High sensitivity gas-density profilometry for laser- and beam-driven plasma acceleration experiments

Status report

Lucas Schaper

Group for Accelerator Physics, Universität Hamburg,
and Group for Linear Accelerator Research (FLA), FH Division, Deutsches Elektronen-Synchrotron DESY

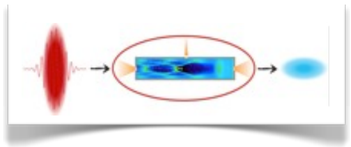
N. Delbos, L. Goldberg, T. Kleinwächter, A. Maier, J. Osterhoff,
C. A. J. Palmer, M. Schnepp, J.-P. Schwinkendorf

In collaboration with S. Hooker and his group

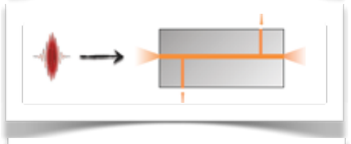
Part of the ***LAOLA*** collaboration

Alexander von Humboldt
Stiftung/Foundation

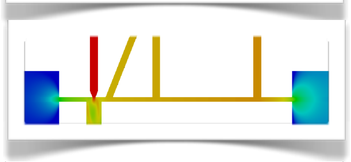
Outline



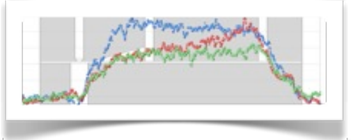
> Motivation



> Controlled injection mechanisms

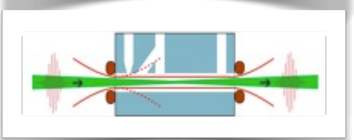


> Target simulation and fabrication

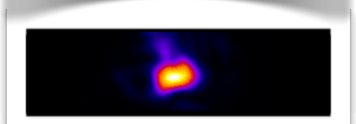


> Longitudinal gas density profile and absolute calibration

> Transverse density shaping and single shot guiding



> Discharge seeding



> Summary and conclusion

Plasma acceleration: Stability and reproducibility

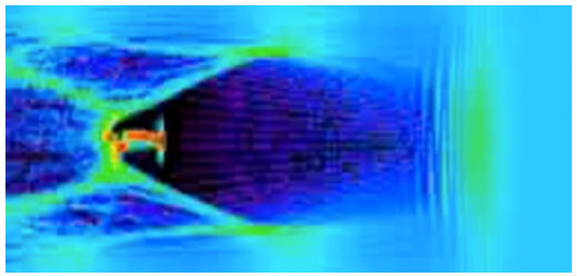
Electron beam fluctuations may originate from

variations in
laser pulse parameters
→ spatial and temporal energy profiles, pointing

variations in
target conditions
→ spatial and temporal 3D density profile

amplified through nonlinear processes

→ e.g. wavebreaking, …



Improve control over and stabilize crucial laser parameters

e.g. Popp *et al.*, Phys. Rev. Lett. 105, 215001 (2010)
Gonsalves *et al.*, Phys. Plasmas 17, 056706 (2010)

Develop stable, tailored plasma sources

e.g. Osterhoff *et al.,* Phys. Rev. Lett. 101, 085002 (2008)

energy spread

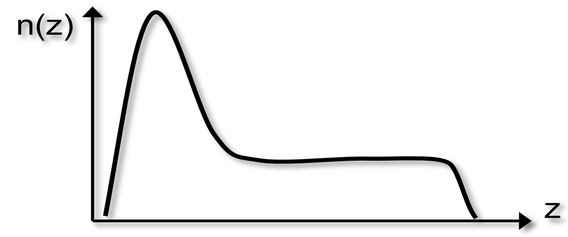
Control of phase-space population by controlled injection

dephasing

longitudinal profile taper

Controlled injection: Various mechanisms to be compared

> Density down ramp injection



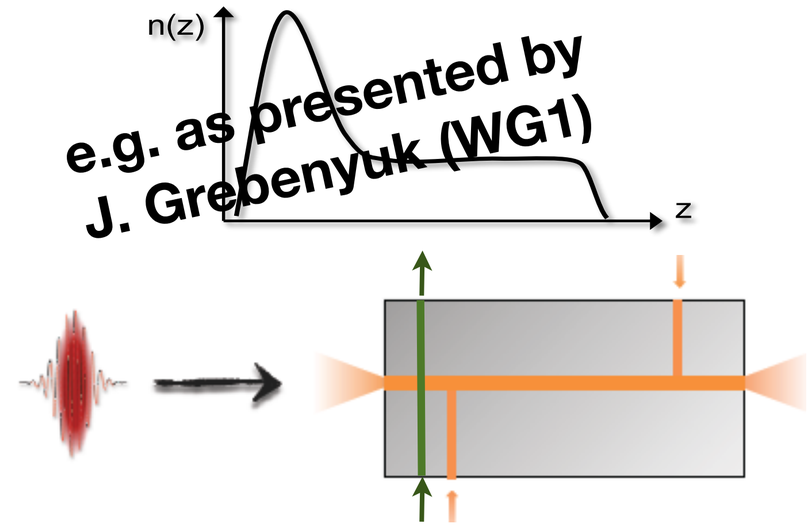
Controlled injection: Various mechanisms to be compared

> Density down ramp injection

Controlled injection: Various mechanisms to be compared

> Density down ramp injection

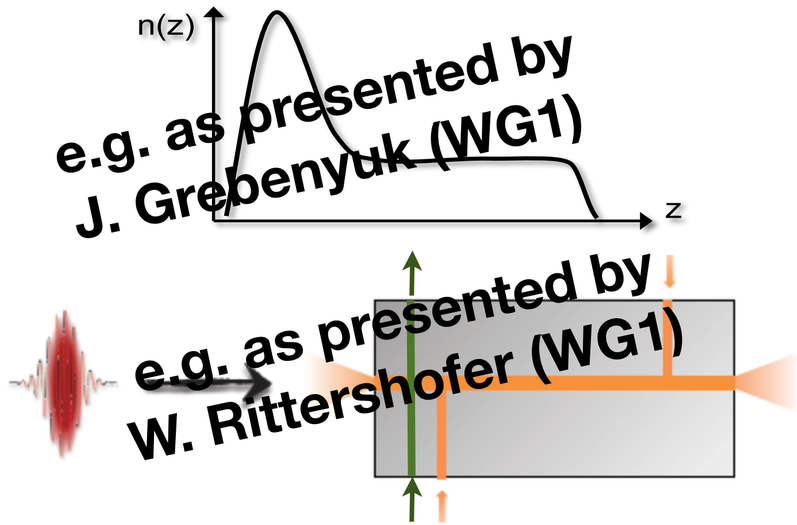
> Ionisation injection



Controlled injection: Various mechanisms to be compared

> Density down ramp injection

> Ionisation injection

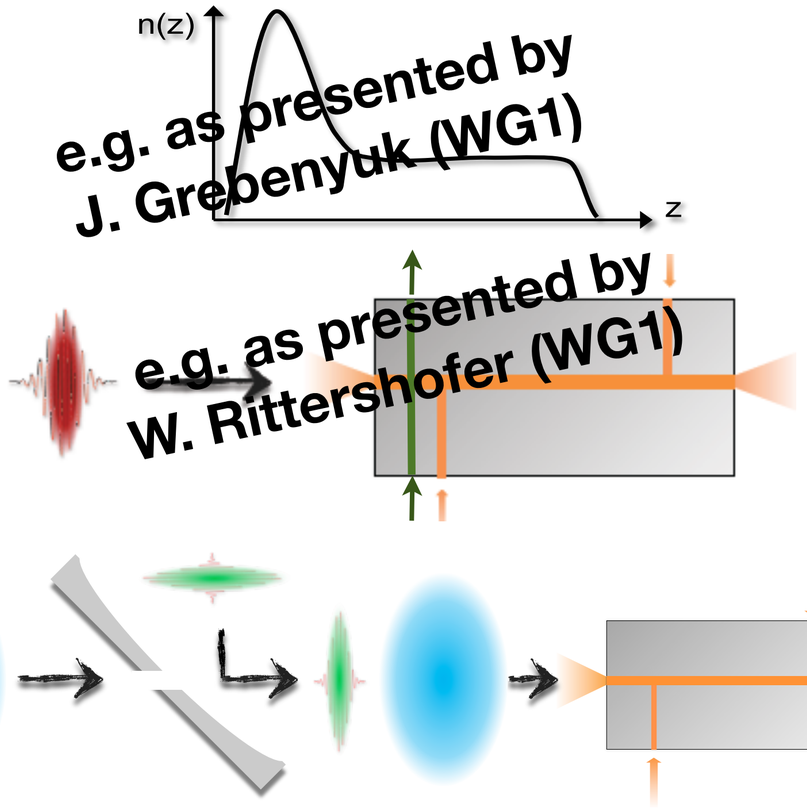


Controlled injection: Various mechanisms to be compared

> Density down ramp injection

> Ionisation injection

> mediated ionisation injection

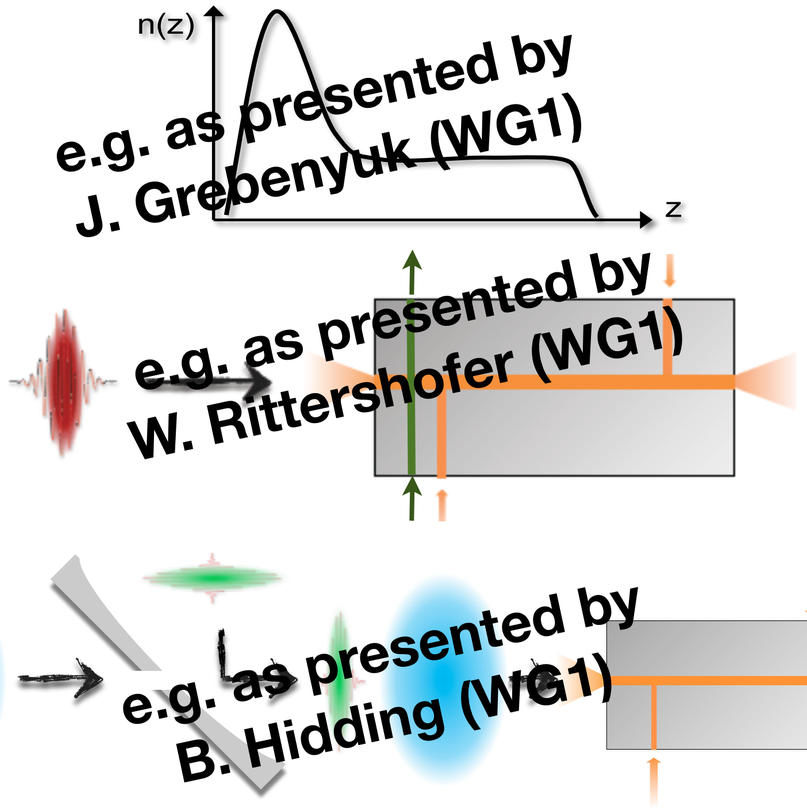


Controlled injection: Various mechanisms to be compared

> Density down ramp injection

> Ionisation injection

> mediated ionisation injection



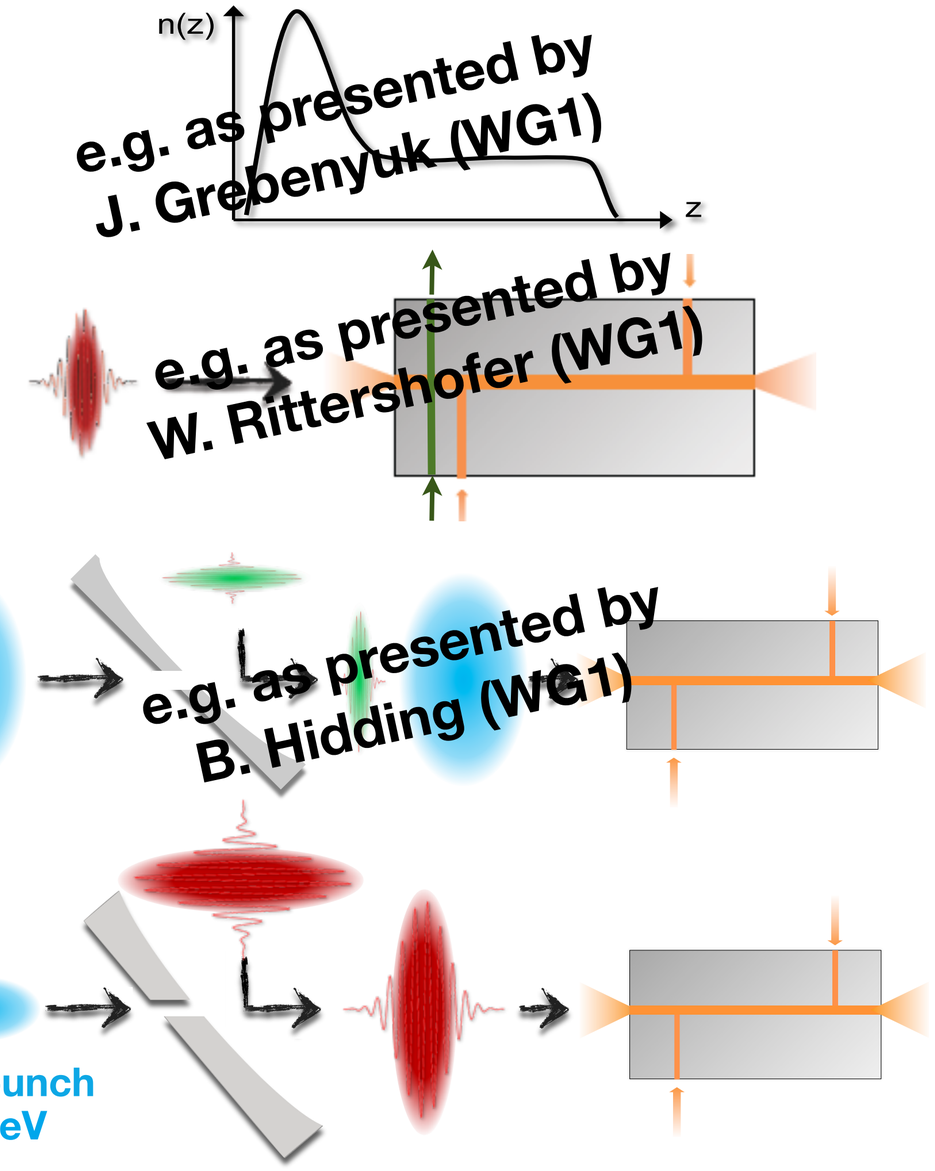
Controlled injection: Various mechanisms to be compared

> Density down ramp injection

> Ionisation injection

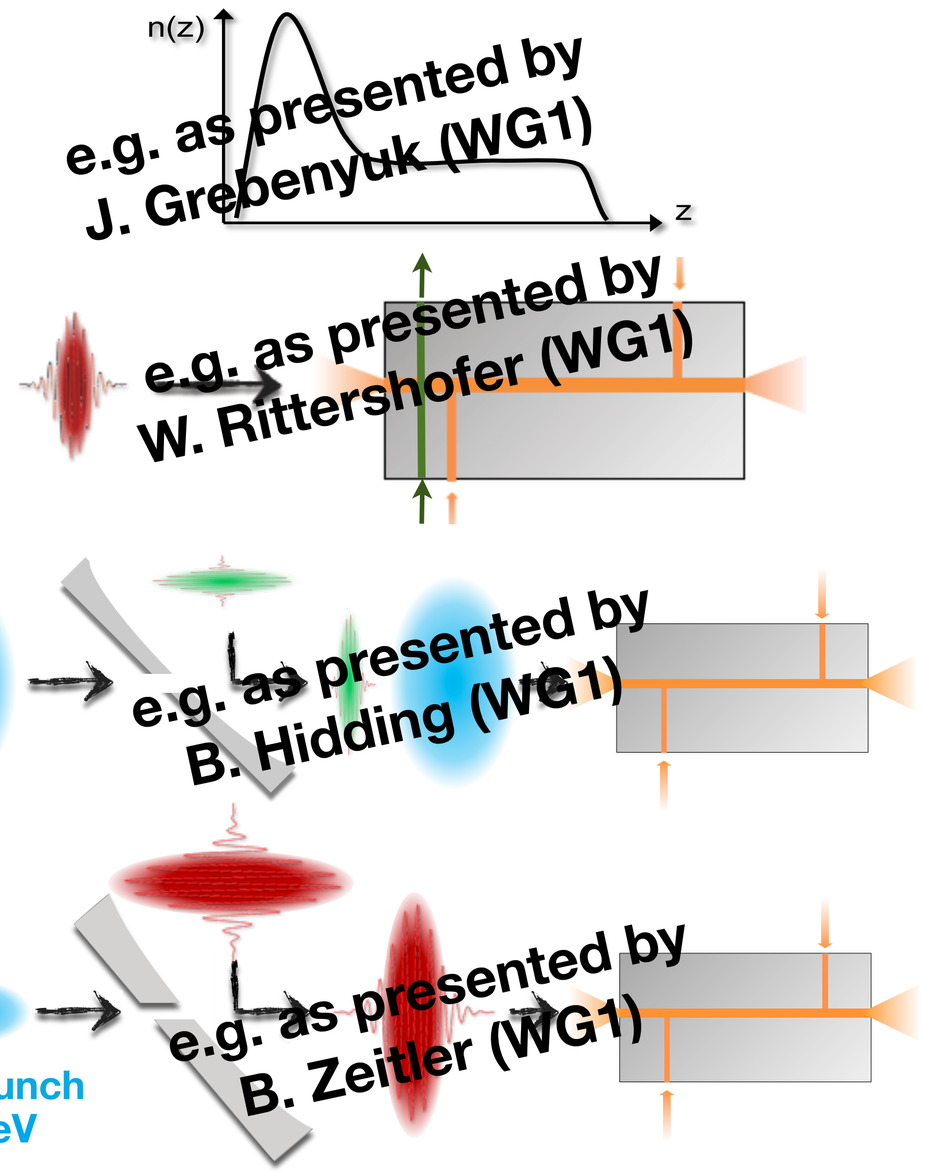
> mediated ionisation injection

> External injection



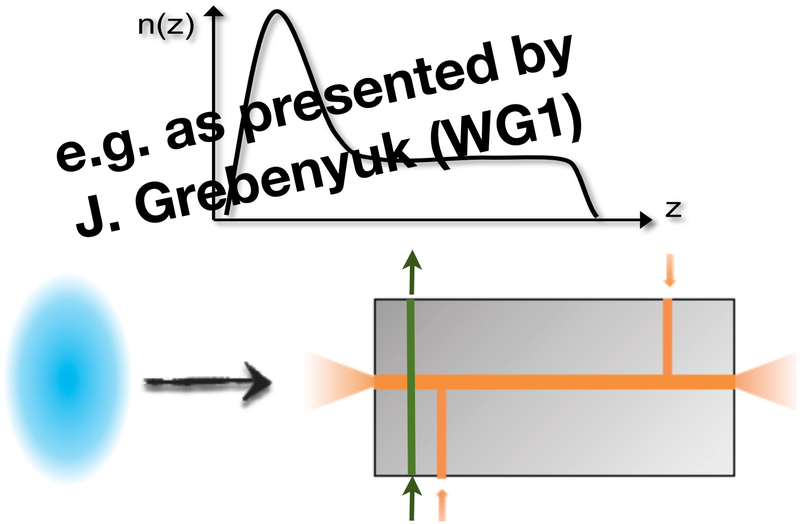
Controlled injection: Various mechanisms to be compared

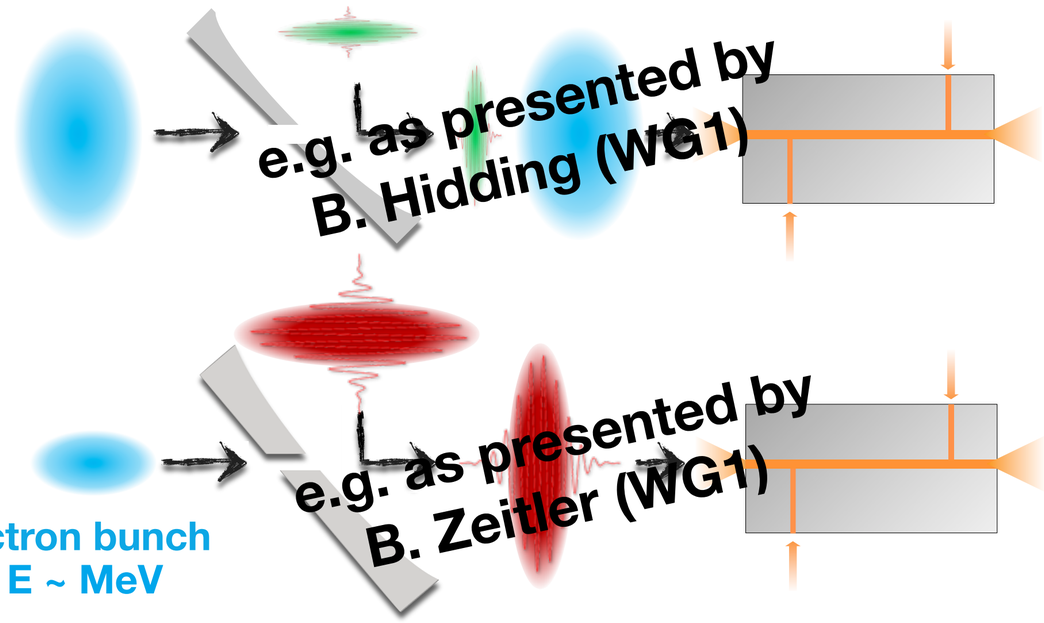
- Density down ramp injection
- Ionisation injection
- mediated ionisation injection
- External injection



Controlled injection: Various mechanisms to be compared

- Density down ramp injection
- Ionisation injection
- mediated ionisation injection
- External injection





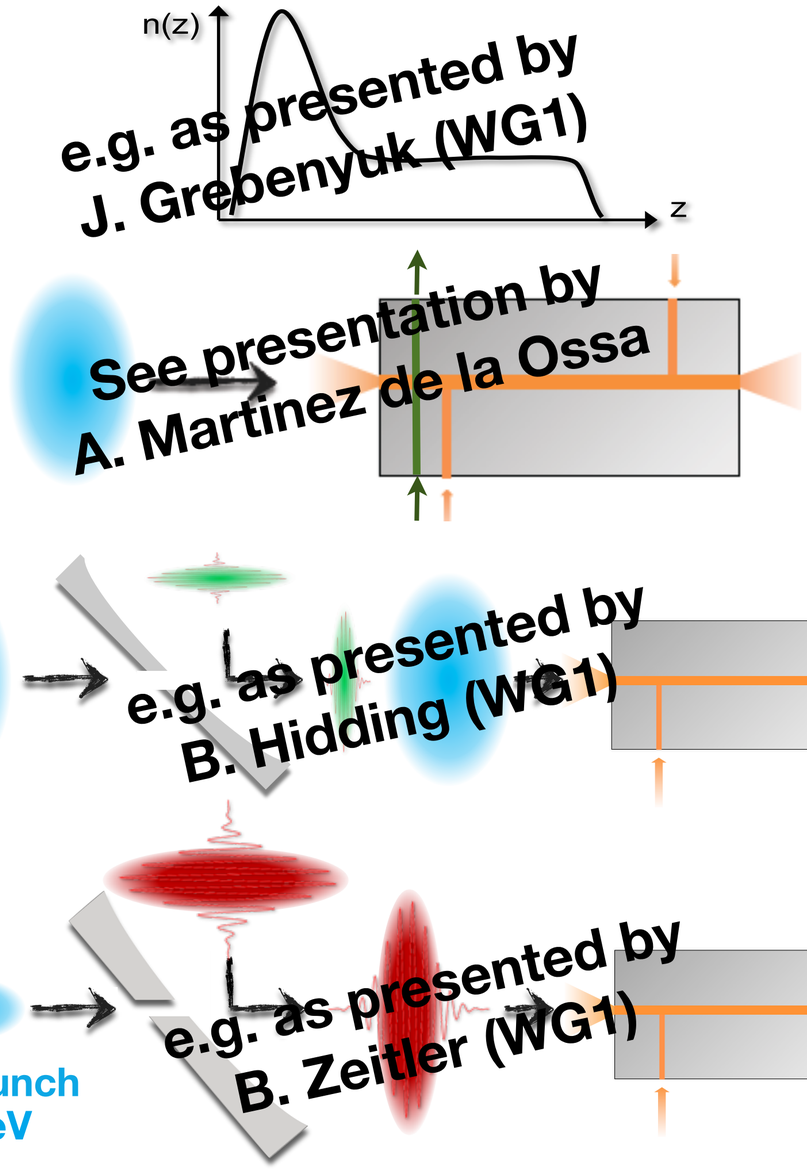
Controlled injection: Various mechanisms to be compared

> Density down ramp injection

> Ionisation injection

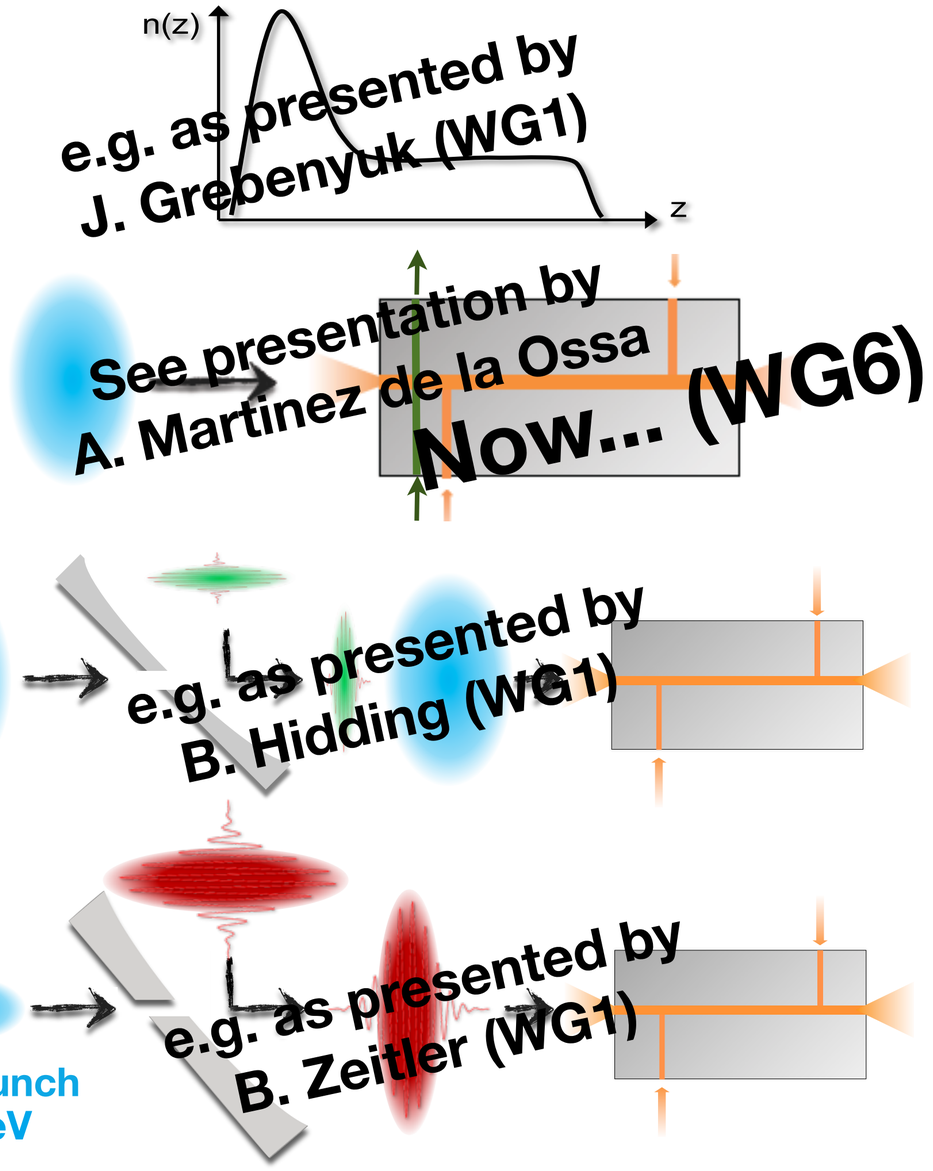
> mediated ionisation injection

> External injection



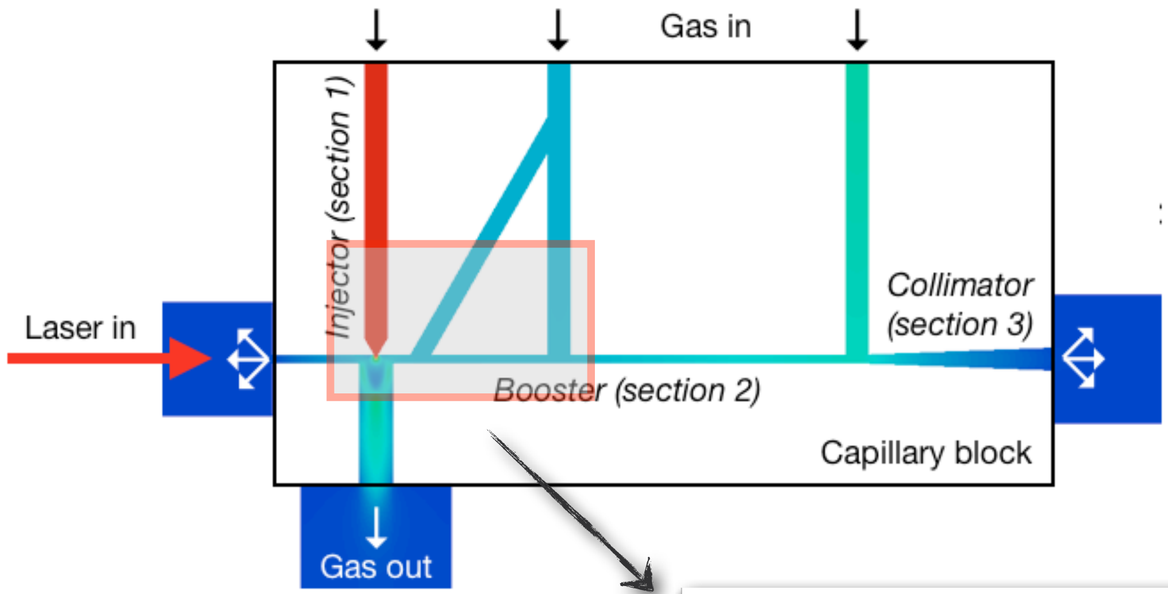
Controlled injection: Various mechanisms to be compared

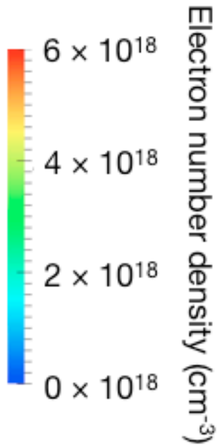
- Density down ramp injection
- Ionisation injection
- mediated ionisation injection
- External injection

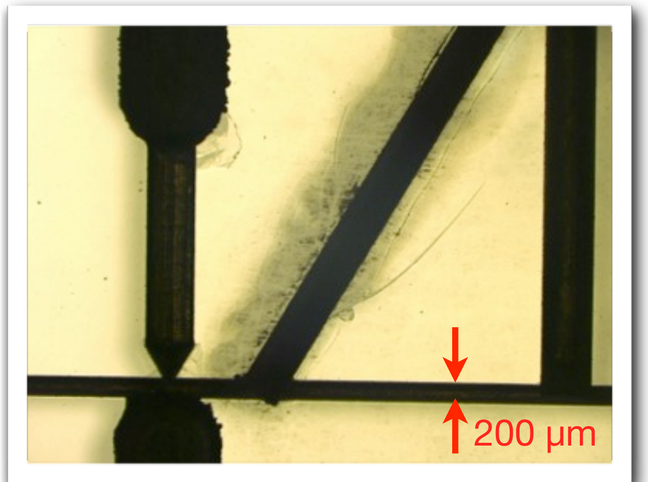


The goal: development of tailored plasma sources for controlled electron injection, acceleration and emission

Example: Segmented capillary discharge waveguide (injector, booster, collimator)



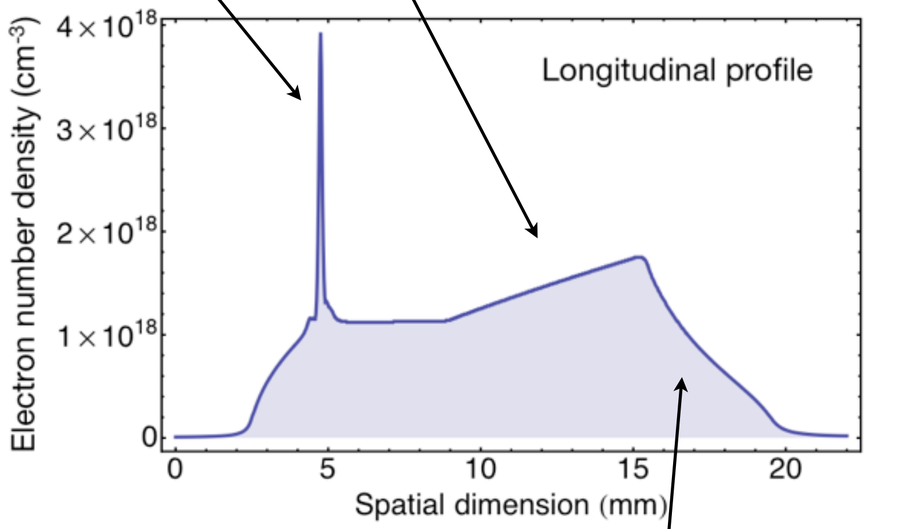




Femtosecond-laser machining into sapphire

C. G. R. Geddes, *PRL* **100**, 215004 (2008)

W. Rittershofer, *Phys. Plasmas* **17**, 063104 (2010)

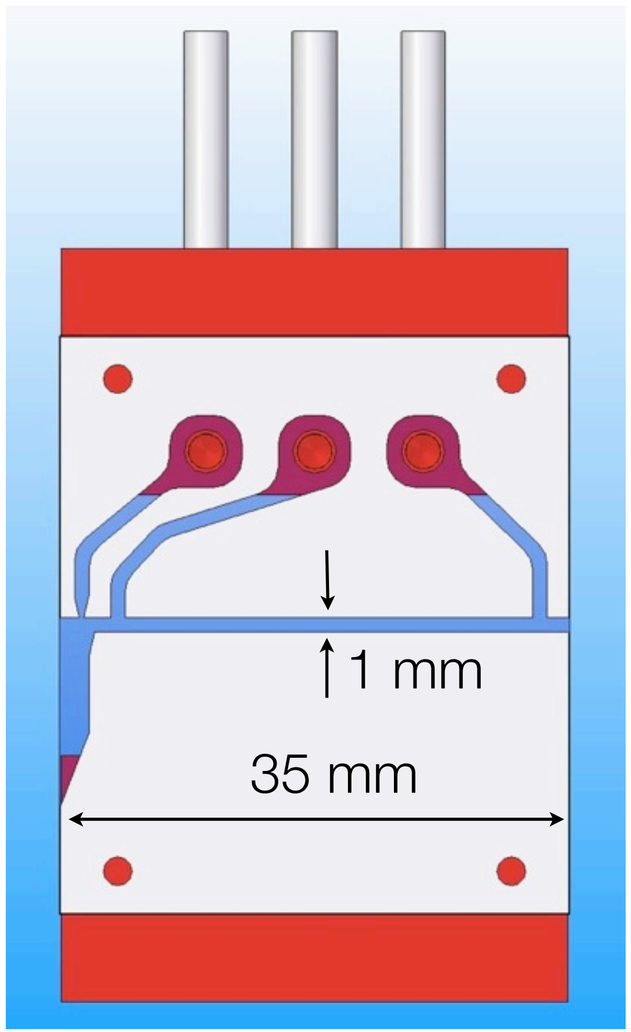


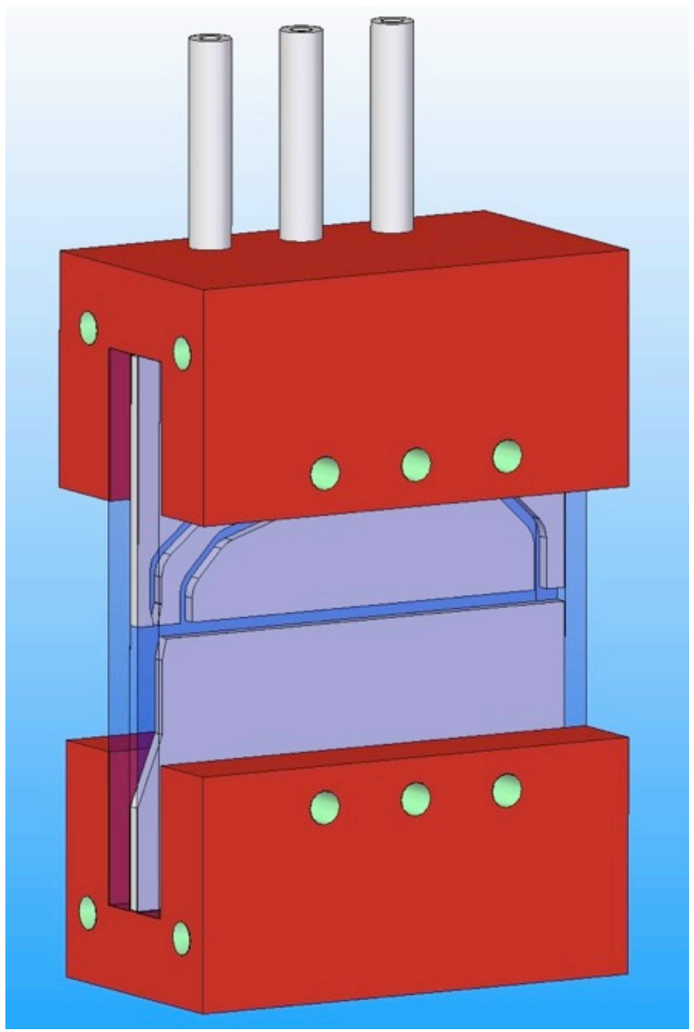
T. Mehrling, *Master Thesis*
C.M.S. Sears et al, *Phys. Rev. ST Accel.Beams* **11**, (2008) 101301

Full 3D simulations with fluid code OpenFOAM

The goal: development of tailored plasma sources for controlled electron injection, acceleration and emission II

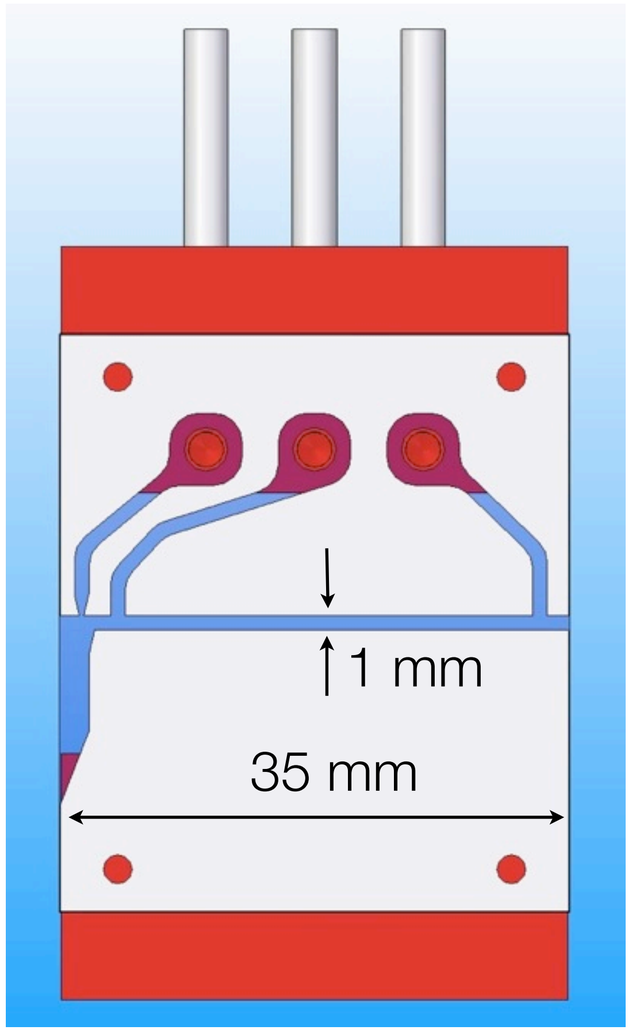
Example: Density tapered gas cell, features similar to capillary

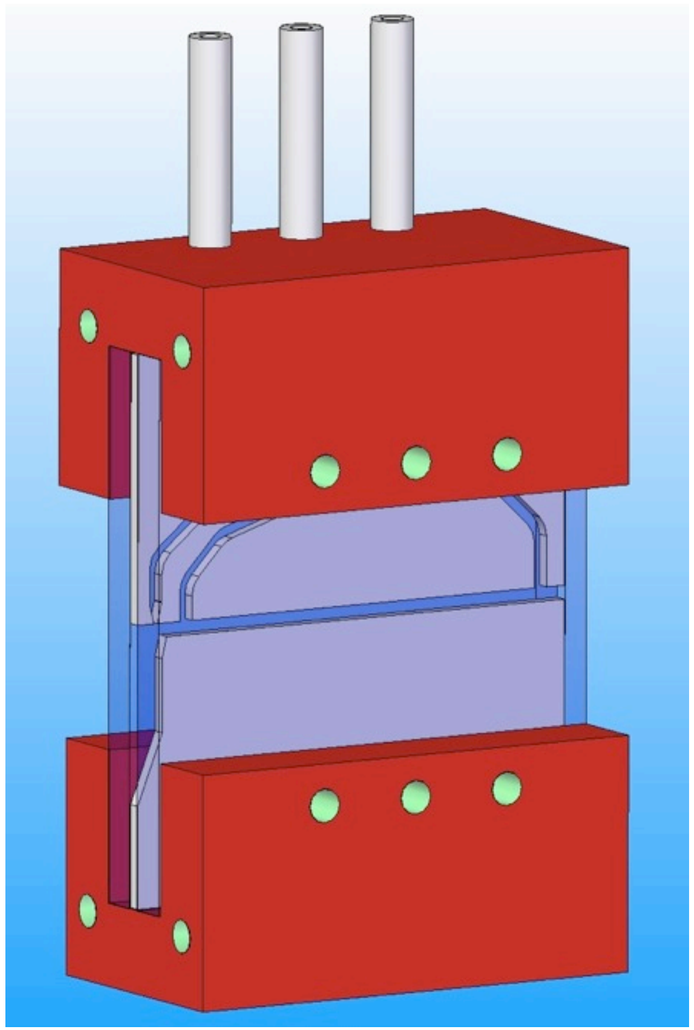


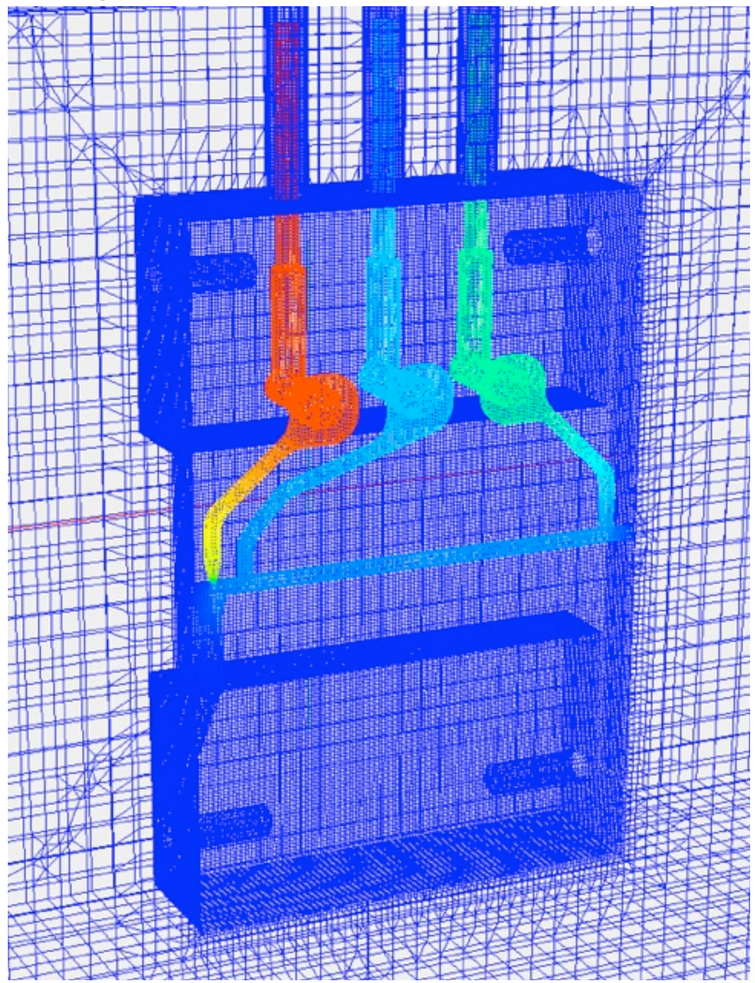


The goal: development of tailored plasma sources for controlled electron injection, acceleration and emission II

Example: Density tapered gas cell, features similar to capillary



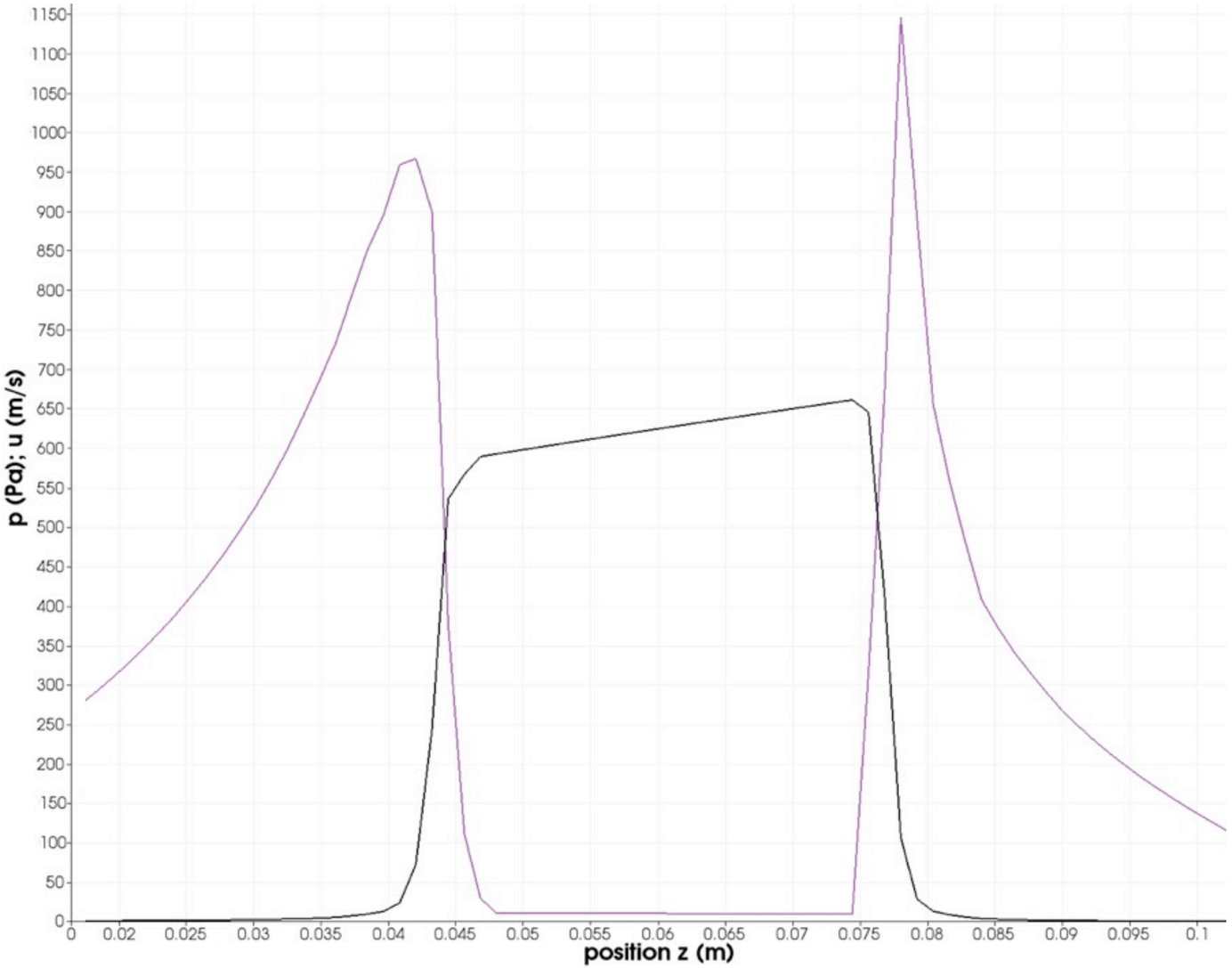


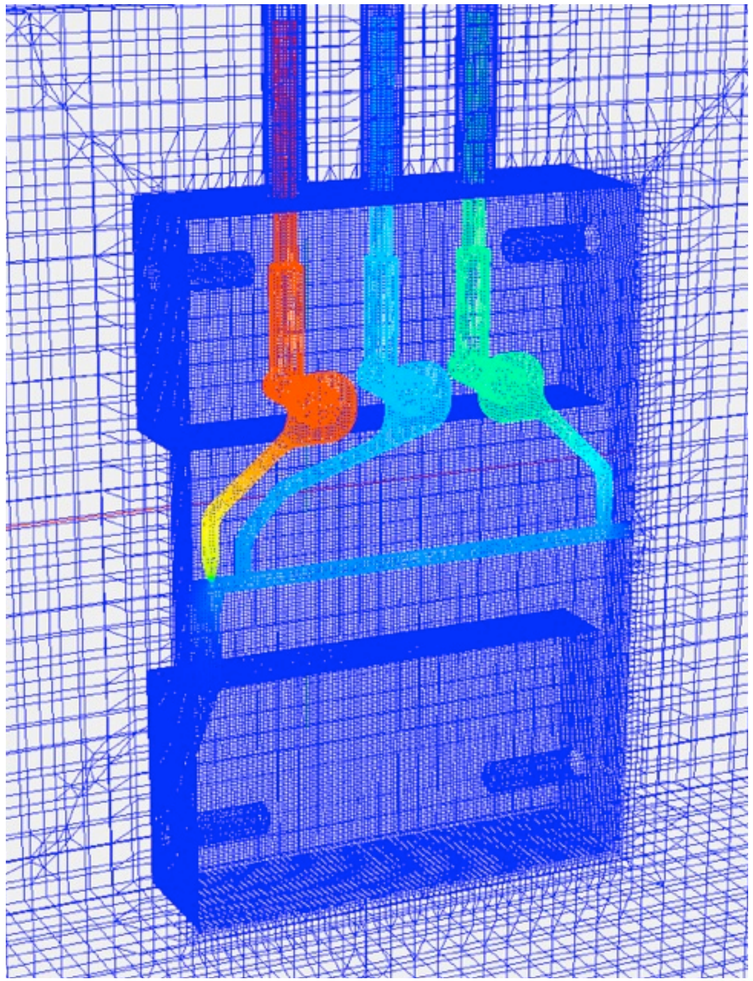


Full 3D simulations with fluid code OpenFOAM

The goal: development of tailored plasma sources for controlled electron injection, acceleration and emission II

Example: Density tapered gas cell, features similar to capillary

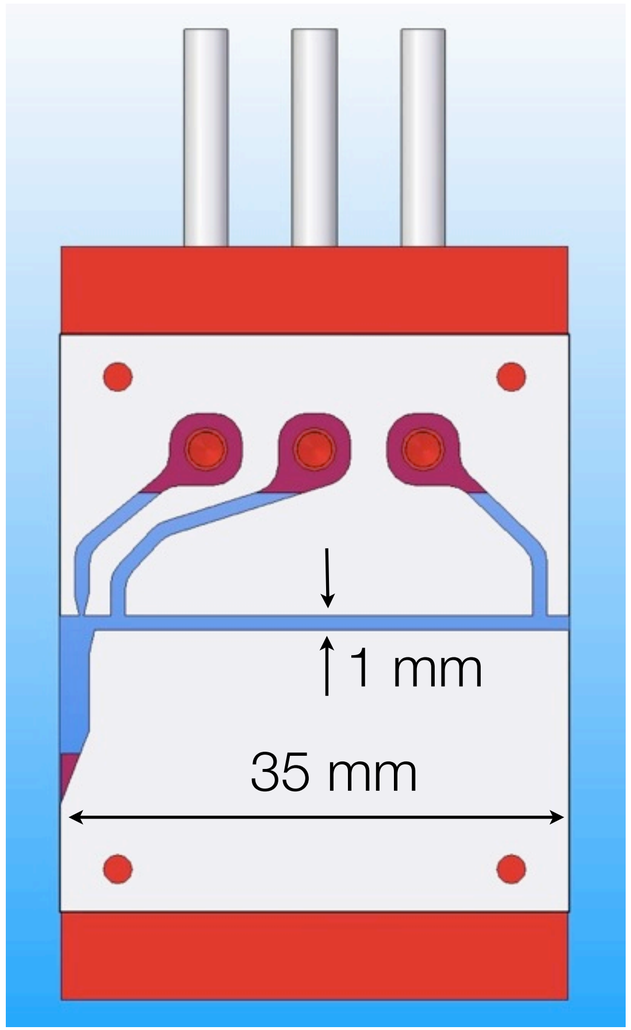


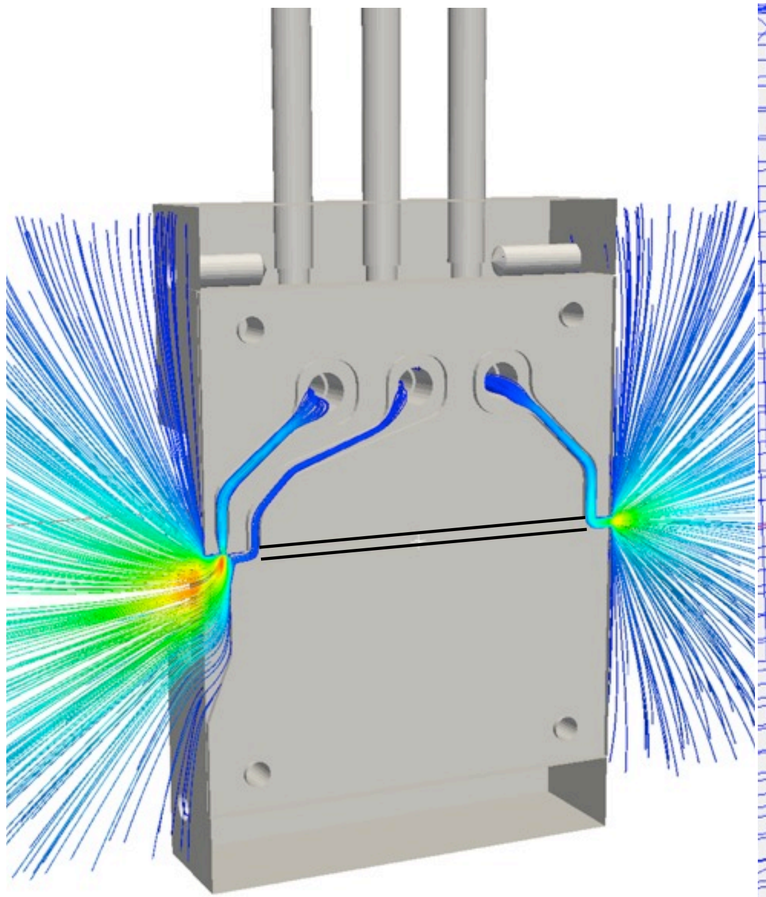


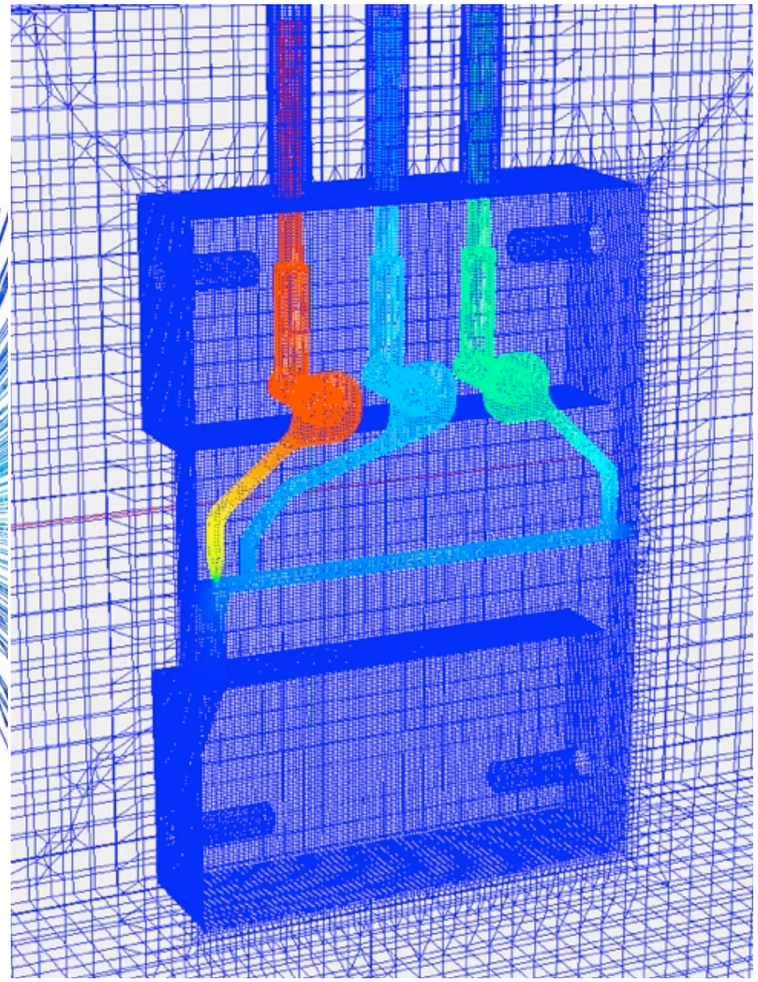
Full 3D simulations with fluid code OpenFOAM

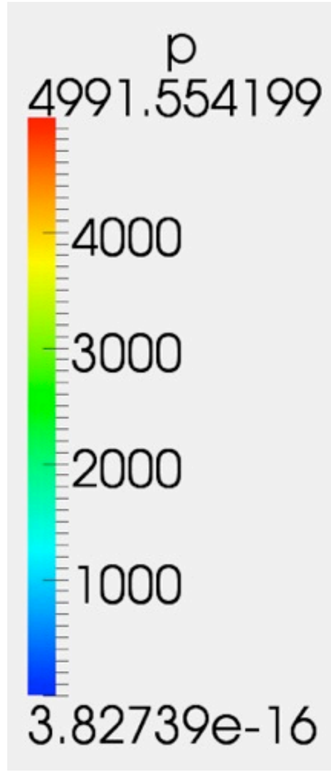
The goal: development of tailored plasma sources for controlled electron injection, acceleration and emission II

Example: Density tapered gas cell, features similar to capillary









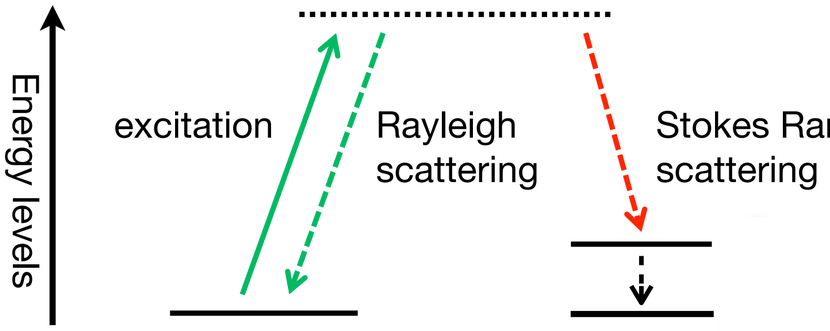
Full 3D simulations with fluid code OpenFOAM

Raman scattering diagnostics: Setup

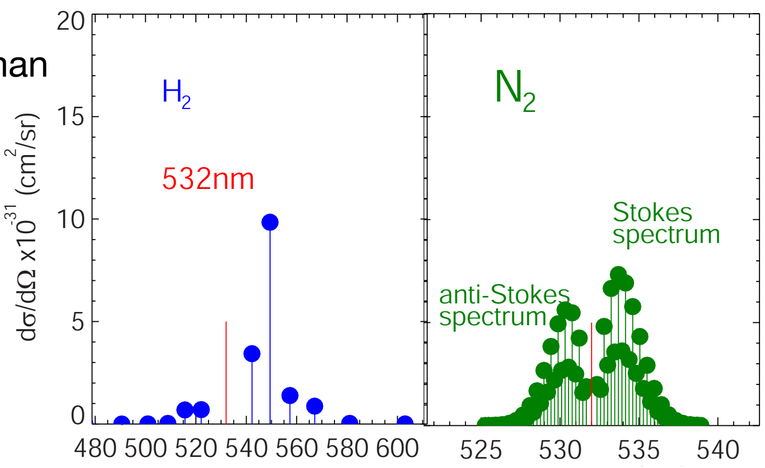
Technique: Raman scattering for longitudinal profile

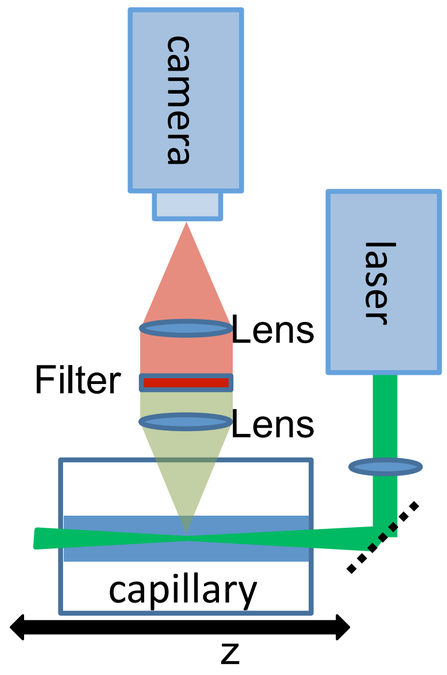
- scattered intensity proportional to gas density: $I_{Raman} = n_{Gas} \cdot \sigma \cdot I_{Laser}$
- non resonant technique → filters can be used

→ T. Weineisen *et al.,* Phys Rev STAB **14**, (2011) 050705



R. Scannell et al. Rev. Sci. Instrum. **81**, (2010) 045107

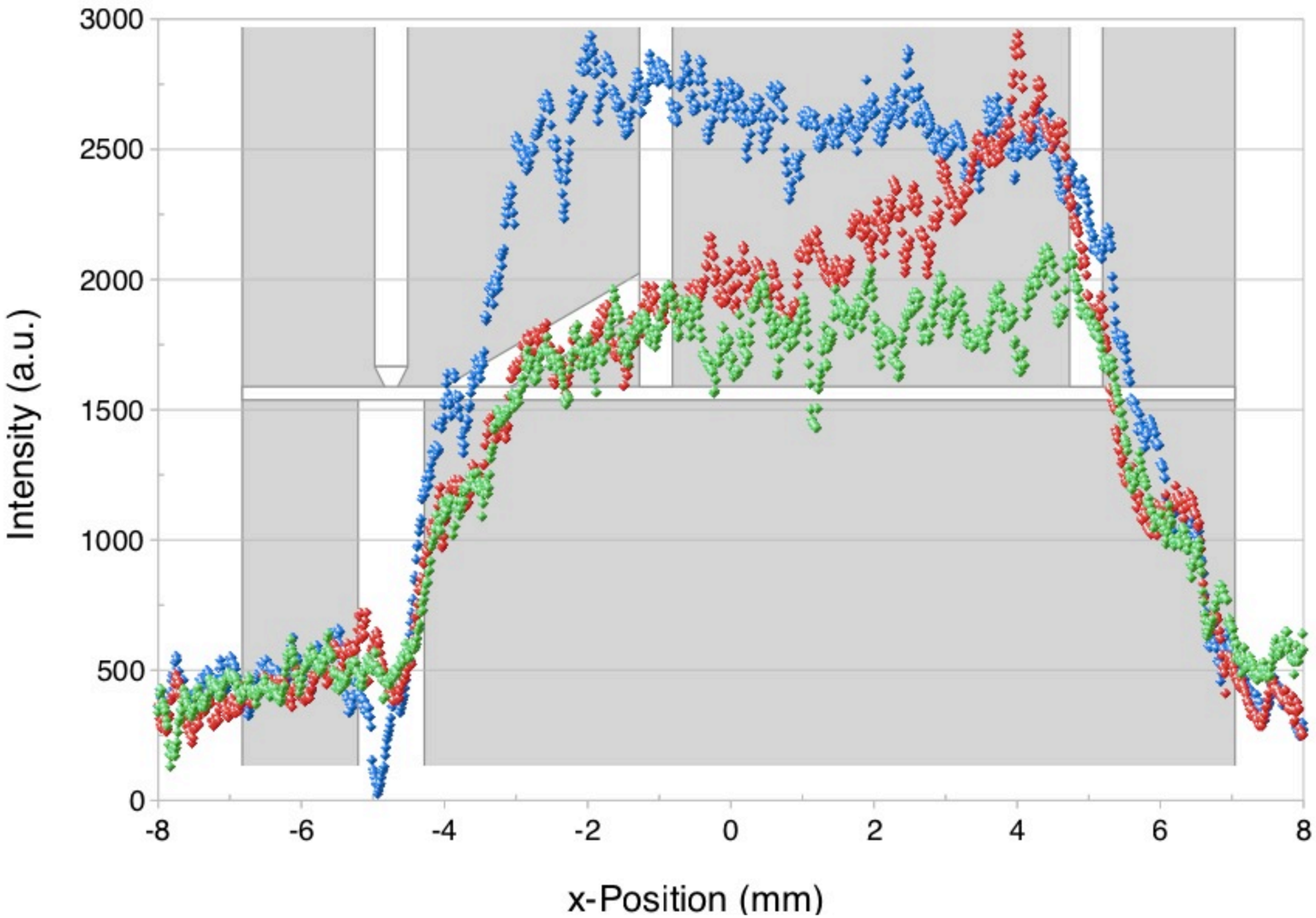


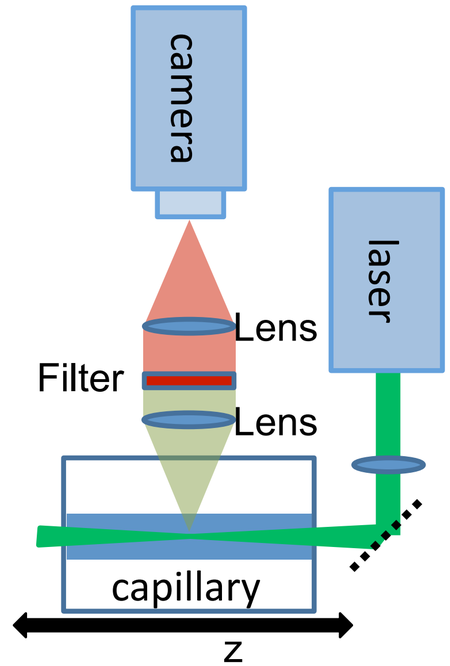


- demonstrated sensitivity:**few 10^{18} cm^{-3}**
- PW lasers (e.g. BELLA at LBNL) and external injection (e.g. at REGAE) require **few 10^{17} cm^{-3}**
- Ionization injection experiments: dopant densities down to **low 10^{15} cm^{-3}**

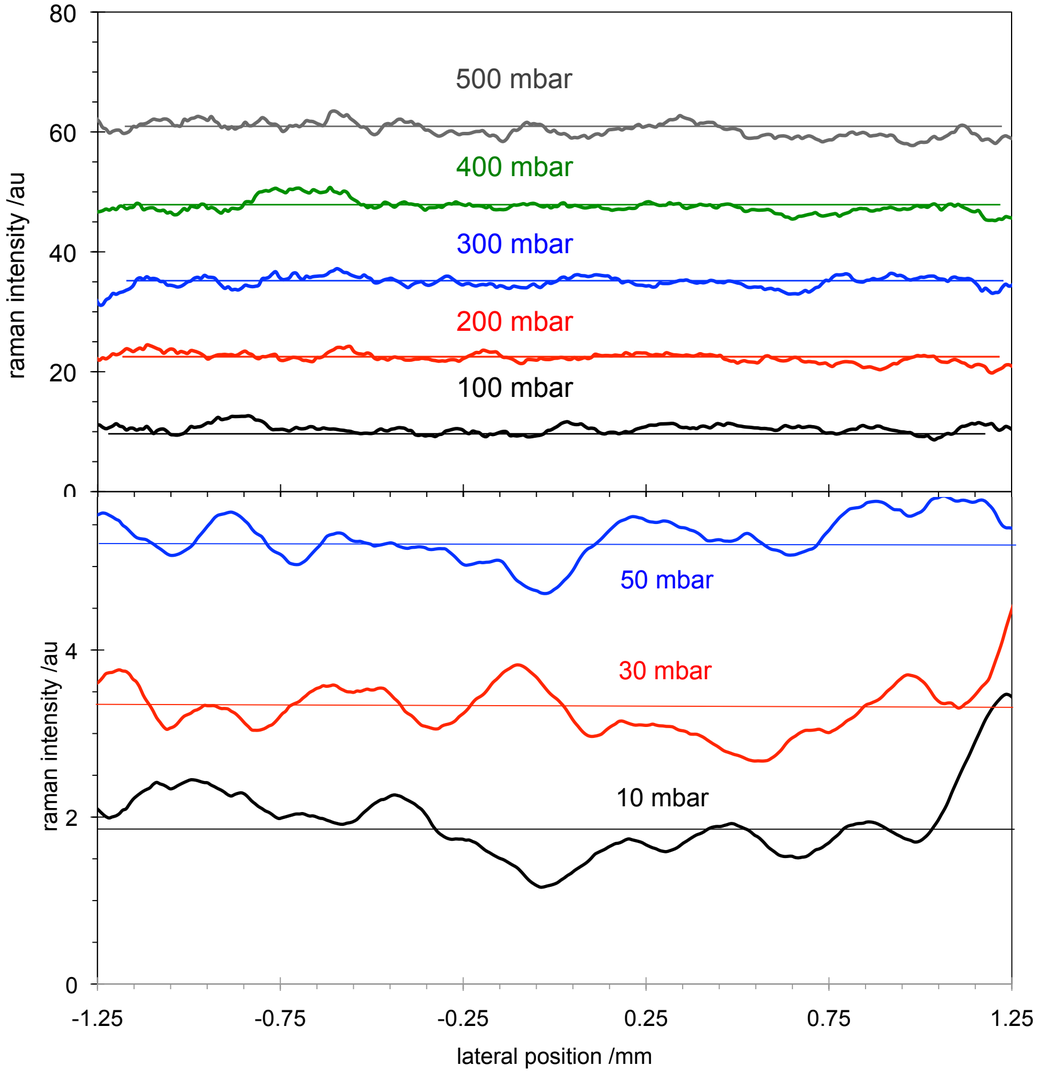
N2: Shift to first vibrational band = 2329 cm^{-1}
corresponds to 75.2nm (for 532nm excitation)
But: Cross section smaller by 3 orders

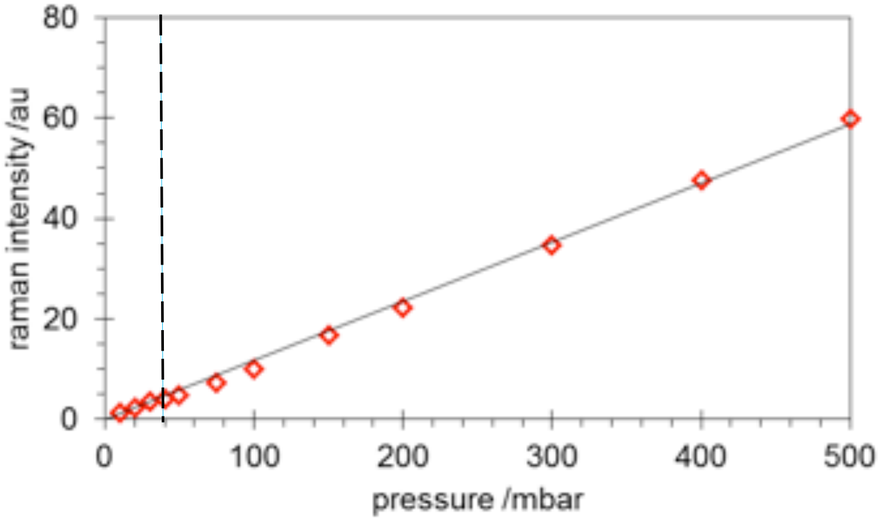
Sensitive diagnostic important for profile characterization

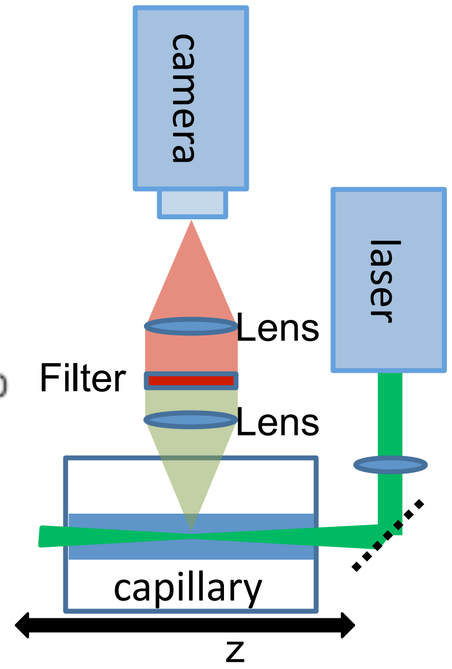




Sensitive diagnostic important for profile characterization



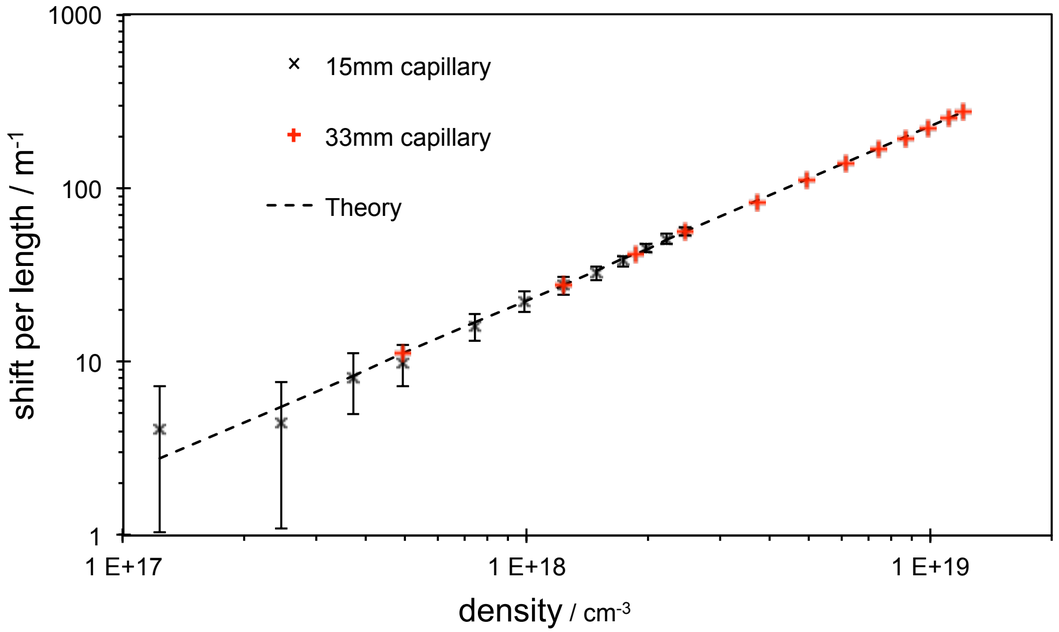


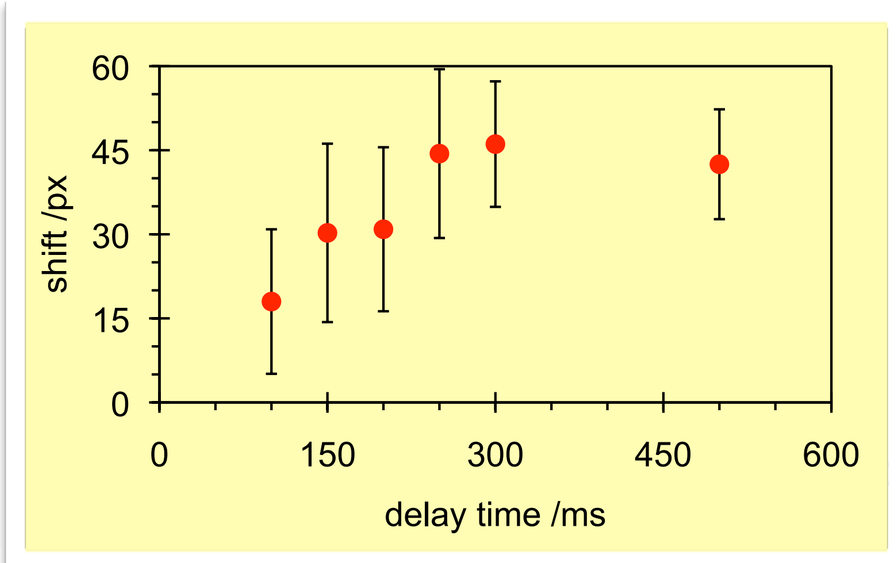


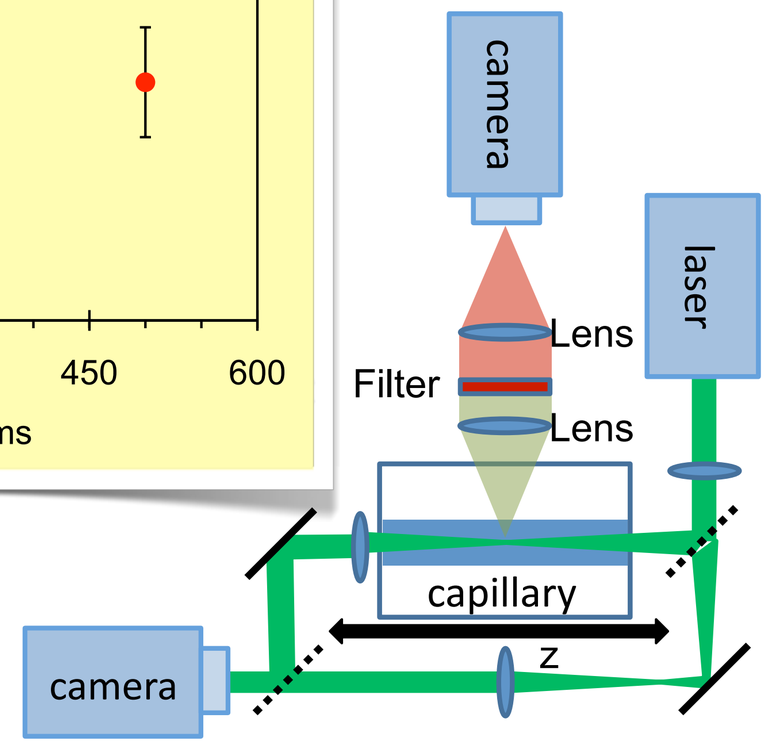
Sensitive diagnostic important for profile characterization

L. F. Schaper *et al.,* in preparation

New technique: Raman scattering combined with longitudinal interferometry







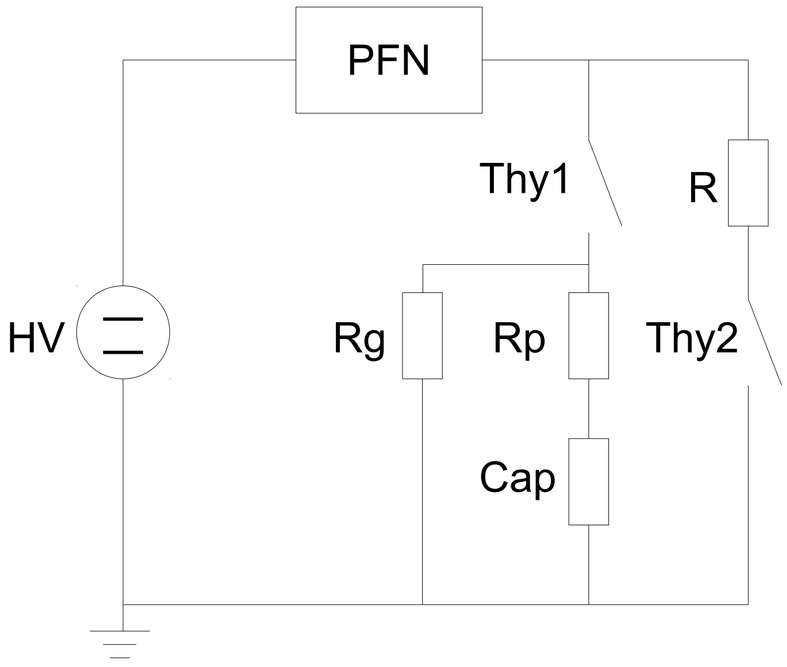
- profile determination by Raman scattering in polished capillaries
- integrated density under profile determined by interferometry

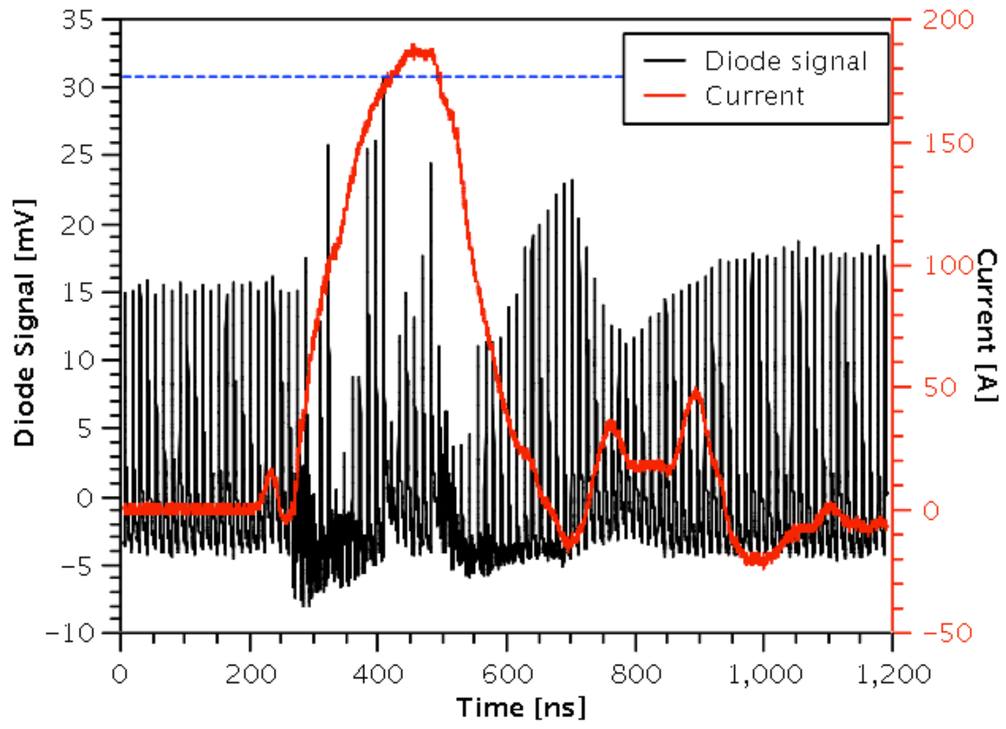
} → reconstruction of profile with high accuracy (currently being done)

Transverse density shaping

Technique: Laser guiding by transverse plasma channel, ignited through electric discharge

- PFN with adjustable pulse duration and either peak current or dI/dt
- Max voltage: 40kV max current: 1.5kA (tested so far) max pulse duration: 400ns
- shot to shot RMS jitter @ 15kV < 5ns

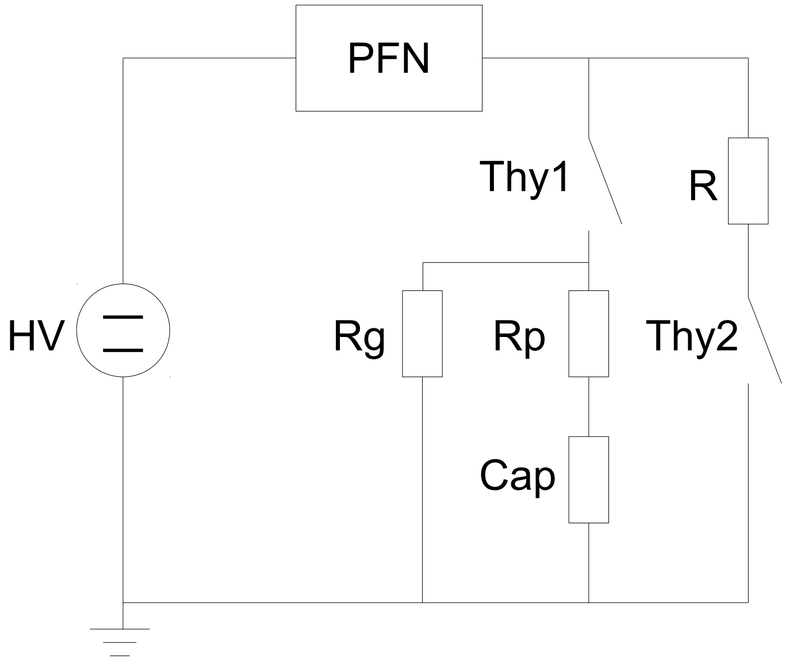


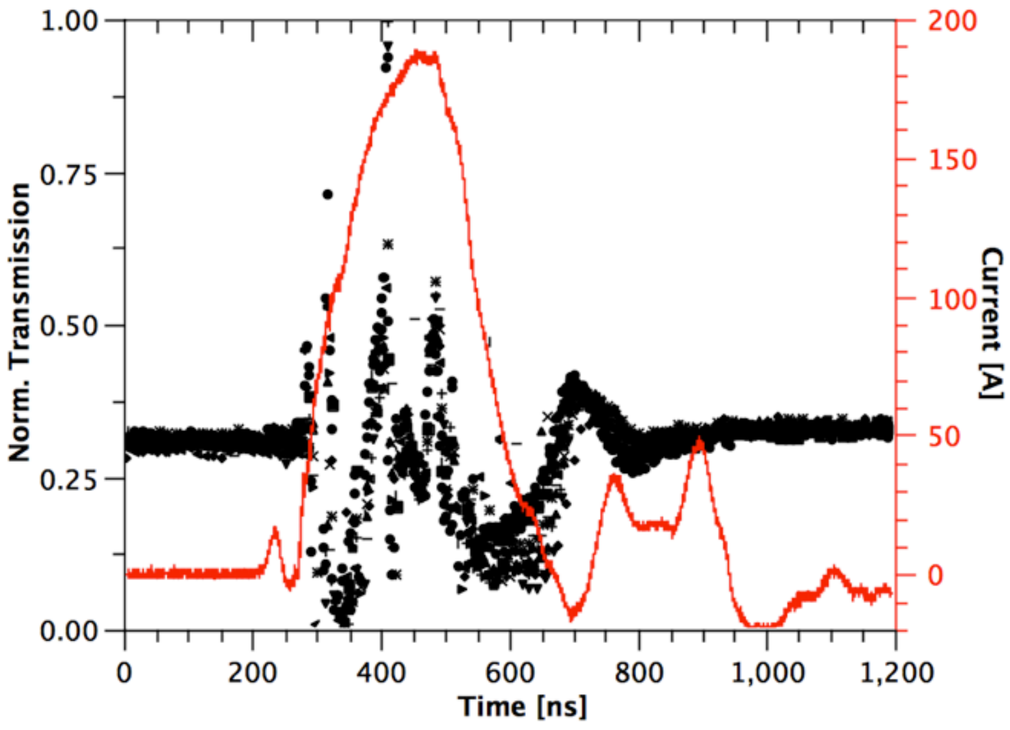


Transverse density shaping

Technique: Laser guiding by transverse plasma channel, ignited through electric discharge

- PFN with adjustable pulse duration and either peak current or dI/dt
- Max voltage: 40kV max current: 1.5kA (tested so far) max pulse duration: 400ns
- shot to shot RMS jitter @ 15kV < 5ns



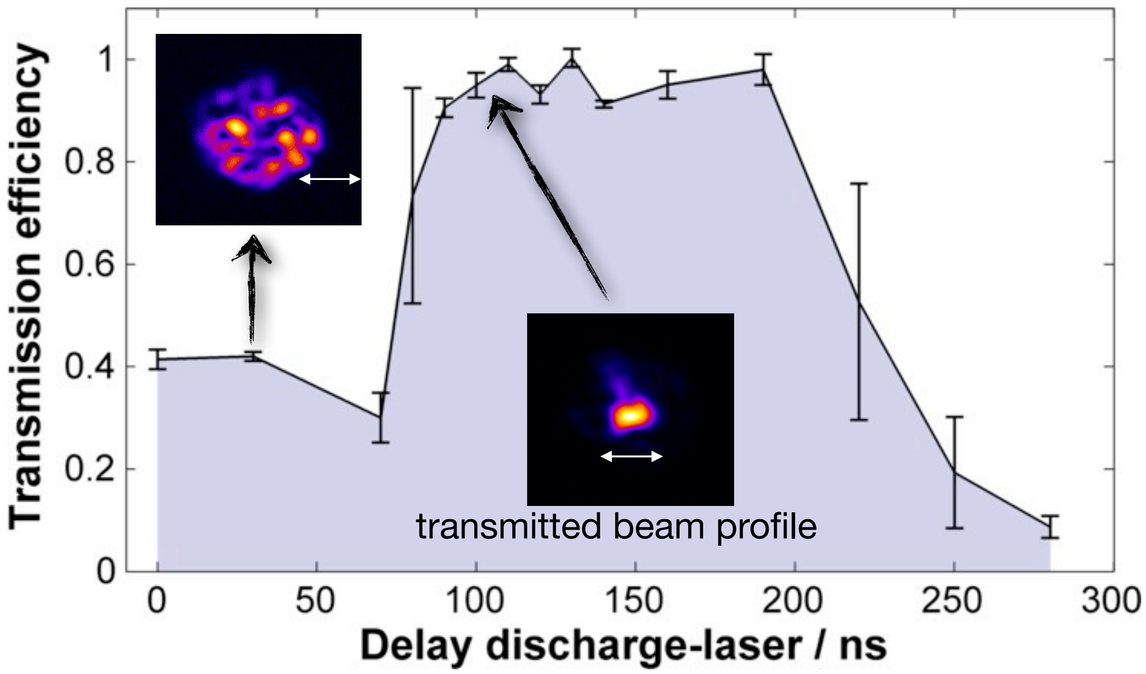


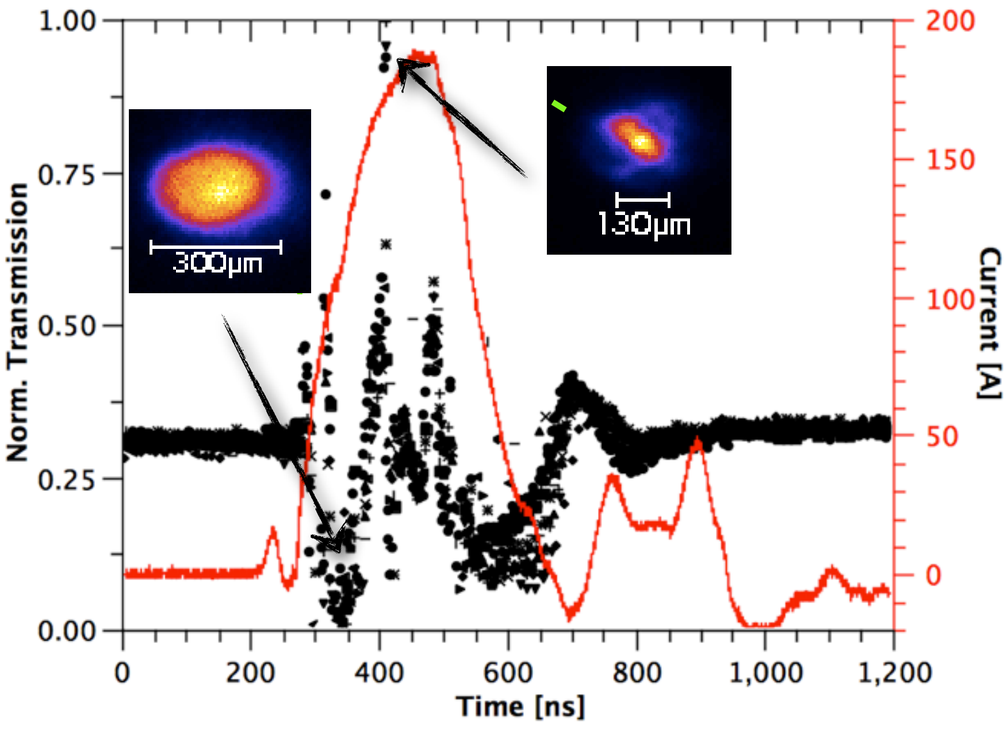
Transverse density shaping

Technique: Laser guiding by transverse plasma channel, ignited through electric discharge

- PFN with adjustable pulse duration and either peak current or dI/dt
- Max voltage: 40kV max current: 1.5kA (tested so far) max pulse duration: 400ns
- shot to shot RMS jitter @ 15kV < 5ns

guiding 15 mm long capillary, laser < 1 mm Rayleigh length





Transverse density shaping

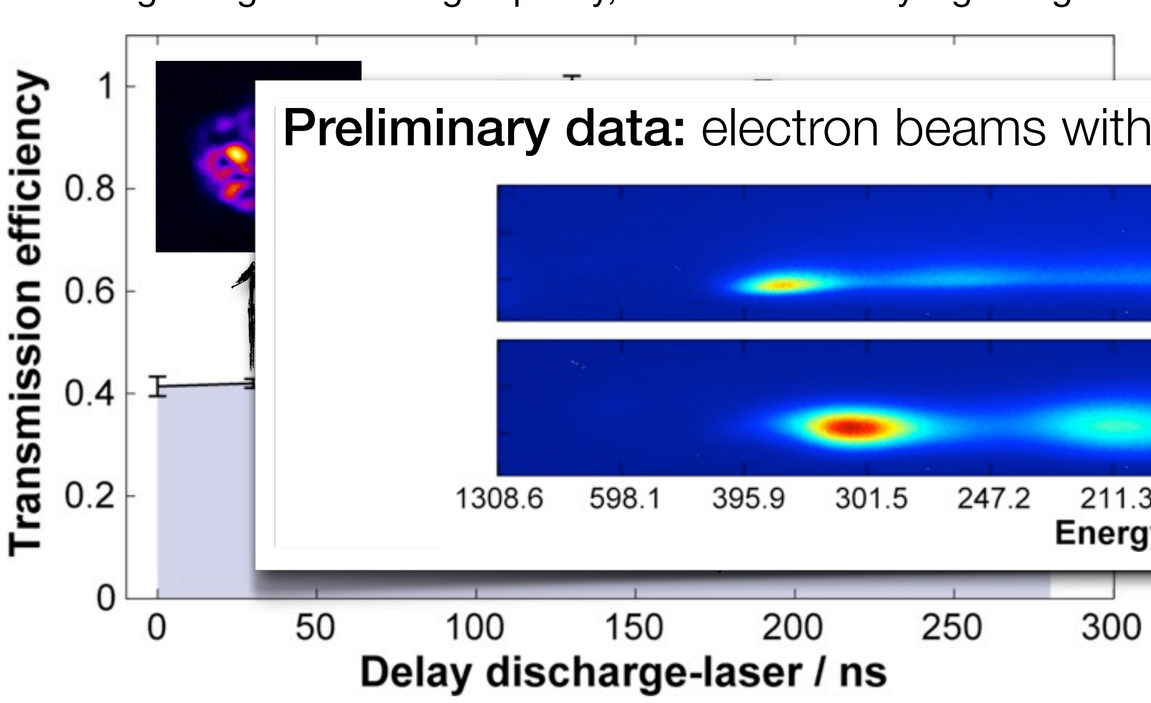
Technique: Laser guiding by transverse plasma channel, ignited through electric discharge

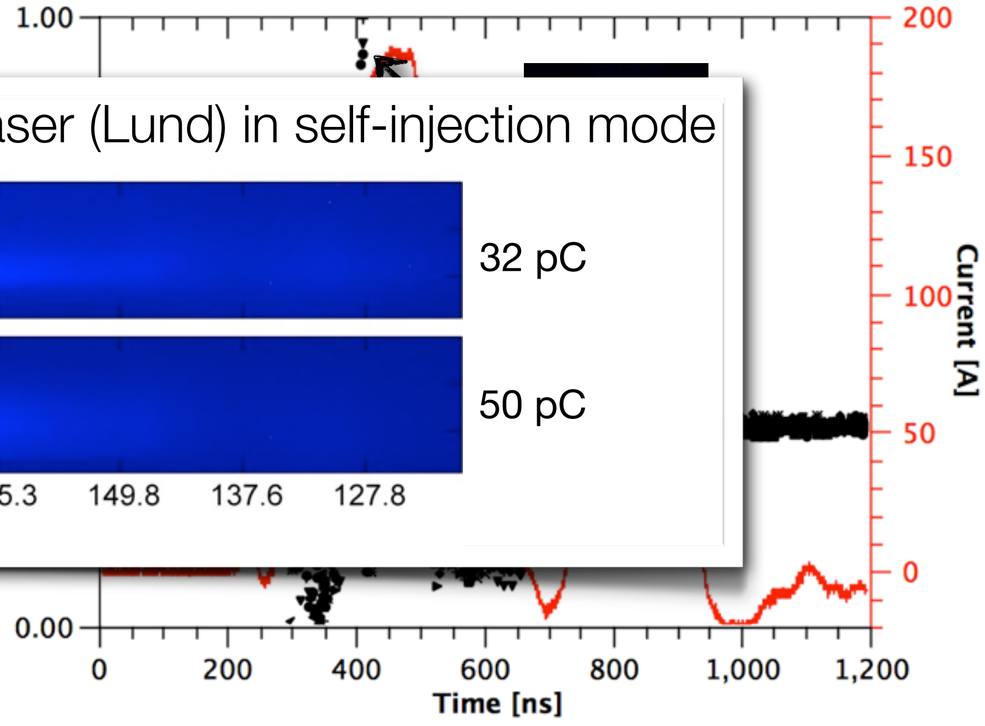
- PFN with adjustable pulse duration and either peak current or dI/dt
- Max voltage: 40kV max current: 1.5kA (tested so far) max pulse duration: 400ns
- shot to shot RMS jitter @ 15kV < 5ns

M. Burza, M. Hansson,
O. Lundh, L. Senje,
C.-G. Wahlstrom

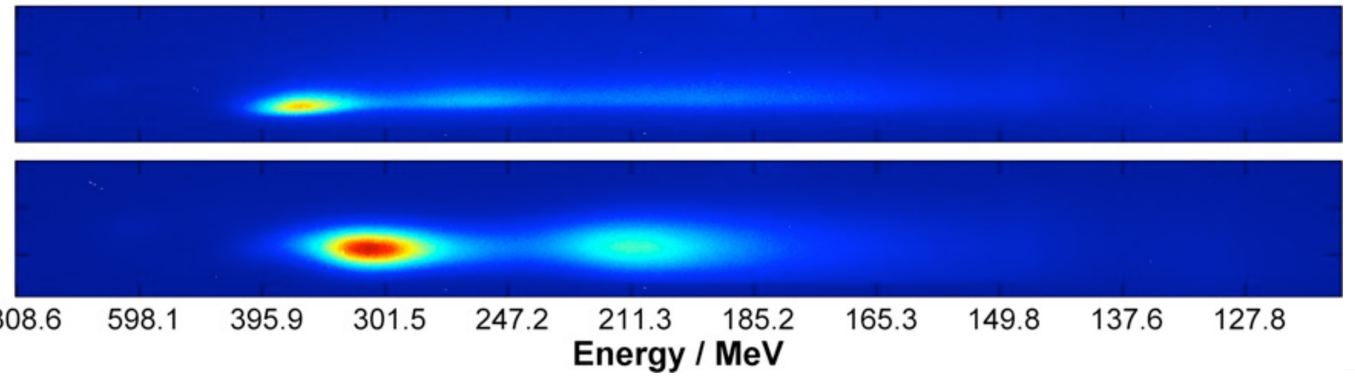
LUND UNIVERSITY

guiding 15 mm long capillary, laser < 1 mm Rayleigh length





Preliminary data: electron beams with 25 TW laser (Lund) in self-injection mode

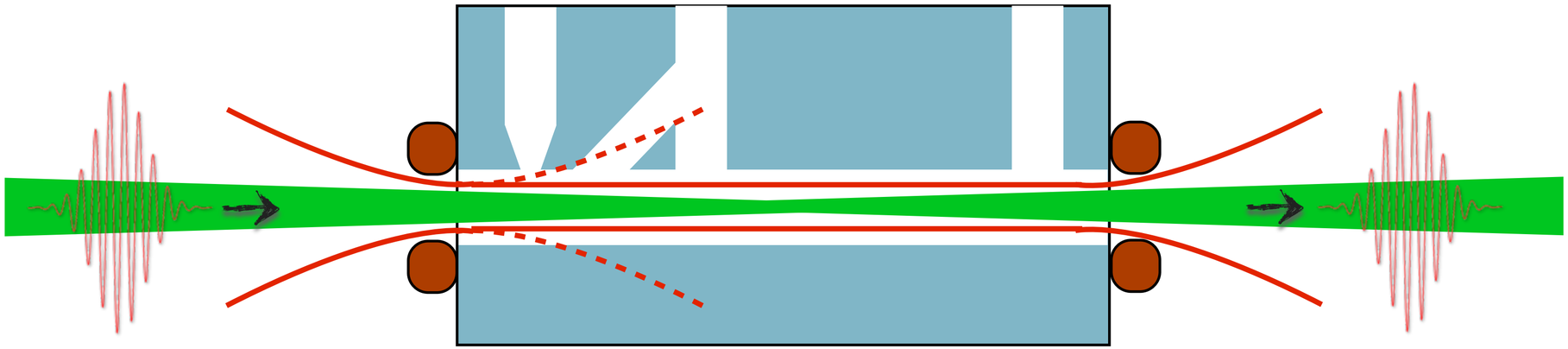


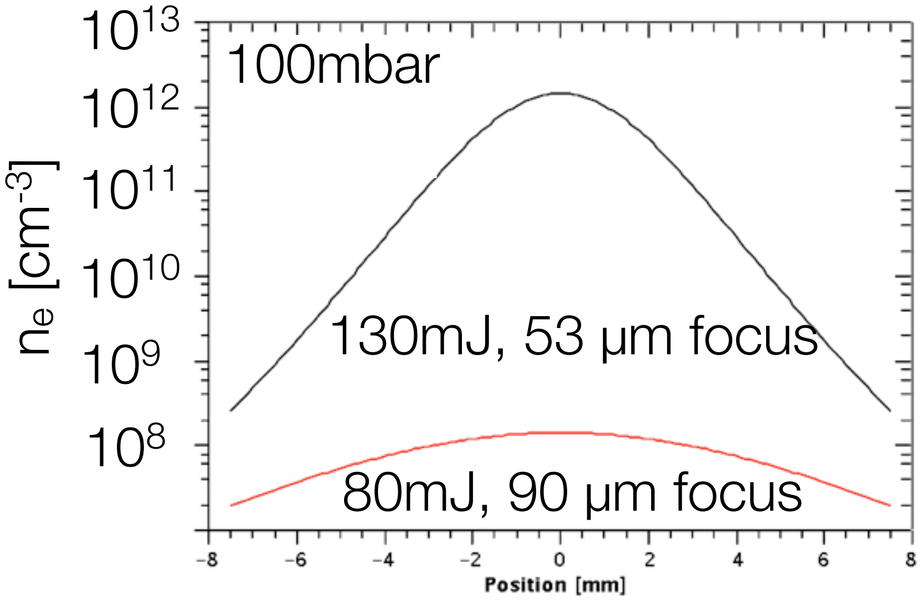
Discharge seeding

Technique: Adding a pulsed laser to partially pre-ionize target via multiphoton-ionization

- Reduction of discharge jitter to level of thyratron switching time (about 1ns)
- Result: lower voltages needed, allows for long targets

HELMHOLTZ ASSOCIATION
Helmholtz Institute Jena



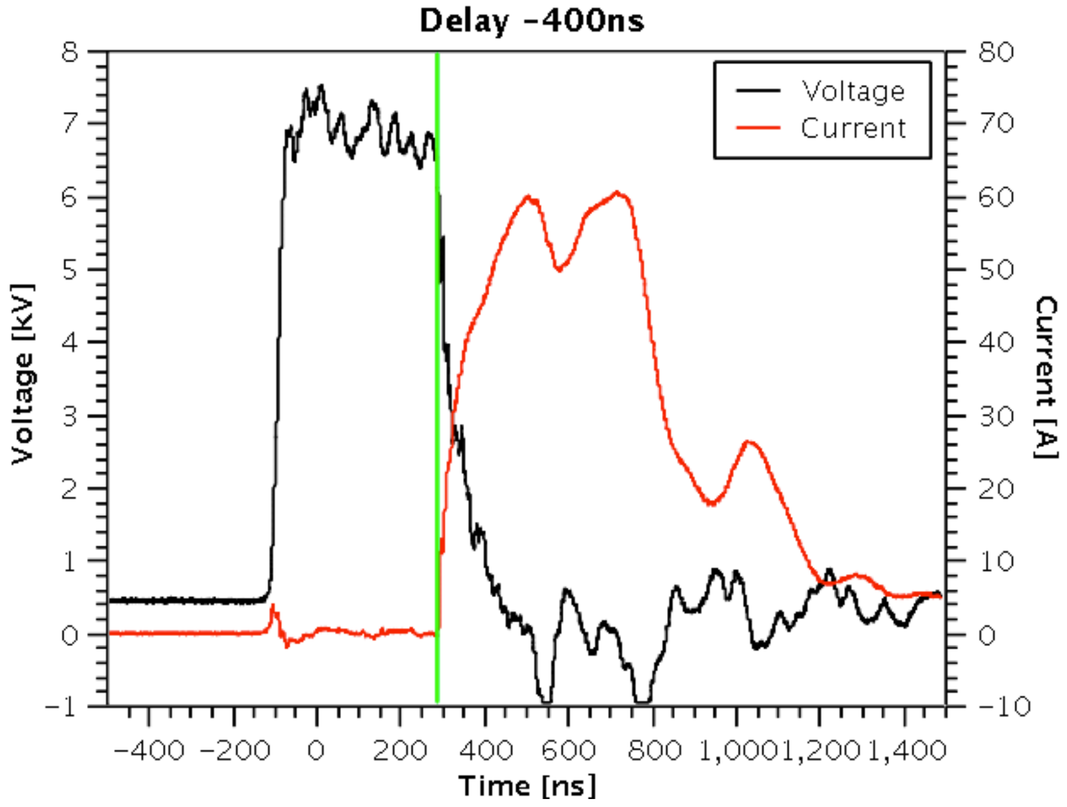


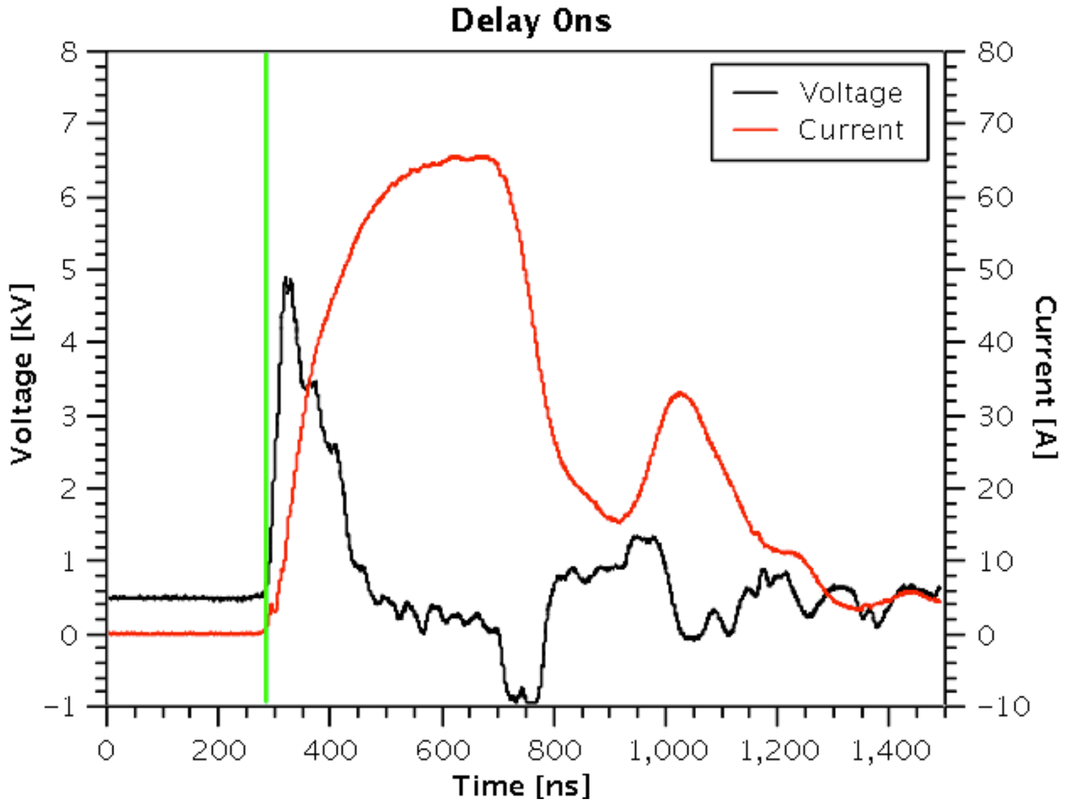
Discharge seeding

Technique: Adding a pulsed laser to partially pre-ionize target via multiphoton-ionization

- Reduction of discharge jitter to level of thyratron switching time (about 1ns)
- Result: lower voltages needed, allows for long targets

HELMHOLTZ ASSOCIATION
Helmholtz Institute Jena



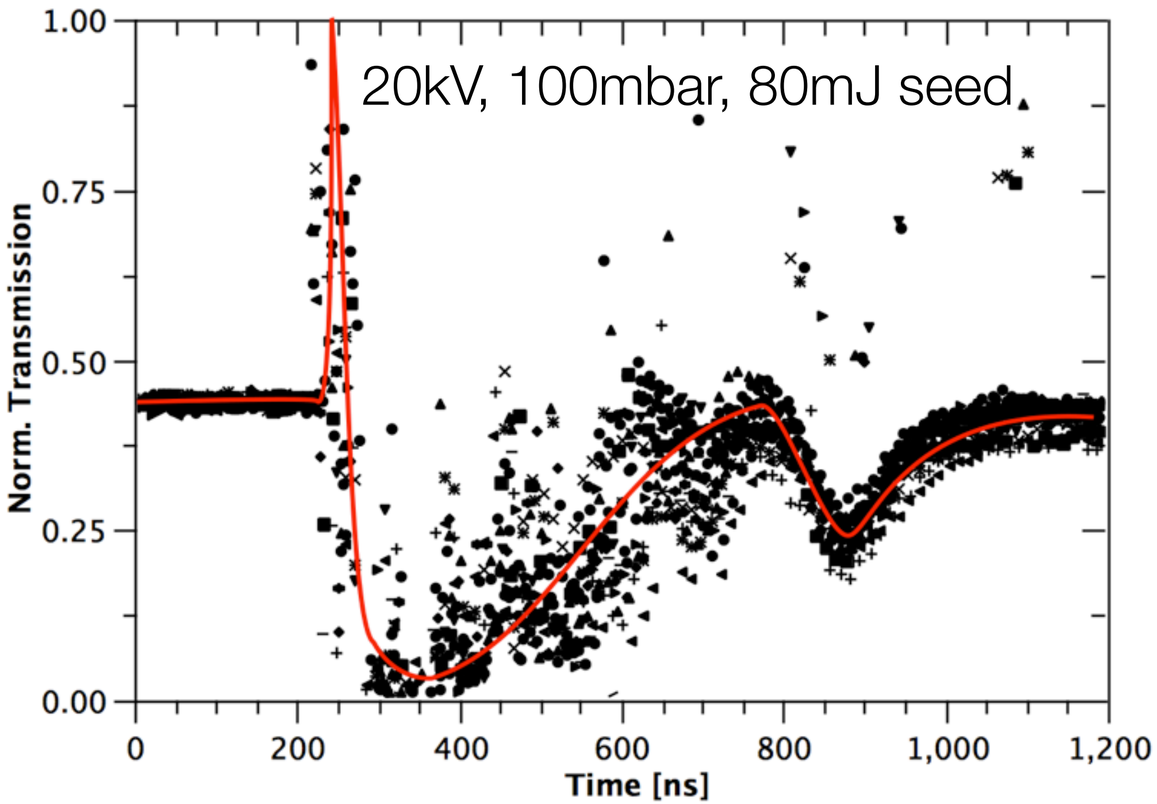


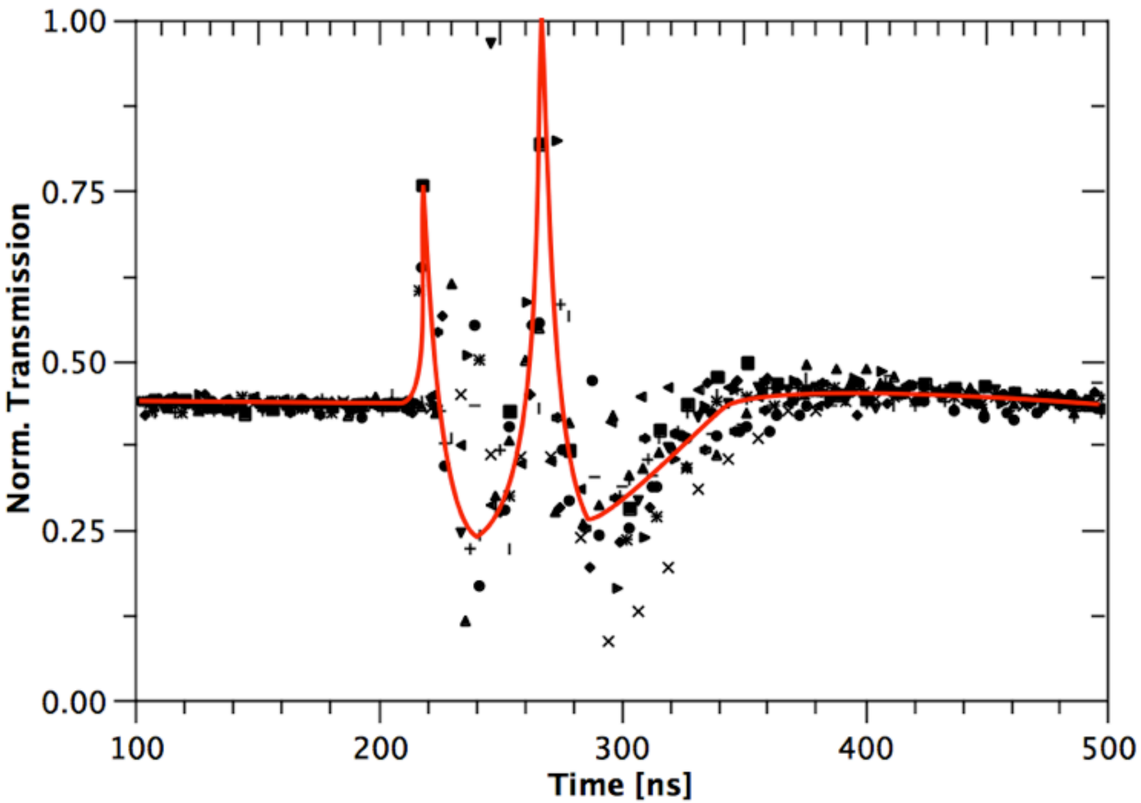
Discharge seeding

Technique: Adding a pulsed laser to partially pre-ionize target via multiphoton-ionization

- Reduction of discharge jitter to level of thyratron switching time (about 1ns)
- Result: lower voltages needed, allows for long targets

HELMHOLTZ ASSOCIATION
Helmholtz Institute Jena





Summary

- Longitudinal density tailoring
  - Relative density profile measurement down to 10^{17} cm^{-3}
  - Absolute density calibration for fringe shifts < $5x10^{-3}$ mm^{-1}
  - results form simulations and measurements agree
- Transverse density shaping
  - PFN allows flexible discharge parameters
  - low discharge-on jitter in typical capillary length at typical voltages of about 20kV
  - High transmission through capillaries with length >> Rayleigh length of the laser
- Discharge seeding
  - increased stability and decrease discharge time lag
  - stable operation at lower voltages, longer capillaries possible
  - BUT: Not guiding (so far)

Alexander von Humboldt
Stiftung/Foundation

Laserlab
Europe

HELMHOLTZ
ASSOCIATION

Accelerator Research and Development

HELMHOLTZ
ASSOCIATION

Virtual Institute for PWA at FLASH