Research performed and Scientific Results obtained in the frame or the ENR project

NanoDust in Metal Tokamaks

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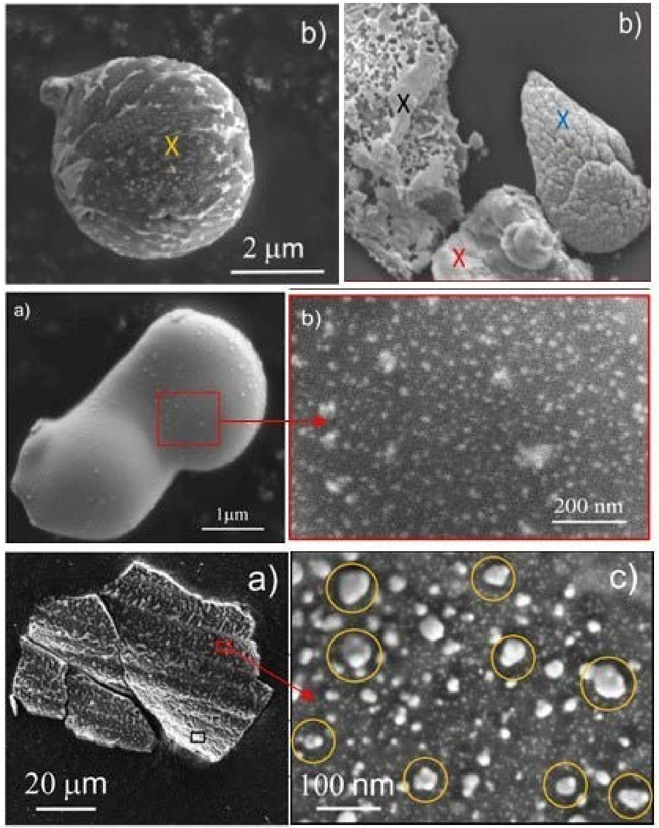
EUROfusion Science Meeting on results of ENR projects
2021-2023, October 24, 2024 (dinescug@infim.ro)

Dust in Tokamak discharges - particles collected in WEST



Example of dust particles collected on the WEST divertor;

Two distinct dust populations:

- W particles with micrometers up to tens of micrometers size
  caused by the off-normal events (droplets emitted due to high thermal load) or delamination of W coatings;

- W particles with dimensions in the range of nanometers
  caused by condensation of vapors above microsize particles or to ion metallic clusters growing in presence of W sputtering.

S. Peillon et al., Nuclear Materials and Energy 24 (2020) 100781

C. Arnas et al., Nuclear Materials and Energy 36 (2023) 101471

Laboratory dust study : managing discharges to explore separately the effects of melting and evaporation, of evaporation, of sputtering

- Tokamak discharges – simultaneous melting AND evaporation/vaporization AND sputtering;

- Microarcs – local deposition of energy at surface

Lessons learnt

Excluding sputtering: Experiments where melting and vaporization counts

-leads to microparticles and nanoparticles
-microparticles are spherical, like solidified droplets

- Hollow Cathode Discharges – hot electrodes in plasma

Excluding melting: experiments under action of sputtering and evaporation

-leads to nanoparticles and microparticles
-microparticles formed from agglomerated nanoparticles

V. Marascu et al., Appl. Sci. **2020,** 10, 6870
V. Marascu et al., Mater. Res. Express **2020 7,** 065509
C. Stancu et al., Materials **2023,** 16, 6853
V. Marascu et al., Coatings **2023**, 13, 503

- Sputtering discharges

Excluding melting and evaporation: Experiments with only sputtering present

DUST-FORM project

Research questions

Project structure and scientific approaches

Is the production of nanometric particles enhanced by gases used in detachment (laboratory experiments)?

WP3 : Experimental investigation of W and Be dust particles formation

(IAP-INFLPR -*Gheorghe Dinescu - responsible for WP*, IRFM).

- search for enhanced sputtering and nanoparticle formation in magnetron experiments (W targets in presence of Ne, Ar, Kr);

-search for particle production during high energy deposition by laser on surfaces (pulsed laser deposition on Be surfaces);

-collect particles in WEST;

How such nanoparticles nucleate, growth and evolve in plasmas?

WP2 : Modelling of dust particle production kinetics through plasma/surface interaction under edge plasma conditions. (CNRS-LSPM - *Khaled Hassouni- responsible for WP*, IRFM, PIIM);

- consider physical phenomena as melting, evaporation, nucleation from vapors, and growth in modelling the dust formation;

How such nanoparticles influences the edge plasma?

WP1 - Edge plasma integrated simulation with impurity and dust transport (CEA- IRFM - *Nicolas Fedorza*ck responsible of the WP, PIIM, LSPM);

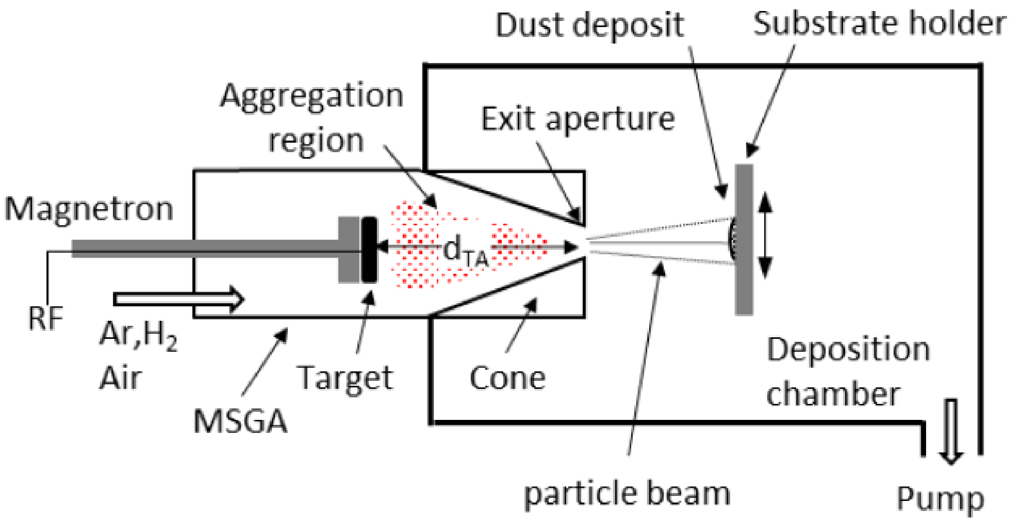
-use numerical codes for edge plasma simulation in presence of dust;

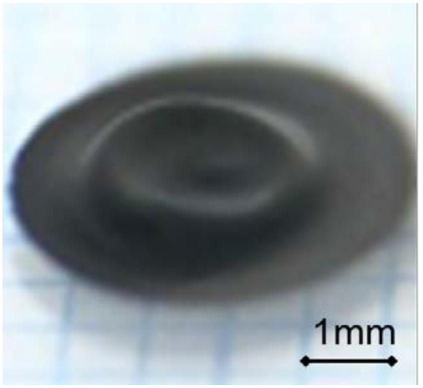
I. Is the production of nanometric particles enhanced by gases used in detachment (laboratory experiments)?

Focus on sputtering, magnetron discharges

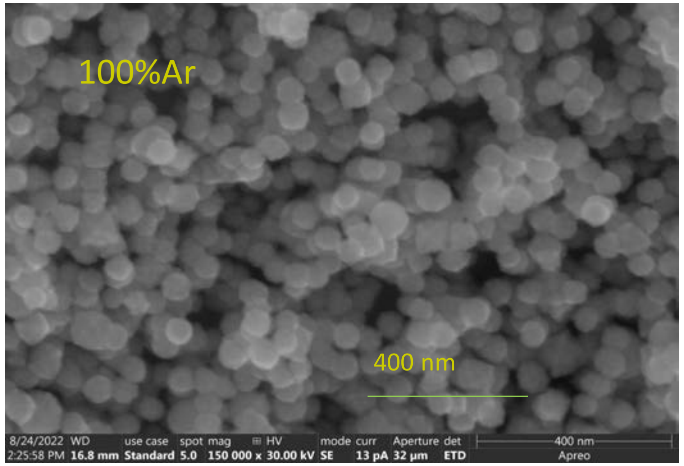
Making W nanoparticles by Magnetron Sputtering Gas Aggregation Technique – MSGA

W target; H_2, D_2 admixed with sputtering gases (Ar, Ne, Kr) and impurities (O_2, N_2, H_2O vapors); gas rates 0-10 sccm; p_{aggreg} ~ 0.7 mbar; p_{dep}~ 0.08 mbar; RF power: 80-130 W





spot on collector



SEM, particles

⇩ opportunity

Particles collected on substrate, can be extracted and studied separately

Focus on the effect of gases on dust formation rates and dust characteristics

Example: characteristics and dust formation in H_2 plasmas injected with high-Z inert gases (Ar, Kr, ...) in relation with divertor plasma detachment (ENR project)

The impact of injecting Ar on the dust formation rates in hydrogen plasma

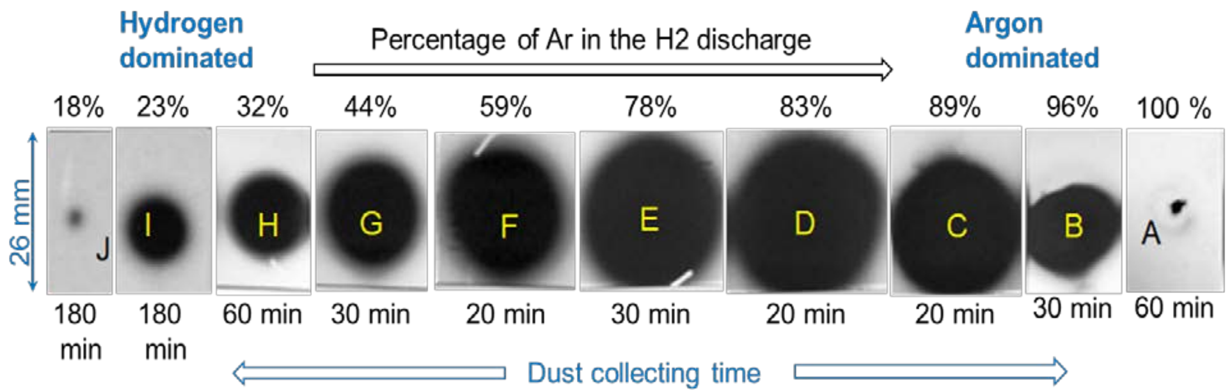
Variable, the percentage of Ar in H_2 + Ar plasma

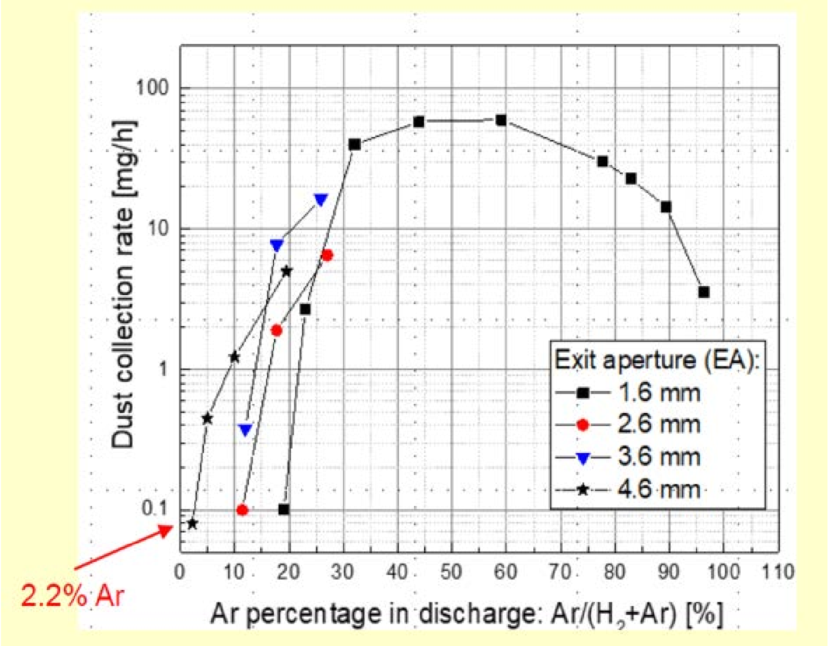
- Ar/(H_2+Ar): 0 –100 %
- p_{aggreg} ~8 x10^{-2} mbar;
- p_{coll} ~ 5x10^{-3} mbar
- P_{RF} ~ 80 W
- Collecting time: 20 -180 min

The mass of dust was measured by weighing the collectors before and after dust deposition

Conclusion: up to 20% injection of Ar in H_2 increases the dust formation rates more than 10^2 times.

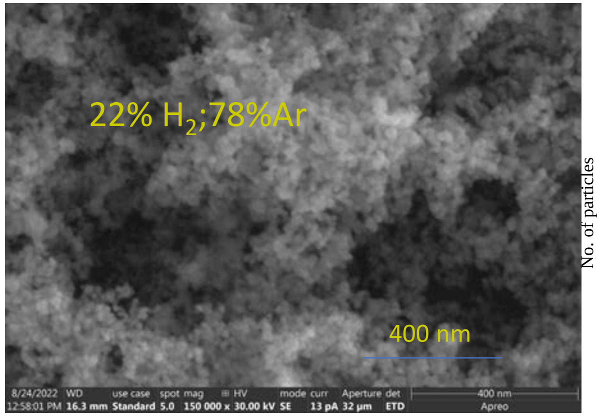
Spots of collected particles(extraction aperture 1.6 mm)

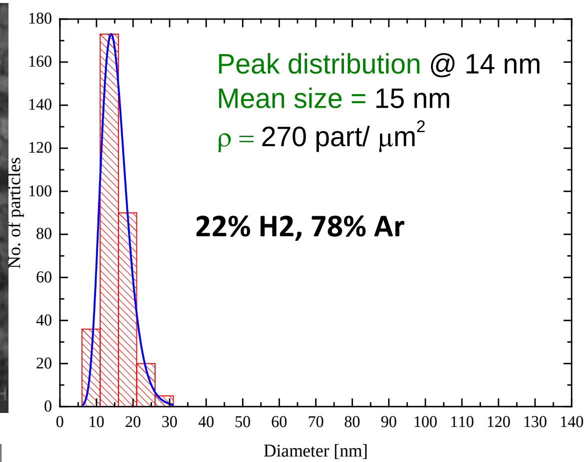


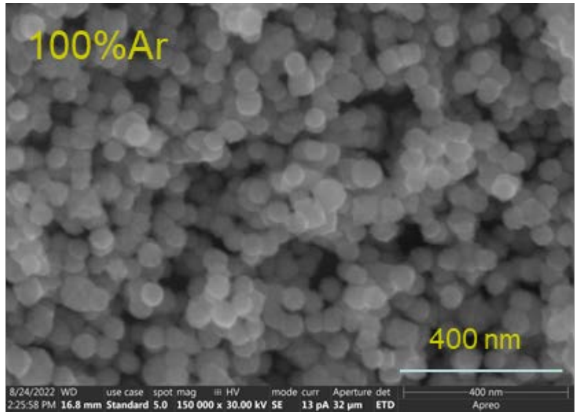


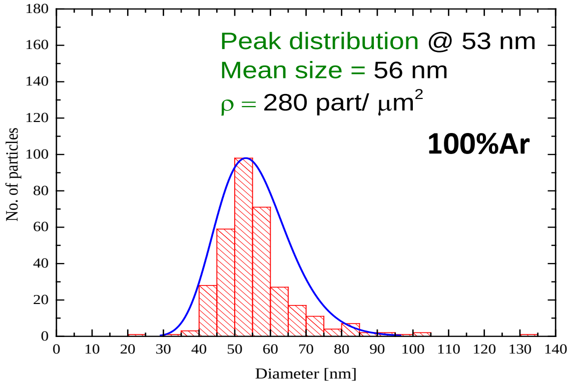
Collected dust rate upon the argon content

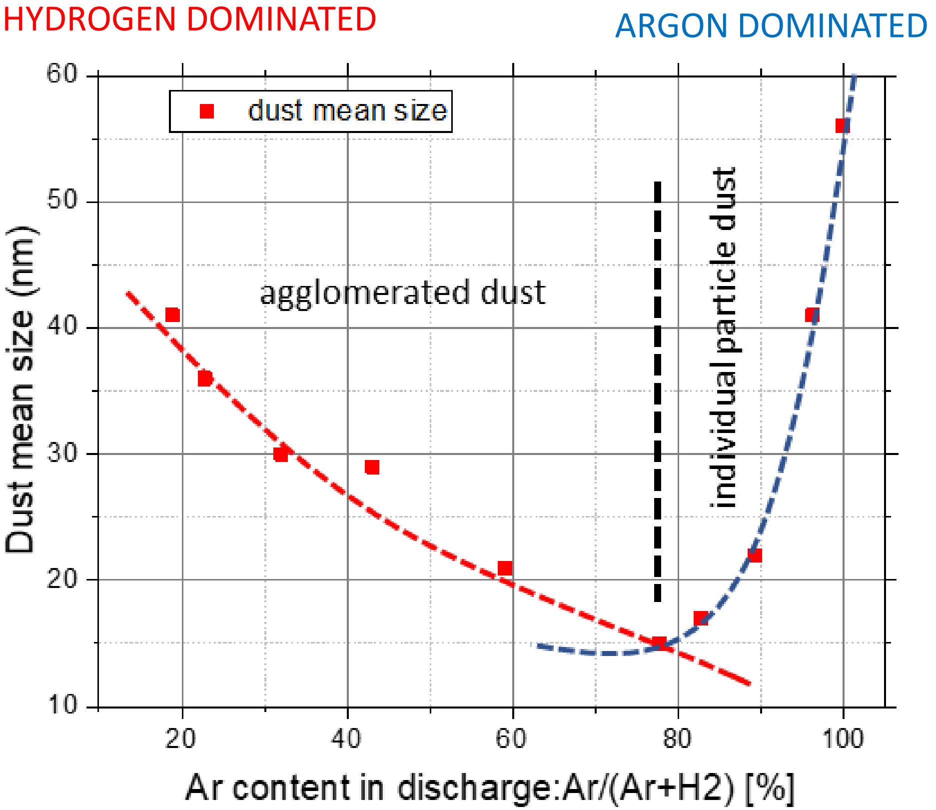
Evaluation of the effect of injecting Ar on particle size











Size of the collected dust upon the percentage of Ar injected in discharge (exit aperture of 1.6 mm).

Conclusions:

- Size of particles is much smaller in H_2 dominated discharges
- Fusing of particles is observed, agglomeration process is favored in H_2 dominated discharges;

Lessons learnt from sputtering discharges

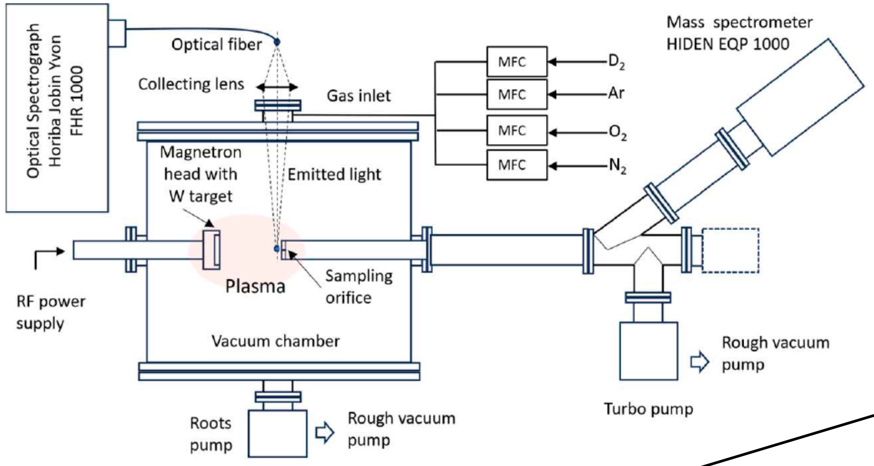
- Sputtering leads to W nanoparticles;
- Injecting Ar in hydrogen may increases drastically (x 100) the particles production rates;
- Nanoparticle size and dust morphology depends strongly upon the percentage of Ar injected in H_2:
    - hydrogen dominated discharges – small size and agglomerated dust;
    - argon dominated discharges – higher nanoparticle size, individual particles in the dust.

T. Acsente, et al. 2015, *Eur. Phys. J. D*, 69, 161;
T. Acsente, et al., 2017, *Materials Letters*, 200, p 121.
T. Acsente et al.. In: Mieno, T. , Hayashi, Y. , Xue, K. , editors, 2020, *Progress in Fine Particle Plasmas* https://www.intechopen.com/chapters/71477 doi: 10.5772/intechopen.9173
T. Acsente et al. 2021 *J. Phys. D: Appl. Phys*. 54 02LT01
T. Acsente et al. *Coatings* **2024**, 14, 964 (https://doi.org/10.3390/coatings14080964)

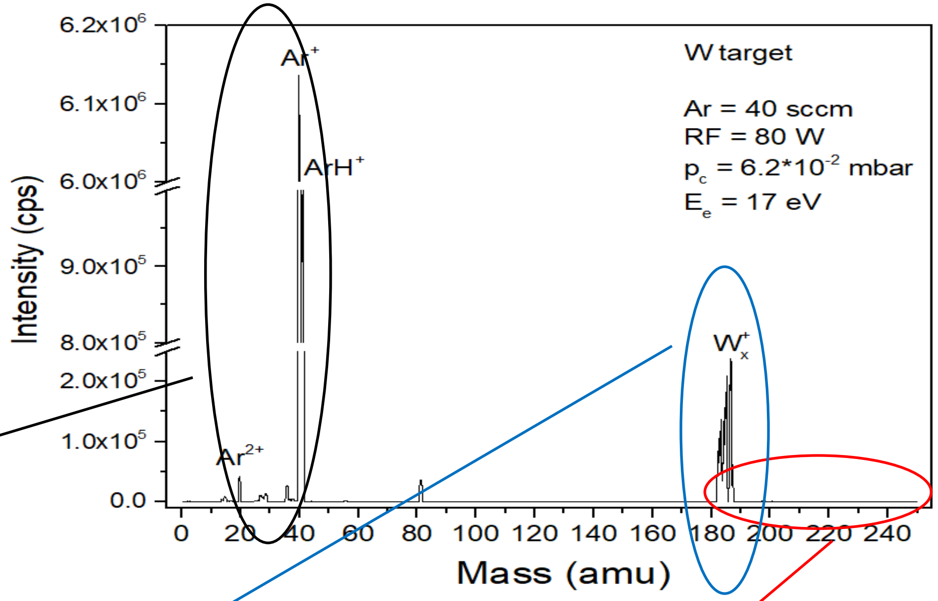
W species in sputtering W/H_2(D_2) /Ar plasmas and their behavior upon injecting Ar in H_2 discharge

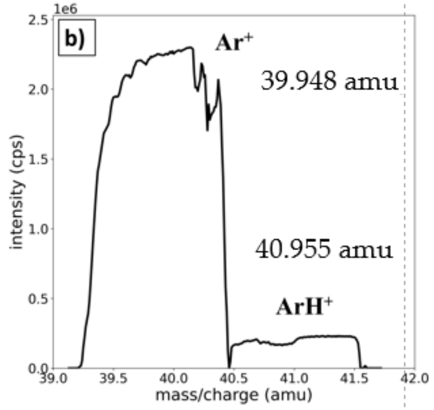
W species in sputtering H_2 (D_2)/Ar plasma – mass spectrometry

MS setup

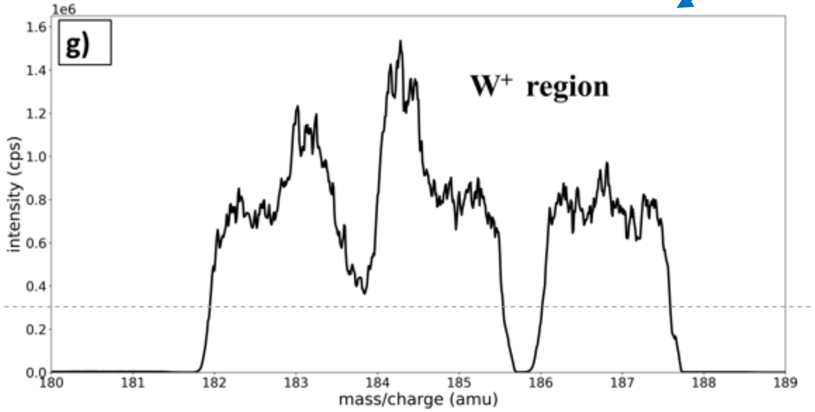


Mass spectrum of Ar plasma with W target

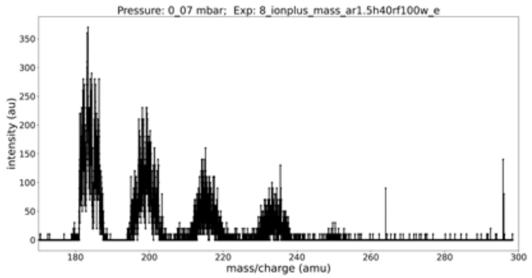




Focus on sputtering ion region (Ar^+ region)



Focus on sputtered species: W^+ region

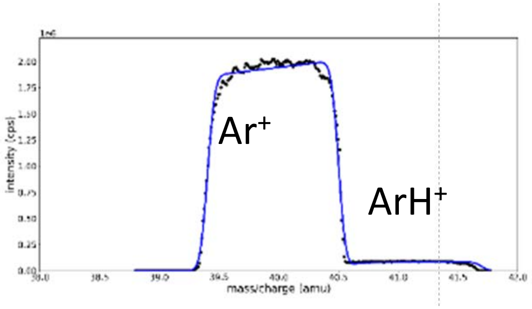


Noisy region 190-250 amu

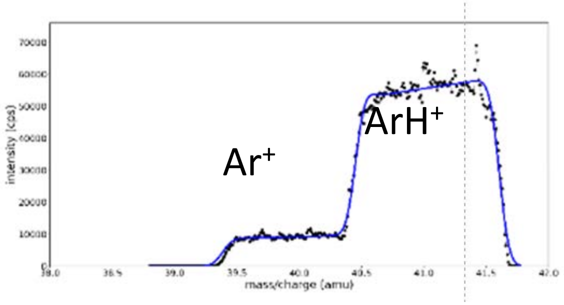
Will be discussed later!

Ar^+, ArH^+ zone: Behavior of sputtering ions upon Ar percentage in H_2

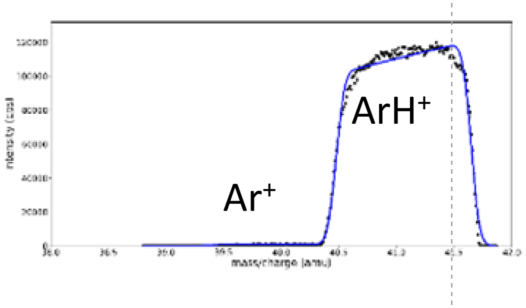
H_2 = 0%
(Ar only)



H_2 = 5%
Ar =95%

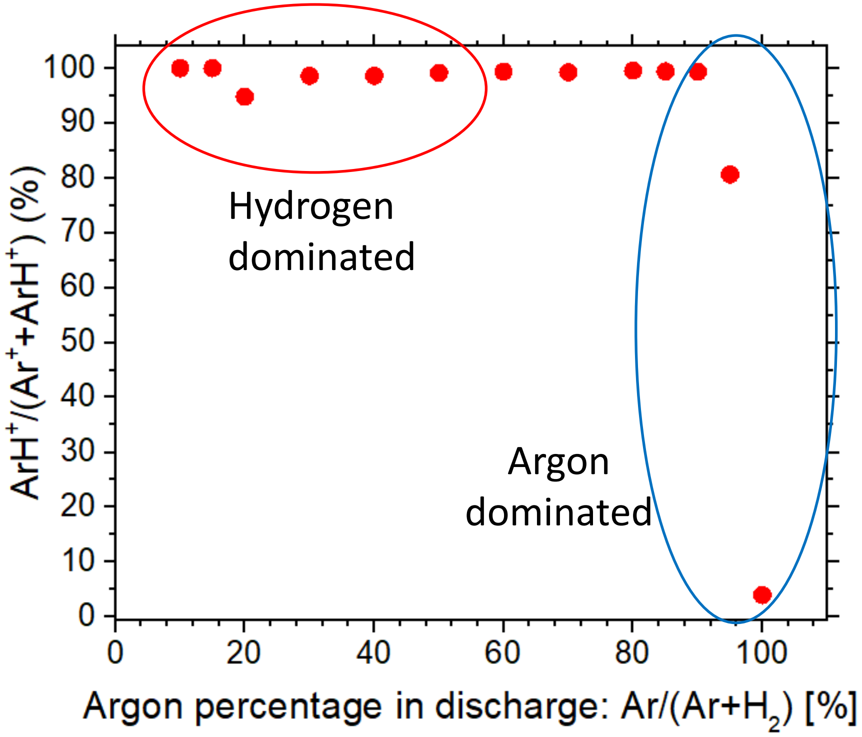


H_2 = 90%
Ar = 10%



H_2 causes the conversion of Ar^+ in ArH^+

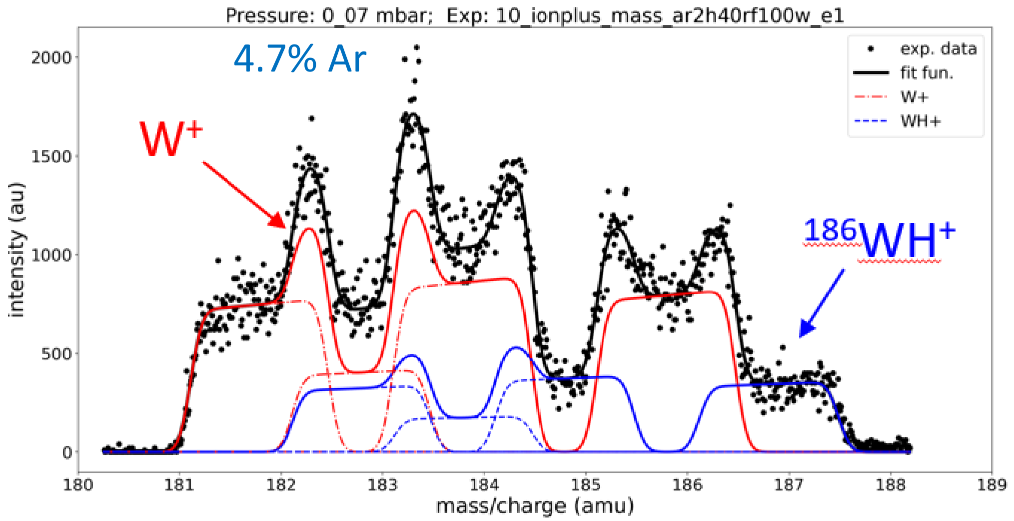
Evaluation of the ratio $\frac{ArH^+}{Ar^+ + ArH^+}$

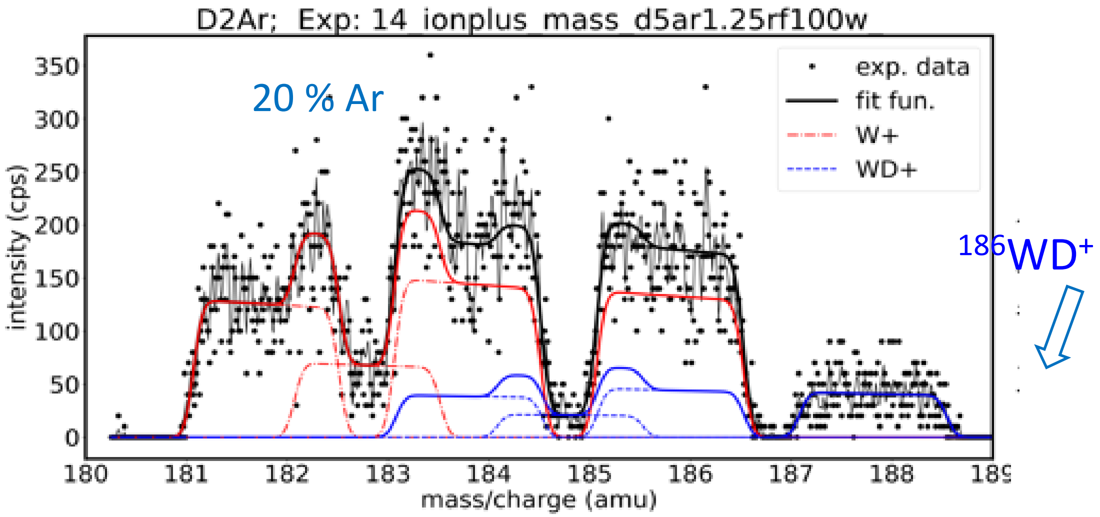


Lesson: In Hydrogen (Deuterium) dominated discharges injected with Ar the sputtering process is sustained by ArH^+

T. Acsente et al. **2024** *Plasma Chem. Plasma Proc*. (https://doi.org/10.1007/s11090-024-10499-z)

W^+ zone: Evidence for WH and WD species in sputtering H_2 (D_2) plasmas





Identified species: W^+, WH^+, WD^+

Development of a fitting procedure

C. Craciun et al., Molecules 2023, 28, 5664, 28155664 (https://doi.org/10.3390/molecules)

Fitting the W^+ region

Two contributions in signal, each with 4 components:

1) assignable to W^+ peaks,
2) assignable to WH^+ species.

please notice that it is similar for WD^+:

G. Dinescu et al., Molecules **2024**, 29(15), 3539

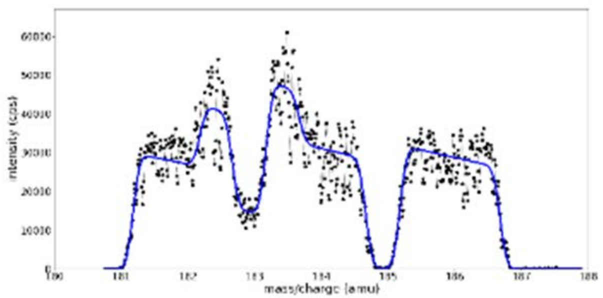
WD detected in Tokamak (OES):

ASDEX, TEXTOR: S. Brezinsek et al. **2019**, *Nuclear Materials and Energy*, vol. 18, pp. 50-55,

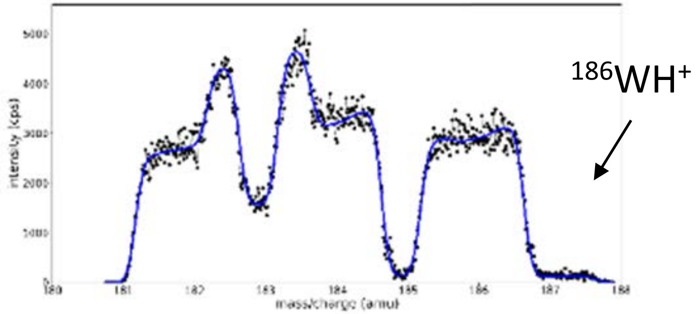
EAST: *Q. Zhang et al. Nuclear Materials and Energy,* **2022,** vol. 33, p. 101265,.

Is the WH^+ percentage significant?

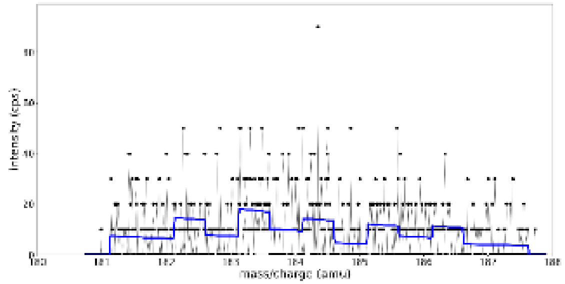
H_2 = 0%
(Ar only)



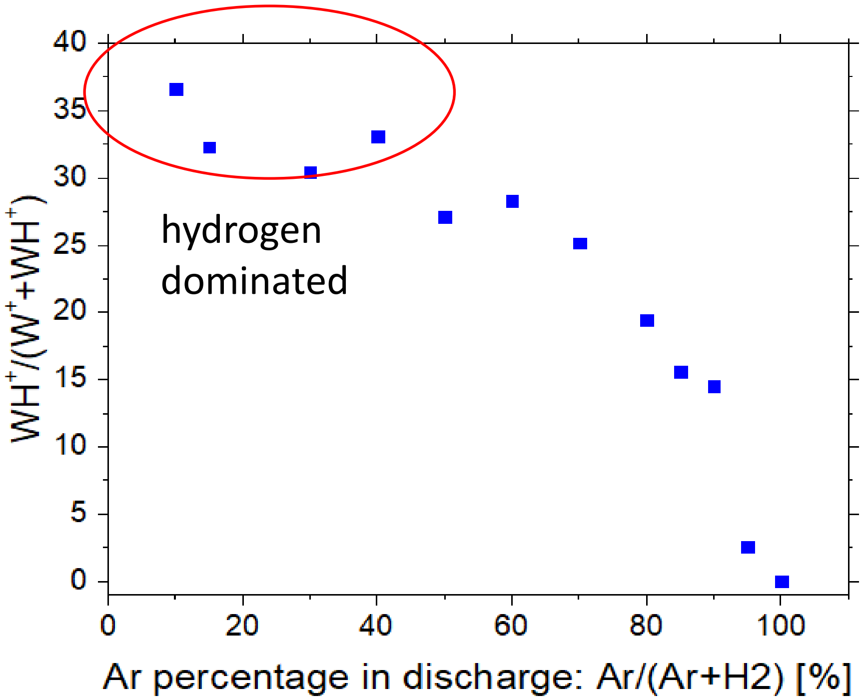
H_2 = 5%
Ar =95%



H_2 = 90%
Ar = 10%



Evaluation of the ratio $\frac{WH^+}{W^+ + WH^+}$

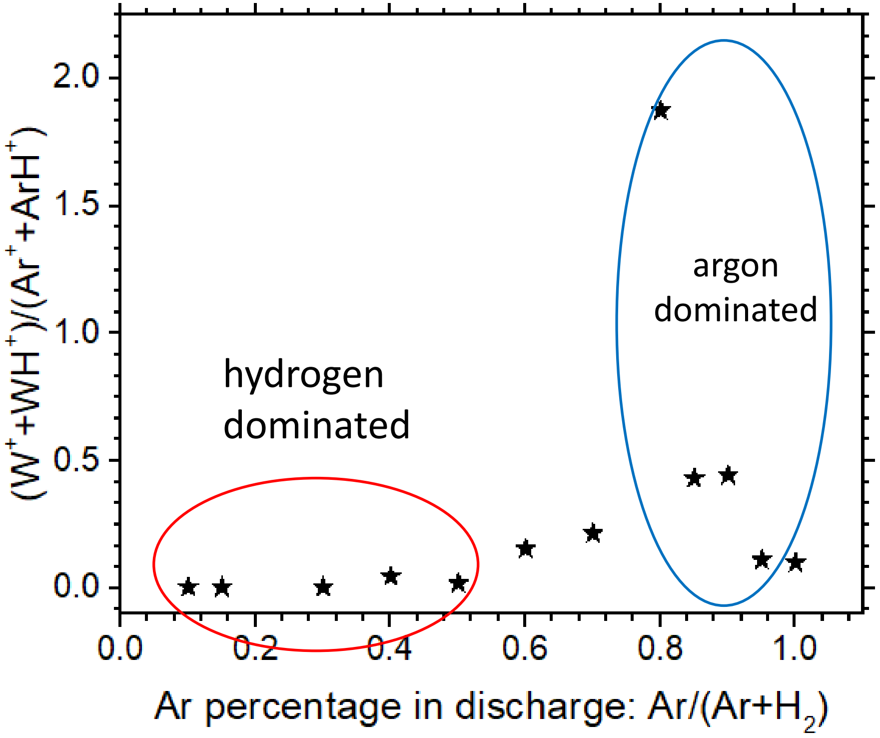


Lesson: Not-negligible WH^+ percentages: $WH^+/(W^+ + WH^+)$ ~30 - 40 % for gas ratios $Ar/(Ar+H_2)$ ~ 10-20%

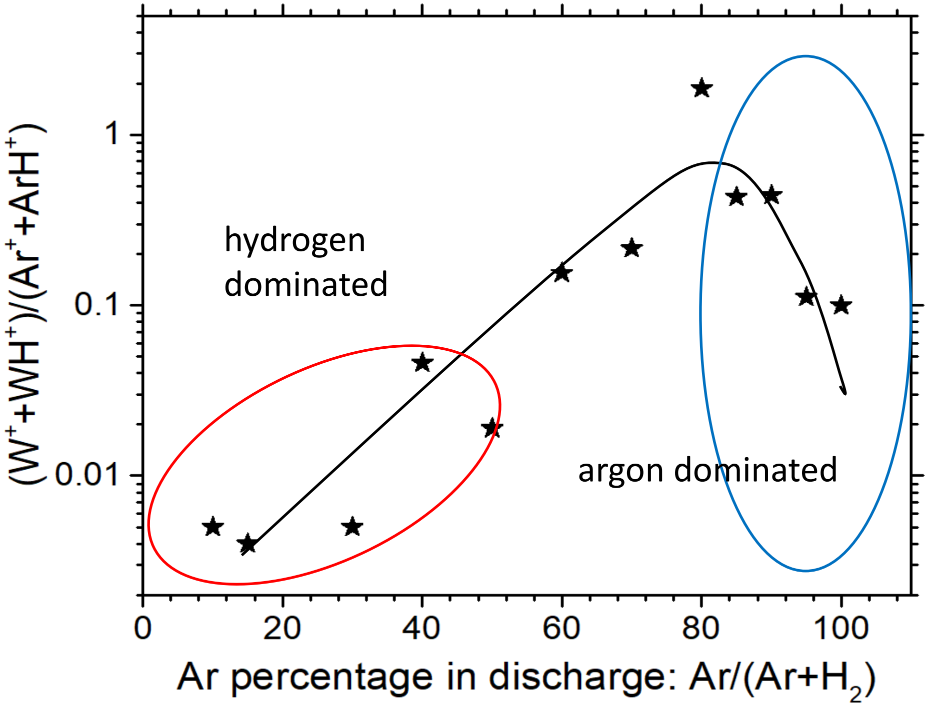
Rough evaluation of the behavior of the sputtering rate

Ratio of the number of W species found in plasma per number of incident sputtering ions ~ $\frac{W^+ + WH^+}{Ar^+ + ArH^+}$ roughly describe the sputtering rate

linear Oy scale



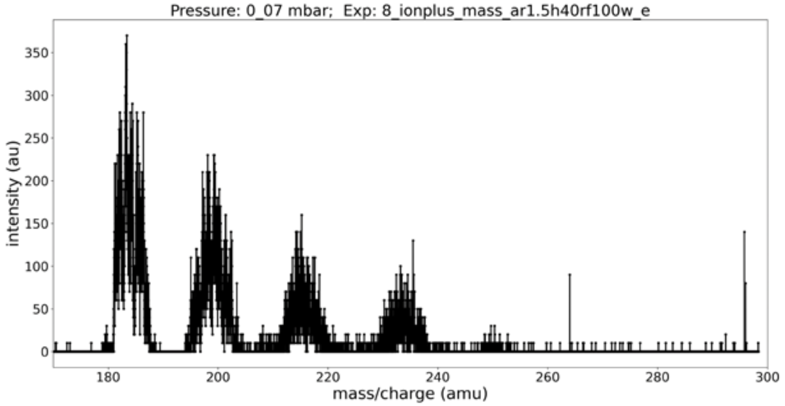
logarithmic Oy scale



- Lesson: Hydrogen dominated discharges: the sputtering rate increases with Ar content

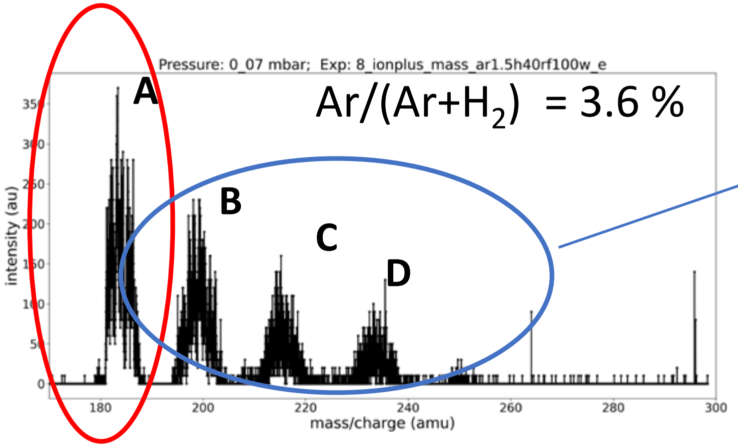
It will be used latter in discussion!

The noisy region 200-250 amu:
assignment of peaks to species

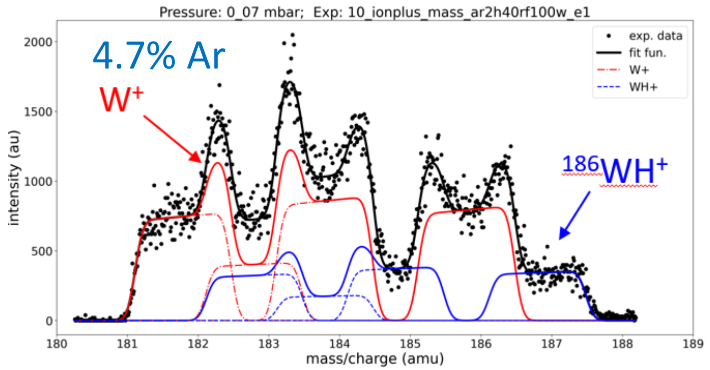


S. D. Stoica et al., Plasma Process Polym. **2024**, e2300227 (https://doi.org/10.1002/ppap.202300227)
G. Dinescu et al., Molecules **2024**, 29(15), 3539 (https://doi.org/10.3390/molecules29153539

W species in sputtering $H_2(D_2)$ -dominated plasma: mass spectrometry



group A : clearly assigned to W, WH^+ peaks



Which is the origin of the group of peaks: B,. C, D...

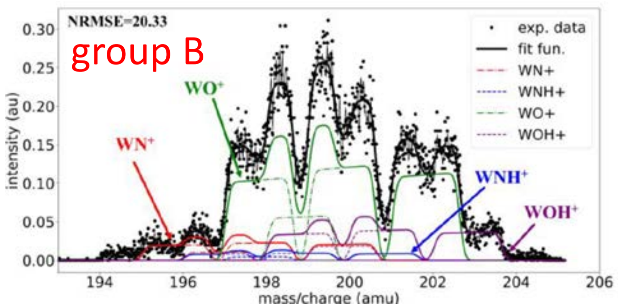
Experimentally observed that the B,C,D... peaks :

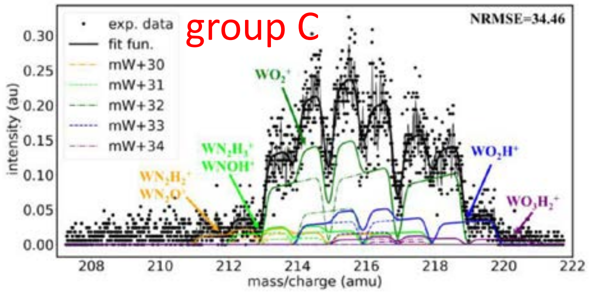
- increase by increased Ar in H_2 discharge
- increase by adding O_2 in discharge
- increase by adding N_2 in discharge

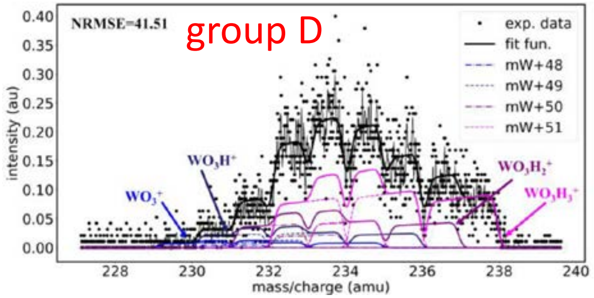
Hypothesis: chemical combinations of one W atom with impurity O, N, H (or D) atoms; we injected O_2 and N_2 gases to confirm

Evidence for $WO_xN_yD_zH_t^+$ molecular tungsten species in hydrogen (deuterium) plasmas with O_2, N_2 impurities in contact with W surfaces

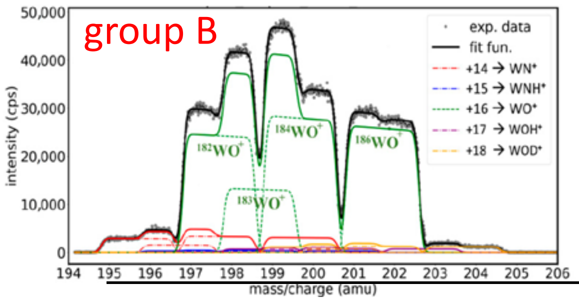
W/H_2/Ar + impurities

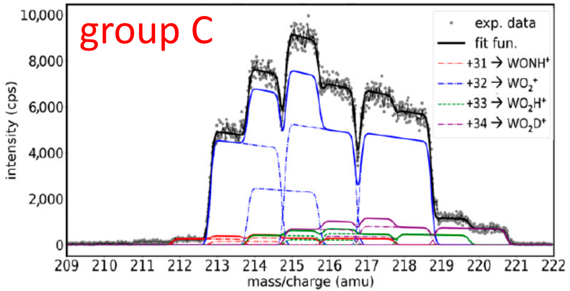


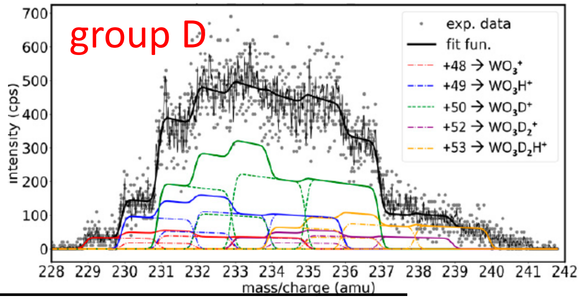




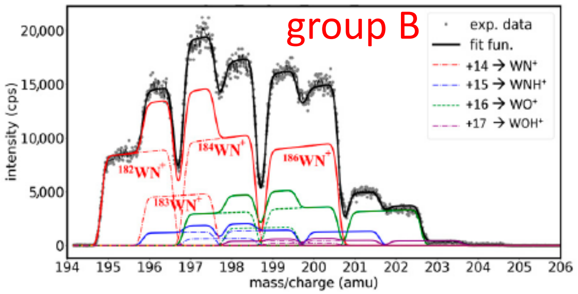
W/D_2/Ar + O_2

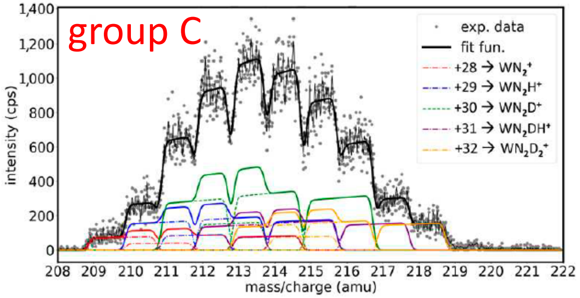


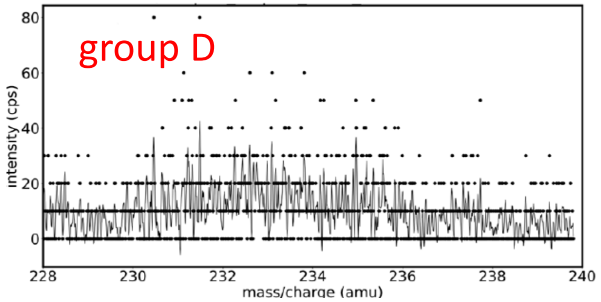




W/D_2/Ar + N_2





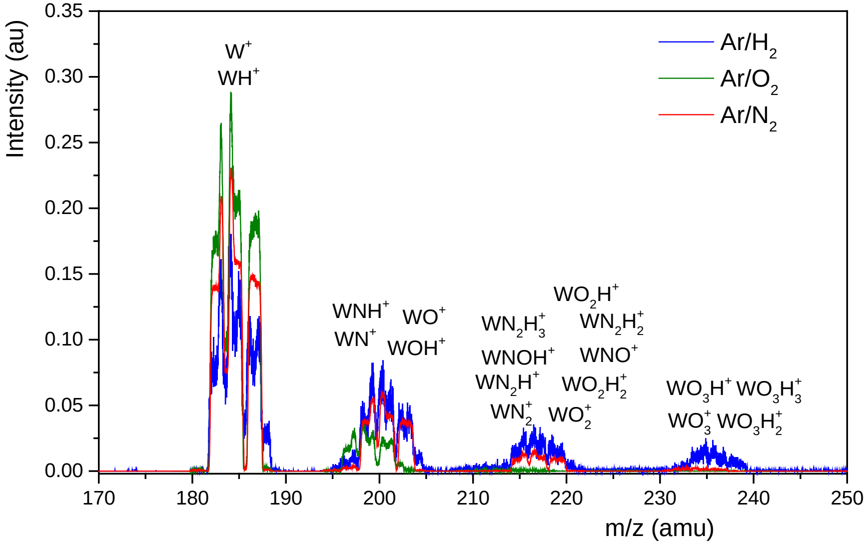


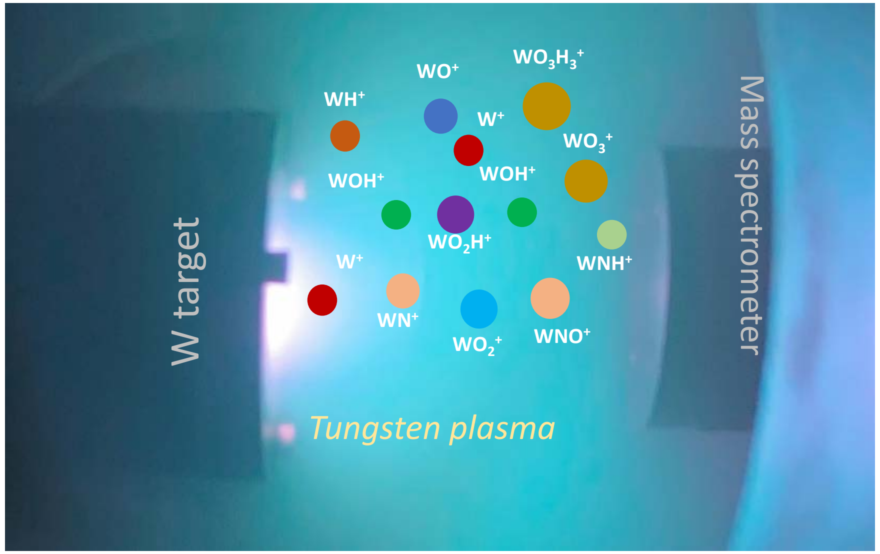
WO^+, WOH^+, WN^+, WOD^+,
WND^+, $WNHD^+$

WO_2^+, WO_2H^+, WO_2D^+, WN_2^+,
WN_2H^+, WN_2D^+, WN_2DH^+, $WN_2D_2^+$

WO_3^+, WO_3H^+, $WO_3H_2^+$, $WO_3H_3^+$, WO3D+,
WO_3DD_2+, $WO_3D_2H^+$, $WN_3H_xD_y^+$ is in noise

Lessons learnt from plasma investigation of hydrogen (deuterium) dominated sputtering plasmas in contact with W surfaces





New findings:

- The material released from the W surface is found not only as W atoms, but also as tungsten molecular compounds formed in reactions with $H_2(D_2)$, O_2, and N_2 gas;
- In W/H_2/Ar plasma the species identified in the mass range 180-250 amu and can be described by the general formula $WO_xN_yH_z$ (x=0-3; y=0-3; z=0-3).

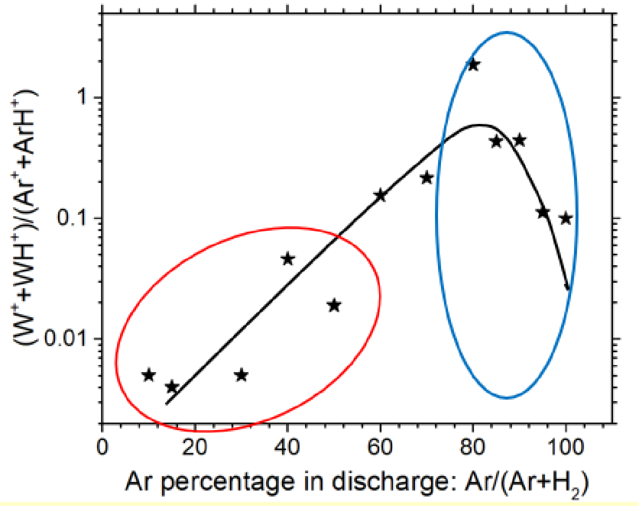
  S. D. Stoica et al., Plasma Process Polym. **2024**, e2300227
- In W/D_2/Ar plasma the species identified in the mass range 180-250 amu and can be described by the general formula $WO_xN_yD_zH_t$ (x =0–4, y=0–3, z=0–3, t=0–5.).

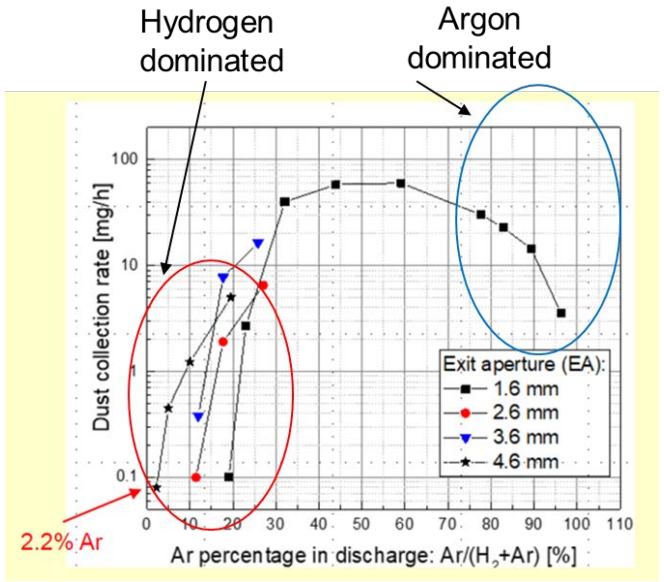
  G. Dinescu et al., Molecules **2024**, 29(15), 3539

Insights into dust formation mechanisms

Hydrogen plasmas in contact with tungsten
surfaces in presence of small percentages of Kr

How species transform to dust: an experimental journey in the mechanism of dust formation





SPECIES

nucleation

growth

DUST

Mechanisms of dust formation, questions:

Is dust formed at surface?

Is dust formed in volume?

Micron size dust can be formed?

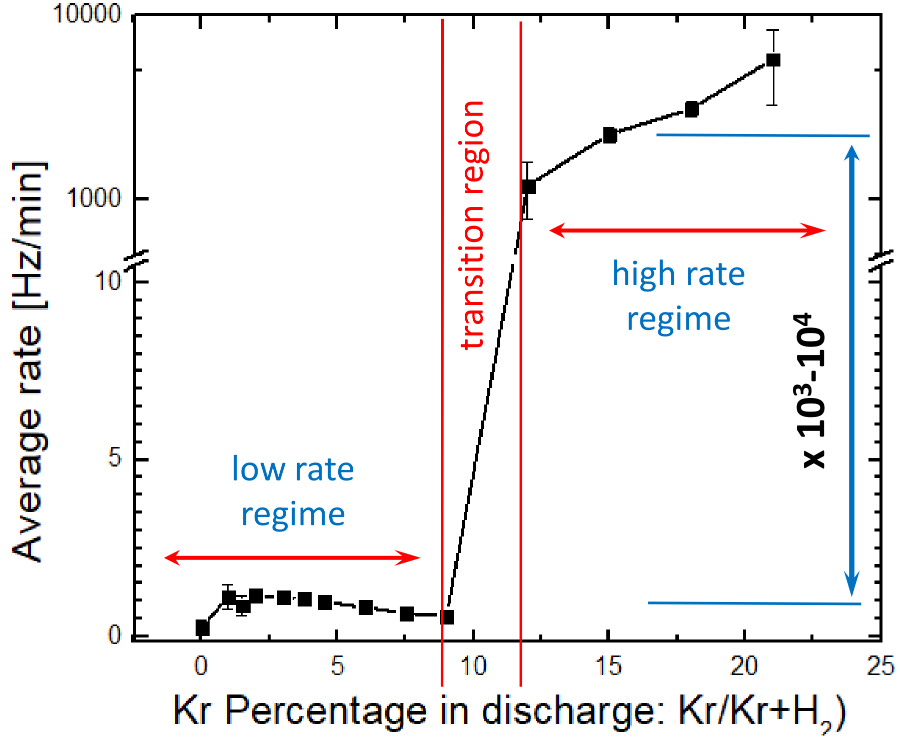
Experiments for answering:

- Quartz crystal microbalance (QCM) for determining deposited mass –
- used simultaneously with SEM to observe the dust .
- Experiments in H_2 injected with Kr!

Dust formation rates upon the injected gas percentage

QCM results: Kr injected in H_2 plasma

Experimental details: MSGA system,
Sputtering power=100 W, p=0.07 mbar,
gas ratios $Kr/(H_2+Kr) = 0 - 22$ %



Dependence of mass rate upon $Kr/(H_2+Kr)$ gas ratio (average upon 3 independent measurements)

Remarks:

-at Kr percentages less than ~8-10% the dust collection rates are very low (QCM frequency variations ~1Hz/min) - low rate regime;

-at Kr percentages higher than ~15% the dust collection rates are extremely high (10^3-10^4 Hz/ min) – high rate regime;

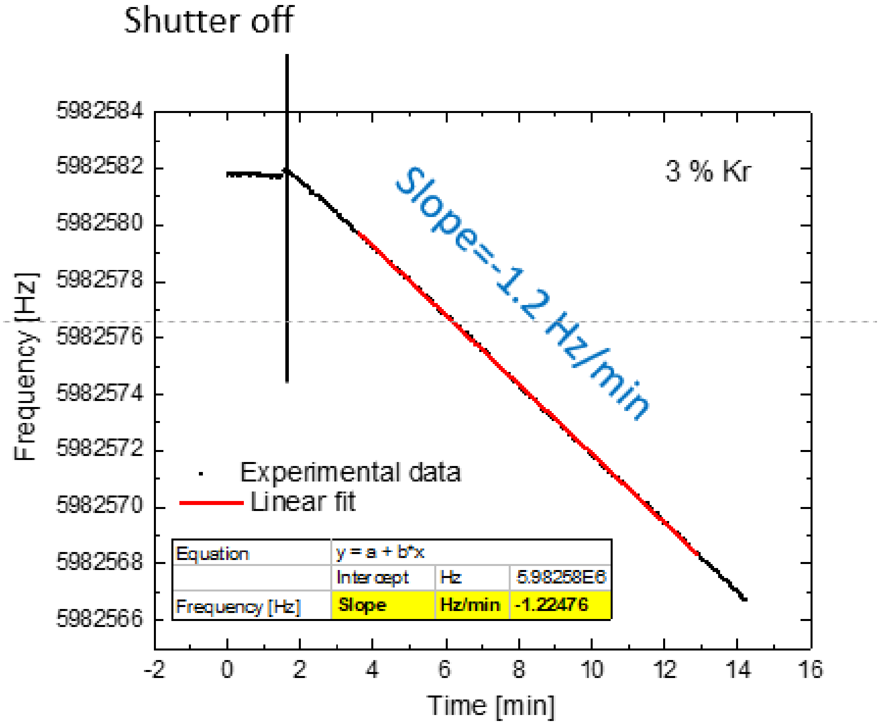
- there is a transition region in the process, associated with a critical Kr percentage in the range 8-13%; once exceeded the critical value an **explosive increase (10^3-10^4 times)** of dust production rate is observed.

Conclusion: There is a critical value of Kr percentage leading to explosive increase of dust formation rate

Low-rate regime – dust collection rate versus dust morphology

Low-rate regime (3%Kr)

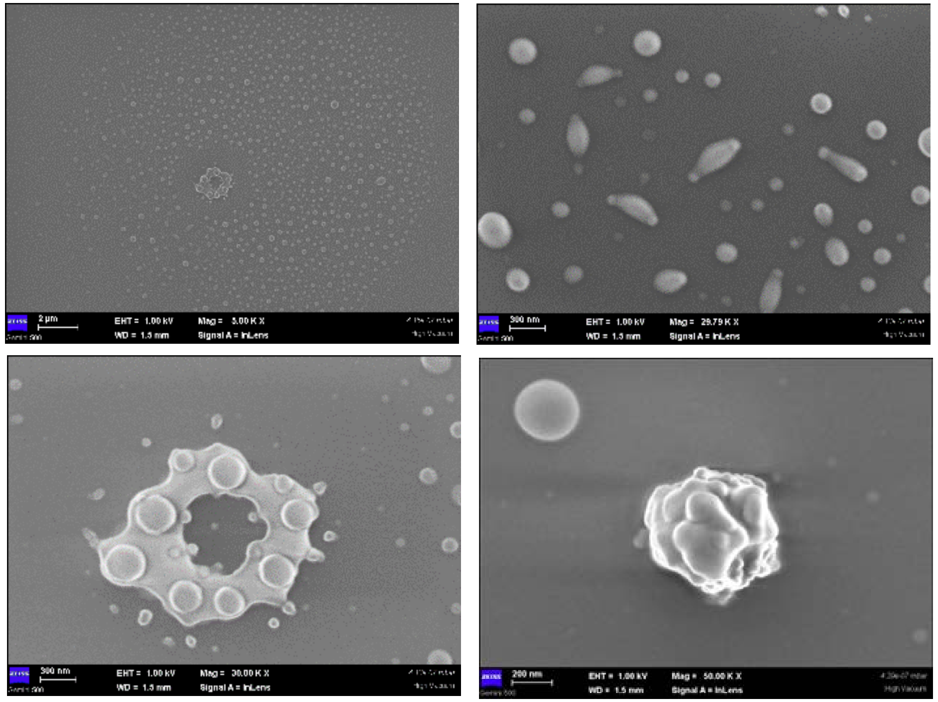
MSGA system,
Sputtering power=100 W, p=0.07 mbar,
gas ratios Kr/(H_2+Kr) = 3 %



Equation	y = a + b*x		
	Intercept	Hz	5.98258E6
Frequency [Hz]	Slope	Hz/min	-1.22476

QCM rate : Continuous mass increase

Images of collected dust, collecting time: 3 h



- Many nanometric particles but also of micron size;
- The nanoparticles surround the big particles;
- Some of nanoparticle seem melted;
- High-size particles made from many fused nanoparticles

Dust aspect: Discontinuous and non-uniform coverage

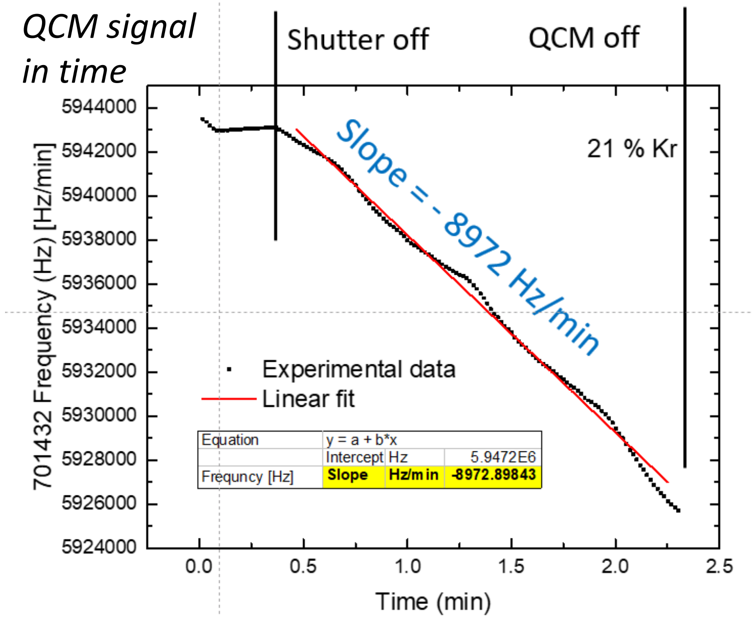
Contradiction: QCM indicates a continuous increase of mass on substrate; SEM indicates discontinuous surface coverage, big particles, even micron size!

High-rate regime – dust collection rate versus dust morphology

High rate regime (21% Kr)

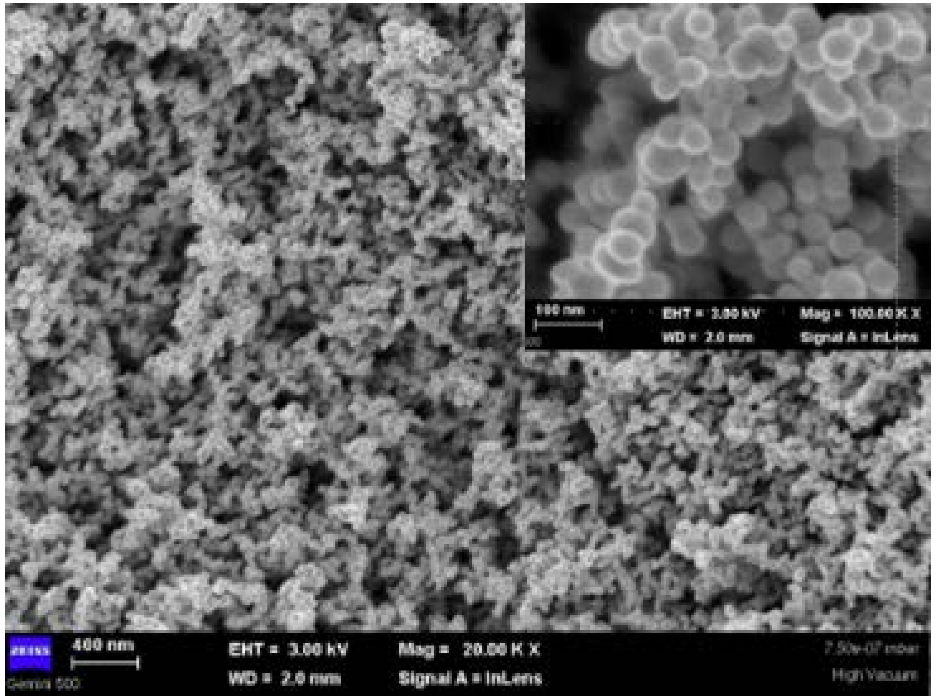
Experimental details:
MSGA system,
Sputtering power=100 W,
p=0.07 mbar,
gas ratios Kr/(H_2+Kr) = 21 %

QCM signal in time



Continuous mass increase

Dust deposited on the QCM crystal during a high-rate deposition (21% Kr)



Individualized, round particles with sizes in the range 50-100 nm are well distinguished.

Dust aspect: uniform, continuous coverage of the substrate with nanoparticles

QCM and SEM results are converging!

Dust growth mechanisms

Low-rate regime - Growth by a surface mechanism:

- diffusion of the W atoms on surface and concentration around centres of nucleation;

- formation of small-size clusters and nanoparticles distributed on surface;

- migration on substrate and fusion of clusters and small-size nanoparticles, larger particles formed by coalescence;

- larger particles keep increasing in size ending eventually in a reduced number of large particles, even of micron size. – sputtering can lead to micron size dust

High-rate regime - Growth by a volume mechanism:

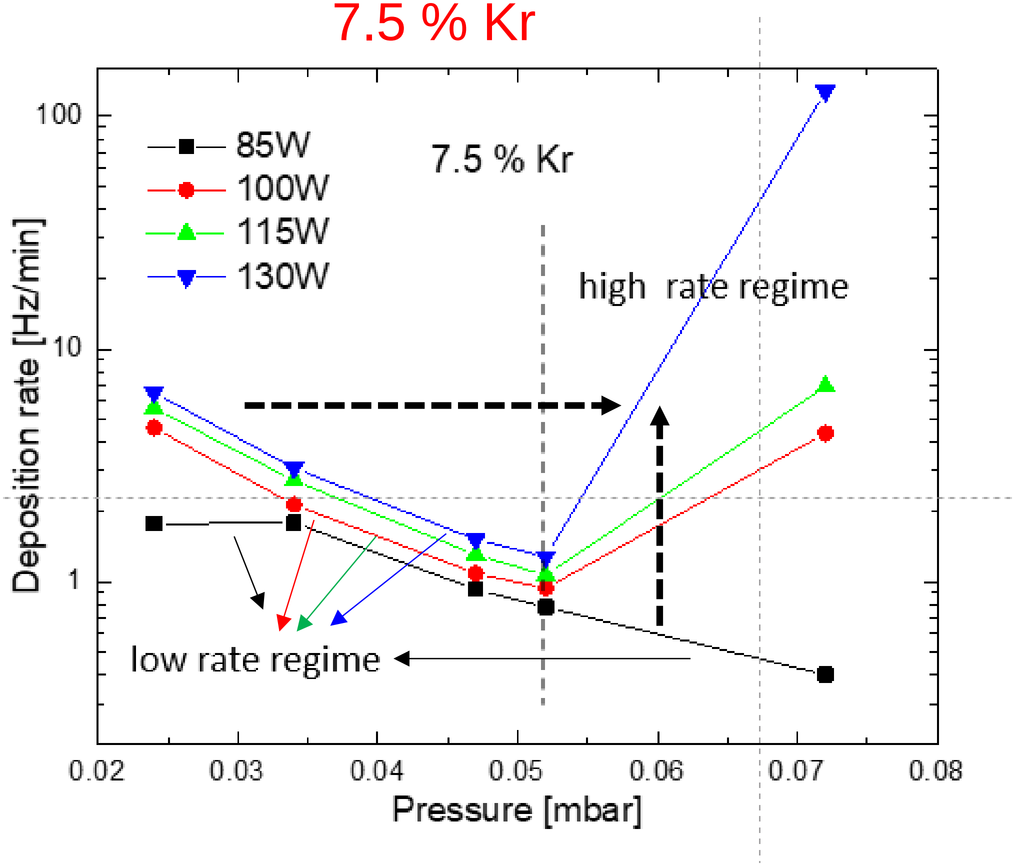
-high concentration of W species in the gas phase, favours nanoparticle formation by volume nucleation and growth by atom addition;

-volume processes prevail on surface processes and particles formed in volume are collected; -

Lesson learnt: with increasing sputtering rate, a **critical value of the W species concentration** in plasma is reached, when the mechanism of particle formation switches from surface processes, to volume processes!

Triggering the high-rate growth mechanism by power and pressure

7.5 % Kr



QCM deposition rates upon pressure (7.5 % Kr; RF power varied in the range of 85-130 W).

Results confirming that high-rate regime is related to volume processes

Dependence upon power (85 W versus 130 W at p=0.06 mbar):
- the transition is not present at 85 W (black curve);
- the transition is obvious at higher power (130 W, violet curve);

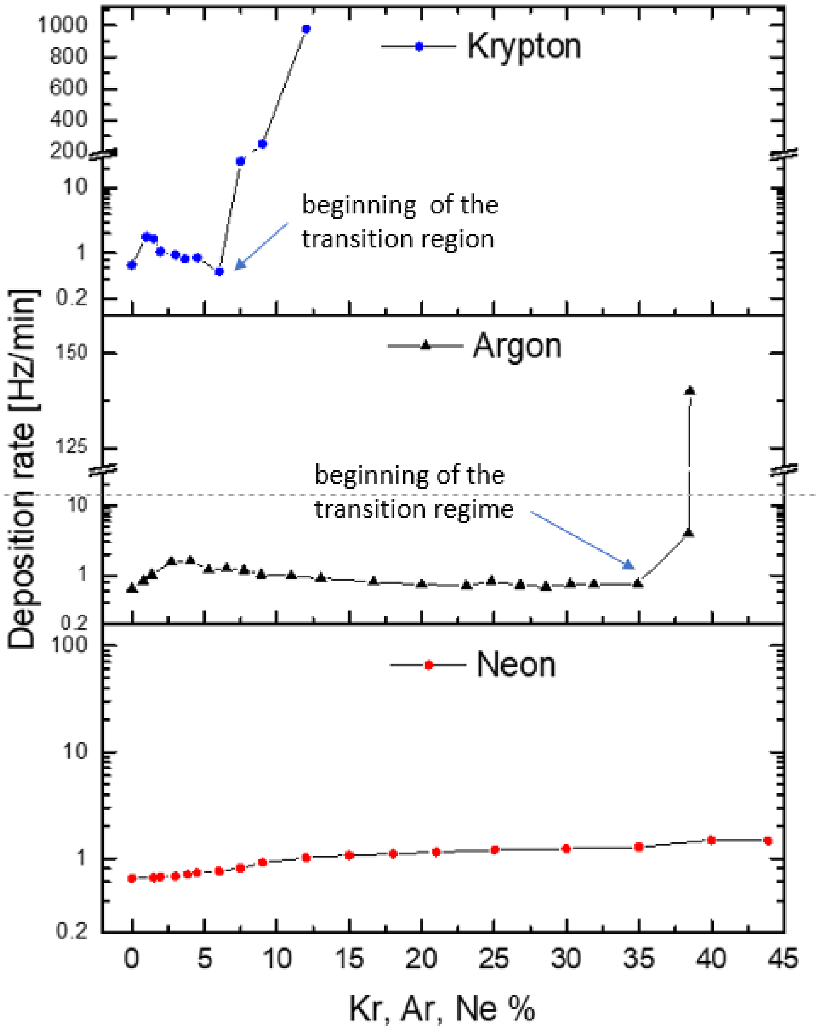
Explanation: the increased number of available W species at higher power enhances the volume nucleation and growth;

Dependence upon pressure (curves at 100, 115, 130 W):
- low-rate regime at 0.03 mbar
- high-rate regime at 0.06 mbar

Explanation: the increased number of collisions at higher pressure enhances the volume nucleation and growth

Effect of gas nature on the dust formation rate

p=0.07 mbar, P= 130 W



Deposition rates upon Kr, Ar, Ne content

Hydrogen dominated plasmas in contact with tungsten surfaces in presence of small percentages of Ne, Ar , Kr

The transition region is identified:

- at the lowest content of Kr (about 8-10 % percentage in the Kr/(Kr+H_2) discharge)
- at a higher content of Ar (about 35-37 % percentage in the Ar/(Ar+H_2) dischargee)
- not reached for Ne (in the limit of 45 % maximum value of Ne/(Ne+H_2) used);

Conclusion: In the series Ne, Ar, Kr, if Ne is a good radiator it should be the selected candidate for radiative cooling of the tokamak divertor, followed by Ar, and as last solution by Kr.

II. How such nanoparticles nucleate, growth and evolve in plasmas?

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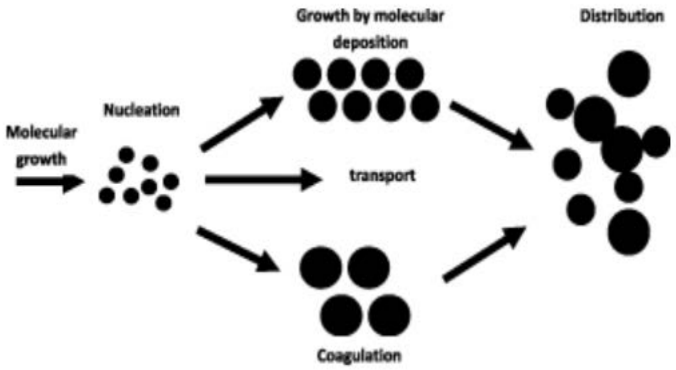
G. Tetard et al 2024, J. Phys D.: Appl. Phys. 18, **57** 185202; https://doi.org/10.1088/1361-6463/ad256a

Modelling, research directions



-nucleation and growth by coagulation - condensation of vapours on colder surfaces in the equilibrium metal vapor;

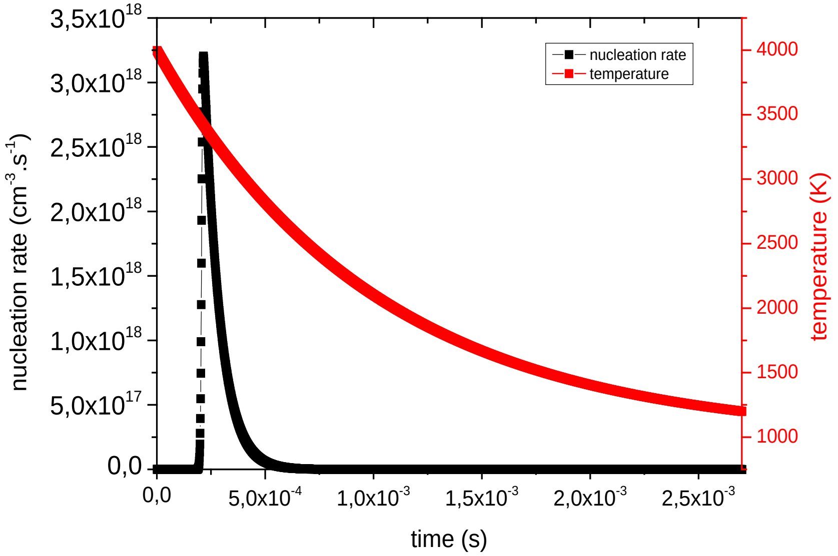
-development of a simplified aerosol model extended to include charged particles, and its verification;

- investigation of formation and stability of neutral and ionized W_n clusters in respect with W, W^+ species addition (up to n=40) by Ab initio and classical molecular dynamic simulations nucleation and growth.

Nucleation and growth inside the equilibrium metal vapor after a thermal quench

A thermal quench of the equilibrium tungsten vapor (that may be produced or that surrounds a tungsten droplet emitted after an anomalous event) is simulated and the nucleation inside the vapor is investigated – Simulation conditions : T_0=4000 K, t_{quench}=1 ms

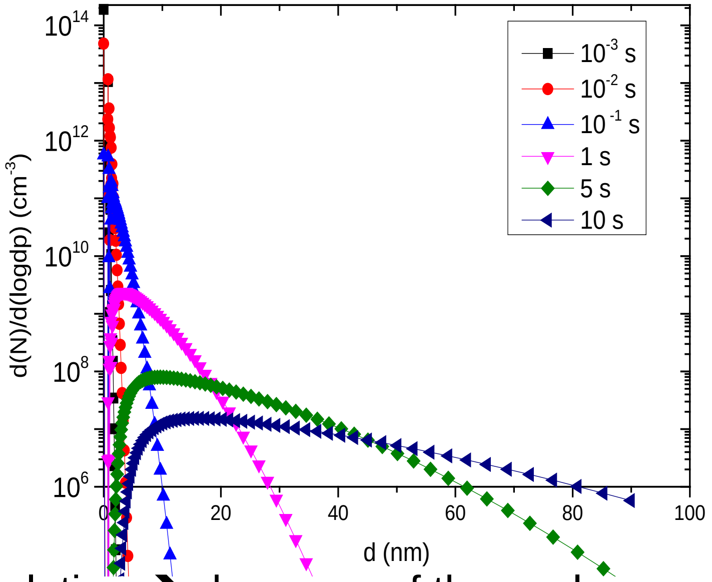
Nucleation rate and temperature variation during the thermal quench



➔ Nucleation delay: to reach the critical supersaturation

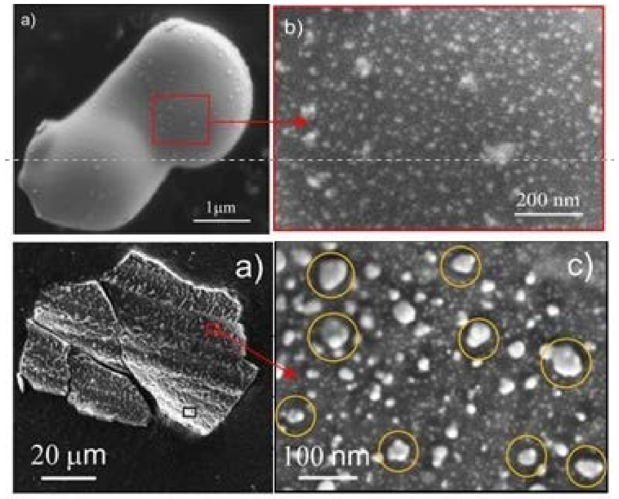
➔ Nucleation burst

Particle size distribution evolutions after the nucleation burst



Coagulation ➔ decrease of the nucleus population

➔ formation of larger particles and a wide particle size-distribution



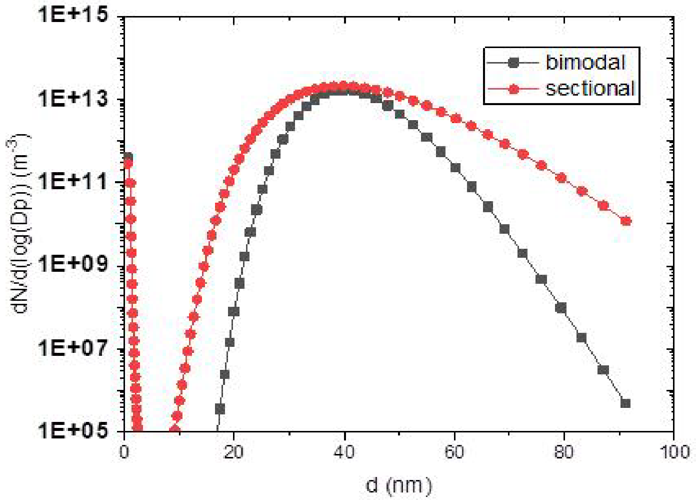
Explain the nanoparticle formation on solidified droplets or solid surfaces (collected dust samples from WEST)

Development of a simplified aerosol model that work in plasma conditions (charged particles present) and its validation

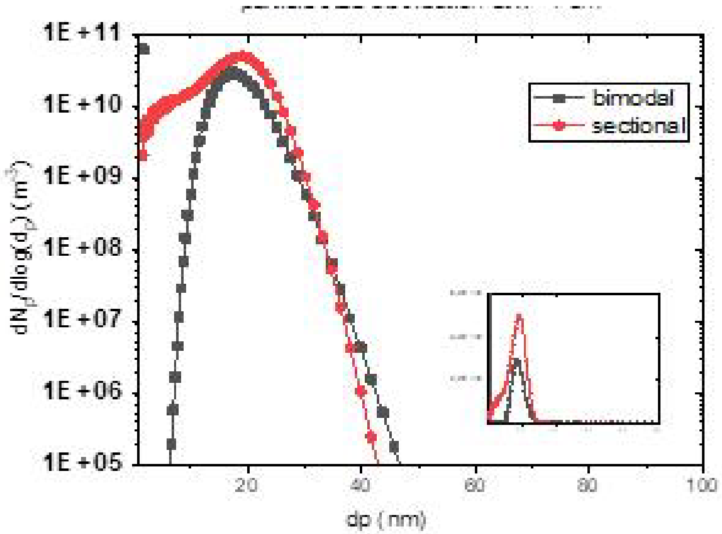
Problem: models based on cross-sections (sectional models) leads to costly simulation and can be hardly integrated in plasma transport models

Approach: use a two-mode aerosol distribution model, consisting of a two particle size distributions (PSD), namely a single size nucleation mode (described by a Dirac function) and a core mode resulted following the particles growth (described by a log-normal distribution)

Validation of the model by comparison distributions calculated with the simplified two-mode model with the detailed sectional approach



Particle size distributions for a stationary plasma growth dominated by molecular sticking



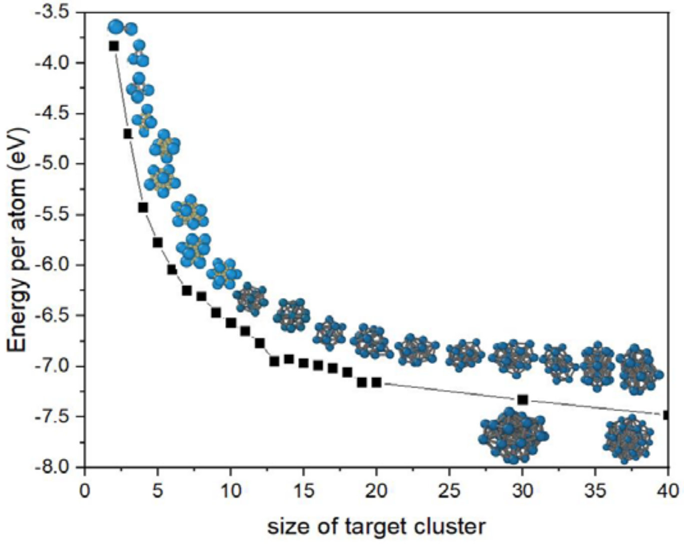
A time-varying radiofrequency plasma. Complex aerosol dynamics and PSD deviate from a bimodal

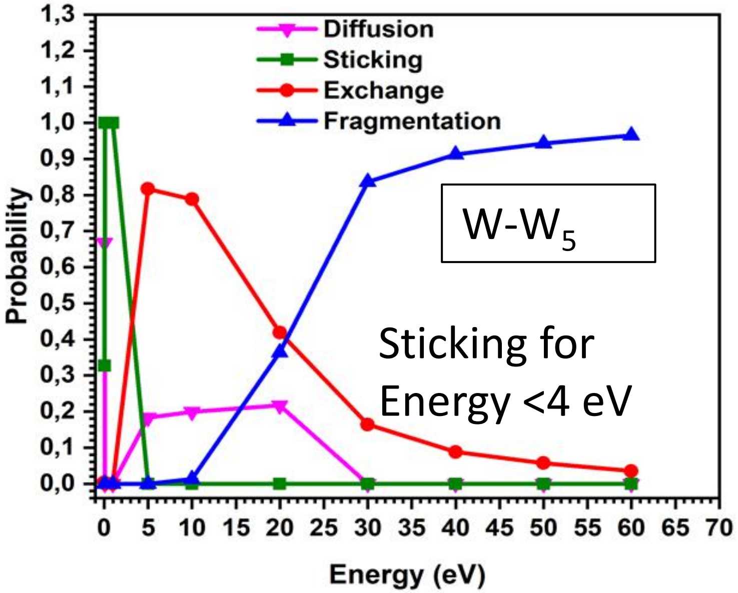
<u>Result:</u> Availability of a simplified aerosol dynamics model that may be easily coupled to multidimensional plasma/tokamak models

Investigation of neutral cluster growth through neutral tungsten addition

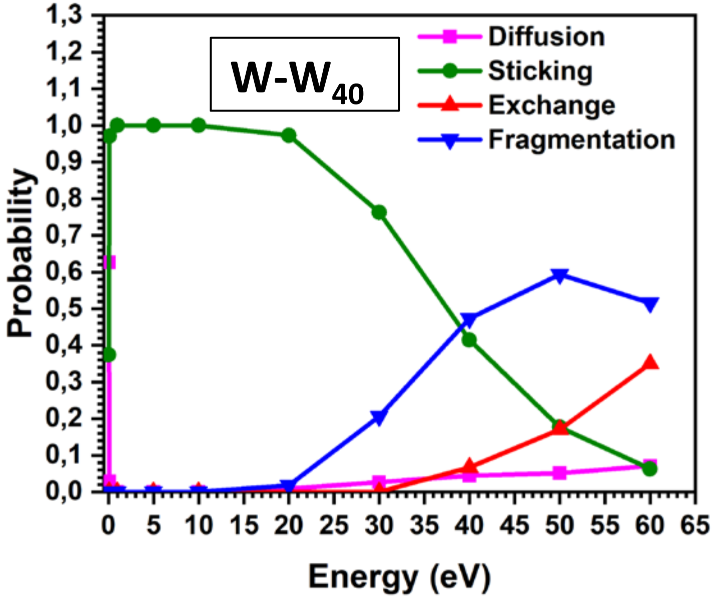
Identification of stable neutral clusters upon their size (classical MD)

Investigate the collision dynamics between neutral clusters and neutral atoms





Sticking for Energy <4 eV



1- Sticking and growth is favored by increasing size ➔ the small clusters are less prone to remain in life

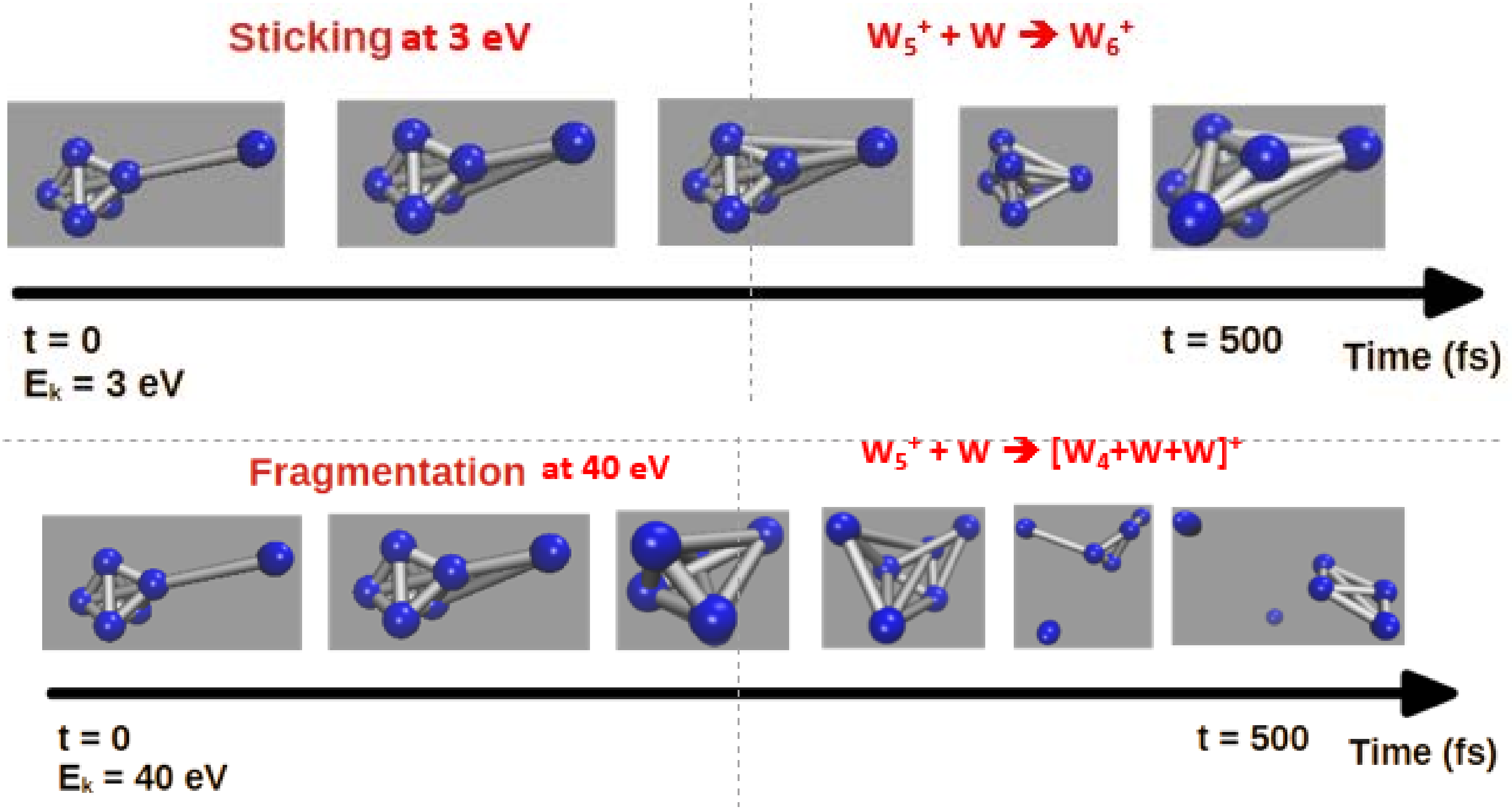
2- For W-W_{40}, sticking is almost the only process taking place for Energy <20-25 eV

Result: The particles size distributions (PSD) of the neutral clusters can be calculated.

Investigation of growth through charged clusters – in work

1. Identification of stable ionic charged clusters upon their size (by DFT)
2. Select those energies for which sticking is possible for neutral cluster collisions
3. Perform Ab initio MD (time consuming) for those energies only

Example,
case of $W+W_5^+$

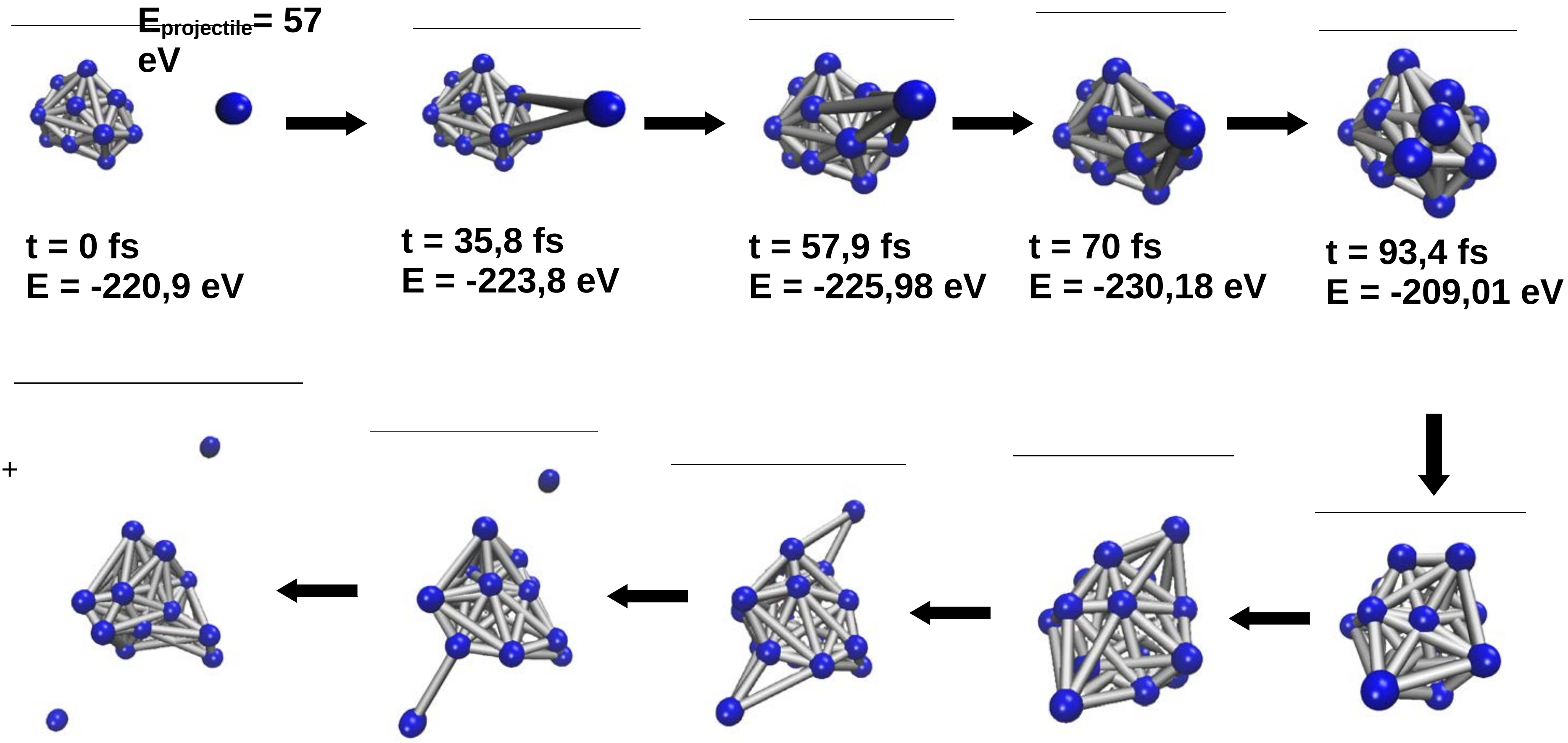


Collision energy is the determining factor for sticking or fragmentation

Example W+W_{20}^{+}: Fragmentation through charged tungsten cluster collision

Example,

case of W+W_{20}^{+}



$E_{projectile}$= 57 eV

t = 0 fs
E = -220,9 eV

t = 35,8 fs
E = -223,8 eV

t = 57,9 fs
E = -225,98 eV

t = 70 fs
E = -230,18 eV

t = 93,4 fs
E = -209,01 eV

t = 140 fs
E = -222,9 eV

t = 177,5 fs
E = -212,93 eV

t = 240 fs
E = -199,84 eV

t = 295,9 fs
E = -195,39 eV

t = 390 fs
E = -197,56 eV

observe the fm scale

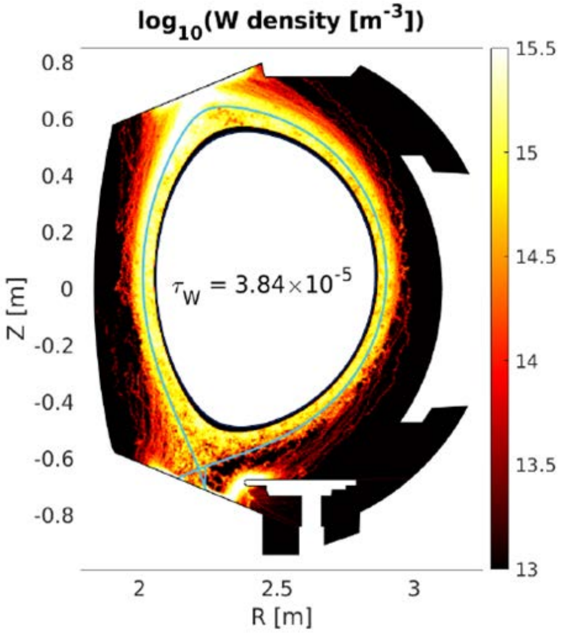
III. Edge plasma integrated simulation with impurity and dust transport

Nicolas Fedorczak, G. Ciraolo, H. Yang
IFRM, CEA

Tungsten sputtering and migration solved with ERO2.0

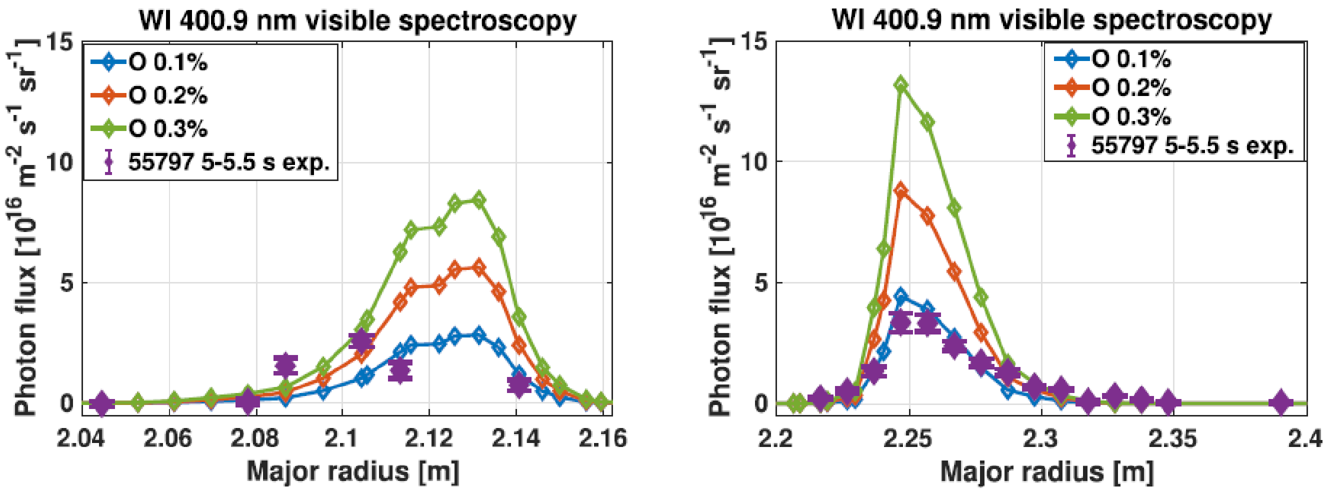
- Monte Carlo kinetic solver for tungsten sputtering and migration
- Uses SOLEDGE plasma background (no self consistent coupling yet, especially on radiated power)

S. DI GENOVA



W atoms 2D density distribution calculated with ERO2

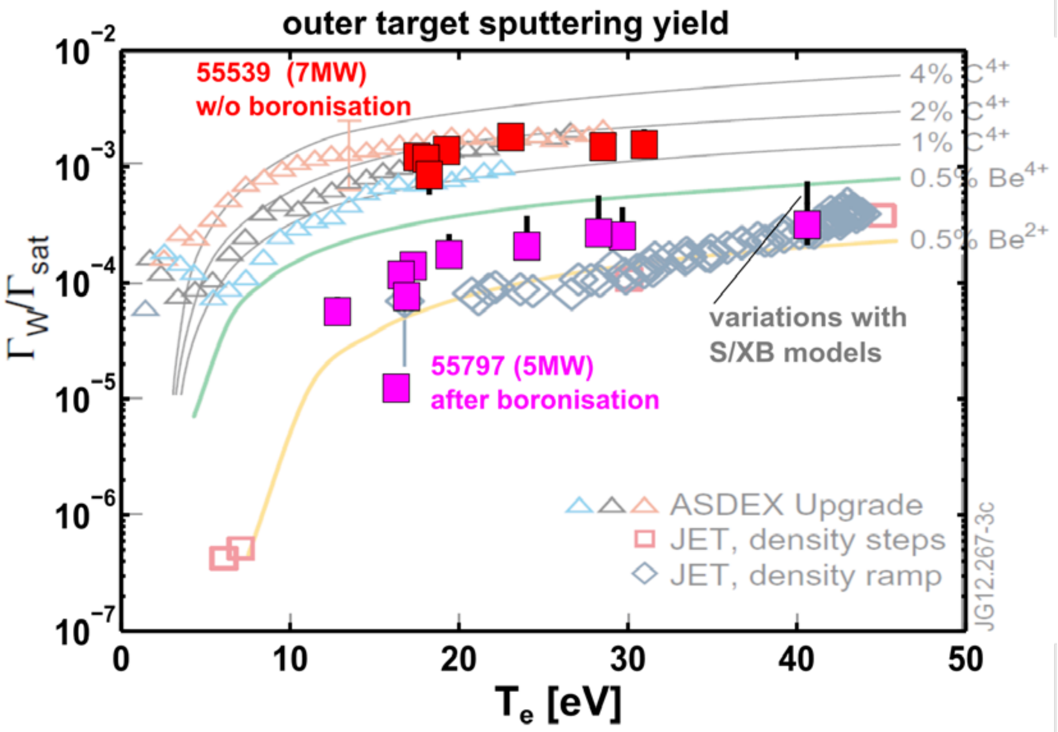
lower divertor sources ERO2 / experiment



Gross surface tungsten sources (simulated with ERO2) consistent with experiment (data given by visible spectroscopy)

Standard experimental conditions in WEST gives tungsten sputtering yields of ~ 1. 0 E-4 - 1.0 E-3 in the divertor

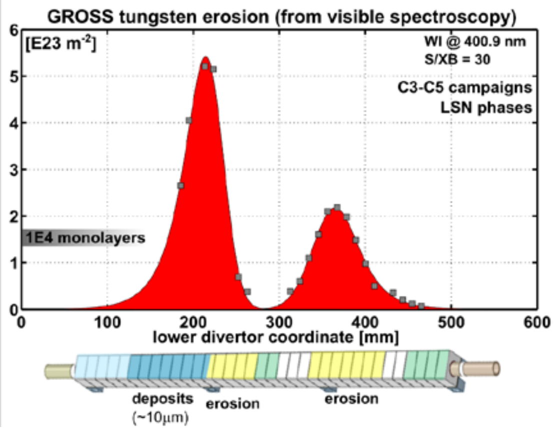
- Measured with visible spectroscopy and Langmuir probes
- Coherent with JET-ILW & ASDEX-Upgrade



Ratio of the tungsten flux at divertor (measured by visible spectroscopy) over the deuterium flux striking the target (measured by Langmuir probes)

Global inventory of plasma particle & energy fluencies on WEST divertor

- plasma wetted area ~ 1 m^2
- 3.5 hours of diverted plasma exposure
- Deuterium fluency ~E26 m^{-2}
- Gross tungsten erosion ~ few μm

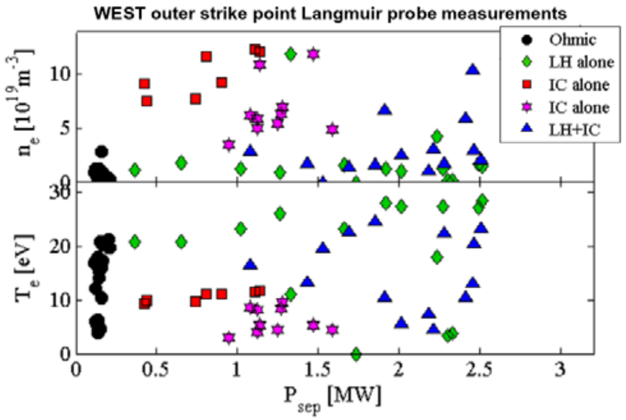


Fluencies of B-C-O-N-W impurities computed across every campaigns (spectroscopy)

→ to link with collected dust properties

Divertor regimes monitored (density/temperature)

- domain for SOLEDGE simulations
- conditions for dust models

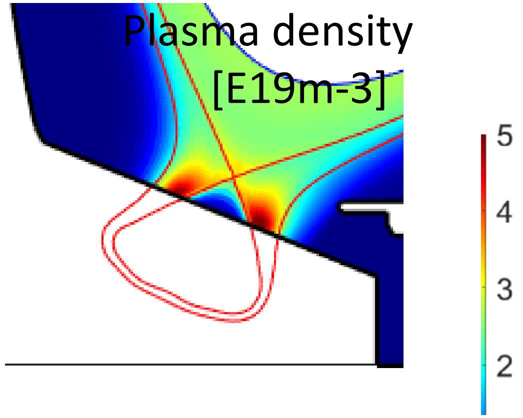


EUROfusion Science Meeting on results of ENR projects 2021-2023, October 24, 2024

Simulations

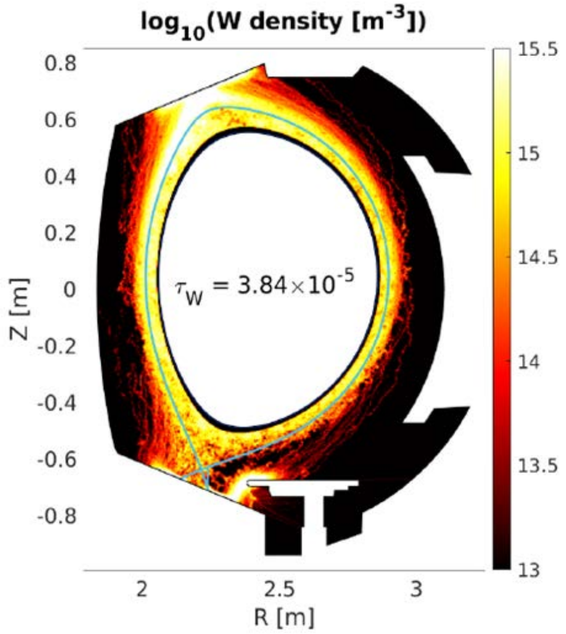
Set of SOLEDGE backgrounds representing WEST scenarios, achieved:

- Scans of density, power, low-Z concentration
- Up to divertor detachment



Set of ERO-2 simulations for distribution of tungsten ions, achieved:

- maps of tungsten density & erosion/deposition
- on selected SOLEDGE backgrounds



Results

- Achieved: impurity and plasma properties from simulations & experiments available
- Model of dust dynamics with DUMBO not achieved → lack of time and manpower issue

Summary of the results - I

Laboratory dust (details from *dinescug@infim.ro*)

- Nanometric dust is common to all experiments where W vapors or W atoms are present;
- Sputtering leads to W nanoparticles;
- Injecting Ar in hydrogen may increase drastically (x 100) the particles production rates (gravimetry data);
- Nanoparticle size and dust morphology depends strongly upon the percentage of Ar injected in H_2: low Ar content - small size and agglomerated dust, large Ar content - higher dust size, individual particles in the dust.

Plasma species, Hydrogen (Deuterium) dominated discharges injected with Ar:

- Injecting Ar changes the sputtering process: sputtering is performed by ArH^+ ions
- Increasing Ar content increases the sputtering rate (mass spectrometry data)
- Not-negligible WH^+ percentages: $WH^+/(W^++WH^+)$ ~30 - 40 % for gas ratios $Ar/(Ar+H_2)$ ~ 10-20%
- Tungsten molecular compounds formed in reactions with $H_2(D_2)$, and O_2, and N_2 impurities (generic formulas $WO_xN_yH_z$ (x=0-3; y=0-3; z=0-3), or $WO_xN_yD_zH_t$ (x =0–4, y=0–3, z=0–3, t=0–5)

Summary of the results - II

Dust formation mechanisms (Hydrogen (Deuterium) dominated discharges injected with Kr, Ar, Ne):

- Surface mechanism - low dust formation rate (encountered at low sputtering rates);
- Volume mechanism - high dust formation rate (related to volume nucleation and W species addition);
- The high-rate dust formation regime can be triggered by favoring the nucleation and W species addition (via collisions - by increasing pressure, or via concentration of W species released in plasma – by increasing sputtering gas concentration or sputtering power);
- Nanometric dust may lead to micron size dust in case of surface mechanism - by fusion and agglomeration of nanoparticles;
- *Answer to one of the project motivations:* In respect to a minimal sputtering risk, Ne should be selected as first candidate from the series Ne, Ar, Kr gases used for radiative cooling of the tokamak divertor, followed by Ar, and as last alternative by Kr .

Summary of the results - III

Modelling the dust nucleation and growth (khaled.hassouni@lspm.cnrs.fr **)**

- Availability of modeling of nucleation rates and particle size distribution functions in cases of a thermal quench of the equilibrium tungsten vapor (example vapors surrounding a W droplet emitted after an anomalous event) – morphology of particle collected in WEST;
- Availability of a simplified aerosol model describing the particles distribution functions in plasmas, that may be easily coupled to tokamak transport model models;
- Availability of data and procedures for determining the stability of neutral and charged clusters;
- Availability of data and procedures to describe the collision dynamics between neutral and charged clusters and W atoms, leading to the probabilities for sticking or fragmentation.

Edge plasma simulation with impurity and dust transport (*Nicolas.FEDORCZAK@cea.fr*)

- WEST: impurity and plasma properties from simulations & experiments available.

More details in the Publications:

- C. Craciun, S.D. Stoica, B. Mitu, T. Acsente, G. Dinescu, Mass spectra fitting as diagnostic tool for magnetron plasmas generated in Ar and Ar/H gases with tungsten targets, *Molecules* **2023**, 28 566; https://doi.org/10.3390/molecules28155664
- C. Arnas, A. Campos, M. Diez, S. Peillon, C. Martin, K. Hassouni, A. Michau, E. Bernard, N. Fedorczak, F. Gensdarmes, C. Grisolia, E. Tsitrone and the WEST team, Micron-sized dust and nanoparticles produced in the WEST tokamak, Nucl. Mater. Energy **2023**, 36, 101471; https://doi.org/10.1016/j.nme.2023.101471
- S.D. Stoica, C. Craciun, T. Acsente, B. Mitu, G. Dinescu Evidence for molecular tungsten ionic species presence in impurity-seeded hydrogen plasma in contact with W surfaces, *Plasma Processes and Polymers* **2024** e2300227; https://doi.org/10.1002/ppap.202300227
- G. Dinescu, C. Craciun, S.D. Stoica, C. Constantin, B. Mitu, T. Acsente Tungsten Molecular Species in Deuterium Plasmas in Contact with Sputtered W Surfaces *Molecules* **2024**, 29, 3539. https://doi.org/10.3390/molecules29153539 ; pinboard 38223
- T. Acsente, S.D. Stoica, C. Craciun, B. Mitu, G. Dinescu, Enhancement of W Nanoparticles Synthesis by Injecting H2in a Magnetron Sputtering Gas Aggregation Cluster Source Operated in Ar, *Plasma Chemistry and Plasma Processing*, **2024**, https://doi.org/10.1007/s11090-024-10499-z
- T. Acsente, E. Matei, V. Marascu, A. Bonciu, V. Satulu, G. Dinescu *Deposition of W Nanoparticles by Magnetron Sputtering Gas Aggregation Using Different Amounts of H_2/Ar and Air Leaks* Coatings **2024**, 14, 964. https://doi.org/10.3390/coatings14080964
- G. Tetard, A. Michau, S. Prasanna, K. Hassouni An effective approach for aerosol dynamics modeling in dusty plasma J. Phys D.: Appl. Phys. **2024**, 18, 57 185202; https://doi.org/10.1088/1361-6463/ad256a
- C. Arnas, A. Campos, M. Diez, E. Bernard, C. Brun, C. Martin, F. Gensdarmes, S. Peillon, E. Tsitrone and the WEST team, Dust collection after the high fluence campaign of the WEST Tokamak, submitted to *Nucl. Mater. Energy,* **2024**

Raised questions, problems that might be approached in future in the EUROfusion research programme

Laboratory and modeling research

- Perform similar experiments with N_2 as injected gas (for completing data on the impact of gases used for divertor plasma detachment);
- Investigation of the process of molecular W species formation: ejected from surface (sputtering, sublimation) or formed in volume (association reactions);
- How the new identified molecular species impact on the nucleation process?
- Is there instrumentation/interest in the community to detect larger mass molecular species containing more than one W atom? ($W_nO_xN_yD_zH_t$, with $n=2,3,4...$ – a mass spectrometer in the range 0-1000 amu is needed!);
- Perform a similar research for boronized W surfaces if it is of interest;
- Continuate the work for covering the modeling of growth from cluster sizes – to nanoparticle sizes

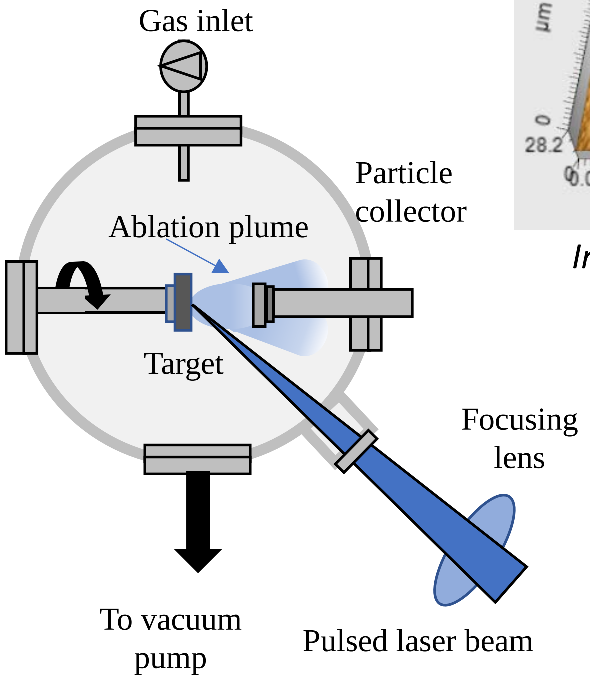
Fusion machines research

- How the molecular species ($WO_xN_yH_z$, $WO_xN_yD_zH_t$) influence the presently known balance and transport of W material in Tokamak ?
- Are there existing interest and tools to detect W molecular species in Tokamak?
- Continuate the work for integration of dust growth and transport modelling research in Tokamak codes.

Thank you for your patience !

Supplementary material

Producing W nanoparticles under high energy laser deposition on W surfaces



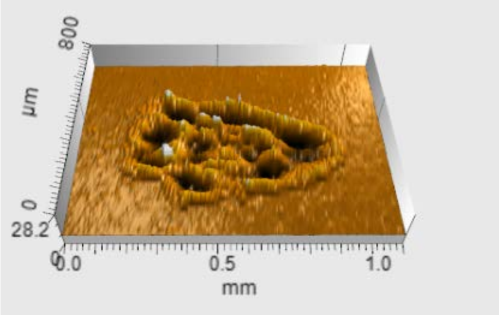


Image of the crater at W surface

Fixed parameters

- Nd - YAG pulsed laser
- λ=266 nm, 4-6 ns pulse duration,
- 10 Hz repetition rate
- Fluence=2.5 J/cm^2 (~ 400 MW/cm^2)
- Distance target - substrate = 4.5 cm

Variable parameters

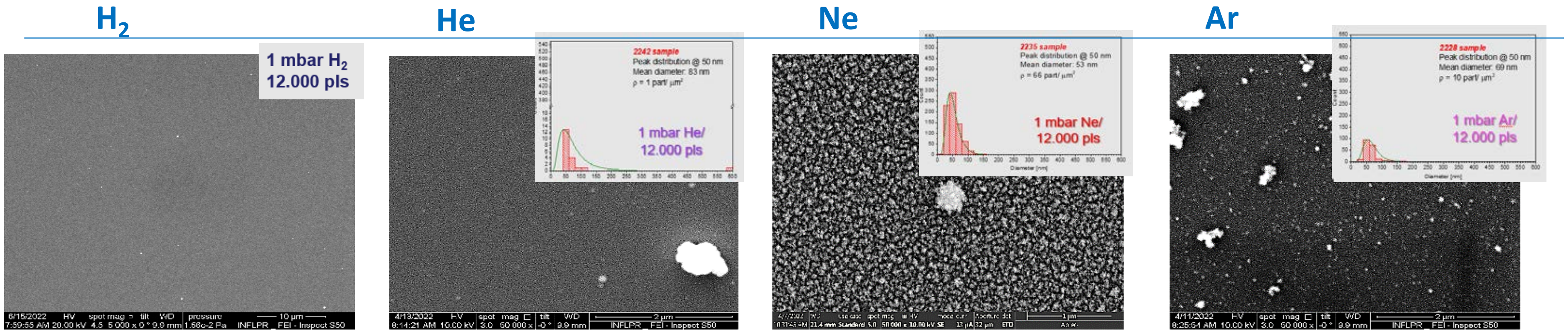
- Different Z-gases: vacuum, H_2, He, Ne, Ar ...
- Different gas pressure: 10^{-2}, 1,3, 5, 7 mbar...

Source of material: W target
Surface processes: melting, vaporization;
Particle evolution: gas phase;

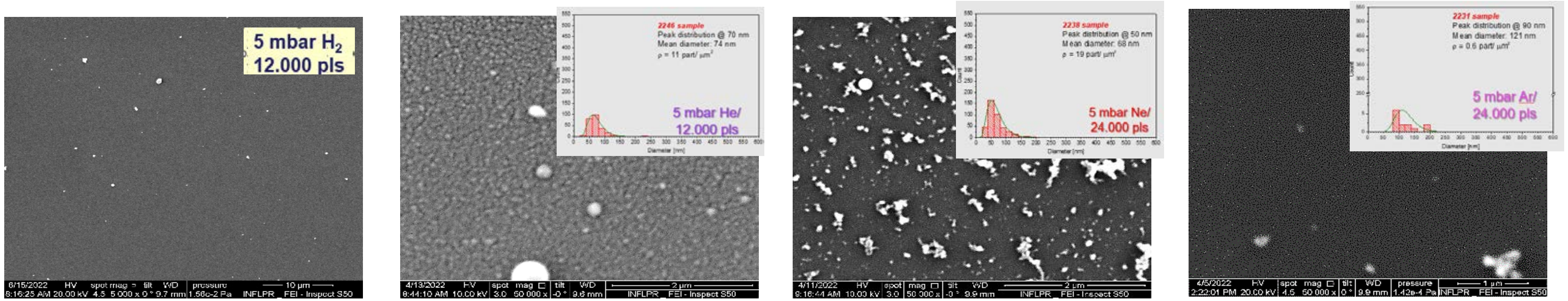
Questions:

- How the nature of background gas influences the nanoparticles production ?
- How the pressure influences the nanoparticles production ?
- Chemical composition?

Producing W nanoparticles under high energy laser deposition on W surfaces – morphology dependence upon gas type and pressure



pressure 1 mbar



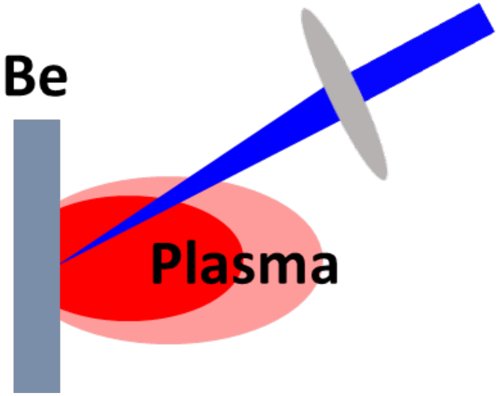
pressure 5 mbar

- Hydrogen (H_2) promote thin film deposition, not particles;
- Tungsten particles (sizes 20-100 nm, cluster-film like) are found mainly in high-Z gases and at larger pressure;
- The particles are arranged in agglomerated cluster geometries; some droplets may appear, mainly in He.

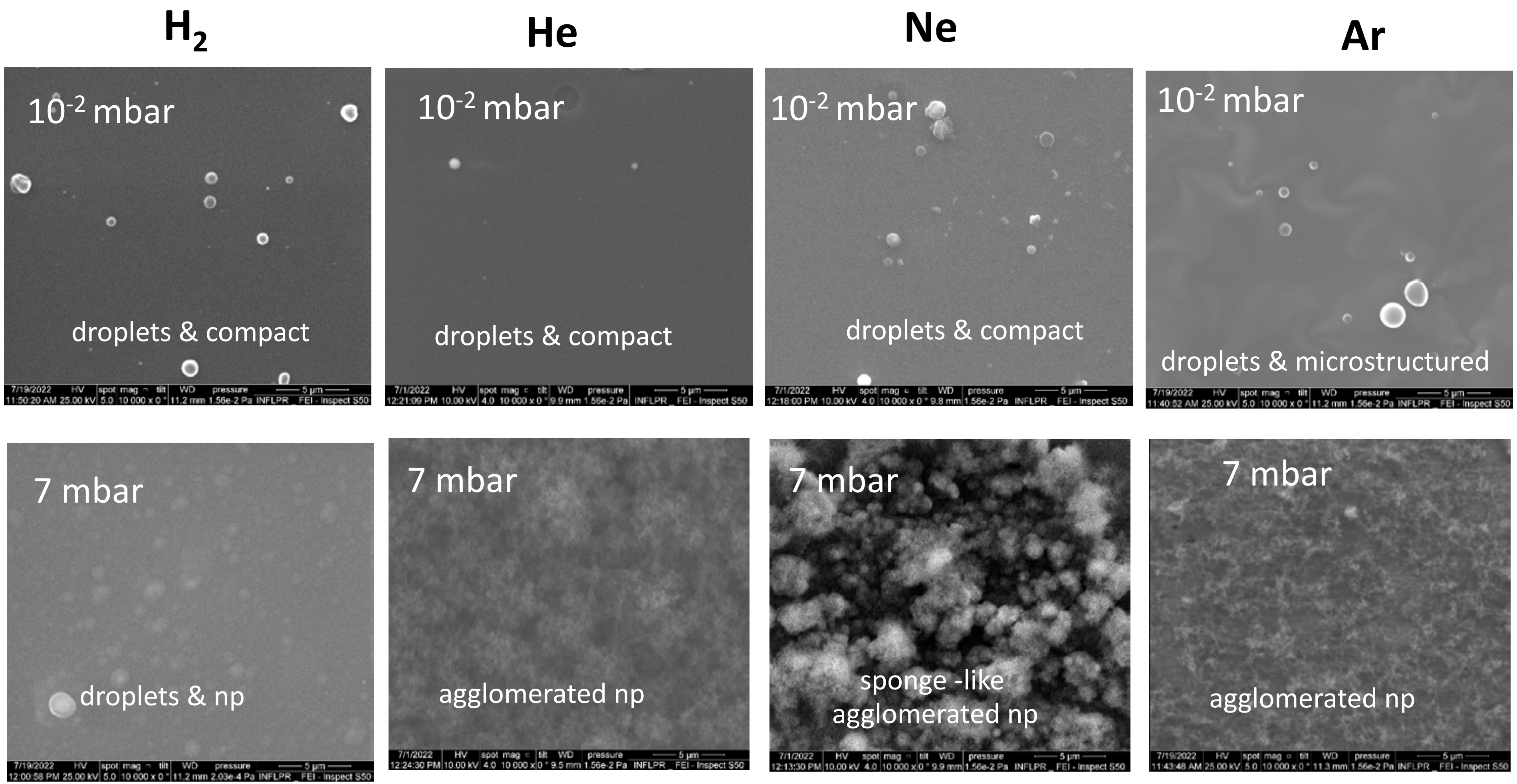
(dinescug@infim.ro)

Be particle production via high energy laser deposition on surface

Setting up the laser ablation system at Be facility
Particles obtained: influence of background gas and pressure



Gas nature and pressure influence on the deposited Be material



Results:

- Be is prone to producing droplets and thin films at low pressure, whatever the gas;
- At higher pressure the nanoparticles and nanostructured are agglomerated;