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Screening conditions in a magnetized plasma with electron beam, with application to ripple trapped electron losses

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1-Introduction : trapped electrons losses in ripple

In Tore Supra , electrons are accelerated by lower hybrid waves in the direction parallel to the confinement magnetic field, in order to drive non-inductive current. But electrons have also on increase of their perpendicular velocity, then 10% of the most energetic electrons get trapped in the magnetic ripple between 2 adjacent toroidal coils, thus forming a beam. Under the ripple trapping conditions, most of beam energy is perpendicular (100keV) and few hundreds eV are implied in parallel energy. Then fast electrons drift along iso B curves to reach the Vertical Port (VP) located at the top of the tokamak chamber (*fig. 1*). The electron beam follows a banana trajectory and the vertical step per bounce is millimetric (*fig. 2*), so the 20 mm wide protection represented by a cooled copper tube is assumed to protect the VP entrance from this energetic flux. Nevertheless, this beam is able to go beyond the copper tube and creates a hot spot on the steel panel edge able to melt the metal (*fig. 2*).

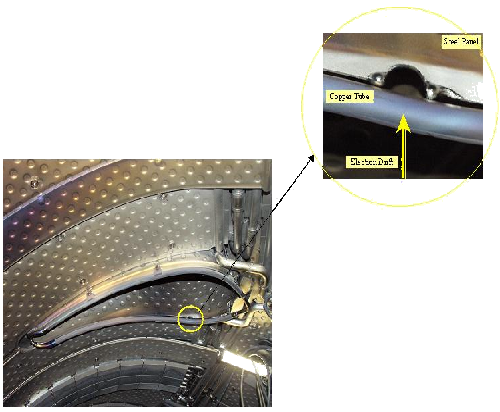

Figure 1 : *Melting of the steel panel at the VP entrance due to fast electron beam deposition*

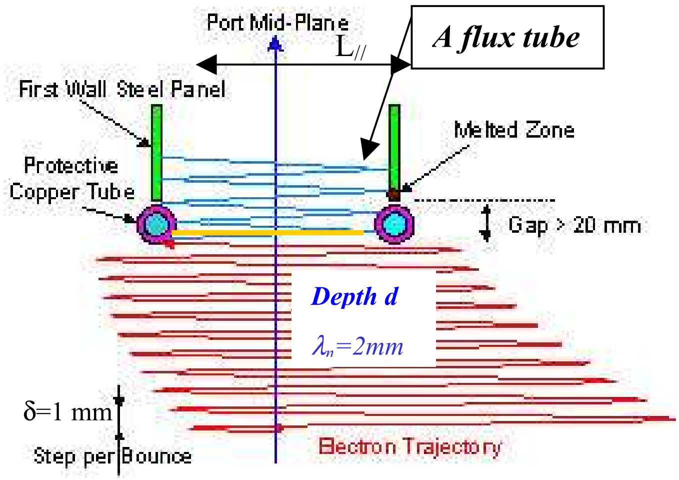

Figure 2**(1)** : *Fast trapped electron trajectory and geometry of the vertical port in the Z-ϕ plane*

We can explain this deviation by means of sheaths localized at the end of each flux tubes between the cooled copper tube and walls. In some conditions, these sheaths are able to repel sufficiently a part of the beam density deeper in the VP. So we use a beam-sheath theory, which reveals 4 flux deposition regimes. : 2 associated with the beam and 2 with finite flux tube length. Indeed the sheath length is proportional to the Debye length and a function of the beam velocity and density. So it increases while entering deeper in the VP because the background plasma density decreases exponentially with depth d (see coordinates on *fig. 2*), with a typical gradient length λ_n=2mm. Eventually the sheath length can reach the flux tube length and screening conditions are modified. For next parts , we intoduce the *table 1* that shows all symbolic notations used in equations and their typical value in Tore Supra :

f_i	Ion distribution velocity	Drifting Maxw.
f_{e1}	Thermal electron velocity distribution	Maxwellian
f_{e2}	Supra thermal electron velocity distribution	Drifting Maxw.
n_i	Ionic density	5.10^{17} m^{-3}
v_{iT}	Ionic parallel thermal velocity	4.10^4 m/s
$v_{i//}$	Ionic parallel drift velocity	4.10^4 m/s
n_{e1}	density for thermal electrons	5.10^{17} m^{-3}
v_{e1T}	parallel thermal velocity for thermal electrons	2.65 10^6 m/s
n_{e2}	density for supra thermal electrons (beam)	6.2→6.5 10^{15} m^{-3}
v_{e2T}	parallel thermal velocity for supra thermal electrons	2.65 10^6 m/s
$v_{e2//}$	parallel drift velocity for supra thermal electrons (beam)	10^7 m/s
v_s	Sheath equivalent velocity $v_s = \sqrt{\frac{2e\Phi_{sheath}}{m_e}}$	4.10^6→2.10^7 m/s

Table 1 : *definitions of variables and value of plasma parameters at the entrance of the VP used in following theories and simulations.*

2- Physical model and theory : electron beam repelled by sheaths

At the end of a flux tube (*fig. 2*), in front of wall surface, the sheath maintains electron and ion particle outfluxes equal to respect the plasma quasi neutrality. Because beam electrons have on average more parallel kinetic energy than thermal ones, the repelling potential has to increase with the beam flux at sheath edge. We obtain this potential by using the Tskhakaya model(2) which is based on the fluxes equality :

$$\int_{-\infty}^{0} v.f_i(v)dv = \int_{-\infty}^{v_s} v.f_{e1}(v)dv + \int_{-\infty}^{v_s} v.f_{e2}(v)dv \qquad \textbf{[1]}$$

This constitutes the theory 1 that allows us to predict the fraction of the beam which will be repelled at each bounce in the VP (*fig. 3*). From theory 1 we obtain 2 flux deposition regime in the VP for which sheaths are free ($L_{sheath}< L_{//}/2$). For the first, regime a, beam flux Γ_{e2} is lower than Bohm flux Γ_{Bohm}, the sheath potential is approximately the floating potential and then whole flux of the beam is absorbed by the wall while part of thermal electrons are repelled to balance electron and ion outflux. In regime b, beam flux is greater than Bohm flux. Then the sheath potential approaches the supra thermal energy of electron beam in order to repel whole thermal electron flux and a part of beam flux.

Theory 2 takes into account the increase of the sheath length with *depth d* in the VP and thus their junction when $L_{sheath} > L_{//}/2$ (*fig. 4*). An obstructed sheath potential is always lower than a free sheath one because the screening is partial . Therefore the electron beam are less repelled by sheath and flux deposition is faster. So we obtain the next 2 regimes, regime c and d, which correspond to regime a and b but with lower sheath potential and so more flux deposition. To predict this partial screening and then the new value of the sheath potential due to these obstructed sheaths, we use the potential profile (*Eq.[2]* & Stangeby model[3]) of the sheath and extract it at half the flux tube length. The potential decreases brutally when sheaths join themselves, which is verified by a PIC code[4] on *fig. 4*.

$$\frac{d^2\Phi}{dx^2} = -\frac{e}{\varepsilon_0} n_i \left[\sqrt{\frac{\Phi_s}{\Phi}} - \exp\left(\frac{\Phi - \Phi_s}{kT_{e1}} \right) \right] \rightarrow \Phi(x) \rightarrow \Phi_{sheath} = \Phi(L_{//}/2) \qquad \textbf{[2]}$$

x is the flux tube coordinate, Φ is the sheath potential profile, T_{e1} is the electron temperature of the background plasma and Φ_s the sheath potential obtained with Eq.[1]. Equation [2] does not include the beam contribution but gives the shape of a sheath potential profile which is integrated between 0 and the sheath potential given by Tskhakaya model in which the beam is included.

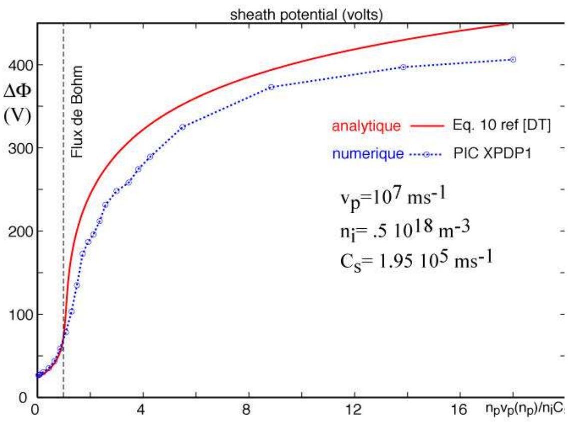

Figure 3 : *Sheath potential as a function of beam flux at sheath entrance $n_p v_p$, normalized to ion outflux (Bohm flux $n_i C_s$). For free sheaths ($L_{sheath} < L_{//}$).*

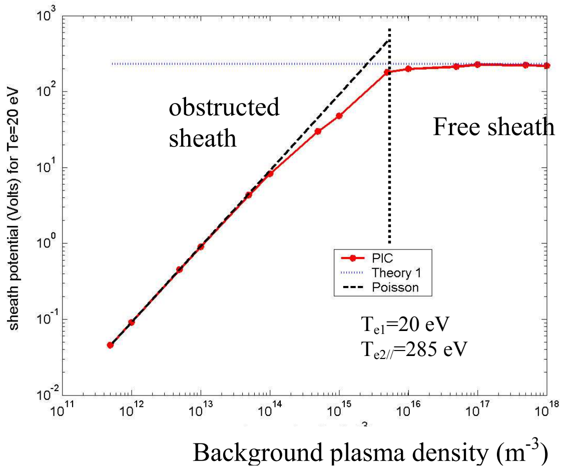

Figure 4 : *Sheath potential as a function of mean ion density along flux tube.*

Poisson : $\Delta\Phi = -\frac{e(n_i - n_e)}{\varepsilon_0}$ *in the sheath*

3- Simulation results : fast electron beam deposition in the Vertical Port

The simulation parameters are defined to be the closest from the physical ones in Tore supra (table 1). Simulations consider 4 distinct flux deposition trajectories (figure 5) which are in fact a combination of the regimes we described previously. We consider here the beam density, which is equivalent to the beam flux Γ_{e2} because velocity distribution is maintained constant during each bounce. Trajectories ①,②,③ and ④ correspond to the way followed by the beam in the VP.

Trajectory description : n_{e2Lim} is a limit density for which there is a bifurcation of the trajectory (*fig. 5*), it depends on the number of bounces *i* of the beam in the VP, C_s, $v_{e2//}$ and n_i the ion density at VP entrance d=0 $n_{e2Lim} = \sum_{i=0}^{\infty} n_i \frac{C_s}{v_{e2//}} \exp\left(-\frac{i\delta}{\lambda_n}\right)$ with δ the vertical step length between 2 bounces (*fig. 2*).

① $\boldsymbol{n_{e2} > n_{e2Lim} \leftrightarrow \Gamma_{e2}(d=0) = 3.25\ \Gamma_{Bohm}, L_{//} = 5cm}$, *theory 1 only is used,* the beam is able to reach the end of the VP, the deposition is always in regime *b*.

② $n_{e2} > n_{e2Lim}$ ↔ $\Gamma_{e2}(d=0) = 3.25\ \Gamma_{Bohm}$, $L_{//}=5cm$, *theory 1 and 2 are allowed,* deposition begins in regime *b* and for a given background plasma density, it passes in regime *d* and in regime *c* at the end when the potential becomes very small. When background plasma density is too tiny, the beam deposit as in vacuum.

③ $n_{e2} < n_{e2Lim}$ ↔ $\Gamma_{e2}(d=0) = 3.1\ \Gamma_{Bohm}$, $L_{//}=5cm$, *theory 1 only is used,* the fast electron beam deposits very rapidly on the 2 first cms of the steel panel at the VP entrance, the deposition is always in regime *a*.

④ $n_{e2} < n_{e2Lim}$ ↔ $\Gamma_{e2}(d=0) = 3.1\ \Gamma_{Bohm}$, $L_{//}=3mm$, *theory 1 and 2 are allowed*, deposition is faster than for trajectory 3, because it begins in regime *a* and when $L_{sheath} > L_{//}/2$ it passes in regime *c*.

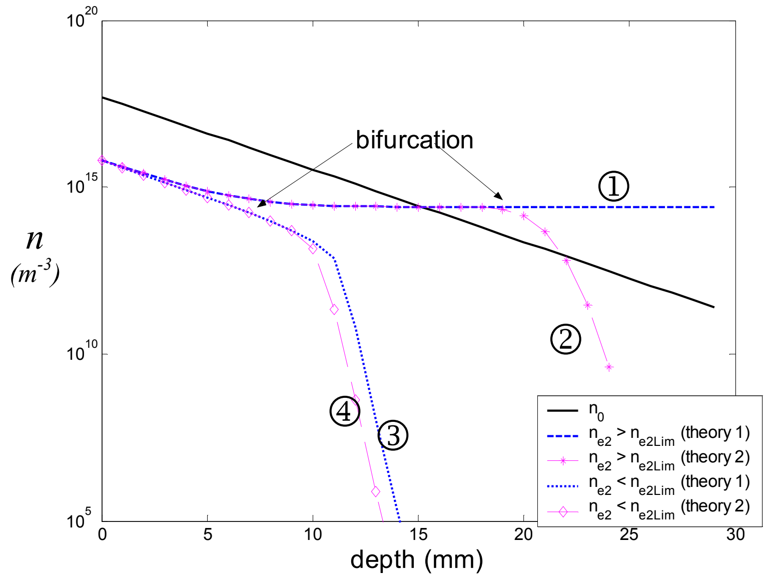

Figure 5 *: Evolution of beam density with depth d in VP (see figure 2) for 4 cases*

Conclusion : Heat fluxes deposition on the vertical port (VP) can be understood with a beam+sheath theory including the fact that the sheaths can be obstructed when their length becomes greater than flux tube length. By this way, we identify 4 deposition regimes : 2 free sheath regimes and 2 obstructed sheath regimes. Beam flux deposits either at the entrance of the VP along first 2cm behind the copper tube or until the end of the VP when beam flux is high and for free sheath. Obstructed sheaths make the repulsive potential for electrons decrease and so accelerate the flux deposition. In experiment, different regimes and brutal transition can occur in space in the VP along drift trajectory and it could also occur in time during a shot, which would confirm our theoretical results. As for ITER, we could only predict that damages on VP will be less important than in Tore Supra because fraction of electrons trapped in ripple will be weaker (1%) and edge plasma density will be higher, so beam flux would completely deposit on the cooled protection. Due to a reduction of δ (the step between 2 bounces) and a faster power deposition, hot spots would still exist and should be evaluated in further works.

References :

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