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The PION code

L.-G. Eriksson

Association EURATOM-CEA, CEA/DSM/IRFM, CEA-Cadarache, St. Paul lez Durance, France

T. Hellsten

[2]Association Euratom-VR, KTH, Stockholm, Sweden

Outline

- Introduction
- Power deposition model
- Fokker-Planck model
- Modified dielectric tensor due to non-thermal ions
- Experimental validation
- Conclusions

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Introduction

- In the late eighties at JET quantities directly affected by ICRF heated fast ions began to be measured routinely (non-thermal neutron rates, fast ion energy contents etc.)
- The experimentalists started to ask why the useless theory types, in spite of their fancy codes, could not model the measured quantities.
- It was quite clear that with the computers 15 years ago it would be very challenging combine a full wave code even with 2D Fokker-Planck code.
- We therefore started to develop simplified modelling that, as we see it, contains the most essential elements. The result was the PION* code.
- PION is run routinely in CHAIN2 at JET

*L.-G. Eriksson, T. Hellsten and U. Willén, Nucl. Fusion **33** (1993) 1037.

Power deposition model

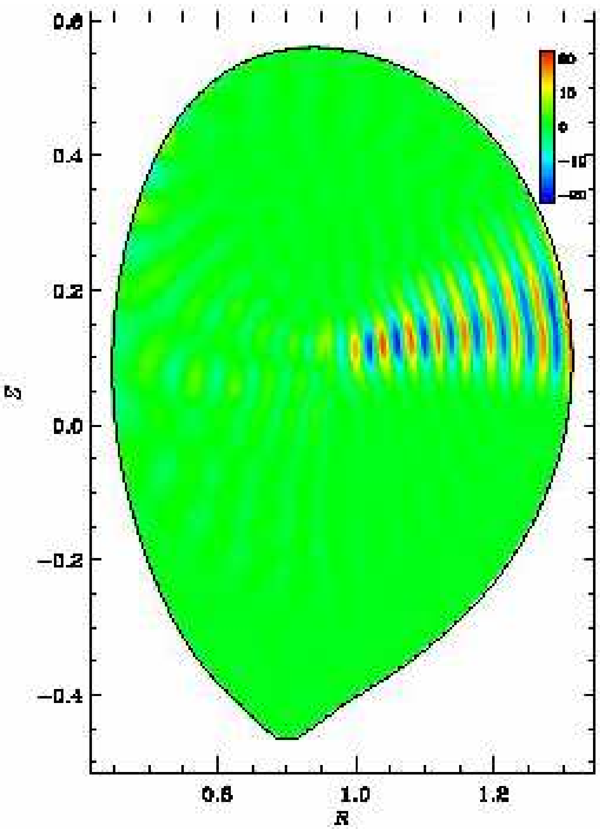
- The power deposition model was developed by Hellsten and Villard*
- It is based on a fundamental observation of the behaviour of wave fields in a Tokmak

T. Hellsten and L. Villard, Nuclear Fusion **28**, 285 (1998).

Wave fields for strong & weak damping

LION code*

E_R



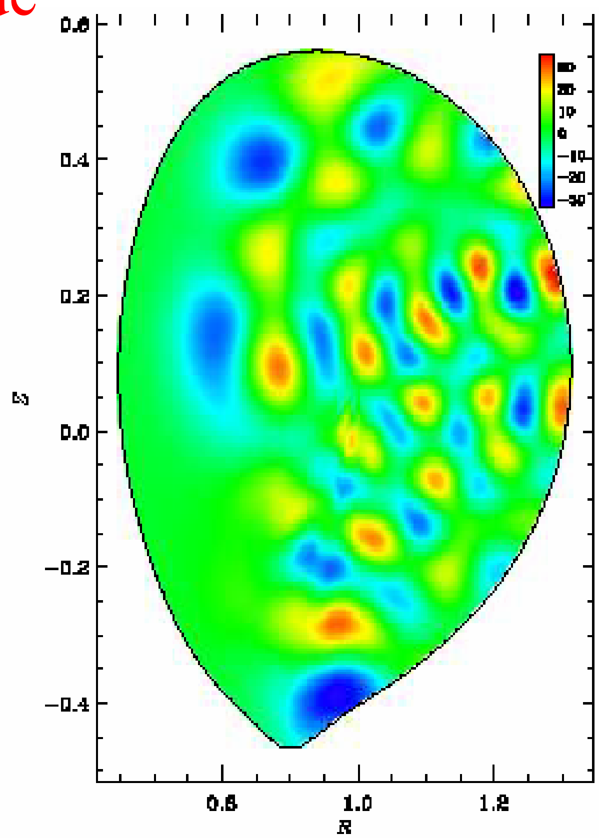
JET,
(H)D

$n_H/n_D \sim$ 5%.

$T_{\|H}$= 20keV

N_ϕ=25

E_R



JET,
(^{3}He)D

n_{He}/n_D ~5%.

$T_{\|He}$= 5keV

N_ϕ=25

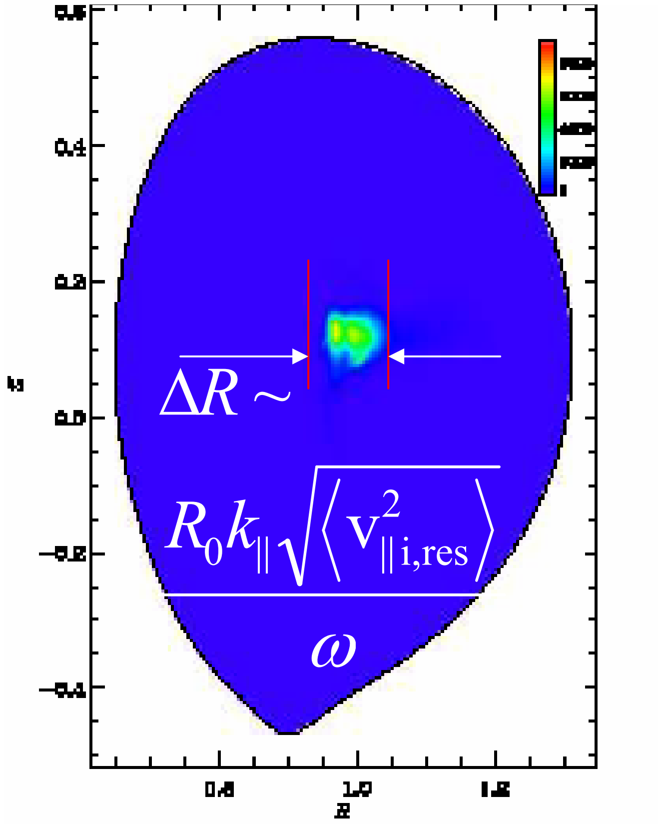
Strong damping, focussing of the wave at first passage.

Weak damping, the wave field fills much of the cavity;

*L. Villard et al., Computer Physics Reports **4**, 95 (1986).

Strong

Total absorbed power

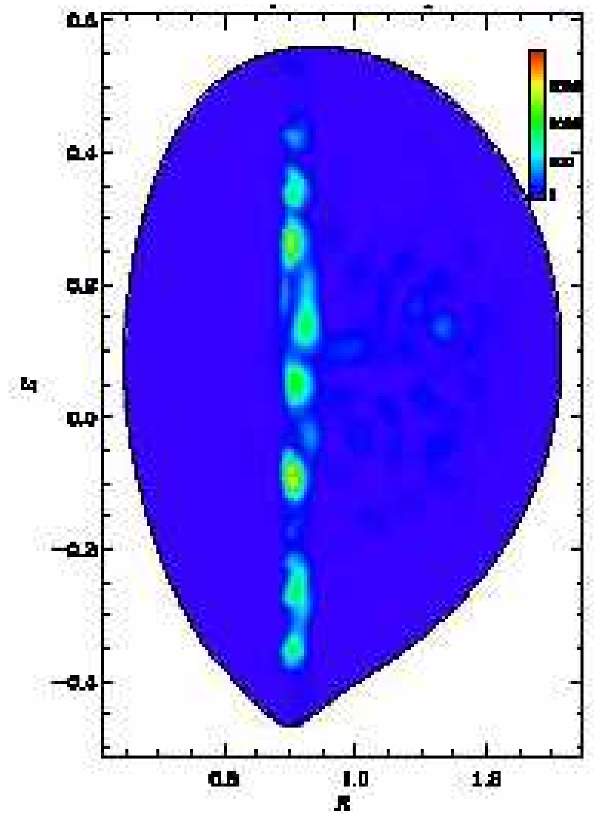


$$\Delta R \sim \frac{R_0 k_\parallel \sqrt{\left\langle v_{\parallel i,res}^2 \right\rangle}}{\omega}$$

Power deposition controlled by Doppler broadening of the cyclotron resonance ($\omega - k_\parallel v_\parallel = n\omega_{ci}$)

Weak

Total absorbed power



Power deposition determined by wave field distribution and the absorption strength along the cyclotron resonance and

- In a case with medium strong absorption, there will be a mix of the two fundamental cases.
- From the power deposition point of view, two quantities are important to estimate well:
  - The averaged square parallel velocity of the resonating ion species.
  - The damping strength of the different species.
- Both depend on the distribution function of the resonating species.

It is important to have a consistency between the power deposition and Fokker-Planck calculations.

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- Ansatz for the flux surface averaged Poynting flux (or power absorbed within a flux surface).

$$P(s) = P(s=1)\left[\alpha \overline{P}_S(s) + (1-\alpha)\overline{P}_W(s)\right]$$

$$\overline{P}_S(s) = \sum_j \overline{P}_{S,j}(s)$$

Represents limit of strong damping.

$$\overline{P}_S(s) = \sum_j \overline{P}_{S,j}(s)$$

Represents limit of weak damping.

$$\alpha = \alpha(a_s) \approx a_s^2$$

a_s is the single pass absorption coefficient calculated in the mid-plane

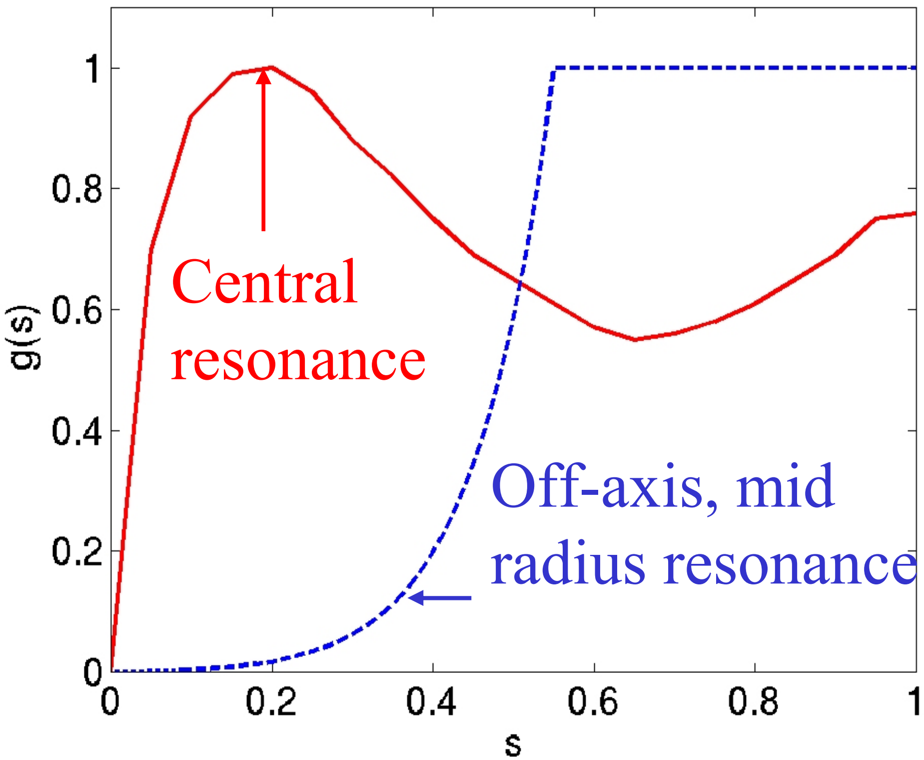
- Flux surface averaged power density

$$p(s) = \frac{dP(s)/ds}{dV/ds}$$

- The strong damping, $P_S(s)$, can easily be computed by a simple ray-tracing (now used instead of model[1]).

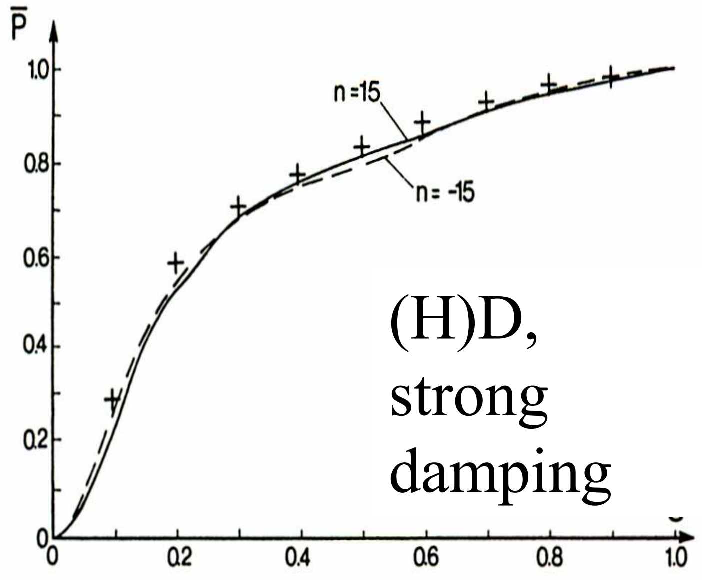
- Ansatz: $$\overline{P}_{W,j}(s) = C\int_0^s g(s')a_j(s')ds' \quad ; \quad \sum_j \overline{P}_{W,j}(1) = 1$$

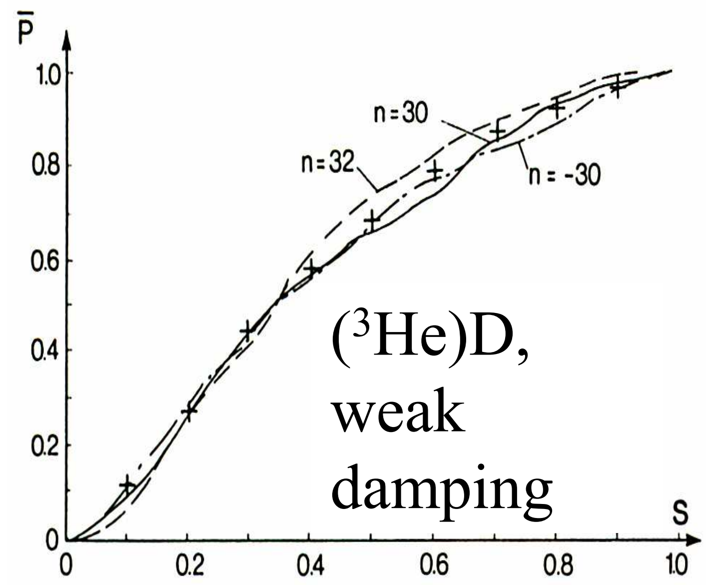
- $g(s)$ was obtained by averaging power depositions in the weak limit, calculated by the LION code, over small changes in toroidal mode numbers and densities.

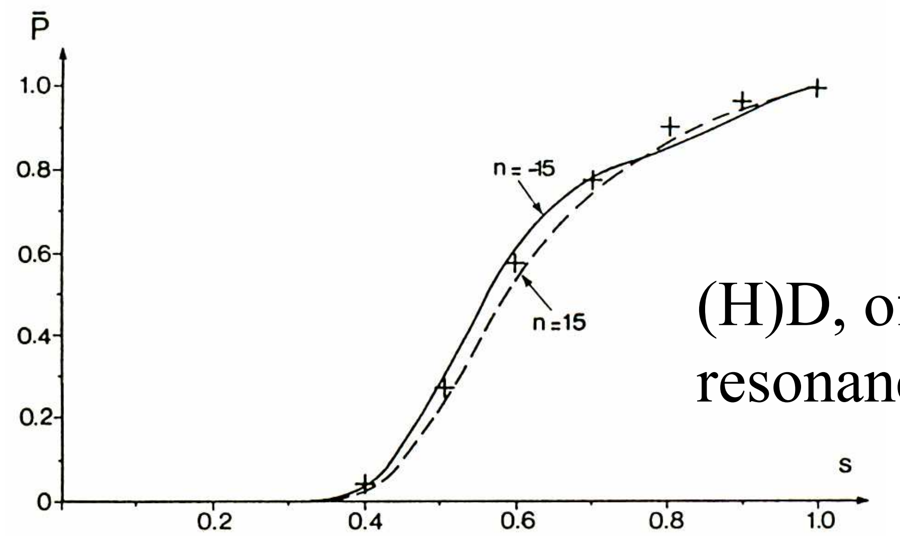


[1]T. Hellsten and L. Villard, Nuclear Fusion **28**, 285 (1998).

- Examples of comparison between the model and the LION code.







Fokker-Planck model

- The problem when one starts to do modelling on real experiments is that the power densities normally are very high, several MW/m^3 are typical in e.g. JET.
- Fast ions in the multi MeV range are therefore created.
- The 2D Fokker-Planck codes available at JET at the time (late eighties) could cope with 0.1- 02 MW/m^3.
- We therefore decided to go for a simplified 1D Fokker-Planck model.

- In PION a 1D Fokker-Planck equation equation for the pitch angle averaged distribution function,

$$F(\mathrm{v}, s, t) = \int_{-1}^{1} f\left\langle \frac{\mathrm{v}}{\mathrm{v}_{\|}} \right\rangle \xi d\xi \Big/ \int_{-1}^{1} \left\langle \frac{\mathrm{v}}{\mathrm{v}_{\|}} \right\rangle \xi d\xi$$

($\xi = \mathrm{v}_{\|0}/\mathrm{v}$) is solved:

$$\frac{\partial F(\mathrm{v}, s, t)}{\partial t} = \overline{C}(F) + \overline{Q}(F)$$

A finite difference scheme with adaptive time step and grid is used to solve the 1D Fokker-Planck equation.

- Approximate form of the RF operator

$$\overline{Q}(F) = \frac{1}{\mathrm{v}^2}\frac{\partial}{\partial \mathrm{v}}\left[\mathrm{v}^2 D_{RF}(\mathrm{v})\frac{\partial F}{\partial \mathrm{v}}\right]$$

$$D_{RF}(\mathrm{v}) = K_0 \int_{\xi_R}^{1} \left(\frac{B_R}{B_1}\right)^{1/2} \frac{1-\xi^2}{\left(\xi^2-\xi_R^2\right)^{1/2}} H(\mathrm{v}_{\perp \mathrm{R}})\xi d\xi$$

$$H(\mathrm{v}_{\perp \mathrm{R}}) = \left| E_+ J_{n-1}\left(\frac{k_\perp \mathrm{v}_{\perp R}}{\omega_{\mathrm{ci}}}\right) + E_- J_{n+1}\left(\frac{k_\perp \mathrm{v}_{\perp R}}{\omega_{\mathrm{ci}}}\right)\right|^2$$

$K_0 \sim |E_+|^2$ Is normalised to give the power density obtained from the power deposition code.

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- From the solution of the Fokker-Planck equation we can easily calculate the following quantities.

$$\gamma_{+}^{j} = \frac{p_{+}^{j}}{p_{+}^{M,j}} \quad , \quad \gamma_{-}^{j} = \frac{p_{-}^{j}}{p_{-}^{M,j}} \quad , \quad \gamma_{c}^{j} = \frac{p_{c}^{j}}{p_{c}^{M,j}}$$

- Where
  - +/-/c denotes powers absorbed due o the $|E_+|^2$ / $|E_-|^2$ /2Re($E_+ E_-^*$) components of the electric field;
  - M denotes the absorption by a equivalent Maxwellian

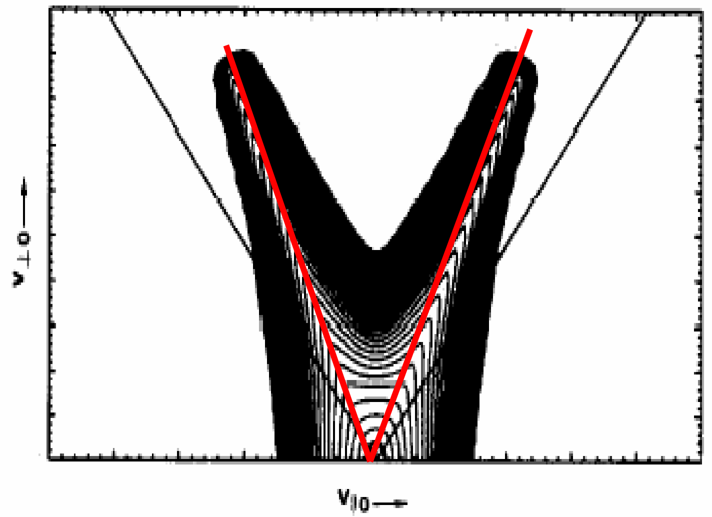
- The averaged parallel velocity of a species at the cyclotron resonance is estimated with a formula,

$$\left\langle v_{\parallel,j}^2 \right\rangle \approx \frac{1}{n_j}\int_0^\infty \xi_{eff}^2(v) F_j(v) 4\pi v^2 dv$$

$$\xi_{eff}^2(v) = \frac{1}{3}\frac{1+\left(\frac{v}{v_*}\right)^2}{1+\left(\frac{v}{v_*}\right)^2+\left(\frac{v}{v_*}\right)^4}$$

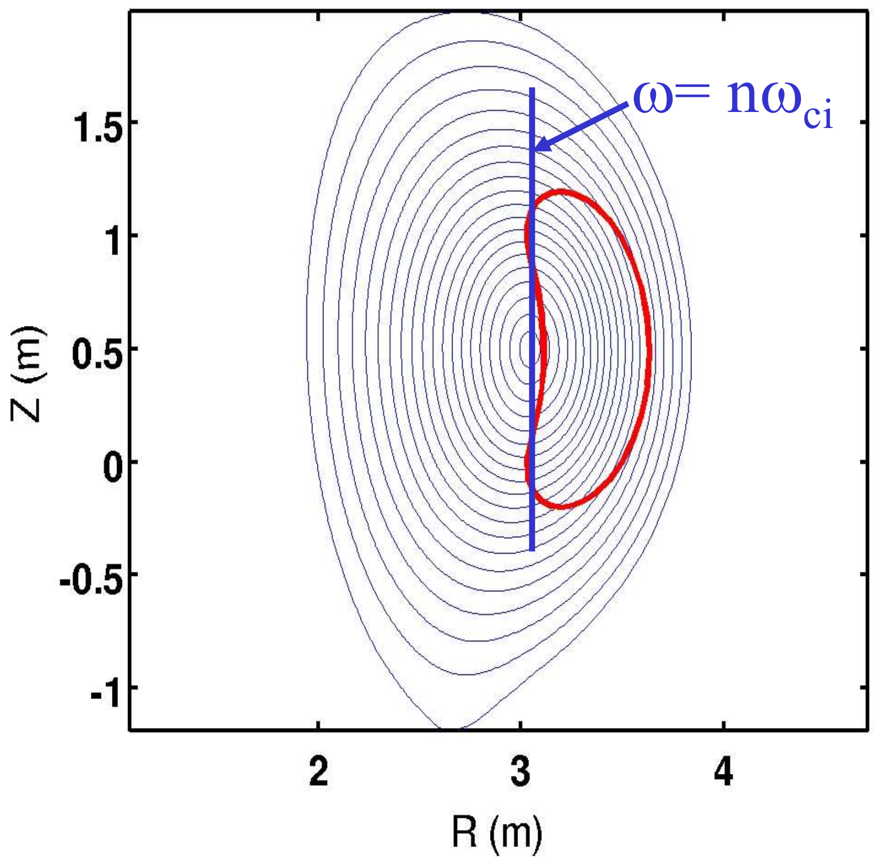
$$v_* \sim v_\gamma$$

$\xi_0 = \xi_{0R}$



- The physics basis is that the strength of the pitch angle scattering ~ $(v_\gamma / v)^3$.

- It soon became obvious that the orbit width of typical ICRF heated ions can be very large in machines like JET.
- The resonating ions tend to be trapped and pile up with their turning points close to the exact cyclotron resonance.



- The collision coefficients at non-thermal energies are therefore averaged over orbits of trapped particles with turning points close to the resonance.
- The fast ion pressure profile, the profiles of collisional power transfer etc. are re-distributed over the same orbits.

Influence of the distribution function on the power deposition

- The absorbed power density can be written as

$$p_c^j(\vec{E}) = \frac{\omega}{2\pi}\Big\{|E_+|^2\left[\mathrm{Im}(\varepsilon_{xx}^{\alpha} + \varepsilon_{yy}^{\alpha}) - 2\,\mathrm{Re}\,\varepsilon_{xx}^{\alpha}\right] +$$
$$|E_-|^2\left[\mathrm{Im}(\varepsilon_{xx}^{\alpha} + \varepsilon_{yy}^{\alpha}) + 2\,\mathrm{Re}\,\varepsilon_{xx}^{\alpha}\right] +$$
$$2\,\mathrm{Re}(E_+E_-^*)\,\mathrm{Im}(\varepsilon_{xx}^{\alpha} + \varepsilon_{yy}^{\alpha})\Big\}$$

- Using the gamma factors discussed earlier we calculate the anti-Hermitian parts of the dielectric tensor.

- We have for a general distribution function:

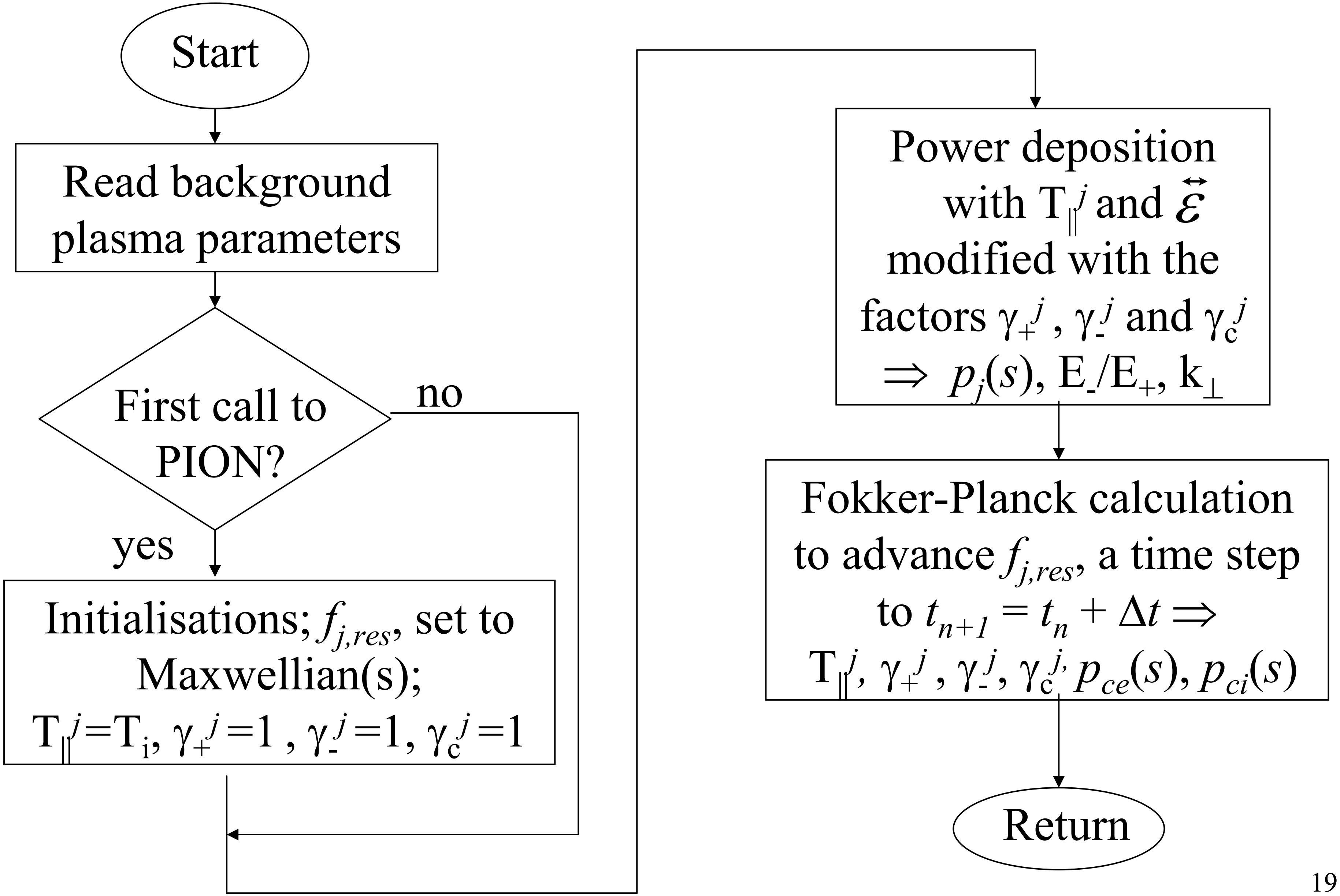
$$\mathrm{Im}(\varepsilon_{xx}^{j}+\varepsilon_{yy}^{j})-2\,\mathrm{Re}\,\varepsilon_{xy}^{j}=\gamma_{+}^{j}\left[\mathrm{Im}(\varepsilon_{xx}^{M,j}+\varepsilon_{yy}^{M,j})-2\,\mathrm{Re}\,\varepsilon_{xy}^{M,j}\right]$$

$$\mathrm{Im}(\varepsilon_{xx}^{j}+\varepsilon_{yy}^{j})+2\,\mathrm{Re}\,\varepsilon_{xy}^{j}=\gamma_{-}^{j}\left[\mathrm{Im}(\varepsilon_{xx}^{M,j}+\varepsilon_{yy}^{M,j})+2\,\mathrm{Re}\,\varepsilon_{xy}^{M,j}\right]$$

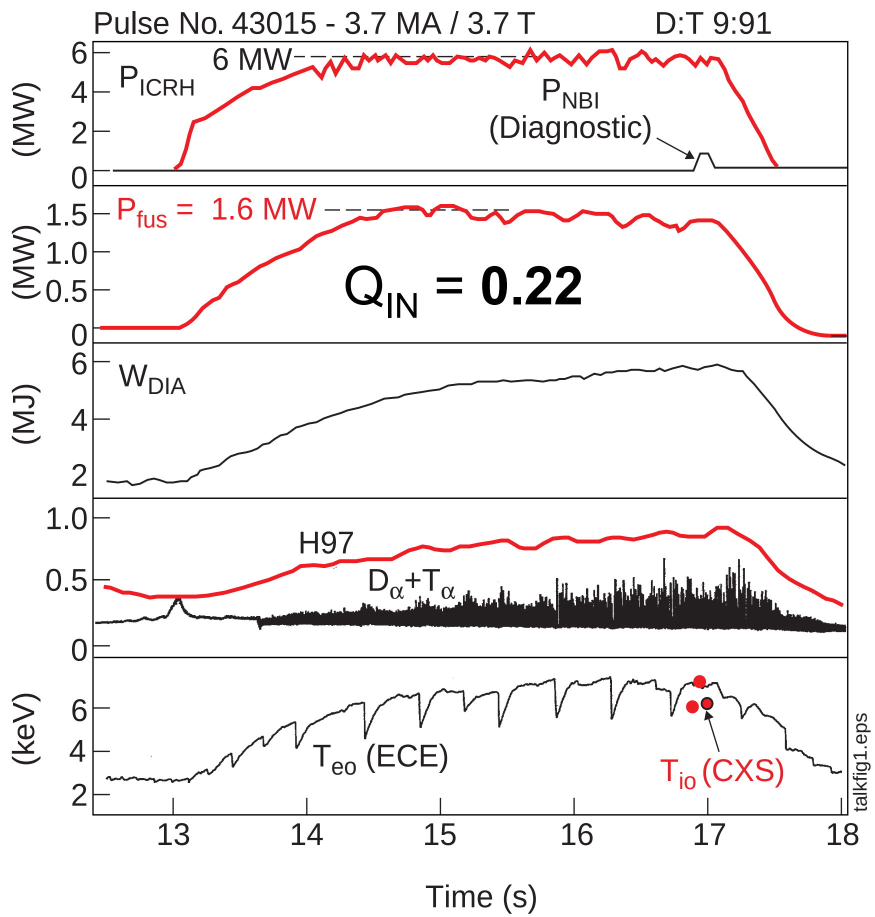
$$\mathrm{Im}(\varepsilon_{xx}^{j}-\varepsilon_{yy}^{j})=\gamma_{c}^{j}\left[\mathrm{Im}(\varepsilon_{xx}^{M,j}-\varepsilon_{yy}^{M,j})\right]$$

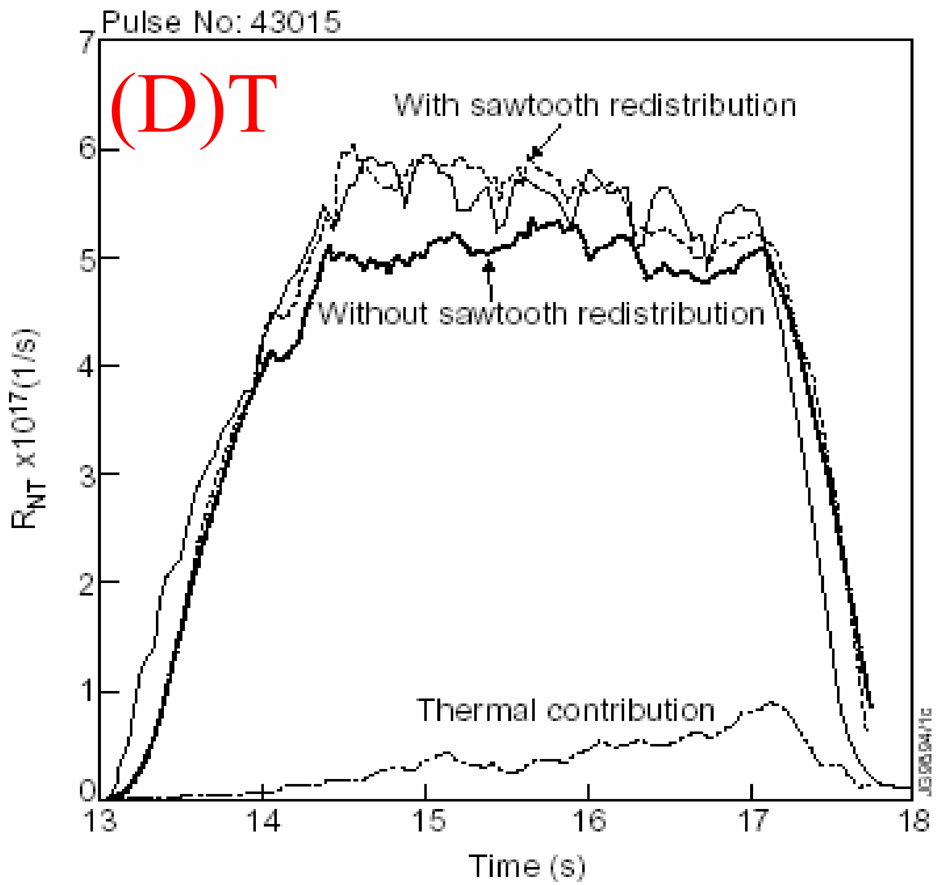
- Three equations ⇒ we can solve for the three unknowns: $\mathrm{Im}\,\varepsilon_{xx}^{j}$, $\mathrm{Im}\,\varepsilon_{yy}^{j}$ and $\mathrm{Re}\,\varepsilon_{xy}^{j}$
- By using Kramers Kronig’s relations we can also calculate approximate expressions for the Hermitian parts of the dielectric tensor

Flow chart: call to PION



Analysis of JET discharges



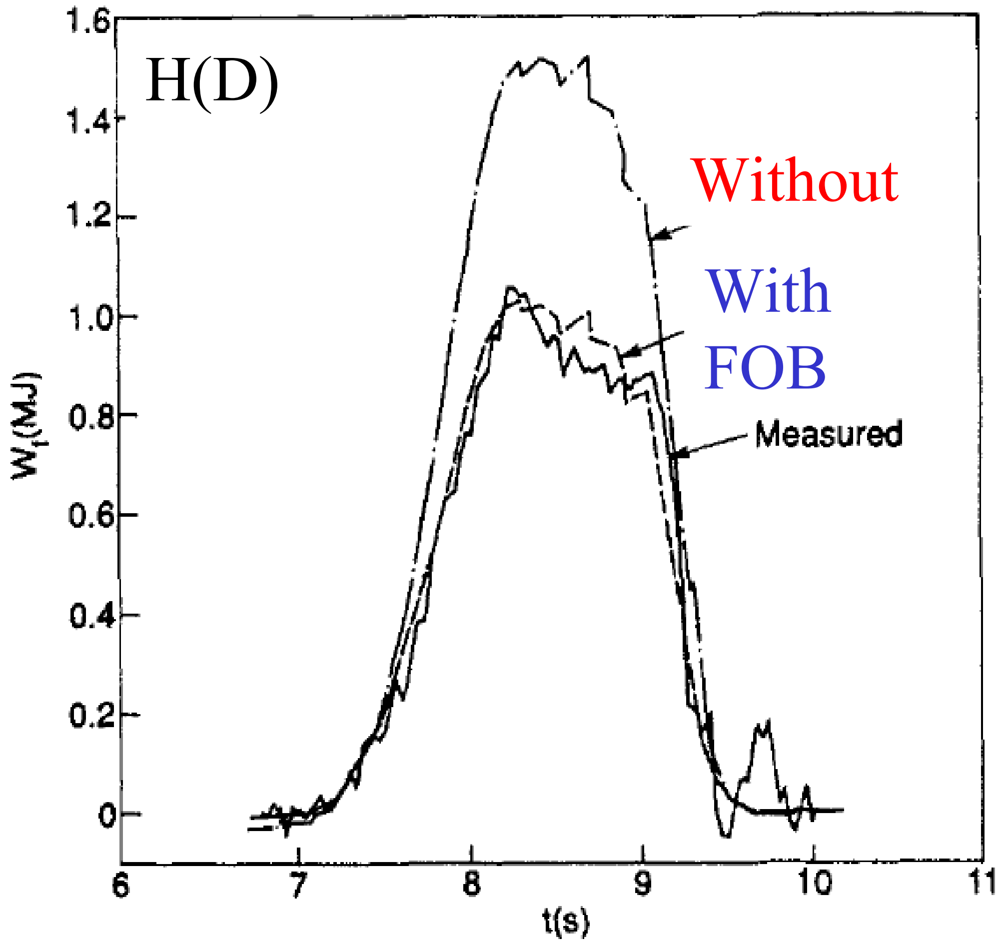


- Modelling in good agreement with experiment.

D. Start, D. Start et al., Nuclear Fusion **39**, 321 (1999);
*L.-G. Eriksson, M. Mantsinen et al., Nuclear Fusion **39**, 337 (1999).

Finite orbit width (FOW) effects

- The first version of PION did not include FOW.
- The figure shows a comparison with experimental results with and without modelling of FOB in PION.
- Conclusion: if you want to do serious modelling of ICRF heated JET plasma don't even think about leaving out finite orbit width effects.



#12298; n_{e0}= 3.6 x 10 19 m^{-3}
T_e= 7.0; P_{ICRF}=8.0 MW.

Conclusion

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- The PION approach includes the most important effects of ICRF heating in a simplified way.
- The results obtained tend to be robust.
- PION has been extensively benchmarked against JET results.
- Obviously, the PION approach has many limitations, e.g. cases with directed wave spectra and strong ICRF induced spatial transport cannot be handled.
- For detailed studies of ICRF physics a more comprehensive approach is needed.

Second harmonic T heating in DT