# Computer modeling of contamination and cleaning of EUV source optics

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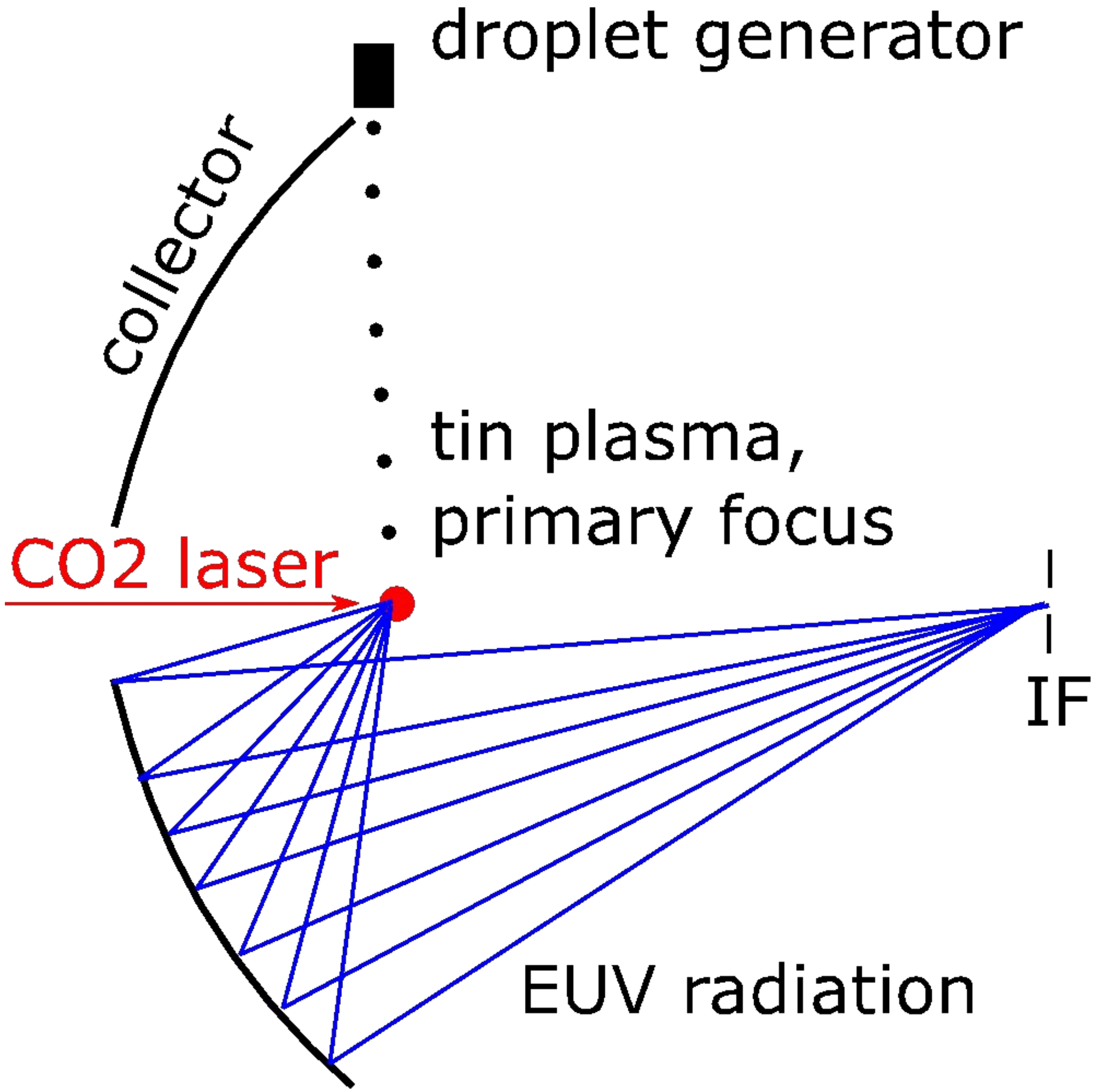
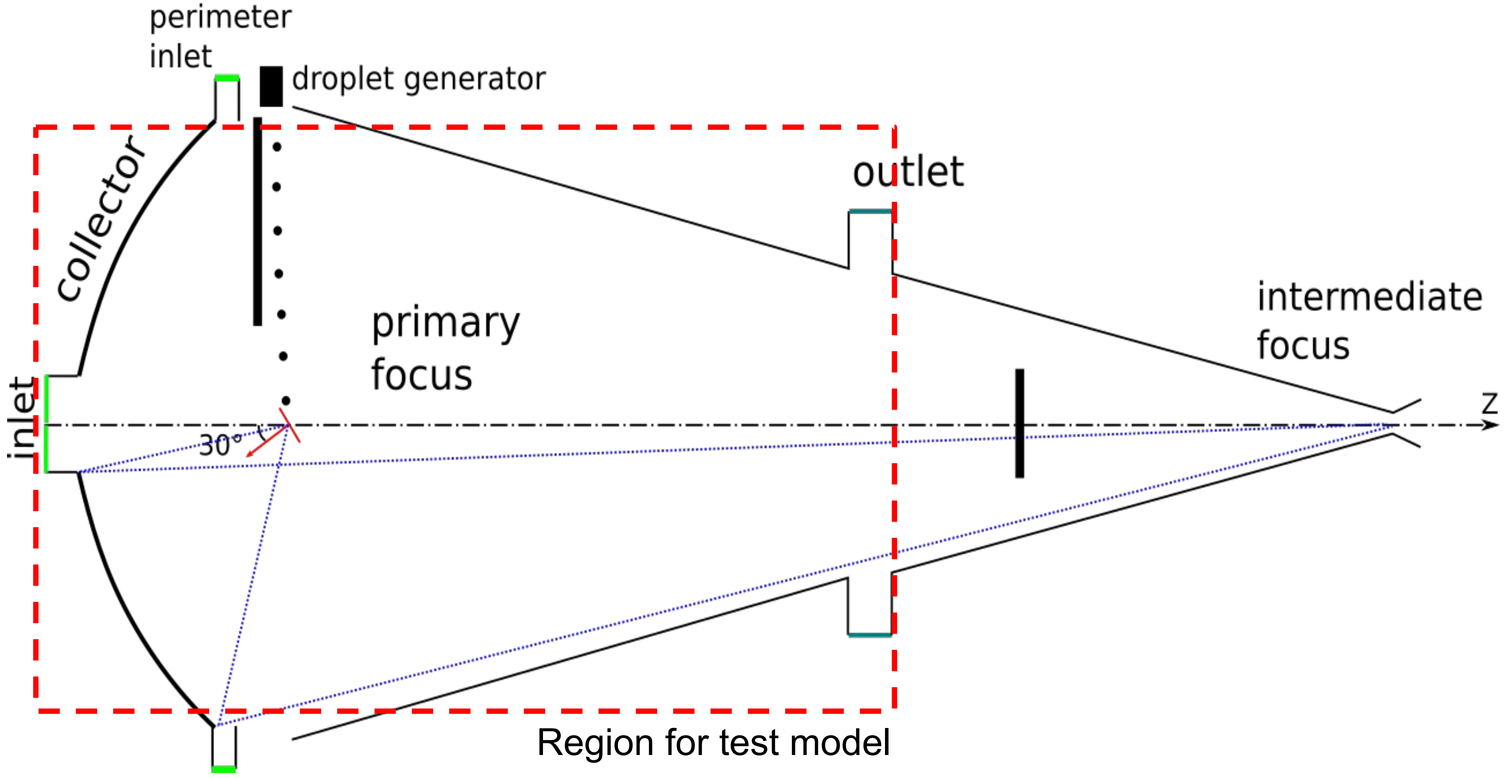
# Motivation for flow model



- Collector mirror need to be protected from tin debris
- Two main approaches:
  - Gas flow
  - Gas flow + B-field
- Goal: fast transient 3D model for flow + plasma conditions

# Test configuration of LPP EUV source chamber



Target:

- Disk-like Sn target, mass equal to 30 μm droplet

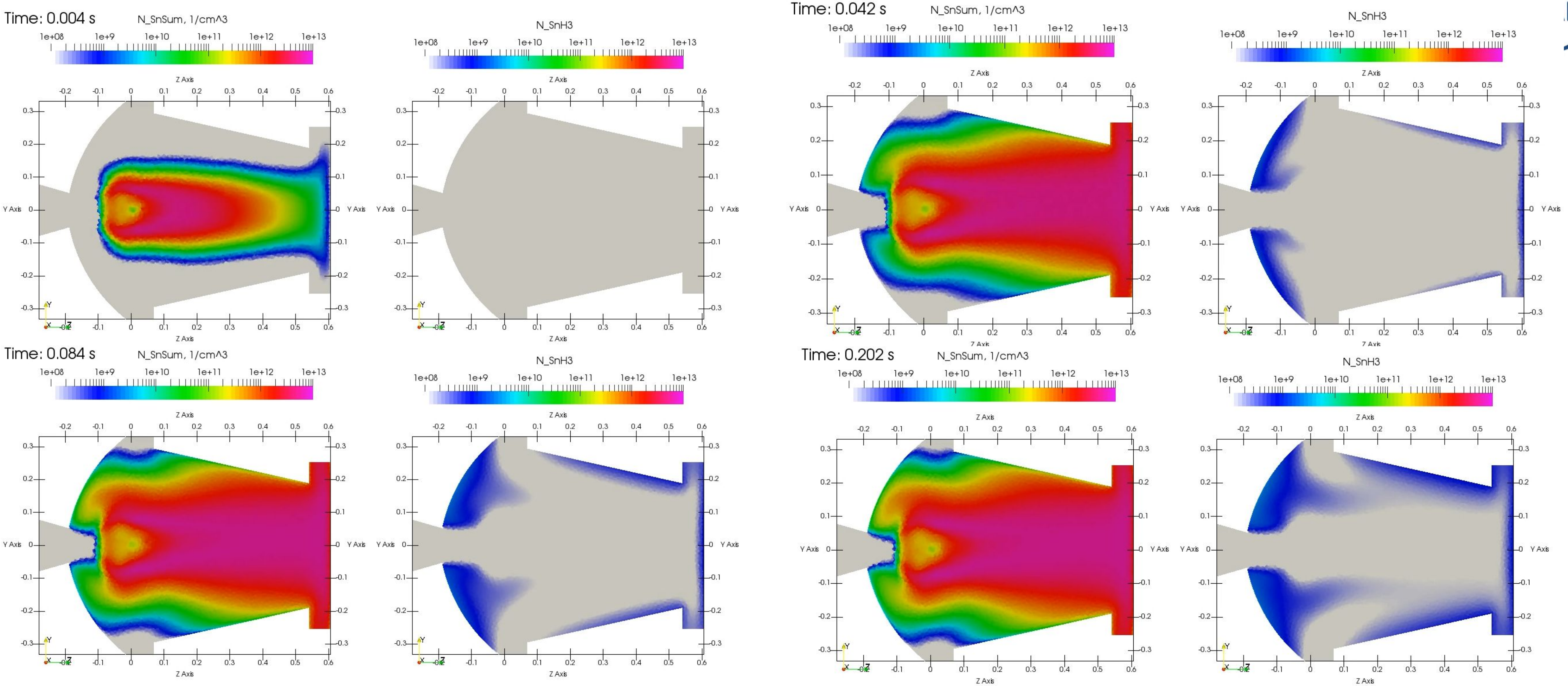
Laser:

- $CO_2$ main pulse
- 50 kHz operation frequency
- Tuned to ~250W to IF

Gas protection:

- $H_2$ central flow
- $H_2$ perimeter flow

# Transient simulation for test configuration



Tin vapour reach collector. This simulation resulted in net removal of tin for the most part of the collector. (see slide 16)

# Included physics

- Gas heating due to ions stopping
- Spectrally resolved  WUV radiation absorption in gas
  - Reflection from collector, EUV to IF
- H2 dissociation, recombination

- Multi component diffusion
- Particulate debris tracking
- Set of surface & volume chemical reactions
  - Tin deposition to surfaces
  - Tin cleaning by atomic hydrogen

- Disturbance of the tin droplets trajectory by flow field

# Relevant time & space scales hierarchy

(1) Laser pulse & hot tin plasma
- t <  500 ns, h < 1mm

Not resolved,
input data

(2) Ions stopping & radiation absorption
- t ~ 1 μs,   h ~ chamber size

Partially resolved,
time scale
integrated out

(3) pulse-to-pulse repetition time
- t ~ 10 μs

(4) Transport processes in chamber
- t  > 10 ms, h ~ chamber size

(5) Tin cleaning and deposition on the collector mirror
- t > 1 hour

Transient CFD

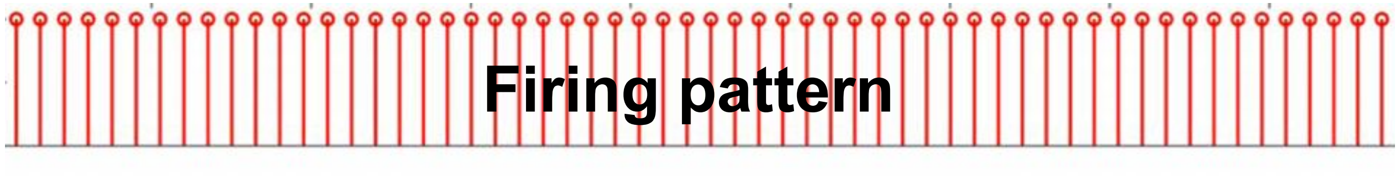
# Model approach: CFD + plasma source

EUV plasma characteristics

- Ions: angular - energy distribution + charge states
- Radiation: angular resolved spectrum

Plasma energy-mass-momentum source for CFD

- Particle tracing for ions
- Ray tracing for radiation



Computational fluid dynamics for multi-component gas

- Mesh accounts for complex vessel geometry

# Tin cleaning model

- Tin cleaning agent
    - Atomic hydrogen vs ions
    - Ratio of ion and radical fluxes to the collector
    - Energy distribution of ion flux

- Tin cleaning product and redeposition
    - $SnH_4$ vs $SnH_x$

# Tin cleaning agent

Tin etching by H radicals and by H2 plasma was observed in many experiments:

- D. J. W. Klunder et al., SPIE 5715 (2005)

….

- O.V. Braginsky et al., J. Appl. Phys. 111 (2012)
    - Sn is etched by atoms, probability is → 0.5e-5 SnH4 per At.H
    - Sn may be etched also by ions, but with low overall contribution
    - Ion energy below 20eV.
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13 years

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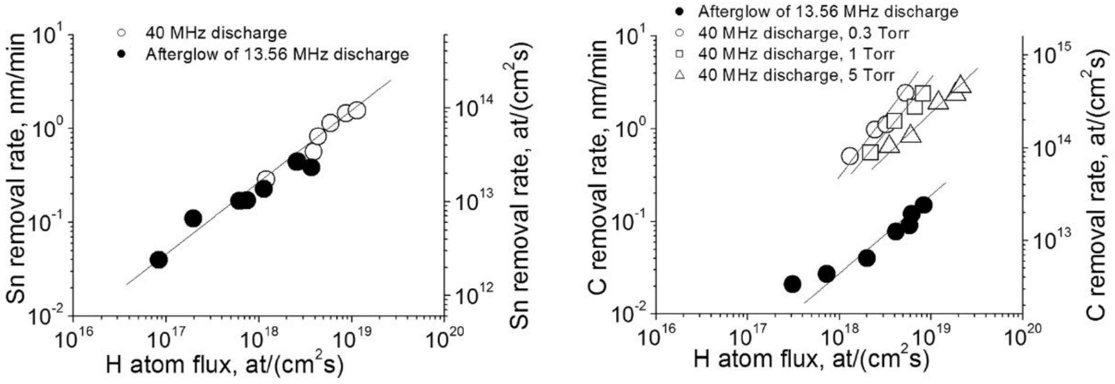


Sn cleaning by ions can be 10 -- 100x more efficient then by atoms, but still have small contribution in these experiments.

In order to translate to the EUV source chamber model:

- Expected ratio of ions to radicals fluxes
- Expected energy distribution function of the ion flux on the collector mirror

# Estimation of ions to radical ratio for fluxes on the collector

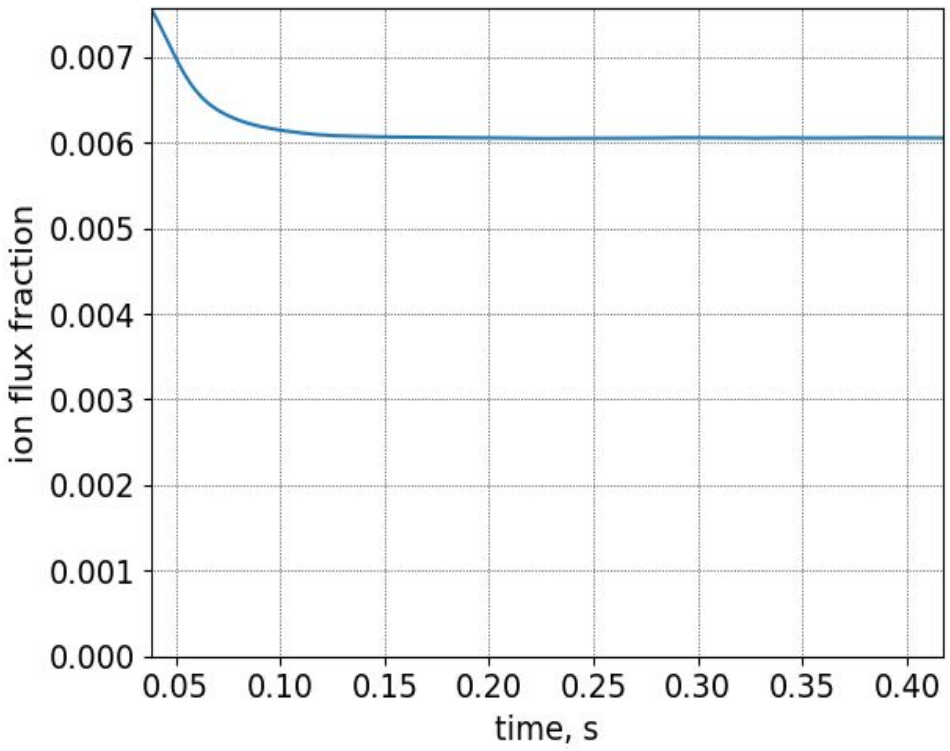
Recombination of ions:

- $H_2^+$, $H_3^+$ lost due to two-body dissociative recombination in volume
- $Sn^{+n}$ to $Sn^{++}$ lost charge due to charge exchange with H2
- $Sn^{++}$ , $Sn^+$ and $H^+$ recombine via collisional radiative process

Recombination of H radicals:

- Atomic hydrogen recombination in volume is a very slow
- Recombination on the surface is a main sync

flux ratio Hions/(At.H + Hions)



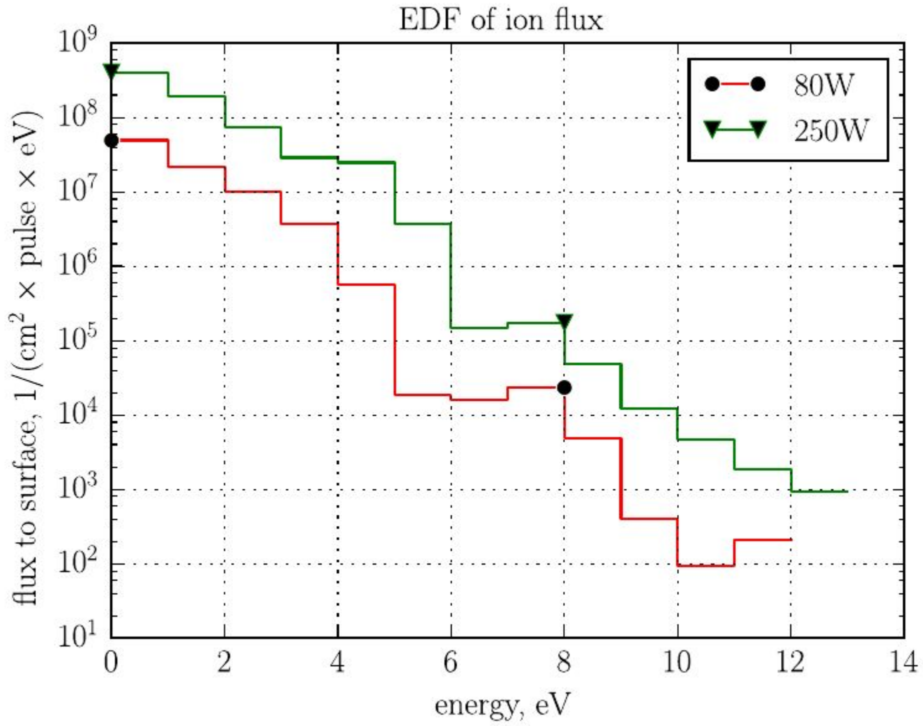
# Estimation energy distribution function (EDF) of the ion flux to the collector mirror

- EUV radiation forms plasma in front of the collector mirror
- Escape of fast photo electrons to the walls facilitate of plasma sheath formation
- Ions are accelerated by the sheath potential
    - Once plasma near the mirror cools down → ion energy drops to near gas temperature level

Way to estimate -- Particle-in-Cell model for the EUV induced plasma applied locally near the collector mirror.

- Te cools down quickly to almost room temperature due to collisions with gas

- Most ions impact surface with very low energy.



IEDF over 1us, after 1us T_e is about 1000K

Most ions are cold → At.H provides most of tin cleaning

# Tin cleaning products and redeposition

Common assumptions are:

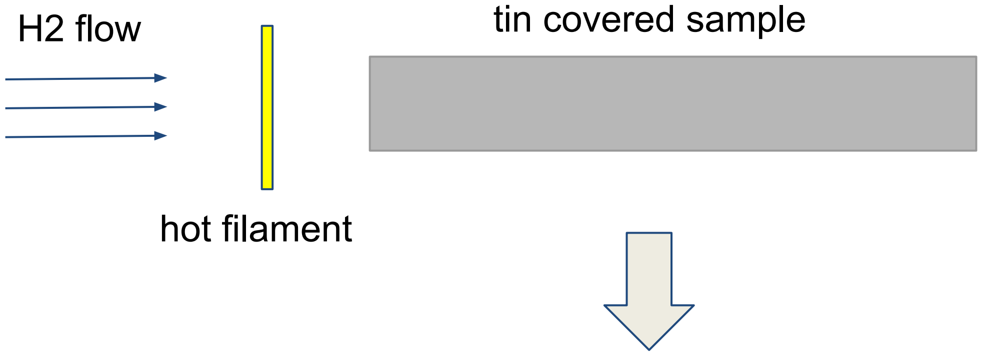
- Tin etching is $Sn + 4H \rightarrow SnH_4$
- Redeposition is due to $SnH_4$
  - $SnH_4$ decomposition is EUV or plasma induced
  - Thermal decomposition rate is too low (Tamaru 1956)
- Direct measurements of SnH4 decomposition yields no effect

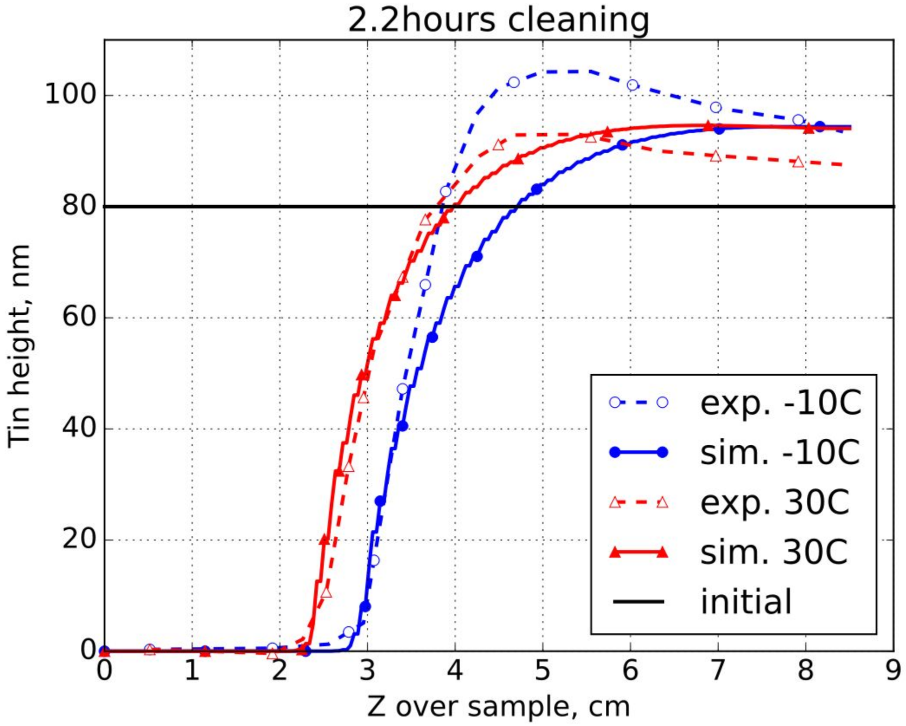
For other systems it is known that intermediate products can be much more reactive, e.g. $CH_3$ vs $CH_4$; $SiH_3$ vs $SiH_4$ etc.

- Proposed set of reaction:
  - Sn + xH → SnHx
  - SnHx + surface → redeposition
  - SnHx + H + M → SnH4

# Tin cleaning model key experiment → filament + lateral flow

experiment by Piter van Zwolle and Maarten van Kampen

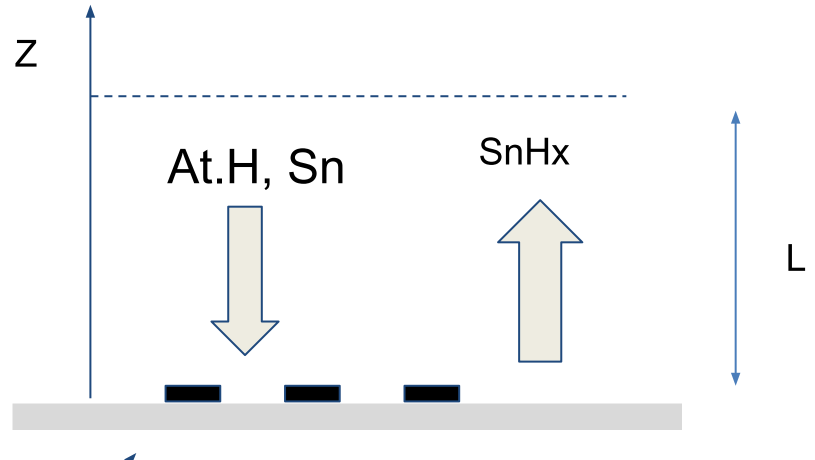




- Tin is pre-deposited on the sample
    - initial profile is uniform

- Spatial distribution of tin over sample after exposure show measurable redeposition
    - The amount of redeposition is inconsistent with rate for $SnH_4$ decomposition

# 1D analytical example: effect of tin redeposition



Assumption:

- Tin covers only part of the surface, PAC = S_covered/S_total
- fluxes of H and Sn are constant

- For H radicals and Sn the surface is a “sync term”
  - Sn deposits with  g ~ 1
  - H radicals recombine with g ~ 1e-4 .. 0.1
- For SnHx the surface with tin is a source
  - SnHx is produced due to etching
  - Need to be transported any by diffusion and flow
  - Efficiently redeposits back on Sn

Balance between contamination and cleaning

- In 1D approximation, with diffusive transport only:

$$F_{Sn} = \gamma^{etch} \cdot F_H \cdot PAC \left(1 - \frac{\gamma_{SnH_x} \cdot PAC}{\gamma_{SnH_x} \cdot PAC + \frac{4D_{SnH_x}}{V_{SnH_x} L}}\right)$$

- For PAC → 0 redeposition is not important
- For PAC ~ 1,  redeposition is important, but the transport of SnHx limit cleaning rate
- Pressure effect → increase of pressure limits the transport, thus reduce cleaning rate

# Modelling of collector contamination/cleaning

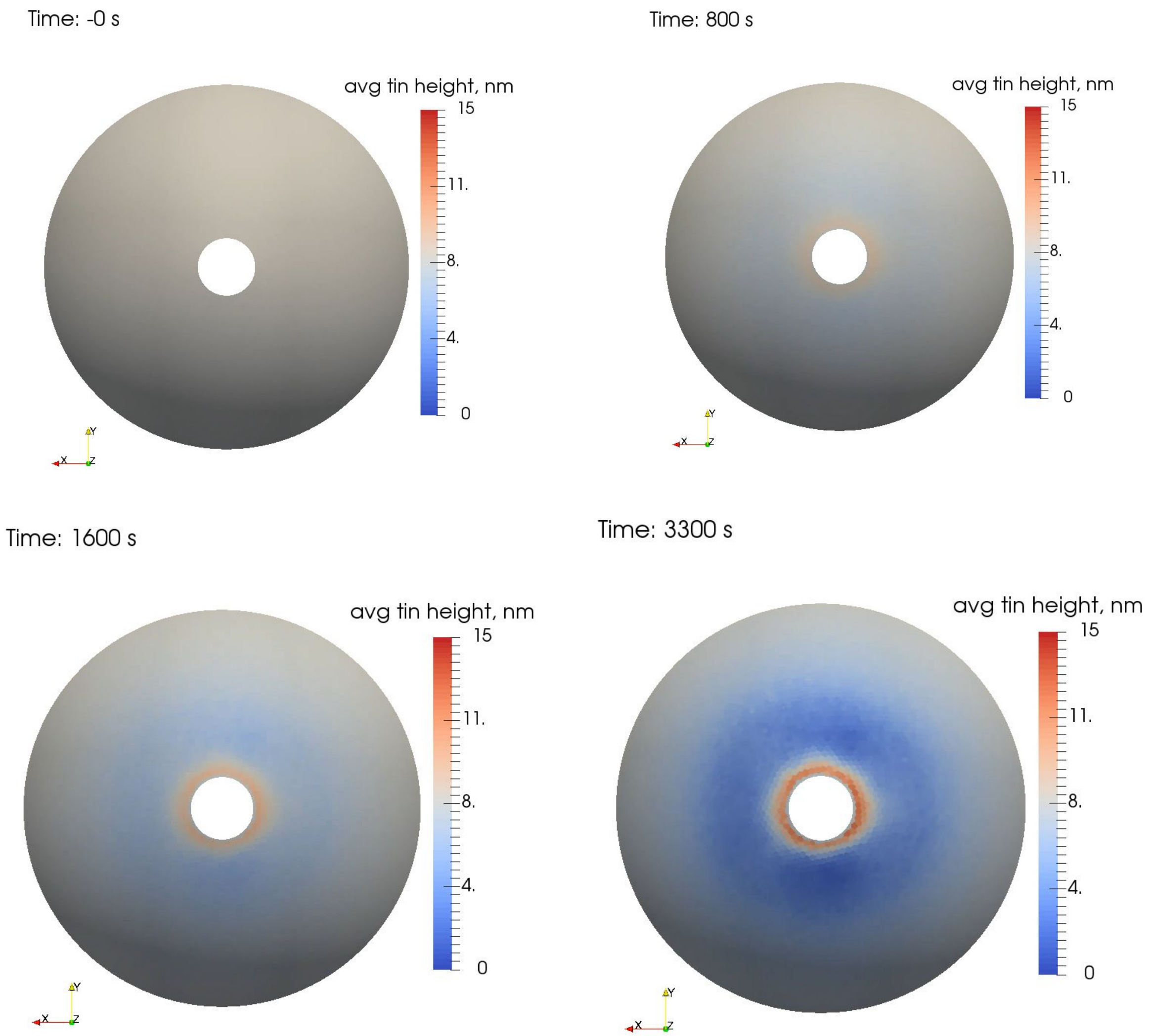
- Full model needs to define H, Sn, SnHx fluxes and deposited tin on all surfaces in the source chamber

- In order to provide quantitative results the amount of tin on the surface should be an output
    - Dirty surface → increase of H recombination. Steady model frequently results in all dirty collector.

- Model approach: transient fully coupled model for flow + source terms + species transport. Iteratively solved to prescribed tolerance.
    - If flow is steady → solve species transport only
    - If flow is unsteady, e.g. start of pulses → can resolve with small time step.

- Internal scheme is unconditionally stable:
    - dt ~ 1e-6s to resolve pulses
    - dt ~ 1e-4s to resolve flow restructure
    - dt ~ 100s to resolve cleaning/deposition

test simulation results:



Net cleaning of the collector can be realised

# Conclusions

- We have developed 3D transient model that couples energy and momentum input from tin plasma to the flow in the EUV source chamber
- The model takes into account tin deposition and cleaning from surfaces. Main etch product is assumed to be chemically active SnHx
- The model have ability to smoothly vary time step from pulse-to-pulse (~1e-6s) resolution to characteristic times (~100s) of cleaning processes
- The model can be used to optimize the chamber geometry, flow structure etc. for regime during source operation