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Improvement of the equilibrium reconstruction of TCV by including polarimetric and interferometric measurements

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Introduction

The equilibrium reconstruction on TCV is presently based on signals of 38 magnetic probes and 38 flux loops and on the measurements of currents in the poloidal field coils as well as induced currents in the vacuum vessel.
Source functions of quantities like pressure, toroidal field and electron density are expressed in terms of the poloidal flux [1]. The number of terms per quantity varies usually between 1 and 3. Hofmann and Tonetti could show that the addition of 10 vertical interferometer and polarimeter chords improves the precision of equilibrium parameters significantly assuming an error of 2% of the maximum value of the Faraday rotation measurement [1]. It was also possible to increase the number of terms of the source functions. For this purpose density and pressure profiles were assumed which were expected to be realistic.
At that time real plasma conditions for TCV were still unknown. Now, after 1 year operation of TCV with 4 interferometer chords it is at least possible to assume realistic density profiles in order to simulate Faraday rotation measurements and test the sensitivity of the reconstruction code on these measurements.
Present FIR polarimeter systems achieve sensitivities of about 0.2 to 0.1 degree Faraday rotation [2,3]. This report shows that for a variety of real TCV plasmas the extension of the existing FIR interferometer to a 14 channel interferometer/polarimeter with a precision of 0.2 degrees can improve the performance of the reconstruction code significantly.
TCV was designed also for extensive ECRH experiments using up to 6 gyrotrons with 0.5MW power each for second harmonic and up to 3 gyrotrons with 0.5MW power each for third harmonic heating giving a total of 4.5MW power of ECRH. We show that the expected changes in the current density profile can be detected with a polarimeter system with 0.2° precision.

The equilibrium reconstruction code LIUQE

The equilibrium reconstruction code LIUQE basically solves the Grad-Shafranov equations. The source function $p' = dp/d\psi$ (p = pressure, ψ = poloidal flux), TT' ($T = RB_{tor}$, R = large radius, $T' = dT/d\psi$) and n_e (electron density) are expressed in terms of the poloidal flux. Cases where the pressure profile is shifted with respect to the flux are not treated with this code. Such profiles arise when the toroidal rotation velocity is high due to tangential beam injection. TCV however is not equipped with neutral beams. The code finds by a series of iterations the best solution for the poloidal flux using magnetic measurements, current measurements and optionally interferometer, polarimeter, Thomson scattering and diamagnetic measurements.

Hofmann and Tonetti [1] simulated with calculated equilibria and density profile from JET the signals of an interferometer/polarimeter with 10 vertical equally spaced chords. They showed that the RMS error of different parameters obtained from the code could be reduced by a factor of two if a precision of the Faraday rotation of 2% of the maximum value was assumed.

LIUQE was successfully applied to almost all plasma shots made up to now by using only magnetic and current measurements.

Selected shots for the simulation

For more realistic scenarios we made simulations using real plasma shots in TCV during the last period. We selected shots of different type, shape, density etc. (table 1). The density ranges from $1.7 \cdot 10^{19} m^{-3}$ to $8.9 \cdot 10^{19} m^{-3}$, the current from 249kA to 710kA. Four D-shaped plasmas, two double X-point L-mode plasmas and two sinfgle X-point plasmas are in the list. Only a single ELMy H-mode plasma is included. ELM free H-mode plasmas have very broad density and pressure profiles which cannot be fitted accurately without pressure measurements (see remarks below). So ELM free H-mode plasmas are not included in this study.

Shot	time/s	I_{plasma} /kA	$\langle n_e \rangle / 10^{19} m^{-3}$	α	q_0	li	β_{tor}/ %	κ_{edge}	δ_{edge}	Type/ Mode
5509	0.5	710	6.2	0.50	0.83	0.72	1.5	1.98	0.40	D/L
5599	1.0	256	1.7	0.59	0.80	1.17	0.2	1.44	0.20	D/L
6060	0.5	507	8.0	0.16	0.89	0.77	1.3	1.87	0.79	DX/L
6259	0.5	249	2.5	0.49	0.89	0.98	0.4	1.47	0.22	D/L
6286	0.8	372	8.9	0.34	1.05	0.71	1.4	1.63	0.59	Xb/He
6596	0.28	317	6.5	0.32	0.97	0.87	0.6	1.67	0.42	Xt/L
6615	0.5	373	5.9	0.38	0.79	0.99	0.7	1.73	0.39	D/L
6698	0.7	247	4.2	0.33	1.19	0.78	0.7	1.53	0.80	DX/L

Table 1: Parameters of the plasmas used for the simulations (Type : D = D-shaped, Xb,Xt : X-point on bottom/top, L = L-mode, He = ELMy H-mode)

Simulation of the Faraday rotation

For the simulation of the Faraday rotation the reconstruction code was first applied once using only the magnetics and current inputs. The poloidal magnetic field distribution was calculated from the poloidal flux. For shot 5509 a pure parabolic density profile was assumed since only one interferometer channel was available. For all other shots density profiles of the type $n_e(\psi) = (\psi/\psi_0)^\alpha$ were fitted to the measurements of the 4 channels FIR interferometer. For pure ohmic L-mode plasma α was usually in the range of 0.6 to 0.16. In ELM free H-mode plasmas density profiles in TCV are very flat which means α is smaller than 0.1.
The 14 vertical chords of the simulated interferometer/polarimeter were positioned almost equally distributed over the plasma cross section (R = 683, 709, 735, 761, 787, 828, 854, 88, 906, 932, 973, 999, 1025, 1051mm) by taking into account the special geometry of TCV. Figure 1 shows the positions of the chords on the flux contour of shot 6060. The interferometer and the polarimeter signals were calculated using the fitted density profile and the poloidal magnetic field obtained from the reconstruction.
Random noise was added to the signals used for the reconstruction and a new reconstruction was applied. This procedure was performed 100 times for each equilibrium. The RMS value of some equilibrium parameters were evaluated for different levels of noise on the polarimeter signals and for reconstruction not using polarimeter measurements (table 2). A typical Faraday rotation profile for shot 6060 is shown in figure 2.

Error on	Mag	0.4°	0.2°	0.1°
Currents	200A	200A	200A	200A
Voltages	0.7V	0.7V	0.7V	0.7V
Fluxes	7.5mVs	7.5mVs	7.5mVs	7.5mVs
$B_{poloidal}$	0.01T	0.01T	0.01T	0.01T
Line integrated density	$10^{17}m^{-2}$	$10^{17}m^{-2}$	$10^{17}m^{-2}$	$10^{17}m^{-2}$
Faraday rotation	not used	0.4°	0.2°	0.1°

Table 2 : Error levels imposed to the input signals for the equilibrium reconstruction code.

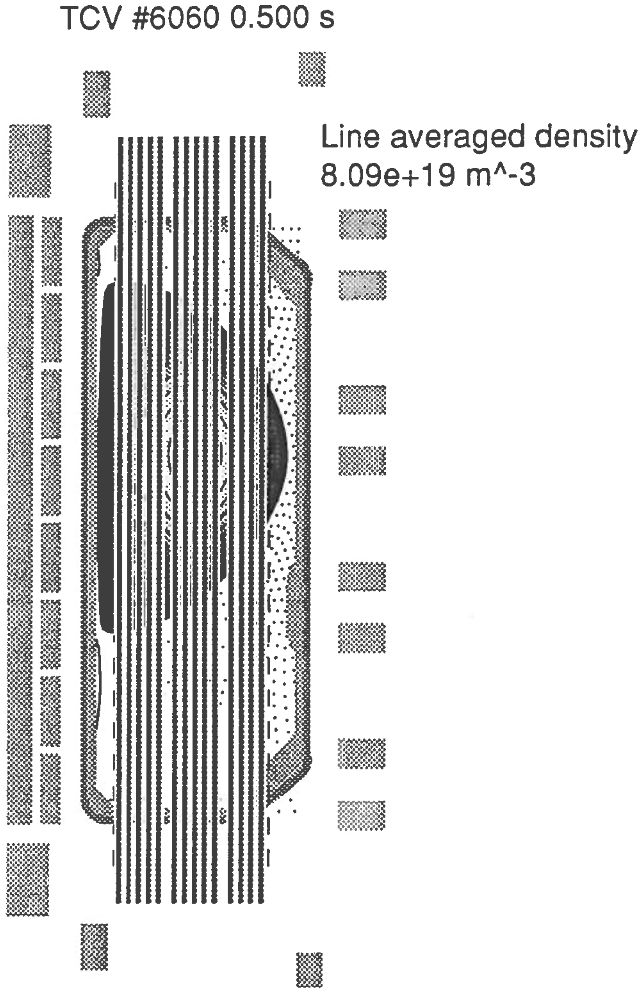

Fig. 1: Flux contours of shot 6060 and position of the 14 polarimeter chords

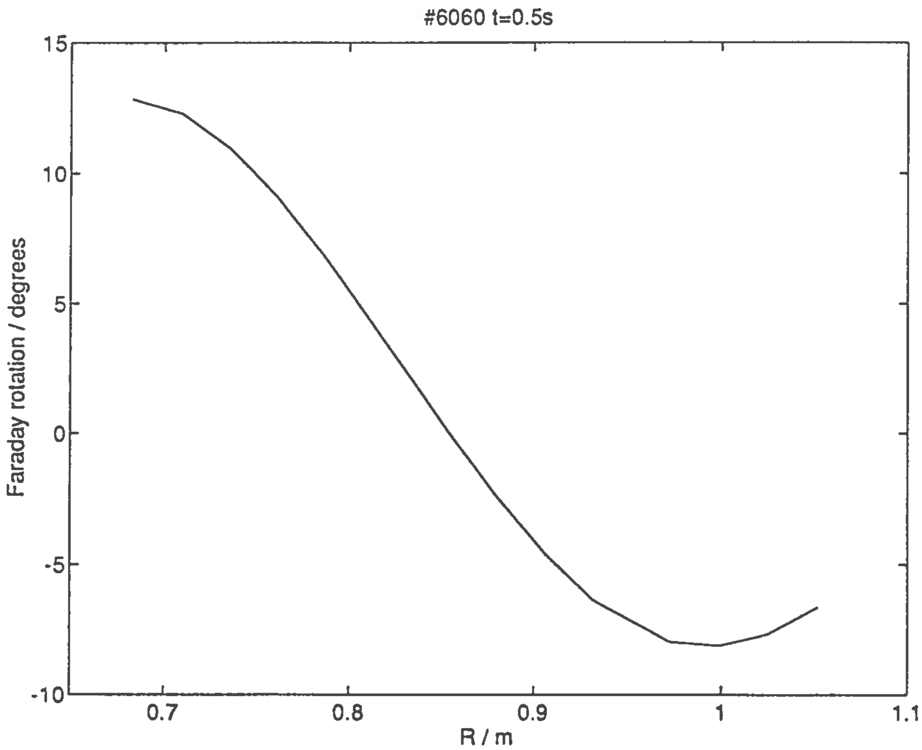

Fig. 2: Faraday rotation profile for shot 6060

Sensitivity study

The RMS fluctuations of different equilibrium parameters (q_0, l_i, β_{tor}, r_{axis}) were studied.

1) q_0

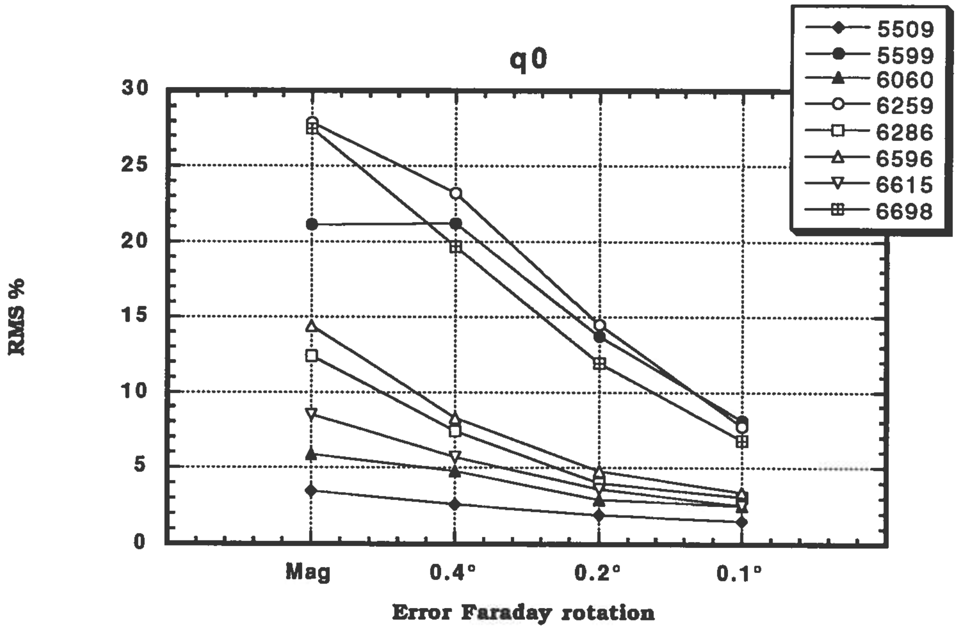

Fig. 3 : RMS fluctuation of q_0 for different noise levels on the polarimeter measurements (mag : no polarimeter measurements included)

Compared with the reconstruction without polarimeter signals the fluctuations of the central safety factor can already be reduced by having a noise level of 0.4° on the polarimeter measurements. A noise level of 0.2° which is achievable with today's polarimeter techniques [2,3] reduces the RMS fluctuations already by more than a factor of 2. It should be pointed out that this improvement was found also for very low density shots like no.5599 and 6259 for which the maximum Faraday rotation angle is only about 2° !! The absolute RMS fluctuation is however largest for these shots since together with 6698 these are the shots with the lowest currents and fields in this study.
The lowest absolute RMS fluctuations were obtained with shots with highest eleongations and currents in this study (5009,6060).

2) l_i

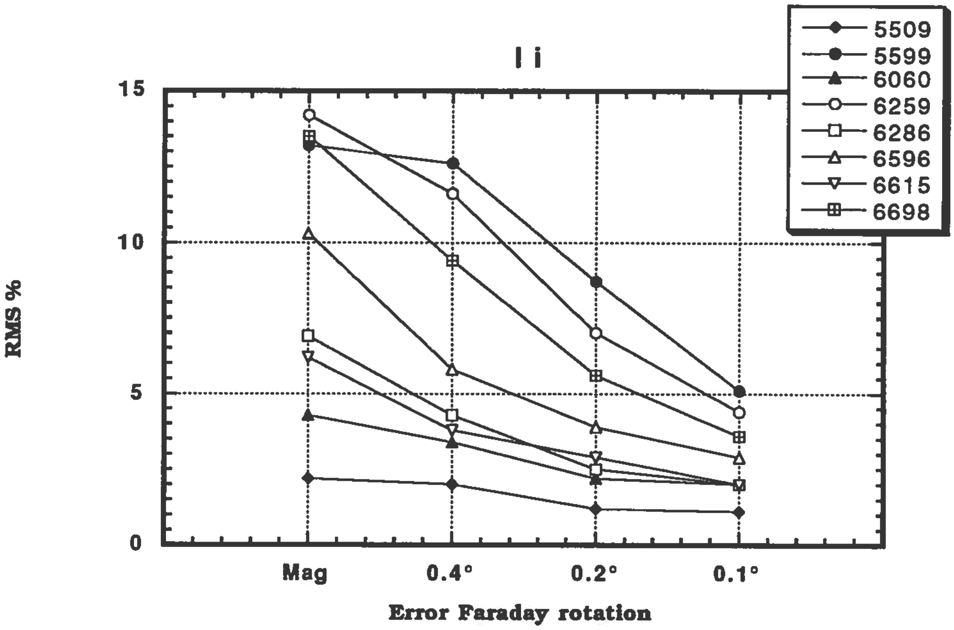

Fig. 4 : RMS fluctuation of l_i for different noise levels on the polarimeter measurements (mag : no polarimeter measurements included)

The internal inductance behaves exactly in the same way as q_0. Improvements by more than a factor of 2 can be achieved with a noise level of 0.2° for the Faraday rotation.

3) β_{tor}

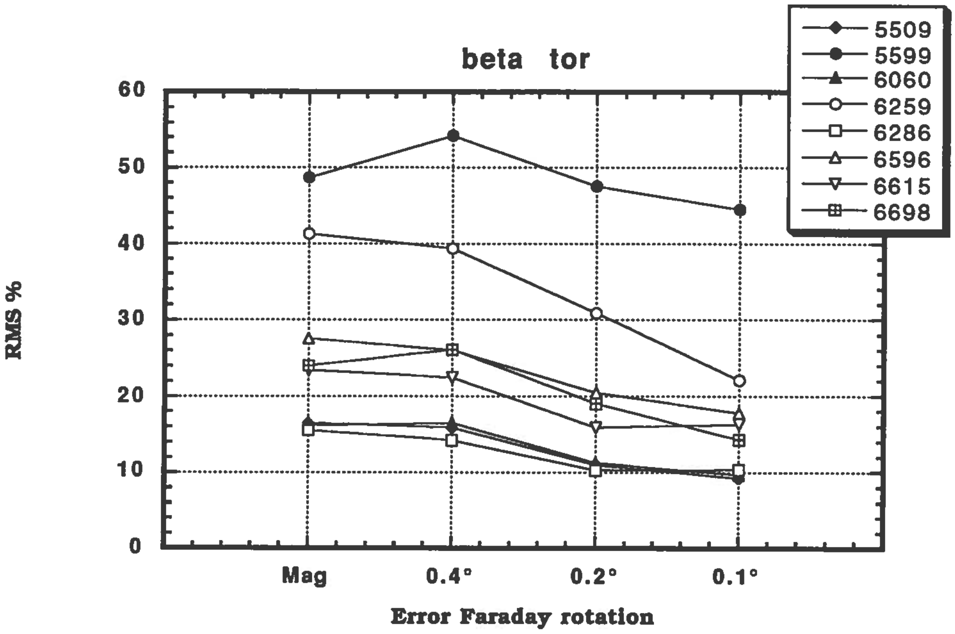

Fig. 5 : RMS fluctuation of β_{tor} for different noise levels on the polarimeter measurements (mag : no polarimeter measurements included)

For β_{tor} the improvement by reducing the noise of the Faraday rotation is smaller. To reduce the RMS fluctuation by a factor of 2 the Faraday rotation noise must be reduced to at least 0.1°! Especially for the very low density shot no. 5599 the improvement is very small. This behaviour reflects the fact that Faraday rotation measurements contain little information on the pressure distribution. The absolute smallest RMS fluctuations are again obtained for highly elongated plasmas.

4) r_{axis}

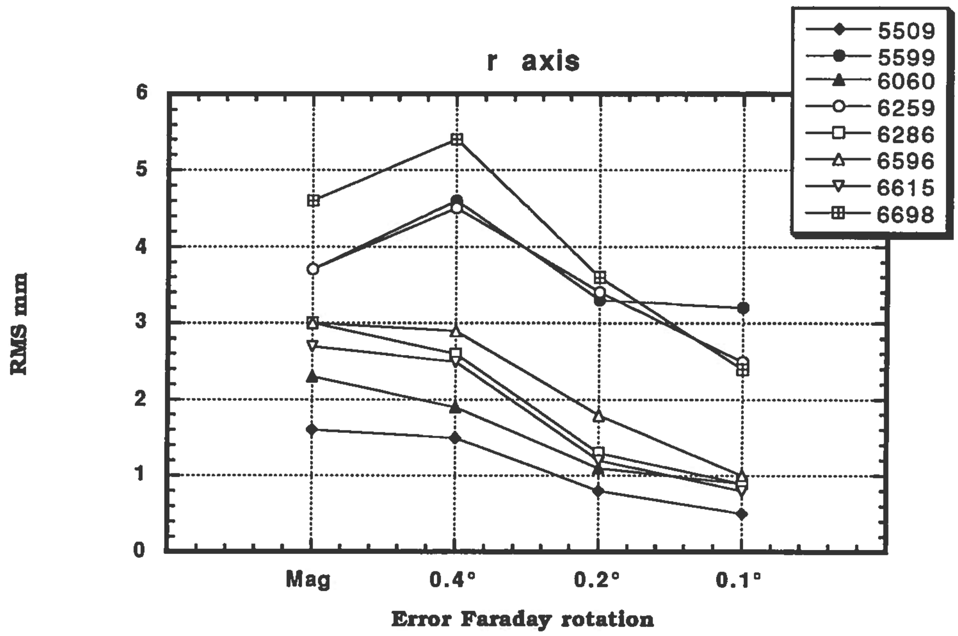

Fig. 6 : RMS fluctuation of r_{axis} for different noise levels on the polarimeter measurements (mag : no polarimeter measurements included)

For the radial position of the magnetic axis an improvement by almost a factor two can be achieved by an Faraday rotation noise of 0.2°. The final precision of the position of the magnetic axis can than be smaller than 2mm in medium density plasmas.

H-mode plasmas

Simulations for H-mode plasmas using the measured density profiles show generally a higher fluctuation in the equilibrium parameters. When polarimeter channels were used these fluctuations could be reduced only by a smaller amount. The reason for this behaviour is the fact that, in the absence of pressure measurements, LIUQE normally assumes the plasma pressure to be proportional to the poloidal flux. This assumption is fairly well satisfied in L-mode plasmas but is not in agreement with typical H-mode profiles
Accurate reconstruction of H-mode plasmas requires pressure source functions with more than one free parameter. These source functions are available in LIUQE but the additional parameters cannot be determined without pressure measurements. We think that the information which will be delivered by the Thomson scattering will put more constraints on the pressure profiles and will allow a higher number of source function parameters especially.

ECRH effects

At TCV ERCH will be used to tailor the current profile distribution in order to reduce the internal inductance l_i which will improve the vertical stability of highly elongated plasmas. It was calculted that assuming 800eV central electron temperature 4MW deposited inside the q=2 surface could produce an internal inductance of 0.68 while 2MW generate an internal inductance of 0.9.
We calculated therefore four theoretical equilibria with almost the same current and elongation but different li. The current density profiles in a horizontal plane through the magnetic axis are shown in figure 7. Figure 8 shows the contour plot of the poloidal flux for one of these shots.

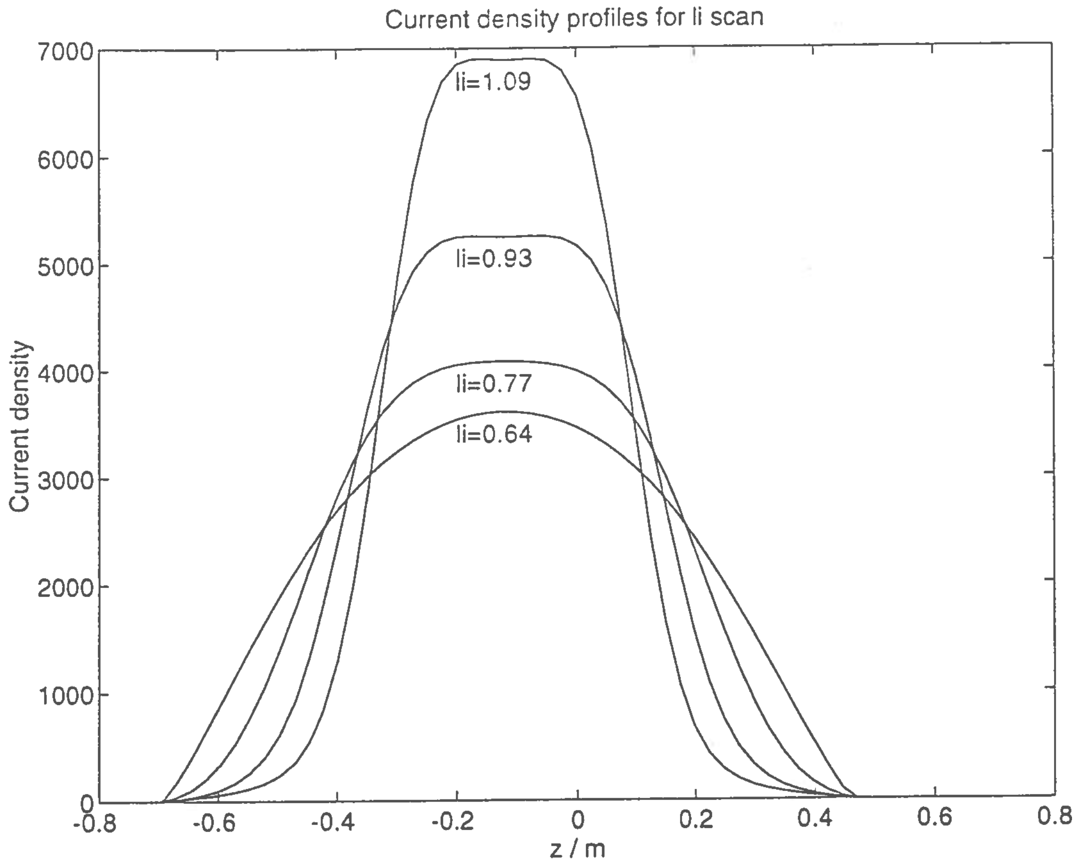

Fig. 7 : Current density profiles of shots with constant I_p and κ but different l_i

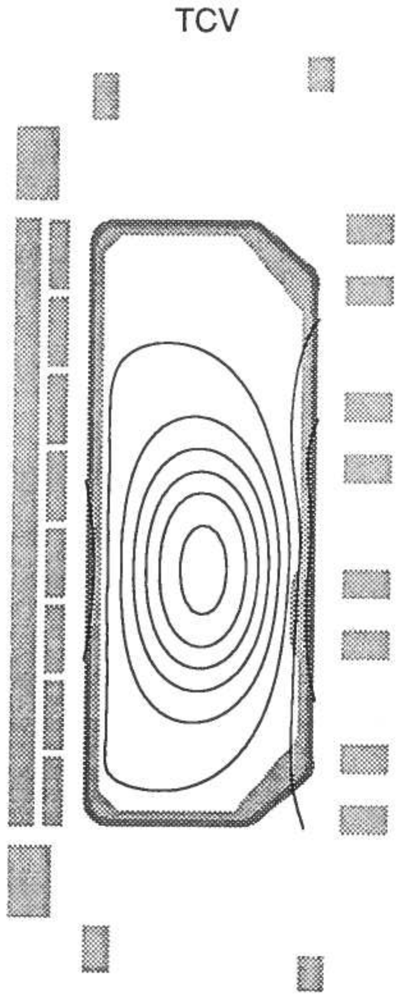

Fig. 8 : Contour plot of the poloidal flux of an equilibrium used for the simulation of ECRH effects.

Assuming realistic density profiles with a=0.3 the Faraday rotation was calculted (figures 9 and 10). It shows clearly that with a precision of 0.2° a change of 0.1 of li can be detected in the maxima of the Faraday rotation profile.

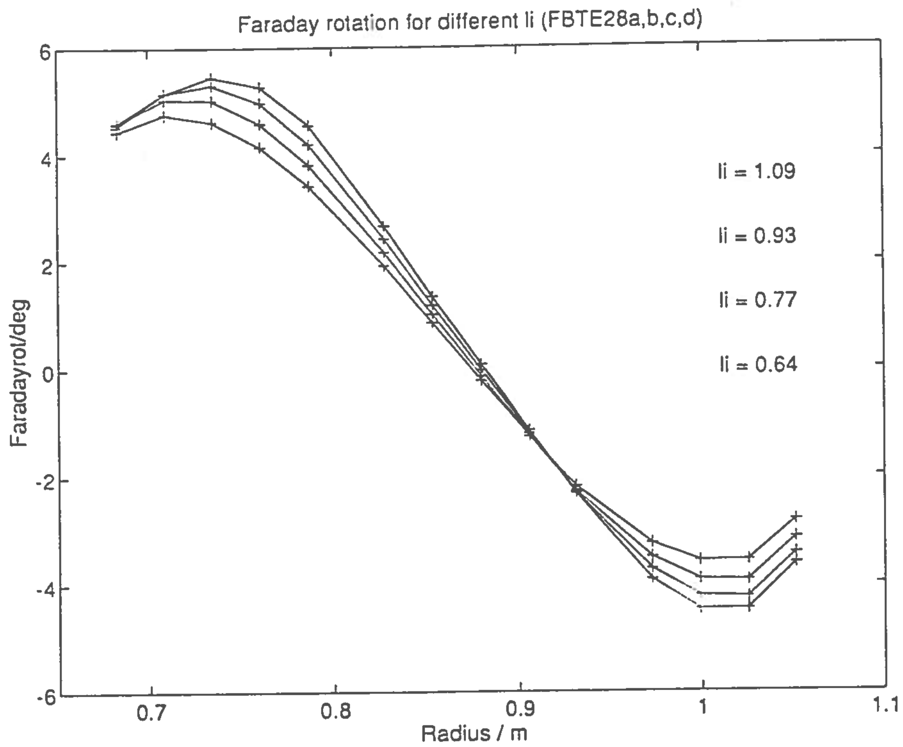

Fig. 9 : Faraday rotation profiles of shots with constant I_p and κ but different l_i.

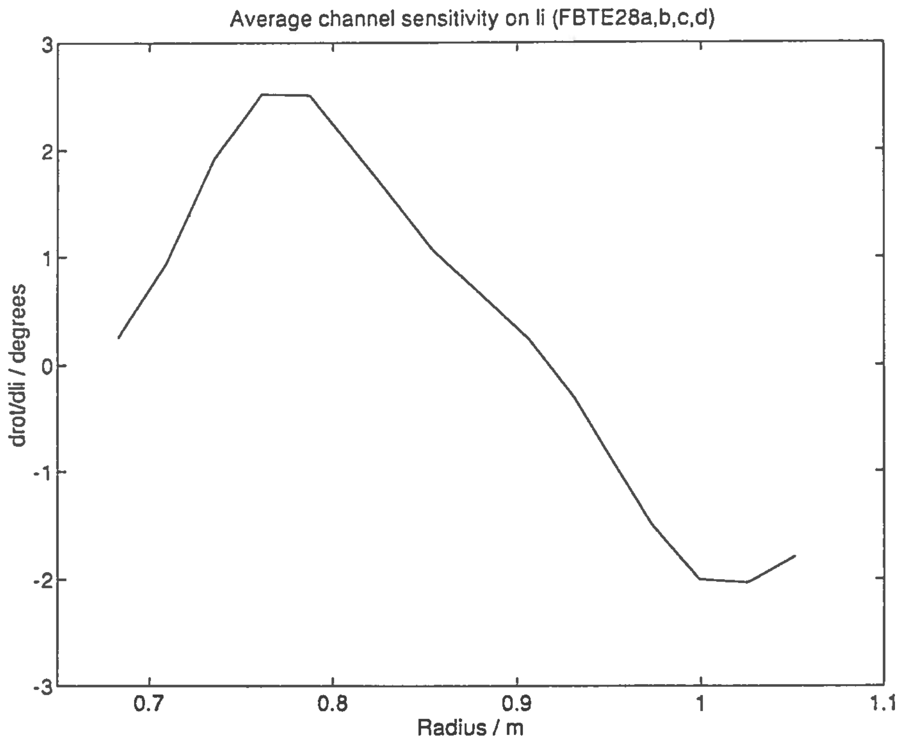

Fig. 10 : Sensitivity of Faraday rotation on l_i.

References

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[2] H.Soltwisch; Rev.Sci.Instrum. **57**, 1939 (1986)

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