Overview of optical plasma diagnostics for novel accelerators

CNR-INO
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ILIL
Laboratorio
Irraggiamento
Laser
Intensi

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& L. A. Gizzi

EAAC 2019 – Elba

Lay out of the presentation

-) *Introduction: Scope and Motivations*

-) *Optical density diagnostics and application examples*

-) Conclusions

NOTE - Content adapted from:

F. Brandi and L. A. Gizzi, High Power Laser Sci. Eng. 7, e26, 2019

Scope

-) An overview of optical based diagnostics to measure and monitor the background plasma density in plasma acceleration stages:

- *Free expanding gas jet* (subsonic and supersonic)
- *Flowing gas cell* (continuous flow or pulsed)
- *Plasma channels* (laser produced and capillary discharges)

-) Diagnosis of the Plasma wake and of the electron bunch is of critical importance.
The issue is treated in details in a number of recent works:

PHYSICAL REVIEW X 9, 011046 (2019), M. F. Gilljohann, H. Ding, A. Döpp, J. Götzfried, S. Schindler, G. Schilling, S. Corde, A. Debus, T. Heinemann, B. Hidding, S. M. Hooker, A. Irman, O. Kononenko, T. Kurz, A. Martinez de la Ossa, U. Schramm, and S. Karsch

Rev. Mod. Phys. 90, 035002, 2018, M. C. Downer, R. Zgadzaj, A. Debus, U. Schramm, and M. C. Kaluza.

Physics of Plasmas 25, 056704 (2018), A. Cianchi, M. P. Anania, F. Bisesto, E. Chiadroni, A. Curcio, M. Ferrario, A. Giribono, A. Marocchino, R. Pompili, J. Scifo, V. Shpakov, C. Vaccarezza, F. Villa, A. Mostacci, A. Bacci, A. R. Rossi, L. Serafini, and A. Zigler

Free-electron density in plasma

Density measurement is Ubiquitous in all Plasma applications

-) Debye length: $\lambda_D = [\varepsilon_0 K_B T / e^2 \mathbf{N_e}]^{1/2}$

-) Plasma frequency: $\omega_p = [\mathbf{N_e} e^2 / m_e \varepsilon_0]^{1/2}$

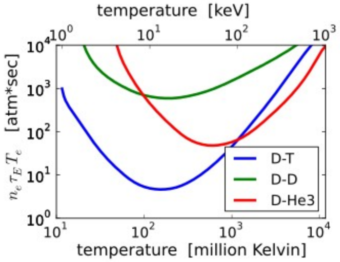
-) Refractive index: $n = [1-(\omega_p/\omega)^2]^{1/2} \cong 1-½(\omega_p/\omega)^2 = 1\text{-}4.5\text{x}10^{-16}\ \mathbf{N_e}\lambda^2 \rightarrow$ $n - 1 \propto N_e$

-) Group velocity: $V_g = c[1-(\omega_p/\omega)^2]^{1/2} \rightarrow$ $V_g * V_p = c^2$

-) Plasma wake:

Wave breaking field: $E_0(V/m) \cong 96\ [\mathbf{N_e}(cm^{-3})]^{1/2}$

Plasma wavelength: $\lambda_P(\mu m) \cong 3.3\text{x}10^{10}/[\mathbf{N_e}(cm^{-3})]^{1/2}$



-) Nuclear Fusion: Triple product = **Density** x Temperature x Time

Motivations

A **change of paradigm** is under way in the field of plasma acceleration: after decades of *fundamental research, discoveries and break-through* in the generation of multi-GeV electron bunches, nowadays much effort is devoted towards the ***practical application*** → the design and realization of user oriented infrastructures (EuPRAXIA: up to 5GeV, <1% energy spread, etc.) and also towards high repetition up to 1 KHz rate sources (Laser and acceleration stages).

This forward step requires a **dedicated approach** aiming at the development of stable and **fully controllable plasma accelerator stages.**
In this context, the definition, development and deployment of **robust** and **sensitive** diagnostics is of critical importance to achieve the final goal.

Example: $N_e \sim 5\times10^{17}$ cm^{-3} within <10% → sensitivity < 5×10^{16} cm^{-3}

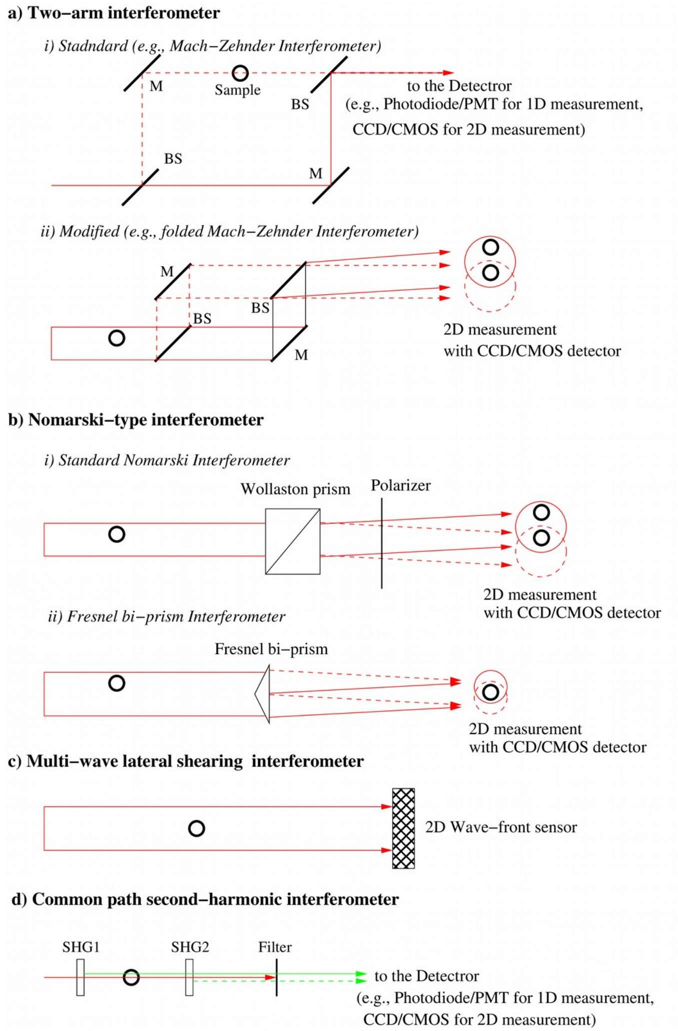
Optical plasma density diagnostics

-) **Interferometry**: quantitative, various configurations, also for neutral gas density $\mathbf{N_g}$ (e.g. hydrogen)

-) **Shadowgraphy**: mainly qualitative, sensitive to the second derivative of the density ($\partial^2 N_e/\partial x^2$)

-) **Optical Emission Spectroscopy**: quantitative, simple configuration, no need of through line of sight

Main Interferometric methods



ai) Standard two-arm interferometers, e.g., M-Z,

aii) Modified two arm-interferometers
Self-referenced, easier to set-up and control

b) Nomarski-type
Quasi-common path, self-referenced

$\Delta\varphi = 2\pi/\lambda \int_L [n(\lambda,l)-1]\, dl \propto \boldsymbol{\int_L N_e(l)\, dl}$.

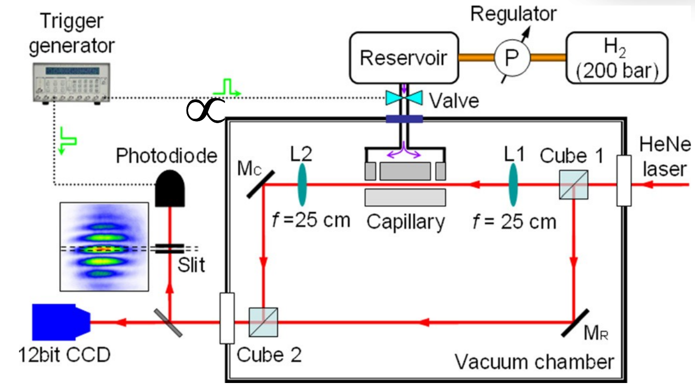
c) Wave front sensor
Easy to implement, sensitive to phase gradient

d) Second-harmonic interferometer
Common path, sensitive to dispersion

Two-arm interferometers examples

-) Standard two-arm interferometers (TAI).
laser beam divided into distinct sample and reference arms following different geometrical paths,

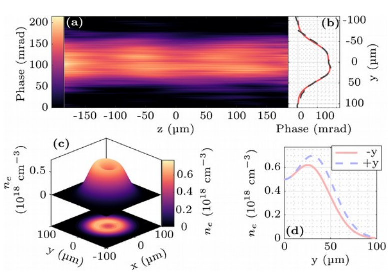
$$\Delta\varphi = 2\pi/\lambda \int_L [n_g(\lambda,l)-1]\, dl \propto \int_L N_g(l)\, dl.$$

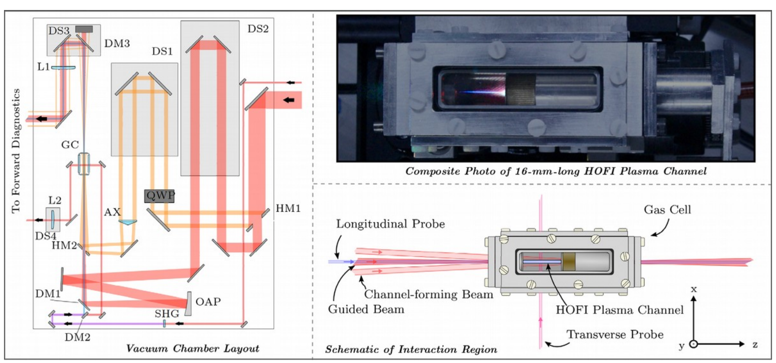


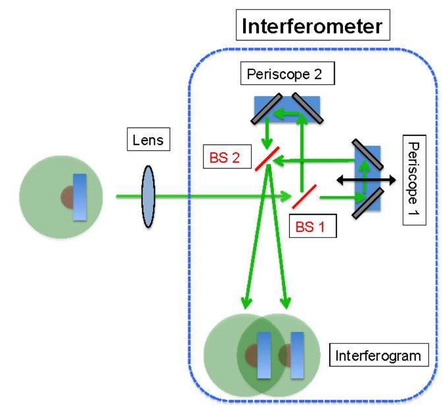
J Ju and B Cros J. Appl. Phys. 112 , 113102 2012

-) Modified (folded) two-arm interferometers.

Self-referenced



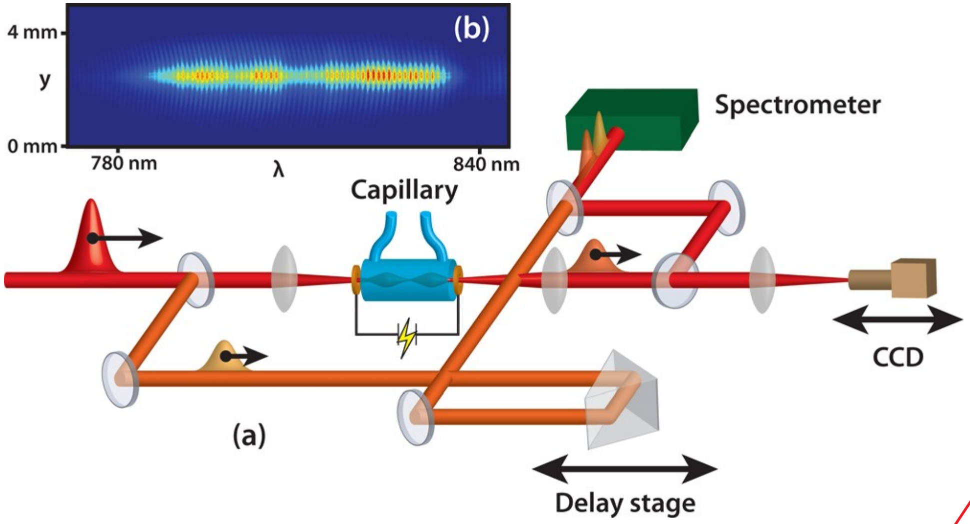


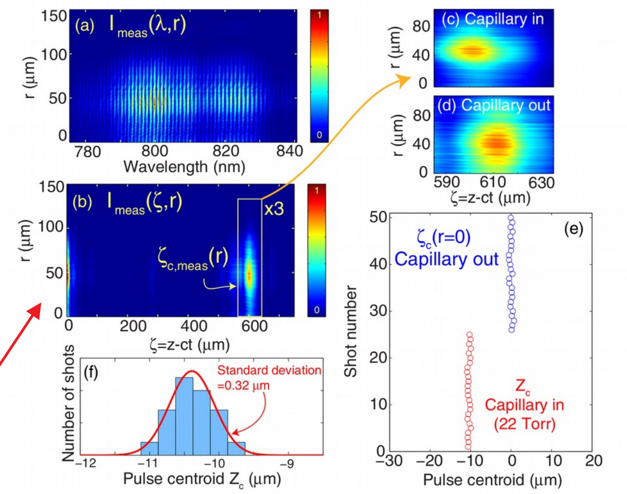


R.J. Shalloo, C. Arran, A. Picksley, A. von Boetticher, L. Corner, J. Holloway, G. Hine, J. Jonnerby, H. M. Milchberg, C. Thornton, R. Walczak and S.M. Hooker PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 041302 (2019)

J. Park, H A Baldis, and H Chen, High Pow. Laser Sci. Eng., 4, e26, 2016

Spectral Domain two-arm Interferometry

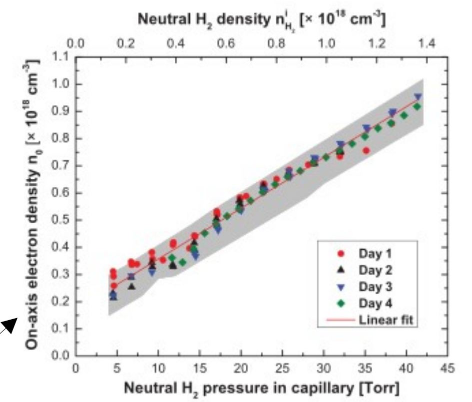




Measure the spectrum of two broad-band pulses with time delay **τ** :

$$I(\omega)=I_R(\omega)+I_S(\omega)+[I_R(\omega)I_S(\omega)]^{1/2}\cos(\Delta\varphi-\omega\boldsymbol{\tau})$$

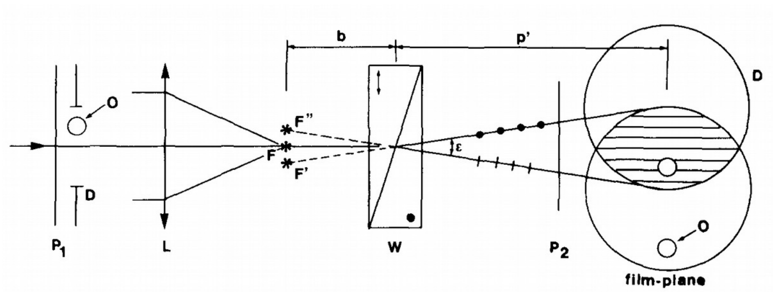
The Fourier Transform of I(ω) gives two symmetric peaks at **±τ** and the group velocity in the plasma channel can be calculated as $V_g/c = [c(\boldsymbol{\tau}_{vac}-\boldsymbol{\tau}_p)/L_p + 1]$



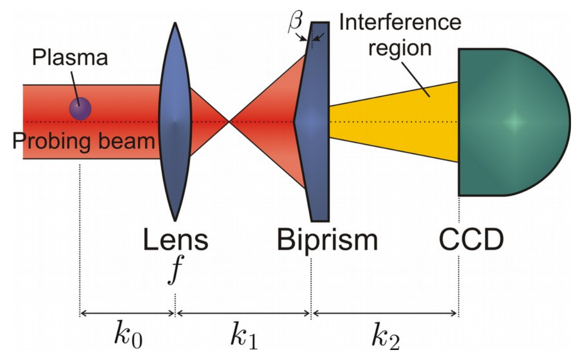
J. van Tilborg, J. Daniels, A. J. Gonsalves, C. B. Schroeder, E. Esarey, and W. P. Leemans, PHYSICAL REVIEW E 89, 063103 (2014)
J. Daniels, J. van Tilborg, A. J. Gonsalves, C. B. Schroeder, C. Benedetti, E. Esarey, and W. P. Leemans, PHYSICS OF PLASMAS 22, 073112 (2015)

Nomarski type interferometers

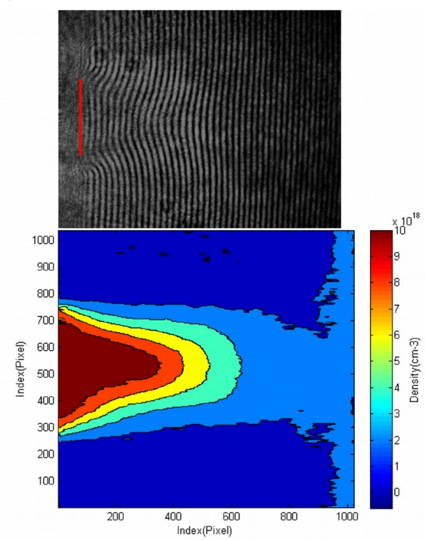
Self-referenced, quasi common-path



R. Benattar, C. Popovics and R. Sigel
Rev. Sci. Instrum. 50, 1583, 1979



M. Kalal, O. Slezak, M. Martinkova and Y J Rhee
J. Korean Phys. Soc., 56, 287, 2010

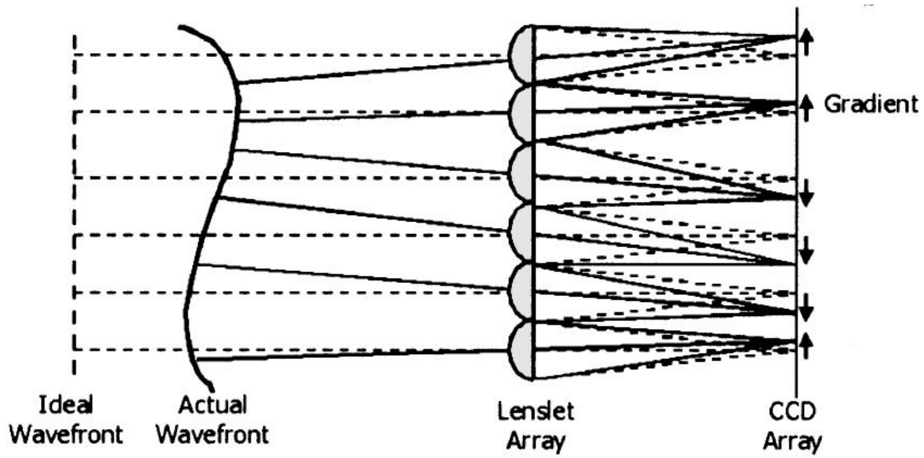


Neutral gas density
Supersonic gas jet

F. Brandi and L.A. Gizzi, High Power Laser Sci. Eng. 7, e26, 2019

WaveFront Sensors: principles

-) The phase is measured on a **wave-front sensing device.**
-) **Easy implementation** and robustness.
-) The methodology is ***sensitive to the transverse gradient of the phase***.
-) Actual phase value is retrieved with a **reconstruction algorithm.**

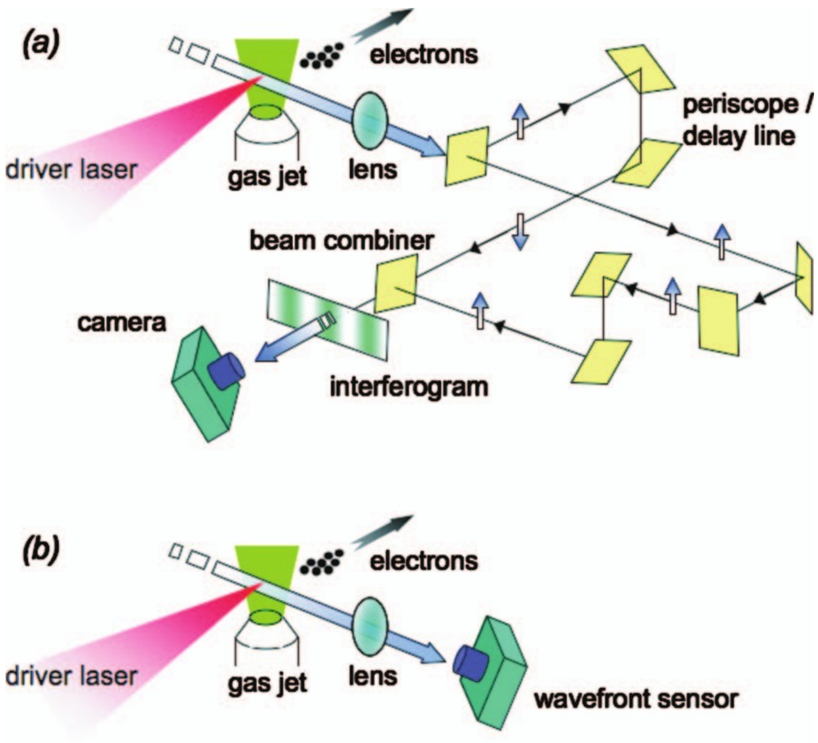


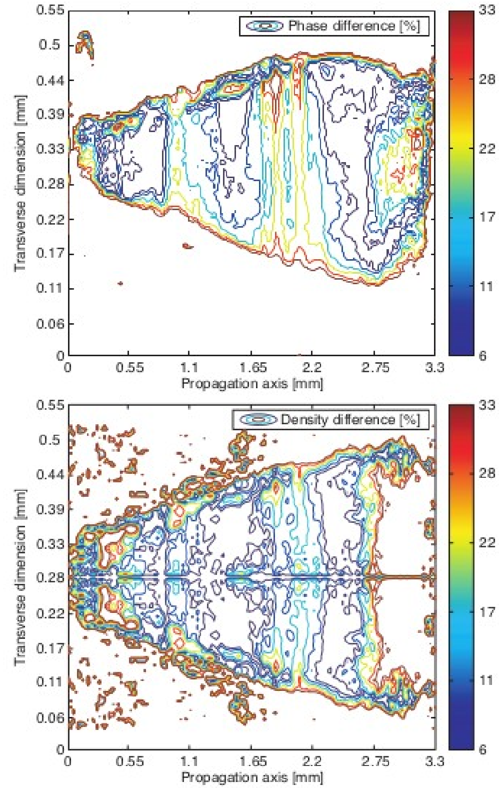
K. L. Baker, J. Brase, M. Kartz, S. S. Olivier, B. Sawvel, and J. Tucker
Rev. Sci. Instrum., 73, 3784 , 2002

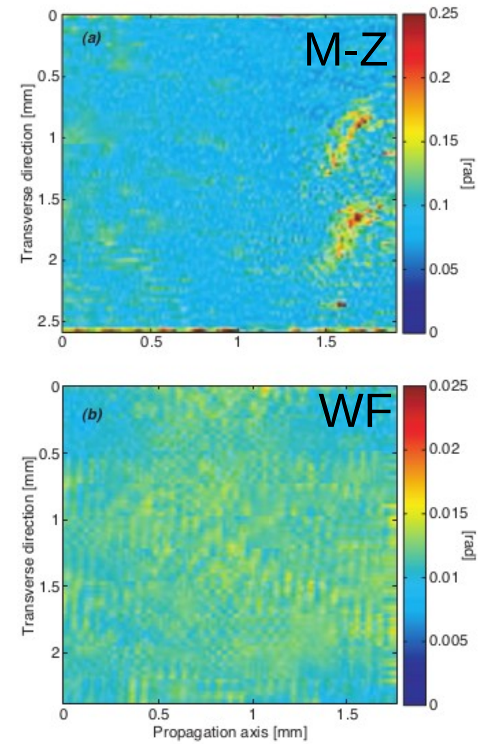
-) Quandri-wave lateral shearing achieved with **diffractive elements** commercially available

J.-C. Chanteloup Appl. Opt. 44, 1559 (2005)

WaveFront Sensor - Interferometry



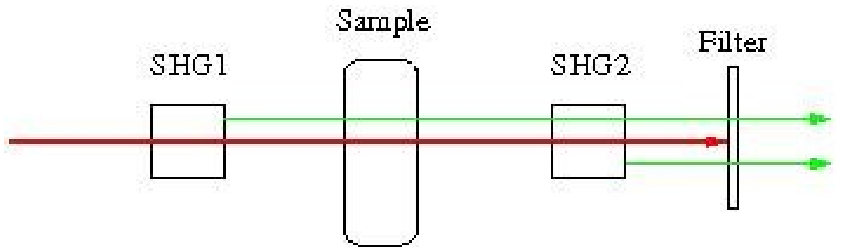




The difference in the measured values is 10-20%. The base noise averaging over 188 maps is 95.7 mrad for the modified M-Z and 11.4 mrad for the WF sensor

G.R. Plateau, N.H. Matlis, C.G.R. Geddes, A.J. Gonsalves, S. Shiraishi, C. Lin, R. A.van Mourik, and W.P. Leemans, Rev. Sci. Instrum. 81, 033108, 2010

Second-Harmonic Interferometry Principles



-) Interference takes place **between the two SH beams** generated before and after the sample;

-) The measured phase difference is **$\Delta\varphi = 4\pi/\lambda \int_L [n(\lambda)-n(\lambda/2)]\, dl \propto \int_L N_e(l)\, dl$.**

(compared with **$2\pi/\lambda \int_L [n(\lambda)-1]\, dl$** for two-arm interferometer).

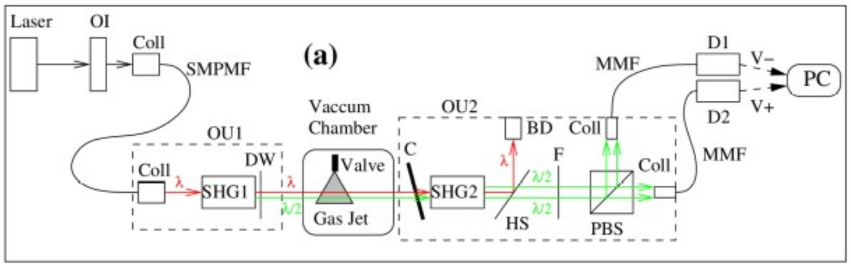
Characteristics:

1) **fully common-path** → easy to implement, **insensitive to vibrations** enabling **high sensitivity**;
2) **compact, versatile, reliable**;
3) High-sensitivity and accuracy;
4) ultra-fast measurements doable.

F. A. Hopf, A. Tomita, and G. Al-Jumaily, Opt. Lett. 5, 386 (1980).
F Brandi and F. Giammanco, Opt. Lett. 2007

Second-Harmonic Interferometry
Pulsed gas jet

Series 99 Parker pulsed valve



F Brandi and F. Giammanco, Opt. Express **19,** 25479 (2011)

Measurement within single fringe→ high Sensitivity ~ 1 mrad,
Accuracy ~ 1%,
Time resolution ~ 1 μs

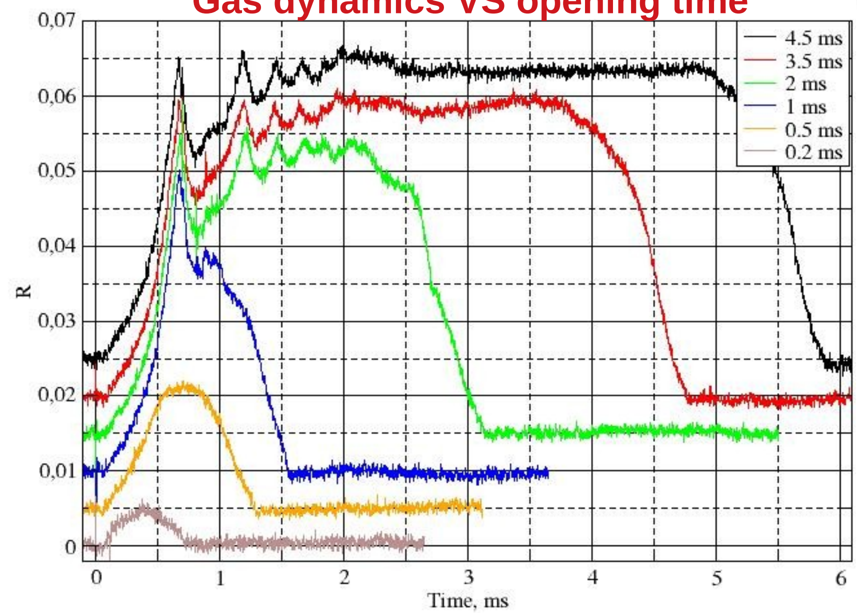
Other application examples:

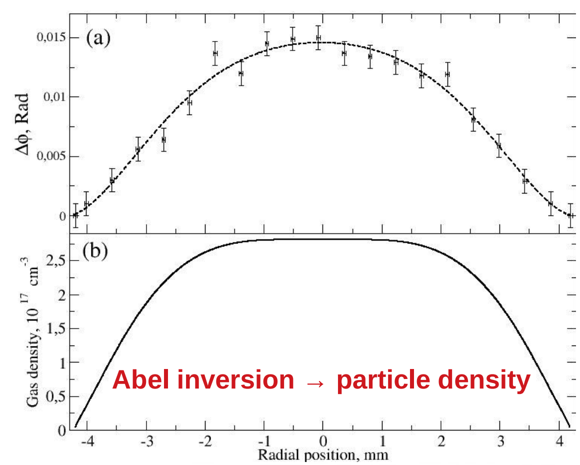
-) **Electron density measurements**
Rev. Sci. Instrum. **80**, 113501 (2009)

-) **Picosecond SHI and THI**
Opt. Lett. **33**, 2071 (2008)

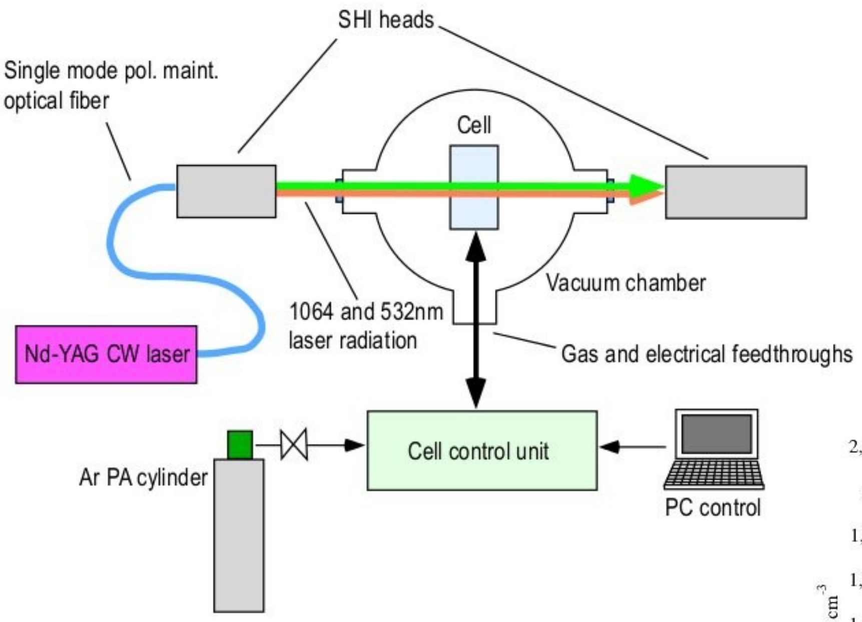
-) **High spatial resolution SHI (60 micron)**
Laser Phys. Lett. **10**, 056003 (2013)

Gas dynamics VS opening time

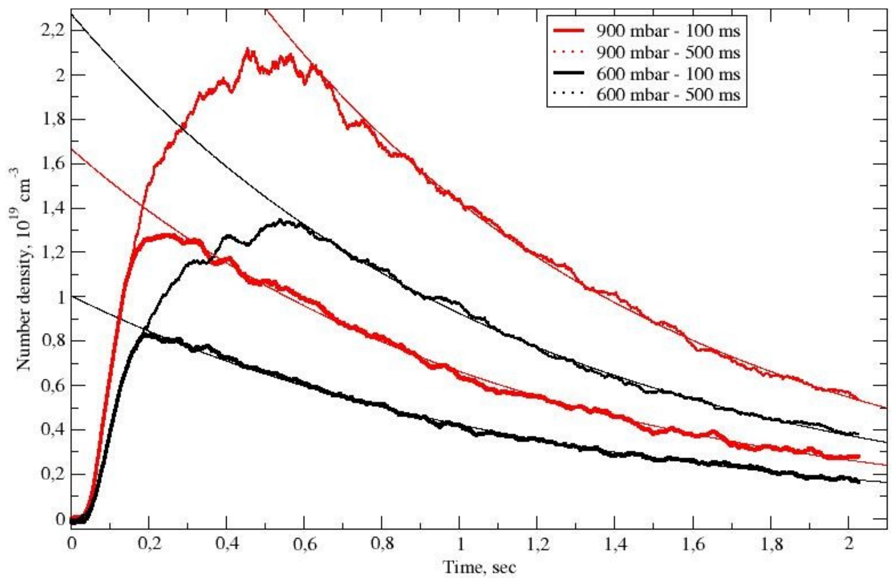




Second-Harmonic Interferometry
Pulsed flowing gas cell



SL-ALC by SourceLAB

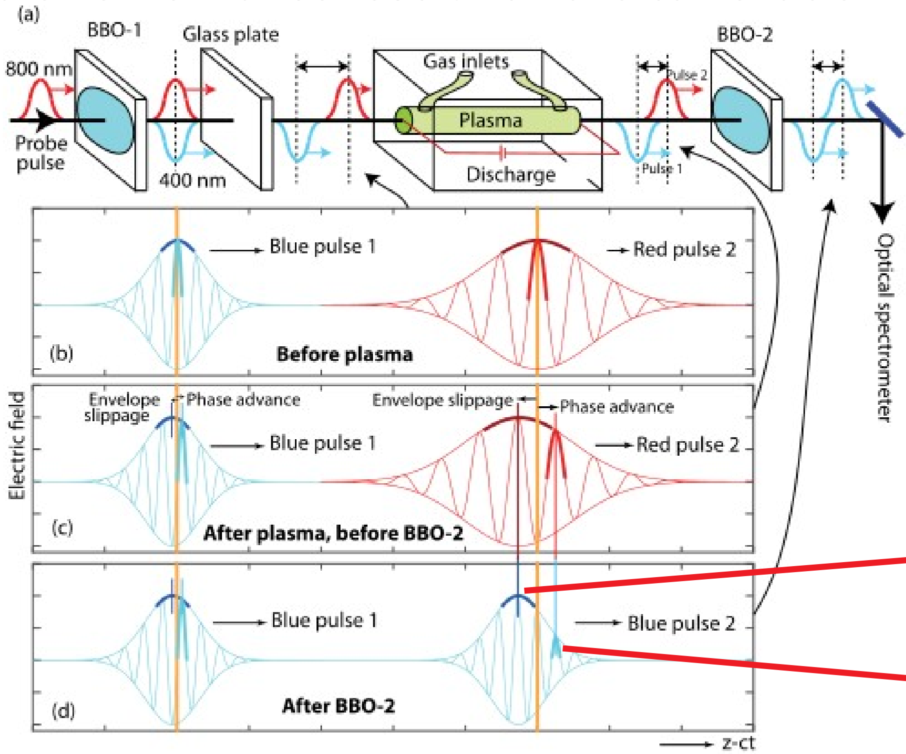


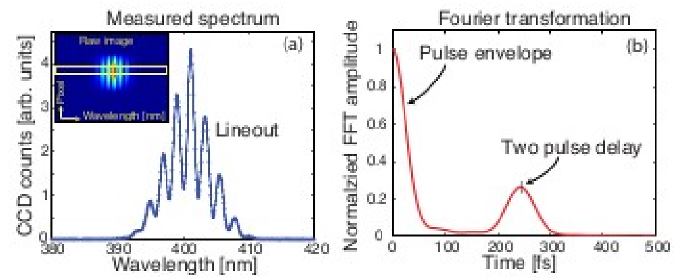
F. Brandi, F. Giammanco, F. Conti, F. Sylla', G. Lambert, and L. A. Gizzi, Rev. Scient. Instrum. **87**, 086103 (2016).
F. Brandi, P. Marsili, F. Giammanco, F. Sylla' and L. A. Gizzi, J. Phys.: Conf. Ser. **1079**, 012006 (2018).

Spectral Domain SHI: Application to capillary discharges

1) **Common-path design overcome the limitation of two-arm spectral domain interferometry**

2) $I(2\omega)=I_1(2\omega)+I_2(2\omega)+[I_1(2\omega)I_2(2\omega)]^{1/2}\cos(\Delta\varphi-2\omega\tau)$ → simultaneous ***delay and phase*** measurement ***enhance resolution*** and can enable ***fringe tracking*** for high density/long plasma





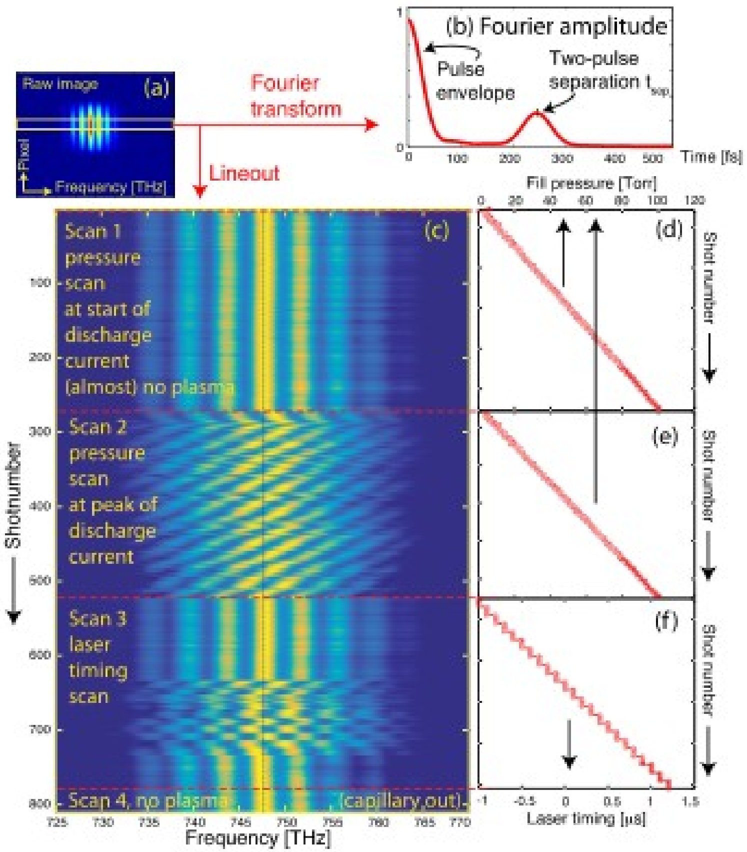
$$V_{phase} * V_{group} = c^2$$

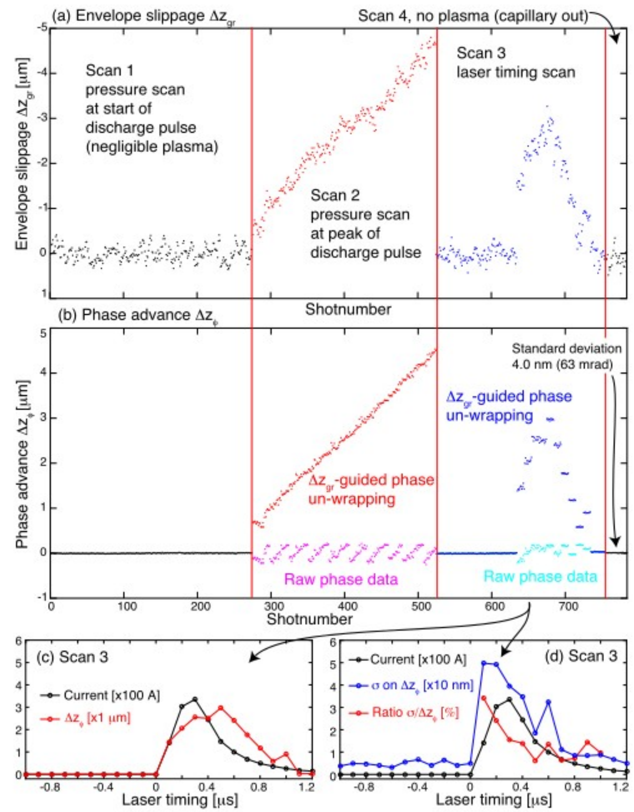
$$\Delta z_{group} = -\,3/2[\omega_p/2\omega]^2 L_p$$

$$\Delta z_{phase} = +\,3/2[\omega_p/2\omega]^2 L_p$$

J van Tilborg, AJ Gonsalves, EH Esarey, CB Schroeder and WP Leemans, Optics Letters 43(12) 2776-2779 (2018)
J van Tilborg, AJ Gonsalves, EH Esarey, CB Schroeder and WP Leemans, Phys. Plasmas 26, 023106 (2019)

Spectral Domain SHI: results





Group delay measurement phase sensitivity: 2.84 rad (< 2π → fringe tracking)

Spectra phase measurement phase sensitivity: 63 mrad

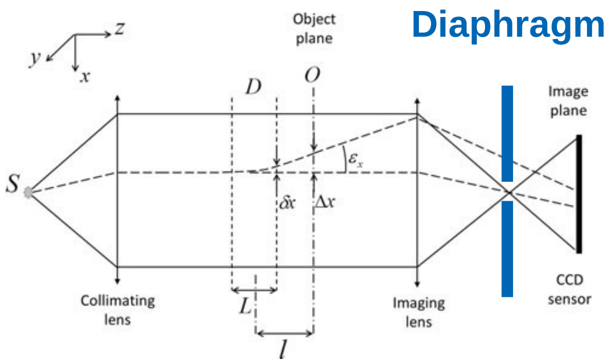
J. van Tilborg, A. J. Gonsalves, E. Esarey, C. B. Schroeder, and W. P. Leemans, Phys. Plasmas 26, 023106 (2019)

Shadowgraphy Imaging

-) sensitive to the **second spatial derivative of n** → mainly **qualitative:**

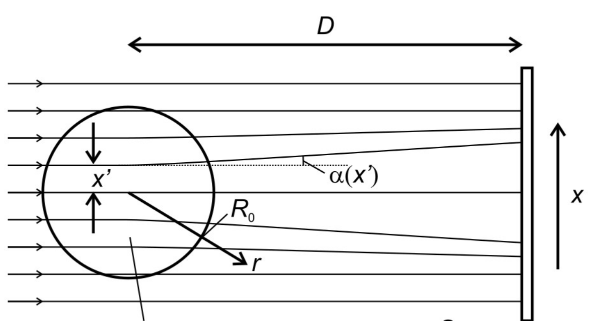
-) some quantitative information - assuming sample geometry and with computational analysis
[PHYSICAL REVIEW E 95, 023306 (2017), MF Kasim, L Ceurvorst, N Ratan, J Sadler, N Chen, A Sävert, R Trines, R Bingham, PN Burrows, MC Kaluza, and P Norreys; J. Phys. D: Appl. Phys. 49 (2016) 155204, A Boné, N Lemos, G Figueira and JM Dias]

-) easy to implement in **combination with other diagnostics**, e.g., interferometry



Imaging design

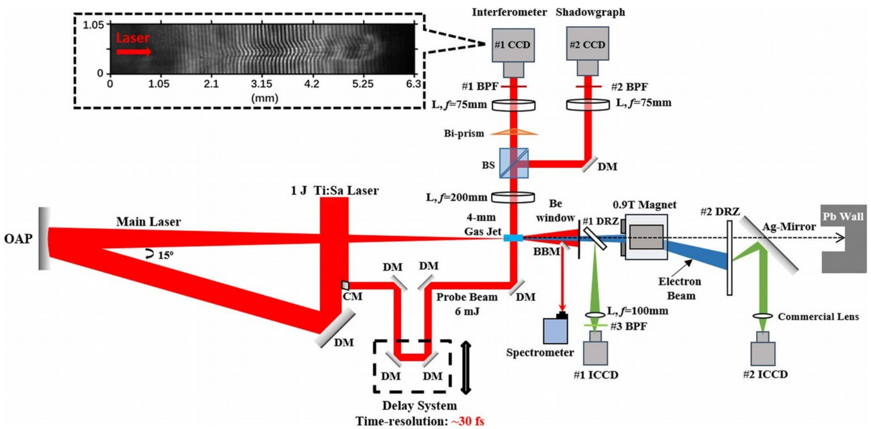
C. Mauger, L. Mees, M. Michard, A. Azouzi. S. Valette, Exp Fluids (2012) 53, 1895

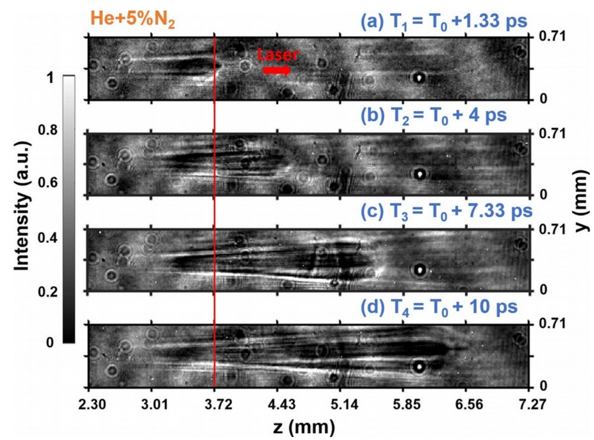


Straight through shadowgraphy

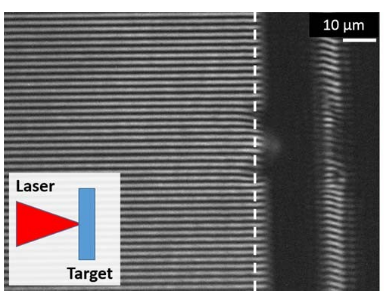
R. Ono, Y. Teramoto and T. Oda, J. Phys. D: Appl. Phys. 43 (2010) 345203

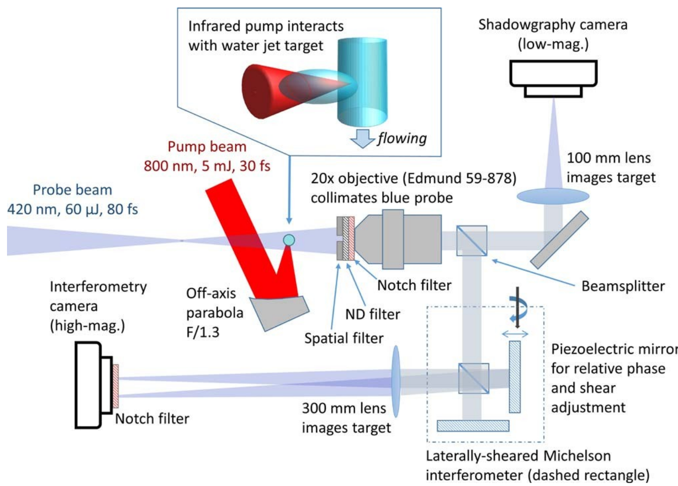
Shadowgraphy measurements

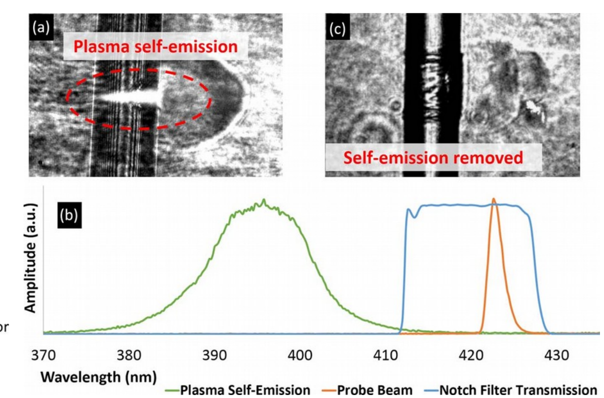




S Li, Q Zhao, N A M Hafz, S Weng, K Gao, M Mirzaie, G Li, Q Ain and J Zhang, Plasma Phys. Control. Fusion 60 085020 2018







S. Feister, J. A. Nees, J. T. Morrison, K. D. Frische, C. Orban, E. A. Chowdhury, and W. M. Roquemore, Rev. Scient. Instrum. 85, 11D602 (2014)

Stark broadening in Hydrogen

Origin: Broadening of the emission lines due to the effective electric field:

$$N_e = C(N_e,T)\ \Delta\lambda^{3/2}$$

$C(N_e,T)$ is a slowly varying function of N_e and T, and $\Delta\lambda$= FWHM of the emission line (e.g., H_α at 656.3 nm, and H_β at 486.1 nm)

[Griem, H.R. Spectral Line Boradening by Plasmas; Academic Press: Cambridge, MA, USA, 1974]

Examples (T~ few eV)

$$N_e = 10^{16}\ cm^{-3} \rightarrow \Delta\lambda(H_\beta) \sim 1.0\ nm$$

$$N_e = 10^{17}\ cm^{-3} \rightarrow \Delta\lambda(H_\beta) \sim 4.8\ nm$$

NOTES:

1) avoid spurious lines from contaminants (like oxygen, silicon, aluminum, e.g., from ablated capillary material)

2) assume negligible Doppler broadening, e.g., in atomic hydrogen:

$$\Delta\lambda_{doppler} = 7.13x10^{-7}\ T^{1/2}\ \lambda,$$ where T is in Kelvin (1 eV = 11604 K)

H_α, λ=656.3 nm, T = 4 eV → $\Delta\lambda$ = 0.10 nm

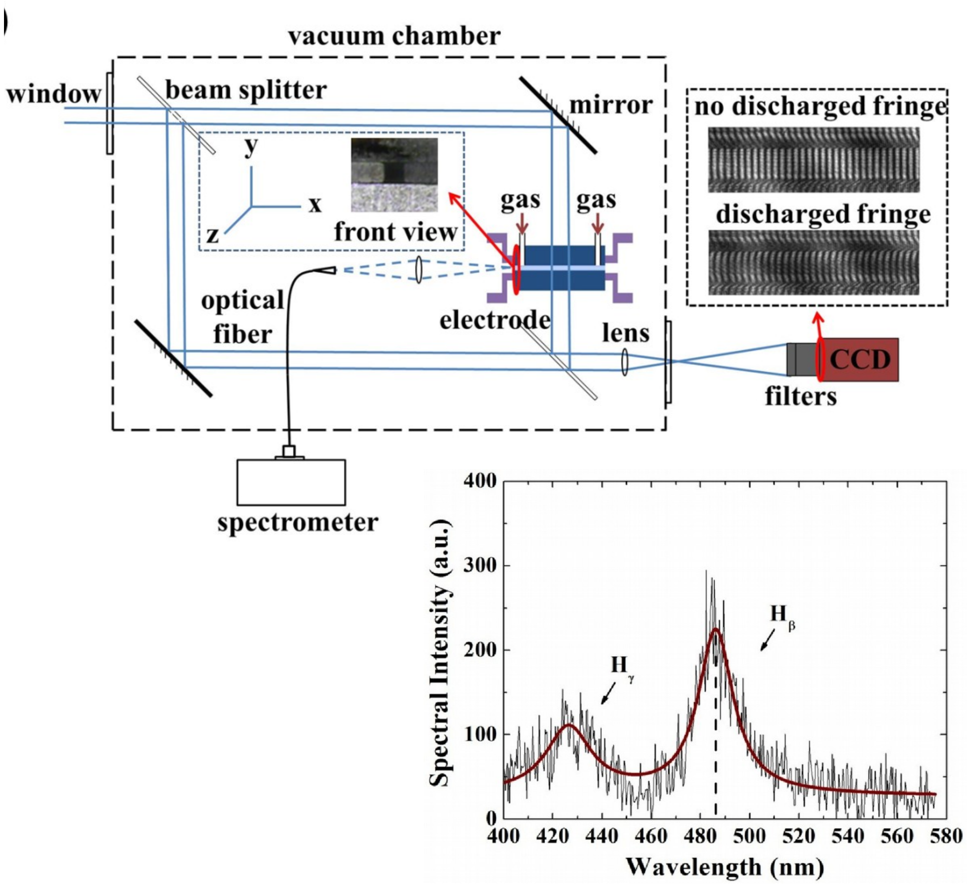
H_β, λ=486.1 nm, T = 4 eV → $\Delta\lambda$ = 0.07 nm

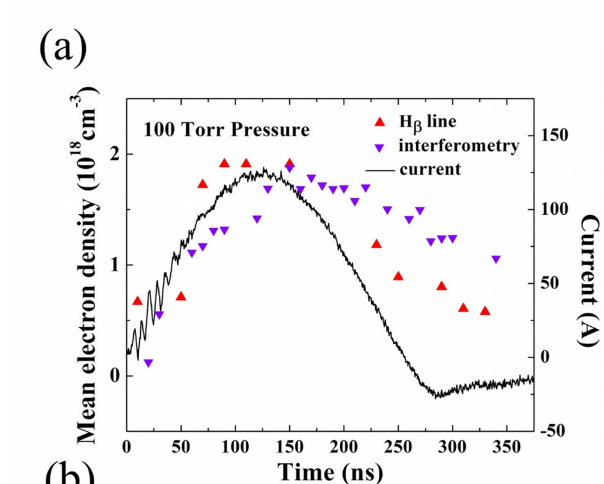
Merits:

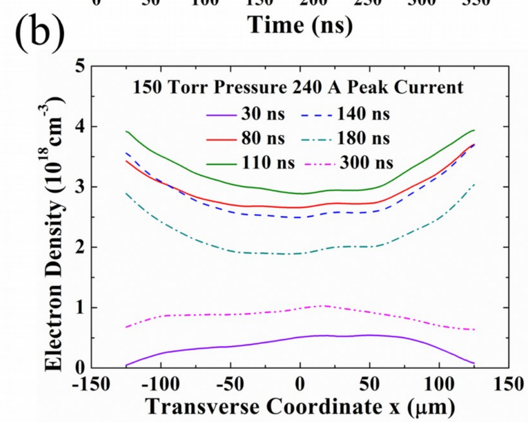
can be implemented without a through line of sight and gives an estimate of the local density

Stark broadening measurements

Square Discharge capillary: Stark broadening H_β VS Interferometry



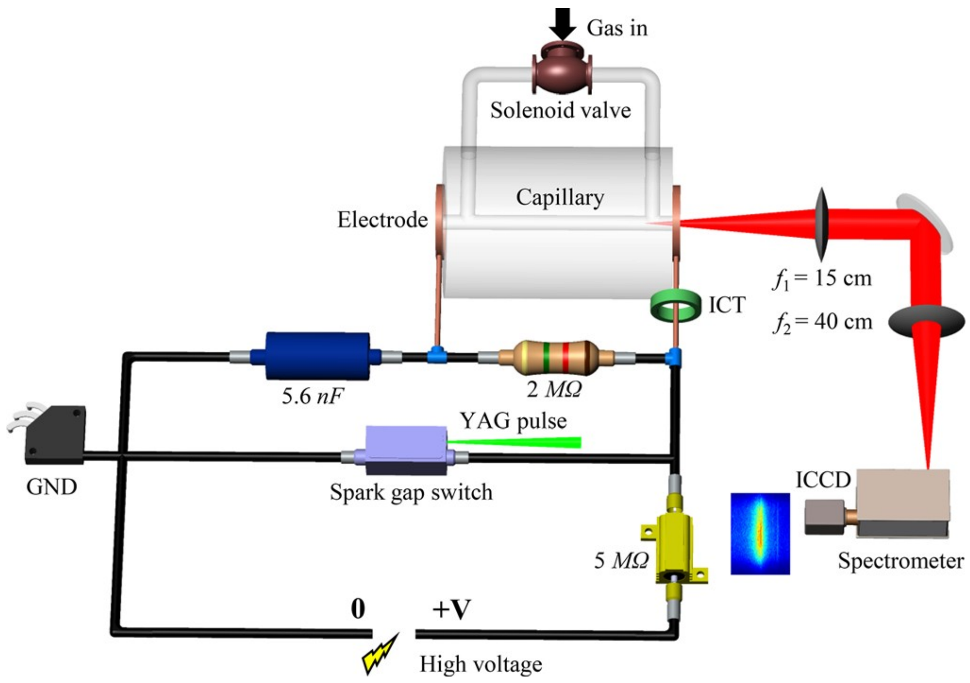


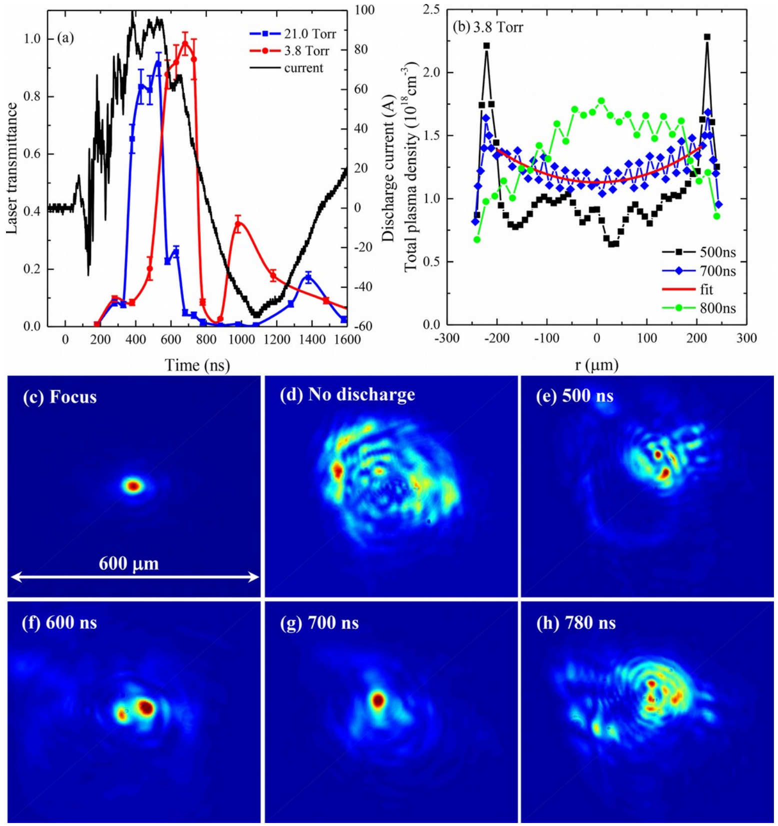


D.G. Jang, M.S. Kim, I.H. Nam, H. Jang and H. Suk, J. Instrum. 2012

Stark broadening measurements

Hybrid discharge capillaries: up to 60-mm-long with a diameter of 500 μm, made of polymethyl methacrylate (PMMA) - H_α

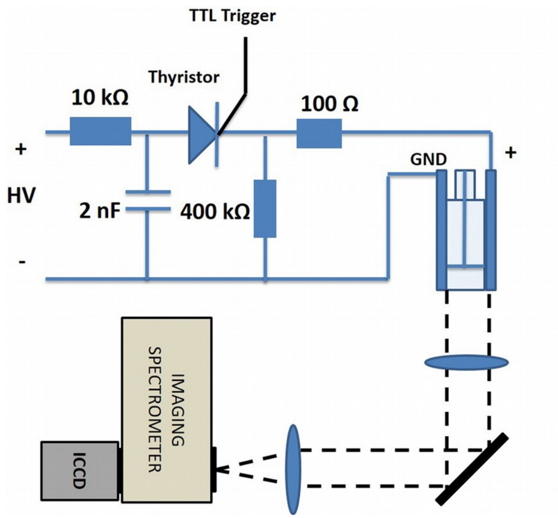


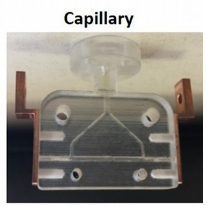


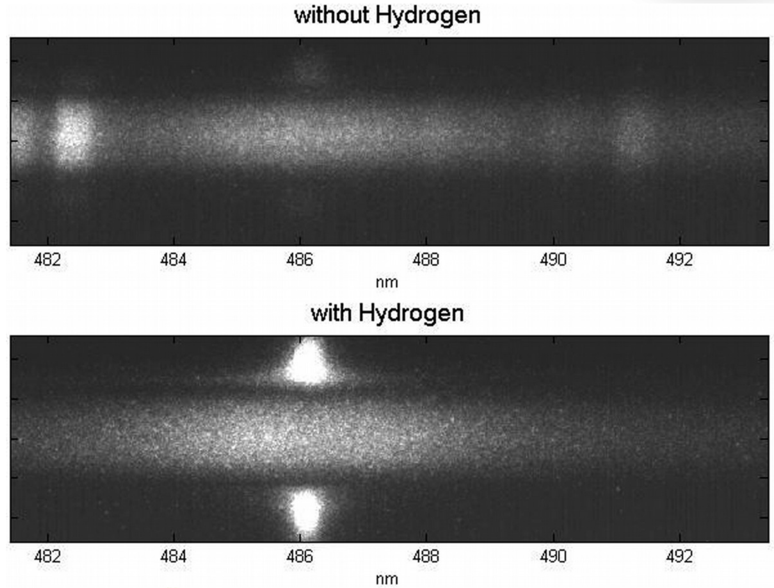
Z Qin, W Li, J Liu, J Liu, C Yu, W. Wang, R Qi, Z. Zhang, M Fang, K Feng, Y Wu, L Ke, Y Chen, C Wang, R Li and Z Xu, Phys. Plasmas 25, 073102 (2018)

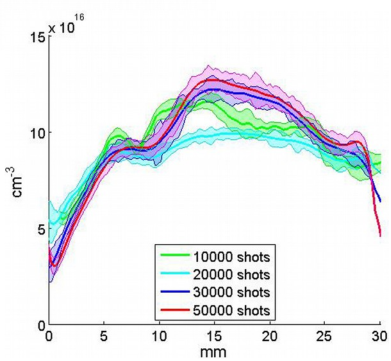
Stark broadening measurements

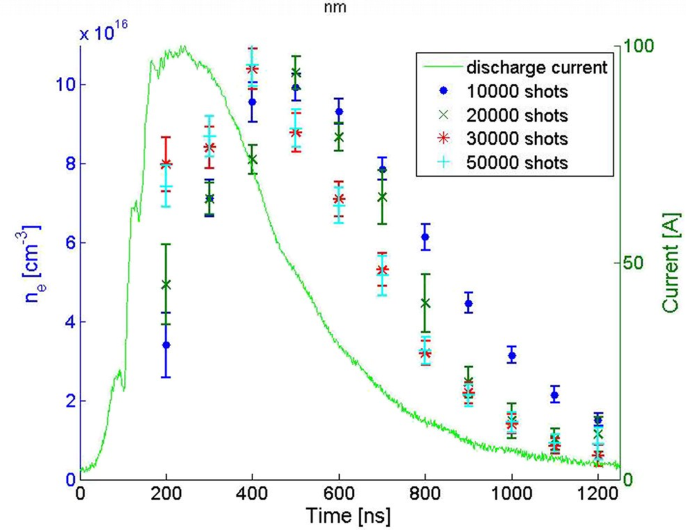
3D printed hybrid discharge capillaries - H_α











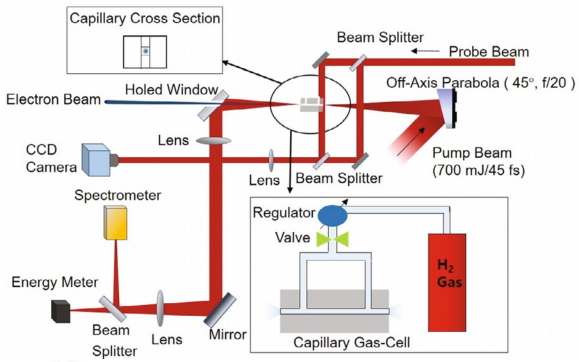
F. Filippi, M. P. Anania, A. Biagioni, E. Chiadroni, A. Cianchi, Y. Ferber, M. Ferrario, and A. Zigler, REV. SCIENT. INSTRUM. 89, 083502 (2018)

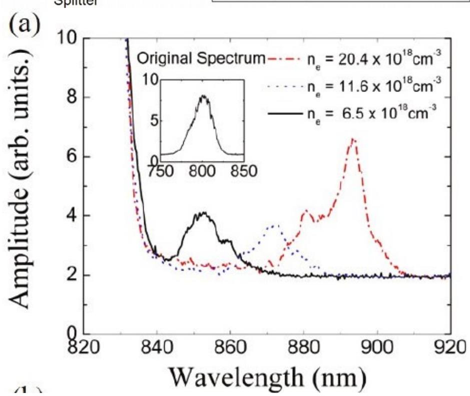
Raman scattering measurements examples

Measurements of the Raman scattering of the laser photons by the plasma:

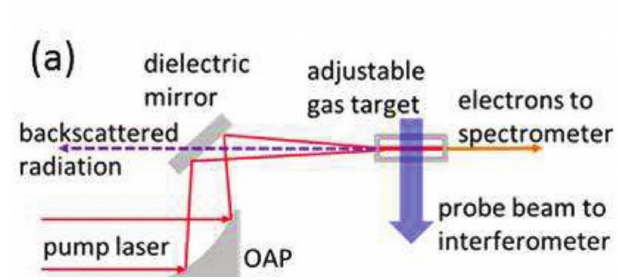
$$\omega_{Raman} = \omega_{laser} - \omega_P \rightarrow \mathbf{N_e}[10^{19}cm^{-3}] = 1.11\times10^{8}\,(1/\lambda_{laser} - 1/\lambda_{Raman})^2$$

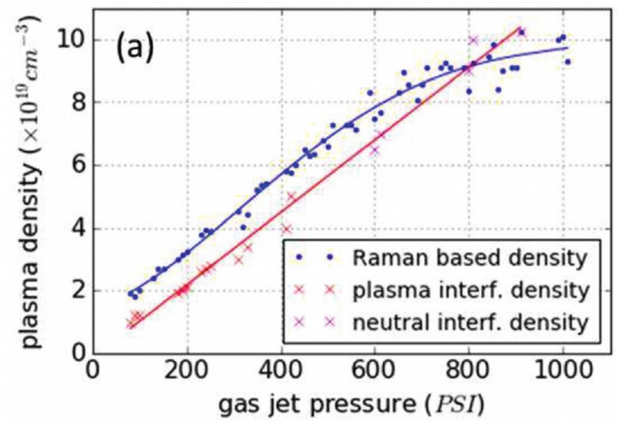
Forward scattering in a capillary





Backward scattering in a gas jet





Need to resolve Raman scattering radiation
→ relatively high $\mathbf{N_e}$ (> 10^{18} cm^{-3})

Linear SRS model break-down at high intensity and density

I. Nam, M. Kim, S.-w. Lee, D. Jang and H. Suk
J. Korean Phys. Soc. **69**, 957, 2016

D. Kaganovich, B. Hafizi, J. P. Palastro, A. Ting,
M. H. Helle, Y.-H. Chen, T. G. Jones, and D. F. Gordon
Phys. Plasmas **23**, 123104 (2016)

Conclusions

-) there is a **plethora of non invasive optical-based methodologies** for density measurements in plasma and neutral gas;

-) **Interferometric techniques** give a quantitative evaluation of the **line integrated density** (free electron and neutral gas), require a through line of sight; **common path quasi-common path and TAI folded designs** are the most suitable to be implemented in a **user oriented accelerator facility**;

-) Shadowgraphy can be implemented **in parallel with Interferometry**, providing an easy way to monitor the laser produced plasma.

-) **Optical emission spectroscopy** does not require a through line of sight and provide information on the actual **local electron density value**;

-) Finally, a portfolio of different methodologies do exist where to look about optical plasma density diagnostics tools when designing new facilities during Alignment, Tuning and Operation of plasma based acceleration stages, with some R&D required (e.g., ultra-fast time domain SHI)

Acknowledgments

WP3
lead by B. Cros, Z. Najmudin