Linear / HHF devices capabilities for W and B dust studies

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Outline

- Evolution of dust inventory – issues to address
- What has been learnt in linear machines experiments
- Unsolved and new dust issues
- New possible experiments for W and B dust

Dust issues to address

Evolution of dust inventory

- Dust-plasma interaction

i. Dust transport (dynamics/ ‘trajectories’)→ accumulation sites
ii. Dust vaporization (heat balance)→ impurity production

- Dust-wall interaction

i. Dust-wall collisions (outcome: sticking or re-bouncing), crucial for accumulation sites
ii. Remobilization (consequences: e.g. disturbance of start-up)

Concepts and tools: dust-plasma interaction

- Dust-plasma interaction

i. Dust transport → accumulation sites

ii. Dust vaporization → impurity production

Dust transport codes

A spherical dust particle/droplet is injected with given initial conditions into a given plasma background.

Equations for the time evolution of the dust position, mass, enthalpy/temperature and (floating) electric potential

$$M_{\mathrm{d}} \frac{\mathrm{d}^2 \vec{r}_{\mathrm{d}}}{\mathrm{d}t^2} = \vec{F}_{\mathrm{tot}} \qquad \frac{\mathrm{d}M_{\mathrm{d}}}{\mathrm{d}t} = \Gamma_{\mathrm{tot}} \qquad \frac{\mathrm{d}H_{\mathrm{d}}}{\mathrm{d}t} = Q_{\mathrm{tot}} \qquad I_{\mathrm{tot}}(\varphi_{\mathrm{d}}) = 0$$

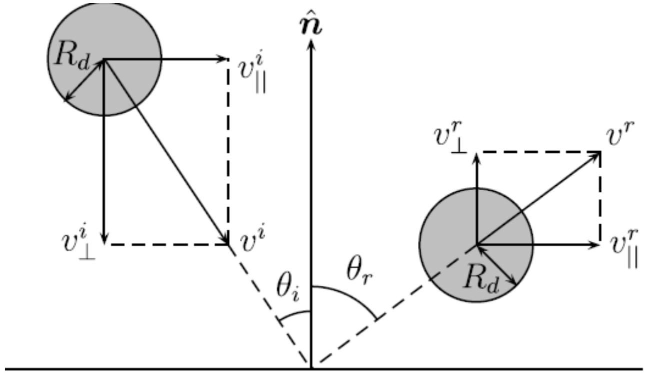
The total current and heating power include contributions from the relevant surface processes:

electron and ion collection, thermionic and electron-induced electron emission, ion-induced electron emission, ion neutralization and backscattering, thermal radiation, vaporization

$$I_{\mathrm{tot}} = I_{\mathrm{e}} + \sum_j I_{\mathrm{i},j} + I_{\mathrm{EIEE}} + I_{\mathrm{IIEE}} + I_{\mathrm{TE}}$$

$$Q_{\mathrm{tot}} = Q_{\mathrm{e}} + \sum_j \left(Q_{\mathrm{i},j} + Q_{\mathrm{i},j}^{\mathrm{bs}} + Q_{\mathrm{i},j}^{\mathrm{neut}} \right) + Q_{\mathrm{EIEE}} + Q_{\mathrm{IIEE}} + Q_{\mathrm{TE}} + Q_{\mathrm{rad}} + Q_{\mathrm{vap}}$$

Concepts and tools: dust-wall interaction



- Dust-wall interaction

i. Dust-wall collisions (outcome: sticking or re-bouncing)

ii. Remobilization (consequences: e.g. disturbance of start-up)

Theoretical results from:

- impact mechanics: elastic–perfectly plastic adhesive spheres impacts, outcome - adhesive velocity and normal restitution coefficients

  Gradual reduction of normal velocity → value below the adhesive velocity → dust is adhered to the wall.

  Size selectivity; smaller dust stucks easier, larger dust requires more collisions

- contact mechanics : valid for smooth surfaces at intimate contact, metallic bonding due to the sharing of the delocalized valence electrons between the two bodies $|F_{\mathrm{a}}| = 3\pi\Gamma R_{\mathrm{d}}/2 \propto R_{\mathrm{d}}$

  (Γ is the interface energy)

- surface physics : long range weak induced multipole interactions produce adhesion, Lifshitz theory of van der Waals forces $|F_{\mathrm{a}}| = |F_{\mathrm{vdW}}| = \frac{A_H}{6z_0^2} R_{\mathrm{d}}$

with $z_0 \simeq 0.4\mathrm{nm}$ of the order of the lattice parameter and A_H the non-retarded Hamaker constant (can be calculated provided that the optical permittivity of a given material is available at an extended frequency range)

Experimental strategies : dust-plasma interaction

- Dust-plasma interaction

i. Dust transport → accumulation sites
ii. Dust vaporization → impurity production

Injection experiments

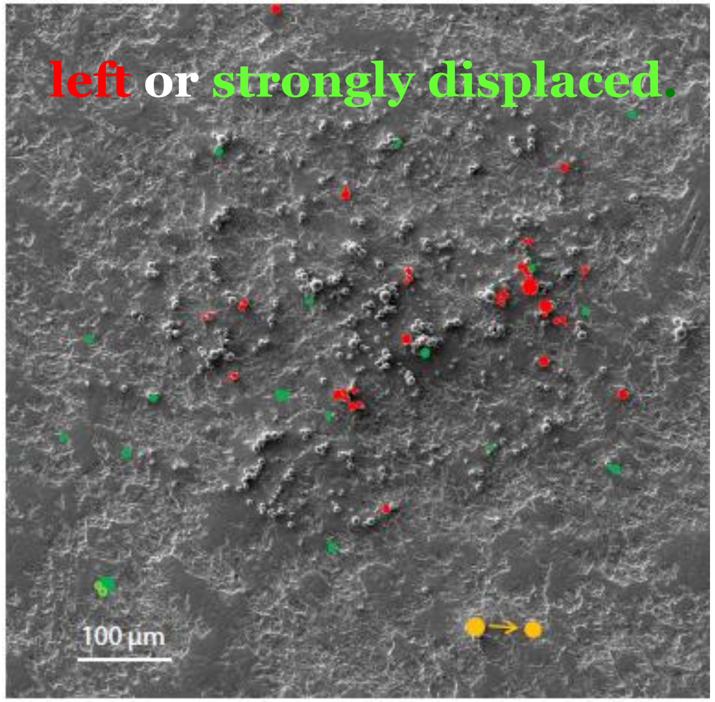
- Inject known/pre-characterized dust population
- Most comprehensive outcome: spectroscopy + cameras
- ‘Good enough’ for initial studies: cameras
- ‘Almost for free’ but still useful: collection plate

Experimental strategies: dust-wall interaction

➢ Dust-wall interaction

i. Dust-wall collisions (outcome: sticking or re-bouncing)

ii. Remobilization (consequences: e.g. disturbance of start-up)

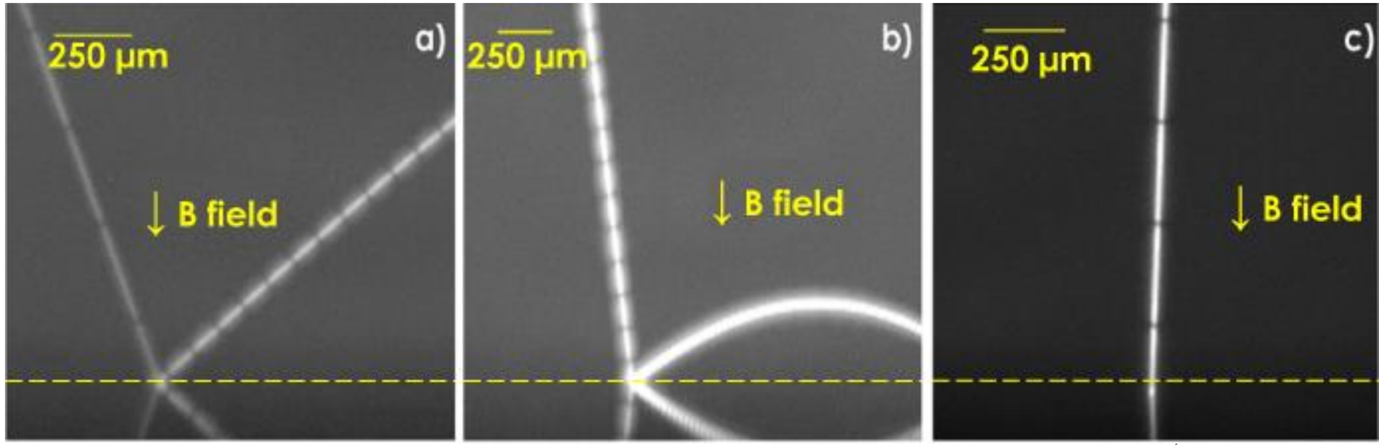


Remobilization

- Methodology for dust deposition through light gas gun, SEM overlaying pre/post exposure
- Samples exposed to plasma (different angle to plasma flow)

Collisions

- Injection + witness plate + cameras



Complementary (out of plasmas)

- Vacuum furnace
- Electrostatic detachment measurements

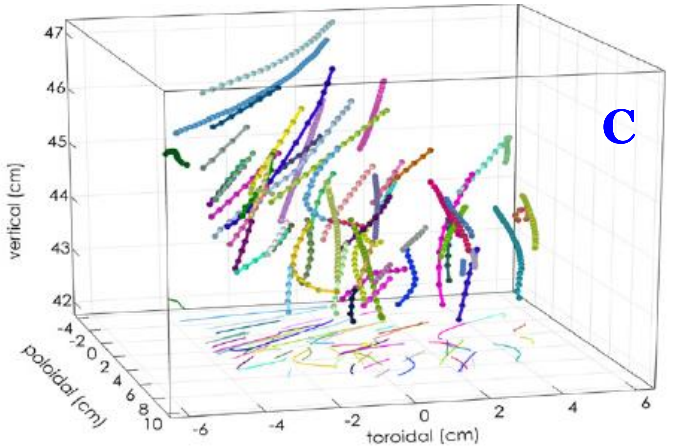
Experiments 2014 - 2018
under the auspices of ENR (2014) , WP-PFC
and WPTE (plus other machines)

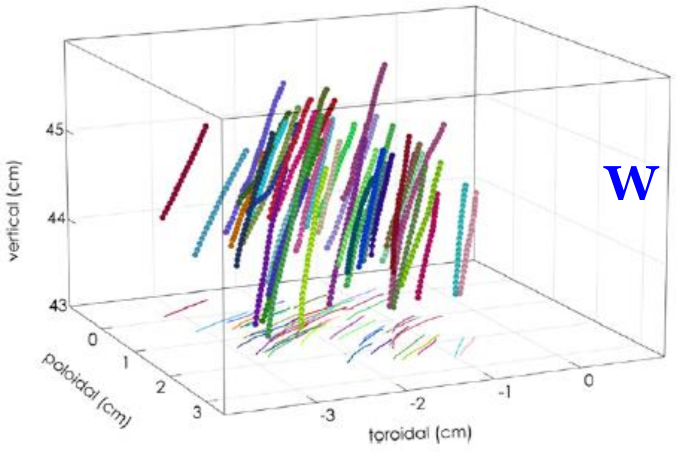
Dust-plasma interaction: examples

TEXTOR: Shalpegin et al PPCF **57** 2015

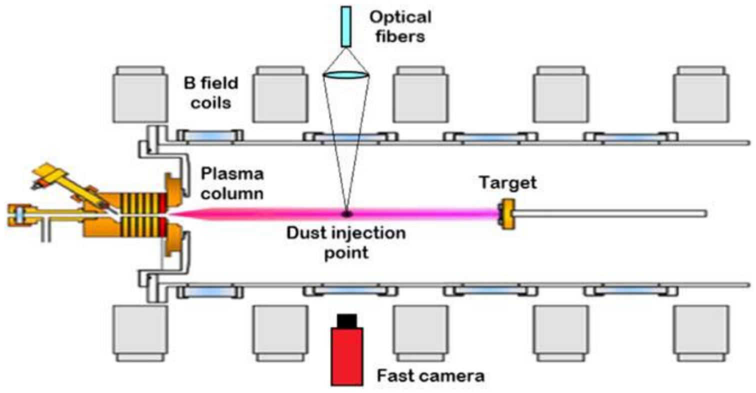
Pilot PSI W dust: Vignitchouk et al PPCF **60** 2018

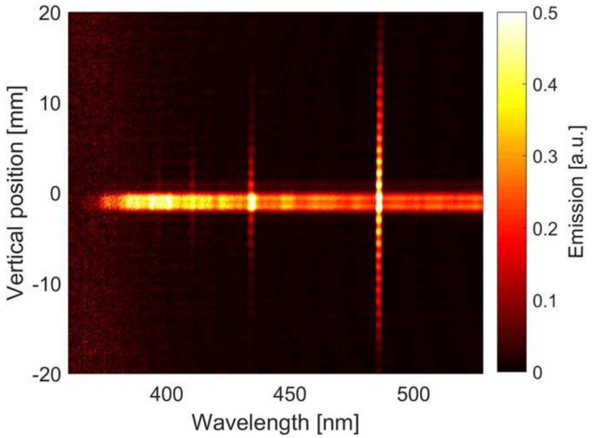
Cameras are great BUT
no insight on heat balance

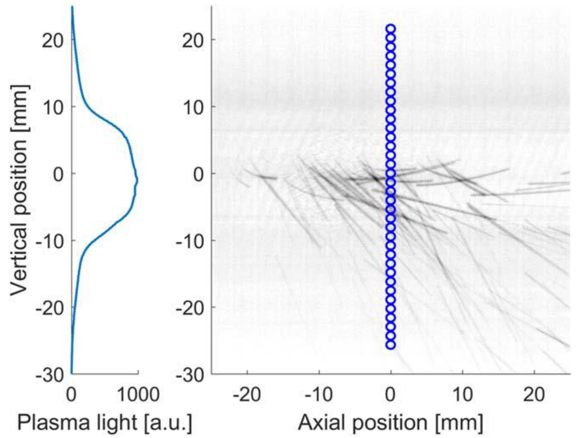


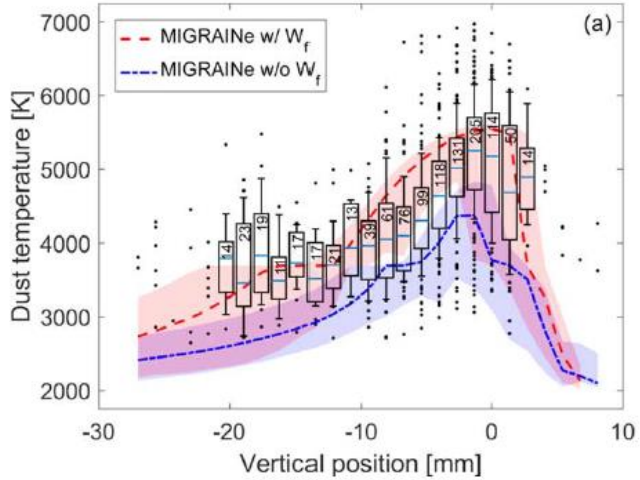


Initial conditions + Inertial motion =
Fit anything









Cameras + Spectrometer = Dust temperature

Dust remobilization in plasma environments (linear devices)

Tolias *et al,* PPCF **56,** 025009 (2016); Ratynskaia *et al,* NME **12,** 569 (2017); De Angeli *et al,* NME **12**, 536 (2017); Ratynskaia *et al,* NME **17**, 222 (2018)

Seven experimental campaigns carried out in Pilot/Magnum PSI between 2014-2018 under the auspices of ENR (2014) and WP-PFC (2015-2018).

Linear plasma device	Experimental focus	Main conclusions
1st Pilot-PSI campaign	**Stationary plasma exposures**, W polydisperse dust, normal and oblique B-field	(1) Clusters, large dust remobilizes (2) Less activity at oblique incidence (3) Not much remobilization overall
2nd Pilot-PSI campaign	**Stationary plasma exposures**, re-exposures of samples, W polydisperse dust, emphasis on oblique B-field	(1) Confirmation of above conclusions (2) No hysteresis
3rd Pilot-PSI campaign	**Transient plasma exposures**, first W monodisperse dust, first single ELMs	(1) Wetting induced coagulation (2) No isolated melting
4th Pilot-PSI campaign	**Transient plasma exposures,** single ELMs with normal and oblique B-field, W dust, first castellated samples	(1) Confirmation of above conclusions (2) No enhanced activity during ELMs (3) Dust does not move towards gaps
5th Pilot-PSI campaign	**Transient plasma exposures, c**astellated samples, first multiple ELMs, W dust and first Be proxies	(1) Gaps efficiently trap existing dust (2) Dust unlikely to reside into gaps (3) No enhanced activity during multiple ELMs
1st Magnum-PSI campaign	**Transient plasma exposures,** Multiple ELMs, W dust and Be proxies (Cu, Cr, Al)	(1) Growth of very large dust (2) Chemical effects + mixed materials
2nd Magnum-PSI campaign	**Transient plasma exposures**, Be proxies	Source and liquid metal contamination -> no conclusions

Dust remobilization in plasma environments (fusion devices)

Tolias *et al,* PPCF **56**, 025009 (2016); Ratynskaia *et al,* NF **56** 066010 (2016); Weinzettl *et al,* FED **124** 446 (2017); Bykov *et al,* NME **12**, 379 (2017); Ratynskaia *et al,* NF **58**, 106023 (2018); De Angeli *et al,* NF **59**, 106033 (2019).

Many experimental campaigns carried out in fusion devices under the auspices of WPTE (ASDEX-Upgrade) and by our own initiative (TEXTOR, EXTRAP-T2R, DIII-D, COMPASS, FTU).

Fusion device	Experimental focus	Main conclusions
TEXTOR campaign (2013)	**Stationary plasma exposures**, first L-mode experiments with Mo & Ti dust	Proof of principle of the ability to prepare samples with pre-adhered dust in a controlled manner
EXTRAP-T2R campaign (2013)	**Stationary plasma exposures**, first experiments with polydisperse W dust	Not much remobilization overall
DIII-D campaigns (2015-2016)	**Transient plasma exposures**, first ELMy H-mode experiments with W dust, also C and Al dust	Confirmation of wetting induced coagulation
COMPASS campaigns (2015-2016)	**Transient plasma exposures**, ELMy H-mode experiments with W and Be proxy dust	Localized remobilization due to arcing
ASDEX Upgrade campaign (2016)	**Transient plasma exposures**, ELMy H-mode experiments with W and Be proxy dust, castellated samples	Confirmation of most of our Pilot-/Magnum PSI observations
FTU campaign (2017)	**Pure magnetic discharges,** W and Fe dust exposed to pure magnetic discharges (no plasma)	Remobilization of ferromagnetic dust by magnetic moment force

Unresolved issues:
Irregular dust

Irregular dust

All W dust remobilization, adhesion, impact and injection experiments conducted with spherical W dust (spheroidized by passing through a plasma torch)

- necessary for reproducibility of the experiment
- necessary for comparison with the theory / modelling
- relevant for tokamaks (W dust generated mainly by droplet splashing, with surface tension leading to spherical shapes)
- spheroidization leads to low porosity (thus material properties of bulk samples can be used)

Irregular shape should

- affect dynamics by altering collection
- introduce spinning, rotation now possible also under symmetric plasma conditions
- drastically alter adhesion, local radius of curvature at contact should substitute radius
- drastically affect remobilization (multiple contact points, rolling possibilities etc)

Boron dust

- is more likely to be irregular in tokamaks (through delamination of co-deposits)
- could be treated as spherical in dust dynamics codes (provided that it promptly melts, see surface tension)
- should be treated as irregular in remobilization problems

New issue:
Boron dust

Surface processes at a glance: dictate heat balance

Boron has not been studied as much as W & Be, as far as ion / electron surface interactions are concerned

secondary electron emission: experimental normal incidence data available, angle of incidence dependence can be extrapolated from other well-studied low-Z elements (Be, C).

electron backscattering: no reliable experimental data available, MC simulations of electron transport (e.g. GEANT4) can yield accurate results for the incident energy and incident angle dependence.

low energy reflection: no reliable experimental data available, extrapolations from Si might be accurate, theoretical calculations based on the invariant embedding principle are possible but are demanding.

ion-induced kinetic emission: few experimental data available, enough to construct an empirical dependence.

ion-induced potential emission: no reliable experimental data available, the empirical Baragiola and Kishinevsky formulas should be applicable for singly charged ions, the empirical Winter formula should be applicable for multiply charged ions but requires extrapolations.

thermionic emission: the Richardson-Dushman formula is applicable provided that the band gap is added to the work function.

ion backscattering: MC data are available for particle and energy yields (TRIM) and have been fitted to the empirical Eckstein formulas for the incident energy and incident angle dependence, this concerns the H, D, T, He, B ions for the energy dependence and only the D ions for the incident angle dependence.

physical sputtering: MC data are available for the sputtering yields (TRIM) and have been fitted to the empirical Eckstein-Preuss formulas for the incident energy and incident angle dependence, this concerns the H, D, T, He, Ne, O, B ions for the energy dependence and only the D,B ions for the incident angle dependence.

Material properties at a glance: dictate thermo-mechanical response

Boron has not been studied as much as W & Be, as far as high temperature properties are concerned

thermophysical (mass density, latent heats, thermal conductivity, specific isobaric heat capacity)

mechanical (Young's modulus, Poisson ratio, yield strength, yield strength size-scaling parameter, limiting pressure)

thermal (hemispherical emissivity, work function, effective Richardson constant)

fluid (dynamic viscosity, surface tension, vapor pressure)

other (surface energy, frequency dependent optical constant)

The situation depends on the property, but few experimental results are generally available at high temperatures. The situation is worse in the liquid phase, for which measurements are even sparser.

Experimental results might have to be combined with first principles results (DFT-MD modelling, with B interaction potential that is uniformly accurate from room temperature through the normal boiling point), if available.

Relatively extensive-in-frequency optical data are available from measurements of the boron dielectric permittivity, which constitute the input that is necessary for the calculation of the adhesive force from the Lifshitz theory of van der Waals forces and for the calculation of the hemispherical emissivity,

Are new experiments necessary?

Are new experiments necessary?

- Plasma-surface and plasma-wall interaction models are valid for any homogeneous dust composition, but contain numerous material constants that are adopted from experiments, theory or simulations. Some material constants will have to be approximated by best guesses → Dust injection experiments should be helpful.

- It is difficult to make projections for the behavior of B dust based on the experience with W dust because of the many competing effects. For instance, because boron is essentially a semi-conductor, thermionic emission will be low but secondary electron emission will be high (even for SOL electron temperatures). However, again, the strength of the competing affects depends on material constants that can be very uncertain → Dust injection experiments should be helpful.

- Many positive effects of boron powder injection have been observed in recent experiments (possibility of real time wall conditioning, pedestal control, heat exhaust and energy confinement improvement). Dust modelling can assist in the understanding of these benefits and optimization of the technique. Conversely, B powder droppers are already installed in devices and can be used for controlled (low density) powder injection experiments.

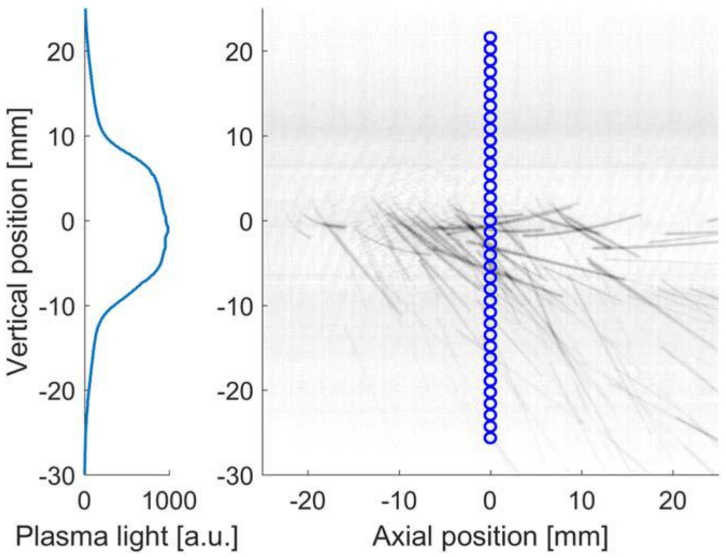
- Given the strong effect of irregular shape on adhesion / remobilization, it would be wise to repeat some of the controlled remobilization experiments. Note that only irregular B dust is commercially available.

Injection experiments

- What dust: B dust, big dust for ablation, B powder

- Needs:
- Well-characterized plasma profiles: uncertainties will kill the purpose
- Injector: controlled injection, ideally not too long tube to plasma
- Plasma: ideally large homogeneous volume
- Cameras – 'a must'
- Spectroscopy – ideally
- Collection plate – 'for free'

- Goal: insight on the heat balance (or at least dynamics)
- Trajectories – life time
- Spectroscopy – dust temperature, information from ablation cloud?
- Collection plate – size reduction



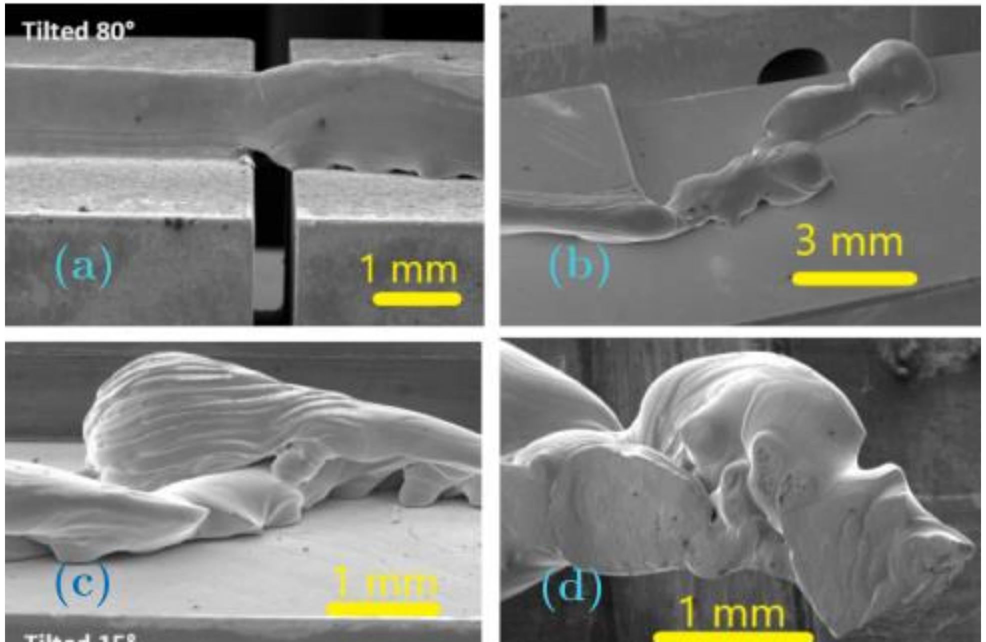
Pilot PSI W dust injection

Injection experiments: droplets

- Molten dust : W and B
- Collisions
- Remobilization of splashed droplets: depends on droplet size, speed upon collision and temperature of the substrate

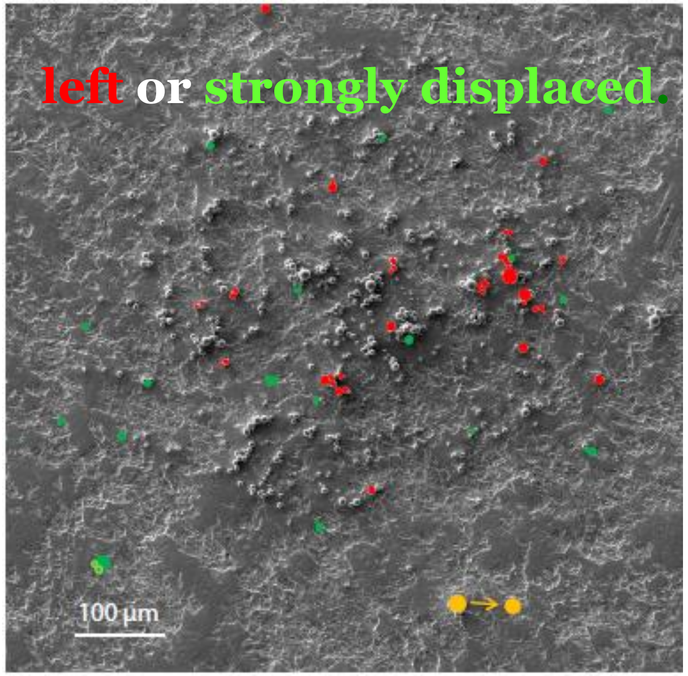
Spin-off

Stability of molten W bridges formed in recent AUG and WEST experiments?



Remobilization experiments

- Irregular W   (WEST collected dust?)
- Irregular B dust
- Normally cheap and easy experiments with clear and useful outcome but in case of irregular dust extra complication arises – untrolled adhesion and issues with transportation
- Needs: SEM in the host laboratory prior to exposure and post exposure



Overlaid SEM prior – post exposure to ***Pilot-PSI***

B dust generation experiments

- ➢ Delamination under plasma exposure?

- ❖ B film on W exposure

- ❖ Prepare samples in labs with sputtering discharges

Summary

Summary

- Droplet survival and dust inventory predictions require realistic input of dust release (size, speed) and dust termination conditions. These are problems that involve more contact mechanics, solid mechanics and fluid dynamics than plasma-surface interactions.
- Dust-plasma interaction however defines vaporization losses= impurity production

- The contact side of dust remobilization modelling can be based on surface physics models but fusion relevant peculiarities lead to extra complications (surface roughness, surface contamination, prolonged heating).

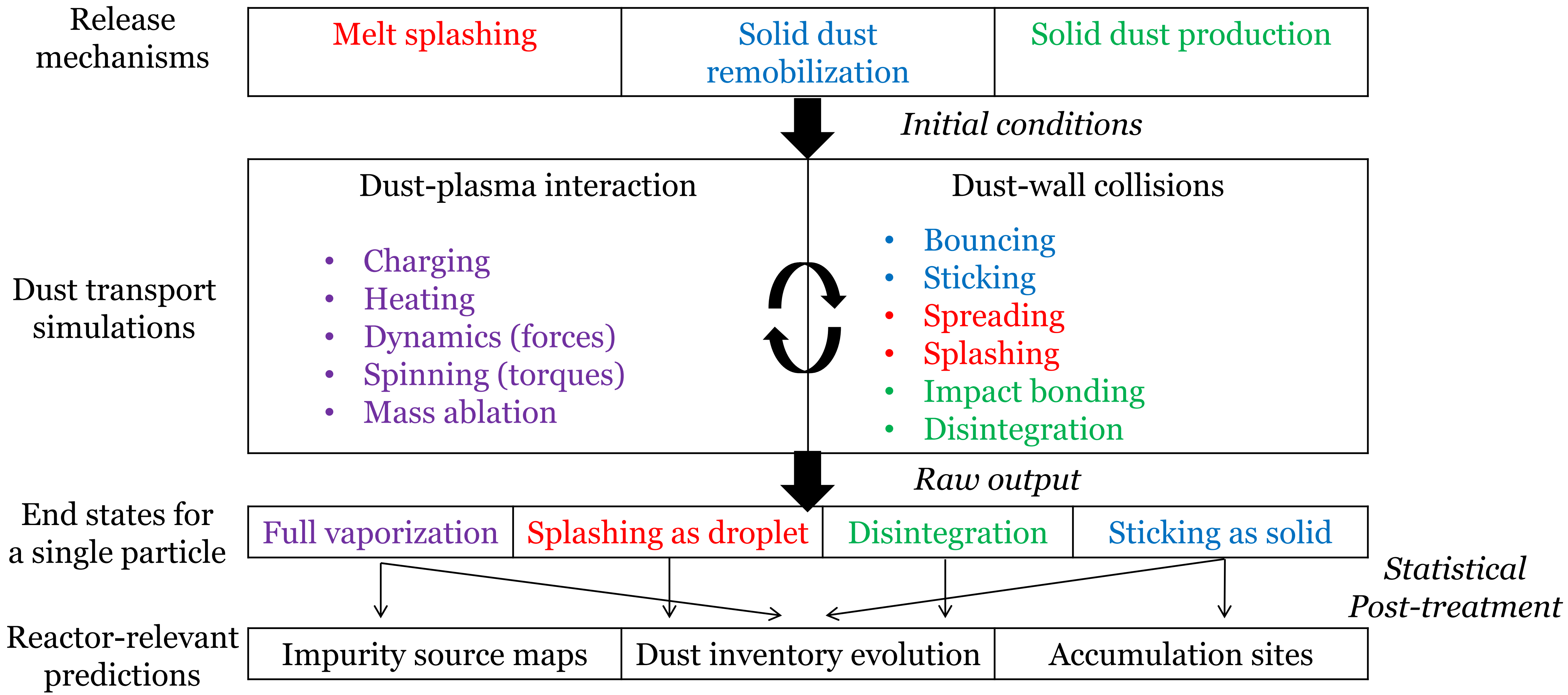
- Remaining dust issues: irregular W: relevant for remobilization (see start-up) however relevance for dust transport is to be discussed further (see melting in plasma=spherical droplet)

- New dust issues: B dust. The main complexities (i) material properties, (ii) irregular shape.

- Dust injection and dust remobilization experiments in linear machines proved highly useful in the past and can shed light on unresolved and new dust issues.
- Lessons learnt from numerous previous dust campaigns should allow for better design of the new experiments and/or to set reasonable expectations

Extra slides

Dust inventory evolution



Fluid dynamics problems
Contact mechanics problems
Solid mechanics problems
Plasma-body interaction problems

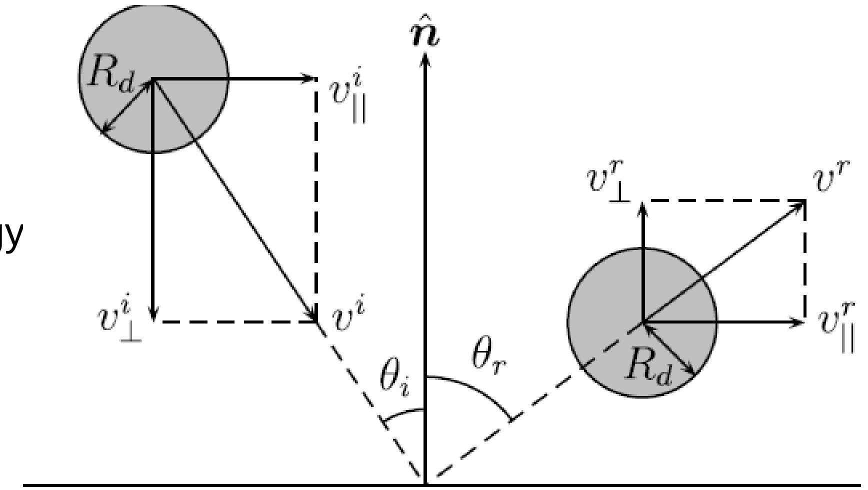
Main theoretical results from impact mechanics, contact mechanics and surface physics

Main quantities of interest : normal impacts

Adhesive velocity $v_s^{\rm adh}$ in elastic-adhesive impacts (Newton's equation+ JKR theory)
Johnson, Kendall, Roberts, *Proc. R. Soc. A* **324** (1971) 301)

$$v_{\rm s}^{\rm adh} = \frac{\sqrt{3}}{2}\pi^{1/3}\sqrt{\frac{1+6\times 2^{2/3}}{5}}\left(\frac{\Gamma^5}{\rho_{\rm d}^3 E^{*2} R_{\rm d}^5}\right)^{1/6} \simeq \text{few m/s}$$

$\rho_{\rm d}$, $R_{\rm d}$ are dust mass density, radius, E^* the reduced Young modulus, Γ the interface energy
For $v_\perp^i \le v_s^{\rm adh}$ adhesion forces make grain stuck to the surface, while
for $v_\perp^i > v_s^{\rm adh}$ collision is inelastic owing to the irreversible work $\frac{1}{2} m_{\rm d} \, (v_s^{\rm adh})^2$



Yield velocity $v_{\rm y} = \frac{\pi^2}{2\sqrt{10}}\left(\frac{p_{\rm y}^5}{\rho_{\rm d}\, E_{*4}}\right)^{1/2}$ in elastic-perfectly plastic impacts

$p_{\rm y}$ is limiting contact pressure, typically $1.6 - 2.8\ \sigma_{\rm y}$, where $\sigma_{\rm y}$ is the yield strength
For W $p_{\rm y} = 4\sigma_{\rm y}$ based on experiments Tolias *et al*, *NME* **12** 524 (2017)
For $v_\perp^i > v_{\rm y}$ dust impact energy is enough to cause plastic deformation, while
for $v_\perp^i \le v_{\rm y}$ the collision is totally elastic *when ignoring adhesion*

Basic picture:

- gradual reduction of normal velocity → value below the adhesive velocity → dust is adhered to the wall
- Size selectivity; smaller dust stucks easier, larger dust requires more collisions

- Outcome of collision can be predicted by restitution coefficients $e_\perp$ (rebound to incident speed ratio) the normal impact of elastic–perfectly plastic adhesive spheres [Thornton and Ning, *Powder Technol.* **99** 154 (1998)], $e_\perp$ function of $v_\perp^i$, $v_s^{\rm adh}$ and $v_{\rm y}$

Adhesion: contact mechanics picture

- In order to remobilize dust, plasma induced forces need to overcome adhesion.

- Pull-off force minimum normal force to separate two bodies. In the JKR model, for the sphere-plane case:

$$|F_{\mathrm{a}}| = |F_{\mathrm{po}}| = 3\pi\Gamma R_{\mathrm{d}}/2 \propto R_{\mathrm{d}}$$

  valid for smooth surfaces at intimate contact, metallic bonding due to the sharing of the delocalized valence electrons between the two bodies

- Plasma forces ($\propto R_{\mathrm{d}}^2$) and gravity ($\propto R_{\mathrm{d}}^3$) cannot detach 10 μm sized W dust, for ITER divertor parameters

$$F_{\mathrm{po}} \sim 10^2 F_{\mathrm{id}}^{\mathrm{sc}} \sim 10^3 F_{\mathrm{id}}^{\mathrm{abs}} \sim 10^3 F_{\mathrm{E}} \sim 10^6 F_{\mathrm{g}}$$

Tolias, Ratynskaia, De Angeli *et al, PPCF* **56** 123002 (2016)

- Size scalings (linear versus quadratic, cubic) suggest that larger dust can remobilize more easily.

  For sphere-sphere case, substitute R_{d} with $R_{\mathrm{eff}}^{-1} = R_{\mathrm{d1}}^{-1} + R_{\mathrm{d2}}^{-1}$, agglomerates can remobilize more easily

Adhesion: surface physics picture

- Contact mechanics models implicitly assume that *extremely short range strong metallic forces* produce adhesion. JKR theory, DMT theory and generalizations (classical contact mechanics).

- Surface physics models explicitly assume that *long range weak induced multipole interactions* produce adhesion. Lifshitz theory of van der Waals forces (thermal quantum field theory).

$$|F_{\mathrm{a}}| = |F_{\mathrm{vdW}}| = \frac{A_H}{6z_0^2} R_{\mathrm{d}}$$

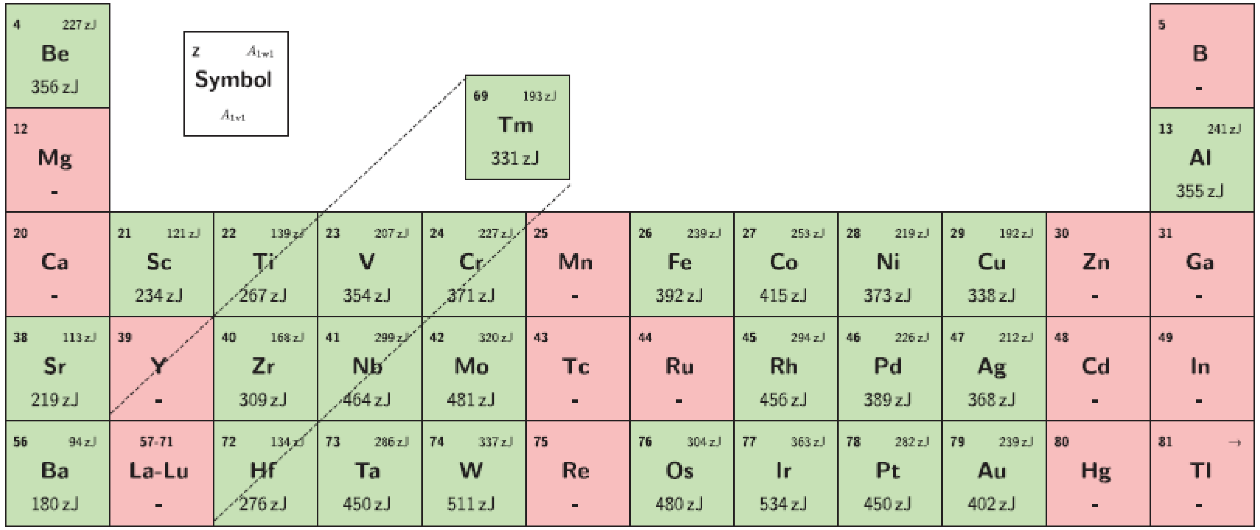
with A_H the non-retarded Hamaker constant and $z_0 \simeq 0.4\mathrm{nm}$ of the order of the lattice parameter.

- Hamaker constant can be calculated provided that the optical permittivity of a given material is available at an extended frequency range

$$A_H = -\frac{3}{2} k_{\mathrm{b}} T \sum_{n=0}^{\infty} \int_0^{\infty} x \ln\left\{1 - \left[\frac{\epsilon_1(\imath\xi_n) - 1}{\epsilon_1(\imath\xi_n) + 1}\right]^2 e^{-x}\right\} dx$$

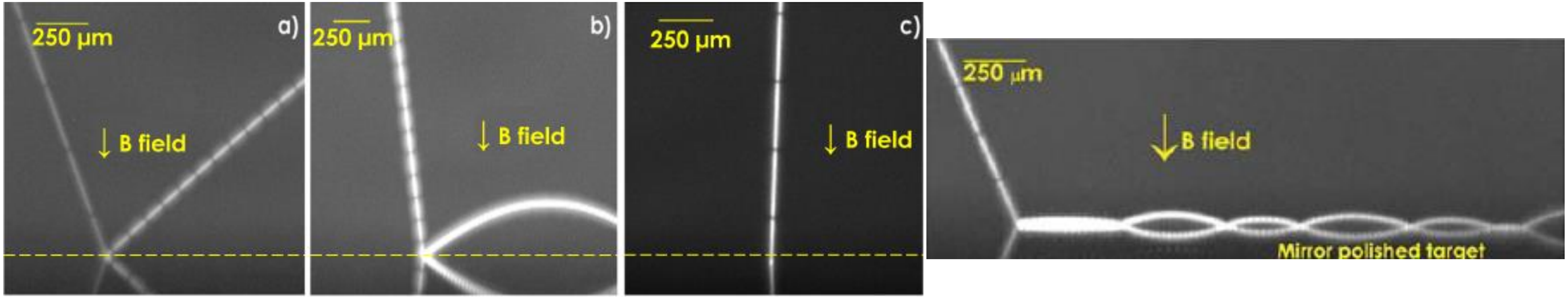
$$\epsilon(\imath\xi_n) = 1 + \frac{2}{\pi}\int_0^{\infty} \frac{\omega \Im\{\epsilon(\omega)\}}{\omega^2 + \xi_n^2} d\omega \quad \text{with } \xi_n = \frac{2\pi n k_{\mathrm{b}} T}{\hbar}$$

non-retarded calculations [P. Tolias, Fus. Eng. Des. **133**, 110 (2018); P. Tolias, Surf. Sci. **700**, 121652 (2020)] and even fully relativistic retarded calculations possible [P. Tolias, Surf. Sci. **723**, 122123 (2022)].



Dust impact validation in plasma environments (Pilot-PSI)

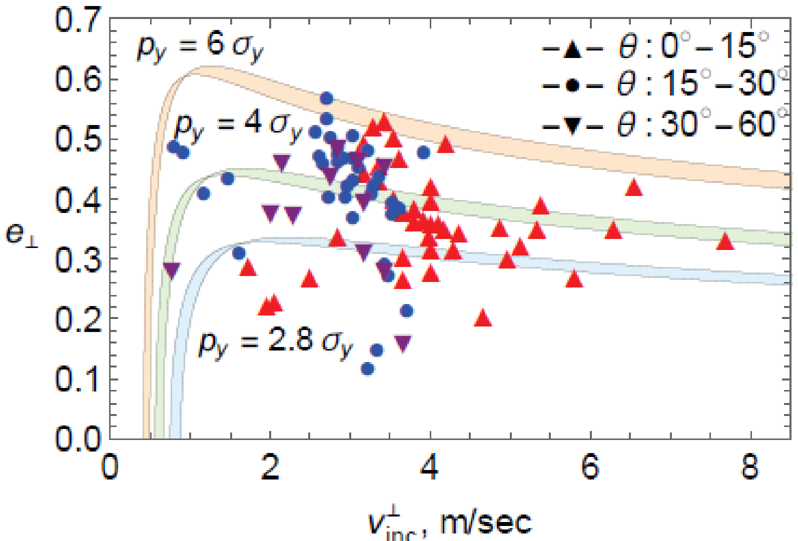
Spatial resolution down to 6.5 μm/pixel achieved in Pilot-PSI (spherical 5-25μm W dust) Shalpegin *et al* NF 55 (2015) 112001



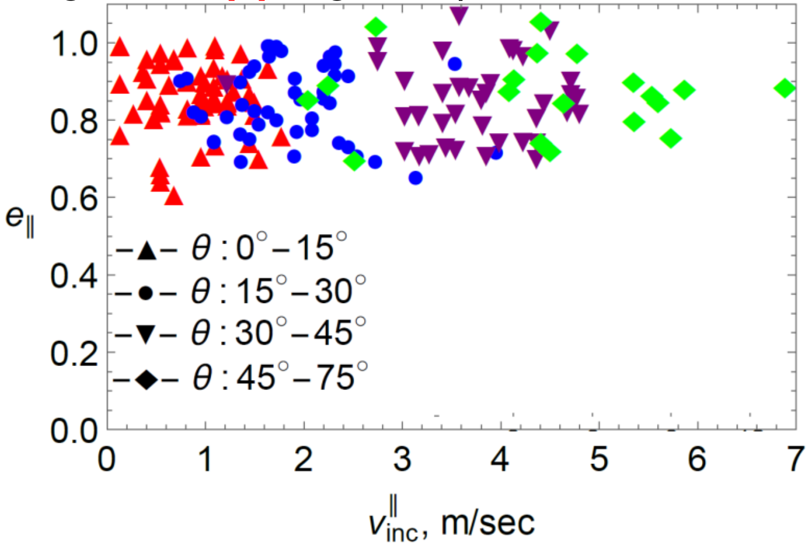
***(a)** small loss of normal velocity, $e_\perp = 0.7$, $e_{||} = 0.95$; **(b)** substantial loss, $e_\perp = 0.2$, $e_{||} = 1$; **(c)** sticking ; **(d)** multi-bouncing*

Plasma not relevant for instantaneous impacts

- Dissipation of $v_\perp$ due to adhesive and plastic losses & nearly preserved $v_{||}$ (near frictionless contact)
- No rebound when (i) normal velocity < sticking value (ii) High temperature



Thornton and Ning approach, elastic-perfectly plastic adhesive spheres Powder Technol. 99 (1998)



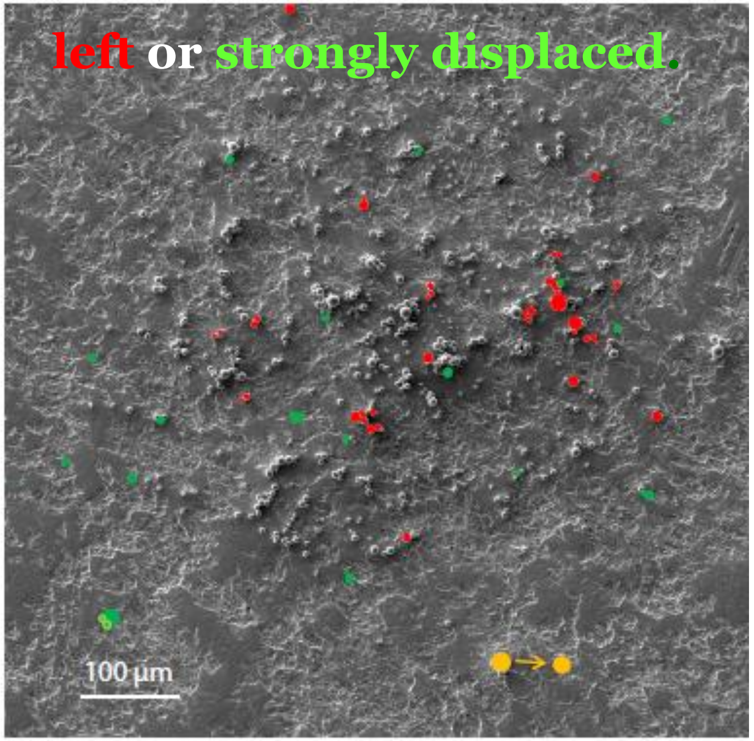
Dust remobilization in plasma environments (cross-machine)

Cross-machine study: W-on-W exposures in linear devices, reverse field pinches, tokamaks.

Tolias *et al*, PPCF **56,** 025009 (2016); Ratynskaia *et al*, NME **12** 569 (2017)

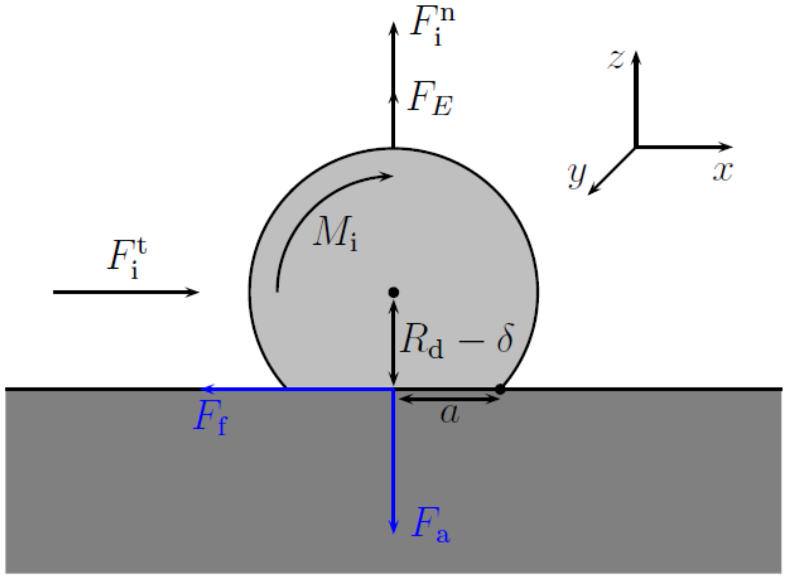
- Similar results despite the strong variation of the plasma parameters.
- *On average*, large dust grains ($\gtrsim 10\mu$m) and agglomerates remobilize much more easily, as expected from simple scalings → smaller dust expected to reside on PFCs.
- Overall dust remobilization rate is higher than estimated, but still not massive

Overlaid SEM prior – post exposure to ***Pilot-PSI***



Direct lift-up condition: $F_i^n + F_E > F_p$

1. JKR or van der Waals models?
2. Do we estimate plasma forces correctly?



Sliding condition: $F_i^t > \mu_s(F_p - F_i^n - F_E)$

Depends on static friction coefficient value

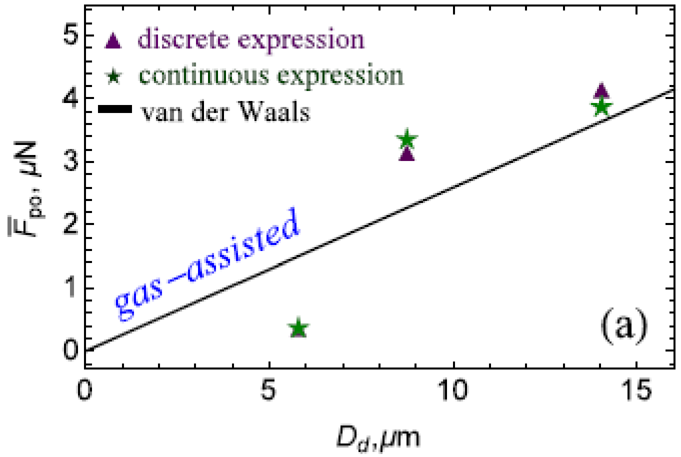
Rolling condition: $M_i + F_i^t(R_d - \delta) > a\,(F_p - F_i^n - F_E)$

In the typical small deformation limit $R_d \gg a,\ \delta$

G. M. Burdick, *et al.*, J. Nanopart. Res. 3 (2001) 455
M. A. Hubbe Colloids Surf. 12 (1984)

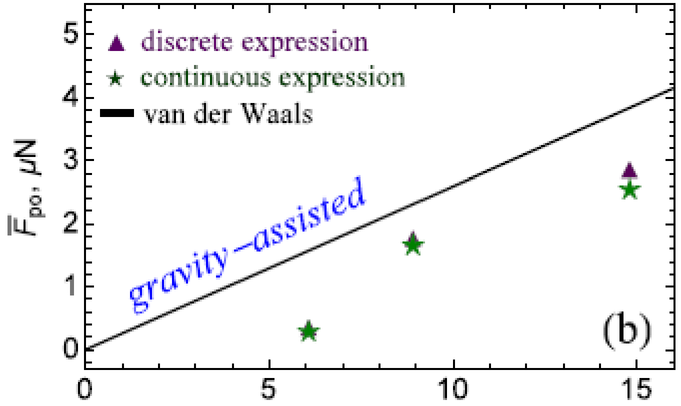
W-on-W adhesion: measurements

- First measurements of W-on-W adhesion with *electrostatic detachment method* for spherical monodisperse μm W dust (high purity, no porosity, excellent conductivity) Riva *et al*, *NME* **12** 593 (2017).
- Similar results by other groups with AFM Peillon *et al, J. Aerosol Sci.* **137** (2019).

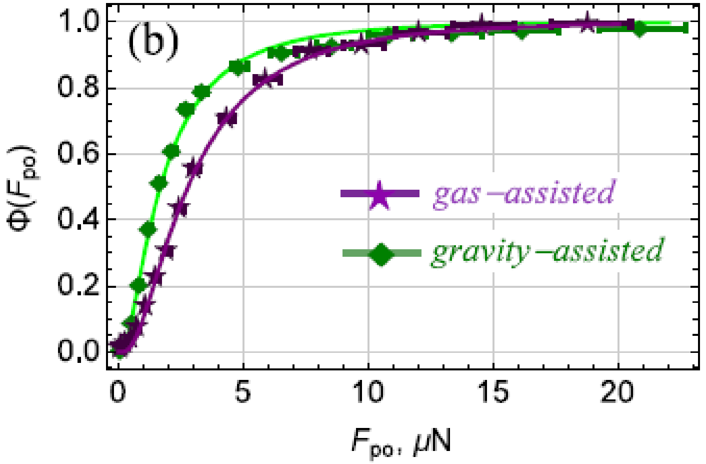


- Contact mechanics models (JKR, DMT) overestimate the adhesion force by ~ 2 orders of magnitude. The standard van der Waals expression agrees well with experiments.

- **Surface roughness ~ of few nm suffices to switch the dominant contact force from metallic bonding to van der Waals attraction →** equivalent to dramatic decrease of surface energy



- Measurements have quantified the effect of the dust deposition technique, beryllium coating thickness, atmospheric contaminants, thin oxide layers, surface roughness and prolonged heat treatment on W-on-W adhesion.
  Riva *et al*, NME **12** 593 (2017); Peillon *et al, J. Electrostat.* **88**, 111 (2017)
  Tolias *et al,* NME **15**, 55 (2018); Tolias *et al,* NME **18**, 18 (2019);
  Peillon *et al., J. Aer.Sci.* **137** (2019); Tolias *et al.,* NME **24**, 100765 (2020)



- Adhesive force distributions are also available beyond the mean value character of the pull-off force [Tolias *et al,* NME **15**, 55 (2018)]. The added probabilistic component is due to the omnipresent nano-roughness statistical variations.

Heating effects: molten dust / droplets

- In isothermal conditions, wetting dynamics result from the balance between capillary forces, which *promote liquid spreading towards a small equilibrium contact angle in case of metals*, and inertial/viscous effects which tend to resist fluid motion
- Re-solidification also hinders spreading (transient heat loads and/or for substantial temperature difference between the liquid and the solid substrate)

The final result is dictated by the hierarchy of the time scales [Ratynskaia *et al.*, NF **64,** 036012 (2024)]:

Capillary	$\sqrt{\rho_d h L^2/\sigma}$	with h the melt thickness, L along the direction of spreading, σ the surface tension
Viscous	$\rho_d h^2/\mu$	with μ the dynamic viscosity
Solidification	$\rho_d h^2 \Delta h_f / k\Delta T$	with ΔT the temperature dif. between phases, k the thermal conductivity, Δh_f the latent heat
Inertial	h/v	with the melt flow velocity

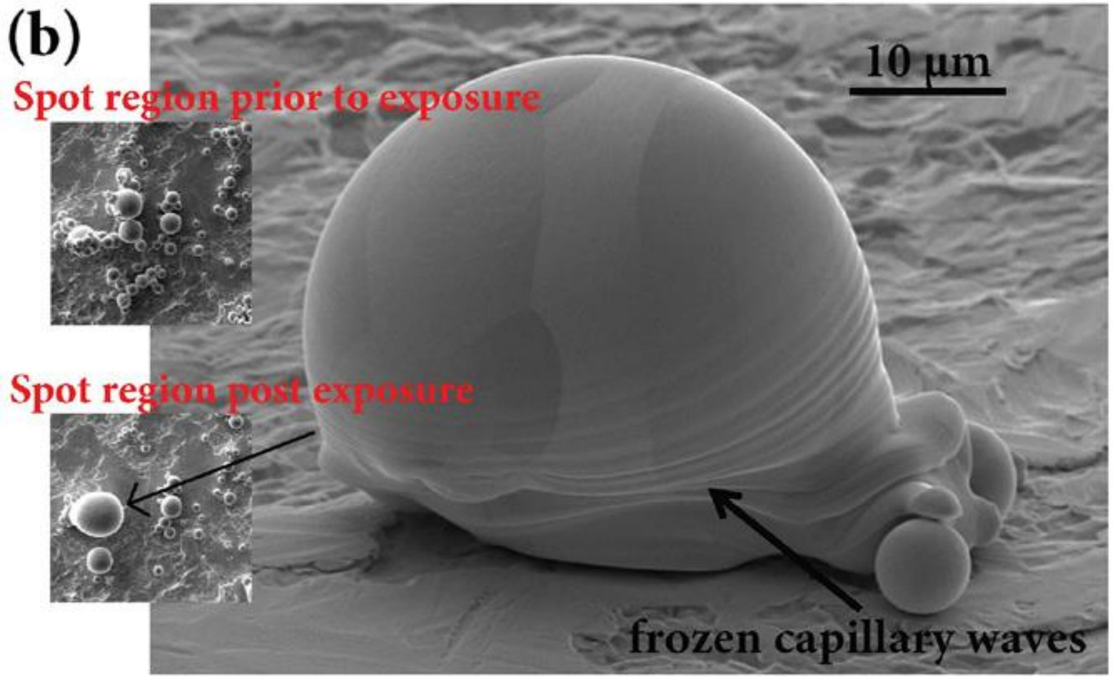
In terms of characteristics the outcome depends on

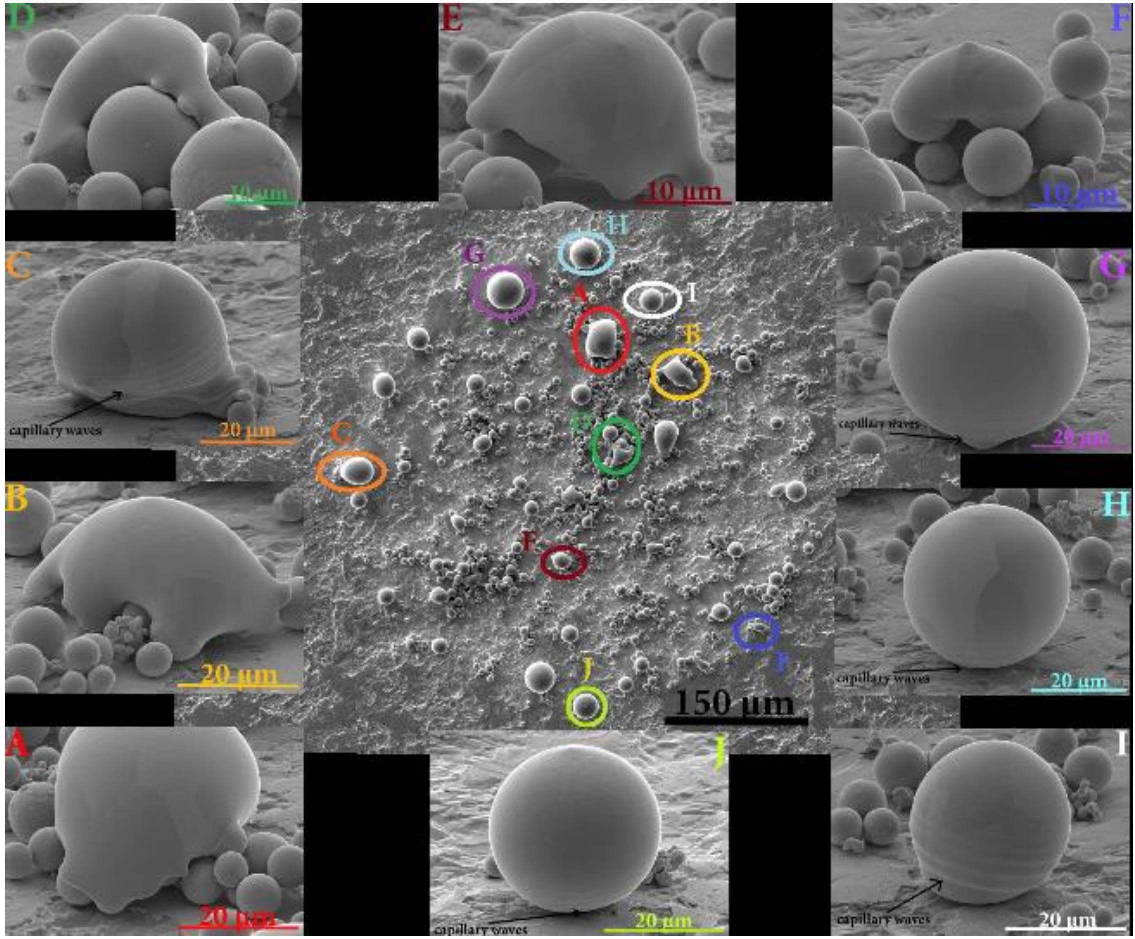
- melt speed
- melt depth (droplet size)
- melt and PFC temperatures
- heat loads and exposure time

Remobilization under ELM-like heat loads: Wetting induced coagulation

No observation of melting of isolated dust grains: despite large statistics

Recurring evidence of top-bottom wetting: especially for monodisperse dust





Strong interplay between wetting and resolidification (short ELM duration): Spreading dynamics do not fully evolve, signature capillary waves frozen by resolidification Ratynskaia et al, NF **56** (2016) 066010

Exposure to single Pilot-PSI ELM-like pulse:
$t = 1\text{ms},\ \bar{q} = 200\text{MW/m}^2, \angle\mathbf{B} = 90°$

Adhered dust on hot surfaces

- Prolonged heat treatments in vacuum furnaces at temperatures below the W recrystallization range lead to increase of the W-on-W adhesion force up to two orders of magnitude irrespective of the dust size [Tolias *et al, NME* **24** 100765 (2020)]

- Atomic diffusion at the contact area slowly eliminates the omnipresent nanometer-scale surface roughness, switching the dominant interaction from long-range van der Waals-like to short-range metallic bonding-like.

- Confirmed also in the fusion relevant but less controlled environment of the GyM linear device.

- Transition from van der Waals models to JKR models. In temperature space (for long exposure times), the adhesion force is a sigmoidal function of the temperature [Tolias *et al, manuscript in preparation* (2024)]