Similarities between nuclear fusion reactors and space vehicles

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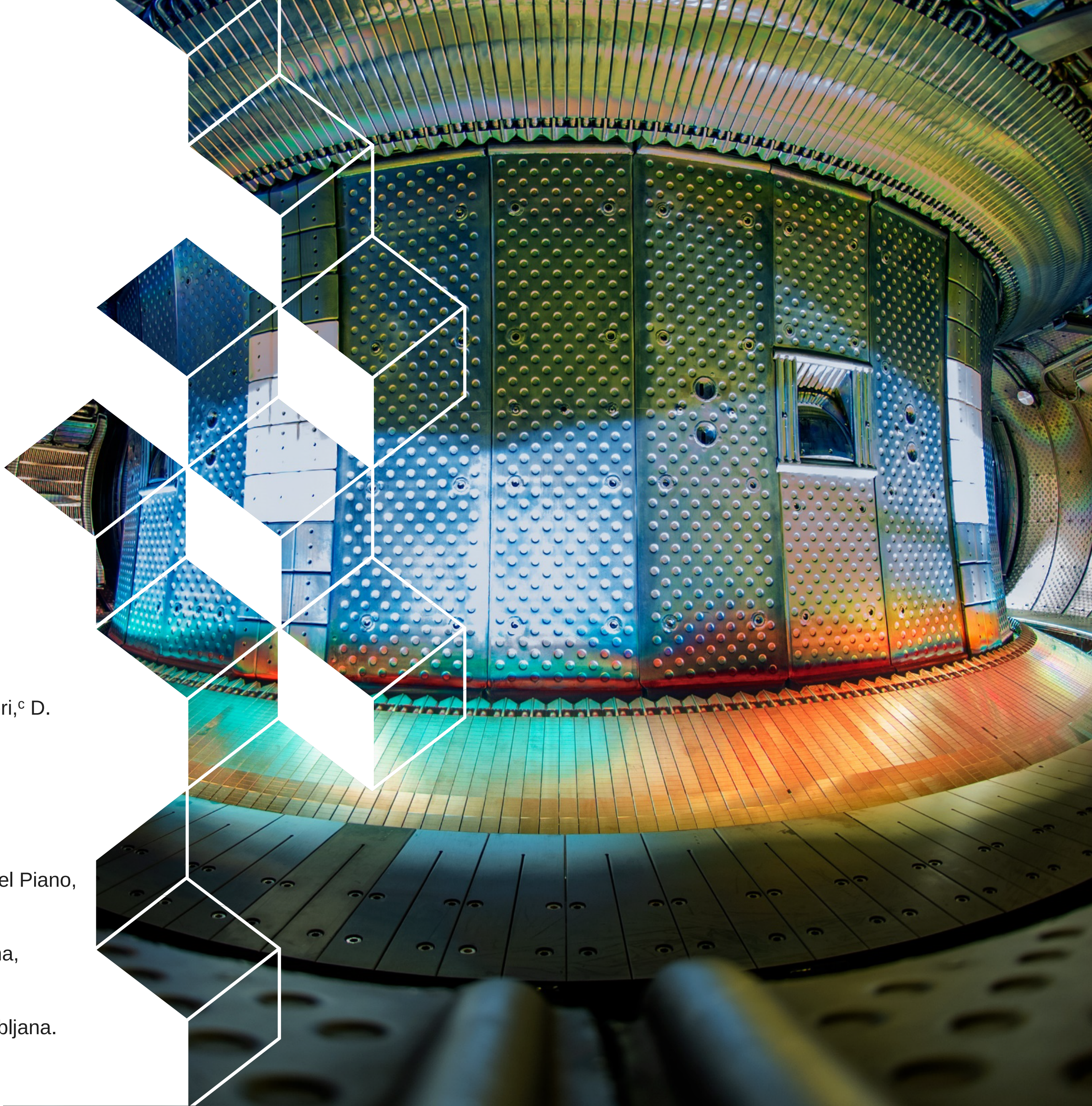


The theme of this talk

Entry of a space vehicle into a planetary atmosphere involves constraints due to friction.

This friction leads to intense heating of the vehicle.

In tokamaks, hot plasma escapes from the magnetically confined region and impinges on the walls of the vaccum vessel. The plasma particles arrive at the wall with velocities similar to those encountered by space vehicles entering an atmosphere.

Tokamaks are thus a tool on Earth able to test materials for space vehicles because of their unique loading conditions available in quasi steady state (several minutes, similar to the duration of an atmospheric entry).

The formation of a plasma around the space vehicle makes the comparison with tokamaks even more interesting. This will be the main theme of this presentation.

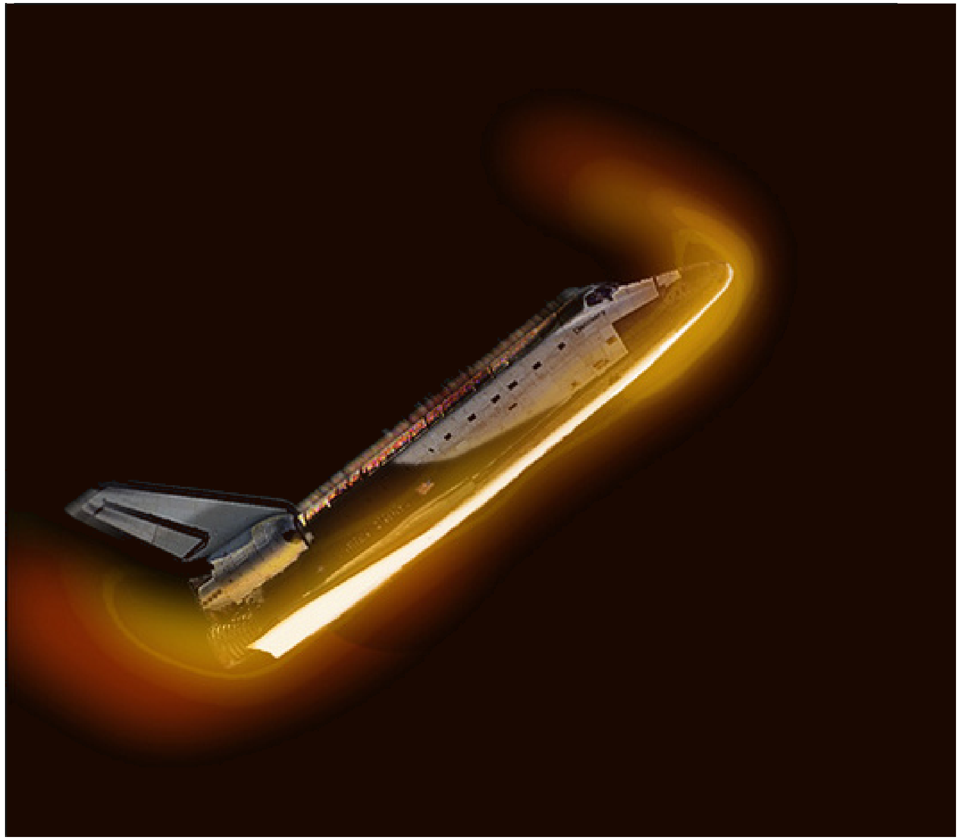
We present new results concerning thermionic emission from hot surfaces bombarded by intense plasma flux.

The similarity between fusion reactors and space vehicles (upon entry into a planetary atmosphere) resides in the particle loading conditions to which they are subjected.

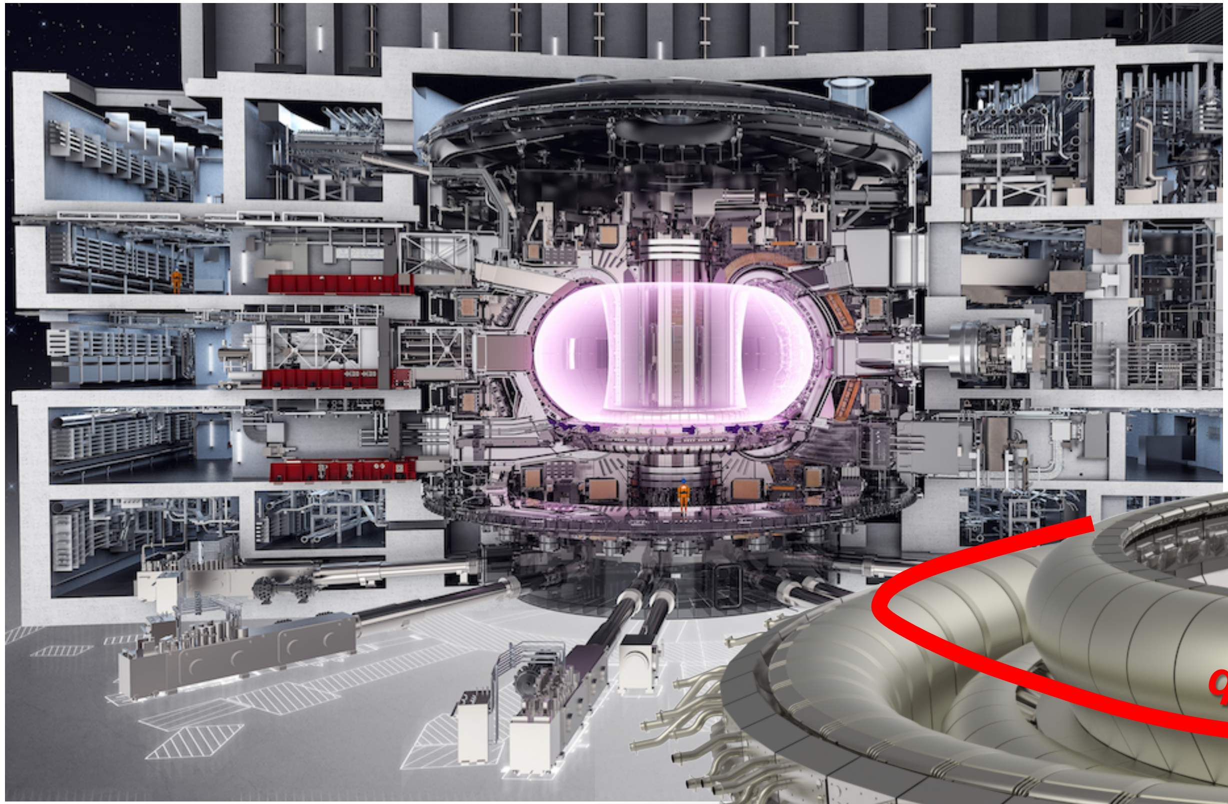
A space vehicle that enters a planetary atmosphere impacts it at high speeds (10-100 km/s)

The kinetic energy of the impact causes intense heating of the vehicle's armour, and possibly ablation, depending on the speed of the vehicle and the material used for the armour.

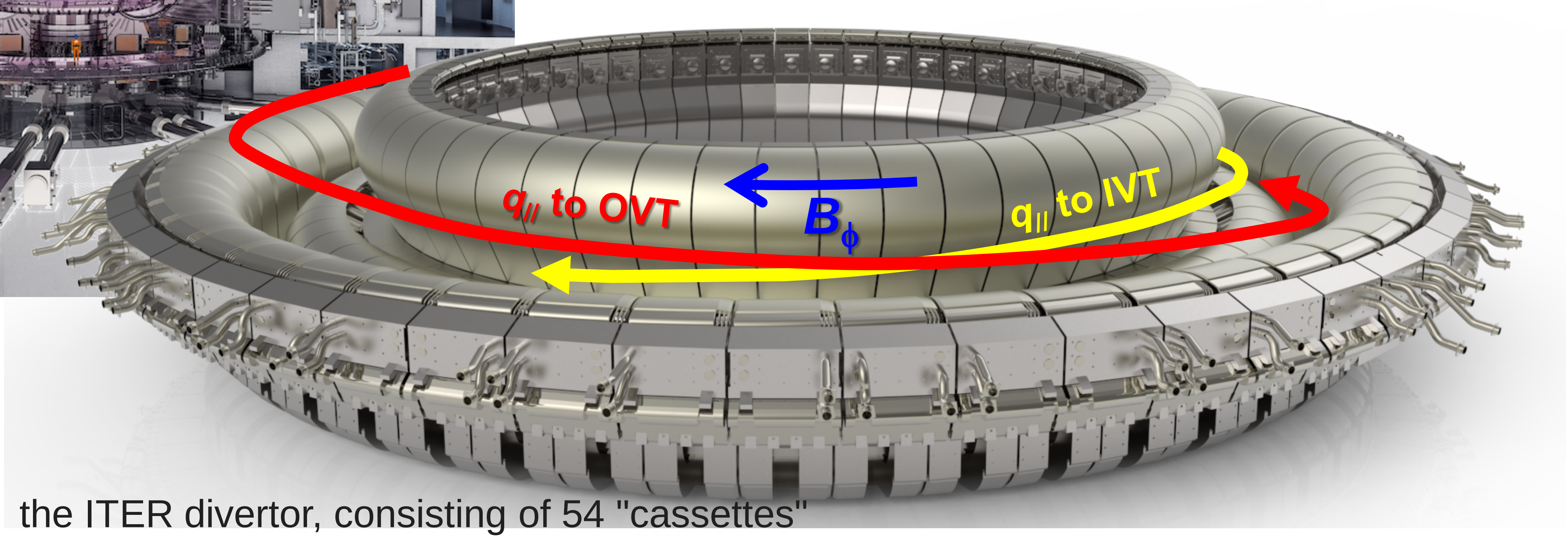
A sad example that illustrates the importance of the problem is the Columbia space shuttle. The tiles on the belly of the shuttle were carefully shaped to avoid extreme heating of exposed leading edges. One missing tile lost during launch lead, upon atmospheric re-entry, to overheating and a cascade failure of neighbouring tiles, with the horrible result we all remember.



Tokamak divertors experience similar heat flux to space vehicles entering an atmosphere at hypersonic speeds



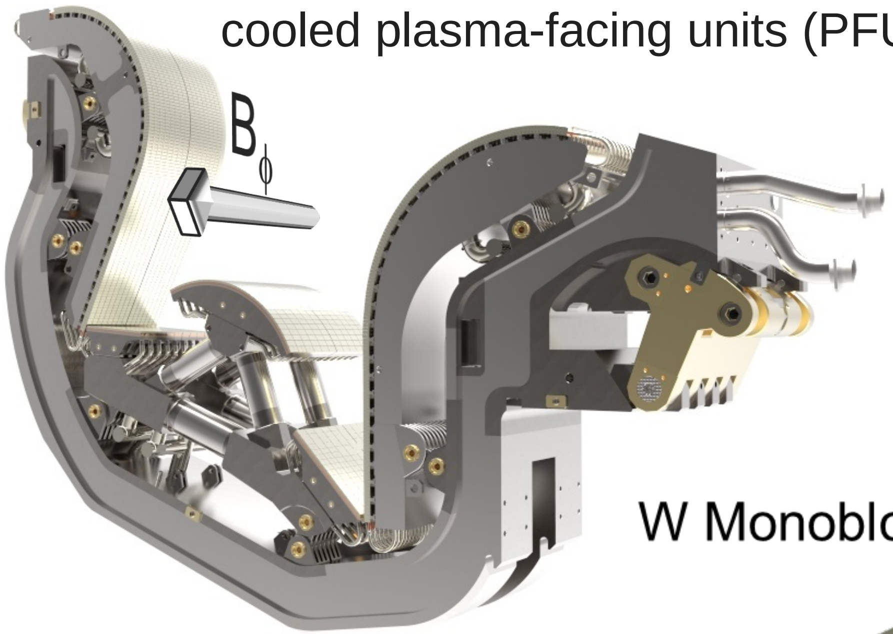
impact velocity of plasma particles upon the divertor is the same as spacecraft velocity upon atmospheric reentry (10 - 100 km/s)



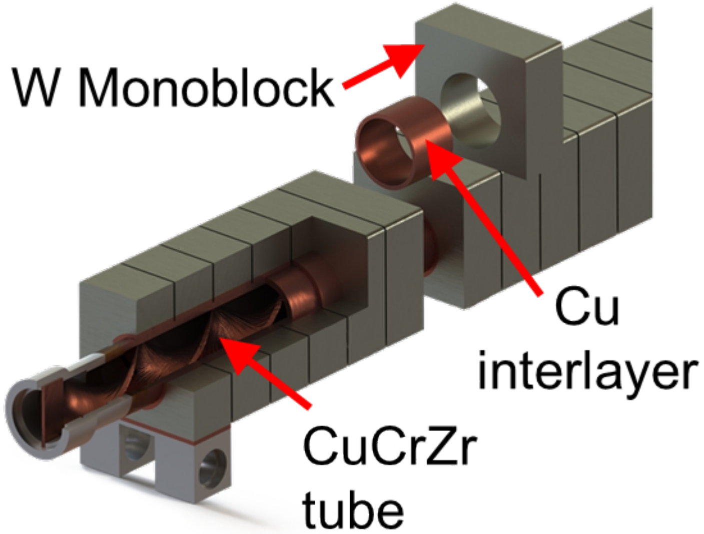
the ITER divertor, consisting of 54 "cassettes"

Similar to space vehicles, a tokamak divertor has to be carefully shaped to avoid cascade failure due to an exposed leading edge

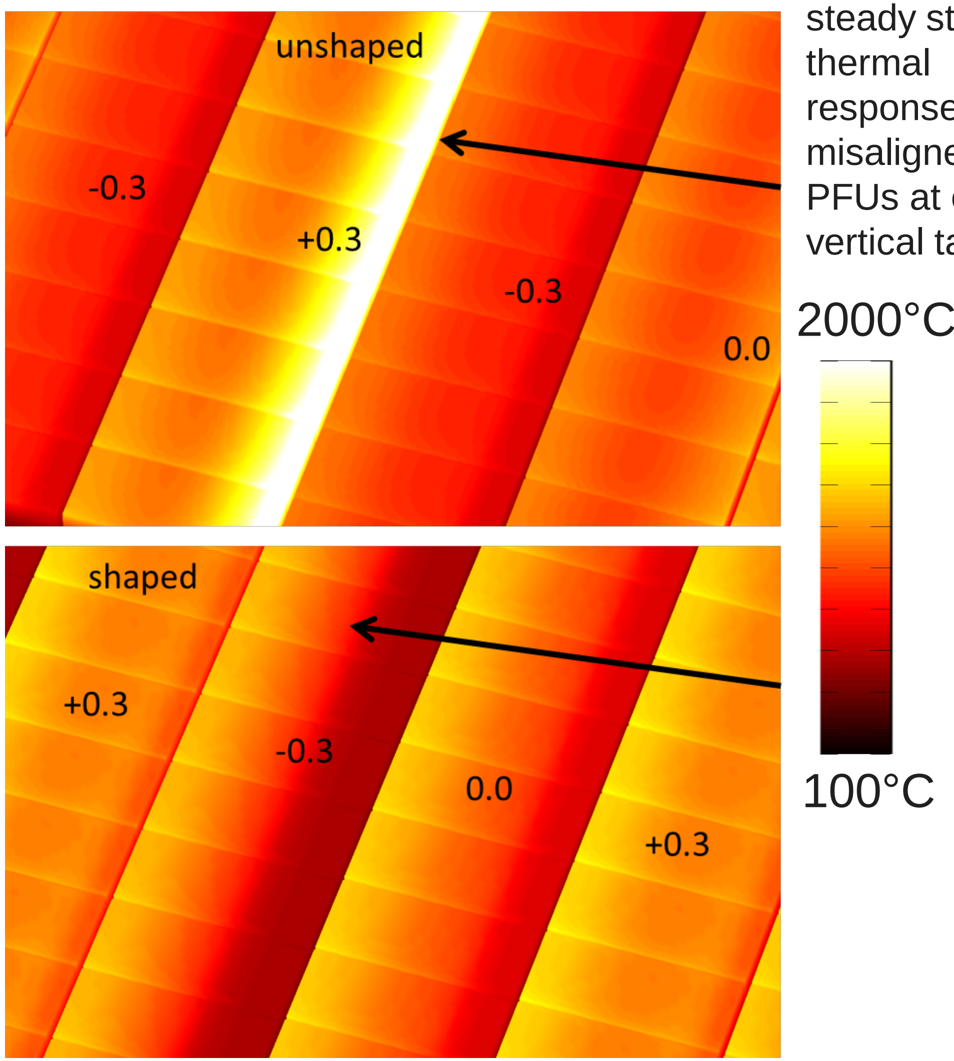
an ITER divertor cassette consisting of water-cooled plasma-facing units (PFUs)



plasma-facing surfaces are bevelled to avoid exposed leading edges



exploded view of part of a PFU



steady state thermal response of misaligned PFUs at outer vertical target

Super-heated surfaces emit electrons.
We want to understand how these emitted electrons interact with the plasma in which they are immersed

Is thermionic emission a good or a bad thing ?

Richardson-Dushman law predicts the emitted electron current density as a function of surface temperature

$$J_s = AT_s^2 exp\left(-\frac{W_f}{T_s}\right)$$

$A=6\times10^6$ A m^{-2} K^{-2} for tungsten
W_f = 4.54 eV is the work function of the metal

Herring C. and Nichols M. 1949 Rev. Mod. Phys. 21 185

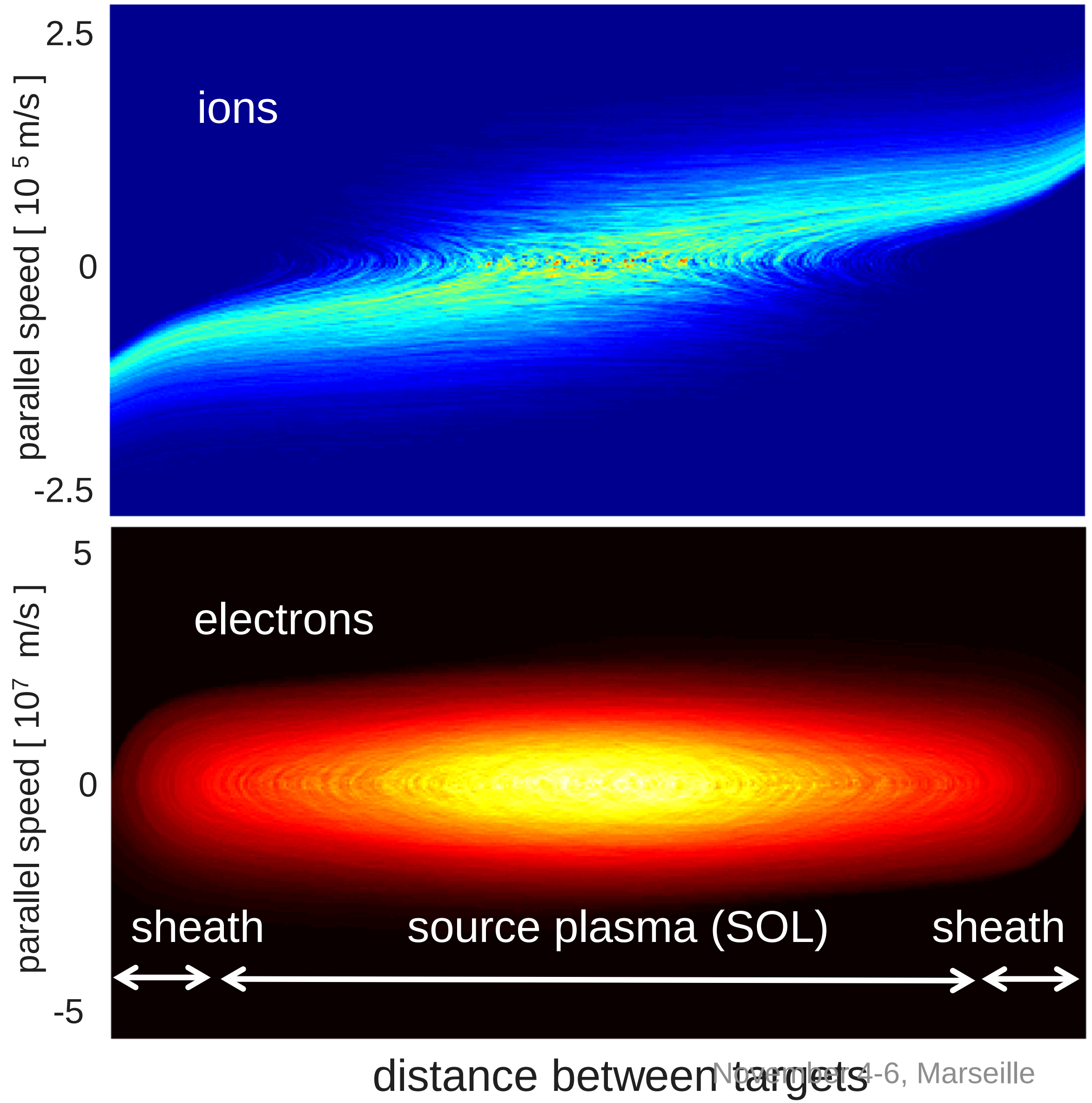
Integrated models are needed to study self-consistent interaction between targets and plasma

First fully self consistent model including upstream plasma and sheath physics!

Source of thermal plasma between two targets (could be two divertor targets, or two sides of monoblocks)
-represents transport of plasma into the gaps between objects

Collisionless sheath,
no electron emission,
no interactions with neutrals

Ions flow to targets at sound speed, electrons mostly confined by sheaths



Electron emission modifies sheath properties

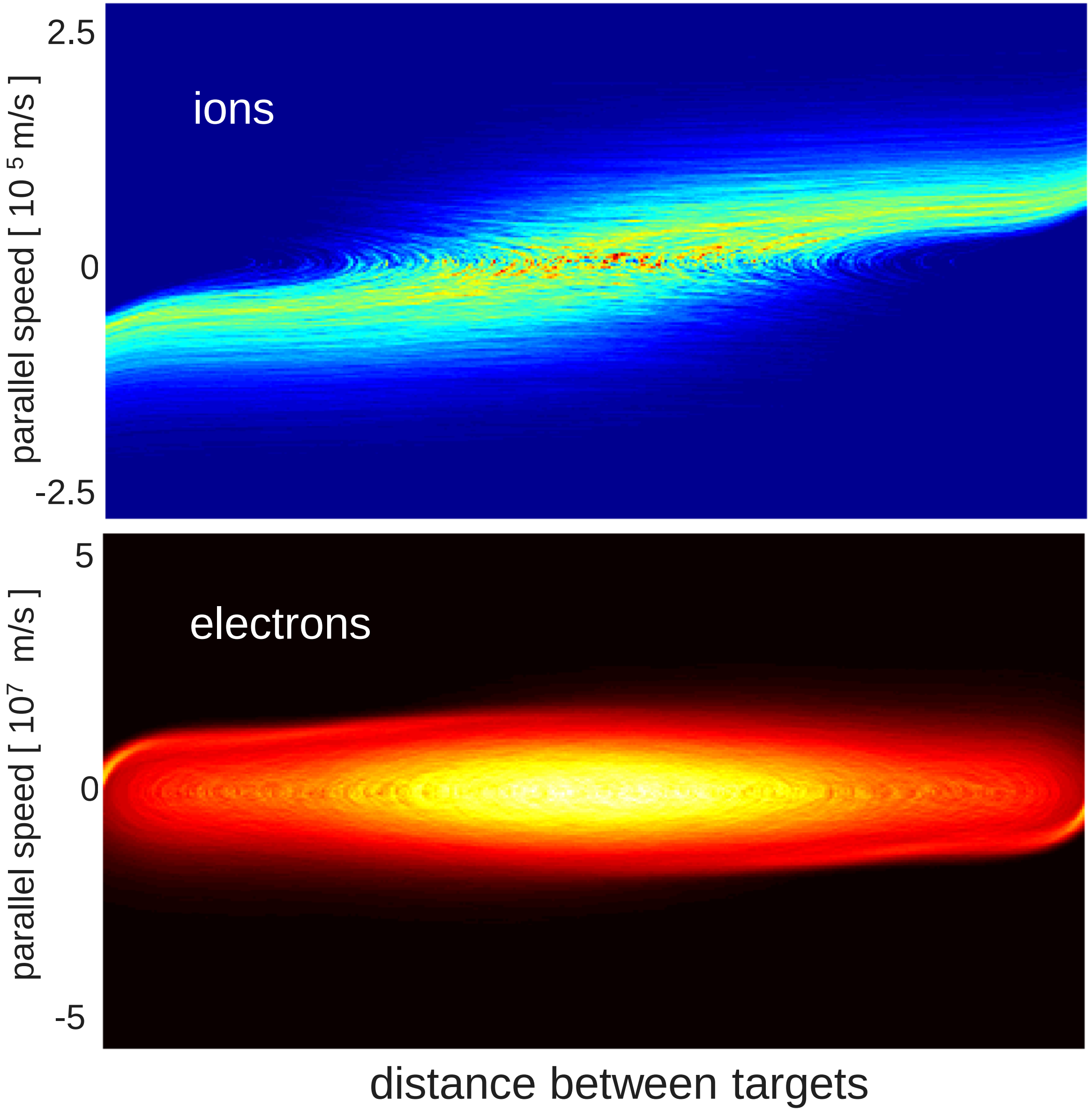
"Weak emission"
Emitted current is less than electron current from plasma

an emitted electron is like an absorbed ion, electrically

sheath potential decreases to maintain current balance
more plasma electrons reach wall
$J_e = J_i + J_{emit}$

Increased heat flux to wall due to the decrease of sheath potential?
WRONG see later

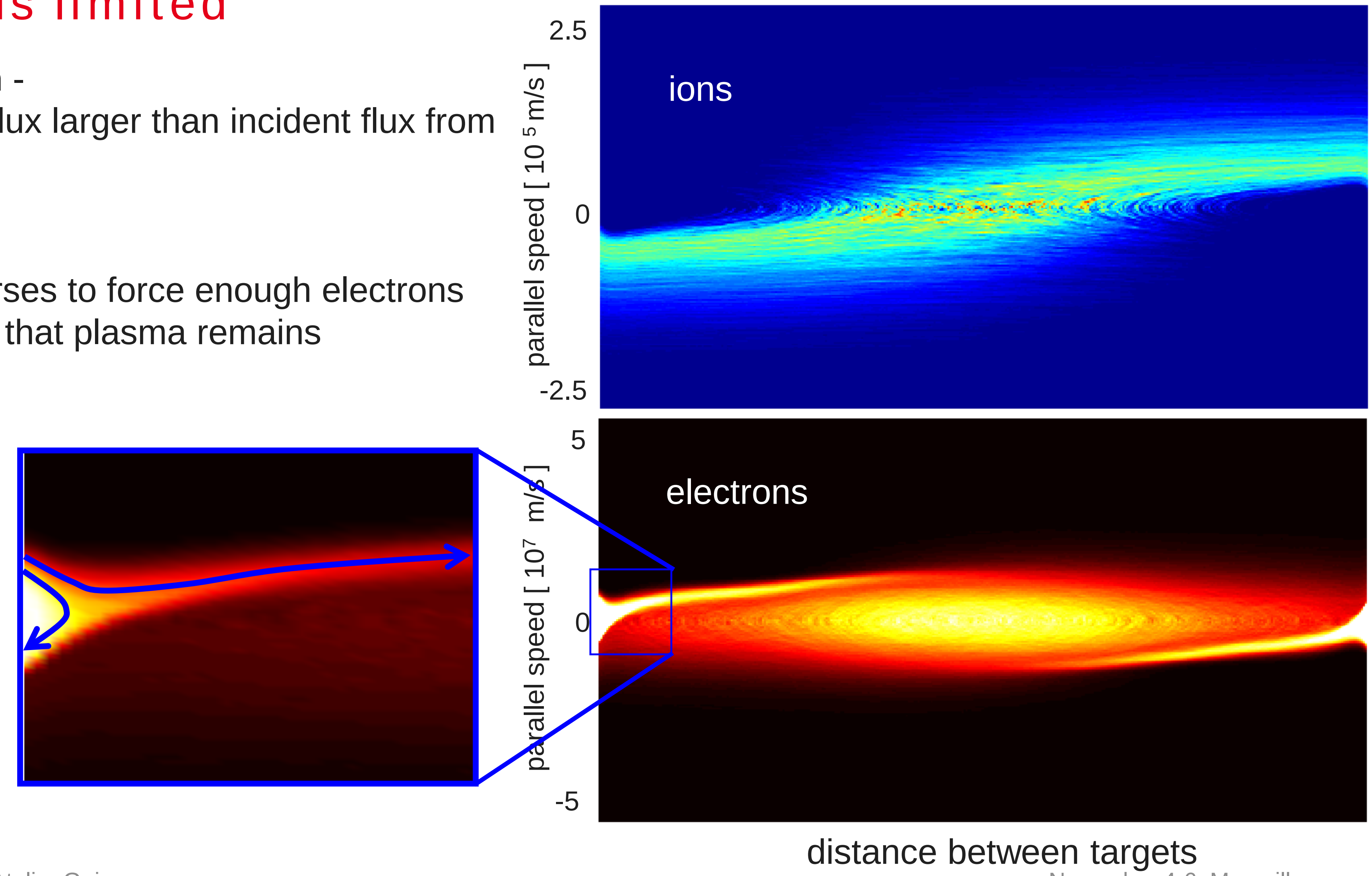
All emitted electrons escape and merge with SOL plasma by collisions



The emitted electron current that can be released into the plasma is limited

Strong emission -
emitted electron flux larger than incident flux from plasma

"virtual cathode"
electric field reverses to force enough electrons back to wall such that plasma remains quasineutral



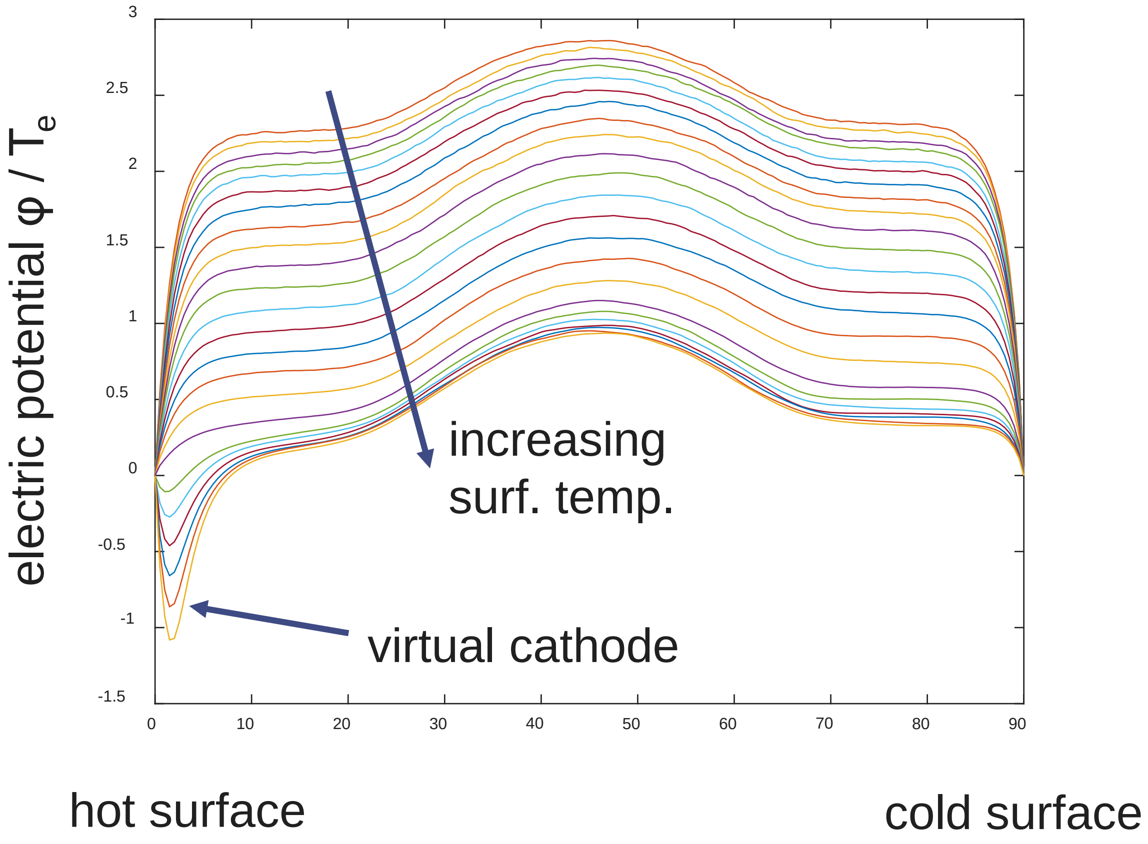
The advent of the virtual cathode (reversal of sheath electric field) imposes a limit on the current of emitted electrons that can cross the sheath and escape into the plasma - space charge limited (SCL) regime

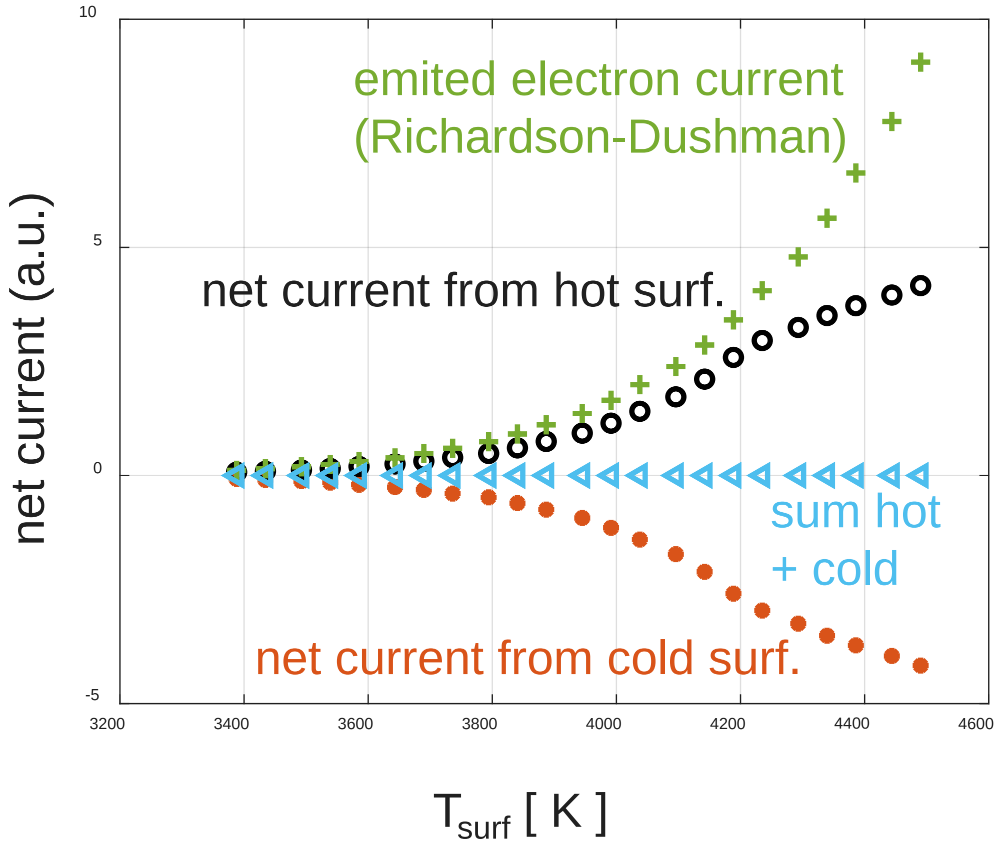
Hobbs,Wesson, Heat flow through a Langmuir sheath in the presence of electron emission. Plasma Phys. (1967) 9:85–7.
-predicts the SCL current for floating sheath (no net current to the surface)

Takamura, Ohno, Ye, Kuwabara, Space-charge limited current from plasma-facing material surface. Contrib Plasma Phys. (2004) 44:126–37.
-predicts the SCL current for an electrically biased surface

M. Komm et al 2020 Nucl. Fusion 60 054002
-PIC simulations with an imposed voltage drop (-3T_e) between sheath edge and wall (results consistent with Takamura, but physically inconsistent because the sheath voltage drop is that of a naturally floating sheath, whereas emission drives a current into the quasineutral plasma)

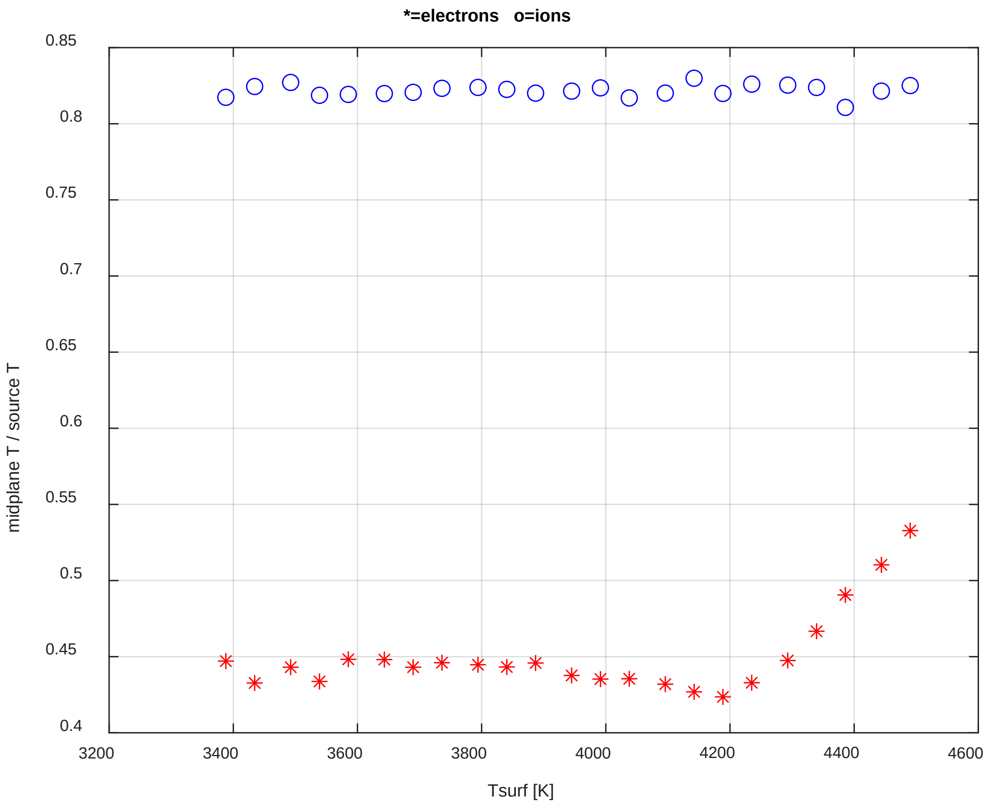
The sheath potential drop in the presence of emission is uniquely determined by how much emission current from a hot surface the quasineutral plasma can return to neighbouring surfaces



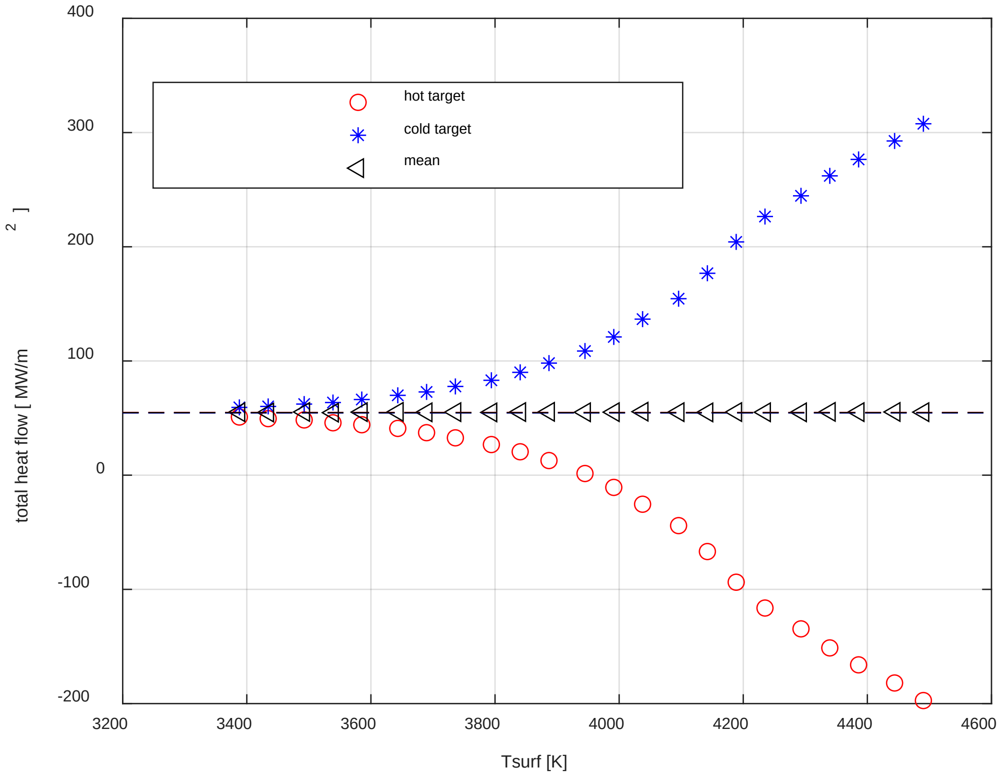


The sheath potential of the cold surface adapts in a self-consistent way and sets the maximum SCL current that can be released from the hot surface into the plasma

Emitted electrons collide with plasma electrons and can either heat it, or cool it, depending on the ratio of the surface temperature to the temperature of the source plasma



Electron emission COOLS the emitting surface when the its intensity is great enough



Emitted electrons carry with them the work function of the hot surface they leave (4.54 eV for tungsten), and deposit it on the cold target.

This constitutes a self-protection mechanism provided by nature.

An example of a real-life application of this cooling mechanism

Hanquist and Boyd | Plasma Cooling for Hypersonic Vehicles

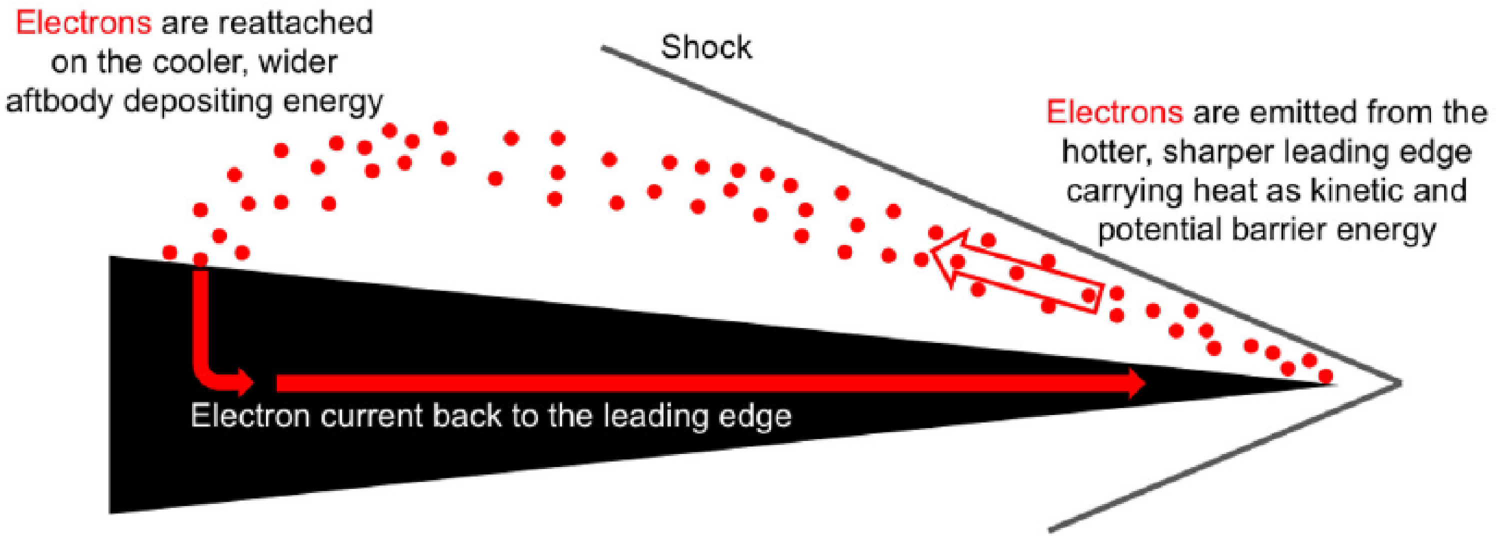


FIGURE 3 | Electron Transpiration Cooling schematic. Reproduced from Hanquist et al. [9], with the permission of AIP Publishing.

Hanquist, Boyd (2019) Plasma Assisted Cooling of Hot Surfaces on Hypersonic Vehicles. Front. Phys. 7:9. doi: 10.3389/fphy.2019.00009

Conclusion

Self-consistent kinetic simulations of a full plasma system including thermionic emission of electrons from a hot surface into a quasineutral plasma indicate that :

-the space charge limited current is determined by the sheath potential of the hot target, which develops self-consistently with the entire quasineutral plasma and the sheath potential of the cold target to which the current is returned

-emitted electrons can modify the quasineutral plasma, either heating or cooling it

-thermionic emission can provide an important cooling mechanism that limits the surface temperature under intense particle bombardment

Tokamaks provide a unique test bed for developing materials for hypersonic entry of space vehicles into planetary atmospheres

Due to the kinetic energy of particles hitting a divertor, or the kinetic energy of a space vehicle hitting an atmosphere, ablation is an issue (not particularly a plasma physics problem)

In collaboration with CEA/CESTA (Bordeaux, team leader Alexis Casner) we are going to test materials for hypersonic space vehicles in the WEST tokamak (Cadarache, team leader Didier Mazon).
PTC HyFAR WEST
Two experimental tools are being constructed to test low-ablation ceramics:

1) A rapid mobile sample holder equipped with thermocouples to study erosion of hard ceramics in the scrape-off layer of WEST under brief 0.1 s exposures

2) A mobile sample holder installed in the divertor to try to ablate ceramics by directly exposing them to the full parallel heat flux in steady state