

Cryogenically Cooled Copper Photocathode in a CW SRF Photoinjector

Laser heating and thermal stability

Dmitry Bazyl

Deutsches Elektronen-Synchrotron DESY, Hamburg

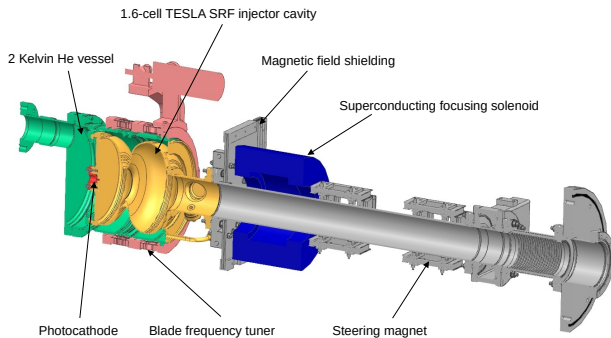
D. Bazyl, K. Floettmann, E. Vogel and I. Zagorodnov

*Multiphysics analysis of cryogenically cooled photocathode
in a continuous wave SRF injector cavity*

Phys. Rev. Accel. Beams **29**, 013402 (2026) doi:10.1103/9jyv-hfxy



Thread-mounted Cu photocathode in the 2 K Nb back wall; direct cooling by He II.



Beam parameters	
bunch repetition rate [kHz]	100 - 1000
bunch charge [pC]	20 to 100
transverse emittance [μm]	0.2 to 0.4
beam energy [MeV]	> 4

RF parameters	
resonant frequency [GHz]	1.3
axial peak E-field [MV/m]	> 40

Cathode specification	
material	copper
assembly	thread-mounted to backwall

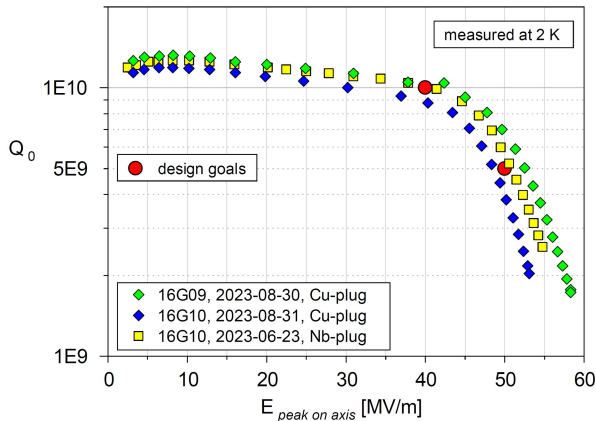
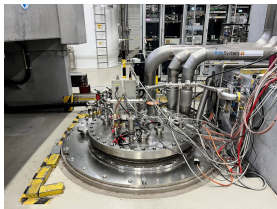
RF qualification with low-RRR Cu plugs at 2 K.

Thermal calculations below assume Cu RRR = 300 and 50 MV/m axial peak field.

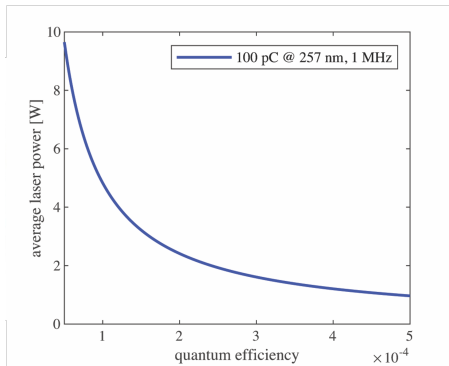
Cavity assembly
prior 'Q vs E' test



Test cryostat: measuring E-field
vs Quality factor at cryogenic
temperature 2 K



Thermal-study QE assumptions for the plug after preparation and cooldown.



100 pC at 1 MHz, 257 nm

$$P_{\text{inc}} = \frac{Q_b f_{\text{rep}}}{e \text{QE}} \frac{hc}{\lambda}$$

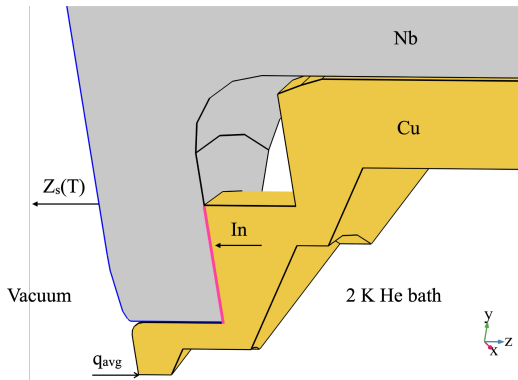
Reference beam current: 100 μA .

Laser-power cases: 2 and 5 W incident.

Incident UV	2 W	5 W
Required QE	2.4×10^{-4}	9.6×10^{-5}
Absorbed heat	1.28 W	3.20 W

$$P_{\text{abs}} = (1 - R)P_{\text{inc}}; \text{ assumed } R = 0.36.$$

QE = 5×10^{-5} would require **9.65 W incident UV** at the reference beam current.



Cu–He II cooling path

Conduction through the plug and Kapitza resistance at the wetted surface.

Cu–In–Nb thermal contact

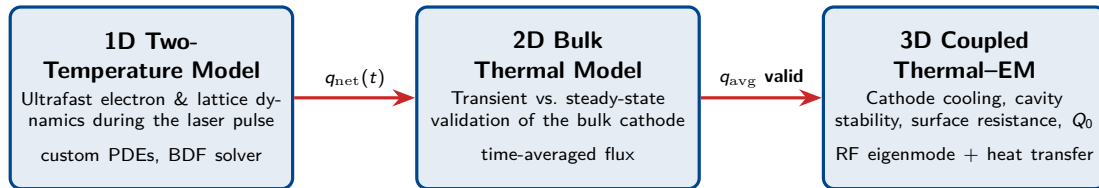
Heat transfer into the RF-active Nb back wall through the indium-sealed joint.

Quantities evaluated

Surface $T_e(t)$ and $T_l(t)$ during UV excitation.

Maximum temperature at the Cu–He interface.

Nb temperature distribution and integrated RF loss.



- All implemented in a single COMSOL Multiphysics v6.3 environment.

$$C_e \partial_t T_e = \partial_x (K_e \partial_x T_e) - G(T_e, T_l)(T_e - T_l) + S_{\text{laser}},$$

$$C_l \partial_t T_l = G(T_e, T_l)(T_e - T_l).$$

Low-temperature electron-phonon limit

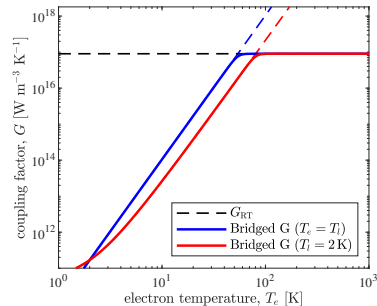
$$G_{\text{low}}(T_e, T_l)(T_e - T_l) = \Sigma_0(T_e^5 - T_l^5).$$

$T_0 = 2 \text{ K}$, $L_x = 50 \mu\text{m}$, $\text{Cu RRR} = 300$.

For a higher-fidelity microscopic description of electron-phonon energy transfer at cryogenic temperatures, see

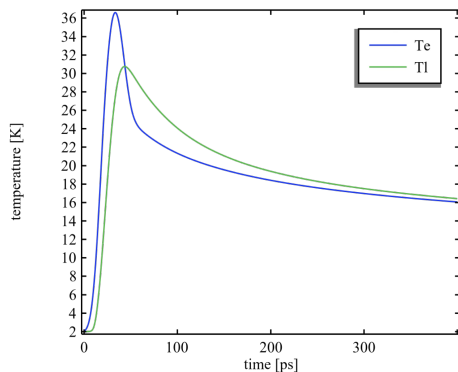
F. Banfi, F. Pressacco et al. 10.1103/PhysRevB.81.155426

Coupling interpolated between the low- T limit and $G_{\text{RT}} = 9 \times 10^{16} \text{ W m}^{-3} \text{ K}^{-1}$.

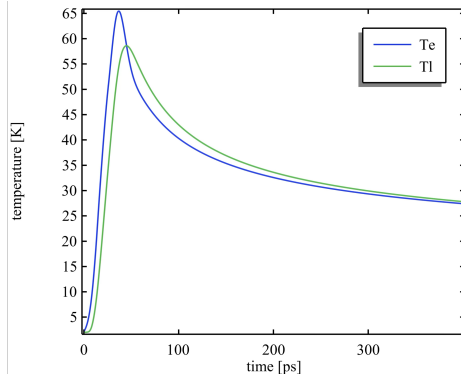


$E_{\text{inc}} = 2 \mu\text{J}$, $\sigma_t = 8 \text{ ps rms}$, $\lambda = 257 \text{ nm}$, $T_0 = 2 \text{ K}$; top-hat illumination.

$r_{\text{spot}} = 430 \mu\text{m}$; $F_{\text{abs}} = 2.2 \text{ J/m}^2$.

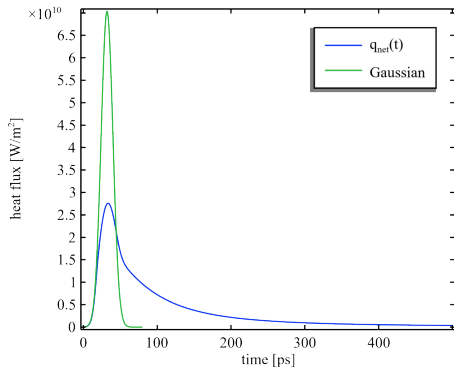


$r_{\text{spot}} = 215 \mu\text{m}$; $F_{\text{abs}} = 8.8 \text{ J/m}^2$.



Nominal peaks: $T_e \simeq 36.5 \text{ K}$ and $T_l \simeq 30.5 \text{ K}$.

Qualitative temporal-profile comparison.



Interface to the diffusive bulk

Effective deposition depth: $d_p = 83 \text{ nm}$.

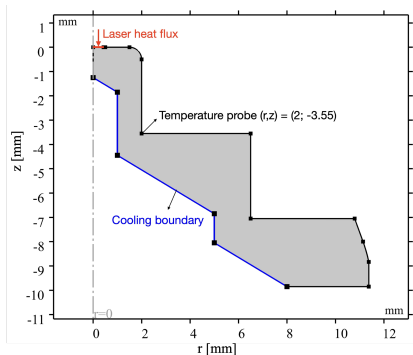
Flux evaluation plane: $x_{\text{int}} = 2 \mu\text{m}$.

$$q_{\text{net}}(t) = \left[-K_e(T_e, T_l) \frac{\partial T_e}{\partial x} - K_l(T_l) \frac{\partial T_l}{\partial x} \right] \Big|_{x=x_{\text{int}}}$$

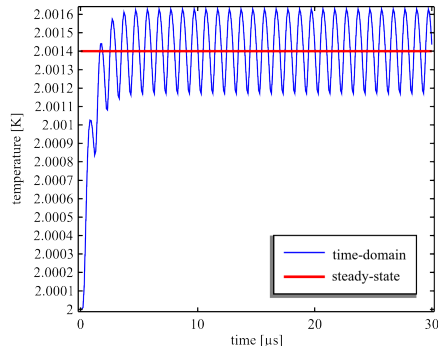
Bulk-model excitation: periodic repetition of $q_{\text{net}}(t)$ at 1 MHz.

2D axisymmetric Cu model; ideal cooling at 2 K; $P_{\text{inc}} = 2 \text{ W}$, $f_{\text{rep}} = 1 \text{ MHz}$.

Cu probe adjacent to the indium-seal position.



Blue: pulse train; red: stationary solution.

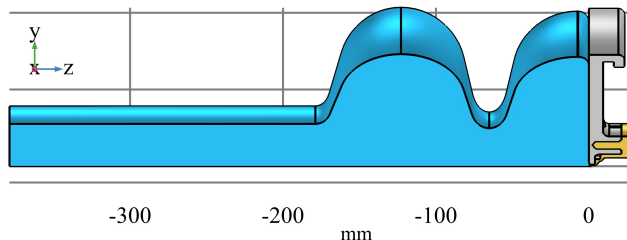


$\langle T_{\text{transient}} \rangle = T_{\text{stationary}} = 2.0014 \text{ K}$ after approximately $6 \mu\text{s}$.

The comparison supports stationary treatment of the mean temperature near the contact.

One-eighth of the 1.6-cell cavity.

Cu plug Nb back wall RF vacuum



Temperature-dependent Cu and Nb conductivity; $RRR = 300$.

Estimated nominal $R_{tc} = 10^{-3} \text{ K m}^2/\text{W}$; 1.3 GHz, $E_{\text{peak}} = 50 \text{ MV/m}$.

Stationary laser source

$$q''_{\text{avg}} = \frac{(1 - R)P_{\text{inc}}}{A_{\text{spot}}}$$

Kapitza boundary at $T_b = 2 \text{ K}$

$$q'' = h_K(T_s)(T_s - T_b), \quad h_K = aT_s^3$$

Clean Cu: $a = 1000 \text{ W m}^{-2} \text{ K}^{-4}$.

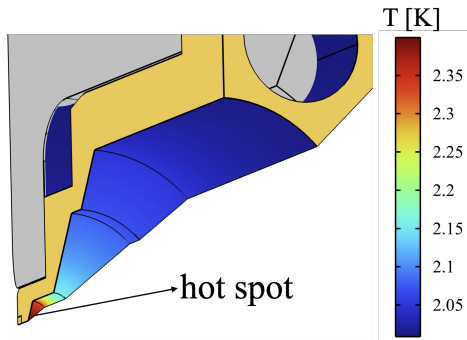
BCP Nb: $a = 400 \text{ W m}^{-2} \text{ K}^{-4}$.

Cu–In–Nb contact

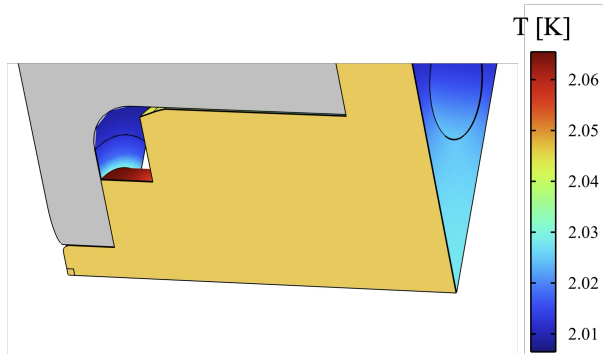
$$T_{\text{Cu}} - T_{\text{Nb}} = q'' R_{tc}$$

$$P_{\text{inc}} = 2 \text{ W}, P_{\text{abs}} = 1.28 \text{ W}, T_b = 2 \text{ K}.$$

Baseline 2.40 K



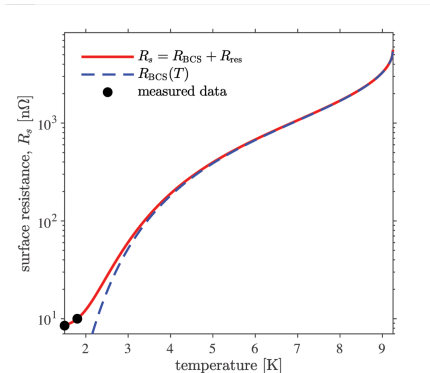
Modified 2.07 K



Modified plug at **5 W incident**: peak wetted-Cu temperature $\simeq 2.14$ K.

Solid-side temperatures; different colour scales.

Single-phase cooling; boiling onset and critical heat flux are outside the model.



Niobium surface resistance

$$R_s(T) = R_{\text{res}} + R_{\text{BCS}}(T)$$

$$R_{\text{BCS}} \propto \frac{f^2}{T} \exp\left[-\frac{\Delta(T)}{k_B T}\right]$$

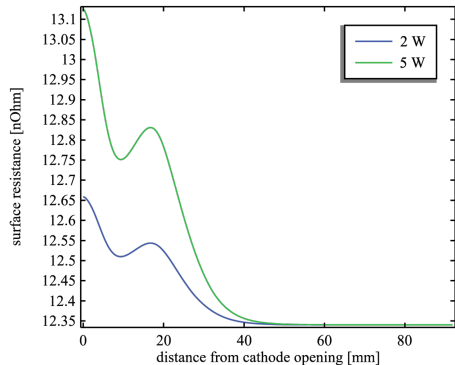
Black points: measured low-temperature resistance of cavity 16G09.

The fitted residual resistance is $R_{\text{res}} = 8.3 \text{ n}\Omega$.

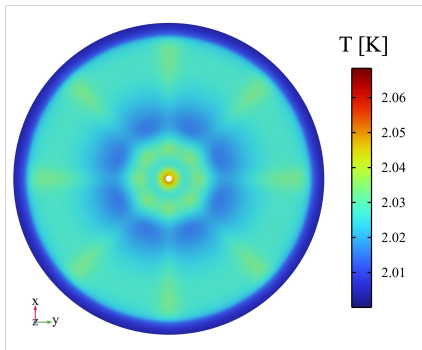
Local $R_s(T)$ provides the RF dissipation term in the coupled thermal calculation.

The temperature-dependent RF boundary is applied to the Nb back wall in the 3D model.

Laser-heated R_s : 2 and 5 W incident.



Nb back wall: coupled 5 W result.

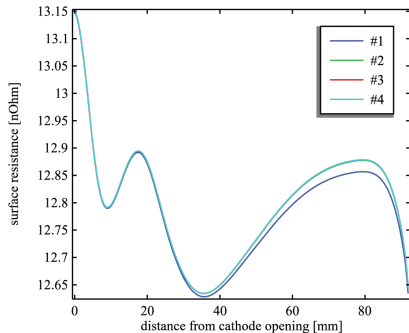


$$P_d = \frac{1}{2} \int_S R_s(T) |H_t|^2 dS, \quad H_t(0) = 0 \quad (\text{TM}_{010}, \pi \text{ mode})$$

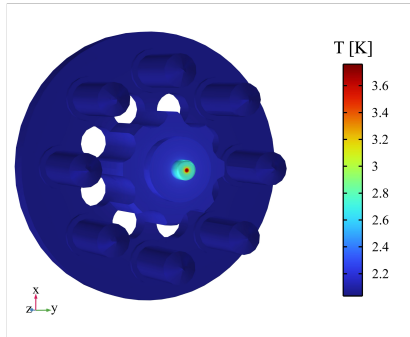
The heated Nb region is localized near the cathode opening, where the magnetic weighting is small.

Modified plug, single-phase cooling: $T \longrightarrow R_s(T) \longrightarrow P_{\text{RF}} \longrightarrow T$.

Convergence by iteration 2.



Mean Cu maximum $\simeq 3.6$ K at the emitting side.



Back-wall RF loss: **1.109 W at uniform 2 K $\rightarrow$ 1.140 W coupled (+2.8%).**
The increment is predominantly RF self-heating.

Key conclusions

We can use steady-state (time average) laser power for thermal design studies. Why important: time-domain simulations with 8 ps rms laser pulses with repetition rate of 1 MHz are computationally expensive. Steady-state approach allows fast way for engineering design investigations.

Thermal constraint (i.e. QE and incident laser power) is Cu-He interface. Laser induced heating has no impact on the SRF gun. Why important: Cu plug design must aim for efficient cryogenic cooling. Cu-Nb interface is less relevant for overall thermal stability.

TTM for Cu temperatures starting in deep cryogenic range can be useful for some applications (see Maxson 10.1016/j.nima.2016.08.032)

dmitry.bazyl@desy.de

$$G_{\text{low}} = \Sigma_0 \sum_{k=0}^4 T_e^{4-k} T_l^k$$

$$G = (G_{\text{low}}^{-n_b} + G_{\text{RT}}^{-n_b})^{-1/n_b}$$

$$\Sigma_0 = 2.1 \times 10^9 \text{ W m}^{-3} \text{ K}^{-5}$$

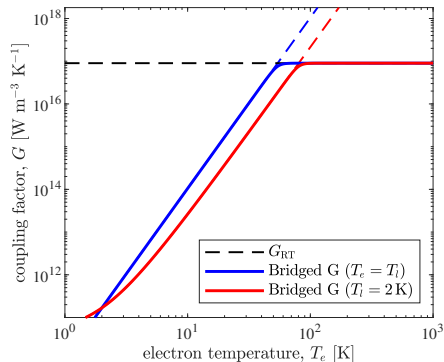
$$G_{\text{RT}} = 9.0 \times 10^{16} \text{ W m}^{-3} \text{ K}^{-1}$$

$$n_b = 4$$

At equilibrium: $G_{\text{low}} = 5\Sigma_0 T^4$.

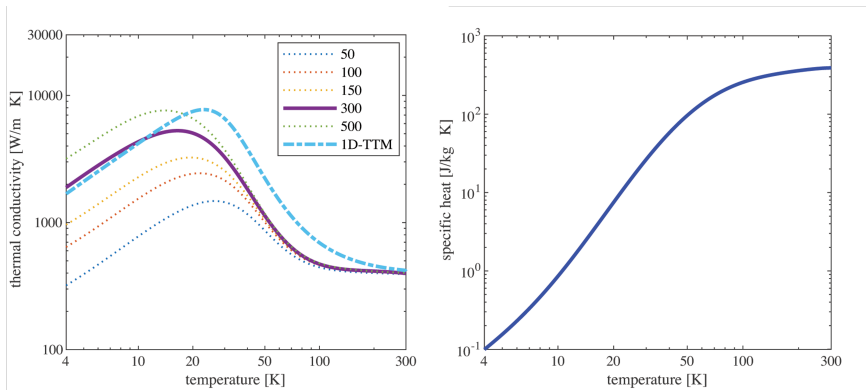
$$G_{\text{low}}(T_e, T_l)(T_e - T_l) = \Sigma_0(T_e^5 - T_l^5).$$

The bridge interpolates between low-temperature theory and the room-temperature reference value.



Equilibrium Cu conductivity and specific heat for the bulk model.

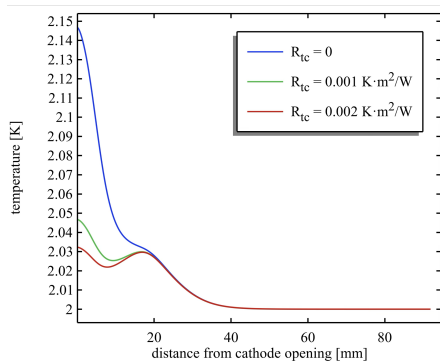
Reference purity: $RRR = 300$. The dashed curve compares the 1D-TTM conductivity in the equilibrium limit.



$P_{\text{inc}} = 5 \text{ W}$; $R_{\text{tc}} = 0, 0.001 \text{ and } 0.002 \text{ K m}^2/\text{W}$ (ideal, nominal and twice nominal).

Nb peak: 2.03–2.15 K.

Variation is localized near the cathode opening.



Integrated back-wall loss: $< 1\%$ variation.

Peak wetted-Cu temperature varies by about 6 mK.

