Characterization of LYSO scintillator screen for future diagnostic of PWFA beams

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Abstract

Plasma wakefield acceleration is capable of producing high charge bunches with femtosecond pulse duration. Novel diagnostic techniques for these bunches are being investigated for the FLASHForward project at DESY. As part of a planned diagnostic setup with high spatial resolution, coated scintillator screen that can reflect the laser and be used for the electron beam diagnostics are needed. For this purpose, tests for preliminary characterization and determining damage threshold of a LYSO-type scintillator screen was performed and is reported here.

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1 Introduction and motivation

Plasma wakefield acceleration (PWA) is one of the most promising techniques that can be used in future colliders and light sources. It is able to achieve much greater accelerating gradients and produce much shorter beams than the conventional accelerators. Traditional accelerating structures are made of metal (normal or super-conductive). The properties of the materials impose a limit to the accelerating gradient due to the breakdown of the accelerating structure walls at high fields. The "accelerating structures" in PWA is the plasma, a material which is not "damageable", therefore this acceleration technique doesn't exhibit the same limitations. The highest accelerating gradient achievable in conventional RF cavities is around 100 MeV/m, while in PWA accelerating gradients on the order of 10-100 GeV/m can be achieved.

Plasma acceleration was first proposed by T. Tajima and J. Dawson in 1979 [1]. However, laser and beam technologies were not as advanced as today at the time. During the following years, parallel development of laser and beam technology occurred. In the recent years, plasma acceleration has been able to produce desirable high-quality electron beams [2]. However, characterization of the highly transient wakefield structure and the short electron pulses produced by these wakes are challenging.

1.1 Plasma wakefield acceleration

A plasma is a state of matter in which electrons and nuclei are not bounded together. When high-intensity lasers or relativistic charged particle bunches traverse the plasma the electrons are driven away from the driver, while the ions are not affected by it as they are heavier. In such way, regions with high charge density are created and strong electric fields are formed. When the driver beam causes total separation of the electrons and ion charges, maximum acceleration can occur: this regime is nonlinear and the cavity that is formed in the plasma that can trap and accelerate charged particles is called "bubble". The wakefield and the resultant "bubble" can be produced by high power short pulse lasers or by highly relativistic particle beams. In Laser Wake Field Acceleration (LWFA), plasma wakes are created by a femtosecond-short laser pulse, and in Plasma Wake Field Acceleration (PWFA), a charged beam particle is used to induce the wake.

While LWFA has been studied a lot in the last decades, there are some advantages in using a particle bunch to drive the wake instead of using a laser beam, for example:

- the phase velocity of the particle beam traveling through the plasma density is higher than the laser since the particles travel at close to speed of light while the laser propagates at its group velocity, leading to longer acceleration length (1 meter for PWFA, 100 mm for LWFA);

- strongly transverse focusing plasma avoids or reduces expulsion of the beam (unlike the defocusing/diverging laser);
- low dark current as a result of increased wake phase velocity (but this can make trapping charges for the PWFA beam challenging).

For all these reasons PWFA seems very promising and FLASHForward group at DESY is dedicated to studying this technique and its challenges. The initial goal of FLASHForward is to produce high-quality beams. Ultimately, FLASHForward project aims to demonstrate, possibly for the first time, Free-Electron Laser (FEL) gain, by beam driven plasma wakefield accelerated electron beams.

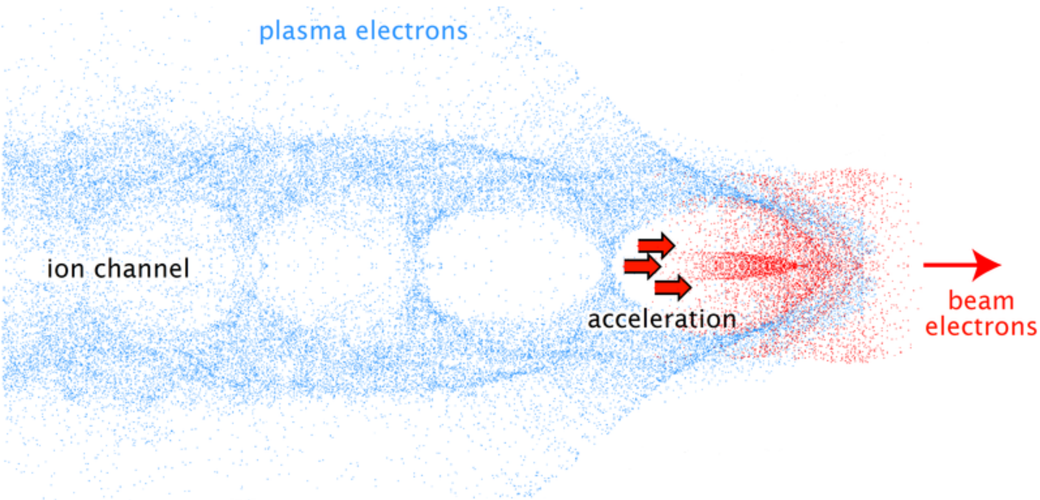

Figure 1: Illustration of the wake created by an electron bunch traveling inside the plasma (illustration by Rasmus Ischebeck).

1.2 Scintillator screens as diagnostic tools

Scintillator screens represent a powerful tool for diagnostic in many fields of physics, in particular in high energy physics. In recent years, scintillator screens have been studied as an alternative way to optical transition radiation (OTR) based beam diagnostic for highly energetic electrons for FELs [3] as it can reduce/cancel coherence effects and have femtosecond spatial resolution.

Therefore scintillator screen can also be used in imaging the electron bunch in PWFA, however, the copropagating laser used for ionizing the gas could cause damage in such screens, compromising the whole experiment. Therefore it is necessary to understand whether the screen will be able to bear high-intensity radiations of the laser.

The scintillator screen characterized in this report will be used as diagnostic in the FLASHForward facility: high energy electron bunches are created copropagating with high-intensity laser and the presence of the laser's electric field may interfere with the diagnostic of the electron bunch. Therefore it is necessary to separate the electron bunch from the laser pulse: the scintillator screen is used to meet this task as it is able to reflect the laser while not blocking the electron bunch. The problem with this setup is that the laser used in FLASHForward has very high intensities, so no material is able to work closer than 10 meters from the beam waist. For this reason, it is necessary to know whether the LYSO screen will be able to function properly at a distance of 10 meters away from the focus of the laser.

2 Experimental setup

2.1 Scintillator screen

The screen that is the candidate for test and diagnostics is a LYSO-type screen with dimension 36.5x29x0.2 mm, CRY019 by Crytur [4]. The test screen for the measurement discussed here is 0.2 mm thin CRY019 strip and it was coated by metal and multilayer dielectric layers to reflect the laser pulse.

2.2 Method of beam characterization

The laser used in the FLASHForward experiment is a 25 TW Ti:Sapphire laser. For the test set up described here, the secondary beam of the FLASHForward Ti:Sapphire laser, probe beam, is used. The typical properties of the beam used in this experiment are the following:

Table 1: Probe beam properties.

Wavelength	800 nm
Radius	5 mm
Repetition rate	10 Hz
Energy per pulse	3.5 mJ
Pulse length	25-56 fs

There are two types of damage that can limit the utility of the LYSO screen: damage due to heat and damage due to intensity. Typically the heat damage is discussed in terms of flux or fluence of the beam J/cm^2 with relatively long durations (nanosecond long). The damage of concern here is the intensity based damage due to short (femtosecond long) pulses. To determine the damage intensity threshold accurately the energy focused, spot size and pulse length at the probe must be carefully measured. Beam duration is measured using GRENOUILLE technique [5]. We assume all pulses have approximately the same length.

2.2.1 Beam energy measurement

As shown in Figure 2, beam energy was estimated sending part of the probe beam to a calibrated CCD camera. To this end, a dielectric mirror was put at an angle of 45° with respect to the beam axis: the transmitted beam went to the camera, the reflected beam proceeded to the remaining experimental setup. The intensity recorded by the camera is proportional to the energy of the beam. In order to know the conversion relation given a certain setup, the energy of a set of beams was measured by a calorimeter after the lens focusing on the target and compared to the images recorded by the camera. This data was used as a reference. The camera is equipped with filters in order to avoid saturation and damaging. Gain and distance from the lens focusing on the camera were chosen in order to have a small but not saturated beam image.

2.2.2 Beam spot size measurement

The probe beam initial spot size is around $w_{in} = 50\,\text{mm}$ and the peak intensity is low, approximately on the order of few thousands of W/cm^2. In order to achieve higher intensities and smaller spot sizes, a proper experimental setup must be defined. The following facts were taken into account when defining the experimental setup:

- high intensities are required;
- plano-convex lenses are preferred over biconvex lenses due to lower aberration when magnification is not between 0.2 and 5;
- small z_R compared to the sensibility of screen positioning leads to difficulties in finding the focus;
- limited space for the experimental setup;
- due to its many modes, a Ti:Sapphire laser would have the best intensity profile only at focus.

In the experiment, one plano-convex lens was used to focus the beam. The scintillator screen was put perpendicular to the direction of propagation of the beam, positioned at the focal plane. In order to measure the beam spot size, a BASLER acA1300-30gm camera was placed in front of the screen forming a small angle with the propagation direction; the beam spot size was measured from the scattered light recorded by the camera.

2.3 Final setup

The final setup is shown in the following image.

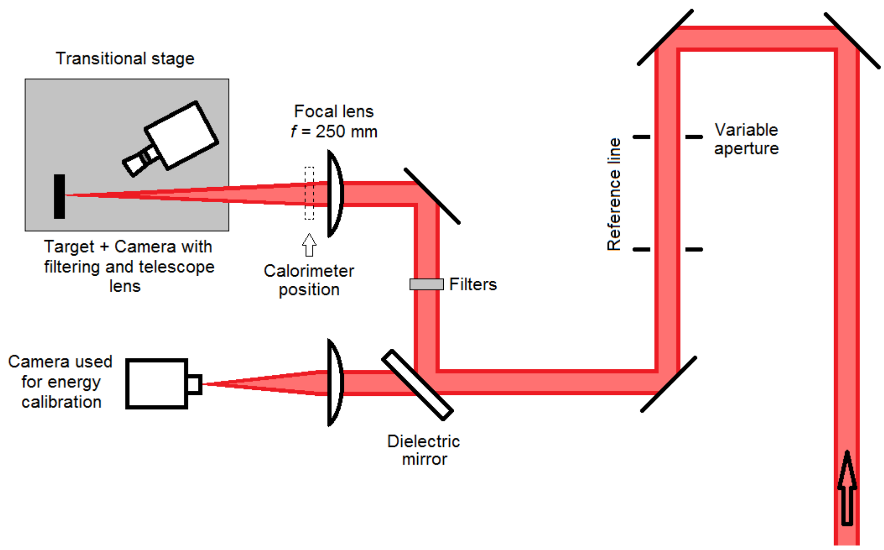

Figure 2: Experimental setup.

The following optical elements are used:

- $\varnothing$50.8mm broadband mirrors;
- apertures;
- plano-convex lenses: $f = 250$ mm; $f = 100$ mm;
- dielectric mirror BB4-E03 by Thorlabs;
- BASLER acA1300-30gm cameras;
- filters: ND2.0, ND3.0 and ND4.0.

The screen and the camera were mounted on the stage, so the camera didn't need to be refocused every time the screen is moved. The camera is put on the stage and focused on the screen at the beginning of the experiment the focusing is not changed during the experiment to avoid inconsistencies.

3 Experimental results and analysis

Different beam energy and beam repetitions are used in order to investigate the damage threshold of the scintillator screen.

Table 2: Probe beam properties.

Identification number	Filtering	Aperture size	Time of exposure [sec]
1	ND4	Almost closed	60
2	ND4	Half-opened	60
3	ND4	Fully opened	60
4	ND3	Almost closed	120
5	ND3	Fully opened	120
6	ND2	Half-opened	120
7	ND2	Fully opened	120

3.1 Beam energy

3.1.1 Calibration of image with calorimeter

Three data set at different aperture sizes were taken (open aperture, middle size aperture, and small size aperture). Each one has 700 images and 600 energy measurements. The number of images is greater as the camera begins to save data immediately while the calorimeter begins saving data only after a certain threshold is reached, so after removing the obstacle used to block the laser from the beam trajectory: the first image of the beam corresponds to the first energy measurement.

The energy of the beam should be proportional to the total intensity recorded by the camera: each pixel records a certain intensity proportional to the number of photons hitting the pixel. Therefore, the total intensity is estimated as the sum of the intensities over all pixels. The conversion between the intensity recorded by the camera (I) and energy (E) is evaluated using a linear fit $I = a + b \cdot E$, one for the data with the open aperture, one for the data with not-fully open apertures.

Additionally, the background must be taken into account which can be evaluated by averaging the intensities on the border of each image, away from the beam, or it can be evaluated by averaging the intensities recorded while the beam was blocked. The first method is preferable when possible as it doesn't take assume that the background doesn't change during the measurements. However, the beam with the open aperture is so large that even along the borders it isn't negligible, as the background evaluated with the first method is much greater than the one evaluated with the second method (while this doesn't happen with middle and small size aperture). The second method is used in such case. The fact that backgrounds evaluated with the second method are compatible regardless of the recording time (it is the same for open, middle and small size aperture, taken at different times) supports the hypothesis that the background is stable during the measurements and therefore the second method is applicable.

The fact that the beam is so wide that it is not negligible along the borders of the CCD has also some implications on the energy conversion: data taken with the open aperture will have a certain conversion value, as the intensity of the beam is not fully recorded by the camera, while data taken with medium or small size aperture will have another conversion value, as the intensity of the beam is fully recorded by the camera.

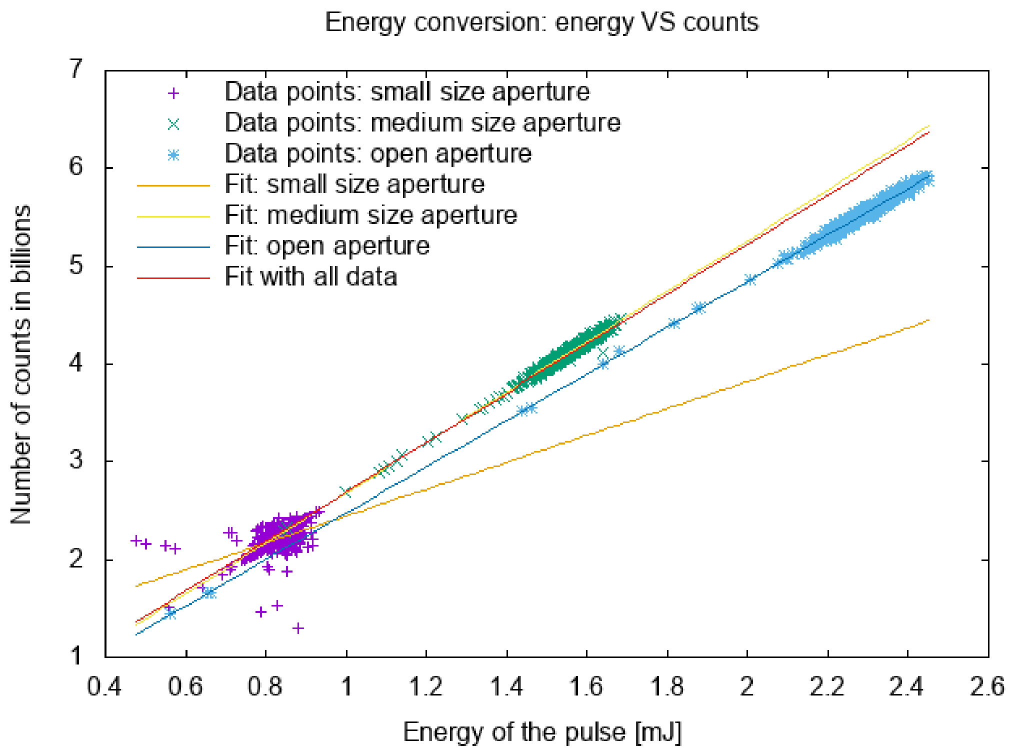

Figure 3: Energy conversion plot.

As it can be seen in Figure 3, data with the open aperture are clearly fitted by other parameters. Thus, using a fit that takes into account all data would be wrong, as it underestimates the energy of the beams taken with the aperture fully open.

Table 3: $I = a + b \cdot E$ fit parameters.

Parameters	Small-medium aperture size	Open aperture
a [a.u.]	0.10 ± 0.01	0.10 ± 0.01
b [a.u./mJ]	2.582 ± 0.008	2.372 ± 0.005

3.1.2 Energy measurements

Given the conversion values, energy for every setup is evaluated. For a set of 50 images from the energy-related camera, the mean value of the total intensity of a set is used as the estimate of the average beam energy for that particular setup.

Table 4: Beam energies.

Identification number	I in billions	Energy [mJ]
1	2.57±0.09	0.96±0.03
2	5.6±0.2	2.13±0.07
3	5.9±0.2	2.45±0.09
4	2.5±0.2	0.94±0.06
5	5.8±0.4	2.4±0.2
6	5.3±0.3	2.02±0.07
7	5.8±0.4	2.4±0.2

3.2 Beam spot size

For every setup, a set of 50 images of the screen hit by the beam with an ND5 filter (or ND6 if needed) was taken: the presence of the filters does not change the beam spot size, but it diminishes the scattered light to the level appropriate for measuring the beam spot size in which the camera is not saturated or damaged. A Gaussian fit is used in order to estimate the beam spot size. The fit is done choosing a range of few pixels around the brightest pixel. The fit is done both vertically and horizontally and the average of the two resulting widths is used as the final estimation. The presence of the background is managed by adding a constant variable to the Gaussian fit.

In almost all setups in the images two spots were present. This is due to the fact that the screen has two surfaces, with only one reflective, so if the reflective surface is not the closer surface to the laser two spots will be seen. For data analysis, the same spot was always used consistently.

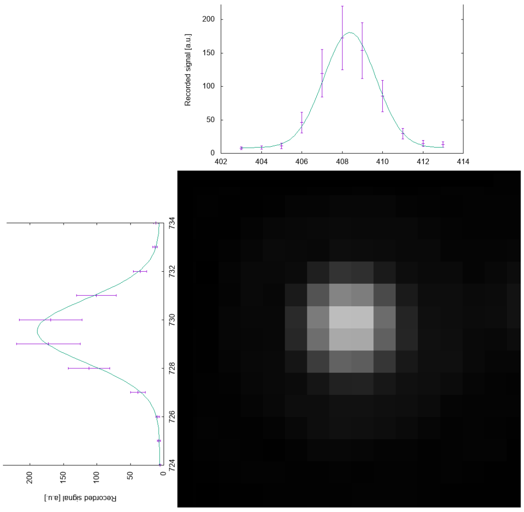

Figure 4: Spot size and Gaussian fit.

Table 5: Beam spot sizes.

Identification number	Beam spot size [μm]
1	8.9 ± 0.7
2	11 ± 1
3	8.7 ± 0.3
4	8.9 ± 0.7
5	11.5 ± 0.4
6	12 ± 1
7	11.5 ± 0.4

The resolution of the camera is about 9 μm, which was estimated to be smaller than the beam sizes measured. However changing the aperture should have changed the beam spot size (smaller aperture should have bigger spot sizes for a Gaussian beam – See appendix A) but this effect is not seen. Therefore it is likely that the camera resolution was not good enough. In this case, the values obtained would be upper-bound estimates and result in large error bars.

3.3 Peak intensity calculated

High peak intensity is responsible for intensity damage. The beam length, important in this damage mechanism was measured for another experiment on the same optical table to be $\sigma_t = 40 \pm 10$ fs.

Table 6: Peak intensity.

Identification number	Peak intensity [TW/cm^2]	Relative error
1	0.8 ± 0.1	15 %
2	1.1 ± 0.2	16 %
3	2.0 ± 0.3	13 %
4	8 ± 1	15 %
5	12 ± 2	13 %
6	90 ± 13	15 %
7	116 ± 16	13 %

3.4 Fluence calculated

Fluence is responsible for heat damage to the screen.

Table 7: Fluence.

Identification number	Fluence [J/cm^2]	Relative error
1	0.04 ± 0.02	51 %
2	0.06 ± 0.04	63 %
3	0.10 ± 0.03	27 %
4	0.4 ± 0.2	54 %
5	0.6 ± 0.2	30 %
6	5 ± 2	51 %
7	6 ± 2	30 %

3.5 Observed Damage

To see whether the screen was damaged by the laser or not the screen was illuminated by white light before and after the shooting session: if the beam damaged the screen a white spot of scattered light was anticipated.

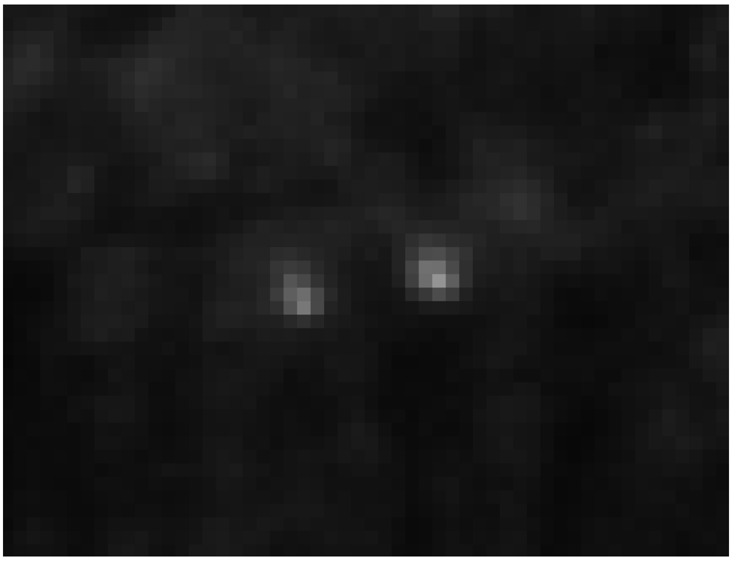

Figure 5: Damage done after shooting with ND2.

Damage was seen only when shooting laser with ND2 filters.

4 Fine tunning the setup and next steps

The same setup can be used, after adjustment for better focusing and resolution, for further measurements in the region between 10 and 90 TW/cm^2. Based on what was learned from calculations and setups presented here, the following additional steps can be considered next: changing the aperture size, and using different filter (e.g. using ND1.3).

A possible way to see whether the damage to the screen was due to intensity or heat is by exposing the screen to a few pulses. If any damage is seen in single shot, the damage is caused by the high intensity. If no damage is seen in single shot mode, the damage done by exposing the screen for multiple shoots is due to heat effects.

A microscope lens system can be used on the camera to evaluate more accurately the beam waist.

The setup can also be used to see whether the screen would exhibit back emission. A monochromatic filter for $f = 800$ nm can be put in front of the camera in order to block scattered laser light, if the camera is recording a signal, then the screen is emitting radiation and back emission can be measured.

5 Conclusion

After 10 meters from the beam waist the FLASHForward laser will have a peak intensity equal to 1.812 TW/cm^2 and a fluence of 0.09084 J/cm^2.

Table 8: Final results.

Exposure time [s]	Peak intensity [TW/cm^2]	LYSO screen response
60	0.8 ± 0.1	–
60	1.1 ± 0.2	–
60	2.0 ± 0.3	–
120	8 ± 1	–
120	12 ± 2	–
120	90 ± 13	Damage
120	116 ± 16	Damage

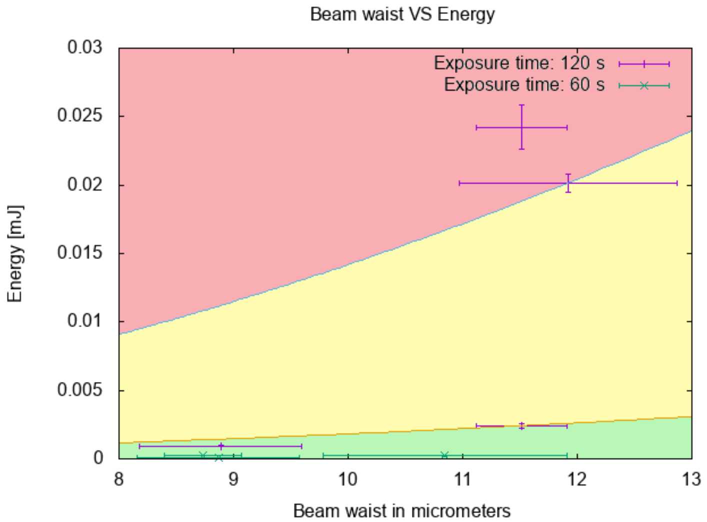

Figure 6: Energy vs. Beam width (at 40 fs): beam in red area is going to damage the screen; yellow area must be investigated; beam in green area is not going to damage the screen.

Therefore, at distance 10-12 meters from the focus of the ionizing laser, there will not be any heat damage on the screen. With the current data, intensity damage can not be fully ruled out and a second measurement after fine tunning the designed set up is needed.

Appendices

A Gaussian Beam

A Gaussian beam is a beam of monochromatic electromagnetic radiation with transverse electric and magnetic field amplitude profiles given by the Gaussian function; this also implies a Gaussian intensity profile.

The behavior of a Gaussian beam is given by some key parameters: the beam waist w_0, defined as the the distance from the center in which the intensity is $1/\mathrm{e}^2$ times the peak intensity; the Rayleigh length z_R associated to a beam with a beam waist equal to w_0 and wavelength λ is given by the following formula:

$$z_R = \frac{\pi w_0^2}{\lambda}\,; \tag{1}$$

the Rayleigh length is associated with divergence of the beam. The beam radius $w(z)$ at a certain distance z from the focus point is given by the following formula:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \,. \tag{2}$$

The power of a pulse with length σ_t can be calculated from the following formula:

$$P_0 = \frac{E}{\sqrt{2\pi}\sigma_t} \,. \tag{3}$$

The peak intensity $I(z)$ can be calculated given the power of the beam and its waist:

$$I(z) = \frac{2P_0}{\pi w^2(z)} = \frac{2P_0}{\pi w_0^2} \frac{1}{1 + \left(\frac{z}{z_R}\right)^2} \,. \tag{4}$$

When using a Gaussian beam, the change of the beam waist after entering a lens of focal length f is given by the following formula:

$$w_f = \frac{\lambda f}{\pi w_0} \,, \tag{5}$$

where w_0 is the initial beam waist and w_f is the beam waist after entering the lens.

B Python codes

B.1 Calibration of image with calorimeter

```
import numpy as np
import math
from PIL import Image

leftlimit = 20
rightlimit = 1280 - leftlimit
setnumber = 600
basicname = 'Basler_acA1300-30gm__21727698__20170831_'
suffMin = '164558711_'
suffMid = '165437766_'
suffMax = '164104591_'
tiffext = '.tiff'
txtext = '.txt'
calorynameMin = 'MinEnergy'
```

```
calorynameMid = 'MiddleEnergy'
calorynameMax = 'FullEnergy'
beginnumMin = 26
beginnumMid = 30
beginnumMax = 24

for num in range(1,beginnumMin):
    imm = Image.open(basicname+suffMin+str(num).zfill(4)+tiffext)
    background = np.array(imm)/1.0
    if num == 1:
        bckgrndMinA = background.mean()
    else:
        bckgrndMinA = np.append(bckgrndMinA, background.mean())
bckgrndMin = bckgrndMinA.mean()
print bckgrndMin

for num in range(1,beginnumMid):
    imm = Image.open(basicname+suffMid+str(num).zfill(4)+tiffext)
    background = np.array(imm)/1.0
    if num == 1:
        bckgrndMidA = background.mean()
    else:
        bckgrndMidA = np.append(bckgrndMidA, background.mean())
bckgrndMid = bckgrndMidA.mean()
print bckgrndMid

for num in range(1,beginnumMax):
    imm = Image.open(basicname+suffMax+str(num).zfill(4)+tiffext)
    background = np.array(imm)/1.0
    if num == 1:
        bckgrndMaxA = background.mean()
    else:
        bckgrndMaxA = np.append(bckgrndMaxA, background.mean())
bckgrndMax = bckgrndMaxA.mean()
print bckgrndMax


for num in range(beginnumMin,beginnumMin+setnumber):
    imm = Image.open(basicname+suffMin+str(num).zfill(4)+tiffext)
    energyccd = np.array(imm)/1.0
    background = energyccd[950:960, :]
    bckgrnd = background.mean()
    integralccd = energyccd.sum() - bckgrndMin*energyccd.size
```

```
    errccd = math.sqrt(energyccd.sum() + background.std()**2)
    if num == beginnumMin:
        integralarray = integralccd
        errintegral = errccd
    else:
        integralarray = np.append(integralarray, integralccd)
        errintegral = np.append(errintegral, errccd)

for num in range(beginnumMid,beginnumMid+setnumber):
    imm = Image.open(basicname+suffMid+str(num).zfill(4)+tiffext)
    energyccd = np.array(imm)/1.0
    background = energyccd[950:960, 0:10]
    bckgrnd = background.mean()
    integralccd = energyccd.sum() - bckgrndMid*energyccd.size
    errccd = math.sqrt(energyccd.sum() + background.std()**2)
    integralarray = np.append(integralarray, integralccd)
    errintegral = np.append(errintegral, errccd)

for num in range(beginnumMax,beginnumMax+setnumber):
    imm = Image.open(basicname+suffMax+str(num).zfill(4)+tiffext)
    energyccd = np.array(imm)/1.0
    background = energyccd[:, 1275:1280]
    bckgrnd = background.mean()
    integralccd = energyccd.sum() - bckgrndMax*energyccd.size
    errccd = math.sqrt(energyccd.sum())#+ background.std()**2)
    integralarray = np.append(integralarray, integralccd)
    errintegral = np.append(errintegral, errccd)



calorym = np.loadtxt(calorynameMin+txtext)
calorym = np.append(calorym, np.loadtxt(calorynameMid+txtext))
calorym = np.append(calorym, np.loadtxt(calorynameMax+txtext))

calorym = calorym*1000
integralarray = integralarray/1000/1000/1000
errintegral = errintegral/1000/1000/1000
conversion = calorym/integralarray
print conversion.mean()
print conversion.std()

def func1(x, a, b):
    return a + b*x
```

```
par1 = np.array([0.4,2])

def func1var(x, m):
    return m*x
par1var = np.array([0.385])

def func2(x, f, g, h):
    return f + g*x + h*x**2
par2 = np.array([0,0,0])

def func2var(x, g1, h1):
    return g1*x + h1*x**2
par2 = np.array([0,0])



fitval = open('FIT'+basicname+'.txt', 'w')

for value in optimization.curve_fit(func1var, calorym,
    integralarray, par1var, errintegral):
    fitval.write(str(value))

fitval.close()
```

B.2 Beam spot size

```
import numpy as np
import math
from PIL import Image
from scipy import misc
import scipy.optimize as optimization

basicname = 'Basler acA1300-30gm (22033907)_20170831_'
suff = '172830412_'
tiffext = '.tiff'
txtext = '.txt'
verticalfit = 964
horizontalfit = 404
left = 950+9
right = 960+9
top = 400-1
bottom = 410-1
```

```
sx = 'SX'
dx = 'DX'
cx = 'CX'
direc = dx

for num in range(1,51):
    imm = Image.open(basicname+suff+str(num).zfill(4)+tiffext)
    if num == 1:
        rifr = np.array(imm)/50.0
    else:
        rifr = rifr + np.array(imm)/50.0

rifrGauss = rifr[top:bottom+1, left:right+1]

for num in range(1,51):
    imm = Image.open(basicname+suff+str(num).zfill(4)+tiffext)
    imm1 = np.array(imm)
    if num == 1:
        rifrErr = (rifr - imm1)**2
    else:
        rifrErr = rifrErr + (rifr - imm1)**2

for num1 in range(top,bottom+1):
    for num2 in range(left,right+1):
        rifrErr[num1,num2] = math.sqrt(rifrErr[num1,num2]/49.0)

def gaussian(x, A, m, s, bg):
    return A*np.exp(-(x-m)**2/(2.0*s**2))+bg


fitval = open(direc+'fit'+'.txt', 'w')

fitval.write('Spot position: '+str(verticalfit)+',
    '+str(horizontalfit)+'\n')
fitval.write('Range: '+str(left)+'-'+str(right)+',
    '+str(top)+'-'+str(bottom)+'\n')

fitval.write('\n Horizontal fit \n')
par1 = np.array([140,verticalfit,1.5,3])
for value in optimization.curve_fit(gaussian, range(left,right+1),
    rifrGauss[horizontalfit-top, :], par1, rifrErr[horizontalfit,
    left:right+1]):
    fitval.write(str(value))
```

```
fitval.write('\n \n Vertical fit \n')
par1 = np.array([140,horizontalfit,1.5,3])
for value in optimization.curve_fit(gaussian, range(top,bottom+1),
    rifrGauss[:, verticalfit-left], par1, rifrErr[top:bottom+1,
    verticalfit]):
    fitval.write(str(value))

fitval.close()

fitval = open(direc+'horiz'+'.txt', 'w')

for num in range(left,right+1):
    fitval.write(str(num)+' '+str(rifrGauss[horizontalfit-top,
        num-left])+' '+str(rifrErr[horizontalfit, num])+'\n')

fitval.close()


fitval = open(direc+'vertic'+'.txt', 'w')

for num in range(top,bottom+1):
    fitval.write(str(num)+' '+str(rifrGauss[num-top,
        verticalfit-left])+' '+str(rifrErr[num, verticalfit])+'\n')

fitval.close()


print '\n Horizontal fit \n'
par1 = np.array([140,verticalfit,1.5,3])
for value in optimization.curve_fit(gaussian, range(left,right+1),
    rifrGauss[horizontalfit-top, :], par1, rifrErr[horizontalfit,
    left:right+1]):
    print str(value)


print '\n Vertical fit \n'
par1 = np.array([140,horizontalfit,1.5,3])
for value in optimization.curve_fit(gaussian, range(top,bottom+1),
    rifrGauss[:, verticalfit-left], par1, rifrErr[top:bottom+1,
    verticalfit]):
    print str(value)
```

6 References

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