Design and Characterisation of Supersonic Nozzles for Shock Front Electron Injection in Laser Wakefield Acceleration

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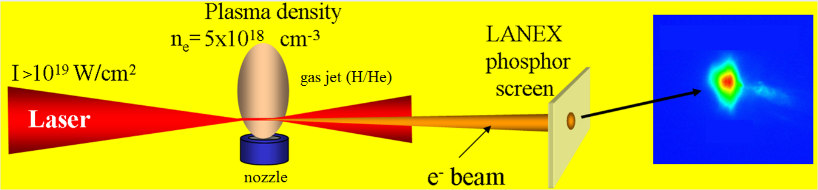
Ludwig-Maximilians-Universität
München

Talk at the 32nd IMPRS Workshop Munich, Germany

Laser Wakefield Acceleration: a short overview

principle of LWFA:



- energy gain per length: up to the TeV/m range (SLAC: 100 MeV/m)
  → smaller and cheaper sources for high energy electrons
  → brilliant X-ray sources

Laser Wakefield Acceleration: a short overview

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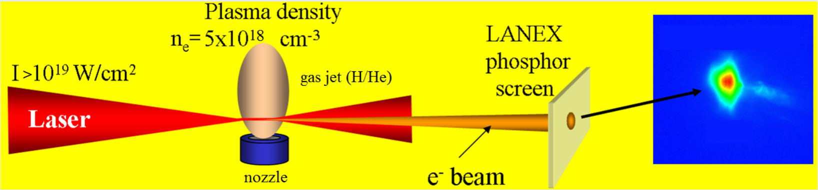
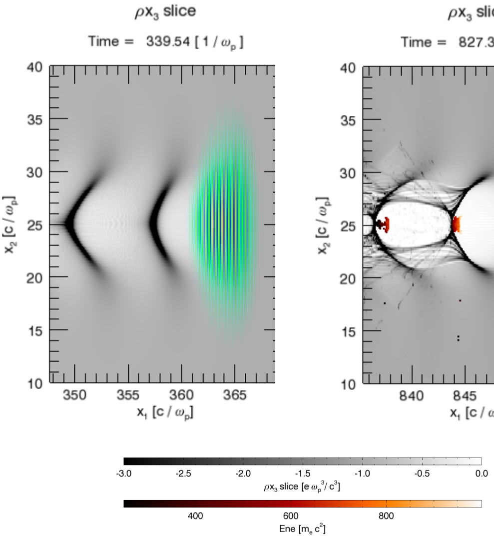


- energy gain per length: up to the TeV/m range (SLAC: 100 MeV/m)
  → smaller and cheaper sources for high energy electrons
  → brilliant X-ray sources
- still challenging:
  - stable and precise electron injection
  - monoenergetic electron beams

LWFA: PIC simulation



by courtesy of M. Gilljohann

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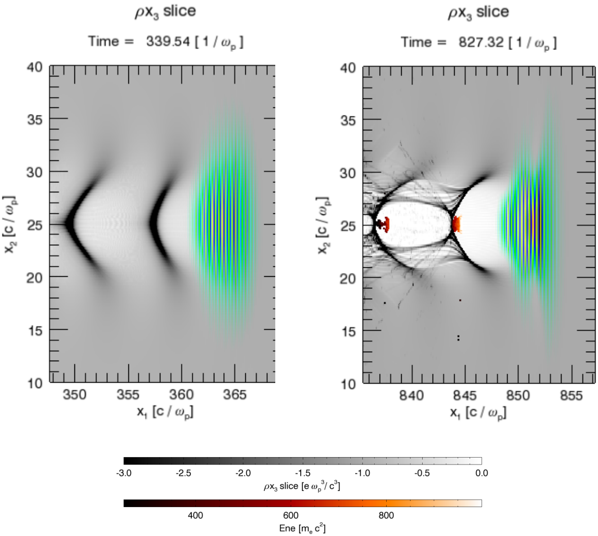

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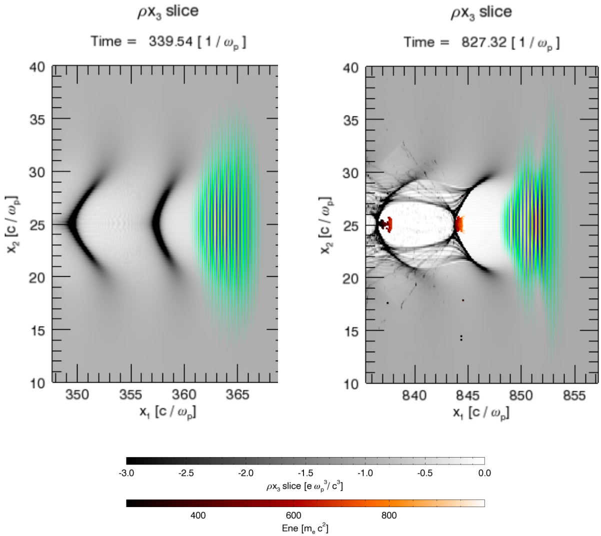
LWFA: PIC simulation



by courtesy of M. Gilljohann

Shock-front Injection

- goal: quasi-monoenergetic electrons
  $\longrightarrow$ spatially and temporally limited injection
  $\longrightarrow$ shock-fronts in supersonic gas jets
  $\longrightarrow$ realisation with a razor blade

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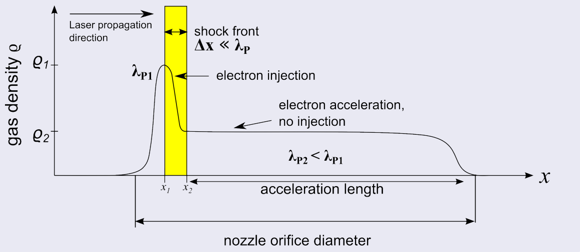
gas density profile for quasi-monoenergetic electrons:



Nozzles for LWFA

- requirements for supersonic nozzles:
  - orifice diameters: 5 mm and 7 mm
  - maximum gas density at the orifice: $\rho_E = 5 \cdot 10^{18}$ cm^{-3}
  - maximum backing pressure: $p_B = 50$ bar
  - extremely uniform gas density profile
  - adaptation for H_2 and He
- Computation of nozzle parameters by 1D isentropic flow theory

Determination of nozzle parameters

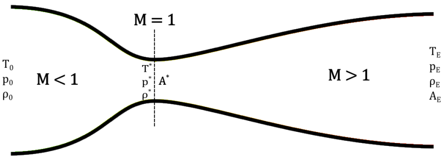
Nozzle flow equations:

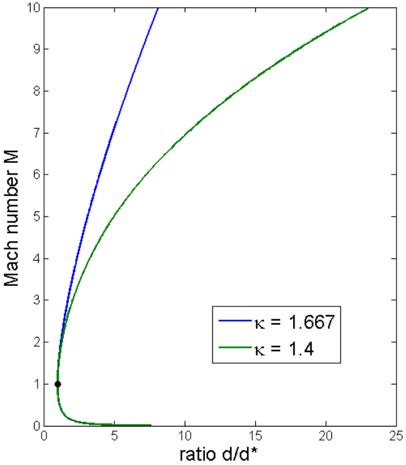
$$\frac{T}{T*} = \left(\frac{2}{\kappa+1} + \frac{\kappa-1}{\kappa+1}M^2\right)^{-1}$$

$$\frac{\rho}{\rho*} = \left(\frac{2}{\kappa+1} + \frac{\kappa-1}{\kappa+1}M^2\right)^{\kappa-1}$$

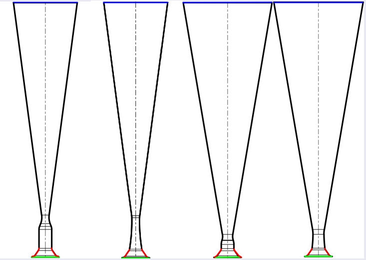
$$\frac{p}{p*} = \left(\frac{2}{\kappa+1} + \frac{\kappa-1}{\kappa+1}M^2\right)^{\frac{\kappa-1}{\kappa}}$$

$$\frac{A}{A*} = \frac{1}{M}\left(\frac{2}{\kappa+1} + \frac{\kappa-1}{\kappa+1}M^2\right)^{\frac{\kappa+1}{2(\kappa-1)}}$$



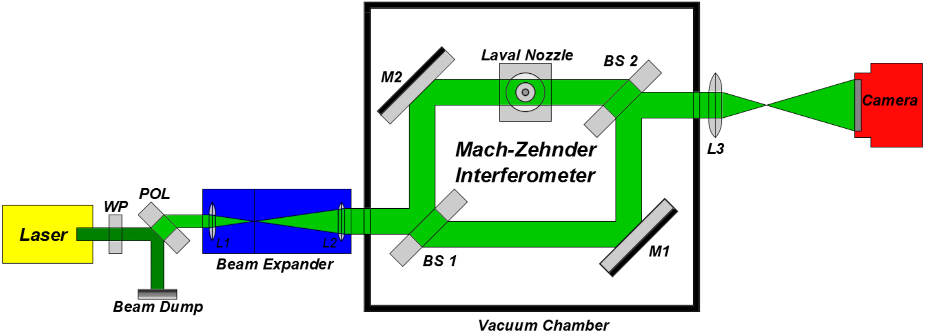


Laval nozzles:

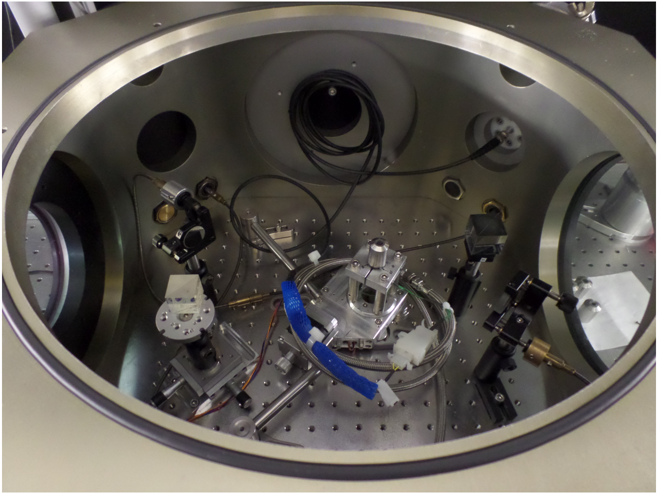


- 4 stainless steel EDM-machined Laval nozzles ($\sim$ 800 € each) produced by two different companies
- two different shapes
- optimized for mono- and diatomic gases (He/Ar or H_2/N_2)

Experimental Setup



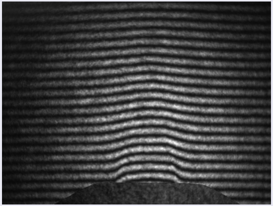
Experimental Setup



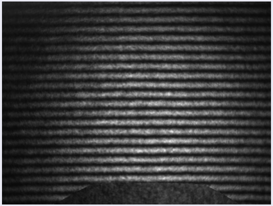
Interferometry

Mach-Zehnder interferograms:

- gas jet:



- reference image without gas flow:



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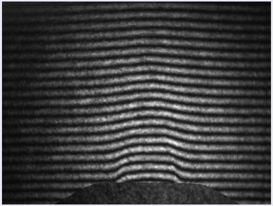

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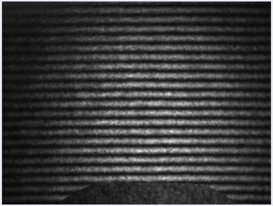
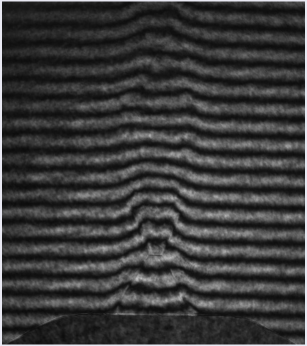
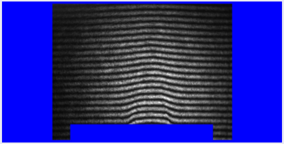


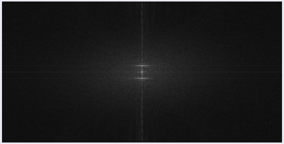
comparison: Mach cone of a supersonic gas jet propagating in air



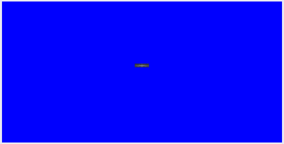
Determination of the phase shift



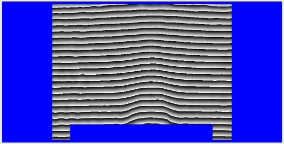
zero padded and masked interferogram



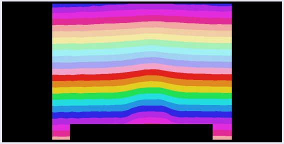
Fourier transform of the interferogram



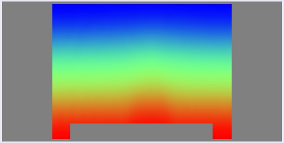
bandpass filter mask



Fourier backtransformed image

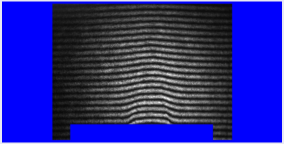


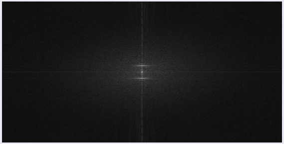
step function for phase unwrapping

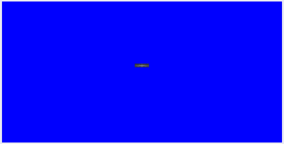


unwrapped phase distribution

Determination of the phase shift


zero padded and masked interferogram


Fourier transform of the interferogram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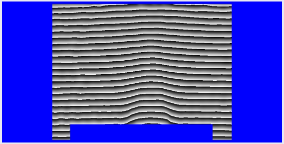
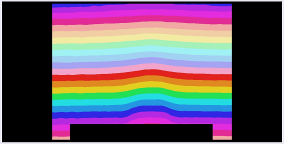

Fourier backtransformed image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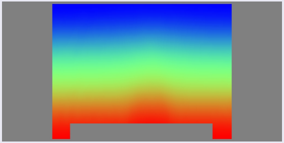
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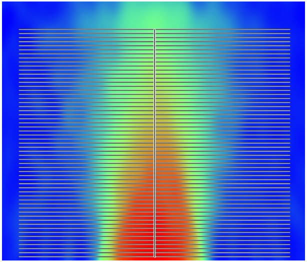
phase difference between original and reference phase

Tomography

- Determination of the phase shift for equidistant angles from 0° to 180°
- Radon Transform + filtered back-projection (convolution)

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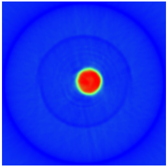
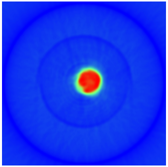
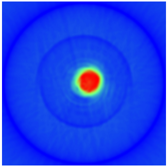
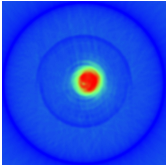
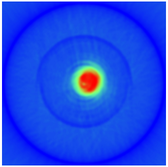
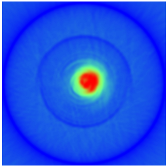

$z = 0.1$ mm

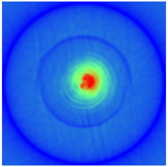

$z = 0.7$ mm

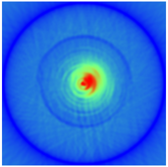

$z = 1.3$ mm


$z = 1.9$ mm


$z = 2.5$ mm

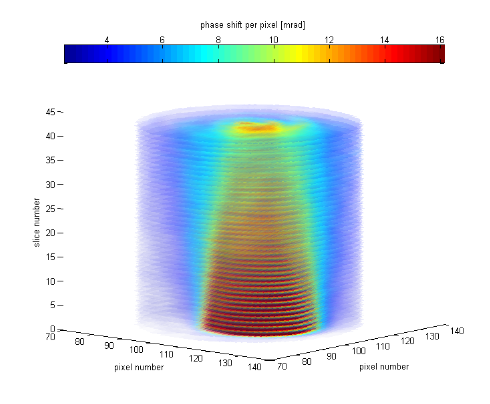

$z = 3.1$ mm


$z = 3.7$ mm


$z = 4.3$ mm

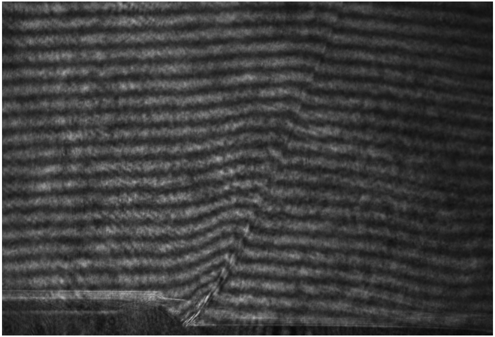
Tomography

3D reconstruction of the gas jet:



- finally: density reconstruction via Gladstone-Dale relation

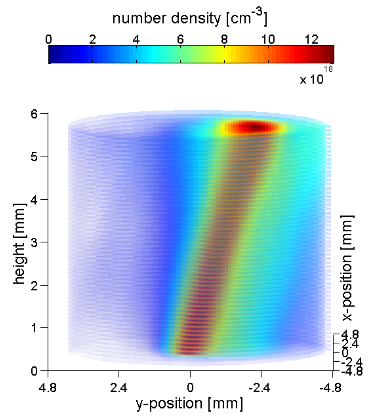
Tomography of Gas Jets with Shock Fronts



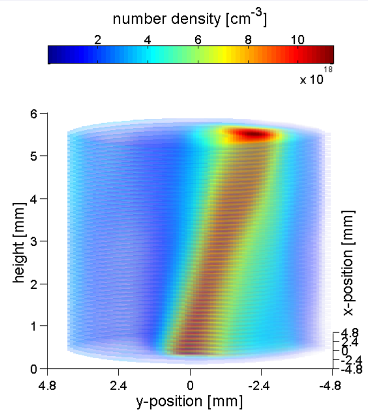
- expected size of shock front: $\sim 5\ \mu m$
- blurring by diffraction of the laser at the shock front (length of the shock front up to 5.7 mm)
- adaptation of bandpass filtering algorithm

Tomography of Gas Jets with Shock Fronts

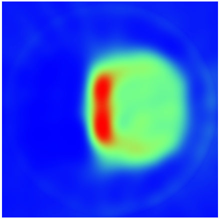
3D reconstruction:



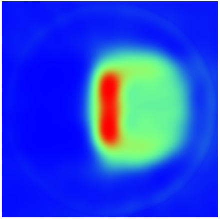
orifice: 5 mm; Ar



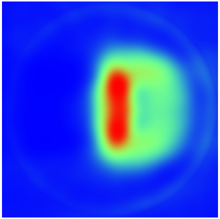
orifice: 7 mm; N_2



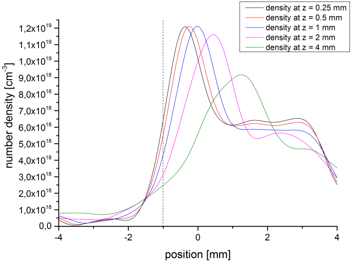
$z = 0.5$ mm

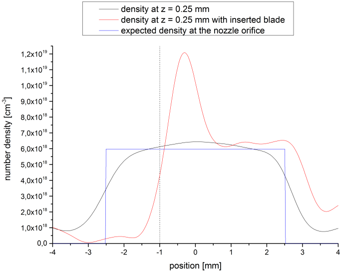


$z = 1$ mm



$z = 2$ mm





nozzle orifice diameter: 5 mm; gas: Ar

Thank you for your attention!

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Further Questions?

Feel free to ask!