FRACTURED SUPERADIABATICITY FOR WAVE HEATING/CURRENT DRIVE

D.W. Faulconer

Laboratoire de Physique des Plasmas - Laboratorium voor Plasmafysica
Association "Euratom-Etat belge" - Association "Euratom-Belgische Staat"
Ecole Royale Militaire - B 1000 Brussels - Koninklijke Militaire School
Trilateral Euregio Cluster

ABSTRACT

So-called superadiabatic behavior of single particles driven periodically in a magnetic confinement device can limit their energy increase and notably pose a problem in heating and current drive, particularly for energetic particles of low collisionality such as are found near the hot center of large tokamaks or as result from injection of high energy neutral beams. Minority heating of tangentially co-injected 40keV ^{3}He neutral beam ions in the TEXTOR tokamak (i.e. cyclotron resonance at their fundamental frequency) presents such a weakly collisional situation. In a first approach we neglect collisions and evaluate numerically the counterbalancing effects of superadiabaticity versus (wave-induced) stochasticity. Sweeping of wave frequency is examined, not only as a means of phase randomization but of exploiting the phase recapture phenomena associated with the superadiabatic regime (partially broken or "fractured" superadiabaticity). To avoid overlarge decentering of the minority ion resonance layer, a repeating series of sweeps is indicated. A single one of these sweeps is studied here.

THE ROUGH IDEA

Consider the cyclotron resonance heating of a single minority species ion in the toroidally and poloidally delimited, constant amplitude RF field depicted in Fig.1. This field distribution models a magnetosonic wave launched by a single antenna pair driven in phase, with full absorption taking place at its first passage of the resonance region around the layer $\omega=\omega_{c^3He}$. Noting that the heating wave has $\mathbf{E} \cdot \mathbf{B_O} \approx 0$, one has for kinetic energy W and magnetic moment μ ($=mv_\perp^2/2B_O$) during a single ion transit of the wave region:

$$dW/dt = Ze\mathbf{v} \cdot \mathbf{E} \approx Ze\mathbf{v_\perp} \cdot \mathbf{E_\perp} = Zev_\perp E_\perp \cos\psi \qquad (\psi(t)=\psi_E(t) - \psi_c(t))$$

$$d\mu/dt \approx B_O^{-1}dW/dt = Zev_\perp E_\perp \cos\psi/B_O \qquad\qquad (1)$$

(the second equation follows from constancy of unperturbed μ and the relative change in B_O in the course of the interaction being small). The variations of W and μ are seen to depend on the angle between $\mathbf{v_\perp}$ and $\mathbf{E_\perp}$, ψ. If this angle's behavior is reproduced (modulo 2π) over successive transits (or multiples of transits) of the heating zone where $E_\perp \neq 0$, W and μ increments of given sign are also reproduced, resulting in large cumulative change in these variables. Steady change in the two quantities eventually modulates the phase reproduction leading to a smooth periodic behavior on a time scale of many transits and no net heating. Values at successive arrivals (or multiples of arrivals) at a given toroidal position map out either an island or a passing trajectory in W-ψ and μ-ψ action-angle spaces [1], where in view of a periodic dependence on it, we consider ψ's value at arrival modulo 2π. When $E_\perp$ is large enough to cause neighboring islands to overlap, particle behavior in these spaces becomes stochastic (despite the absence of collisions) and wave heating occurs.

With the island centers being functions of heating wave frequency ω, a moderate **sweep in frequency** causing the islands to drift toward increasing W and μ ($d\omega/dt>0$) could result in steady increase in island particle energy/magnetic moment (nonstochastic heating). By the same token, a frequency sweep in the opposite direction could lead to a steady decrease in these

quantities. To test these possibilities suitably perturbed drift equations of single particle motion in the fields of Fig.1 have been integrated numerically with wave frequency being swept, time dependent ω (and $k(\omega)$) distinguishing our approach from other work [1-3]. The highly structured wave field used also differs from the simpler ones employed in the first two references (Ref.3 uses a field generated by the ALCYON code). It is worth remarking that the link between frequency sweeping and motion of island-like structures has been previously studied with regard to instability and particle transport [4-5].

IMPLEMENTATION

Turning to the model in more detail, as in experiment the beam ions are taken to be near the <u>center</u> of the tokamak plasma column of circular poloidal section shown in Fig.1, this allowing us to consider that parallel ion guiding-center (g.c.) velocity deviates only moderately from constancy (no banana trajectories). Consistent with this we neglect ion drifts across $\mathbf{B}_O$. Focusing on centrally located particles also allows development of quantities in powers of r/R_O (r and R_O are minor and on-axis major radii of the torus); with introduction of the drift approximation (W and μ constant when $E_\perp=0$) one arrives at a greatly simplified analytic description of the ion gyro- and guiding center motions in regions of zero heating field. An ion's cyclotron motion causes a corresponding fluctuation in the wave spatial dependence it sees. Expansion of this rapidly fluctuating component produces a sum of terms having subphases of the form:

$$\psi_n = k(t)(x_{gc}(t) - x_{antenna}) - \int_{const}^{t} \omega(t') - n\omega_c[x_{gc}(t')]dt' \qquad (2)$$

(x is the abscissa in the poloidal section; k<0 in Eqn.(2)) so when a linear approximation to the time dependences of frequency, wave number, and coordinate x_{gc} is made across the toroidally restricted heating region, quadratic dependence of ψ_n results, yielding a single-interaction result from the integrated right members of Eqns.(1) in terms of Fresnel integrals. Due to the high velocity at which the g.c. traverses the limited integration domain, the standard procedure of calculating the single-pass interaction by means of the stationary phase approximation proves inaccurate, this being important in view of the nonlinear nature of the heating interaction.

The W,μ,ψ increments due to $\mathbf{E}_\perp$ calculated for a given passage of the field region are taken to be impulses received at the toroidal center of this region. This reduces our problem to a finite-difference calculation over consecutive field encounters in the spirit of earlier work (e.g. Ref.1); what is essentially new is the use of frequency sweeping to augment heating.

RESULTS

For computations 40keV beam ions were taken to be co-injected on the outer equatorial plane at a toroidal position displaced from the antenna center by one-eighth toroidal revolution in the counter direction, with $\omega=\omega_{c3He}$ on-axis initially. Results of studies of single beam particles, using TEXTOR parameters given below and with $E_\perp=1kVm^{-1}$, are presented in figures 2 and 3. The original data for these plots gave values pointwise at each passage of a given toroidal position, with points where no field interaction took place being omitted; to clarify the temporal sequence, successive points have been connected. In Fig.2 is shown the history of a beam particle with initial pitch angle set maximum (0.05radian) where the rate of frequency sweep is such as to allow the particle's entrainment in a rising island-like behavior; note that for this case q=1.0 (r=0.1155m) has been chosen and that the particle passes through the field interaction region at a fair distance from the resonance surface. Entrainment begins when successive values of the angle ψ, considered without the modulo operation, differ by only a fraction of 2π. By the end of the 3ms time interval shown the particle has undergone an 884-fold increase in μ, and W has increased to 3.25 times its initial value. In the absence of frequency sweeping, behavior is superadiabatic with μ and W changing by respective factors 1.39 and 1.001. As anticipated, a frequency sweep of negative sign can entrain a particle at large pitch angle in an analogous downward motion, reducing its pitch angle, μ and kinetic energy; one might speculate that such an interaction could allow net energy input to waves from a population of particles [5]. We return to this question at the end of the next paragraph. Fig.3

presents the more typical case of a particle of the same initial pitch angle which explores the entire range of poloidal angle (q=1.036,r=0.1335m); residence at plateaus (off-resonance interaction) is punctuated by uniformly increasing (nonstochastic) jumps in μ corresponding to particle passages in the vicinity of resonance. Increases over the 3ms period are much lower than for q=1.0 with respective augmentations of μ and W by factors 192 and 1.50, whereas when frequency is not swept μ cycles rather irregularly with final increases of μ and W by respective factors 4.61 and 1.01. Putting q$\neq$1 has introduced extreme sensitivity to sweep rate (μ (W) factors drop to 15.6 (1.04) if rate increases 1%!). Use of $E_\perp$=3kVm^{-1} in this case leads to augmentation by factors 595 and 2.53 for μ and W when frequency is optimally swept at 5.04 10^{7}Hz s^{-1}, compared to respective values 19.6 and 1.04 in the no-sweep case.

With the same TEXTOR q-profile as was used for the single-particle studies above, individual beam particle contributions have been summed over the beam cross-section; beam particles are initially distributed uniformly in ψ_C and, to maximum values of 0.15m and 0.05 radian, in minor radius and pitch angle. The peaked curve B in Fig.4 displays the increase over 3ms of average beam particle energy W as a function of the rate of frequency sweep. The maximum increase, 6.17keV, occurs for the optimal sweep rate df/dt=0.4 10^{7}Hz s^{-1} and is over six times that seen without sweep (0.918keV at df/dt=0). Raising field amplitude from $E_\perp$=1kVm^{-1} to 3kVm^{-1} resulted no longer in a peaked behavior of W increase, the rightward descent being replaced by plateauing at a roughly constant value around 24keV from df/dt=0.6 10^{7}Hz s^{-1} onward; comparison with a 8.61keV increase without sweep shows diminished relative effect of optimized sweeping. The more rapidly an in-phase particle migrates in μ, the more rapidly its ψ will dephase at constant frequency f; alternatively, the more rapidly must frequency be swept if phase coherence of ψ is to be maintained (i.e. the optimal sweep rate should increase). The rate of migration in μ increasing with $E_\perp$, one thus expects the optimal sweep rate also to increase with $E_\perp$, an expectation borne out in moderate degree by comparison of the rate for peaking found above (0.4 10^{7}Hz s^{-1} with $E_\perp$=1kVm^{-1}) with that for plateau onset (0.6 10^{7}Hz s^{-1} with $E_\perp$=3kVm^{-1}). One might suspect sweeping of frequency to be doing little beyond randomizing particle relative phase ψ between successive encounters with the field region, the loss of phase memory removing superadiabatic limitation on growth of average μ and W. This possibility was tested by randomizing the cyclotron phase ψ_C between encounters, this producing the flat curve C in Fig.4 for $E_\perp$=1kVm^{-1}. Near the optimal sweep rate the much larger increases in W found without randomization exclude the latter as dominant mechanism, though coincidence of the curves B and C could indicate the contrary at the higher sweep rates. For $E_\perp$=3kVm^{-1} the flat curve calculated with ad hoc randomization lies only several keV below the plateau found earlier. Phase randomization is thus not excluded as possible dominant mechanism over this plateau region and may be weakening the coherence-based relation of optimal sweep rate to $E_\perp$ foreseen above. Application of negative sweep rates of magnitude comparable to or greater than optimal ones gives energy increases similar to those seen with phase randomization, possibly reflecting the latter as underlying mechanism. The reduction of μ and W by such negative sweeps noted in the previous paragraph could be playing a minor role in diminishing increases somewhat below those seen with randomization, for $E_\perp$=3kVm^{-1}.

CONCLUSION

In summary, the application of optimized upward sweeping of wave frequency gives increases in heating rates of the beam configuration studied by factors 6.72 (2.82) for $E_\perp$=1kVm^{-1} (3kVm^{-1}). Downward sweeps of similar magnitude give reduced increases. The influences of weak collisions undergone by beam particles and absence of single-pass wave absorption in TEXTOR remain to be examined.

The TEXTOR parameters used in these calculations are: f(t=0)=25MHz, R_O=1.85m, $x_{antenna}$=0.4m, B_O=2.45946T (embedding a 0.1m Shafranov shift; values without shift are $x_{antenna}$=0.5 and $B_O(R_O$=1.75m) = 2.6T). Wave properties were evaluated from the cold fast wave dispersion equation with effective parallel k value of 3m^{-1} and n_H=0.3 10^{19}m^{-3}, n_D=4.5 10^{19}m^{-3}, n $_{3He}$=0.6 10^{19}m^{-3}, whence k(t=0)=-32.928m^{-1} in Eqn.(2). $E_\perp$ comprised solely the resonant circularly polarized field component. An antenna pair of 0.6m toroidal width was modeled.

REFERENCES
1. T.H. Stix, *Waves in Plasmas*, AIP, New York, 1992; Sect. 17-14 links cyclotron resonance heating to the standard mapping discussed in Chapt. 16, wherefrom curves are calculated exhibiting island and passing behavior of particles with transition to stochasticity (see Figs. 16.10-16.12). Here $u_\perp$ plays a role analogous to μ above.
2. P. Helander and M. Lisak, Physics of Fluids B: Plasma Physics, **4**, 1927-34 (1992).
3. V. Bergeaud, 8th European Fusion Theory Conf., Como 1999, Invited Talk; paper submitted to Physics of Plasmas.
4. C.T. Hsu et al., Phys. Rev. Lett. **72**, 2503-2507 (1994).
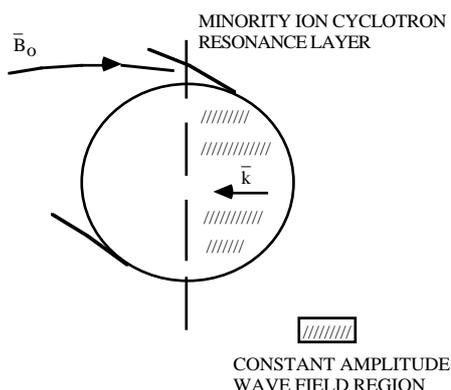5. H.E. Mynick and N. Pomphrey, Nuc. Fusion **34**, 1277-1282 (1994).

Fig.1 Distribution of RF heating field over poloidal section of tokamak with dashed line showing position of cyclotron resonance layer about which minority ions absorb the wave. Field amplitude is taken constant over toroidal sector occupied by antenna and zero elsewhere. Confining field $\mathbf{B}_O$ is also shown.
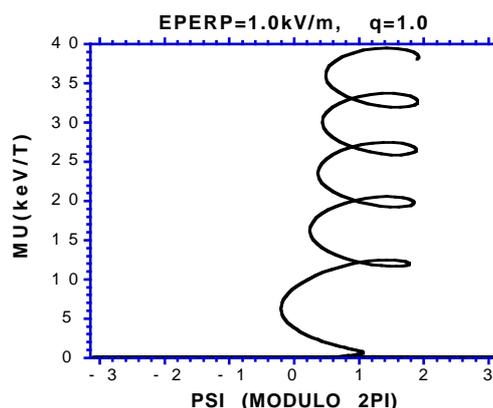

Fig.2 Entrainment of a particle at r=0.1155m in a rising island-like behavior. Safety factor value q=1.0 favors coherence of the motion over time (compare Fig.3). Note roughly half of 3ms period shown spent at low μ values before rapid rise begins. df/dt=5.2 10^7Hz/s.
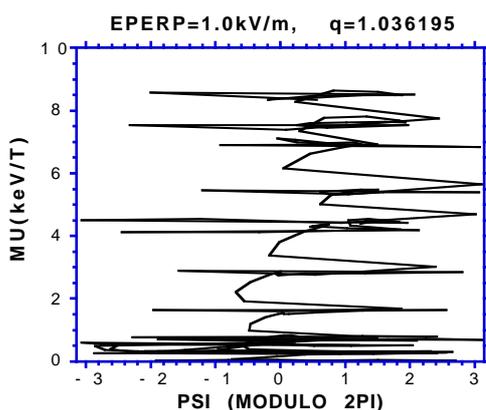

Fig.3 Single particle at r=0.1335m exploring full range of poloidal angle (q≠1.0) for 3ms, exhibiting overall nonstochastic behavior of μ. Off-resonance interactions (plateaus) alternate with systematic increases (passages near resonance). df/dt=1.0 10^7Hz/s.
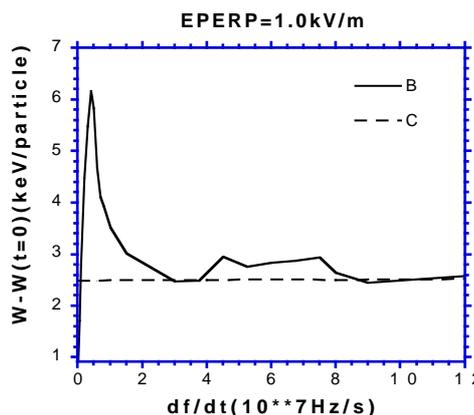

Fig.4 Average energy gain per beam particle in 3ms versus frequency sweep rate without (B) (with (C)) ad hoc randomization of ψ_c between heating field interactions. Over six-fold peak increase in heating with sweep; curve C shows randomization a plausible mechanism at higher sweep rates, not at lower ones.