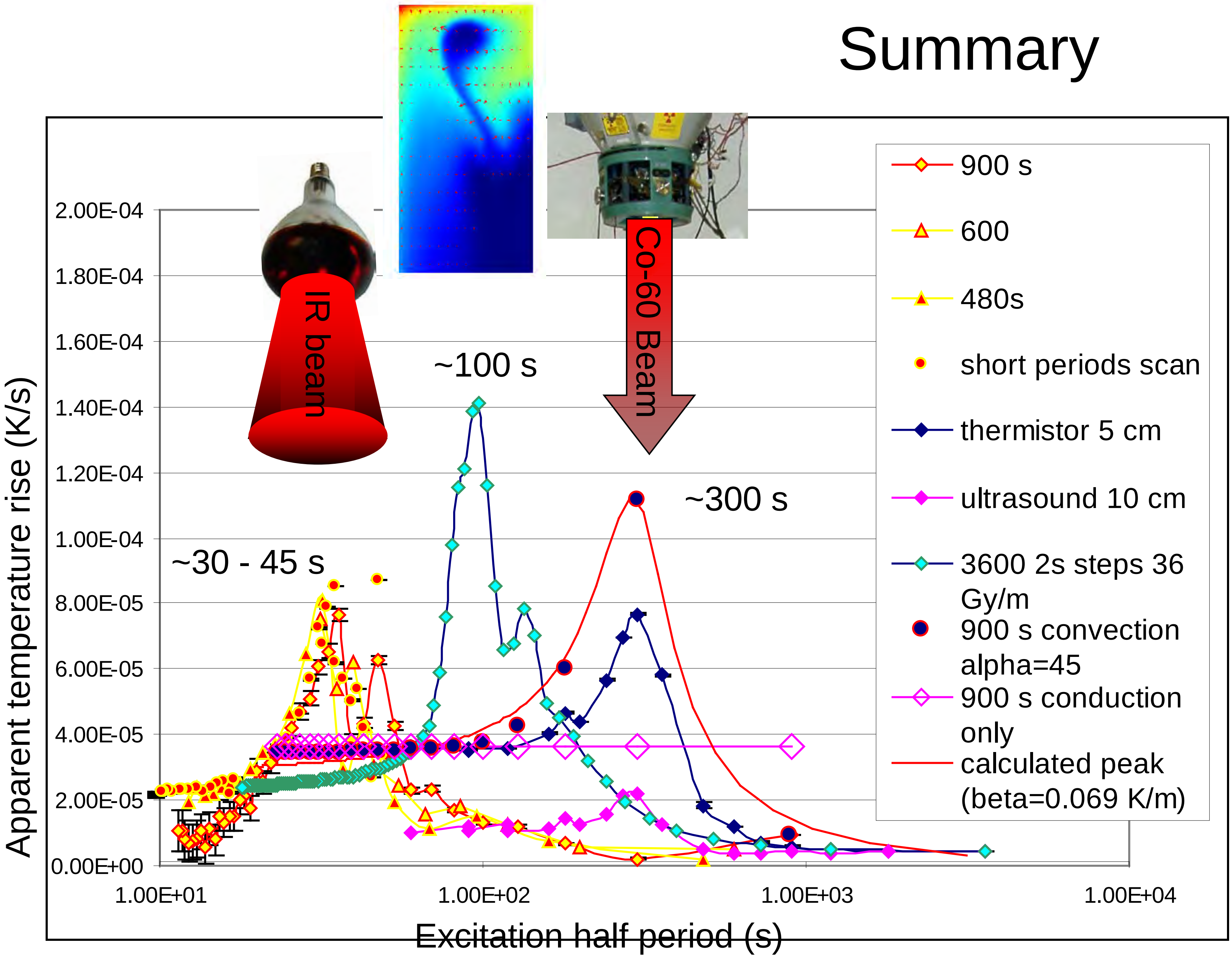
Summary



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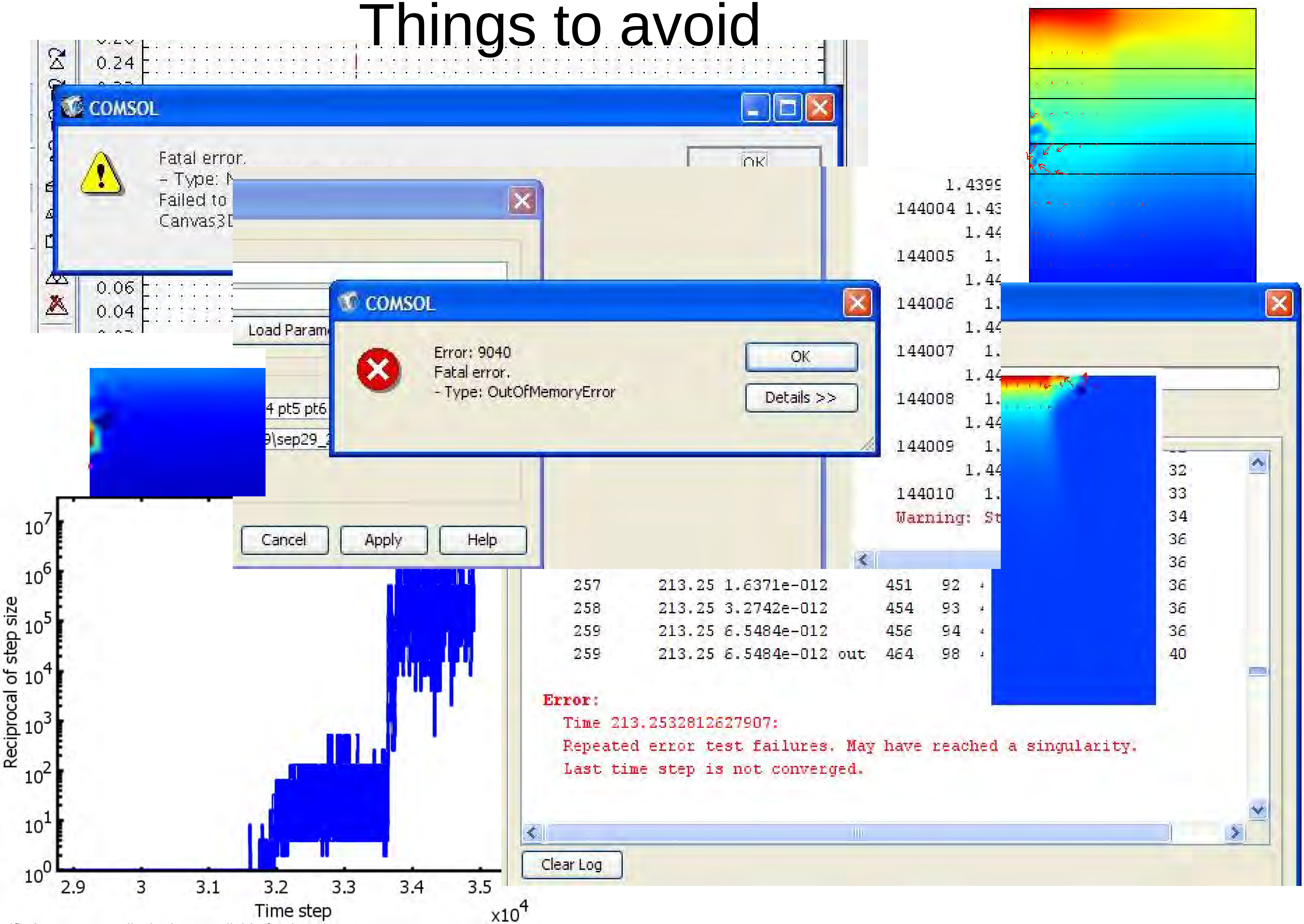
Things to avoid



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Poster Section

Linear Convection and Conduction in Cylinders of Water Exposed to Periodic Thermal Stimuli

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