Thermal limits of a freeform ring-shaping head for a multimode fibre laser

Laser welding head at 1030 nm, ring of 3 / 2 mm diameter, laser power from 6 kW to 40 kW

Application

In a welding head, a freeform mirror turns the beam of a fibre laser into a ring on the work piece. At several kilowatts the optics absorb part of the beam and heat up, and the ring grows and loses energy. This note asks how much power the head can take, and what limits it.

Modelling approach

We modelled the head from the fibre face to the work piece, with its coatings, mounts and water cooling. The ring is traced with real rays from the whole fibre face, through the hot optics at each laser power. We accept the ring if at least 85 % of the power falls inside it, and if its uniformity, diameter and width stay within tolerance.

1 The head

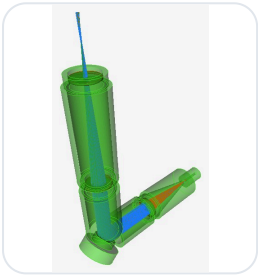


Figure 1. The head as modelled in etendue. A lens collimates the beam from the fibre. A copper freeform mirror, folded at 45° on a water-cooled block, shapes it. A second lens focuses the ring through a protective window. **Table 1.** Main parameters.

PARAMETER	VALUE	PARAMETER	VALUE
Laser power	6 kW	Collimating lens focal length	150 mm
Wavelength	1030 nm	Focusing lens focal length	300 mm
Fibre core, numerical aperture	200 µm, 0.1	Ring outer diameter	3 mm
Beam parameter product	8 mm·mrad	Ring width	0.5 mm

2 The ring against laser power

in specification up to 10 kW

How far can the power go? With the mirror designed for cold optics, up to 10 kW. The ring grows with the heat, and at 12 kW only 84.8 % of the power falls inside it.

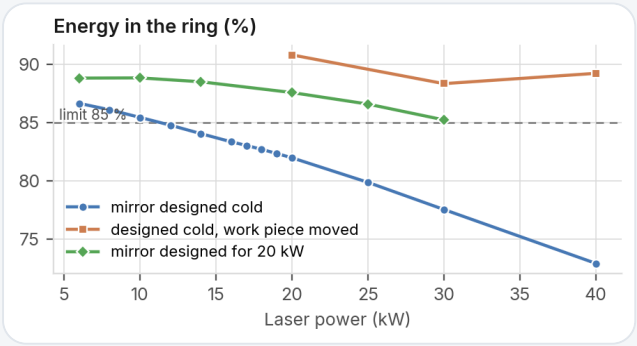


Figure 2. Energy in the ring against laser power. With the work piece moved, each power has its own best position.

10 kW
Highest power with the mirror designed for cold optics, Gaussian heat model.

40 kW
With the work piece 3 mm closer to the window.

6 to 30 kW
With a mirror designed for 20 kW.

40 ppm
Window absorption accepted at 6 kW, 2 times the clean coating.

3 What limits the power

What limits the power? The protective window. It absorbs about as much as each lens, but it loses its heat only through its rim, and the ring shaper concentrates the beam on its axis. The cooling circuits are not the limit. Once the stray light is traced into the hot state, the tube that holds the fibre limits first (page 2).

39 K
Temperature rise of the window at 6 kW.

7 K
Temperature rise of the warmest lens at 6 kW.

30 W
Heat removed by the water-cooled mirror block at 6 kW.

6 µm
Growth of the ring diameter per kW.

What limits the power, and what to change

The protective window heats far more than the lenses. Moving the work piece or designing the mirror for the hot optics extends the range.

Table 2. The ring at each laser power

Mirror designed for	Used at (kW)	Outer diameter (mm)	Uniformity	Energy (%)	Criteria met
cold optics	0	3.042	0.197	87.9	4 of 4
cold optics	6	3.077	0.164	86.6	4 of 4
cold optics	10	3.099	0.161	85.4	4 of 4
cold optics	12	3.111	0.163	84.8	3 of 4
20 kW	0	2.924	0.226	88.5	4 of 4
20 kW	6	2.956	0.213	88.8	4 of 4
20 kW	10	2.977	0.194	88.8	4 of 4
20 kW	14	2.999	0.178	88.5	4 of 4
20 kW	25	3.056	0.156	86.6	4 of 4
20 kW	30	3.090	0.154	85.2	4 of 4
cold optics, moved −3 mm	40	3.018	0.199	89.2	4 of 4

Criteria: energy at least 85 %, outer diameter within 5 %, width within 10 %, uniformity below 0.25 (a limit chosen for this demonstration). Blue rows: mirror designed for the hot optics at 20 kW. Last row: work piece moved towards the window.

Table 3. Heat to remove

Laser power (kW)	Absorbed by the optics (W)	Removed by the mirror block (W)	Window rise (K)
6	19	30	39
10	31	50	65

The mirror block also takes the light from the edge of the fibre that misses the mirror, 12 W at 6 kW.

Heat of the stray light, coated head

35 W
On the uncooled tube next to the fibre at 6 kW: +20 K.

12 kW
Highest power, Gaussian heat model.

5 kW
Highest power, heat of the traced light.

Why the window limits the power

The window is cooled only at its rim, into a holder without water cooling. The ring shaper also concentrates the beam on the axis where it crosses the window. The window becomes a thermal lens, and the ring grows by about 6 µm per kW.

A dirty window absorbs more. At 6 kW the ring stays in specification up to 40 ppm per face, 2 times the clean coating.

What does not help

Better cooling. With weaker water cooling of the mirror, the ring still meets its criteria at 6 kW. Cooling the window holder changes nothing, because silica conducts heat too poorly.

What helps

Moving the work piece towards the window brings the ring back. The range reaches 40 kW, one power at a time.

A mirror designed for the hot optics at 20 kW meets all criteria from 6 to 30 kW, and with cold optics too.

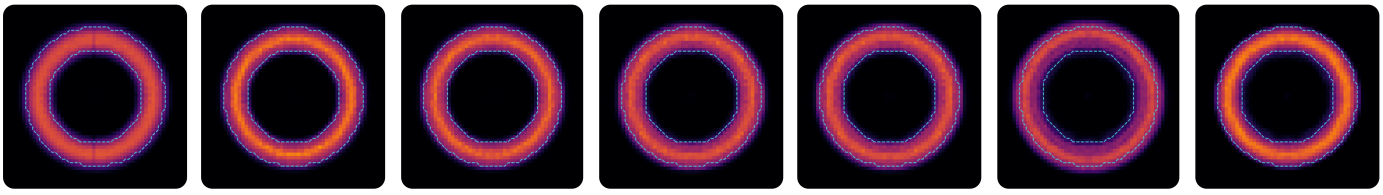
Conclusion

Treat the protective window as the critical part. Specify its coating absorption, and replace it before 40 ppm per face. Cool the tube that holds the fibre.

Stray light heats the head

The coating reflections add 0.03 W around the ring, but 2.2 W return near the fibre core (÷9 with the window tilted 2°). Traced into the hot state, they heat the tube that holds the fibre: at 6 kW the fibre moves 67 µm and the ring widens. The Gaussian model puts this heat on the cooled mirror block.

Figure 3. The ring on the work piece for each design, power and window



Designed for a point source
83.9 % · 3.00 mm

Designed for the real fibre
87.9 % · 3.04 mm

Hot, 6 kW
86.6 % · 3.08 mm

Hot, 18 kW
82.7 % · 3.14 mm

Dirty window, 80 ppm at 6 kW
82.7 % · 3.14 mm

Hot, 40 kW
72.9 % · 3.27 mm

40 kW, work piece moved −3 mm
89.2 % · 3.02 mm

Irradiance over ±2 mm, same colour scale for every map. The dashed lines mark the target ring. Under each map: energy in the ring, green when the ring meets all four criteria, red otherwise, then the outer diameter.