ECRH power deposition in ASDEX Upgrade

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ECRH power deposition in ASDEX Upgrade

In ASDEX Upgrade we aim at very localised power deposition by beam focusing and/or by mode mixing.

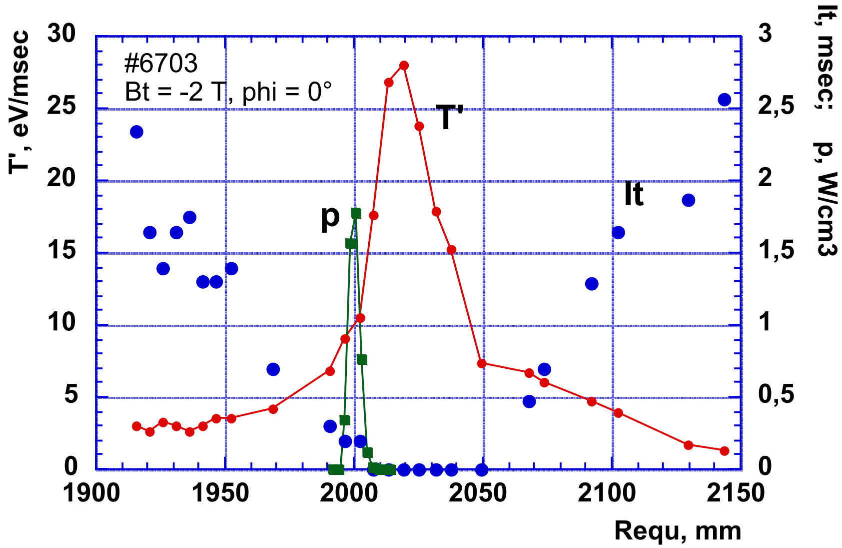
The resulting beam is then approximated by a Gaussian beam for deposition calculations with TORBEAM.

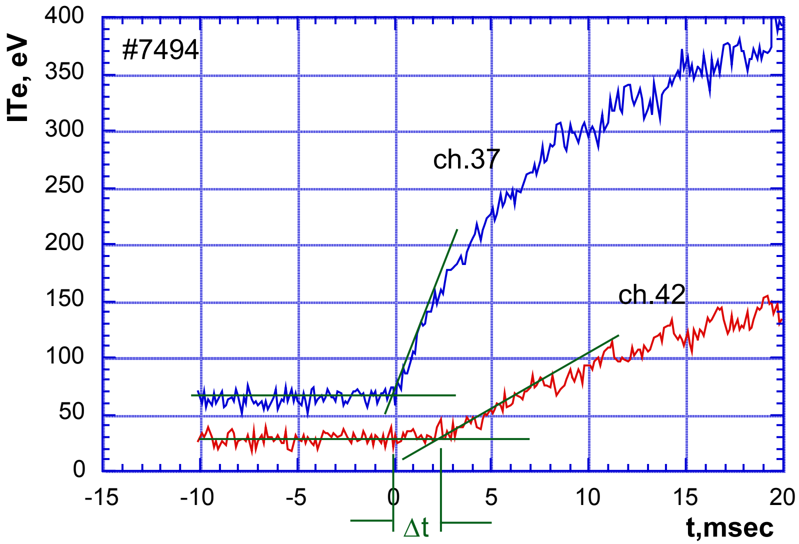
These calculations give a 1/e halfwidth of 5 to 25 mm, depending on the launching angle.

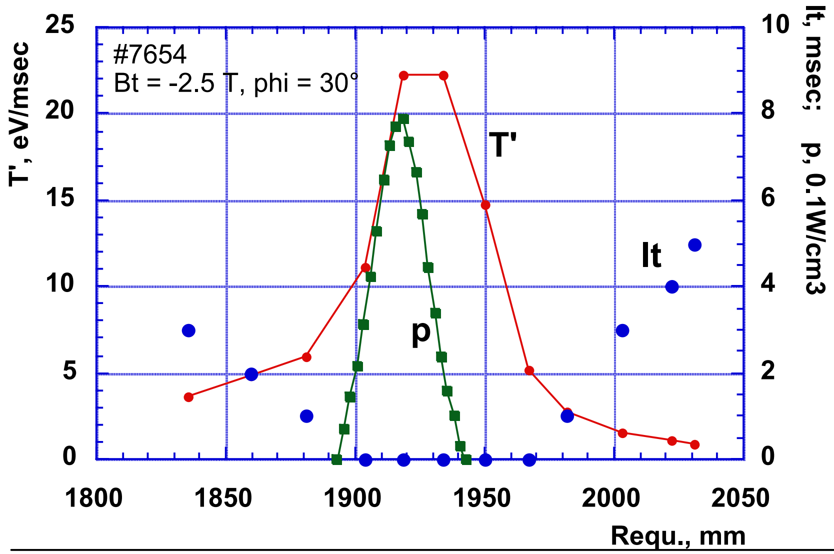
We have tried to determine the deposition profile in different ways:

from dTe/dt during switch-on/off
from modulation
from pulse simulation with a transport code

ECRH power switch-on/off







Outside of the deposition zone we get a time delay in the temperature rise

Narrow or wide deposition (Toray) lead to similar dTe/dt profile

ECRH power switch-on/off

Simple model: infinite plane geometry, homogeneous plasma

Diffusion equation: $$\partial T/\partial t = \frac{2}{3\chi}\cdot\partial^2 T/\partial x^2 - b\cdot T + \frac{2}{3n_e}\cdot p(x,t)$$

Switch-on with Gaussian deposition: $$p(x,t) = \frac{p_0}{\sqrt{\pi}w}\cdot\exp(-x^2/w^2)\cdot H(t)$$

Solution: $$T(x,t) = \frac{3p_0}{2n_e}\cdot\frac{\tau}{w}\cdot\frac{e^{b\tau}}{\sqrt{b\tau}}\cdot\left\{\Phi_m\left[\sqrt{b\tau(1+t/\tau)},\gamma\right] - \Phi_m\left[\sqrt{b\tau},\gamma\right]\right\} \quad (1)$$

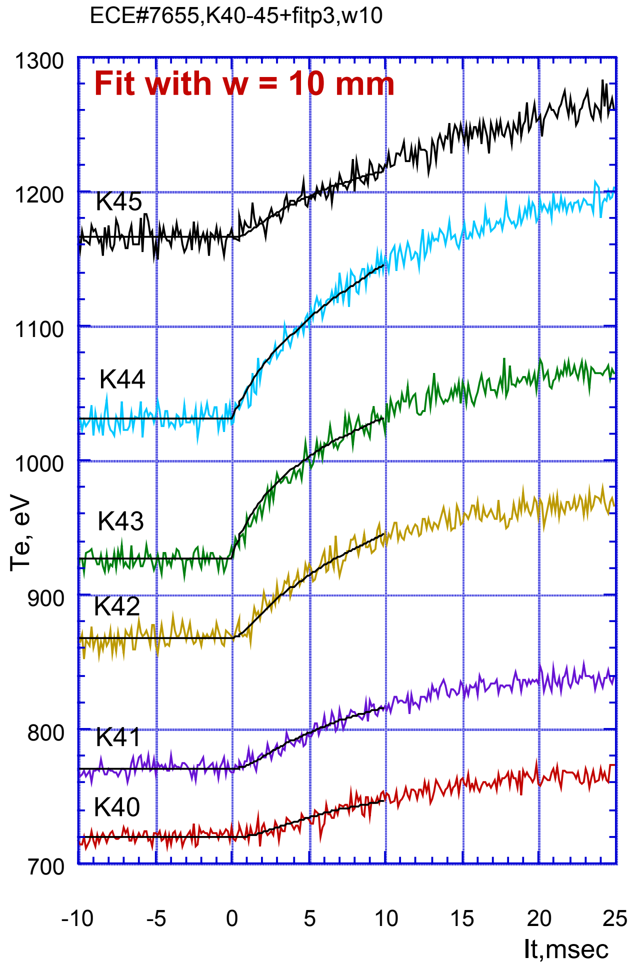
with $\Phi_m(\alpha,\gamma) = \frac{2}{\sqrt{\pi}}\int_0^\alpha e^{-\xi^2-\gamma^2/\xi^2}\,d\xi$ (modified error function)

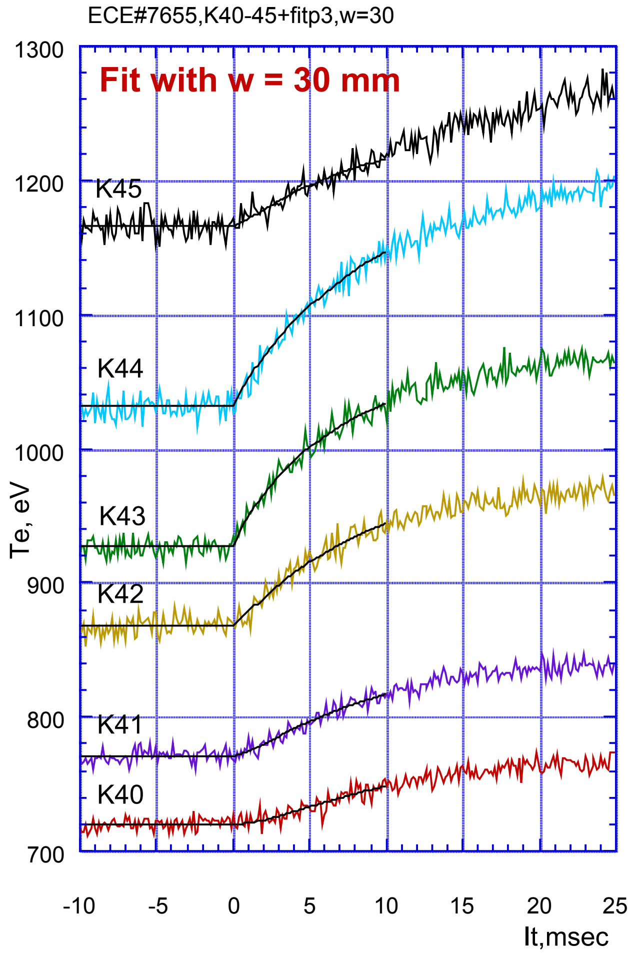
and $\tau = 3w^2/8\chi$ characteristic time for diffusion

and $\gamma = \frac{x}{w}\cdot\sqrt{b\tau}$ normalised coordinate

(F.Leuterer et al., Europhys. Conf. Abstr 21A (1997) Vol.IV, 1477)

ECRH switch-on/off, fit of equ.(1) to data





Fits starting with different profile width are equally good

ECRH power switch-on/off

$$T(x,t) = \frac{3p_0}{2n_e} \cdot \frac{\tau}{w} \cdot \frac{e^{b\tau}}{\sqrt{b\tau}} \cdot \left\{ \Phi_m \left[\sqrt{b\tau(1+t/\tau)}, \gamma \right] - \Phi_m \left[\sqrt{b\tau}, \gamma \right] \right\}$$

For very short time t/τ << 1 we obtain from a series expansion

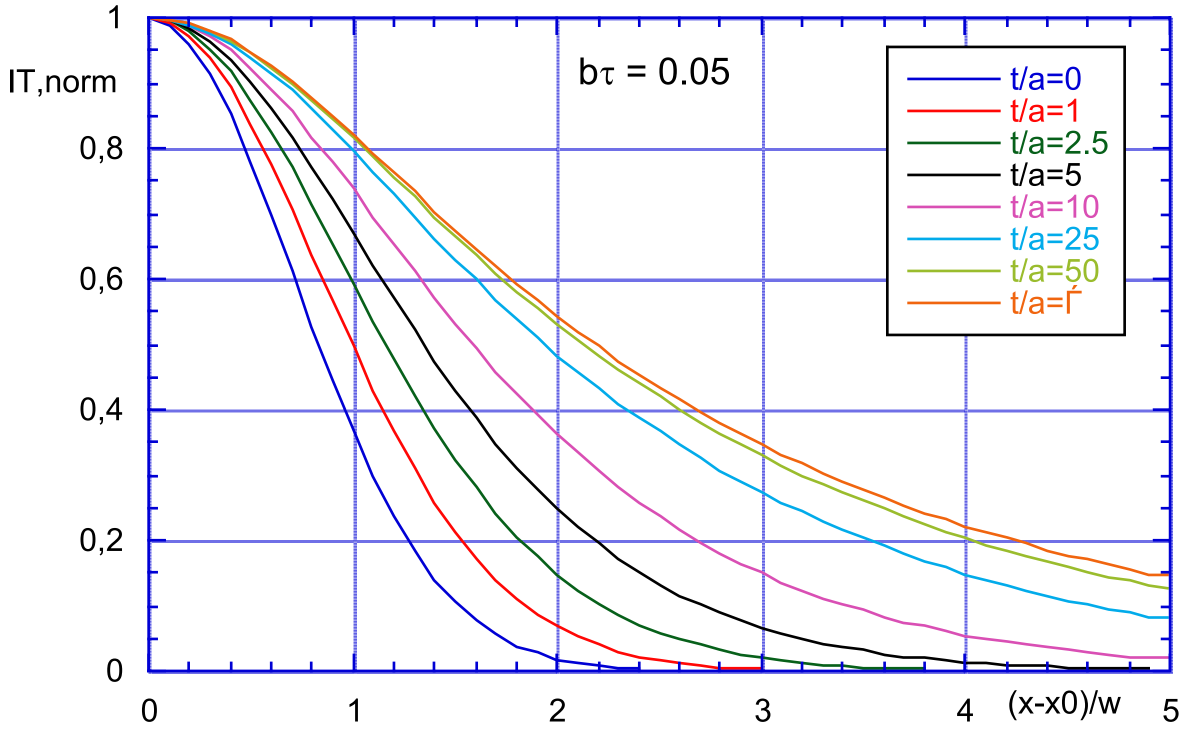
$$T(x,t) = \frac{3p_0}{2n_e w\sqrt{\pi}} \exp(-x^2/w^2) \cdot t$$

i.e. the temperature profile is equal to the deposition profile and grows linearly with time

$\tau = 3w^2/8\chi$ Example: w = 15 mm, χ = 1 m^2/sec => τ = 85 μsec

For longer times diffusion becomes important,
and for t/τ >> 1 the information of the initial profile is practically lost

ECRH power switch-on/off



Normalized temperature profiles at different times
after switch-on of ECRH heating

After 10 characteristic times the profile is more than a factor of 2 wider

After very long time the profile is limited by damping

Modulated ECRH power deposition $T(x=0)$

Modulated deposition: $$p_{ecrh}(x,t) = \frac{p_0}{\sqrt{\pi} w} \cdot \exp(-x^2/w^2) \cdot \exp(-i\omega t)$$

In the deposition centre we get

$$T(x=0,t) = \frac{i \cdot p_o}{\frac{3}{2} n_e \sqrt{\pi} w \omega \mu} \quad \cdot \quad F(z) \quad \cdot \quad \exp(-i\omega t)$$

First factor: temperature oscillation if there were no diffusion, i.e. χ = 0.

Second factor: describes impact of heat diffusion

$$F(z) = -i\pi z \exp(-i\frac{\pi}{2} z^2) \left[\frac{1+i}{2} - C(z) - iS(z)\right]$$

C(z) and *S(z)* are Fresnel integrals.

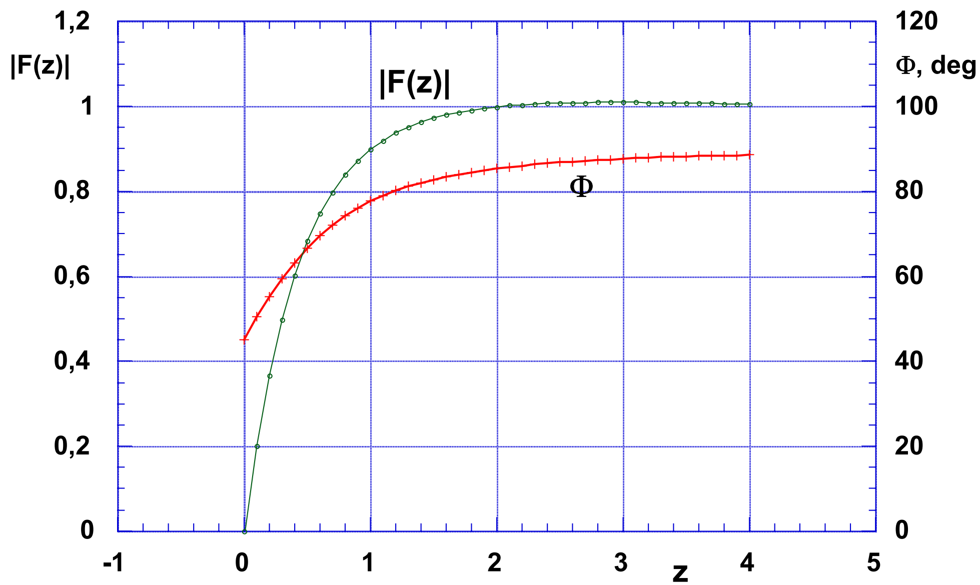
$$z = \sqrt{\frac{2}{\pi}\eta\mu} = \frac{w}{2}\sqrt{\frac{3\omega}{\pi\chi}(1+i\frac{b}{\omega})}$$

***F(z)* depends on :** modulation frequency ω
deposition profile width w
heat diffusivity χ
(damping b)

(F.Leuterer et al., NF 43 (2003) 744)

Modulated ECRH power deposition $T(x=0)$

$$T(x=0,t)=\frac{i\cdot p_o}{\frac{3}{2}n_e\sqrt{\pi}w\omega\mu}\quad\cdot\quad F(z)\quad\cdot\quad \exp(-i\omega t)$$



Magnitude of the function *F(z)* and phase of $T(x=0,t)\sim i\cdot F(z)$ no damping *b* = 0

|*F(z)*| varies between 0 and 1

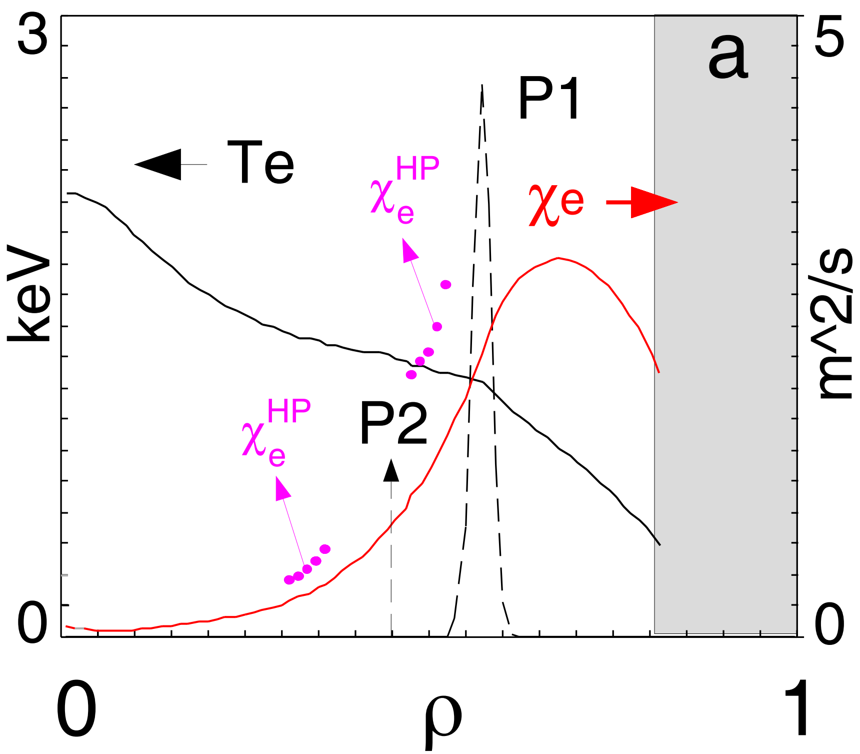
the phase of $T(x=0)$ varies between 45° and 90°

Only for large $z=w\sqrt{3\omega/4\pi\chi}$, |F(z)| is constant, i.e. independent on frequency

Modulated ECRH power deposition $T(x=0)$

cw ECRH power deposited at $\rho > \rho_{hw}$ -> low χ at ρ_{hw}

Reason: χ depends on local temperature gradient
(F. Ryter et al., Phys. Rev. Lett.86 (2001) 2325, and Phys.Rev.Lett. 86 (2001) 5498)



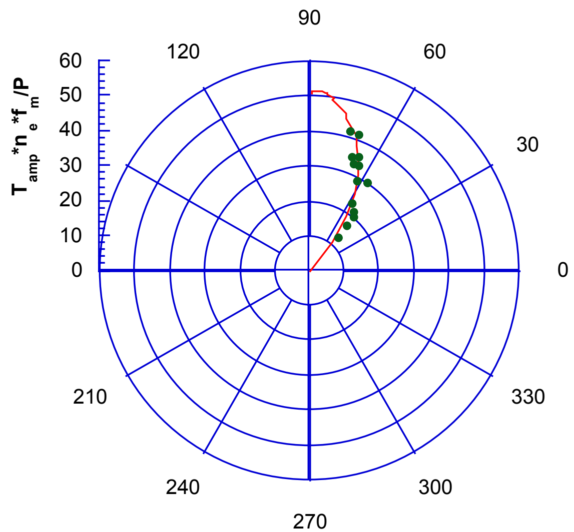
P1: cw ECRH,

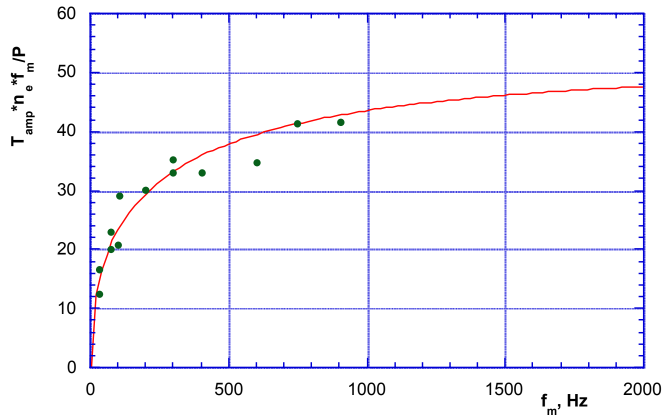
P2: modulated ECRH

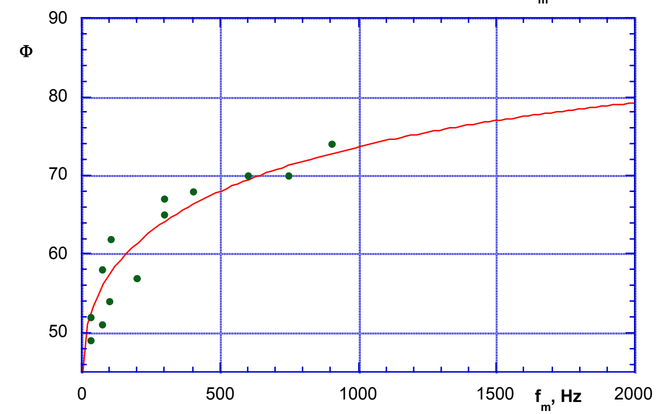
Modulated ECRH power deposition $T(x=0)$

Frequency scan, narrow profile, low χ

We plot: $\frac{T(x=0)\cdot n\cdot f}{P_{ECRH}} \propto F(z)$







Fit results:

χ **= 1.2 m²/sec** (heatwave χ = 1.1m2/sec)

w = 23 mm (TORBEAM: w = 13 mm)

With these values the paramter z becomes z = 0.28 at the lowest frequency of 30 Hz used in this scan, and justifies the neglect of damping

Fit to the simple model

Modulated ECRH power deposition, cylindrical geometry

In cylindrical geometry we can derive from a result by X.L.Zou et al, NF 43 (2003) 1411:

$$T_e(r = r_{dep}, t) = T_{e0} \cdot G(r_{dep}, a, w, \alpha_n, \chi, \omega, b) \cdot e^{-i\omega t}$$

with $$G = 2\sum_{n=1}^{\infty} \frac{J_0(r_{dep}/a \cdot \alpha_n)}{J_1^2(\alpha_n)} \cdot I_{sp}(\alpha_n, w, r_{dep}) \cdot \frac{1}{1 - i2\chi\alpha_n^2/(a^2\omega\mu)}$$

and $$I_{sp}(\alpha_n, w, r_{dep}) = a^2 \int_0^1 (r'/a) J_0(r'\alpha_n/a) e^{-(r'/a - r_{dep}/a)^2/(w/a)^2} d(r'/a)$$

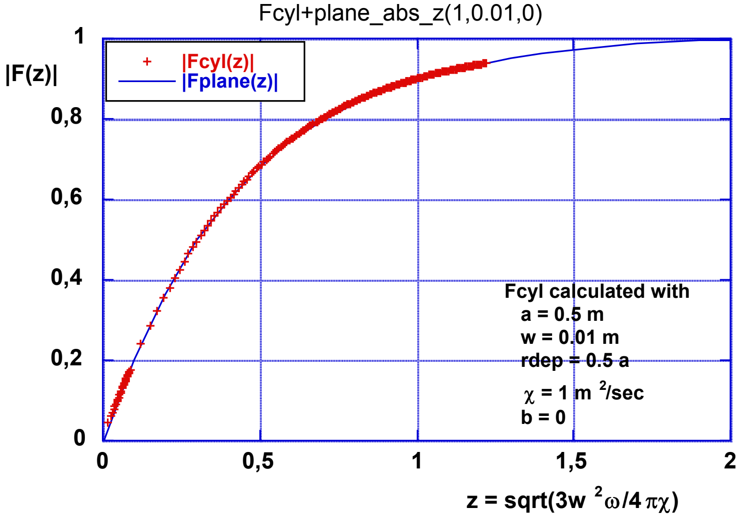
The corresponding solution in plane geometry is :

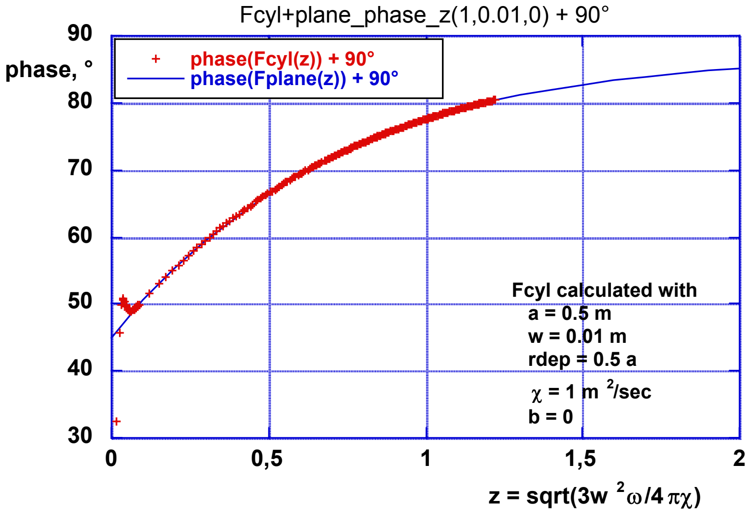
$$T_e(x = 0, t) = T_{e0} \cdot F(z) \cdot e^{-i\omega t}$$

with $F(z) = -i\pi z \exp(-i\frac{\pi}{2}z^2)\left[\frac{1+i}{2} - C(z) - iS(z)\right]$ and $z = w\sqrt{3(\omega + ib)/(4\pi\chi)}$

The function *G( )* cannot be expressed in terms of the parameter *z* like *F(z)* , however, both functions coincide as long as reflections of the heatwave from the boundaries can be neglected.

Modulated ECRH power deposition, cylindrical geometry

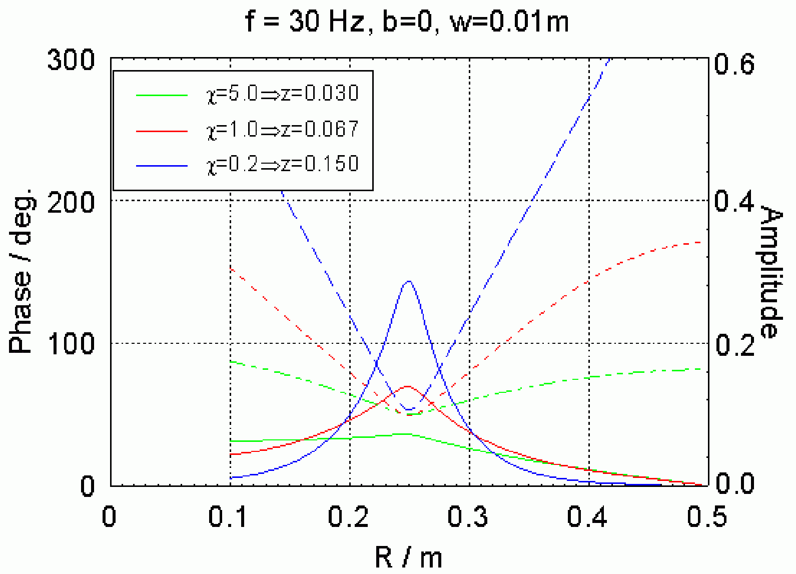


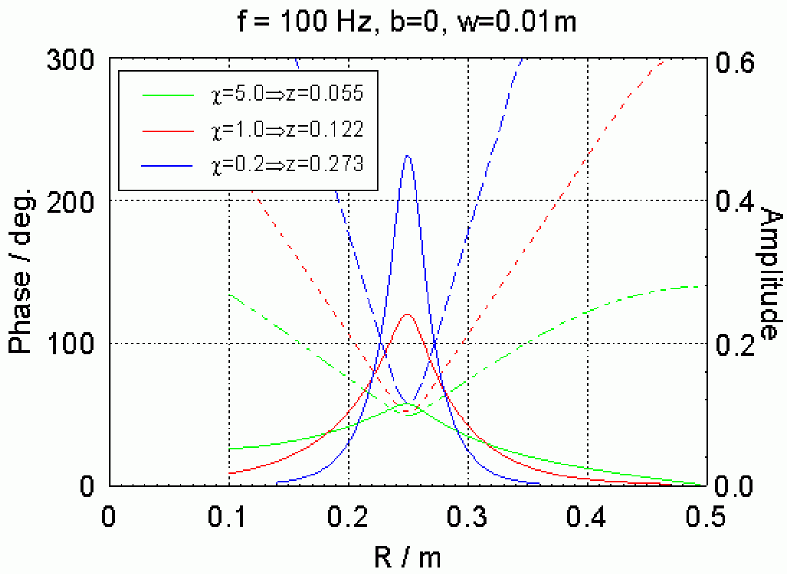


The functions Fplane(z) and G(z) coincide as long as the boundaries are sufficiently far from the deposition centre.

In this example we have a = 0.5 m and r_{dep} = a/2, and χ = 1 m^2/sec. In this case G(z) and F(z) start to become different for z < 0.65 corrsponding to f < 30 Hz.

Modulated ECRH power deposition, cylindrical geometry



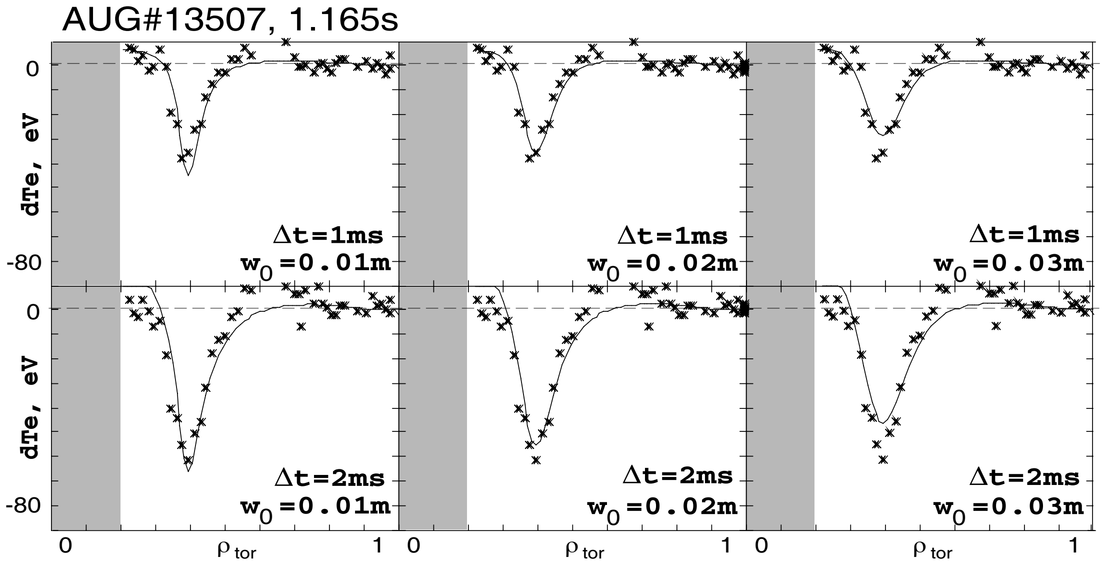


At high heat diffusivity the amplitude in the centre is still high => effect on $T(r_{dep})$

At low heat diffusivity the amlitude in the centre is low => no effect on $T(r_{dep})$

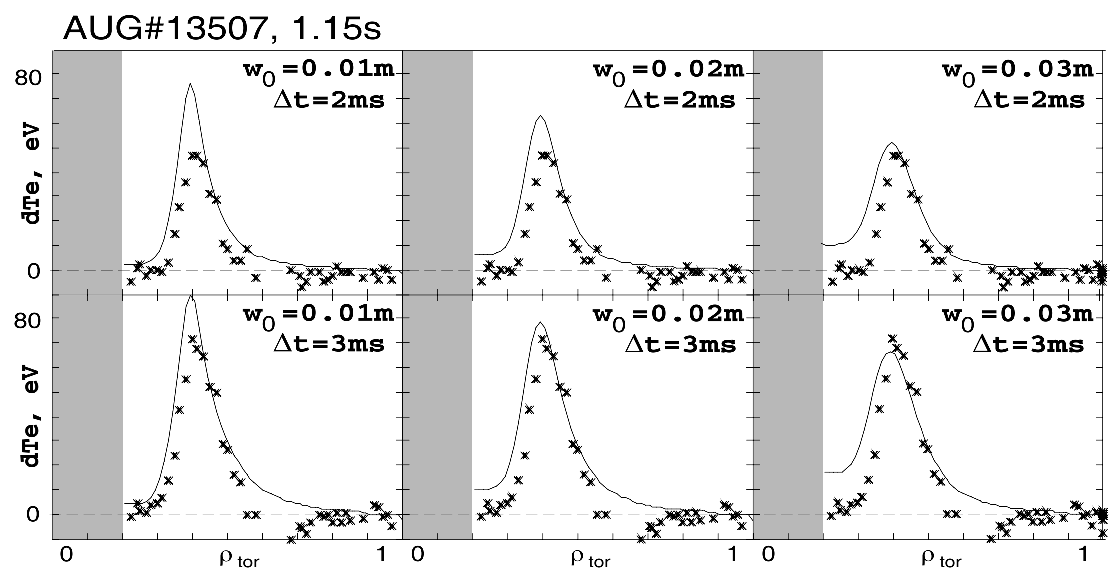
There is a lower limit for the modulation frequency below which the application of the function F(z) is not allowed. This limit depends on χ and r_{dep}.
For ASDEX Upgrade we get $f_{lim} \approx 1.76\ \chi/r_{dep}^2$, and F(z) can be applied for f≥30 Hz

ASTRA simulation of a switch-on/off event



switch-off

transport model:
Nordman H. et al.
NF 30 (1990) 983
with critical (grad Te)/Te



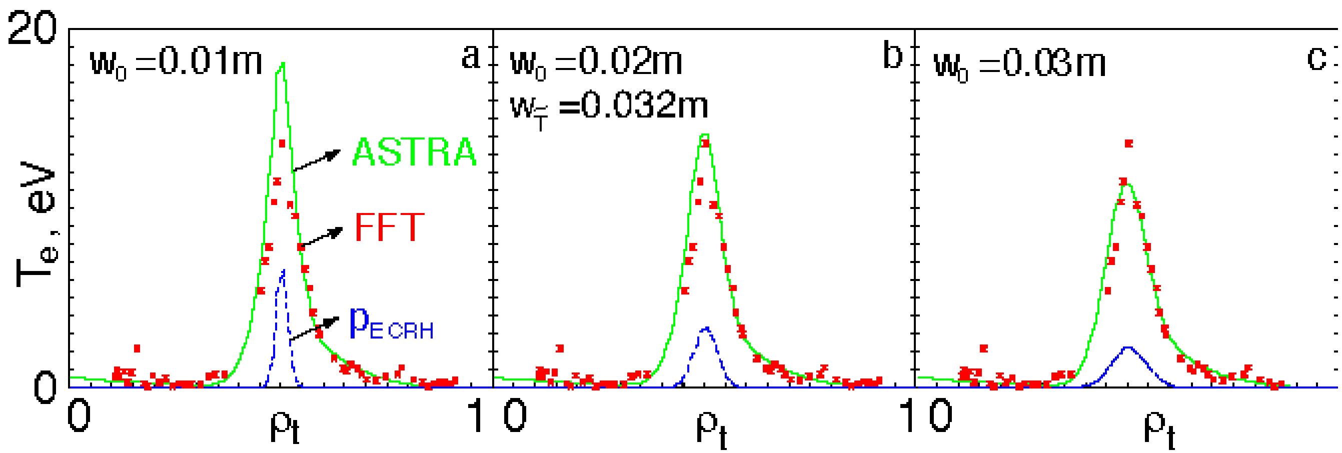
=> w <≈ 20 mm

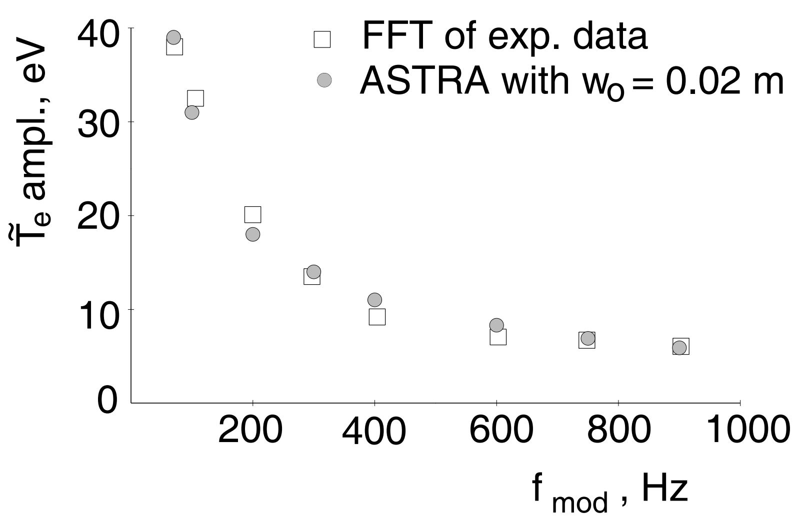
(TORBEAM: w = 11 mm)

switch-on

(K.Kirov et al., PPCF 44 (2002) 2583)

ASTRA simulation of modulated deposition





transport model:
Nordman H. et al.
NF 30 (1990) 983
with critical (grad Te)/Te

=> w ≈ 20 mm

(TORBEAM: w = 13 mm)

(K.Kirov et al., PPCF 44 (2002) 2583)

ECRH deposition in ASDEX Upgrade

In ASDEX Upgrade the ECRH beams are focused to produce narrow deposition profiles in all cases. We have tried to verify these narrow deposition profiles.

But: with ECE we measure not in the immediate deposition volume, rather some distance away on the same flux surface, => flux surface averaged width

Switch-on/off technique requires a time interval for the determination of the change in Te which is usually longer than the characteristic time for diffusion.

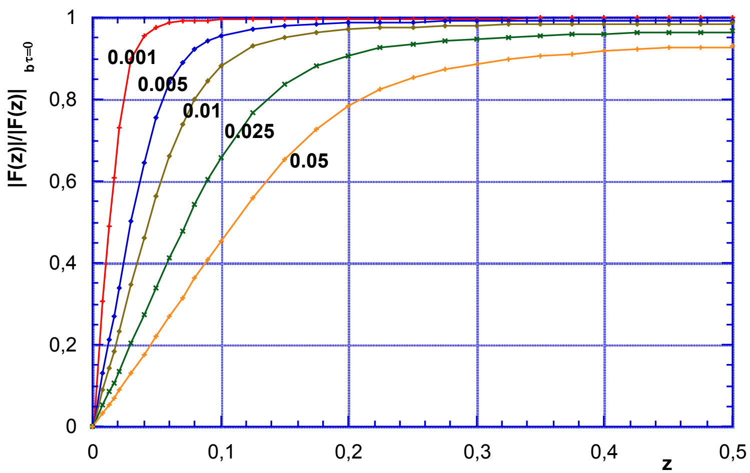
From phase and amplitude of the modulated temperature in the ECRH deposition centre we can derive the deposition width.

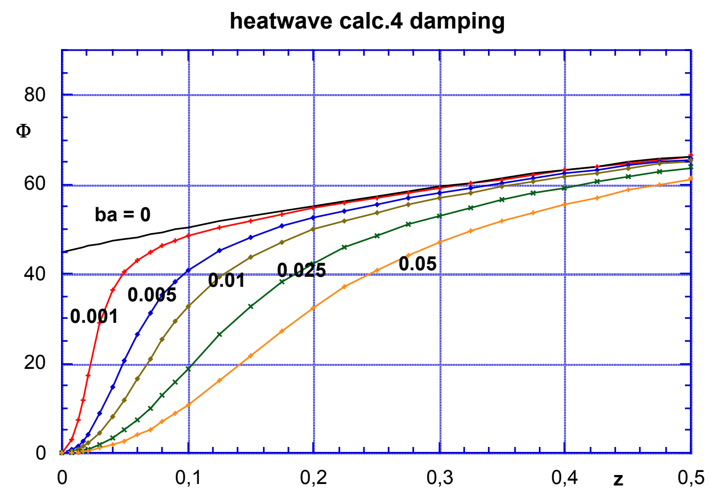
The deposition has also been checked by simulations with the ASTRA code using a critical temperature gradient transport model.

All results gave a profile width which is 1.5 to 2 times wider than that calculated with TORBEAM, which assumes instantaneous distribution of energy on the flux surface.

$|F(z)|$ and phase of $T(x=0)$ with damping:

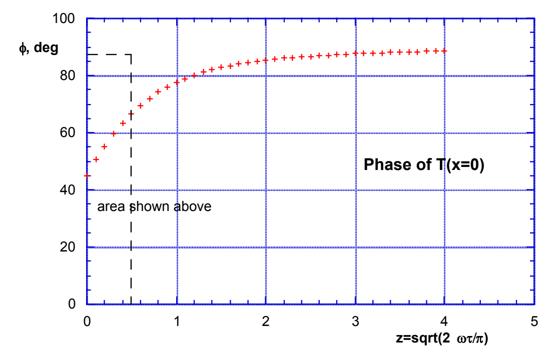
Damping enters through the term $\mu = 1 + ib/\omega$ and is important at low frequency.





Damping reduces $|F(z)|$ and the phase of

It is important only for low values of z.



For the experiments described in the

following we estimate $b\tau \approx 0.0035$ to 0.014

Experimental results

Estimate of damping:

plasma: $n_e = 2 \cdot 10^{19}$ m^{-3}, $T_e = 2$ keV, $T_i = 0.5$ keV

Ohmic heating variation: $p_{oh} = \frac{\partial p_{oh}}{\partial T} \cdot T$

with $p_{oh} = \eta_n \cdot j^2$, $\eta_n = 3\eta_s$, and $\eta_s = 2.8 \cdot 10^{-8} / T_e^{3/2}$, $[\Omega m, keV]$

for $\ln\Lambda = 17$ and $Z_{eff} = 2$ ==> $b_{oh} \approx 20$ sec^{-1}

Electron -Ion energy exchange: $p_{ei} = \frac{\partial p_{ei}}{\partial T} \cdot T$

with $p_{ei} = \frac{3}{2} n_e (T_e - T_i) \cdot \frac{1}{\tau_{ei}}$, and $\tau_{ei} = \frac{m_i}{2m_e} \cdot \tau_e = \frac{m_i}{2m_e} \cdot 1.09 \cdot 10^{16} \cdot \frac{T_e^{3/2}}{n_e Z_{eff} \ln\Lambda}$, $[\sec, m^{-3}, keV]$

for $\ln\Lambda = 17$ and $Z_{eff} = 2$ ==> $b_{ei} \approx 2$ sec^{-1}

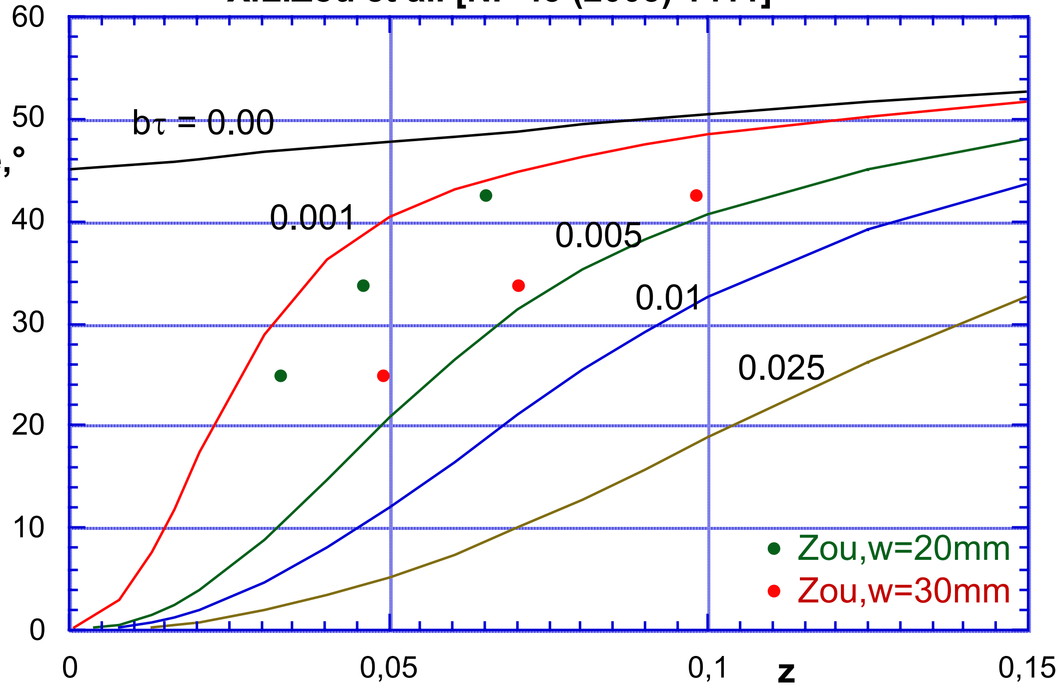
==> $b = b_{oh} - b_{ei} \approx 18$ sec^{-1}

At the lowest frequency used of 30 Hz ==> $b/\omega \approx 0.1$
For the narrow profile and the low diffusivity case we get $b\tau \approx 0.0035$ at $z \approx 0.14$
For the broader profile and the low diffusivity case we get $b\tau \approx 0.012$ at $z \approx 0.26$

Modulated ECRH power deposition $T(x=0)$

Damping becomes important at low modulation frequencies
Example: Tore Supra, fmod = 1.79 Hz and 2. and 4. harmonics

comparison with data from
X.L.Zou et al. [NF 43 (2003) 1411]

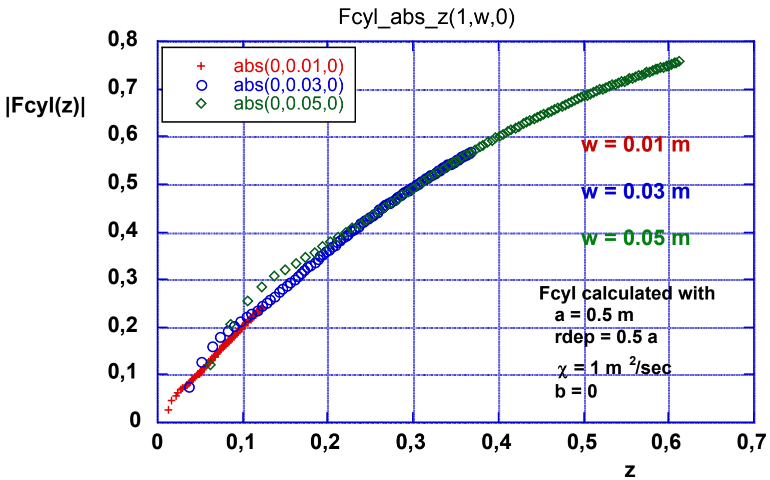


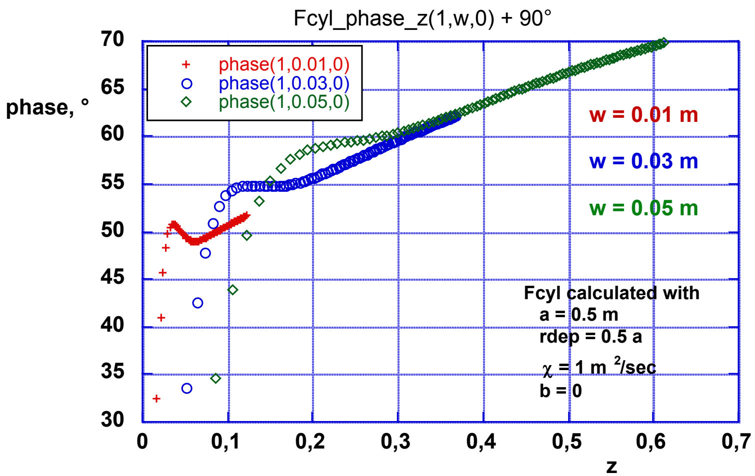
calculated with

1/b = 50 msec
χ = 1 m²/sec

=> bτ = 0.003
=> bτ = 0.007

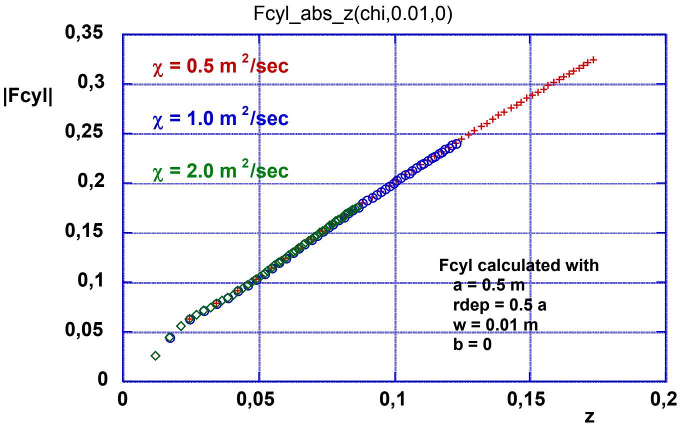
Modulated ECRH power deposition, cylindrical geometry

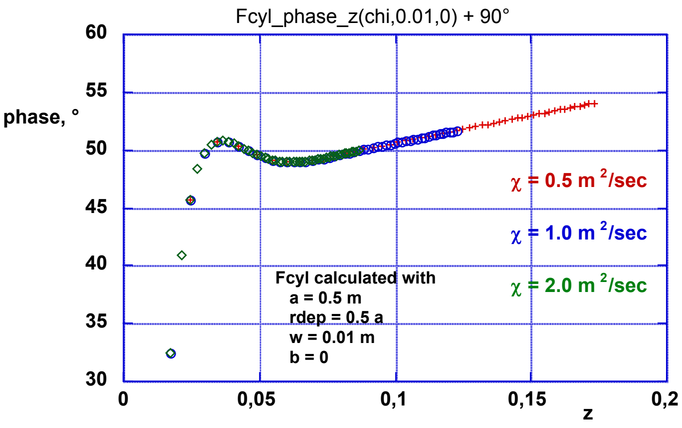


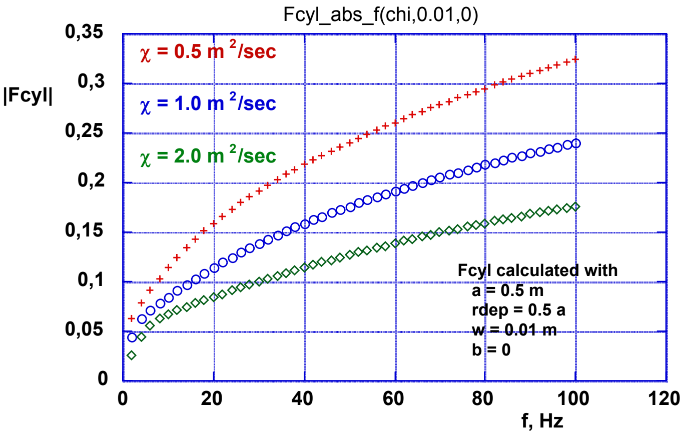


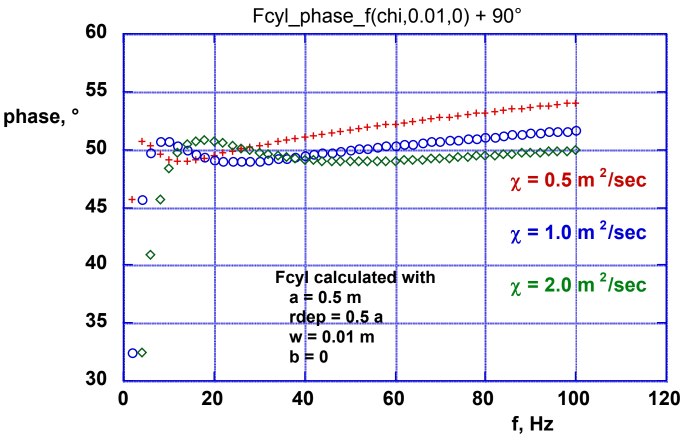
Differnt profile width shifts the perturbation to higher values of z since z ~ w

Modulated ECRH power deposition, cylindrical geometry





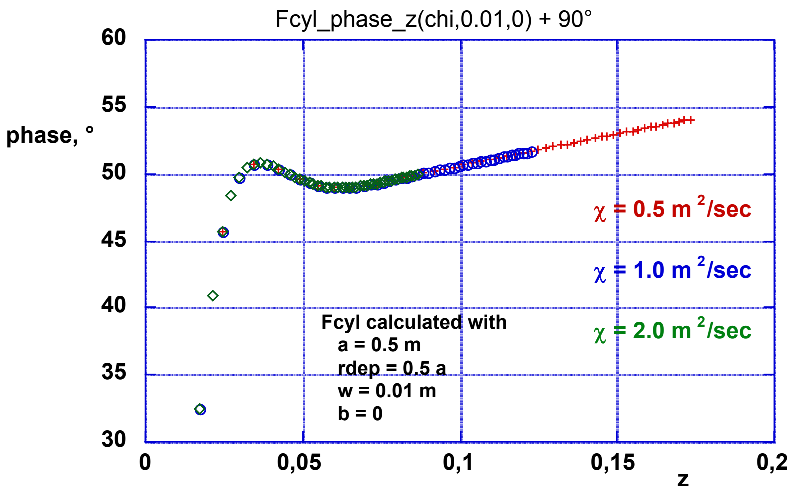


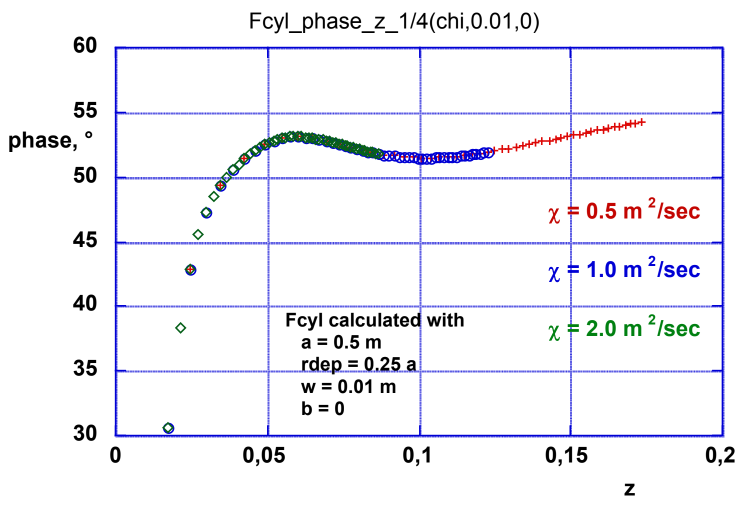


increasing χ shifts the perturbation to higher frequency,
but it remains at a constant value for $z \sim \mathrm{sqrt}(f/\chi)$

A perturbation occurs when the heatwave amplitude in the centre is not low enough

Modulated ECRH power deposition, cylindrical geometry





For a deposition closer to the centre the cylindrical case deviates from the plane case already at higher a value for z, corresponding to a higher frequency.

A perturbation occurs when the heatwave amplitude in the centre is not low enough.

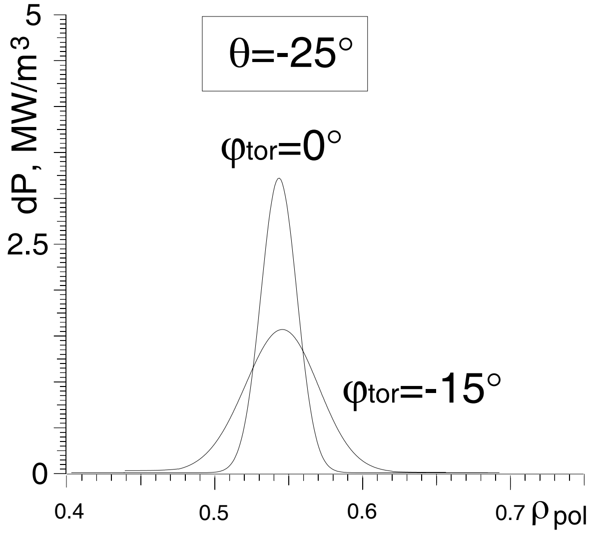
In ASDEX Upgrade this occurs for: $\sqrt{\frac{3\omega}{4\chi}}r_{dep} = z\sqrt{\frac{\pi}{w}}r_{dep} \leq 2.9$

Experiments on modulated ECRH power deposition

<u>Discharge:</u> low density, $2 \cdot 10^{19}$ m^{-3}
ohmic heating and cw ECRH with 0.8 MW at ρ = 0.3 or 0.6

a) Frequency scan:
frequencies from 30 Hz to 900 Hz

b) Variation of profile width w:
w is changed by launching at different toroidal angles w.r.t. magn. field



TORBEAM calculation of deposition profiles:

1 : ϕ_{pol} = 25°; ϕ_{tor} = 0°

3 : ϕ_{pol} = 25°; ϕ_{tor} = 15°

High field side deposition

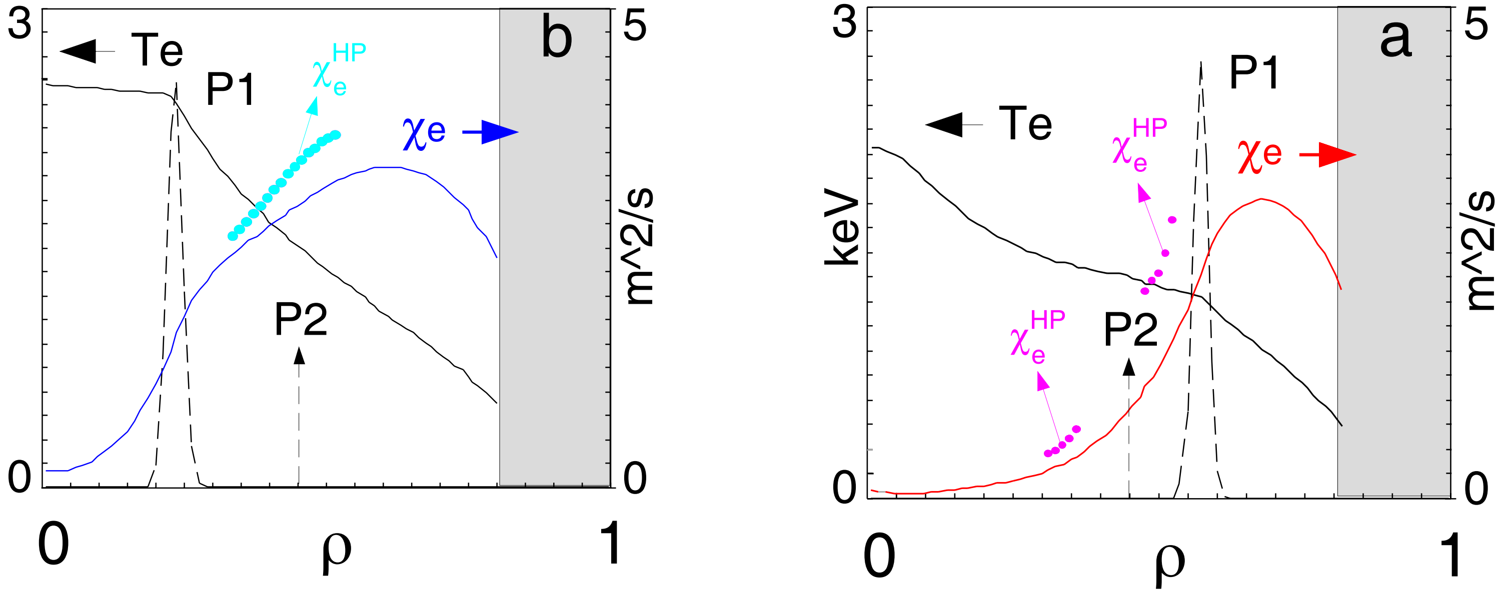
(TORBEAM: E.Poli et al., Phys.Plasmas 6 (1999) 5)

Experiments on modulated ECRH power deposition

c) χ-variation:

Cw ECRH power deposited at $\rho < \rho_{hw}$ -> high χ at ρ_{hw}
Cw ECRH power deposited at $\rho > \rho_{hw}$ -> low χ at ρ_{hw}

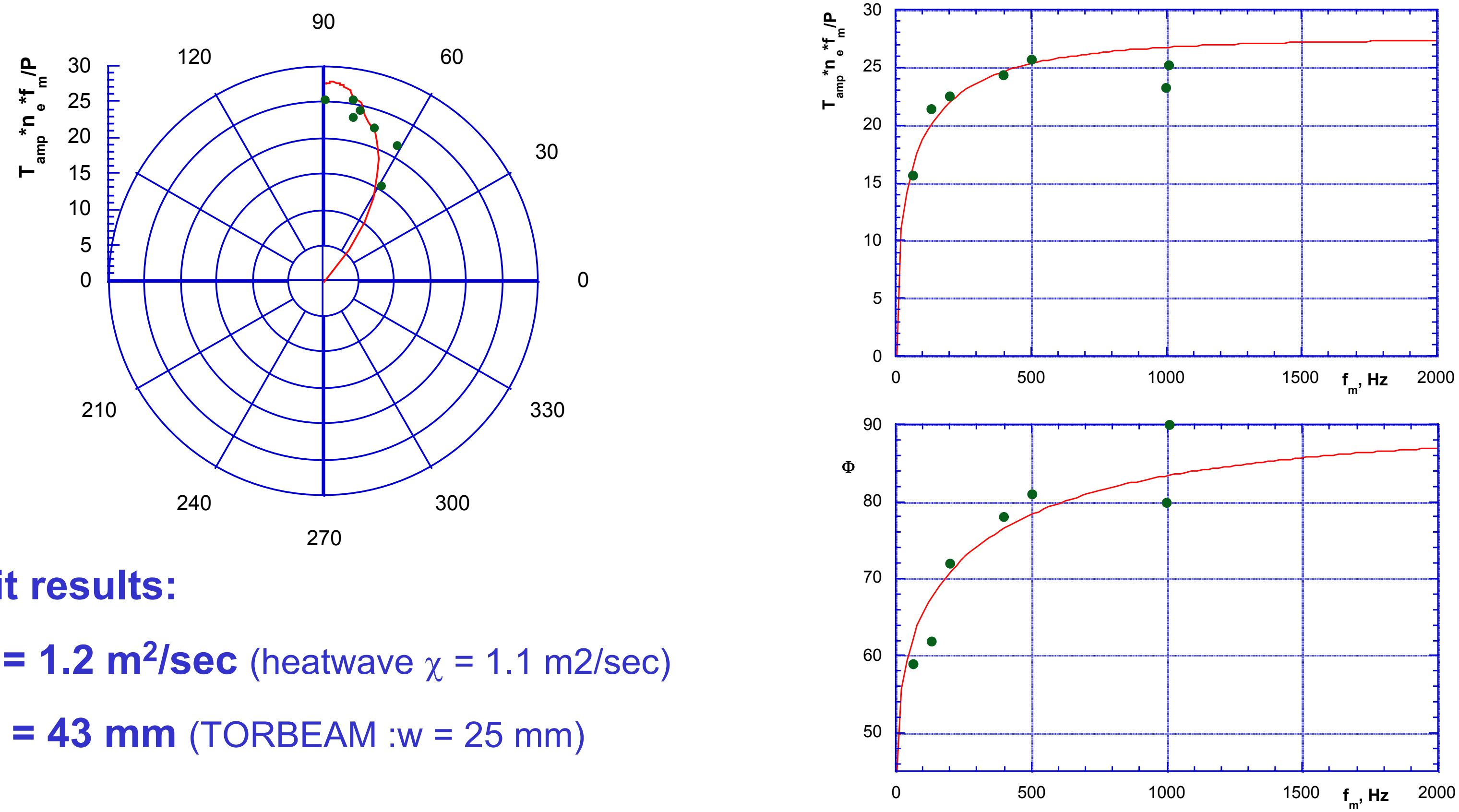
Reason: χ depends on local temperature gradient
(F. Ryter et al., Phys. Rev. Lett.86 (2001) 2325, and Phys.Rev.Lett. 86 (2001) 5498)



P1: cw ECRH, P2: modulated ECRH

Modulated ECRH power deposition $T(x=0)$

Frequency scan, broad profile, low χ



Fit results:

χ = 1.2 m²/sec (heatwave χ = 1.1 m2/sec)

w = 43 mm (TORBEAM :w = 25 mm)

Broader deposition profile -> lower value for $T(x=0)$ and larger central phase angle in agreement with the simple model