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Limitations of the power threshold for fiber amplifiers with both the Brillouin and transverse mode instabilities

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Background

- ✓ Fiber amplifiers are the subject of great interest due to their multi-kW output powers.¹
- ✓ Both the Brillouin and transverse mode instabilities can impose limits on the operating power of high-energy lasers.
- ✓ Using the phase-matched model for the transverse mode instability (TMI) leads to a large computational speedup.²
- ✓ Modeling the Brillouin instability (BI) and TMI in a single simulation makes it possible to observe interaction between BI and TMI.

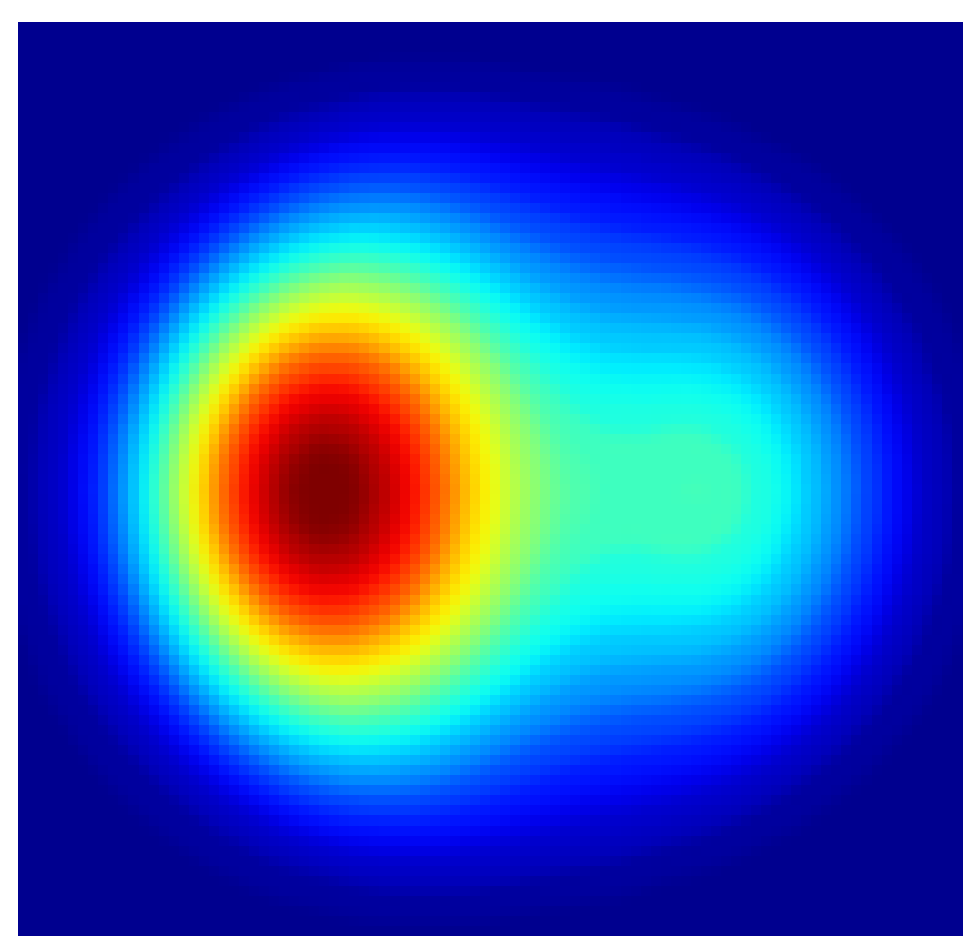
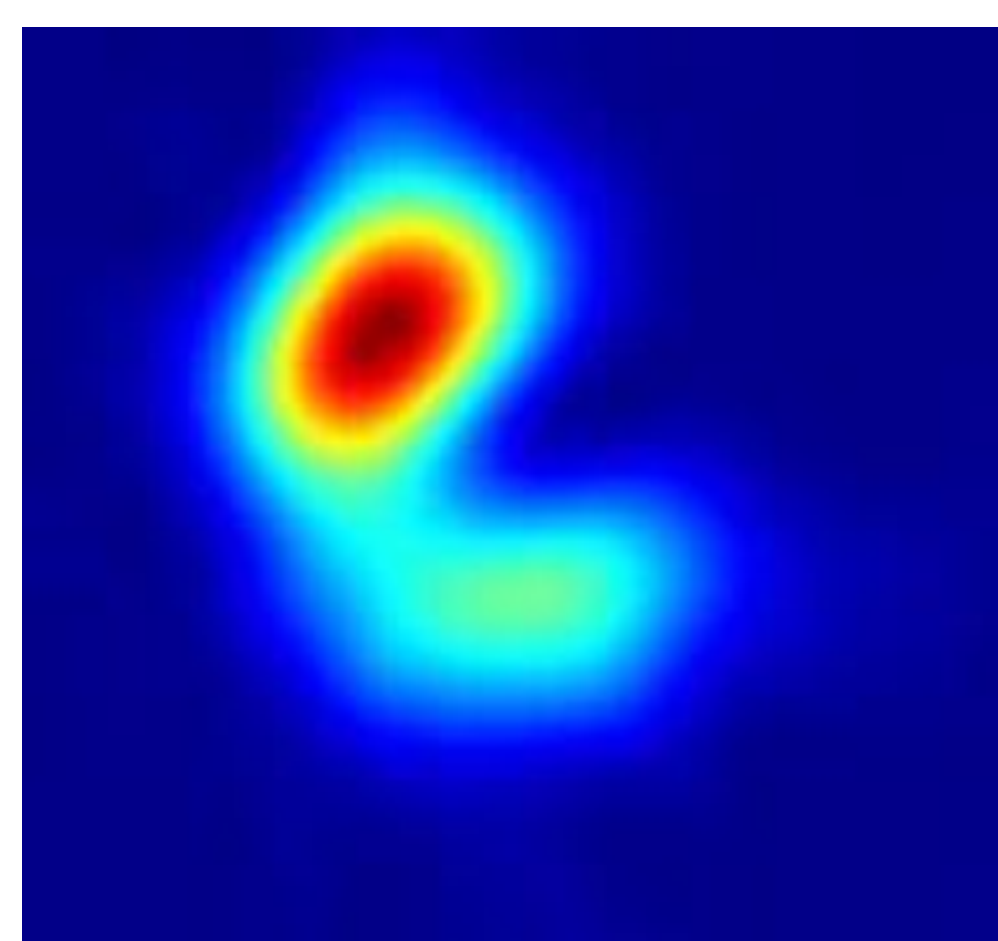
Goals

- ✓ Efficiently model BI and TMI so that simulations are rapid
- ✓ Study the interaction between BI and TMI

How TMI is observed

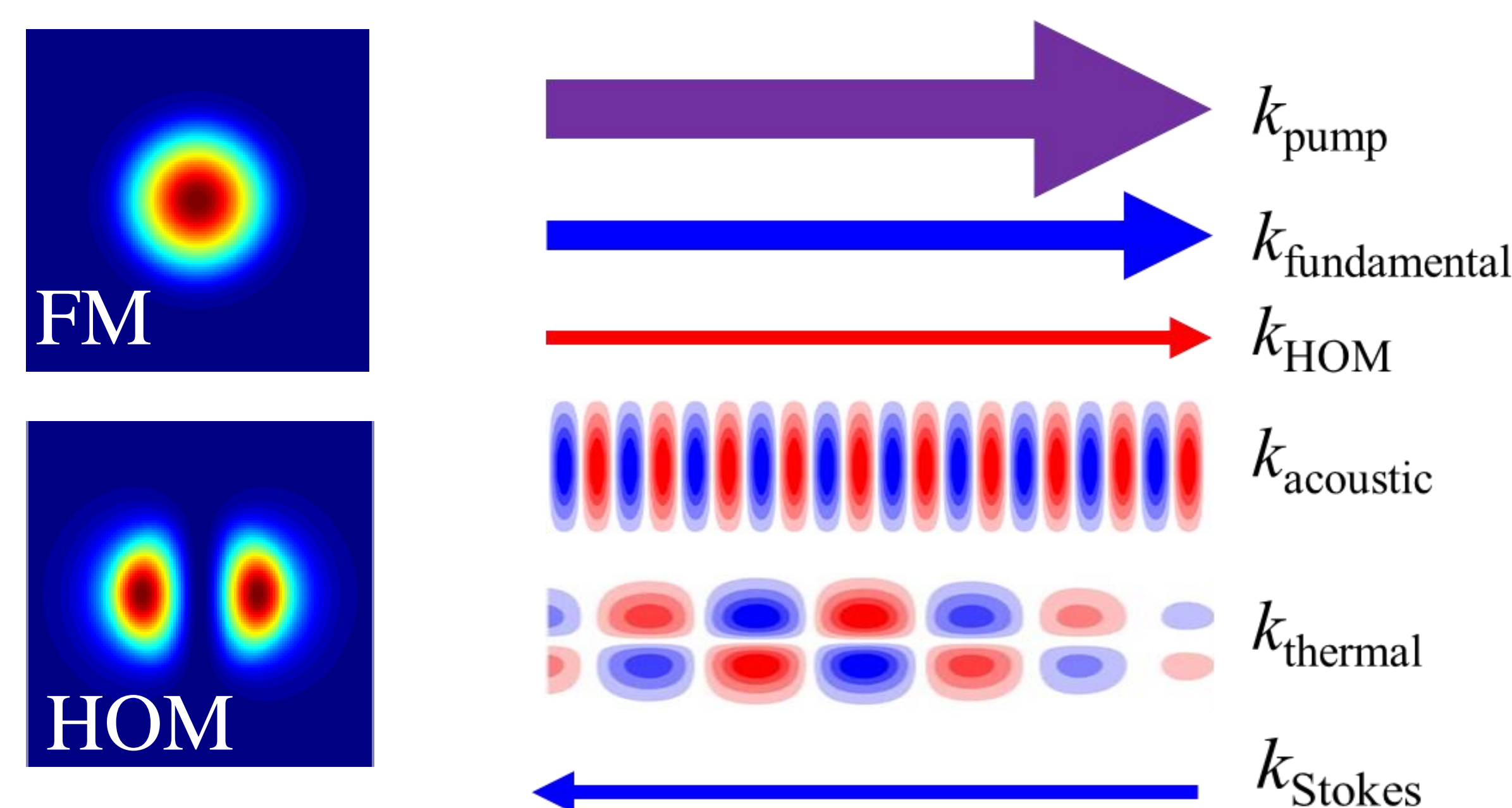
Experiment³

Simulation



The output mode profile unpredictably changes as a function of time, which degrades the beam.

Modes considered for BI+TMI



Modeling BI + TMI requires optical, thermal, and acoustic modes.

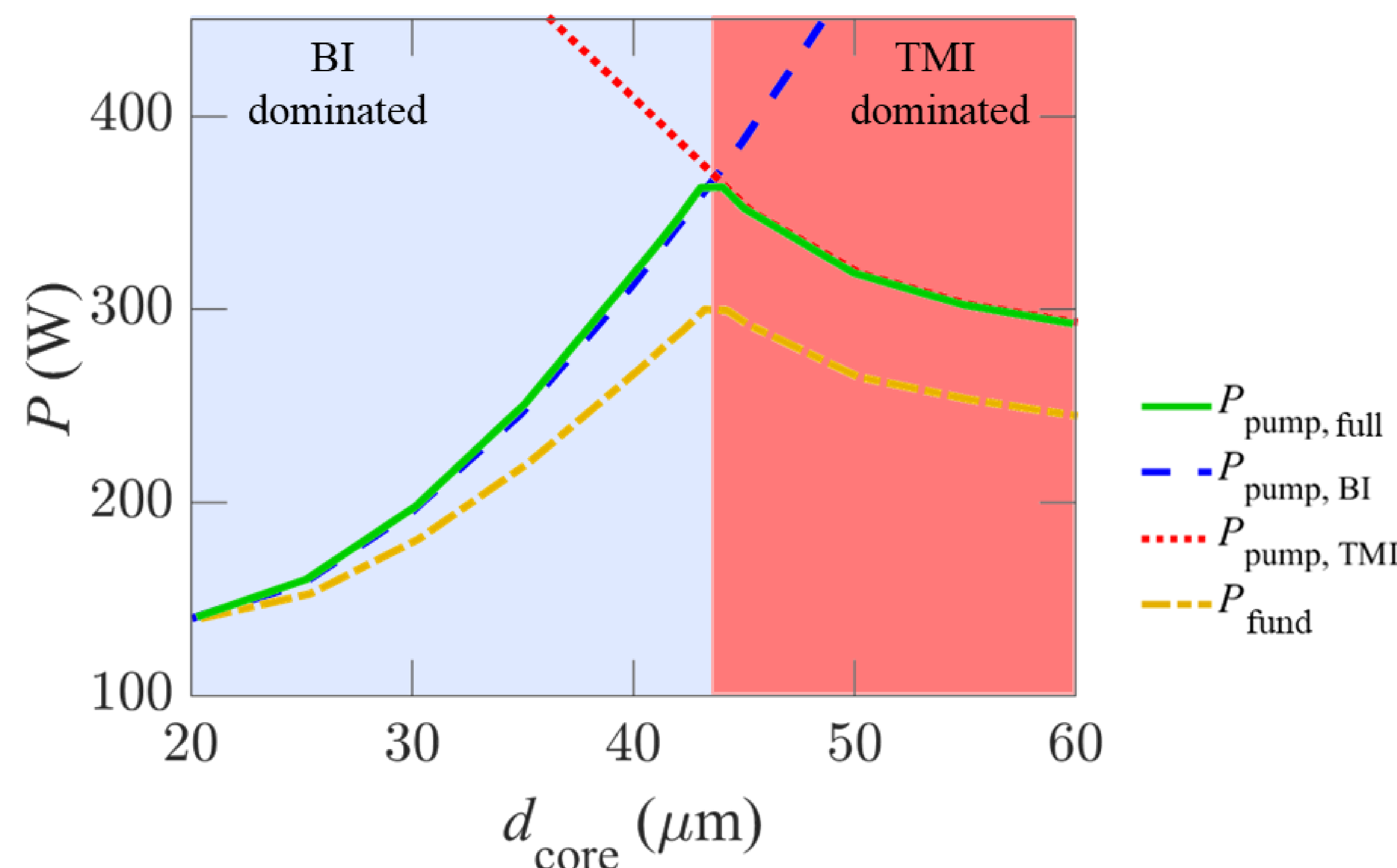
BI equations with TMI gain terms⁴

$$\begin{aligned} \frac{dA_1}{dz} + \frac{1}{v_g} \frac{dA_1}{dt} &= c_{11}A_1 + c_{10}A_0 \\ -\frac{dA_S}{dz} + \frac{1}{v_g} \frac{dA_S}{dt} &= c_{00}A_S + ikA_0\rho^* \\ \frac{d\rho}{dt} + \pi\Delta v_{B\rho} &= i\frac{\Lambda}{A_{eff,l}}A_0A_S^* + f \end{aligned}$$

$$\begin{aligned} c_{00} &= \frac{i\omega^2}{\beta c^2} n_0 \int d^2\mathbf{r}_\perp |\varepsilon_0|^2 \Delta n_0 \\ c_{01} &= \frac{i\omega^2}{2\beta c^2} n_0 \int d^2\mathbf{r}_\perp \varepsilon_0^* \cdot \varepsilon_1 \Delta n_+ \\ c_{10} &= \frac{i\omega^2}{2\beta c^2} n_0 \int d^2\mathbf{r}_\perp \varepsilon_0 \cdot \varepsilon_1^* \Delta n_- \\ c_{11} &= \frac{i\omega^2}{\beta c^2} n_0 \int d^2\mathbf{r}_\perp |\varepsilon_1|^2 \Delta n_0. \end{aligned}$$

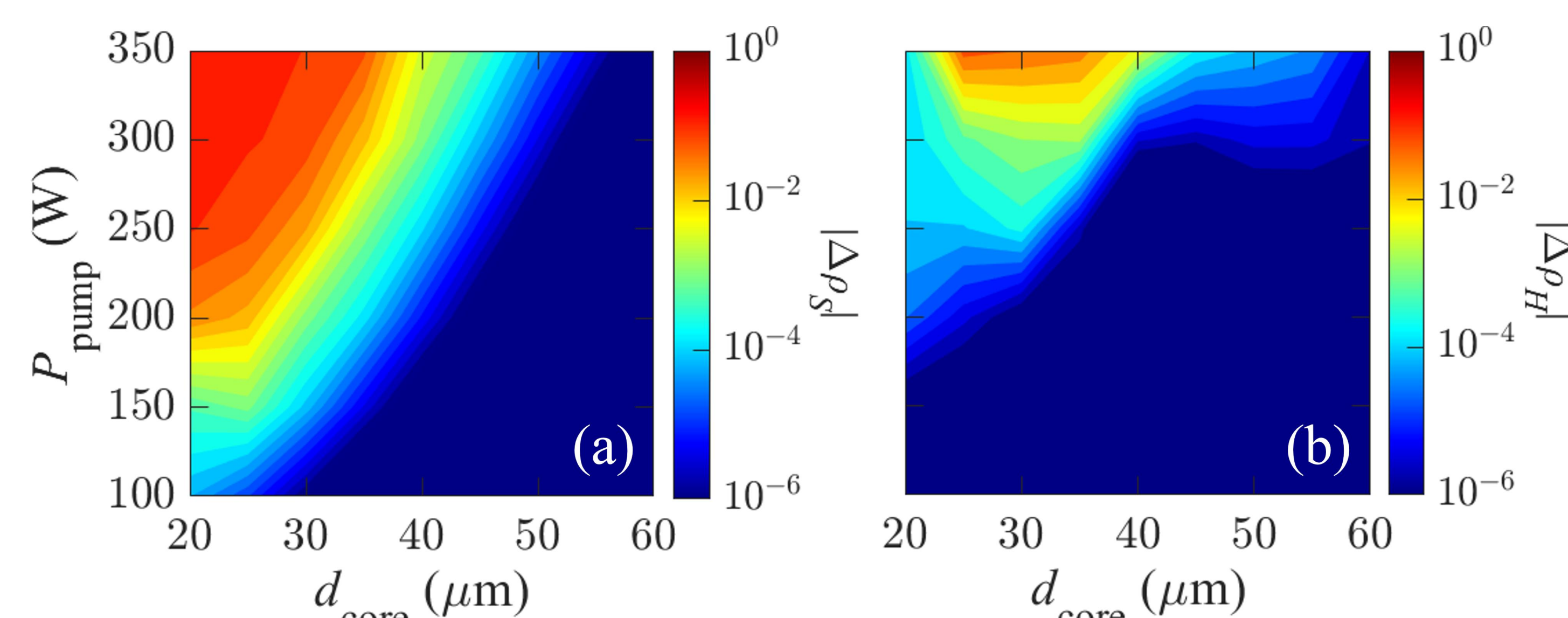
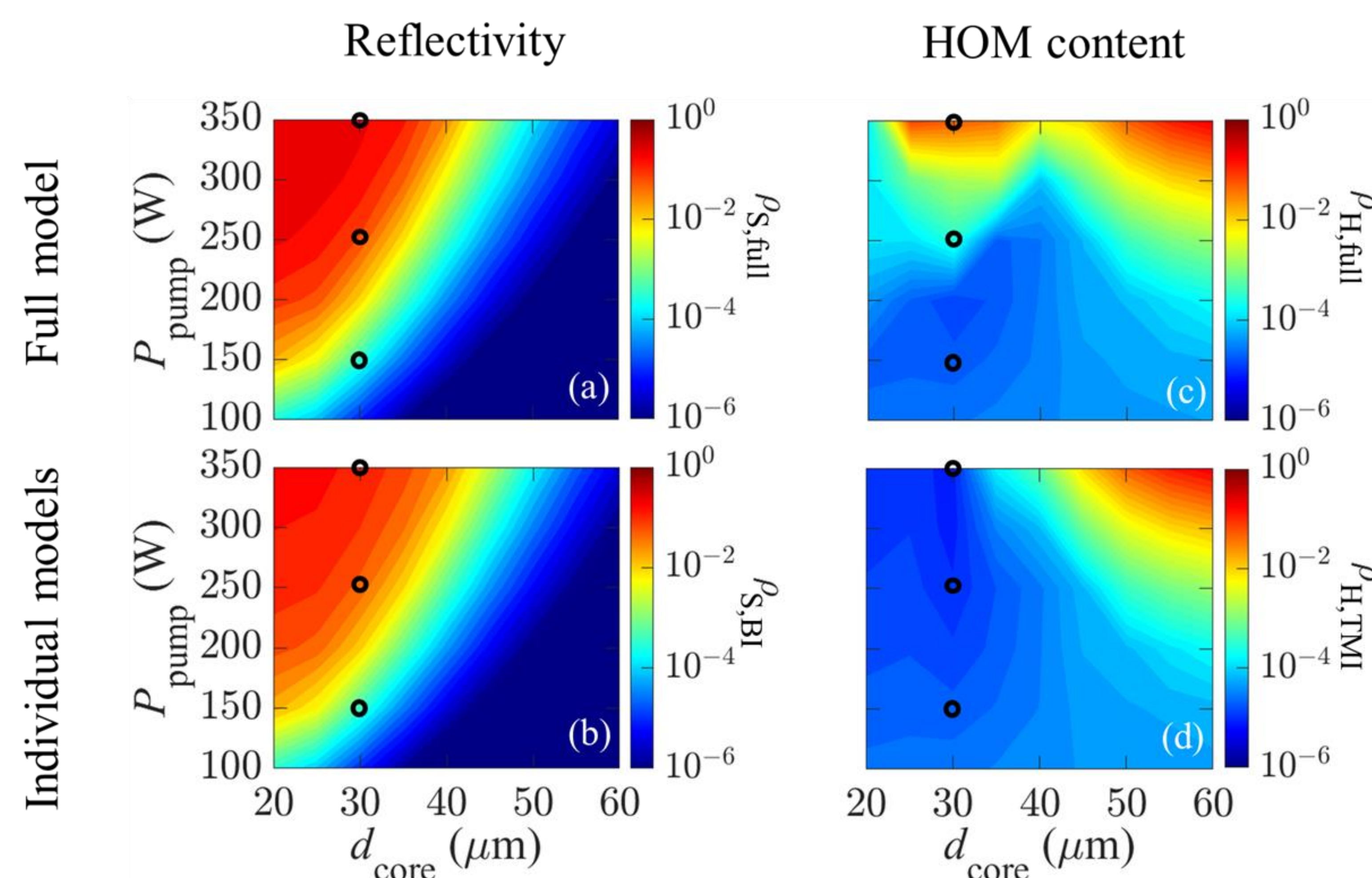
TMI contributes to the gain terms in the BI equations⁴

Power threshold when considering BI and TMI⁴



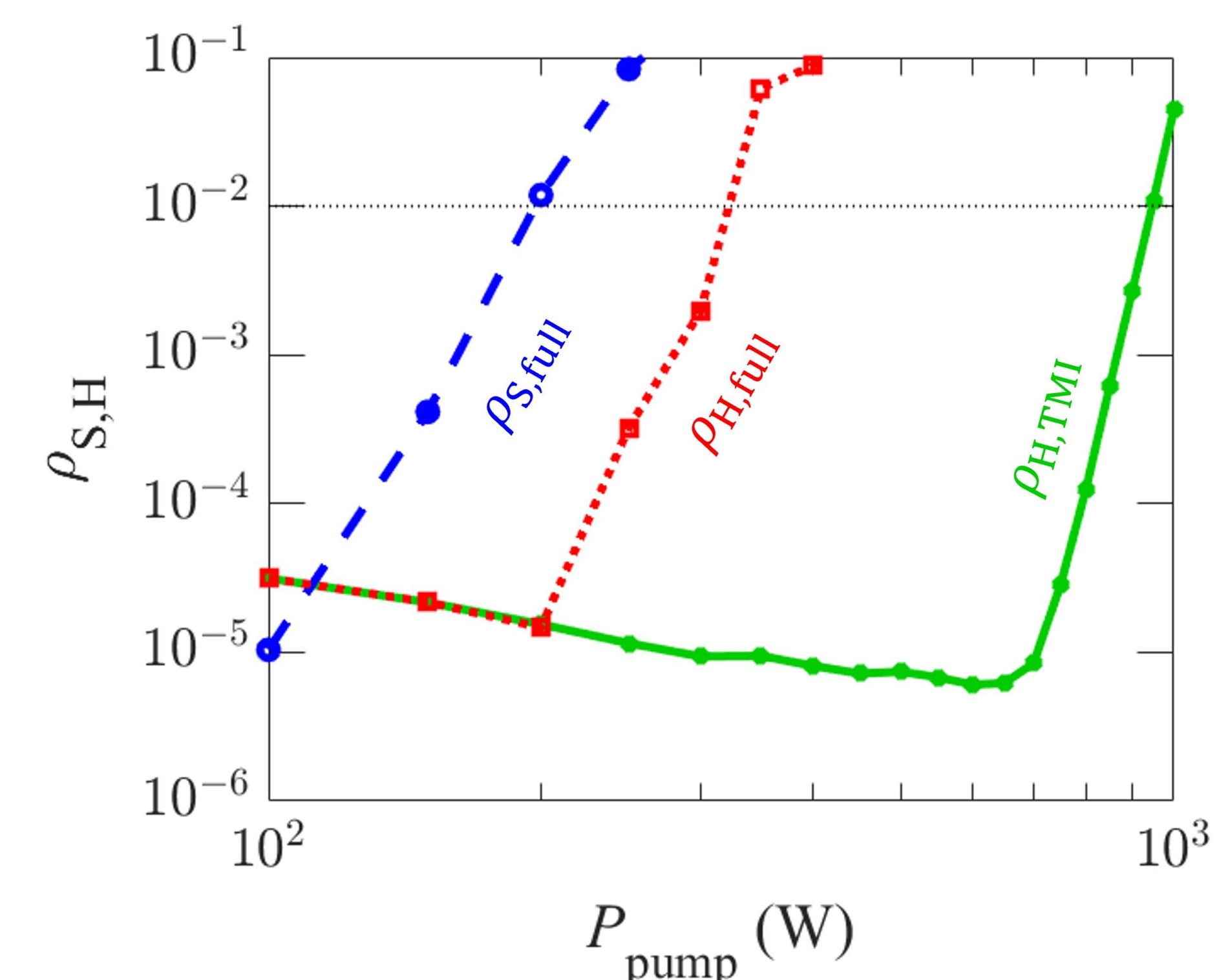
Below the 1% threshold definition, the full BI+TMI power threshold closely follows the threshold for the individual effects.

Pump power threshold when considering BI and TMI⁴



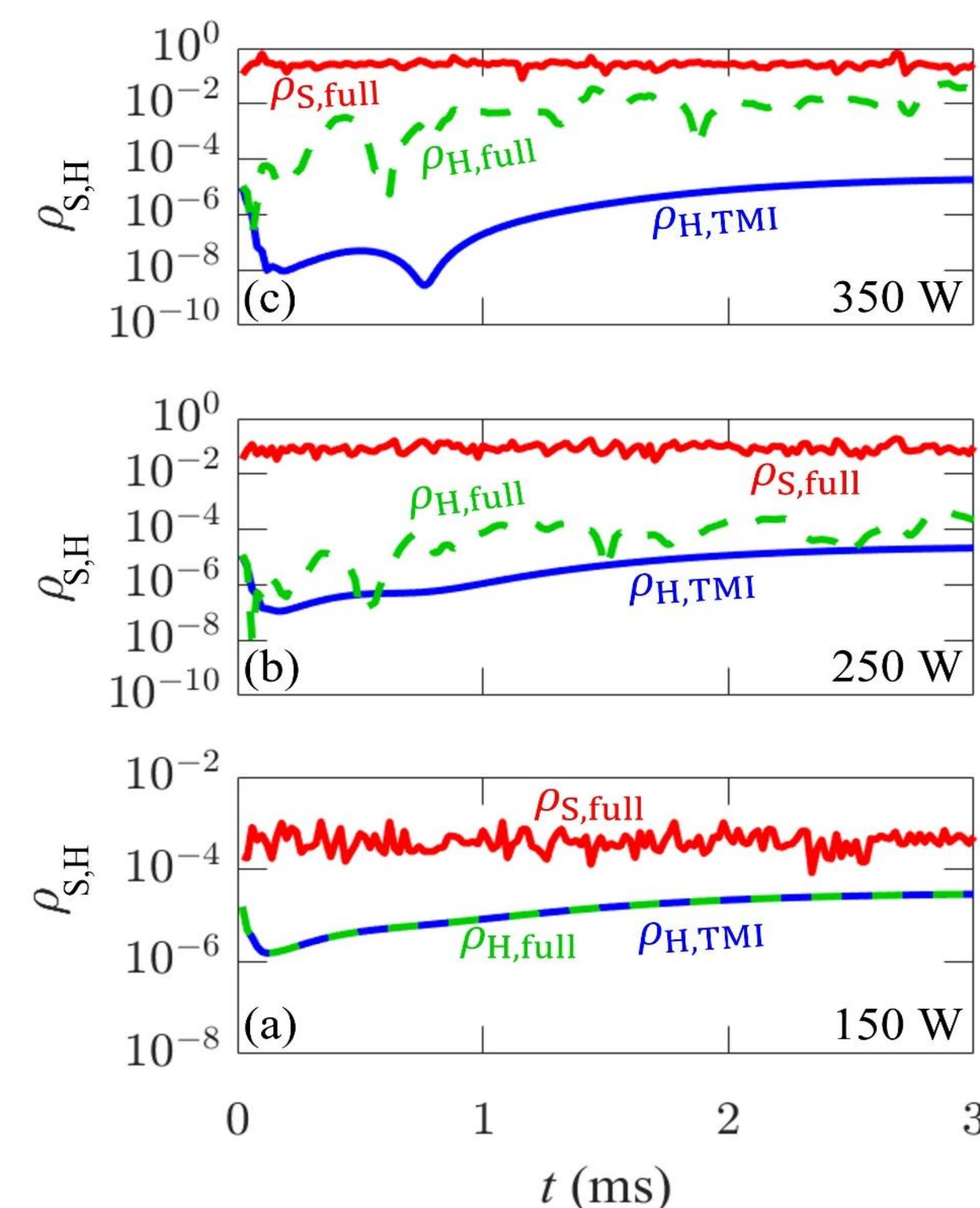
There is negligible difference in the reflectivity contour shape between models. There is a difference in the HOM content contours between models.

Onset of HOM content due to BI



At low reflectivity, there is negligible difference in predicted HOM content.

Reflectivity and HOM content at different power levels⁴



- With low reflectivity, there is a negligible interaction.
- With higher reflectivity, the BI triggers TMI.

Conclusions

- ✓ Transverse mode instability (TMI) and Brillouin instability (BI) can limit operating powers for fiber amplifiers.
- ✓ Under 1% reflection or HOM content, the pump power threshold for the full model mimics the threshold for each individual effect.
- ✓ At larger pump powers, when reflectivity is greater than 1%, BI may trigger TMI.

References

- [1] M. N. Zervas, *et al.*, J. Sel. Topics Quantum Electron **20**(5), (2014).
- [2] Menyuk, *et al.*, Opt. Express **29**(12), (2021).
- [3] H.-J. Otto, *et al.*, Opt. Express **20**(14), (2012).
- [4] Young, *et al.*, Opt. Express **30**(22), (2022).