Simulation of laser propagation in plasma chamber including nonlinearities by utilization of VirtualLab 5 software

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Abstract

PITZ is a facility for test and optimization of high quality electron sources. Plasma Wave Acceleration (PWA) is a new way to accelerate electrons. To reach a high beam-electron energy, laser ionization is a crucial key of PWA. The aim of this work is how to use VirtualLab5 software (trial version) to generate a simple setup to simulate the laser profile in a plasma chamber. However, the trial version is limiting the memory to calculate a complicated object such as a Gaussian beam propagating through an axicon. A simpler setup, a plane wave propagating though the axicon, was evaluated. Finally, the last setup, a Gaussian beam propagating though a focusing lens and an aperture, which blocks some part of the beam, is equivalent to the setup of the experiment; it also was calculated and compared with the setup without blocking. The result shows that the plasma chamber should be set around the focal point.

Contents

1 Introduction

The main goal of the Photo Injector Test Facility at DESY Zeuthen site (PITZ) is test and optimization of photo injectors for Free-Electron Lasers (FELs) e.g. FLASH and XFEL in Hamburg. The main focus of PITZ is to produce an intense electron beam with a very small transverse emittance and rather small longitudinal emittance. An overview of the PITZ beam line is schematically shown in Fig. 1 [1].

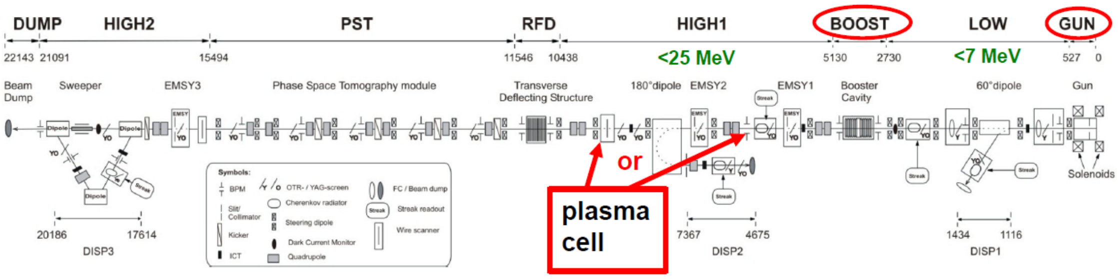


Figure 1: PITZ beam line

However, a new way to accelerate electrons called Plasma Wave Acceleration (PWA) was proposed. In this way, electrons can be accelerated to very high energy over very short distances. To reach a high beam-electron energy, a laser is used to ionize atoms or molecules to generate a plasma medium which transforms electromagnetic energy from a laser pulse or particle beam into the kinetic energy of accelerated electrons by letting the so-called driver excite large-amplitude plasma density waves. Consequently, laser ionization is an essential key of Plasma Wave Acceleration [2]. The Particle Driven Plasma Wave Acceleration (PDPWA), which uses a charged particle as a driver, will become a novel challenge of PITZ in this time.

In the first part of this report, the physical concepts of Plasma Wave Acceleration and also laser propagation in the plasma chamber are introduced. Then VirtualLab 5 software which is used to simulate the laser profile in the plasma chamber is described. Finally, simulation results, discussions and conclusions are presented.

2 Objectives

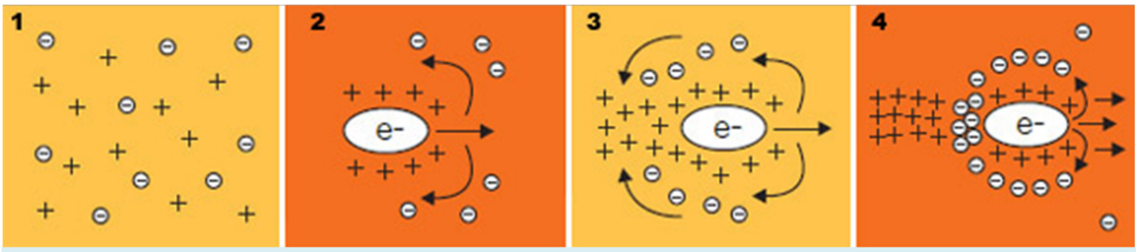
Firstly, it is very important to understand the basics of plasma acceleration, laser beam propagation and ionization. Then learning how to use VirtualLab5 software is intended to generate a simple setup to simulate the laser profile in a plasma chamber, for example, the case of Gaussian beam laser propagating through an axicon to confine the laser beam in a plasma chamber.

3 Physics of Plasma Wave Acceleration

The basic concept of the Particle Driven Plasma Wave Acceleration involves the passage of an ultrarelativistic charged particle bunch through a stationary plasma. The plasma may be formed by ionizing a gas with a laser or through field ionization by the Coulomb field of the relativistic bunch itself [2].

In a plasma chamber, electrons move around freely. Because the much heavier ions barely move, they are left unshielded. Some distance behind a driver, the electrostatic force exerted by the ions on the electrons pull them back, creating an electron density peak. The resulting pattern of alternating positive and negative charges, called a plasma wave or laser wake, supports a longitudinal electric field [3].

In single-bunch experiments carried out with ultrashort electron bunches, the head of the bunch creates the plasma and drives the wake as shown in Fig. 2. The wake produces a high-gradient longitudinal field that in turn accelerates particles in the back of the bunch [2].



1.A plasma, made of positive ions and free electrons before an electron bunch enters.
2.The electron bunch enters the plasma, repelling all the free electrons from its path, and attracting the positive ions. The moving electron bunch leaves a wake of positive ions behind it as it passes.
3.The displaced free electrons are now attracted to the mass of positive ions behind the electron bunch.
4.The free electrons in their new position further accelerates the electron bunch.

Figure 2: Particle Driven Plasma Wave Acceleration which uses an electron bunch as a driver [4]

Ideally, one would instead place a separate, short 'witness' bunch containing a sufficient charge to be efficiently accelerated at the appropriate phase behind the drive bunch, as schematically shown in Fig. 2(b). However, it becomes more challenging to find appropriate techniques to craft two bunches spaced in time by roughly one plasma wave period [2].

Laser ionization is an important part of study in PDPWA, because a plasma medium can be generated by a very high-intensity laser beam. A typical laser produces a Gaussian beam which has high intensity in its Rayleigh Range. However, there are many ways to control the high-intensity laser beam to propagate in a plasma chamber, without interfering with the coming charged particle bunches taking into account that the plasma chamber is also surrounded by devices and instruments. For example, letting a Gaussian beam propagating through an axicon can dictate the beam described by the Bessel function between the axicon and the region of z_{max} as indicated in Fig. 4[5].

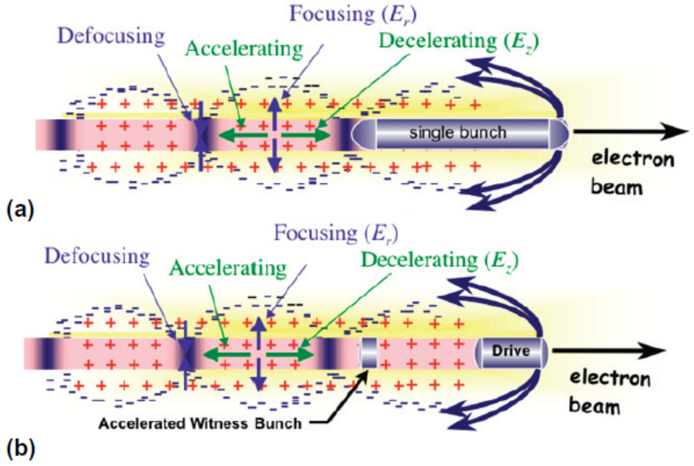


Figure 3: Physical mechanism of the PDPWA for (a) previous single-bunch experiments and (b) the two-bunch case [2].

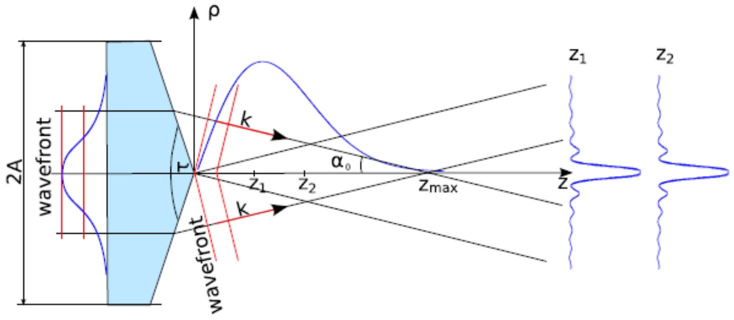


Figure 4: Formation of a quasi-Bessel beam (QBB) by a perfect axicon illuminated by a Gaussian beam with a beam waist placed on the axicon front surface [5].

4 VirtualLab 5 software

The VirtualLab software was developed to model a large variety of optical components as for example refractive, diffractive, hybrid, Fresnel and GRIN lenses, diffractive optical elements, diffusers, beam shapers, diffractive beam splitters, computer generated holograms, phase plates, gratings, elements with free form surfaces and micro lens arrays. In addition light sources with different properties as for example degree of coherence, color and polarization can be used [6].

VirtualLab was developed by the concept of Field Tracing to perform these simulations. Field Tracing unifies optical modeling techniques ranging from geometrical optics to electromagnetic approaches. It enables the simulation of optical systems including diffraction, interference, partial coherence, aberrations, polarization and vectorial effects [6].

The basic concepts of this software may be summarized as follows (from User's Manual in [6]):

1. Light sources generate the light to be propagated through a system.
2. Optical systems are described by light sources, ideal and real components and detectors.

They are combined in the Light Path Diagram.
3. Light propagation through free space and components is done by selections of propagation operators. They range from geometrical to physical optics.
4. Alternatively to or in combination with describing real components, ideal components may be used for rapid system investigation.
5. Detectors to evaluate the quality of light fields or the effect of light to matter may be introduced in any homogeneous region of the system.
6. Session Editors assist to set up optical systems for modeling task.
7. The Parameter Run Document allows to configure a series of experiments in VirtualLab.

5 Result and Discussion

The Parameter Run allows users to calculate any results, such as Virtual Screen, Power and Beam Parameters, at a series of positions on the optical axis by using the Identity Operator function. Consequently, all the results can be calculated at any positions after the last optical objects of this program.

5.1 Case 1 is a Gaussian beam propagating through an axicon ($z_{max} = 54.228$ mm).

A Gaussian beam with a beam waist placed on the axicon front surface was set. To try to reproduce results from [5] to test the accuracy of program, parameters from [5] were applied to the program. According to the results from [5], a Bessel beam region which would be used to create ionized atoms for PWA experiments, were expected. A ring structure on screen the after z_{max} was also anticipated.

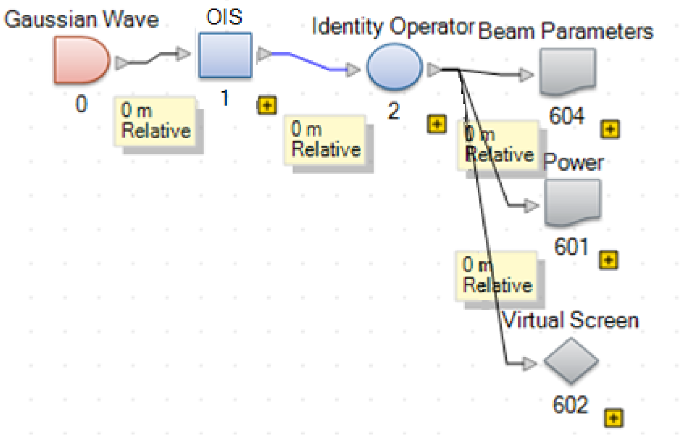


Figure 5: A diagram of the case 1 experiment in VirtualLab 5.

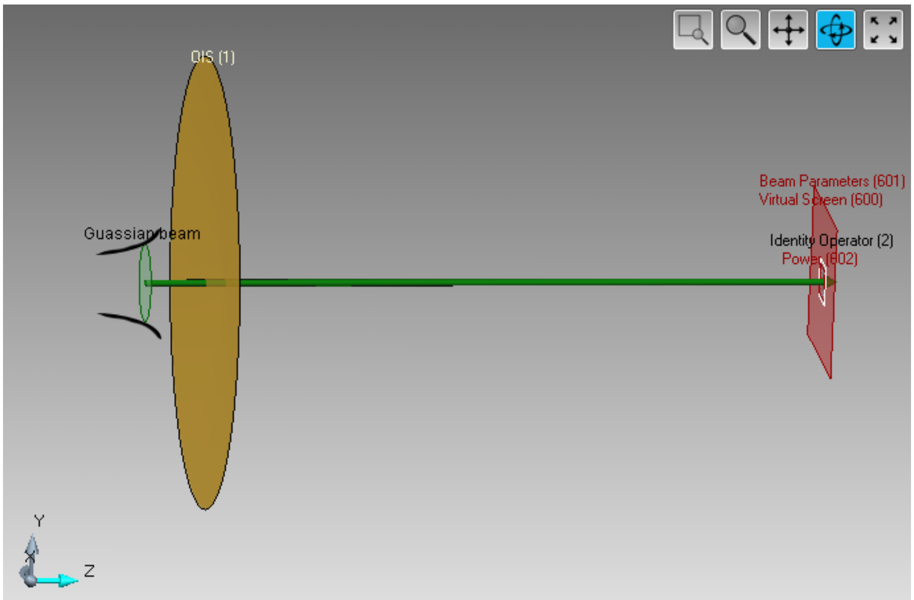


Figure 6: Experimental set-up. Beam waist of incident Gaussian beam = 2140 μm, wavelength = 1064 nm; axicon:apex angle = 170^0.

Unexpected results, e.g. non-circular symmetric structures on Virtual screens, occurred as shown in Fig. 7.

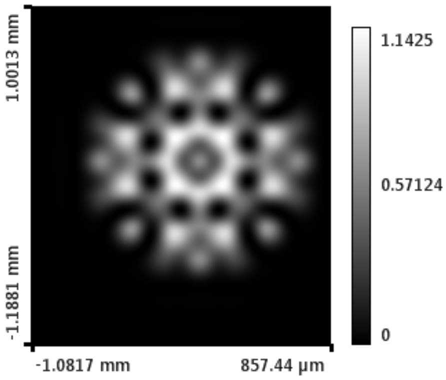
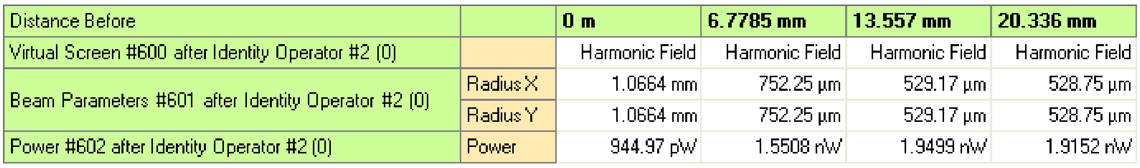


Figure 7: Squared amplitude on Virtual Screens after the axicon for case 1 in the early setup.

However, the way to solve this problem is to increase the numerical accuracy factor of the axicon. This increases the details which can be covered by the simulation, being especially important when simulating an axicon with its sharp tip. Consequently, the expected results are shown in Fig. 8.

Fig. 8 shows the Bessel beam region as the squared amplitude on Virtual Screens before $z_{max} = 54.228$ mm as expected. Unfortunately, the trial version is limiting the memory to calculate, for a complicated object like case 1, it cannot calculate anymore. Thus, a simpler setup was calculated as case 2.



Distance Before		**0 m**	**6.7785 mm**	**13.557 mm**	**20.336 mm**
Virtual Screen #600 after Identity Operator #2 (0)		Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field
Beam Parameters #601 after Identity Operator #2 (0)	Radius X	1.0664 mm	752.25 µm	529.17 µm	528.75 µm
	Radius Y	1.0664 mm	752.25 µm	529.17 µm	528.75 µm
Power #602 after Identity Operator #2 (0)	Power	944.97 pW	1.5508 nW	1.9499 nW	1.9152 nW

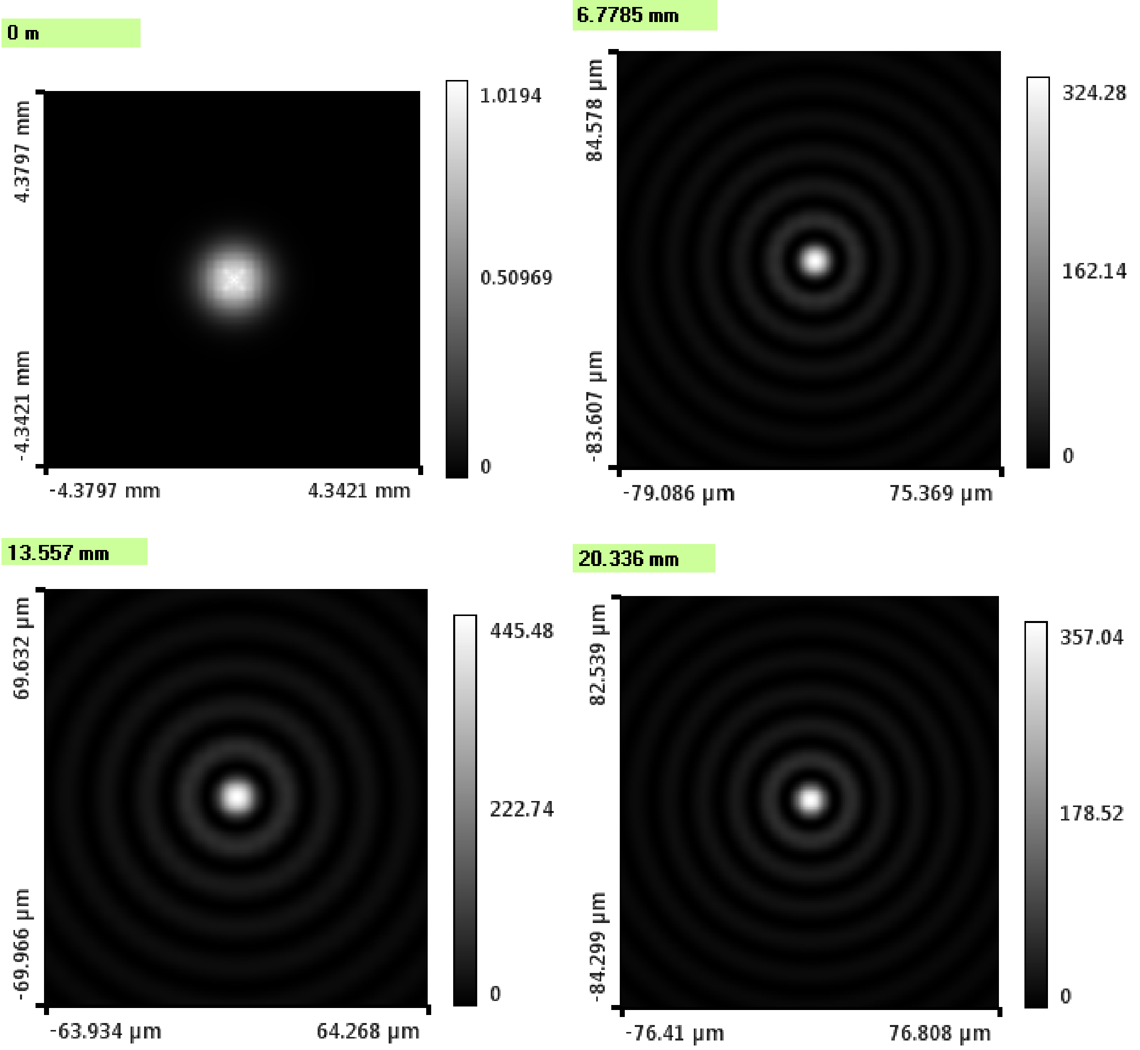


Figure 8: Output of the program: Squared amplitude on Virtual Screens at a series of position after the axicon for case 1

5.2 Case 2 is a plane wave propagating though an axicon.

Case 2 was considered as simpler setup for the program, because the program will generate less field area for a plane wave. As a result, the program will use less memory to calculate this setup.

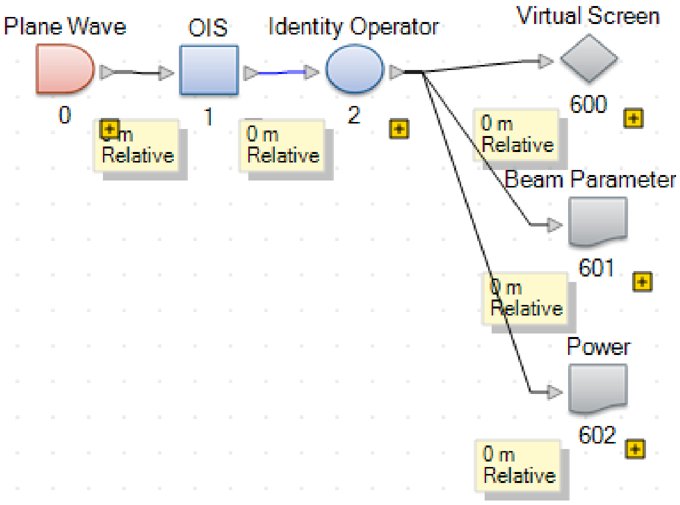


Figure 9: A diagram of the case 2 experiment in VirtualLab 5.

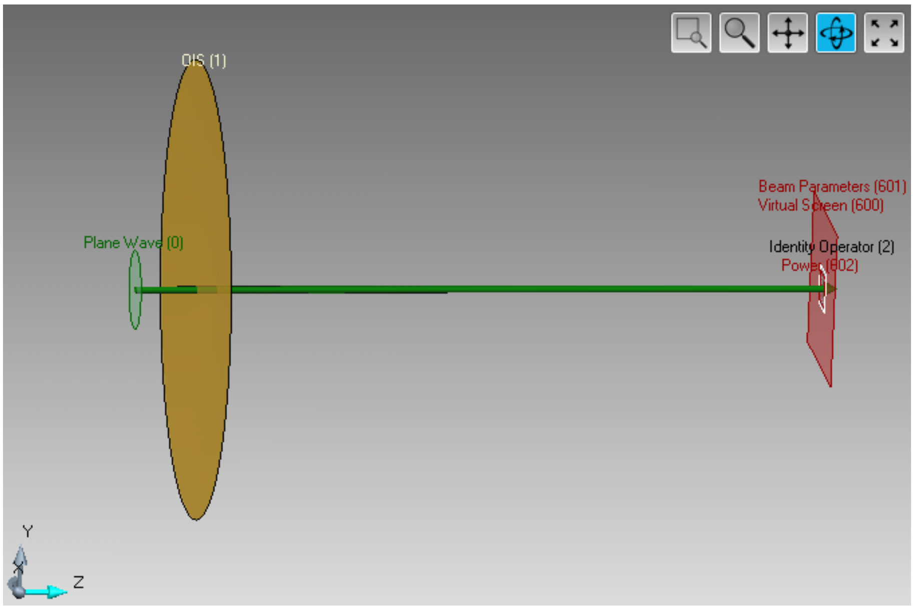
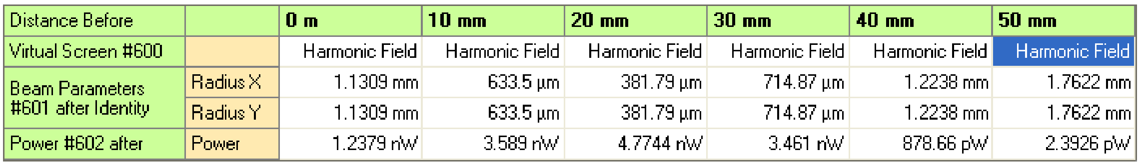


Figure 10: Experimental set-up. Plane wave diameter = 2140 μm, wavelength = 1064 nm; axicon:apex angle = 170^0.



Distance Before		**0 m**	**10 mm**	**20 mm**	**30 mm**	**40 mm**	**50 mm**
Virtual Screen #600		Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field
Beam Parameters #601 after Identity	Radius X	1.1309 mm	633.5 µm	381.79 µm	714.87 µm	1.2238 mm	1.7622 mm
	Radius Y	1.1309 mm	633.5 µm	381.79 µm	714.87 µm	1.2238 mm	1.7622 mm
Power #602 after	Power	1.2379 nW	3.589 nW	4.7744 nW	3.461 nW	878.66 pW	2.3926 pW

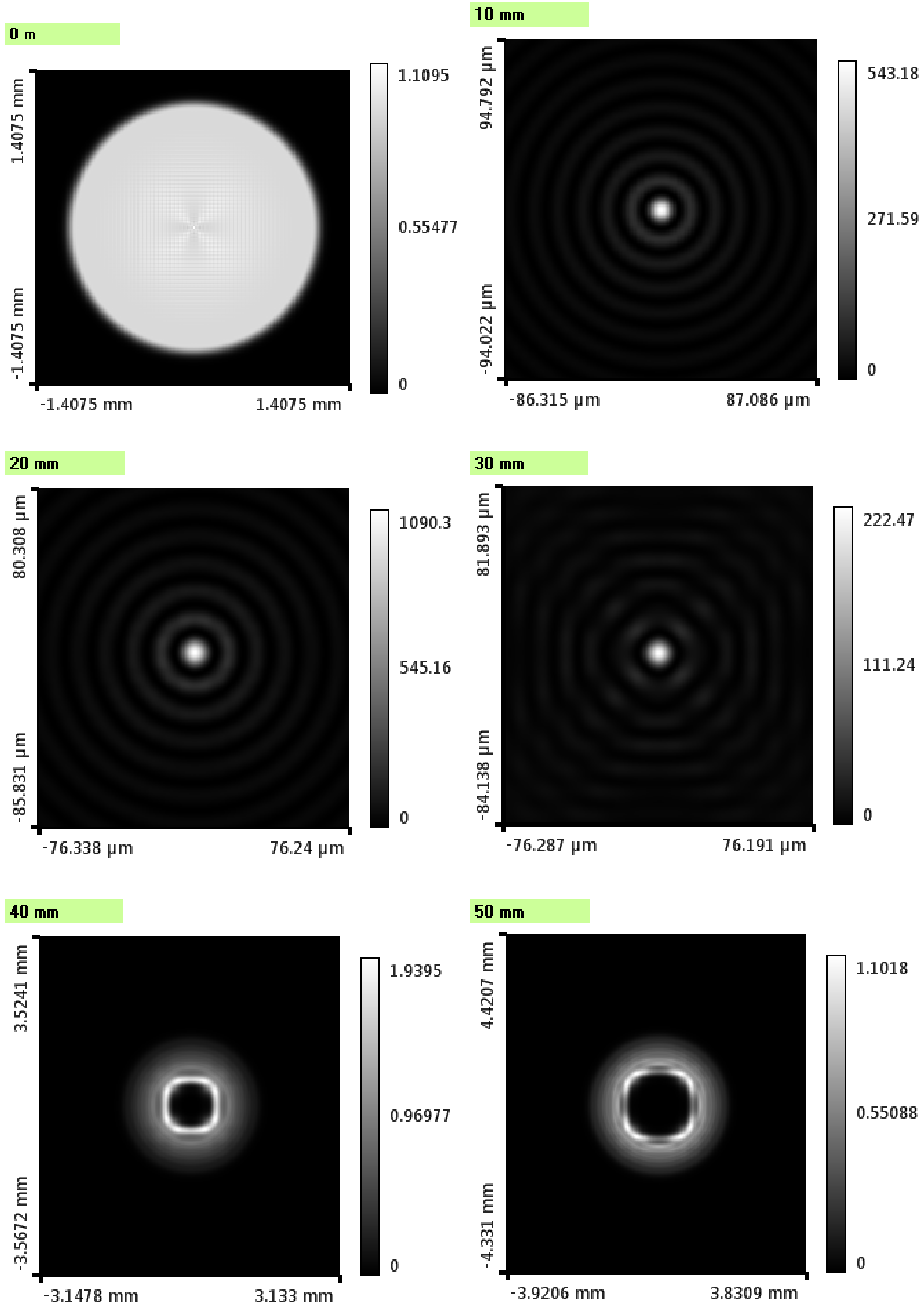


Figure 11: Output of the program: Squared amplitude on Virtual Screens at a series of position after the axicon for case 2

Fig. 11 shows the Bessel beam region and the ring structure as the squared amplitude on Virtual Screens as expected, however, zmax for this case is shorter than case 1. Thus, case 2 cannot be represented as case 1.

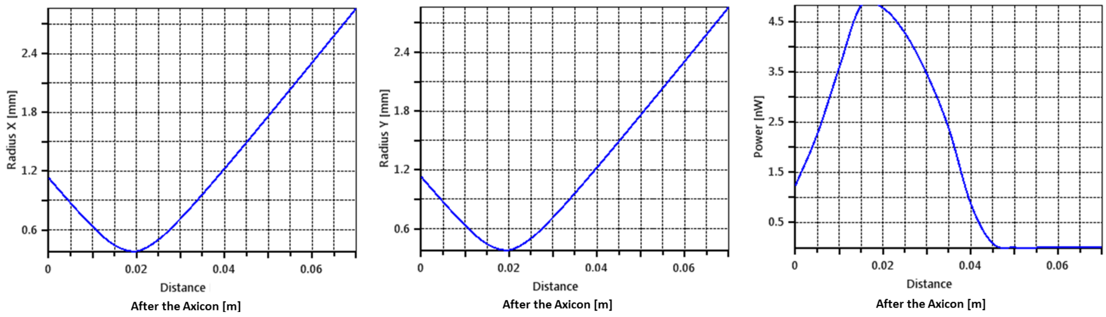


Figure 12: Plot of a beam radius on (left) x-axis and (center) y-axis at distance after the axicon.(right) plot of the beam power on a 1 mm x 1 mm detector and distance after the axicon.

Case 1 and Case 2 were used to understand how to use the program, and also showed a performance of the trial version, what the trial version can do. The full version is expected to have a better performance.

5.3 Case 3 is a Gaussian beam propagating though a focusing lens and an aperture. The beam waist of the Gaussian beam is placed on the lens front surface).

In the experiment, a free space at the entrance of a plasma chamber for a particle beam coming will be needed. In general, a mirror with a small aperture set in front of the plasma chamber was proposed as shown in Fig. 13. However, it will be equivalent to a simple set up, case 3 in Fig. 14 and Fig. 15.

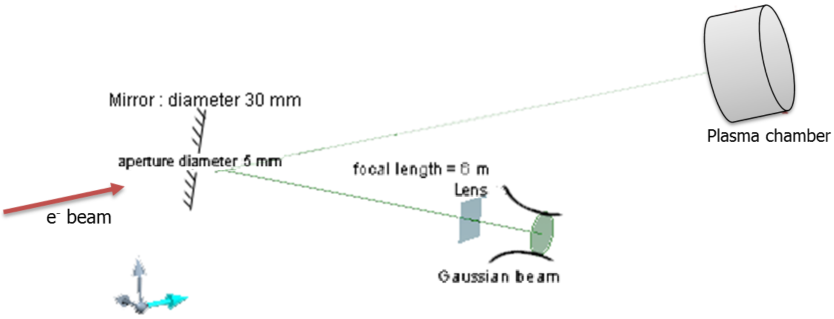


Figure 13: Motivation of case 3 set up.

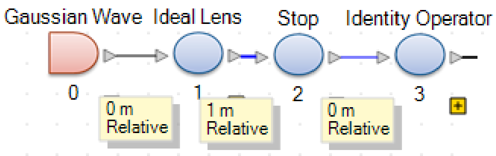


Figure 14: A diagram of the case 3 experiment in VirtualLab 5.

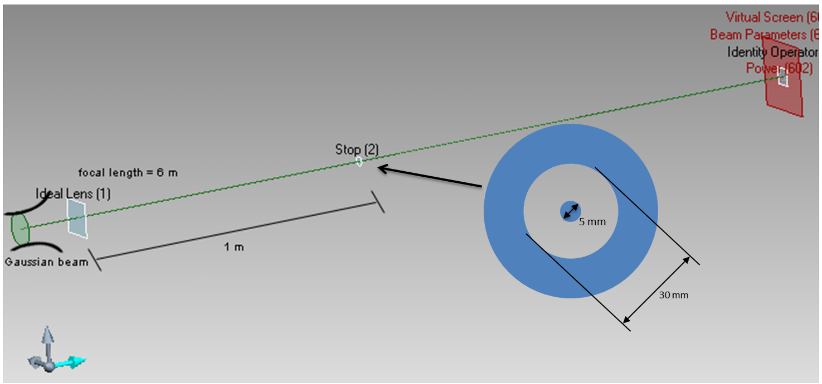
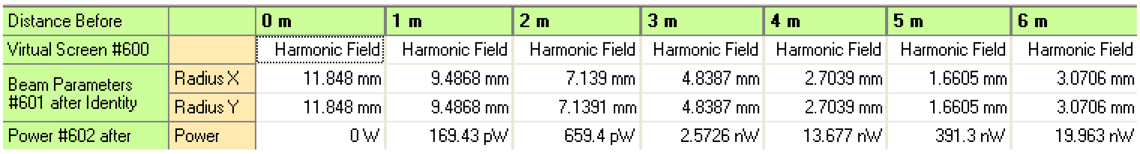
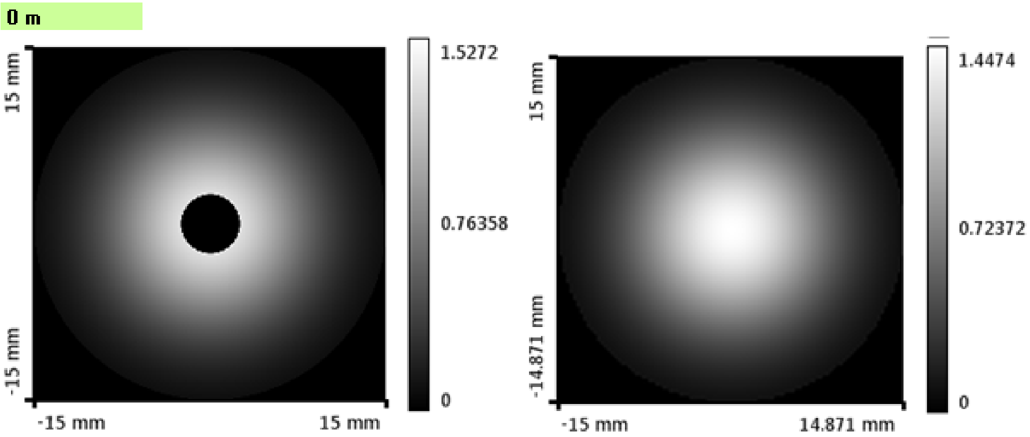
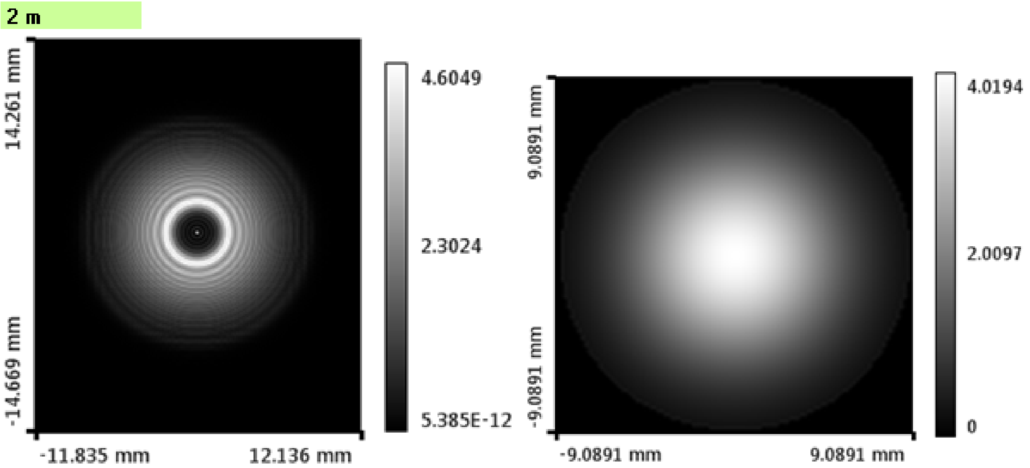


Figure 15: Experimental set-up. Beam waist of incident Gaussian beam = 30 mm, wavelength = 800 nm; lens: focal length = 6 m; 5 mm-diameter stop with a 15 mm-diameter aperture.



Distance Before		0 m	1 m	2 m	3 m	4 m	5 m	6 m
Virtual Screen #600		Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field	Harmonic Field
Beam Parameters #601 after Identity	Radius X	11.848 mm	9.4868 mm	7.139 mm	4.8387 mm	2.7039 mm	1.6605 mm	3.0706 mm
	Radius Y	11.848 mm	9.4868 mm	7.1391 mm	4.8387 mm	2.7039 mm	1.6605 mm	3.0706 mm
Power #602 after	Power	0 W	169.43 pW	659.4 pW	2.5726 nW	13.677 nW	391.3 nW	19.963 nW





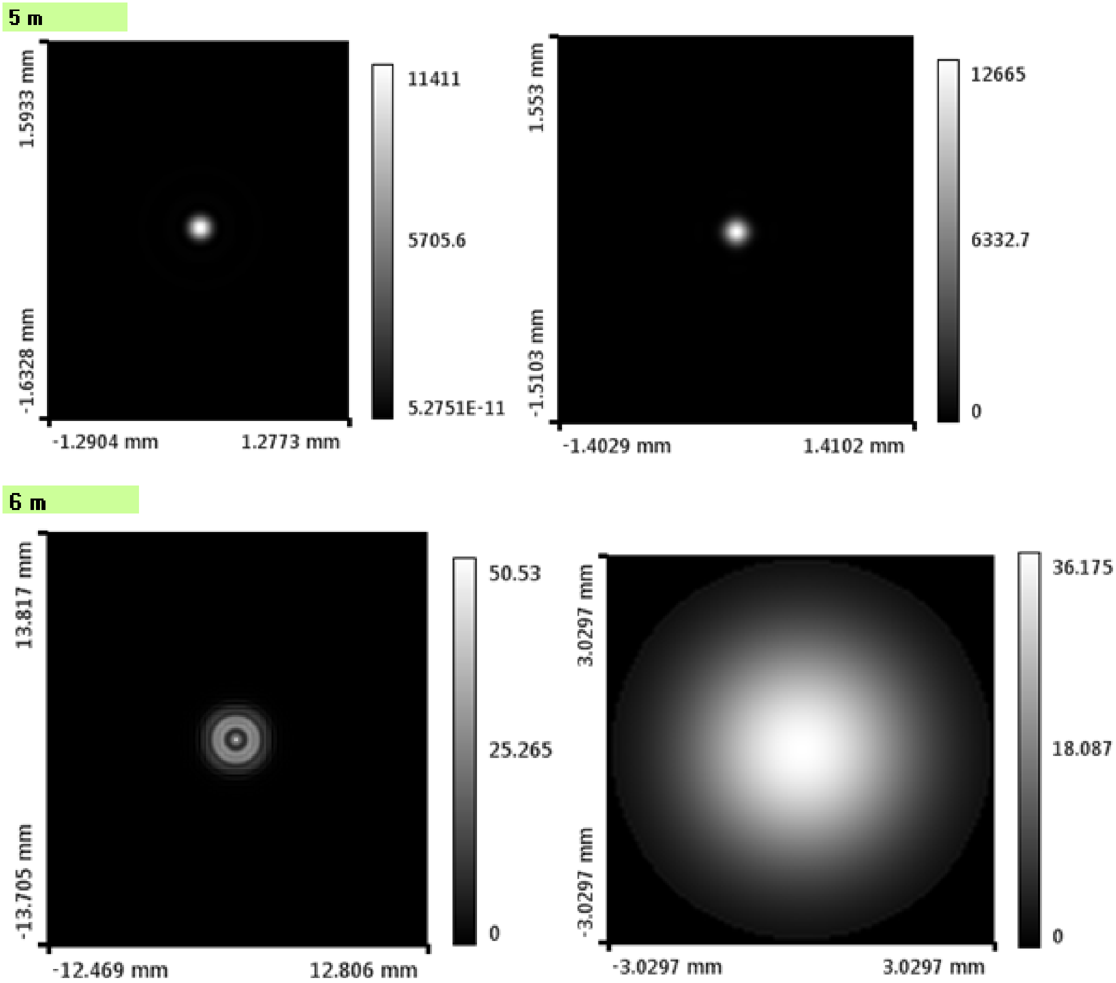


Figure 16: Output of the program: Virtual Screens at a series of position after (left) the stop with an aperture for case 3, and (right) an aperture (diameter of 30 mm) without stop.

Remark: the left-side plots cannot be zoomed in anymore; the right-side picture cannot be zoomed out anymore, because of screen's resolution limits. Instead a proper scaling was expected.

A stop blocks some part of the Gaussian beam; it causes loss of laser beam in the center of the plasma chamber inevitably far from the focal point. However, when it propagates around the focal point, there exists the beam propagating at the center of the Virtual Screen. It means the plasma chamber should be set around the focal point.

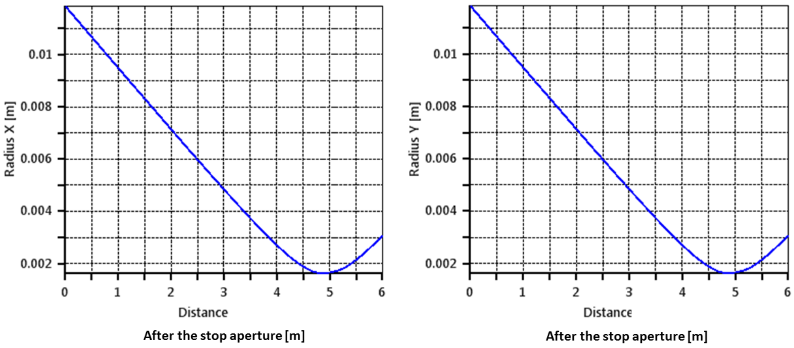


Figure 17: Plot of a beam radius on x-axis and y-axis at distance after the stop with an aperture.

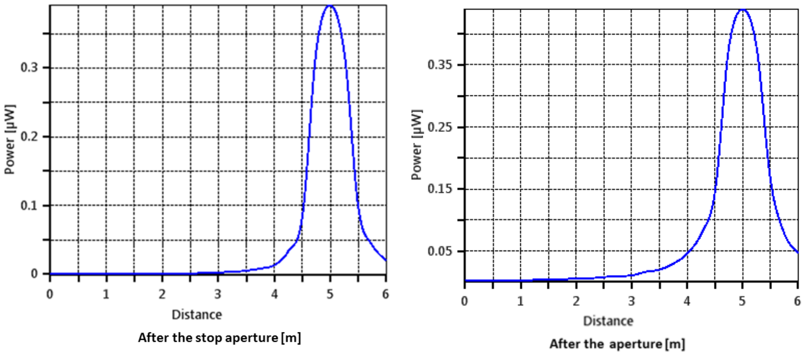


Figure 18: Plot of the beam power on a 1 mm x 1 mm detector and distance (left) after the stop with an aperture, and (right) after the aperture without stop.

6 Conclusions

The basics of plasma acceleration, laser beam propagation and ionization were studied. How to use VirtualLab5 software was also studied to generate a simple setup and compare its results with a literature. Unfortunately, the trial version is limiting the memory to calculate, it cannot calculate a complicated object like a Gaussian beam propagating through an axicon for studying how to confine the laser beam in a plasma chamber. However, a part of the Bessel beam region on Virtual screen of the program was shown as mentioned in the literature. A simpler setup, a plane wave propagating though the axicon, was calculated completely. These showed the performance of the trial version; a better performance of full version is expected. Finally, the last setup, a Gaussian beam propagating through a focusing lens and an aperture, was studied to understand laser propagating though the plasma chamber in the experiment. This setup blocking some part of the beam is equivalent to the setup of the experiment; it also was compared with the setup without blocking. When it propagates far away of the focal point, there exists no beam propagating at the center of the Virtual Screen. Thus, the plasma chamber should be set around the focal point.

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