NONLINEAR MODELING OF ECRH/ECCD*

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OUTLINE

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- **Kinetic description**
- **The Fortran codes ECNL and TORBEAM**
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Introduction

Models of Power Absorption

Linear Theory:

Standard theory, presently applied in most cases

a) Quasilinear wave-particle interaction (perturbation analysis is valid).
b) Non-oscillating part of the distribution function is assumed to be Maxwellian.
c) Ray and beam tracing codes

Quasilinear Theory:

Standard theory, presently applied in some cases

a) Quasilinear wave-particle interaction.
b) Non-oscillating part of the distribution function is non Maxwellian.
c) Bounce averaged Fokker-Planck codes

Nonlinear Theory: Reality!!

a) Nonlinear wave-particle interaction (perturbation analysis is not valid).
b) Non-oscillating part of the distribution function is non Maxwellian (computed from an integral equation).
c) Kinetic equation solver: ECNL

Cyclotron Resonance - 2$^{\mathrm{nd}}$ Harmonic X-Mode

Cyclotron resonance line

$$\omega - n\omega_c - k_{\|}v_{\|} = 0. \tag{1}$$

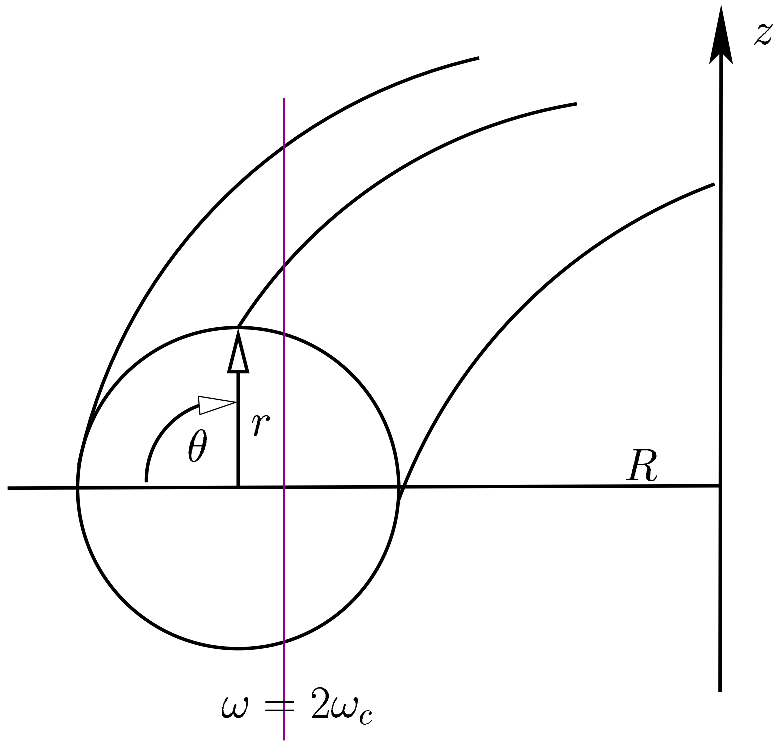
Width of the resonance zone in velocity space

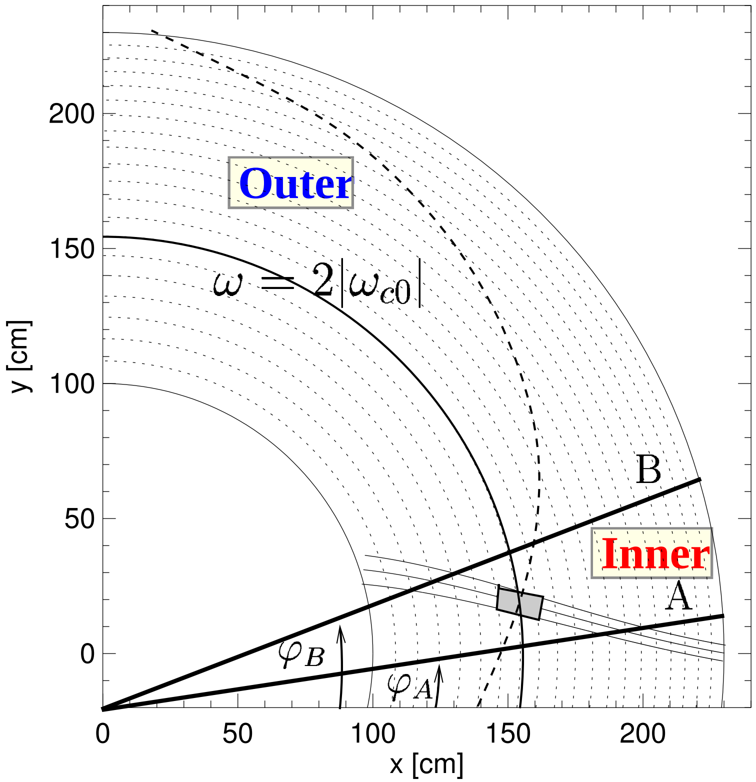
- Broadening of (1) due to finite parallel beam width $\Rightarrow \Delta v_{\perp,L}$.
- Broadening of (1) due to nonlinear effects $\Rightarrow \Delta v_{\perp,NL}$.

$$\Delta v_{\perp,L} \sim \frac{c^2 v_{\|}}{\omega L_b v_{\perp}}, \qquad \Delta v_{\perp,NL} \sim c\sqrt{\frac{E_0}{B_0}}. \tag{2}$$

- $\Delta v_{\perp,L} \gg \Delta v_{\perp,NL} \Rightarrow$ linear theory is applicable.
- $\Delta v_{\perp,L} \ll \Delta v_{\perp,NL} \Rightarrow$ change in the derivative of the distribution function, f, is strong such that, in the resonance zone, f becomes symmetric around the resonant value of $w_{\perp} = m_e v_{\perp}^2/2$.

Problem Geometry





Inner region (containing resonance zone):

- Exact orbits from solution of equations of motion in the wave field.
- Full kinetic description including gyromotion.
- Neglect of Coulomb collisions.

Outer region:

- Handled by conventional Monte Carlo method.
- Neglect of wave-particle interaction.

Kinetic Description

Kinetic equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{e}{c}\mathbf{v} \times \mathbf{B}_0 \cdot \frac{\partial f}{\partial \mathbf{p}} + \underbrace{e\left(\tilde{\mathbf{E}} + \frac{1}{c}\mathbf{v} \times \tilde{\mathbf{B}}\right) \cdot \frac{\partial f}{\partial \mathbf{p}}}_{\text{wave-particle interaction}} = \underbrace{\hat{L}_c f}_{\text{Coulomb collisions}}$$

f, t	distribution function, time
$\mathbf{v}$, $\mathbf{p}$	particle velocity, particle momentum
e, c	electron charge, speed of light
$\tilde{E}$, $\tilde{B}$	wave electric and magnetic field
B_0	equilibrium magnetic field
$\hat{L}_c$	Coulomb collision operator

Inner region

Transitions probabilities (see Kamendje et al., Phys. Plasmas **10** (1), 75 (2003) for more details).

Outer region

Mapping technique (see Kasilov et al., Phys. Plasmas **9**, 3508 (2002) for more details).

The Fortran codes ECNL and TORBEAM

ECNL: ITP TU-Graz

- Monte Carlo kinetic equation solver.
- It implements a nonlocal nonlinear model of wave-particle interaction.
- It solves the equation of energy conservation law, $\nabla \cdot \mathbf{S} + P_{\rm abs} = 0$, along the beam propagation path in a tokamak geometry using an iterative algorithm.
- Output: electron distribution function, profiles of the absorption coefficient, of the absorbed power density and of the EC current density along with the total driven current and the global efficiency.

$\Uparrow$

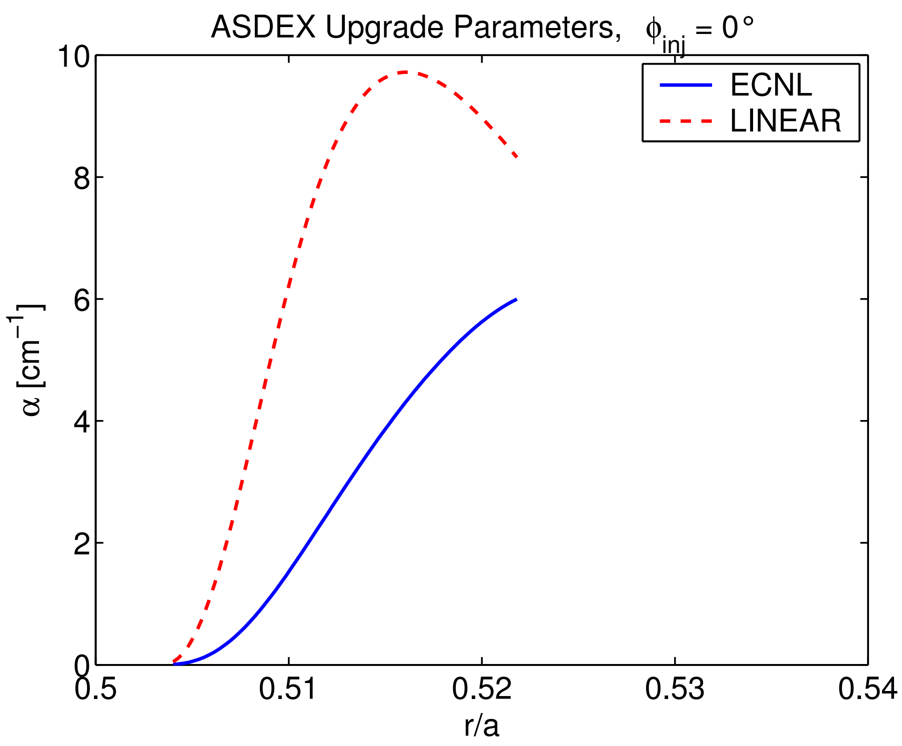
Interface

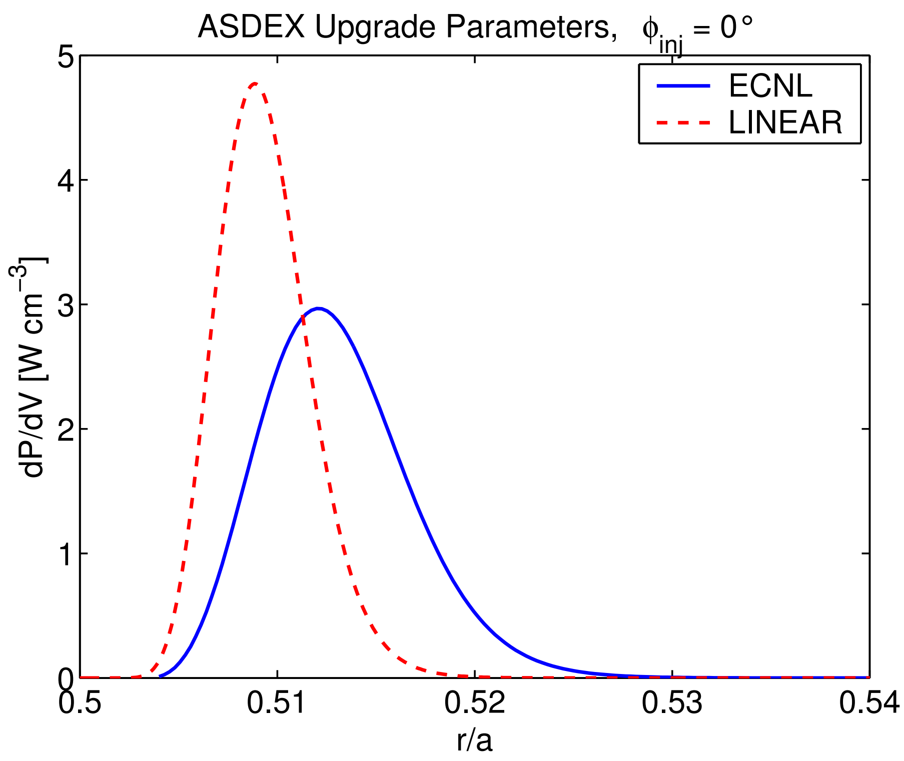
$\Downarrow$

TORBEAM: IPP-Garching

- Beam tracing equations are solved in a tokamak geometry for arbitrary launching conditions.
- The power absorption is computed using a local linear model of wave-particle interaction. The absorbed power density profile as well as the linear parallel current density profile are typical output.

ASDEX-Upgrade: Perpendicular Injection

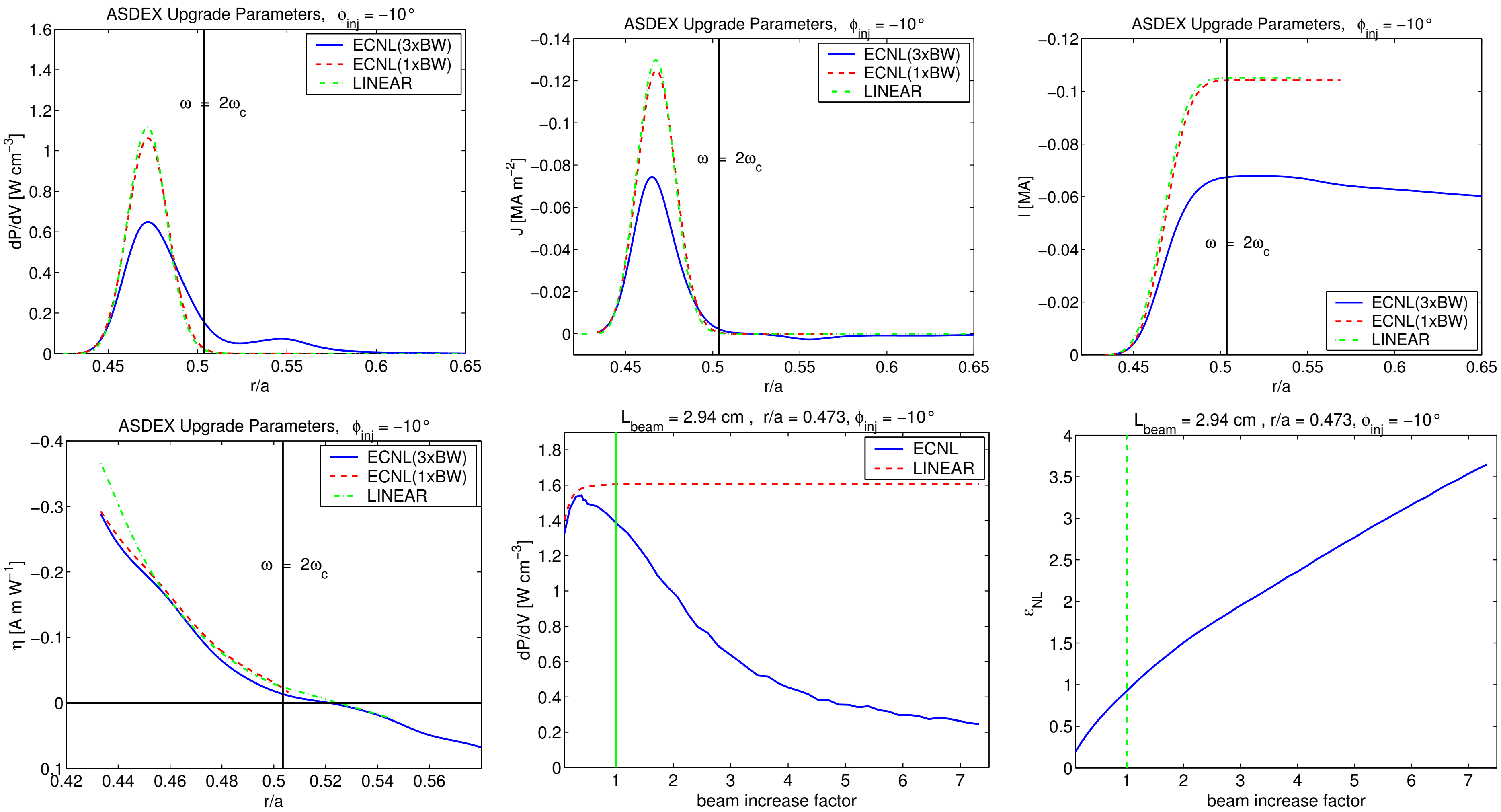




- Reduction of the absorption coefficient by a factor $\approx 2 - 5$.

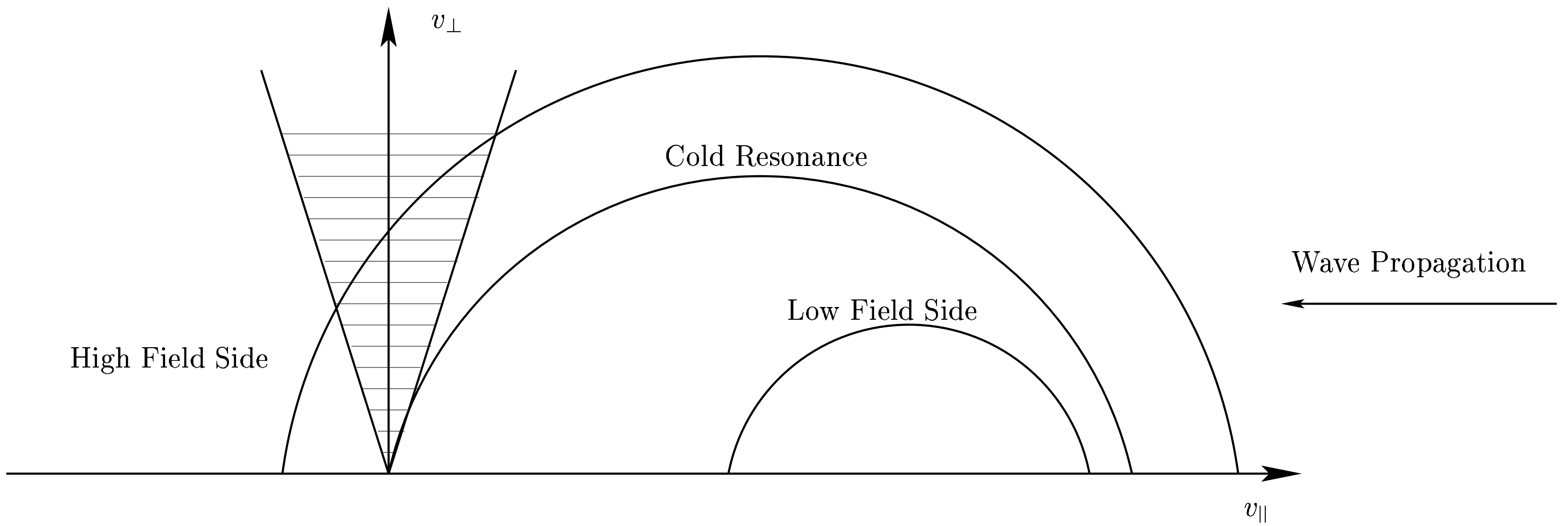
- Broadening of the absorbed power density profile as consequence of nonlinear effects of wave-particle interaction.

ASDEX-Upgrade: Nonlinear Effects due to Beam Width



- Results suggest a feasible experiment based on measurement of total current.

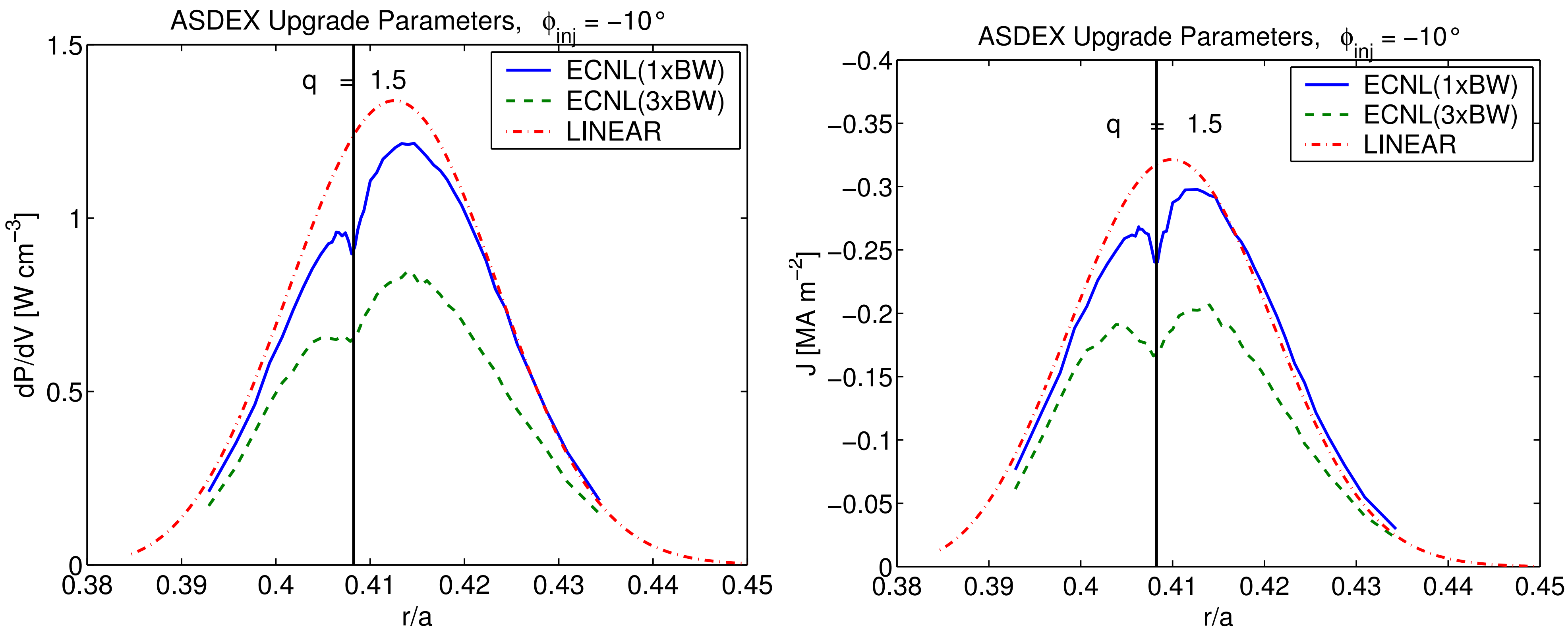
Resonance Curves in Velocity Space



Towards ECRH/ECCD modeling for ITER

- In ITER ECRH/ECCD applications mainly for neoclassical tearing mode (NTM) control and stabilization.
- NTM's: Instabilities $\Rightarrow$ Islands formation $\Rightarrow$ confinement degradation.
- Low order rational magnetic surfaces in tokamaks are resonant surfaces for NTM's.
- Control and stabilization of NTM's are an essential issue for tokamak operation.
- ECCD currently applied to compensate the loss of current within the island (ASDEX-Upgrade, ...).

ASDEX-Upgrade: On and near Rational-q Flux Surfaces

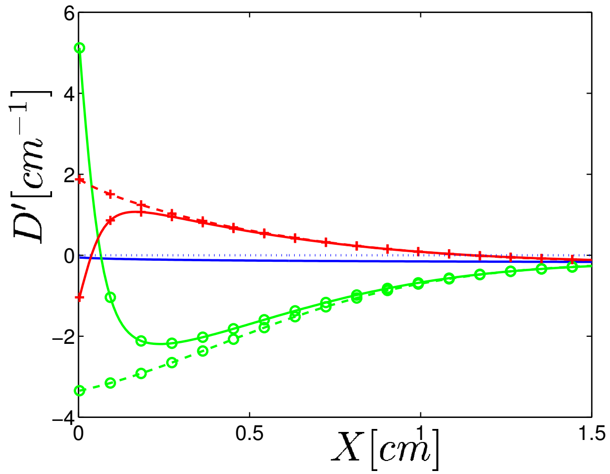


- ECCD appears to be sensitive to low order rational-q tokamak flux surfaces.
- With increasing beam width (increasing nonlinearity) the region of reduced absorbed power and driven current tends to broaden.
- Feature outside of reach for bounce average Fokker-Planck codes.

NTM Stability index: Δ'

$$\frac{4\pi}{\eta_{nc}c^2}\frac{\mathrm{d}w_0}{\mathrm{d}t} = k_0\Delta' + \sqrt{\epsilon}\frac{k_1\beta_{pe}L_q/L_p}{w_0} \qquad (3)$$

- (1): dynamical equation for the island half-width, w_0, where k_0 and k_1 are numerical constants, $\beta_{pe} = 8\pi p_e/B_\theta^2$, L_p is electron pressure length scale, $L_q = (\mathrm{d}\ln q/\mathrm{d}r)^{-1}$; q is the safety factor.
- Δ' very sensitive to the second derivative of the current density profile.



Linear model: dashed
Nonlinear model: solid
Without current drive: no markers
With co-current drive: circles
With counter-current drive: crosses

- Changing the sign of $\Delta' = D'(0) \Rightarrow$ acting against the evolution of the island width.
- At present, "active" NTM control is being performed.
- Nonlinear feature on rational surfaces opens the door for "passive" control mechanism.

Conclusions

- The tokamak geometry has been implemented in ECNL.
- ECNL has been benchmarked and combined with TORBEAM using an interface.
- Good agreement between all models for cases where the linear theory is applicable.
- Broadening and shift of the absorption profile in case of perpendicular injection.
- In ECCD nonlinear reduction of absorption might appear for wider beams. They are to be expected in ITER, therefore, nonlinear effects might be important there.
- Shift of the absorption profile would cause the reduction of the total EC current.
- It has been found that power absorption and current generation are sensitive to rational-q flux surfaces.
- This feature might be important and useful for NTM stabilization.

Outlook

- Consideration of real magnetic geometry and general topology (islands) in the region outside the beam (Mapping code for tokamak).
- ECCD modeling for ITER.
- ECRH/ECCD modeling for O-Mode Propagation.