Plasma Radius Measurement using Schlieren Imaging

Wigner Institute Meeting

Anna-Maria Bachmann

Max-Planck-Institute for Physics, Munich
bachmann@mpp.mpg.de

April 8, 2016

AWAKE

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

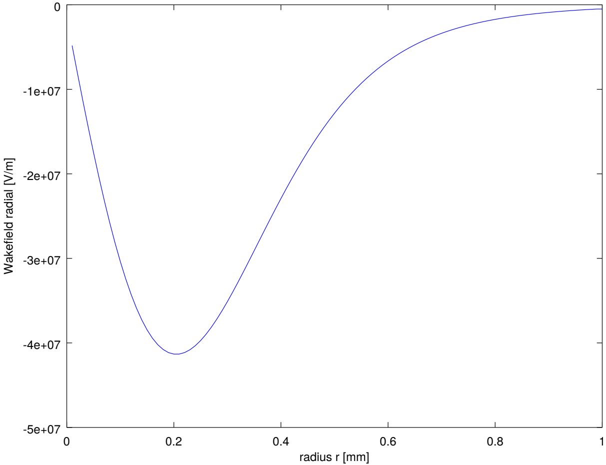
HEINRICH HEINE
UNIVERSITÄT DÜSSELDORF

Transverse Component of Wakefield

Radial wakefield at $\zeta = 0$, i.e. at the front of the beam

Parameters

- Particle density $n_0 = 10^{15}\,\mathrm{cm}^{-3}$
- Beam size $\sigma_r = \sigma_z = 1/k_p \approx 0.17\,\mathrm{mm}$

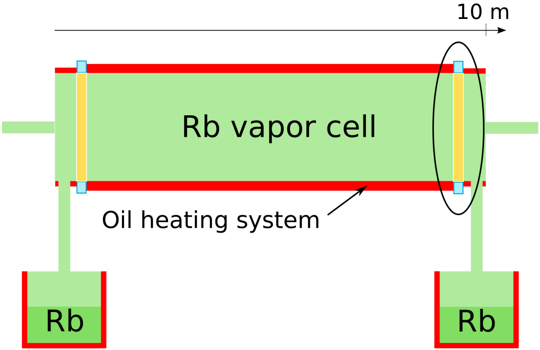


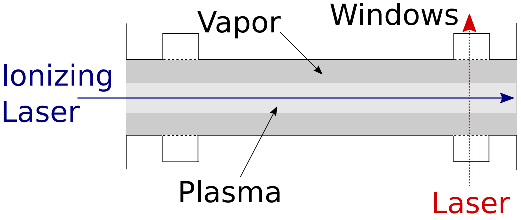
$\Rightarrow$ Focusing impact on atoms with $r \lesssim 1\,\mathrm{mm}$

$\Rightarrow$ Requirment of plasma radius $r_{plasma} \gtrsim 1\,\mathrm{mm}$

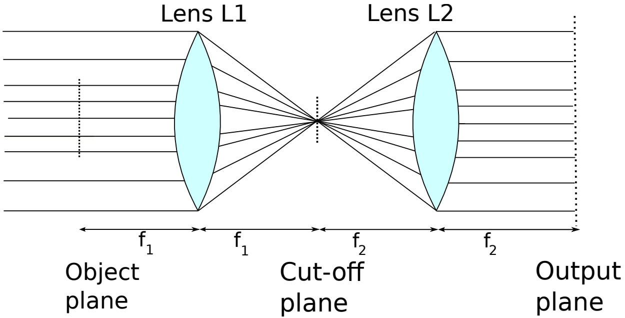
Plasma Radius Measurement at AWAKE

Schlieren Image through windows at the end of the cell





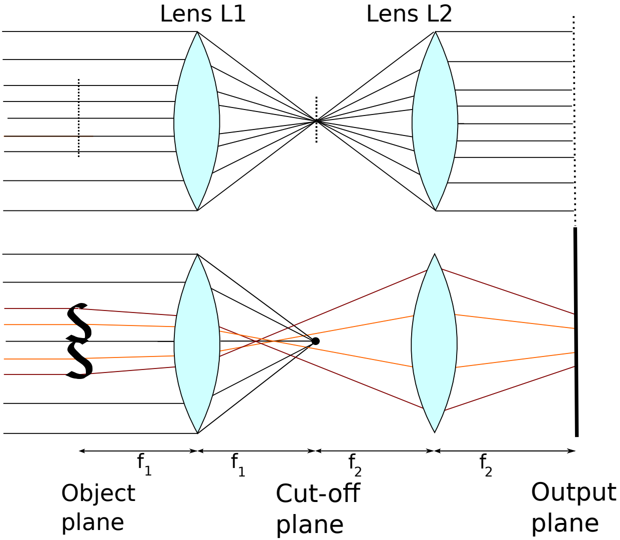
Principle of Schlieren Imaging



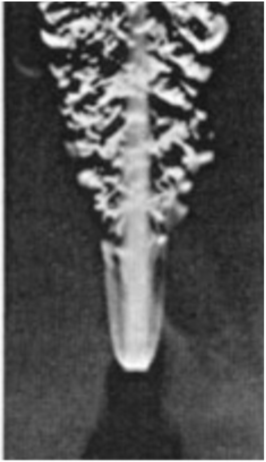
Principle of Schlieren Imaging

Blocking of non-deflected rays

→ only deflected rays reach screen



Schlieren Image of Density Perturbations



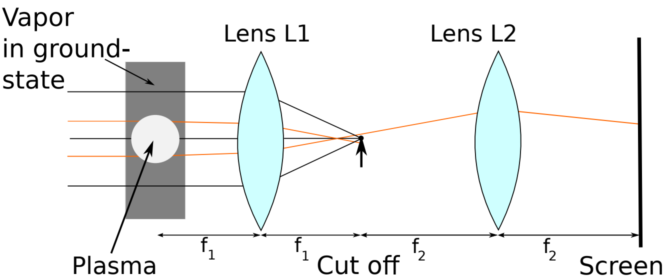
Schlieren photo of a turbulent flame of an oxy-acetylene torch[1]

[1] SETTLES, G.S.: *Schlieren and Shadowgraph Techniques*. Springer, 2001

Plasma Radius Measurement using Schlieren Imaging

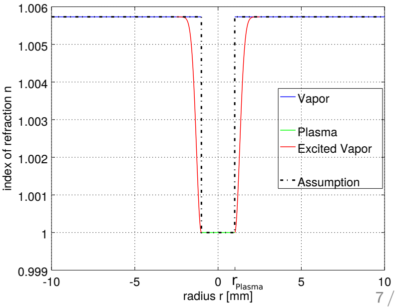
Parameters

- Beam size
  $\sigma_{beam} = 5\,\mathrm{mm}$
- Plasma radius
  $r_{plasma} = 1\,\mathrm{mm}$
- Focal lengths
  $f_1 = 500\,\mathrm{mm}$,
  $f_2 = 100\,\mathrm{mm}$
- Laser detuning
  $\Delta\omega = 20\,\mathrm{GHz}$

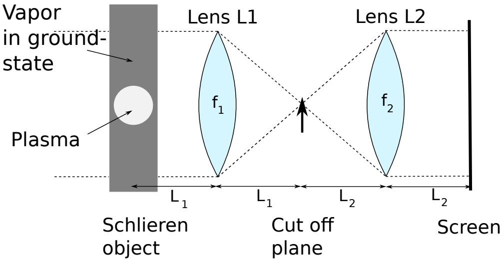


Index of refraction

- for vapor
  $$n(r) = RE\left(\sqrt{1 + \frac{N_i(r)\,e^2}{\epsilon_0\,m_e}\sum_{j\neq i}\frac{f_{ij}}{({\omega_{ij}}^2 - \omega^2 - \frac{i\,\omega}{\tau_{ij}})}}\right)$$
- for plasma
  $$n = \sqrt{1 - \frac{\omega_{pe}^2}{\omega^2}}$$



Formulas of Fourier Optics



Propagation over z along optical axis [2]

$$S_0(\vec{k}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} u_0(\vec{r}) \exp(-i\,\vec{k}\vec{r})\ d^2\vec{r}$$

$$u_1(\vec{r}, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S_0(\vec{k}) \exp(i\,z\sqrt{k_0^2 - \vec{k}^2}) \exp(i\,\vec{k}\vec{r})\, d^2\vec{k}$$

Phase Shift through Object

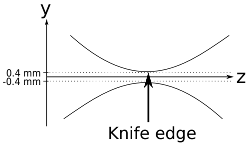
$u_1(\vec{r}) = u_0(\vec{r}) \cdot \exp(\mathrm{i}\,\Phi)$ with Φ phase shift through object

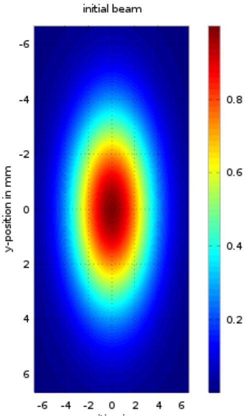
[2] HECHT, E.: *Optics (4th ed.)*. Addison Wesley, 1987

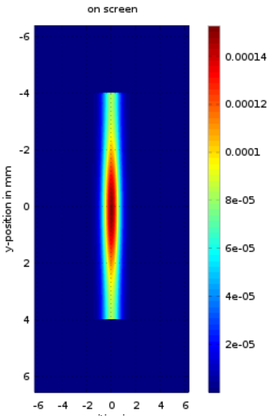
Gaussian Beam - No Object - Horizontal Knife Edge

Parameters:

- Standard derivation of Gaussian beam: $\sigma_r = 5\,\text{mm}$
- Focal lengths and propagation distances $f1 = L1 = 500\,\text{mm}$, $f2 = L2 = 100\,\text{mm}$
- Position horizontal knife-edge: $y = 0.04\,\text{mm}$







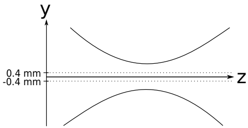
Very low intensities on the screen ($I/I_0 \approx 1.4 \cdot 10^{-4}$)

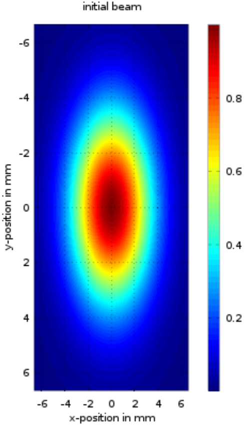
$\Rightarrow$ All rays are blocked by object in focal plane

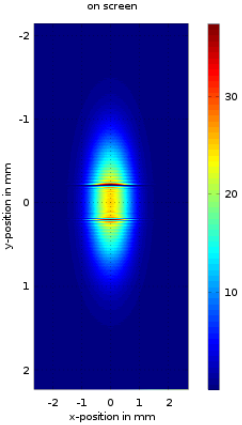
Gaussian Beam - Plasma Column - No Cut Off

Parameters:

- Standard derivation of Gaussian beam: $\sigma_r = 5\,\mathrm{mm}$
- Focal lengths and propagation distances
  $f1 = L1 = 500\,\mathrm{mm}$, $f2 = L2 = 100\,\mathrm{mm}$
- Radius of plasma column: $r_{plasma} = 1\,\mathrm{mm}$







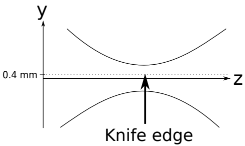
Contours of the plasma column due to diffraction

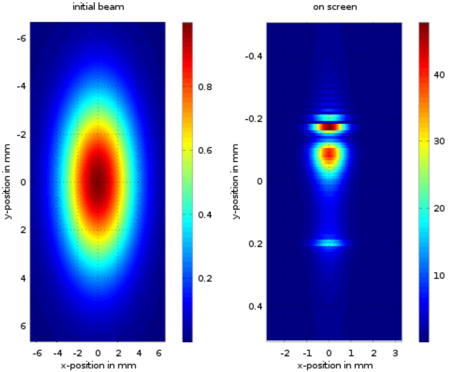
⇒ Information about the size
⇒ No information about the shape

Gaussian Beam - Plasma Column - Horizontal Knife Edge

Parameters:

- Standard derivation of Gaussian beam: $\sigma_r = 5\,\text{mm}$
- Focal lengths and propagation distances
  $f1 = L1 = 500\,\text{mm}$, $f2 = L2 = 100\,\text{mm}$
- Radius of plasma column: $r_{plasma} = 1\,\text{mm}$
- Position horizontal knife-edge: $y = 0.04\,\text{mm}$





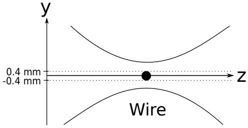
Half of the plasma column and its contour is imaged

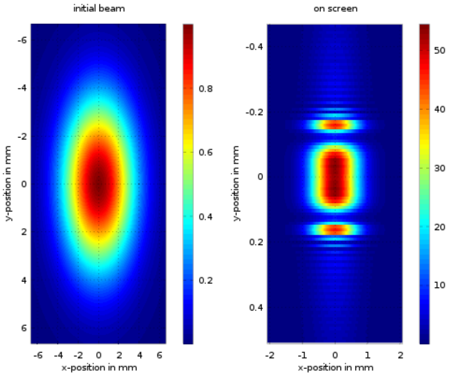
$\Rightarrow$ Information about the size
$\Rightarrow$ Information about the shape

Gaussian Beam - Plasma Column - Horizontal Wire

Parameters:

- Standard derivation of Gaussian beam: $\sigma_r = 5\,\mathrm{mm}$
- Focal lengths and propagation distances $f1 = L1 = 500\,\mathrm{mm}$, $f2 = L2 = 100\,\mathrm{mm}$
- Radius of plasma column: $r_{plasma} = 1\,\mathrm{mm}$
- Position horizontal wire: $y = 0\,\mathrm{mm}$





Whole plasma column is imaged

⇒ Information about the size ⇒ Information about the shape

Conclusion

Main goals:

- Study of the possibility of the measurement
- Proof ionization
- Measure a plasma radius of $r > 1\,\text{mm}$ after $10\,\text{m}$ rubidium

AWAKE

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

HEINRICH HEINE
UNIVERSITÄT DÜSSELDORF