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ECCD Feasibility Study for RFX-mod

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Introduction

The Reversed Field Pinch (RFP) configuration is made possible by a dynamo mechanism which converts poloidal to toroidal magnetic flux. This flux–conversion mechanism is sustained by current driven tearing instabilities, which, however, are also often responsible for magnetic field stochastization and transport degradation. Beside new relevant improvements obtained in the RFX-mod device with an extended set of active control coils [1], important results were achieved on RFP devices in recent years with an improvement of plasma performances by means of an active inductive–control of the poloidal current (pulsed poloidal current drive – PPCD) [2]. However, it is expected that a larger degree of flexibility could be achieved by employing an adjustable radio-frequency (rf) heating and current drive system to control current profile around the reversal of the toroidal component of the confining magnetic field. In the past the attention in the RFP community has been paid mainly to waves in the Lower Hybrid range of frequencies [3], which however have a marginal operation window in the Reversed Field eXperiment (RFX) [4]. Traditional electron cyclotron resonance heating (ECRH) schemes based on the launch and direct absorption of 1$^{\text{st}}$ harmonic O–mode and 2$^{\text{nd}}$ harmonic X–mode suffers from severe wave accessibility constraints in RFPs which typically operate with overdense plasmas ($\omega_{\text{pe}}/\Omega_{\text{ce}} \gg 1$, except for a thin edge layer). However, recent measurements on MST of ECRF emission of the X– and O– mode, explainable in terms of electron Bernstein (EB) waves born in the plasma core [5], have triggered an interest in EBW applications to heat and current drive in RFPs [6], on the basis of the principle of reciprocity. Once the EBWs are excited, they are efficiently absorbed close to the electron cyclotron harmonics. The main issue with these waves is how to excite them inside the plasma, and two schemes have been demonstrated in the last few years in Tokamaks and Stellarators. Here we discuss the operational window for such schemes in RFX-mod as a preliminary step of the feasibility study of an ECCD system.

ECRH in RFPs

For the profiles of the poloidal and toroidal components of the confining magnetic field, B_θ and B_φ, we adopt a simplified version of the $\mu\&p$ model, which still reproduces finite pressure effects:

$$B_\varphi = B_0 \cdot J_0\big(f(x)\big), \quad B_\theta = B_0 \cdot g(x) \cdot J_1\big(f(x)\big) \tag{1}$$

with $f(x) = \int \mu(x')dx'$, $\mu(x) = 2\Theta_0\,(1 - x^\alpha)$, $g(x) = f(x)/(2\Theta_0\,x)$, $B_0 = \mu_0 I_p/(\pi a)$, and $J_{0,1}$ are the Bessel functions of the first kind of order 0 and 1. For RFX-mod the minor radius is 0.46 m. The parameters Θ_0 and α of the model are such that Eq. (1) describes tokamak equilibria for $\alpha, \mu \ll 1$ and RFP equilibria for $\alpha, \mu > 1$. The final goal is to have the waves absorbed in the plasma periphery close to the reversal layer to mimic and eventually overcome the beneficial effects of PPCD. Figure 1 shows the electron cyclotron frequency f_{ce} and the reversal parameter F at the reversal layer as functions of the parameters (α, Θ_0) of Eq. (1). The values in Fig. 1 are obtained for a plasma current $I_p = 1$ MA and can be rescaled to other values of I_p by a simple multiplication by the plasma current in MA units. Due to the active control coils installed in RFX, plasma currents larger than 1 MA are routinely achieved.

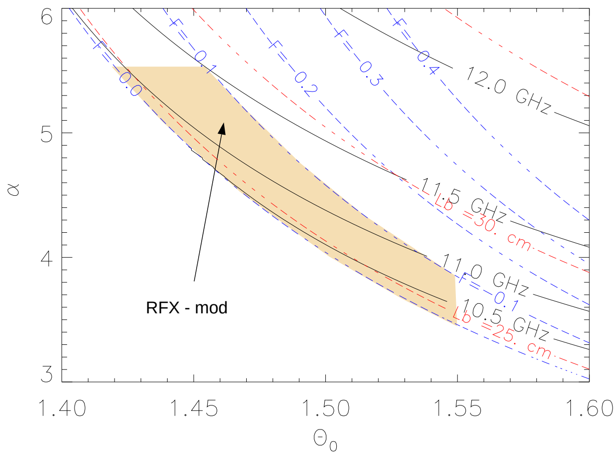

Fig. 1: f_{ce} at the reversal layer for RFX-mod and at 1 MA of plasma current as function of the equilibrium parameters (α, Θ_0) of (1). The dashed lines are the contour levels of the reversal parameter F, defined as $B_\phi(x = 1)$ normalized to the total toroidal magnetic flux. The dotted lines are the values of $L_B = B/(\partial B/\partial x)$ at the reversal.

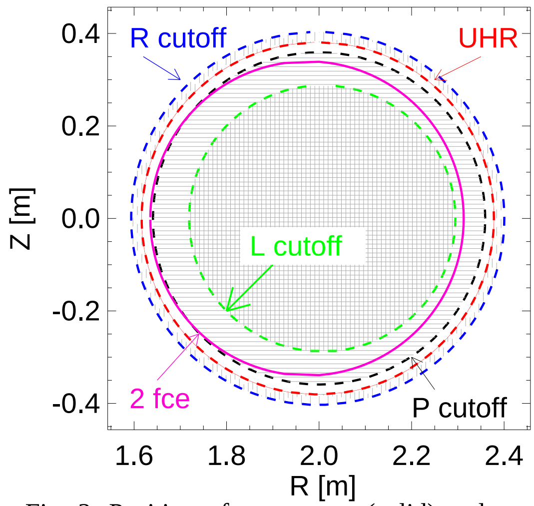

Fig. 2: Position of resonances (solid) and cutoff (dashed) in a poloidal section of RFX-mod for $f = 28$ GHz, $I_p = 1$ MA, $n = 2.5 \cdot 10^{19}$ m^{-3} (in Stix's notation). The vertically and horizontally hatched regions are not accessible respectively to X-mode and O-mode.

In the frame of EC propagation, RFP plasmas are special for at least three aspects. First, like spherical Tokamaks, several Stellarators and some Tokamaks, RFPs operate with overdense plasmas, i.e. $\omega_{pe} > \Omega_c$. This narrows the operation window for direct 2nd harmonic X-mode heating (i.e. without tunneling through evanescence regions). A larger operative window is available for 2nd harmonic O-mode heating. However, this scheme suffers from low absorption, which not only makes the scheme inefficient but might overload the first wall. The second characteristic is the almost symmetric (with respect to the magnetic axis) behaviour of the module of the confining magnetic field. Thus the resonance and cutoff layers are almost circular and centered at the magnetic axis, as shown in Fig. 2. It follows that any launching position (including the inboard side of the device) is inherently “low field side”. Thus, “high field side” schemes for the excitation of EC and EB waves are not applicable. Finally, the low confining magnetic field obliges to work at low frequencies to have low EC harmonics (1st and 2nd) inside the plasma. As a consequence, all the aforementioned cutoffs and resonances occur close to each other in a distance of the order of the vacuum wavelength or less, as in the case considered in [6]. This condition favours tunnelling and mode conversion effects such as the mode-conversion in EBWs of the slow X–mode propagating towards the UHR. Once the EBWs are generated at the UHR, they propagate back towards the plasma core and they are efficiently absorbed at the electron cyclotron harmonics. With an off-middle-plane launch, EBWs can drive current because of an unidirectional $n_{\|}$ (hereafter, $n_{\perp}$ and $n_{\|}$ are the perpendicular and parallel components of the refractive index) shift due to curvature and magnetic shear [7]. According to the experimental CD efficiency with EBWs [8], for RFX-mod parameters it seems achievable a driven current of 0.1 kA for each 1 kW of absorbed power. There are mainly two schemes to excite EBWs and they differ for the way the slow X-mode is excited inside the plasma.

X–B scheme The launched fast X–mode tunnels through the evanescence layer defined by the R–cutoff and the UHR and mode-converted to the slow X-mode [9]. Then, the slow X-mode propagates up to the L-cutoff where it is reflected back towards the UHR. In a RFP this scheme works also in absence of L–mode cutoff since on the high field side the X-mode can encounter the UHR on the high field side. In the best conditions the conversion is $C = 4\exp(-\eta_X)\left[1-\exp(-\eta_X)\right]$ with the Budden parameter η_X [9]:

$$\eta_X = 2\pi^2\,\frac{L_n}{\lambda}\,\frac{\sqrt{X}\alpha}{\sqrt{\alpha^2+2(L_n/L_B)}}\,\sqrt{\frac{\sqrt{1+\alpha^2}-1}{\alpha^2+(L_n/L_B)\sqrt{1+\alpha^2}}} \approx 2\pi^2\,\frac{L_n}{\alpha\,\lambda}\,\sqrt{X\,\left(\sqrt{1+\alpha^2}-1\right)} \tag{2}$$

with $\lambda = c/f$ the vacuum wavelength, $X = \omega_{\rm pe}^2/\omega^2$, $\alpha = \omega_{\rm pe}/\Omega_{\rm ce}|_{\rm UHR} = \sqrt{X/(1-X)}$, and $L_n = n/(\partial n/\partial x)$ and $L_B = B/(\partial B/\partial x)$ are respectively the density and magnetic field scale lengths. Typically in RFX $L_B \gg L_n$ at the reversal surface (see Fig. 1). If $L_n \gg \lambda$ the evanescence layer is too large for the wave to tunnel through it. However, if $L_n \ll \lambda$ the waves encounters a sharp transition of the refraction index which causes a reflection. In RFX the edge value of L_n is approximatively 2 cm for I_p up to 0.8 MA [10]. Thus, at 28 GHz $L_n \approx \lambda$. Since the dynamo is working mostly in the region of the reversal, the EBWs has to be absorbed almost locally. Thus, it is desirable to have either the 1$^{\rm st}$ or the 2$^{\rm nd}$ harmonic close to the UHR. However, in both cases the best transfer conditions are for plasma density very low at the UHR, of the order of few 10^{16} m^{-3}. This low density values together with high density fluctuations at the RFP edge rules out the applicability of this scheme in RFX.

O–X–B scheme. The O–mode launched with an optimal angle is mode–converted to slow X–mode immediately beyond the P cutoff [11]. The optimal angle is defined by the spatial closeness of the O-mode cutoff and the L-cutoff of the slow X–mode. The mode conversion efficiency is:

$$T(n_{\perp}, n_{\|}) = \exp\left\{-2\pi^2\frac{L_n}{\lambda}\sqrt{\frac{Y}{2}}\left[2(1+Y)\,(n_{\|,\rm opt}-n_{\|})^2+n_{\perp}^2\right]\right\} \tag{3}$$

with $Y = \Omega_{ce}/\omega$, and $n^2_{\parallel,\mathrm{opt}} = Y/(Y+1)$ the optimal launch condition. Also for this scheme, it is advantageous having the mode conversion where the density gradient is higher because of the presence of L_n/λ in the exponent. With the constraint of having either the 1st or the 2nd harmonic close to the $\omega_{pe} \approx \omega$ layer, the density required at the reversal are $\approx 2 \cdot 10^{18}$ m^{-3} and $\approx 8 \cdot 10^{18}$ m^{-3}, respectively. The RFX edge turbulence in RFX has toroidal characteristic lengths of $1.5 \div 4.5$ cm [12], long enough not to compromise the optimal launch conditions, i.e. $n_\perp \approx 0$ and $n_\parallel \approx n_{\parallel,\mathrm{opt}}$. Using the formulas in [11], Figure 3 shows the effect on the conversion efficiency (3) of the density fluctuation for three correction lengths.

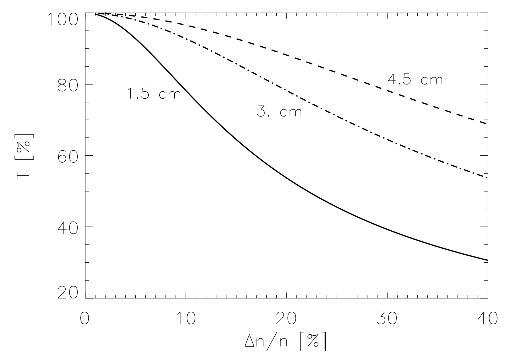

Fig. 3: Transmission coefficient for optimal launch conditions in presence of density fluctuations.

Having the 2nd harmonic resonance close to the reversal layer allows to work at higher frequencies, namely few tens GHz, suitable for a quasioptical launcher. In particular a steerable launcher would allow to optimize the O-X-B scheme and explore the X-B scheme as well.

In this preliminary study, the O-X-B scheme appears to be the most promising in RFX-mod device in the MA operation regime, with a deposition zone approximatively centered around the surface of toroidal field reversal. Throughout analysis requires a study of the best conditions for transferring power to the slow X-mode beyond the edge evanescence layer. This will be addressed with ART code (ray tracing code for mode-converted EBWs), successfully applied to the W7-AS Stellarator[13] and TCV Tokamak [14]. However, because of the discussed RFP peculiarities special treatments and refinements in ART code will be necessary.

References

[1] PACCAGNELLA, R., ORTOLANI, S., ZANCA, P., et al., Physical Review Letters **97** (2006) 075001.

[2] BOLZONELLA, T., MARTIN, P., MARTINI, S., et al., Phys. Rev. Lett. **87** (2001) 195001.

[3] UCHIMOTO, E., CEKIC, M., HARVEY, R. W., et al., Physics of Plasmas **1** (1994) 3517.

[4] BILATO, R. and BRAMBILLA, M., volume 485, pp. 202–206, AIP, 1999.

[5] CHATTOPADHYAY, P. K., ANDERSON, J. K., BIEWER, T. M., et al., Physics of Plasmas **9** (2002) 752.

[6] M. CENGHER, J.K. ANDERSON, V. S. and FOREST, C., Nuclear Fusion **46** (2006) 521.

[7] FOREST, C. B., CHATTOPADHYAY, P. K., et al., Physics of Plasmas **7** (2000) 1352.

[8] LAQUA, H. P., MAASSBERG, H., MARUSHCHENKO, N. B., et al., Phys. Rev. Lett. **90** (2003) 075003.

[9] RAM, A. K. and SCHULTZ, S. D., Physics of Plasmas **7** (2000) 4084.

[10] GREGORATTO, D., GARZOTTI, L., INNOCENTE, et al., Nuclear Fusion **38** (1998) 1199.

[11] LAQUA, H. P., ERCKMANN, V., HARTFUSS, H. J., LAQUA, H., et al.., Phys. Rev. Lett. **78** (1997) 3467.

[12] SCARIN, P., AGOSTINI, M., CAVAZZANA, R., et al., Journal of Nuclear Materials **363-365** (2007) 669.

[13] VOLPE, F., LAQUA, H. P. Review of Scientific Instruments **74** (2003) 1409.

[14] MUECK, A., CURCHOD, L., CAMENEN, Y., et al., Physical Review Letters **98** (2007) 175004.