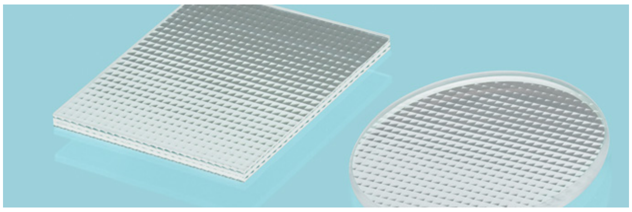
Design Rules for Array Type Homogenizers

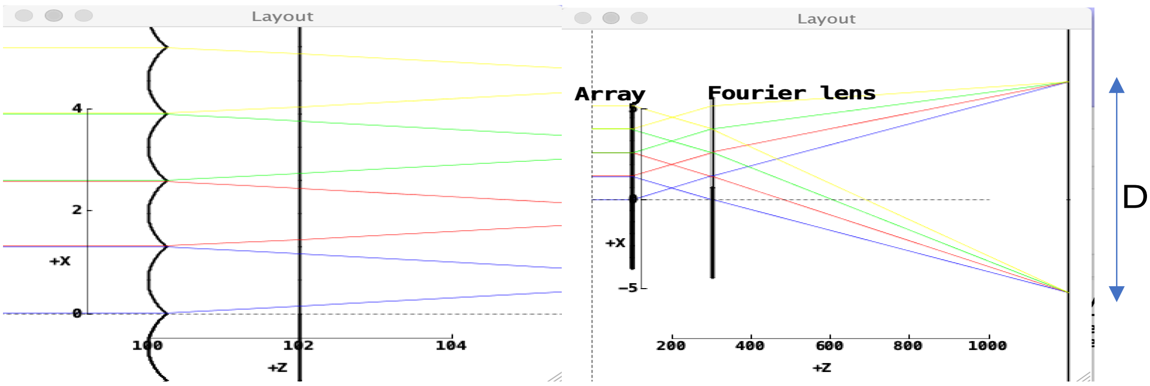
Microlens arrays (MLA) can be used with excimer lasers to create **integrating homogenizers** ensuring uniform intensity illumination of a part, or mask, whose image is projected onto the part.



The image here shows a double-sided array with a 2D grid of cylindrical microlenses, commonly referred to as **XCyl arrays**.

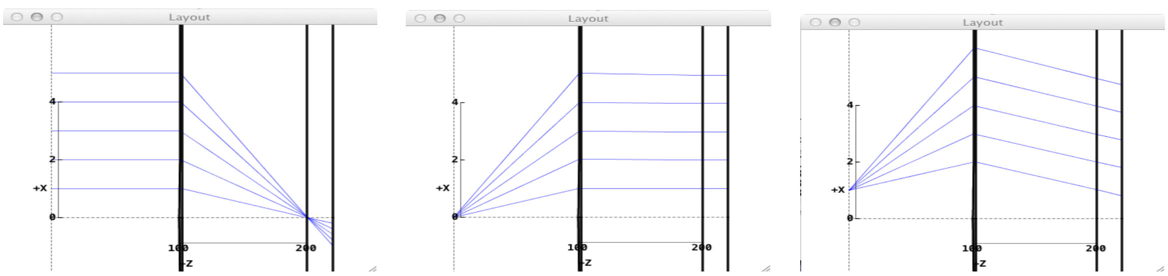
1D cylindrical arrays provide homogenization in one axis only, and in some cases hexagonal arrays of spherical elements have also been used.

In the **Beam 4** simulation views following, rays (coloured) propagate from left to right At left, a schematic detailed cross section of the array. At right with the lateral scale (vertical here) highly expanded. a ray tracing of the MLA together with a focussing lens;- commonly referred to as a **Fourier lens**. Each element of the array acts together with the Fourier lens to image its back focal plane onto the Fourier lens focal plane. The array effectively chops the input beam (left) into segments (indicted here by different colours), and superimposes these different segments in the target plane (right); thus each location on the target is illuminated by contributions from different parts of the beam, hence smoothing out the effect of inhomogeneities in the original beam profile; unwanted structure in the beam is 'diluted' by the superposition of the different contributions from each lenslet in the MLA.

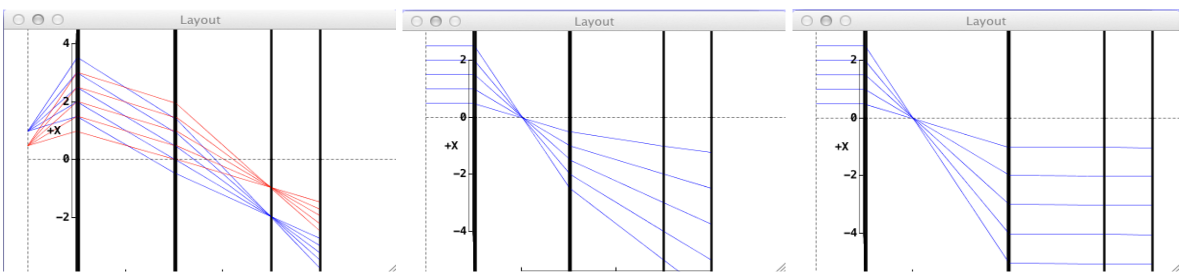


The width of the final distribution **D** is equal to **p** x **Ff/Fa**, where **p** is the **array pitch** (i.e. microlens size) and **Ff** & **Fa** are the focal lengths of the Fourier lens and MLA respectively. However, this simple explanation hides some complexity…

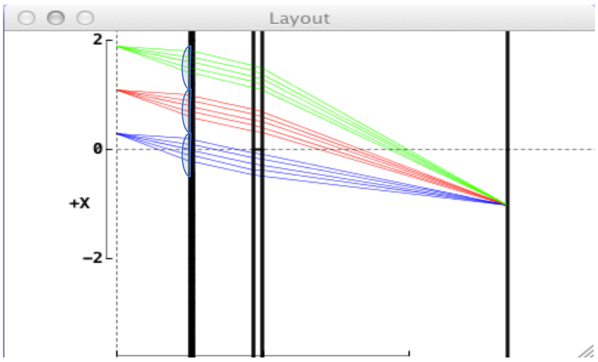
Pretty much the first thing we learn about a lens is that, in the paraxial approximation where aberrations are negligible, initially parallel rays are brought to a point (the focus) and conversely that rays emanating from a point in the focal plane are made parallel, also for an off-axis point:-

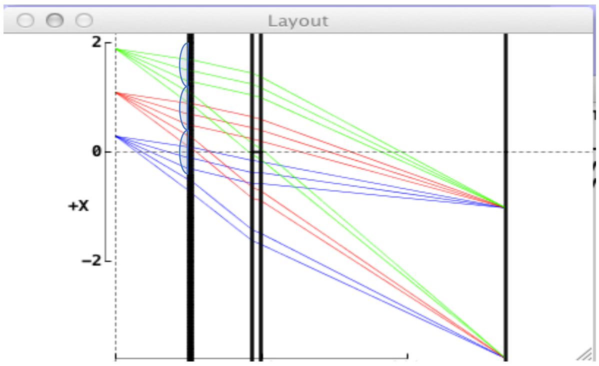


Thus, two lenses can image a point source or sources, where lateral distances are multiplied by the ratio of the lens focal lengths, giving rise to the notion of magnification. Note this occurs independently of inter-lens separation, but if in addition the latter is equal to the sum of the focal lengths then initial ray directions are also preserved (inverted), as is most obvious by examining initially parallel rays (at right). Such an arrangement of lenses is termed an optical relay.



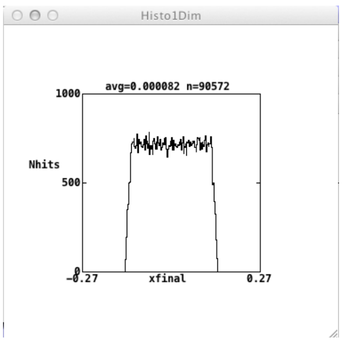
Each element of the lens array behaves in exactly the same way with respect to the Fourier lens; the difference is only that, unlike the case above, the lens element is limited in size, and moreover bounded by neighbouring elements in the array, so that there is a limit to input ray fan size. Since array elements are offset w.r.t the Fourier lens axis, each element in the array maps a different object point into the same image point, ***provided*** that all rays starting from that point fall into the same element. If not,- i.e. if the ray fan size is too big;-,-then we have the situation at right This is important, see later.

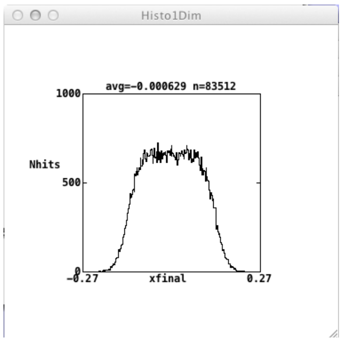


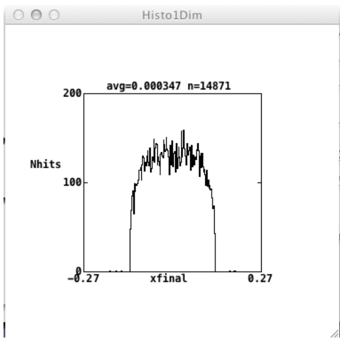


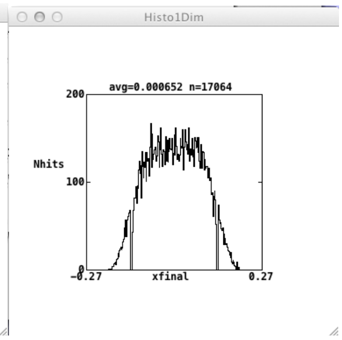
One or Two Arrays ?

In the absence of divergence, a single array used as above would produce the ideal **top hat shaped beam** left; in the real world, the profile is more like 2nd from left Why? Consider just the patch of beam in the back focal plane of one element of the array. Because of beam divergence, some of the photons near the edges of the patch miss that array element, leading to Fig3. However the photons that 'miss' are not lost but as above enter the nearest neighbor elements where they are also imagined by the Fourier lens, but with a lateral offset equal to **D**, so that the combined effect is as indicated at right below.



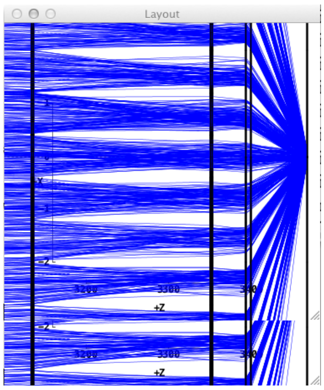


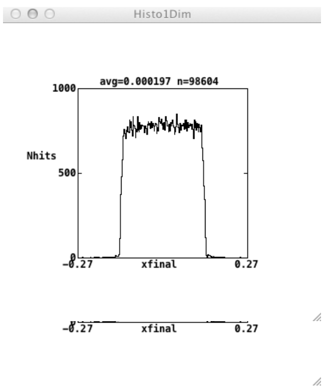


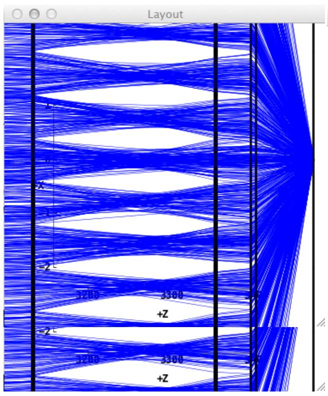


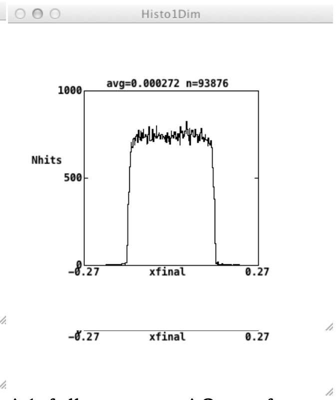
For arrays of short f.l., leading to large D, and particularly where a mask will be used to trim off the edges of the beam, this effect can be tolerable because short f.l. means fewer photons lost into neighbouring elements in this way, and also that edge effect becomes negligible compared to the overall size of the beam spot D.

If not, an **illumination array A1** can be used, often in or close to the back focal plane of the **imaging array A2.** At left, an illuminating array A1 with significantly longer focal length than the imaging array A2, and whose job is to ensure that no photons from the illuminating patch will fall into neighbouring lens array elements. A somewhat shorter ROC also works,



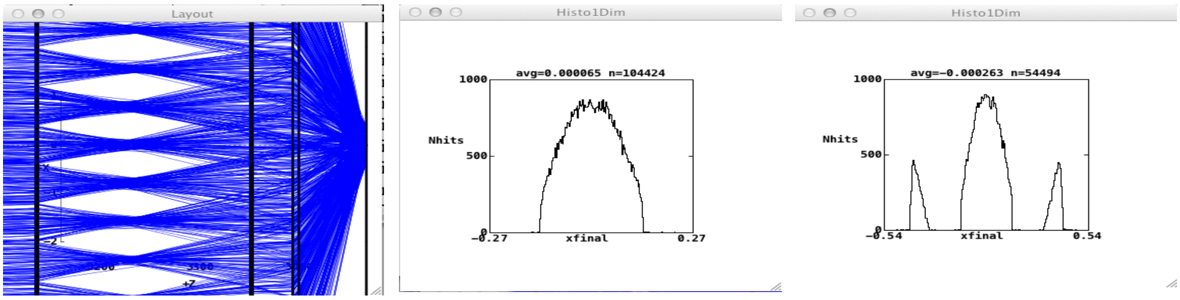






(right), with beam waists between the arrays. One has always to avoid hot spots from A1 falling onto A2, so for e.g. f.l. cannot should not be the same.

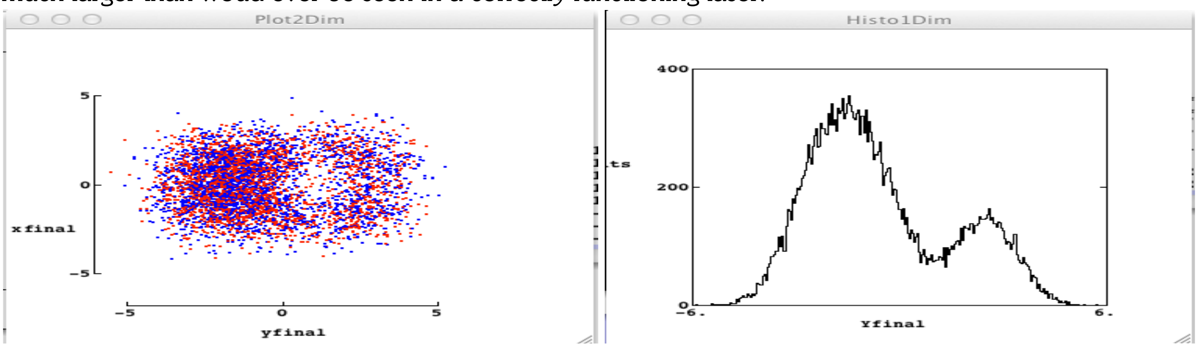
However if the f.l. of A1 is too short then the elements of A2 are now overfilled. The resulting profile (centre overleaf) is puzzling, until one widens the field of view to see that contributions falling into neighbouring elements now appear as satellite spots;- because in this arrangement photons from the upper edge of any illumination patch enter the **lower** edge of the corresponding element, but if they miss because of overfilling, they fall into the ***upper*** edge of the neighbouring element. However small satellite spots can be a useful aid to alignment!



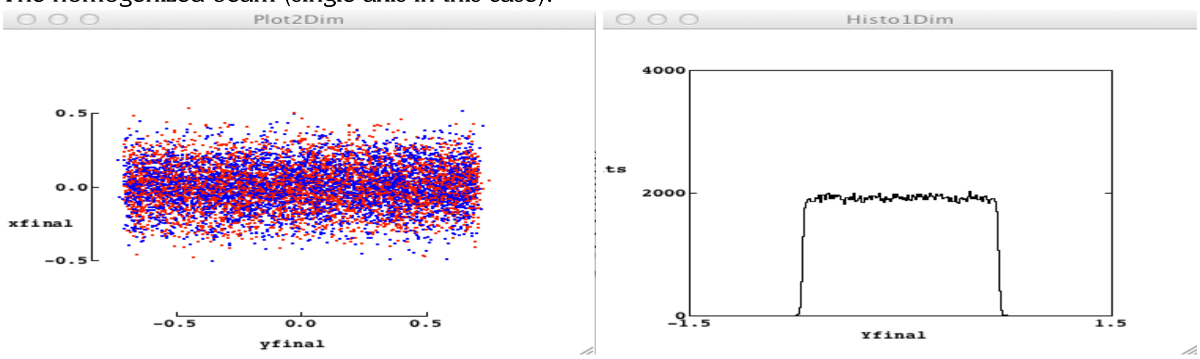
Another good reason for using an illumination array is that joint areas in the imaging MLA may be geometrically ill-defined, and can make spurious contributions to the final intensity distribution; for e.g if they were small planar sections this would lead to an axial hot spot of the resulting parallel rays being focussed by the Fourier lens.

The degree of homogenization depends on the number of segments, in general more is better, but 7x7 or 9x9 is already acceptable for many applications, and N is in the end offset by the difficulty of making very small lenslets with sufficient f.l. and surface precision, and also by the fact that once lenslet size approaches coherence length of the laser there can be interference effects between neighbouring contributions; this is particularly true when coherence length increases as the beam is expanded in the already low divergence short direction, and for small P. Note that beam divergence in the horizontal direction Dl is typically 3-4X Ds ; expanding the beam in V direction reduces Ds so divergence anisotropy can easily be 8:1,- with later consequences.

To see how all this works in practice, here is a simulation of a laser beam with a gigantic defect (hole in the beam), much larger than woud ever be seen in a correctly functioning laser.



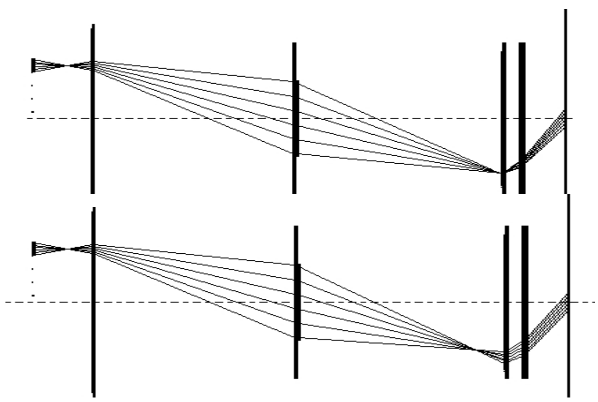
The homogenized beam (single axis in this case):-



Field Lens

Where homogenizers are used to illuminated masks in projection systems, a **field lens** FL is generally necessary just before the mask to optimize pupil filling in the projection lens, leading to the complete layout shown here.

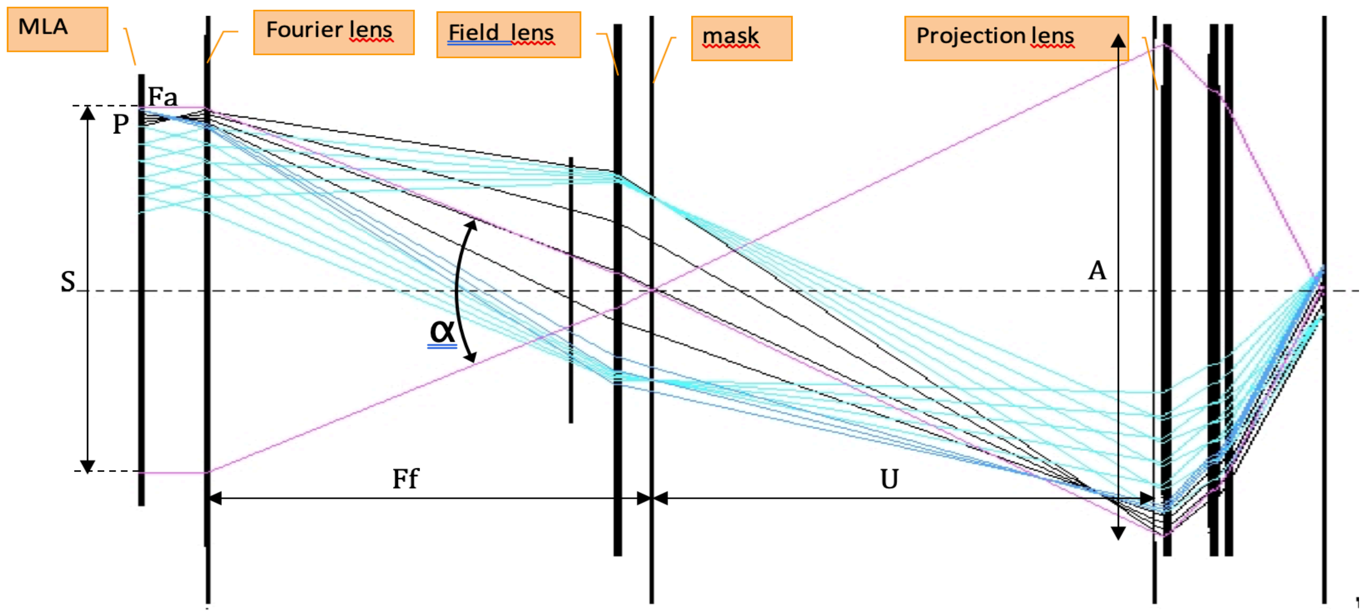
However, note that perfect matching of ray bundles to projection lens aperture means that the MLA foci are imaged onto the image lens first element,- not nice. Better is to select FL power to place the focus array in a pupil a little in front of(or behind) the image lens, as shown here.



Numerical Aperture.

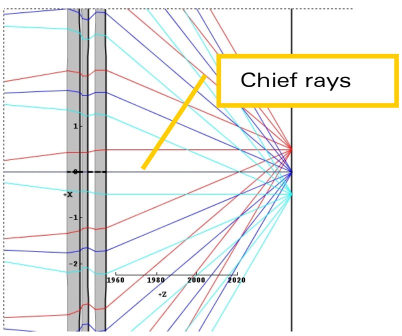
An excimer beam has usually different size in long L & short S directions,- typically L = Sx2-2.5. To maximize efficiency of homogenization systems one can use a cylindrical BET to make the beam approximately square in shape, but inevitably reducing divergence in this axis & therefore increasing coherence length, with increased risk of interference.

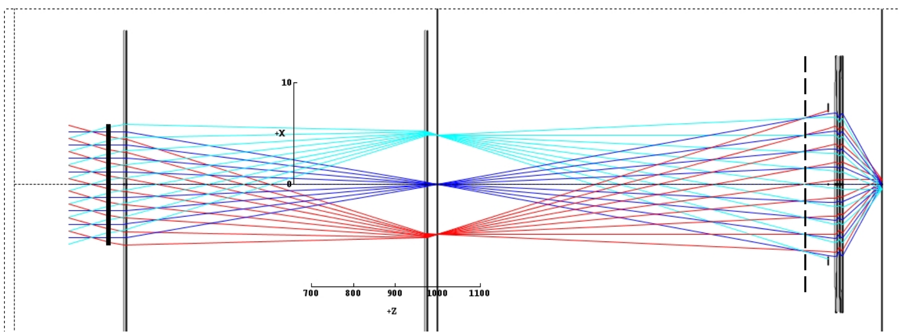
Let us suppose that the *nominal* size of the beam(probably along the diagonal) is S. Suppose array pitch is P, typically in the range 0.5-5mm, and the cylindrical lens elements that make up the array have a focal length Fa,- with some limitations on what is commercially available or technically possible.



As before, the segments are overlapped in the focal plane of the focus lens Fc, and the homogenized spot size in the mask plane is simply D= p x Ff/Fa. The full angular spread of the beam indicate by the mauve lines, is α, where α= S/Ff. Optimum filling into the projection lens pupil is achieved by imaging the back focal plane of the array (almost, avoiding hot spots) into the lens pupil as shown; the ray bundle cannot be smaller. Clearly, the projection lens aperture A must be big enough to accept the illumination cone α, at the object distance U,- i.e. A/U must be > S/Ff, or, for a given projection lens & beam size, Ff must be >SxU/A, placing a lower limit on D once Fa is selected. Note that for a projection lens of focal length Fp at demagnification D, object distance U = Fp x (D+1); whilst final spot size T= P x Ff/Fa / D.

Where processing will be deep, for e.g. hole drilling, the ideal situation is **telecentricity in image space**, so that feature axes will be normal to the part surface. To achieve this condition, the field lens has to be such as to place the beam waist array is in the back focal plane of the lens(dashed line in the plot below) rather than at the first surface, with consequences for the location of a turning mirror or dichroic.





Numerical apertures of homogenization system and projection lens should be matched. High Fa/P means small, flat lenslets, which are more difficult to fabricate accurately, whilst inaccurate lens form will give poor homogenization, defeating the object. Higher U/A in the projection lens means a larger aperture, shorter focal length lens,- i.e. higher numerical aperture for a lens which has to be diffraction limited. Given the very limited choice of optical materials(and therefore refractive index μ) in the UV, this becomes both difficult & expensive. Finally, smaller S,- for e.g. by contracting H rather than expanding V,- which will reduce α. This will also reduce the number of segments used (reducing homogeneity if too few), and also increase the e.d. on the delicate homogenizer array.

Note that the necessity to match n.a. disfavours large beams, small spot sizes & high demag. Thus, array type homogenizers are in general not suitable for high e.d. applications over minimal fields,- where they are not really needed either!, but better suited to large area processing at moderate e.d.