NEGATIVE ION AND HELICON WAVE PHYSICS ON THE RESONANT ANTENNA ION DEVICE (RAID)

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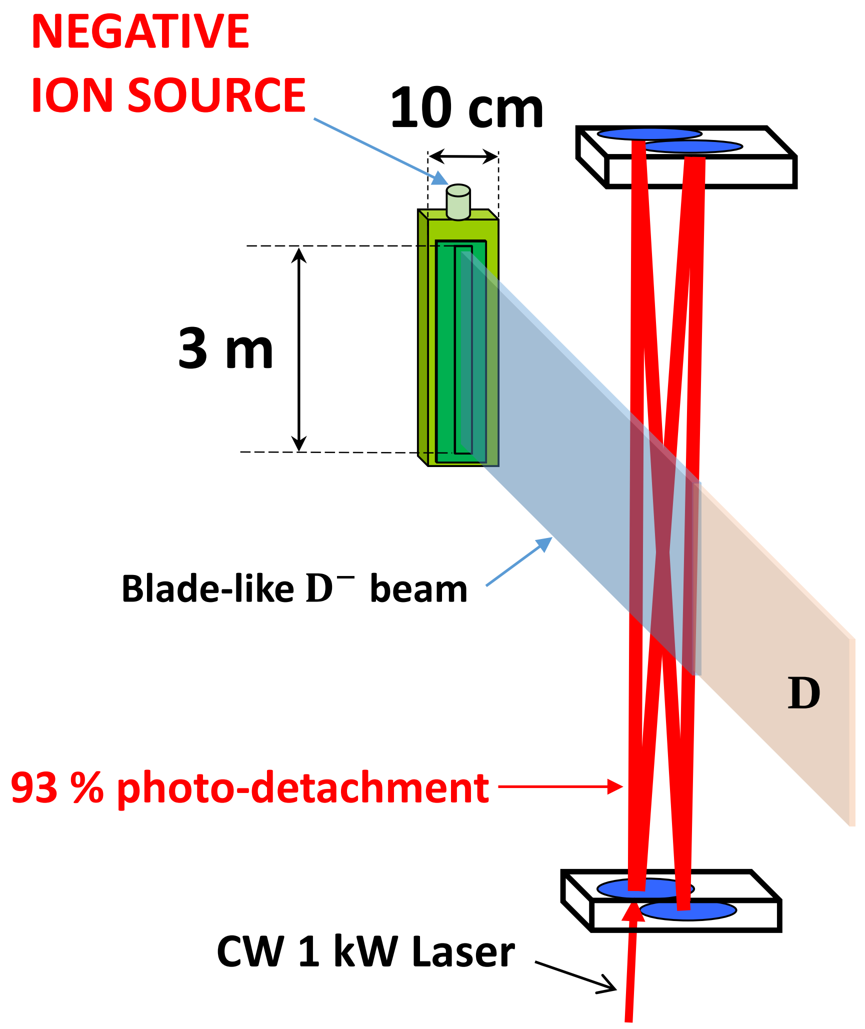
The 6th International Symposium on Negative Ions, Beams and Sources, 3rd-7th September 2018, Novosibirsk

WHICH NEGATIVE ION SOURCE FOR DEMO?

	DEMO[1]
Species	D^-
Beam Energy [keV]	800
Current [A]	34
Filling pressure [Pa]	0.2
Beam on time [s]	7200
Extracted e-/D- fraction	<1
Neutralization efficiency	>0.65

[1] P. Sonato et al., *Conceptual design of the beam source for the DEMO NBI: main developments and R&D achievements*, Nucl. Fusion **57** 056026



The Cybele concept for DEMO NBI

(Iaroslav Morgal's presentation at 14:30)

Can a helicon source be an option?

➢ Challenges for plasma physics and technology

OUTLINE

1) The Resonant Antenna Ion Device (RAID)

2) Experimental study of the helicon plasma source in $\mathrm{H_2}$ and $\mathrm{D_2}$ plasmas

2.1) 3D plasma profiles and helicon wave measurements

2.2) Negative ion population measurements

- **Optical Emission Spectroscopy (OES)**
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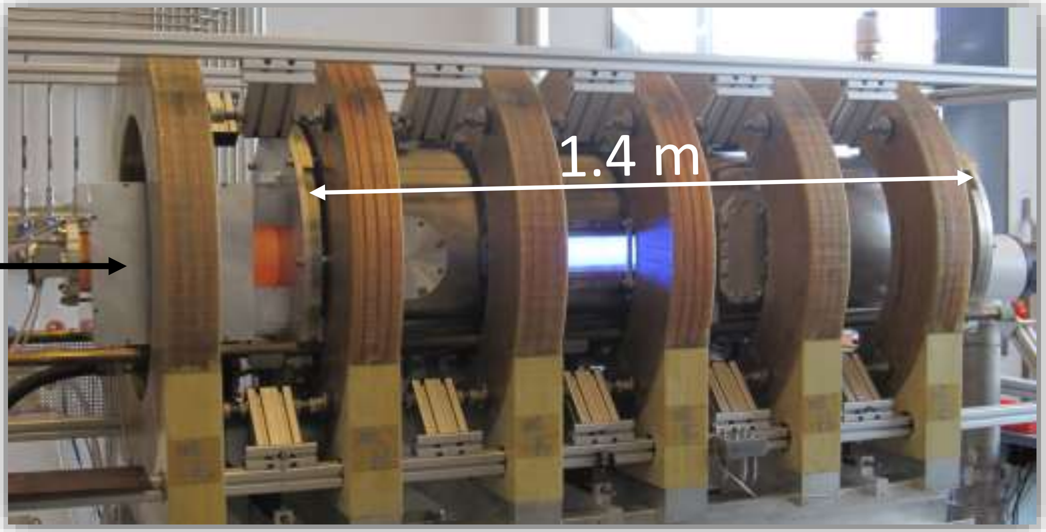
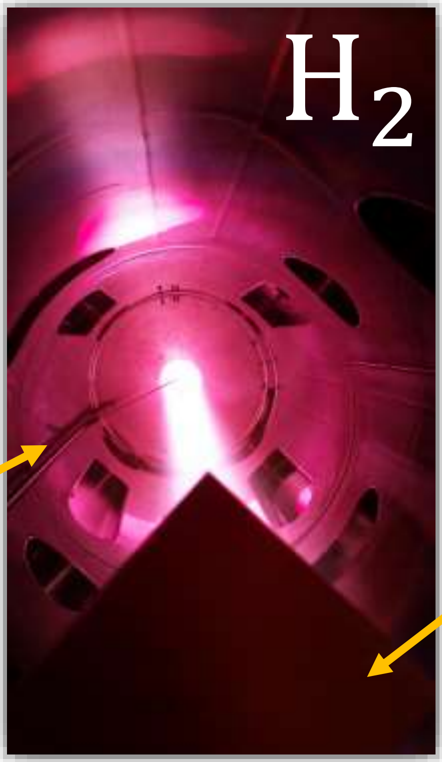
- **Langmuir Probe Photodetachment**

3) Summary and Outlook

THE RESONANT ANTENNA ION DEVICE (RAID)

Birdcage resonant antenna

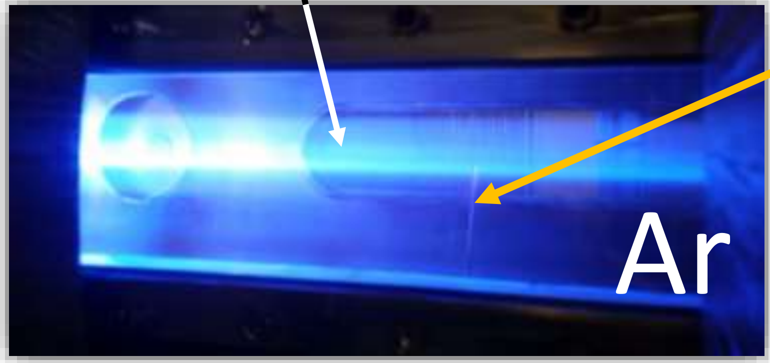


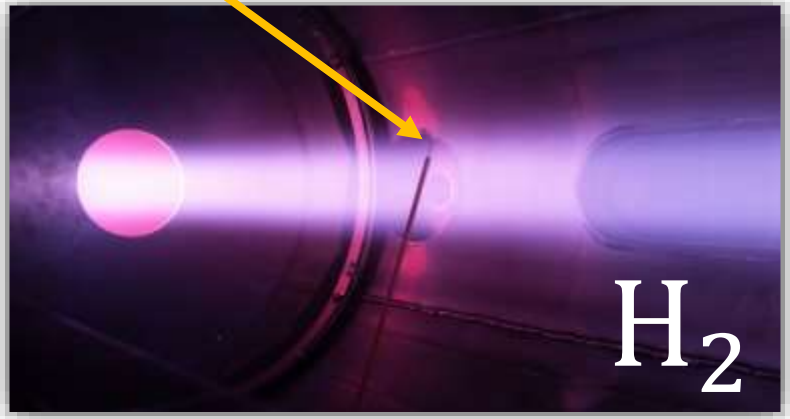


Water cooled end-plate

2-axis probe mounting for 3D plasma measurements

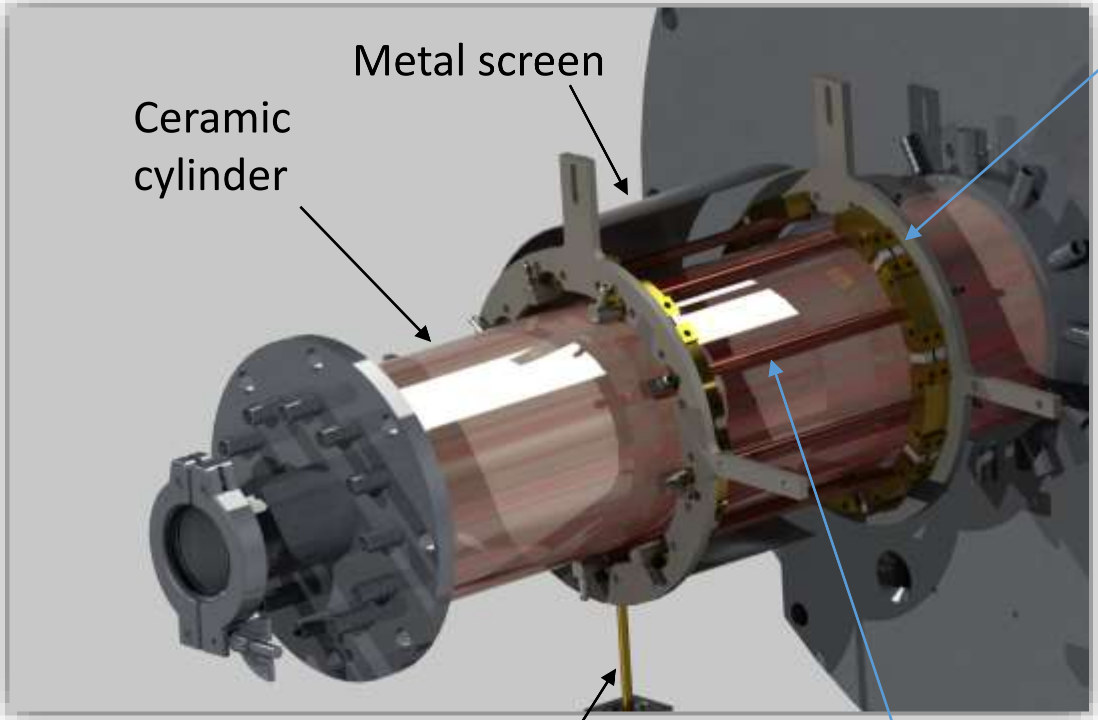
“Blue core” → signature of helicon wave

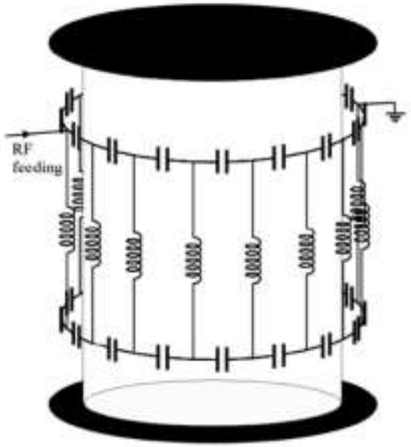


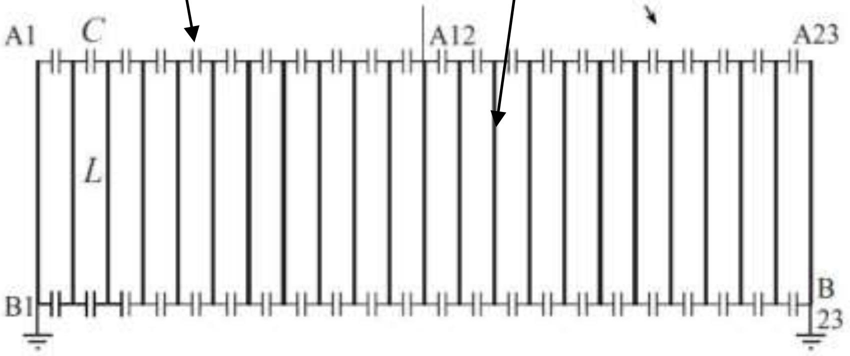


I. Furno et al., *EPJ Web of Conferences* **157,** 03014 (2017)

PLASMA SOURCE: BIRDCAGE ANTENNA







Resonance frequencies:

$$\omega_m = \frac{1}{\sqrt{C\left(M + 2L\sin^2\left\{\frac{m\pi}{2N}\right\}\right)}}$$

m = 1, 2,… N-1

Ph. Guittienne et al., *J. Appl. Phys.* **98,** 083304 (2005)

Operating frequency: 13.56 MHz

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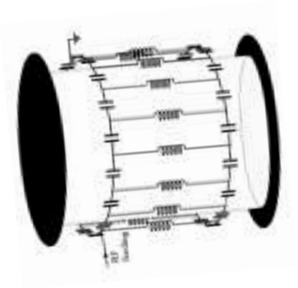
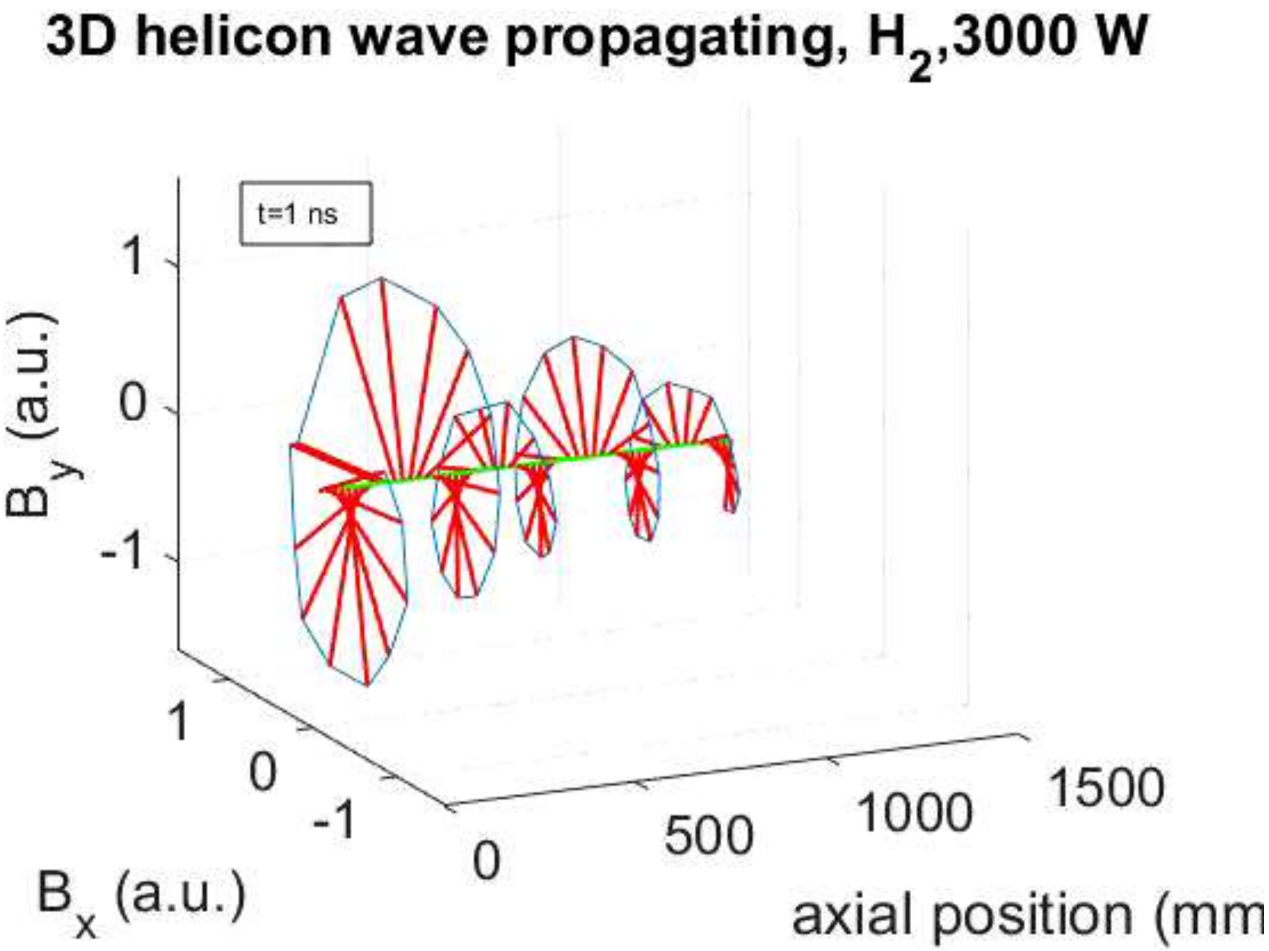
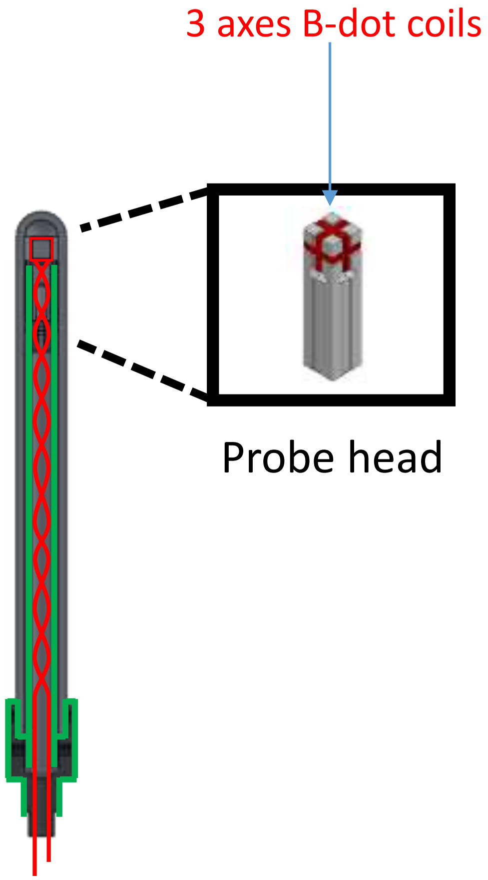
A HELICON WAVE PROPAGATES ALONG THE PLASMA COLUMN

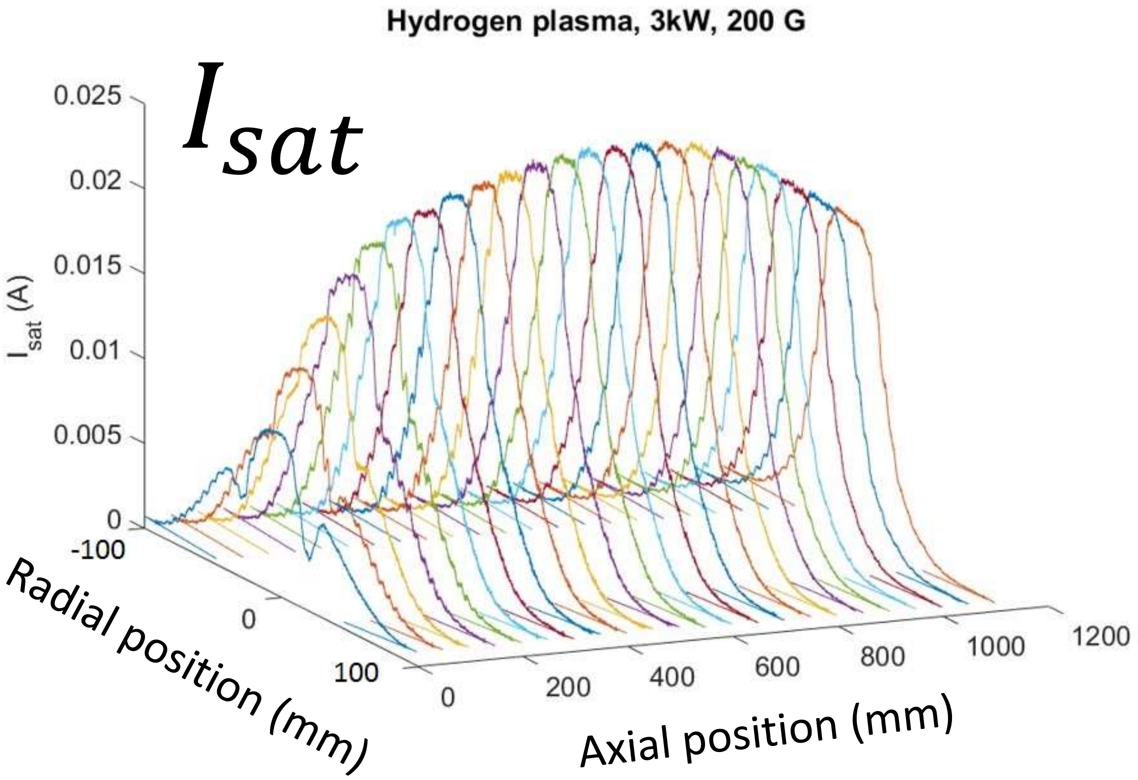


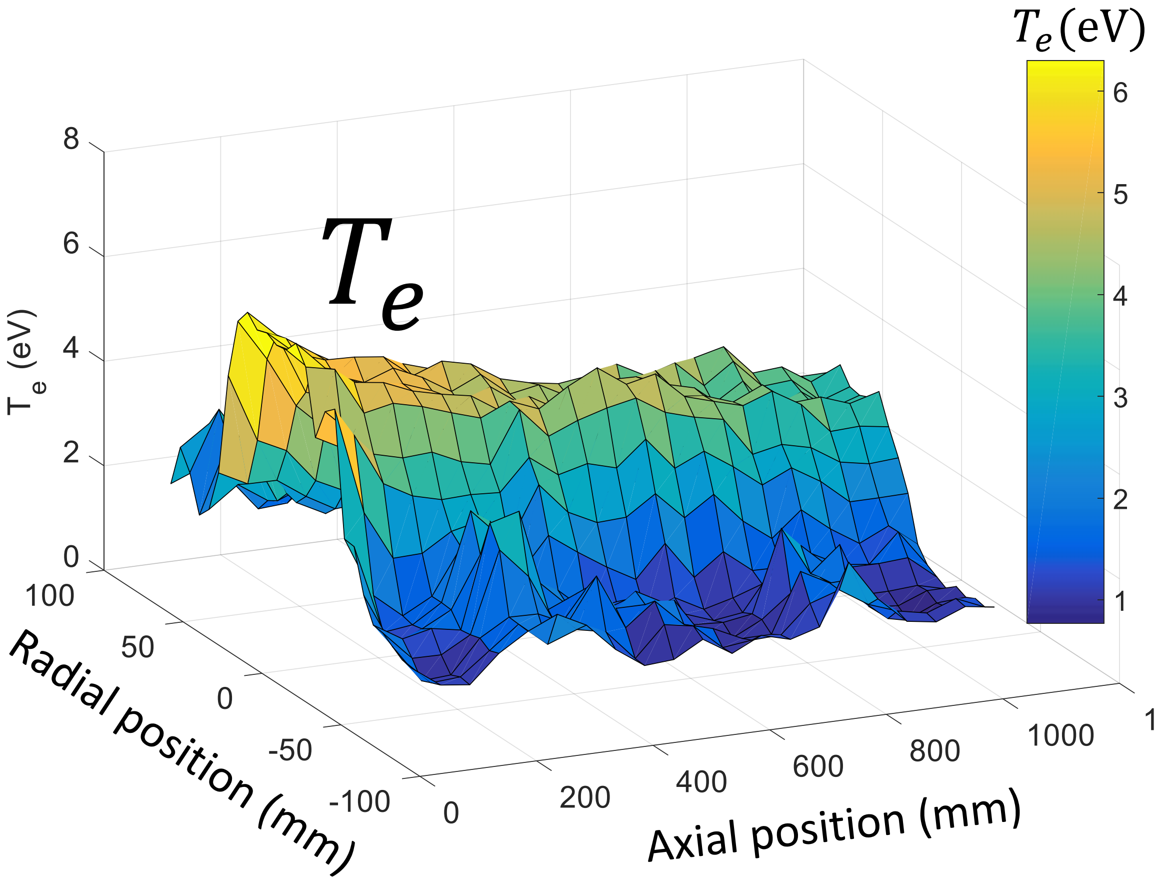




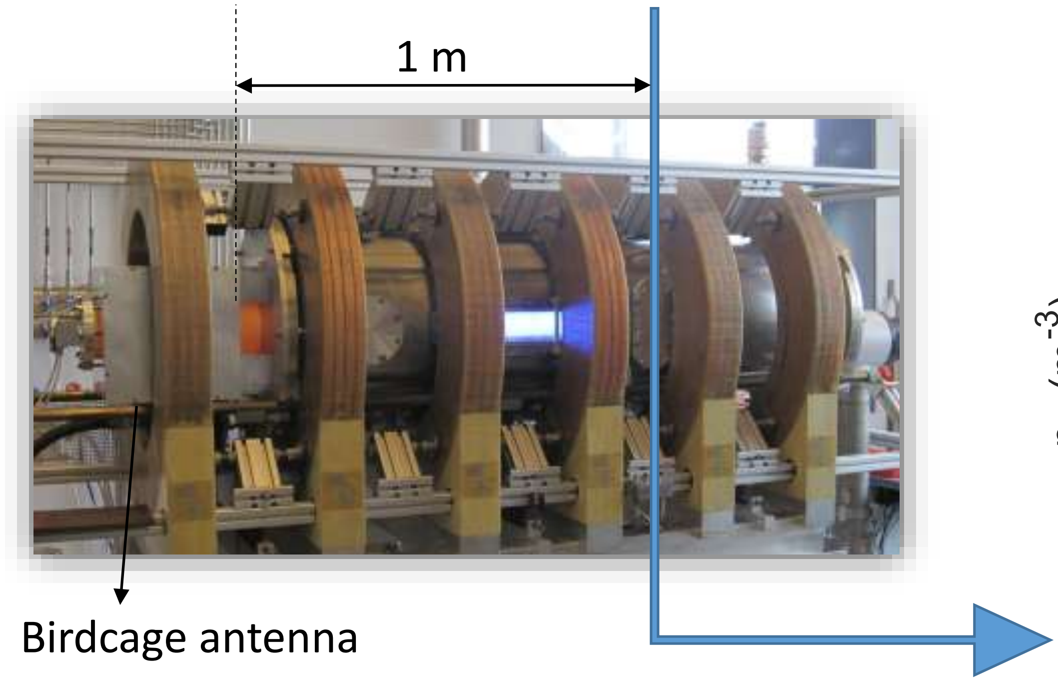
Schematic of the magnetic probe

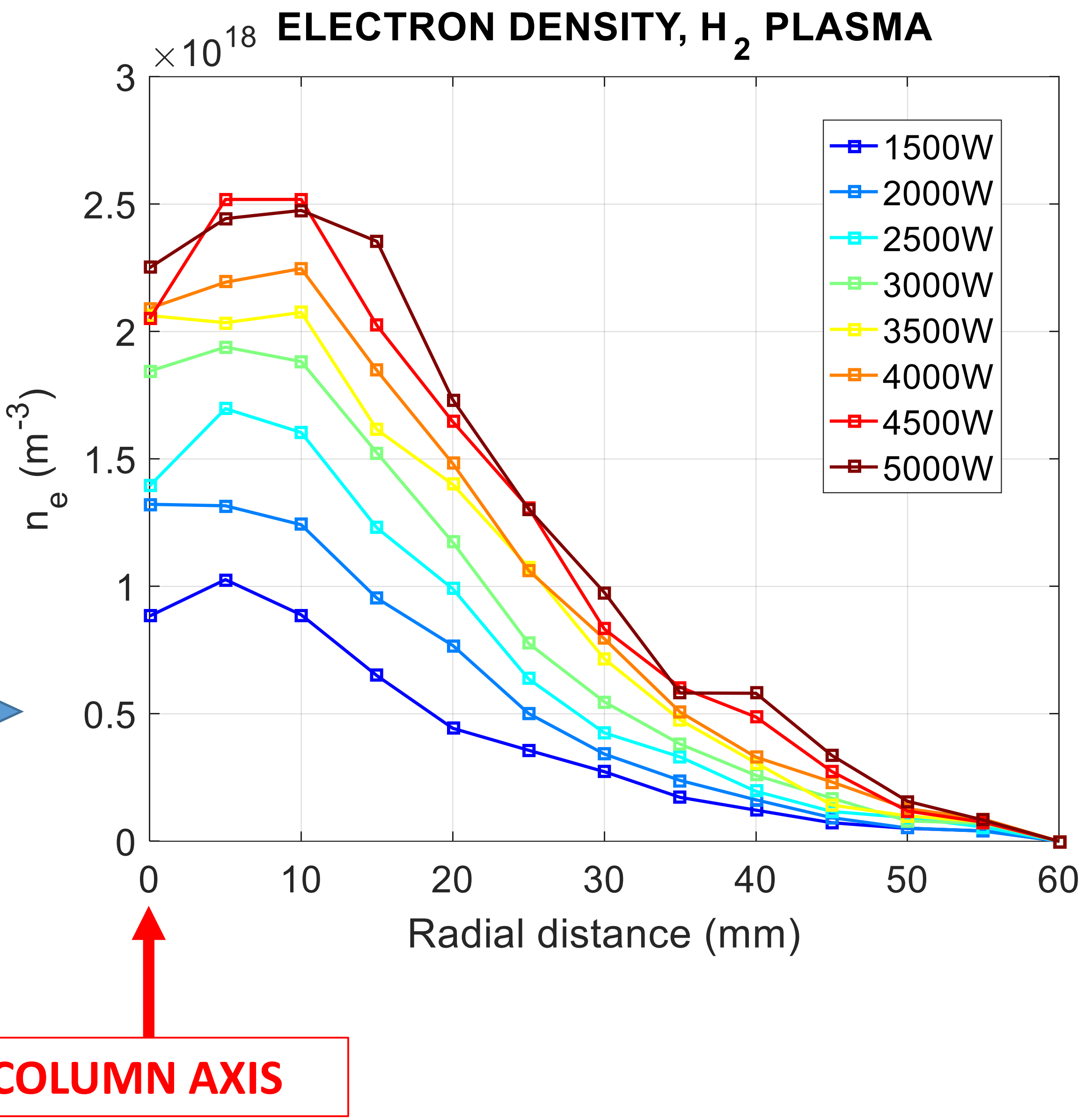
3D MEASUREMENTS SHOW PEAKED DENSITY AND TEMPERATURE PROFILES





RF POWER AFFECTS ELECTRON DENSITY PROFILES





Electron density profiles are calibrated with a 100 GHz microwave interferometer

PEAKED T_e PROFILE IS FAVORABLE FOR VOLUME PRODUCTION OF NEGATIVE IONS

$$H_2 + e^- \rightarrow H_2^* + e^-$$

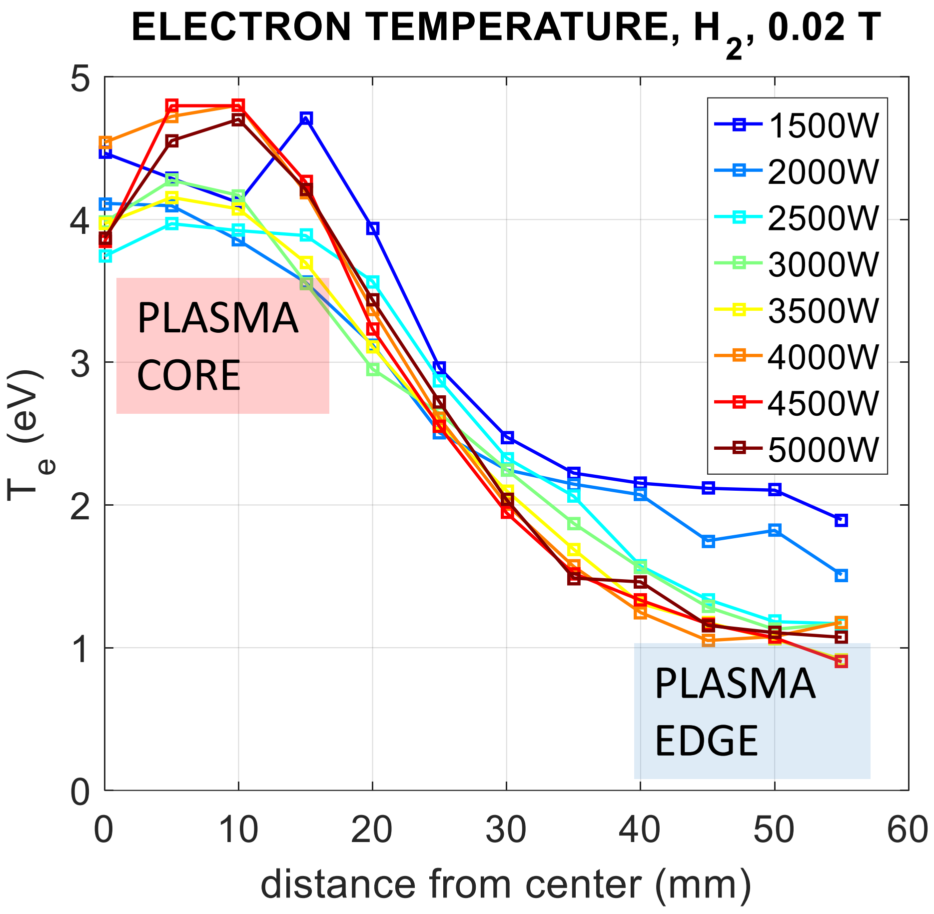
PLASMA CORE

Ro-vibrational excitation of H_2

$$H_2^* + e^- \rightarrow H^- + H$$

PLASMA EDGE

*Temperature profile favorable for **volume production** of* H^- *(**dissociative attachment**)*



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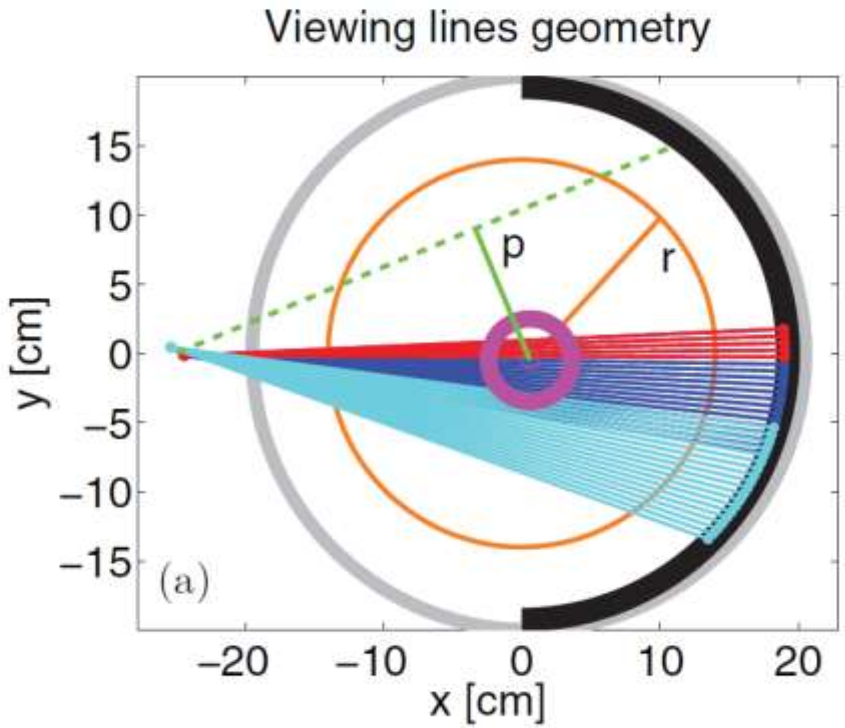
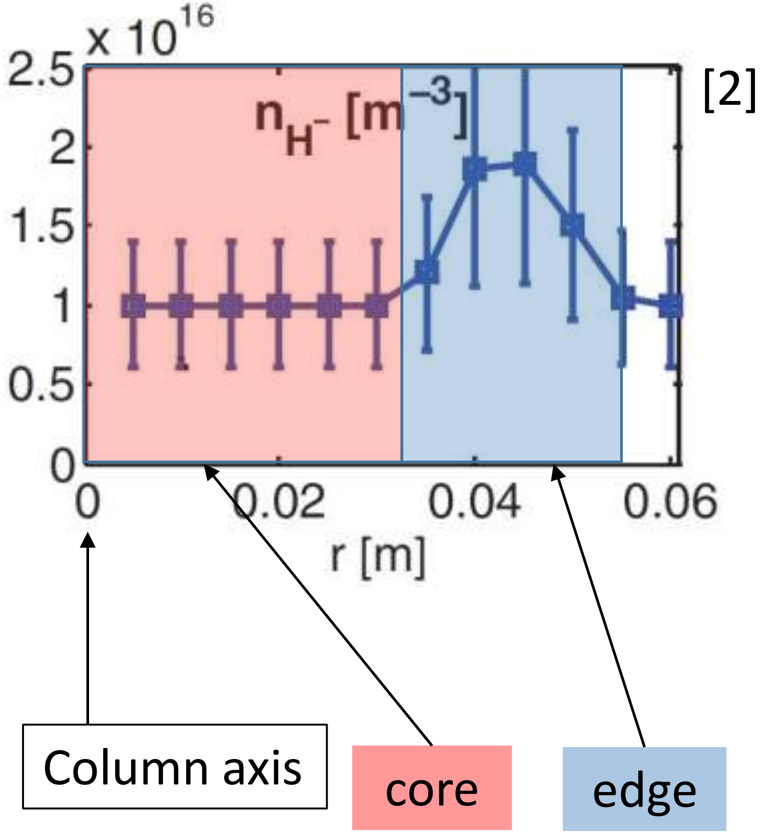
OPTICAL EMISSION SPECTROSCOPY REVEALED NEGATIVE ION DENSITY PEAKED OFF AXIS



Line emission profiles are interpreted by YACORA [1]



[1] Wünderlich D., Dietrich S. and Fantz U. 2009 J. Quant. Spectrosc. Radiat. Transfer **110** 62-71
[2] Marini C. et al. Nucl. Fusion **57** (2017) 036024

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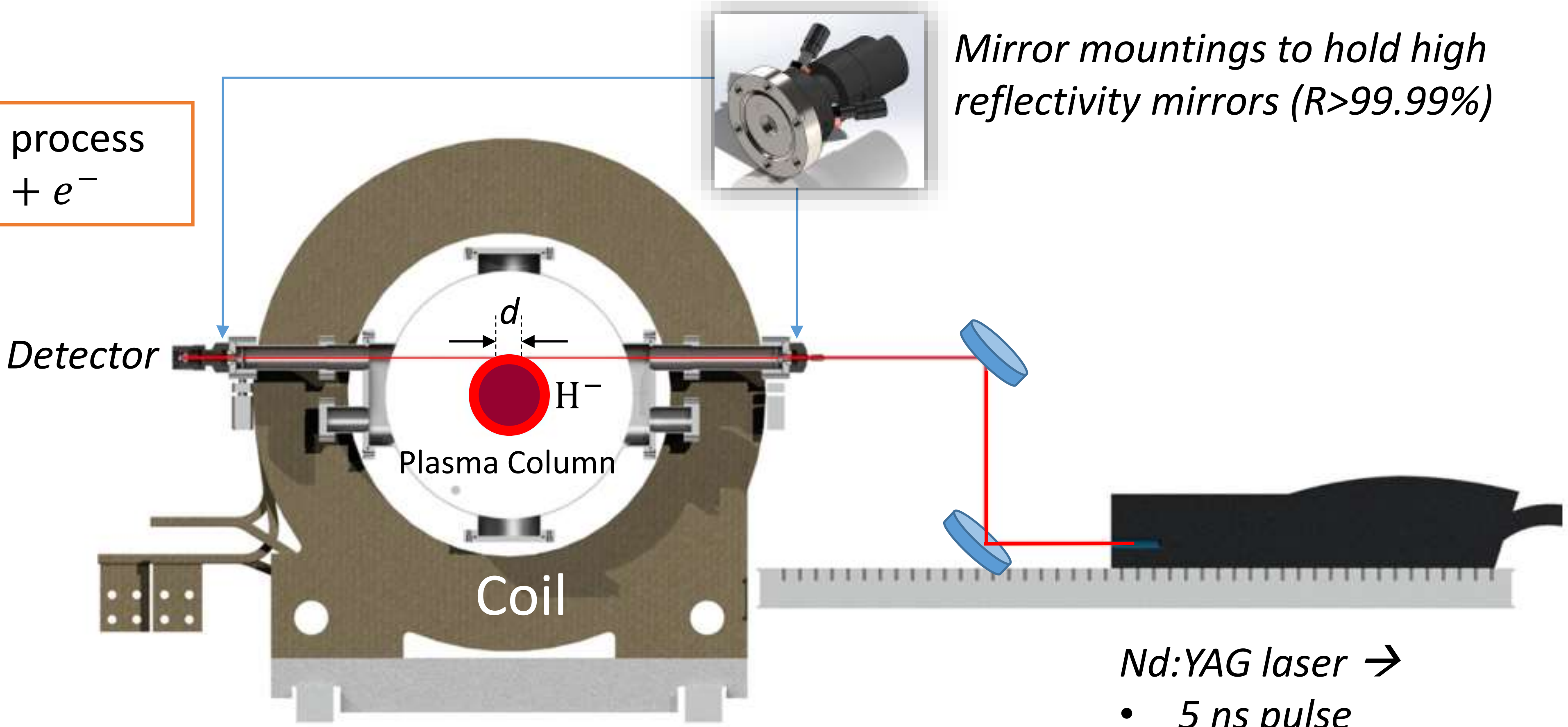
CAVITY RING DOWN SPECTROSCOPY TO MEASURE LINE-INTEGRATED NEGATIVE ION DENSITY

Photodetachment process
$$H^- + h\nu \rightarrow H + e^-$$

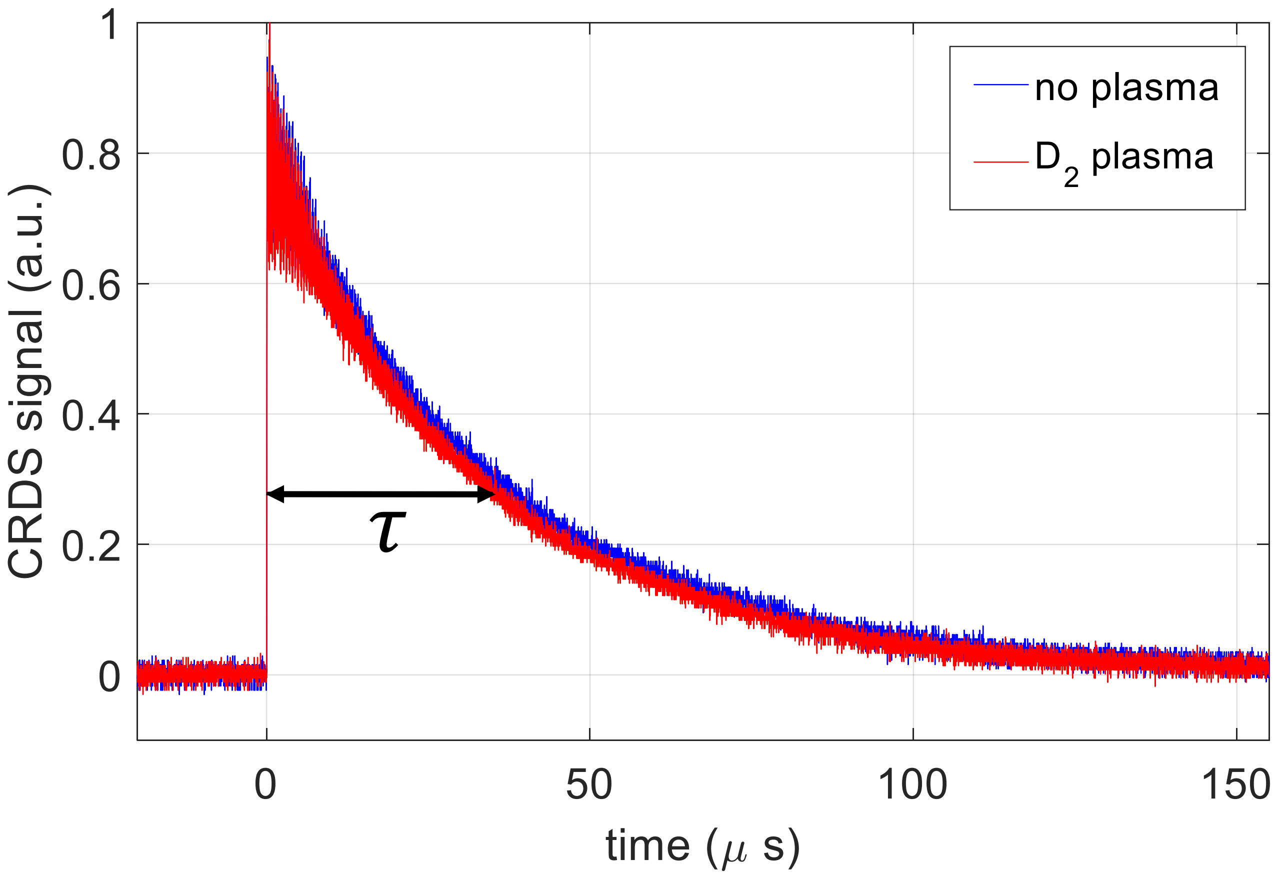
Mirror mountings to hold high reflectivity mirrors (R>99.99%)



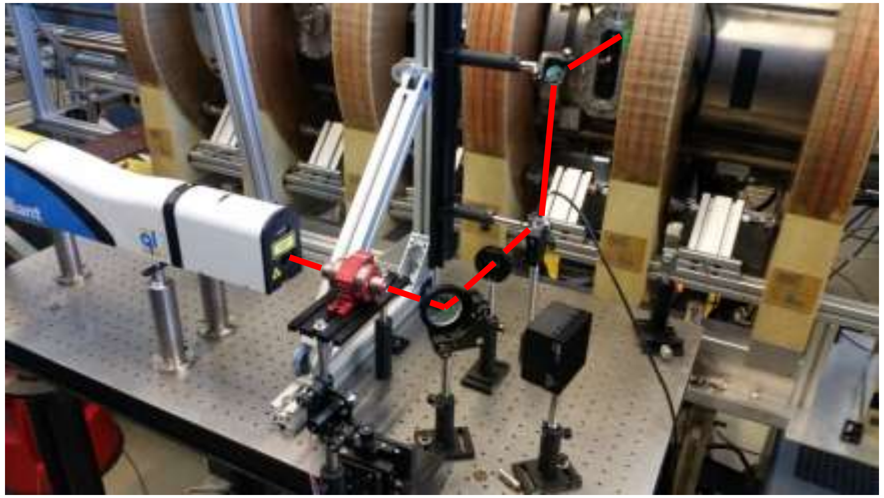
Nd:YAG laser →
- *5 ns pulse*
- *10 Hz repetition rate*

The extinction time of light in the optical cavity depends on medium absorbance

RING-DOWN SIGNAL SHOWS AN EXPONENTIAL DECAY



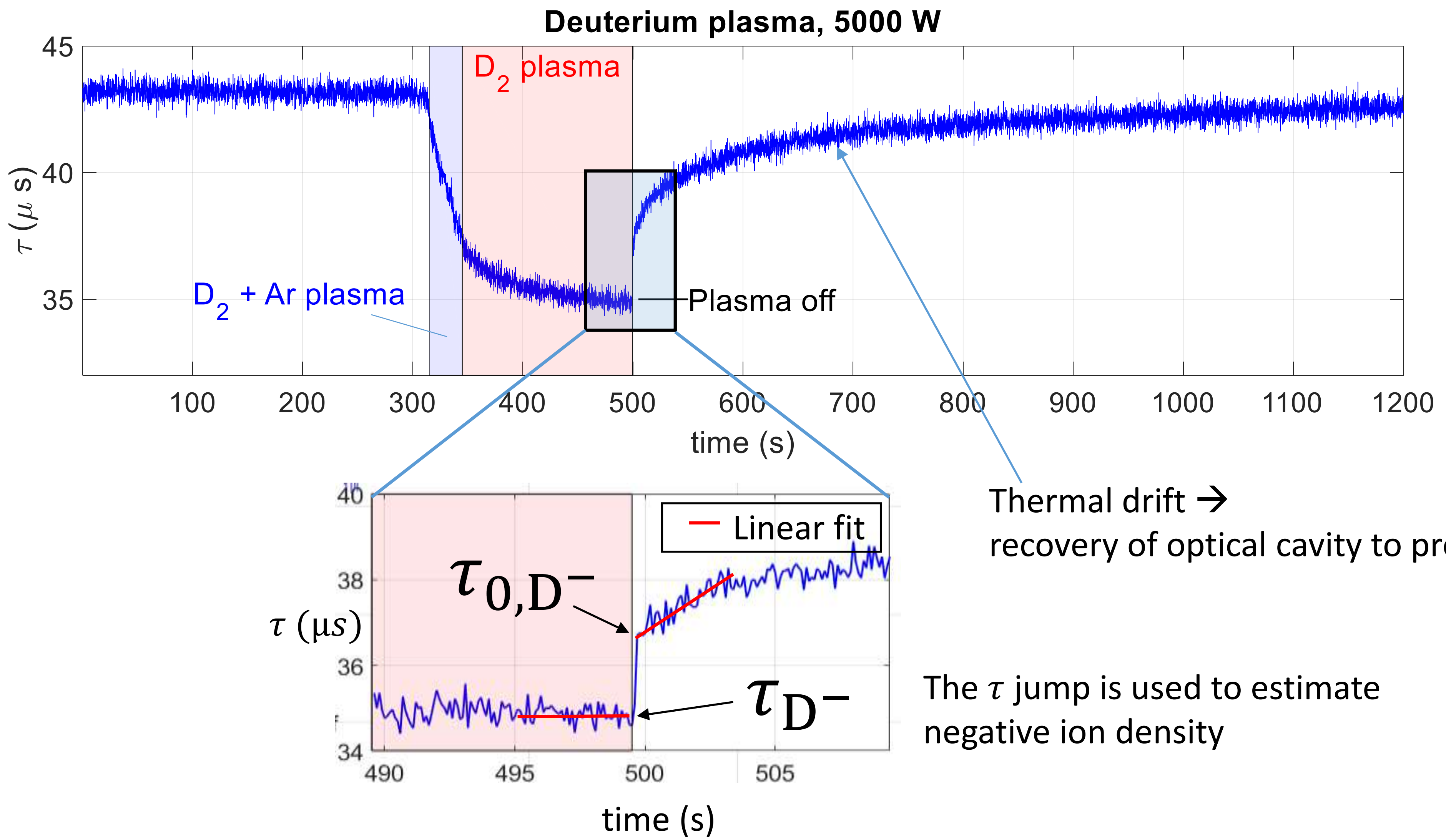
Tipical decay signals in two conditions: in vacuum (no plasma) and in a $\mathrm{D_2}$ *plasma*



A photo of CRDS experimental setup

$$\bar{n}_{\mathrm{D}^-} = \frac{L}{c\sigma d}\left(\frac{1}{\tau} - \frac{1}{\tau_0}\right)$$

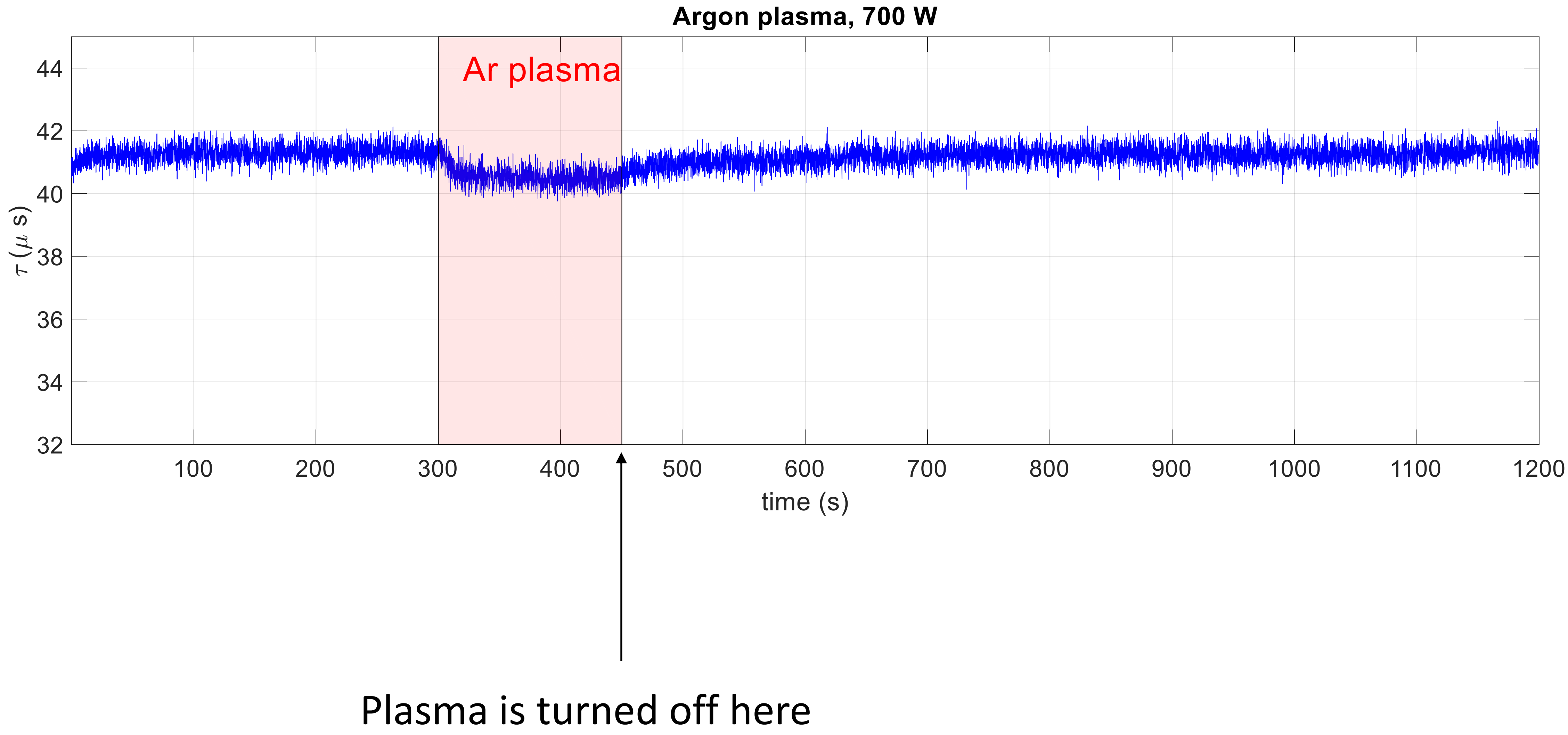
A JUMP OF τ IS OBSERVED WHEN D_2 PLASMA IS TURNED OFF: DISAPPEARANCE OF NEGATIVE IONS



Thermal drift →
recovery of optical cavity to pre-discharge value

The τ jump is used to estimate negative ion density

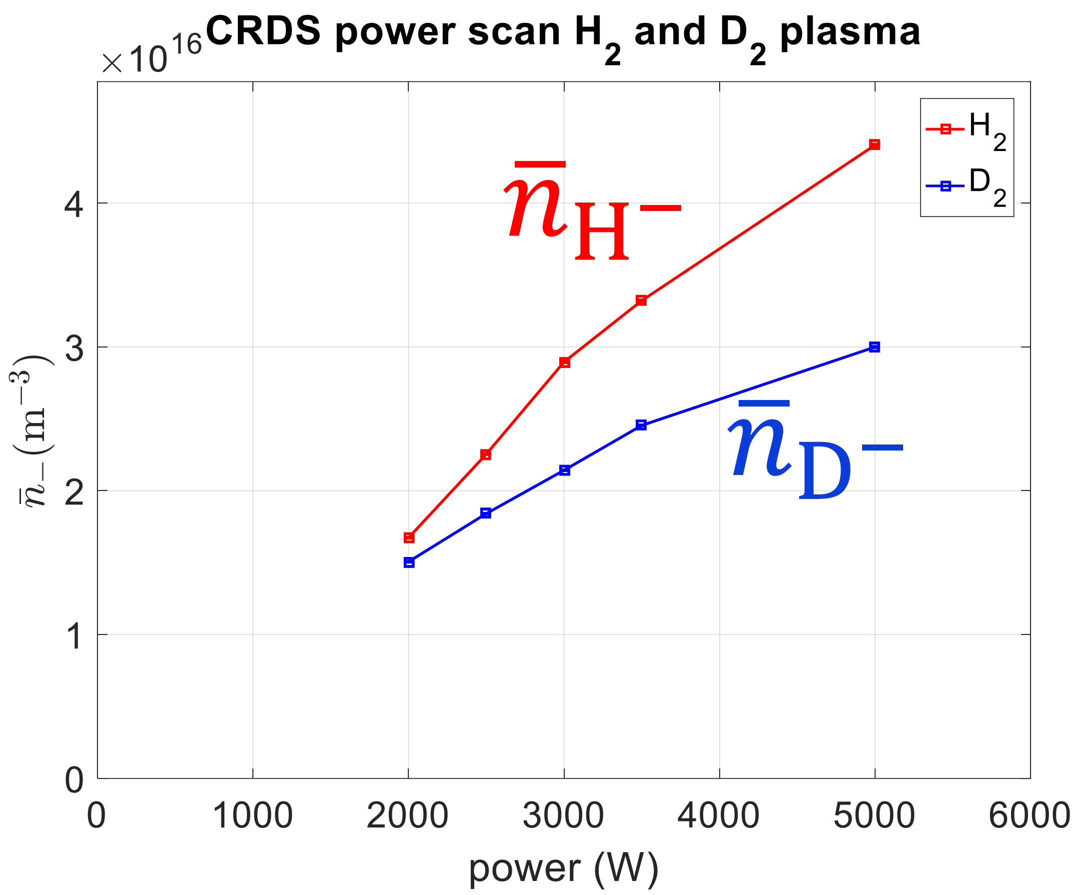
NO JUMP OF τ IS OBSERVED WHEN Ar PLASMA IS TURNED OFF



LINE-INTEGRATED NEGATIVE ION DENSITY INCREASES WITH POWER

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER



Average negative ions densities increase with power

R. Agnello et al. *Cavity Ring-Down Spectroscopy to measure negative ion density in a helicon plasma source for fusion neutral beams* (submitted to Review of Scientific Instruments)

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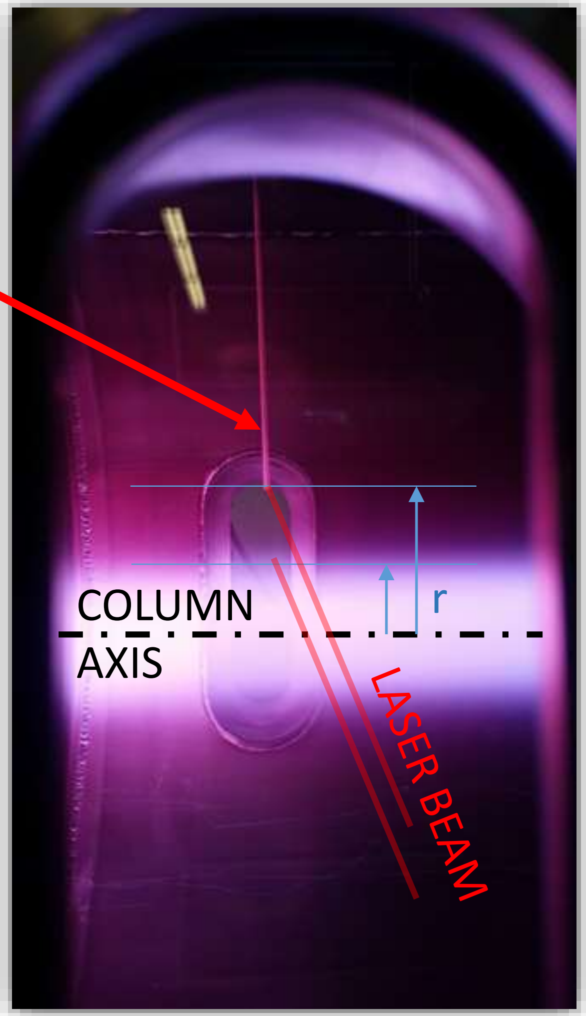
LASER PHOTODETACHMENT TO MEASURE NEGATIVE ION DENSITY PROFILES

Negative ion density n_- can be calculated from:

$$\frac{n_-}{n_e} = \frac{i_{pd}}{i_{dc}}$$

i_{pd} → photodetachment current
i_{dc} → direct electron current

Langmuir probe



LASER PULSES PHOTODETACH ELECTRONS FROM NEGATIVE IONS $\mathbf{H}^-/\ \mathbf{D}^-$

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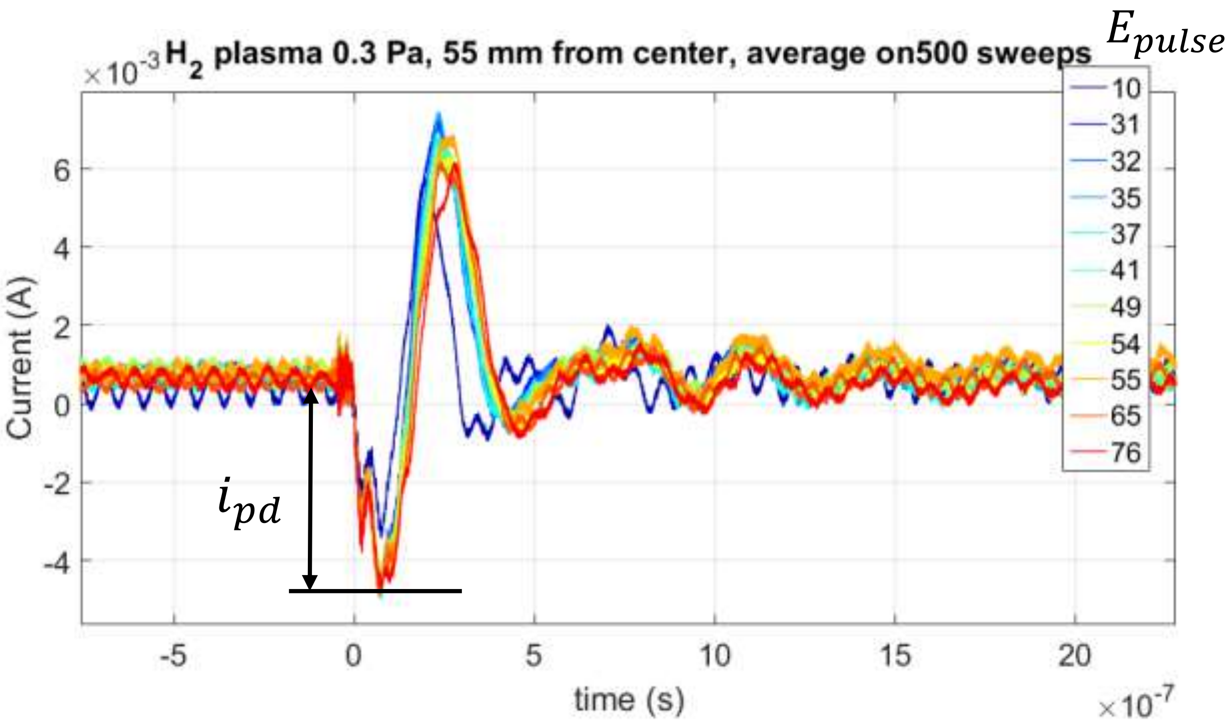
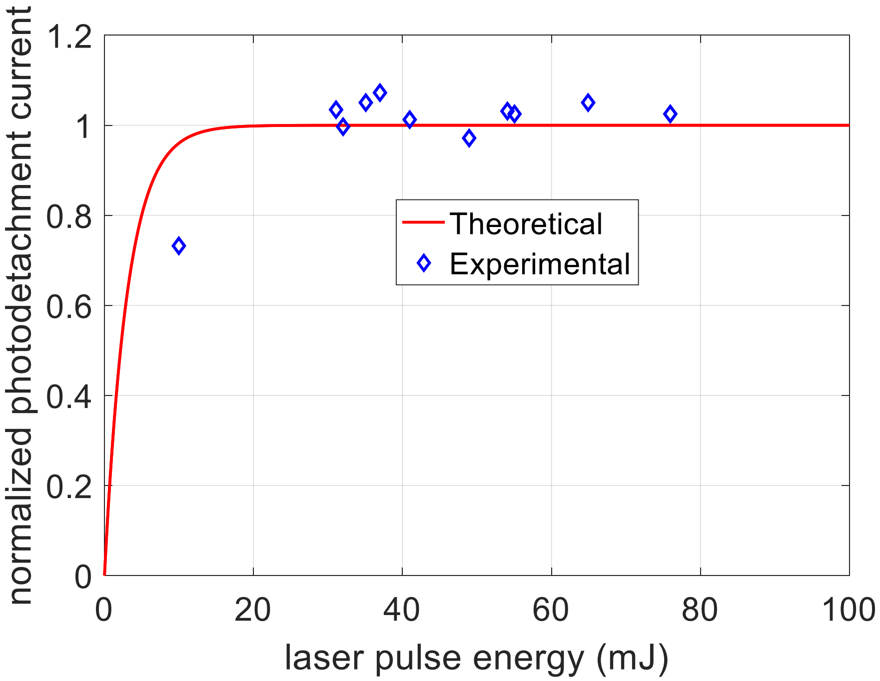
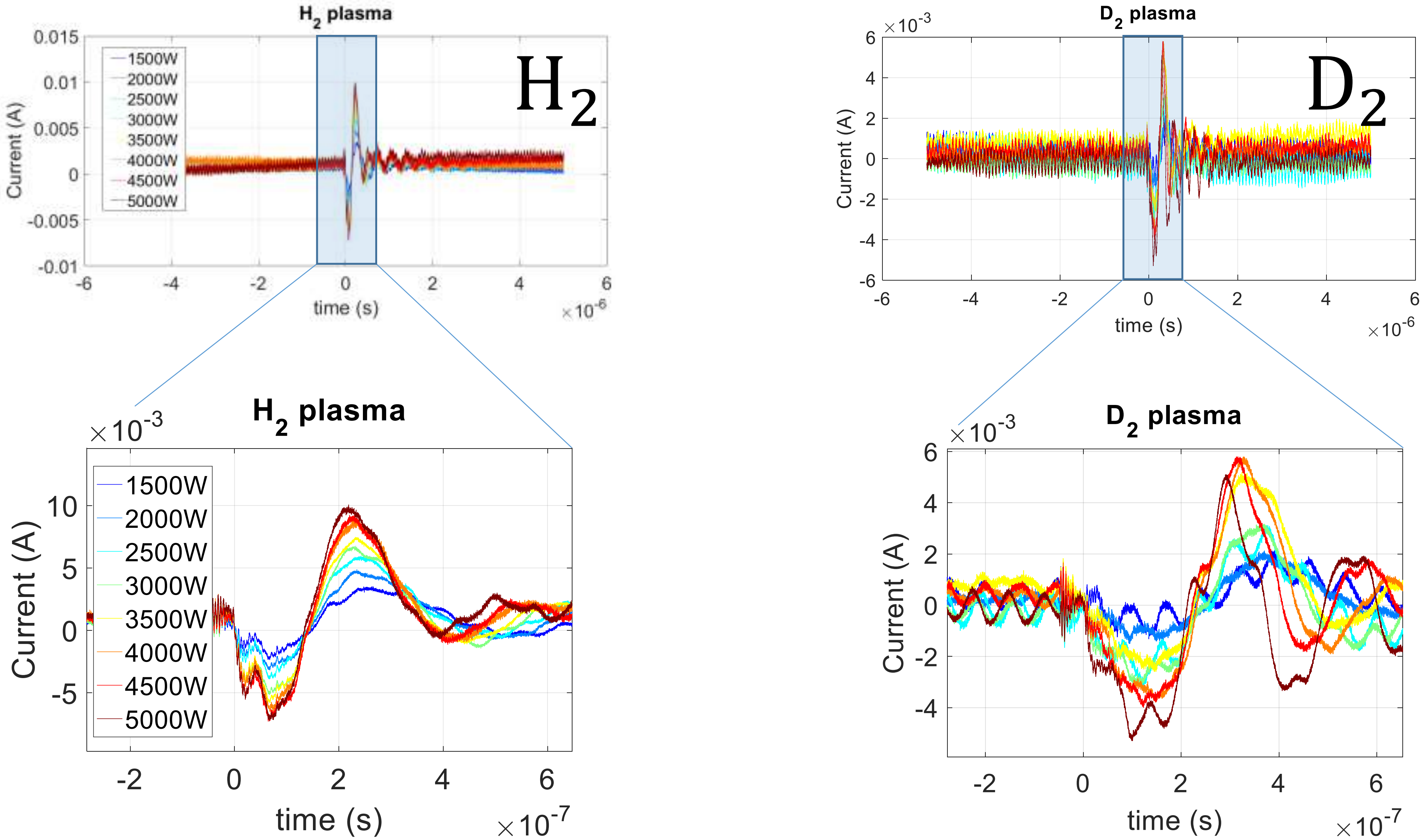
SWISS PLASMA CENTER



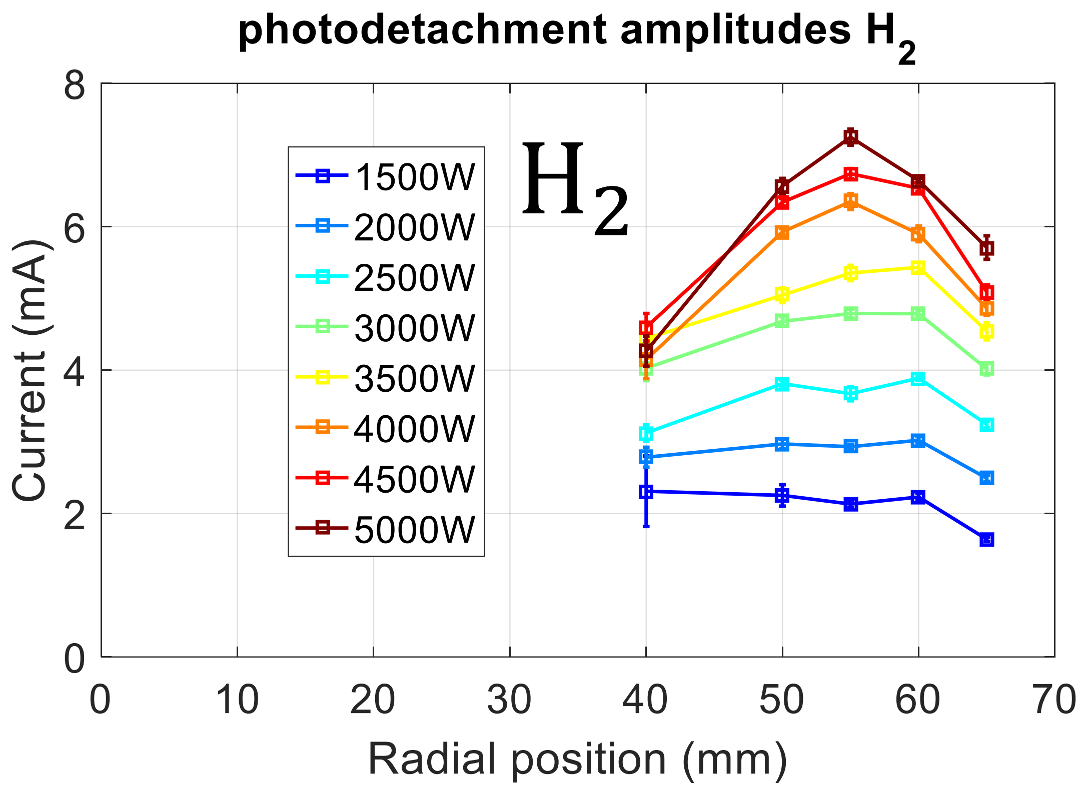


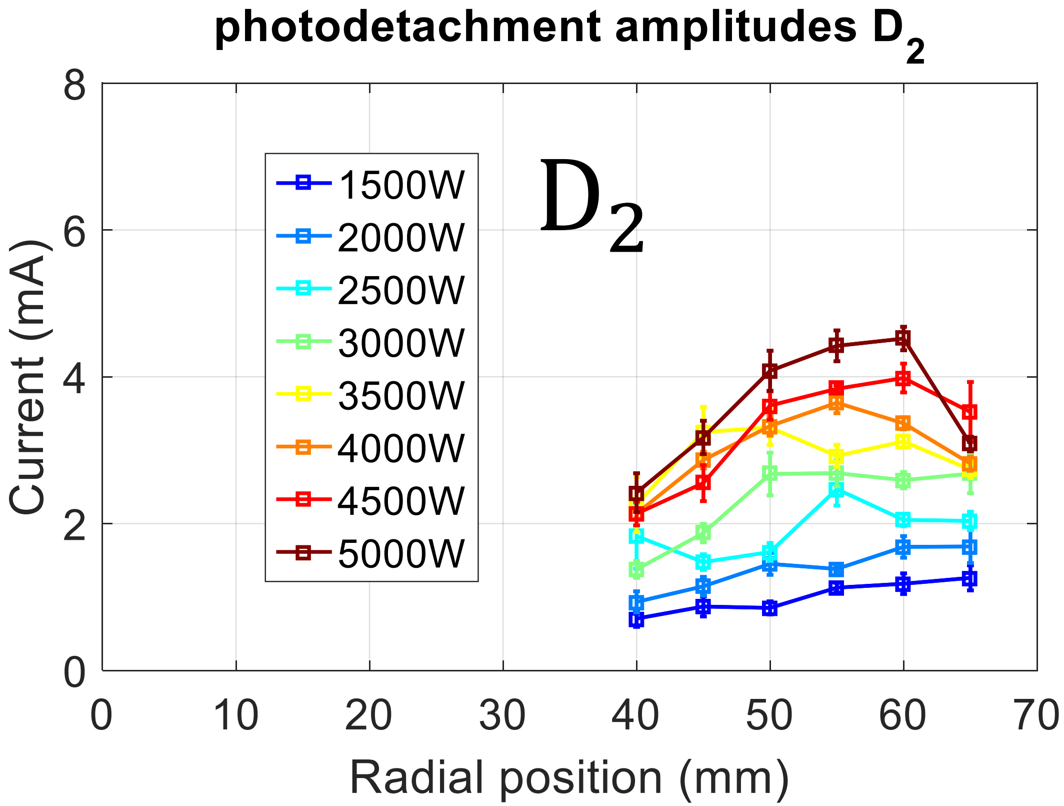
$$\frac{\Delta n_-}{n_-} = 1 - exp\left(-\frac{\sigma}{h\nu}\frac{E}{S}\right)$$

TYPICAL PHOTODETACHMENT SIGNALS IN H_2 AND D_2 PLASMAS



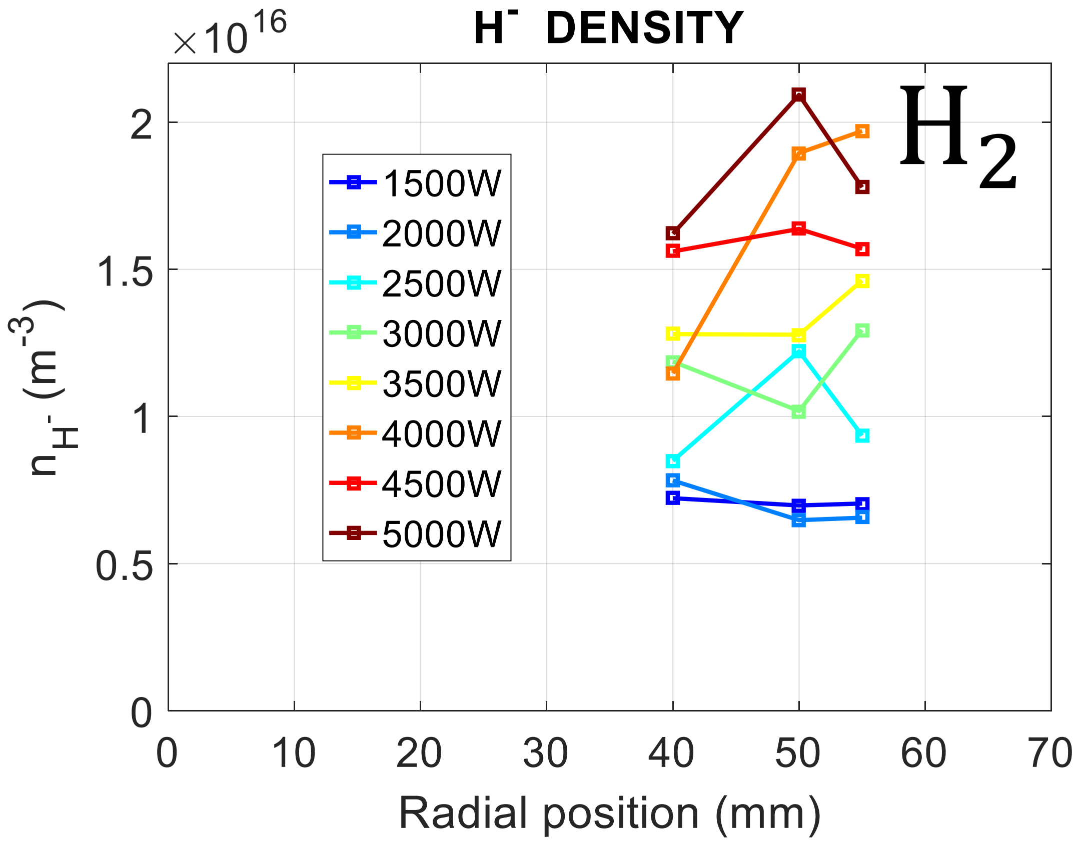
PHOTODETACHMENT AMPLITUDES INCREASE ON PLASMA EDGE

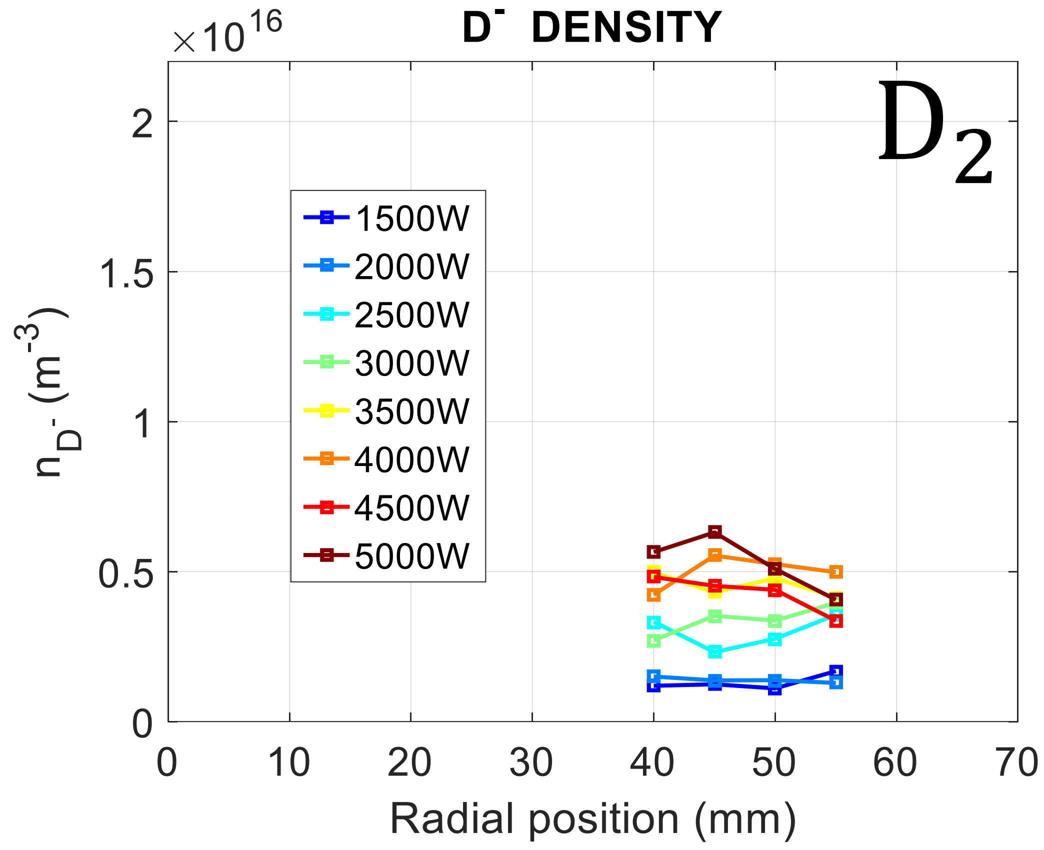




$$\frac{n_-}{n_e} = \frac{i_{pd}}{i_{dc}}$$

n_{H^-} AND n_{D^-} INCREASE WITH POWER





COMPARISON BETWEEN NEGATIVE ION DENSITIES OBTAINED WITH DIFFERENT DIAGNOSTICS

SWISS PLASMA CENTER

NEGATIVE ION DENSITIES AT 3.5kW RF POWER

	H_2	D_2
	n_{H^-}	n_{D^-}
OPTICAL EMISSION SPECTROSCOPY	$(2.3 \pm 1) \times 10^{16}\ \mathrm{m^{-3}}$	$(4.5 \pm 2) \times 10^{16}\ \mathrm{m^{-3}}$
CAVITY RING-DOWN SPECTROSCOPY	$3.3 \times 10^{16}\ \mathrm{m^{-3}}$	$2.5 \times 10^{16}\ \mathrm{m^{-3}}$
LP PHOTODETACHMENT	$1.3 \times 10^{16}\ \mathrm{m^{-3}}$	$0.5 \times 10^{16}\ \mathrm{m^{-3}}$

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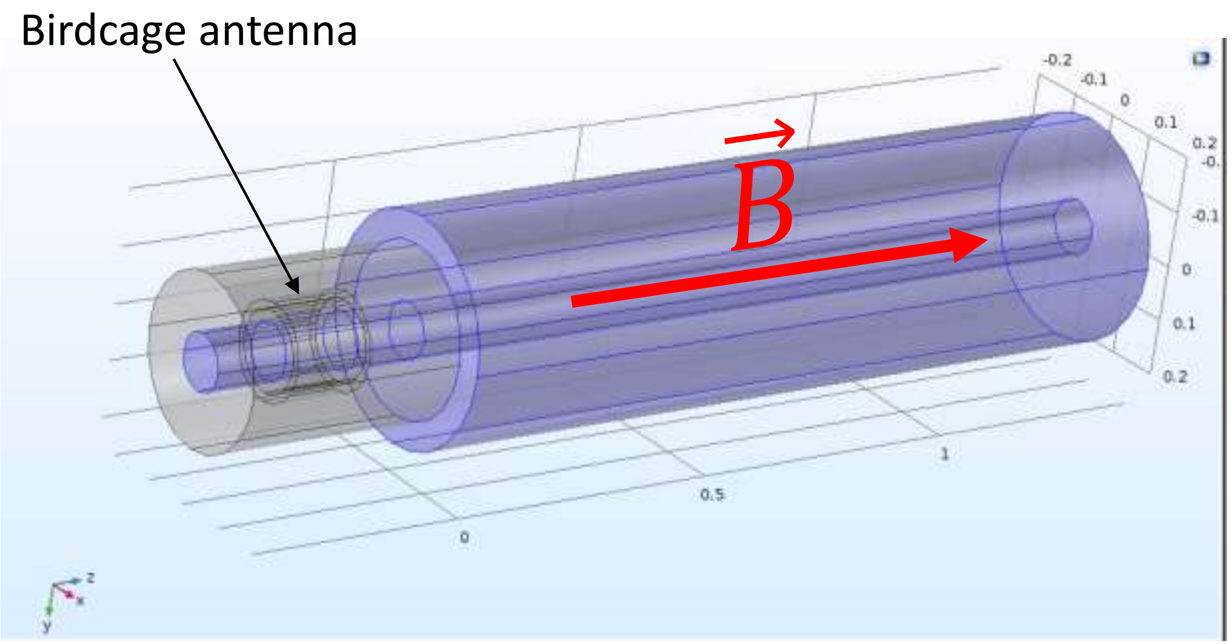
SUMMARY

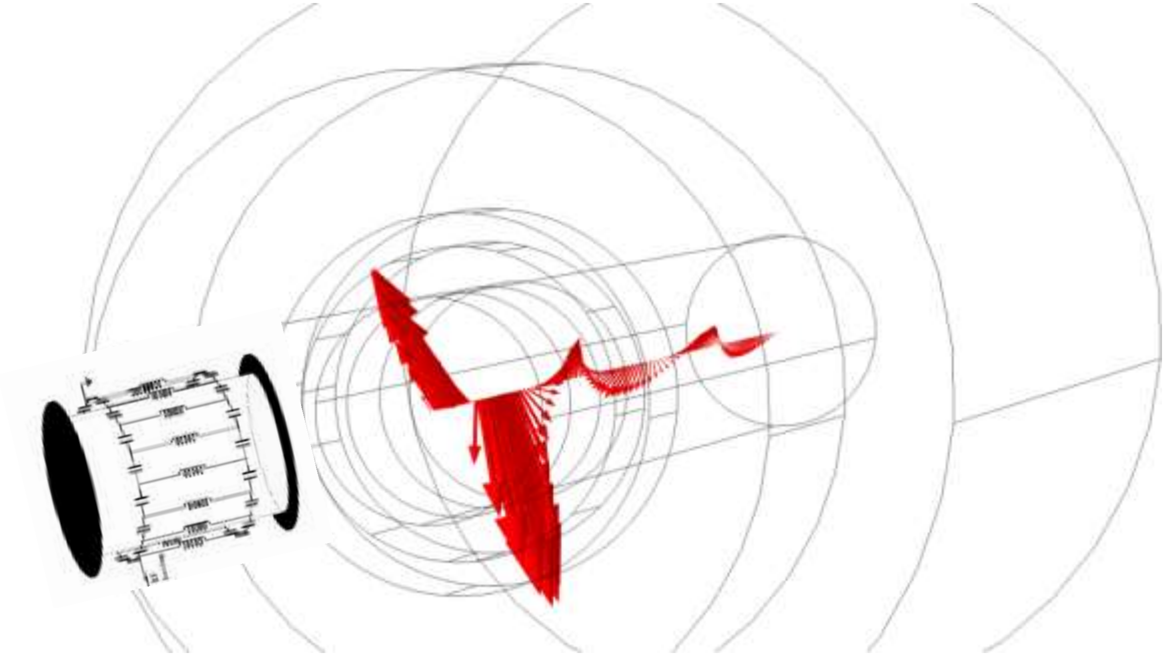
- Demonstrated the production of a dense and homogeneous plasma column in $\mathrm{H_2}$ and $\mathrm{D_2}$ up to 5kW of injected power and the propagation of a helicon wave

- Negative ion diagnostics (OES, CRDS and LP photodetachment) show a negative ion population and density increasing with RF power in $\mathrm{H_2}$ and $\mathrm{D_2}$ plasmas.

OUTLOOK: COMSOL NUMERICAL SIMULATIONS TO STUDY HELICON WAVES



A plasma distribution is considered in the shaded volume



Radial electric field vector along the z-axis

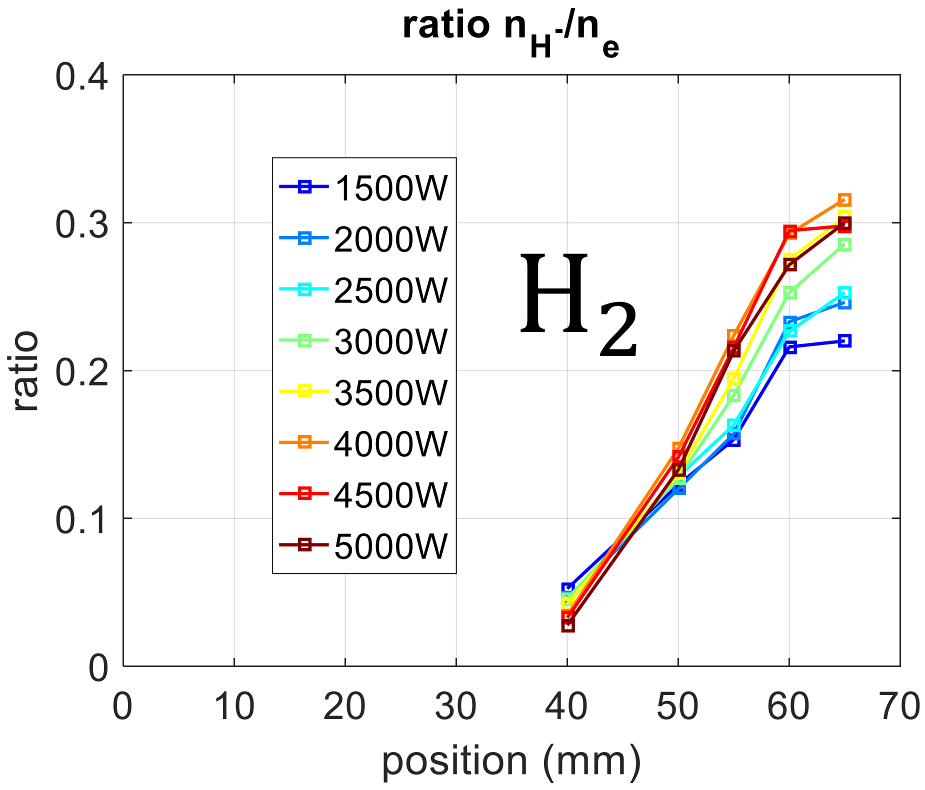
$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} = k_o^2 \,\overline{\overline{\chi}}\, \vec{E}$$

In the next future

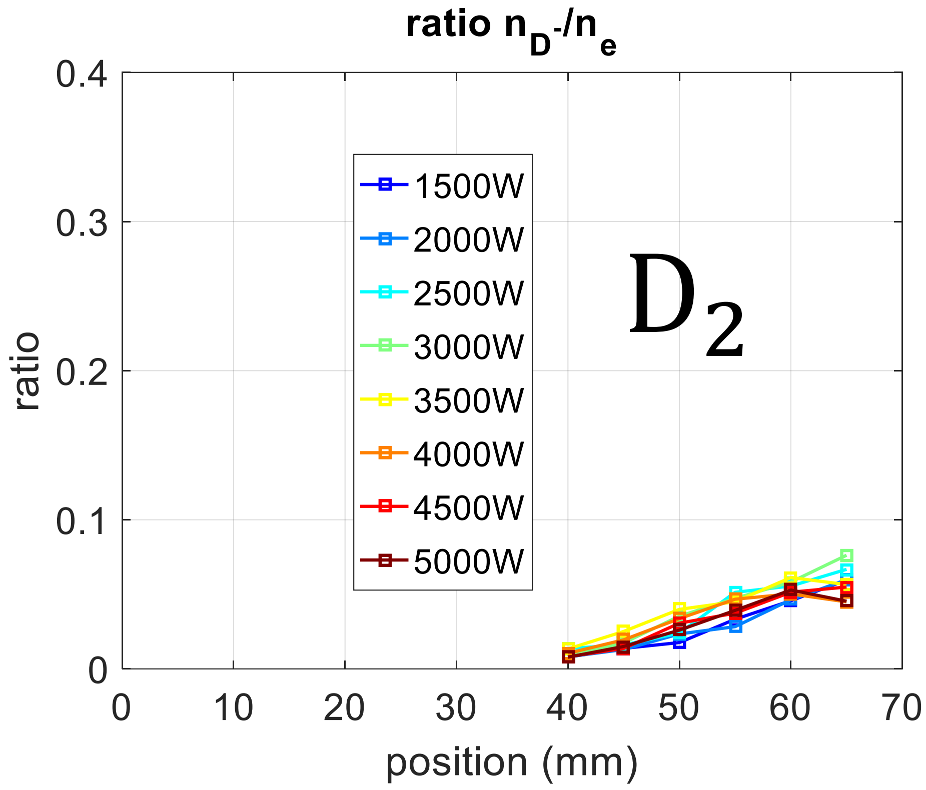
- Time dependent model
- Include transport and diffusion

Thank you for your attention

Backup: Ratios n_{H^-}/n_e and n_{D^-}/n_e increase on edge and are independent on electron density

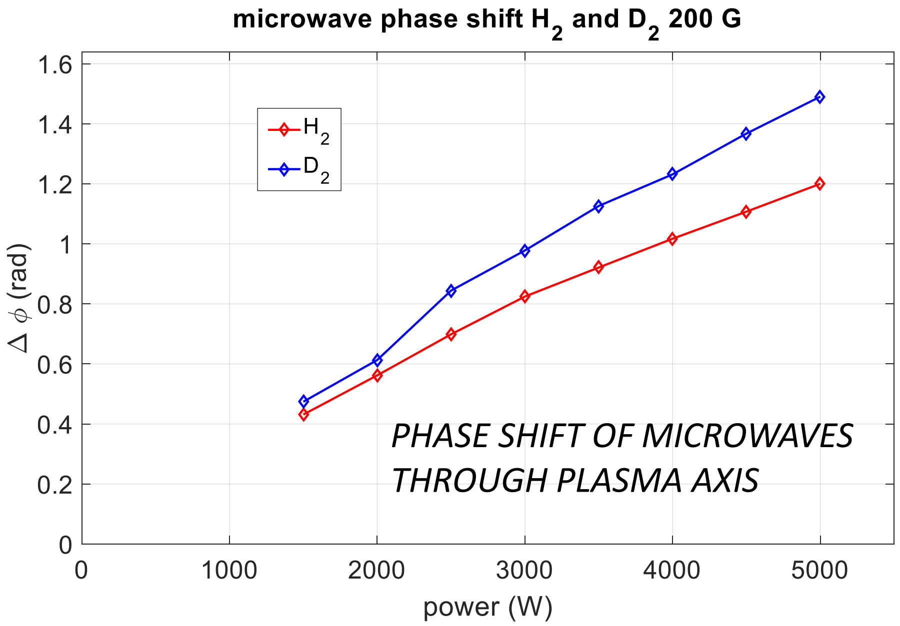


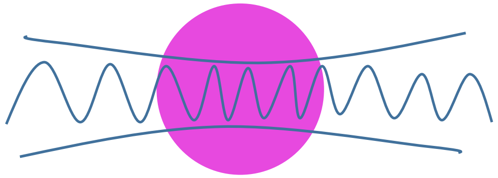
In agreement with spectroscopy

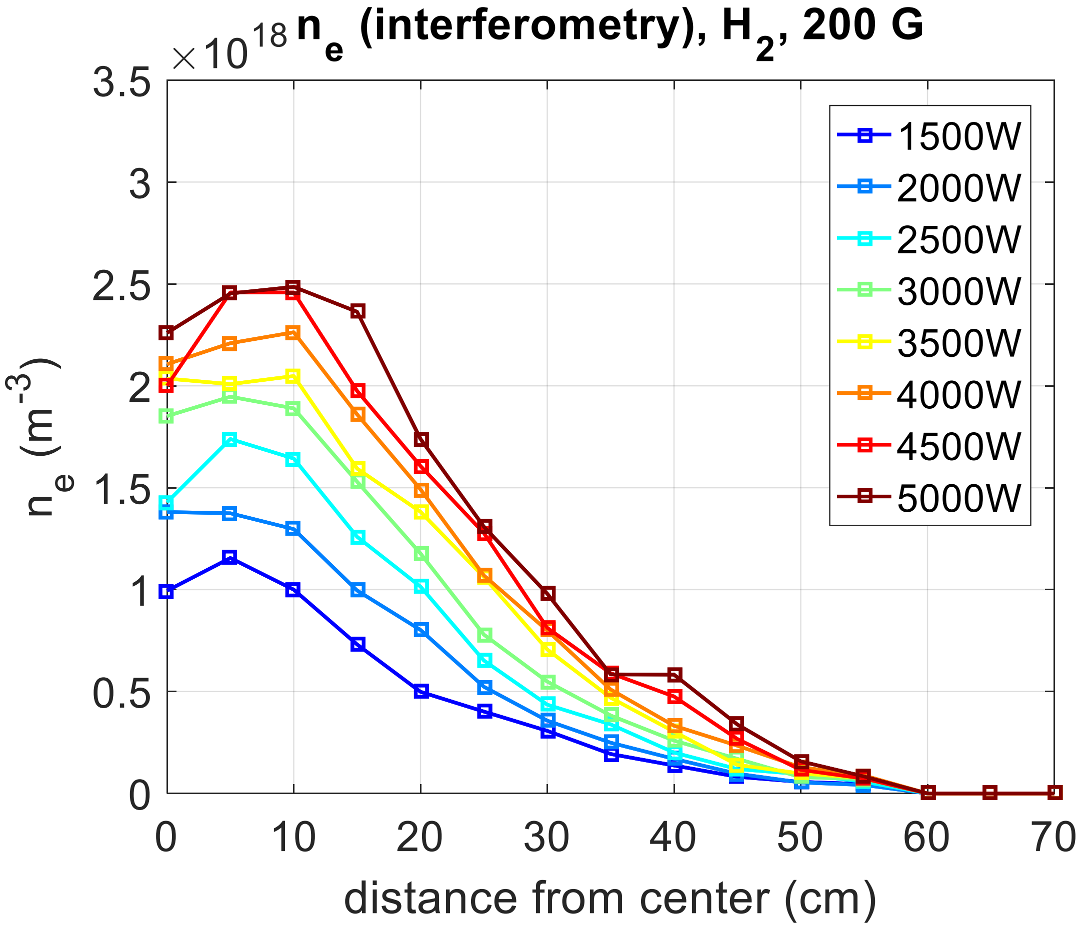


No agreement with spectroscopy

Backup: n_e profiles are calibrated by interferometric measurements



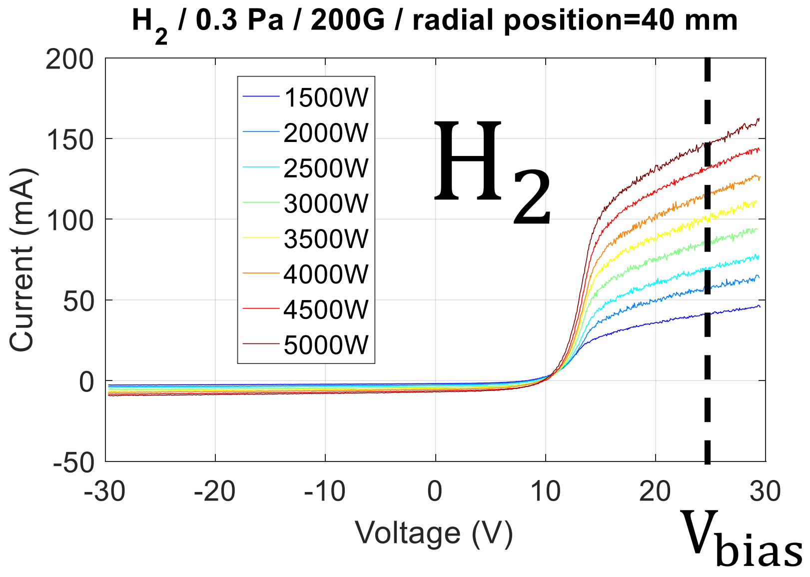


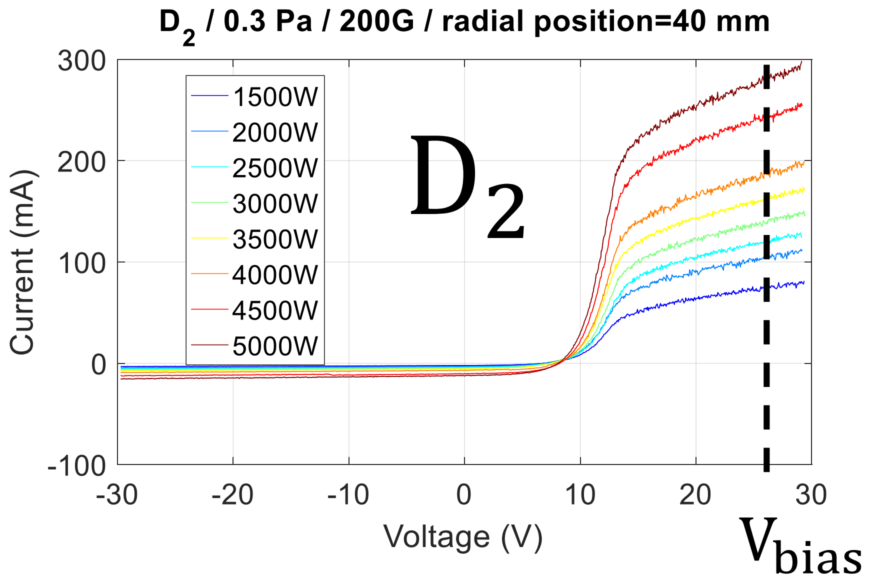


$$\Delta\varphi = \frac{e^2}{2\omega c \varepsilon_0 m_e} n_{e,peak} \int n_{e,norm} dl$$

IV sweeps are used to extract plasma parameters: I_{dc}, the electron current collected at $\mathrm{V} = \mathrm{V_{bias}}$

$40\ mm$





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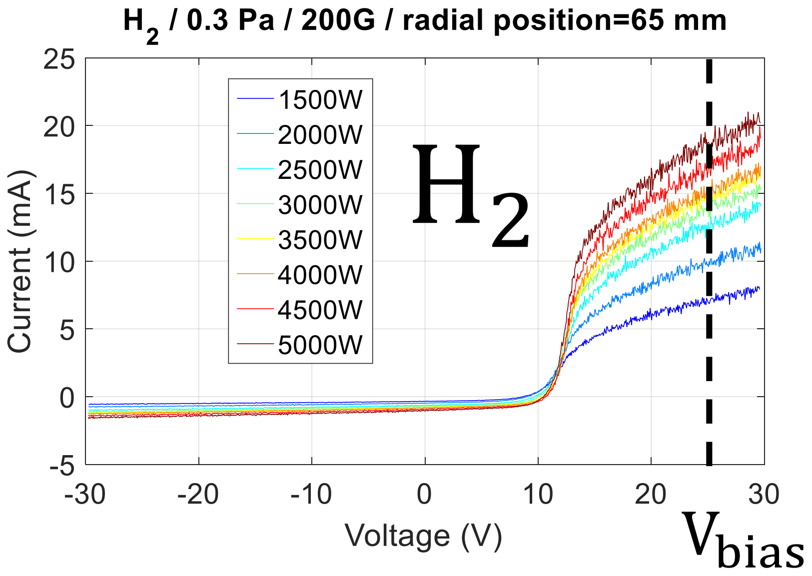
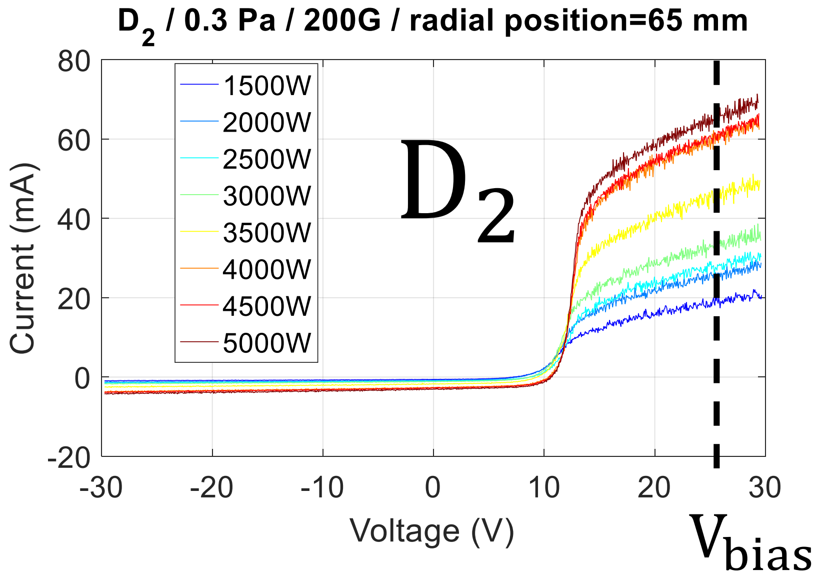
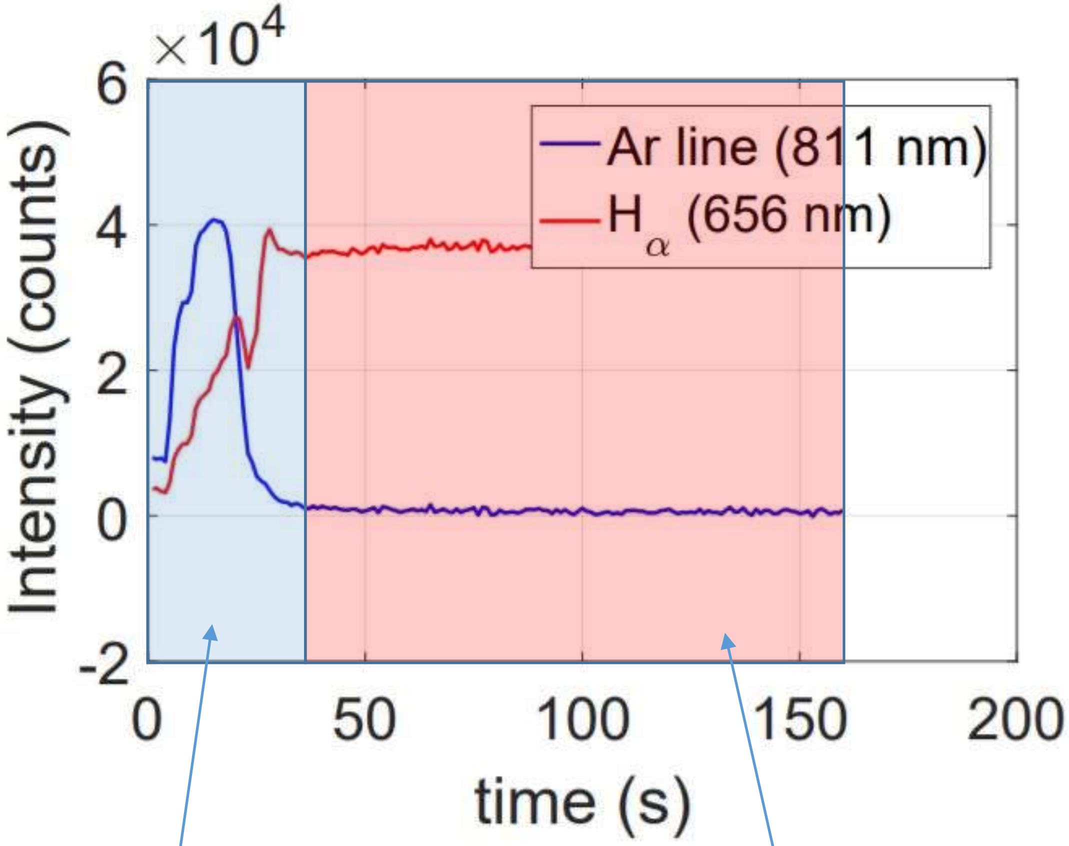
$65\ mm$





Backup: Ar and H light during plasma ignition



$Ar + H_2$ plasma

H_2 plasma