Sol and divertor physics

Lecture by N. Vianello

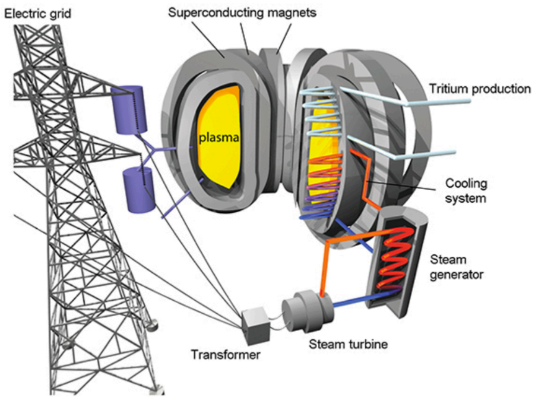
The motivation for a divertor: the exhaust problem

We have the following reaction giving an alpha particle and neutrons.

- Nuclear reaction

$$D + T \rightarrow \underbrace{{}^{3}\text{He (3.5 MeV)}}_{\text{α-particle}} + \underbrace{n \text{ (14.1 MeV)}}_{\text{neutrons}}$$

- Neutrons leave the plasma into power conversion system and will be used for net energy production



what neutrons do? they are used for power conversion

No magnetic field ↓ so they can go outside

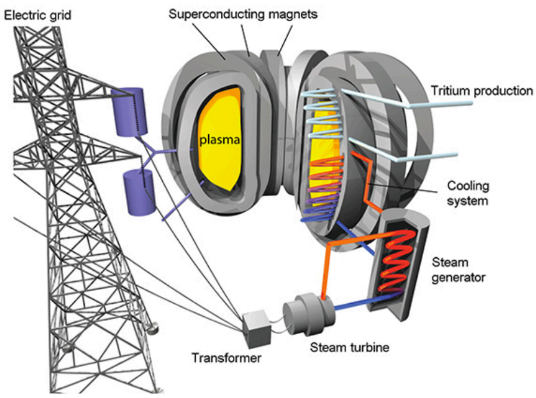
Neutrons are those that will be used for power conversion. These are not combined by any magnetic field, so they can go outside and their energy is transferred to the surrounding blanket. They will help the production of tritium and after they will slow down and their energy will be converted into electric power via a general turbine.

- Nuclear reaction

$$D + T \rightarrow {}^{3}\text{He (3.5 MeV)} + n \text{ (14.1 MeV)}$$

- Neutrons leave the plasma into power conversion system and will be used for net energy production

- Alphas heat the plasmas and then need to be exhausted



what α do?

Then we have the alpha particles which are more energetic - 3.5 MeV - and basically will heat the plasmas. In principle, our plasma is sustained by the heating coming from the alpha particles. This will be done through collisions with the thermal and bulk plasmas, both ions and electrons. Then at a certain point they will lose their energy and this means that they need to be exhausted. So they need to be take away from the main plasmas.

Plasma sustained by heating coming from α ↓ loose their energy and need to be exhausted

So the meaning of the exhaust problem is to find a solution for that is called the ‘?’ - the alpha particles after the release of energy - to have a proper control of the intrinsic impurities that we have in a plasma and are coming from an interaction with the plasma facing components, to properly control the fueling of neutral particles, to control the heat exhaust - we need a proper way to control and direct the power which is flowing through the scrape-off layer.

for what is needed the exhaust problem?

Transformer

- The roles:
  - Helium hash removal
  - Impurity control
  - Fueling Neutral particle control
  - Heat Exhaust
  - Minimize material damage as erosion and melting

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And also, you need to do this while keeping the plasma facing component in a safe condition, so minimizing the material damages, erosion, melting because, basically, all the future devices, all the fusion reactors, will have likely metallic walls.
More advanced configuration or advanced tokamaks will have liquid metals.

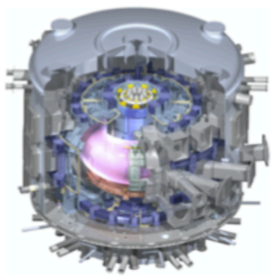
Severity of exhaust problem

flux to be withstand in a tokamak

ASDEX-Upgrade

Major radius: 1.65m

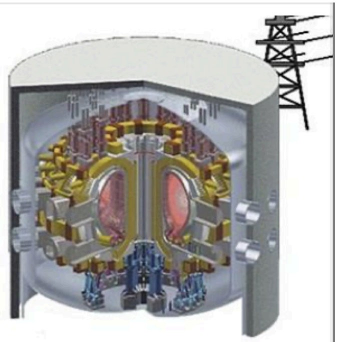
$q_\perp$ 40 MW/m^2



ITER

Major radius: 6.2m

$q_\perp$ 100 MW/m^2



DEMO

Major radius: ~ 9m

$q_\perp$ 350 MW/m^2

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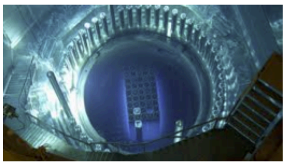
How much heat flux do we need to withstand in a tokamak? We start from medium-sized tokamak, like ASDEX. It is a relatively high-power discharges or, better, it is a very high P over R, the amount of power can be injected with respect to the size is very large. It's one of the largest present in operation. Nevertheless, the amount of heat flux that we can expect, the perpendicular heat flux is of the order of 40 MW/m^2. This is a relative big number.

Then we move to the second step - so ITER -. It has a larger radius, the amount of power will be larger because of the alpha particles. And so the rough estimate of the power that the plasma needs to withstand is of the order of 100 MW/m^2.
Keep in mind that we are talking about the perpendicular power. This can be much larger whenever we have transients, like ELMs - so the amount of energy which is released through the ELMs is much higher.

And then if you go up to the DEMO scale, the amount of power will be even larger.

To make these numbers in a context, we have the comparison with what the present technologies need to withstand with like the shuttle or the rockets. We are in a much wider, much higher range, so the problem is pretty serious.



$q_{\perp} \sim 1\text{MW}^2$

$q_{\perp} \sim 5\text{MW}^2$

$q_{\perp} \sim 80\text{MW}^2$

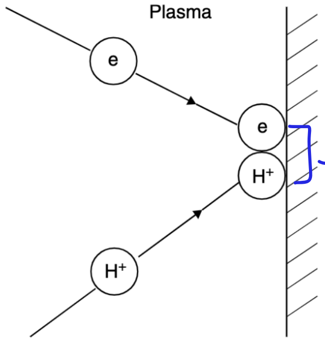
Solid surface interaction with a plasma: PWI

We have done all the descriptions of the plasmas with the magnetic fields that can confine the plasmas. In any case, we have a vacuum vessel surrounding your plasma. And at a certain point, the plasma, whenever it moves from the confined to unconfined region, so whenever it moves outside towards what it is called the last closed flux magnetic surfaces, it will touch the materials.

Plasma from confined to unconfined region → it moves towards the last closed flux surface touching the material

- Any solid surface inserted into a plasma constitutes a very strong particle sink
- If charged particles strike a solid surface they tend to stick long enough to recombine
- For insulating or electrically isolated surfaces, opposite charges stick and produce *surface recombination*
- Thus we have a plasma sink not a mass sink
- This *recycling* process can happen in steady-state condition whereby plasma charged pairs are lost at the same rate as recombined neutrals re-enter the plasma

PLASMA SINK: we loose particles and gain neutrals



particle sink

charged particles that strike a solid surface

RECOMBINE

NEUTRALS AGAIN

weak bond towards solid surface

released with low energy

Any solid surface, which is inserted into plasmas, constitutes a very strong particle sink. In other words, when the plasma constituents, so electron and ions, will touch the solid surface, they tend to recombine. They tend to become again neutrals. These neutrals have a weak bond towards the solid surfaces and therefore, they are released.

But they are released generally with a relative low energy. In other words, a solid surface is called a plasma sink in the sense that we lose plasma, we lose charged particles, and we gain, instead, neutrals. This is not a mass sink, so we don't lose mass, basically.

RECYCLING PROCESS

The process, according to which the plasma that touches the wall is then released, as soon as possible is called **recycling**. This process can happen in a steady state condition. It means that the rate at which the plasma is lost is equivalent to the rate of the recombined neutrals re-entering the plasma itself. This can be a sort of steady state problem. This recycling is at the basis of the sustainment of the plasma. So keep in mind that whenever you have discharges, most of the plasma fueling is done not only through the gas puffing, not only through the pellet puffing, if any pellet will be inserted, and neither through the NBI, because NBI do not only transfer momentum and energy to the plasma, but the large majority of the fueling to the plasmas is done with the recycling process. So through the release of neutrals from the plasma facing components.

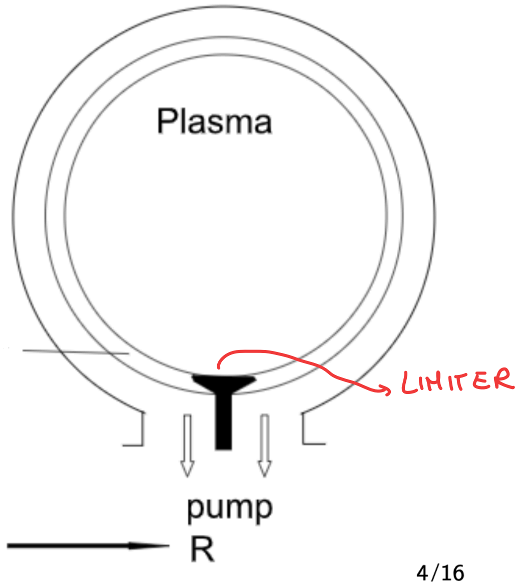
RECYCLING : rate at which the plasma is lost = rate of recombined neutrals

- basis of plasma sustainment
- majority of the fueling, so through the release of neutrals

part of the plasma exposed to the vacuum vessel → high withstanding capabilities for heat flux

The limiter configuration and simple SOL

- Solid surface eventually inserted by purpose to provide controlled Plasma Wall Interaction
- Historically first solution proposed is the limiter solution (with toroidal or poloidal limiters)
- Clear identification of the LCFS (separatrix) and the SOL
- Can be described by fluid approach as far as self collisional mean free paths of electrons and ions lower than parallel connection length $\lambda_{ee}, \lambda_{ii} \ll L_{\|}$



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LCFS: last closed magnetic surface before touching the material

SOL: part of plasma outside the LCFS
↳ B field touching the solid surface

In the past when we had cylindrical devices or toroidal devices with a cylindrical concession, it was used a limiter, which is a part of the plasma, exposed with respect to the vacuum vessel, and which has generally higher withstanding capabilities in terms of heat flux. This is to localize the plasma wall interaction. The presence of a limiter, like the black solid piece in the slide, clearly identifies the last closed flux surfaces and the scrape-off layer.

The last closed flux surface is just the last closed magnetic surface before touching the material. And the scrape-off layer is the part of the plasmas which is outside this last closed flux surface. In the scrape-off layer what happens is that the magnetic fields are not anymore closing on themselves, but they are touching the solid surfaces. This implies that you will have a lot of parallel transport because plasma particles, ions and electrons, are basically free to move along the magnetic field lines. The parallel transport is generally much faster than the perpendicular one. And this parallel transport will intercept the solid surfaces.

PARALLEL TRANSPORT

fluid approach for the SOL

The general treatment of the scrape-off layer is done by a fluid approach - we will not provide any kinetic description of the scrape-off layer. The fluid approach is valid whenever the collisional mean-free path of the electron and ions is lower than the parallel connection length. Or in other words, if the plasma particles are allowed to make many interaction, many collisions before touching the solid surfaces. And this is the general description.

if plasma particles are allowed to make collisions before touching the solid surface

NO KINETIC DESCRIPTION

Keep in mind that we will not make any kinetic description. Nevertheless, some of the physics which is occurring at the region very close to the target, to the solid surfaces could require a kinetic description.

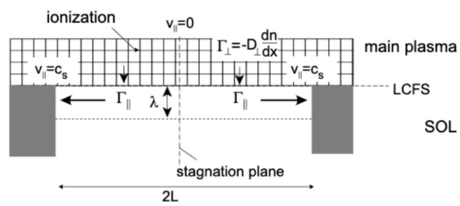
release of neutrals

We have said at the beginning that since we have the plasma particles, that touch the SOL, we will have a release of neutrals. Also the neutrals have a mean free path, that is the length before which the neutrals are still neutrals and are not ionized.

mean free path of neutrals

simple SOL →

- If the neutral m.f.p. is long enough to pass through the SOL and they are ionized inside the main plasm, then we are in the condition of Simple SOL
- To describe the characteristics of simple SOL we need to describe better the interaction of a plasma with solid wall



If the neutral mean free path is long enough to pass through the scrape-off layer, this means that they are ionizing inside the plasmas. And if we can describe the scrape-off layer just purely through the description of the plasma and without taking into account the neutral plasma interaction, then we are in the so-called simple scrape-off layer.

Characteristics of simple SOL

First of all, to describe the characteristics of the simple scrape-off layer, we need to describe what happens whenever the plasma touches the solid wall.

SHEATH

This is the concept of sheath. We are dealing basically with plasmas or with particles which are flowing along the field lines and these field lines intersect the wall. Given the fact that the electrons are faster than ions because of the mass, whenever they touch the wall, the wall tends to be charged negatively.

On the other hand, if you have a sort of charged negative solid surface, there is an electric field that builds up and this is done in order to ensure that the plasma remains quasi-neutral. You know that the plasma is unable to withstand strong electric field in the medium plasma cell or particle imbalance.

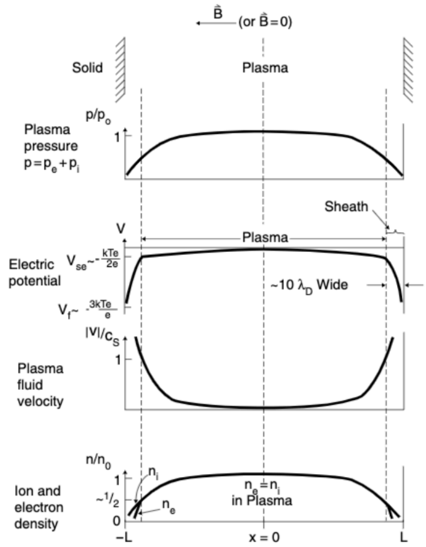
ambipolar electric field

↳ to ensure the plasma remains quasi-neutral

So the electric field, which is called ambipolar, builds up in order to ensure to have equal ion-electron losses. As said, electrons are lost faster. This means that we have a repelling electric field which builds up in order to repel electrons and accelerate ions and this ensure that the flux of ion and electrons finally at the wall will be equivalent. IMPORTANT (*)

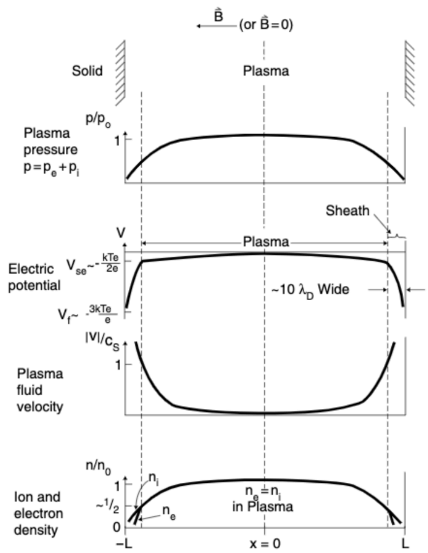
- electrons are lost faster → repelling electric field to repel e- and accelerate ions → flux of ions = flux of electrons

- In presence of a solid wall higher electron mobility charge up the wall negatively $\Longrightarrow$ ambipolar electric field builds up to ensure equal ion/electron loss $\rightarrow V_{wall} \approx -3kT_e/e$ w.r.t. plasma potential



You can demonstrate basically that the voltage difference between the unperturbed plasmas and the value at the ~~sheet~~ sheath - so the value that occurs whenever the magnetic field lines intercept the wall - is proportional to the electron temperature. And this is basically what it is called the **floating potential.**

- In presence of a solid wall higher electron mobility charge up the wall negatively $\Longrightarrow$ ambipolar electric field builds up to ensure equal ion/electron loss $\rightarrow V_{wall} \approx -3kT_e/e$ w.r.t. plasma potential
- Electrostatic potential shielded within a Debye length $\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}}$
- Shielding is not perfect. pre-sheath electric field of the order of $E \approx kT_e/2eL$
- Ions are accelerated in the pre-sheath up to the sheath entrance velocity $v_{se} = c_s = \sqrt{\frac{k(T_e+T_i)}{m_i}} \Longrightarrow$ Bohm criterion
- At sheath entrance density is $n_{se} = \frac{1}{2} n_0$



shielding

In other words, the electrostatic potential that builds up is in any case shielded and this is the shielding that occurs within what it is called a Debye length or a Debye ~~sheet~~ sheath. This means that whenever you put a charged point into the plasma, which is at a different potential with respect to the surrounding plasma, there is a cloud of plasmas which builds up around this point. And this cloud of charged particles is built up in order to ensure that the potential is shielded and the shielding occurs within the Debye length or close to the Debye length.

The shielding is not perfect. So this means that there is also what it is called a pre-sheath of electric field that is still proportional to the temperature of the electrons.

What happens if you have a potential which is at the lower values with respect to the plasma potential? What it will happen is that the ions are accelerated. This acceleration of ions ensure that the plasma is quasi-neutral, and the flux of ions and electrons towards the plasma surface is constant.

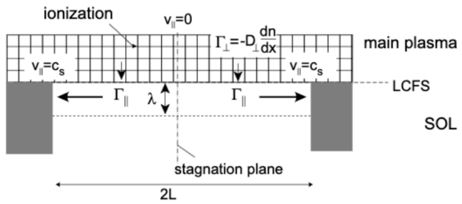
The ions are accelerated up to ion sound velocity → This criteria is also called a **Bohm criterion**. On the other hand, the fact that you build up these potential differences between the solid surfaces and the plasmas means also that you have different local densities of the plasma itself, and at the entrance of the sheath - so up to the region where ion and electrons have the same densities - the density is actually one-half of the densities in the unperturbed cases or quite far apart from any solid surfaces.

So, in the simple scrape-off layer approximation, with no sources of particles in the SOL because we have said that the nuclei are ionized in the confine region - you can also draw a simple relation between the diffusion and the scrape-off layer width.

What is the scrape-off layer width? Why it is so important? The width of the SOL is a typical scale length or logarithmic scale length according to which the plasma densities decrease starting from the LCFS.

SOL width
↓
typical scale length according to which the plasma densities decrease from the LCFS

- In the simple SOL approximation with no source of particle in the SOL, simple relation holds between diffusion and SOL width
- This is obtained by the equality between the Total particle outflow crossing the LCFS $\phi_\perp$ to the total particle flow towards the 2 solid surfaces $\phi_\parallel$



diffusive transport across the LCFS

$$\phi_\perp = -D_\perp^{SOL}\frac{\mathrm{d}n}{\mathrm{d}r}_{LCFS}2Lw = -D_\perp^{SOL}\frac{n_{LCFS}}{\lambda_n}2Lw$$

particle outflow crossing LCFS

$$\phi_\parallel = 2w\int_{r=LCFS}^{\infty} nc_s\mathrm{d}r \approx 2w\frac{1}{2}n_{LCFS}c_s\lambda_n \quad \text{with} \quad n(r) = n_{LCFS}e^{-\frac{r}{\lambda_n}}$$

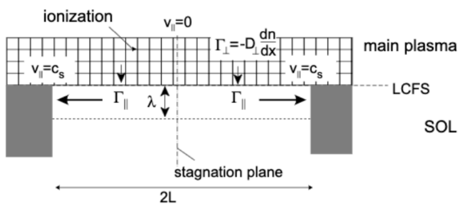
particle flow towards the 2 solid surfaces

The determination of the relation between the flux and the key length of the densities is give by equality between the total particle outflows crossing the last closed surfaces, which we call ϕ perpendicular, to the total particle flows towards the two solid surfaces that is ϕ parallel. In other words, since we have no production of plasmas because there is no interaction with the neutrals in the scrape-off layer, we assume that all the flux which come across the last closed flux surfaces perpendicularly are then taken apart and bring the two last closed flux surfaces by a parallel transport.

So if we assume a simple description according to which we can describe a diffusive transport across the last closed flux surfaces, we can describe the flux as proportional to the gradient of the densities via a diffusive coefficient and then we take into account the perpendicular flux across the last closed flux surface.

The gradient can be simply described by the formula if we assume that we have an exponential of the densities, which is what you also observe experimentally.
If you take this and you put this equal to the parallel flux, which is just the integral of the last closed flux surface to the intercepting wall of the parallel flux - we already said that the ions are basically accelerating up to the ions sound speed - you end up with the formula below, which at the very end brings to a definition of the typical scale length of the scrape-off, assuming that there is no interaction with the neutral and there is just a diffusive transport across the flux.

- In the simple SOL approximation with no source of particle in the SOL, simple relation holds between diffusion and SOL width
- This is obtained by the equality between the Total particle outflow crossing the LCFS $\phi_\perp$ to the total particle flow towards the 2 solid surfaces $\phi_{||}$



$$\lambda_n = \sqrt{\frac{2D_\perp^{SOL} L}{c_s}}$$

→ definition of the typical scale length of the scrape-off
① no interaction with neutrals
② Diffusive transport

This is a general simple description that give you an idea about which are the process es that are important.

(1)

PARTICLE FLUX ESTIMATE → PARALLEL FLUX

Flux of e- and ions intercepting the first wall

Now we would like to estimate which are the flux of electrons and ions, which are intercepting the first wall, so the parallel flux. For the ions, we already said that they are basically accelerating up to the ions sound speed. So the flux of the ions intercepting the wall are the densities at the sheath entrance multiplied by the ions sound speed. For the electrons, we can assume that this is sort of a Maxwellian distribution.

- The corresponding ion and electron parallel flux to the target can be estimated remembering that electrons distributions remains Maxwellian even in retarding electric field

$n_{se} = \frac{1}{2} n_0$ ↓ at sheath entrance

ion flux to target; electron flux to target

$$\Gamma_t^i = n_{se} c_s, \quad \Gamma_t^e = \frac{1}{4} n_{es} \underbrace{\exp(eV_s/kT_e)\sqrt{\frac{8kT_e}{\pi m_e}}}_{\text{Maxwellian}} \implies \frac{eV_s}{kT_e} = 0.5 \ln\left(2\pi \frac{m_e}{m_i}\right)(1+T_i/T_e) \approx 3$$

This Maxwellian distribution can be shown that remains valid even if we have a retarding electric field. In other words, the flux of the electrons at the target is proportional to the electron densities at the sheath entrance, which is the last point where electron-ions have the same densities and then to the typical description of the Maxwellian distribution accounting for where we have a potential drop, the sheath potential.

ION FLUX = ELECTRON FLUX

(*) estimate of the potential drop/sheath

So this can be estimated in a sense that we can start from this description. We know that at the very end, we should have equal ion to electron flux at the wall. And this is why the sheath is built up. This implies that we can have an estimate of the potential drop, of the potential sheath, which is proportional to the ratio of electron to ion masses, to the ion to electron temperature, which can be assumed as a first order approximation equal, even though experimentally it is not. And this give you basically a typical factor of the ratio between the electron temperature and the potential at the sheath entrance, which is of the order of three.

For the Langmuir probe, this is why we always said that the potential at the target is approximately three times lower than the typical electron temperature.

(2) HEAT FLUX ESTIMATE

So these are the estimate of the particle flux. What we are also interested in is the estimate of the heat flux. The heat flux is related to the particle flux through what it is called the sheath transmission factor. In other words, the large majority of the heat flux is by convection. This is why there is a sort of proportionality between the particle flux and the heat flux. And the factor of proportionality is called the sheath transmission factors.

particle flux ∝ heat flux

↳ sheath trasmission factors for ions and electrons

These sheath transmission factors are different according to the electrons and ions. For the electrons, we need to consider both the sheath and the pre-sheath drop. Therefore,

5.5

- The corresponding ion and electron parallel flux to the target can be estimated remembering that electrons distributions remains Maxwellian even in retarding electric field

$$\Gamma_t^i = n_{se} c_s, \quad \Gamma_t^e = \frac{1}{4} n_{es} \exp(eV_s/kT_e) \sqrt{\frac{8kT_e}{\pi m_e}} \implies \frac{eV_s}{kT_e} = 0.5 \ln\left(2\pi \frac{m_e}{m_i}\right)(1+T_i/T_e) \approx 3$$

- Heat flux related to particle flux through the sheath transmission coefficients $\gamma_{i,e} = \frac{q_{i,e}}{kT_e \Gamma_t}$
- For electrons considering sheath and pre-sheath drop $\gamma_e = 5.5$
- For the ion the computation is not straightforward: if ion distribution is maxwellian then $\gamma_i = 3.5$
- The flux is then computed as $q_t^{i,e} = \gamma_{i,e} n_{es} c_s k T_e$

the sheath transmission factor of the electrons is 5.5 in general.

For the ions, the computation is slightly more complicated. If we assume still to have a Maxwellian distribution of the ions, you can ~~be~~ show~~n~~ that it is of the order of 3.5.

These are just number, but they are useful whenever you want to estimate the amount of heat flux that you can expect, given the fact that it is much easier to measure the particle flux. So if you assume that you are taking your Langmuir probes and you put it into the plasmas, then you can measure the current that is flowing along these Langmuir probes, you can deduce the parallel particle flux and from the particle flux, you can deduce as well the heat flux, or at least the convective component of the heat flux.

General description of the parallel transport in the SOL

We can have a better description of the parallel transport in the scrape-off layer.

Why is this important? Because at the very end, this is what you need to know in order to get the proper dimensioning of the plasma facing component. So you need to know how much heat flux is flowing parallel to the target in a divertor configuration.

We will make a simple 1D approach.

KNOW HOW MUCH HEAT FLUX IS FLOWING PARALLEL TO THE TARGET IN A DIVERTOR CONFIGURATION !

- Identified the ion and electron heat flux to the target as related to the corresponding particle flux
- Need to determine the eventual spatial distribution. 1D approach with detail description in (P. C. Stangeby 2000; Unterberg 2017)

1D description on parallel transport

parallel dimension on

We start the description on the parallel transport by taking into account the density conservation equation in steady state. Steady state means that the plasma continuity equation does not have a direct dependence on the temperature. Now, description is not done in a simple scrape-off layer approximation. We take into account that there might be neutrals and there might be local forces in the scrape-off layer. So in 1D - where the one dimension that we take and look at is the parallel one - the density conservation equation has the form below where this S_p is just the source of particle coming from the neutrals.

We need to couple the continuity conservation equation to the ion momentum

- Density conservation equation in steady-state

couple both

$$\frac{\partial}{\partial z}(n_{i,e}V_{\parallel i,e}) = S_p$$

source of particles coming from neutrals

- Ion momentum conservation in steady state

only parallel component of the velocity

ion E ion pressure

$$\frac{\partial}{\partial z}(m_i n v_{\parallel i}^2 + p_i) = enE + \boxed{R_{ie}} + \boxed{R_n}$$

- R_{ie} being the friction force caused by electron collisions: $R_{ie} = m_e(v_e - v_i)\nu_{ei}n + 0.71n\partial kT_e/\partial_z$
- R_n being the friction force due to collisions with neutrals $R_n = -m_i(v_i - v_n)\langle\sigma v\rangle_{CX} n_n n + m_i v_n S_p$ where we implicitly assumed that momentum loss due to Charce eXchange is dominant mechanism for ions

conservation equation in steady state. The formula above is the formula we are dealing with where we have the ion pressure, the ion energies - it needs to take into account only the parallel component of the ion velocities multiplied by the mass of the ion - and then you have the electric field and the friction force which is caused by collision between electrons and ions and the one caused by neutrals.
The friction force for ion-electron collision is clearly proportional to the collision frequency between electrons and ions and to the differences of velocities between electrons and ions. And then there is another term which is due to the gradient of the temperature due to the fact that the gradient of the temperature is a force acting on the charged particles.

Then we have the friction forces with the neutrals. These friction forces again do depend on the cross-section and the main cross-section which is interesting for any change of parallel momentum is the charge exchange processes. The friction of the neutrals depends also on the densities of the neutrals and the density of the plasma particles and also on the local sources of the neutrals.

Here we are only taking into account the charge exchange as a dominant mechanism for the ion momentum losses.

If we do the same for the electrons, then we neglect the mass of the electrons - we give them much smaller inertia - therefore, the momentum balance equation to have a

- Density conservation equation in steady-state

$$\frac{\partial}{\partial z}(n_{i,e} V_{\parallel i,e}) = S_p$$

- For the electron we rely on the small inertia and momentum balance is written as

$$\frac{\partial p_e}{\partial z} + enE = -m_e(v_e - v_i)\nu_{ei} - 0.71n\frac{\partial kT_e}{\partial z}$$

where we kept the friction term for ion-electron momentum exchange

dependence still on the parallel electric fields has a similar dependence on the friction force between electrons and ions.

Since we are dealing with the plasma, we would like total plasma momentum equation, so we sum up the momentum equation of the electrons and the ions.

- Density conservation equation in steady-state

$$\frac{\partial}{\partial z}(n_{i,e} V_{\parallel i,e}) = S_p$$

- The total plasma momentum equation results then in

$$\boxed{\frac{\partial}{\partial z}(m_i n v^2 + p_i + p_e) = -m_i(v_i - v_n)\langle\sigma v\rangle n_n n + m_i v_n S_p(z)}$$

TOTAL PLASMA MOMENTUM EQUATION

- We recognize that the main force acting on $m_i n v^2$ is the pressure gradient with no effect from electric field. Strong uncertainty come from the unknown of $T_\parallel$
- We need to move to higher momentum and compute the parallel energy equation

We end up canceling the direct dependence on the electric field and also the friction force between electrons and ions is equal in module and opposite in sign with respect to the friction force of ion to electrons.
In other words, what we end up with the total momentum balance is just that we take into account the charge exchange processes, and we take into account the presence of the neutrals for the particle sources.

We start from the first order momentum balance equation, but we need to go up in higher momentum in order to compute the proper parallel energy equation.
We have the parallel energy equation for the electrons and ions. We are in state state 1D description.

- Ion energy conservation

$$\frac{\partial q_{\|,i}}{\partial z} = \frac{\partial}{\partial z}\left[\boxed{\left(\frac{5}{2}T_i + \frac{1}{2}m_i v_i^2\right) n v_i}\ \boxed{-\kappa_{0,i} T_i^{5/2}\frac{\partial T_i}{\partial z}}\right] = env_i E + Q_{eq} + Q_{Ei}$$

- Electron energy conservation equation

$$\frac{\partial q_{\|,e}}{\partial z} = \frac{\partial}{\partial z}\left[\boxed{\frac{5}{2}T_e n v_e}\ \boxed{-\kappa_{0,e} T_e^{5/2}\frac{\partial T_i}{\partial z}}\right] = -env_i E - Q_{eq} + Q_r + Q_{Ee}$$

- With Q_{eq} arising because of thermal equilibriation collision between electrons and ions, Q_r the Joule heating term, Q_{Ei} resulting from ion-neutral interaction and Q_{Ee} is the energy loss for electrons because of inelastic collisions which ionize or excite neutrals
- Ion conduction $\kappa_{0,i} \approx 60 \ll \kappa_{0,e} \approx 2000$ because of a $m^{-1/2}$ dependence

What we have in the ion equation is the kinetic energy - which is coming from the mass of the ion -, we have a component which is proportional to the convective term and then two quantities which are related to the ion conduction. The energy conservation equation is equalized to the components coming from the electric fields.
We have a component which is arising because of the thermal equilibration collision between the electrons and ions, a component which is coming from the joule heating term, then a component which is coming from the ion-neutral interaction and the component which is coming from the inelastic collision, which ionize or excite the neutrals.
In other words, for the ions, what matter most are the ion-neutral interaction, so the fact that the ion and the neutrals are interacting by a charged exchange process and they're

losing or gaining energies. For the electrons, you need to Take the inelastic collision in the process of ionization, which basically is a drain of energies for your system.

On the other side, you have the conduction and you have a coefficient of conduction for ions and electrons, which ~~are~~ is pretty much different one respect to the other, and indeed, what matters most is only the electron conduction. Electron conduction is higher because there is a mass dependence, reverse mass dependence.

Assuming that the electron and ion have equal temperature, then we can define a single pressure and take into account a single definition of the temperature. We end up with the three formulas below which properly describe the parallel transport along the scrape-off layer: momentum balance, continuity equation and the energy balance.

- For $T_e = T_i$, defining the total pressure $p = p_e + p_i$ we have a simplified form

formulas which properly describe the parallel transport along the scrape off layer

$$\frac{\partial(nv)}{\partial z} = S_p$$ momentum balance

$$\frac{\partial}{\partial z}[(m_i v^2 + 2kT)n] = -m_i v\langle\sigma v\rangle n n_n$$ continuity equation

$$\frac{\partial}{\partial z}\left[\left(\frac{1}{2}m_i v^2 + 5kT\right) nv - \kappa_{0,e} T_e^{5/2}\partial T_e/\partial z\right] = Q_r + Q_E$$ energy balance

This description holds whenever you are dealing with the scrape-off layer, either in a limiter or in the divertor configuration.

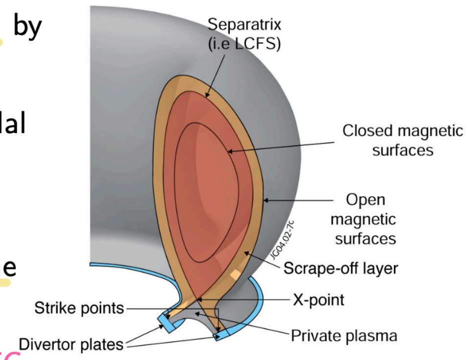
Divertor configuration

The limiter configuration has been abandoned and followed by the divertor configuration. Why the divertor configuration? There's a drawback of using a limiter into the plasma: you just put a bulk solid surface into the plasmas, which can withstand sufficient heat and particle flux, and this will define properly the last closed flux surfaces, but there is a lot of pollution because if you just take into account that the interaction is happening also on the top of the limiter, this means that the neutrals are clearly injected into the plasmas directly. Not only the neutrals, but also the impurities.

drawbacks of limiters

And given the fact that the limiters were done typically in a solid metal to withstand much higher flux - this implies that you have a high-z materials which are injected directly into the plasmas and these are not beneficial because they radiate a lot and you're using your energy and power via radiation. This motivated the movement towards what it is called the divertor configuration.

- Limiter configuration not ideal to reduce plasma pollution by impurities generated by PWI
- Introduced the divertor configuration, generated by poloidal field coil where PWI occur far from confined region → Ionization source in within SOL volume
- Guarantee better pumping efficiency, lower heat flux at the target.
- Realized by reduce plasma temperature in front of the PFC and establishing a temperature gradient along the magnetic field
- Described by the 2 point model (P. C. Stangeby 2018, 2000; P. Stangeby 2020a,b) which describe relation between upstream and target condition



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X-Point ↳

The divertor configuration is determined by the fact that via a proper tailoring of the magnetic field, you define a point, which is a x-point, a null of poloidal magnetic field. The x-point describes properly a confined region from an unconfined region. This implies that the region where the interaction between the plasma and the solid surface is happening is far apart from the confining region. So there is no single interaction of confined plasmas with a solid surface. This implies as well that all the ionization source, so the neutrals which are recycled through the plasma interaction, is primarily into the scrape-off layer volume.

No interact of confined plasmas with a solid surface

This is not entirely true in the sense that this depends on the typical temperature that you add into the scrape-off layer because your ionization profiles have a strong dependence on the temperature of the plasmas and on the densities of the plasmas.
So a residual ionization may occur as well into the confining region. Nevertheless, the larger majority is in the scrape-off layer, and also the impurities are better compliant.

better pumping

Furthermore, the presence of the divertor configuration can guarantee a better pumping efficiency because the neutrals are localized more close to where the large majority of the interaction is entering, which is in those points where the magnetic fields are intersecting the plasmas - this is originally called the divertor plates. And if you put the pump close to the divertor plates where most of the neutrals are recycling, then you have much higher capabilities of pumping, much higher pumping efficiency.

reduce the heat flux at target surfaces

There is also another improvement guaranteed by the fact that you have the divertor configuration and you will be able to properly act on the plasmas in order to reduce the heat flux at the target surfaces. This is done somehow naturally in the sense that we will define the relation between the densities and the temperature at the last closed flux surfaces and the densities and the temperature that you get at the target, so where the plasma touches the wall. And then we have also to have additional cooling down of the plasmas in front of the target to ensure that the heat flux is in within the withstanding capabilities of your material.

2 POINT MODEL ↓ relation between upstream and target for parallel transport

So the introduction of the divertor configuration reduces the plasma temperature in front of the plasma facing component. This is done by establishing appropriate temperature gradient along the magnetic field. The simple description of the relation between the condition at the upstream - at the separatrix entrance - and the condition at the target - so the condition at the region where the plasma touches the wall - is done by the so called of 2 point model. And the 2 point model is what is used for a first order approximation of the description between the upstream and downstream condition, taking into account only or mainly parallel transfer.

- Unfolding the SOL, if ionization occurs in a region close to the target, the **heat condution** dominates $\Longrightarrow$ conduction limited regime
- The parallel heat flux is thus related to the parallel temperature gradient:

$$q_{\parallel} = \frac{P_{SOL}}{A_{\parallel}} = -\kappa_{0,e} T^{5/2} \frac{\partial T}{\partial z_{\parallel}}$$

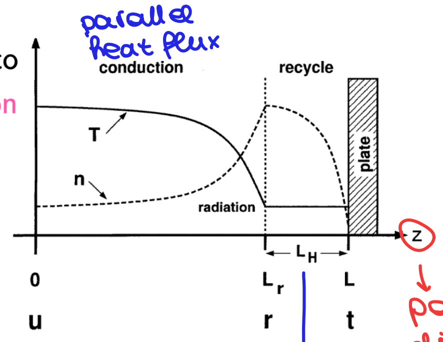
- Integrating the previous equation

$$T(z_{\parallel}) = \left[T_t^{7/2} + \frac{7}{2} \frac{P_{SOL}/A_{\parallel}(L_{\parallel} - s_{\parallel})}{\kappa_0, e} \right]$$

which for $T_u \ll T_t$ we obtain $\boxed{T_u \simeq \left(\frac{7}{2} \frac{P_{SOL}/A_{\parallel} L_{\parallel}}{\kappa_{0,e}} \right)^{2/7}}$

TEMPERATURE UPSTREAM AT THE SCRAPE-OFF LAYER

parallel heat flux



parallel direction

neutrals are emitted from target plate and confined in this region → low mfp
↓
recycling and ionization in front of the plate

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So we have a divertor configuration and what is called a plate. The neutrals are generally recycling close to the target.
The figure above just describes a magnetic flux tube, which is unfolded from upstream, so from the separatrix entrance, up to the target and z is the parallel direction. The simple assumption that you can do is that the neutrals are basically emitted from the target plate, and they are confined in a region which is not far apart from the plate.
In other words, you are assuming that your mean free path of the neutrals is short enough, and most of the recycling and ionization occurs in front of the plate.
The neutrals are not moving upstream towards the scrape-off layer or towards the target. This is a simple assumption.

CONDUCTION LIMITED REGIME
↓
flux via parallel conduction

You can also assume that the parallel heat flux is basically driven by conduction and so, we are in what it is called a conduction-limited regime. This implies that the parallel flux, which is the flux which is entering or crossing the separatrix, is basically conducted to the target via parallel conduction. This means that your parallel flux is just the ratio between the power which is crossing the separatrix P_{SOL}, and the section of your flux tube $A_{\parallel}$, which is unfolded in this simple description, and it is proportional to the temperature gradient.

ingredients that are setting the temperature at the separatrix entrance
↓
- power P_{SOL}
- geometrical dimension of the divertor

- The parallel heat flux is thus related to the parallel temperature gradient:

$A_{\parallel}$: section of flux tube

$$\boxed{q_{\parallel} = \frac{P_{SOL}}{A_{\parallel}} = -\kappa_{0,e} T^{5/2} \frac{\partial T}{\partial z_{\parallel}}}$$

parallel heat flux

- Integrating the previous equation

$$T(z_{\parallel}) = \left[T_t^{7/2} + \frac{7}{2} \frac{P_{SOL}/A_{\parallel}(L_{\parallel} - s_{\parallel})}{\kappa_0, e} \right]$$

which for $T_u \ll T_t$ we obtain $\boxed{T_u \simeq \left(\frac{7}{2} \frac{P_{SOL}/A_{\parallel} L_{\parallel}}{\kappa_{0,e}} \right)^{2/7}}$

This equation can be easily integrated and we can also determine typical profiles of the temperature along the flux tube.

What it is important to notice is that the temperature is almost constant along the flux tube, and the strong temperature gradient occurs only close to the plate.

You can somehow think of this happening because forces which act in order to modify the parallel temperature gradient are basically due to the sink of the energy, which is coming from the interaction with the neutrals.
Since we are assuming that the neutrals interaction is in a region which is close to the plate, this implies that any temperature gradient is basically occurring close to the plate.

Furthermore, starting from the equation which describes the temperature along the flux tube, if we assume that the temperature of the target is much higher than the temperature of the upstream, we have a simple relation which describes the temperature at the scrape-off layer upstream.

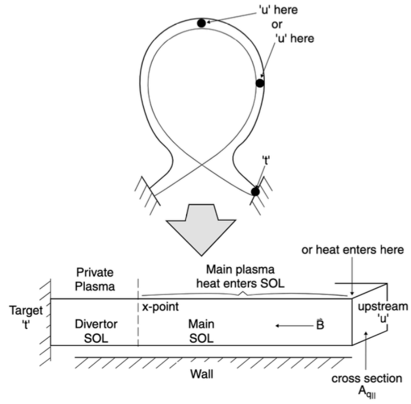
This is important because it tells you that despite the type of densities you are operating in, despite the type of heating metal that you are using, the ingredient which is setting the temperature at the separatrix entrance is basically the power and the typical geometrical dimension of the divertor. This is the parallel condition.

The basis of the two-point model is that we would like to find a proper way to relate the condition that you are getting upstream to the condition that you are getting downstream. And the condition that you are getting upstream is what you can also control at least as far as temperature is related to engineering parameters, which are dimension and power.

Unfolding the SOL: 2 point model

The two-point model is based on simple considerations, where we take into account the particle balance, the pressure balance, and the power balance.

- Particle balance: neutrals recycling from the targets are ionized in thin layer close to the target and parallel flow limited to the same region where particle accelerate up to sheath velocity entrance
- Total pressure balance: $p + nmv^2$ =constant which in the case of $T_e = T_i$ implies $p = 2nkT$ and dynamic pressure $\neq 0$ only close to the target with $v_t = c_{st} = \sqrt{2kT_t/m_i}$
- Power balance: Since $v = 0$ almost entirely in the SOL then conduction dominated dynamic with $T_u^{7/2} = T_t^{7/2} + \frac{7}{2} q_\parallel \frac{L_\parallel}{\kappa_{0e}}$. No volumetric power loss assumed (very thin ionization layer) then $q_\parallel = q_t = \gamma n_t k T_t c_{st}$



acceleration of ions close to the surface

For the particle balance we are assuming that the neutrals are recycling from the target and ionized in a thin layer which is close to the target. Furthermore, the presence of the target or the presence of the solid surfaces implies that you have acceleration of ions close to the surfaces. There is no other source of momentum along the flux tube. This implies that your flow of plasmas will be basically zero along the flux tube apart from the last part of the plasmas where it is accelerated by the presence of the sheath.

This has implication also in terms of pressure balance. The pressure is assumed to be constant, it is proportional to the kinetic pressure and to the plasma pressure.
So, in the case of equal ion to electron temperatures, and taking into account the fact that the velocity is zero along the flux tube apart to the velocities that are close to the target, the constant pressure balance implies that the pressure can be basically equalized to $p = 2nkT$.

The dynamic pressure is different to zero, only close to the target where we can assume the velocity is basically equal to the ion sound speed.

heat flux dominated by conduction

If you take into account now the power balance, since the velocity is zero, almost entirely in the scrape-off layer, then this implies that the power balance or the heat flux is basically dominated by conduction, whereas the convection will be quite limited. We are in the condition of conduction limited and dominated, we have already seen that there exists a relation which holds between the upstream temperatures and the target temperatures.

NO POWER LOSSES
↓
ionization in a thin layer close to target

We are assuming for the moment that there are no volumetric power losses. This is done taking into account as an assumption of the two point model that the ionization is limited to a thin layer just close to the target.

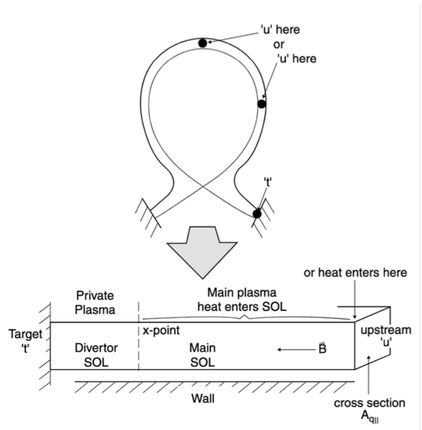
This implies that the parallel heat flux at the target, given that there is no ionization and no other power losses, is basically the convective flux of the electrons multiplied by the temperature at the target.

If we now combine all this information together, we have a relation which relates the pressure at the target and the pressure upstream , a relation between the temperature of the target and the temperature of the upstream and then we have the definition of the parallel flux taking into account the ion sound speed at a sheath entrance.

- Combining all these information together we have:

relation for pressure at the

$$\boxed{\begin{aligned} 2n_t T_t &= n_u T_u \\ T_u^{7/2} &= T_t^{7/2} + \frac{7}{2} q_\parallel \frac{L_\parallel}{\kappa_{0e}} \\ q_\parallel &= q_t = \gamma n_t k T_t c_{st} \end{aligned}}$$



A bit of math. What is important is to properly describe the relation between the quantities.

- We derive now n_t, T_t, T_u from n_u and $q_\parallel$

power crossing the separatrix

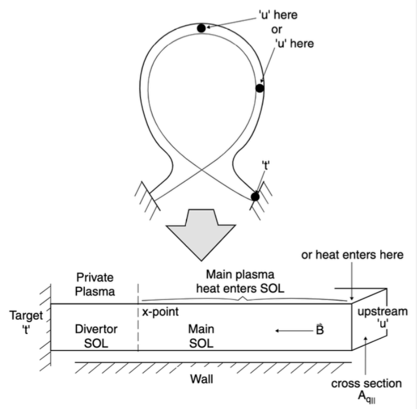
$$T_u \simeq \left(\frac{7}{2}\frac{q_\parallel L_\parallel}{\kappa_{0e}}\right)^{2/7}$$

t: target

$$T_t = \frac{m_i}{2e}\frac{4q_\parallel^2}{\gamma^2 e^2 n_u^2 T_u^2} \simeq \frac{m_i}{2e}\frac{4q_\parallel^2\left(\frac{7}{2}\frac{q_\parallel L_\parallel}{\kappa_{0e}}\right)^{-4/7}}{\gamma^2 e^2 n_u^2} \propto \frac{q_\parallel^{10/7}}{L_\parallel^{4/7}\boxed{n_u^2}}$$

$$n_t = \frac{n_u^3}{q_\parallel^2}\left(\frac{7}{2}\frac{q_\parallel L_\parallel}{\kappa_{0e}}\right)^{6/7}\frac{\gamma^2 e^3}{4m_i} \propto \boxed{n_u^3}\, q_\parallel^{-8/7} L_\parallel^{6/7}$$

$$\Gamma_t = \frac{q_\parallel}{\gamma e T_T} = \frac{\boxed{n_u^2}}{q_\parallel}\left(\frac{7}{2}\frac{q_\parallel L_\parallel}{\kappa_{0e}}\right)^{4/7}\frac{\gamma e^2}{2m_i} \propto n_u^2 q_\parallel^{-3/7} L_\parallel^{4/7}$$



We already said that the upstream temperature is basically defined by the amount of flux which is flowing parallel, and this is also related to the amount of flux which is crossing the separatrix. So $q_\parallel$ is the power which is crossing the separatrix.

e) The temperature of the target is what you want to minimize in order to reduce the plasma wall interaction and the damages to the plasma facing component. It is inversionally proportional to the densities upstream. There is a strong inverse dependence between the temperature and the densities of the target.

Minimize the heat flux → operate at higher densities

Why this is important? Because basically, this implies that whenever you want to minimize the heat flux at the target in order to preserve your plasma facing component, you need to operate at higher densities. This is also important because operations at higher densities are the operations which ensure the larger fusion power production.

2) The density at the target is also strongly dependent on the density upstream. So, why is it true that you can increase as far as you can the density upstream in order to reduce the temperature? You need to keep in mind that, in any case, you are also increasing your density at the target. And this increase of the density at the target has consequences because this implies that your physical sputtering is also increasing.

3) The flux at the target is proportional to the power and to the density.

So, there is a combination of beneficial effect in terms of reducing temperature and let's say a drawback, which is the increasing of the local densities and the sputtering. Sputtering implies that also you have much more recycling neutrals - more neutrals which are ejected.

It is interesting now how the power and the pressure ~~is~~ are reduced because of the neutral interaction.

We have not taken into account any other processes along the flux tube and any power losses coming from radiation or charge exchange.

Nevertheless, these processes happen and actually, they are used in order to ensure that we have a condition at the target which is safe from the operational point of view. We want to increase the radiation and we want eventually to increase also the momentum losses in order to ensure that you have a target in a safe condition.

Modified 2Point model

If you take into account the volumetric power losses which are coming from radiation and charge exchange losses, then you can assume that the parallel flux flowing along the flux tube is related to the flux at the target, but it also depends on all these volumetric power losses which are proportional to the parallel flux via proper quantities.

parallel flux along the flux tube related to the flux at the target

- We need to account the effect of Volumetric power losses due to radiation and charge exchange losses, $q_{rad}^{SOL} + q_{CX}^{SOL} = f_{pow} q_{\|}$ which modify the power balance equation as

$$(1 - f_{pow}) q_{\|} = q_t = \gamma k T_t n_t c_{st}$$

- The momentum equation is modified to account for **momentum losses** which are due to volumetric momentum losses (e.g. friction with neutrals, viscous forces, volume recombination) as well as *effective volumetric losses* due for example by cross-field transport:

$$2 n_t T_t = f_{mom} n_u T_u$$

- Some residual convection still remain, which tend to reduce the temperature gradient. We therefore introduce a conduction factor f_{cond} so that $q_{\|,cond} = f_{cond} q_{\|}$

On the other hand, you have also possible losses of momentum coming from volumetric momentum losses (friction within neutral, viscous forces, friction with impurities, ...).

Similar to what we have done before, so the definition of a sort of effective momentum or effective volumetric power losses, we can define a sort of effective volumetric momentum losses. And this has an implication in the definition of the pressure balance equation. There might be still some residual convection. Before we said that we were assuming the proper only conduction limited because we have made a strong assumption that the velocities of the ions are basically zero along the flux tube apart from just a tiny region in front of the target. Nevertheless, some residual convection might remain.
And this basically tends to reduce the temperature. We also introduce a factor which account for residual conduction.

If we take now all these further possible processes, we can modify slightly the two-point model description. We need to take into account the residual conduction, even though you can clearly see that the dependence on conduction is quite low - it's at the power two over seven. So the upstream temperature is basically unaffected by any momentum losses or volumetric power losses and there is only a small variation due to the convection.

upstream temperature unaffected by any momentum losses or volumetric losses
ONLY SMALL VARIATION due to convection

- The upstream temperature is modified accordingly and in the condition of $T_t \ll T_u$ we have

$$\boxed{T_u \simeq \left(\frac{2}{7}\frac{f_{cond} q_\| L_\|}{\kappa_0 e}\right)^{2/7} \propto f_{cond}^{2/7}}$$

temperature upstream

T_u unaffected by momentum loss or volumetric power loss and small variation due to the convection

- Target temperature strongly reduced by volumetric power loss and increase by momentum loss

$$\boxed{T_t \propto \frac{(1-f_{pow})^2}{f_{mom}^2 f_{cond}^{4/7}}}$$

temperature at the target → dependence on volumetric power losses

If you take into account the target temperature, in this case, it has a stronger dependence on the volumetric power losses. This is important because in the processes of the detachment basically what happens is that you increase as much as you can your volumetric power losses via strong fueling and strong interaction with the neutrals or at least as a consequence for the target change, or eventually via radiation via impurities. This is one of the method that we ensure in order to have a lower target temperature.

increase the volumetric power losses ↓ to have lower target temperature

On the other hand, the target temperature is strongly reduced by volumetric power losses and is strongly increased by momentum losses. Correspondently, the ratio between the upstream and the target temperature has a clear tendency or a clear dependence on the convection. You can see that the convection tends to reduce and to eliminate the parallel temperature gradient.

- Correspondingly the ratio of upstream and target temperature results in

$$\boxed{\frac{T_u}{T_t} \propto \frac{f_{cond}^{6/7} f_{mom}^2}{(1-f_{pow}^2)}}$$

→ tendency of convection to reduce the parallel temperature gradient

with the clear tendency of convection to reduce/eliminate the parallel temperature gradient

- The target density results in

$$\boxed{n_t \propto \frac{f_{mom}^3 f_{cond}^{6/7}}{(1-f_{pow})^2}}$$

target density

We recognize a robust effect of momentum dissipation in suppressing target density

If you now look at the target densities and the dependence on the different quantities, we clearly recognize a robust effect which is due to the momentum dissipation in suppressing the target ~~temperature~~ density. In other words, all these processes may also have an effect in suppressing the target densities.

stronger modification ↓ due to momentum losses ↓ reduction of the flux to target

We introduced all these additional processes to tell also that the particle flux is modified and the stronger modification is due to the momentum losses, which again reduces the flux to target.

- Finally the target particle flux is modified as

$$\boxed{\Gamma_t \propto \frac{f_{mom}^2 f_{cond}^{4/7}}{1 - f_{pow}}}$$ → strong contribution of momentum losses

and thus with a strong contribution of momentum loss in reducing fluxes to the target

This is easy to be understood because at the end we take into account that the flux is due basically to the velocities of the impinging ions - any process which ensures a loss of momentum and a loss of velocities is acting in reducing the flux.

loss of momentum and velocities → reduce the flux

Divertor regimes

If you now take into account all the processes that we have described, we can define three different linear regimes for the divertor.

For a given $q_{\|u}$ input in a flux tube it is generally observed that as n_u is increased the target T_t decreases and the corresponding flux tube passes through different regimes:

1. Sheath limited Regimes where small temperature gradients exists and $q_{\|}$ is constrained by sheath condition. $\Gamma_{\|}$ and pressure approximately constant along the flux tube
2. High Recycling Regime a.k.a. *Conduction limited regime* where $q_{\|}$ is constrained by sheath condition and temperature conduction. Significant drop of T_e, $T_t \ll T_u$, $\Gamma_{\|,u} \ll \Gamma_{\|,t}$ but momentum is still constant along the flux tube
3. Detachment regime with significant reduction of the power and particle fluxes to the target with associated pronounced pressure drop

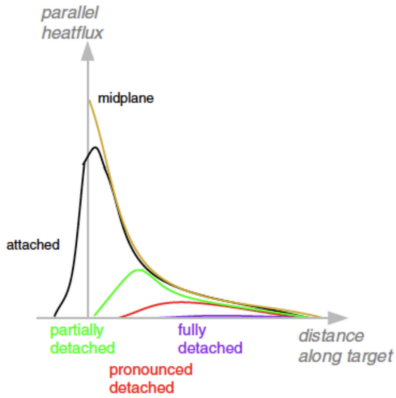
There is one regime which is called the **sheath limited regime**. This occurs at high power, low densities in general and small temperature gradient exists close to the target. It is the regime where the condition or the assumption we made at the beginning that the temperature gradient is confined in the tiny region close to the target holds matter. Also, these are the conditions where the parallel heat flux is basically due to the sheath condition. This ensures that your pressure balance is preserved, so the pressure is preserved along the flux tube and it is constant. This regime, from the point of view of the plasma facing component, is the most demanding because basically, you have no way that the amount of heat flux that you have at the target is the higher possible based on the power that is crossing to the separatrix. So there is no dissipation of heat flux along the flux tube.

The second regime is called a **high recycling regime** or conduction limited regime. Again, the parallel heat flux is constrained by the sheath condition and the temperature conduction. But nevertheless, in this condition, there is a strong drop of temperature between upstream and downstream. These high recycling regimes, nevertheless, do preserve the momentum.

Finally, you have what is called a **detachment regime**. Detachment describes processes according to which the plasma is physically separated by the target somehow. In this case, there is a significant reduction of the power and the particle flux to the target and there is a pronounced pressure drop from upstream and downstream.
Detachment regimes are those regimes where future devices are foreseen to operate. ITER is foreseen to operate in what is called a partial detachment regime. Partial detachment means that the region, the flux tube just across what is called a near scrape-off layer - so the region just outside of the separatrix - will be detached through the target. Future devices like DEMO will operate in what is called a full detachment. So the plasma will be detached from the target in all the radial directions. And this is important because this is the only way that we can ensure survival of the plasma facing component.

If you want to see this from the point of view of the heat flux, we can look at the image below.

For a given $q_{\|u}$ input in a flux tube it is generally observed that as n_u is increased the target T_t decreases and the corresponding flux tube passes through different regimes:



(Kallenbach *et al.* 2015)

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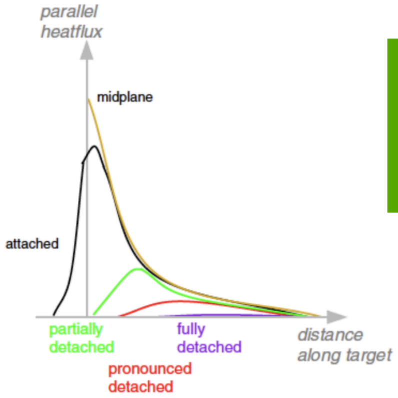
This is basically a radial profile of the heat flux of the target. The zero is basically the strike point, which coincides to the separatrix upstream. In yellow, you have the heat flux profiles upstream and then you have the three conditions. So the sheath limit is attached where we have these profiles in black. If partially detached, you can see that there is a significant drop of heat flux from upstream to the target in a certain region of the plasma, close to the separatrix. We have a pronounced detachment where the reduction of heat flux is occurring in a wider region of the SOL and then we have a full detachment. A full detachment should be preserved whatever happens, so even also during the transients, meaning during the transition from H mode to L mode, during the sawtoothing event, which you can see as well in the target, and eventually during the ELMs.

Keep in mind that the DEMO class devices are thought to operate without ELMs. ITER will operate in what is called mitigating ELMs regimes. In other words, it will operate with a resonant magnetic perturbation in order to ensure not to have significant ELMs suppression. But demo needs to operate in conditions which are even more demanding, so in conditions where there is no ELMs at all.

For a given $q_{\parallel u}$ input in a flux tube it is generally observed that as n_u is increased the target T_t decreases and the corresponding flux tube passes through different regimes:



But what we can expect to be the λ_q in future devices?

(Kallenbach *et al.* 2015)

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Can we foreseen which is typically the length of the heat flux? And is this important? Yes, this is important to know basically how fast the heat flux decays whenever we cross the separatrix, so the decay length of the yellow curve. This is important to know because this basically determines the heat flux withstanding capabilities or withstanding constraints of any material which is of the target.

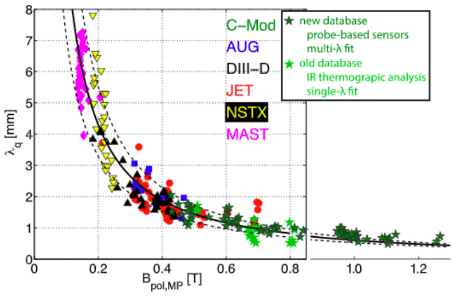
The need for exhaust solution: λ_q scaling

The heat flux decay length has been estimated, or at least there has been a longer extensive analysis of the typical heat flux decay length in the near-scrape-off layer.

- ITPA multi-machine database suggest only the poloidal magnetic field is statistically important (Eich *et al.* 2013)

$$\lambda_q = (0.63 \pm 0.08) B_{pol}^{-1.19\pm0.08}$$

- Recent extension to ITER relevant poloidal magnetic field (Brunner *et al.* 2018) suggest the validity up to a predicted $\lambda_q^{ITER} \leq 1$mm
- The predicted heat flux exceed the engineering material limit set to approximately 10 M/m^2 or bit higher (to avoid W material re-crystalization (Pitts *et al.* 2019)). We need mitigation strategy



ITPA is a multi-machine database which has been determined at the beginning of 2010 and what it has been seen is that on a statistical basis, the heat flux decay length depends only on the poloidal field, or in other words, it depends only on the dimension of your devices and on the current where this will operate. Such a multi-scale database has been determined only in a sheath-limited condition. We have data up to 1.2 Tesla in poloidal field, with data coming primarily from C-mode because C-mode is one of the smaller machine and it is allowed to operate at high toroidal field.

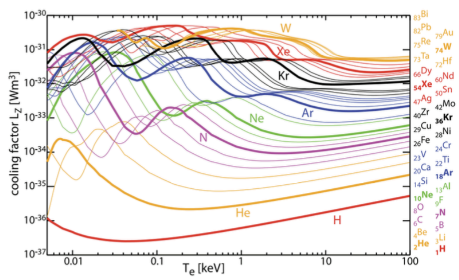
Why this was so threatening? First of all, this was threatening because if you project to the values which are foreseen for ITER, this implies that according to this scale, ITER should have an heat flux decay length of 1 minute, which is pretty small.
What does it implies to have a decay length so small? This implies that if you project the heat flux down to the target, the amount of flux will be deposited in a very narrow region in a radial extent. And this has clear implication from the point of view of the mechanical resistance of the plasma facing component.

This was threatening because of the possibility of melting: this was the main constraint, because when you melt a tungsten, it will have a full tungsten crystallized. And this re-crystallization reduced the mechanical properties of the tungsten. So, the average number that we can deal with is of the order 10 MW/m2 or slightly higher.
We need to find a proper way to reduce this heat flux and to ensure that the plasma is at least partially detached or fully detached.

Radiative divertor

We have seen that there is a strong dependence on the volumetric power losses coming from radiation, which has beneficial effect in terms of reduction of heat flux at the target.

- Extrinsic impurity injected to increase radiation and provide tolerable heat load
- Scenario foreseen for ITER operation (Ne injection) to achieve partial detachment of the OSP
- For DEMO higher radiation fraction needed (90 % of P_{sep}) needed



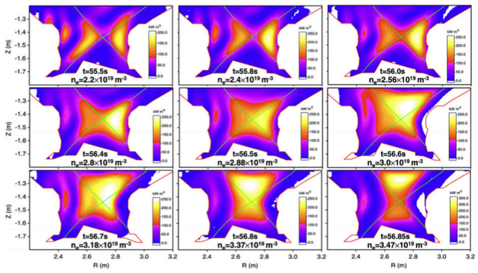
(Pütterich *et al.* 2019)

This means that the operation in future devices are foreseen with the injection of extrinsic impurities (e.g., noble gasses). In present devices this is done with nitrogen. Nitrogen do have a bad habit to bound with the hydrogen, so it is forbidden in operation in nuclear environment because it can also bound with the tritium and therefore produce a tritium ammonia, which is quite a dangerous to be treated.

Therefore, the future operation will be done likely with the neon or even higher z, for example, argon.

What you can see in the plot above is what it is called the cooling factor. So, the capabilities of radiation of a different specie at the different ionization stage is a function of the temperature. You can see that the neon will have quite high cooling factor at the values of temperature that you can expect to have in ITER.

- Extrinsic impurity injected to increase radiation and provide tolerable heat load
- Scenario foreseen for ITER operation (Ne injection) to achieve partial detachment of the OSP
- For DEMO higher radiation fraction needed (90 % of P_{sep}) needed
- Drawback appearance of a MARFE (multifaceted asymmetric radiation from the edge) and corresponding radiative collapse



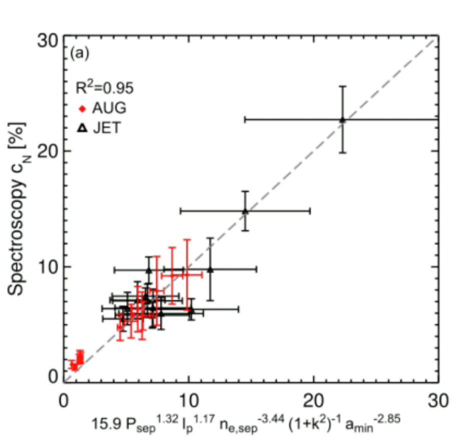
(Huber *et al.* 2007)

On the other hand, there are also possible drawbacks in terms of impurities because impurities need to be confined in a certain region, like the SOL, because if they are able to penetrate with a substantial factor into the confined region, they tend to radiate a lot and to cause what is called MARFE. A MARFE, which is a multifaceted asymmetric radiation from the edge, is a dangerous mechanism according to which physically the impurities penetrates the region. They start to emit a lot, likely close to the x point and this emission causes a radical collapse of outer plasmas. So, you need to find a proper way for the impurities, the proper amount of impurities to be injected in order to be sure to have enough radiation to cool down the divertor without polluting the plasma too much or without entering in what is called MARFE. There are also other regimes, methodologies according to which you can somehow control the position of this stronger radiation. What is seen is that the control of this position can be done by a combination of power and a real-time influx of impurities.

If you are able to keep this radiation front confined just close to the x point, you can enter a different regime which is called x-point radiator. This x-point radiator is quite appealing in view of DEMO because it ensure to have almost 90% of the energy radiation fraction. And keep in mind that DEMO will need to operate with a radiation fraction. So, amount of power dissipated by a radiation quite high, or 90%. This radiation fraction is in any case kept in a localized region, which is this region around the x-point.
This x-point radiator has also the possibility to enter regimes without the ELMs. So, in other words, you need to inject the sufficient amount of impurities to ensure to have strong enough radiation to cool down the divertor to be in full detachment, but this radiation should be confined in a tiny region close to the x-point. This can be done in real time and by controlling the divertor position. If you put in the right position, you do not enter this dangerous radially collapse, but you enter a beneficial and rather good confinement condition where you have no ELMs, strong radiation, while keeping the confinement at a reasonable high level. And this is what it is called the x-point radiator.

Which is the amount of impurities that you need, the impurity concentration? This is quite important to be determined because you need to be sure to have enough to cool down, but not too high to cause a radially collapse. There are several theories which have been developed in order to determine the proper impurity concentration for the detachment. There are three main theories, listed below.

- Different models proposed for determining impurity concentration needed to provide detachment
  - **Goldston scaling** which focus on separatrix density (Goldston *et al.* 2017) $c_z \propto \frac{P_{sep}}{B_p(1+\kappa)^{1.5} f^2_{GW,sep}}$
  - **Reinke scaling** which focus on machine size (Reinke 2017) $c_z \propto B_T^{0.88} R^{1.33}$
  - **Kallenbach scaling** which focus on momentum and energy loss $c_z \propto \frac{P_{sep}/R}{p_{div}\lambda_{int} R^{rz}}$
- Experimental results on multimachine scaling provide hints towards Goldstone scaling with a further dependence on minor radius



(Henderson, IAEA 2020, IAEA2023)

Two of them have a strong dependence on the separatrix. There are other dependencies, like the one on the elongation, on the shape, on the densities where you are operating, on the GW factor - that is the ratio between the density that you have and the GW density.

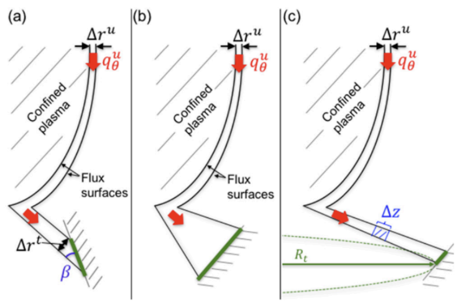
Experimentally, what has been determined is the proper concentration of nitrogen in order to get proper detachment. It has been done in two devices, and so the experimental evidences suggest that the proper theory describing the concentration is the one of Goldstone. We have a strong dependence on the poloidal field, and this is a beneficial effect. You can also play a bit with the elongation in order to have a better and more favorable concentration and achieve the condition you are looking for.

Geometrical effect on heat flux

There are other possibilities to mitigate the heat flux, and this can be done, for example, by a modification of the magnetic geometry.

1) For example, you can properly tilt the poloidal plane. If you tilt the poloidal plane and you think about the projection of the parallel flux, it will be spread on a wider surface and this has strong beneficial effect.

- Grazing angle reduce the amount of parallel heat flux perpendicular to the surface $q_\perp = q_\parallel \sin\alpha$
- Tilting the divertor plate on the poloidal plane of an angle β already drastically reduce the perpendicular heat flux
- Increase flux-surface separation at the target by increasing the poloidal flux expansion $f_x = \Delta r_t / \Delta r_u = B_\theta^u B_\phi^t / B_\theta^t B_\phi^u$



(Theiler *et al.* 2017)

- Increase the target radius. Extension of 2PM to include the variation of the major radius along the divertor leg brings (Kotschenreuther *et al.* 2010; Petrie *et al.* 2013)

$$T_e^t \propto \frac{q_\parallel^{10/7}(1-f_{pow})^2}{n_u^2 L_\parallel^{4/7}} \frac{R_u^2}{R_t^2} \qquad n_e^t \propto \frac{n_u^3 L_\parallel^{6/7}}{q_\parallel^{8/7}(1-f_{rad})^2} \frac{R_t^2}{R_u^2}$$

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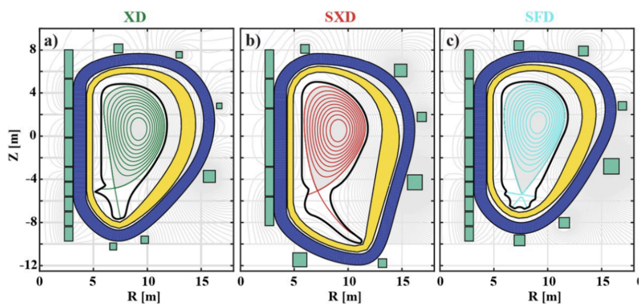
You can play with what is called the poloidal flux expansion, which is basically the ratio 2) between the width of the flux tube upstream with respect to the width of the flux tube at the target. This is the second figure in the slide.
This can be determined, and you can play with the flux expansion by a proper tailoring of the poloidal and toroidal field and the target. If you are increasing your flux expansion, basically you are spreading the heat flux on larger surfaces at the target.

The third possibility is to increase the target radius and the beneficial effect can be 3) described if you extend the 2point model taking into account the differences of radius between upstream and downstream. And what you can see is that the target temperature is basically proportional to the ratio between the quantities in the slide, so if you increase the target radius, you reduce the target temperature.

Alternative divertor configuration

There are other possibilities, which are called alternative divertor configurations. These are alternatives with respect to the standard lower single null operation, which is the one adapted for present tokamaks like ITER.



(Reimerdes, Ambrosino, *et al.* 2020)

- Alternative divertor proposed to the standard Lower Single Null adopted for present tokamaks and ITER
- Exploitation of flux flaring at the target (X-divertor), of large R_t effect (Super-X divertor)
- Additional solution known as Snowflake configuration suggested (Ryutov & Soukhanovskii 2015) with the inclusion of a second X-point

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There are several possible different divertor configuration, some of them are considering the flaring of the flux at the target, which is called x-divertor - the flaring is the expansion of the flux tube close to the target, similar to the flux expansion described before.

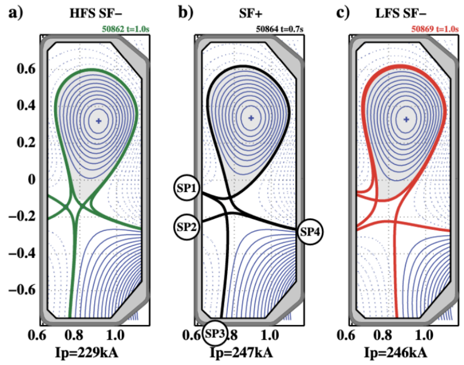
There is what it is called a super x-divertor, where you take the outer leg, and you put it quite far apart, so you have the beneficial effect of the target, and this can be combined as well with the proper local flaring close to the target.

There are other possibilities where you inject a second x-point, and that is called the snowflake divertor. The snowflake divertor has different topologies, according to which the second x-point is actually in the brighter flux region and in the common flux region (?). It has beneficial effect because what happens is that it is spreading the power - which is in conventional divertor split between the outer targets - in four different positions, four different targets. Nevertheless, this type of configuration is quite demanding from the point of view of the magnetic configuration, because it requires a lot of power for having a second x-point inside the vacuum vessel. Therefore, even though it is explored in present devices, it is very unlikely to be adopted in a future fusion power plant.

Just for you to know, DEMO central team, which is the team that is presently making the conceptual design of DEMO, is still adapting the standard Lower Single Null, eventually with a bit of longer divertor leg, with a bit of flux expansion, and it is relying on the capabilities to have a full detachment of plasma even before the L-H transition, and eventually to work a bit with the strike (?) point sweeping, so moving the stripe point during the discharges in order to ensure to spread the power on a larger surface.

Are alternative divertor configuration compatible with full detachment or an x-point radiator? Yes, actually there are several possibilities. What happens is that whenever you inject impurities, the x-point is sitting basically in the region between the two x-points, and if you put the second x-point even down close to the target, which is called the x-point target, a radiator can confine that the radiation front just very close to the target. These are all beneficial effects. In principle, there is a combination of proper baffling (?): having the baffling of the configuration is a geometrical effect where you put your strike point in a region, in a divertor chamber, which is quite close. And this is a beneficial effect because basically what happens is that the neutrals bond back and forth, but they are confined into the divertor chamber. And this enhance your momentum losses, your power losses, and this ensure easier achievement of detachment.

- Zoo of possible SF configuration exists, mainly SF+ and SF- (with second X-point in the private or common flux regione)
- Provide power sharing distribution among the 4 SPs (Maurizio *et al.* 2018), radiation mainly localized within the 2 X-points (Reimerdes, Duval, *et al.* 2017) and modification of SOL transport (Tsui *et al.* 2021)



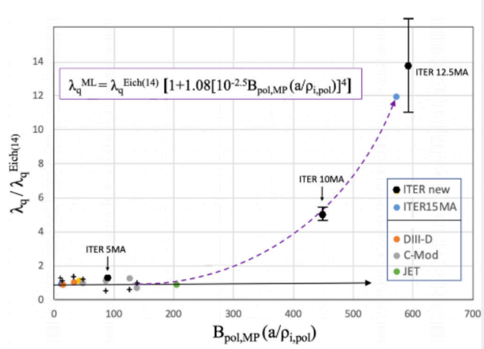
(Reimerdes, Duval, *et al.* 2017)

It has been observed in present devices that the advanced divertor configuration can detach at lower densities and you have a mitigation of the flux by a factor of 2 or 3. So, the effects are beneficial. The drawback is the complication from the engineering point of view.

Extrapolation to future devices: the quest for anomalous transport

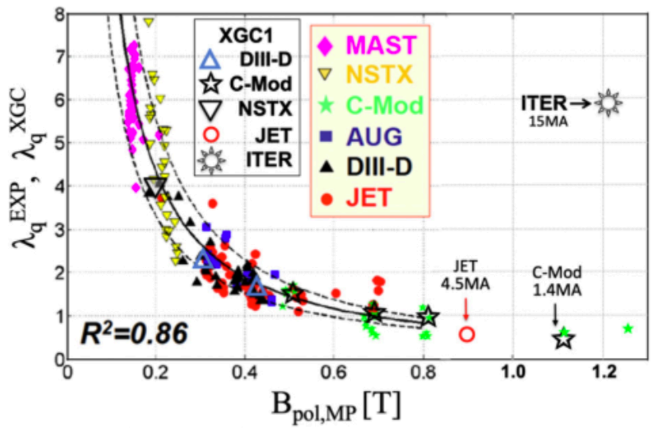
We have seen the multi-machine scaling of the heat flux decay length, which has a very challenging prediction for ITER, more or less 1 mm in attached conditions.

- Present state of the art gyrokinetic code able to mimic the observed scaling (Chang *et al.* 2021)
- Whenever extended to future devices higher λ_q foreseen due to a change of the underlying physical mechanism with TEM in weakly collisional plasma as efficient transported of electron heat and mass
- Machine learning approach suggests a scaling compatible with the observed ITPA database as well as giving additional physical insight



(Chang *et al.* 2021)

In order to see what will happen afterwards, so in devices which are larger and operating higher current, you need to rely only on numerical simulations. But those numerical simulations should have a self-consistent description of the transport. Present state of the art of gyrokinetic codes is now able, actually, to mimic the observed scaling. In the plot below, you have some points - the empty symbol - which are the numerical simulations coming from this gyrokinetic code. They are matching pretty well the experimental observation, up to the cases of C-mode, so up to very high poloidal field.



(Chang *et al.* 2021)

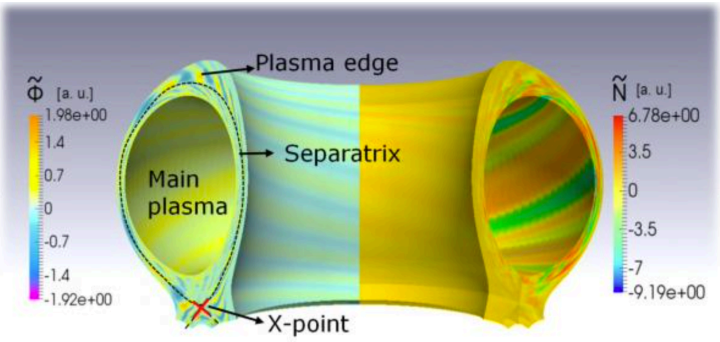
Nevertheless, for ITER, we do see a strong increase of the heat flux decay length, which could be beneficial in the sense that all the threat caused by the exhaust problem for ITER will be clearly released because five millimeter will be clearly very efficient. These are for the moment only numerical simulation, and there is up to now only one high fidelity code, which has been able to take all this from the numerical point of view.

The higher lambda-q, the higher heat flux, is actually foreseen, because there will be a change of radial transport foreseen for ITER with respect to what we are facing right now in present devices.

What will happen is that we will have a transport, which is dominated by different types of instabilities. It won't be dominated by instabilities driven by the ion temperature gradient, but rather by the fraction of trapped electrons and also by the fact that the radial electric fields, which build up generally in present devices across the separatrix, will be weaker. And therefore, you will have more turbulent plasmas around the separatrix: this will help spreading and increasing your radial transport. This will alleviate the parallel heat flux to the target, and will cause eventually some concern about the transport towards the first wall.

Anomalous transport in the SOL

In other approaches so far, we have concentrated on the parallel transport, because we assume basically that the power which is crossing the separatrix is flowing parallel to the target entirely.



- In all the approach used so far we concentrate on parallel transport but SOL is a combination between parallel, perpendicular and sources.
- The perpendicular transport is strongly anomalous with source of free energy coming primarily from separatrix where strong gradient resides (as well as possible damping mechanism as $\omega_{\mathbf{E}\times\mathbf{B}}$). SOL acts as well below the X-point

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Nevertheless, the scrape-off layer dynamics is a combination between parallel, perpendicular, and sources. Sources are sources of all particles, there is no source of heat in the scrape-off layer.

In the perpendicular transport is strongly anomalous. Anomalous means that it can't be described by any classical diffusion, and neither by any classical effect.
Such anomalous transport will be treated in the second lecture and we will see it depends primarily by gradients, which build up just inside the confined region, just inside the separatrix.

This type of instabilities will also have dumping, motivated by the presence of electric fields or by the presence of the shear of the magnetic field.

- Various global code currently in development Tokam3X, GBS, GRILLIX as example, all including em effects as well as neutrals based on fluid approach. Extension to gyrofluid or gyrokinetic approach in progress

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Conclusions

- We clarify the importance of SOL and Divertor in view of Fusion exploitation
- Divertor and upstream conditions are tightly linked: density and upstream power set the conditions at the target as well as the regime. True as well the opposite (e.g. neutral pressure at the target set he $n_{e,sep}$)
- A global assessment need an experimental and modeling approach beyond the standard diffusive and 2D SOL approach.
- Remember that PEX is considered as a possible showstopper for fusion exploitation
- Remember this is clearly an incomplete review/lecture where we left apart many topics: PWI, Liquid Divertor, Proper atomic physics occurring at the target ...

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Thus, what we have done: we have tried to clarify the importance of the scrape-off layer and Divertor in view of the Fusion exploitation. In the Eurofusion roadmap, it has been clearly stated that the exhaust problem was one of the possible showstoppers in view of any demo design. This has indeed motivated a lot of investment for machine announcement. ASDEX has started the operation with a new divertor, which will allow exploration of advanced divertor configuration as a possible solution for the problem.
We will have DTT, which has been conceived in order to provide exploration of divertor configuration and design at high power in metallic devices and in view of a solution to exhaust problems.

The divertor and upstream conditions are tightly linked, so the density and the upstream power set the condition at the target, as well as the regimes. It is also the opposite, in the sense that the amount of recycling that you have at the end of the target, which is due to the recycle particle, basically have a strong influence on the amount of densities that you can achieve upstream.
A global assessment needs both an experimental and modeling approach. This has been treated generally via a standard 2D scrape-off layer approach, treating the transport in a pure diffusive approach.
As we have seen, the exploitation to future devices would need a better description of the transport.
We didn't talk a lot about the plasma wall interaction, so the type of interaction: physical sputtering, chemical sputtering, the type of materials, what happens to the materials. And

we didn't talk about the liquid divertor, which is one possible solution, and the proper atomic physics of the target.

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