Controlled tungsten melting and droplet ejection studies in ASDEX Upgrade

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Outline

- Introduction and experimental set-up.
- Trajectories and life time of ejected W droplets.
- W penetration to confined plasma.

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Key issues for a tungsten divertor in ITER

Apart from surface damage issues (talk by J. Coenen)

⇨ **Where will material ejected from melt layers be transported?**

⇨ **How much of evaporated tungsten will become ionised?**

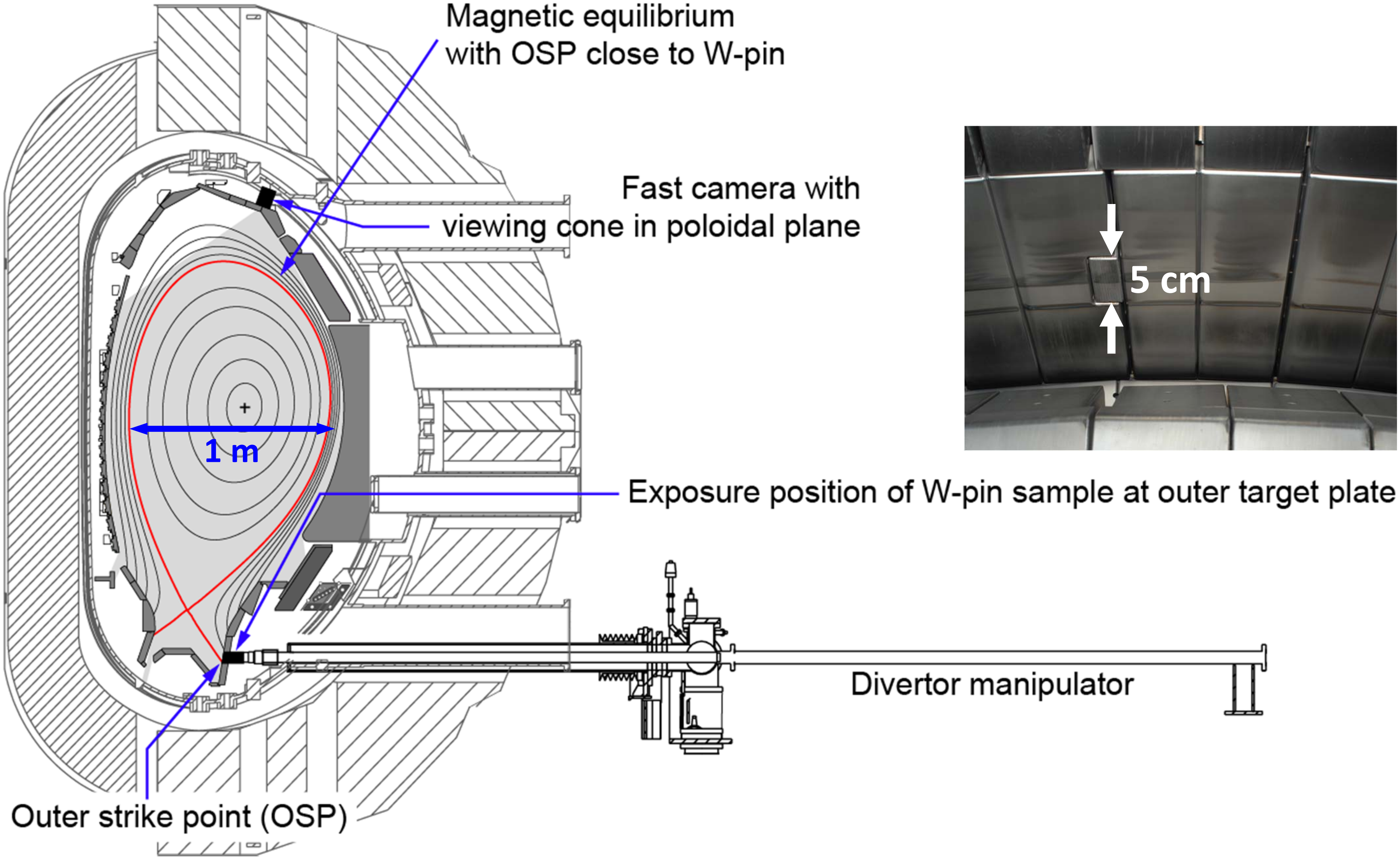
⇨ **What is the resulting W leakage to the confined plasma?**

Experimental procedure

- ❑ Use divertor manipulator in ASDEX Upgrade to place small W-rod protruding above surface at outer target plate.
- ❑ Induce melting, droplet ejection and evaporation in near strike-point plasma.
- ❑ Determine trajectories of ejected material by fast VIS range camera systems.
- ❑ Quantify resulting W penetration to confined plasma by VIS range divertor and VUV core plasma spectroscopy.

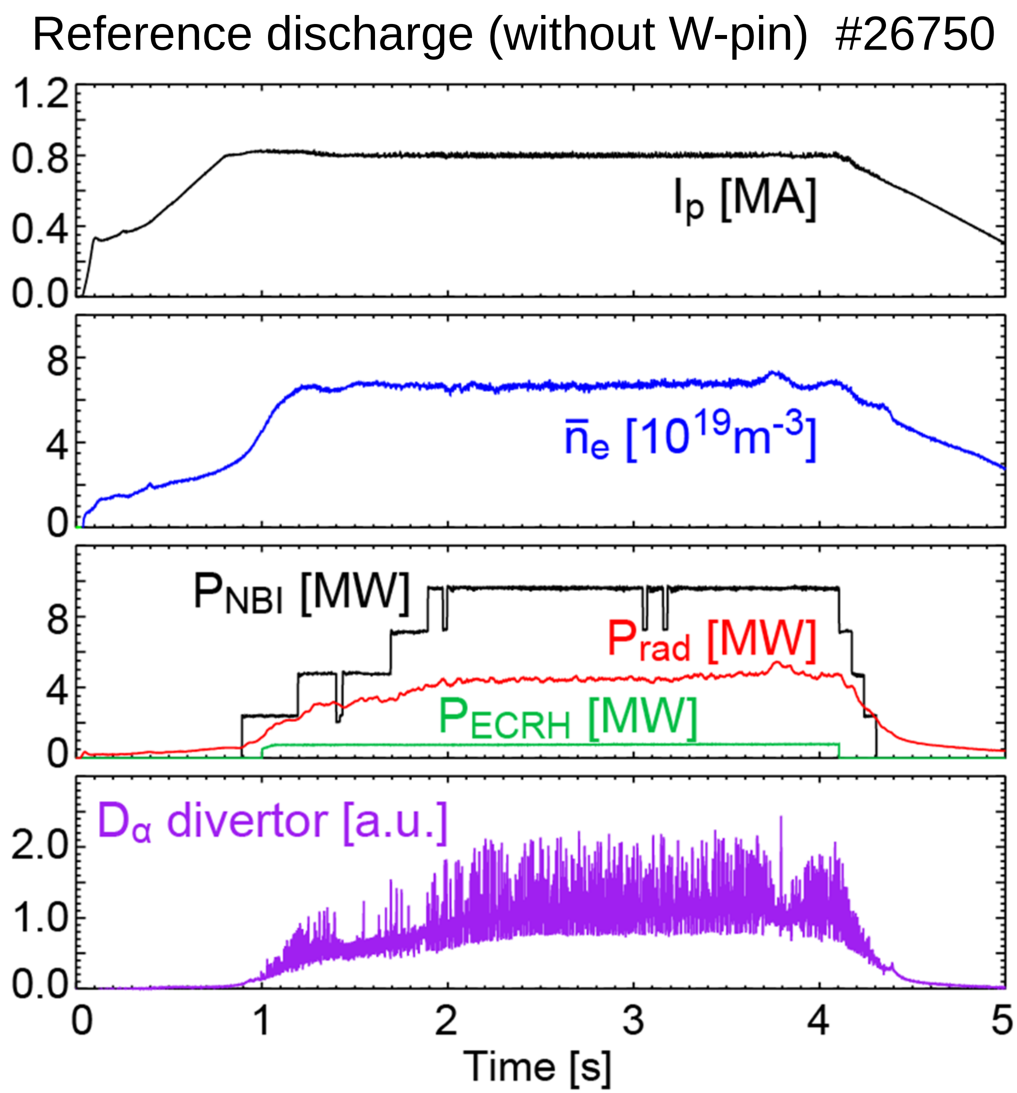
➩ Experimental input to assess potential consequences for ITER tungsten divertor.

ASDEX Upgrade divertor manipulator

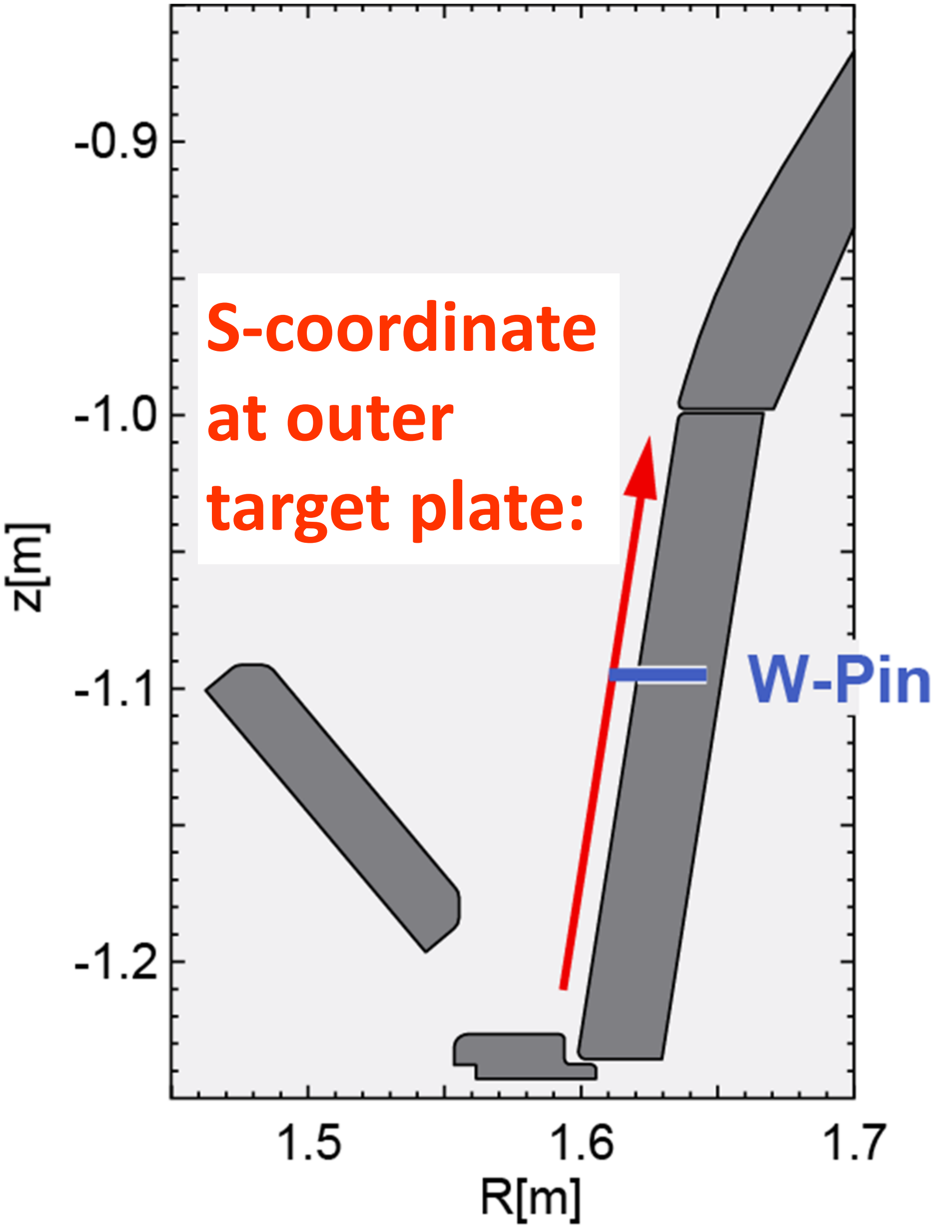


Discharge conditions

- H-mode, 0.8MA, -2.5T
- 3 experiments with variation of
  - NBI power: 6MW / 10MW
  - density: 6.5-7×$10^{19}m^{-3}$
- 0.8MW ECRH



Melting induced by OSP shift towards W-pin



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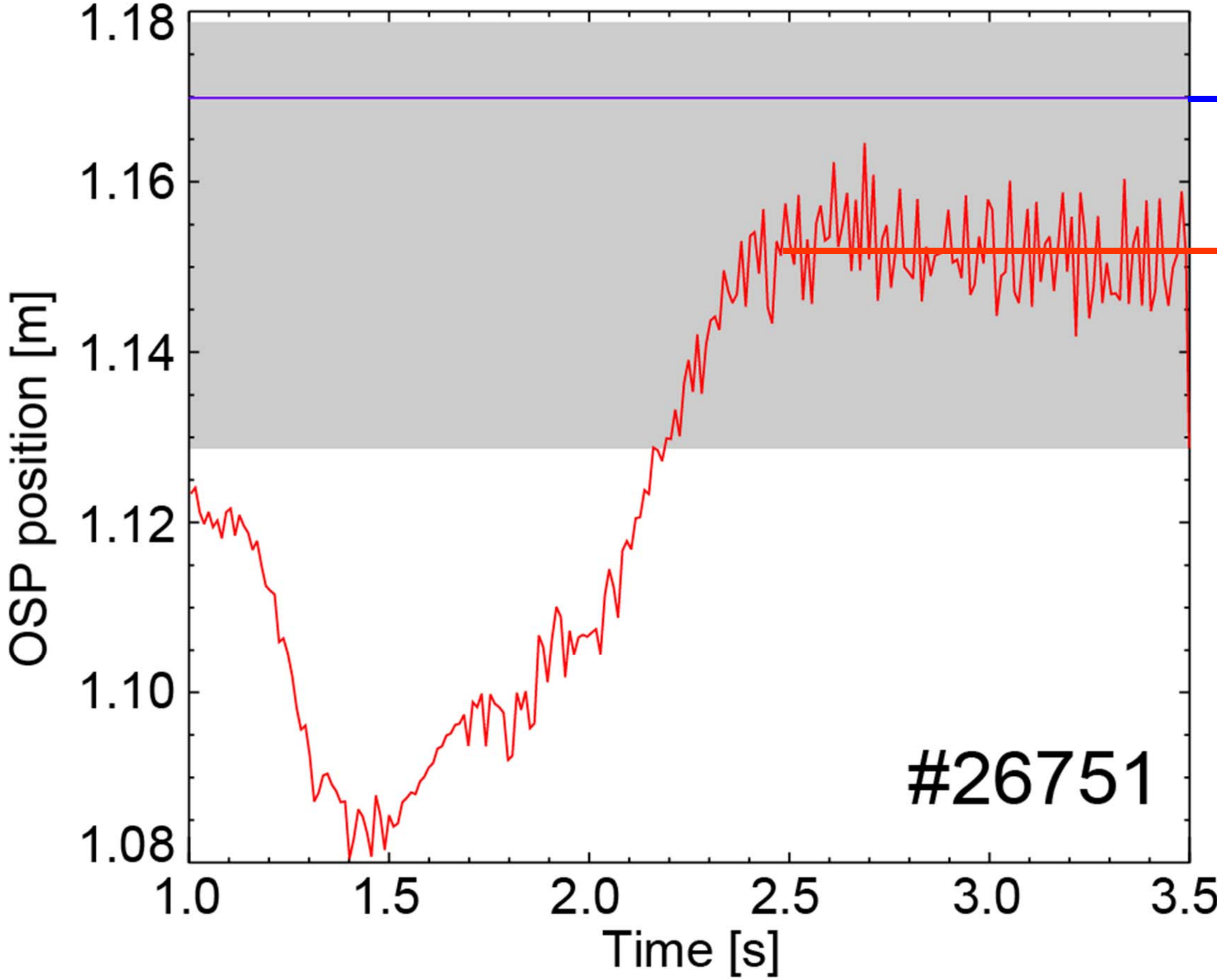

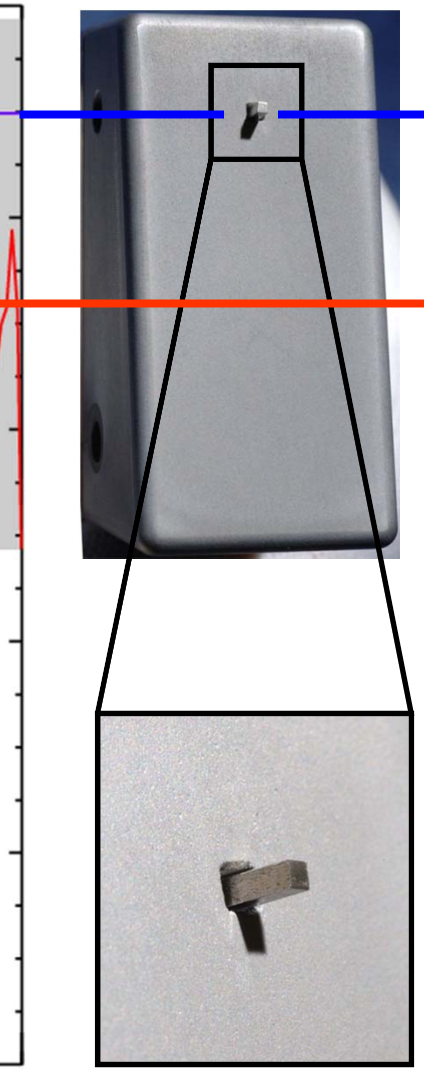

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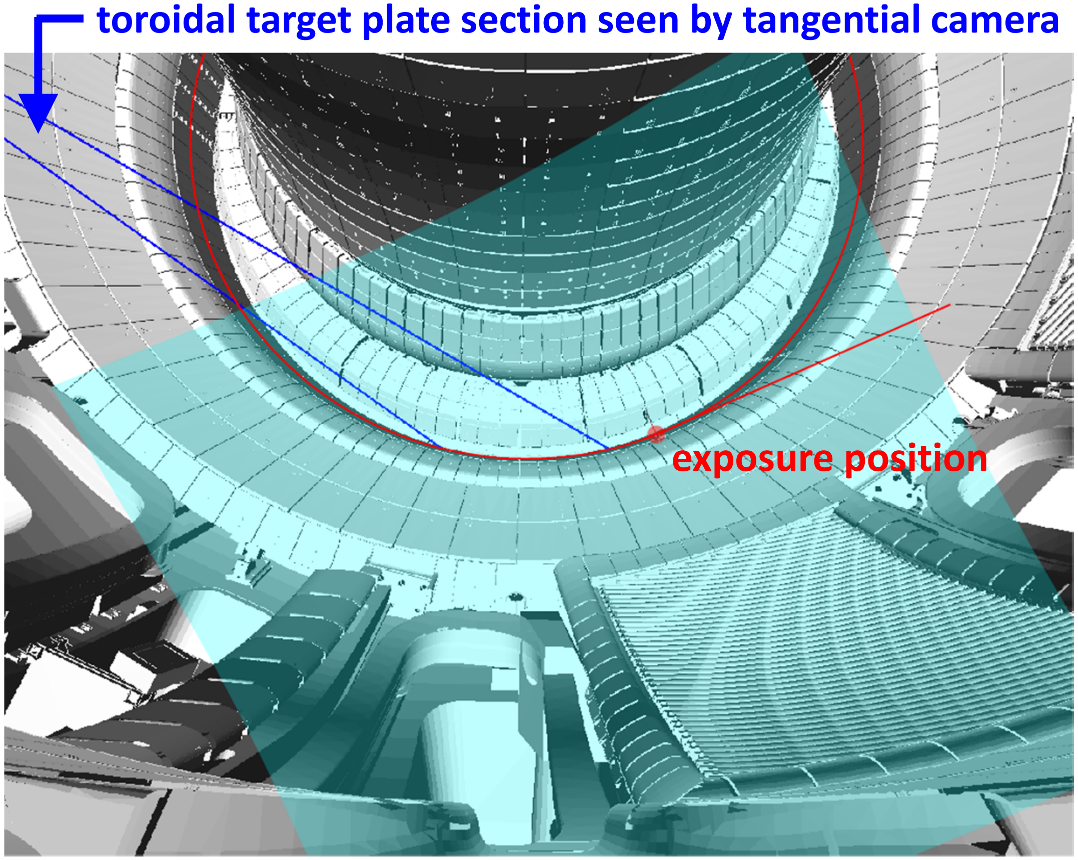
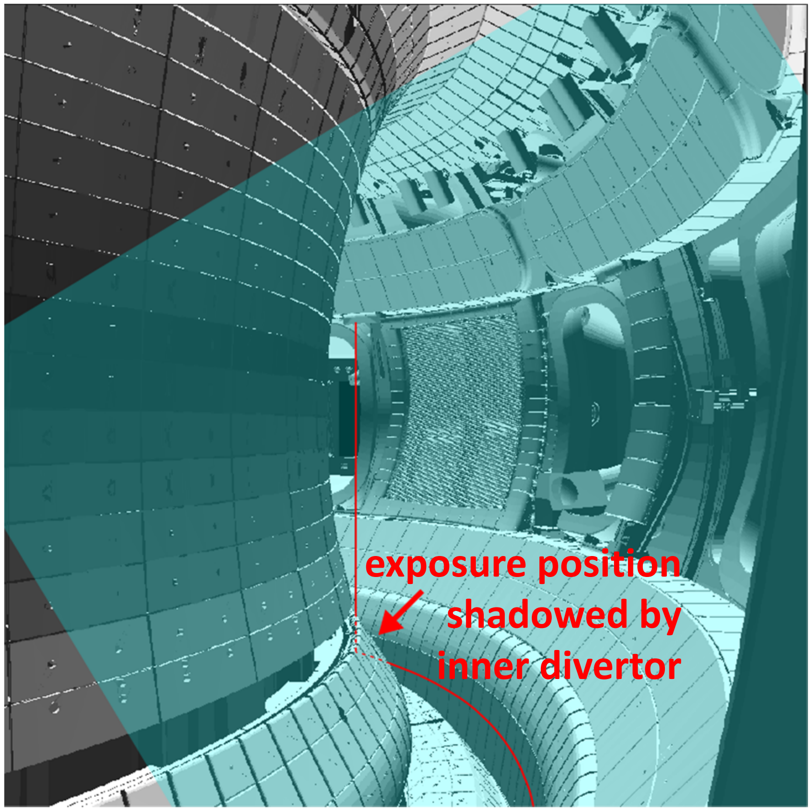
Field of view for fast cameras

View vertically down

Tangential view

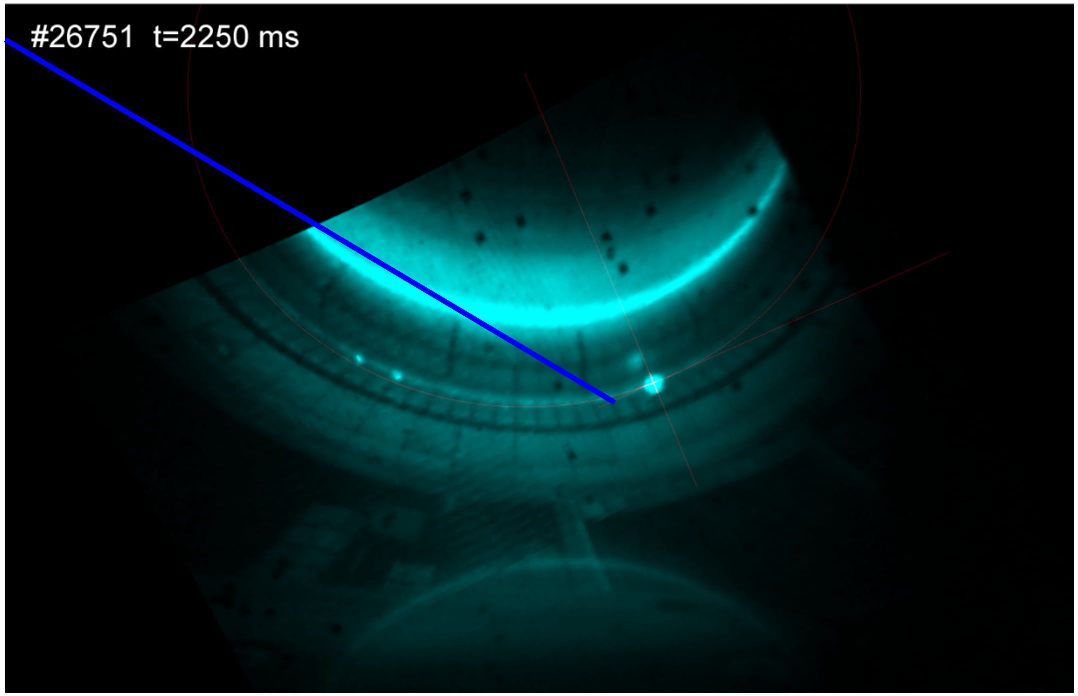




Both cameras equipped with H_α / H_β rejection filter to improve contrast

#26751 - Time sequence from 2.25s-2.36s, Δt=5ms

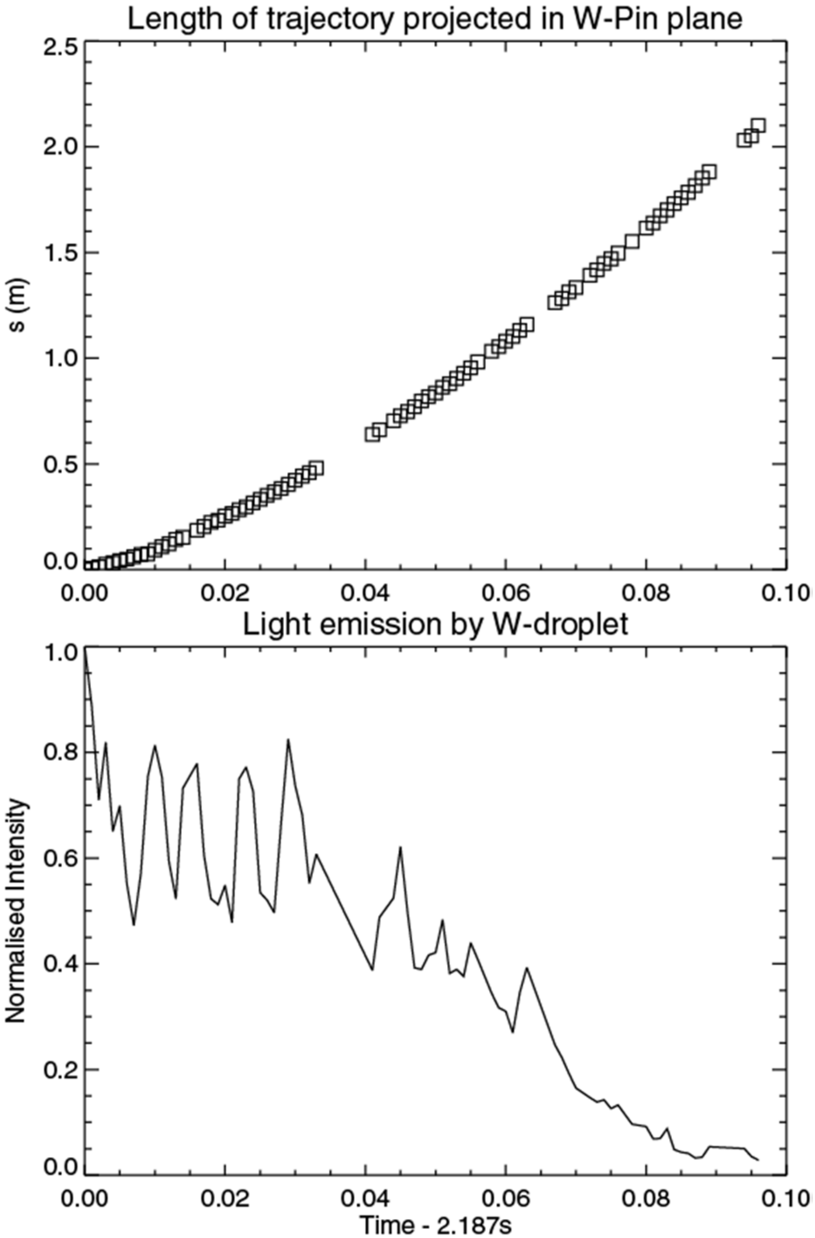
View vertically down



- ❑ Ejection of droplets into divertor plasma.
- ❑ Droplets move always downstream.
- ❑ Droplets eventually move upwards against gravity & poloidal B-field direction.

Tangential view

Droplet motion

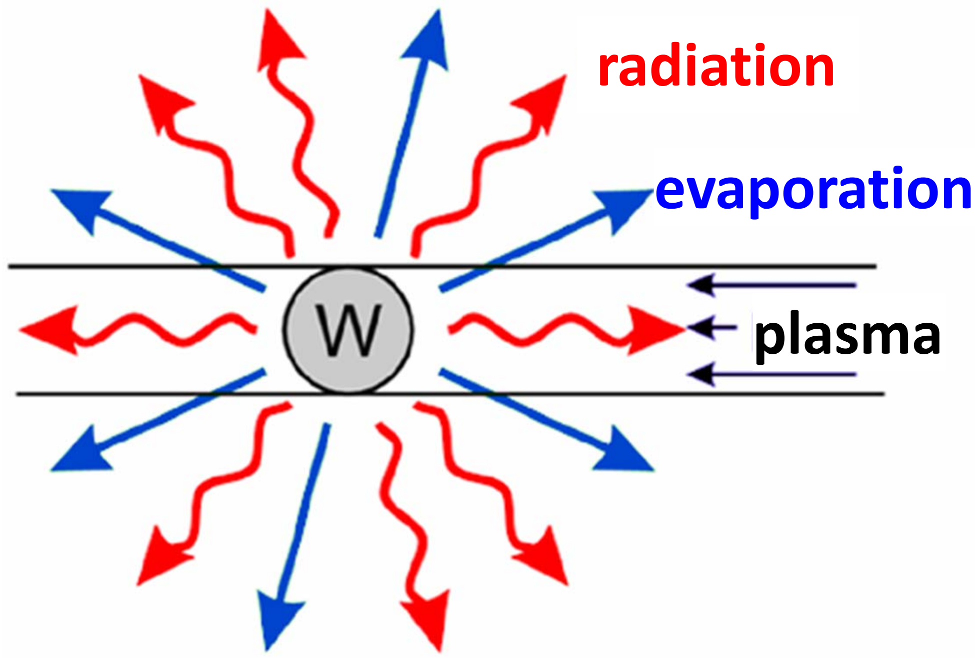


- ❑ **Droplet acceleration decreasing over time.**
- ❑ **Average acceleration ≈ *400m/s*^{2}.**

- ❑ **Light emission modulated by ELM impact.**
- ❑ **Intensity decreases over time:**
  - **Evaporation.**
  - **Droplets move to cooler regions.**

Droplet evaporation model

Power flux to droplet leads to
evaporation and thermal radiation.

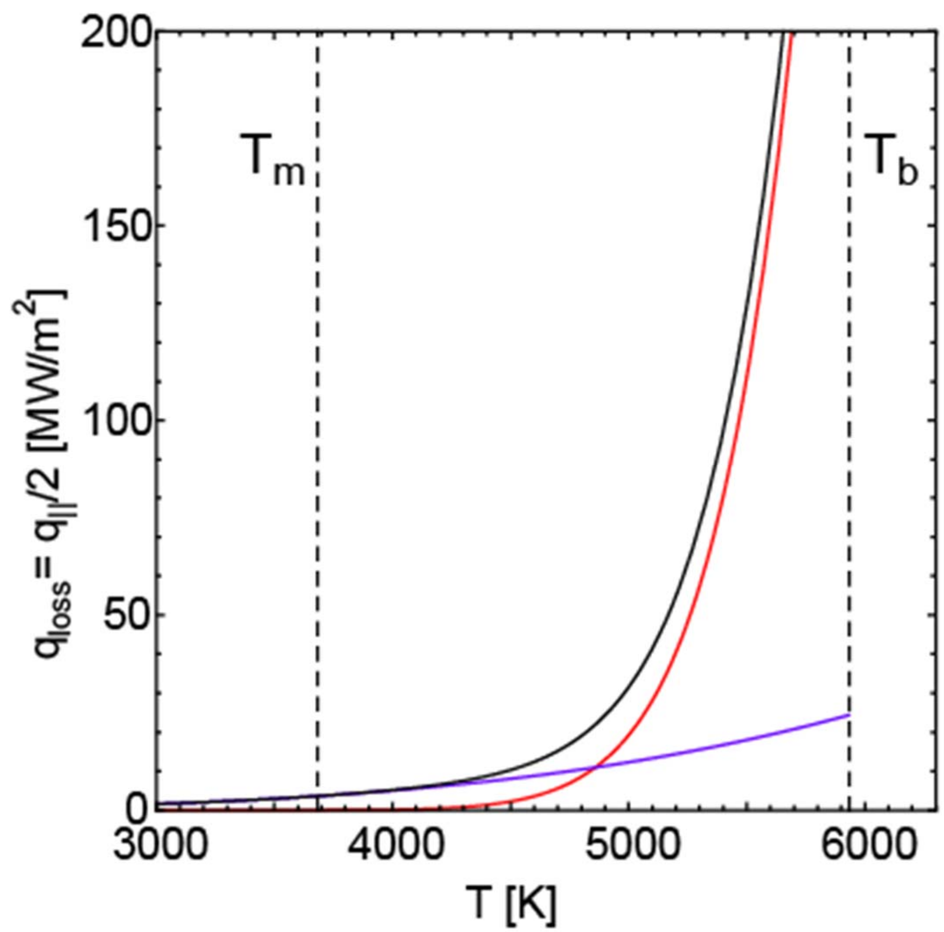


Droplet evaporation model

Power flux to droplet leads to
evaporation and thermal radiation.

$$\frac{1}{2}q_{\|} = \Gamma_{vap}\frac{\Delta H_{vap}}{N_A} + \varepsilon_T \sigma T^4$$

$$\Gamma_{vap} = \frac{p_m e^{-\frac{\Delta H_{vap}}{N_A k_B}\left(\frac{1}{T}-\frac{1}{T_m}\right)}}{\sqrt{2\pi m_W k_B T}}$$



- **Power flux balance determines droplet temperature.**
- **T does not depend on radius.**

Droplet life time

Time evolution of droplet evaporation

$$\frac{dN_W(t)}{dt} = \frac{d}{dt}\left(\rho_W \frac{4\pi}{3} r^3(t)\right) = -4\pi r^2(t)\Gamma_{vap}(t)$$

⇩

$$\frac{dr(t)}{dt} = -\frac{1}{\rho_W}\Gamma_{vap}(t)$$

Life time at constant power flux $\tau = r_0\,\rho_W \big/ \,\overline{\Gamma}_{vap}$

$$r(t) = r_0 - \frac{1}{\rho_W}\int_0^t \Gamma_{vap}(t')dt'$$

Evaporated fraction *f* assuming Δm=20 mg ejected as *k* droplets using plasma parameters @ OSP

k	**1**	**10**	**100**
τ (s)	**3.07**	**1.42**	**0.66**
f	**0.09**	**0.20**	**0.39**

τ >> 100 ms typical time along flight trajectories

Forces on the droplets I

Toroidal acceleration mainly due to plasma friction and droplet ablation.

Typical values for strike point plasma conditions and 10µm droplet radius: a_{abl}=50m/s², a_p=400m/s².

$$a_{abl} = \frac{F_{abl}}{m} \approx \frac{3}{4\sqrt{2\pi m_W} \rho_W} \Delta p_{vap}(q_\parallel)$$

$$a_p = \frac{F_p}{m} \approx \frac{1}{4 m_W \rho_W} \frac{n_e (kT_e + kT_i)}{r}$$

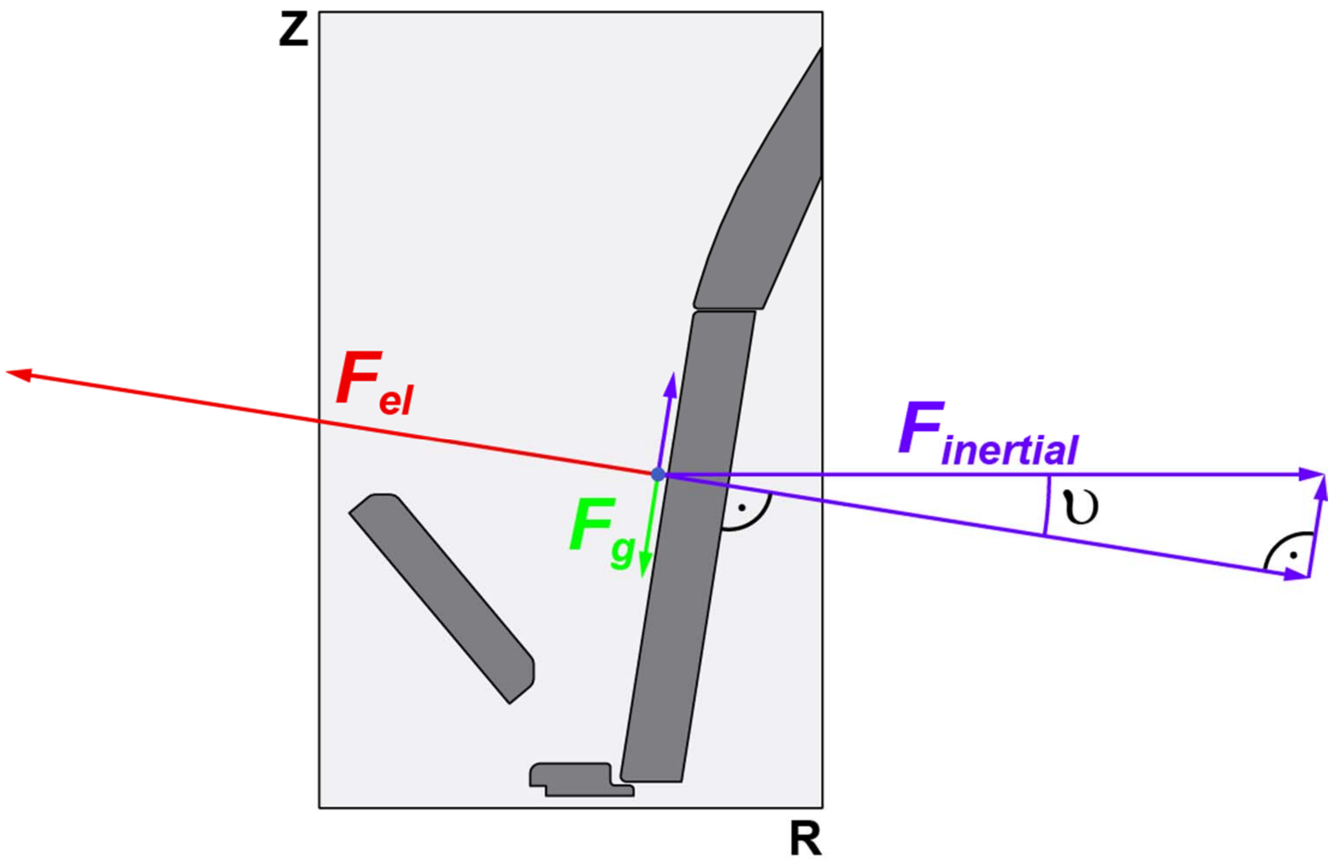
S. I. Krasheninnikov et al., Phys. of Pl. 11 (2004) 3141.

Forces on droplets II

$$\frac{F_{el}}{m} = \frac{QE}{m} \approx \frac{9\varepsilon_0}{m_W \rho_W} \frac{T_e E(d)}{r^2} \triangleq \frac{v_t^2}{R} \cos \upsilon + g \sin \upsilon$$

Droplets glide over target plate surface due to electro-static repelling force in magnetic pre-sheath.

Vertical motion is determined by components of zentrifugal force and of gravity force along target plate.



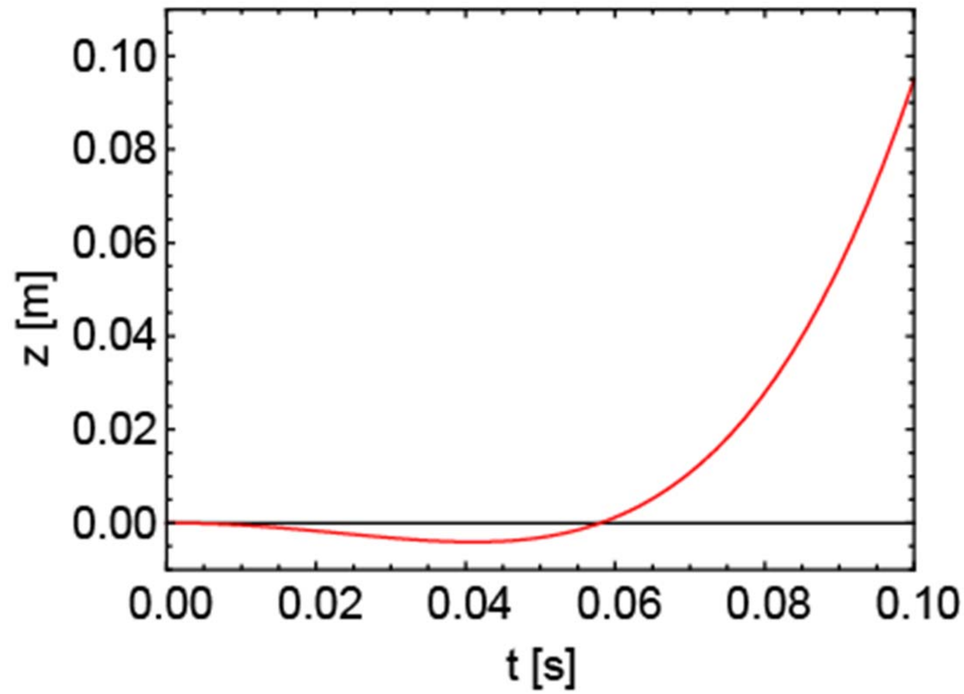
Forces on droplets II

Vertical motion is determined by balance of vertical component of zentrifugal force and gravity force:

$$a_z(t) = \frac{v_t^2(t)}{R}\sin\vartheta - g\cos\vartheta$$

$$v_t(t) = a_t t$$

Time evolution of vertical distance from origin for measured tangential droplet acceleration:



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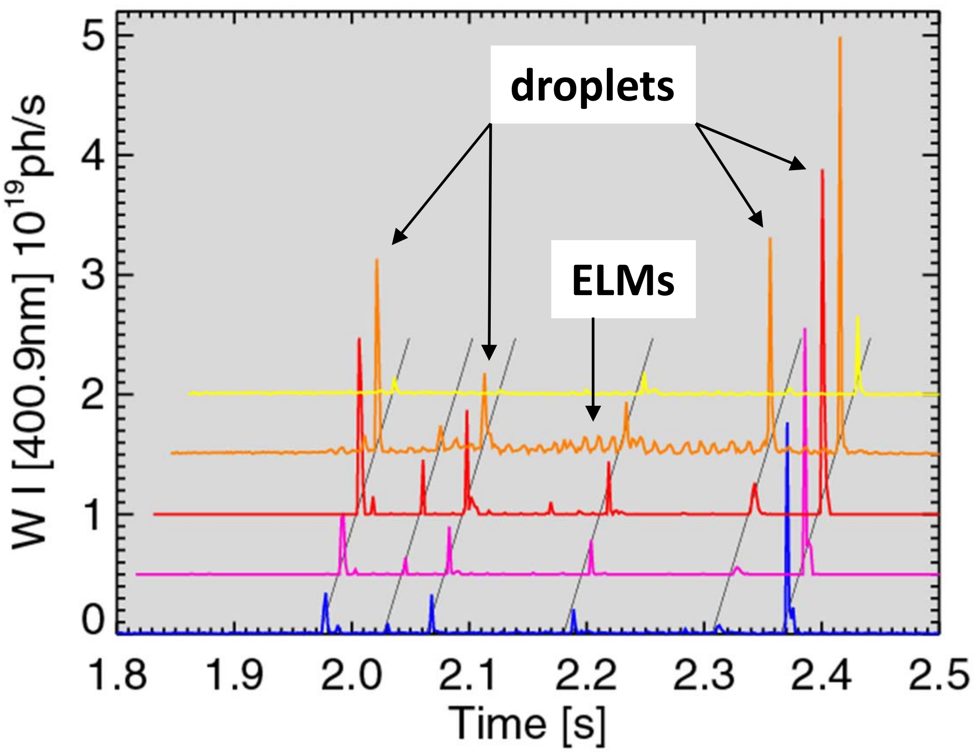
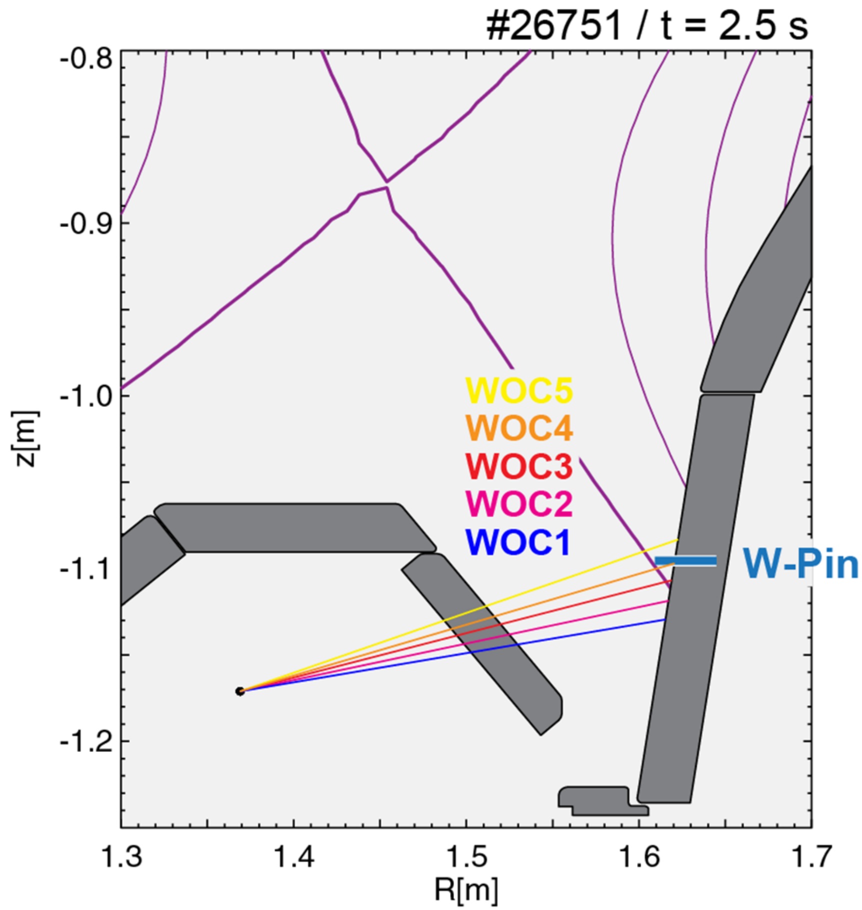
Local tungsten source at W pin

Each droplet ejection leads to a short increase of the local W source.

The W-pin is in addition eroded by ELMs.





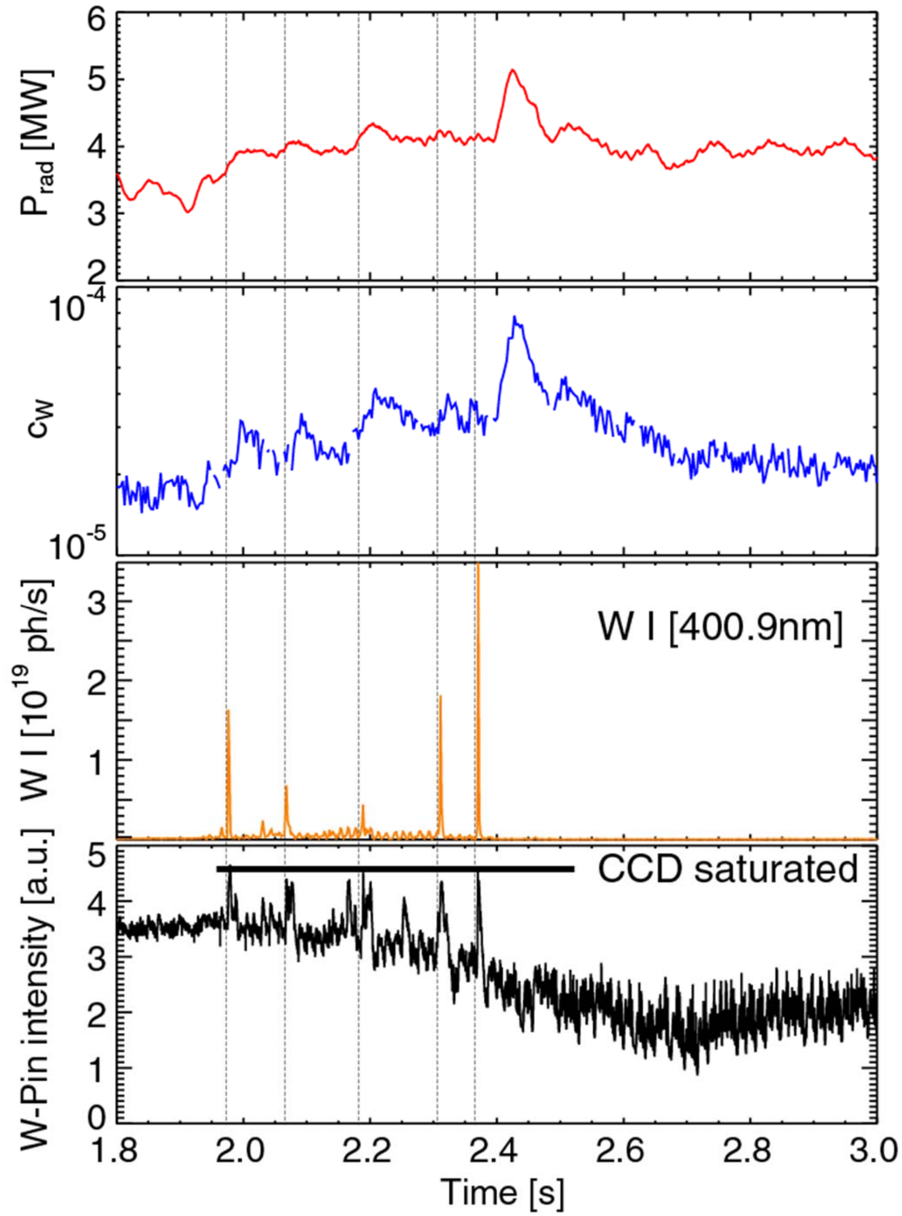
Resulting W contamination of confined plasma

In a 0D model the number of tungsten ions inside separatrix, N_W, is linked to W source, Φ, particle confinement time, τ_W and source screening factor, *S*.

$$\frac{dN_W(t)}{dt} = \bar{\Phi}_W^{core} + \frac{\Phi_W(t)}{S} - \frac{N_W(t)}{\tau_W}$$

From the measured evolution of c_W and the W divertor source one can derive the divertor screening factor.

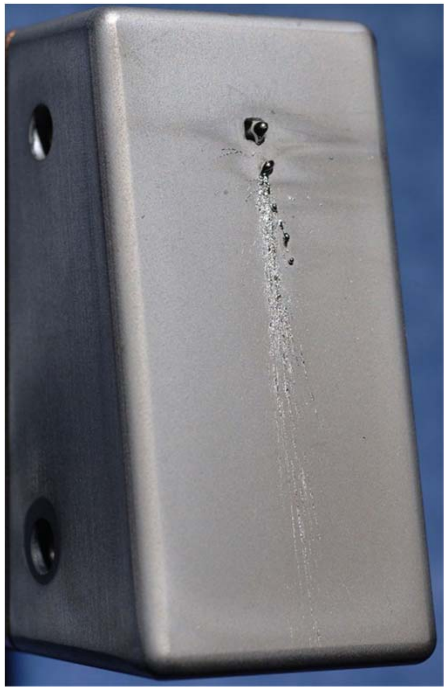
$$\int_{t_0}^{t_1} \frac{\Phi_W(t)}{S} dt = \frac{1}{\tau_W} \int_{t_0}^{t_1} \left(N_W(t) - \bar{N}_W \right) dt$$



Molten remains after exposure

Before exposure

#25514 / P_{NBI}=6MW



- ❑ Deviation from vertical in direction of plasma flow.
- ➩ Droplets accelerated in plasma.
- ❑ Molten W dripping down welds to W-layer on graphite body of sample.
- ❑ Mass loss without local deposits
  Δm=20.6mg @6MW #25514
  Δm= 9.3mg @10MW #25623
  Δm=16.5mg @10MW #26751

W divertor retention

Evaporation based on vapour pressure and balance between heating by || power flux and cooling by black-body radiation and evaporation heat during 100ms residence time ⇨
30% of lost pin mass.

Relate this number to W throughput in confined plasma ⇨

S_{div} ≈ 120 (#26751), 165 (#25623), 200 (#25514)

Comparing to SOL screening factor from laser ablation, S_{SOL}≈11 ⇨

Divertor retention factor ≈ 10-20 comparable to result from $W(CO)_6$ injection studies (Geier et al., Plasma Phys. Contr. Fusion 44 (2002) 2091).

Summary

- W droplets ejected by melt events at a target plate can survive travelling through the plasma over distances of several meters toroidally.
- Vertical inclination of target plates causes ejected droplets to travel upwards.
- Penetration of evaporated W fraction to confined plasma comparable to that of tungsten sputtered at the target plate.