Evaluations of Parameters Stability for S-Band RF Gun Cavity Due to Effects of Pulsed RF Heating

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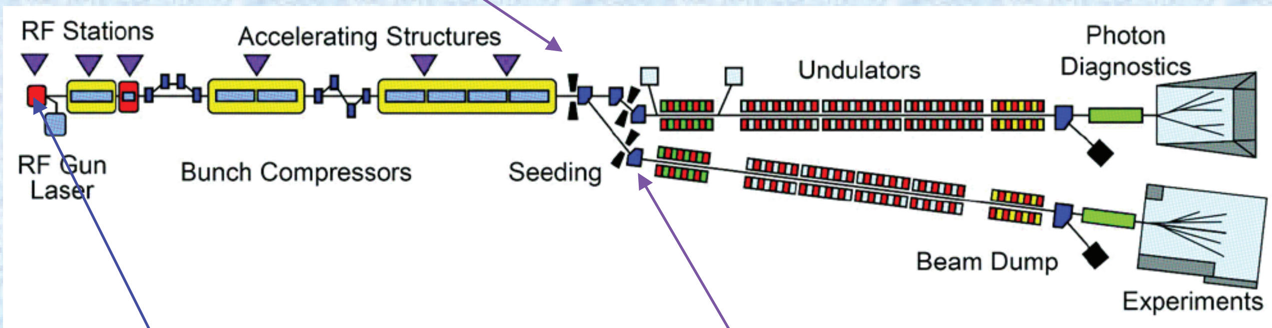
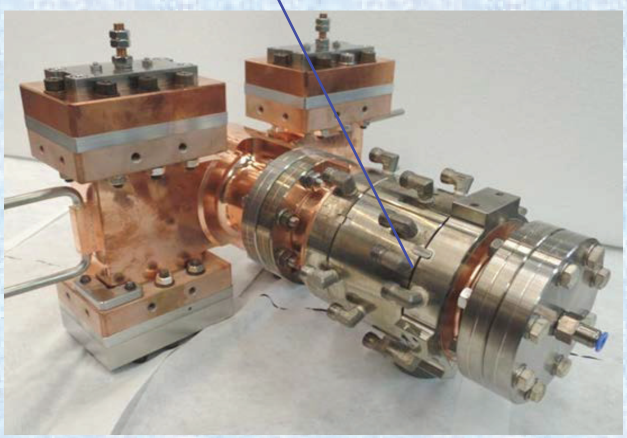
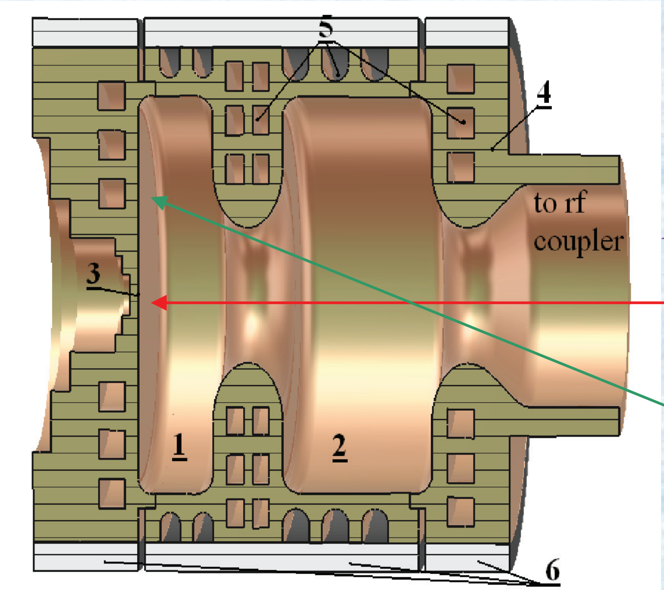
The RF gun cavities with photo cathode now are commonly used for generation of short and bright electron in modern Free Electron Laser (FEL) facilities.





S band HRRG RF gun cavity for the CLARA project.

One of the critical requirements to the linear accelerator based FEL facilities with laser seeding is high arrival time stability of the electron bunches. Essential impact on the arrival time gives the amplitude and phase of the pulsed RF field in the gun cavity. Some times is requested stability: A~0.01%, ϕ~0.01 degree.(?)



Simplified3D model of the gun cavity. 1 - half cathode cell, 2 - full cell, 3 - position of photo cathode, 4- cavity copper body, 5 - cooling channels, 6 - stainless steel jacket

To provide electron bunches with small transverse emittance the gun operate in pulsed mode with:

$$E_c \sim 120 \frac{MV}{m}$$

$$H_s \sim 250 \frac{kA}{m} \quad P_{smax} \sim 4.5 \cdot 10^8 \frac{W}{m^2}$$

Effects of the pulsed RF heating take place during RF pulse τ~ (3- 6) μs, then the temperature at some parts of the cavity surface Tsmax rises up to (19 - 30)C^o.

Temperature rise of the cavity during RF pulse leads to thermal deformations and change of the cavity parameters. It directly lead to deviations in the amplitude and the phase of the RF field in the cavity.

Problem description

Classical coupled problem of transient thermal deformations.

source of elastic wave

$$div(gradT(\vec{r},t)) - \frac{\rho_m C_p}{k_c}\frac{\partial T(\vec{r},t)}{\partial t} - \frac{\alpha_t E_Y T_0}{3k_c(1-2\nu)}\frac{\partial div\vec{u}}{dt} = 0,$$

$$\frac{3(1-\nu)}{(1+\nu)}grad(div\vec{u}) - \frac{3(1-2\nu)}{2(1+\nu)}rotrot\vec{u} - \alpha_t gradT(\vec{r},t) - \frac{3(1-2\nu)\rho_m}{E_y}\frac{\partial^2\vec{u}}{\partial t^2} = 0,$$

Heat diffusion, 10^{-2} m/sec

Wave equation for elastic wave, $4.5\ 10^3$ m/sec

$$V_l = \sqrt{\frac{E_y(1-\nu)}{2\rho_m(1+\nu)(1-2\nu)}}$$

$\rho_m, C_p, k_c, \alpha_t, E_Y$ and ν ← materials parameters

For temperature rise T_s and penetrations depth D_d estimation 1D.

$$T_s = \frac{2P_s\sqrt{\tau}}{\sqrt{\pi k_c \rho_m C_p}}, \quad \alpha_d = \frac{k_c\tau}{\rho_m C_p}, \quad D_d = \sqrt{\alpha_d \tau},$$

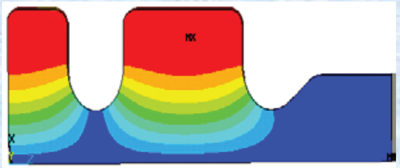
$\tau = 1\ \mu s,\ 3\ \mu s,\ 6\ \mu s$ and $10\ \mu s$

$D_d = 10.7\ \mu m,\ 18.5\ \mu m,\ 26.2\ \mu m$ and $33.8\ \mu m$

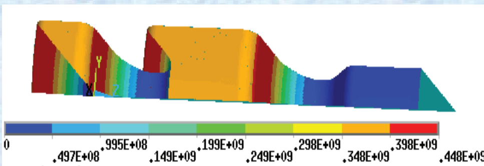
Two processes that differ by five orders of magnitude in the propagation velocities and spatial dimensions. Distance between the surface and cooling channels is of ~ 3 mm. The travel time of elastic wave is of ~1.2 μs is shorter than RF pulse duration. During RF pulse we should expect interaction of the forward wave from surface with backward waves, reflected from violations of cavity body homogeneity.

Numerical procedure, ANSYS, model calibration

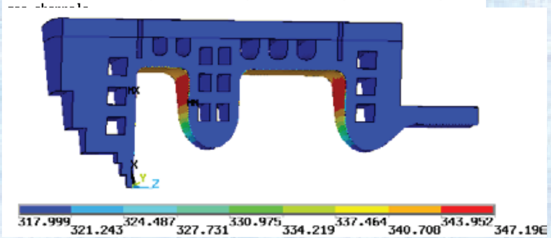
RF



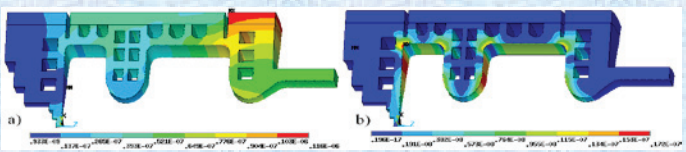
P_l



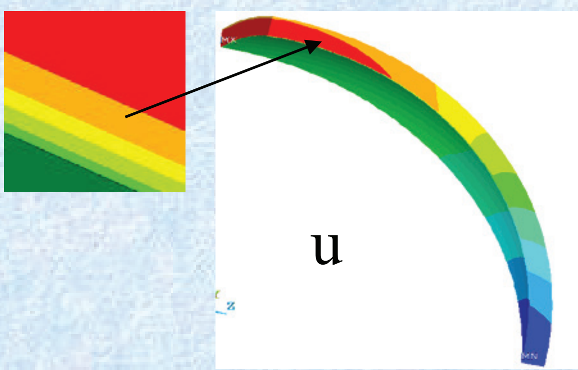
T(t)



u

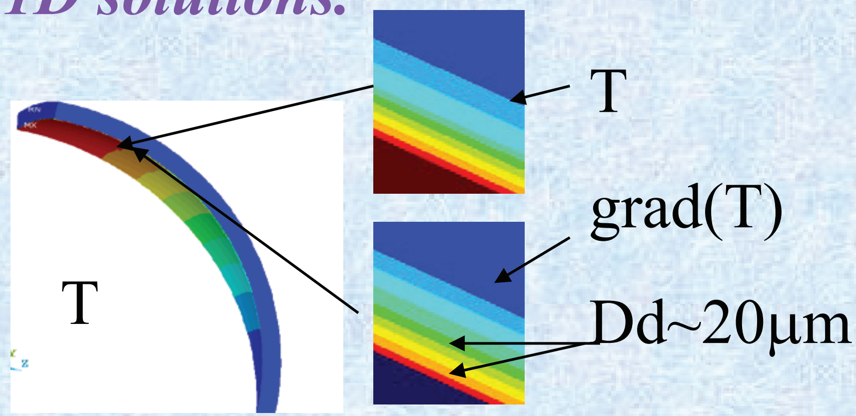


Static or transient

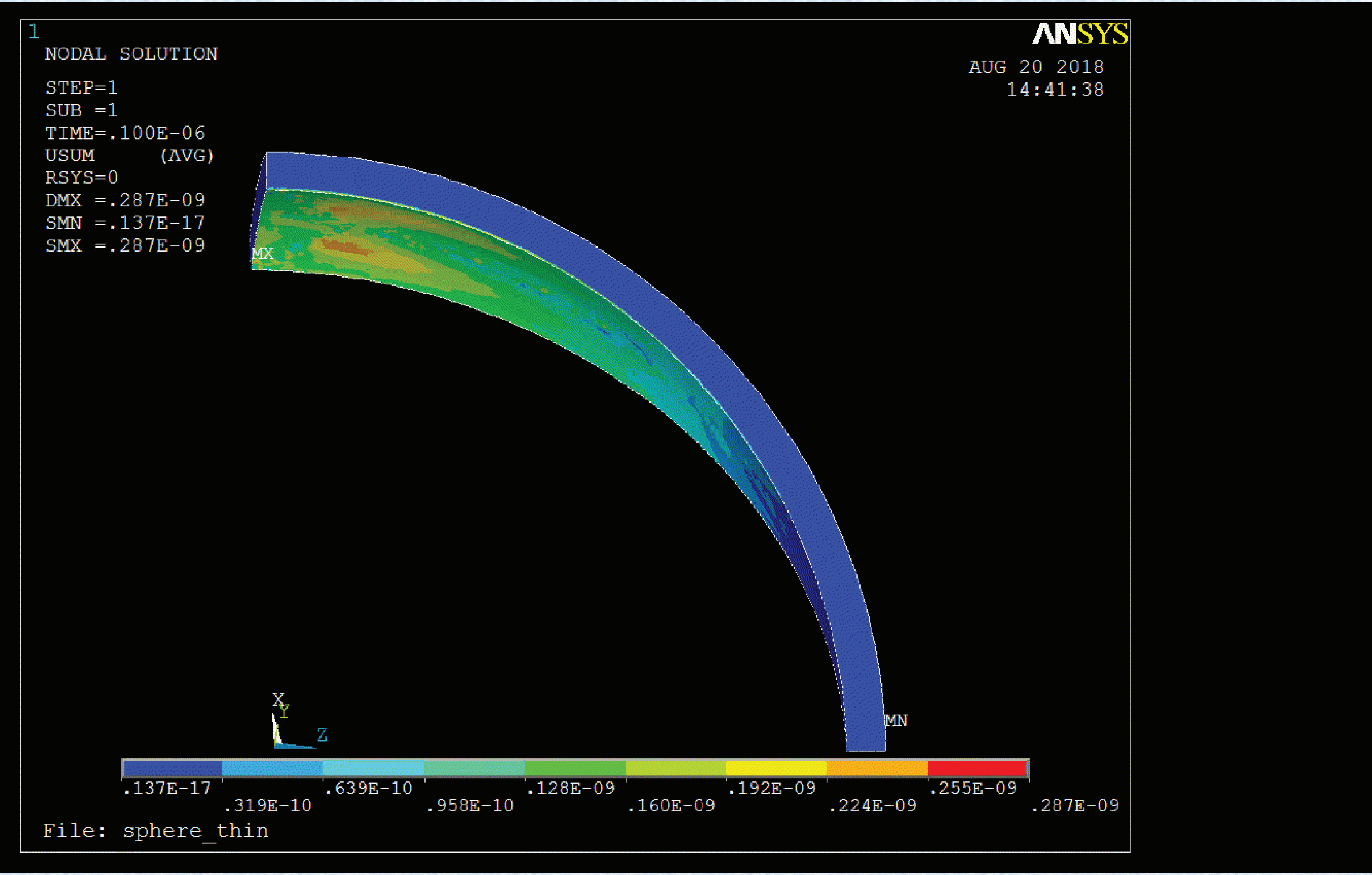


The problem is to describe precisely both T and especially grad(T) in the layer D_d~10μm at the background of ~80mm gun dimensions.

Calibration with hollow spherical cavity – allows analytic (static u) and numerical 1D solutions.



The deviations between analytic and numerical results in units of percents was fixed for further simulations.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MN
X
Y
Z
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.160E-09
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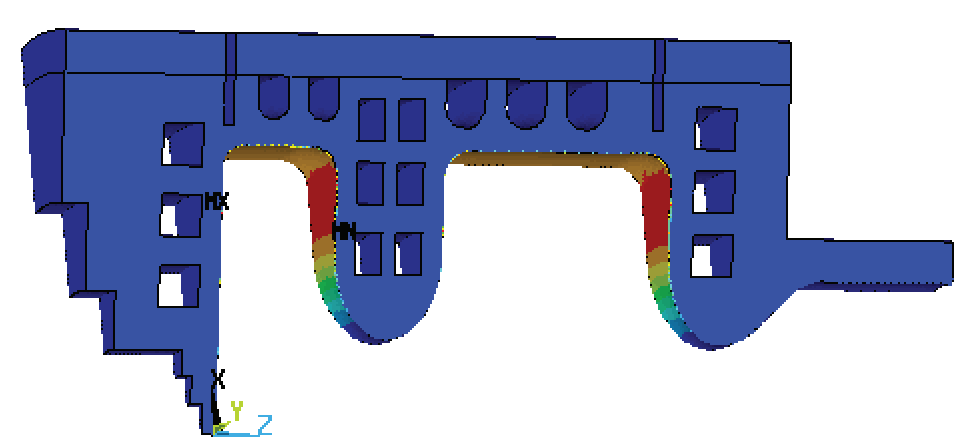
.224E-09
.255E-09
.287E-09
File: sphere_thin

Temperature distributions

$$T_s = \frac{2P_s\sqrt{\tau}}{\sqrt{\pi k_c \rho_m C_p}}$$

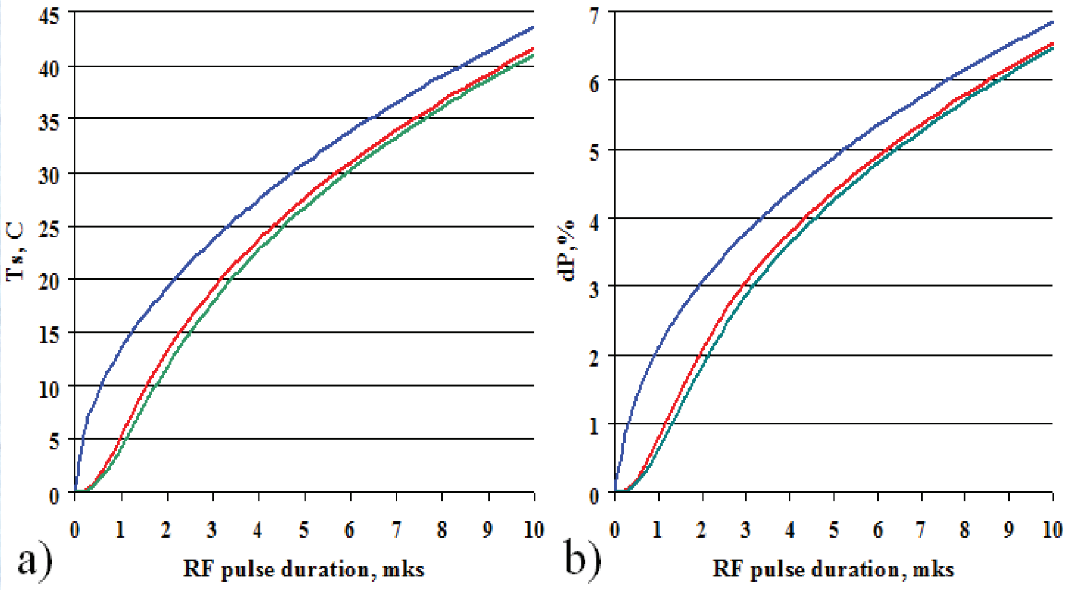


For rectangular Pl pulse the estimations for Ts works fine. With the precision of Dd, distribution Ts reflects the surface distribution of Ps.

$$P_l = P_s = const, 0 \leq t \leq \tau$$

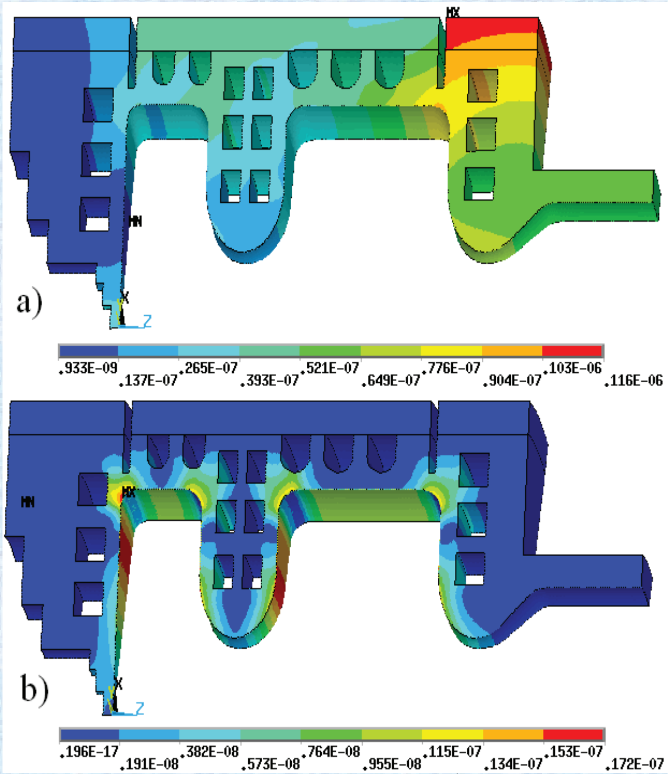
$$P_l = P_s(1 - e^{-\frac{t}{\tau_c}})^2, 0 \leq t \leq \tau$$

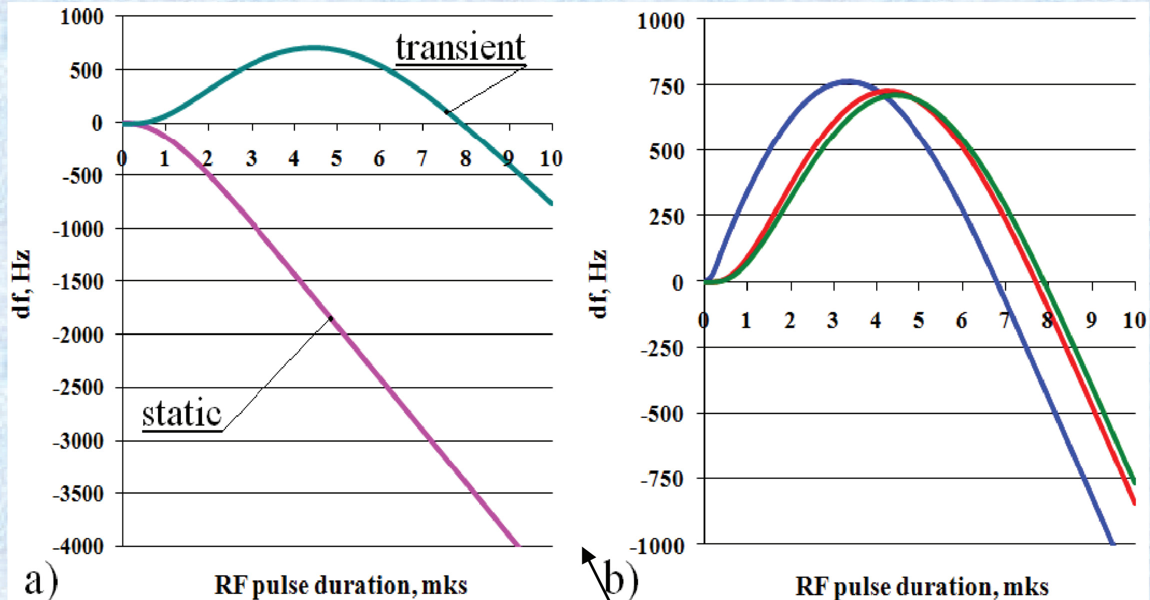
$$\tau_{c1} = 0.62\mu s \text{ and } \tau_{c2} = 0.76\mu s$$



Time dependence of max. temperature rise of the surface T_{smax} (a) and relative increase of RF losses (b) for rectangular (blue) and accretive with τ_{c1} (red) or τ_{c2} (green) P_1 pulse.

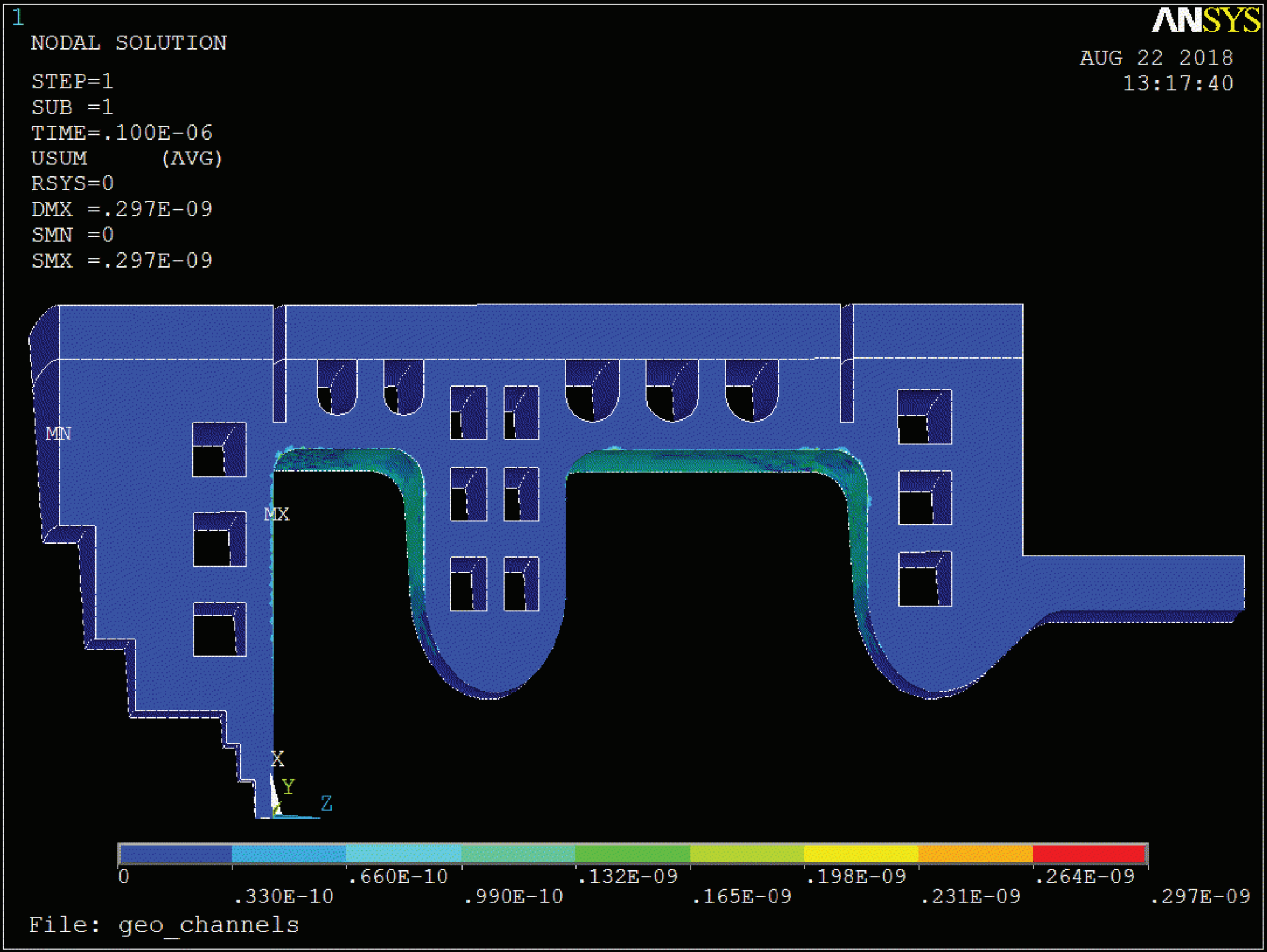
Displacements distributions





Cavity detuning during τ_{c1} P_l pulse for static and transient approximations (a) and transient detuning for rectangular (blue curve), accretive with τ_{c1} (red) or τ_{c2} (green) $P_l$pulses (b).

Displacements after τ=4.5µs, τ_{c1} RF pulse for static (top) and transient (bottom) approximations.
Important!



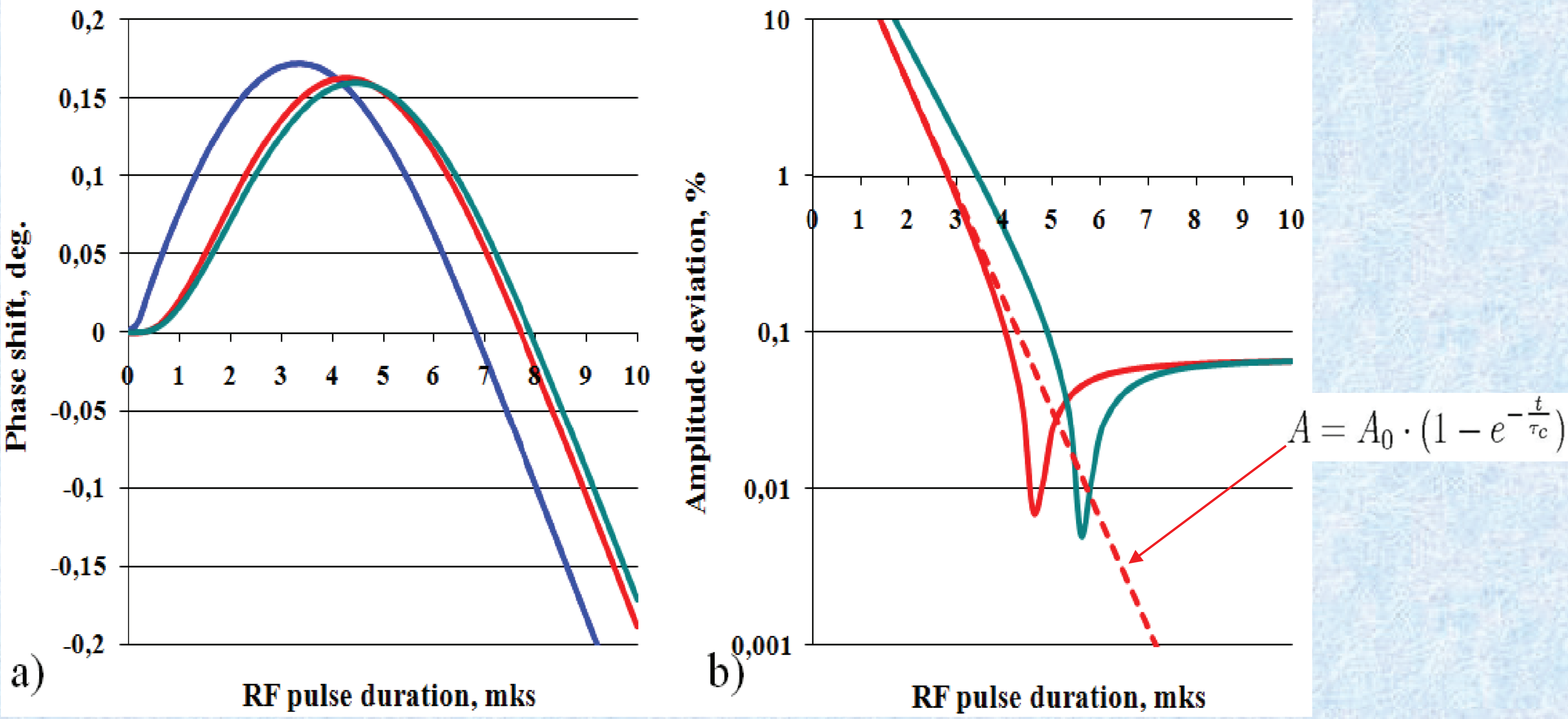
1
NODAL SOLUTION
STEP=1
SUB =1
TIME=.100E-06
USUM (AVG)
RSYS=0
DMX =.297E-09
SMN =0
SMX =.297E-09
ANSYS
AUG 22 2018
13:17:40
MN
MX
X
Y
Z
0
.330E-10
.660E-10
.990E-10
.132E-09
.165E-09
.198E-09
.231E-09
.264E-09
.297E-09
File: geo_channels

Impact on RF field stability

$$A = A_0\sqrt{\frac{1-\rho_0^2}{1+(\frac{2Q_l df}{f_0})^2}}cos(\omega t - \phi), \phi = arctg(\frac{2Q_l df}{f_0}),$$

Temporal dependence of the phase shift of RF oscillations (a) and relative value of amplitude deviations for P_l pulses (b)

$Q_0 = 12190$ and $Q_l = 5870$, $\frac{2Q_l df}{f_0} \approx 2.7 \cdot 10^{-3}$



Summary

For typical operating modes of S-band RF gun cavities the effects of pulsed heating during the the RF pulse are manifested not only in the growth of surface temperature but also in small but unavoidable thermal deformations. During a short RF pulse these deformations are essentially non-stationary. Both surface temperature rise and cavity thermal deformations result in changes of own quality factor and cavity resonance frequency even during few microseconds long RF pulse.

This report presents results of numerical simulation of both the cavity parameters change and related deviations of the RF field amplitude and phase for typical operating regime.

ACKNOWLEDGEMENT

The work is supported by STFC contract N 4070193704

Thank You for attention!