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Laser wakefield acceleration self-guiding in noble gas mixes

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ABSTRACT

Laser wakefield acceleration (LWFA) is a technique for accelerating charged particles to high energies over centimeter-scale distances, which has led to a new breed of compact particle accelerators. In order to keep laser intensity at ~10^{19} W/cm^2 over this distance, diffraction from the beam waste at focus must be limited. Self-guiding, where the laser-generated plasma causes refraction back toward the laser axis along the beam path, has been demonstrated previously in LWFA plasma using pure helium gas. We demonstrate self-guiding measurements in He/Ne and He/Kr gas mixtures showing self-guiding in neon and in low concentrations of krypton.

INTRODUCTION

Laser wakefield acceleration

Laser wakefield acceleration (LWFA) uses a short pulse laser to create an accelerating structure for electrons. Unlike traditional particle accelerators (which are many kilometers in length), LWFA accelerates electrons to GeV energies over lengths on the order of centimeters. Monoenergetic energies of up to 0.5 GeV[1] have been reached, and maximum energies of 2.4 GeV[*] have been obtained with a broad energy spread. A "table-top" accelerator using this technology would allow for the proliferation of particle accelerators in many fields.[2]

In order to generate LWFA, a powerful short-pulse laser is focused on a gas-filled target. As the laser pulse propagates through the gas, the gas is ionized via tunnel ionization, a quantum mechanical effect. As the laser's oscillating electromagnetic field interacts with the gas atoms, the potential wells of the bound electrons are distorted, becoming both narrower and shorter. This distortion increases the probability of ionization, allowing for the electrons to escape.[3]

After ionization, the laser's ponderomotive force moves the electrons away from the center of the beam (where the electric field is strongest), while the ions remain there, creating an electrical potential across the gap. This gap is called the "bubble," and the multiple bubbles left behind the laser pulse collectively are called the "wake," leading to the term "wakefield." Any electron injected trapped in the bubble would be accelerated by the potential difference.[3] Figure 1 illustrates the injection of nitrogen electrons into a laser wake.

[*] X. Wang *et al.*, in unpublished *Proceedings of 2012 Advanced Accelerator Concepts Workshop, June 10-15, Austin, TX*

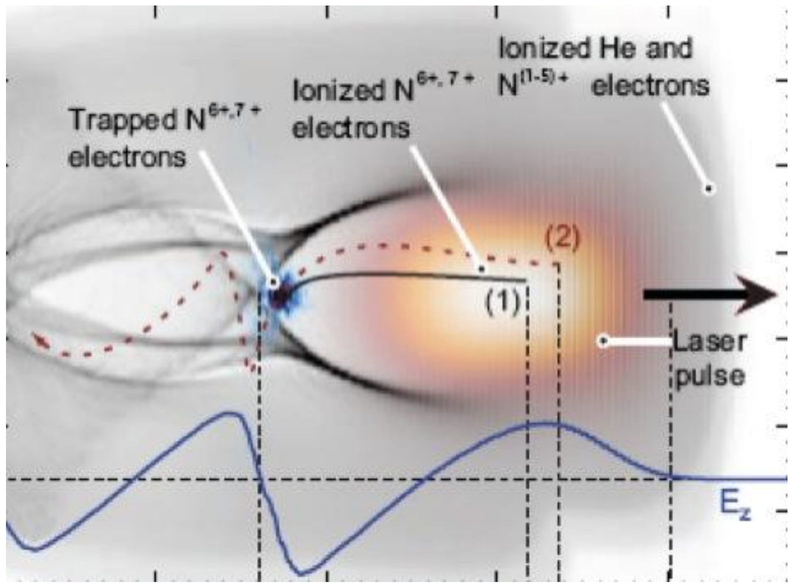

Figure 1: An illustration of electron injection during LWFA.[3]

Self-guiding

As a focused laser propagates through a vacuum, the light diffracts. In order to achieve LWFA, the laser beam must be guided through the plasma with minimal diffraction to maintain sufficient intensity to continue accelerating the electrons. This "self-guiding"[4] can be achieved in a number of different ways, including creating a suitable index of refraction profile within the plasma itself. Light refracts towards areas of higher index of refraction, so if conditions can be created where the area outside the beam path has a lower index of refraction than the axis, the light would be refracted back towards the desired axis.[4]

Helium has been shown to achieve the appropriate index of refraction, η, to prevent light from diffracting from the beam path of the laser.[5] Equation 1 shows the factors impacting the index of refraction of the plasma.[6]

$$\eta = \left(1 - \frac{1}{2}\frac{{\omega_p}^2}{{\omega_o}^2}\left(1 + \frac{\delta n_e}{n_e} - \frac{\langle {a_o}^2 \rangle}{2}\right)\right), \qquad (1)$$

where ω_o is the frequency of the laser, ω_p is the plasma electron frequency, n_e is the electron density, and a_o is the vector potential of the laser.[6] Helium is able to achieve the desired index of refraction gradient because both He electrons can be ionized by fields achieved at the beginning of the laser pulse. Because of this, the electrons are immediately blown out into the wake, leaving only ions in the center of the bubble.[1] The density is therefore high on the edges of the wake and low in the center; the $\delta n_e/n_e$ term thus encourages a favorable index of refraction curve. In addition, the vector potential a_o of the laser is a Gaussian; this term also leads to a favorable profile.

Experiment

Other gases could have other effects, however. If the ionization of electrons occurs later in the laser pulse (for those electrons with higher ionization energies), the electrons will be injected continuously inside the wake. This can lead to a flat or otherwise distorted density profile, changing the effect of the $\delta n_e/n_e$ profile. This experiment will explore different concentrations of high-Z gases (Ne and Kr) in helium to find if self-guiding is possible in gases with more ionization states.

MATERIALS AND METHODS

Laser

This experiment took place at the Jupiter Laser Facility (JLF) at Lawrence Livermore National Laboratory (LLNL), with the Callisto laser. Callisto is a Ti:sapphire laser capable of 200 TW of power in 60 fs. An f/8 off-axis parabolic mirror is used to focus the beam onto the target, with a spot size of w_o=15 μm (beam diameter=30 μm) at the $1/e^2$ intensity point.

Imaging system

In order to test for self-guiding, the beam is imaged as it exits the gas cell. The light transmitted through the gas cell target during the pulse is imaged onto a 14-bit CCD camera with a 10x focusing objective. A two-lens system is set up on the axis of the beam to capture the image at the exit of the gas cell. The imaging system used is shown below in Figure 2.

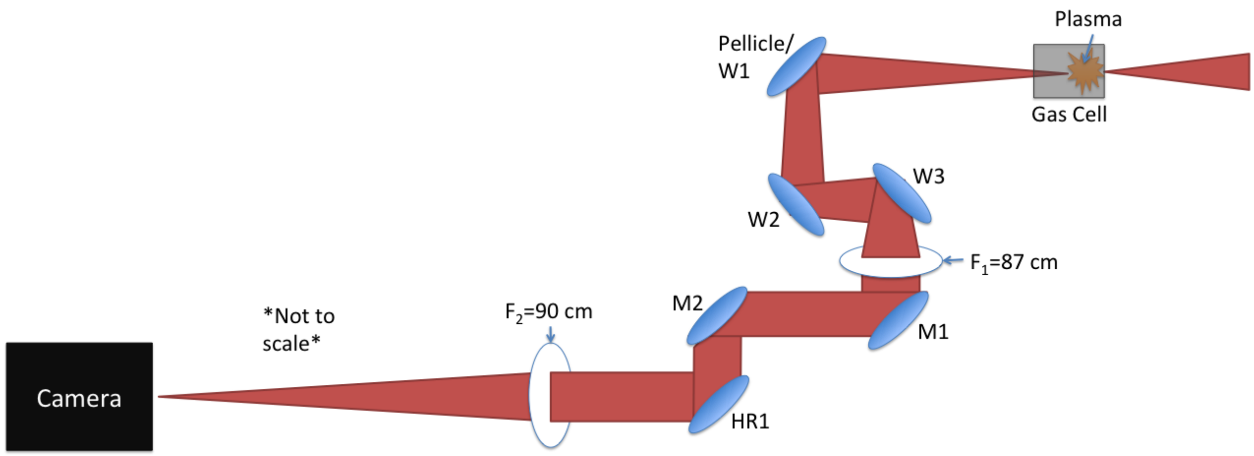

Figure 2: The imaging system which captures the transmitted beam light. The W optics are wedged, the M optics are silver mirrors, and the HR optic is highly-reflective for 775-875 nm. The F values represent the focal lengths of the 2 lenses. The camera has a 10x microscope objective.

Originally, a pellicle was used to deflect the beam from the electron acceleration axis, but a wedge was employed later to achieve higher resolution.

Data analysis

The images obtained during experimentation are analyzed using the MATLAB codes in Appendices A, B, and C.

The images are delineated in the files in pixels, so the imaging system is to be analyzed for magnification and resolution. Images of the 1951 United States Air Force resolution test chart (USAF-1951, Figure 3 below) are taken and analyzed using ImageJ software in order to determine both the resolution and magnification.

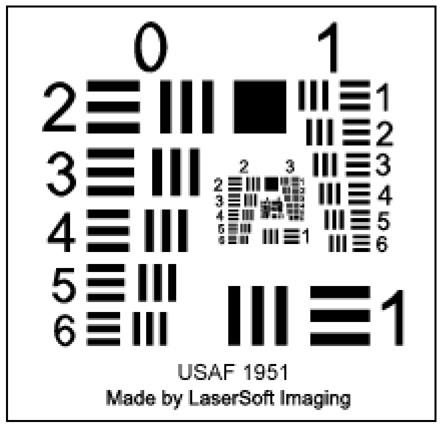

Figure 3: 1951 United States Air Force resolution test chart[7]

Due to a setting in the image capture software, 2^{15} is subtracted from each pixel in the data. Additionally, an average of the background both horizontally and vertically is taken and subtracted from the data to attempt to eliminate background noise. In order to account for saturated pixels in some images, the MATLAB code includes a loop to test for singular saturated points and exclude them for determining local maxima.

MATLAB is used to calculate the maximum intensity and its location on the image. In the case of saturated maxima, the code finds the approximate center of the saturated region and treats that as the maximum. From there, the code takes a lineout of the row and column where the maximum occurs. Then the code finds the full width at half maximum (FWHM) by finding the location of the points within a given variation of the half maximum, and finding the difference between the leftmost and rightmost location values.

Several problems exist with this means of calculating the FWHM. First, several of the images contain saturated data (as a result of improper filtering). Though the code calculates the FWHM, the value is inaccurate as it uses a point mid-curve as the maximum intensity value, while the actual value may be much higher. In order to correct for this error, data with saturated maxima are exported into Microsoft Excel, where a Gaussian fit is performed in order to find a more accurate FWHM value. Second, some data shows multiple peaks. The cause of these peaks will be discussed in the Results and Conclusions sections; however, these data are manually analyzed for FWHM values based on the lineout plots.

In addition to the saturation inaccuracy, maximum intensity values are found to be less useful for other reasons. Neutral density (ND) filters and red glass (RG) filters are used in different amounts in different shots; this occurs because some experimentation was necessary before finding the correct amount of filtering for the images. The RG 830 filter used has attenuation values which are heavily dependent on wavelength, especially around 800 nm light. Since spectrometry data is only available for some shots, an accurate attenuation is impossible to determine. Additionally, ND filters are not entirely neutral, so the wavelength of light does affect their attenuation value, making any intensity calculations based on these values inaccurate unless the spectrum of the beam and the optical transfer function at the corresponding wavelength are measured. As a result, comparison of maximum peak values between shots with different filtering is difficult.

Spot sizes are compared to the unguided beam, which has a diameter of approximately 500 µm (FWHM≈300 µm). Figure 4 shows this image, which was obtained by allowing the 800 nm laser to pass through the gas cell under vacuum.

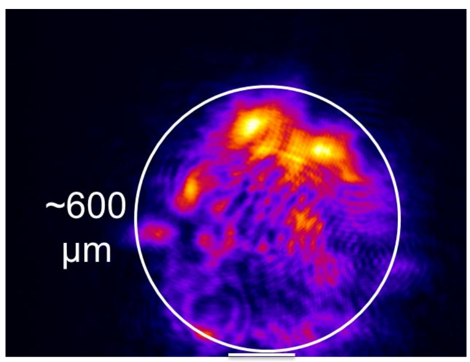

Figure 4: An image of the unguided laser beam

RESULTS

Figure 5 shows an example of an image and the subsequent MATLAB generated lineouts for neon data.

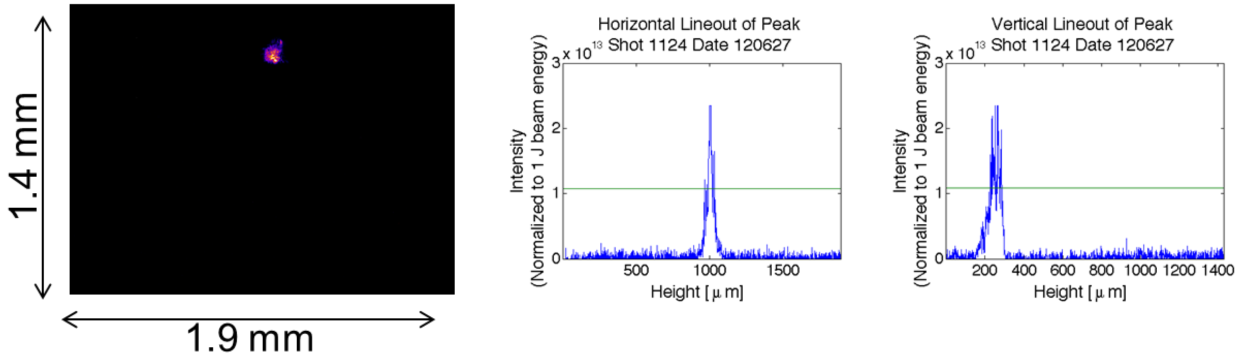

Figure 5: a) Original image of the beam. b) Horizontal lineout. c) Vertical lineout. This shot used 9.5% Ne in He, with a 6.3 J laser pulse.

Figure 6 below shows the results of the FWHM measurements for various concentrations of Ne in He (from 9.5% to 100% Ne, by partial pressure).

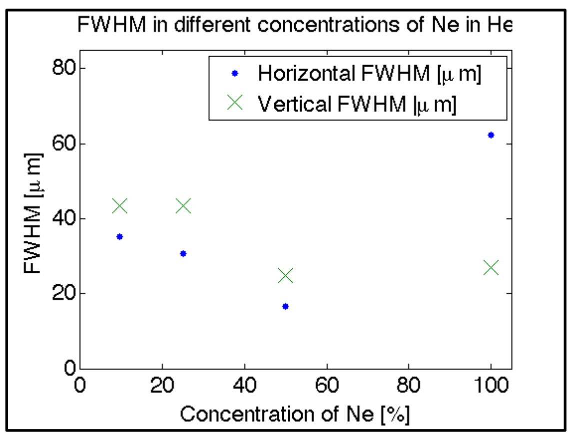

Figure 6: The beam size for various concentrations of Ne in He based on FWHM measurements.

Figures 7 and 8 below show typical krypton data. As Figure 7a shows, the beam has multiple bright spots, all of which have intensity on the same order of magnitude.

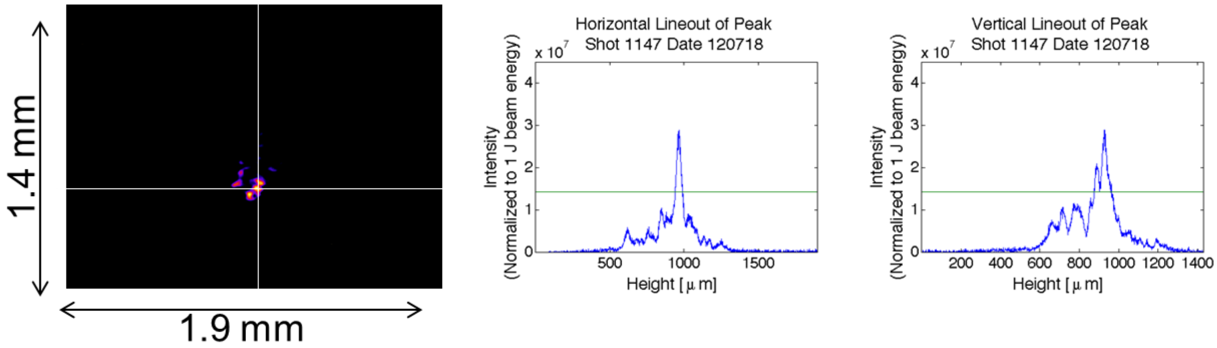

Figure 7: a) Original image of the beam. b) Horizontal lineout. c) Vertical lineout. This shot used 5% Kr in He, with a 8.5 J laser pulse.

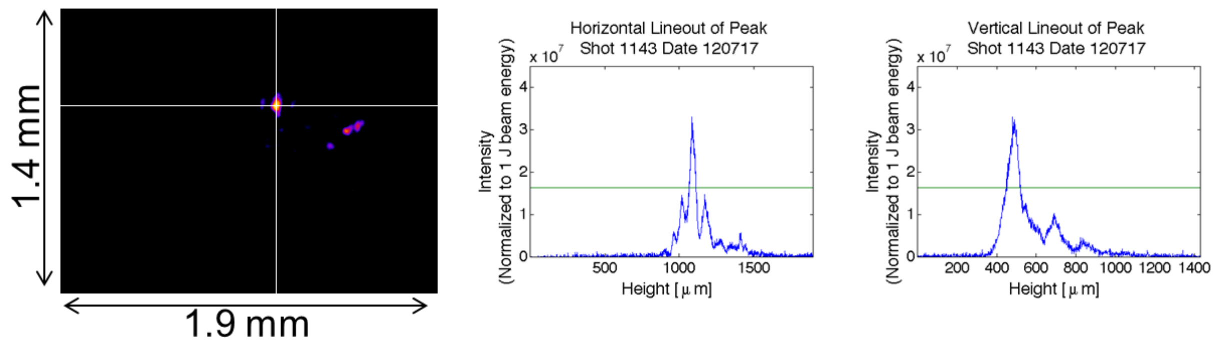

Figure 8: a) Original image of the beam. b) Horizontal lineout. c) Vertical lineout. This shot used 25% Kr in He, with a 6.2 J laser pulse.

CONCLUSIONS

Based on Figures 4 and 6, all neon shots are self-guided. All FWHM values are significantly less than the unguided value.

The krypton shots all show multiple peaks. There are several possible causes for these multiple peaks. As discussed in the Introduction, the self-guiding ability of the plasma is determined by Equation 1. Krypton has electrons whose ionization occurs at much higher energies; as a result, electrons are injected into the plasma closer to the center of the laser pulse. These electrons are born into the center of the bubble, which distorts the density profile. This can create a density profile which is flat across the laser spot (no self-guiding); it can also create an density profile which has multiple peaks (the edges and the center), allowing for self-guiding conditions in two different channels, causing multiple peaks.

Another possible cause is an irregular beam profile. An observation of the beam profile (taken after the experiments were completed) shows large distortions in the beam, including a “hole.” These aberrations could lead to two hot spots guiding through the plasma separately.

It is believed that krypton shows guiding up to 25% concentration. However, given the uncertainty of the data, further study into self-guiding with krypton is necessary.

ACKNOWLEDGEMENTS

There were many people who greatly influenced this experiment. First and foremost, I would like to thank Brad Pollock and Felicie Albert, the team leaders for this campaign (both at LLNL). They were invaluable as mentors, teachers, and co-researchers. Thanks also to Art Pak (LLNL) and Ken Marsh (UCLA) for all their laboratory help and ideas for experimental improvements. Steven Maricle (JLF, LLNL) was incredibly accommodating and helpful as the operator of the Callisto laser. The other interns with whom I worked (Sarah Mills, Brian Severson, and Alex Rigby) were indispensable in the lab, in addition to making the whole experience a more pleasurable one. Jessie Shaw (UCLA) gave excellent guidance during her time at the laboratory. Finally, thanks to my mentor, Siegfried Glenzer, for facilitating the experiment and for taking his time to ensure that the interns all had a rewarding experience.

APPENDICES

Appendix A: Reading .tif images, MATLAB file

```
function [x,y,l,w,spatialdispersion,FI]=readtiff(file, date, energy, ndfilter,
rgfilter, maxes)
%This function reads a tiff image of the forward image. It then corrects
%this image for background, and calculates the spatial dispersion.

%file-number or string giving the file name date-YYMMDD energy-energy of
%shot in J ndfilter-numerical value of ND filtering rgfilter- wavelength
%designation of RG filter (in nm) maxes- 1 if want maxes removed. any other
%number if no.

%Spacial Dispersion calculation
if date<120702
    spatialdispersion=1.17; %[um/pixel]
elseif date<120709
    spatialdispersion=0.5;
elseif date<120711
    spatialdispersion=0.56;
else
    spatialdispersion=0.54;
end

%Reading file and calculating axes values.
file=num2str(file);
date=num2str(date);
filename=['/Users/ma8/Desktop/LAKForwardImage/Callisto June
2012/',date,'/',file,'.tif'];
FI=imread(filename,'tif');
FI=double(FI);

[l,w]=size(FI);
x=linspace(1,w,w);
y=linspace(1,l,l);
x=x*spatialdispersion;
y=y*spatialdispersion;


%Minimum value correction
FI=FI-2^15;

%Average noise subtraction
fitdatax=ones(20,w);

for i=1:20
    fitdatax(i,:)=FI(i,:);
end

fitcorrectx=mean(mean(fitdatax));
FI=FI-fitcorrectx;

fitdatay=ones(l,20);

for i=1:20
    fitdatax(i,:)=FI(i,:);
end

fitcorrecty=mean(mean(fitdatay));
FI=FI-fitcorrecty;
```

```
%ND Filter correction
ndconversion=10^ndfilter;

%RG Filter correction
%rgconversion assumes 800nm light
if rgfilter==830
    rgconversion=3E-2;
else
    if rgfilter==780
        rgconversion=8.3E-1;
    else
        rgconversion=1;
    end
end

%Filter corrections applied
FI=FI*ndconversion/rgconversion;

%Laser energy normalization
FI=FI/energy;
%normalized to 1J

%Removing anamolous maximums
if maxes==1

FItest=FI;
check=0.1;
    for i=1:l
        for j=1:w
            testpoint=FI(i,j);
            if j==1
                if i==1
                    testpoints=[FItest(i+1,j) FItest(i,j+1) FItest(i+1,j+1)  0 0 0 0
0];
                elseif i==l
                    testpoints=[FItest(i-1,j) FItest(i,j+1) FItest(i-1,j+1) 0 0 0 0
0];
                else
                    testpoints=[FItest(i+1,j) FItest(i-1,j) FItest(i,j+1)
FItest(i+1,j+1) FItest(i-1,j+1) 0 0 0];
                end

            elseif j==w
                if i==1
                    testpoints=[FItest(i+1,j) FItest(i,j-1) FItest(i+1,j-1) 0 0 0 0
0];
                elseif i==l
                    testpoints=[FItest(i-1,j) FItest(i,j-1) FItest(i-1,j-1) 0 0 0 0
0];
                else
                    testpoints=[FItest(i+1,j) FItest(i-1,j) FItest(i,j-1) FItest(i-
1,j-1) FItest(i+1,j-1) 0 0 0];
                end
            elseif i==1
                testpoints=[FItest(i+1,j) FItest(i,j+1) FItest(i,j-1) FItest(i+1,j-
1) FItest(i+1,j+1) 0 0 0];
            elseif i==l
                testpoints=[FItest(i-1,j) FItest(i,j+1) FItest(i,j-1) FItest(i-1,j-
1) FItest(i-1,j+1) 0 0 0];
            else
                testpoints=[FItest(i+1,j) FItest(i-1,j) FItest(i,j+1) FItest(i,j-1)
FItest(i-1,j-1) FItest(i+1,j-1) FItest(i+1,j+1) FItest(i-1,j+1)];
```

```
            end
            testratio=abs(testpoints/testpoint);
            testratio=max(testratio,check);
            testvalue=testratio-check;
            count=0;
            for g=1:8
                if testvalue(g)==0
                    count=count+1;
                end
            end
            if count>4
                FItest(i,j)=0;
            elseif testratio(1)==1 || testratio(2)==1 || testratio(3)==1 ||
testratio(4)==1 || testratio(5)==1 || testratio(6)==1 || testratio(7)==1 ||
testratio(8)==1
                FItest(i,j)=0;
            end
        end
    end
FI=FItest;
end
end
```

Appendix B: 3D Plotting of shot data, MATLAB file

```
function plotforwardimage(file, date, energy, ndfilter, rgfilter,maxes)
%This function reads a data file use readtiff.m and plots the image.

%file-number or string giving the file name date-YYMMDD energy-energy of
%shot in J ndfilter-numerical value of ND filtering rgfilter- wavelength
%designation of RG filter (in nm) maxes- 1 if want maxes removed. any other
%number if no.

%**********************
[x,y,~,~,~,FI]=readtiff(file, date, energy, ndfilter, rgfilter, maxes);
file=num2str(file);
date=num2str(date); %Change input date to string for labels

%**********************

figure
mesh(x,y,FI)
shading interp
colorbar
xlabel('Width [\mum]')
ylabel('Height [\mum]')
zlabel('Intensity (Normalized to 1 J beam energy)')
title(['Forward Image, Shot ',file,', Date: ', date])

end
```

Appendix C: Maximum and FWHM calculation, MATLAB file

```
function [x,y,curver,curvec]=spotsize(file, date, energy, ndfilter, rgfilter)
%This function reads a TIFF image and finds the maximum intensity and FWHM
%of the beam spot. Inputs should be the file name, the date [YYMMDD], the
%amount of ND filtering, and the wavelength of RG filtering. The last 2
%inputs should be [0] if n/a.

hp=1.02;
```

```
lp=0.98;

[x,y,l,w,spatialdispersion,FI]=readtiff(file, date, energy, ndfilter, rgfilter, 0);
file=num2str(file);
date=num2str(date);
%**********************
%finding maximum

[x,y,l,w,spatialdispersion,FItest]=readtiff(file, date, energy, ndfilter, rgfilter,
1);
maximum=max(max(FItest));  %finds max, vertical position (row#,pixel#)
[rv,cv]=find(FI==maximum);
findmiddle=length(rv);
middle=round(findmiddle/2);
r=rv(middle);
c=cv(middle);

%**********************
%finding FWHM, vertically and horizontally
curver=FI(r,:); %Horizontal line where maximum falls
minr=min(curver);
avgr=(minr+maximum)/2;
maxFWHMr=hp*avgr;
minFWHMr=lp*avgr;
testpointsr=zeros(1,r);

for i=1:w
    if curver(i)<maxFWHMr && curver(i)>minFWHMr
        testpointsr(i)=curver(i);
    else
        testpointsr(i)=0;
    end

end



FWHMr1=find(testpointsr>0,1,'first');
FWHMr2=find(testpointsr>0,1,'last');
FWHMr=spatialdispersion*(FWHMr2-FWHMr1)
liner=x*0+avgr;
figure
plot(x,curver, x, liner)
%axis([-Inf,Inf,0,2E4])
title({'Horizontal Lineout of Peak';['Shot ',file,' Date ',date]}, 'FontSize',20)
xlabel('Height [\mum]', 'FontSize',20)
ylabel({'Intensity';'(Normalized to 1 J beam energy)'}, 'FontSize',20)
%text(1200,maxFWHMr,['FWHM=',num2str(FWHMr),' \mum'], 'FontSize',12)
set(gca, 'FontSize',18)


curvec=FI(:,c); %Horizontal line where maximum falls
minc=min(curvec);
avgc=(minc+maximum)/2;
maxFWHMc=hp*avgc;
minFWHMc=lp*avgc;
testpointsc=zeros(1,c);

for i=1:l
    if curvec(i)<maxFWHMc && curvec(i)>minFWHMc
        testpointsc(i)=curvec(i);
    else
```

```
        testpointsc(i)=0;
    end

end
FWHMc1=find(testpointsc>0,1,'first');
FWHMc2=find(testpointsc>0,1,'last');
FWHMc=spatialdispersion*(FWHMc2-FWHMc1)
linec=y*0+avgc;

maximum
figure
plot(y,curvec,y,linec)
%axis([-Inf,Inf,0,2E4])
title({'Vertical Lineout of Peak';['Shot ',file,' Date ',date]}, 'FontSize',20)
xlabel('Height [\mum]', 'FontSize',20)
ylabel({'Intensity';'(Normalized to 1 J beam energy)'}, 'FontSize',20)
%text(1000,maxFWHMr,['FWHM=',num2str(FWHMr),' \mum'], 'FontSize',12)
set(gca, 'FontSize',18)
%*********************

end
```

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