

Alternative Solution to Address the Challenge of Negative Ion Sources for Fusion

SARDINE: Solution Alternative pour Relever le Défi des sources d'Ions NEgatifs pour la fusion –

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Outline

Context

Negative-ion source for fusion

The SARDINE project

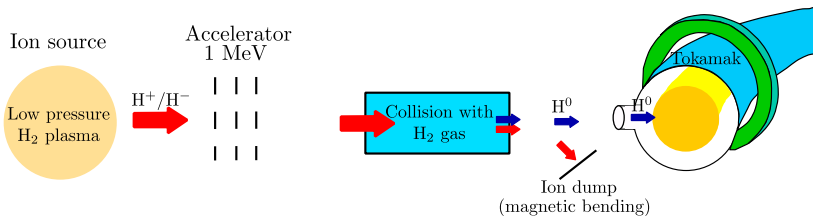
First Results

Conclusion and perspectives

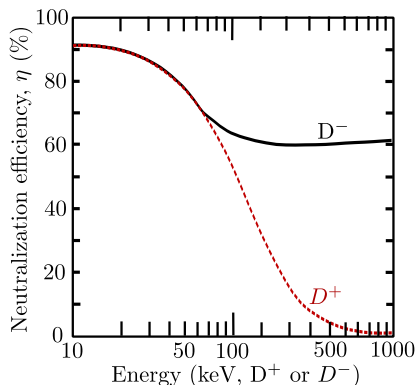
Context

Principle of neutral beam injection

1. Formation 2. Acceleration 3. Neutralisation 4. Injection

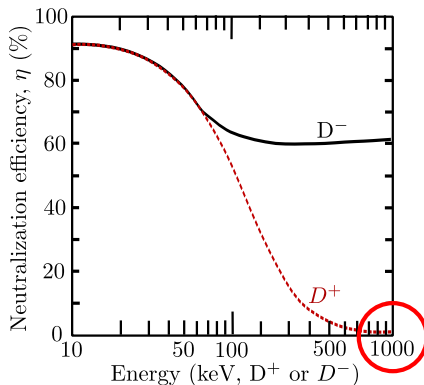


Neutralisation of accelerated ions



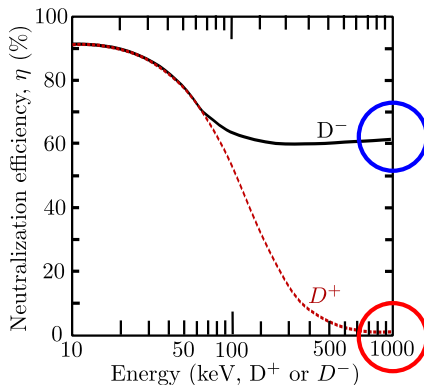
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Neutralisation of accelerated ions



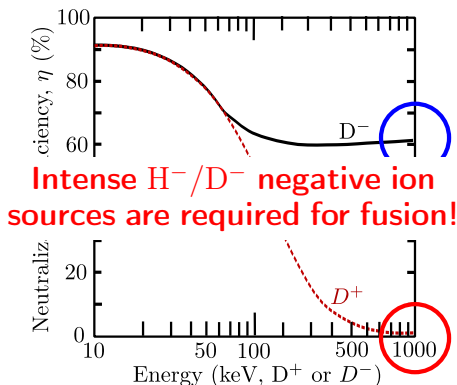
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Production mechanism of H^-/D^-

► Volume production

- Dissociative attachment of electrons to excited H_2 molecules.
- Requires high vibrational excitation and sufficient electron density.
- Typical operating pressure: ~ 1 Pa.
- High co-extracted electron current $\rightarrow$ excessive thermal loads, high-voltage instabilities, and operational limits during long pulses in negative-ion NBI necessary for fusion devices.

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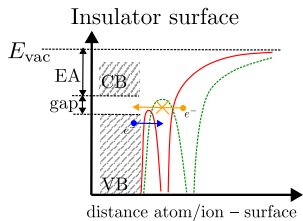
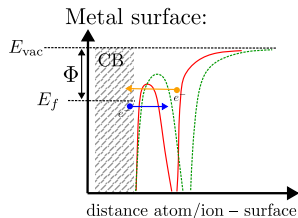
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► Surface production

- Conversion of H atoms and positive ions on a low work-function surface.
- Caesium coating enhances conversion efficiency.
- Operates at lower pressure (~ 0.3 Pa).
- Higher H^- current density and lower co-extracted electron current $\rightarrow$ Preferred for fusion ion sources.

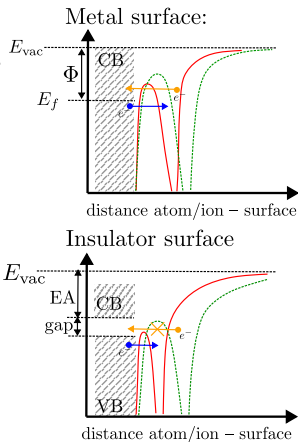
Surface production of H^- ions on metals

- ▶ H atoms and H^+ ions interact with a metallic surface.
- ▶ Positive ions are rapidly neutralised (“memory loss effect”).
- ▶ H^- formation occurs via electron capture from the surface.
- ▶ Electron transfer depends on:
 - ▶ Energy difference between the H^- affinity level and the surface Fermi level.
 - ▶ Distance from the surface and particle velocity.
 - ▶ H^- ions survive only if electron loss back to the surface becomes negligible beyond the freezing distance.



Surface production of H^- insulator/semiconductor

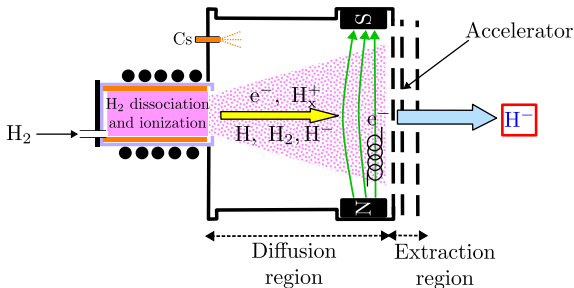
- ▶ Electrons more localised and more tightly bound. Electron capture generally less efficient than on metals. Full neutralisation of incoming positive ions not always achieved.
- ▶ However, Coulomb attraction between the captured electron and the surface hole can enhance H^- formation.
- ▶ Band-gap materials can suppress electron recapture during surface departure.
- ▶ H^- survival probability can therefore be significantly increased.
- ▶ $\rightarrow H^-$ yields can exceed those from metal surfaces by more than an order of magnitude.



Role of Caesium (Cs)

- ▶ Cs lowers the surface work function Φ (Typical metal work function: ~ 5 eV, Cs-coated surface: ~ 2.1 eV, Optimum partial Cs coverage: ~ 1.5 eV).
- ▶ Lower work function increases electron capture probability.
- ▶ Shifts the freezing distance into a region favourable for H^- survival.
- ▶ Allows efficient H^- production from low-energy neutral hydrogen atoms.
- ▶ Results in:
 - ▶ Higher H^- yield, Lower co-extracted electron current.
 - ▶ $\Rightarrow$ Current choice for high-performance sources for fusion applications

Negative-ion source for fusion

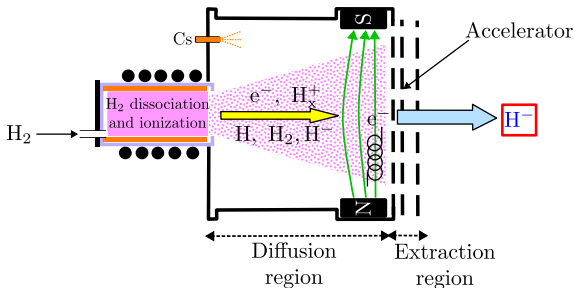


Surface production:
 $H/H^+ + \text{surface} \rightarrow H^-$

- Cs oven evaporates Cs continuously in the source.
- Cs deposits everywhere.

- Material work function is reduced, Electron capture is enhanced

Negative-ion source for fusion



Surface production:

$$\text{H}/\text{H}^+ + \text{surface} \rightarrow \text{H}^-$$

- ▶ Cs oven evaporates Cs continuously in the source.
- ▶ Cs deposits everywhere.

- ▶ Material work function is reduced, Electron capture is enhanced
- ▶ High yield ($\Phi^-/\Phi^+ \simeq 25\%$), tens of A of H^-

Drawbacks of Cs in fusion negative ion sources

- ▶ Continuous Cs injection required to maintain high H^- production (high Cs consumption: $\sim 5 - 10 \mu g \cdot s^{-1}$).
- ▶ Difficult control of the optimum Cs surface coverage.
- ▶ Cs can diffuse into the accelerator region (risk of parasitic beam formation and high-voltage breakdowns, contamination of source and accelerator components).

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- ▶ Long-term operational stability remains a major technological challenge.

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- ▶ Long-term operational stability remains a major technological challenge.
- ▶ **Strong motivation for low-Cs or Cs-free alternatives in future fusion devices.**

The SARDINE project: Motivations

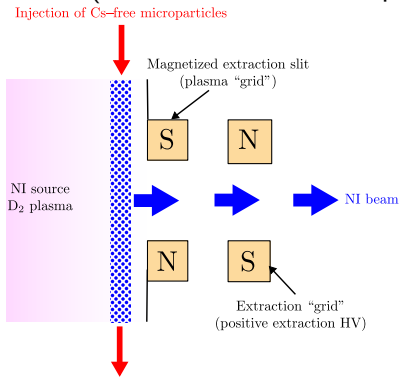
Study of materials enhancing negative-ions production in H_2/D_2 plasmas

Alternative material with:

1. High Yield, $\sim 25\text{mA}/\text{cm}^2$ (40 A of extracted negative ions)
2. Less than one co-extracted electrons per negative-ion
3. Must handle hydrogen plasma exposure
4. Must be regenerated in-situ

The SARDINE project: Main ideas

- ▶ Extend the advantage of the continuous injection of Cs to any material
- ▶ The new materials are used in the form of microparticles that transit into the plasma
(B. Kakati et al., Sci Rep 7, 11078 (2017))



- ▶ Transit $\Rightarrow$ continuous renewal $\Rightarrow$ always clean material
- ▶ Microparticle at floating potential (negative with respect to the plasma) $\Rightarrow$ extraction possible
- ▶ Microparticle close to the extraction $\Rightarrow$ NI not destroyed by e^-

The SARDINE project: Scientific Challenges

1. Identify efficient Cs-free materials

- ▶ Optimise negative-ion production from alternative materials
- ▶ Understand the influence of work function, surface chemistry, contamination, oxidation and erosion

2. Develop the microparticle concept

- ▶ Understand microparticle charging, transport and plasma-surface interactions
- ▶ Predict trajectories, residence times and dispersion in hydrogen plasmas

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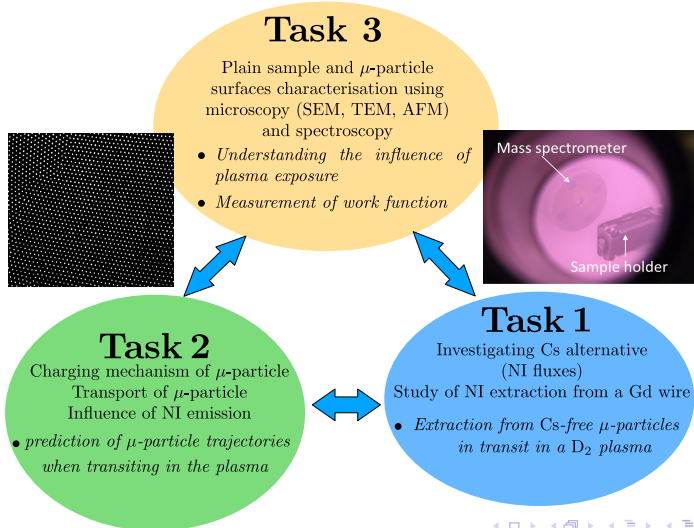
2. Develop the microparticle concept

- ▶ Understand microparticle charging, transport and plasma-surface interactions
- ▶ Predict trajectories, residence times and dispersion in hydrogen plasmas

3. Achieve efficient negative-ion extraction (proof-of-concept)

- ▶ Demonstrate that continuously injected microparticles can replace Cs-coated surfaces
- ▶ Extract ions produced on transiting microparticles
- ▶ Determine optimal plasma conditions, electric fields and source geometry

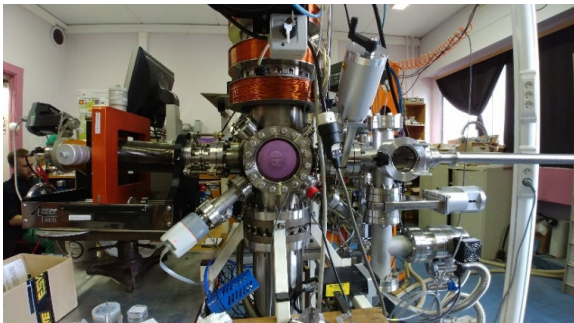
The SARDINE project: Organization



Investigating C_s alternative

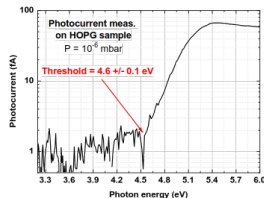
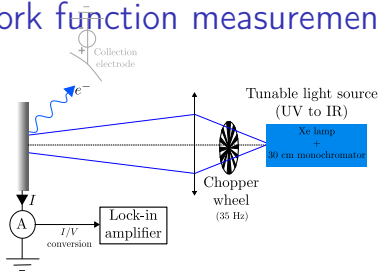
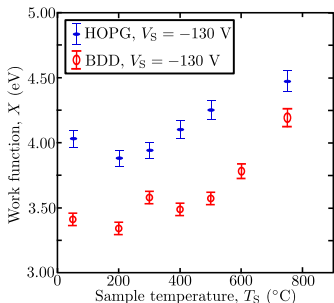
Investigating Cs alternative: Plasma source

- ▶ 13.56 MHz RF ICP plasma (up to 600 W)
- ▶ D₂ plasmas 0.2–2 Pa



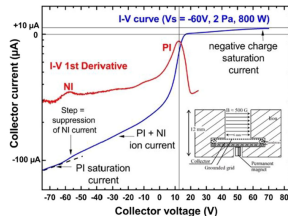
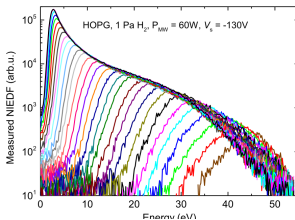
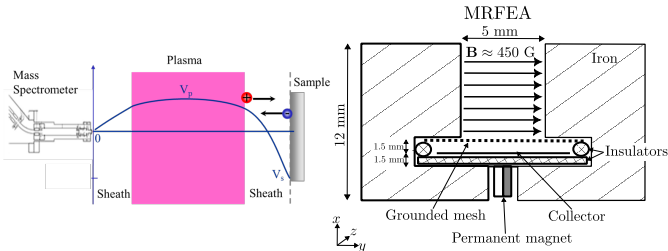
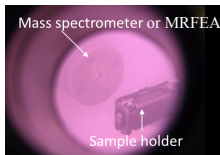
Investigating Cs alternative: Work function measurements

- Photo-emission Yield Spectroscopy (through a UV viewport)



R. Magee et al., Plasma Sources Sci. Technol. 32(7), 075021 (2023)

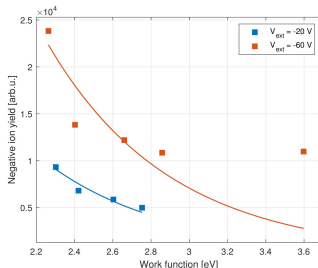
Investigating Cs alternative: NI yield measurements



D. Kogut et al., Plasma Sources Sci. Technol. 26(4), 045006 (2017).
F. Tacogna et al., Eur. Phys. J. D 75, 227 (2021).

Investigating Cs alternative: Gadolinium

- ▶ Gd exhibits the behaviour expected for a metallic surface.
- ▶ Measured work function after Ar sputtering: $\Phi_{\text{Gd}} \approx 2.2 - 2.3$ eV
- ▶ Φ_{Gd} close to Φ_{Cs} (~ 2.1 eV) and significantly lower than the value for pure Gd (~ 2.9 eV).
- ▶ Experimental data reasonably fitted by the expected exponential dependence on $\Phi - EA$.

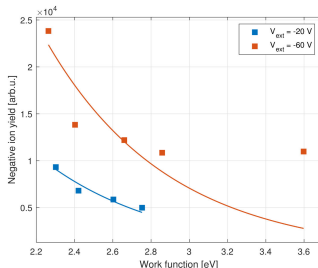


Clear anti-correlation between negative ion yield and work function:

- ▶ higher $\Phi \rightarrow$ lower yield
- ▶ consistent with metallic surface ionisation models

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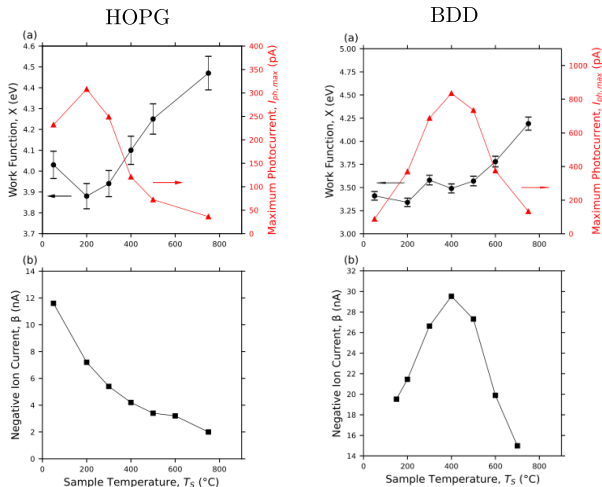
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- ▶ Experimental data reasonably fitted by the expected exponential dependence on $\Phi - EA$.
- ▶ Potentially interesting as microparticles



Clear anti-correlation between negative ion yield and work function:

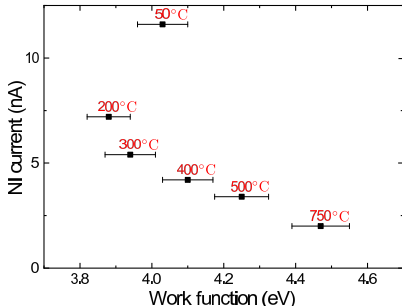
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Investigating Cs alternative: HOPG, PDD and BDD

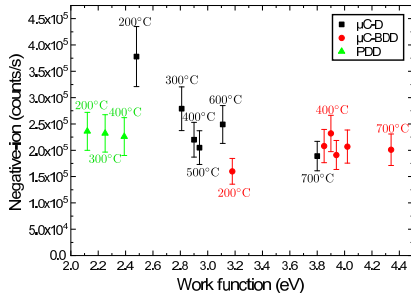


Investigating Cs alternative: HOPG, PDD and BDD

HOPG sample, $V_{\text{bias}} = -130$ V, D_2 plasma, $P_W = 150$ W, $p = 2$ Pa



$V_{\text{bias}} = -20$ V (pulsed), D_2 plasma, $P_W = 150$ W, $p = 2$ Pa

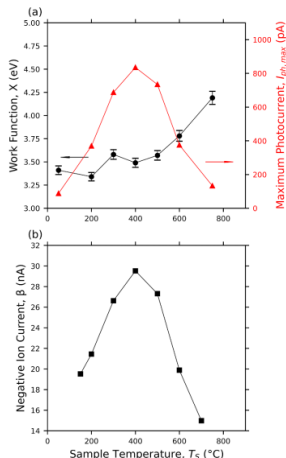


Work function correlates with NI production for HOPG (and μ C-D), but not for BDD (and PDD).

Investigating Cs alternative: HOPG, PDD and BDD

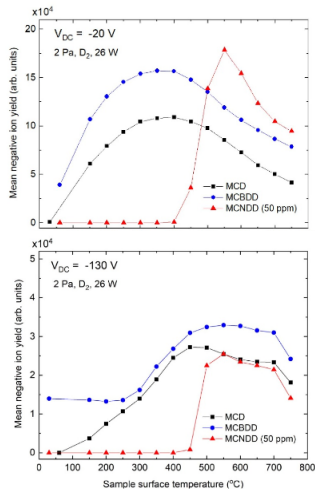
- ▶ Work function correlates with NI production for HOPG, but not for BDD.
- ▶ For diamond, the band gap and electronic structure are as important as the work function.
- ▶ Plasma-exposed BDD exhibits a maximum NI yield at $\sim 400\text{--}500^\circ\text{C}$.
- ▶ Photocurrent closely follows NI current, suggesting a common electron-emission mechanism.

BDD



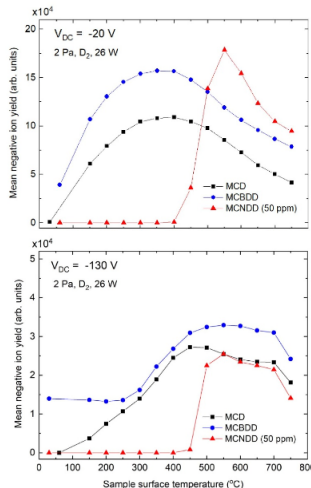
Investigating Cs alternative: NDMCC

- ▶ N doping enhances diamond NI production; optimum at 50 ppm.
- ▶ NI yield depends strongly on temperature; maximum at $\sim 550^{\circ}\text{C}$.
- ▶ Enhancement is strongest under low-energy bombardment; high energies reduce NI yield.



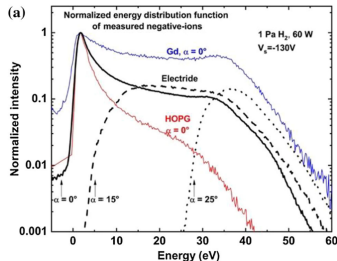
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- ▶ NI yield depends strongly on temperature; maximum at $\sim 550^{\circ}\text{C}$.
- ▶ Enhancement is strongest under low-energy bombardment; high energies reduce NI yield.
- ▶ $\Rightarrow$ N-doped diamond is a promising caesium-free alternative, especially as transiting microparticles (limiting bombardment effects).



Investigating Cs alternative: C12A7 electride

- ▶ Low work function ($\sim 2.4\text{--}2.6\text{ eV}$) with a dielectric-like band structure (efficient e^- capture, reduced NI destruction).
- ▶ NI formation is dominated by backscattered H/D particles capturing electrons at the surface.
- ▶ A smaller sputtering contribution is also observed.
- ▶ Cs-free, chemically and thermally stable, NI yields comparable to HOPG, machinable (microparticles)

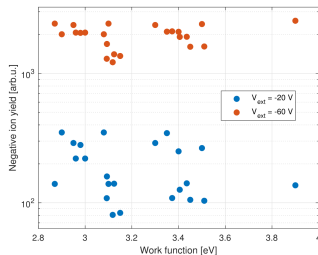


Investigating Cs alternative: C12A7 electrified

⇒ **Optimising surface electronic properties may provide an alternative to Cs.**

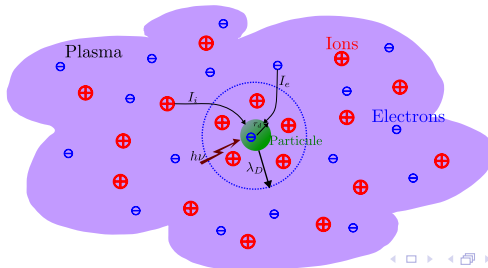
Challenges:

- ▶ NI yield not simply correlated with work function (more complex mechanisms than conventional metallic converters, challenging optimisation).
- ▶ Long-term plasma stability, surface evolution, impurity release, and integration into practical NBI sources.



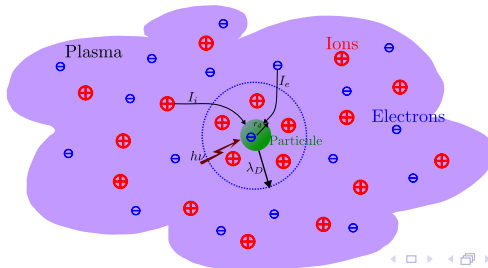
Microparticles as NI source

- ▶ Microparticle charging in negative-ion plasmas.
- ▶ Coupling between particle dynamics, plasma properties and negative-ion production.



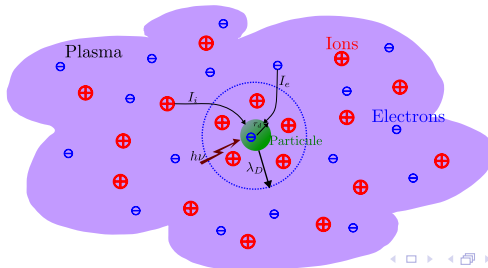
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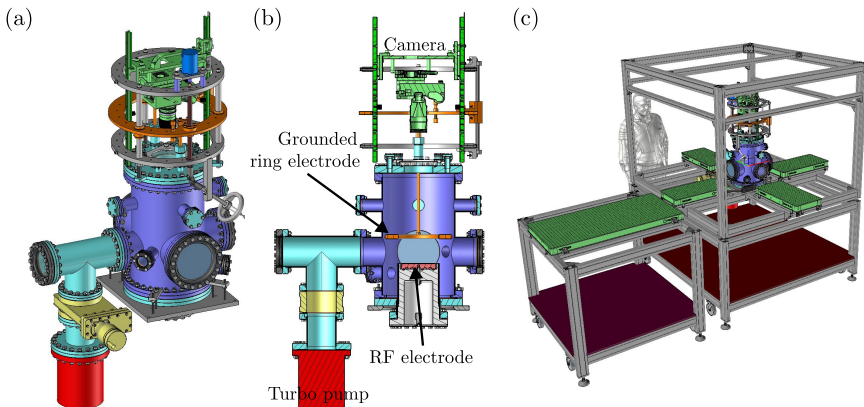
Microparticles as NI source: challenges

- ▶ Microparticle charging in negative-ion plasmas.
- ▶ Coupling between particle dynamics, plasma properties and negative-ion production.
- ▶ Microparticle transport and trajectory control.
- ▶ Efficient extraction of negative ions from transiting microparticles.
- ▶ Avoiding particle contamination of the accelerator.

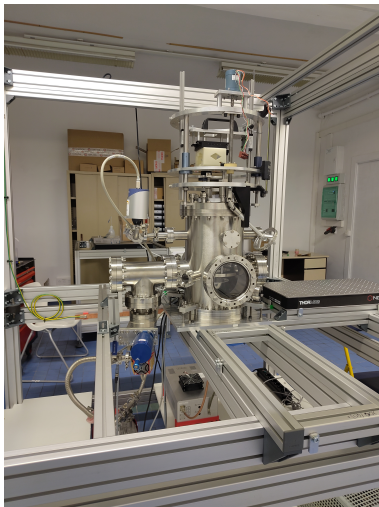


Microparticles as NI source: Experimental device

Design and construction of a dedicated experiment

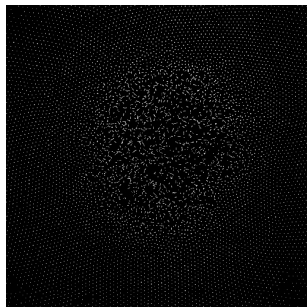


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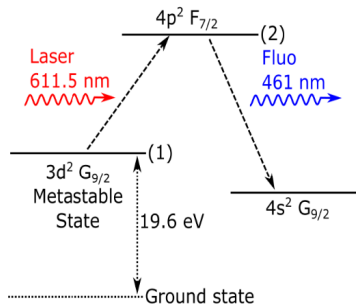
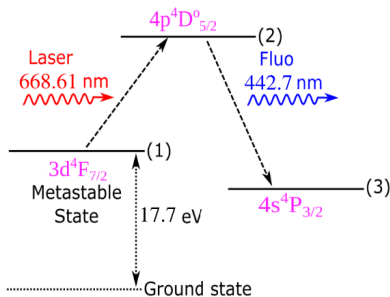
Microparticles as NI source: Diagnostics (I)

- ▶ Electrical diagnostics (V_{rf} , I_{rf} , V_{bias})
- ▶ Optical emission spectroscopy
- ▶ High speed video camera



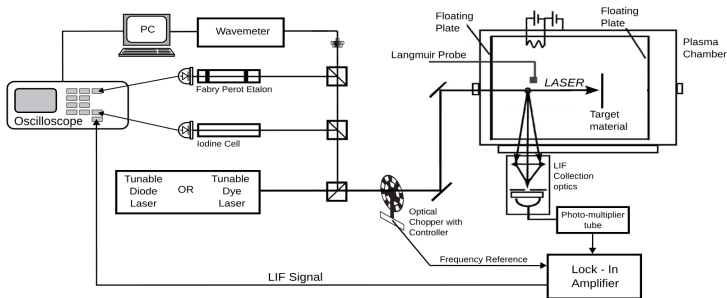
Microparticles as NI source: Diagnostics (II)

Laser induced fluorescence for spatially resolved measurements of ion velocity distribution function (IVDF) allowing the recovery of plasma potential profiles.



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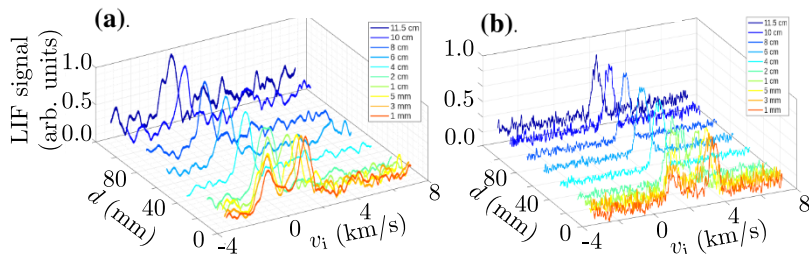
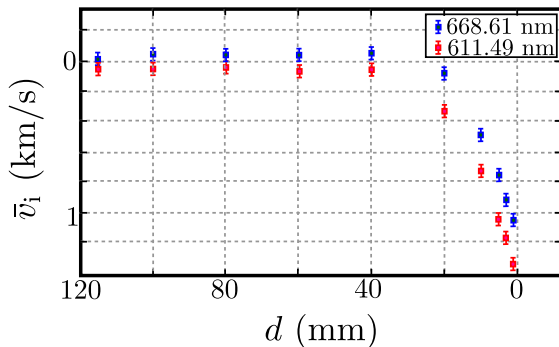


Fig. 6: Evolution of LIF signal as we move towards the W plate for (a) transition at 668.614 nm, and (b) transition at 611.49 nm.

Microparticles as NI source: Diagnostics (II)



Microparticles as NI source: future work

- ▶ Characterise rf sheath with and without microparticles in Ar/H₂ plasmas.
 - ▶ with non NI emitting microparticles
 - ▶ with dust made of material emitting NI
- ▶ Study microparticles dynamics in Ar/H₂ plasmas.
 - ▶ with non NI emitting microparticles
 - ▶ with dust made of material emitting NI
- ▶ Characterise NI emission from a microparticle cloud of candidate materials (electride and NDMCC)

Conclusion and perspectives

Conclusion and perspectives

- ▶ Surface production is the most attractive route for high-current H^-/D^- sources required by fusion NBI systems.
- ▶ Several Cs-free materials show promising NI production:
 - ▶ Gd metal with a work function (almost) as low as Cs.
 - ▶ Diamond-based materials benefit from their band-gap and electronic structure; N-doped diamond improves NI yield (optimum at 50 ppm N).
 - ▶ C12A7 electride combines low work function and dielectric-like properties.
- ▶ Work function alone does not explain NI production in dielectric-like materials; surface electronic structure and plasma-induced surface modifications are also critical.

Conclusion and perspectives

- ▶ Exploit efficient Cs-free materials in the form of continuously renewed transiting microparticles.
- ▶ Combine:
 - ▶ large specific surface area,
 - ▶ reduced contamination and erosion,
 - ▶ favourable NI extraction from negatively charged microparticles.
- ▶ Characterise microparticle charging, transport, and NI emission in H_2/D_2 plasmas.
- ▶ Demonstrate proof-of-concept extraction of NI produced on transiting microparticles and assess scalability towards future fusion NBI sources.

Thank You!

Questions?