

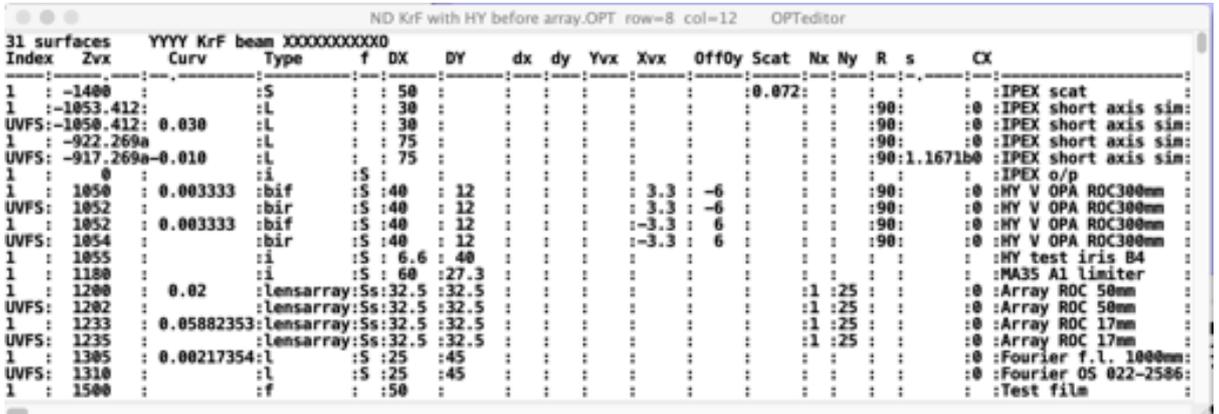
Using Beam4 in Laser Beam Simulations

Beam4 is a **ray tracing program** from <http://stellarsoftware.com> (the brainchild of ML, a retired space sciences professor, & former NASA payload specialist) which has undergone continuous development over 30 years and which has always been excellent value for money; but which since 2015 is both open source & **free!** The B4 download includes an excellent & detailed **Instruction Manual** in .pdf form; the notes here are intended to give just a very quick introduction, concentrating on some of the features that are useful in simulating laser beams, in particular excimer.



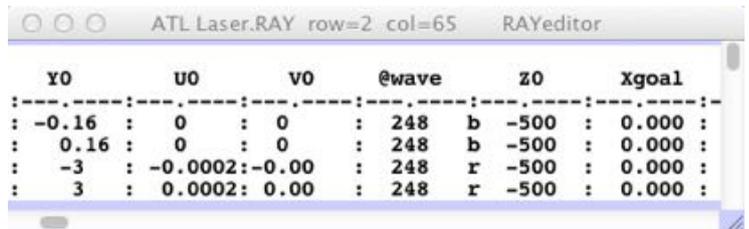
Input Data

In B4, a sequence of optical surfaces of different types, characteristics, locations & orientations are described in an **Optics table** thus:-



Index	Zvx	Curv	Type	f	DX	DY	dx	dy	Yvx	Xvx	Off0y	Scat	Nx	Ny	R	s	CX
1	-1400		S		50							0.072					IPEX scat
1	-1053.412		L		30										90		IPEX short axis sim
UVFS	-1050.412	0.030	L		30										90		IPEX short axis sim
1	-922.269a		L		75										90		IPEX short axis sim
UVFS	-917.269a	-0.010	L		75										90	1.1671b0	IPEX short axis sim
1	0		i														IPEX o/p
1	1050	0.003333	bif	S	40	12			3.3	-6					90		HY V OPA ROC300mm
UVFS	1052		bir	S	40	12			3.3	-6					90		HY V OPA ROC300mm
1	1052	0.003333	bif	S	40	12			-3.3	6					90		HY V OPA ROC300mm
UVFS	1054		bir	S	40	12			-3.3	6					90		HY V OPA ROC300mm
1	1055		i	S	6.6	40											HY test iris B4
1	1180		i	S	60	27.3											MA35 Al limiter
1	1200	0.02	lensarray	Ss	32.5	32.5							1	25			Array ROC 50mm
UVFS	1202		lensarray	Ss	32.5	32.5							1	25			Array ROC 50mm
1	1233	0.05882353	lensarray	Ss	32.5	32.5							1	25			Array ROC 17mm
UVFS	1235		lensarray	Ss	32.5	32.5							1	25			Array ROC 17mm
1	1305	0.00217354	l	S	25	45											Fourier f.l. 1000mm
UVFS	1310		l	S	25	45											Fourier OS 022-2586
1	1500		f	S	50												Test file

..together with a set of starting rays of given position and direction, in a **Ray table**.



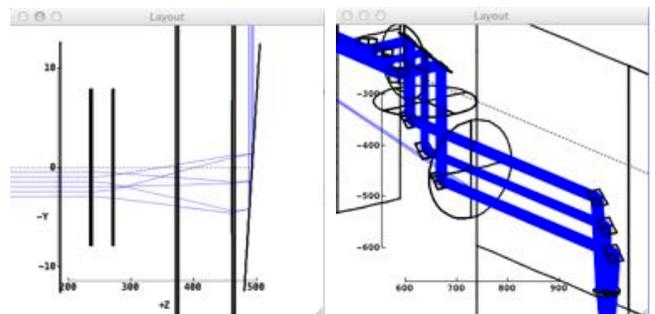
Y0	U0	V0	@wave	Z0	Xgoal
-0.16	0	0	248	b -500	0.000
0.16	0	0	248	b -500	0.000
-3	-0.0002	-0.00	248	r -500	0.000
3	0.0002	0.00	248	r -500	0.000

In the .opt table, refractive surfaces (lens or l), are in pairs to describe the two faces of each optical element, between which is a material, (UVFS here), which consults a **Media table** (not shown) to attribute a refractive index corresponding to the wavelength set in the Ray table by the header @wave.

Output Functions (Run Menu)

Run menu item attributes are set in **Options**.

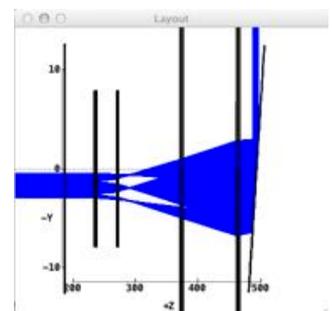
In the Run menu, most obviously, **Layout** displays graphically the fate of each ray, with user selection of scale, viewing angle, aspect ratio etc. Since laser beams are by nature long & thin, it usually helps to use a much expanded vertical scale as here, so the 45° turning mirror here looks a bit funny (left).



For this reason, I usually model the system in a straight line layout though B4 can handle 3D layouts without difficulty (right)

Within the extreme limits of the ray starts, **Random** uses a Monte-Carlo generator to populate the ray distribution, in different ways (set in Options).

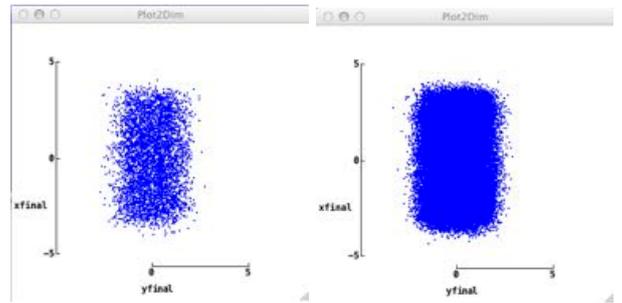
Depending on the complexity of the .opt table, many thousands of rays are traced per second, filling up the display very rapidly. If required, that can be slowed down by requesting a Screen Refresh after a relatively low number of rays (in Options).



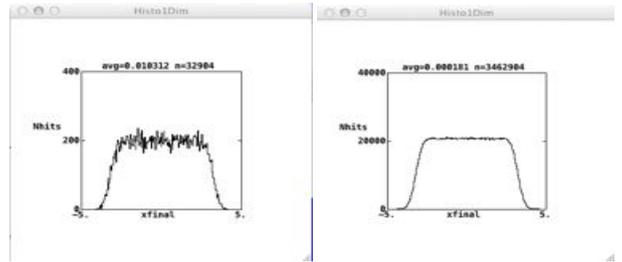
Some Run menu items are only really useful at all when used in conjunction with Random:-

Plot2Dim is a scatter plot of ray arrivals on a selected surface, and can be used to visualize the shape of the beam at different places. N.B. the 'response curve' is different from fax paper, which has a threshold, and thus tends to accentuate a gradual decrease in intensity, whereas Plot2D is linear from zero, but saturates once ray arrival points overlap.

This means that for excimer laser beams the short axis (typically quasi-gaussian profile) the width looks rather exaggerated compared to the more top hat long axis, particularly if too many rays are allowed to run (right). Be sparing with rays. Tip, when running Random, the plot can be reset at will by placing the mouse/trackpad on the plot and very slightly moving it (also Layout, & Histo1D (the latter if so tagged in options).

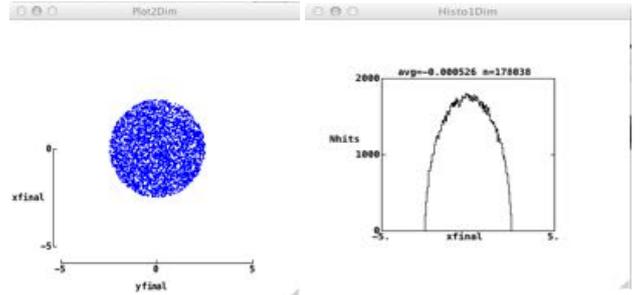


Histo1D is used to look at a profile. More rays reduce statistical noise, but some noise helps to make the profile look more 'real', since typical of the noise seen in real profile measurements. Compared to Plot2D, Histo1D needs lots of rays & set Screen refresh at a high number, I usually use 10,000.

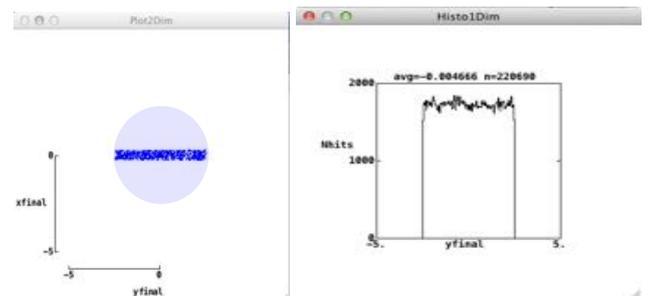


N.B. The profile is that of ALL rays. For e.g. uniform filling of a circular aperture (iris in B4) does NOT give a top hat profile in Histo.

To look at a cross-section of the beam across the diameter one needs to add a thin defining aperture, so that the profile is ONLY of those rays lying close to the aperture diameter; -needs more rays to reach the same height!



(N.B. the pale blue circle is Word generated!)



Perfect Lens

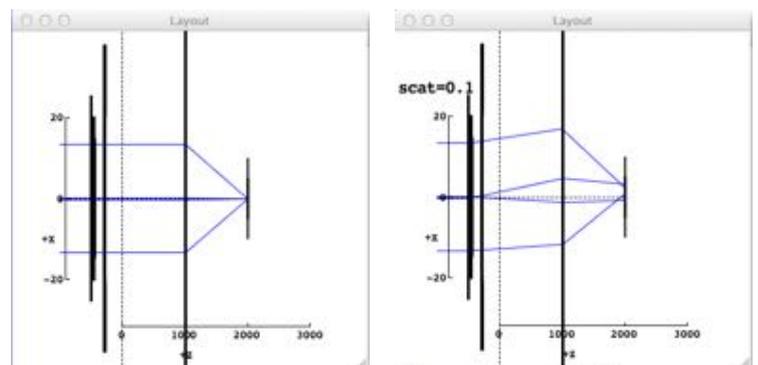
Sometimes, for simulation purposes, we need a lens which will focus all rays to the same target, i.e. which is free of spherical aberration. This is easily done using B4 **AutoAdjust** function where both surface **Curvature** and **Form Factor s** are allowed to float free, thus generating an aspheric surface.

FWHM with Histo1D

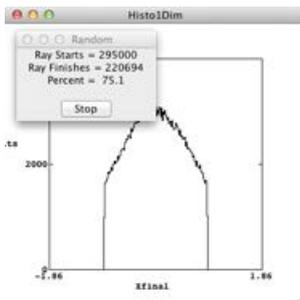
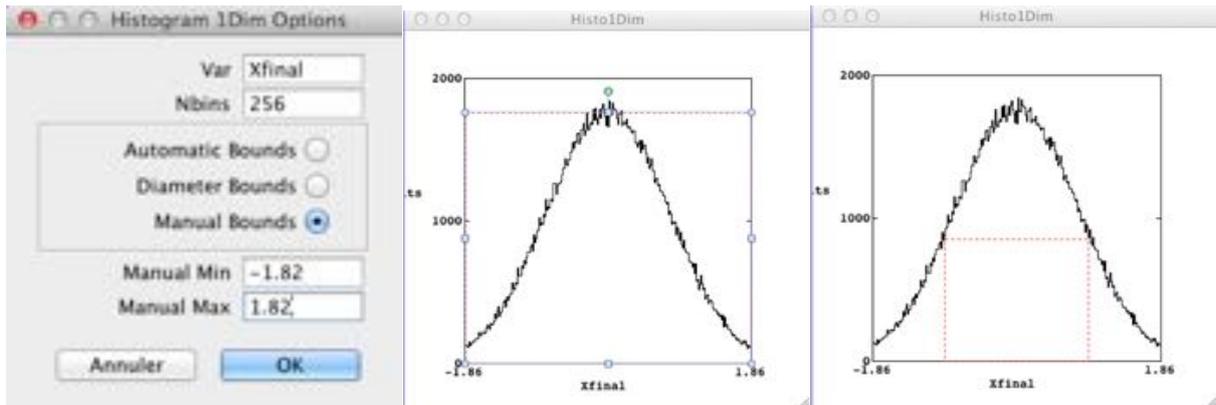
In the .opt table, a **Scat** header is scattering surface which generates a **gaussian FF** profile, and is the best way of simulating excimer laser beams, since those FF profiles are typically quasi-Gaussian.

The value of Scat to use can be quickly set by generating a slit aperture corresponding to the **FWHM width**, and then setting Scat so that 76,5% of rays pass through that aperture.

Why? It helps to go back a bit, using an example where the laser divergence was given as 1,82mrad.



Set Histo1D Upper & Lower limits $\pm 1.82\text{mm}$, run Random, grab & copy to Word, and fit a rectangle as in centre image, then resize to half height & width, easily done by grabbing the corner of the rectangle & dragging to the marked half points on the perimeter. (Older versions of Word did this better) Repeat this procedure using different values of Scat until the half size rectangle fits, as at right. By definition, this profile now has FWHM of 1.82mrad .



At this stage, it is interesting to set a slit in X 1.82mm wide (for a 1000mm focal length lens) and run Histo & Random again.

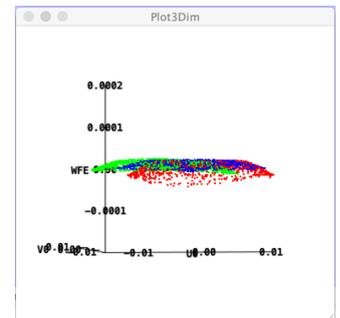
For a gaussian distribution, the number of rays falling within the slit defined by FWHM should be around 76,5% (could be calculated using tabulated Error Functions to evaluate the gaussian integral between those limits; I just estimated using Excel) and of course this is a much quicker way to home in on the value of Scat,; but it only works for a gaussian profile which is what Scat produces *provided* divergence due to ray table U & V values is small), so the FWHM should always be checked using the graphical method.

Simple Optimization

B4 tracks ray arrival **errors w.r.t. some goal** and optical path distance (OPD) for a group of rays starting at a single point, usually by minimizing differences w.r.t to the average for that group, and which is then reported as a **wavefront error WFE**.

Beam 4 AutoAdjust feature will adjust tagged surfaces, for e.g. ROC and/or axial (normally Z) position, - in the pursuit of selected goals, for e.g. to **minimize rms errors on X,Y goals and WFE**, and hence can be used for optimization of simple optics systems.

Plot3Dim can be used as here to display WFE over the lens aperture, different ray groups in different colours.



Lens Arrays

Lens arrays are commonly used as **integrating elements** for beam **homogenization**, and are readily handled by B4, specifying the number of elements N_x across a total width DX , N_y across DY . N.B. Where a 1D array is used, N in the second axis cannot be ignored, even if there is no power in that axis, but has to be set to 1.

Bimodal Surfaces

B4 .opt table accepts **bif**, **bir** & **bim** as headers for **bimodal surfaces**; these were developed for Optec, and are now documented in later releases of the B4 Guide.

Normally, in B4, rays which miss any surface are terminated there, in order to avoid downstream confusion. However, Optec HY beam shaper uses lens elements which are partly inserted into the beam, so **bif** & **bir** are used instead of **lens** to describe the front & rear surfaces of those lenses; **bim** is used for a **bimodal mirror**, largely replacing B4 Groups function.

Rays which miss such a bimodal element continue to propagate rather than being killed, and output functions including Plot2D, Histo1D etc. can be used in the normal way to view the combined result.

However, B4 remains at heart a sequential ray tracer so the two bif/bir elements that comprise the two lenses on a single axis HY beam shaper have to be slightly offset in the propagation direction (normally Z) so that they are encountered sequentially.