DIFFER

Modeling of Electron Cyclotron Current Drive applied for the suppression of magnetic islands in tokamaks

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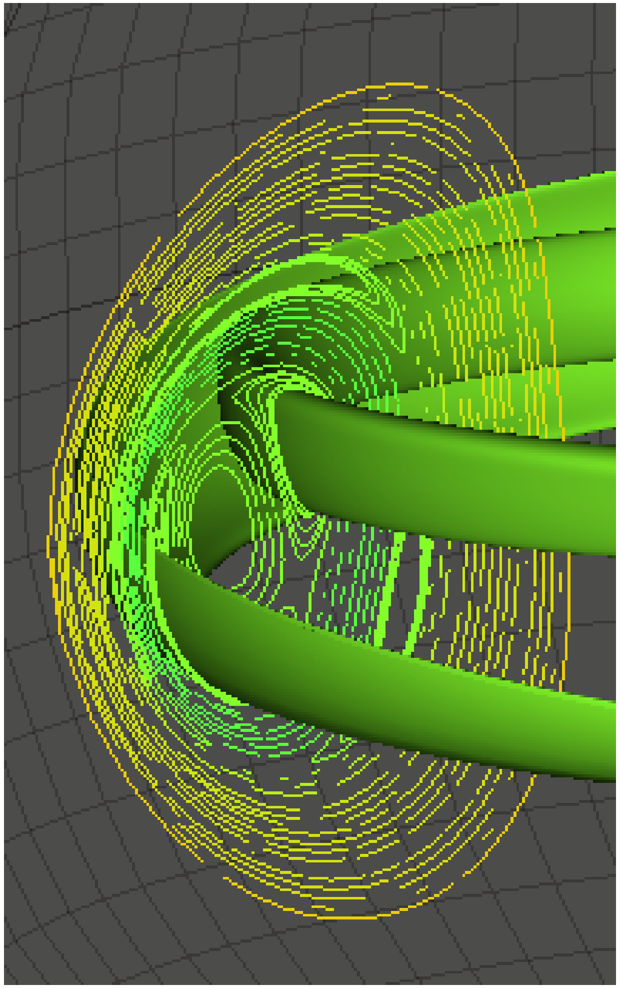
Motivation

- Magnetic islands in tokamaks must be controlled to prevent reduction of performance and disruptions
- Design of effective control strategies requires a reliable model
- ECCD inside islands is main control strategy



Picture © http://www.vacet.org/gallery/fusion.html

Modeling ECCD in magnetic islands

1. Field topology, temperature, and density distributions in presence of magnetic island

   Equilibrium + perturbation model

2. High frequency wave propagation and absorption

   Ray-tracing code (TORAYFOM)

3. Kinetic plasma response and current drive

   Quasi-linear Fokker–Planck code (RELAX)

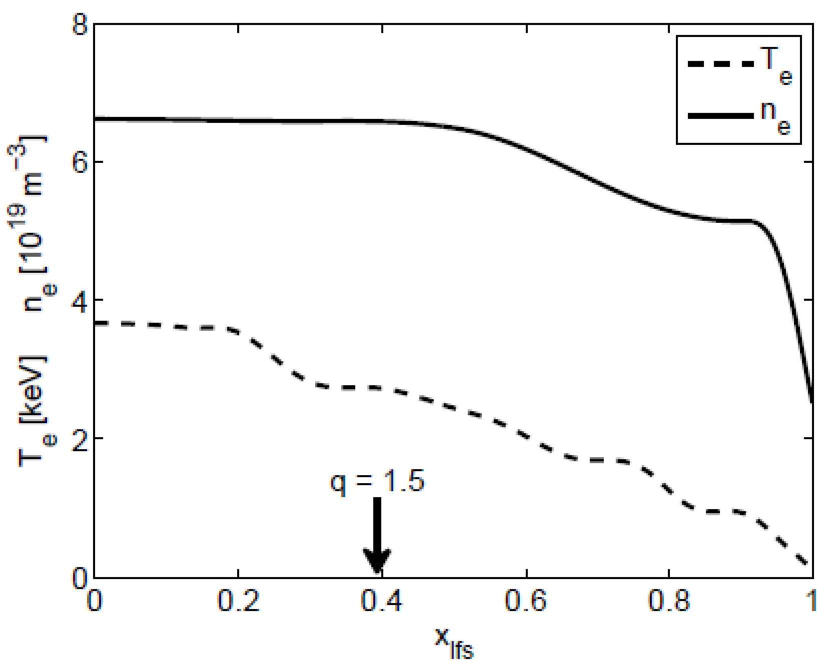
4. Evolution of magnetic island

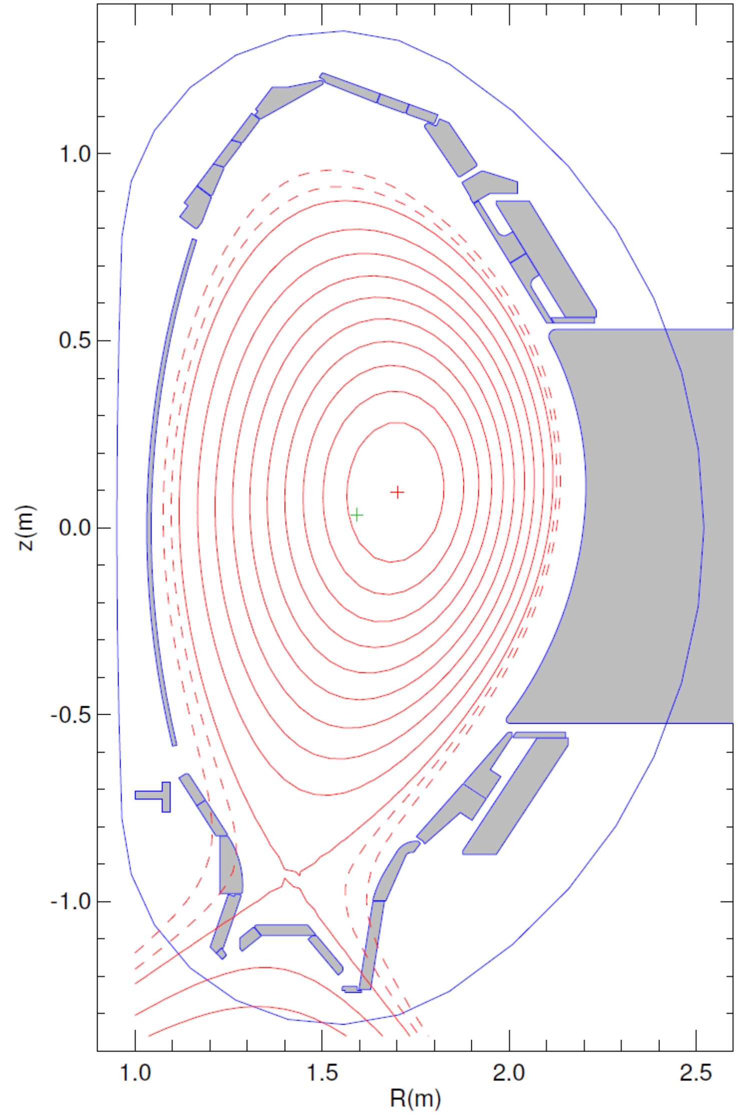
   Generalized Rutherford Equation (GRE)

Field topology and plasma profiles

Example: ASDEX Upgrade #26827

Plasma equilibrium and profiles from IDA Integrated Data Analysis





Adding the magnetic island

Single helicity m=3, n=2 perturbation to poloidal flux

$$\tilde{\psi} = \tilde{\psi}\left(r_{c,s}\right) \frac{r_c^2}{r_{c,s}^2} \frac{\left(1-\frac{r_c}{a}\right)^2}{\left(1-\frac{r_{c,s}}{a}\right)^2} \cos\left(m\theta_s + n\phi + \xi_0\right)$$

Flux surfaces = contours of constant helical flux

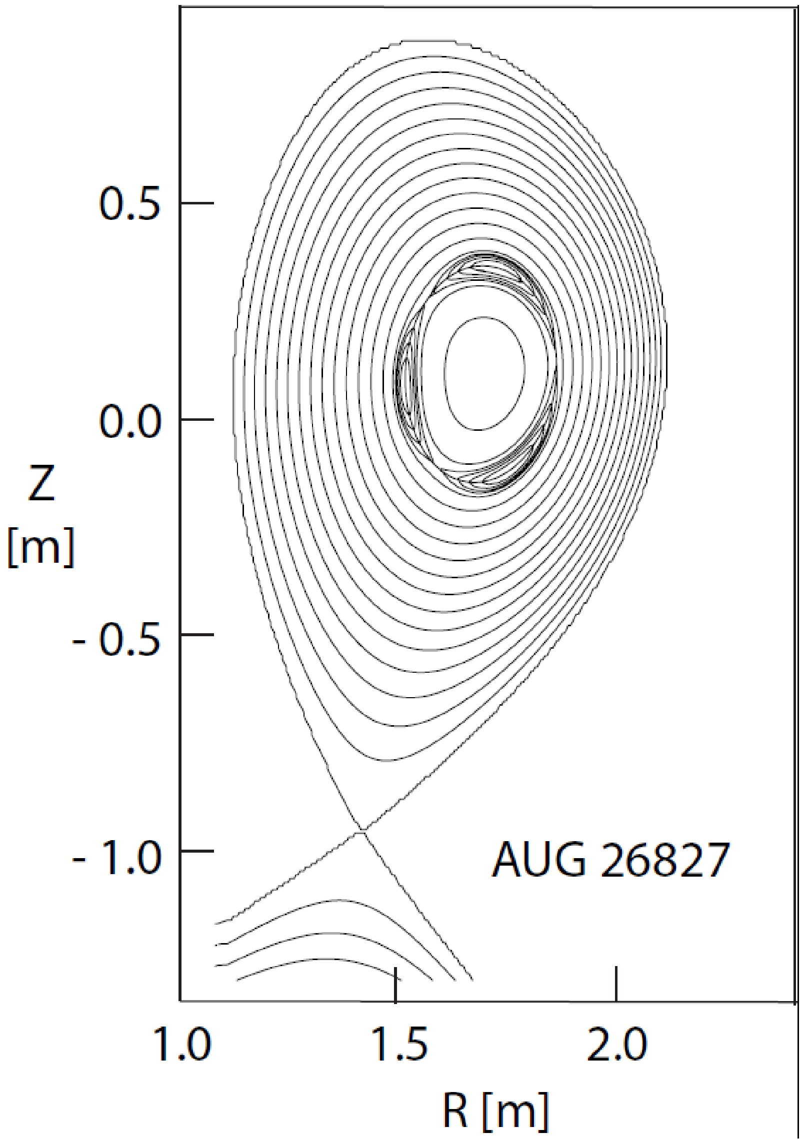
Temperature (density) profile

$r_c > r_{c,s}$: $T\left(r_c,\theta,\phi\right) = T_0\left(\sqrt{\frac{S\left(\psi\left(r_c,\theta,\phi\right),\sigma\right)}{\pi}}\right)$

island: $T_{isl} = T_0\left(\sqrt{\frac{S\left(\psi_{sep},+1\right)}{\pi}}\right)$

$r_c < r_{c,s}$: $T\left(r_c,\theta,\phi\right) = T_0\left(\sqrt{\frac{S\left(\psi\left(r_c,\theta,\phi\right),\sigma\right)}{\pi}}\right) - \Delta T,$

$$\Delta T = T_0\left(\sqrt{\frac{S\left(\psi_{sep},-1\right)}{\pi}}\right) - T_0\left(\sqrt{\frac{S\left(\psi_{sep},+1\right)}{\pi}}\right)$$



Wave propagation and absorption

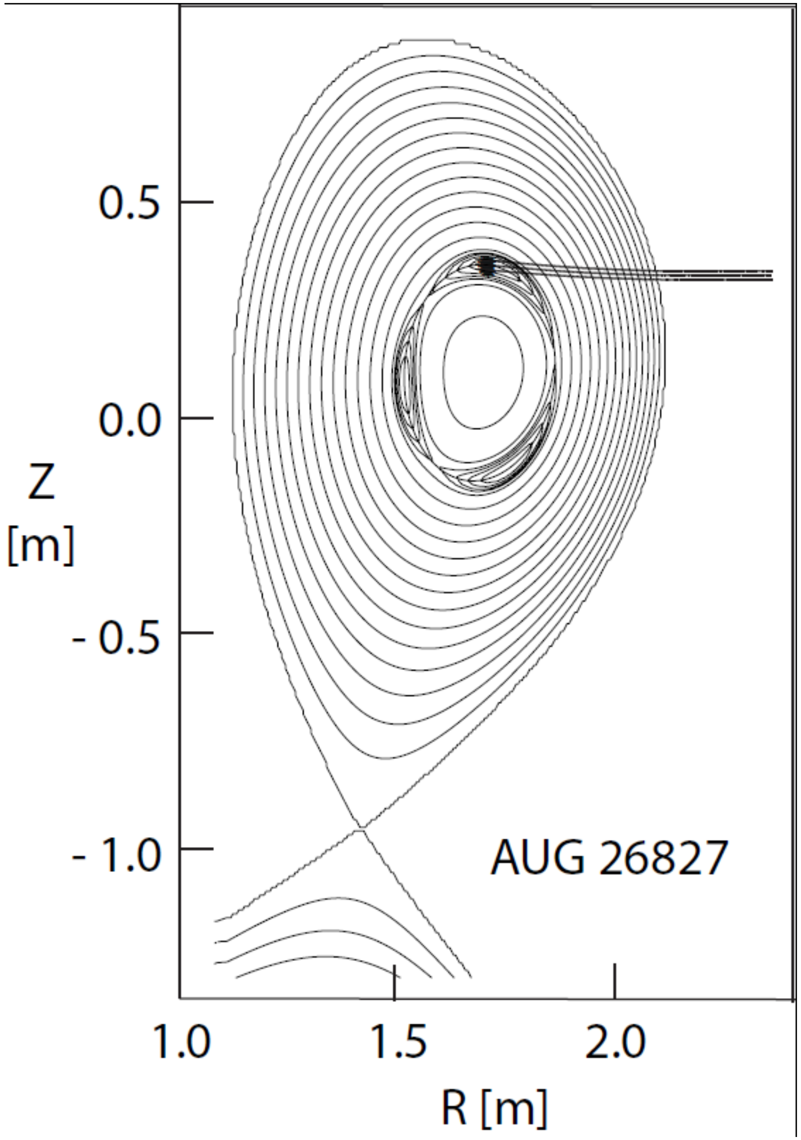
TORAYFOM solves ray traces using cold plasma Appleton-Hartree dispersion relation

Absorption uses (weakly) relativistic lowest order FLR dielectric tensor

Focused Gaussian beam modeled with 9(toroidal) x 41(poloidal) rays

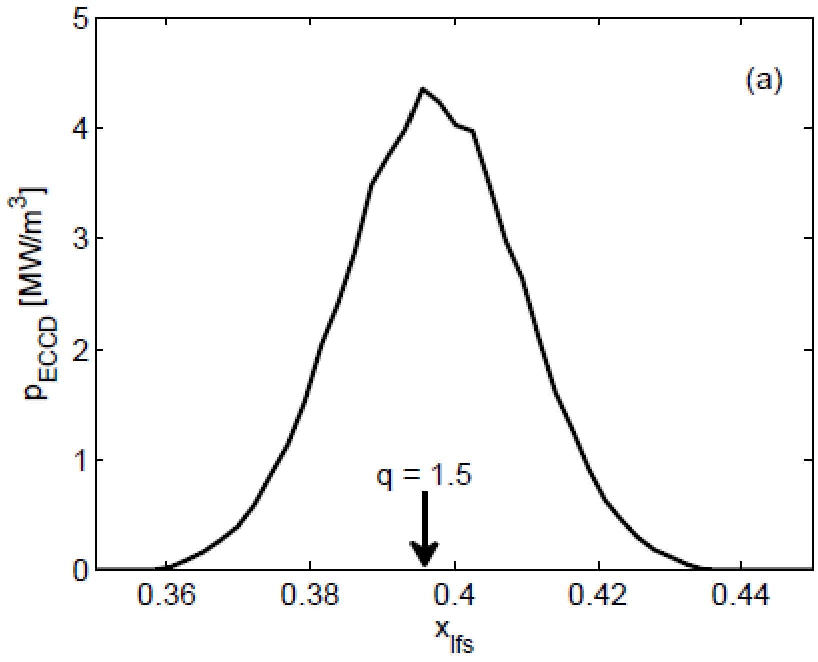
- FWHM (toroidal) 3o (focused)
- FWHM (poloidal) 1.7 cm

Note the ray propagation tangential to flux surfaces

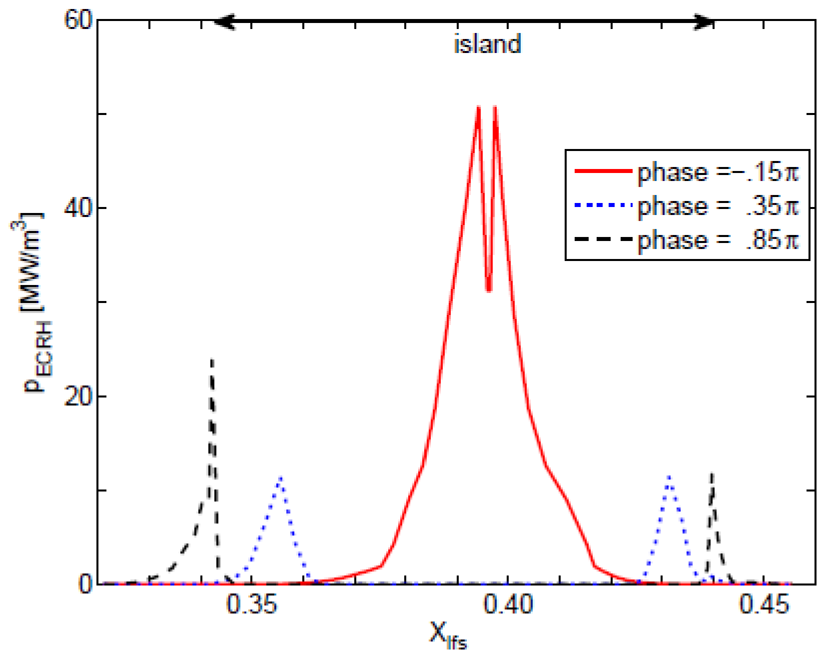


Power deposition profiles (1 MW injected)

Equilibrium topology



Island topology (4 cm wide)



- P(flux surface) projected on normalized LFS minor radius
- Ten fold increase in P inside island -> nonlinear kinetic effects

Kinetic plasma response

Bounce-averaged, quasi-linear Fokker–Planck equation

$$\frac{\partial f_e}{\partial t} = \left\langle \sum_s C\left(f_e, f_s\right) \right\rangle_{\phi_B} - \langle \Gamma_{ql} \rangle_{\phi_B}$$

Balance between collisions and quasi-linear diffusion

Bounce average along single poloidal turn of orbit

$$\langle Q \rangle_{\phi_B} = \frac{1}{\tau_B} \oint Q \frac{\mathrm{d}s}{v \cos\theta}$$

not significantly affected by presence of island, but we do need to take account of the flux surface topology

Nonlinear effects on ECCD

Nonlinear effects when

$$H \equiv p_{\mathrm{ECCD}}\,[\mathrm{MW/m^3}]\,/\,(n_e\,[10^{19}m^{-3}])^2 \gtrsim 0.5$$

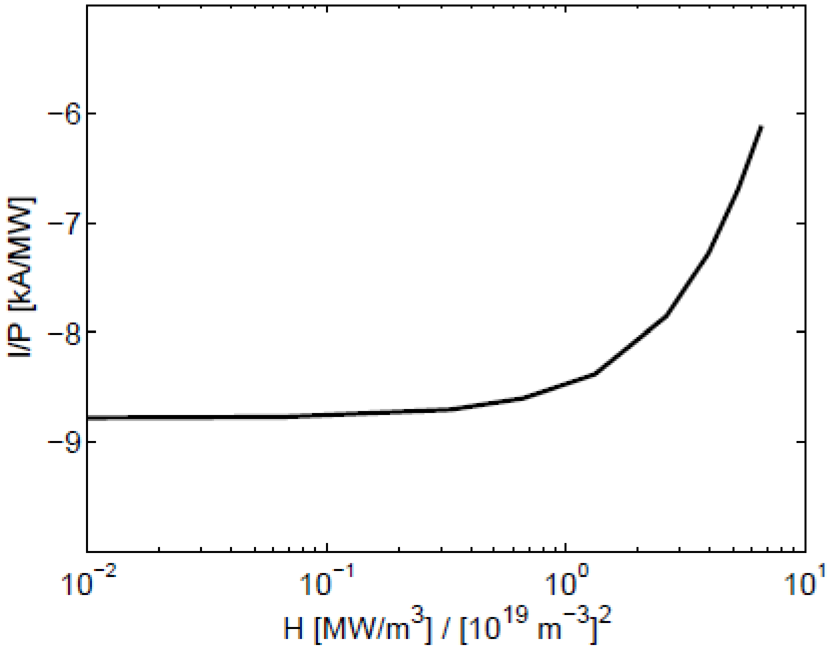
Ref. Harvey et al. PRL 62 (1989) 426

Results of RELAX code

Equilibrium:

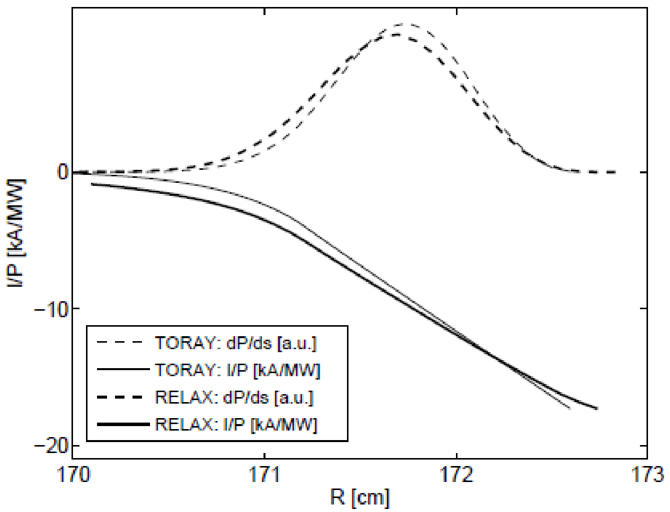
Tangential propagation allows single ray / single surface calculation

Nonlinear effects reduce ECCD efficiency (absolute value)

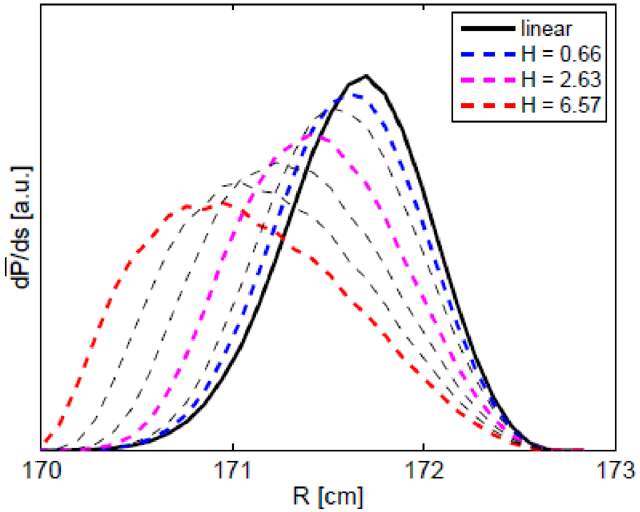


Reduced nonlinear efficiency explained

Local efficiency decreases along ray as resonance is approached



Quasi-linear flattening reduces absorption and shifts power deposition towards resonance



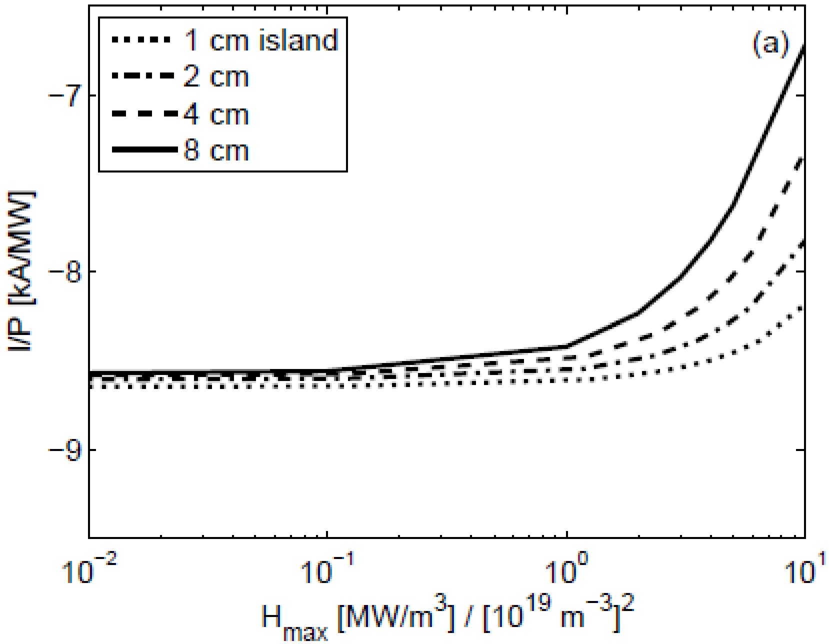
Nonlinear effects inside island

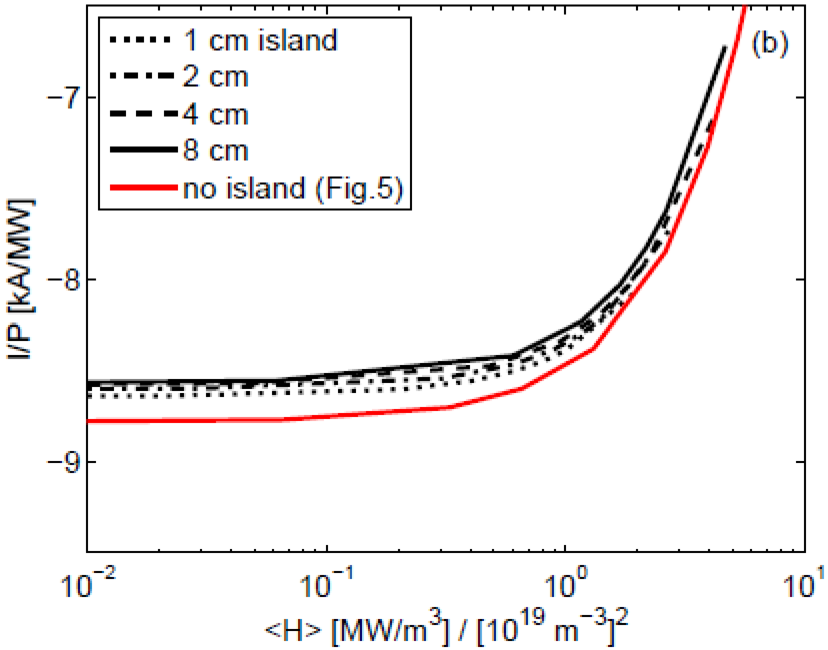
FP equation solved on 40 surfaces:

10 for $r_c < r_{c,s}$, 20 in island, and 10 for $r_c > r_{c,s}$

Island phase fixed for O-point power deposition

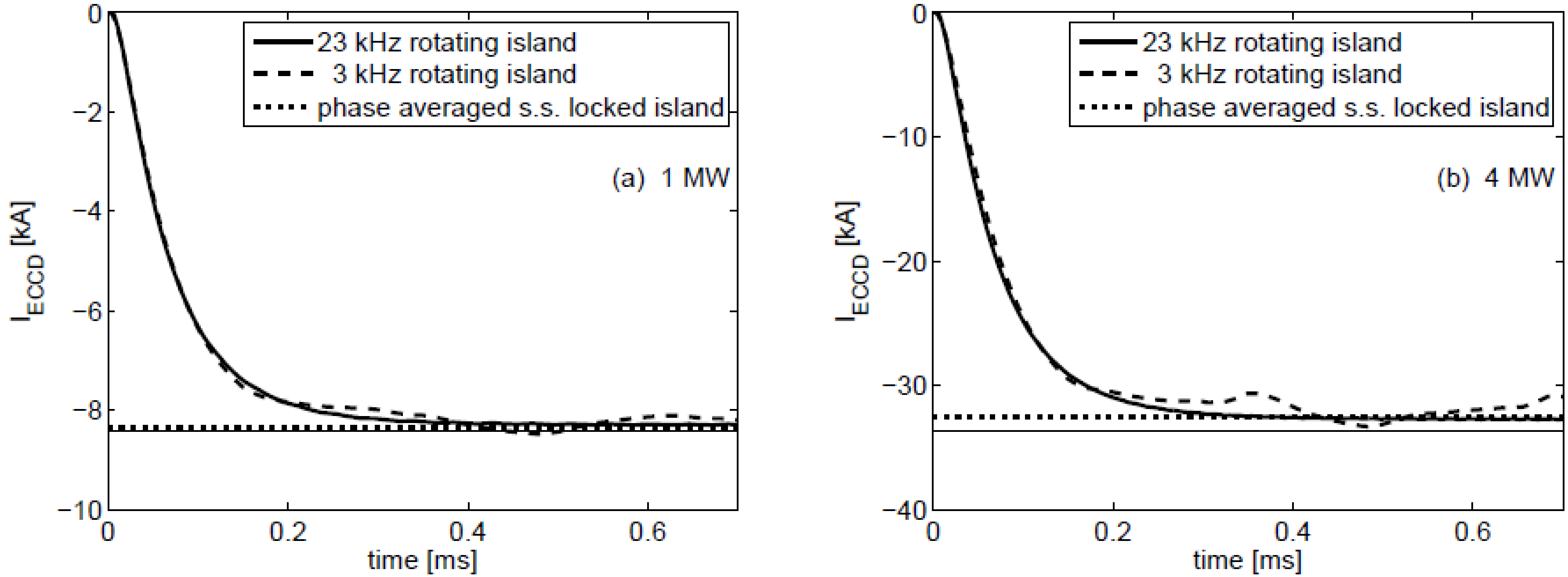
Nonlinear effects are function of averaged H: $< H > \equiv \frac{\int H p_{\mathrm{ECCD}} \mathrm{d}V}{\int p_{\mathrm{ECCD}} \mathrm{d}V}$





Time dependence: rotating 8 cm island

- Averaged over all phases nonlinear effect is weak
- Nonlinear effects result in a minor fluctuation of the total driven current in the case of a rotating island
- 23 kHz (experiment) > collision frequency > 3 kHz



Time dependence: rotating 8 cm island

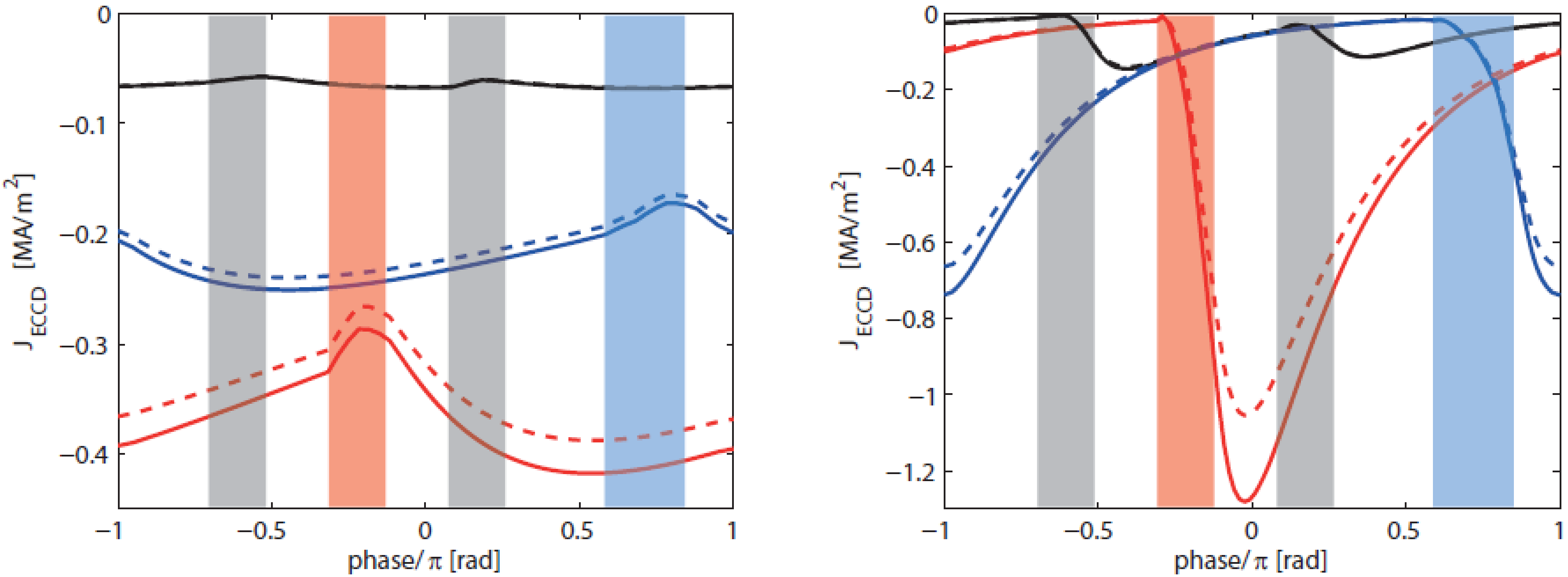
Strong fluctuations in current density inside island

---- O-point
---- Middle of island
---- Just outside separatrix

---- 1 MW
- - - 4 MW

23 kHz

3 kHz



Magnetic island evolution

The generalized Rutherford equation

- obtained by averaging the relevant helicity of Ohm's law over the entire island region

$$0.82\frac{\tau_r}{r_\mathrm{s}}\frac{\mathrm{d}w}{\mathrm{d}t} = r_\mathrm{s}\Delta_0'(w) - r_\mathrm{s}\sum_i \Delta'(\delta j_i)$$

island width evolution any current perturbation

classical stability

- Contribution from ECCD

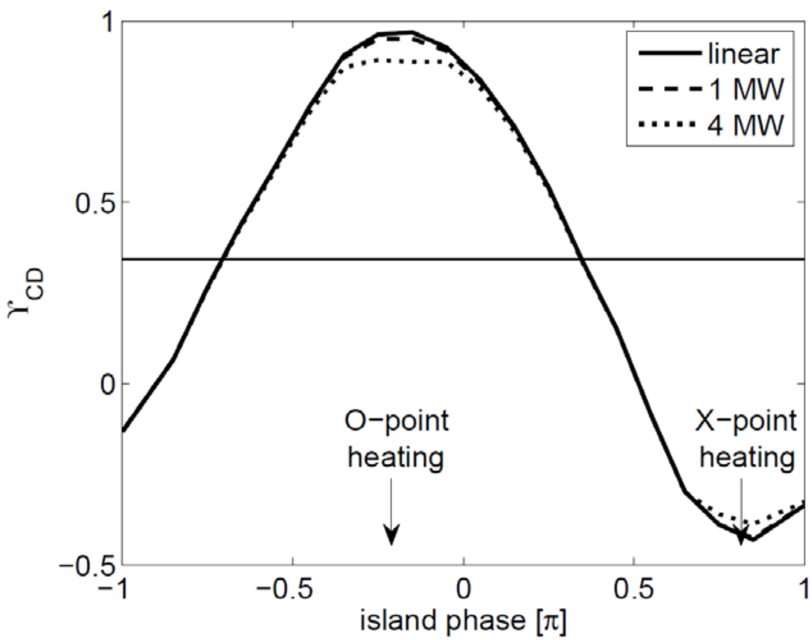
$$r_\mathrm{s}\Delta_\mathrm{CD}' = \frac{16\mu_0 L_\mathrm{q} r_\mathrm{s}}{B_\mathrm{p}\pi w^2}\int_{-\infty}^{\infty}\mathrm{d}x \oint \mathrm{d}\xi\, j_\mathrm{CD}\cos(m\xi)$$

Results for $\Delta'_{\mathrm{CD}} = \frac{16\mu_0 L_{\mathrm{q}}}{B_{\mathrm{p}}\pi} \frac{\eta_{\mathrm{CD,lin}} P}{w^2} \Upsilon_{\mathrm{CD}}$

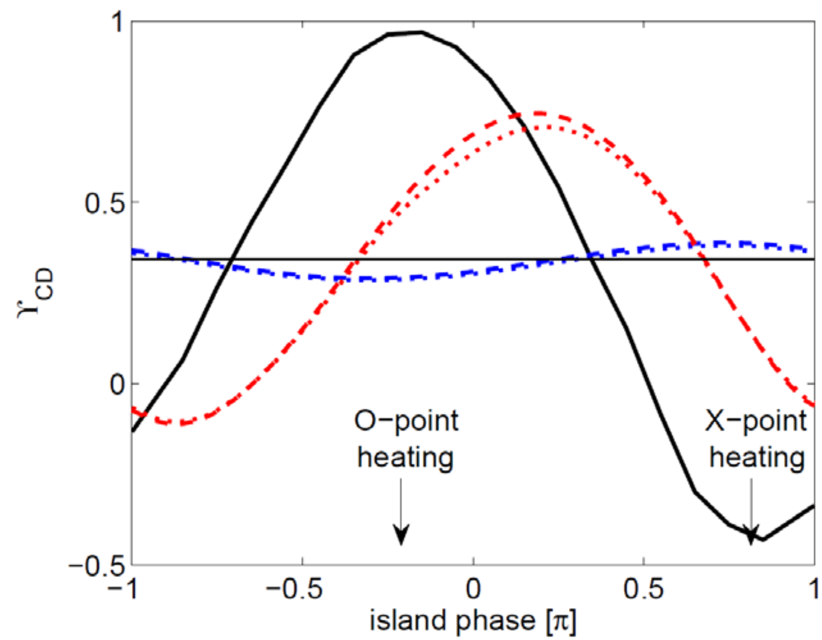
We define the nonlinear shape function Υ_{CD}

$$\Upsilon_{\mathrm{CD}} \equiv \frac{1}{\eta_{\mathrm{CD,lin}} P} \int_{-\infty}^{+\infty} \mathrm{d}x \oint \mathrm{d}\xi J_{\mathrm{CD}} \cos(m\xi)$$

locked mode



23 kHz / 3 kHz rotating mode



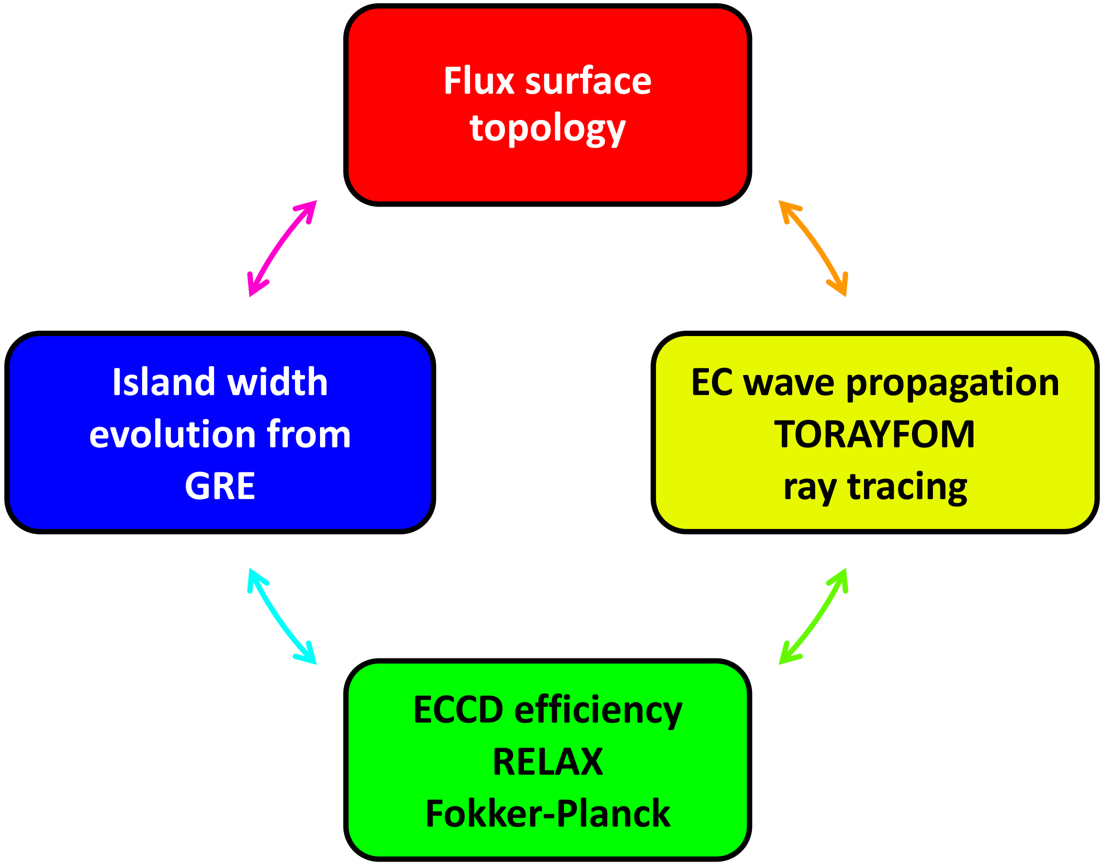
Summary

Ray tracing and Fokker–Planck calculation of ECCD applied for suppression of magnetic islands

- Island topology results in ~ten fold increase of maximum deposited power density
- Nonlinear effects reduce ECCD efficiency
- Especially J(O-point) is reduced in (slowly) rotating/ locked islands
- The stabilizing effect of ECCD is reduced (although negligibly so for experimental condition)

Closing the circle

Self-consistent modeling of magnetic island suppression



Open issues

This still leaves important aspects untreated, for example concerning transport:

- Transport inside magnetic islands
- Transport of energetic electrons
- Influence of RF heating on turbulence
- ...

Lorentz center

Modeling Kinetic Aspects of Global MHD Modes

Workshop: 2-6 December 2013, Leiden, the Netherlands

Scientific Organizers

- Jonathan Citrin, DIFFER Nieuwegein
- Guido Huijsmans, ITER Cadarache
- Barry Koren, TU Eindhoven
- Arthur Peeters, U Bayreuth
- Emanuele Poli, IPP Garching
- Egbert Westerhof, DIFFER Nieuwegein