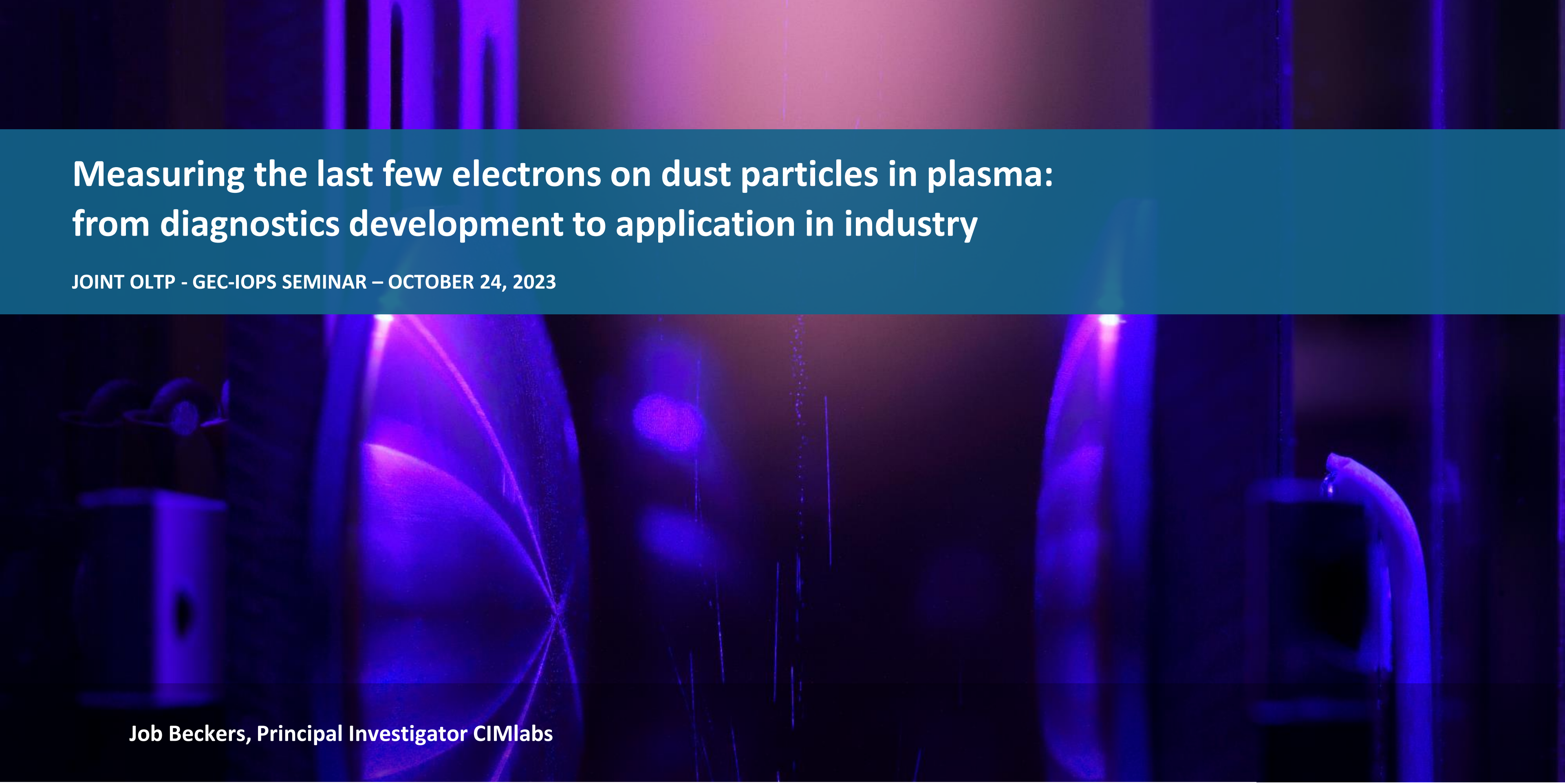

Measuring the last few electrons on dust particles in plasma: from diagnostics development to application in industry

JOINT OLTP - GEC-IOPS SEMINAR – OCTOBER 24, 2023

Job Beckers, Principal Investigator CIMlabs

Complex Ionized Media – department of applied physics – Eindhoven University of Technology

Content

From dusty plasmas to Complex Ionized Media (CIM)

Complex Ionized Media in Extreme Ultraviolet Lithography

Measuring charge on particles

Outlook

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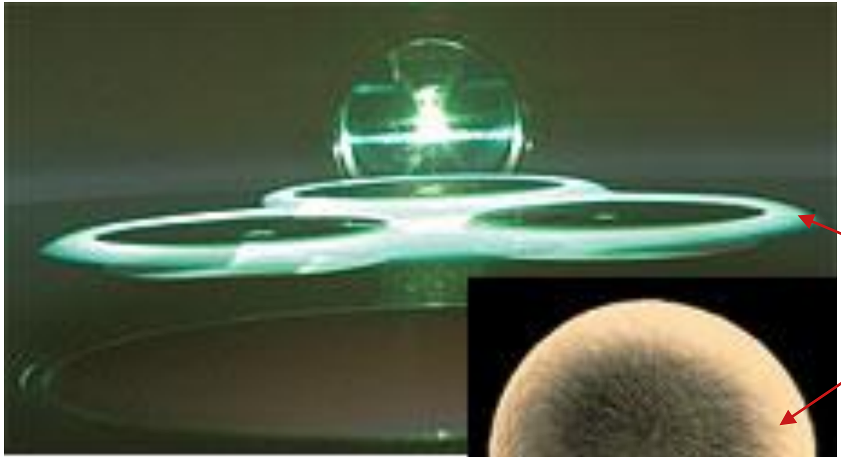
Traditional dusty plasma research



G. S. Selwyn, Plasma Sources Sci. Technol. **3**, 340 (1994)

Research topic of dusty / complex plasma physics was born in the 1990's after discovery of dust particles trapped in plasma.

Dust particles confined in processing plasma above a wafer

Two concepts to explain confinement of particles in (low temperature) plasma

Concept 1

(negative) charging of particles in plasma

- electrons much more mobile than Ions -

Particle charging:

Electrons much more mobile than ions

Negative charging

~10^4 electrons on micron-sized particle !

Concept 2

Plasma self-induced electric fields at its borders

- electrons much more mobile than Ions -

Plasma sheath:

Electron depletion

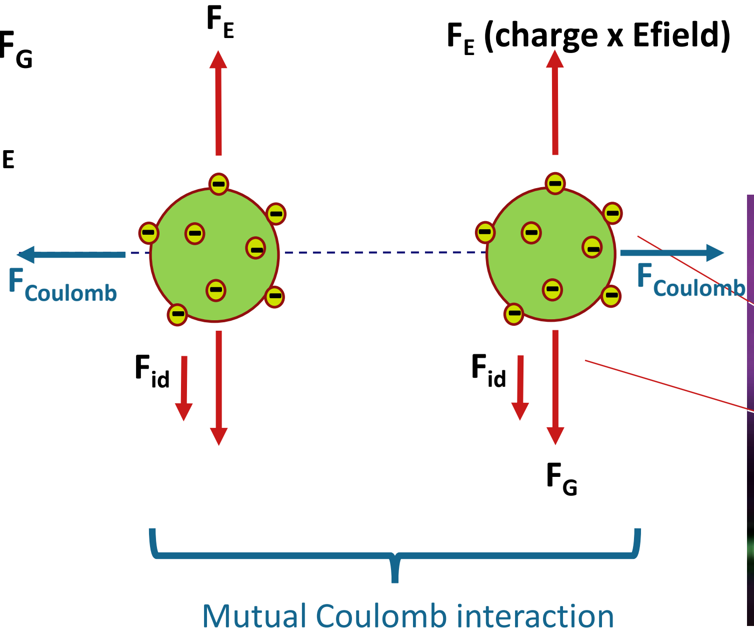
Electric fields up to 10^4 V/m

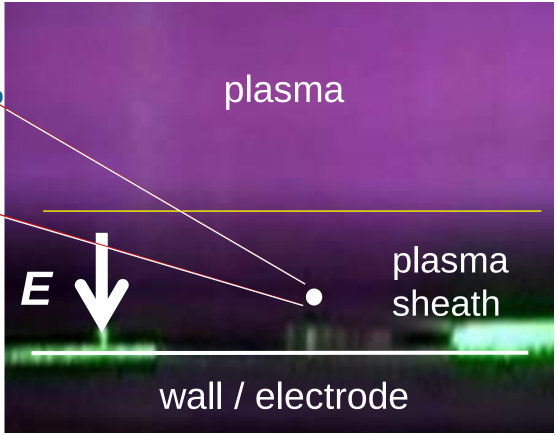
Ion acceleration

Force balance on particle in plasma

Dominant forces:

- **Gravitational force F_G**
- **Electrostatic force F_E**
- **Ion drag force F_{id}**
  (momentum transfer from streaming ions to particle)
- Neutral drag force
- Thermophoresis
- etc.

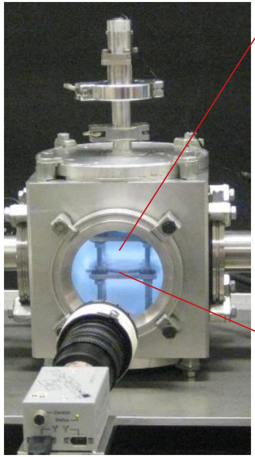


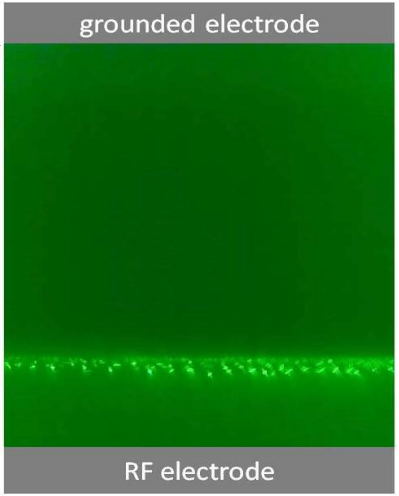


Dust structures as macroscopic model systems

(for fundamental processes such as crystal formation, phase transitions, density waves, etc.)

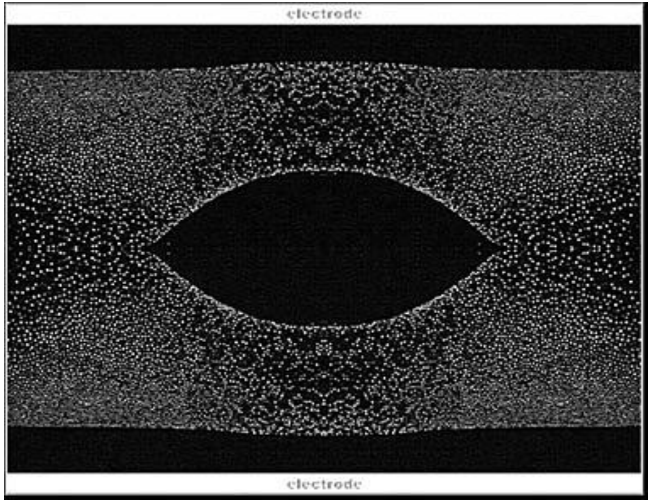
2D structures





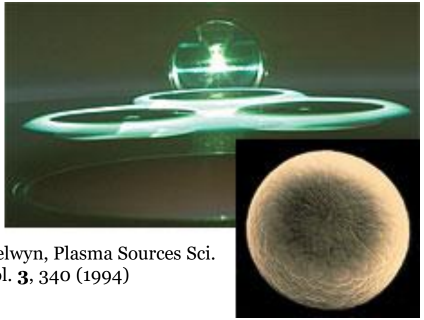
Experiments @ CIMlabs / Eindhoven University of Technology, the Netherlands

3D structures



Experiments @ Max Planck institute for Extraterrestrial physics, Garching, Germany

Traditional dusty/complex plasma research



G. S. Selwyn, Plasma Sources Sci. Technol. **3**, 340 (1994)

Research topic of dusty plasma physics was born in the 1990's after discovery of dust particles trapped in plasma.

Active field for about 10 to 15 year, then faded away as most application problems had been solved.

Relatively large particles in steady state plasmas

Recently renewed interest for the field !!

Reasons: - improved technology / diagnostics
- applications at smaller length scales emerged

From traditional dusty plasma to CIM

Traditional dusty and complex plasma physics

Transition from micrometer to nanometer sized particles

Transition to exotic, transient and non-quasi-neutral plasmas

Appl. Phys. Lett. (2021),
Plasma charging of nm sized quantum dots

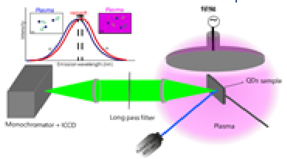
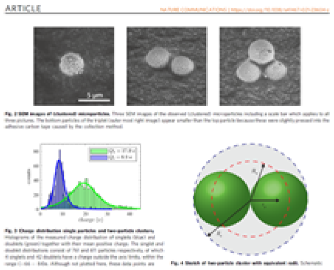


FIG. 1. (Color online) Schematic of the setup used to monitor the laser-induced photoluminescence of quantum dots deposited onto an electrically floating sample and the impact of plasma exposure on it.



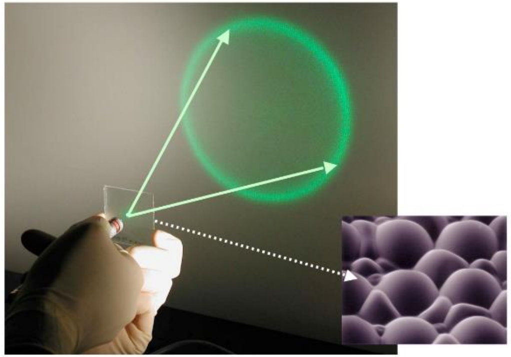
Nature communications (2021),
Cluster charging in afterglow plasma

☺

Applications with “CIM-like” ecosystems @ CIMlabs

Courtesy of VDL

contamination control for **robotic feedthroughs** for ultra-clean systems



Engineered Diffusers™ unique structures project general light patterns.

https://www.smartcity.co.nz/

Synthesis of nanoparticles for fabrication of **optical diffusers**

https://www.smartcity.co.nz/

Plasma-based **Air pollution** measurement technologies

Courtesy of ASML

Contamination control in **EUV lithography**

Content

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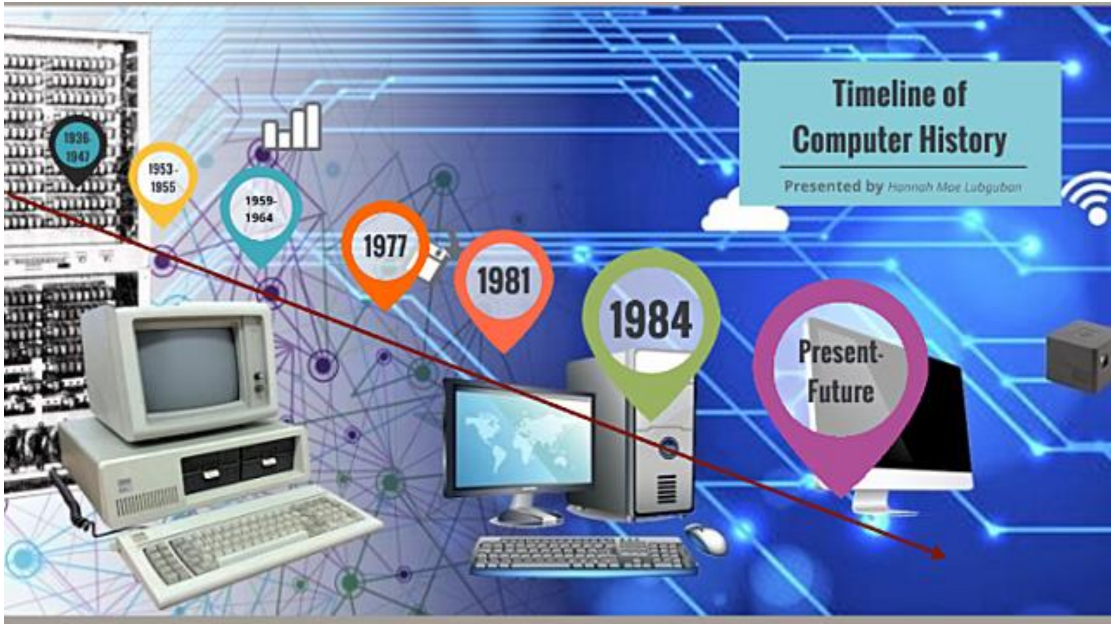
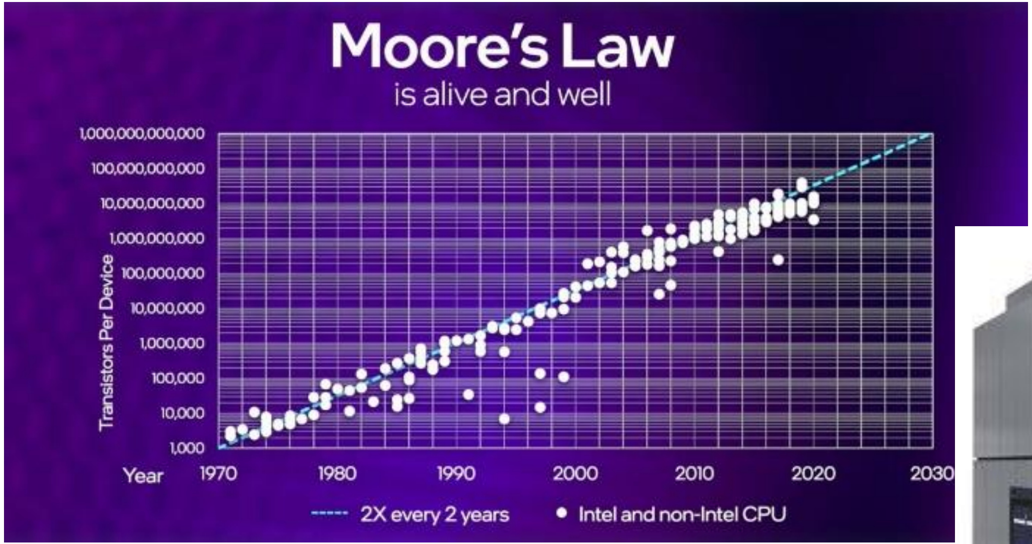
History of computer development



History of Computers timeline | Timetoast timelines

Courtesy of Kruidvat

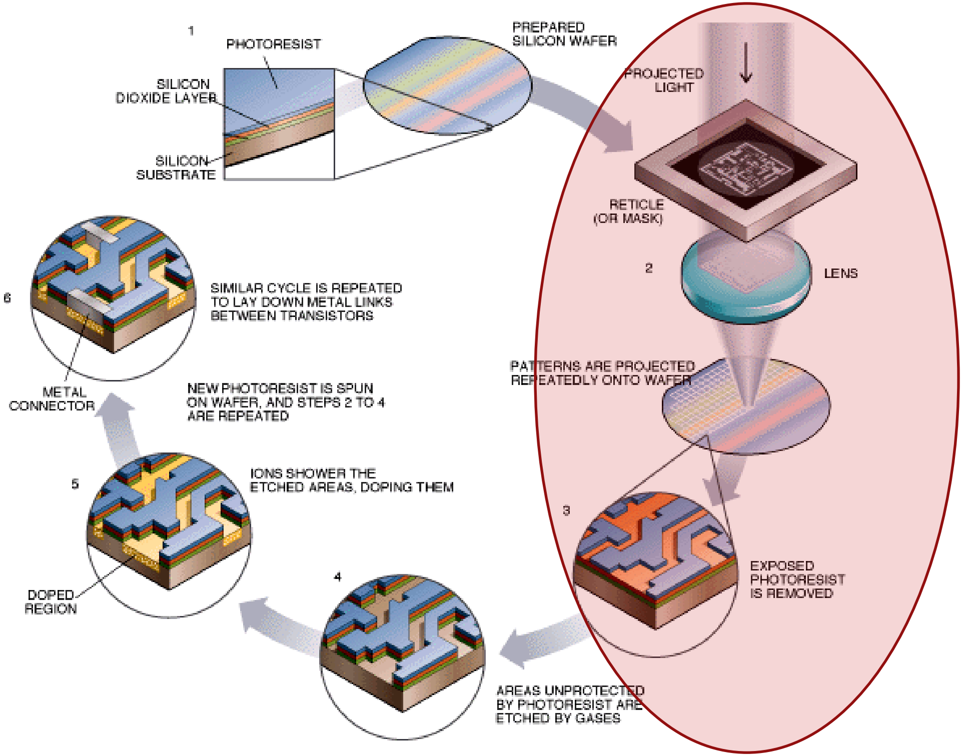
Extreme Ultraviolet (EUV) Lithography



Courtesy of Intel; Screenshot by Stephen Shankland/CNET

Courtesy of ASML

Photolithography



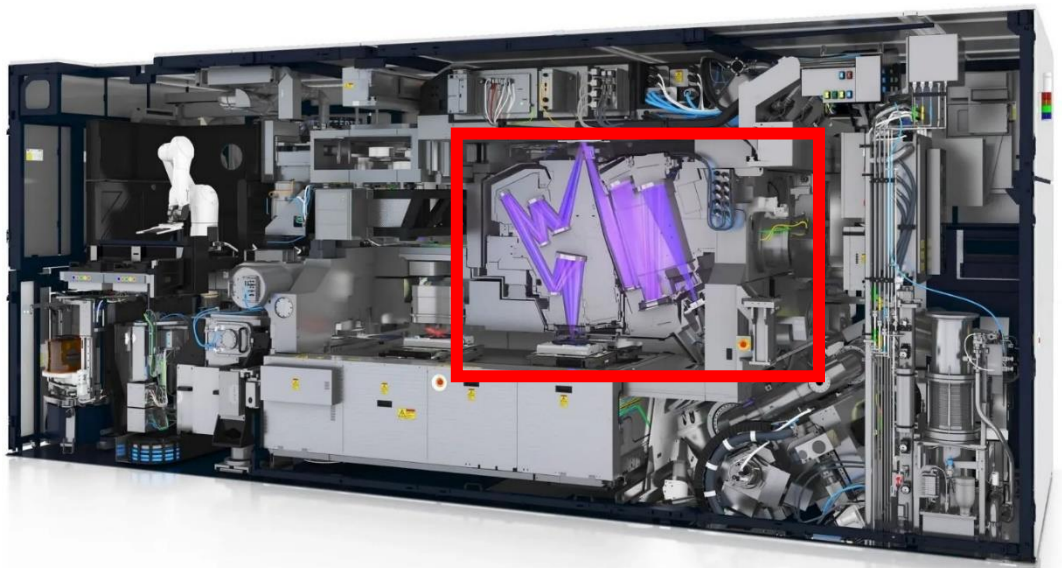
193 nm → 13.5 nm (EUV)

$$CD = k_1 \cdot \frac{\lambda}{NA}$$

Extreme Ultraviolet (EUV) Lithography

Courtesy of ASML

Extreme Ultraviolet (EUV) Lithography

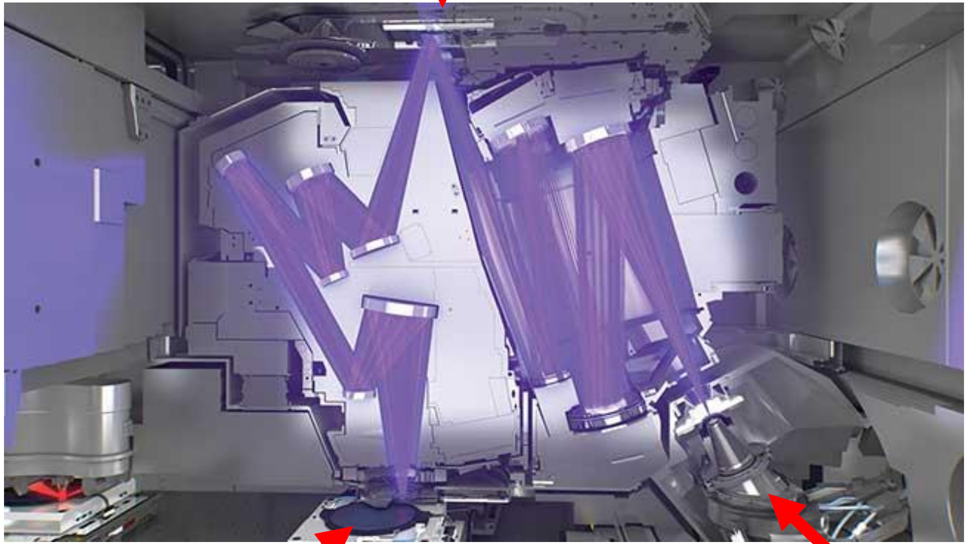


Courtesy of ASML

Courtesy of ASML

EUV Photolithography: the beam path of photons

Reticle / mask

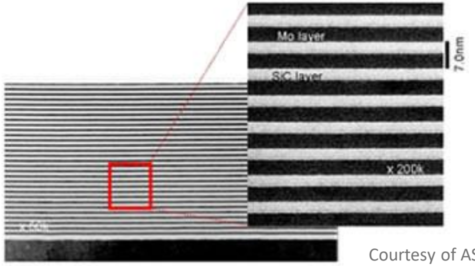


Courtesy of ASML

Wafer exposure

Source of EUV photons

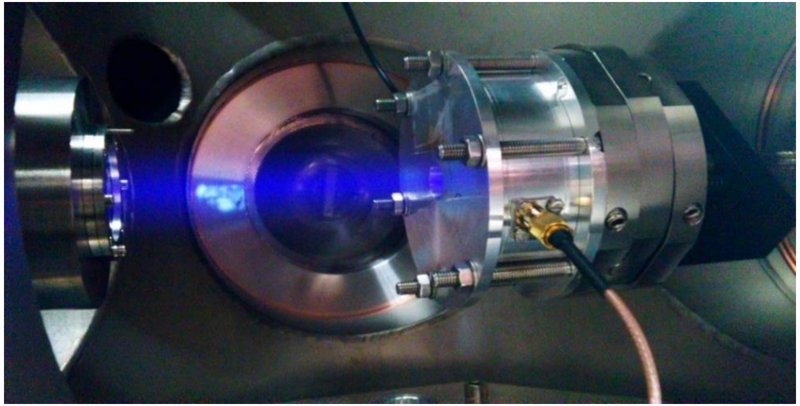
EUV photons interact with
Low pressure H_2 environment
→ plasma

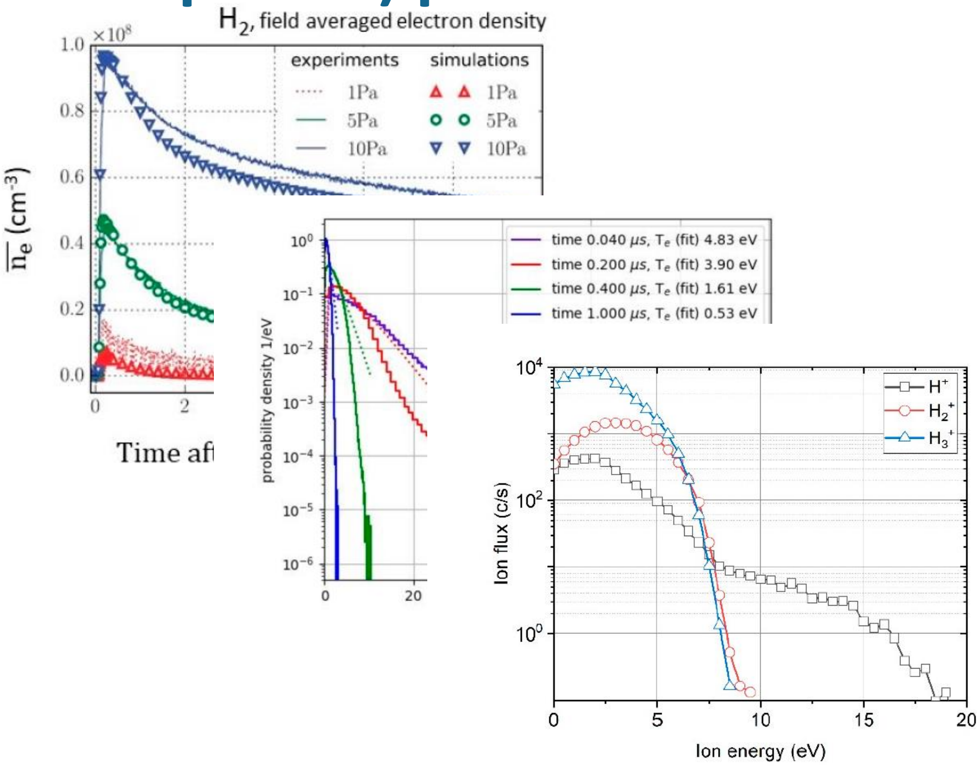


Courtesy of ASML

Multilayer optics
with ~7nm bilayers

EUV-induced (~100 ns, 500 Hz pulsed) plasma





R M van der Horst et al 2014 J. Phys. D: Appl. Phys. **47** 302001

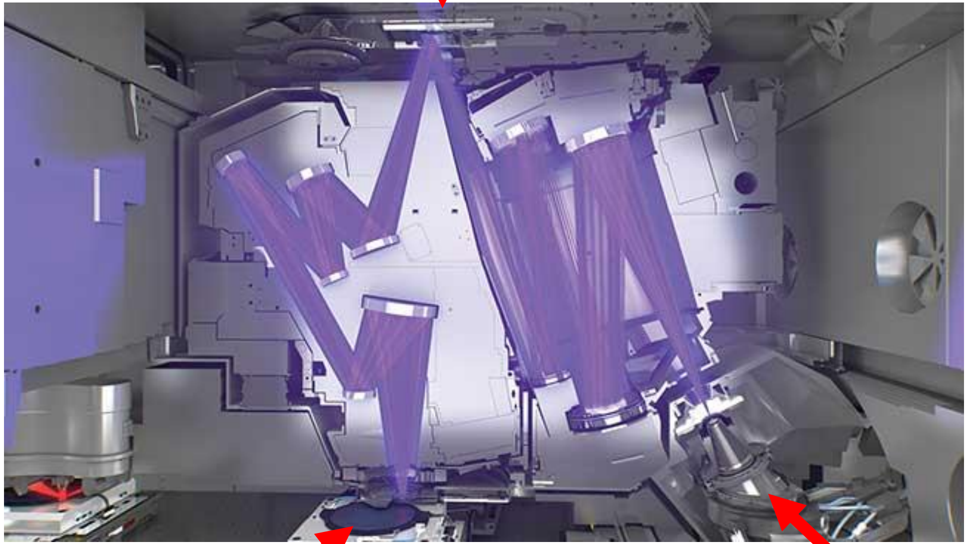
D.I. Astakhov et al. J. Phys. D. Appl. Phys. **2016**, 49, 295204.

T.H.M. Van De Ven al. J. Appl. Phys. **2018**, 123, 063301.

J. Beckers et al. Appl. Sci. **2019**, 9, 2827.

Nano Contamination Control huge topic!

Reticle / mask

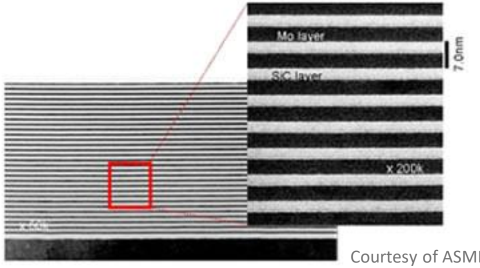


Courtesy of ASML

Wafer exposure

Source of EUV photons

EUV photons interact with
Low pressure H_2 environment
→ plasma



Courtesy of ASML

Multilayer optics
with ~7nm bilayers

Process should be extremely clean

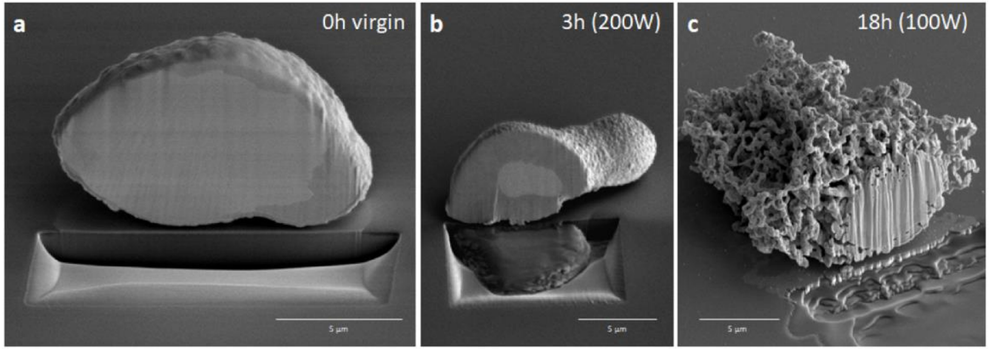
Specs: particle (>40nm) per 10,000 wafers

Sources:

Robotic feedthrough

Courtesy of VDL

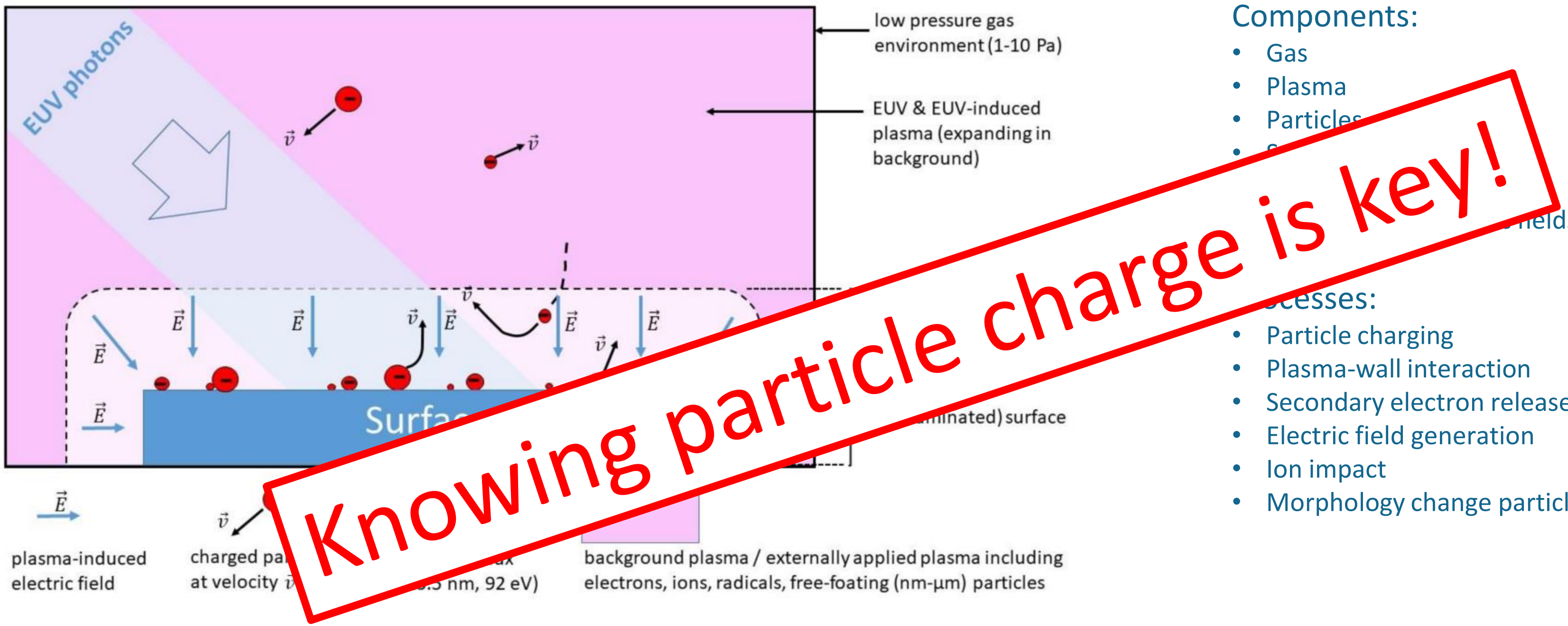
Moving cable slabs



mobilizing particles

D. Shefer et al., J. Phys. D: Appl. Phys. 56 (2023) 085204

Physical eco-system (EUV or otherwise induced plasma)



Components:

- Gas
- Plasma
- Particles
- S
- ields

cesses:

- Particle charging
- Plasma-wall interaction
- Secondary electron release
- Electric field generation
- Ion impact
- Morphology change particles

Content

Traditional methods for dust particle charge measurement

Resonance method for single particles

Mutual particle interactions

Using mode spectra of thermally excited finite clusters

From waves in many particle systems

→ Methods work for micron sized particles

Dust-acoustic waves in nanodustry plasmas

Methods based on charge dependent absorption of infrared light

→ Methods work for nanoparticles

Two (in-situ) diagnostics for charge on nanoparticles

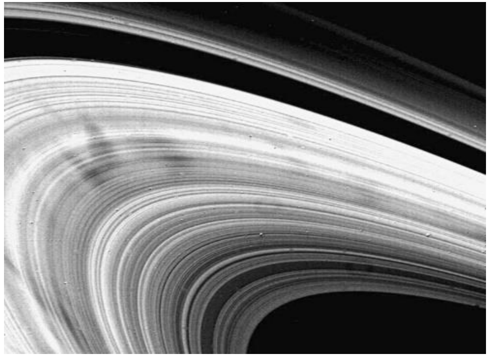
- Based on Laser-induced Photodetachment
  (in combination with microwave cavity resonance spectroscopy and laser light extinction measurements)

- Based on charge-dependence of quantum dot Photoluminescence

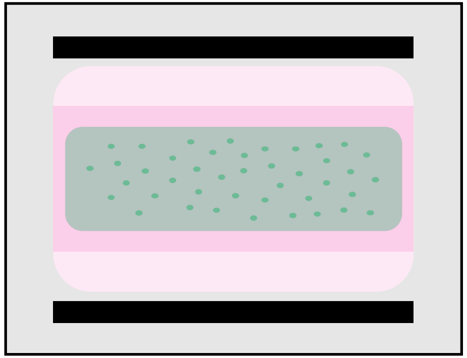
(nano)dusty plasma as a model system

- Plasmas containing nanometer sized particles
- Particles acquire (most often) high negative charge
- Especially at high particle densities plasma-conditions are altered (e.g. electron depletion, change in EEDF)

Courtesy Calvin J. Hamilton



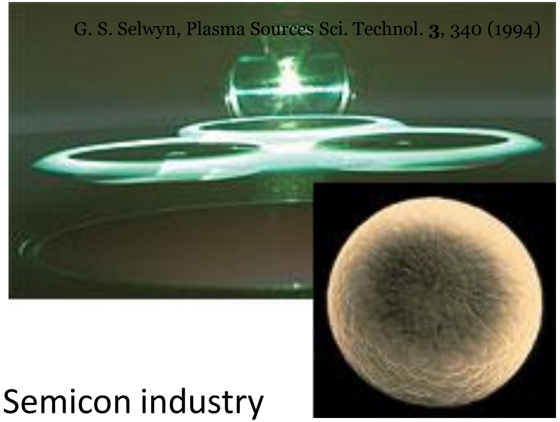
Outer space



Laboratory

(igniting a chemically reactive plasma)

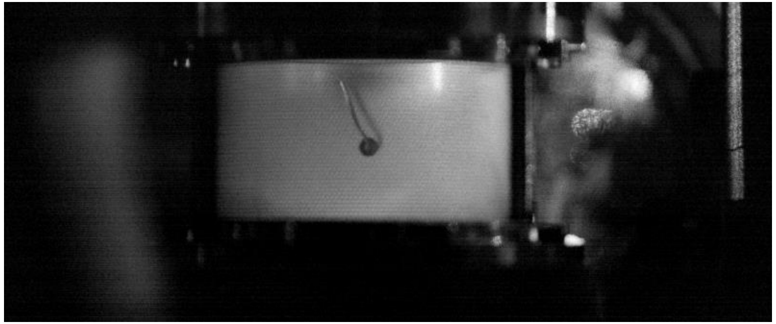
G. S. Selwyn, Plasma Sources Sci. Technol. **3**, 340 (1994)



Semicon industry

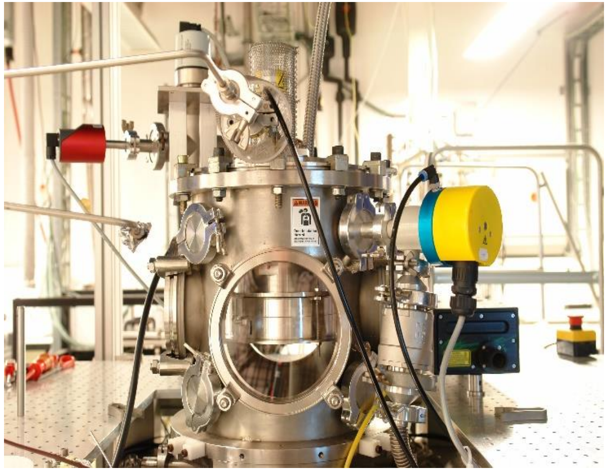
Dust growth in nanodusty plasmas

(laser light scattering visualization of nanoparticles)



Nanodusty plasma without void

Homogeneous density / (relatively) monodisperse size distribution!



Low pressure	10-100 Pa
Radiofrequency (RF) driven:	13.56 MHz
Gases:	Ar, HMDSO

Standard diagnostics:

- Electrical Characterization
- Laser Light Scattering
- Optical emission spectroscopy
- SEM analysis

<u>Stable</u> cloud of plasma-confined nanoparticles with <u>monodisperse size</u> distribution which is <u>homogenously distributed</u> over the volume.

Particle charge measurement from laser-induced Photodetachment: general approach

1. Photodetach charge that the dust particles collected from the plasma & measure the photodetached electrons using microwave cavity resonance spectroscopy (MCRS)

   → Retrieve information about the charge density on the collection of dust particles: Output → $n_d Q_d$

2. Combine Laser-light extinction with MCRS

   → Combination of these two diagnostics with model yields density and size of dust particles: Output → n_d and a_d

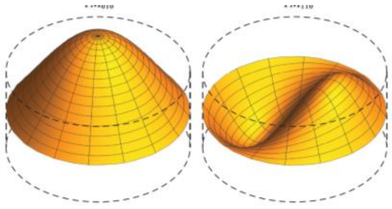
Obtain set of parameters for size a_d, density n_d, and charge Q_d of dust particles

Measuring electron density with Microwave Cavity Resonance Spectroscopy (MCRS)

Plasma operates in cylindrical resonant cavity

Half of side wall made of mesh grid for optical access

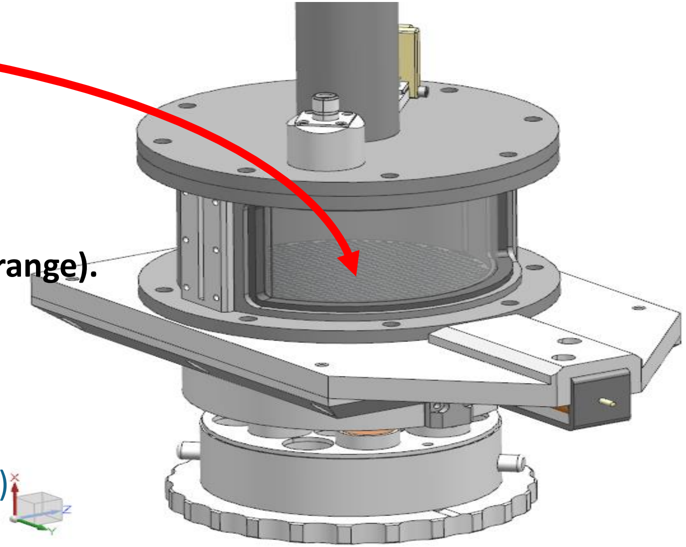
When putting in low power microwave radiation (μW range), standing microwaves can be excited for specific frequencies (in GHz range).



f_{TM010} f_{TM110}

Resonance frequency depends on:

- Geometry
- Permittivity (density of free electrons)



Picture by T.J.A. Staps

By tracking the resonance frequency, we can determine the free electron density (time resolution ~50 ns, lower detection limit: 10^9 m^{-3})

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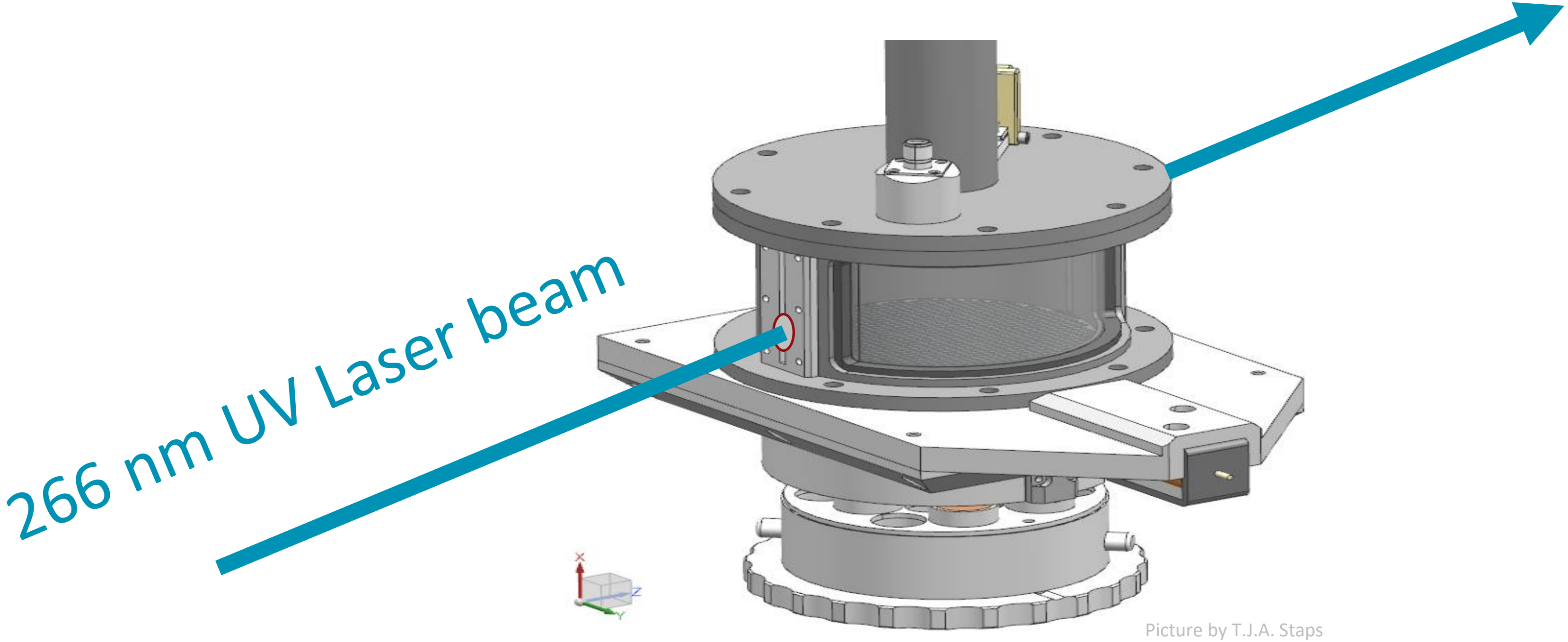
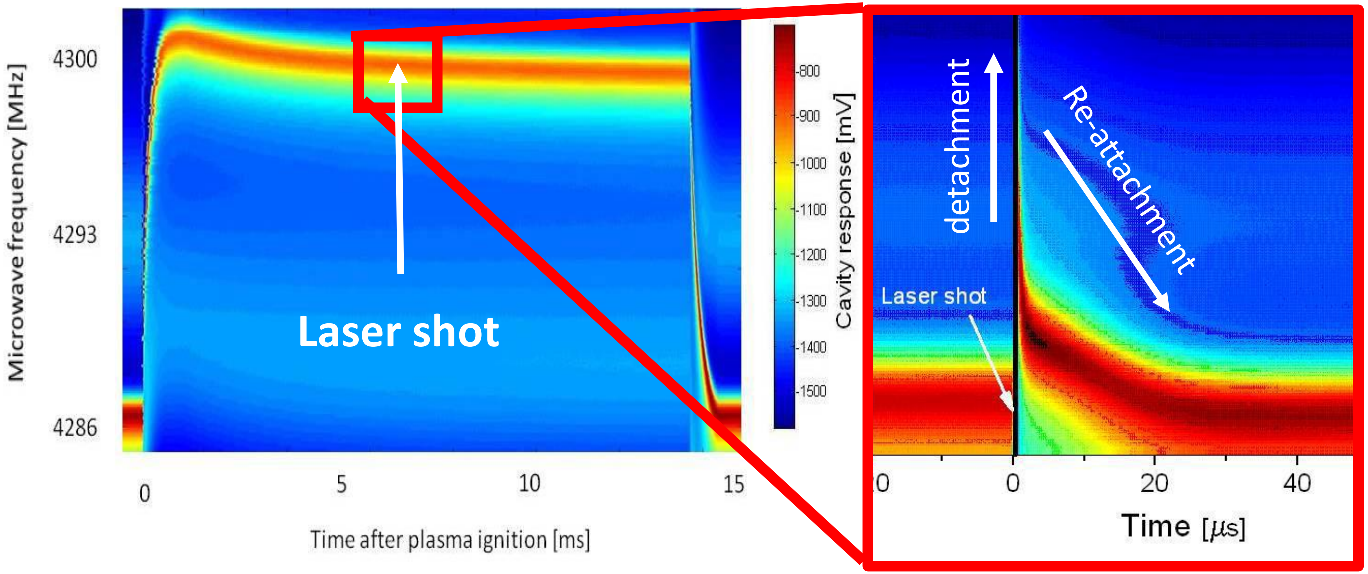
Laser-induced photodetachment (send laser beam through cavity)

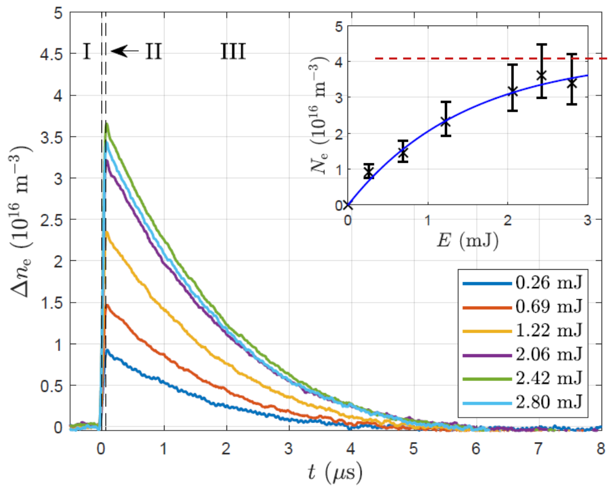


Picture by T.J.A. Staps

Microwave Cavity Resonance Spectroscopy (MCRS) + Laser Induced Photodetachment (LIPD)



Obtaining dust charge density



N_e^{sat} (means all negative charge photodetched)

$$\alpha = \frac{\Delta n_e}{\Delta n_e^{sat}} = 1 - \exp\left(-\frac{\sigma_{det}}{h\nu}\frac{E_{laser}}{S}\right)$$

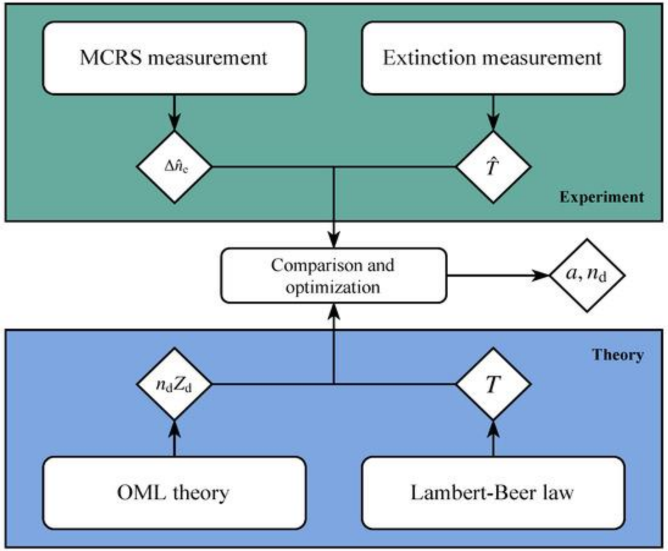
$$N_e^{sat} = Q_d n_d \approx (4.0 \pm 0.1) \times 10^{16}\ {e^-}/{m^3}$$

Majority of negative charge in plasma bound to dust particles (described by the Havnes Parameter)

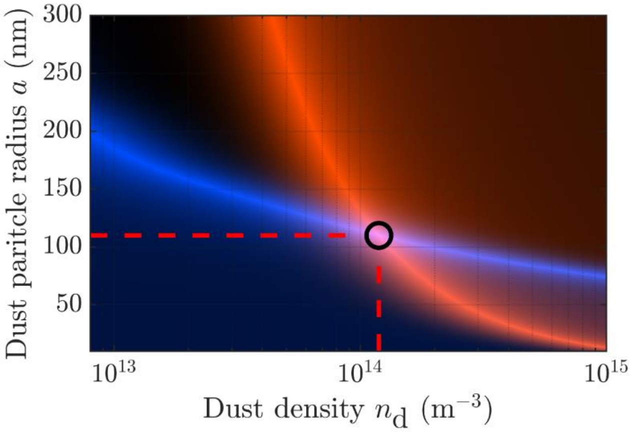
$Q_d n_d$ obtained. Now let's find dust density n_d to retrieve: $Q_d = \frac{Q_d n_d}{n_d}$

T. Staps, T. Donders, B. Platier and J. Beckers, J. Phys. D: Appl. Phys. **55** 08LT01

Obtaining dust density and size from time-synchronized MCRS and laser light extinction measurements



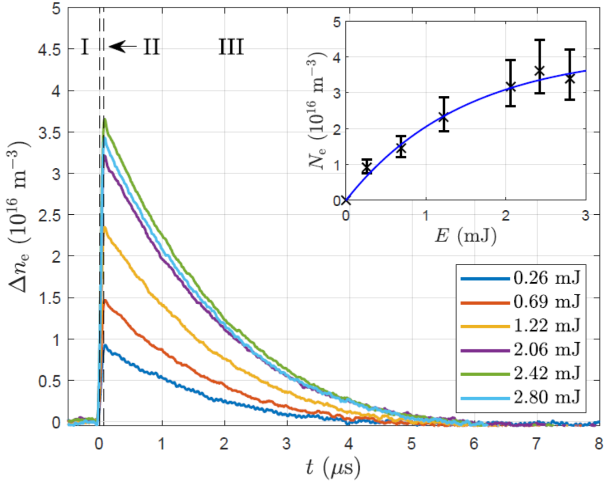
T. Donders, T. Staps and J. Beckers. Appl. Sci. **2022**, 12(23), 12013

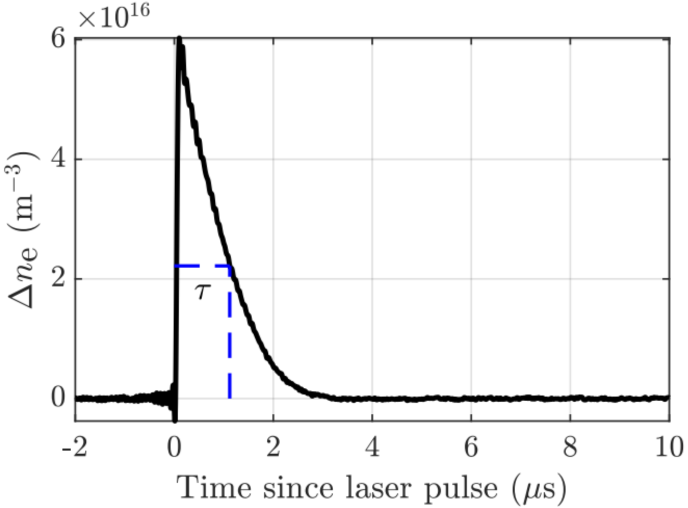


a_d = 110 ± 10 nm

n_d = (1.2 ± 0.2) x 10^{14} m^{-3}

Determining in-situ dust size in another way





T. Staps, T. Donders, B. Platier and J. Beckers, J. Phys. D: Appl. Phys. **55** 08LT01

T. Donders, T. Staps and J. Beckers, Phys. Plasmas 30, 083703 (2023)

Stochastic charging model

Slightly adapted implementation of the work of Cui and Goree (1994)

OML currents to the particle's surface

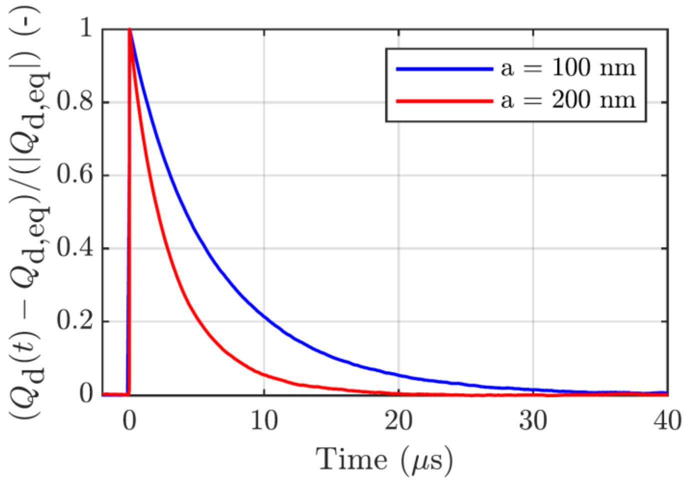
$$I_e = -e n_e \pi a_d^2 \sqrt{\frac{8 k_B T_e}{\pi m_e}} exp\left(-\frac{-e\Phi_p}{k_B T_e}\right)$$

$$I_{i+} = e n_{i+} \pi a_d^2 \sqrt{\frac{8 k_B T_{i+}}{\pi m_{i+}}} \left(1 - \frac{e\Phi_p}{k_B T_{i+}}\right)$$

$$Q_p = C_{sphere}\Phi_p = 4\pi\varepsilon_0 a \Phi_p$$

Transient (re-)charging behavior: $\frac{\mathrm{d}Q_p}{\mathrm{d}t} = I_e + I_{i+}$

For typical values with depleted electron density



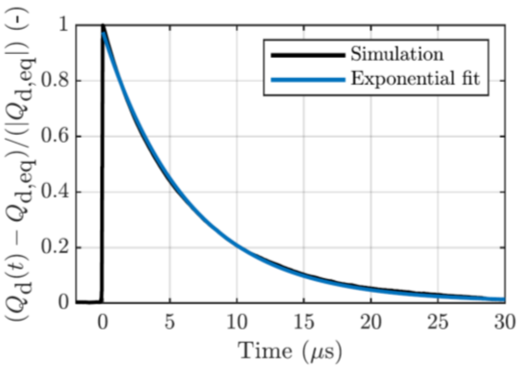
Stochastic charging treating arrival of individual electrons and ion.

From LIPD measurements to particle size

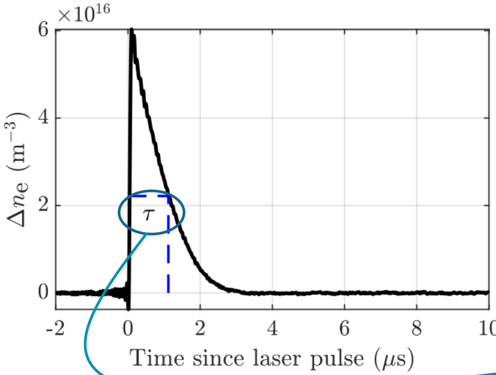
A

1: simulation

For fixed value of a_d (here 100 nm), average 500 simulation runs and obtain typical recharging timescale fit.



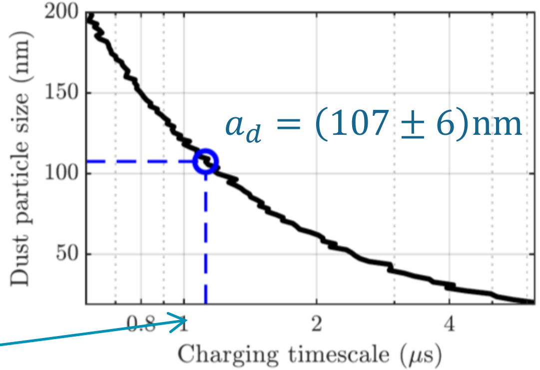
2: measurement



1/e-time: $(1.12 \pm 0.04)\mu s$

3: compare

Find a_d connected to charging time scale in look-up table.



B

Vary a_d and make look-up table (recharging timescale versus r_p)

T. Donders, T. Staps and J. Beckers, Phys. Plasmas 30, 083703 (2023)

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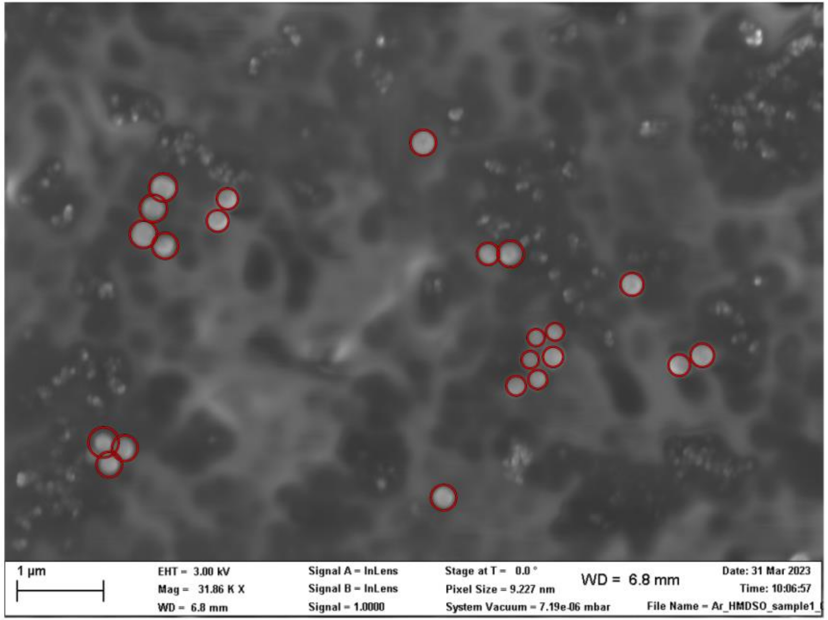
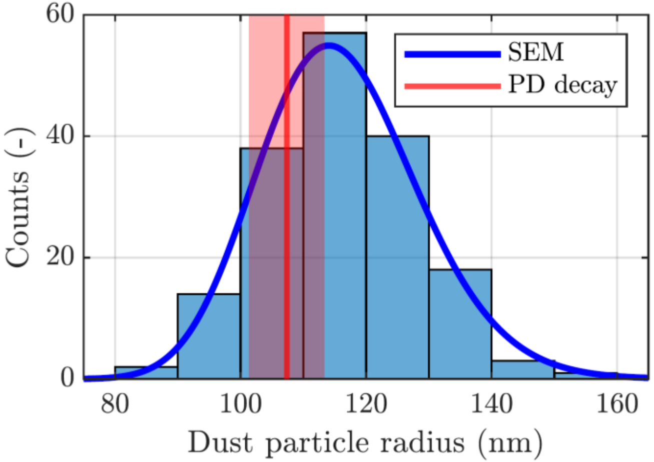
Cross check with SEM analysis

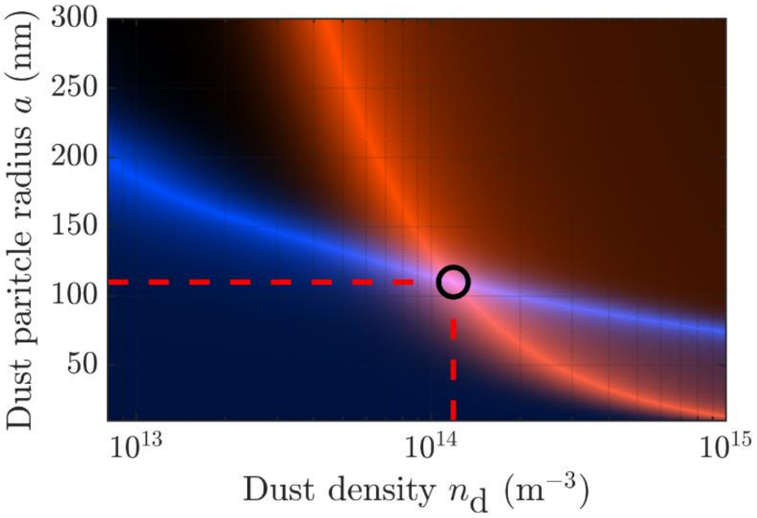
Collected and SEM analyzed N=173 particles
from the same sample





T. Donders, T. Staps and J. Beckers, Phys. Plasmas 30, 083703 (2023)

Merging all diagnostics together for photodetachment sample:



T. Donders, T. Staps and J. Beckers. Appl. Sci. **2022**, 12(23), 12013

a_d = 110 ± 10 nm

n_d = (1.2 ± 0.2) x 10^{14} m^{-3}

From photodetachment measurements we found:

$Q_d\, n_d$ = (4.0 ± 0.1) x 10^{16} m^{-3}

Q_d = (330 ± 70) e^- at particles of 110 nm radius.

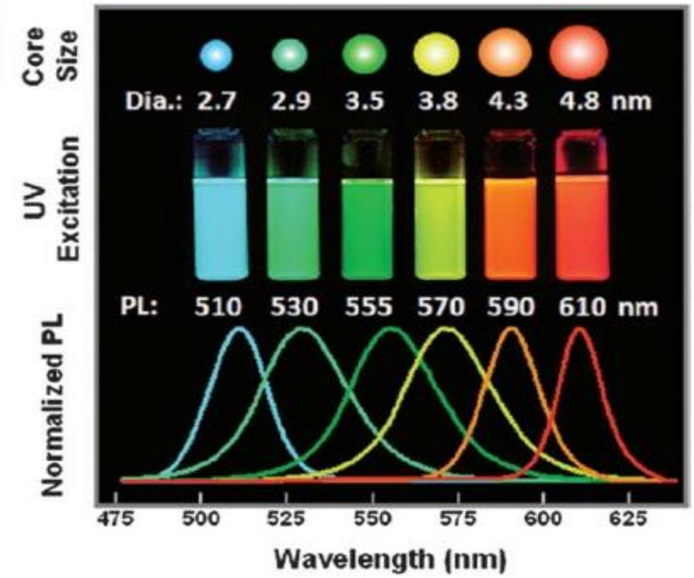
Two (in-situ) diagnostics for charge on nanoparticles

- Based on Laser-induced Photodetachment
  (in combination with microwave cavity resonance spectroscopy and laser light extinction measurements)

- Based on charge-dependence of quantum dot Photoluminescence

Photoluminesence from quantum dots

Colour change when size of QD changes



Cheng et al., Nanoscale, 2013,**5**, 3547-3569

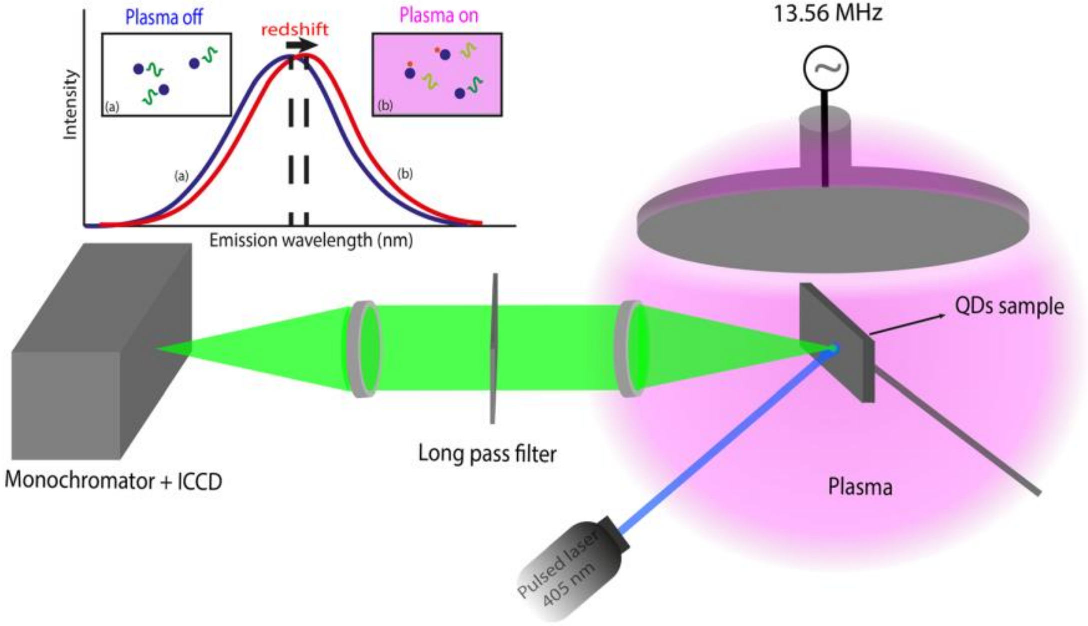
Also colour change when QDs feel electric field

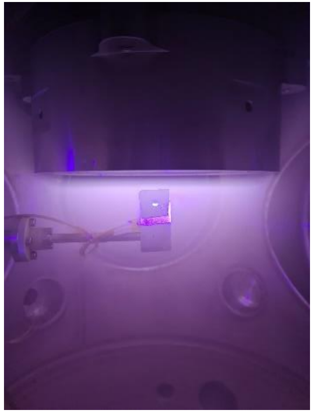
Applying electric field *E* increases the emitted wavelength

$$\Delta\lambda = 0.03\frac{\lambda^2}{hc}\left(m_{\mathrm{v}} + m_{\mathrm{h}}\right) a_{\mathrm{QD}}^4 \left(\frac{2\pi e E}{h}\right)^2$$

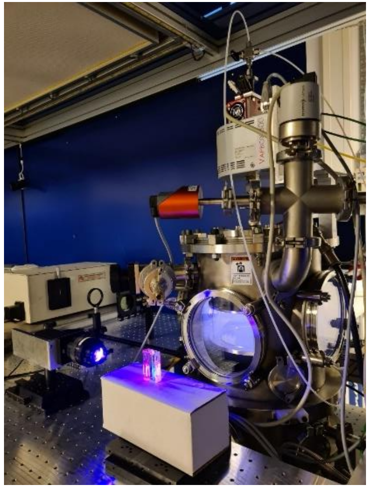
Use quantum dots as small nanometer sized charge probes!

Proof of principle experiments with QDs on sample exposed to pulsed low pressure RF plasma



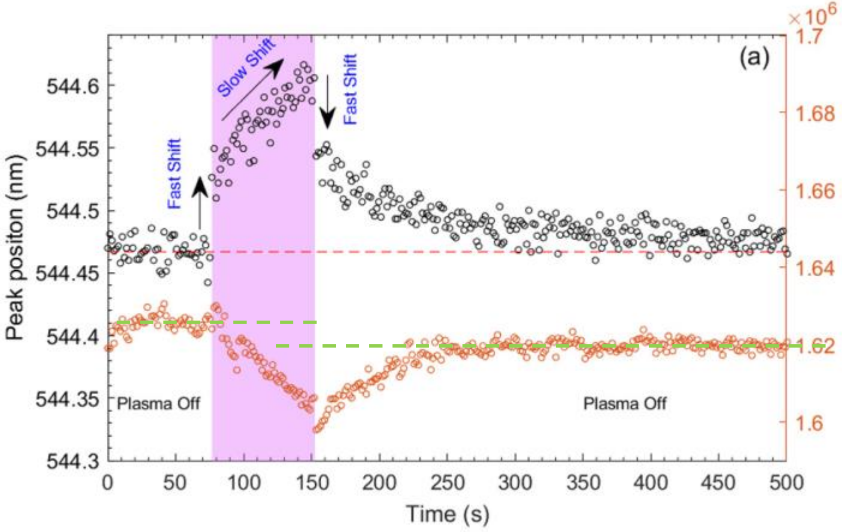


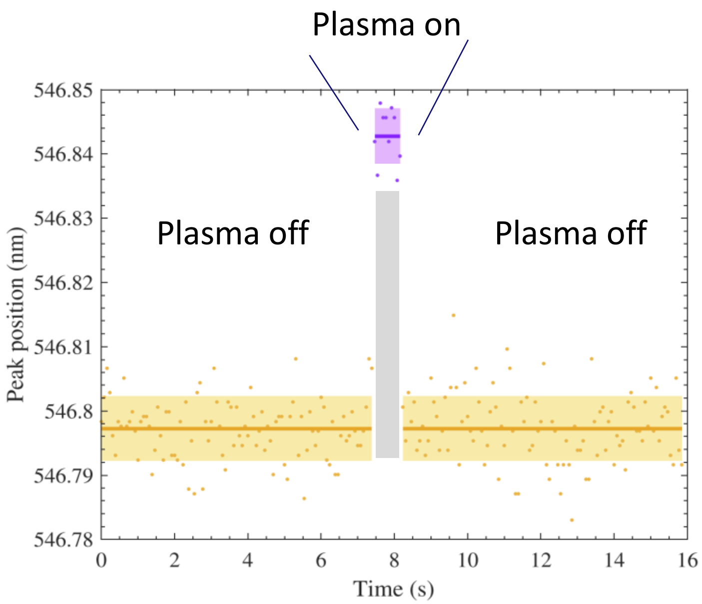
QD material: CdSe/ZnS



Z. Marvi, T. Donders, M. Hasani, G. Klaassen and J. Beckers, APL **119**, 254104 (2021)

Proof of principle experiments with QDs on sample exposed to pulsed low pressure RF plasma





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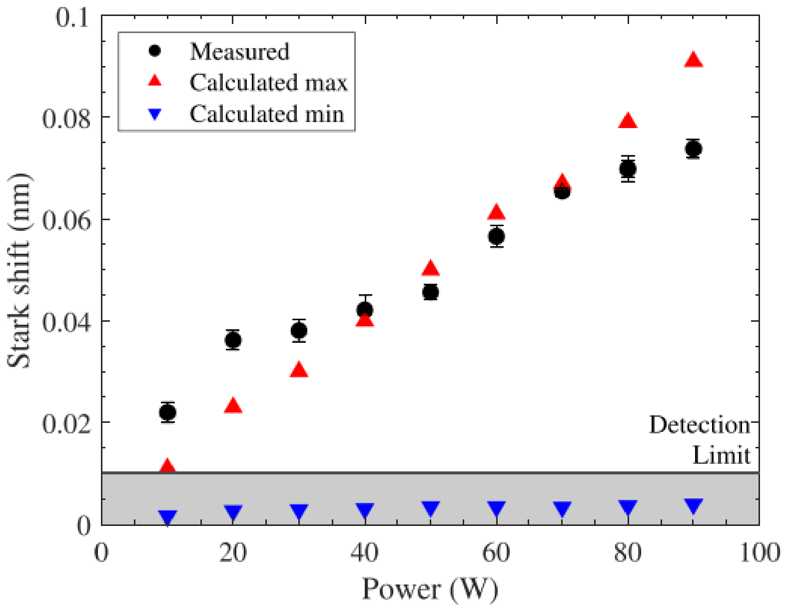
M Hasani, G. Klaassen, Z. Marvi, M. Pustylnik and J. Beckers, 2023 J. Phys. D: Appl. Phys. **56** 025202

Proof of principle experiments with QDs on sample exposed to pulsed low pressure plasma



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- macroscopic electric field (obtained via sheath model and Langmuir probe data) more than order of magnitude too low to explain results.
- Discrete charge model: calculated max. values for expected Stark shift nicely match with measured values.
- Combination of Stark shift measurements and discrete charge modeling to retrieve info about local surface charge density!

Content

From dusty plasmas to Complex Ionized Media (CIM)

Complex Ionized Media in Extreme Ultraviolet Lithography

Measuring charge on particles in plasma

Outlook

Proposed usage quantum dots as surface charge microsensor

M. Pustylnik, Z. Marvi and J. Beckers, J. Phys. D: Appl. Phys. **55** (2022) 095202

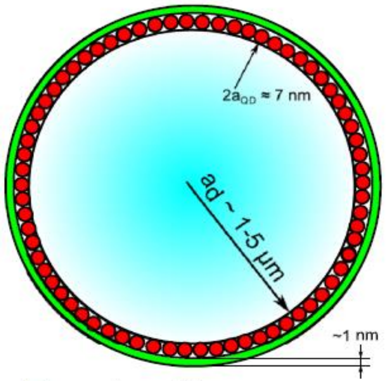
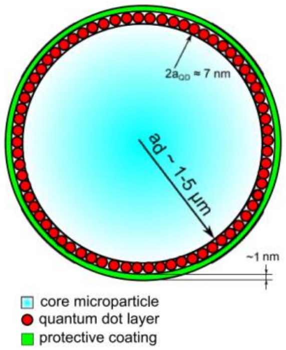
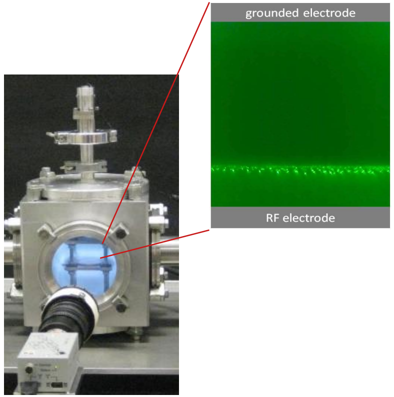


Figure 6. Schematically represented proposed design of a surface charge microsensor in which the surplus electrons will be distributed in the vicinity of the surface and their arrangement will closely correspond to the surface arrangement of the surplus electrons in the proposed model. A microparticle (of $1-5$ μm radius) is coated by a layer of semiconductor QDs (of 6.6 nm diameter). The layer of QDs is then protected against plasma damage and electron electron penetration by a thin ($\sim$1 nm) layer of material with negative electron surface affinity.

- QD coated microparticle
- Can be used to probe particle charge in different plasma regions
- **Combine with Laser Induced Photodetachment to study not only particle charge but also dynamic (re)charging.**

Outlook:
Use momentum in applications to push diagnostic development and physical understanding further





Diagnostics & modeling → fundamental understanding → cool applications ☺

Measuring the last few electrons on dust particles in plasma: from diagnostics development to application in industry

EPS 49TH CONFERENCE ON PLASMA PHYSICS

Thanks to the CIMlabs team and Dr. M. Pustylnik (for joint work on quantum dots)

Job Beckers, Principle Investigator CIMlabs

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