Theory of EC waves - Summary

G. Giruzzi

CEA, IRFM (France)

Main topics

- Advanced ECCD efficiency calculations
- Cyclotron power loss
- ECCD operation diagrams
- Control of MHD modes
- Mode conversion, full-wave theory, EBW applications

List of theory papers

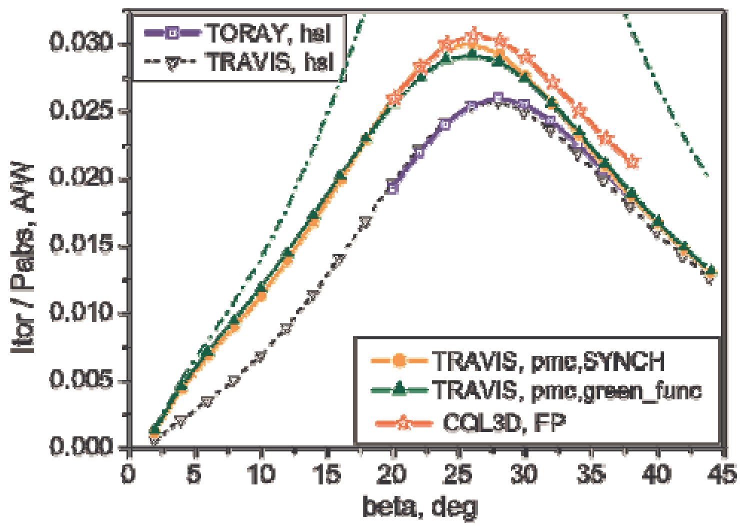
Marushchenko, N.	ECCD models with momentum conservation, finite collisionality, and high T_e
Hu, Youjun	Semi-Relativistic Coulomb Collision Operators for Current Drive Applications
Hu, Yemin	A relativistic theory of electron cyclotron current drive efficiency
Albajar, F.	EC radiative transport in fusion plasmas with an anisotropic distribution of suprathermal electrons
Farina, D.	Feasibility of an ECRH system for JET: wave propagation, absorption and current drive
Nowak, S.	Feasibility of an ECRH system for JET: Neoclassical Tearing Modes stabilization
Witvoet, G.	Control oriented system analysis and feedback control of a numerical sawtooth instability model
Vdovin, V.	O-mode and X-mode coupling effects in toroidal plasmas at fundamental and second EC harmonics
Kalinnikova, E.	Multiple ray-tracing and Fokker-Planck analyses for EBWH/CD experiments in QUEST
Yu, Zhi	Gyrocenter-gauge kinetic simulation of magnetized plasmas at ECRF time scale

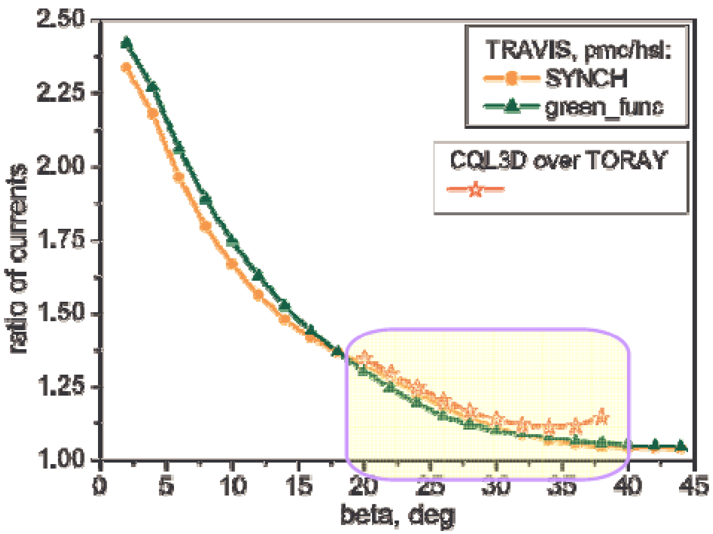
Advanced ECCD modelling: momentum conservation *(N.B. Marushchenko)*

Examples: ITER, equatorial launcher

- Scenario 2: $n_e(0) = 10^{20}\ m^{-3}$, $T_e(0) = 25$ keV, $Z_{eff}(0) = 1.7$

  Plasma parameters guarantee
  i) relativistic effects and **ii)** validity of collisionless limit





- ECCD calculated by TORAY and TRAVIS in *hsl* approach coincide well
- both *pmc* and Fokker-Planck calculations are in a good agreement
- in the main range of interest, *hsl* significantly underestimates ECCD (10% – 30%)

Advanced ECCD modelling: finite collisionality *(N.B. Marushchenko)*

Finite collisionality: NEO-2 code

- NEO-2 solves generalized Spitzer problem by field-line-tracing technique

$$v_{\|}\mathbf{h}\cdot\nabla(\chi F_{eM}) - C^{lin}(\chi F_{eM}) = \frac{1}{l_c} v_{\|} F_{eM}$$

In kinetic transport theory, series in associated Laguerre polynomials of order 3/2 series is applied

$$\chi(\mathbf{r},u,\lambda) = \sum_{m=0}^{M} \chi_m(\mathbf{r},\lambda) L^{3/2}(u^2/v_{th}^2)$$

full version of NEO-2 only for tokamaks is tested (4D → system of 2D)

$$\chi_m(\mathbf{r},\lambda) \equiv \chi_m(\theta,\varphi,\lambda) \rightarrow \chi_m(\theta,\lambda)$$

(for stellarators, the mono-energetic version was successfully benchmarked)

- Corresponding regimes:
  Pfirsch-Schlüter; plateau; banana regime; deep banana regime
- Good convergence to asymptotic limits
- Interesting results due to combination of
  - ✓ magnetic mirroring force
  - ✓ collisional detrapping

Potential form of the semi-relativistic Fokker-Planck coefficients

Define two potential functions,

$$h_b(\boldsymbol{v}) = -\frac{1}{8\pi}\int |\boldsymbol{v}-\boldsymbol{v}'|\gamma'^5 f_b(\gamma'\boldsymbol{v}')d^3\boldsymbol{v}',$$

$$g_b(\boldsymbol{v}) \equiv -\frac{1}{4\pi}\int \left[\frac{1}{|\boldsymbol{v}-\boldsymbol{v}'|}\left(\frac{1}{\gamma'}+\frac{1}{\gamma'^3}\right)+\frac{(\boldsymbol{v}\cdot\boldsymbol{v}'-v'^2)^2}{|\boldsymbol{v}-\boldsymbol{v}'|^3\gamma'}\right]\gamma'^5 f_b(\gamma'\boldsymbol{v}')d^3\boldsymbol{v}'.$$

In terms of these two potential functions, the diffusion and friction coefficients can be written as,

$$\boldsymbol{D}^{a/b}(\boldsymbol{u}) = -\frac{4\pi c_{ab}}{m_a^2}\frac{\partial^2 h_b(\boldsymbol{v})}{\partial\boldsymbol{v}\partial\boldsymbol{v}},$$

$$\boldsymbol{F}^{a/b}(\boldsymbol{u}) = -\frac{4\pi c_{ab}}{m_a m_b}\frac{\partial}{\partial\boldsymbol{v}}g_b(\boldsymbol{v}).$$

ECCD calculations with various collision operators *(Yemin Hu)*

Association Euratom-CEA

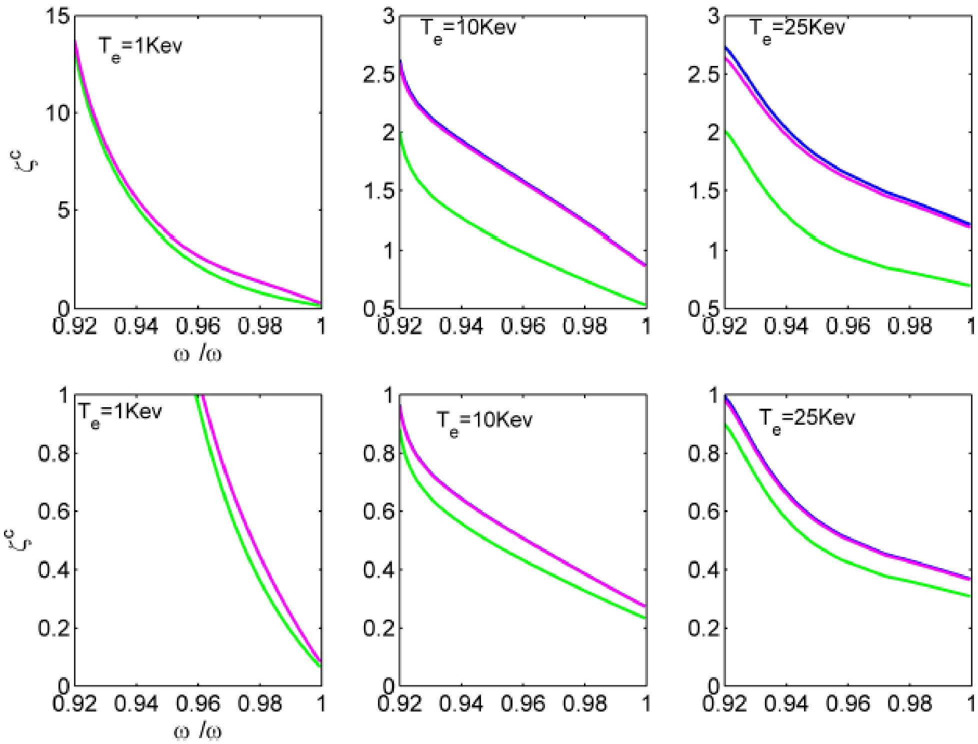


Figure: Dimensionless efficiency ζ^c , as a function of $y = \frac{\omega_c}{\omega}$, evaluated for $n_{||} = 0.4$, $Z = 1.6$ (up three figures) and $Z = 10$ (down three figures) with different electron temperature T_e. The green, blue and magenta line, represent the results from high-velocity limit, semi-relativistic and full-relativistic collision operator model respectively.

Cyclotron power loss with an anisotropic superthermal distribution *(F. Albajar)*

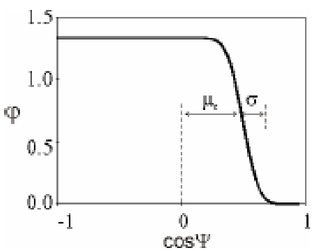
+ M. Bornatici, F. Engelmann !

$$F(\mathbf{p}) = (1-\eta) f_b(\mathbf{p}, T_b) + \eta f_h(\mathbf{p}, T_h)$$

(relativistic) Maxwellian bulk — Suprathermal component 'h'

$$\eta f_h(\mathbf{p}, T_h) = \eta_1 f_h(\mathbf{p}, T_h) + (\eta - \eta_1) f_h(\mathbf{p}, T_h)\varphi(\cos\psi)$$

(relativistic) Maxwellian part — anisotropic distribution



$$\varphi(\cos\psi) = \frac{1}{1+\mu_c}\left[1 + \mathrm{erf}\left(\frac{\cos\psi - \mu_c}{\sigma\sqrt{2}}\right)\right]$$

Pitch angle distribution of the anisotropic component of suprathermals described by a one-sided erf-cone

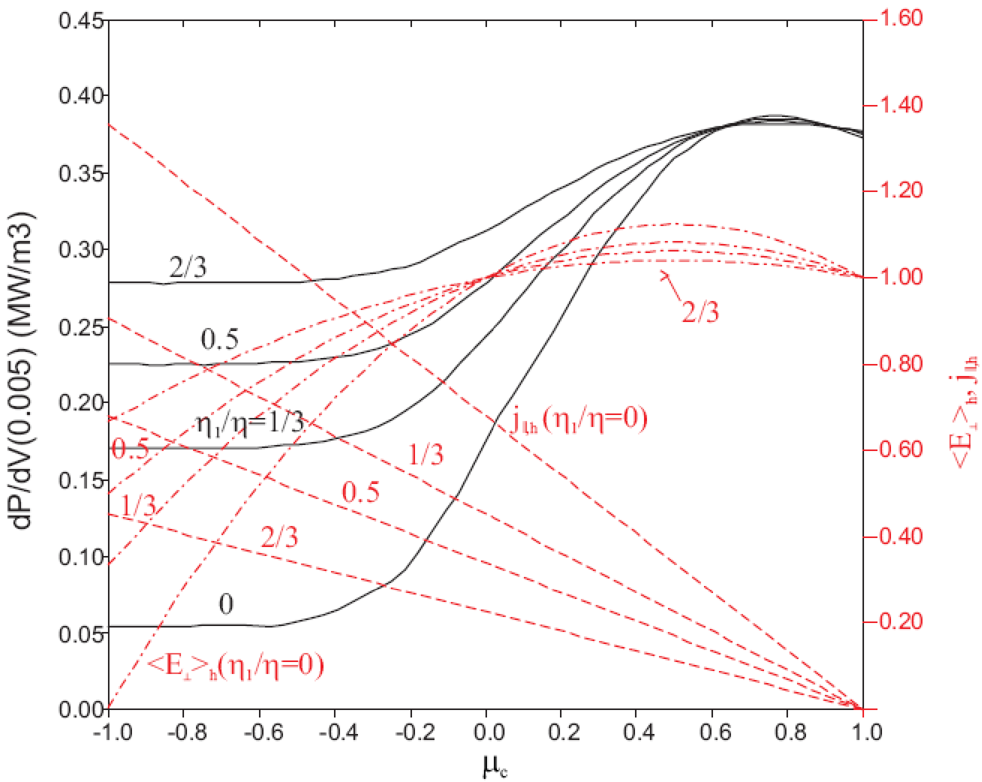
$\mu_c > 0$ One-sided loss-cone covering case of excess of $\mathbf{p}_\perp$

$\mu_c < 0$ Anti-loss-cone covering case of excess of $\mathbf{p}_\parallel$

[P.A. Robinson, Plasma Physics and Controlled Fusion 27, 1985, 1037-1055]

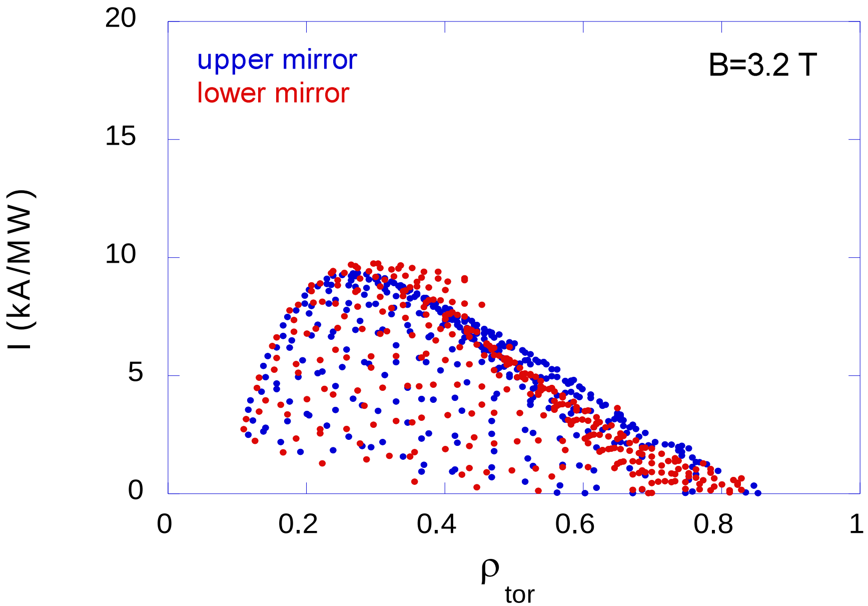
$$\alpha^{(i)} = \alpha_b^{(i)} + \alpha_{h1}^{(i)}\left(1 + \frac{\eta - \eta_1}{\eta_1} A^{(1)}(1+R)\right), \quad A^{(1)} \equiv \frac{1}{1+\mu_c}(1+\mathit{erfx}),$$

⇨ Generalized Kirchhoff's law $I_{bb}^{(i)}\alpha^{(i)} = \frac{\omega^2}{8\pi^3 c^2}\left[T_b\alpha_b^{(i)} + T_h(s)\alpha_{h1}^{(i)}\left(1 + \frac{\eta - \eta_1}{\eta_1} A^{(1)}\right)\right]$

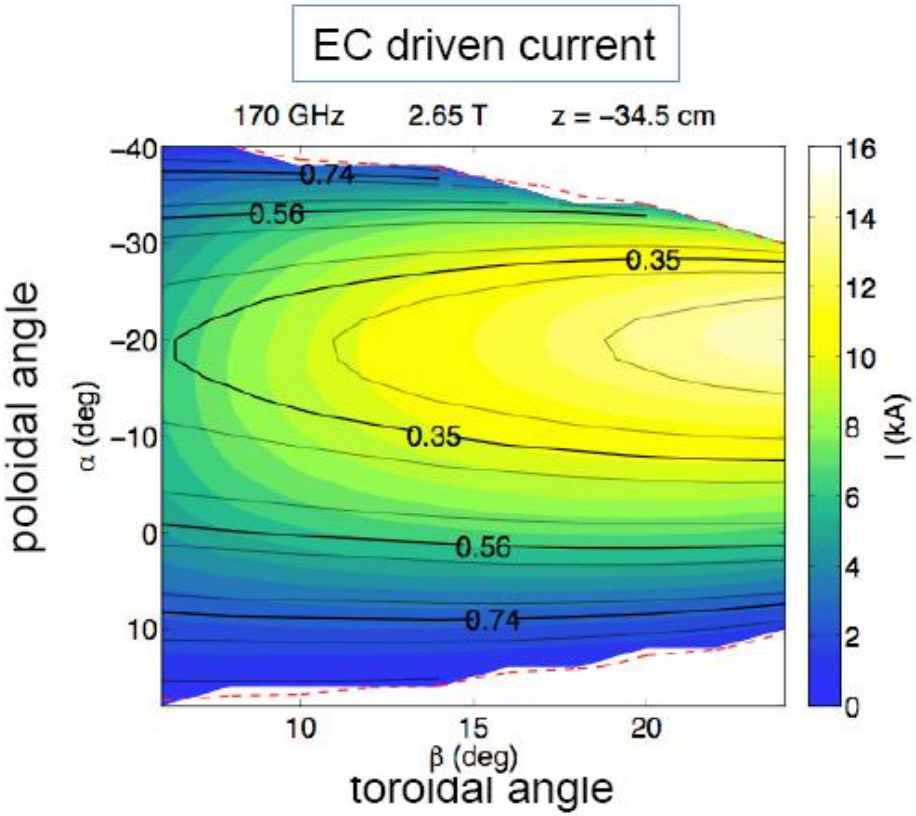


ECCD operation diagrams. Application to JET studies *(D. Farina)*

Association Euratom-CEA



Compact representation of thousands of beam-tracing runs



Istituto di Fisica del Plasma "Piero Caldirola"
Consiglio Nazionale delle Ricerche

EFDA JET

NTM stabilisation by ECCD for JET plasmas (S. Nowak)

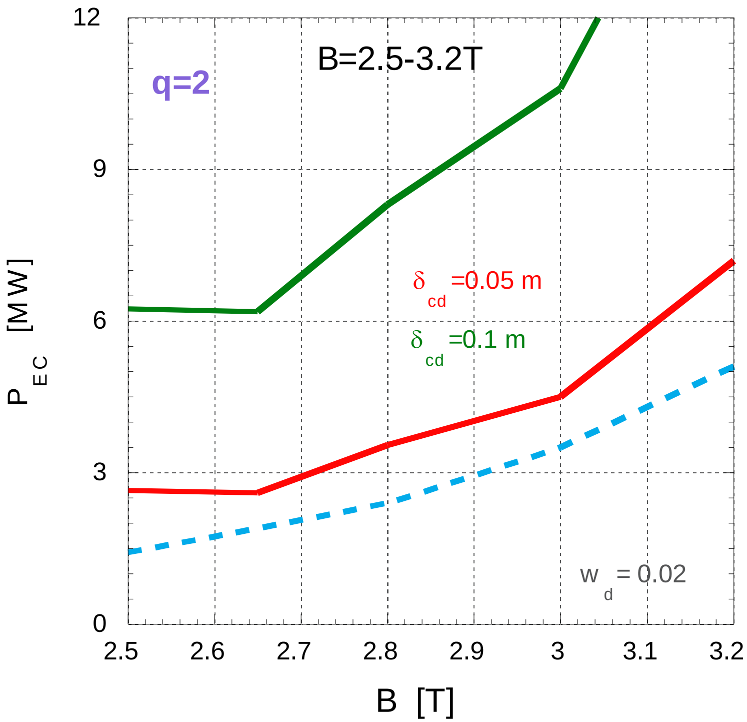
EC power required for island suppression

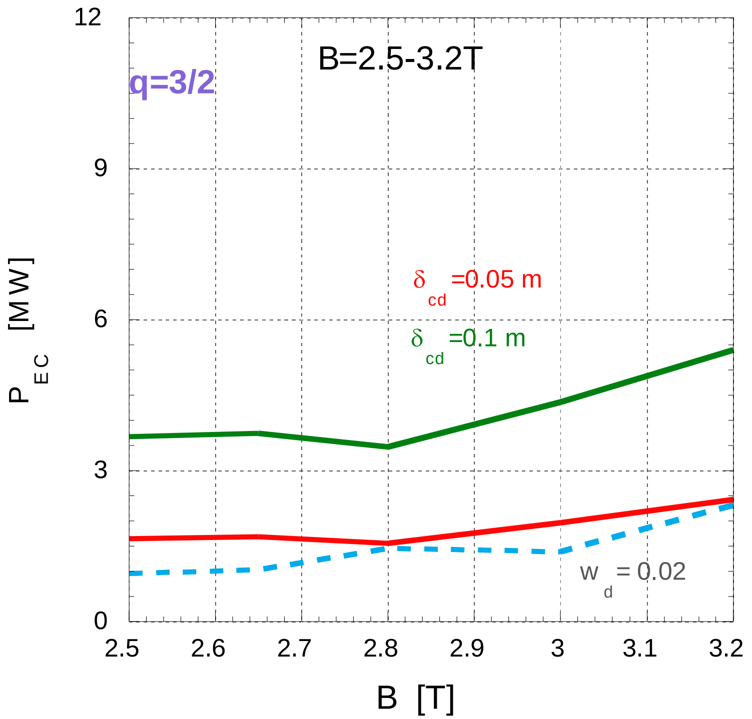
(H-mode, 73344 parameters)

Green: δ_{cd} = 10 cm

Red: δ_{cd} = 5 cm

Cyan: δ_{cd} from beam-tracing





Control oriented system analysis of sawtooth instability *(G. Witvoet)*

System identification and controller design

Estimation dynamics around operating points $\tau_s^i \in [9.25, 11.75]$ using feedback in Fig. 2 (k is the crash number index):

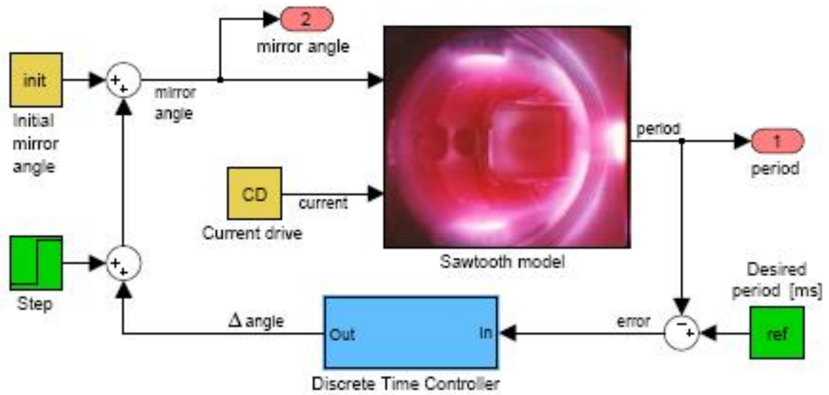


Figure 2: Sawtooth model in a Simulink® closed loop scheme

Technische Universiteit Eindhoven University of Technology

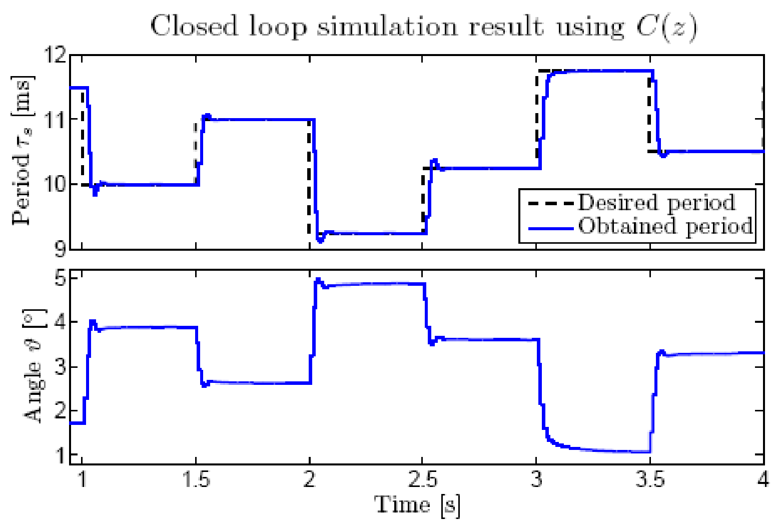


Figure 4: Closed loop simulation result

Sawtooth model and steady state simulations

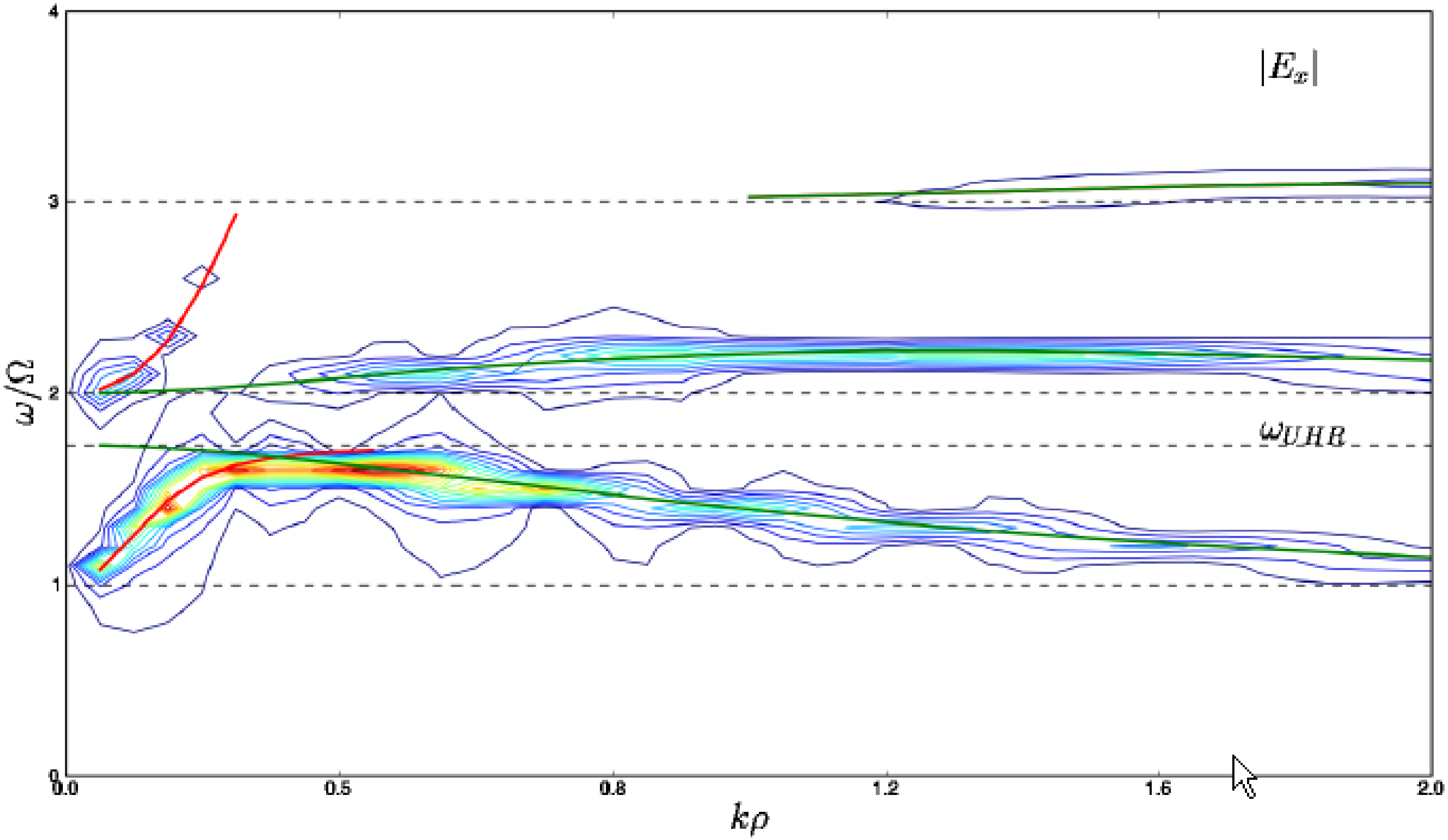
Model: *infinite dimensional impulsive dynamical system*

$$\frac{\partial}{\partial t}B_\theta = \frac{\partial}{\partial r}\left(\frac{\eta}{\mu_0 r}\left(B_\theta + r\frac{\partial}{\partial r}B_\theta\right) - \eta J_{\mathrm{CD}}\right) \quad \text{if } s_{q=1} \le s_{\mathrm{crit}} \quad (1a)$$

$$B_\theta(r,t^+) = \begin{cases} B_\theta(r,t^-) & \text{for } r \ge r_{\mathrm{mix}} \\ \frac{1}{R} r B_\phi & \text{for } r < r_{\mathrm{mix}} \end{cases} \quad \text{if } s_{q=1} > s_{\mathrm{crit}} \quad (1b)$$

Gauge function technique for gyrokinetic theory and application to EBW *(Zhi Yu)*

From X wave to Bernstein Wave

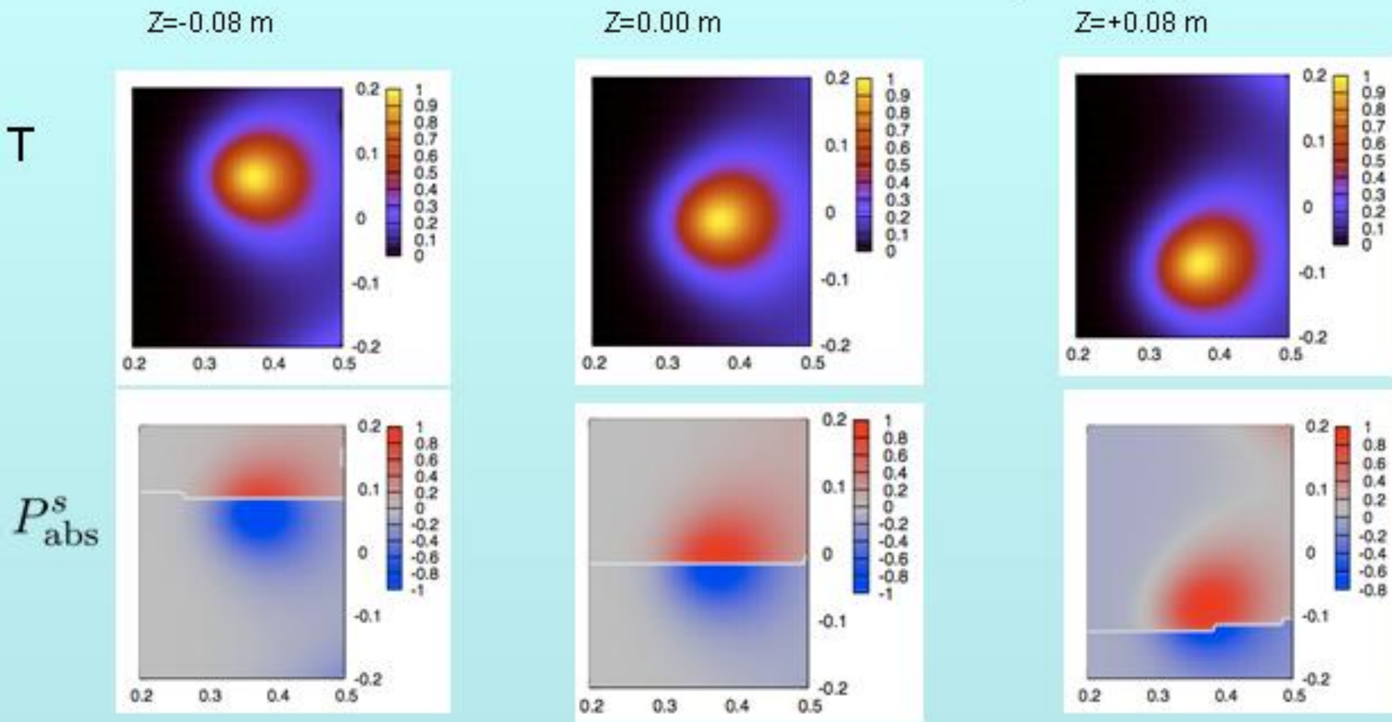


Ray-tracing + Fokker-Planck analysis for EBW in QUEST *(E. Kalinnikova)*

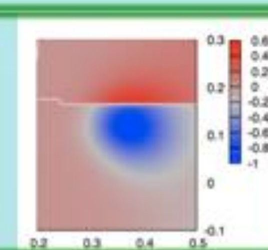
Association Euratom-CEA

irfm cea cadarache

Calculation results for different antenna position (Z)



The synchronous antenna and plasma shift along the z-axis allows to reach large total power absorption for negative direction in the central plasma region.



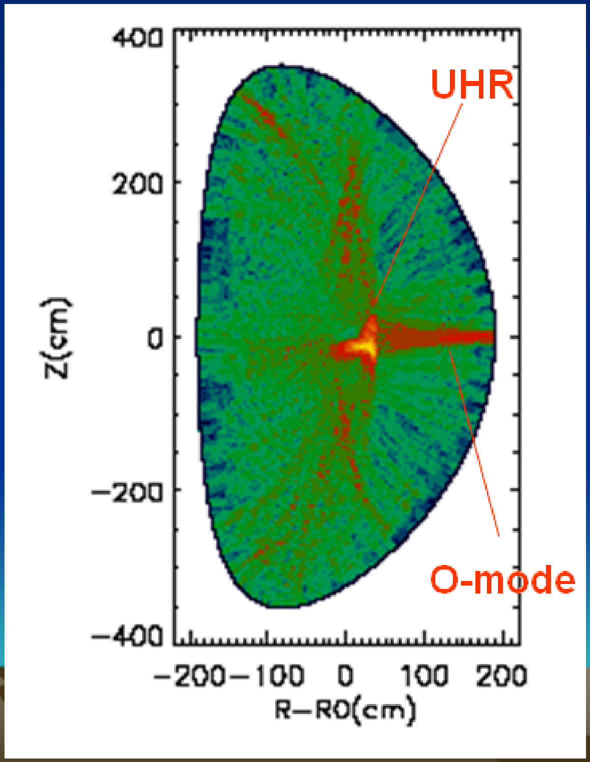
Full-wave calculations *(V. Vdovin)*

Power deposition at fundamental harmonic

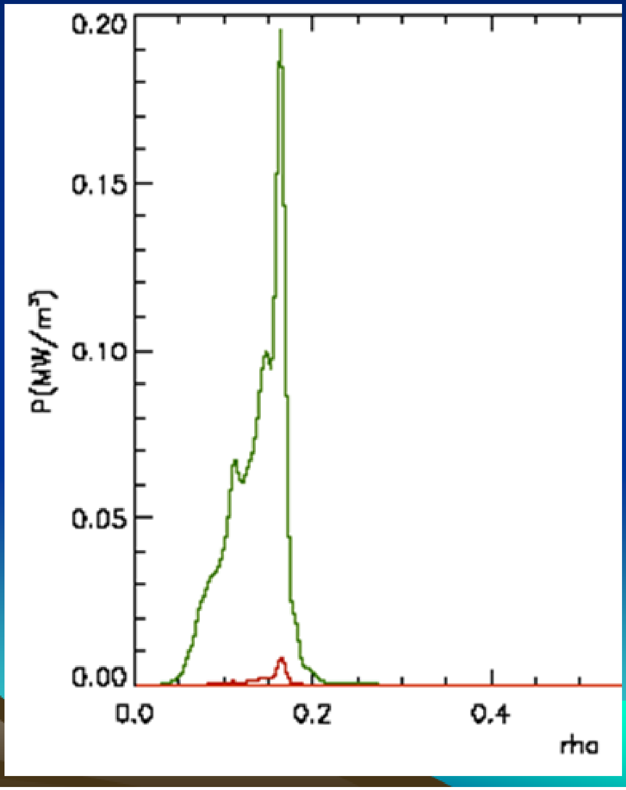
in ITER is defined by UHR position and EBW excitation

F=11.15 GHz, $N_{//}$=0.49, X(UHR)=53.5 cm, X(ω_{ce})= -11.5 cm

|Im(E_z)|



Absorbed power



Conclusions

A quotation from EC8, Gut Ising 1992, theory summary:

"is EC theory too advanced ?"

G. Giruzzi, young (and naive) physicist

Nowadays (EC16, Sanya 2010, theory summary):

- EC theory still very lively, attracting young (and less young) people
- Theoretical aspects **impact on decisions** for huge equipments
- Advanced theory is **everywhere** in EC experiments
- Theory more and more **integrated** in EC projects
- One of the great strengths of this community