# Ion Stiffness Mitigation as a Key for Improved Core Ion Confinement: experimental results in JET and theoretical investigations

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[#] *See Appendix of F.Romanelli et al., Fusion Energy 2010 (Proc.23rd Int. Conf. Daejeon, 2010) IAEA, Vienna (2010)*

In JET it is found experimentally by heat flux scans using ICRH that the ion stiffness level, very high in low rotation plasmas, decreases significantly in the core of high rotation plasmas, thereby allowing $T_i$ profile peaking 2-3 times above threshold. Such stiffness reduction is not observed at outer plasma positions. The hypothesis that rotation allows stiffness mitigation only in regions where the magnetic shear (s) is low has been investigated in heat flux scans and $T_i$ modulation experiments where the q profile has been varied in low and high rotation plasmas. It is found indeed that at low rotation the ions are stiff and bound to threshold, both at low and high s, whilst at high rotation the core $T_i$ peaking is well above threshold when the q profile is flat, and drops when the q profile peaks. s~0.7 is the value below which rotation is effective in reducing ion stiffness.

The results have implications for the understanding of improved ion core confinement in Hybrids or Internal Transport Barriers, both characterized by high rotation and low s. The ion confinement improvement would then be due to a continuous process of stiffness reduction rather than to a transition phenomenon, although some abrupt steps in the process are observed in conjunction with the entrance of a low order rational into a low s region. Analysis of steady-state $T_i$ profile and $T_i$ modulation data shows that Hybrids and ITBs are in general still characterized by turbulent ion heat transport but with extremely low stiffness, allowing $R/L_{Ti}$ well above threshold in the broad region where s is small. Consistently, the ion core improvement has been lost in experiments where rotation has been reduced by enhancing the $B_T$ ripple, even in presence of favorable q profile. Statistical analysis of Hybrid and H-mode databases also indicates that $T_i$ peaking at low s is higher at high than at low rotation, whilst they become similar at high s. It is estimated that ion core improvement due to low stiffness can contribute up to 0.2 to the enhancement of the $H_{98}$ factor in Hybrids (with additional improvement due to increased pedestal and NTM suppression), whilst in ITBs core improvement accounts for the whole $H_{98}$ increase. In standard H-mode, due to peaked q profile, the region of reduced stiffness is narrow and the level of reduction small, so that it does not impact on global confinement. In such case, substituting NBI power with ICRH power does not bring significant differences in $T_i$ profiles, because the higher ICRH core power is compensated by an increased stiffness level due to reduced rotation.

Intense simulation work has been carried out in relation to these results. Commonly used quasi-linear models that take into account a limited part of the turbulence wavelength spectrum predict only a threshold up-shift due to rotation. This may be one reason why they have difficulties in simulating highly rotating Hybrid or ITB plasmas. Instead, the more complete and recent TGLF model shows a marked reduction of ion stiffness with rotation, particularly in the so-called knee region at low flux. It is possible that rotational shear acts suppressing low wavelengths that are stiffer, leaving ion heat transport in the high wavelength part of the spectrum, characterized by lower stiffness. Based on this idea, a modification has been introduced in the Weiland model, making the correlation length parameter dependent to include also the effect of flow shear. Non-linear flux-tube gyro-kinetic runs using GYRO have substantially confirmed the TGLF results, indicating though that great care has to be used to assess numerical results in the region close to marginality, where the whole experimental effect is in fact taking place. Regarding the dependence on s, both TGLF and GYRO yield reduced stiffness at low s, but both at low and high rotation, which seems at variance with experiment. Non-linear global gyro-kinetic runs may help to shed further light on the physics mechanisms underlying the experimental observations.