etendue

LASER MICROMACHINING

Spot size and shape across the field of a galvo scanner with a telecentric F-theta lens

80 W femtosecond laser at 1030 nm, two-axis galvo head, ±18° scan field

Application

In femtosecond micromachining, a galvo scanner moves the spot over the part through an F-theta lens. On axis the spot is small and round. Towards the edge of the field it grows and stretches, and the machine builder usually finds out on the test bench, after assembly. This note asks why the spot degrades at the edge, and what can be done about it.

Modelling approach

We modelled the machine from the laser output to the work piece, with the F-theta lens of a published patent. The beam was propagated to the work piece at the centre and at the edges of the field. The spot is given by its diameter along its long and short axes, measured as in ISO 11146 (second-moment diameter).

1 The machine

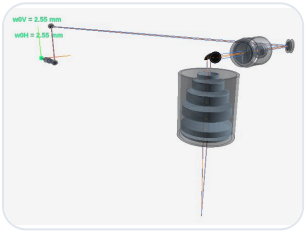


Figure 1. The machine as modelled in etendue, with its mechanical parts. A periscope carries the beam to a beam expander. Two galvo mirrors then steer it into the F-theta lens, which focuses it on the work piece. **Table 1.** Main parameters.

PARAMETER	VALUE	PARAMETER	VALUE
Average power	80 W	Expander magnification	2
Pulse energy, duration	400 µJ, 290 fs	Galvo mirror aperture	14 mm
Wavelength	1030 nm	F-theta focal length	165 mm
Beam transport to the galvos	2.5 m	Scan field	±18°

2 The spot across the scan field

How does the spot change across the field? On axis it is round, 25 µm across. At the X edge it stretches to 151 × 41 µm, because its focus lies 2.2 mm behind the work piece. The Y edge suffers less. Three changes to the machine reduce the effect.

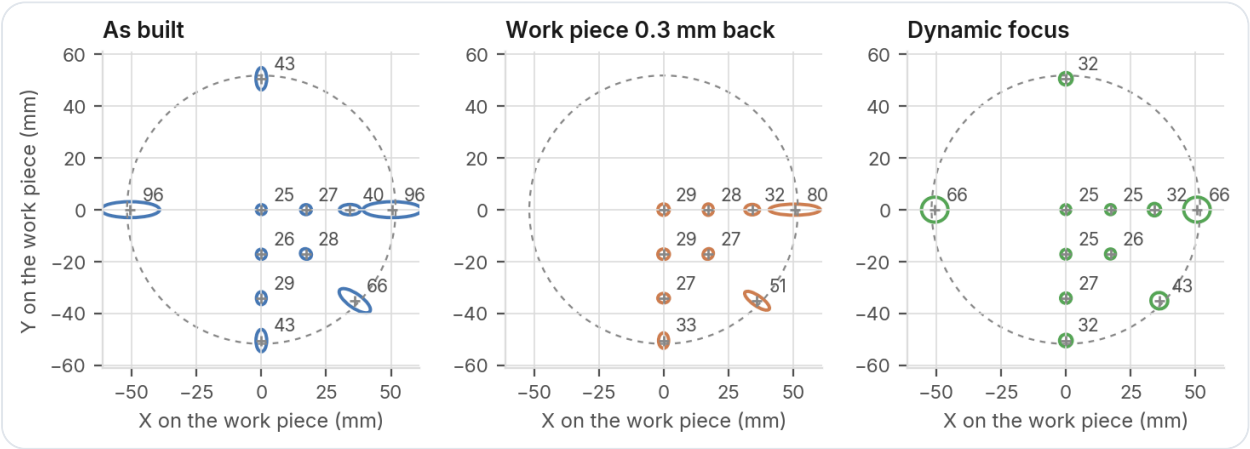


Figure 2. The spot at each scan position, drawn 150 times its real size, with its mean diameter in µm. Left: the machine as built. Centre: the work piece moved 0.3 mm further from the lens. Right: with a dynamic focus. The dashed circle is the ±18° field.

151 × 41 µm
Spot at the X edge of the field, long by short axis. On axis it is 25 µm and round.

42 → 37 µm
Mean spot over a quarter of the field when the work piece is moved 0.3 mm further from the lens.

68 × 64 µm
Spot at the X edge with a dynamic focus, which moves the first expander lens by up to 1.3 mm.

65 → 94 %
Power passed by the galvo mirrors at the X edge, before and after enlarging the second mirror.

Why the spot degrades at the edge, and what to do

The two galvo mirrors see the F-theta lens from two different places. Neither sees a flat focal plane.

Table 2. Spot diameter across the field, long × short axis (µm)

SCAN POSITION	AS BUILT	WORK PIECE 0.3 MM BACK	DYNAMIC FOCUS	POWER PASSED (%)
Centre	25 × 25	29 × 29	25 × 25	97
X, part way, 12°	54 × 27	38 × 27	32 × 32	85
X edge, 18°	151 × 41	131 × 28	68 × 64	65
Y edge, 18°	57 × 28	40 × 26	32 × 32	97
Diagonal edge, 18°	95 × 36	76 × 26	43 × 42	84

The angle is the scan angle on the work piece. The power passed is the share that the two galvo mirrors let through.

Table 3. Effect of the expander magnification, without dynamic focus

Magnification	Spot, centre (µm)	Spot, X edge (µm)	Power passed, centre (%)	Power passed, X edge (%)
1.5	34	118 × 43	100	76
2	25	151 × 41	97	65
2.5	20	186 × 44	91	55

A wider beam focuses to a smaller spot, but its shorter Rayleigh range makes the edge worse, and the mirrors cut off more of it.

Why the spot degrades

The F-theta lens does not focus on a flat plane. Seen from galvo X, at 18° the focus lies 2.16 mm off the work piece along the scan and 0.46 mm across it. The Rayleigh range of the beam is 0.40 mm, so the spot at the edge is far out of focus.

Seen from galvo Y, the error is smaller, 0.73 and 0.13 mm. The two mirrors sit 42 and 58 mm from the lens, so each sees the lens differently. At the X edge the two foci are 1.7 mm apart. No focus setting removes this astigmatism; a lens designed for two mirrors would.

What to do

Moving the work piece 0.3 mm further from the lens costs nothing. The mean spot over the field drops from 42 to 37 µm, but the X edge stays at 131 × 28 µm.

A dynamic focus moves the first expander lens by up to 1.3 mm. The X-edge spot becomes nearly round, 68 × 64 µm.

At the X edge the second galvo mirror cuts off part of the beam, and 65 % of the power reaches the work piece. A second mirror sized for the scan brings it back to 94 %.

Other checks

At the edge, the spot lands 2.4 % short of the f·θ position, so the scanner needs a correction table. The peak fluence on the most exposed mirror is 0.0037 J/cm², well below the 0.2 to 0.7 J/cm² published for femtosecond mirrors. The heat absorbed at 80 W moves the focus by 19 µm at most.

Figure 3. The spot on the work piece at each scan position, and at the X edge with each change



The X edge with each change. Compare with the spot as built, top right.

Each map covers ±90 µm with the same colour scale, the square root of the irradiance. The dashed circle is the spot on axis. The percentage is the power that the two galvo mirrors pass.

Spot diameter as in ISO 11146, from the beam propagation; the power passed by the mirrors is traced with real rays.