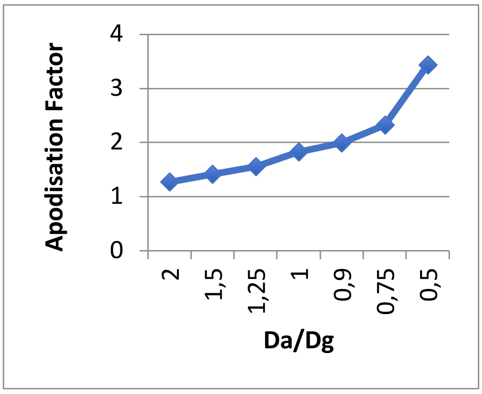
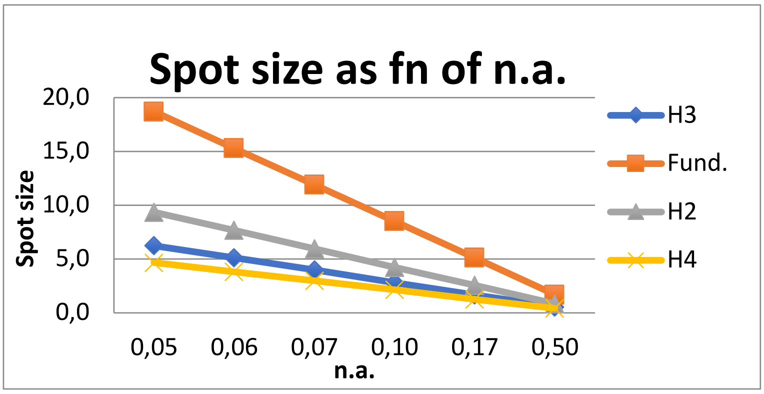
Spot Sizes Using Scan (& other) Lenses

Theory

In the world of the suppliers of scan (& other) lenses for laser processing, a generally accepted 'engineering formula' for spot size is **d=1,27*lambda*f.l./A** referring to 1/e2 dia. for an essentially untruncated **TEM00 Gaussian beam**, about which one can immediately comment as below:-

- No Gaussian beam is untruncated; minor truncation gives insignificant departure from the ideal case, severe truncation leads to some complex maths. The spot is no longer truly Gaussian so the notion of 1/e2 points starts to suffer, but there are tables which attempt to express the resulting beam broadening as an **Apodisation Factor** (this is the 1,27 in the formula above, which is APO=1,27 for a beam diameter Dg only half the diameter of the lens pupil Da; for one the *same* diameter as the pupil one should use APO=1,83, which some suppliers prefer. APO values as a function of Da/Dg are plotted (data from Sill Optics). The ratio f.l./A is the f# of the lens, which is the most important factor influencing spot size at a given wavelength. More generally in use is the **numerical aperture n.a.** of the lens, = 1/(2*f#). N.B. spot size does NOT depend on focal length other than by the fact that it is easier to make short f.l. lenses with high n.a.





- N.B. Shorter wavelength leads immediately to smaller spot sizes, but has to be weighed against laser performance at higher harmonics and the difficulty of making optics for shorter wavelengths. The gain in going to 2nd harmonic is dramatic, with little penalty. 3rd harmonic can offer a useful further gain without too much difficulty, and helps with absorption in transparent materials. The marginal gain in going to 4th harmonic is not worth the effort, 4th harmonic crystal lifetimes remain unpredictable & optics are a headache. Particularly with pulse duration 10ps & shorter (USP), wavelength becomes of secondary importance since multi-photon effects predominate anyway, allowing efficient machining of normally transparent materials.

- No laser emits a perfectly Gaussian beam; the accepted **measure of focusability is M^2**, which in principle is applied as a multiplicative factor to the above, and which for typical lasers is 1.1-1.3 in the IR.

- No optics are perfect, there will always be **aberrations** at some level. Generally one talks of 'diffraction limited' meaning that level is not dominant compared to diffraction effects.

- 1/e2 is useful for optics theory, 1/e or FWHM make more sense for **materials processing**, with a correction factor of √(1/2) or √(ln2/2 in those two cases, but also one finds that the minimum width of feature that can be written depends on the material, even when parameters are tweaked. One would imagine that short pulse lasers would give less material dependence on spot size, but in practice this does not seem to be the case, and processing results with various makes of USP lasers bears this out.

- Practically speaking, an assumption that corrections UP for M^2 & aberrations & DOWN for half power result in a final correction factor not far from unity is probably not far from the truth, and is borne out by experience.

Next point concerns the definition of A which is the effective diameter of the beam at the lens pupil. Since a beam will naturally diverge with distance, or can be expanded with a BET, one might reasonably ask if these two cases are the same, particularly since distances can be relatively long in a complex system. Here is an erudite explanation from optics guru Prof. Leo Beckmann:-

> « The lens knows nothing about the radiation source; it only sees, in the case of such a laser beam, an incoming wavefront with Gaussian intensity profile with a) a given diameter (measured at the 1/e^2 level) & b) with a specific wavefront curvature. More specifically, the lens does not know what caused that curvature - just ordinary beam propagation (according to well-known formulas) or some optics (such as a telescope). The lens now modifies that curvature by its "power", which means, that it just "bends" the incoming wavefront - the only important thing a (perfect) lens really does. Thus a new wavefront emerges from the lens, which is typically made to be concave in the direction of light propagation. Together with the (unchanged !) diameter of the wavefront, such a concave wavefront is associated with a convergent Gaussian beam, the n.a. of which then determines the size of the image waist. «

Prof. Beckmann goes on to point out that the formulae for all of these things are known exactly, but are non-linear, and therefore cannot in principle be neatly tied up in a single 'engineering' formula as above,- whilst allowing that the differences are negligible for distances less than or comparable to the Raleigh range, which are generally on the order of some metres for commercially available lasers.

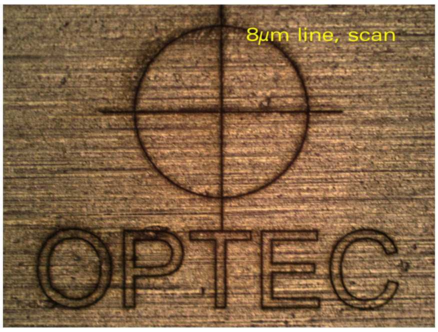
> « …the curvature of the incoming wavefront, which does depend on upstream optics, determines the exact axial position of the focus, though again the differences for naturally & BET expanded beams are small, comparable to the DOF «

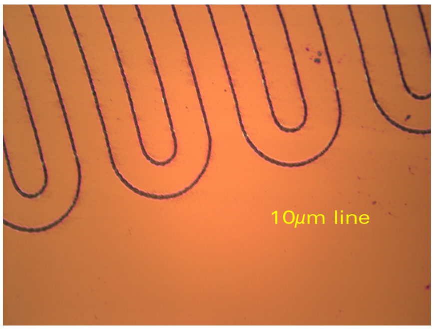
Exact simulations using optical simulation software which can handle wavefronts & gaussian beams, such as Leo Beckmann's own **OpDesign** program, confirm all of these points.

Theory vs Practice

Focus tests using different lenses and writing tracks in brass foil and thin metal films on polymer, with results as follows, each time according to the 'engineering' formula, with no attempt to correct for any of the points noted above, either way; the agreement is remarkable.

lambda	f.l.	A	TEM00	Measurement
1030	160	15	20,1	18,0
1030	25	6	7,9	8,0
515	160	10	15,1	16,0
515	100	10	9,4	10,5
343	100	6	10,5	9,0
343	56	6	5,9	5,0
343	13	9	0,9	<1

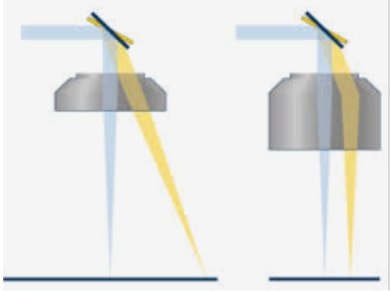




Smaller Spots = higher n.a. Lenses

Scan lenses, particularly those suitable for short pulse lasers, are limited in n.a. Fixed lenses,- i.e. with limited field, based on microscope objectives, do offer n.a. on this order, but also suffer from short w.d. & poor lifetime with short pulses. Fused silica aspherics are now available with n.a. up to approximately 0,45, giving theoretical performance at µm level on 2nd & 3rd harmonics.

Telecentricity



In any scan lens, spot distance from the axis is proportional to galvo mirror tilt theta. In an **f-theta** lens (left) that distance is also proportional to the focal length, but with a larger spot as above. In a lens designed for **telecentricity** (right), there is no such dependence, but clearly the field cannot be larger than the clear aperture of the lens. Telecentric lenses are used for deep drilling & cutting where the beam should be normal to the surface, sometimes controlling taper by precessing around that normal using an additional optical module e.g. https://www.lasea.eu/oem/ls-precess/
Perfect telecentricity is not possible since the two galvo mirrors cannot physically occupy the same axial location.