NTM Prevention by ICCD Control of Fast-Ion-Stabilised Sawteeth

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**See the Appendix of M.L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006), IAEA, (2006)*

MAIN RESULTS

- First demonstration of the effectiveness of ICCD in shortening sawteeth and thus preventing m=3, n=2 neoclassical tearing modes (NTMs) in the presence of a strong fast-ion component and at β_{pol} well above marginal stability, i.e. at values at which NTMs are routinely triggered under identical conditions without a sawtooth-destabilising agent
- The scenario effectively simulates the conditions expected in a fusion reactor such as ITER, where the fast-ion population will primarily be comprised of alpha particles generated by fusion reactions and NTM triggering is expected to occur in the absence of active sawtooth control

MOTIVATION

- NTMs [1] can cause significant loss of confinement in tokamaks (→ITER) [2]
- NTMs are metastable: excited only by finite seed island, but once excited remain unstable
- → Primary strategy to prevent NTMs at low β_N (1-1.5) is to contain seed islands [3]
- Especially deleterious seed islands are associated with crashes of long sawteeth [2], which can occur owing to internal kink stabilisation effect from fast ions

BACKGROUND

- Counter-current propagating ICRF waves near the inversion radius are known to destabilise the internal kink (i.e. shorten sawteeth) [4-5] and are effective even in the presence of fast ions [6]
- This had not been demonstrated yet in a reactor-relevant regime with NBI heating and β_{pol} well above marginal stability for NTMs

STRATEGY

- Two-colour ICRF: core ICRF with co-current propagating wave phasing (→inward pinch) to maximise fast-ion population [8], counter-current propagating wave phasing near inversion radius to destabilise sawteeth [9]
- Hydrogen minority fundamental ICRF: central resonance = 42.2 MHz (+90^o phasing); off-axis (HFS) resonance = 46.2 MHz (-90^o phasing); B_T~2.8 T, I_p~2.2 MA, q_{95}~4.1, $\overline{n}_e$~2.4x10^{19} m^{-3}, H concentration 3-5%

PRINCIPLES OF ICCD

- Complex combination of effects: Fisch (asymmetric resistivity) mechanism (Fig. 2), finite-orbit trapped-ion current (Fig. 3) plus current from radial fast-ion drifts
- The first two effects can be locally strong and comparable to one another [7]

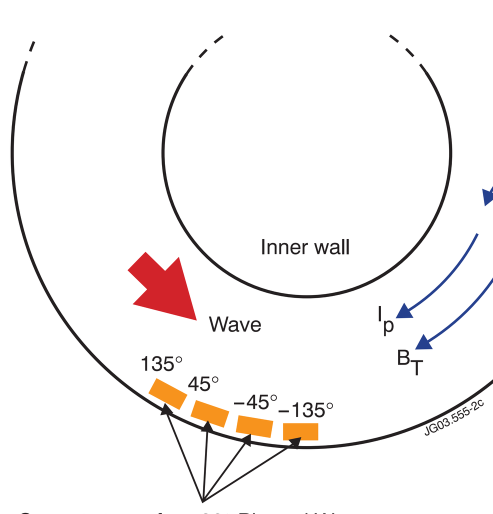

Figure 1. Schematic representation of one of the four ICRF antennae on JET. Each antenna has four current-carrying straps; the phasings of the currents in the straps determine the parallel wave-number spectrum, i.e., the wave directionality (counter-current propagation in the example shown, denoted as -90^o phasing)

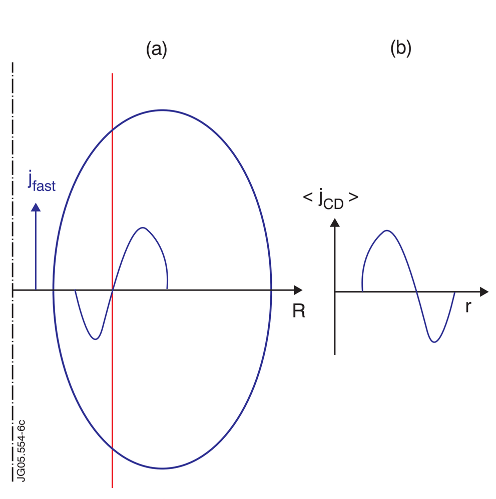

Figure 2. Current density profile driven by ICRF on the HFS through the FIsch mechanism (co-current propagating waves in this example)

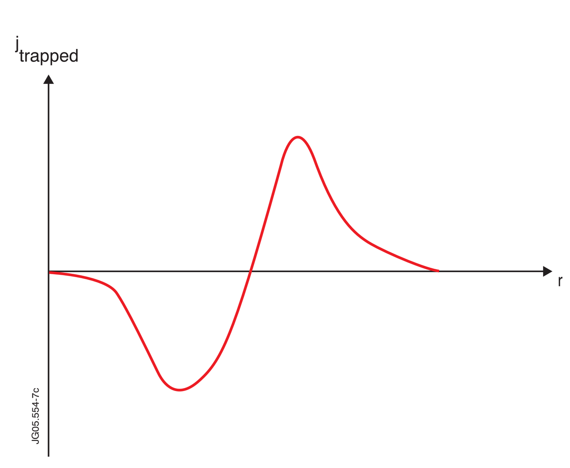

Figure 3. Current density profile driven by ICRF through trapped suprathermal ions owing to finite orbit width effects (direction is independent of antenna phasing)

DEMONSTRATION OF NTM PREVENTION

- With well-tuned 3 MW off-axis ICCD, the sawtooth period is kept consistently shorter than 200 ms at β_N=1.25-1.35, with 3 MW core fast-ion heating (Fig. 4, left)
- Control cases: -90^o ICCD replaced by dipole ICRF (same power, no net toroidal wave propagation: Fig. 4, middle); ICCD removed altogether (Fig. 4, right): sawtooth period > 500 ms, and NTMs are triggered

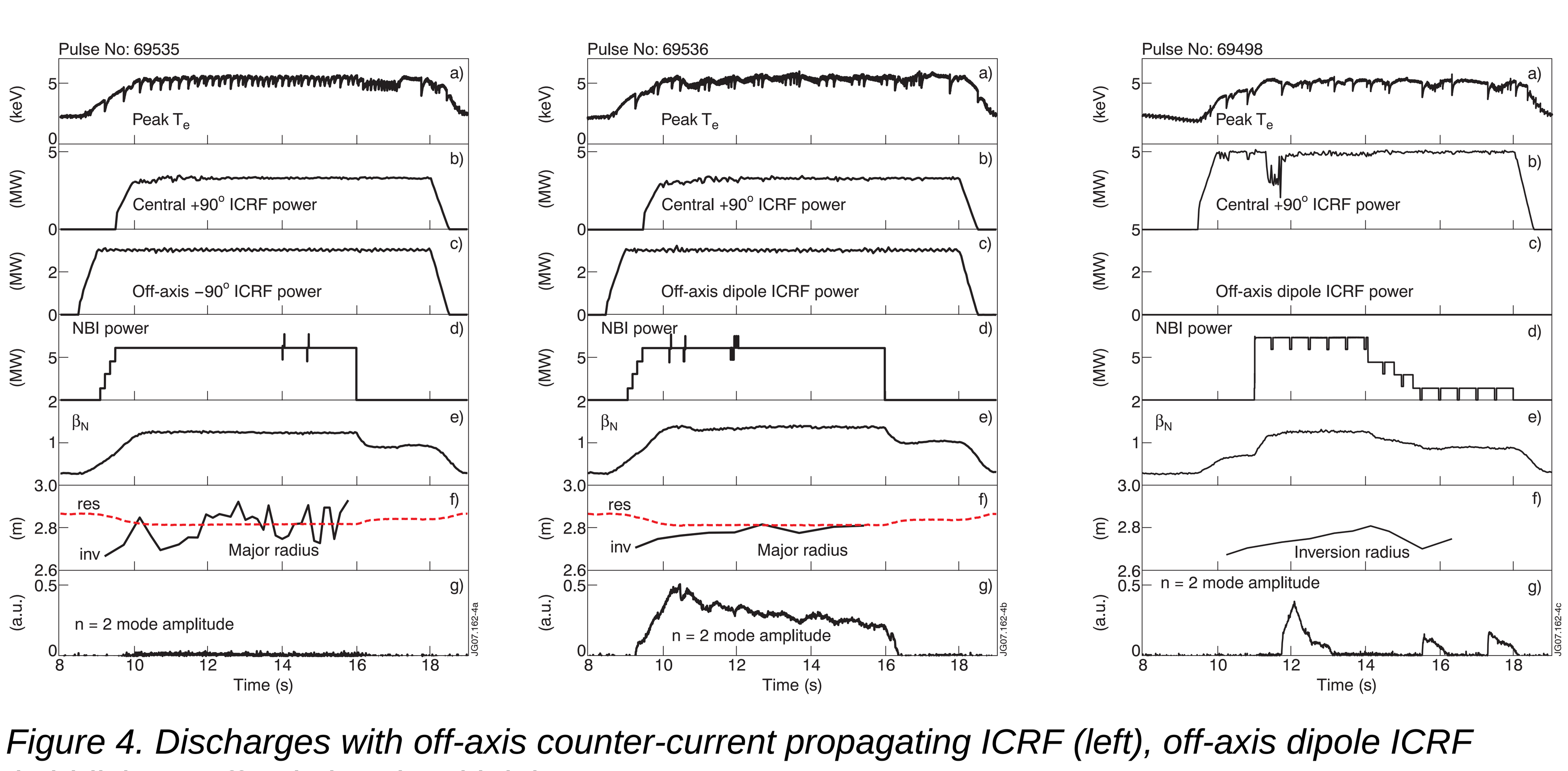

Figure 4. Discharges with off-axis counter-current propagating ICRF (left), off-axis dipole ICRF (middle), no off-axis heating (right)

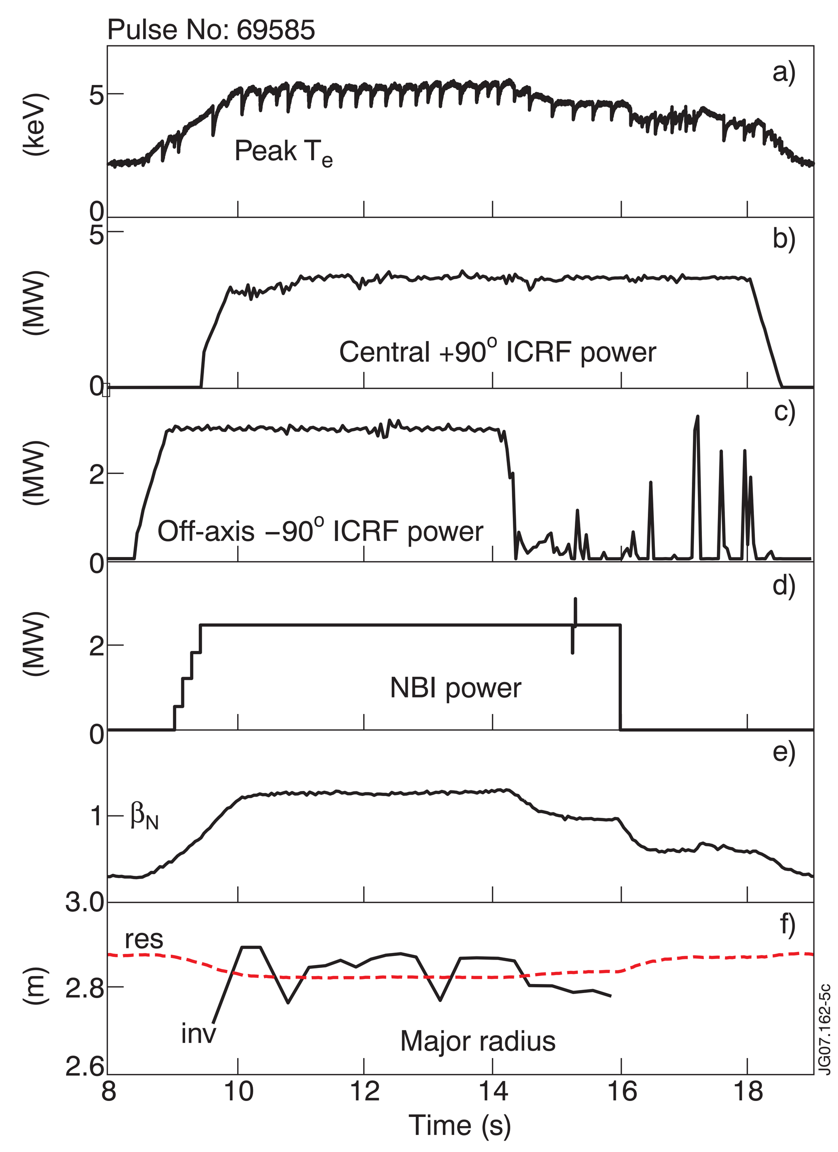

Figure 5. One-shot demonstration. The removal of the off-axis ICCD component at 54.2 s causes the sawtooth period to increase immediately

SENSITIVITY TO ICCD TUNING

- Reliable NTM prevention requires tuning the ICCD frequency with a precision of 0.5% or better (Fig. 6)
- Increase in sawtooth period when resonance moves towards centre excludes that sawtooth shortening is due to fast-ion expulsion from -90^o ICRF
- The optimum ICCD frequency will vary with plasma conditions, β_N, sawtooth period itself
- → feedback control would be desirable in a fusion reactor

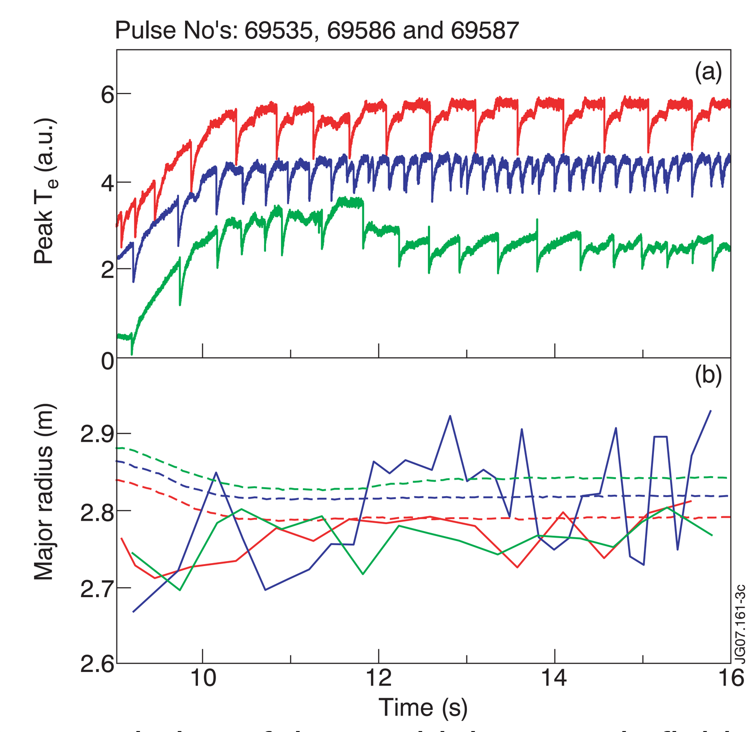

Figure 6. Comparison of three discharges differing by a variation of the toroidal magnetic field of less than 1%: the optimum for sawtooth stabilisation is the blue curve (B_T=2.83 T); the green curve corresponds to B_T=2.85 T and the red curve to B_T=2.81 T. (In (b) the solid curves represent the inversion radius, the dashed curves the resonance radius.)

- BT sweeps can help in determining optimum tuning
- However, in a dynamic situation the effect can be extremely subtle since the relative positions of the resonance and of the inversion radius can vary as plasma conditions drift (Fig. 7)
- Optimum value drifts with β_N as expected from Shafranov shift (Fig. 8)

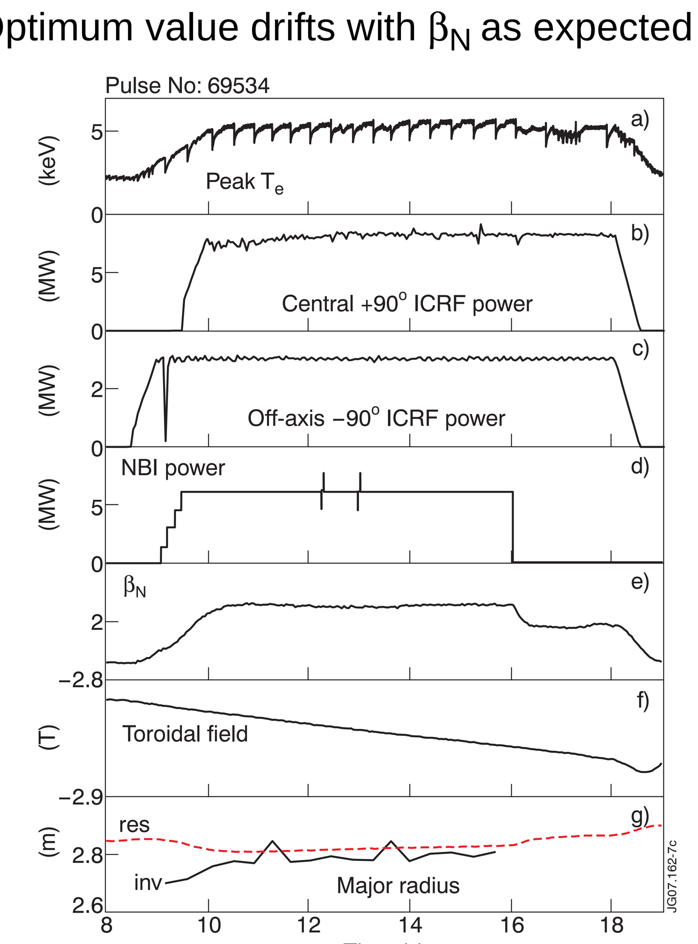

Figure 7. B_T sweep. The optimum sawtooth stabilisation field in static conditions corresponds to the value reached here at 13 s, i.e. 2.85 T

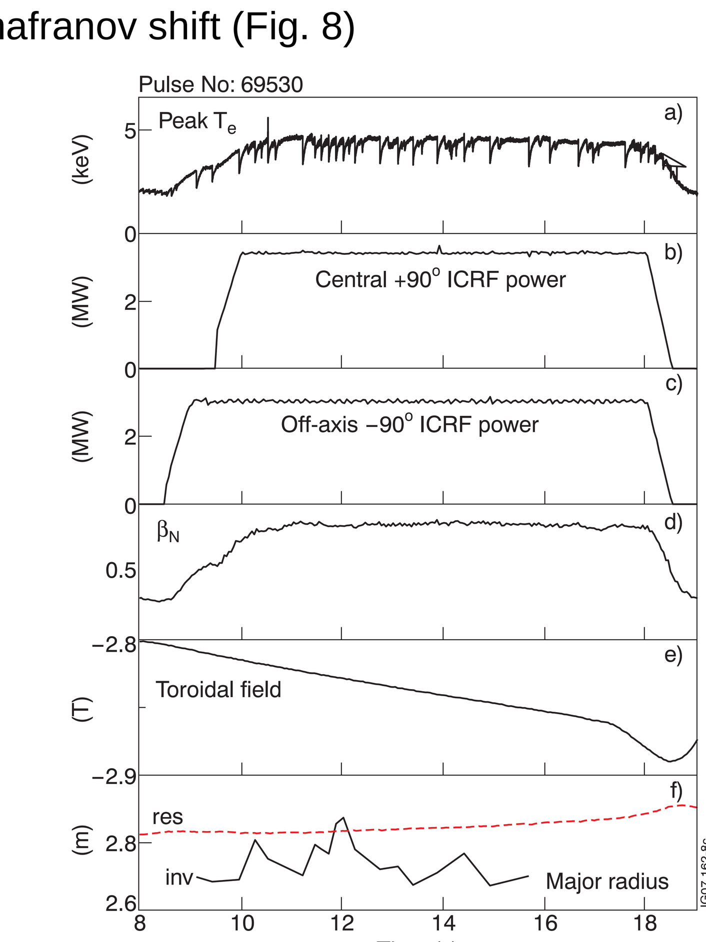

Figure 8. B_T sweep with no NBI heating. The optimum sawtooth stabilisation field in static conditions corresponds to the value reached here at 12 s, i.e. 2.83 T

MODELLING

- Transport modelling underway with a sawtooth crash model [10] using current drive density generated by SELFO Fokker-Planck Monte Carlo code [7]
- Previous analysis consistent with observed sensitivity to ICCD location: if this moves inside critical radius, ICCD contribution becomes stabilising (Fig. 9)

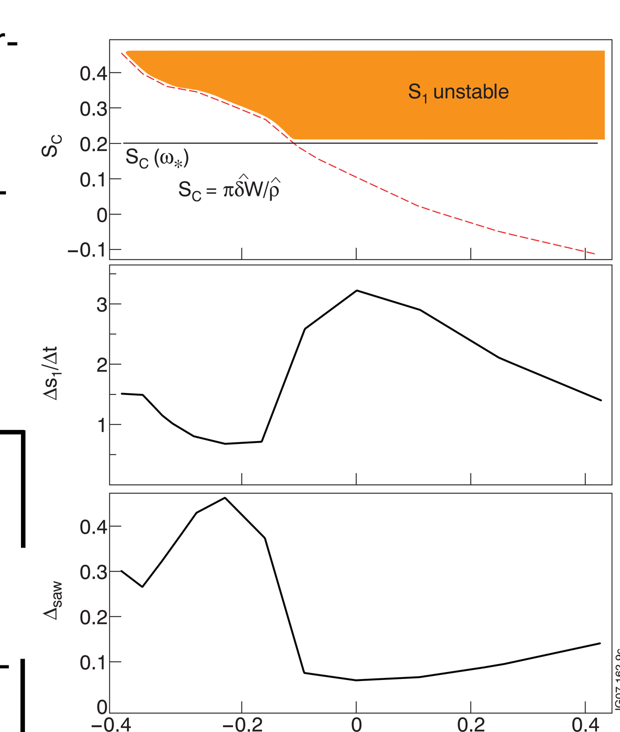

Figure 9. Modelling of shear vs. critical shear and unstable region, and of sawtooth period vs. ICCD deposition location

CONCLUSIONS

- Reliable prevention of NTMs by sawtooth period containment with off-axis ICCD was demonstrated for the first time
- The method is extremely sensitive to the ICCD frequency tuning and suggests the need for feedback control of the frequency

ACKNOWLEDGMENTS

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