UV Probe Beam for Plasma Characterization and Channeling Experiments

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Abstract

The OMEGA EP laser system will be used to study long-scale-length plasmas and the channeling of an ultra-intense infrared short-pulse beam through these plasmas. One of the primary plasma diagnostics will be grid image refractometry (GIR).[1] In GIR a collimated UV beam illuminates a grid that breaks the beam into a two-dimensional array of probe-beam ray bundles. These rays pass through a plasma, where they are affected by refraction. Analyzing the images of the grid then allows one to determine the plasma density. In the standard GIR approach the grid has a large stand-off distance from the plasma and the grid is imaged into the plasma. A new approach is studied here in which the grid is in close proximity to the plasma. The goal of this project was to study the basic optical properties of this GIR system, including the diffraction effects from the grid but ignoring the refraction due to the plasma. A PV-Wave program was written based on a simple ray-trace algorithm that included diffraction from the grid. The image quality was studied for various object planes and grid periods. An optimal position for the grid was found that resulted in crisp images, showing that this approach is viable.

I. Introduction

i. Laboratory for Laser Energetics (LLE)

The primary mission of the University of Rochester's Laboratory for Laser Energetics (LLE) is to study the physics of direct drive inertial confinement fusion (ICF). The controlled fusion of deuterium and tritium holds great promise for solving the world's energy problem. The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, which is largest and most powerful laser in the world, will make a credible ignition attempt by using the indirect drive concept. The OMEGA Laser Facility at LLE is a cornerstone in the US fusion program and plays a major role in the national effort for achieving ignition. With ignition at the NIF on the horizon, scientists work on advanced inertial fusion energy concepts that might be developed into future reactor designs. The laser requirements are relaxed and higher gains than in indirect drive might be possible.

One concept is the fast ignition (FI) concept[2] that uses a conventional high-energy laser facility to compress the fuel capsule and then achieve ignition through a high energy particle beam generated by a separate, high intensity short-pulse laser. One of the primary research objectives of the recently built high intensity OMEGA EP laser facility is to investigate advanced ignition schemes such as fast ignition. The main issue in FI is to bring the particles as close as possible to the compressed core without losing too much of their energy. There are currently two viable FI concepts; one considers targets with a hollow re-entrant cone that keeps a clear path for a high intensity laser so that the particles are generated as close as possible to the dense core. The other is the channeling concept. Channeling employs two co-propagating short-pulse beams; the first pulse is used to push the plasma away and drill a channel close to the core so that the trailing second pulse is guided through the channel without significant energy loss. The second short pulse then produces the energetic particles that will ignite the target.

Channeling experiments are planned on the OMEGA EP laser by using long-pulse UV lasers to generate an extended plasma atmosphere and then send an ultra-intense infrared short-pulse beam through these plasmas. It is important to have optical diagnostics to characterize the pre-formed plasma and to measure the channel. The measurements will be compared to simulation predictions of the plasma density and the formation of the channel. One of the primary plasma diagnostics that will be used in these experiments is grid image refractometry (GIR)[1] with an ultraviolet probe laser with a wavelength of 263 nm.

ii. Grid image refractometry (GIR)

GIR is a technique for determining the two-dimensional density profiles of long scale-length laser-produced plasmas. Fusion plasmas are of the size of up to several millimeters with a density scale-length of several hundreds of micrometers. The density scale-length is defined as $n/(dn/dx)$ at a certain *x*-position in a density profile $n(x)$. The GIR concept employs a collimated UV beam that illuminates a grid so that the beam is split into a two-dimensional array of probe-beam ray bundles. These rays pass through the plasma, where they are refracted. The term “refractometry” is used to indicate that the refractive index of an optical medium is inferred from the refraction angles of this set of probe rays. In the previous method of GIR the grid had a large stand-off distance from the plasma and was imaged into the plasma. A new approach is studied in this project in which the grid is placed in close proximity to the plasma. Figure 1 shows a schematic of the experimental setup.

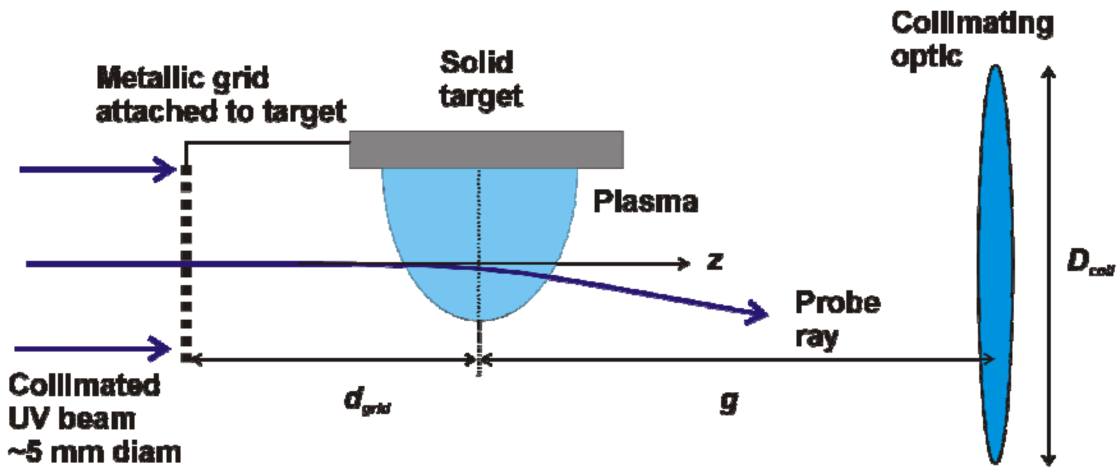

Figure 1: *Schematic setup of a metallic grid placed in the collimated UV beam close to the target for GIR application. Typical parameters are:* $d_{grid} \approx 1$ *cm,* $D_{coll} \approx 10$ *cm,* $g \approx 40$ *cm, and a grid period of* $P = 25$ *μm.*

A collimated laser beam illuminates the grid which splits the beam into an array of pencil beams that pass through a plasma object. The refractive index, $\mu(x)$, inside the plasma varies according to the local electron density, and the amount of refraction that each bundle experiences depends on the gradient of the refractive index $d\mu/dx$. Different planes in the plasma must be imaged onto a detector. The apparent position of each probe ray must be measured for at least two object planes; in the current project three object planes separated by a distance of ~1 mm were chosen. The UV probe light is split up into three beams after transmission through the plasma. Each one images a different object plane onto a CCD camera. The deflection angles (in the x- and y-directions) are obtained by the difference of the associated grid elements in two object planes divided by the distance between those planes. In other words, the slope of each ray is measured by imaging various object planes that are slightly displaced along the beam axis. With this measurement the density contours of the plasma are retrieved using an inversion technique by assuming a cylindrical symmetry in the plasma (the axis of symmetry is along the normal of the solid target).

One issue of the new concept is that diffraction effects are significant. Coherent light passing through an array of slits will diffract. This leads to maxima and minima according to Huygens' Principle, see e.g. Ref. 3. Diffraction will affect the image quality of the grid. As a first step, the basic optical properties, including diffraction from the grid, were studied without taking the refraction in the plasma into account. The image quality will also depend on the distance of the grid from the object plane. In Figure 2 the zero diffraction order and a higher diffraction order are schematically drawn. The grid has a certain distance from the object plane, which is imaged by a lens. If the grid were located in the object plane, a perfect image of the grid would appear. A blurred grid image is expected in the case that the grid is shifted away from the object plane. The rays are no longer combined into a single point in the image plane. This is the result of diffraction. The blurring is minimized the closer the grid is located to the object plane. Image blurring is expected to be more significant for larger distances.

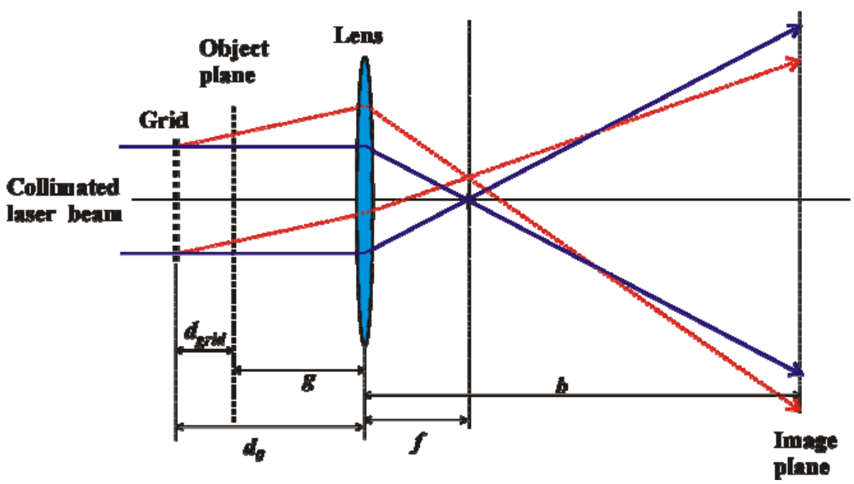

Figure 2: *Different diffraction orders from a grid are imaged. The grid has a certain distance from the object plane that is imaged. As a result, the grid image is blurred due to the different diffraction orders.*

Figure 3 shows a schematic for light diffraction through multiple slits. Diffraction is an effect where a wave, such as a beam of light, deviates from a rectilinear propagation path when passing through a small opening. According to Huygens's Principle, spherical waves emerge from each source point. Interference of those waves after the slit structure may be constructive or destructive depending on the angle θ with respect to the optical axis. One can consider the beam to be broken up into an array of smaller bundles of light that have a certain angle, θ, with respect to the optical axis. The light bundles spread out and interfere with each other creating a pattern. The diffraction pattern is different for a single slit and for multiple slits. In multiple-slit diffraction, which is what occurs in GIR, the pattern produced has a uniform/periodic pattern of peaks and troughs. The intensity distribution in the far field from the diffraction of many slits can be written as a function of the diffraction angle[4]

$$I(\theta) = \frac{I(0)}{N_{slit}} \frac{\sin^2\left(\pi(w/\lambda)\sin\theta\right)}{\left[\pi\left(w/\lambda\right)\sin\theta\right]^2} \frac{\sin^2\left(N_{slit}\pi(p/\lambda)\sin\theta\right)}{\sin^2\left[\pi(p/\lambda)\sin\theta\right]}, \tag{1.1}$$

where N_{slit} is the number of slits, $I(0)$ is the intensity on the optical axis, p is the distance between two adjacent slits (this is also called the grid period), and w is the slit width. The light intensity is a function of the angle θ, which is the angle with respect to the optical axis. Figure 4 shows a calculation of the far field diffraction pattern from 6 slits using Eq. (1.1).

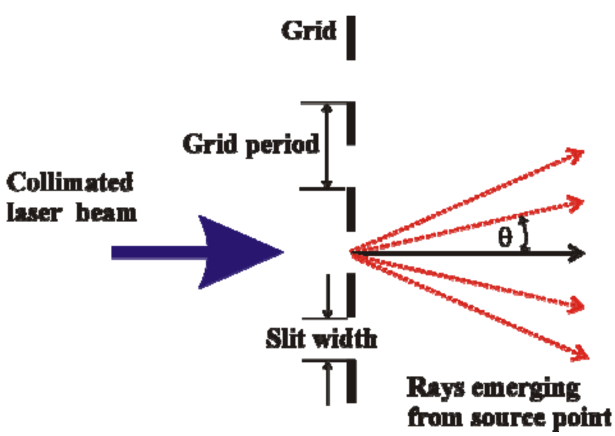

Figure 3*: A collimated laser beam irradiates an array of multiple slits. According to Huygens' Principle, spherical waves emerge from each source point. Interference of those waves after the slit structure may be constructive or destructive depending on the angle θ with respect to the optical axis.*

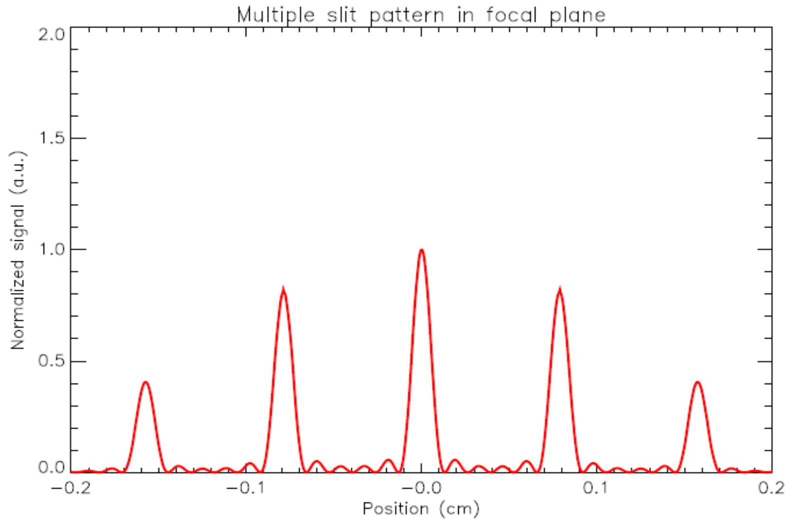

Figure 4: *Interference pattern from a 6-slit grid in the focal plane of a lens.*

II. PV-Wave Program

A PV-Wave program was written for imaging a grid structure including diffraction effects, see Figure 2. The program consists of three functions and a main program that calls upon them. The first of the functions creates an array of points for an object based on parameters given by the user. The main program calculates the final coordinates in the imaging plane, using a ray-trace formula of light through a thin lens, for the specified number of rays emitted from each point at specific angles at three different distances from the object plane. The second function calculates the intensity of each ray using the intensity formula given by Eq. (1.1). The third function creates the array for the image produced by rays. To make sure that the program was running properly, it was tested for the 1:1 imaging case (see Figure 5). In 1:1 imaging, the object is placed at $2f$, or two times the focal length of the lens, from the lens. From this distance, the image produced will be at $2f$ from the lens on the opposite side and will be an inversion of the object. The object and the image will be the same size making it easy to confirm the effectiveness of the program.

In the new GIR system a collimated UV laser beam illuminates a grid that is placed in close proximity to a plasma object (Figure 1). This creates a two-dimensional array of probe beam ray bundles that are passing through the plasma. The rays are refracted in the plasma much like in a lens, but the refraction varies locally. As a result the refraction angle varies over the ray array. The amount of refraction depends on the refractive index in the plasma, which is a function of the free electron density. The refracted light is then collected by a lens, which images the grid onto a detector.[2]

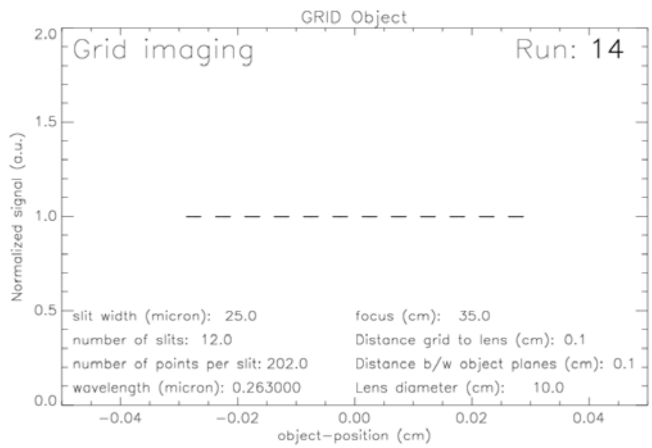

***Figure 5**: 12 slit grid placed at twice the focal length of a lens. The resulting image is identical to the object.*

III. Results

i. 1D Line-outs

The grid image was calculated for various distances from the object plane without a plasma. Figure 6 shows intensity line outs of 1, 2, 3, 5, 6, and 9 mm distances of the grid from the object plane. The line-outs show that the pattern changes significantly when the grid is moved further away from the object plane. At a distance of 0.1 cm the grid pattern is clearly visible. At a distance of 0.2 cm, an additional modulation, which becomes stronger with greater distance, appears superimposed on the grid pattern. At a distance of 0.5 cm the contrast, which is the ratio of the intensity of the peaks and the troughs, is strongly reduced. Placing a grid at this distance would make it difficult to locate the center of each grid element, which is essential for the analysis in GIR. If the distance is further increased, the additional modulation eventually reduces and then at a distance of 0.9 cm a sharp image of the grid appears. It is observed that this cycle of image blurring and re-appearing of sharp grid images continues to occur if the distance is further increased. At multiples of the distance of ~0.9 mm, a sharp image of the grid is obtained. The distance when the first sharp image appears depends on the light wavelength and the grid period.

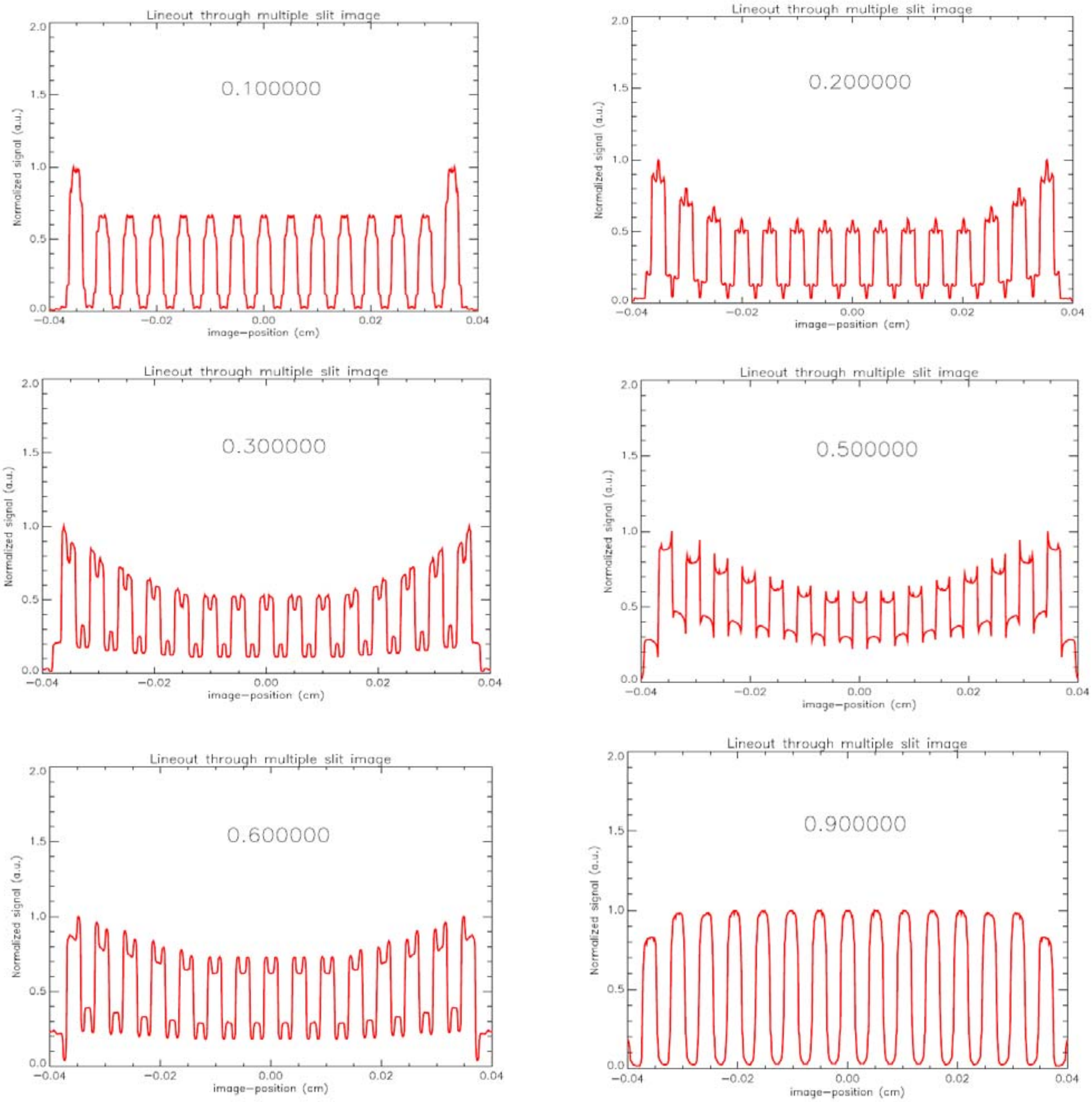

Figure 6*: Multiple slit images were calculated for various object positions. The distances are given in centimeters. The light wavelength was 263 nm, the grid period was 50 µm, and the slit width was 25 µm.*

ii. 2D Contour plots

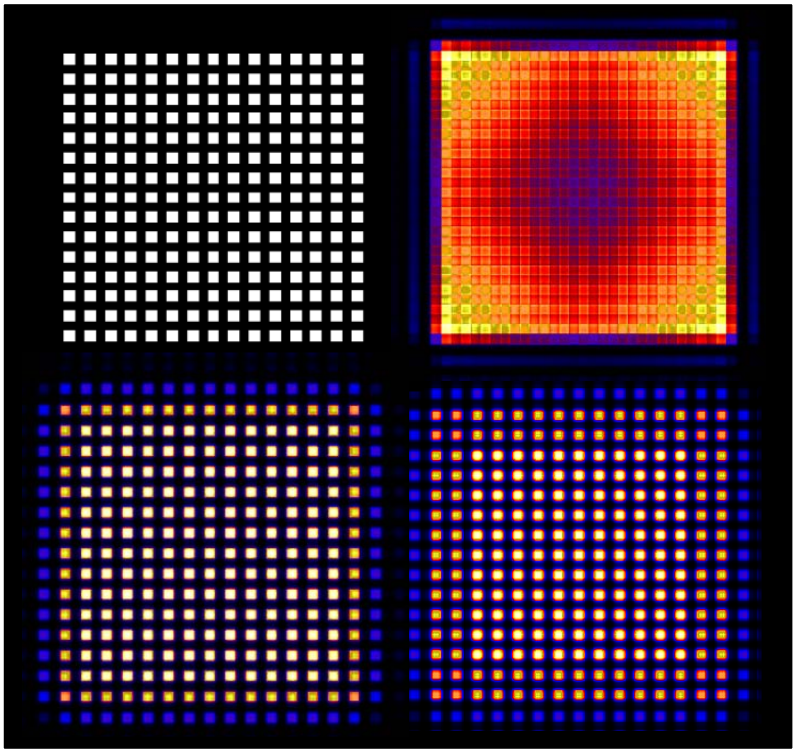

***Figure 7**: Calculated grid images for various distances (0, 0.5, 2, and 1 cm – beginning from top left, clockwise) behind the grid. No plasma was assumed. The light wavelength was 263 nm, the grid period 50 µm, and the slit width was 25 µm.*

Similar calculations as shown in the previous section have been performed for a two dimensional grid (Figure 7). Again, the issue with placing a grid in close proximity to a plasma object is that with increasing distance from the grid, multiple beam interference rapidly leads to a blurring of the grid structure. Figure 7 shows calculated images of a grid at various distances (0, 0.5, 1, and 2 cm) behind the grid. At a distance of 0.5 cm the grid image is strongly distorted and would not be useful for GIR. At certain distances sharp grid self-images appear. This has to be taken into account when placing the grid from the plasma object. This effect is also known as the Talbot effect.

iii. Sharpening and blurring (Talbot effect)

The Talbot effect is a diffraction effect that was first observed in 1836 by Henry Fox Talbot.[5] When a plane wave is transmitted through a grating, Talbot observed that sharp images of the grating appear at certain distances. Forty-five years later, Lord Rayleigh explained Talbot's observation as a result of Fresnel diffraction.[6] He derived a formula for the distance, when the grating structure replicates, which is now know as the Talbot length, $T_n = np^2 / \lambda$, where p is the grating period, λ is the light wavelength, and n is an integer number.

For example, in the case of the GIR application using a grid with 50 µm period, it needs to be placed 9.4 mm away from TCC to be at the exact first Talbot length. The 50 µm period gives sufficient spatial resolution for GIR. Within a distance of ±1 mm from the Talbot length a reasonable image quality is maintained.

Adding plasma in the path of the interfering beam arrays might complicate the data analysis. The problem is that waves from different slits interfere and the unique optical path of each individual beamlet is lost, which is essential for GIR. It is not yet known how plasma refraction and diffraction will affect the grid imaging. A simple estimate is performed to assess this effect (see Figure 8): Considering an interference maximum in the Talbot plane, beams from many slits interfere constructively. Outer slits with a large lateral distance from S1 can contribute to the interference maxima S1 in higher diffraction order, but energy decreases strongly with higher order. Within a distance $x_m = p^2 / m\lambda$, all the interfering beams up to order m stay in a lateral region of less than the grid period, p, which is about the spatial resolution of the technique. Taking an order of m = 5, the corresponding distance is $x_5 \approx$ 2 mm ($p = 50$ μm, λ=0.25 μm), which is comparable to the plasma size. This estimate shows that the diffraction effects are probably tolerable and GIR might be a viable technique when using a grid in proximity to the target. However, this has to be first proven experimentally.

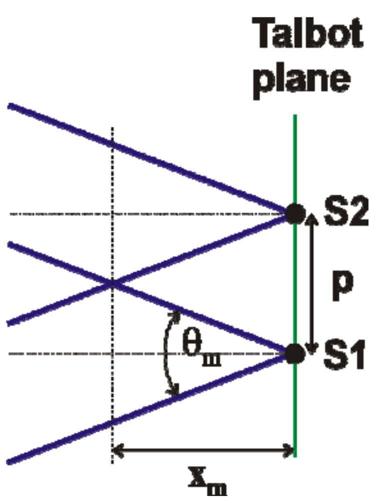

Figure 8: *Schematic showing the cone of beams from multiple slits interfering in the Talbot plane producing a self image of a grid. The angle* θ_m *corresponds to a certain diffraction order m.*

IV. Conclusion

A new approach in grid image refractometry (GIR) has been studied theoretically in which the grid is in close proximity to the plasma object. The project studied the basic optical properties of this GIR system, including the diffraction effects from the grid but ignoring the refraction due to the plasma. A PV-Wave program has been written based on a simple ray-trace algorithm that includes diffraction from the grid. The image quality was studied for various object planes and grid periods. An optimal position for the grid was found that resulted in crisp images, showing that this approach is a promising approach to plasma analysis. It has been shown that the diffraction effects from the grid are due to the Talbot effect, which explains why sharp images of the grid were observed at certain multiple distances of the first Talbot length. The results that were obtained are encouraging and show that the new GIR method might be sufficient in analyzing the refraction effects of the irradiated plasma. It is now important to test the method experimentally and to show that it is a viable method even when refraction in the plasma is taken into account.

V. Acknowledgements

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VI. References

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