Laser-aided plasma diagnostics of a helicon plasma source for fusion neutral beams

Ivo Furno

R. Agnello, Y. Andrebe, H. Arnichaud, P. Blanchard, A.A. Howling, R. Jacquier, G. Plyushchev

Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne, Switzerland

Ph. Guittienne

Helyssen, Route de la Louche 31, CH-1092 Belmont-sur-Lausanne, Switzerland

M. Barbisan, R. Pasqualotto

Consorzio RFX, Corso Stati Uniti 4, I-35127 Padova, Italy

S. Bèchu

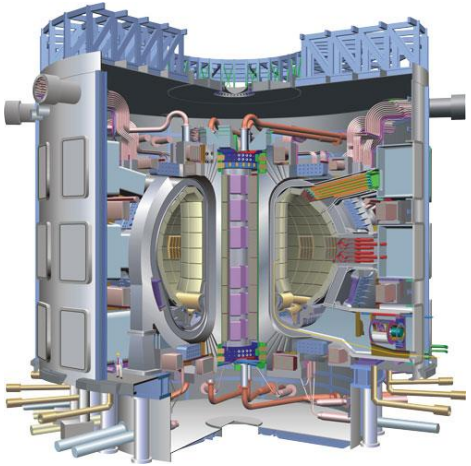
Université Grenoble-Alpes, CNRS, Grenoble INP, LPSC-INP23, 38000 Grenoble, France

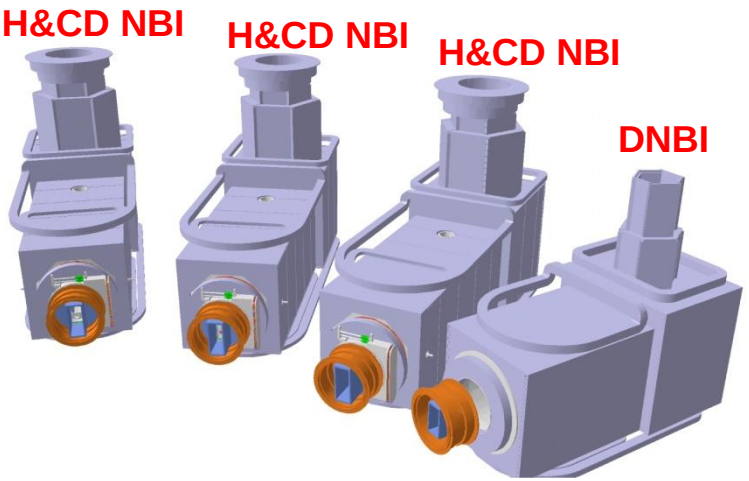
I. Morgal and A. Simonin

CEA, IRFM, F-13108 St-Paul-lez-Durance, France

Swiss Plasma Center

Neutral beams are key to fusion reactors





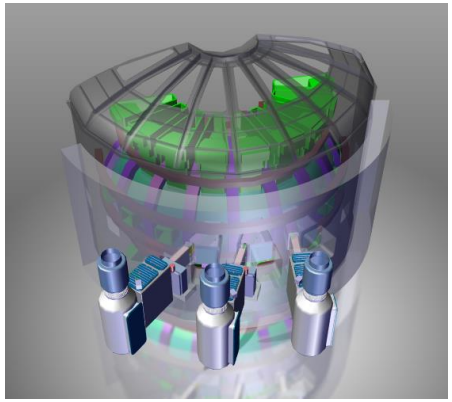
Access to H-mode regime

Achievement of a steady burn

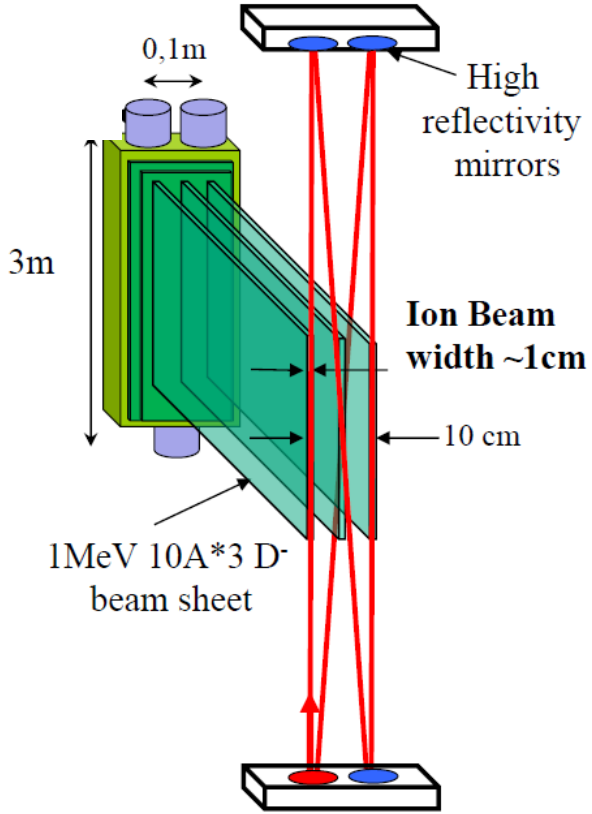
Soft termination of discharge

ITER H&CD NBI	D-
Neutrals Power	16.5MW
Neutrals Energy	1MeV
Beam Current	40A
Pulse length	3600s
Neutralization eff.	~55%

NBs will be a challenge for DEMO



H&CD NBI[1]	D-
Neutrals Power	16.8MW
Neutrals Energy	800KeV
Beam Current	34A
Pulse length	7200s
Neutralization eff.	>70%

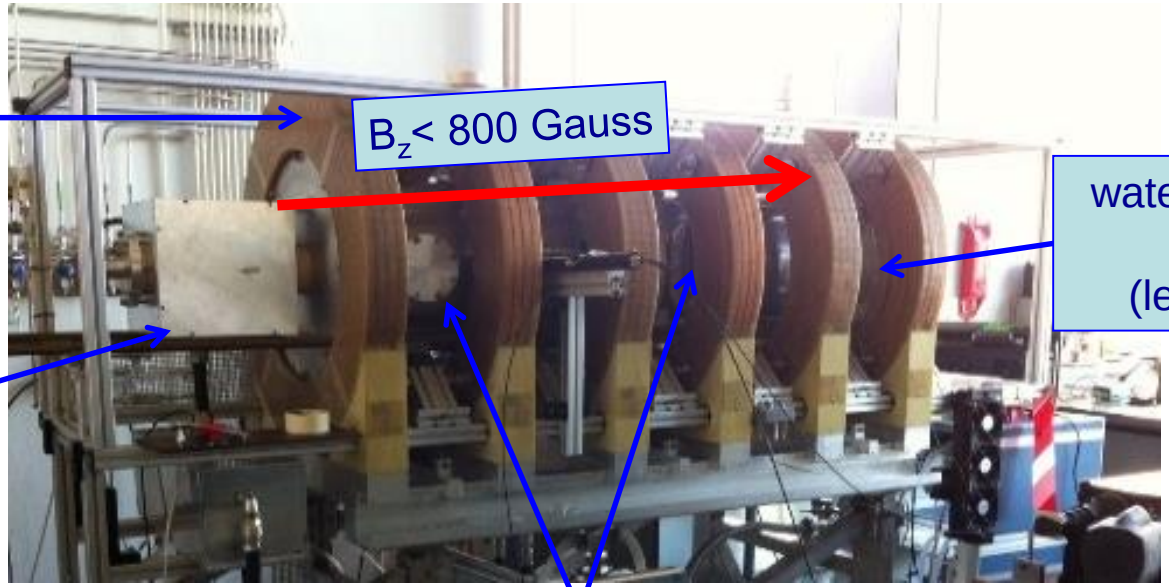


[1] P. Sonato et al., Nucl. Fusion **57** (2017)

[2] A. Simonin et al., Nucl. Fusion **55** (2015)

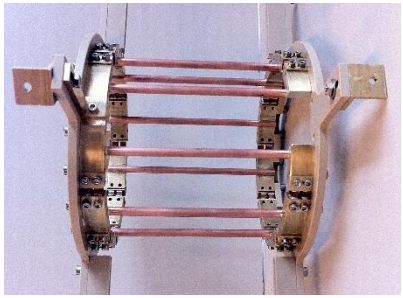
Can helicon plasmas be used to produce negative ions for NBs?

The Resonant Antenna Ion Device (RAID)



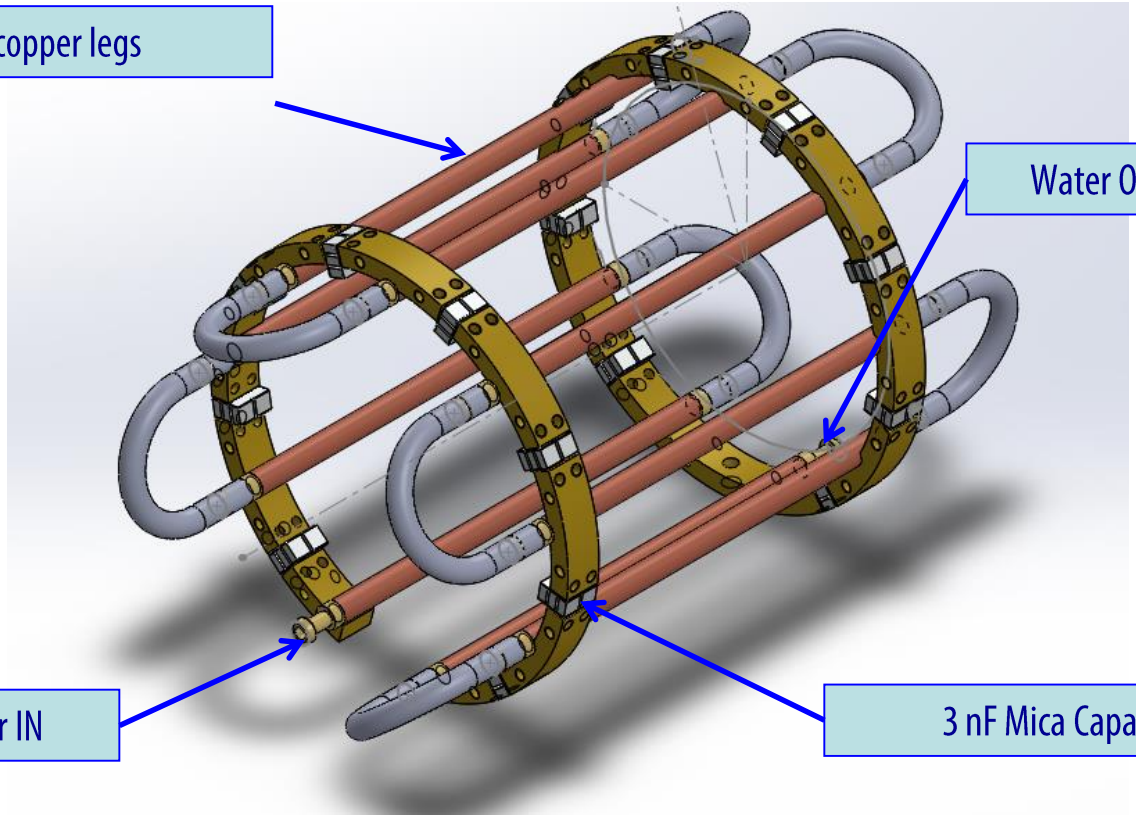
I. Furno et al., EPJ Web of Conferences 157 (2017)

10kW,13.56 MHz resonant antenna



9 water-cooled copper legs

D_{int}=13 cm
L = 15 cm



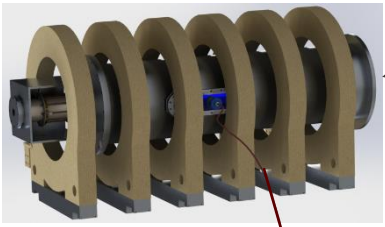
Water OUT

Water IN

3 nF Mica Capacitors

Swiss Plasma Center

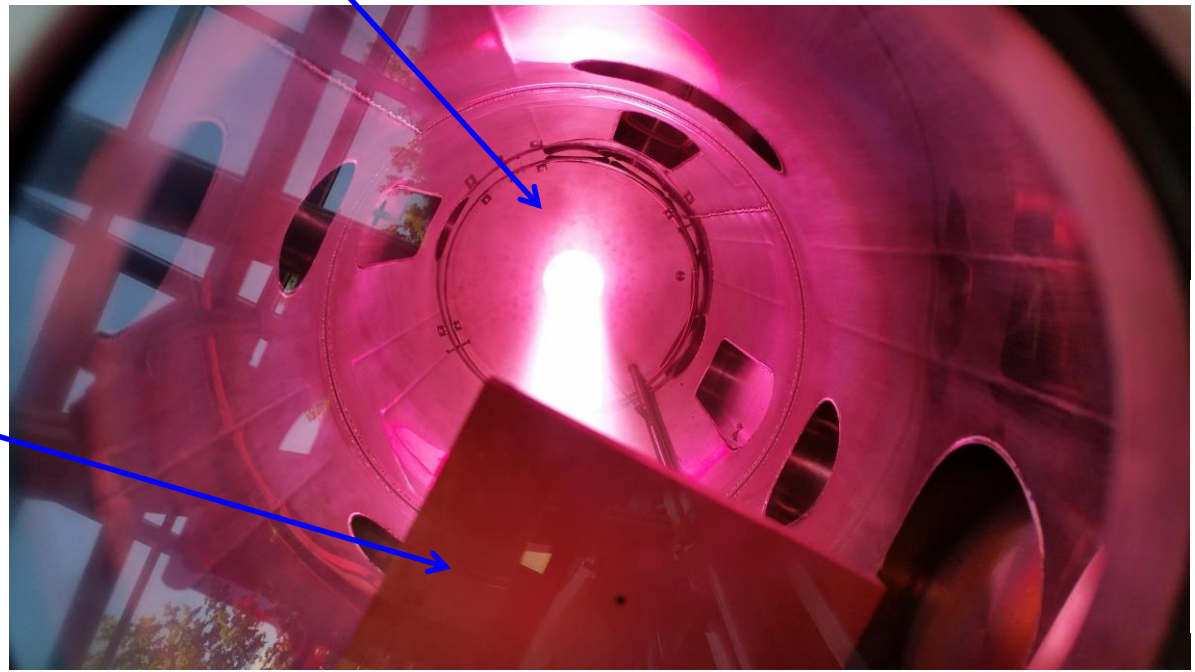
A 3 kW, 0.3 Pa, H_2 plasma



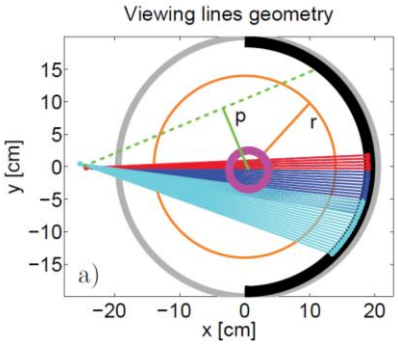
Birdcage antenna

Optical emission spectroscopy

high throughput spectrometer

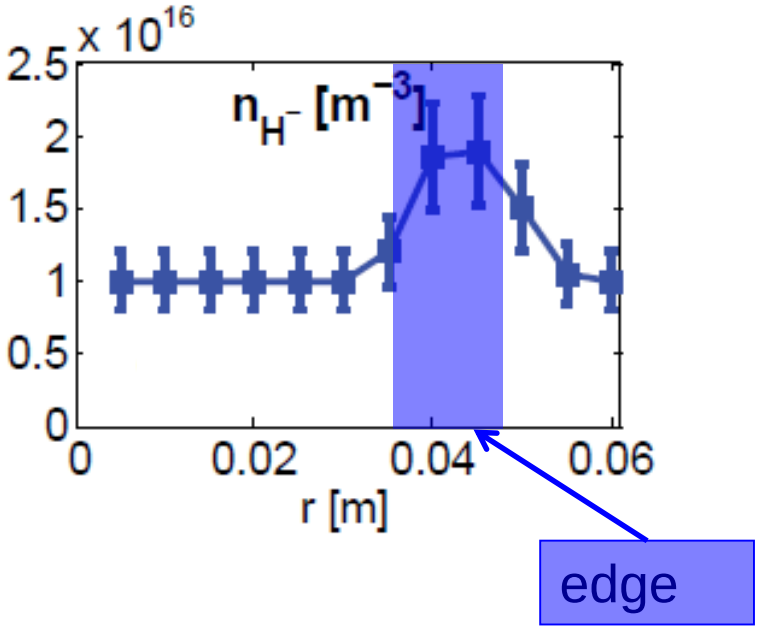


water-cooled end plate



Swiss Plasma Center

OES and collisional-radiative code reveal negative ions in H_2/D_2 plasmas

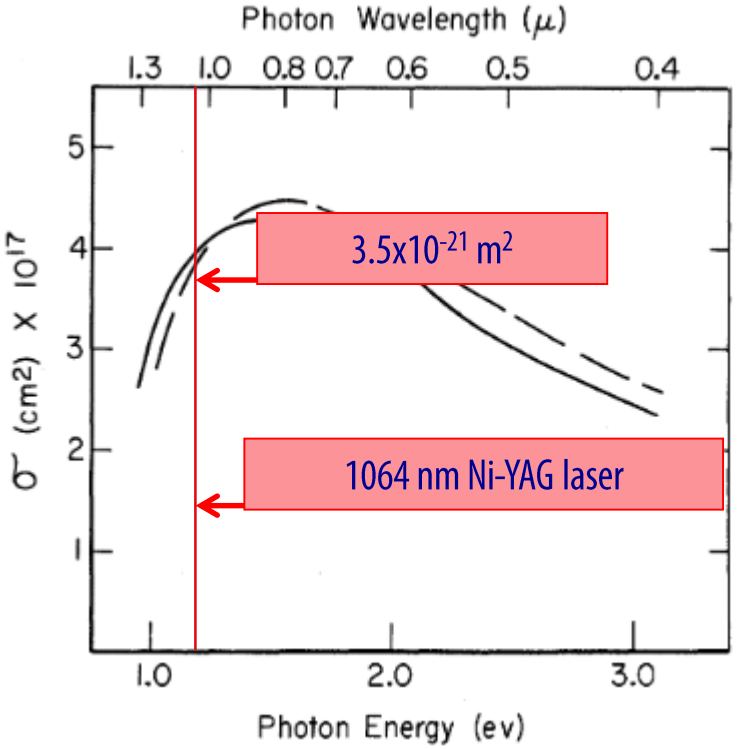


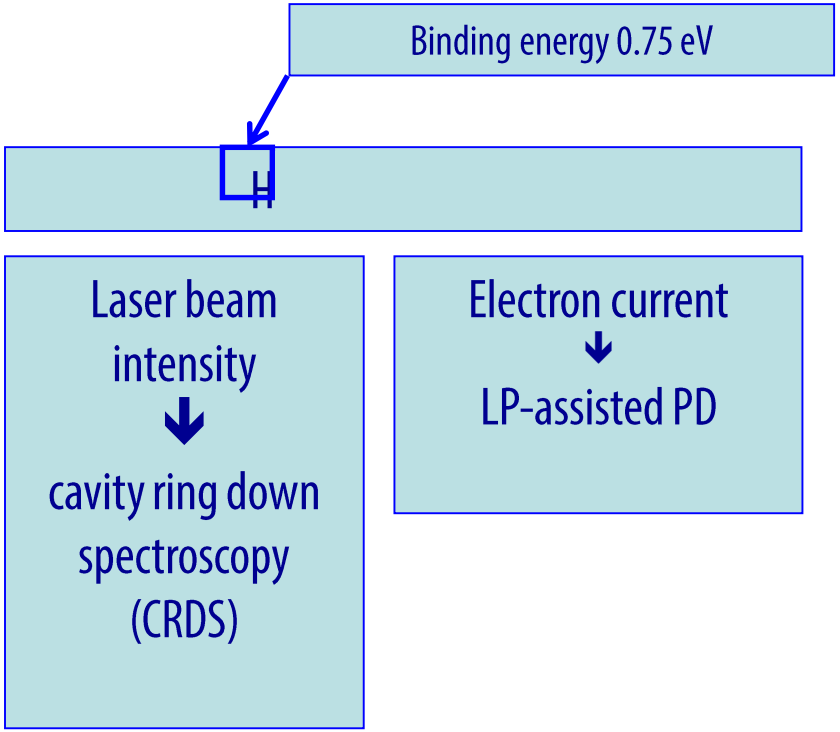
C. Marini et al., Nucl. Fusion **57** (2017) 036024

Outline

- Principle of laser photo-detachment (PD)
- Cavity Ring Down Spectroscopy (CRDS)
- Langmuir probe (LP)-assisted laser photo-detachment
- Results
- Conclusions

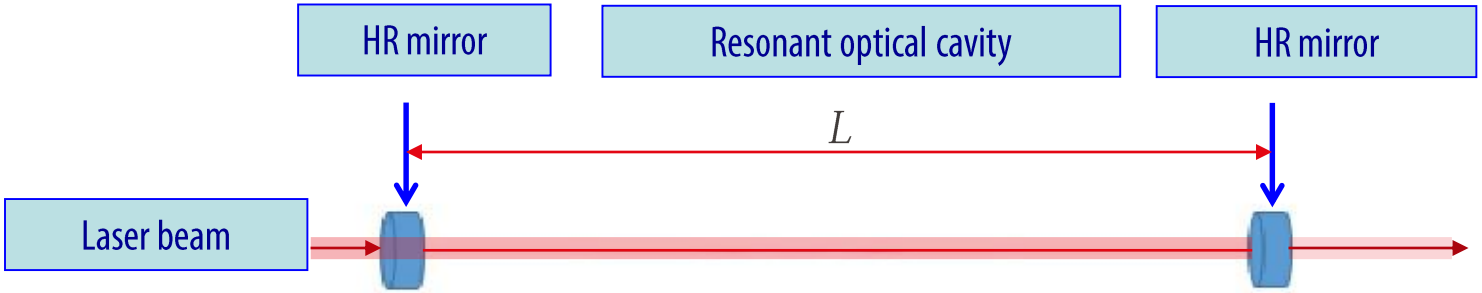
Laser photo-detachment (PD)





S.J. Smith and D. S. Burch, Phys. Rev. Lett. 2, 165 (1959)

Principles of cavity ring down spectroscopy (CRDS)



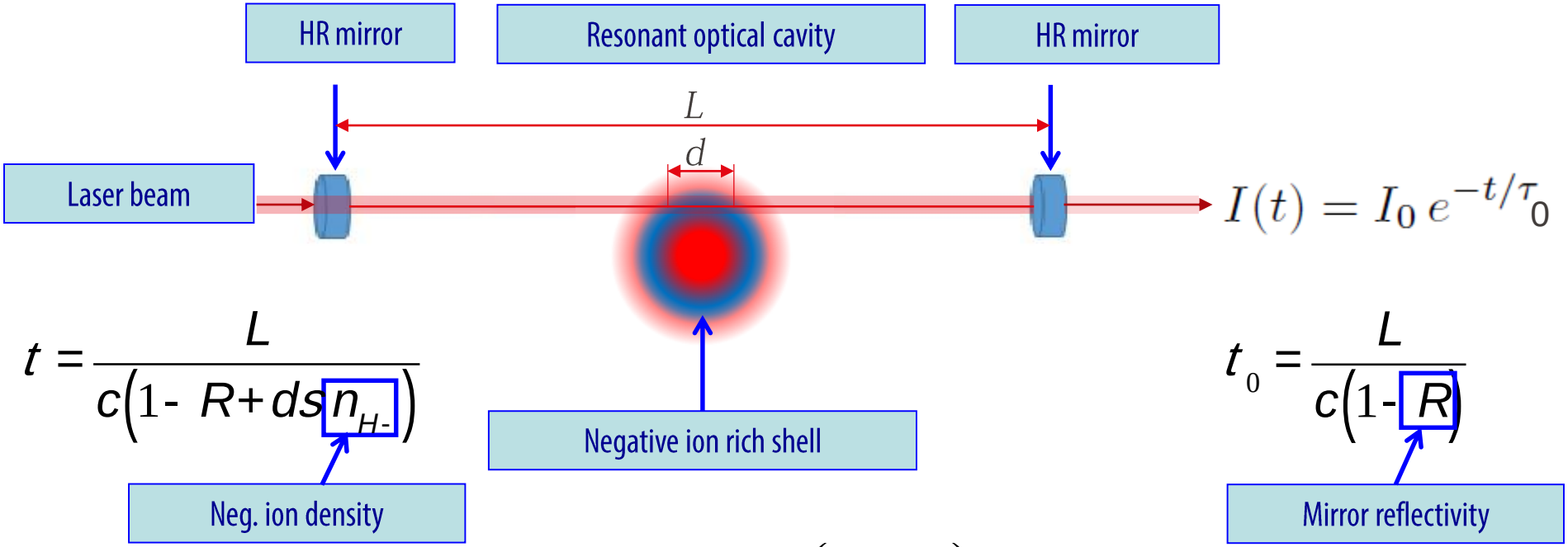
$$I(t) = I_0\, e^{-t/\tau_0}$$

$$t_0 = \frac{L}{c\left(1-R\right)}$$

Mirror reflectivity

Swiss Plasma Center

Principles of cavity ring down spectroscopy (CRDS)



$$\bar{n}_{H^-} = \frac{1}{s}\frac{L}{cd}\left(\frac{1}{t} - \frac{1}{t_0}\right)$$

Swiss Plasma Center

CRDS implementation on RAID

Mirror mount

Neg. ion shell

Port extensions

L=91cm

Ni-YAG laser
7.5W
@ 50 Hz
6ns pulse

APD + 20 GHz
oscilloscope

IR mirrors

Shutters

Swiss Plasma Center

Practical constraints to implement CRDS[1]

FWHM of laser pulse~5ns

1 Avoid overlapping modes in the cavity

$$L_{min} = c\Delta t / 2 = 75cm$$

L=0.91 m

Curv. radius of HR mirrors

2 Stability of the cavity

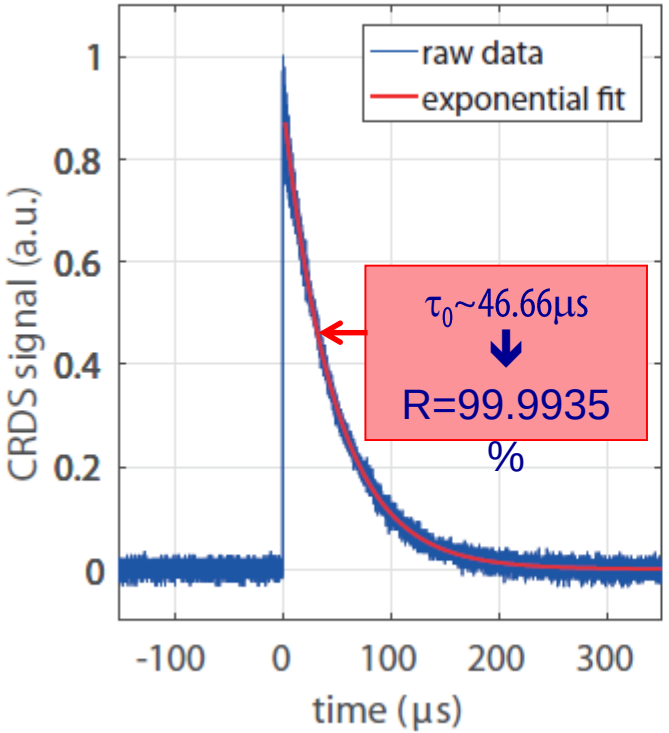
$$0 < \left(1 - L/r\right)^2 < 1$$

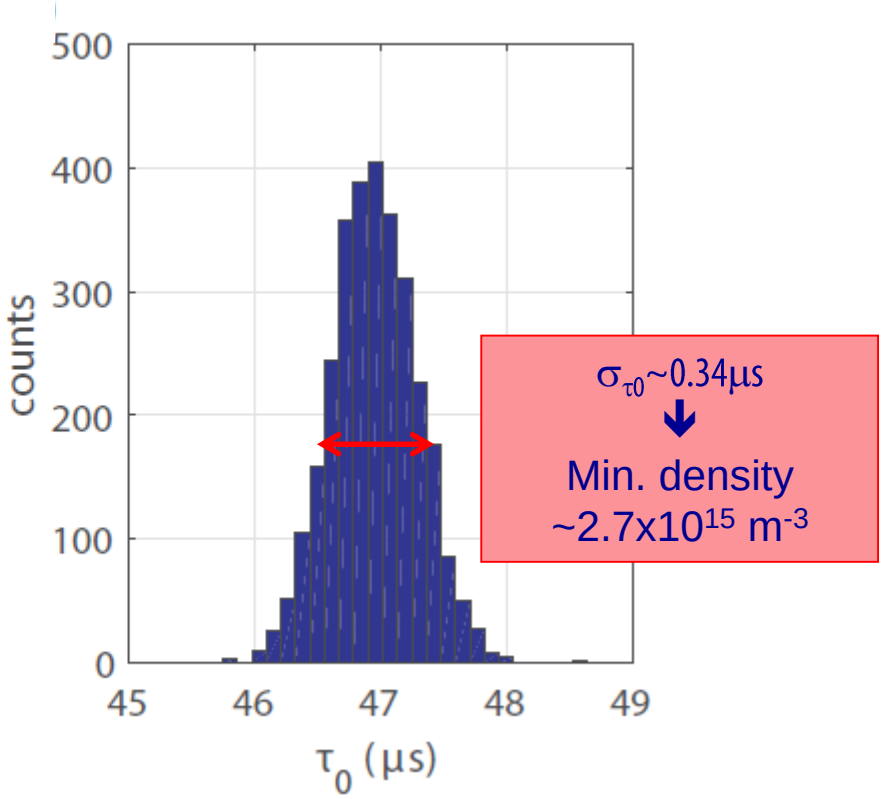
r=1 m

Layertech HR mirrors with nominal R = 99.994% ➔ τ_0 ~50 μs

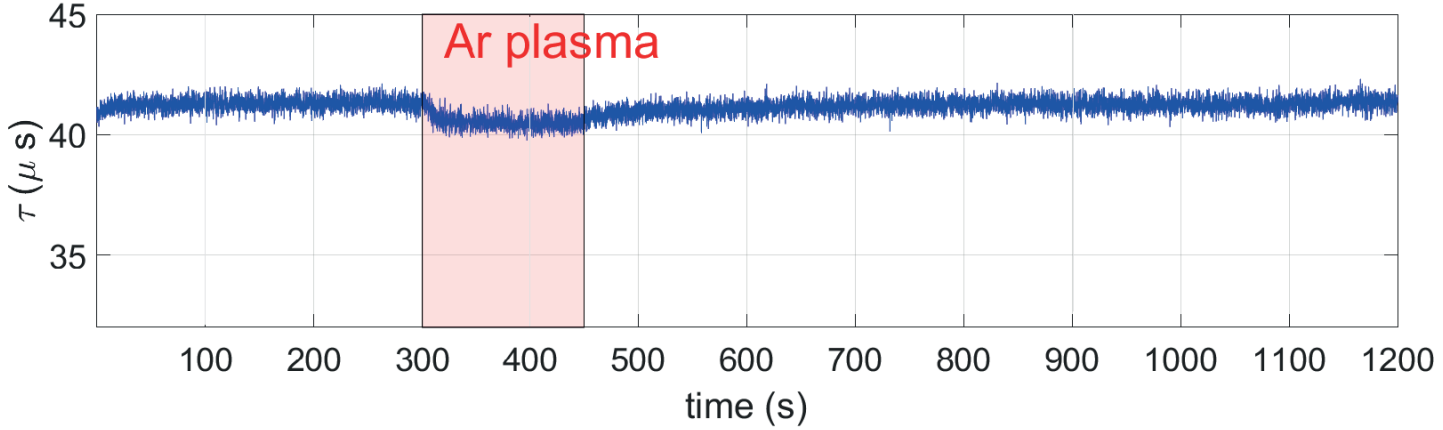
[1] E. A. Bahaa, et al., Fundamentals of Photonics, John Wiley and Sons, Inc. (1991)

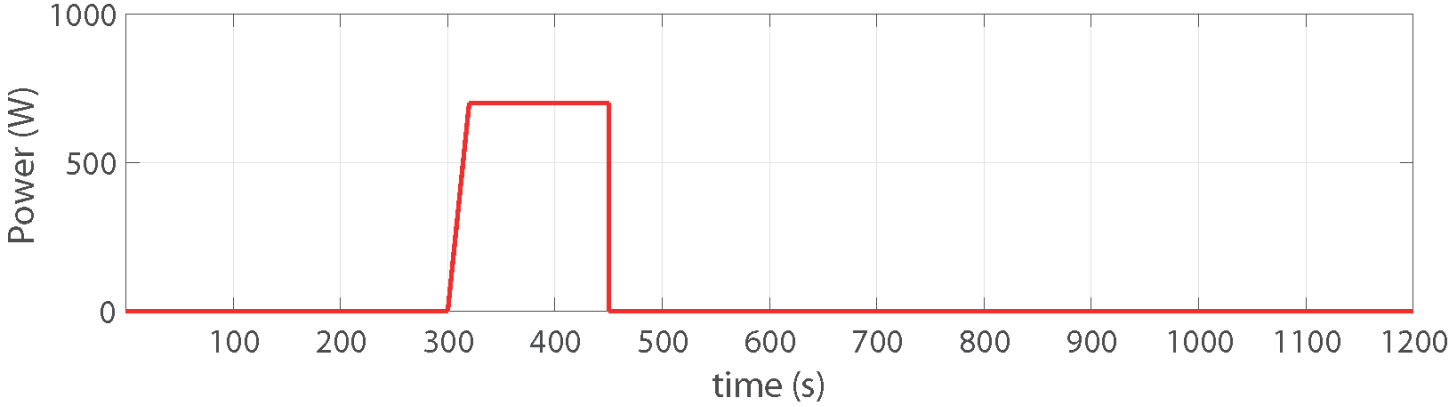
Vacuum measurements consistent with R



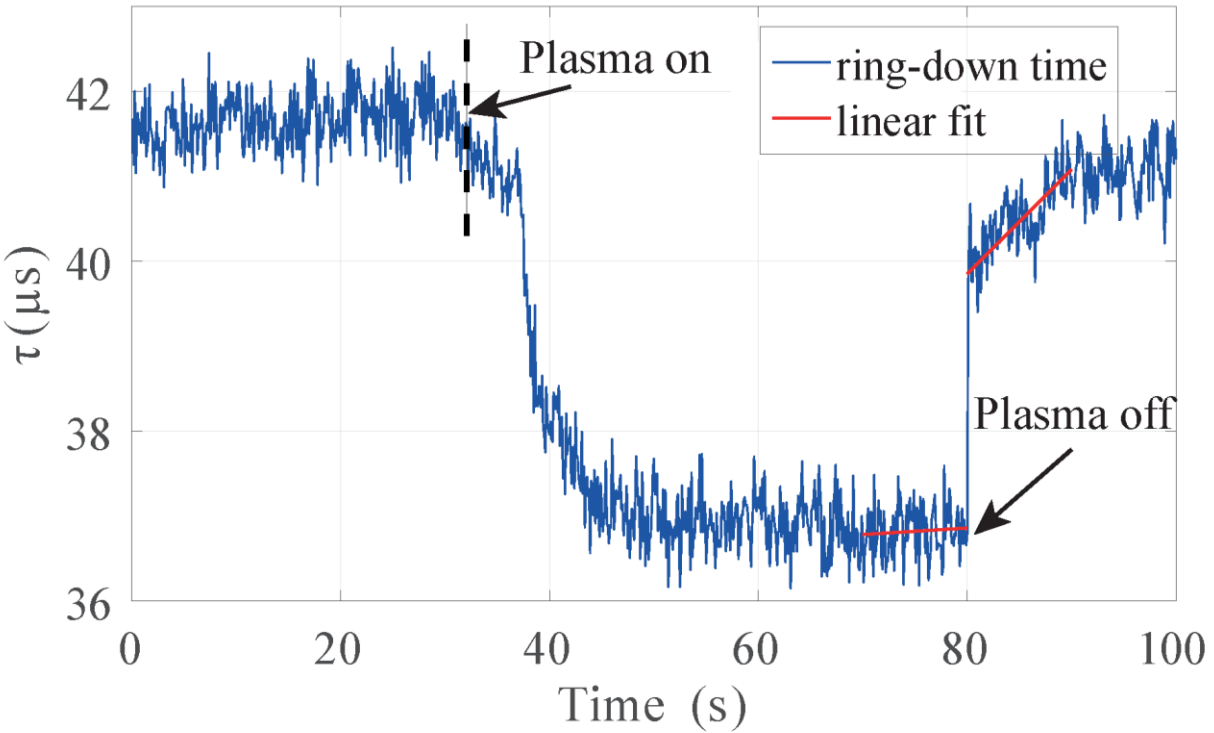


Ar experiments...



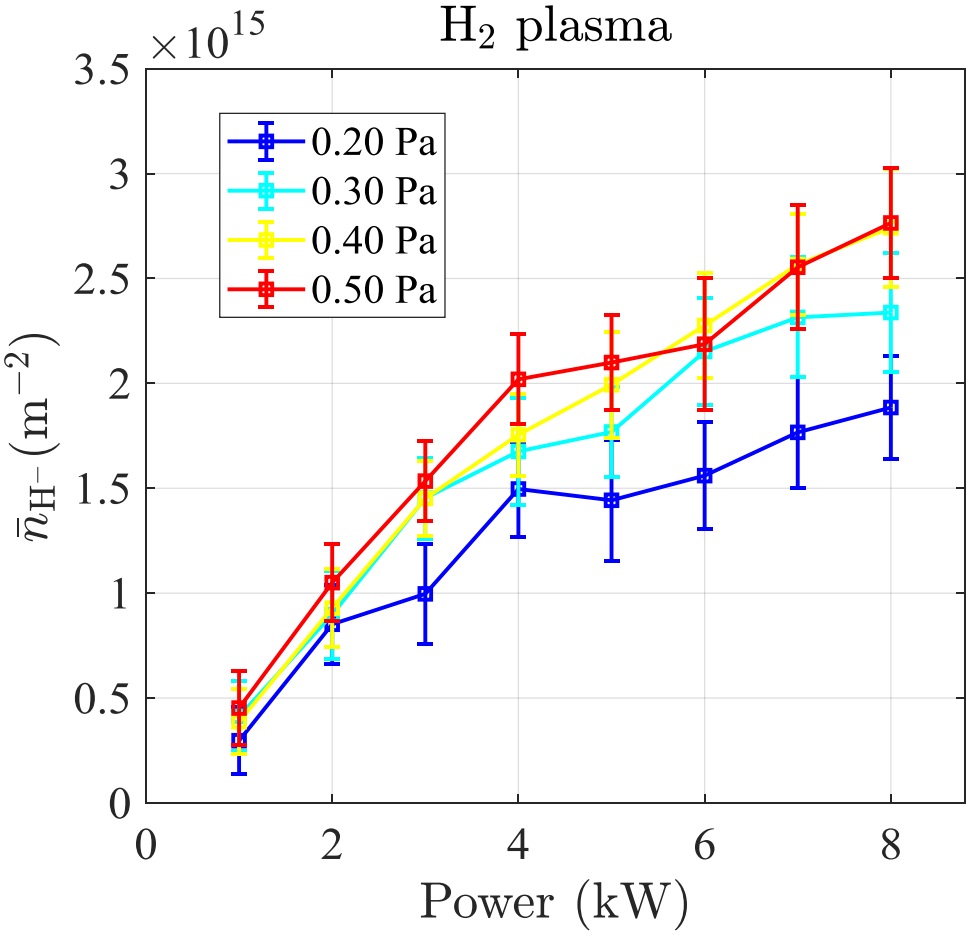


CRDS implementation on the RAID device



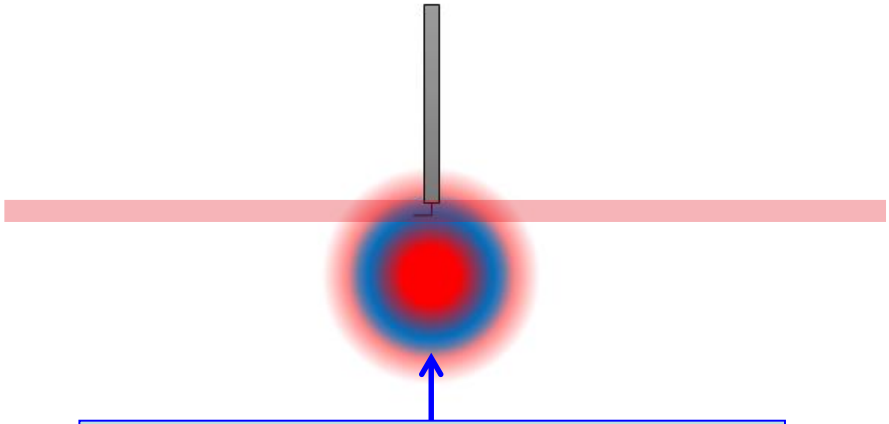
Swiss Plasma Center

CRDS demonstrates the presence of negative ions



Principle of LP-assisted laser photodetachment

LP in e^- sat mode → $i = i_{DC}$

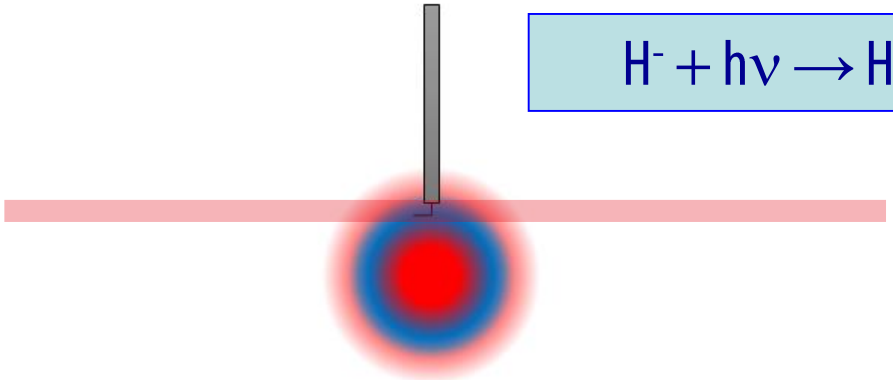


Negative ion rich shell

Principle of LP-assisted laser photodetachment

LP in e^- sat mode → $i = i_{DC}$ → $i = i_{DC} + i_{PD}$

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

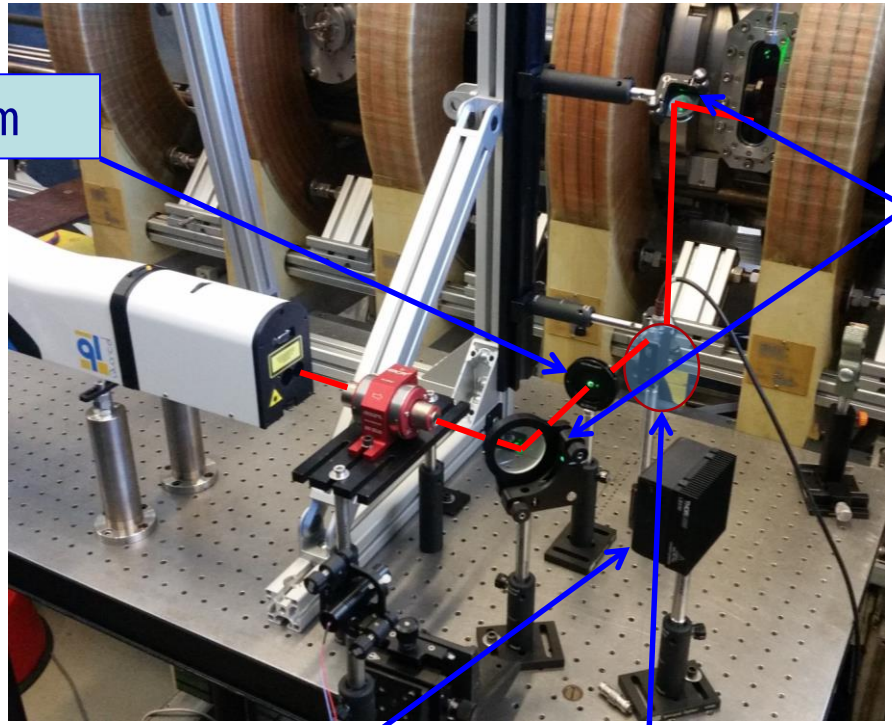


Negative ion rich shell

$$\frac{i_{DC}}{i_{PD}} = \frac{n_e}{n_{H^-}}$$

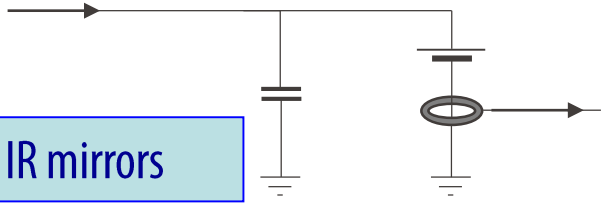
M. Bacal et al., RSI 2000

LP-assisted PD: implementation on RAID



Diaphragm

IR mirrors



Beam dump

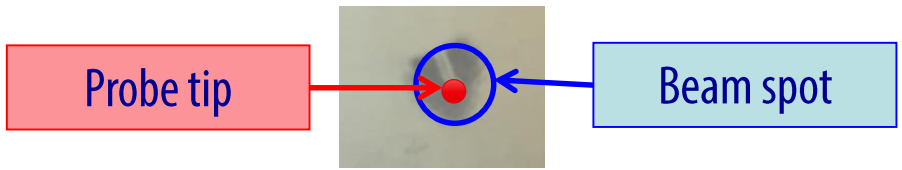
IR photod. for trigger

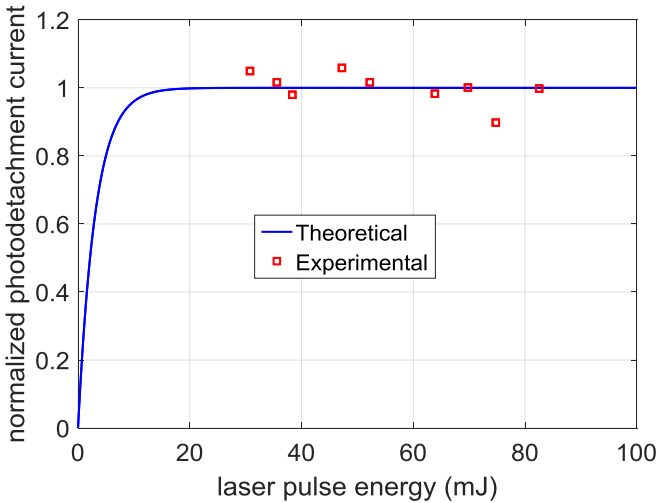
RF compensated L-shaped LP

Practical constraints to implement LP-assisted PD[1]

1. Probe bias must be above the plasma potential
2. PD current independent from beam spot size
3. All neg. ions in the target volume must be PD

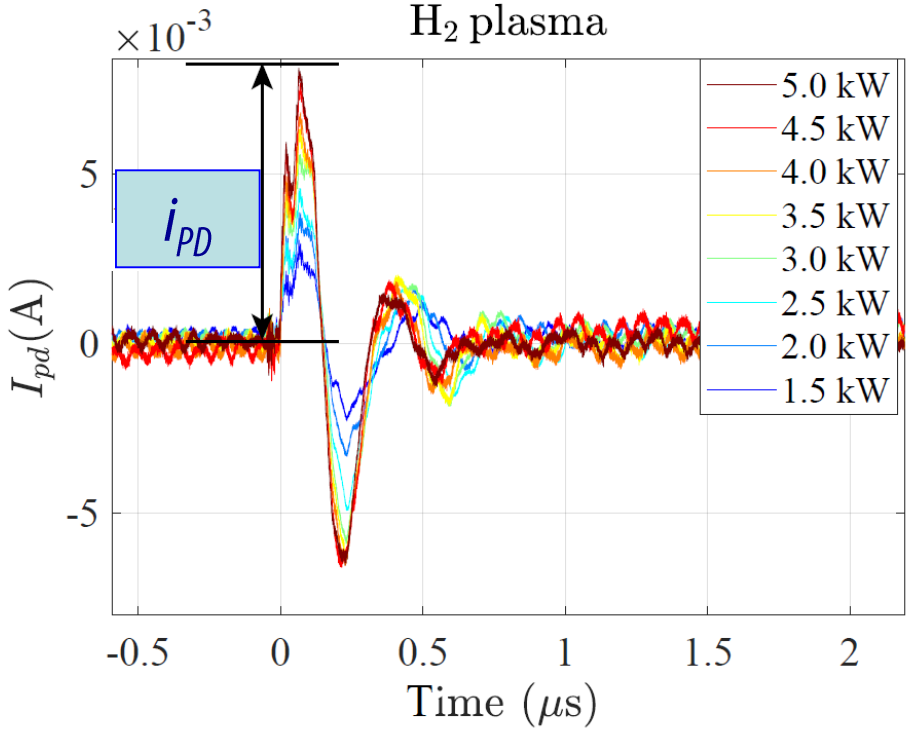
$$\frac{Dn_{H^-}}{n_{H^-}} = 1 - \exp\left(-\frac{sE}{hnS}\right)$$





[1] M. Bacal, et al., RSI 2000

Current time trace reveal photodetached electrons

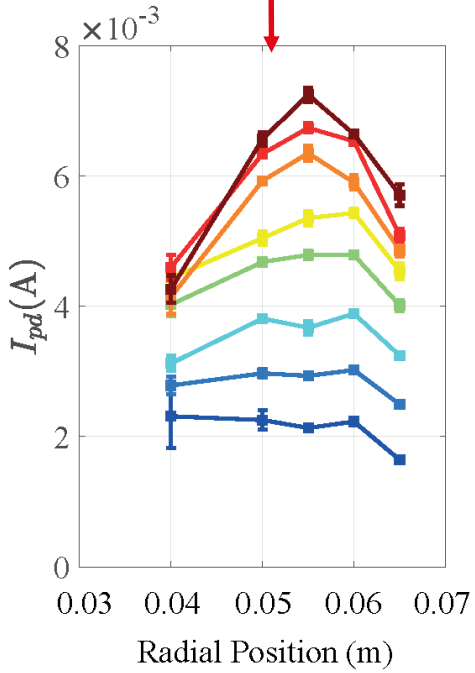


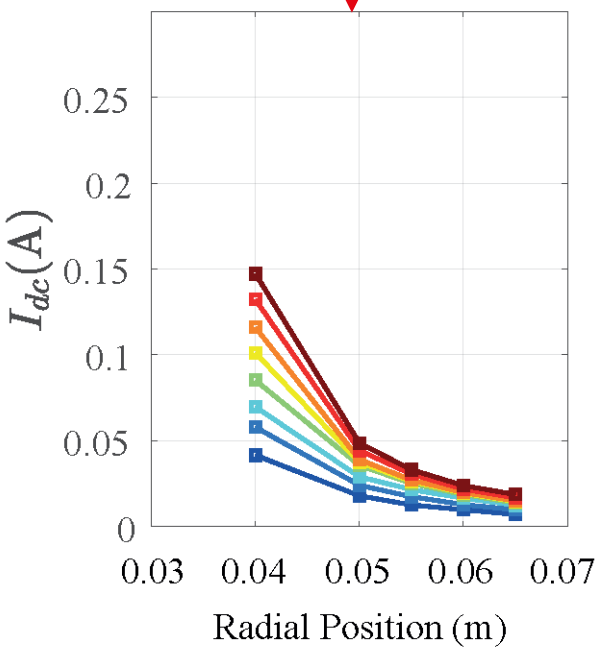
R. Agnello et al., submitted to Nucl. Fusion

Computing n_{H^-} from LP-assisted PD and LPs

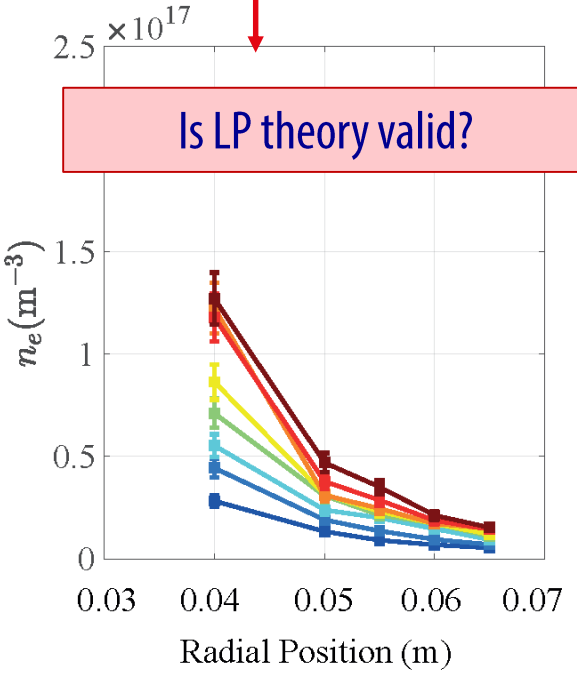
$$n_{H^-} = \frac{i_{PD}}{i_{DC}} n_e$$

Swept LP

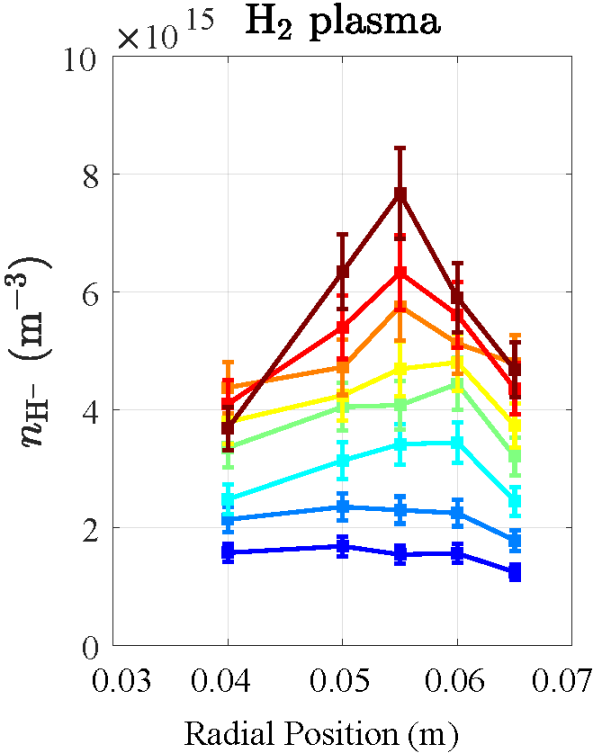


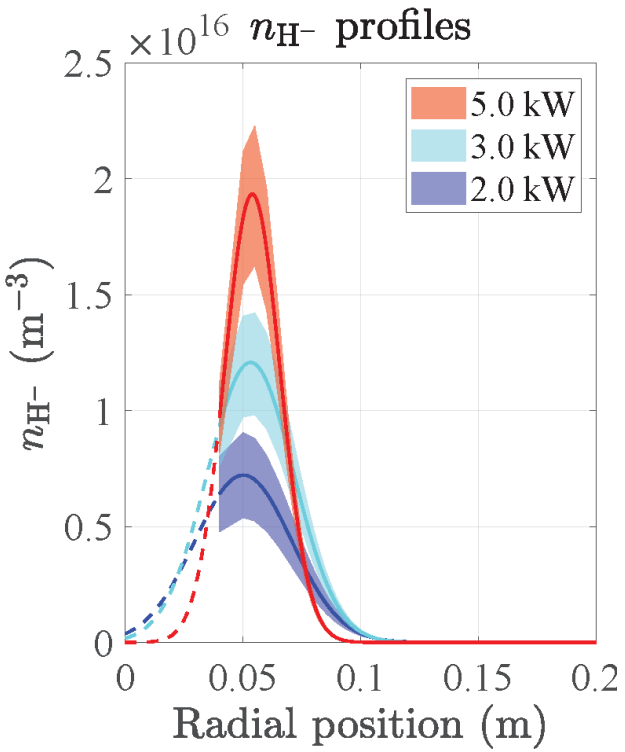


Is LP theory valid?



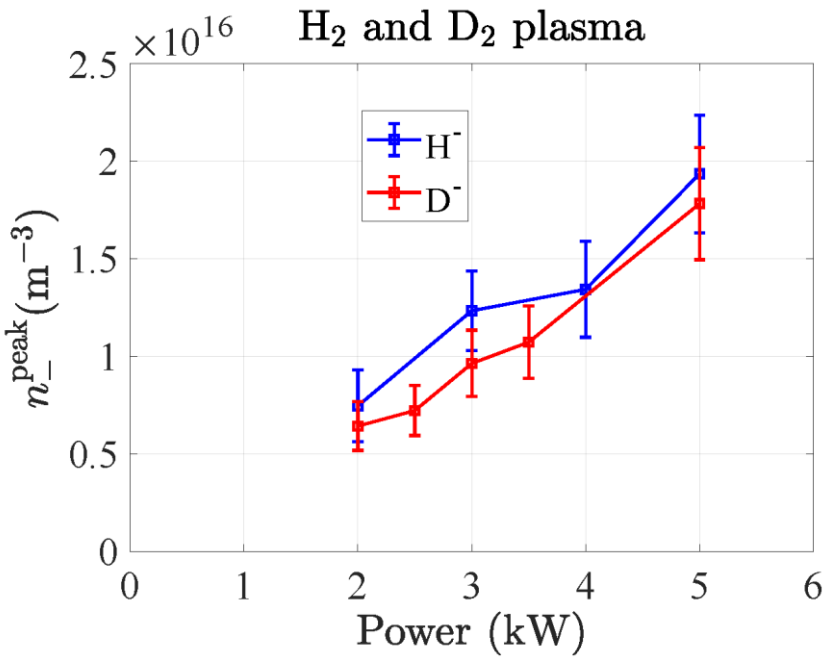
Us





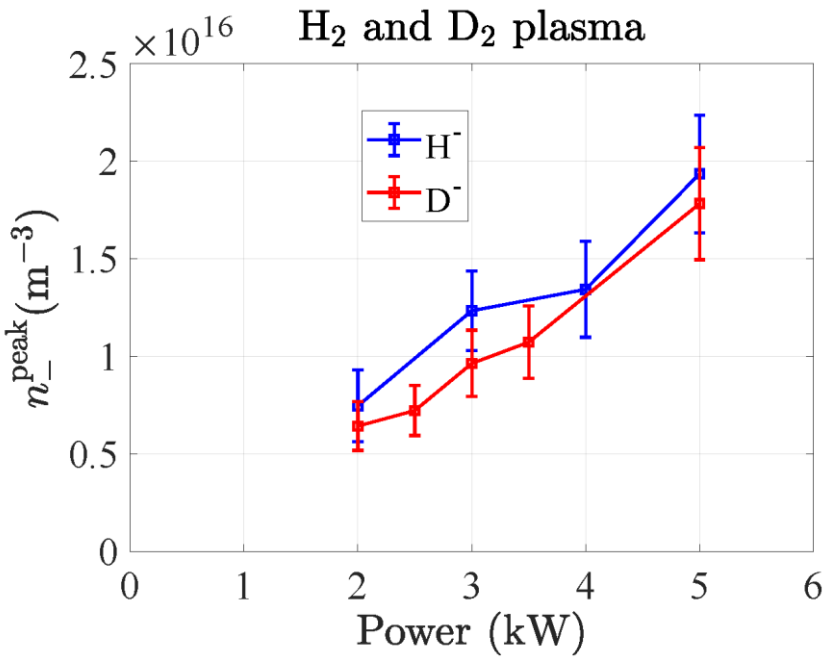
R. Agnello et al., submitted to Nucl. Fusion

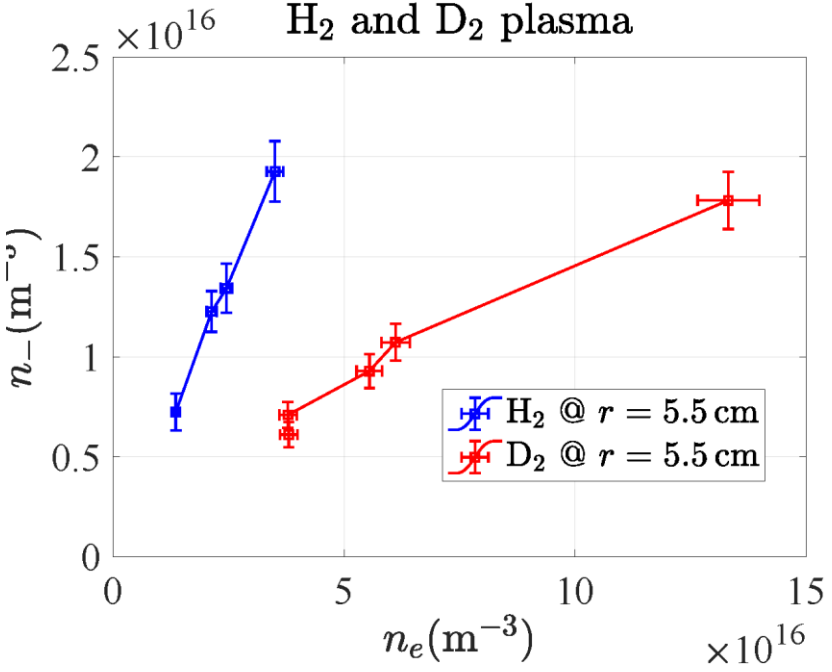
Favorable scaling with power but large e⁻ fraction in D_2



Swiss Plasma Center

Favorable scaling with power but large e⁻ fraction in D_2





Swiss Plasma Center

Conclusions and outlook

- In RAID, helicon plasmas generate a significant negative ion population in H_2/D_2
- Successful use of CRDS and LP-assisted laser photo-detachment
- More laser-based diagnostics
  - ✓ Thomson scattering (P. Blanchard P57)
  - ✓ LIF
- Next: negative ion extraction