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Presentation of GYRODIAG: A new tool to analyze possible scenarios of ECRH heating accessibility

E. Fable

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CRPP

1 Introduction

In the view of a future thermonuclear reactor the different methods of heating the plasma are being scrutinized to optimize the efficiency of ECRH heating, ECCD injection, NBI operation. In this work I analyze, from a global point of view, the different ECH scenarios which can be attractive for an upgrade of TCV, either as regard increase in the toroidal magnetic field B_ϕ, a change in the gyrotron frequencies, the achievement of higher densities and current, the former being limited by the Greenwald density limit [1]. Of the various tools which can be useful to this aim, I concentrated on the CMA (Clemmov - Mullaly - Allis) diagram, this being very powerful to have an easy insight into the different possibilities. The work is divided in the following parts:

1) A section with the mathematical background needed to plot the CMA diagram and to interpret it.

2) Description of the tool *gyrodiag*, a matlab routine to analyze the CMA diagram with many different tunable parameters.

3) Some examples to show the method and to discuss relevant possibilities.

4) Conclusions

2 Physical background

2.1 ECW absorption

The problem is essentially to study the propagation of electromagnetic waves in a plasma, for which the best way is to write down the Maxwell equations and couple them with the kinetic equations for particles, to account for particle-wave interactions, which determine the cut-offs and resonances. The program at the moment implements the case of perpendicular propagation, such that $\mathbf{k} \cdot \mathbf{B} = 0$, where $\mathbf{k}$ is the wave vector; indeed, the dielectric tensor is calculated in the approximation of cold Maxwellian plasma. With these assumptions, the expression for the different parameters is the following. For the ordinary mode (O-mode), defined by $\tilde{\mathbf{E}} \times \mathbf{B} = 0$, the cut-off is simply given by

$$\omega = \omega_{pe} \tag{1}$$

Instead, for the extraordinary wave (X-mode), defined by $\tilde{\mathbf{E}} \cdot \mathbf{B} = 0$, there are three possible limits: the cut-off for the right-handed wave,

$$\omega_R = \frac{\omega_{ce}}{2} + \sqrt{\left(\frac{\omega_{ce}}{2}\right)^2 + \omega_{pe}^2} \tag{2}$$

the cut-off for the left-handed wave,

$$\omega_L = -\frac{\omega_{ce}}{2} + \sqrt{\left(\frac{\omega_{ce}}{2}\right)^2 + \omega_{pe}^2} \tag{3}$$

and the upper-hybrid resonance,

$$\omega_{UH} = \pm\sqrt{\omega_{ce}^2 + \omega_{pe}^2} \tag{4}$$

The lower hybrid resonance is not taken in to consideration, being $\omega \gg \omega_{ci}$. The characteristic frequencies are defined as the electron cyclotron frequency:

$$\omega_{ce} = \frac{eB}{m} \tag{5}$$

and the plasma frequency:

$$\omega_{pe} = \sqrt{\frac{ne^2}{\varepsilon_0 m_e}} \tag{6}$$

n being the (electron) plasma density and m_e the electron mass.

2.2 Greenwald density limits

The Greenwald density limit is an operational constraint which has been empirically modelled on observations on tokamak plasma activity. In this program there are two different formulas which can be adopted. The first is the original formula proposed by Greenwald *et al.* [1], and it is

$$n_G = \frac{1}{\pi}\frac{I_{pl}}{a^2} \tag{7}$$

the second has been proposed in ITER physics 1994, and it is

$$n_G = 0.27\frac{I_{pl}}{a^2} \tag{8}$$

where I_{pl} is the total plasma current in MA and a is the minor radius in m. The result is in units of 10^{20}. In fig. 1 we can see different operational scenarios reached by TCV (database of shots between 1996 and 1997) [3], where it is clearly visible the Greenwald limit (black solid line), and the data, accumulating in a region which almost touch the limit. This means TCV is capable of operating very close to the density limit, thanks to its versatility in plasma shaping and current tayloring. Sometimes, during current ramp-down phase, the plasma finds himself in conditions over the density limit. This diagram is useful to understand that for TCV gyrotron operational scenarios design one has to take in account the performance of TCV as regard density and current reachable numbers.

2.3 Note on the total current calculation

At the moment the program implements automatic calculation of the total plasma current I_{pl} from the values of B_0,R_0,a,q_{95},k,δ. The formula is the same as in the ITER Physics database (1994) cited in [2]:

$$I_{pl} = \frac{5a^2 B_0}{R_0 q_{95}} f(\varepsilon) \frac{\left[1 + k^2\left(1 + 2\delta^2 - 1.2\delta^3\right)\right]}{2} \tag{9}$$

where

$$f(\varepsilon) = \frac{(1.17 - 0.65\varepsilon)}{\left(1 - \varepsilon^2\right)^2} \tag{10}$$

and ε is the aspect ratio defined as $\varepsilon = \dfrac{a}{R_0}$

3 The tool *gyrodiag.m*

It is in the directory */home/fable/PUBLIC/* on *HAL* that the program *gyrodiag* can be found, a *Matlab* routine which performs different type of analysis on the CMA diagram. After running *gyrodiag*, a GUI appears with the first type of CMA, the frequency f as a function of the toroidal magnetic field B_ϕ (fig. 2). The menus are composed of two parts: the standard figure menu, and three menus with specifics of the program, one for setting of physical quantities (menu *Physics*), one for miscellanous parameters (menu *Misc*), and the last for I/O operations (menu *I/O*). There are also two quantities on the top left of the graphic, one of which can be set (*GyroFreq*), the other is calculated (*Ipl [MA]*) from the input value of q_{95}.

The menu *Physics* and *Misc* both contain the submenu *Parameters*, which gives the following settings (fig. 3)

Menu *Misc* has also the following submenus: *Auto-gyro,CMA type,Put gyro,*n_G.

Let us explain the meaning of each quantity.

3.1 Main window parameters

GyroFreq [GHz]: Set the reference frequency ω to be used for normalization in CMA diagram of type 2-5.

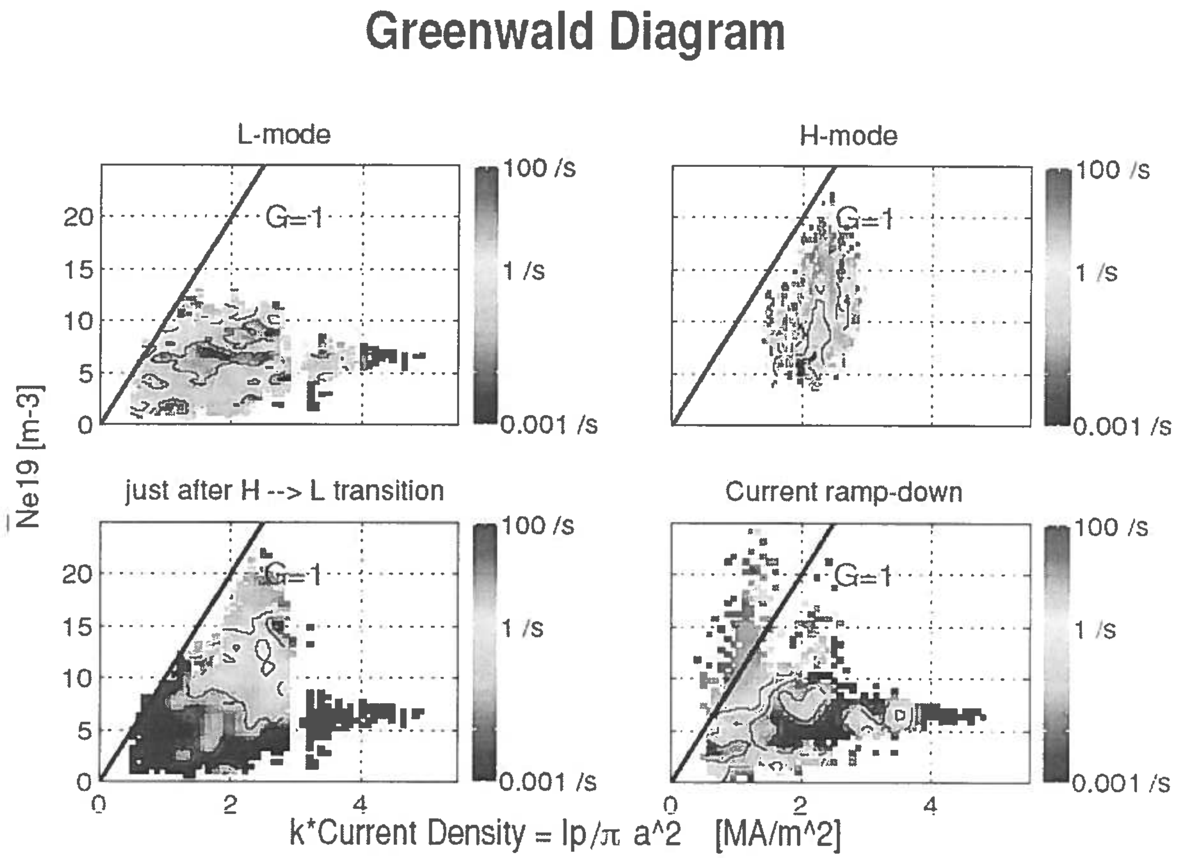
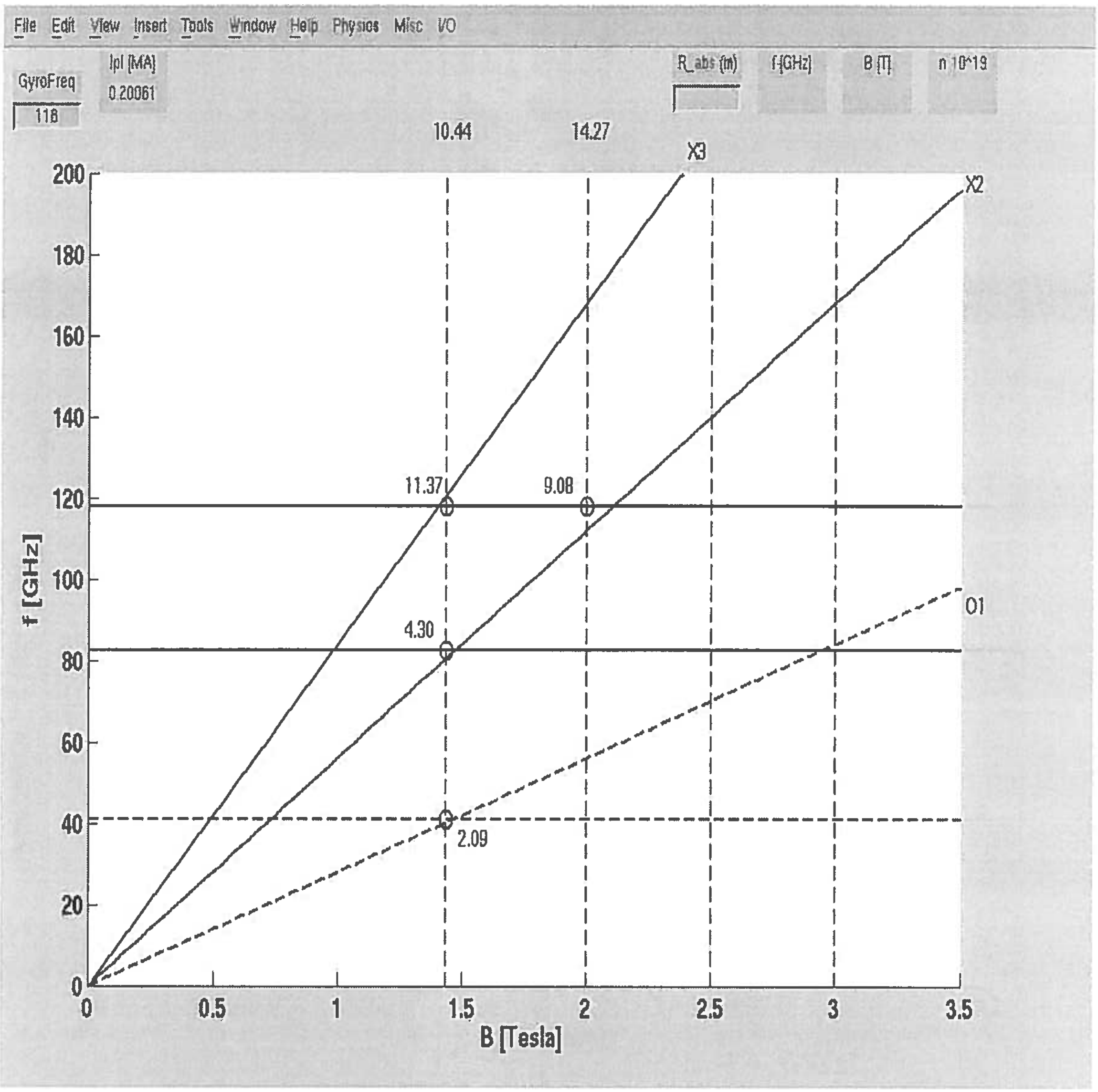


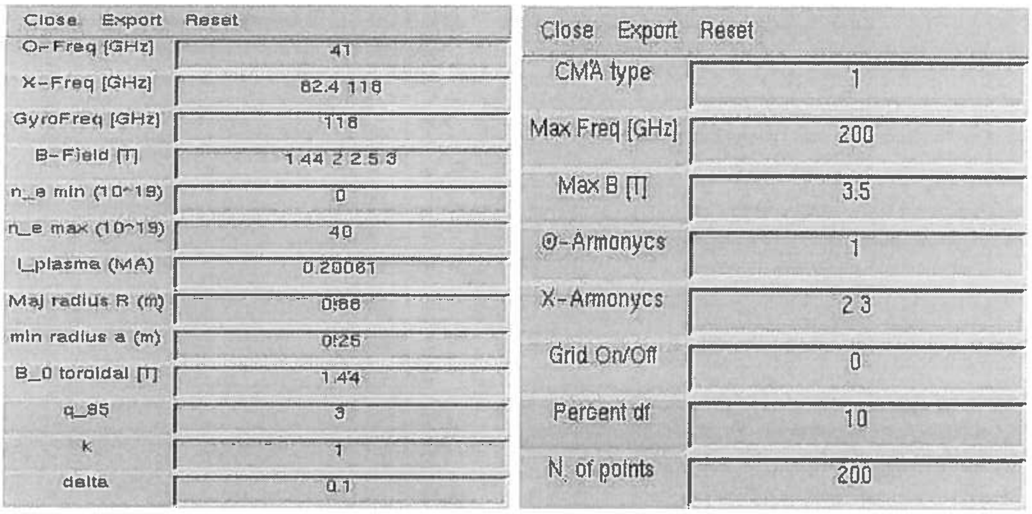
Figure 1: TCV operational diagram showing capabilities of going near the Greenwald density limit for different operational regimes in TCV (database up to 1997)



GyroFreq: 118

Ipl [MA]: 0.20061

Figure 2: *gyrodiag* view: the diagram shows the frequency versus the magnetic field for different propagating modes, the cut-off densities (the numbers at the intersection between the harmonics and the magnetic field vertical lines), and the Greenwald density limit at the same magnetic field (the top red numbers)



O-Freq [GHz]: 41
X-Freq [GHz]: 82.4 118
GyroFreq [GHz]: 118
B-Field [T]: 1.44 2 2.5 3
n_e min (10^19): 0
n_e max (10^19): 40
I_plasma (MA): 0.20061
Maj radius R (m): 0.88
min radius a (m): 0.25
B_0 toroidal [T]: 1.44
q_95: 3
k: 1
delta: 0.1

CMA type: 1
Max Freq [GHz]: 200
Max B [T]: 3.5
O-Armonycs: 1
X-Armonycs: 2 3
Grid On/Off: 0
Percent df: 10
N. of points: 200

Figure 3: *Parameters* settings: *Physics* (left), *Misc* (right)

Ipl [MA]: The total current calculated according to formula 9.
R_{abs} *[m]*: The user, once in CMA type 2-5, can choose to deposite the gyrotron power in a specific radial position. In this case the value of the magnetic field appearing represents the value of the central magnetic field (B_0), to have absorption at R_{abs}.
f [GHz], B [T], $n10^{19}$: these values are produced when the user turns on the *Tracer* option from the *Misc* submenu.

3.2 *Physics* input parameters

O-Freq [GHz]: The frequency of the O-mode which appears as an horizontal line in the CMA type 1 diagram.
X-Freq [GHz]: The same but for the X-mode.
GyroFreq [GHz]: The reference frequency for the normalization in the CMAs > 1.
B-Field [T]: The toroidal magnetic field values which appear as vertical dashed red lines in the CMA type 1.
n_e *min* (10^{19}): the inferior limit for the calculation of plasma frequency from density.
n_e *max* (10^{19}): the superior limit for the same calculation.
Maj radius R (m): The major toroidal radius.
min radius a (m): The minor radius.
B_0 *toroidal [T]*: The reference toroidal magnetic field for CMAs type > 1.
q_{95}: The value of q_{95}.
k: Plasma edge elongation.
δ: Plasma edge triangularity.

3.3 *Misc* parameters

CMA type: can be set directly from *Misc* menu
Max Freq [GHz]: Set the upper limit for frequency axis in all diagrams.
Max B [T]: Set the upper limit for magnetic field axis in all diagrams.
O-Harmonics: Choose the harmonics for the O-mode to be plotted.
X-Harmonics: Choose the harmonics for the X-mode to be plotted.
Grid On/Off: Turn on/off the grid.
Percent df: Set the threshold (percentage of discrepancy) to consider a relevant point to be near the intersection of the vertical red line with the diagonal harmonics (CMA type 1).
N. of points: Number of points to draw diagrams.

3.4 *Misc* submenus

Auto-gyro: This produces the recalculation of the O-mode and X-mode frequencies in the CMA type 1 diagram to be harmonics of the fundamental cyclotron frequency
CMA type: You can choose between different types, indicated as the two quantities (y vs x)
Put gyro: (Not yet implemented)
R coord: Choose the radial coordinate to be shown as resonance location
n_G: Choose between different formulas for the Greenwald density limit

3.5 *Misc / R coord* submenu

The user can choose between the following radial coordinate:
R: The major radius in meters
$(R - R_0)/a$: The normalized minor radius
R/R_0: The normalized major radius

3.6 *Misc* / n_G submenu

This submenu allows the user to choose between the Greenwald density limits formula shown in 7 and 8.

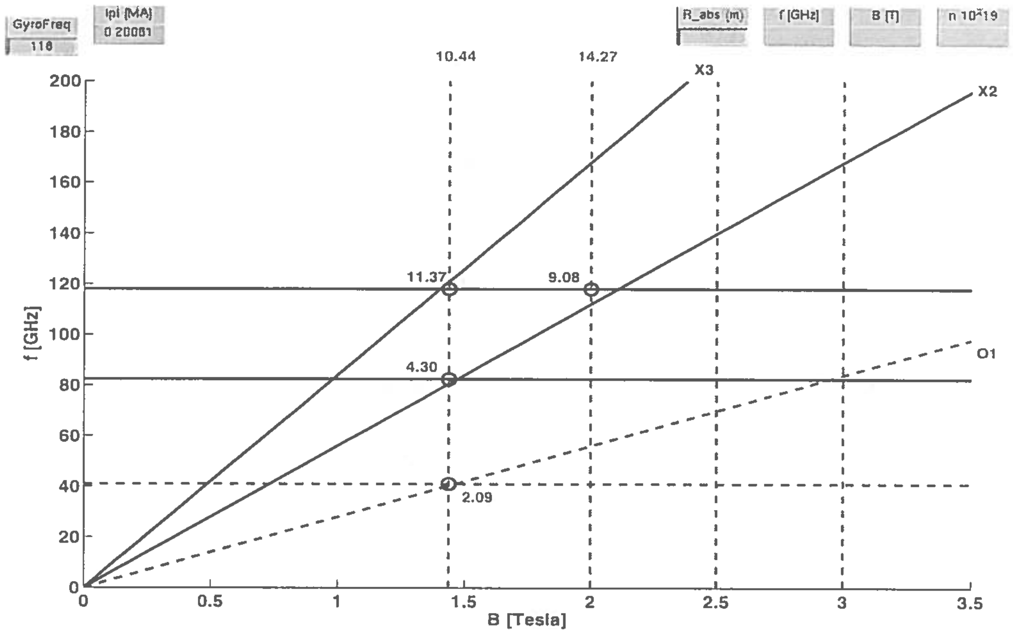
3.7 *Misc / Tracer* submenu

With this option the user can turn on or off the possibility to interactively visualize values of main parameters while moving on the plot. Once turned on, the user has simply to click left button over the figure, than click again to choose which point to evaluate. The values of the frequency, the magnetic field and of the density appear right-top in the main window. In addition, in the MATLAB terminal, there are printed the values of the absorption radii for the different modes, assuming the magnetic field evaluated at the mouse position as the new nominal on-axis magnetic field B_0.

3.8 Note on the total plasma current

3.9 CMA type = 1 (Frequency Vs Magnetic Field)

Begin with type 1 diagram (fig. 4), which plots the frequency f [GHz] as a function of the magnetic field B [Tesla].



GyroFreq 118

Ipl [MA] 0 20061

Figure 4: CMA type 1 diagram, showing accessibility of waves with the frequency versus the nominal magnetic field. Cut-off densities (numbers at the intersection points), and Greenwald density limits (top red numbers) are also shown.

The black solid oblique are the X-mode harmonics, while blue dashed are O-modes. Horizontal are the reference frequencies chosen by the user, colors are coherent with the type of wave. Vertical red dashed lines are the reference magnetic fields; at the top the green value is the Greenwald density limit in units of 10^{19} as calculated by the formula chosen between 7 and 8. The intersections between the horizontal and vertical lines give the cut-off densities for that frequency, but it is evaluated only if the point of intersection is near enough to the reference harmonics (oblique lines); the criterion for this is the value of *Percent df*. With *Auto-gyro* all the horizontal lines are recalculated as harmonics of the fundamental cyclotron frequency.

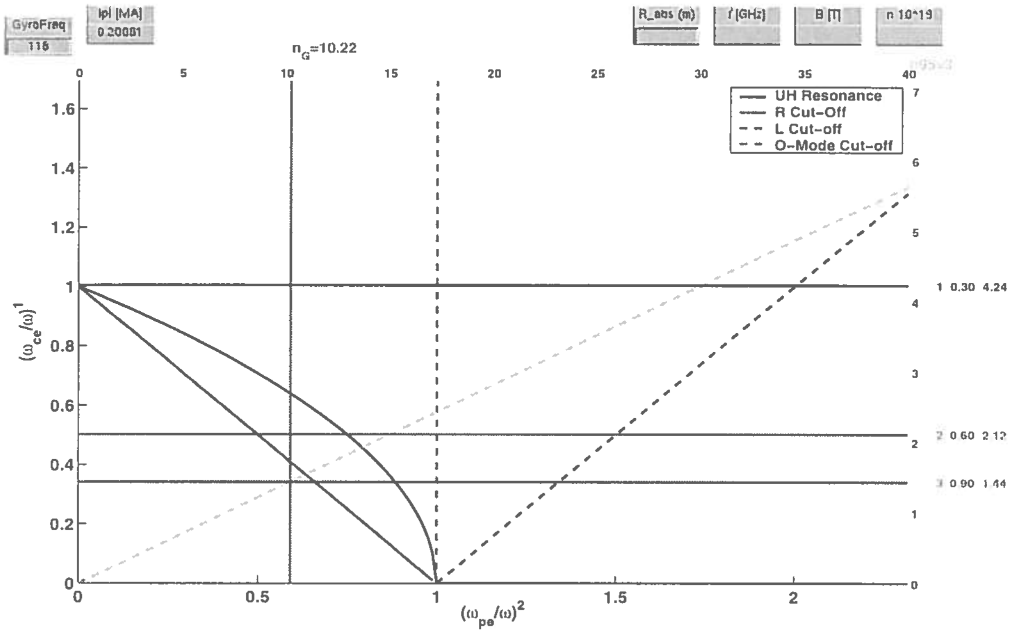


Figure 5: Bindslev-type diagram. The normalized cyclotron frequency versus the normalized plasma frequency diagram is useful to study accessibility of waves to different radial position and density values, also taking in to account Greenwald density limit existence (cyan and magenta lines)

3.10 CMA type > 1 (Normalized frequencies)

By now there are five different types of diagrams the user can choose, which plot the normalized cyclotron frequency $\frac{\omega_{ce}}{\omega}$ versus the normalized plasma frequency $\frac{\omega_{pe}}{\omega}$. Each type of plot has a particular exponent for each of the two variables. For example the type with the written (o_c/o) vs $(o_p/o)^2$ is the Bindslev diagram (fig. 5). Let us explain the different lines not shown in the legend. The horizontal red lines represent the X-mode harmonics $R = R_0$. The black lines are the same for the O-mode (not shown in this example). The vertical magenta line is the Greenwald limit for $R = R_0$, while the oblique dashed cyan line is the same but as a function of B_ϕ. The intersection of the green line and of the red dashed is exactly where $\omega_{ce}(B_\phi) = \omega_{GyroFreq}$. In a future upgrade this diagram will show also some topology of travelling waves, implementing density model profiles. As regard the three numbers at the right of the diagram, appearing at the end of the horizontal harmonics lines, they are: at the left the harmonic number (1,2,3,ecc...), in the middle the radial position where the wave is absorbed, at the right the value of the magnetic field in that location. The absorption radial position is evaluated using $R_{absorption} = R_0 \frac{B_0}{B_{absorption}}$. When the user enters a number in the R_{abs} edit box on the top right, new dashed lines appear, which show the value of the central magnetic field B_0 (most-on-the-right number) one should use to move absorption to that location.

3.11 *I/O* menu

This menu allows the user to save and retrieve data simply writing down directories and file names. The current submenus are: *Parameters*, where the user can set the directory where to save data; *Save*, to save data with specified file name; *Load*, to load data specifying the name of the file; *Quit* allows to quit the program.
Remember that the default directory is the one where the user is when running the program.

4 Examples

Now we analyze some examples of usage of this tool, either for present cases and for future plans.

4.1 TCV nowadays, possible upgrade?

The first case is TCV as it is in present days, characterized by a typical vacuum toroidal magnetic field of $B_0 = 1.44T$, a major radius of $R_0 = 0.88m$ and a minor radius $a = 0.25m$. The gyrotrons presently have the following frequencies: six gyrotrons operate at a frequency of $f = 82.7GHz$ delivering waves at the 2^{nd} harmonic (X2, 3 MW), other three operate at $f = 118GHz$ at the 3^{rd} harmonic (X3, 4.5 MW), for a total of nine gyrotrons. Inserting these parameters the diagrams we obtain are in fig. 9. To produce this example we have chosen the following set of values: $q_{95} = 5$, $k = 1.6$, $\delta = 0.1$, giving a total current $I_{pl} = 0.22MA$. We then ask if a future upgrade can allows for higher magnetic fields and performances.

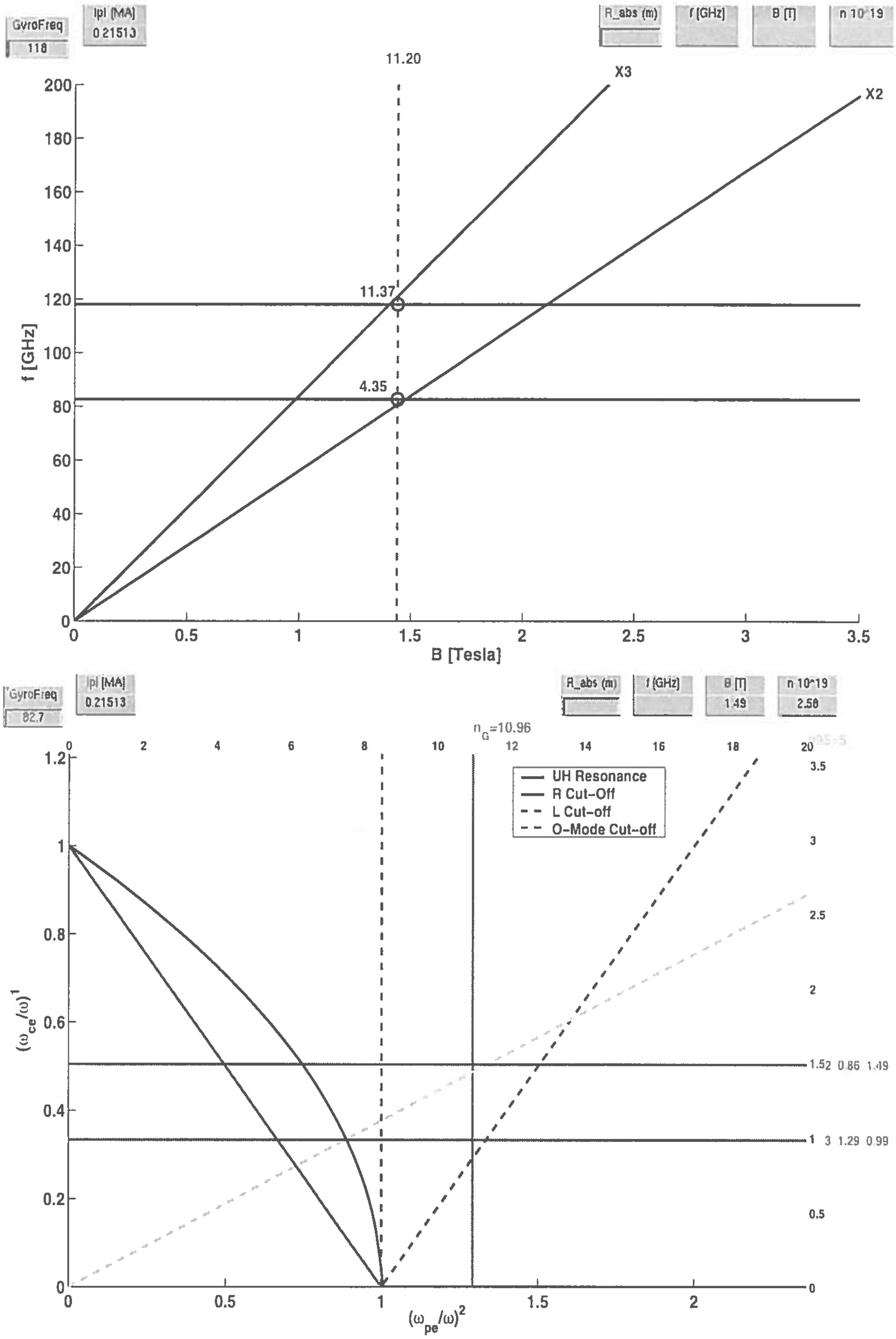


Figure 6: TCV at present state, CMA type 1 & Bindslev-type

We analyze with the same diagrams the possibility of achieving a central magnetic field of $B_0 = 2T$ and using gyrotrons launching at $f_1 = 118GHz$, $f_2 = 120GHz$,$f_3 = 170GHz$. The result is shown in diagrams of fig. 8.

We see that operating with a nominal magnetic field of $B_0 = 2.14T$ permits to work near to the Greenwald limit with the 2nd X-harmonic, although having not a large current (about $I_p = 200kA$) and a rather high $q = 12$. Using the third harmonic X3, at $f = 170GHz$, we can operate very close to the Greenwald limit, with a current of $I_p = 400kA$, and a $q = 6$ with a resonance quite on axis. Because usually absorption efficiency is conditioned by electron temperature T_e, it could be dangerous to go to high density values, thus requiring additional forms of heating. However, a deep analysis of efficiency of heating is beyond the scope of this work.

4.2 ITER case

ITER typical parameters are: $R_0 = 6.2m$, $a = 0.25m$, $B_0 = 5.3T$, $I_p = 15MA$. Two gyrotron frequency operating at $f_1 = 140GHz$ and $f_2 = 170GHz$, launching on the first O-harmonic, and in the 2^{nd} and 3^{rd} X-harmonics. It seems that only the O-mode can operate at $f = 170GHz$, because the cut-off densities of X2 and X3 is well beyond the Greenwald limit which thus imposes restrictions to their accessibility. If we lower the nominal magnetic field to about $B_0 = 3T$, also the X2 represents a good option for heating near the Greenwald limit, at $f = 140GHz$.

5 Conclusions

GYRODIAG has proved to be useful as a new tool to go insight analysis of different type of diagrams of ECRH heating accessibility from a global point of view.

IMPORTANT: *gyrodiag.m* can be used on any computer which has MATLAB installed, version > 6.2. Just copy it from my directory (shown in section 3), and copy also the small function *cround_6.m*, which is used inside the program.

References

[1] M. Greenwald *et al.*, *Nucl. Fusion* **28**, 2199 (1988)

[2] ITER Physics database, *Nucl. Fusion* (1994)

[3] A. Pochelon *et al.*, *5th EFPW, Sesimbra, 10-12 Dec. 1997*

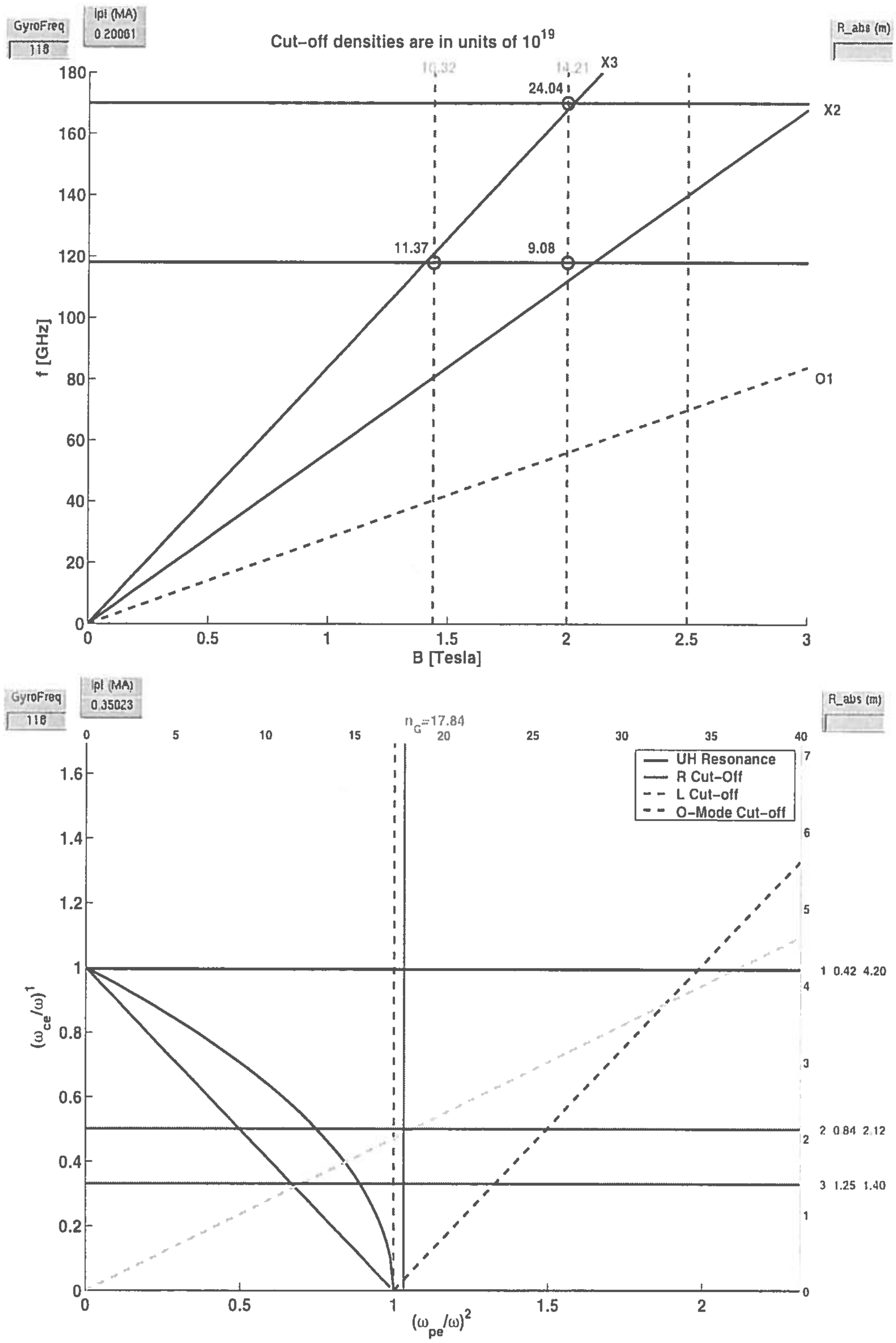


Figure 7: TCV upgrade analysis, CMA type 1 & Bindslev-type

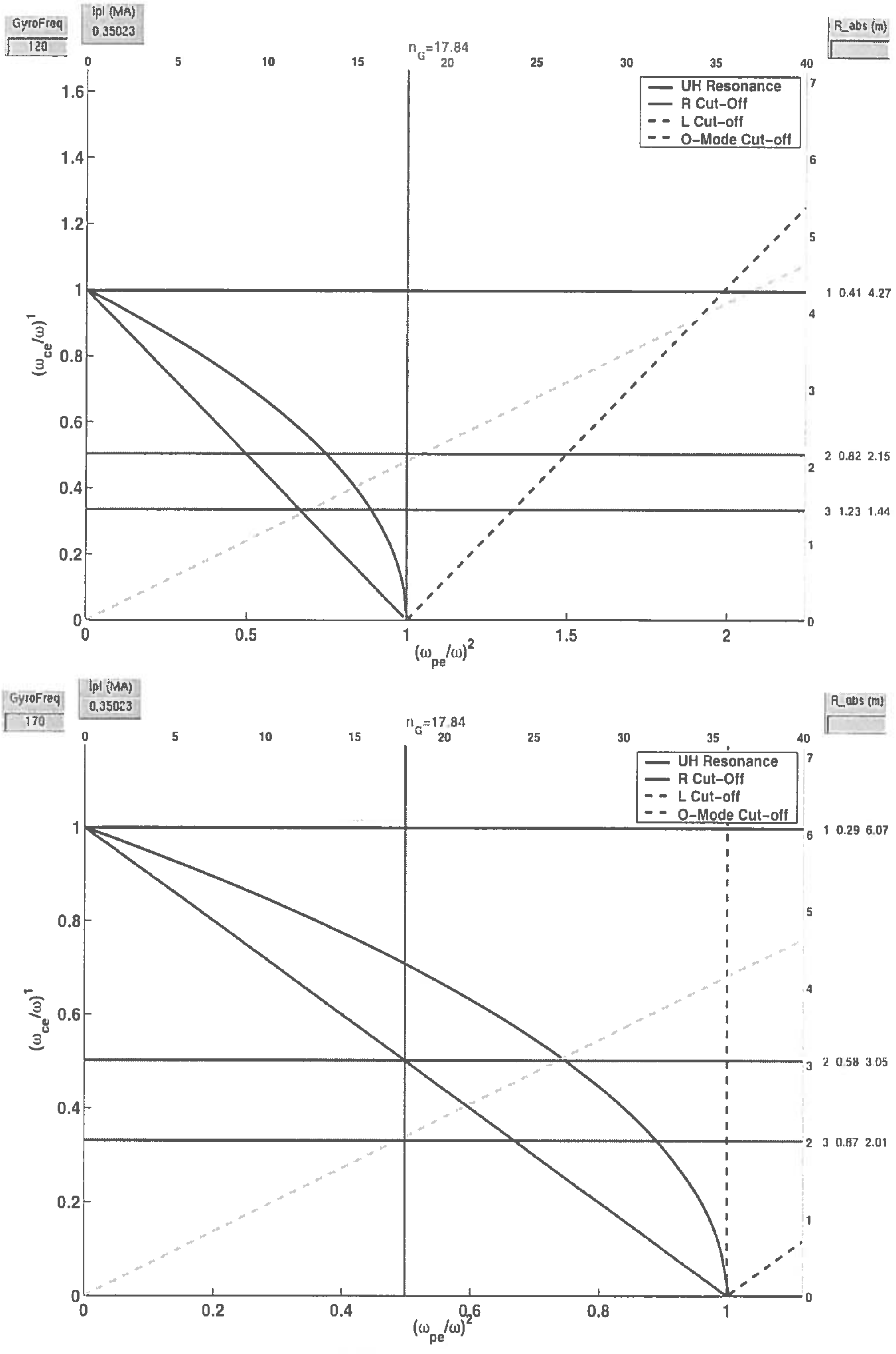


Figure 8: TCV upgrade analysis, again & Bindslev-type

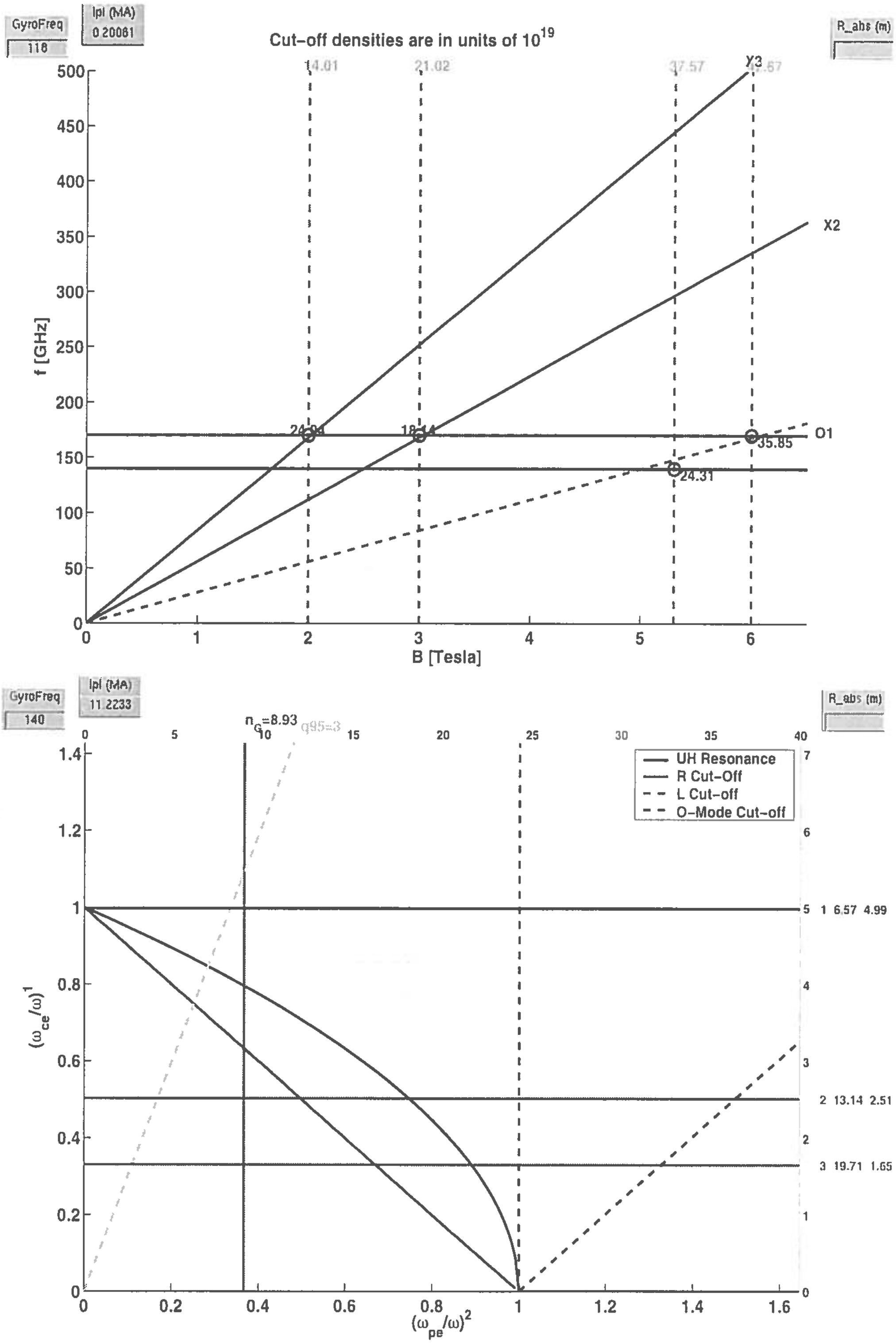


Figure 9: ITER case, CMA type 1 & Bindslev-type