SPD.1 (D006): Semi-empirical analytic description of emitted current escaping from W surfaces

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Motivation and deliverable

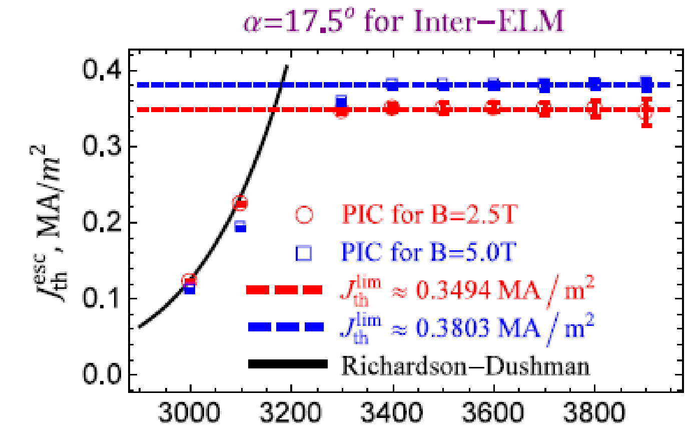
❑Comprehensive PIC simulations of magnetized plasma sheaths in presence of intense thermionic emission (TE) revealed that the strict limitation of the escaping thermionic current is a global characteristic of the space-charge limited regime irrespective of the magnetic field inclination angle (see first figure).

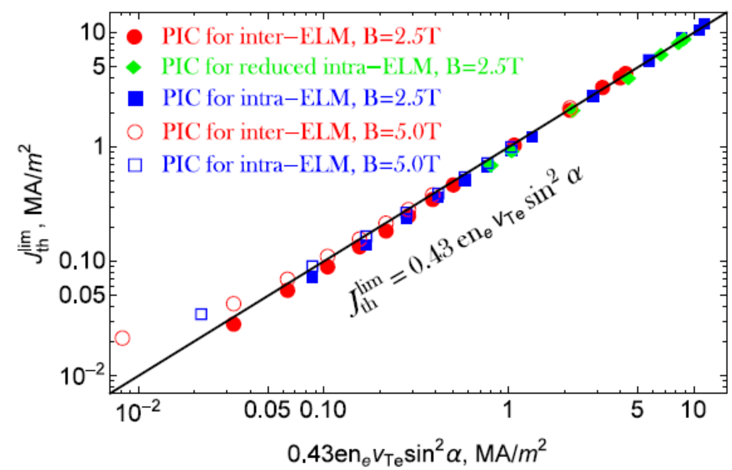
❑An accurate and physically transparent semi-empirical expression has been identified that describes the dependence of the limited thermionic current on the plasma conditions, magnetic field strength and inclination angle (see second figure).

❑The expression is valid within a broad parameter space that corresponds to the inter- & intra-ELM plasmas of contemporary devices and to non-grazing incidence ($\alpha > 5^{o}$). It is valid for any conducting material, despite being acquired from W simulations, since the TE energy distribution is work-function independent.

❑The expression has been implemented in the MEMOS-U code; the escaping current determines the replacement current which leads to the volumetric Lorentz force that drives melt motion [Thoren, Ratynskaia, Tolias & Pitts, PPCF **63**, 035021 (2021)]

❑In the hot intra-ELM ITER plasmas, the emissive sheath regime is much more complicated. Investigations for normal and variable inclination angles are missing.



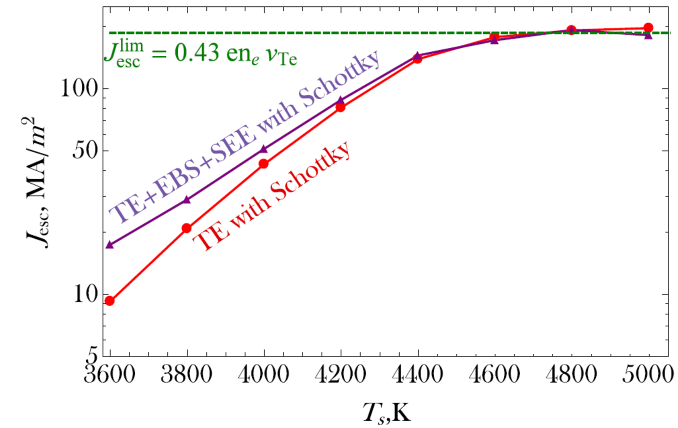


Komm, Ratynskaia, Tolias *et al.* PPCF **59** 094002 (2017)
Komm, Tolias, Ratynskaia *et al.* Phys. Scr. **T170** 014069 (2018)
Komm, Ratynskaia, Tolias & Podolnik, NF **60** 054002 (2020)

Key results in 2020

To properly describe the emissive sheaths that surround hot surfaces during ITER ELMs, PIC codes need to be equipped with state-of-the-art electron emission models. Such a model has been implemented in the SPICE2 2D3V code and comprises of analytical expressions for

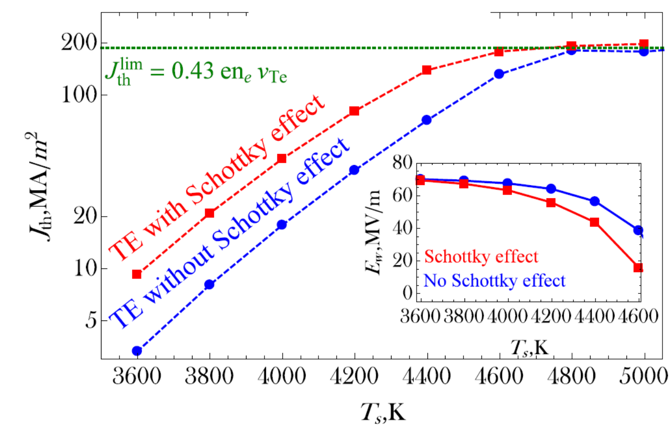
- ✓ the electron current emitted due to field-assisted thermionic emission in the extended Schottky regime
- ✓ the incident energy and angle dependence of the SEE, EBS W yields
- ✓ the energy and angular distributions of the 3 groups of emitted electrons



PIC results for the escaping emitted current as a function of the surface temperature for ITER IVT ELM conditions. The importance of SEE+EBS is evident.

The first PIC simulations confirmed the theoretical expectations for the origin/nature of the emitted current that escapes hot surfaces during ITER ELMs. Focus on normal B-field inclinations (leading edge). [Tolias, Komm, Ratynskaia & Podolnik, NME **25**, 100818 (2020)]

- ✓ Due to the strong incident plasma currents, the transition to the space-charge limited regime occurs at unrealistically high surface temperatures. **Thermionic emission is generally not suppressed by space-charge effects.**
- ✓ Due to the intense normal wall electrostatic fields, contributions from classical barrier escape are comparable to those from quantum tunnelling. **Thermionic emission is weakly coupled with field emission.**
- ✓ Due to the high electron temperatures and strong incident electron currents, contributions from electron-induced electron emission are as important as thermionic emission at the W melting point. Overall, **both SEE and EBS contribute substantially.**



PIC results for the escaping thermionic current as function of the surface temperature for ITER IVT ELM conditions. The importance of the Schottky effect is evident.

Analytical expressions of escaping currents should be developed for implementation in codes

New results in 2021 (effective SEE yield)

Simple strategy

For given sheath potential drop, TE cannot not affect SEE even when a virtual cathode forms (the VC depth is of the order of the TE energy and cannot affect the 10x more energetic SEs).

Perform PIC simulations for varying electron temperatures in the absence of TE and extract the average SEE yield from the ratio of emitted over incident e^{-} current → 16 SPICE2 2D3V simulations for $T_{\mathrm{e}} = 500 - 2000\mathrm{eV}$ and $n = 2.9 \times 10^{20}\mathrm{m}^{-3}$

Compare PIC result with the simple theoretical result

$$\langle\delta\rangle = \frac{\int v_x f_e(v)\delta(E,\cos\theta)\, d^3v}{\int v_x f_e(v)\, d^3v} \Rightarrow (\mathrm{Maxwellian})$$

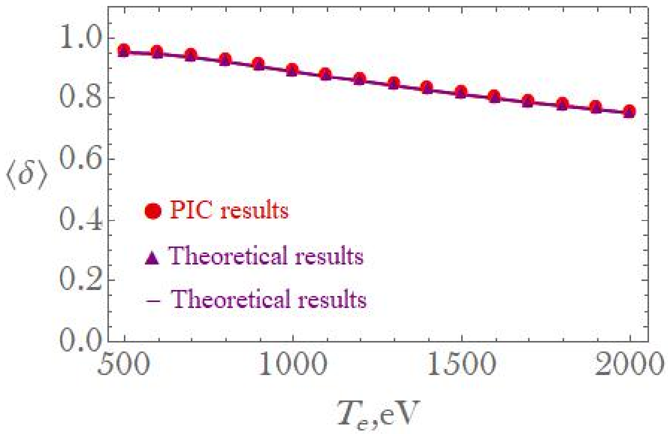
$$\langle\delta\rangle = 2\int_0^{\infty} z e^{-z}\left\{\int_0^1 \delta(T_e z, s) s ds\right\} dz$$

0.08% mean deviations and 0.14% max deviations → Near perfect agreement, but double integral is costly for codes like MEMOS-U

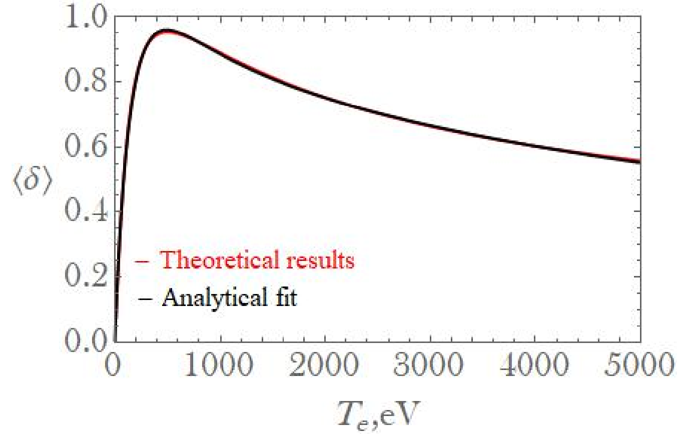
Fit theoretical result to a simple analytical function with a single maximum: calculate $\langle\delta\rangle$ for 500T_{e}s within $T_{\mathrm{e}} = 10 - 5000\mathrm{eV}$, then fit dataset to $\langle\delta(T_{\mathrm{e}})\rangle = a\left(T_{\mathrm{e}}^{b} + cT_{\mathrm{e}}^{d}\right)[1 - \exp(-fT_{\mathrm{e}})]$ with a, b, c, d, f the fitting parameters and T_{e} in eV.

$\langle\delta(T_{\mathrm{e}})\rangle = 2.089(T_e^{-0.0628} - 0.0461T_e^{0.228})[1 - \exp(-0.0058T_{\mathrm{e}})]$

perfect fit with 0.47% avg deviations from the exact result.



Comparison of PIC simulations with simple theory for the average SEE yield in the $T_e = 500 - 2000eV$ range



Comparison of the full theoretical expression for the average SEE yield with a simple analytical fit in the $T_e = 10 - 5000eV$ range

New results in 2021 (effective EBS yield)

Simple strategy

For given sheath potential drop, TE cannot not affect EBS even when a virtual cathode forms (the VC depth is of the order of the TE energy and cannot affect the 100-1000x more energetic BSEs).

Perform PIC simulations for varying electron temperatures in the absence of TE and extract the average EBS yield from the ratio of emitted over incident e^{-} current → 16 SPICE2 2D3V simulations for $T_{\mathrm{e}} = 500 - 2000\mathrm{eV}$ and $n = 2.9 \times 10^{20}\mathrm{m}^{-3}$

Compare PIC result with the simple theoretical result

$$\langle \eta \rangle = \frac{\int v_x f_e(v) \eta(E, \cos\theta)\, d^3v}{\int v_x f_e(v)\, d^3v} \Rightarrow (\mathrm{Maxwellian})$$

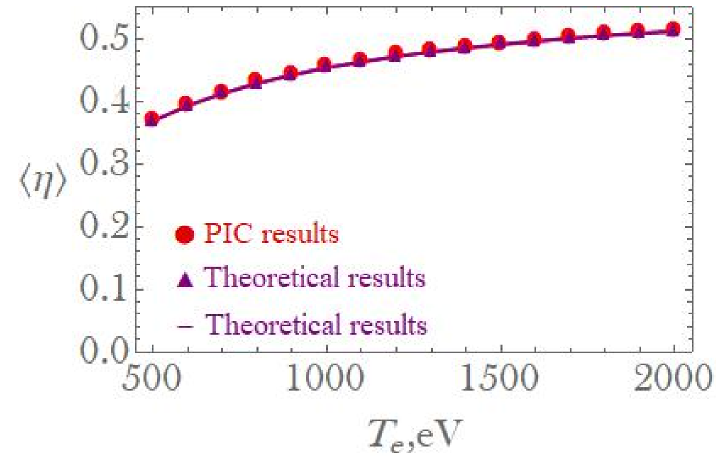
$$\langle \eta \rangle = 2\int_0^{\infty} z e^{-z} \left\{ \int_0^1 \eta(T_e z, s) s ds \right\} dz$$

0.11% mean deviations and 0.22% max deviations → Near perfect agreement, but double integral is costly for codes like MEMOS-U

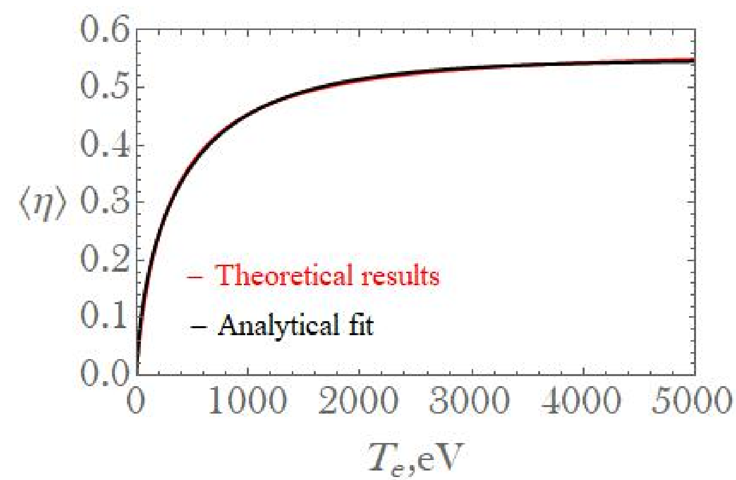
Fit theoretical result to a simple analytical function with a half-sigmoid behavior: calculate $\langle \eta \rangle$ for 500T_{e}s in $T_{\mathrm{e}} = 10 - 5000\mathrm{eV}$, then fit dataset to $\langle \eta(T_{\mathrm{e}}) \rangle = a\,[1 - \exp(-bT_{\mathrm{e}}^{c})]$ with a, b, c the fitting parameters and T_{e} in eV.

$\langle \eta(T_{\mathrm{e}}) \rangle = 0.549[1 - \exp(-0.0171 T_{\mathrm{e}}^{0.670})]$

perfect fit with 0.63% avg deviations from the exact result.



Comparison of PIC simulations with simple theory for the average EBS yield in the $T_e = 500 - 2000eV$ range



Comparison of the full theoretical expression for the average EBS yield with a simple analytical fit in the $T_e = 10 - 5000eV$ range

New results in 2021 (Schottky effect)

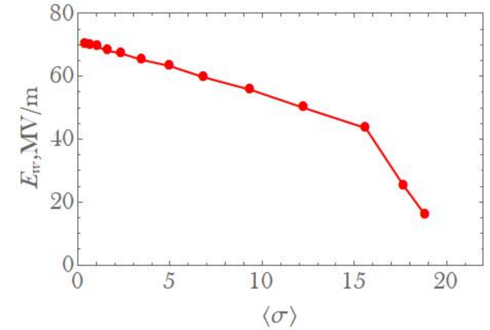
Simple strategy

The Schottky correction depends on the normal electrostatic field at the wall that should depend on the electron temperature, the Debye length and the effective electron emission yield $\langle\sigma\rangle$. No reason to complicate situation with TE+SEE+EBS, include only TE.

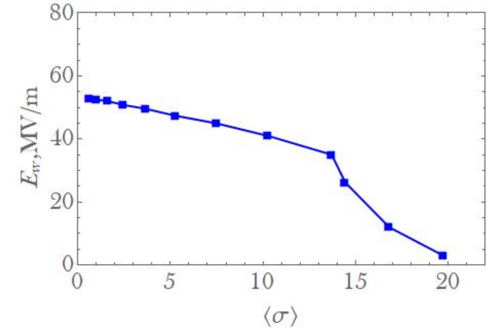
Perform PIC simulations for given electron temperature-density combinations with varying TE (through control of T_s) and extract E_w as a function of $\langle\sigma\rangle$. → 13 SPICE2 2D3V simulations for $T_e = 500\mathrm{eV}$, $n = 2.9 \times 10^{20}\mathrm{m}^{-3}$ with $T_s = 3400 - 4600\mathrm{K}$ AND 12 SPICE2 2D3V simulations for $T_e = 500\mathrm{eV}$, $n = 1.67 \times 10^{20}\mathrm{m}^{-3}$ with $T_s = 3400 - 4500\mathrm{K}$

Initial theoretical efforts have failed to reproduce the PIC results. Need for extremely accurate fit, because the Schottky correction effectively reduces the W work-function and thus there is a high sensitivity to the wall electrostatic field.

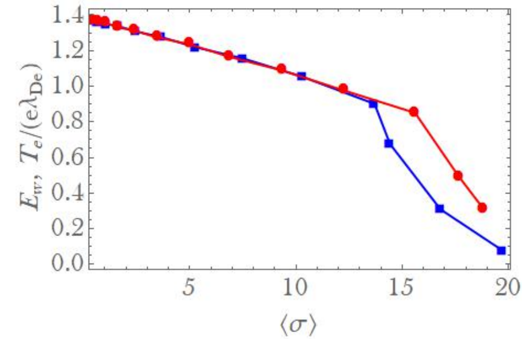
New strategy: set up the Poisson equation for sheath electrostatic potential (plasma electrons and ions, slow emitted electrons), solve numerically, try to fit with an exponential decay whose unknown coefficients are functions of $T_e, \lambda_D, \langle\sigma\rangle$, then calculate the electrostatic field at the wall → the theoretical investigation is ongoing



The PIC wall electrostatic field for $T_e = 500eV$, $n = 2.9 \times 10^{20}m^{-3}$ with $T_s = 3400 - 4600K$



The PIC wall electrostatic field for $T_e = 500\mathrm{eV}$, $n = 1.67 \times 10^{20}\mathrm{m}^{-3}$ with $T_s = 3400 - 4500\mathrm{K}$



Normalized PIC wall electrostatic field for both plasma conditions. E_w depends non-trivially on T_e, λ_D

Timeline for 2021

Comprehensive PIC simulations for normal inclination angles have been employed to construct accurate semi-empirical expressions for the escaping emitted current (as function of the plasma conditions) during ITER ELMs that can be used as input in MEMOS-U simulations. For the aforementioned regime, this necessitated

- ✓ An accurate analytical description for the (incident electron velocity distribution) averaged SEE yield – DONE
- ✓ An accurate analytical description for the (incident electron velocity distribution) averaged EBS yield – DONE
- ✓ An accurate analytical description for the normal surface electrostatic field – NEARLY DONE

Comprehensive PIC simulations for oblique inclination angles will also be performed in order to illustrate the gradual suppression of electron backscattering, secondary electron emission, thermionic emission due to prompt re-deposition. The final goal is again to construct accurate semi-empirical expressions for the escaping emitted current during ITER ELMs also as function of the inclination angle. Complications are expected due to

- ✓ the vastly different energy distributions of the three emitted electron populations which implies a different degree of suppression by prompt re-deposition
- ✓ the strong variations of the surface electrostatic field with the inclination angle (sheath + magnetic pre-sheath voltage drop) which implies a sharply diminishing Schottky effect
- ✓ the formation of a virtual cathode at lower - more realistic - surface temperatures, which implies the coexistence of two suppression mechanisms for part of the parameter space

The first PIC simulations for this task will be carried out soon. Apart from the theoretical complexities, the task requires massive simulations and has been scheduled to be completed within 2022.