Cross-modulation of loop voltage and ECH power in ITER

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Introduction Modulating the auxiliary heating power has long been a tool to study heat deposition and transport in tokamaks [1 and refs therein]. Modulating the voltages applied to the Poloidal Field (PF) coils was used to validate locally linearised and non-linear equilibrium plasma response models. This present paper explores cross-coupling between these two forms of modulation of the plasma, which to our knowledge had not previously received attention. We assume that modulation of the PF coil system at an angular frequency ω will drive a modulated electric field E(t) at this frequency, according to (1). At the same time, modulation of the conductivity driven by additional heating will result in a modulated $\sigma(t)$ (2). The electric current driven by E(t) in the presence of $\sigma(t)$ will be j(t) as given by (3) and its time-averaged value will be given by (4).

$$E(t) = E_0 + \Delta E \cos(\omega t + \phi_E) \qquad (1)$$

$$\sigma(t) = \sigma_0 + \Delta\sigma \cos(\omega t + \phi_\sigma) \qquad (2)$$

$$j(t) = \sigma_0 E_0 + \sigma_0 \Delta E \cos(\omega t + \phi_E) + E_0 \Delta\sigma \cos(\omega t + \phi_\sigma) + \tfrac{1}{2} \Delta\sigma\Delta E \{\cos(\phi_E - \phi_\sigma) - \cos(2\omega t + (\phi_E + \phi_\sigma)\} \qquad (3)$$

$$\langle j \rangle = \sigma_0 E_0 + \tfrac{1}{2} \Delta\sigma\Delta E \cos(\phi_E - \phi_\sigma) \qquad (4)$$

The intuitive result is that any net offset of driven current due to the cross-modulation must be accompanied by a 2ω modulation of the same amplitude, from (3). This simple reasoning neglects diffusion of heat away from the deposition region and neglects the inward diffusion of the poloidal field from the plasma edge. In order to properly and simultaneously handle modulation of heat deposition, transport and the applied poloidal field, a full-tokamak simulator is needed. For this work, the DINA-CH full tokamak simulation code, combined with CRONOS, has been applied to the detailed PF engineering description of the ITER geometry [2 and refs therein]. This work served both to explore the cross-modulation and to further verify the behaviour of the DINA-CH and CRONOS code coupling in cases which had not previously been explored.

Simulation conditions A 15MA ITER scenario, previously used for modelling studies by the combined DINA-CH and CRONOS codes was used as a starting point, with: Ip = 15.1MA, q_{95}=3.55, k_{95}=1.71, δ=0.34, β_p=0.06, l_i=0.72, $n_e(0)=2\ 10^{19}\mathrm{m}^{-3}$. The plasma performance was achieved using a mixture of Neutral Beam Injection (NBI) and Ion Cyclotron Heating (ICH). Sawteeth were avoided to exclude non-linear coupling between electron heat deposition modulation and the sawtooth instability, identified on TCV. The plasma beta was lower than the nominal ITER scenario to reduce the complexity of the bootstrap current. Transport for the first simulations followed the self-normalising KIAUTO model. Modulated ECH deposition was simulated using CRONOS given the ECH upper launchers, with local current drive minimised. PF coil voltage stimulation was provided via the reference signal of the plasma current feedback control loop. The simulations were allowed to settle for 10 seconds and the modulations were then imposed to allow enough time to demodulate the lowest frequency stimulations.

A standard demodulation was used to extract the modulation amplitude and phase of simulated quantities at the stimulation frequency and at the double and triple frequencies. The method consisted of fitting to a set of basis waveforms: $F(t_i) = [1 \;\; (t_i\text{-}\langle t\rangle) \;\; \cos(\omega t_i) \;\; \sin(\omega t_i)]$ where ω is a vector of frequencies. The lowest frequencies, in which only a few periods were simulated, did not allow fitting to an additional term in t^2. The successful demodulation of all quantities was checked by eye.

ECH modulation First application of modulated ECH power showed sinusoidal modulation of the loop voltage, due to the plasma current feedback control loop. This was eliminated by freezing the plasma current feedback control at the start of the modulation of the heating power.

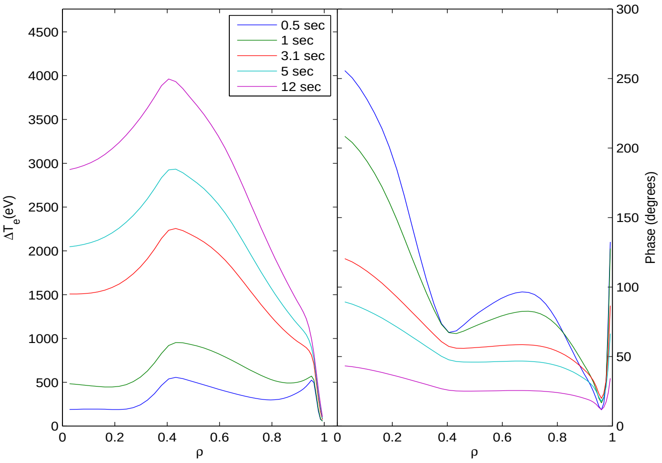

Fig.1:Response of T_e to ECH modulation at five frequencies. LHS shows the T_e amplitude and the RHS shows the response phase wrt power.

Sinusoidal modulation of the ECH power was then simulated with periods of [0.5 1 3 5 12sec] deposited near ρ~0.4. This led to clear synchronous modulated T_e responses, Fig.1. We see both the expected local minimum in phase, and a peak in the modulated amplitude near ρ ~ 0.4. The amplitude of the 2ω modulation of the electron temperature was small. The surprising result was the reduction of the response phase towards the edge of the plasma, whereas we would expect the phase to continue to rise towards the edge. The primary four candidates to explain this were:

- A residual power deposited at the plasma edge, present in the modelling of the deposition;
- The non-local transport model KIAUTO in which changes to internal parameters cause a variation of the normalised transport coefficients throughout the plasma, which in turn could appear as a source term;
- The parametric dependence of the transport coefficients in the KIAUTO model, which would cause, for example, local variations in conditions to appear as a source term;
- Incorrect modelling of the heat transport in the conditions of these simulations.

The edge deposition was eliminated without changing the character of Fig.1. The variation in the self-normalising transport model was turned off by freezing it before the modulation started. The results are shown in Fig.2 and correspond closely to expectation. We therefore conclude that the use of KIAUTO, although appropriate for coarse modelling of scenarios, can generate spurious effects when the variation of the transport inside the self-calibrating model is fast compared with the transport. The model is therefore invalidated for this usage and for the rest of our work we retained the frozen transport model, but using the steady value provided by KIAUTO itself. This first result validates the DINA-CH&CRONOS coupling at these high modulation frequencies, which had not previously been tested.

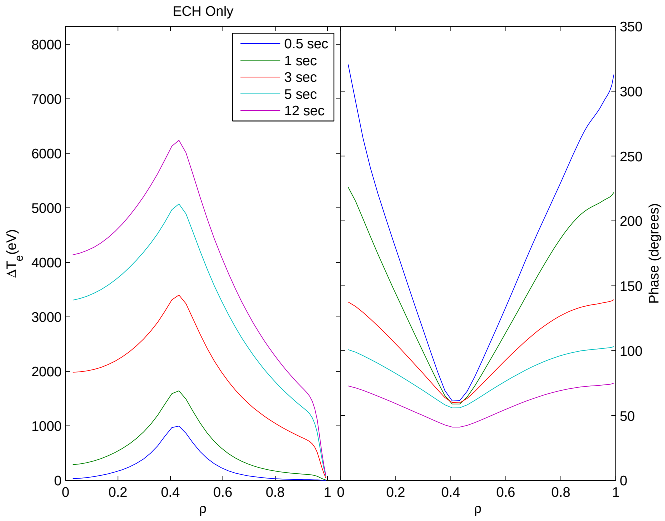

Fig.2: Response of the Te with frozen transport coefficients. LHS shows the response amplitude and the RHS shows the response phase wrt ECH power.

Modulation of the loop voltage Sinusoidal modulation of the plasma current references with the same set of frequencies led to the synchronous current density profile responses, shown in Fig.3. The normalised electric field modulation amplitude drops off rapidly with penetration depth. The penetration depth and the modulation amplitude increase as the modulation frequency decreases, for periods of 0.5, 1 and 3 seconds, but decreases for 5 and 12 seconds. The phase of the response increases continuously as the penetration increases, for all frequencies into about ρ=0.8. From this point inwards, the amplitude of the modulation is small and the phase turns round. A simple explanation has not yet been exposed. The signal is still significant in to ρ~0.8 at the lower frequencies. The amplitude of the 2ω modulation of the normalised electric field is less than 12% of the fundamental frequency amplitude for the lowest two frequencies and below 2% for periods of 3, 1 and 0.5 seconds.

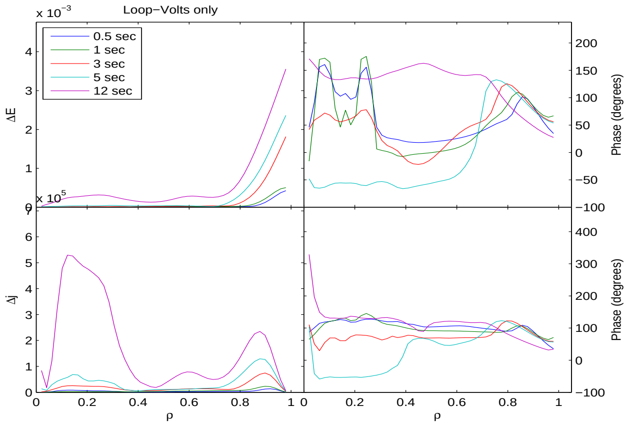

Fig.3: Profile of E(r) (upper row) and j(r) (lower row). LHS shows response amplitudes and RHS show the response phases wrt vessel flux modulation.

We conclude that the inward penetration of the electric field and the resulting modulation of the toroidal plasma current density is well modelled in the outer 20% of the plasma radius, where the modulation is significant. Further into the plasma the amplitude of the response becomes confused with the imperfect non-linear evolution of the equilibrium and cannot be used. However, this limitation is perhaps also due to the short analysis window (10 seconds to recognise a 12 second period modulation in the worst case).

Combined modulation Following the two separate sets of simulations, we proceeded with simulations of the combined modulation. A scan of the upper launcher angle was carried out to deposit the ECH power further out and produced a spatial overlap of the electron temperature modulation and the electric field modulation. The superposition resulted in a local 2ω response of the plasma current density as expected, seen as clear time-signals in Fig.4. This response is attributed to the non-linear cross terms between the linear conductivity response and the linear electric field response, as proposed. The cross-modulation produced a 2ω peak-to-peak current density modulation of the order of 40% of the target plasma current density.

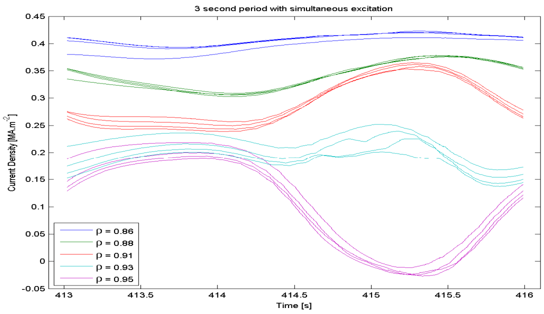

Fig.4: Evolution of the local current density at 5 radii.

Discussion The region with overlapping linearised responses shows a marked 2ω response, as expected, confirming the intuitive reasoning. The radial structure of the 2ω response amplitude has to be understood. Fig.4 shows that the phase of the inward moving perturbation has inverted between ρ=0.95 and ρ=0.86, which does not yet appear in our intuitive reasoning. The 2ω modulation amplitude should translate into a period-averaged offset by selecting the phase between the two modulation sources, to be confirmed in future simulations. The linearity of the cross-modulation with respect to Δσ and ΔE remains to be confirmed.

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