Development of promising techniques for a new generation of plasma diagnostics

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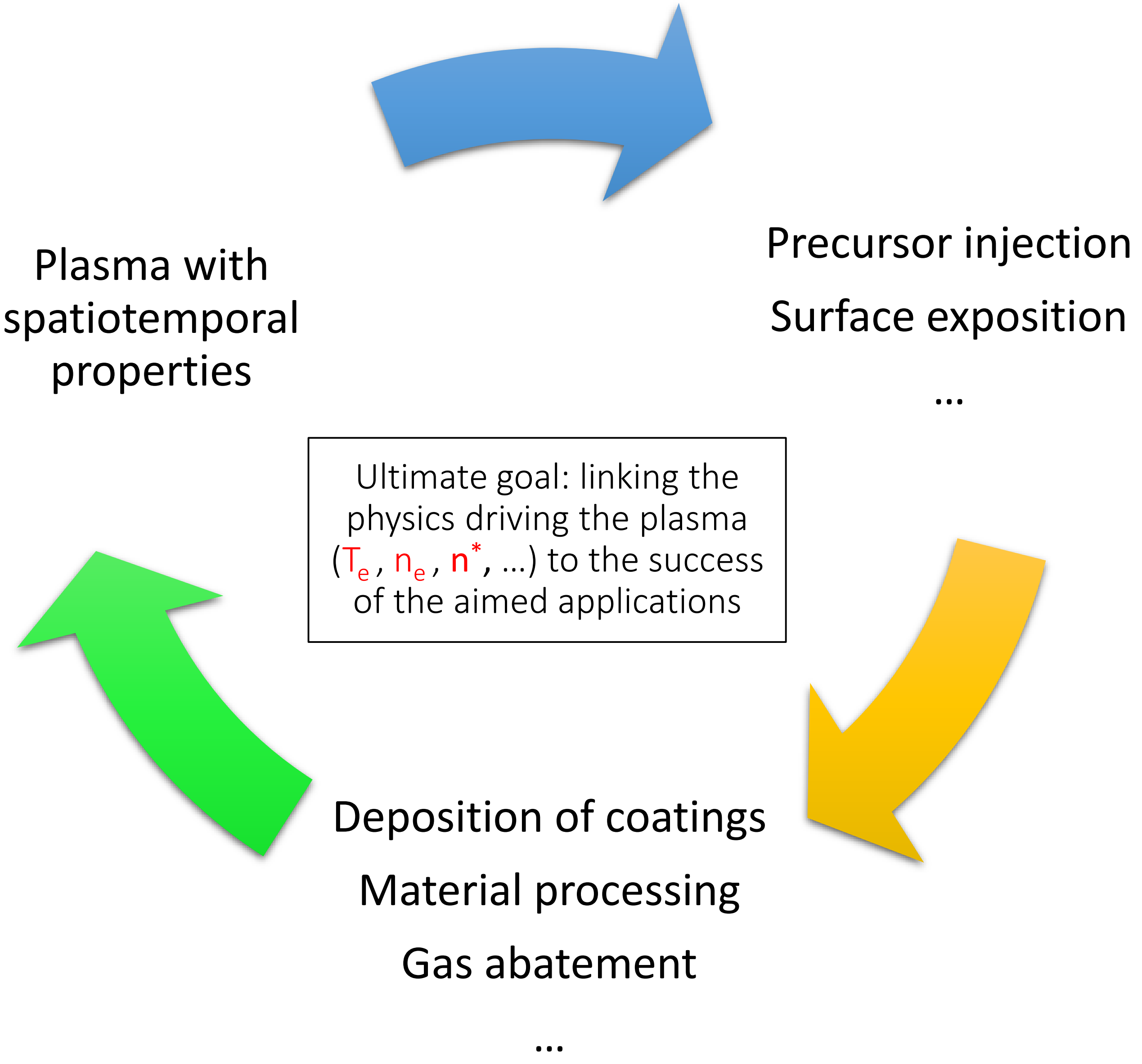
Laura-Isabelle Dion-Bertrand,
Sébastien Blais-Ouellette

Photon etc
A spectrum of solutions

Hubert Jean-Ruel

LightMachinery
Excellence in Lasers and Optics

Motivations



Popular diagnostics:

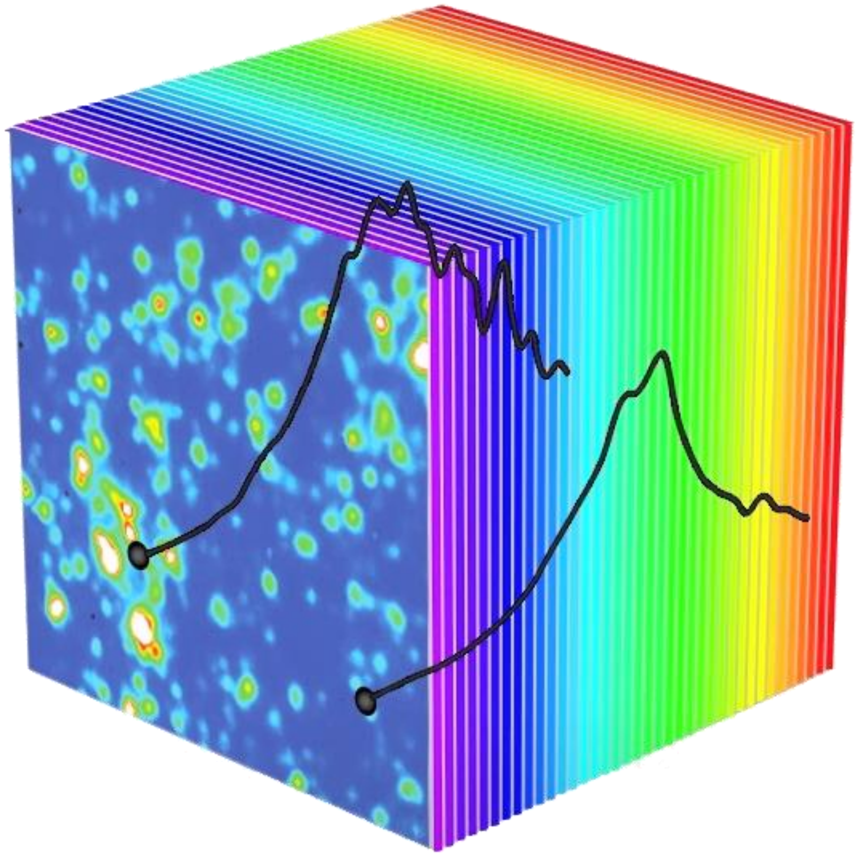
- Probes (Langmuir, thermal…)
- Optical emission/absorption spectroscopy
- Laser diagnostics (LIF, Thomson scattering…)
- Mass spectrometry
- Interferometry
- …

Any other nice technologies out there..?

Hyperspectral imaging

Hyperspectral imaging

Already popular in: Raman imaging, cellular imaging , photovoltaic characterization



Each camera pixel

=

spectrum

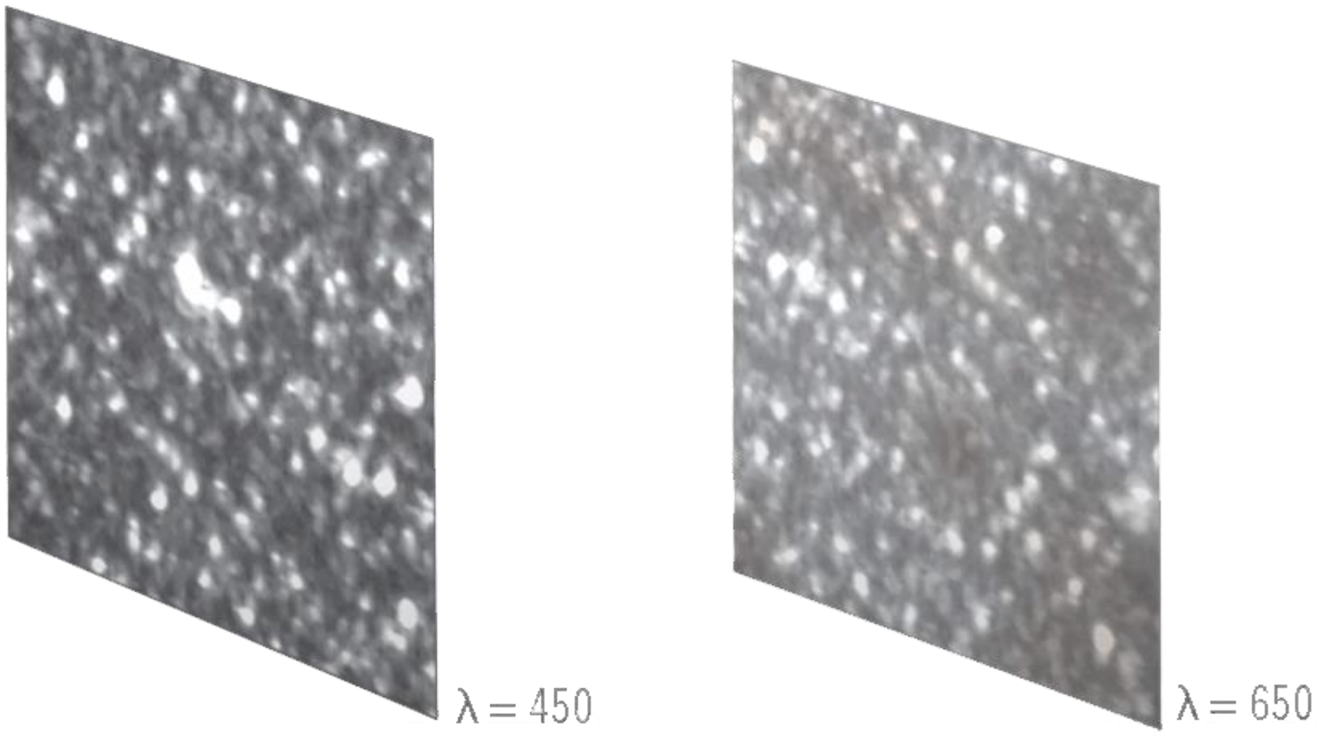
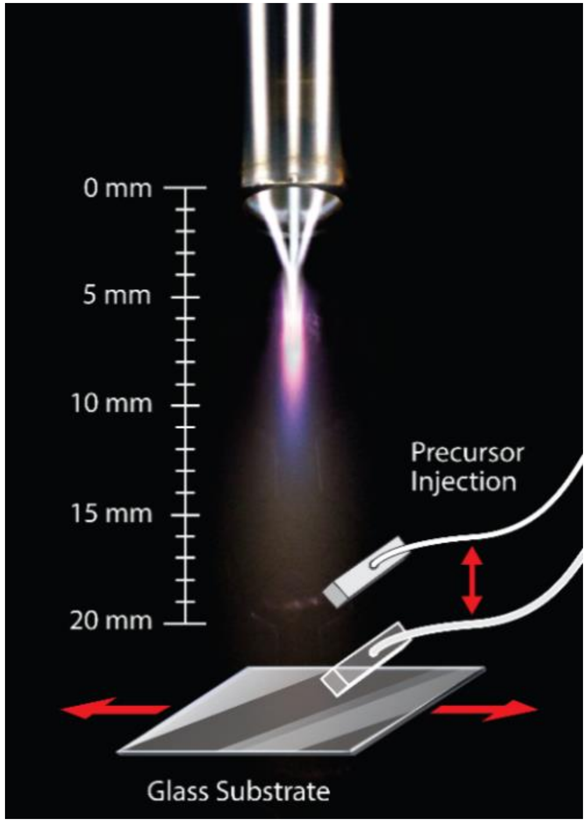


Image for each wavelength!

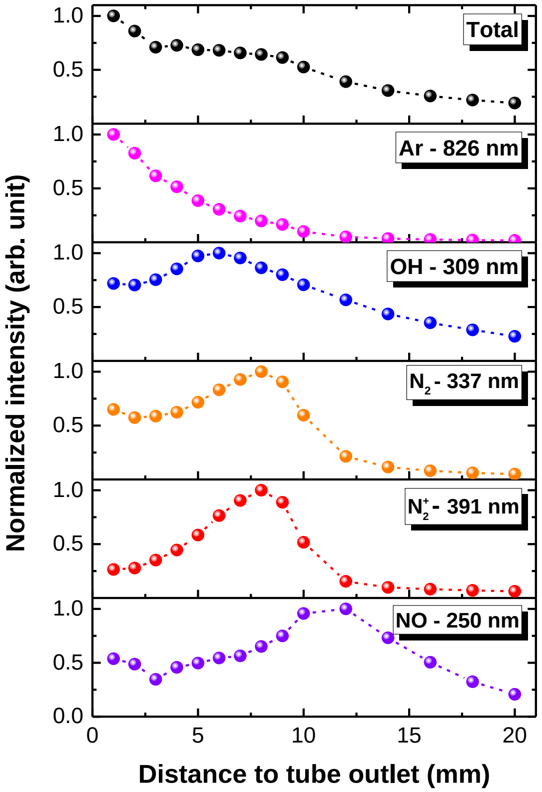
Like having 1000+ filters with a much narrower bandpass

Hyperspectral imaging

Why is this awesome?

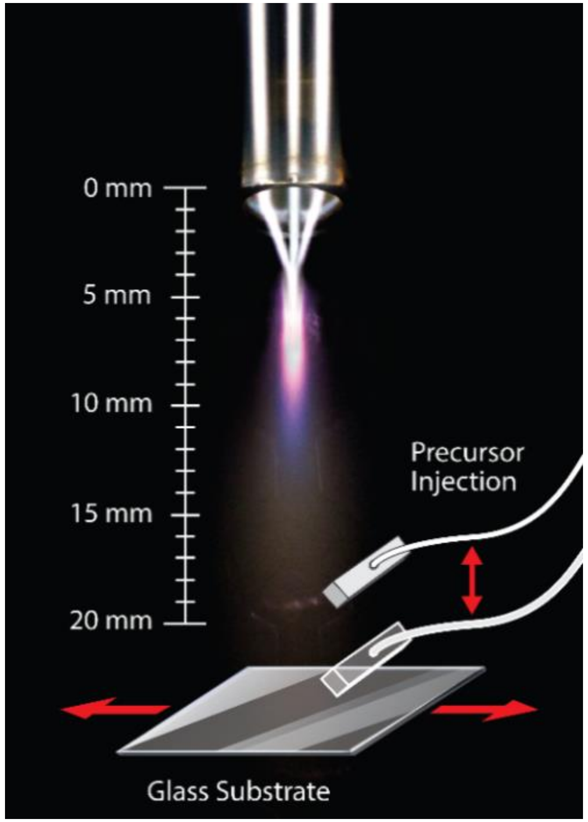


A. Durocher-Jean, I. R. Durán, S. Asadollahi, G. Laroche, and L. Stafford, Plasma Process. Polym. e1900229 (2020)



Hyperspectral imaging

Why is this awesome?



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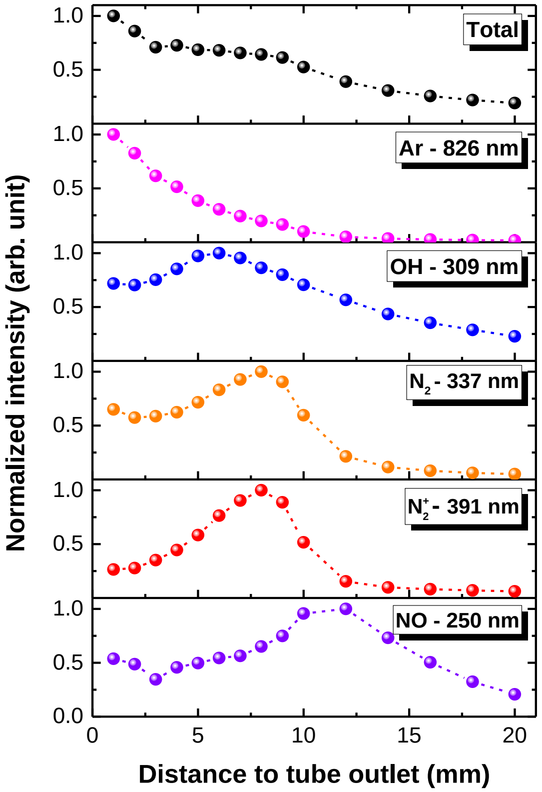
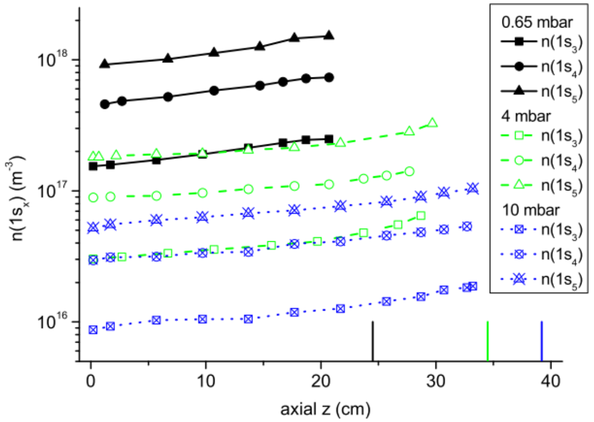
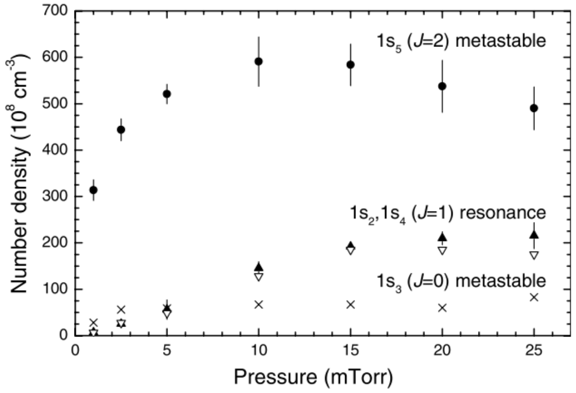
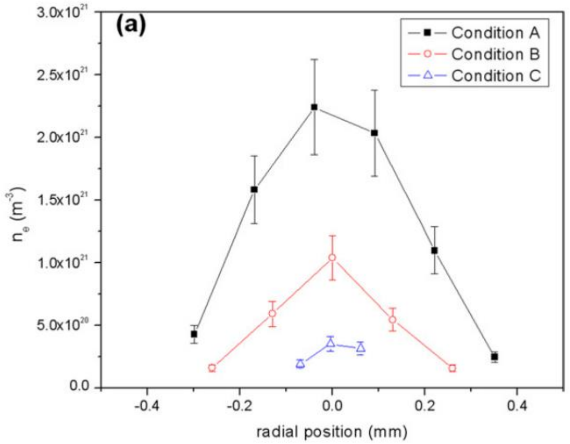
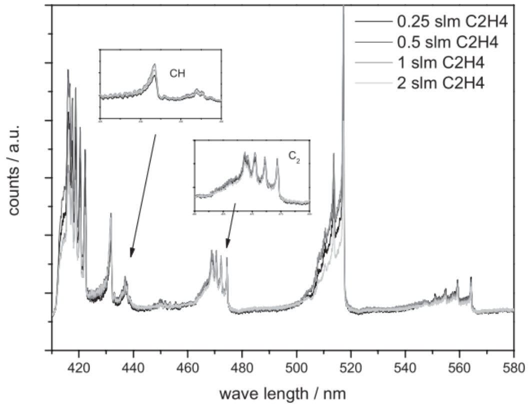








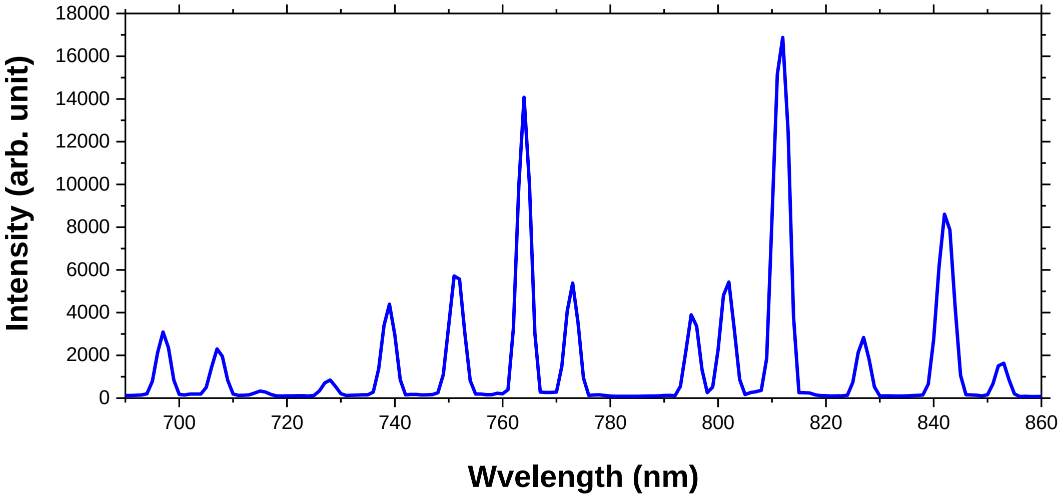


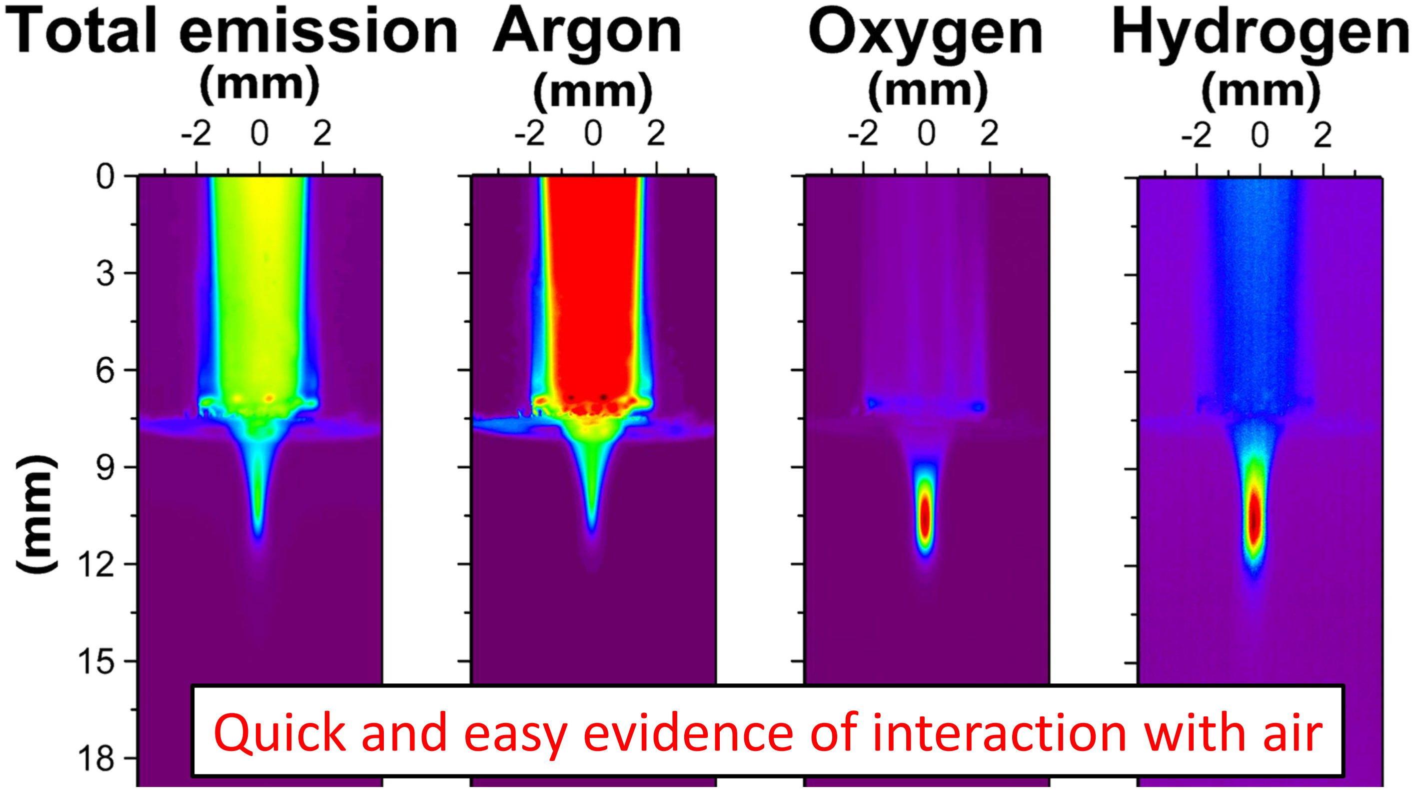
Just how representative of the whole plasma are these measurements?

Hyperspectral imaging

Atmospheric pressure microwave plasma jet

~4 ms integration time
400 - 900 nm
=
Hypercube in <2min

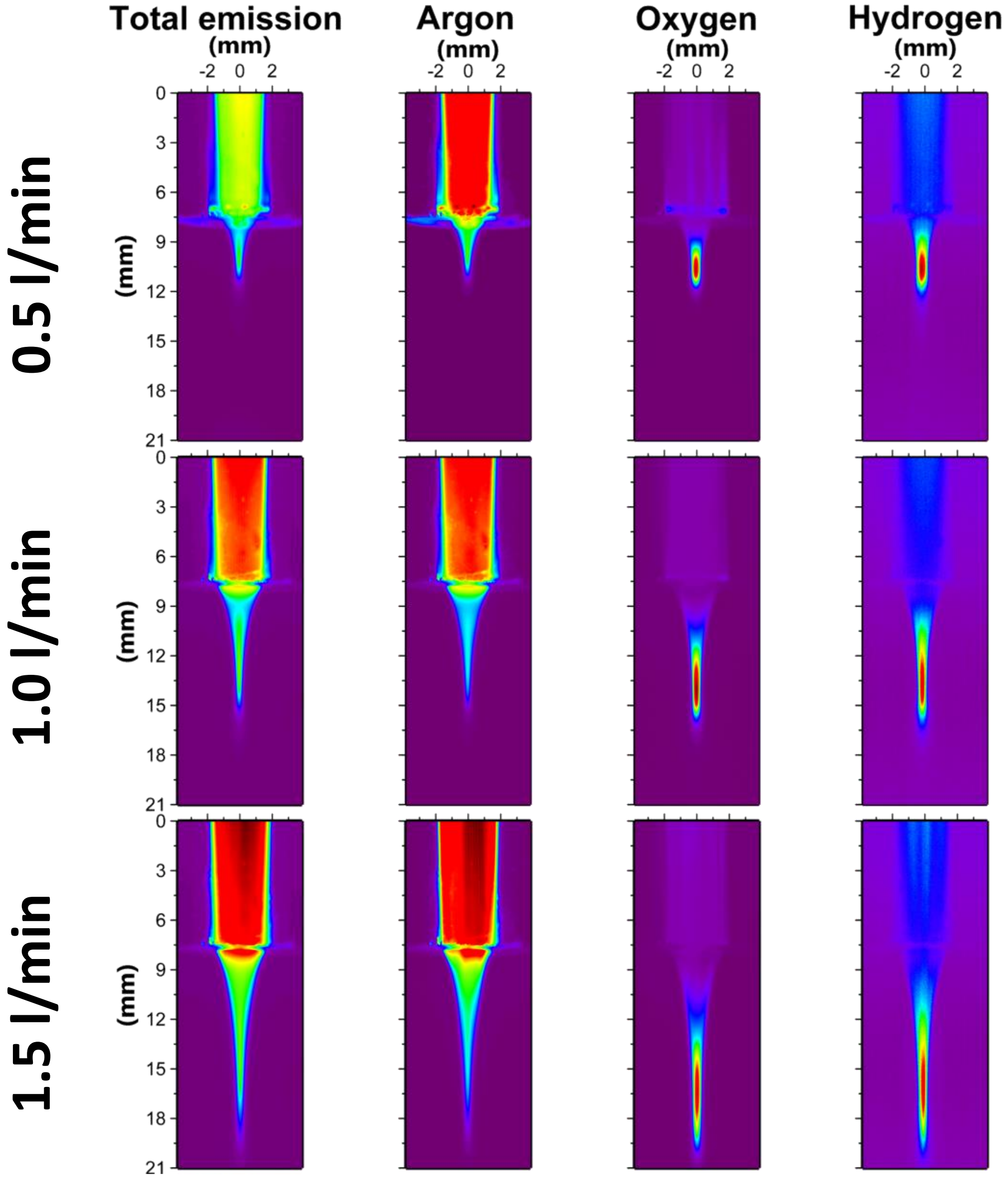




Quick and easy evidence of interaction with air

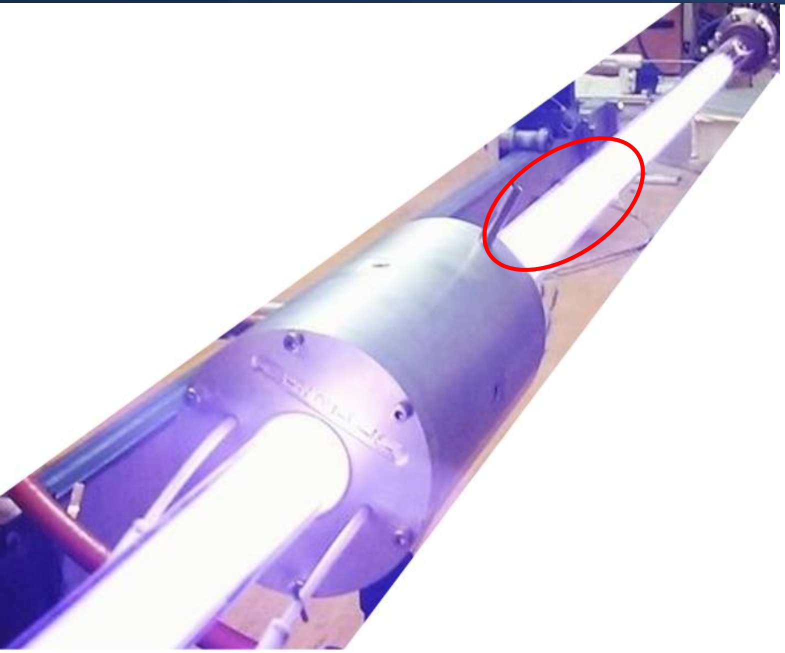
Hyperspectral imaging

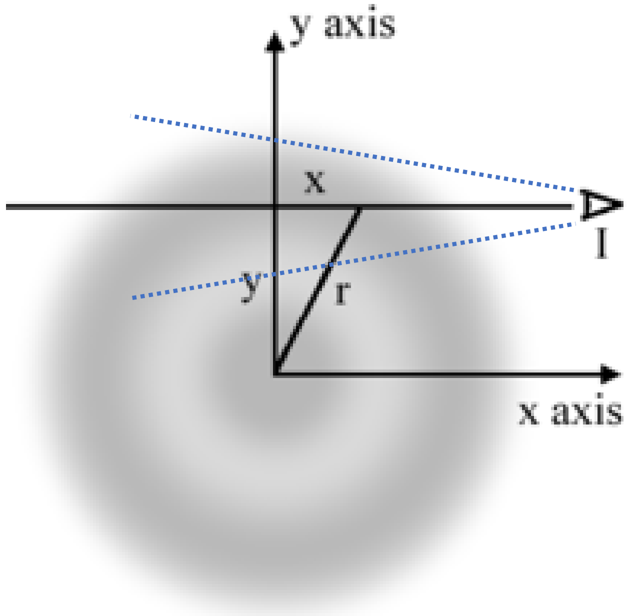
Atmospheric pressure
microwave plasma jet



Influence of the Ar flow rate on the mixing with air

Plasma tomography

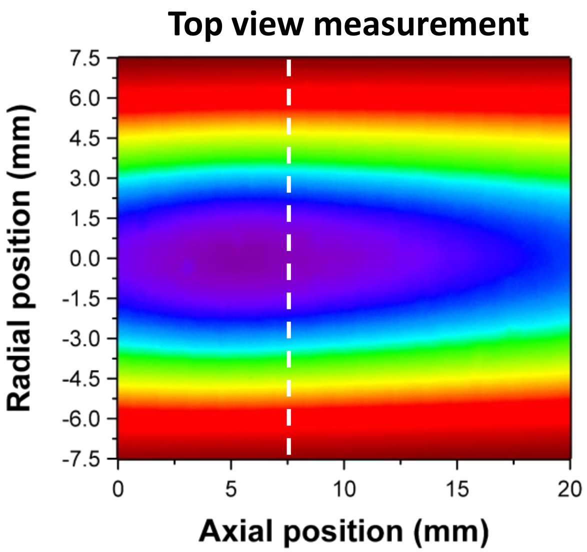


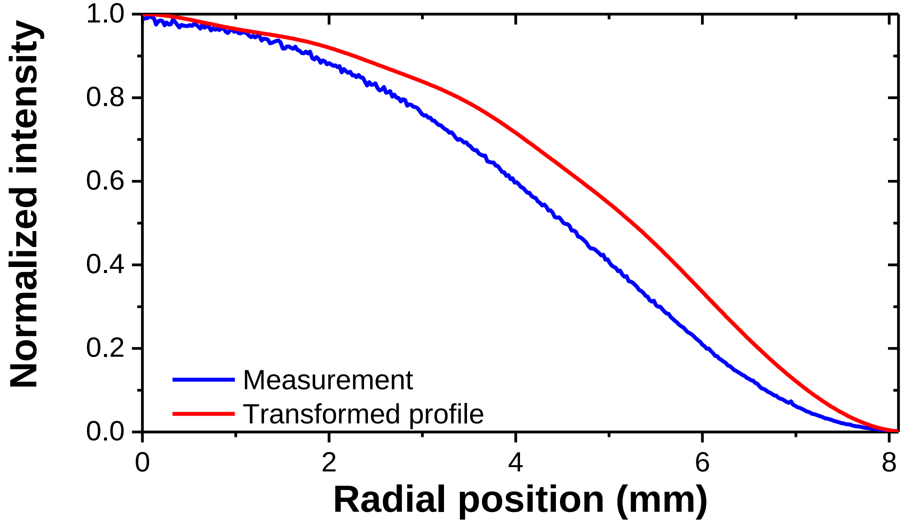


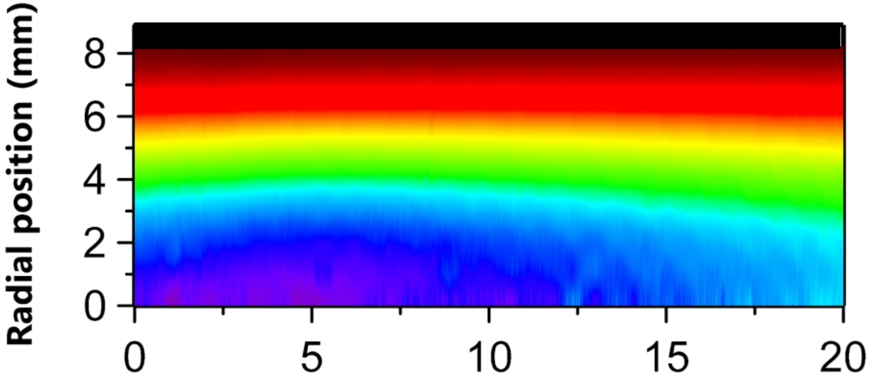
The Abel transform

$$F(y) = 2\int_y^\infty \frac{f(r)r}{\sqrt{r^2 - y^2}}dr \quad \Longleftrightarrow \quad f(r) = -\frac{1}{\pi}\int_r^\infty \frac{dF}{dy}\frac{dy}{\sqrt{y^2 - r^2}}$$

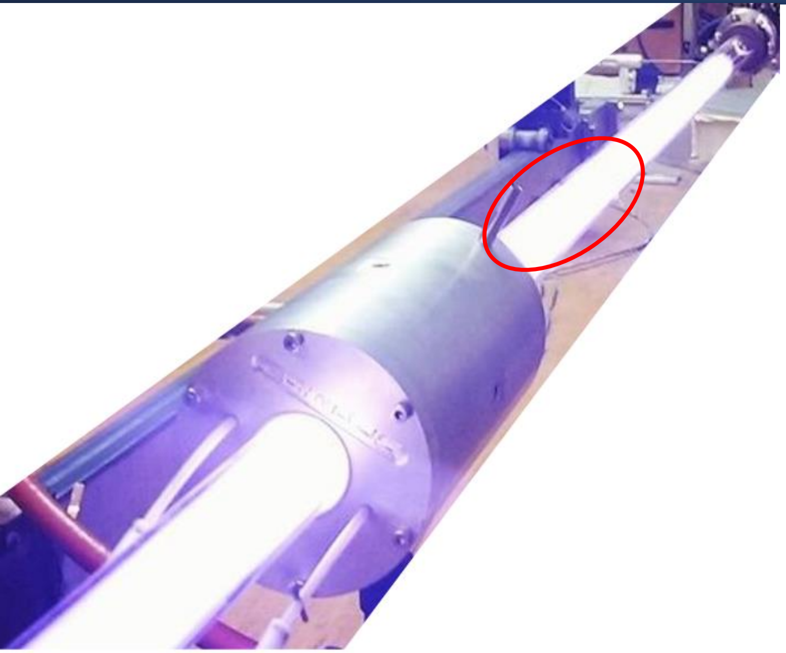
Better spatial resolution = more accurate transform

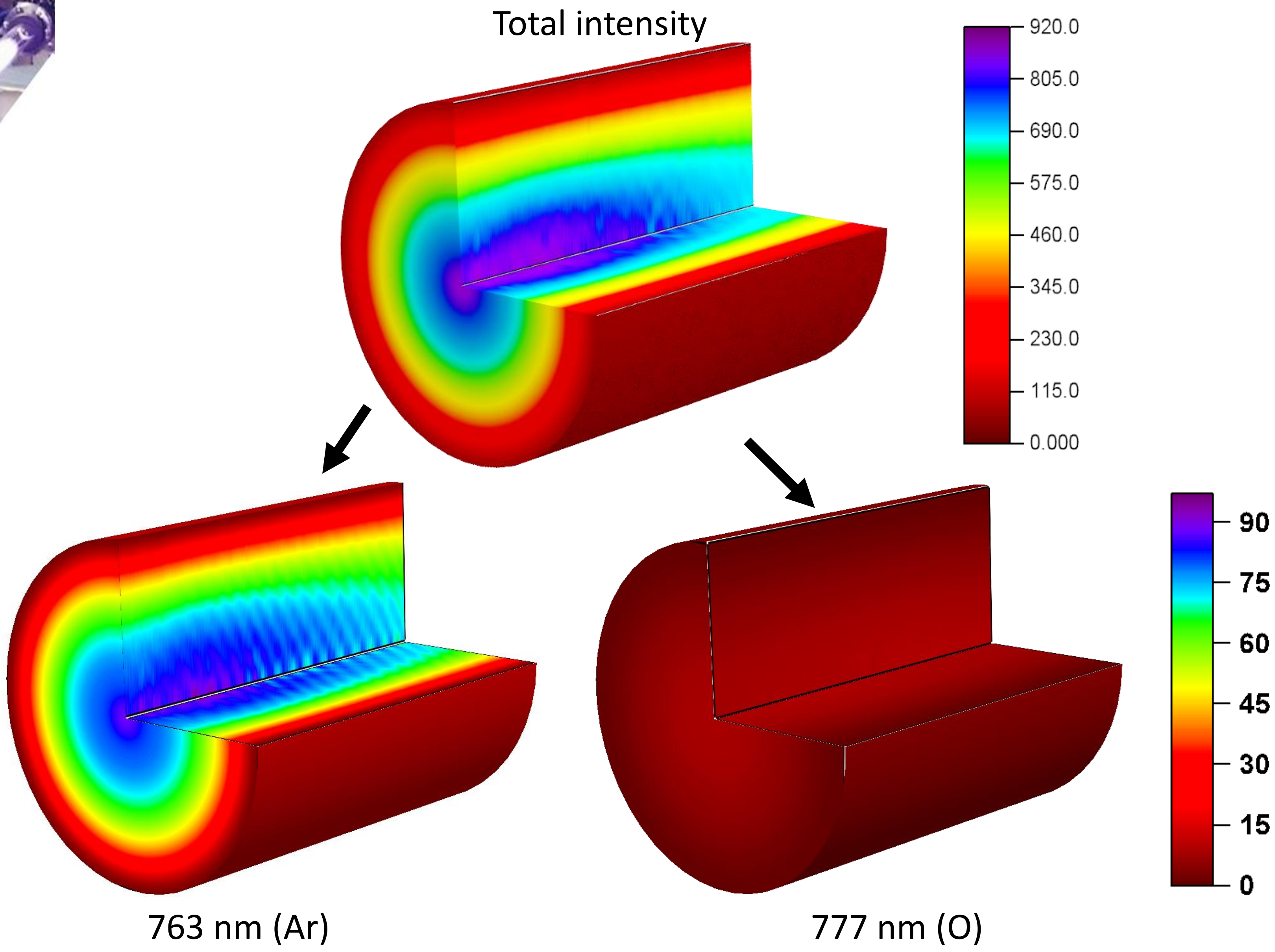




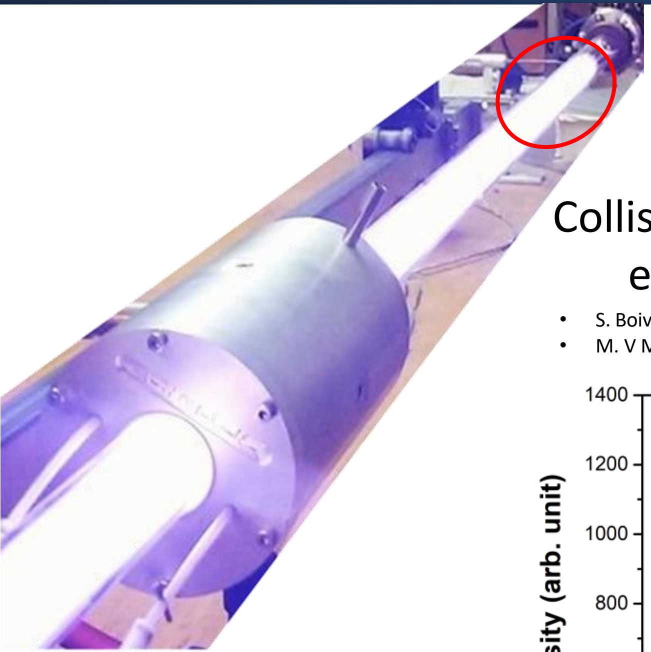


Plasma tomography



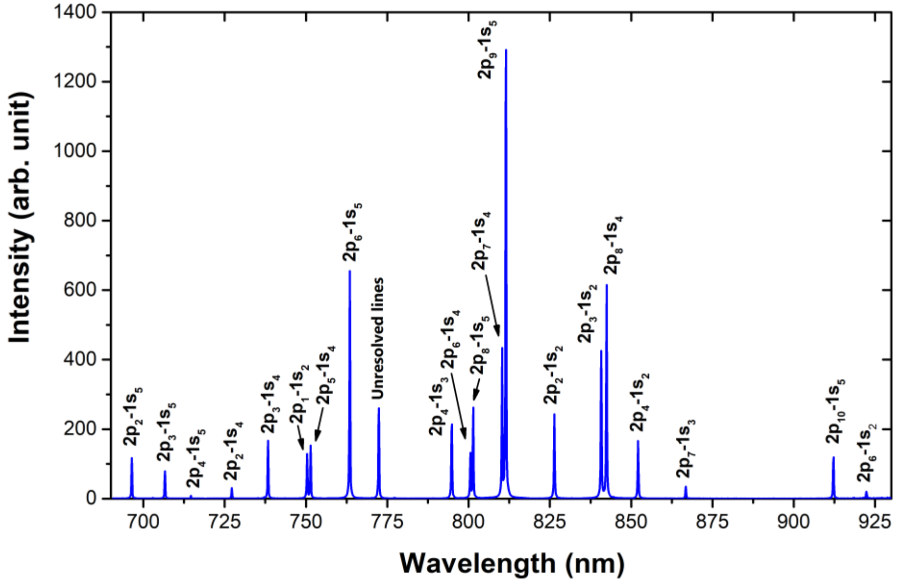


Electron temperature mapping



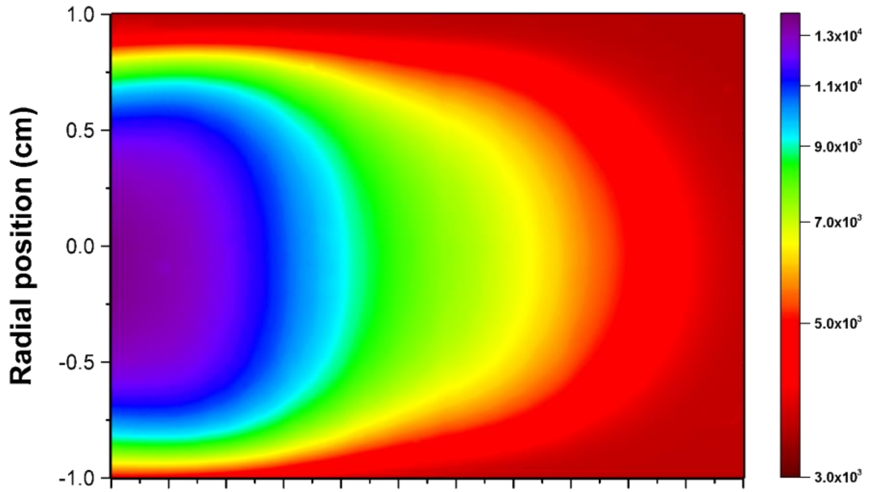
Collisional-radiative model paired with optical emission spectroscopy measurements

- S. Boivin, X. Glad, J. P. Bœuf, and L. Stafford, Plasma Sources Sci. Technol. **27**, 095011 (2018)
- M. V Malyshev and V. M. Donnelly, Phys. Rev. E **60**, 6016 (1999)

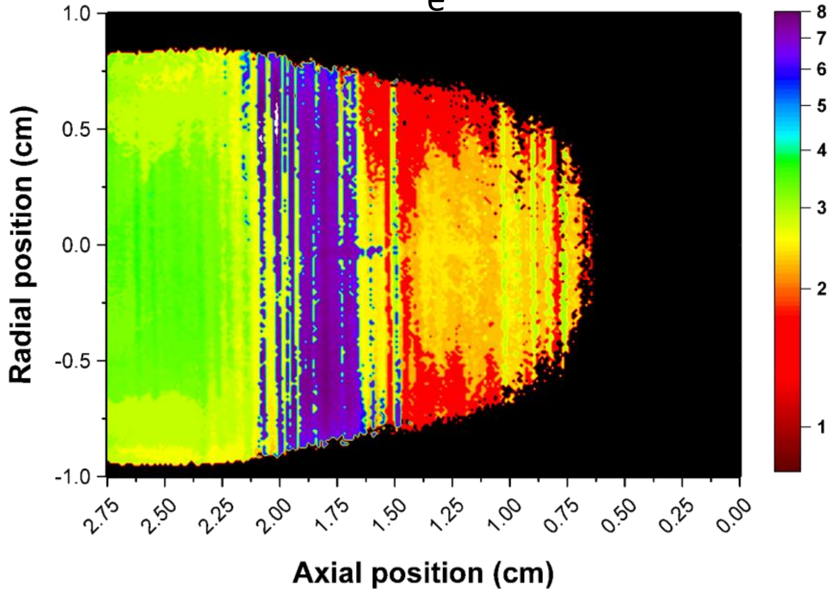


$$I_\lambda = A_{ij} n_{2p_i} = A_{ij} \frac{n_e\left(k_1(T_e)\, n_g + \sum_j k_j(T_e)\, n_{1s_j}\right) + \sum_{k\neq i} k_k\, n_g\, n_{2p_k}}{\sum_j A_{ij}\theta_{ij} + k_2\, n_g + \sum_{k\neq i} k_k\, n_g}$$

Total light intensity

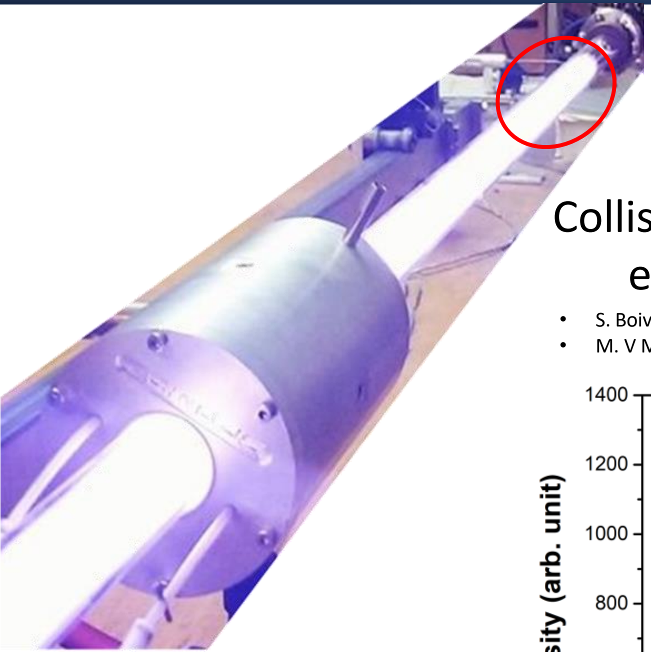


T_e



Complete mapping of T_e along the column end

Electron temperature mapping



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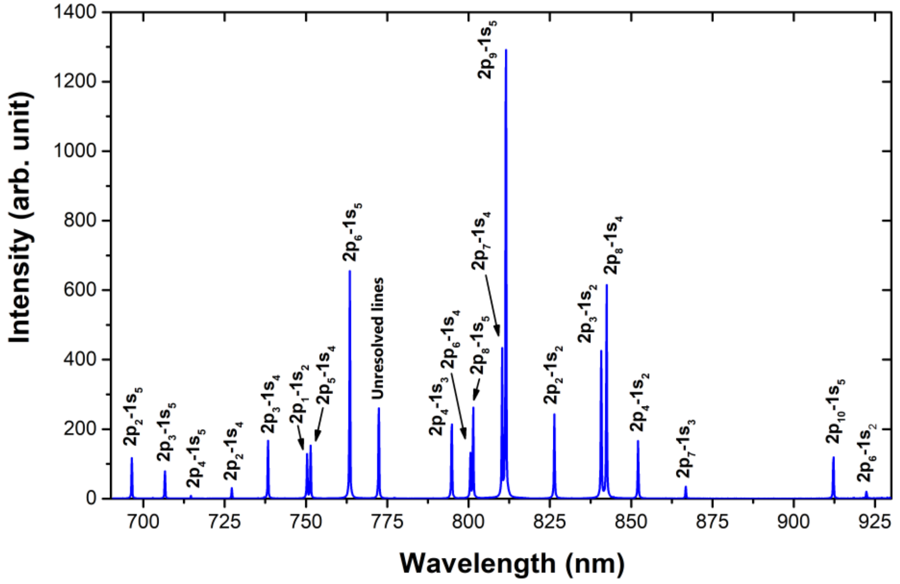
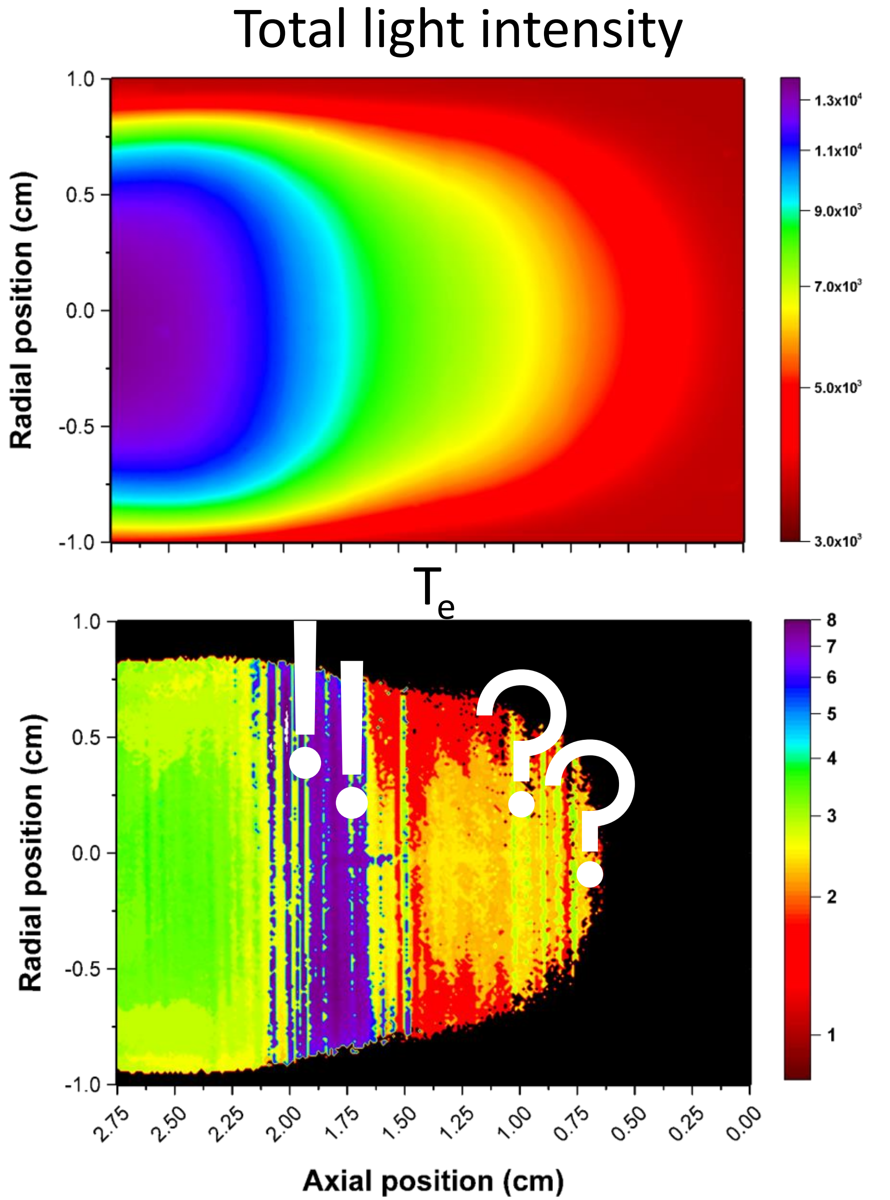


$$I_\lambda = A_{ij} n_{2p_i} = A_{ij} \frac{n_e \left(k_1 (T_e)\, n_g + \sum_j k_j (T_e)\, n_{1s_j} \right) + \sum_{k \neq i} k_k\, n_g\, n_{2p_k}}{\sum_j A_{ij} \theta_{ij} + k_2\, n_g + \sum_{k \neq i} k_k\, n_g}$$

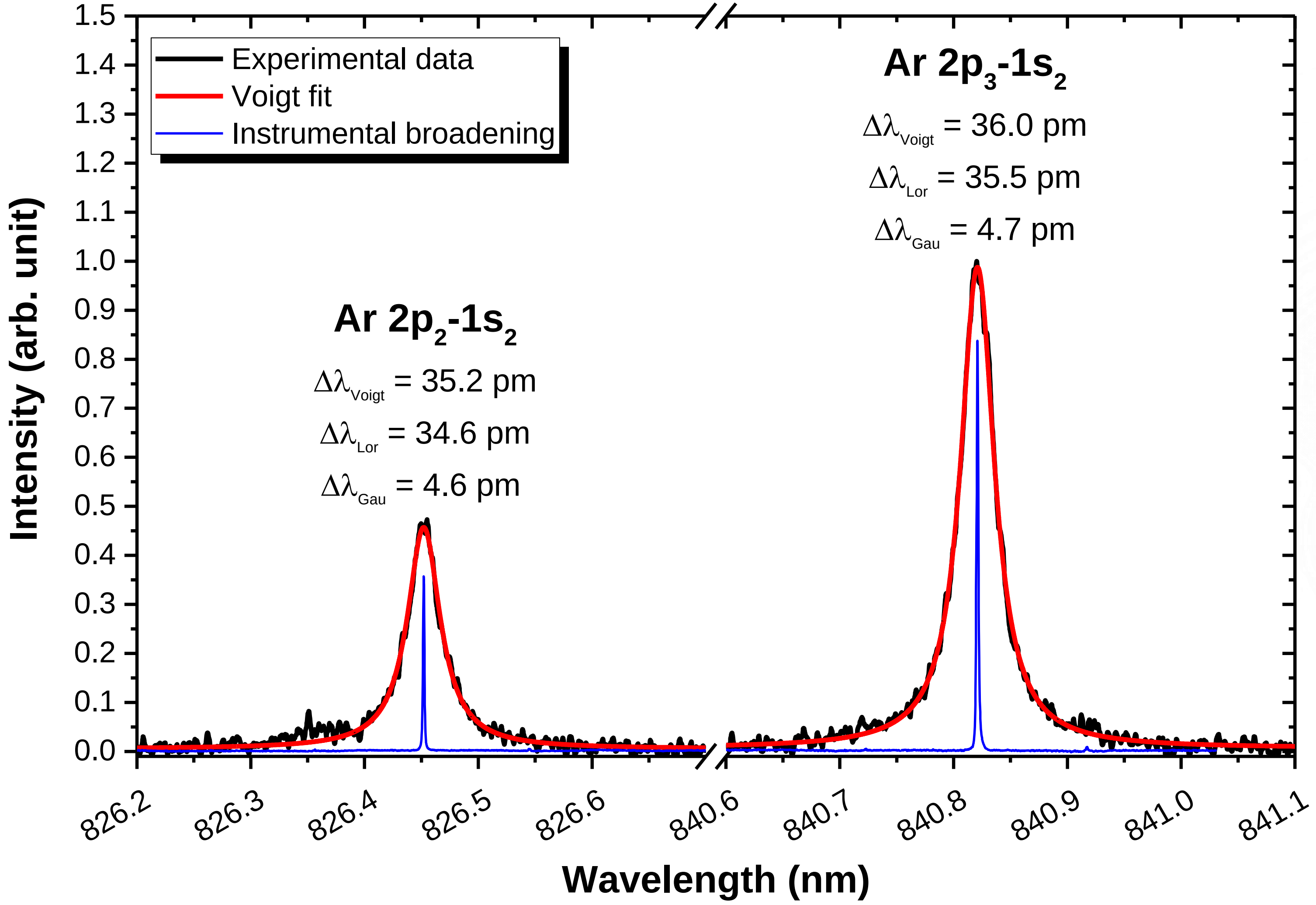


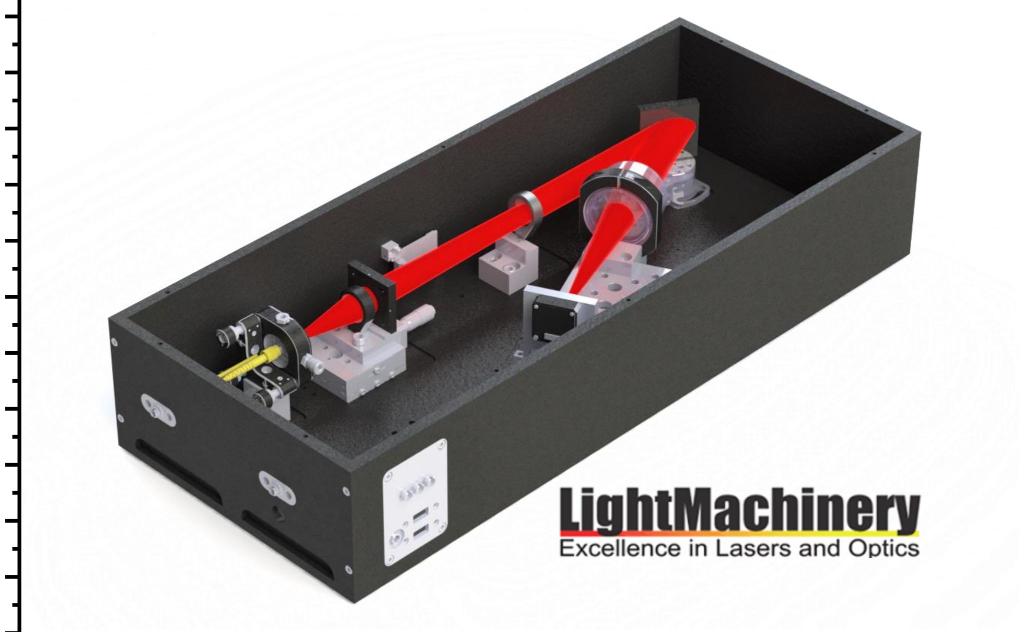
Complete mapping of T_e along the column end

Ultra-high-resolution spectroscopy

Ultra-high-resolution spectroscopy

Already popular in: Brillouin spectroscopy, thin-film characterization, photovoltaic characterization

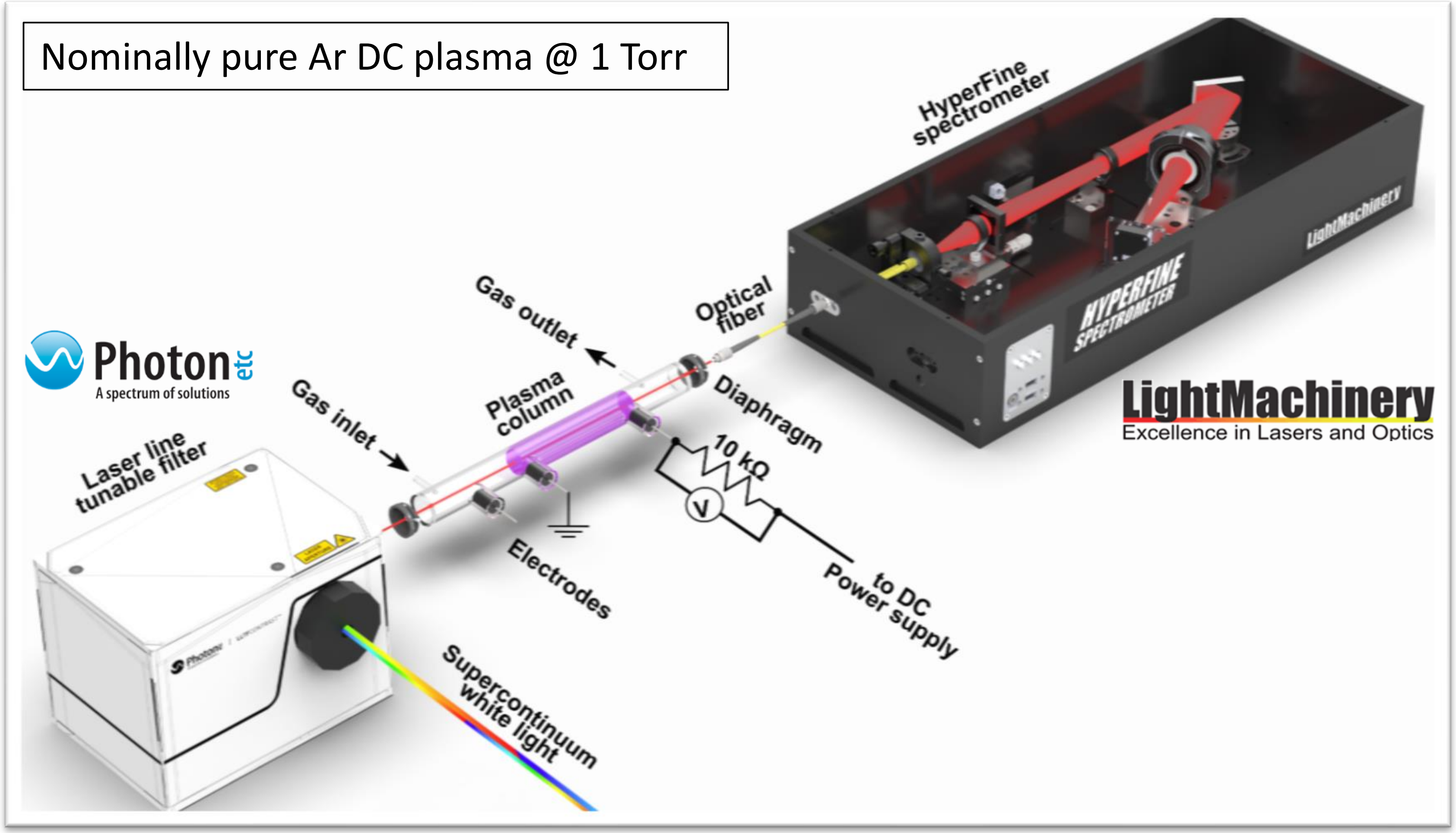




Precise determination of T_g via OES broadening measurements

Ultra-high-resolution spectroscopy

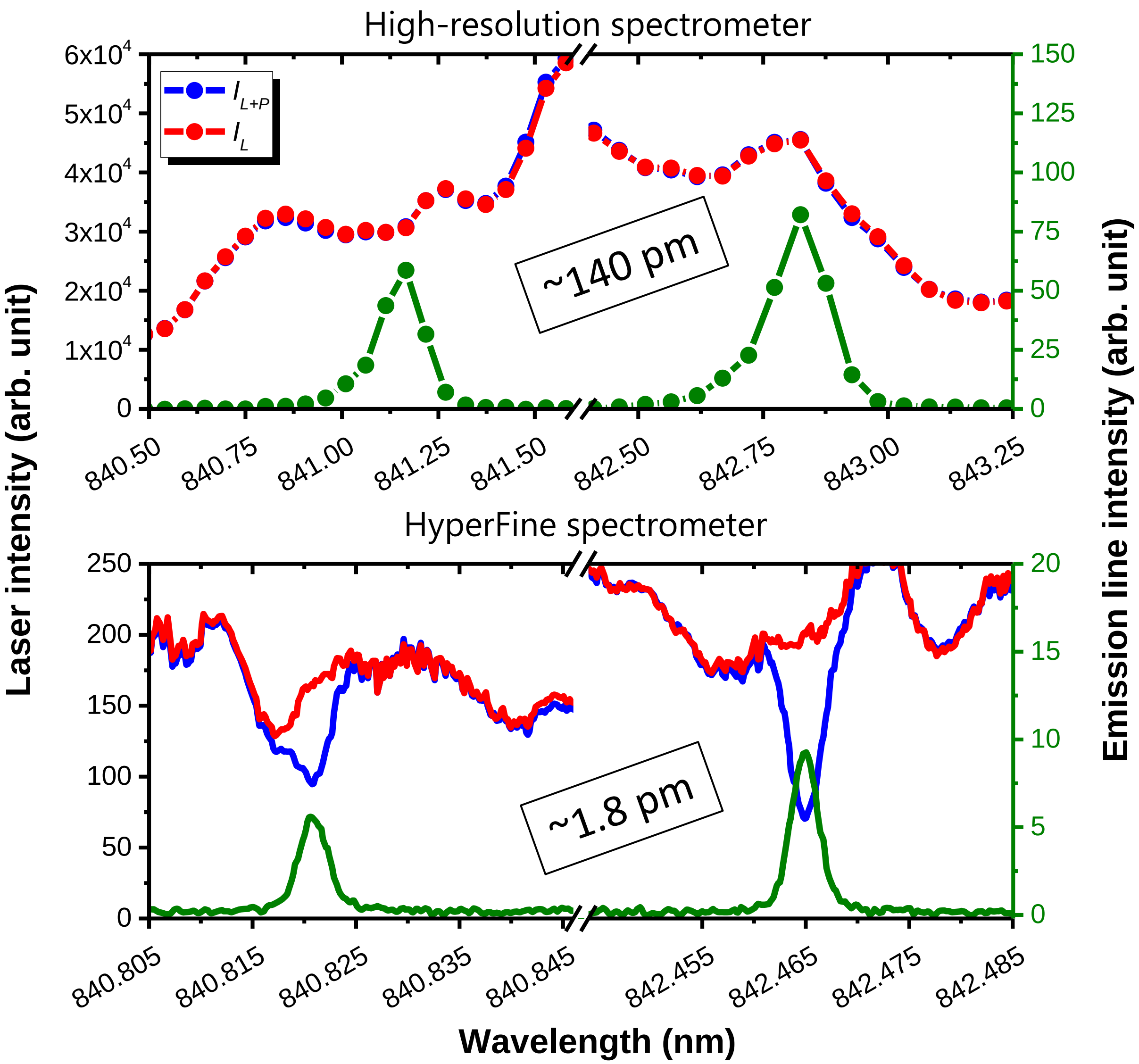
“White light” absorption spectroscopy: obtaining Ar 1s number densities



Supercontinuum laser + laser line tunable filter + ultra-high-resolution spectrometer

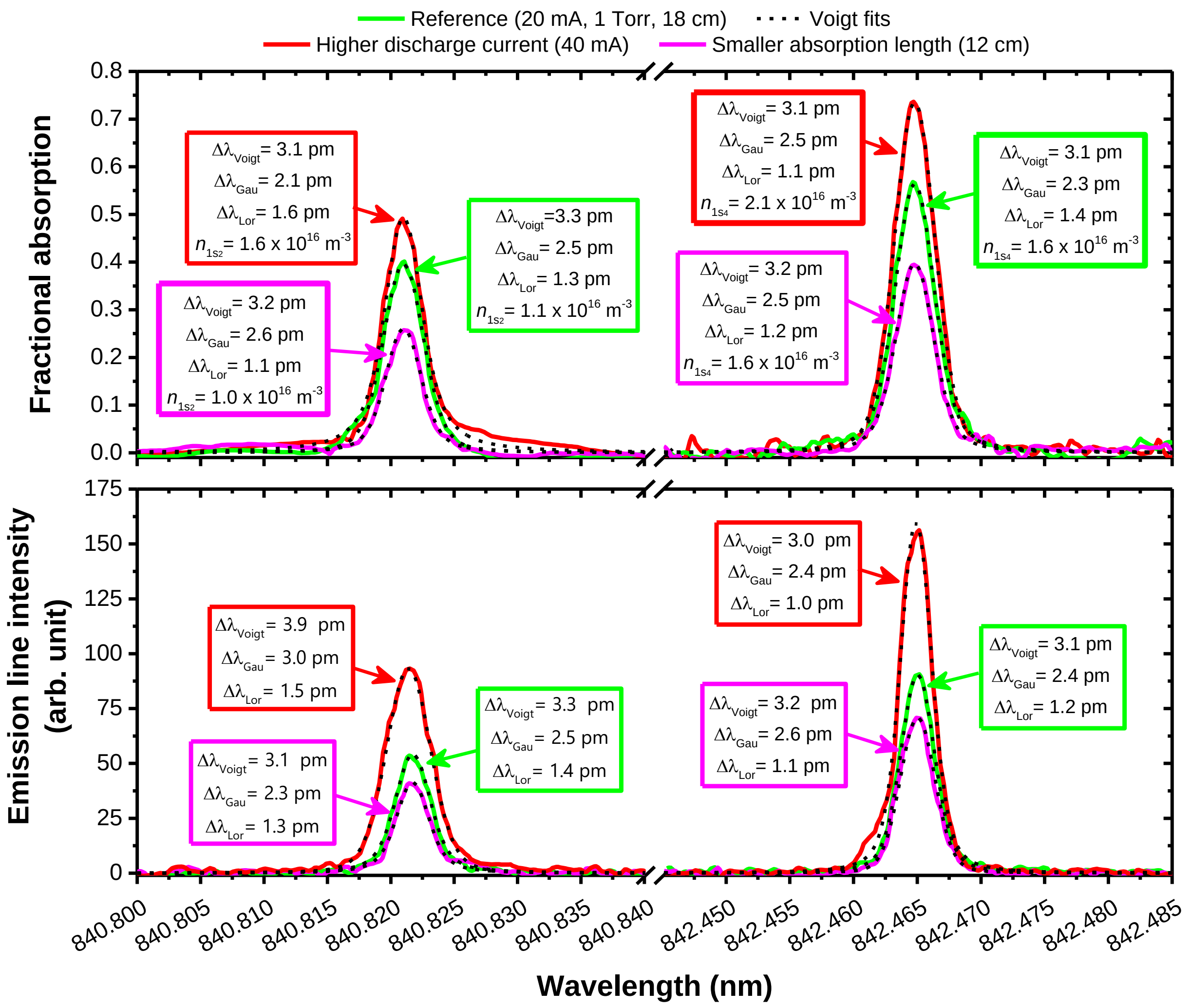
- 400 - 2400 nm
  More potential than spectral lamps
- ~2.5 nm bandpass
  Less invasive than white lights

Ultra-high-resolution spectroscopy



Right spectrometer needed to have reliable measurements!

Ultra-high-resolution spectroscopy



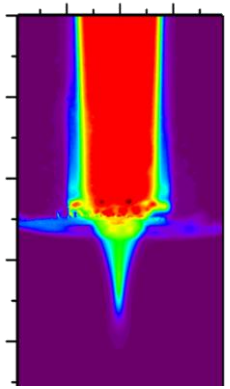
Validation tests:

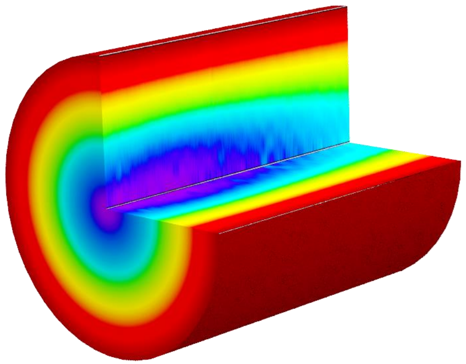
- Absorption profiles match the emission ones
- Gas temperature of 340 ± 40 K
- Ar $1s_2$ and $1s_4$ number density: 10^{16} m^{-3} range
- $n_{1s_2} < n_{1s_4}$
- Number densities increase with discharge current
- Fractional absorption decreases with absorption length but number densities are the same

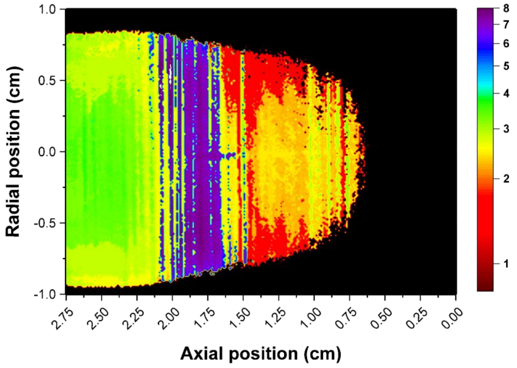
C. M. Ferreira, J. Loureiro, and A. Ricard, J. Appl. Phys. **57**, 82 (1985)
C. M. Ferreira and A. Ricard, J. Appl. Phys. **54**, 2261 (1983)
J. Vlček and V. Pelikan, J. Phys. D. Appl. Phys. **22**, 632 (1989)

Conclusion

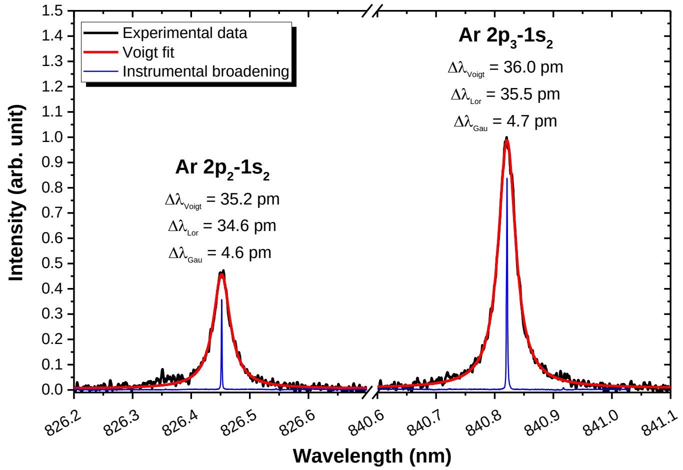
- Hyperspectral imaging offers huge potential, way beyond simple imaging and point-by-point spectroscopy

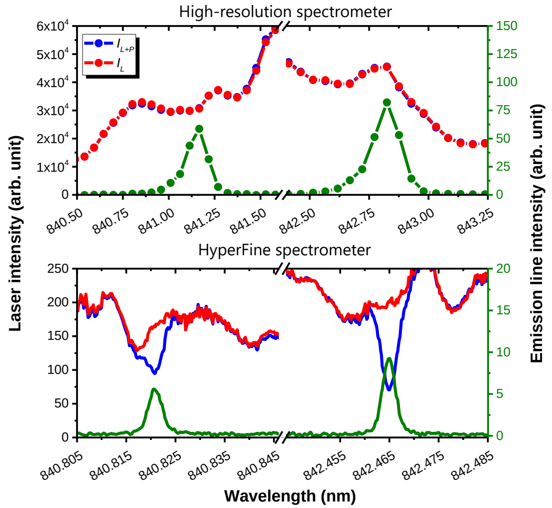


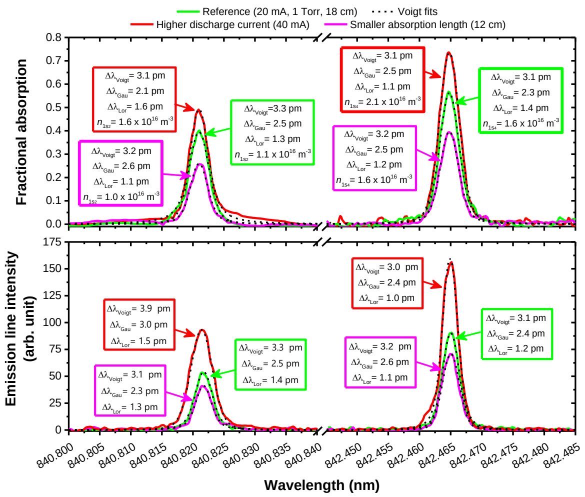




- Ultra-high-resolution allows access to plasma parameters with unprecedented precision







- Currently helping in the developpement of instruments designed specifically for plasma sciences

Acknowledgments

Industrial partners

Photon etc — A spectrum of solutions

LightMachinery — Excellence in Lasers and Optics

Funding organizations

Mitacs

NSERC CRSNG

Chaires de recherche du Canada / Canada Research Chairs

Canada

Thank you for your attention!