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Material selection for mirror substrates exposed to high-power laser beams in the ITER tritium-monitor diagnostic

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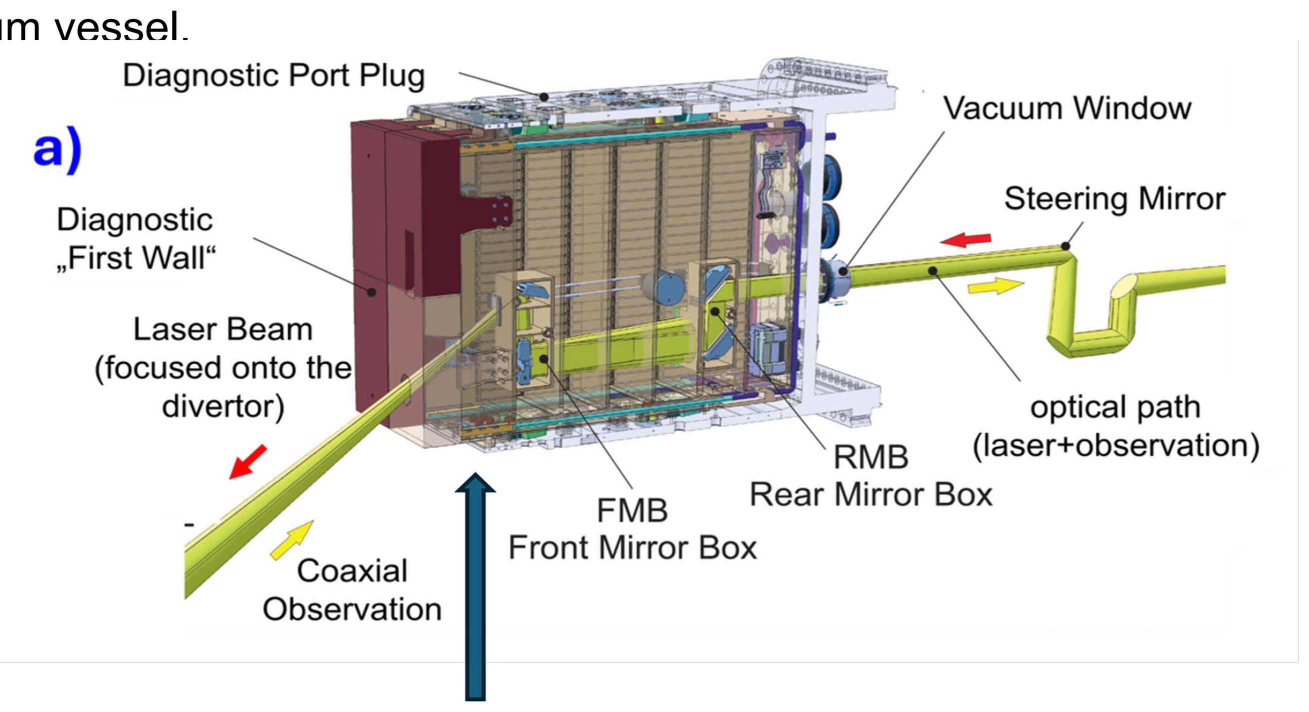
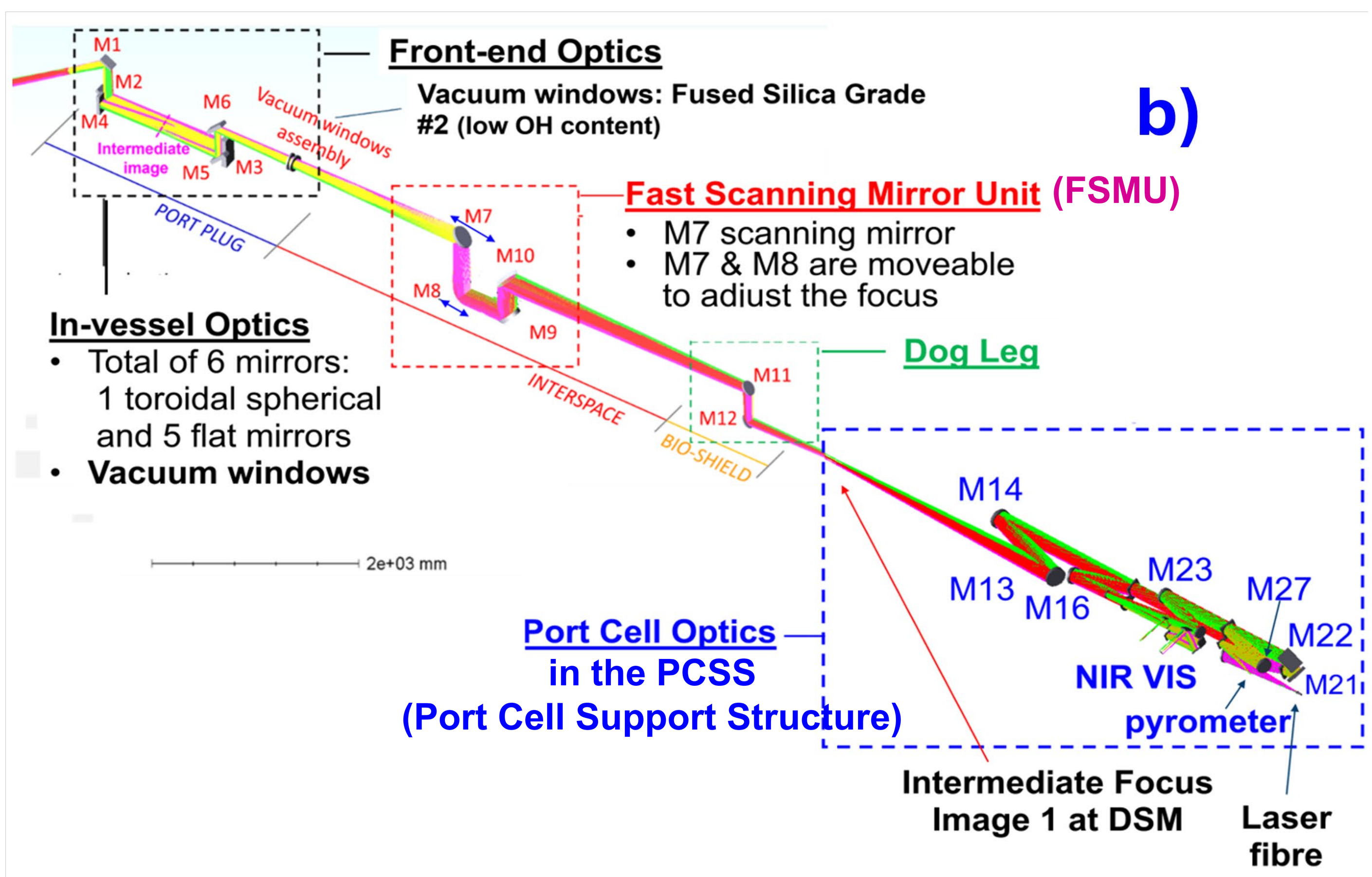
Motivation

One of the most serious challenges for the operation of ITER and future fusion devices is the control of the inventory of the tritium stored inside the vacuum vessel.





As a licensed nuclear facility, ITER must limit the T-retention within the vessel to minimize the risk of potential releases during accidents, with the in-vessel inventory limited to 1 kg.

Critical Heat Flux and Surface Deformation of Mirrors under Gaussian Laser Irradiation

The temperature rise for a Gaussian laser beam with an absorbed power flux density

$q(r) = q_0 exp(-\frac{1}{2}\left(\frac{nr}{R}\right)^2)$, where n is Gaussian shape parameter

$$\Delta T_{Gauss}(r,z,) = T(r,z,) - T_0 = \frac{\bar{q}R^2}{4k}\sqrt{\frac{\alpha}{\pi}}\int_0^{\tau}\frac{dt'}{\sqrt{t'}\left(\frac{R^2}{2n^2}+\alpha t'\right)}exp\left[-\frac{z^2}{4\alpha t'}-\frac{r^2}{4\left(\frac{R^2}{2n^2}+\alpha t'\right)}\right]$$

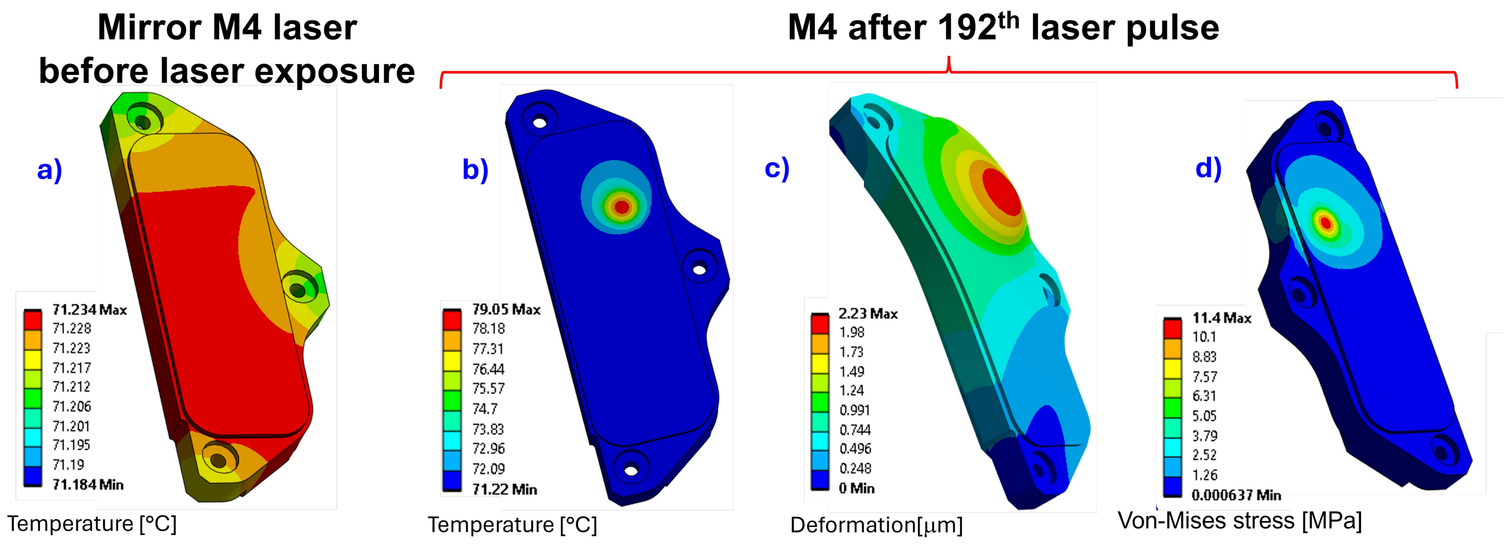
- **Thermal diffusion length:** $d = \sqrt{\alpha\tau}$ (CuCrZr: d ≈ 300–520 μm at τ = 1–3 ms),
  α: thermal diffusivity
- **Laser spot radius, R,** at the mirrors more than 14mm
- **Central temperature rise:** $\Delta T_{Gauss}(0,0,\tau)_{max} = \frac{2}{\kappa}\sqrt{\frac{\alpha}{\pi}}q_0\sqrt{\tau} = \frac{2}{\kappa}\sqrt{\frac{\alpha}{\pi}}Q_f^{peak}$
- $\sigma_t = -\frac{E}{(1-\nu)}\alpha_L \Delta T$ transverse stresses are dominant,
  α_L: linear coefficient thermal expansion coefficient
- **Shear stress:** Much smaller than transverse stress, below yield
- **Surface displacement** $v(\tau) = \frac{1(+\nu)}{1(-\nu)}\alpha_L\int_0^{\infty}\Delta T(z,\tau)dz = \frac{1(+\nu)}{1(-\nu)}\frac{\alpha_L}{c_p\rho}q_0\tau$, max. at the spot centre

Critical heat flux factors for three operational limits:

- ❑ **Critical heat flux factor for plastic deformation damage:**
  $Q_{f,[\sigma]}^{Gauss,peak} = \frac{\kappa[\sigma](1-?)}{2E\alpha_L}\sqrt{\pi/\alpha}$ when σ_t has reached the critical value [σ] strength yield
- ❑ **λ/8 deformation criterion** $Q_{f,\lambda/8}^{Gauss,peak} = \frac{1-\nu}{1+\nu}\frac{C_p\,\rho}{\lambda 8\,\alpha_L\sqrt{\tau}}$
- ❑ **Critical heat flux factor for the gold coating temperature limit:** 520 °C to avoid delamination
  $Q_{f,\Delta T=550°C} = \frac{\kappa}{2}\sqrt{\frac{\pi}{\alpha}}T_{max} = \frac{\sqrt{\pi\,\kappa\,c_p\,\rho}}{2}T_{max}$

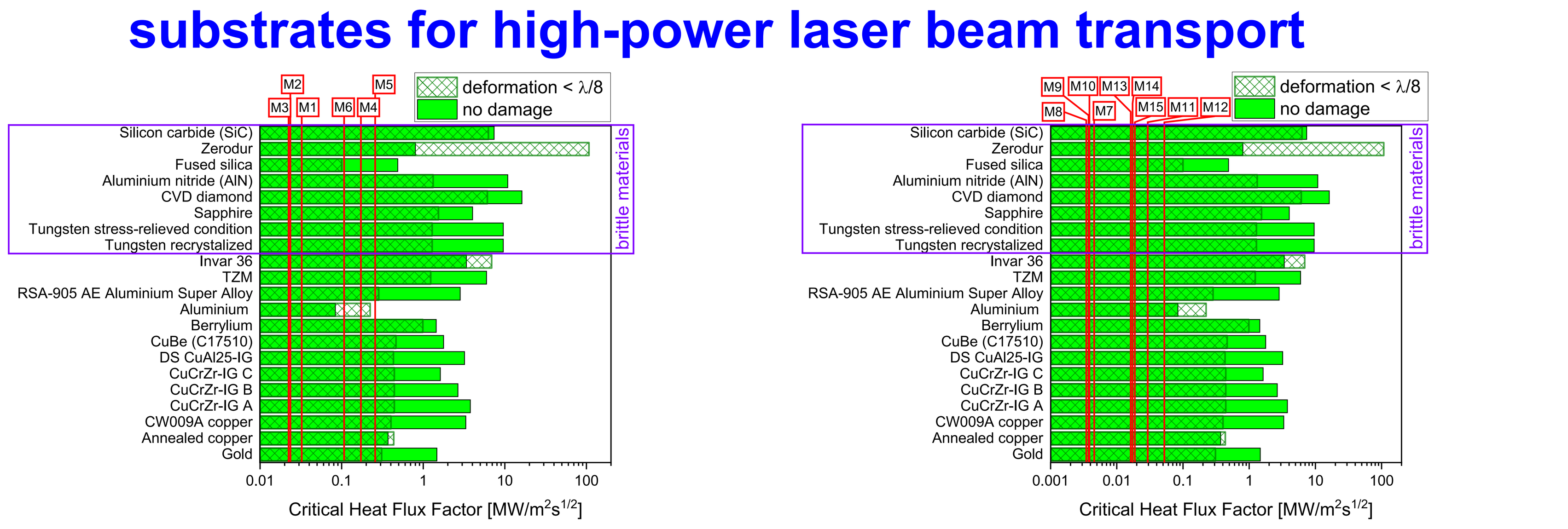
The critical heat flux is reduced for multi–laser-pulse operation compared to single-pulse mode. $Q_{f,[\sigma]}^{Gauss,mp} = \frac{Q_{f,[\sigma]}}{3.35}$ **and** $Q_{f,[\sigma]}^{Gauss,mp} = \frac{Q_{f,[\sigma]}}{2.36}$ **for τ=3ms and τ=1ms, respectively. Nevertheless, it remains significantly above the maximum heat fluxes for the mirrors.**

Thermal Load and Deformation Analysis of In-Vessel Mirrors Under Multi-Pulse Laser Operation



- ❑ The maximum temperature rise after 192 laser pulses is ΔT < 5°C
- ❑ ΔT < 5°C is smaller than the threshold for plastic deformation ($\Delta T_{threshold}$ ≈11.3°C for annealed Cu)
- ❑ The peak von Mises stress (~11 MPa) is far below the yield strength of annealed copper (33.3 MPa), confirming a safe mechanical margin after 192 laser pulses

Critical heat flux factors for various materials suitable as mirror substrates for high-power laser beam transport



The green lines indicate the maximum heat flux factors for mirrors.
For most materials, $Q_{f,\lambda/8}$ is lower than the permanent damage threshold for a single-pulse operation mode. However, materials like recrystallized tungsten, annealed copper and aluminium experience plastic deformation before reaching λ/8.

Material Selection for the T-monitor Diagnostic system (from the analysis results)

Baseline Options:

- **CuCrZr + Au coating:** Selected for in-vessel mirrors and locations within the bioshield (cold dog leg) where high thermal loads are expected. The Au coating ensures high reflectivity and surface stability.
- **Zerodur + Au coating:** Chosen for areas exposed to lower beam power densities, providing dimensional stability and minimal thermal deformation. This material is also employed for the Fast Scanning Mirror Unit (FSMU) and Port Cell Support Structure (PCSS) optics.

Back-up Options:

- **CuCrZr/DS AL-25 with Cu intermediate plate + ZrO_2 protection layers**: Prevents Cu oxidation while maintaining structural and reflective properties.
- **Massive CuCrZr mirrors with polished surfaces**: Suitable for high thermal conductivity and mechanical robustness.
- **CuCrZr + ZrO_2 protection layers**: Provides enhanced oxidation resistance while preserving high thermal performance.

Summary

- Critical heat flux factors were derived for three operational limits: (i) permanent damage thresholds, (ii) gold coating temperature (≤ 520 °C), and (iii) optical deformation (λ/8 at λ = 1.07 μm). Both uniform and Gaussian laser power distribution were considered.
- CuCrZr and Zerodur mirrors meet ITER requirements.
- Even under exposure to 7.85 kW/cm², mirrors operate below plastic and coating limits.
- Surface deformations remain negligible for optical performance.
- Design ensures robust T-monitor operation, supporting ITER's tritium safety requirements.

Website FZJ Fusion