Development of slow and fast wave coupling and heating from the C-stellarator to NSTX

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Development of slow and fast wave heating from the C-stellarator to NSTX

- It is informative to follow the progression of advances in applying ICRF heating on devices at PPPL over the past 5 decades
  - Model C stellarator, ST tokamak, PLT tokamak, TFTR tokamak, NSTX tokamak
  - Some key contributions from modeling, experiments and technology will be emphasized

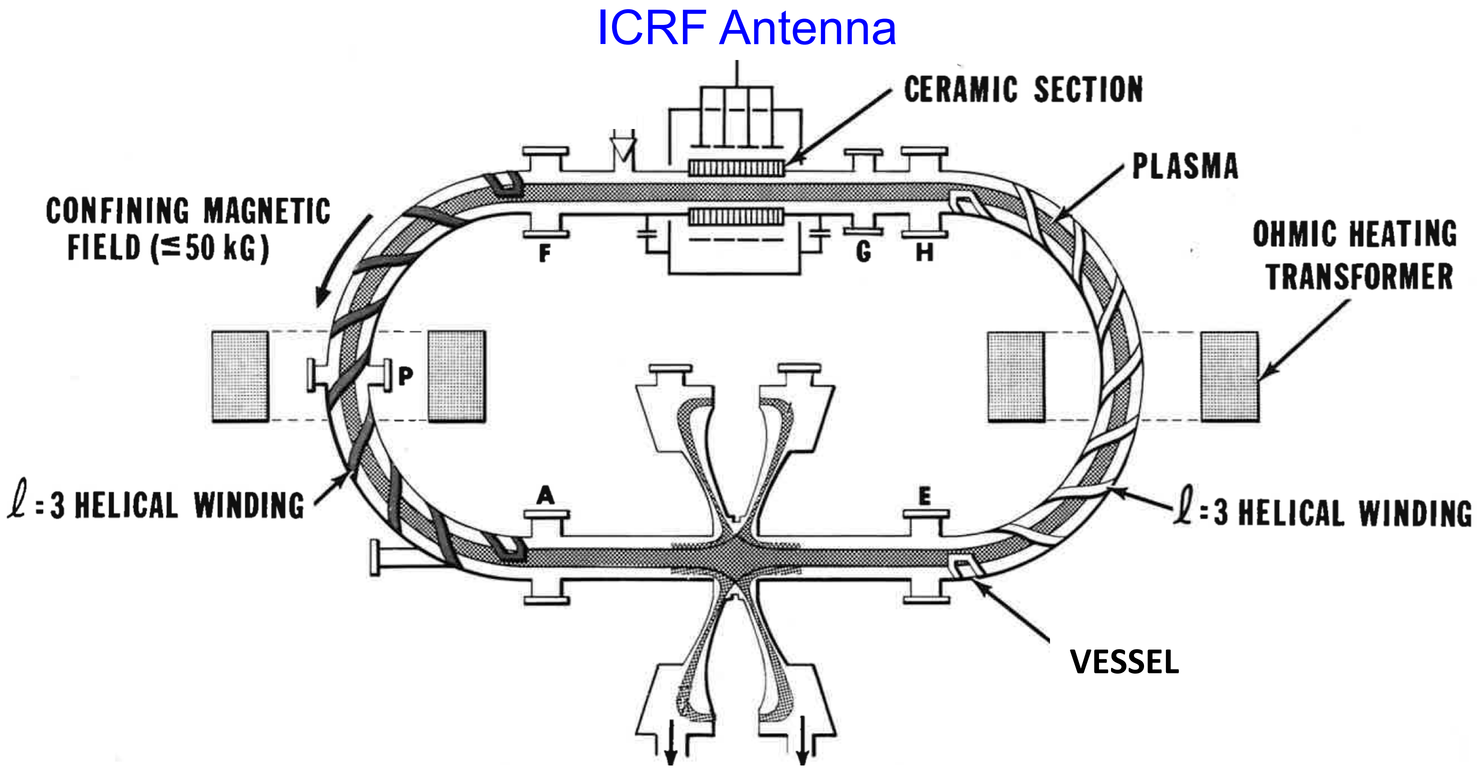
- The ICRF regime progression was
  - Slow wave with $\Omega = \omega/\Omega_{ci} < 1$
    - ➢ Model C – cylindrical geometry
  - Fast wave with $\Omega > 1$
    - ➢ ST – toroidal geometry
    - ➢ PLT – minority ion and second harmonic regimes
    - ➢ TFTR – second harmonic T regime
    - ➢ NSTX – HHFW regime

Model C Stellarator with $\Omega = \omega/\Omega_{ci} < 1$

- Alfven “resonance” shown to be a mode conversion
- Scrape off layer important here for slow wave coupling

Cylindrical straight section of Model C Stellarator ideal for studying wave coupling

Model C Stellarator

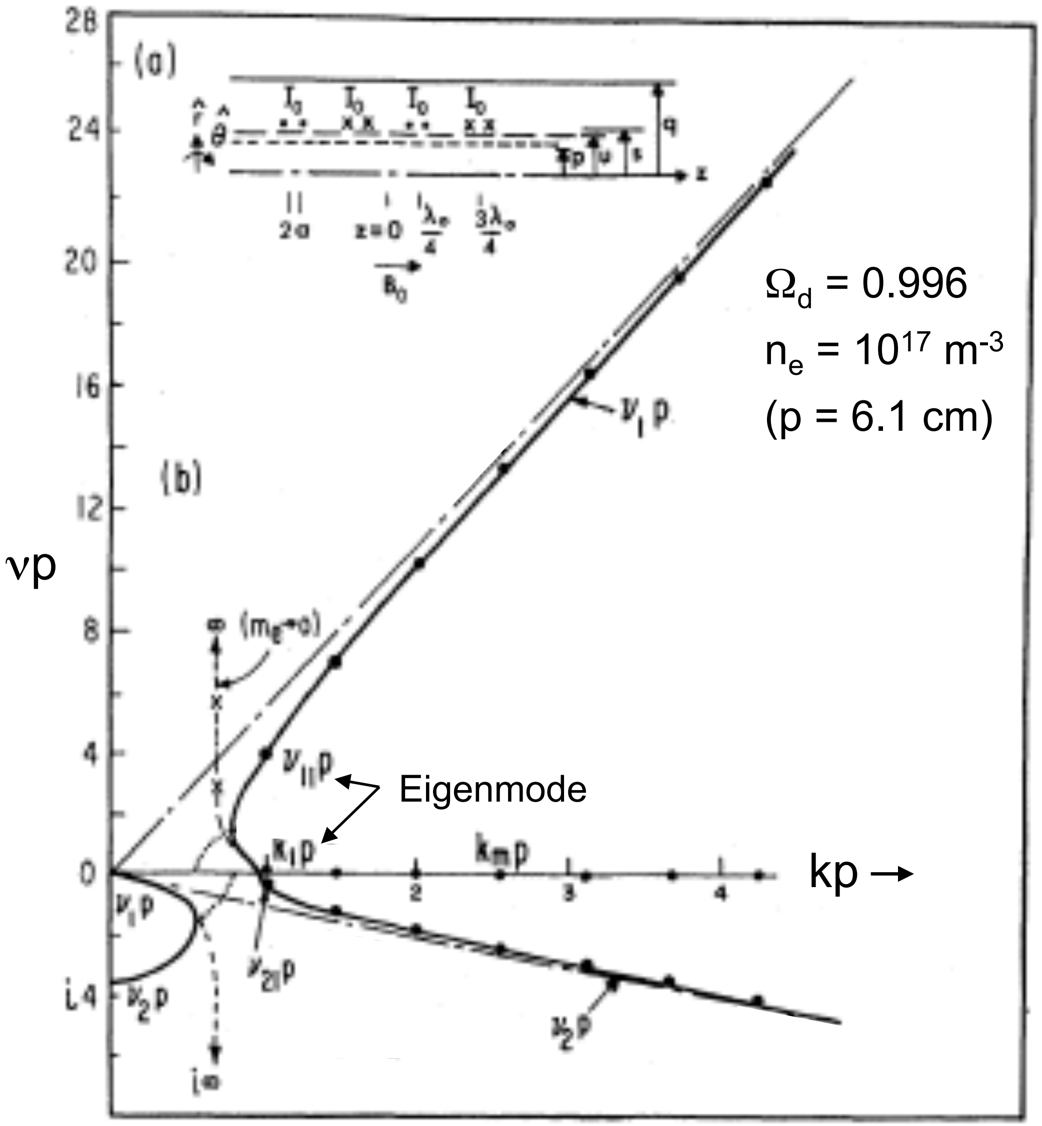


Toroidal divertor to pumps

- Quantitative comparison of coupling obtained with Faraday shield at ceramic
- Toroidal divertor provided scrape off annulus

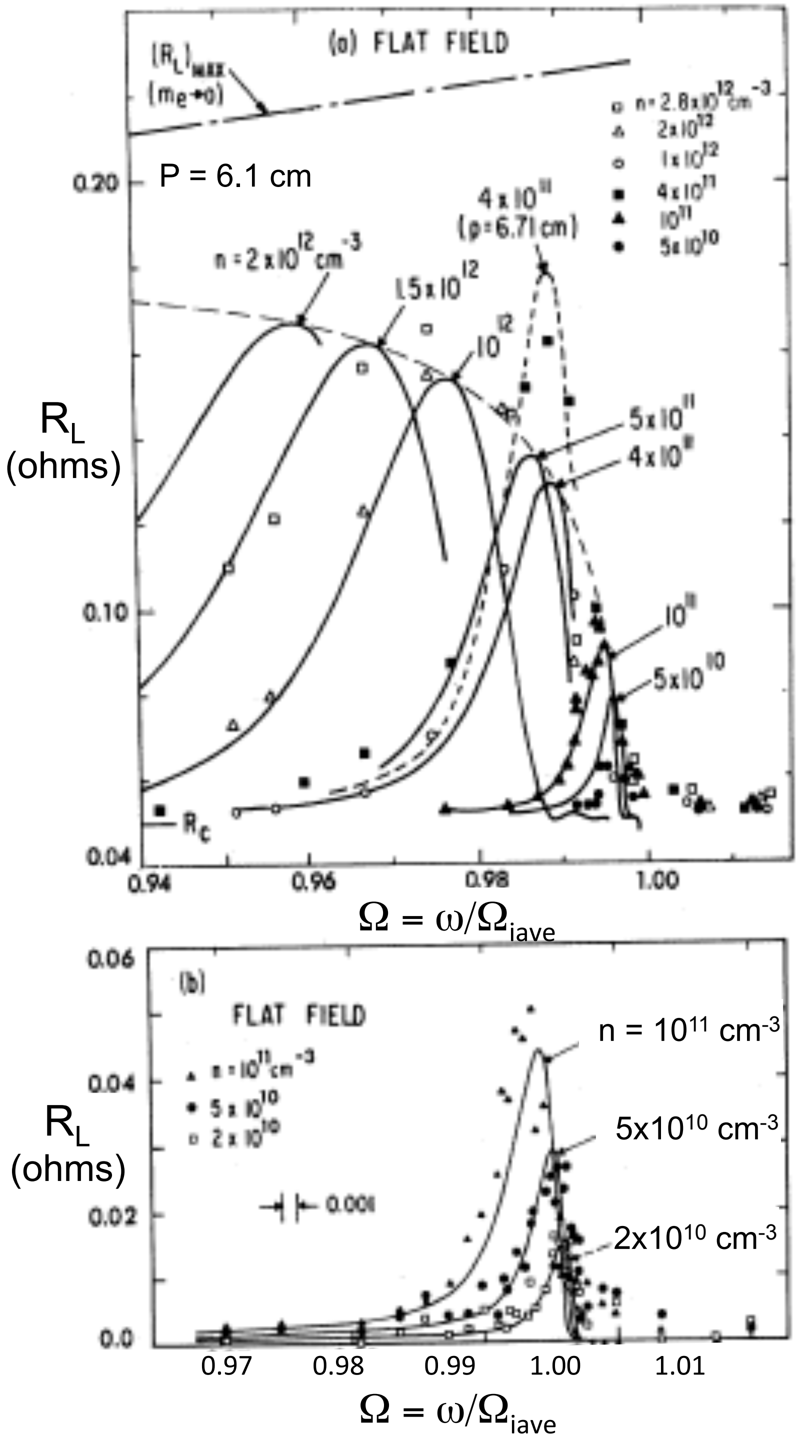
M.A. Rothman et al., *Phys. Fluids* **12**, 2211 (1969)

Alfven resonance $n_{||}^2 = S$ shown to be a mode conversion on the C Stellarator for $\Omega = \omega/\Omega_{ci} < 1$



- Cylindrical geometry on C Stellarator ideal for testing cold plasma theory
- Magnetic field flat to ~ 0.2%
- At $n_e <\sim 2 \times 10^{18}\ m^{-3}$, propagating eigenmodes on mode converted branch only – zero m_e theory omits this branch

DOMINANT INFLUENCE OF ELECTRON INERTIA ON ION CYCLOTRON-WAVE GENERATION IN PLASMA
J. C. Hosea and R. M. Sinclair *PRL* **23** (1969) 3.



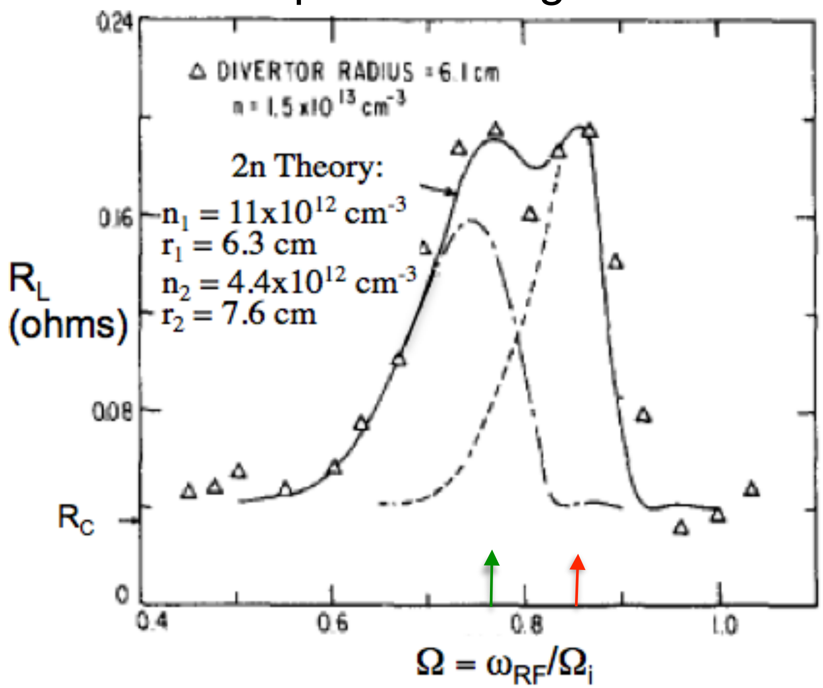
Clear experimental verification of cold plasma theory with mode conversion

- Loading follows theory with mode conversion to very low density
  - without mode conversion R_{Lmax} increases to $\omega/\Omega_{ci} = 1$
  - flat magnetic field gives good R_L match down to $n_e \sim 2 \times 10^{16}$ m^{-3}
- It is essential to include m_e terms for the shear Alfven dispersion relation
- The eigenmode approach for calculating loading is shown to be valid in this cylindrical case

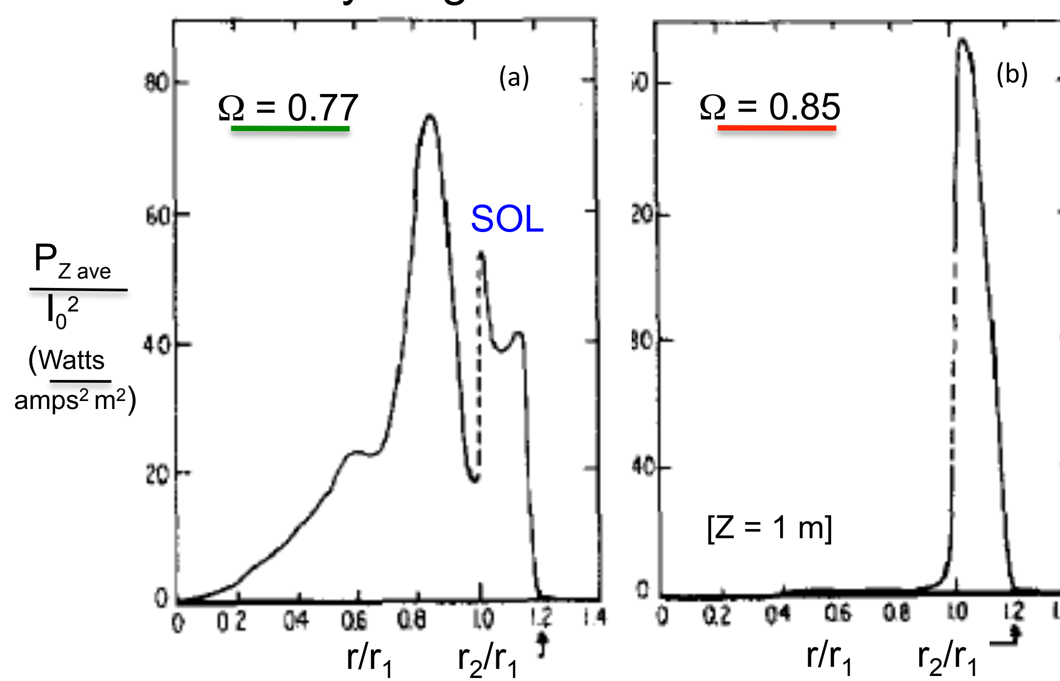
J. C. Hosea and R. M. Sinclair *PRL* **23** (1969) 3.

Annulus (SOL) density accounts for second R_L peak closer to $\Omega = \omega/\Omega_{ci} = 1$

Two peak loading vs Ω



Poynting flux at two values of Ω



- Poynting flux shows that significant RF power flows in SOL at $\Omega \sim 0.77$ and almost all the RF power flows in the SOL at $\Omega \sim 0.85$
  - Important today: can FW dispersion support large RF power flow in SOL?

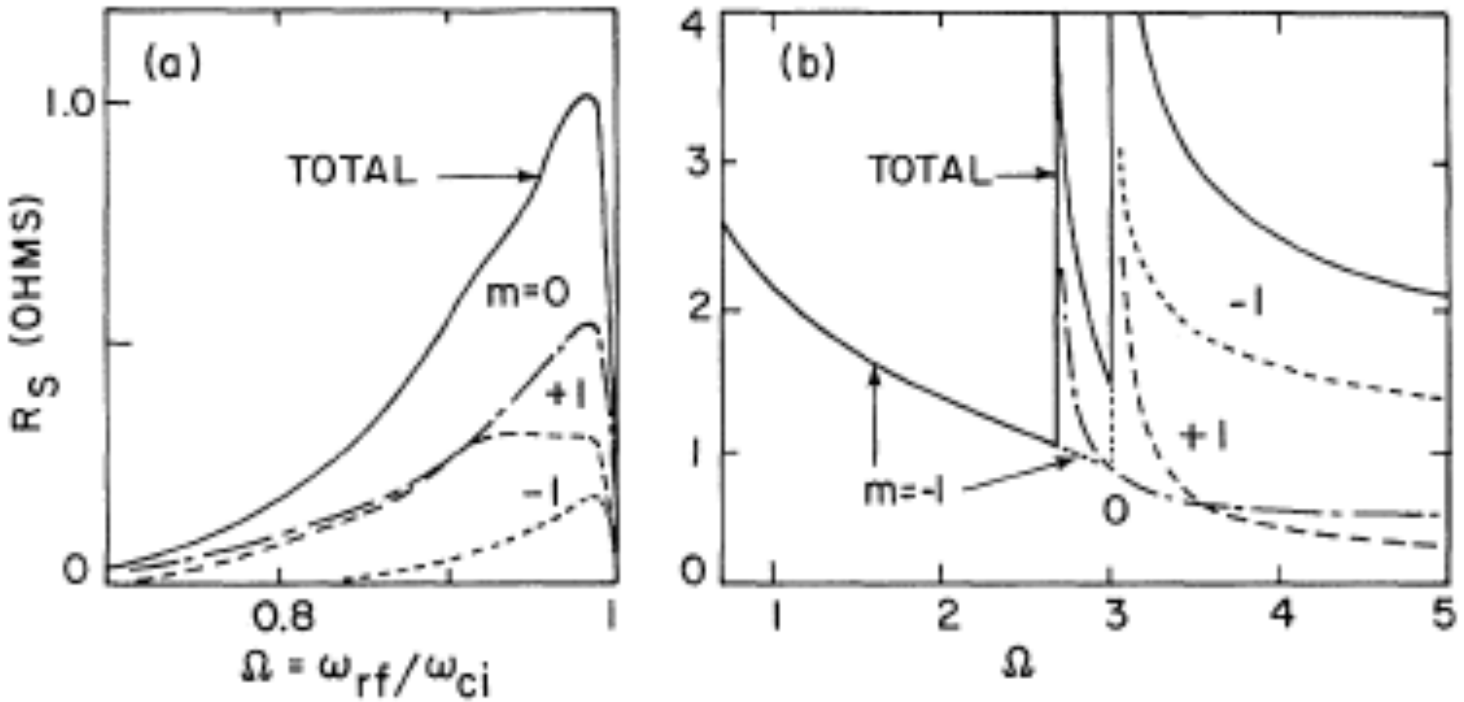
J.C. Hosea and R.M. Sinclair, *Physics of Fluids* **16** (1973) 1268

ST Tokamak: transition to toroidal geometry and fast wave excitation

- Slow and fast waves excited in cross section with damping co-located
- Cylindrical plasma model used for analysis as approximation
- Significant deuterium ion heating observed for short pulses
  - Mode Z heating resulted for longer pulses
- Two Maxwellian ion energy distribution was not understood
  - Minority ion regime was unknown

Cylindrical plasma approximation used to analyze slow and fast wave generation on the ST tokamak

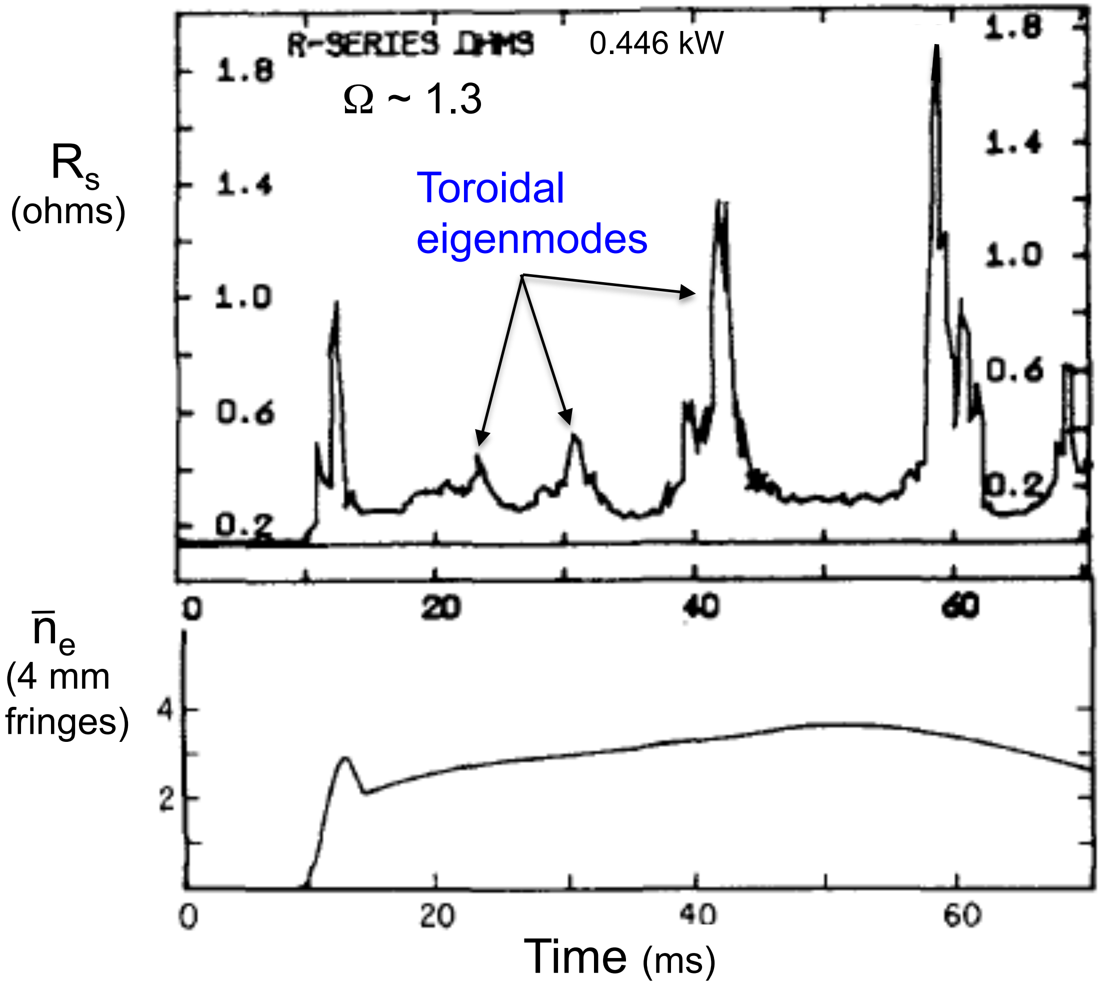
Coil loading contributions for m = 0 and m = ± 1 modes



- m = 0, +/- 1 modes predicted for slow and fast waves
- Question at the time: do toroidal eigenmodes exist in toroidal geometry?
  - that is, are modes coupled and therefore not distinct?

J.C. Hosea and W.M. Hooke, *PRL* **31** (1973) 150

Toroidal eigenmodes observed as density rose and fell

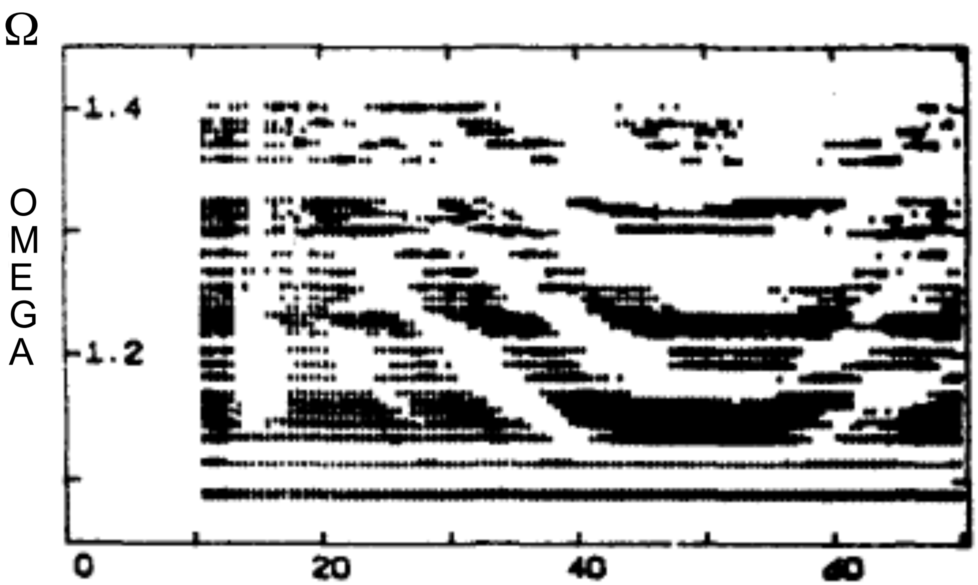


- Toroidal eigenmode observed when density passed through resonance value

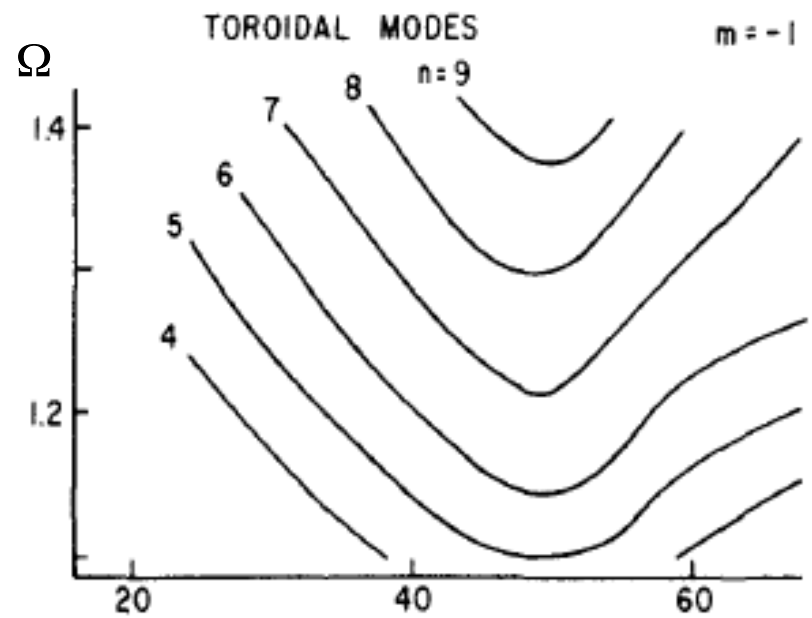
J. Adam, M. Chance, H. Eubank, et al., 5th *IAEA Fusion Energy Conf* **Vol 1**, 65 (Tokyo 1974)

Toroidal eigenmodes shown to exist in loading plot (Z amplitude modulation) in $\Omega = \omega/\Omega_{ci}$ – time space

Experiment



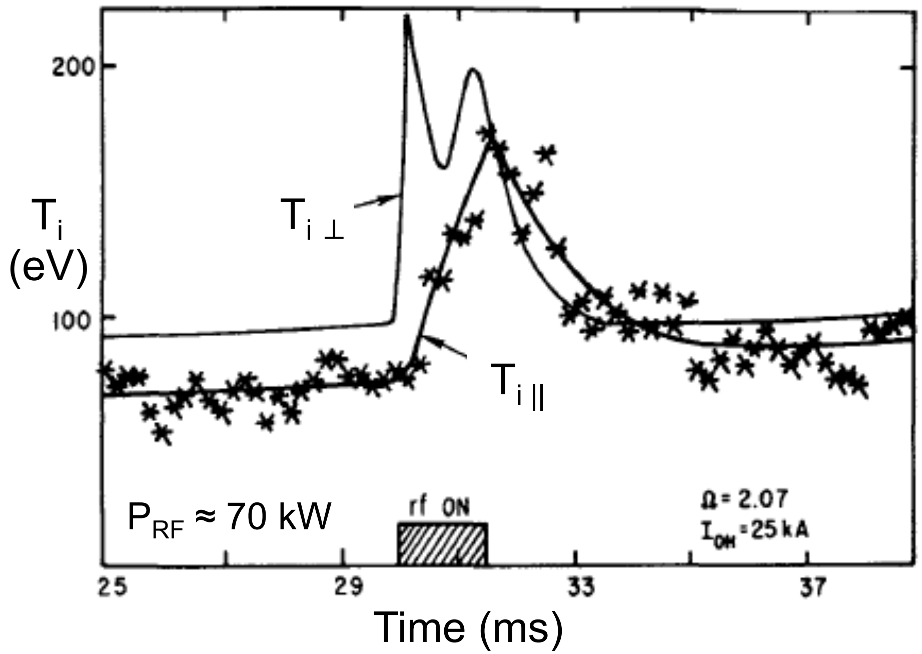
Cylindrical theory



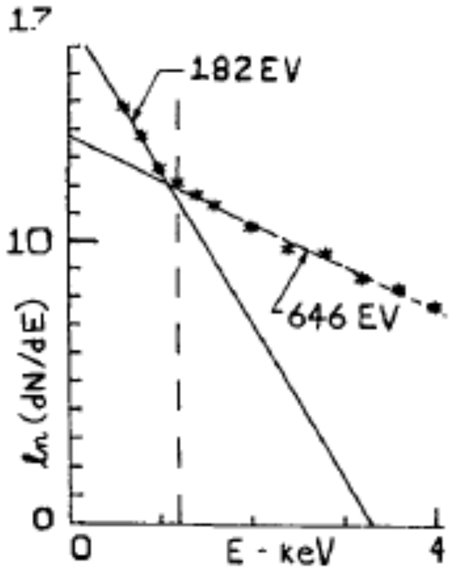
- Location of the toroidal eigenmodes in Ω – time space track the location predicted by the approximate cylindrical theory
- Time dependence comes from the density variation

J. Adam *et al.*, 5th *IAEA Fusion Energy Conf* **Vol 1**, 65 (Tokyo 1974)

Clear heating at $\Omega_d \approx 2$ with charge exchange



- Heating clear for short RF pulse (1.5 ms)
  - $T_{i\perp}$ measured near antenna
  - $T_{i\parallel}$ measured 180° around torus from antenna



- Perpendicular energy distribution was two Maxwellian
  - No mass discrimination
  - Minority heating effect unknown
  - Energetic ions poorly confined in ST

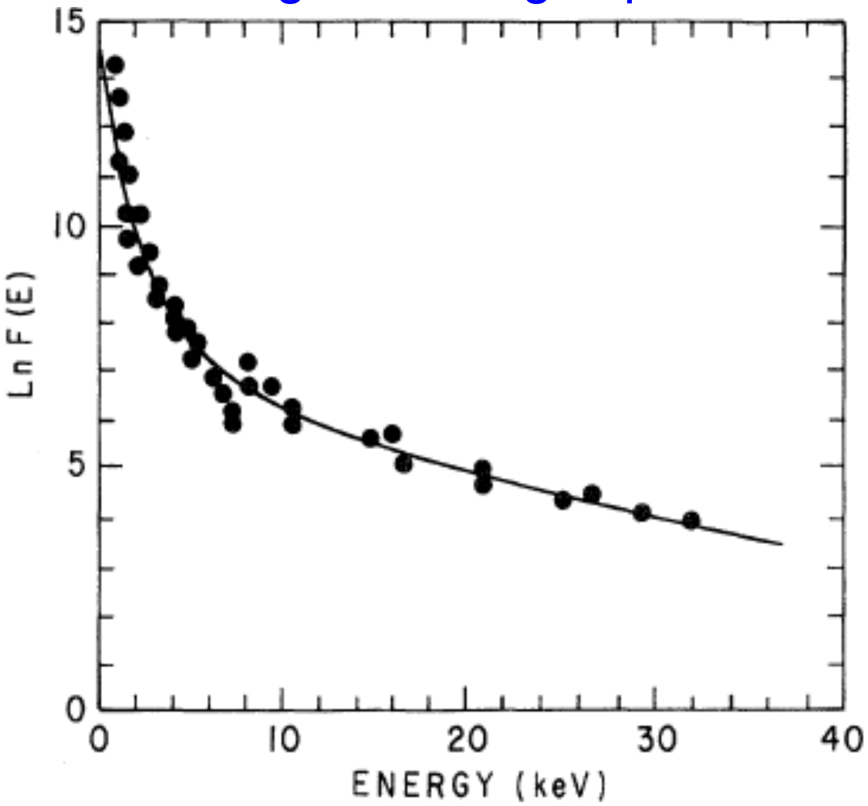
J. Adam *et al.*, 5th *IAEA Fusion Energy Conf* **Vol 1**, 65 (Tokyo 1974)

PLT tokamak: Strong heating in minority regime and in second harmonic regime

- Clear demonstration of minority hydrogen regime
  - Energetic hydrogen energy distribution explains observations on the ST tokamak
- Minority helium-3 regime established
- Alumina cone feedthrough developed for high power operation on PLT
- Second harmonic regime shown to be viable in hydrogen
  - Demonstration that the 2 Ω_T regime should be viable in a D-T plasma

Clear demonstration of two-ion minority heating regime on PLT with mass sensitive analyzer

H charge exchange spectrum



P_{RF} ~ 40 kW

D spectrum is Maxwellian
- ΔT_d ~ 100 eV

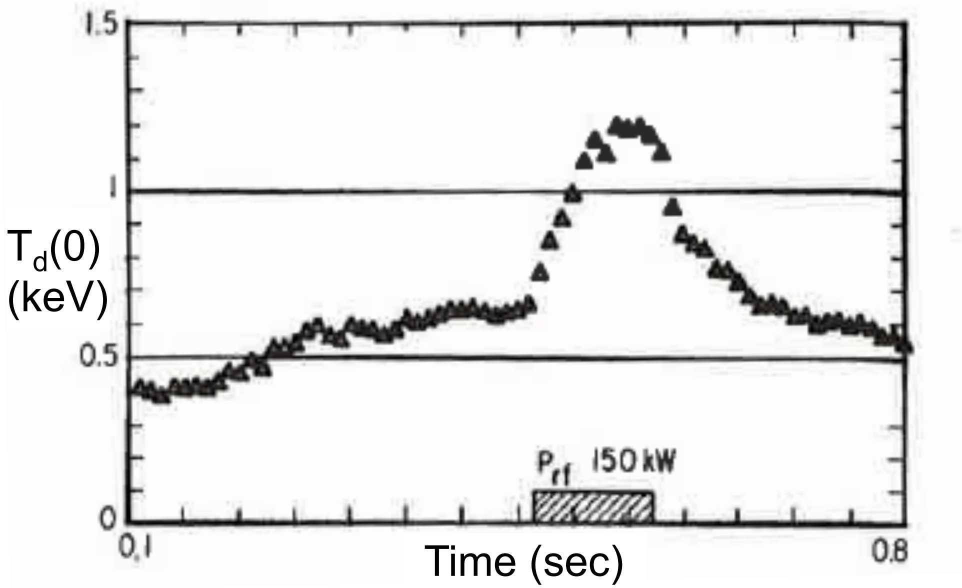
- Mass sensitive analyzer used to separate H and D charge exchange spectra – energetic H distribution explained many of the observations on ST tokamak
- The energetic hydrogen confinement is no longer affected by severe banana-orbit loss cones as on the ST tokamak

J.C. Hosea *et al.*, *PRL* **43** (1979) 1802.

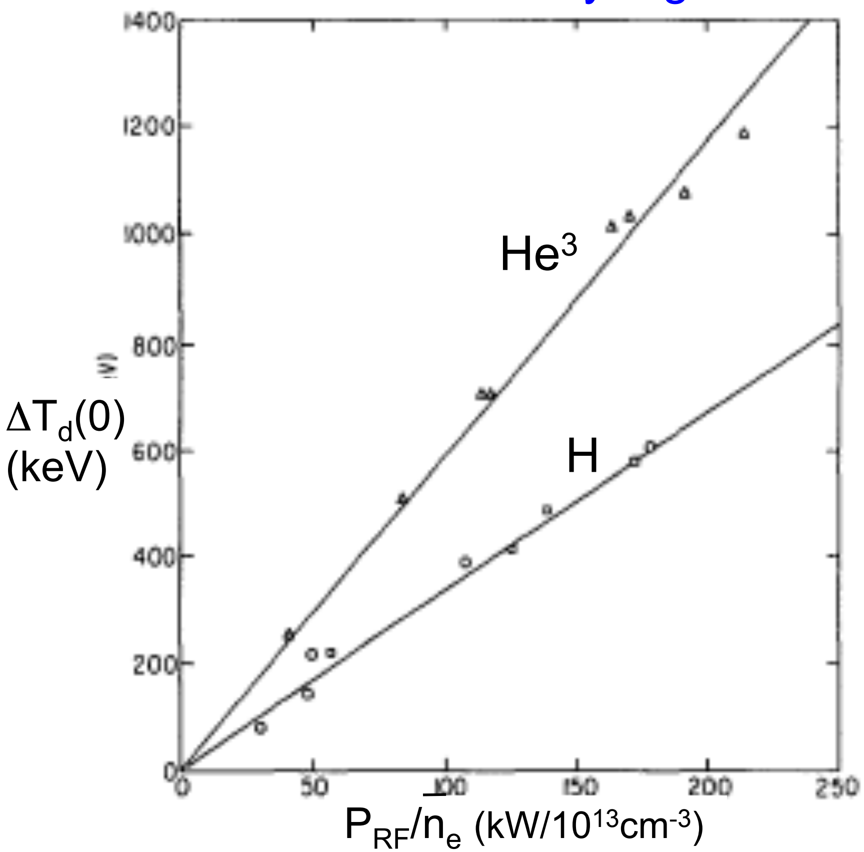
^{3}He selected as minority to optimize ICRF heating after the repair of a TF coil fault

f = 30 MHz matches f_{c3He} at B_T = 3 T

T_d versus time



Scaling of ΔT_d with $P_{RF}/\bar{n}_e$ for ^{3}He and H minority regimes

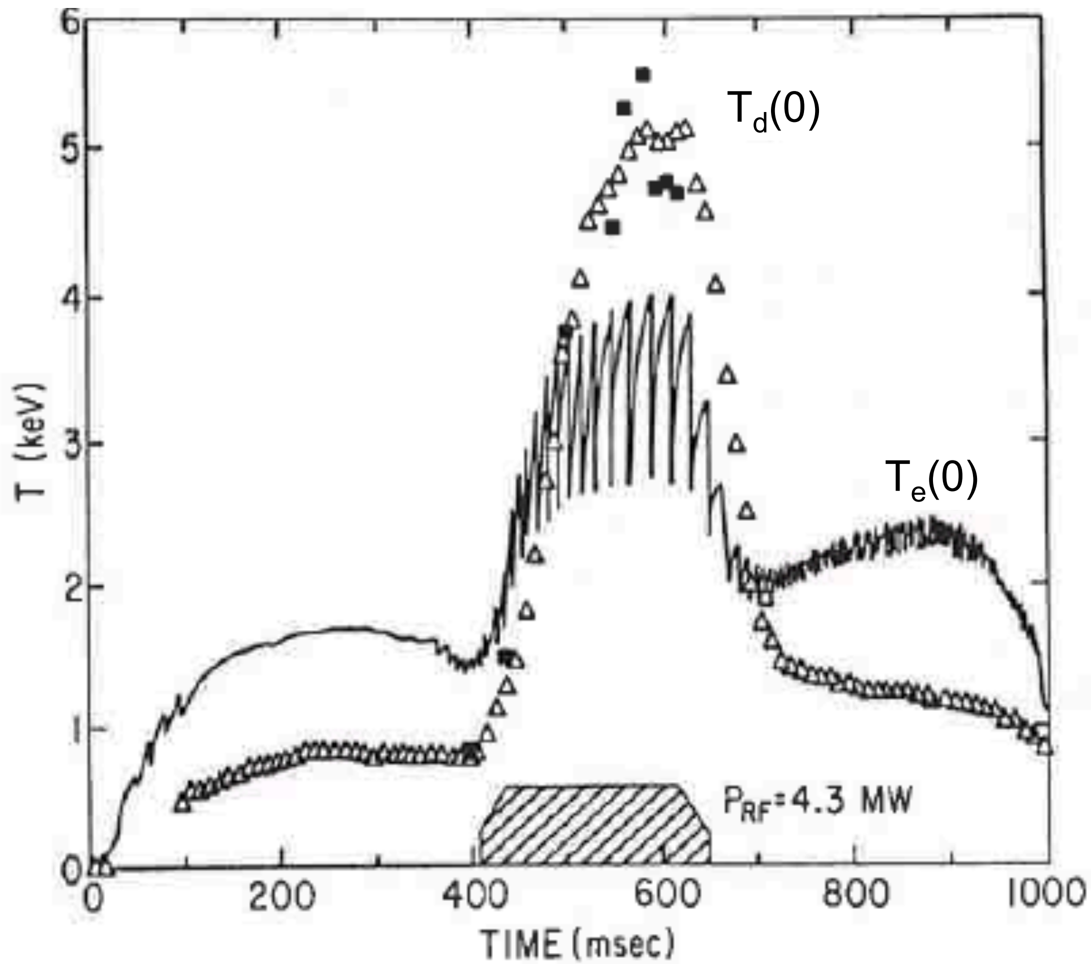


- Heating ~ 65% more efficient for He^3 minority regime than for the H minority regime

J. Hosea *et al., Physics of Plasmas Close to Thermonuclear Conditions* (Varenna 1979) p 571

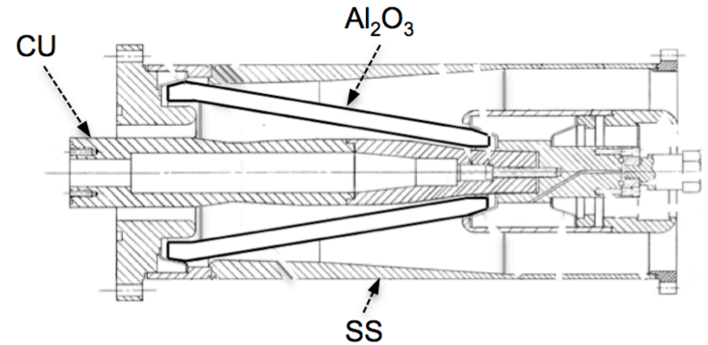
J. Hosea *et al.,8th IAEA Fusion Energy Conf*. **Vol II**, 95 (Brussels 1980)

Large heating increments for deuterium and electrons demonstrated in D-^{3}He ICRF regime on PLT



P_{RF} = 4.3 MW, f = 30 MHz, B_T = 3.3 T,
$\overline{n}_e$ = 3.7 x 10^{13} cm^{-3}, η_{3He} ≅ 5 – 10%

- Development of feedthrough permitted P_{RF} ~ 5 MW operation



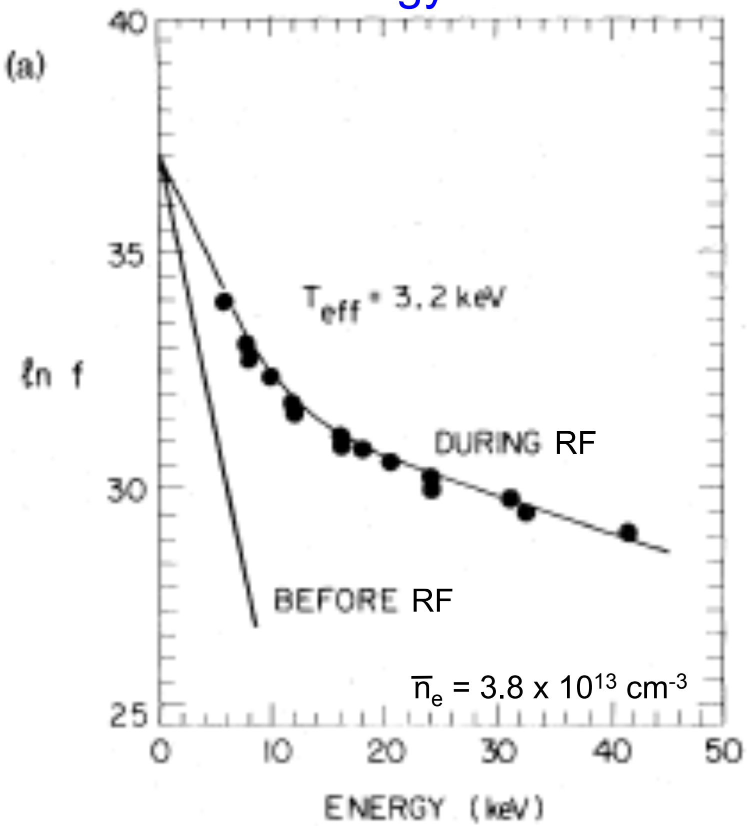
D.Q. Hwang, et al., J. Vac. Sci. and Tech. **28**, 1273 (1982)

- ^{3}He ions well confined on PLT
- Very large sawteeth produced in T_e

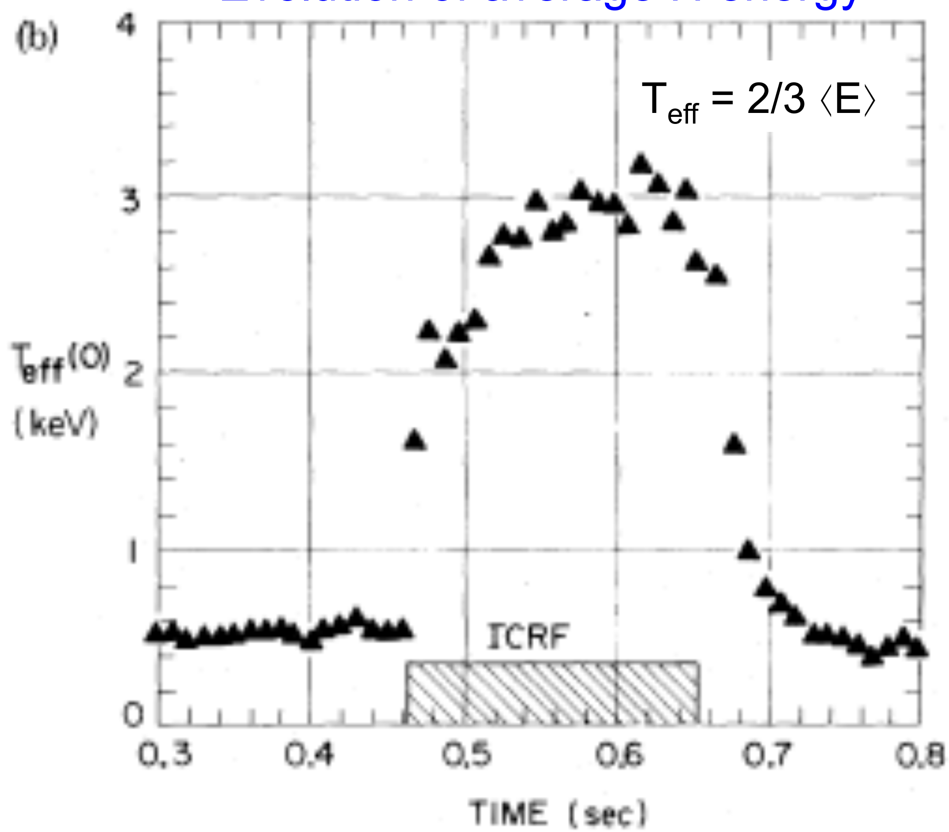
J.R. Wilson, *6th Topical Conference on RF Plasma Heating, AIP* **129**, 28 (Callaway Gardens1985)

Second harmonic H regime demonstrated at P_{RF} ~ 1 MW on PLT

H ion energy distribution



Evolution of average H energy



- Important for showing that 2 Ω_T should be viable for the D-T plasma regime

D.Q. Hwang *et al., PRL* **51**, 1865 (1983)

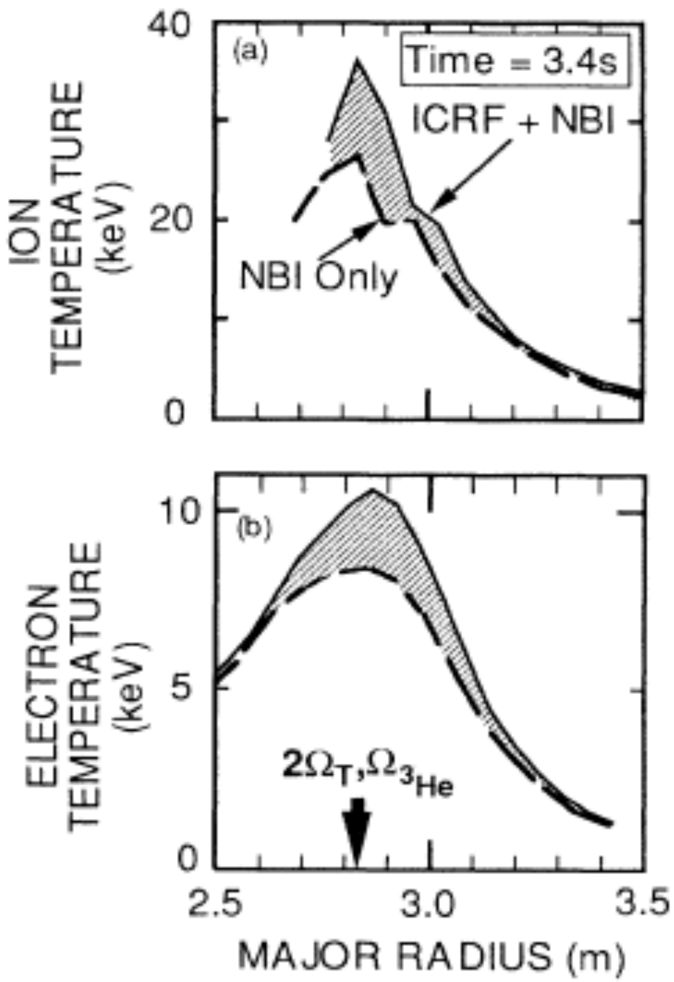
TFTR tokamak: Second harmonic T regime demonstrated

- Strong ICRF ion and electron heating at $2\Omega_{CT}$ on TFTR

2^{nd} Harmonic Tritium Regime Demonstrated On TFTR

$2\ \Omega_{cT}$ ICRF heating is shown here for the hot ion mode

- Case of P_{RF} = 5.5 MW with P_{NBI} = 23.5 MW (60% in T)
- 2 x Ω_{cT} majority heating
- 2% ^{3}He minority fundamental heating assist
- $\Delta T_i(0)$ = 9 keV and $\Delta T_e(0)$ = 2.6 keV with P_{RF}



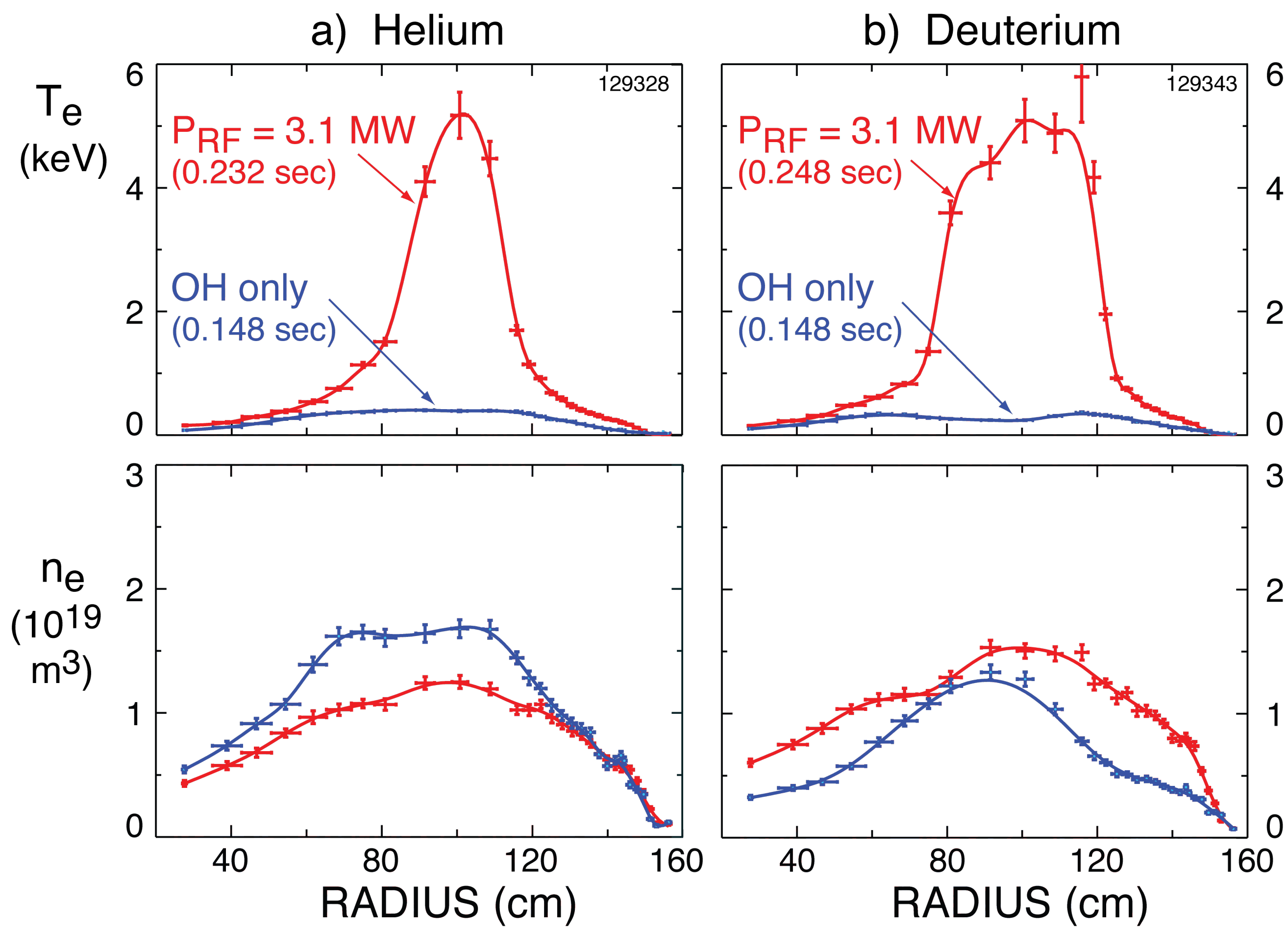
- Ion and electron temperature profiles show strong ICRF central ion and electron heating at $2\Omega_{CT}$ on TFTR

J.R. Wilson *et al., PRL* **75**, 842 (1995)

NSTX tokamak: Transition to high harmonic fast wave (HHFW) regime and close examination of SOL losses

- Strong electron heating with low edge density
- Spiral heat loss pattern on divertor along with strong RF fields in the SOL
- The spiral is attributed to RF rectification of fast-wave far fields

HHFW electron heating for -90° current drive phasing is substantial at low edge density

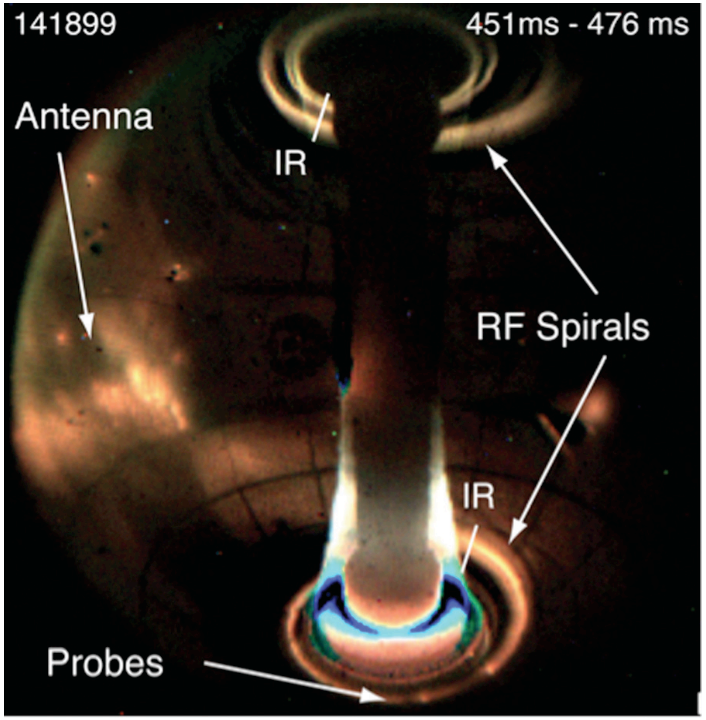


- $T_e(0)$ of ~ 5 keV produced in He and D_2

G. Taylor et al., *18th Topical Conference on RF Plasma Heating, AIP* **1187**, 113 (2009)

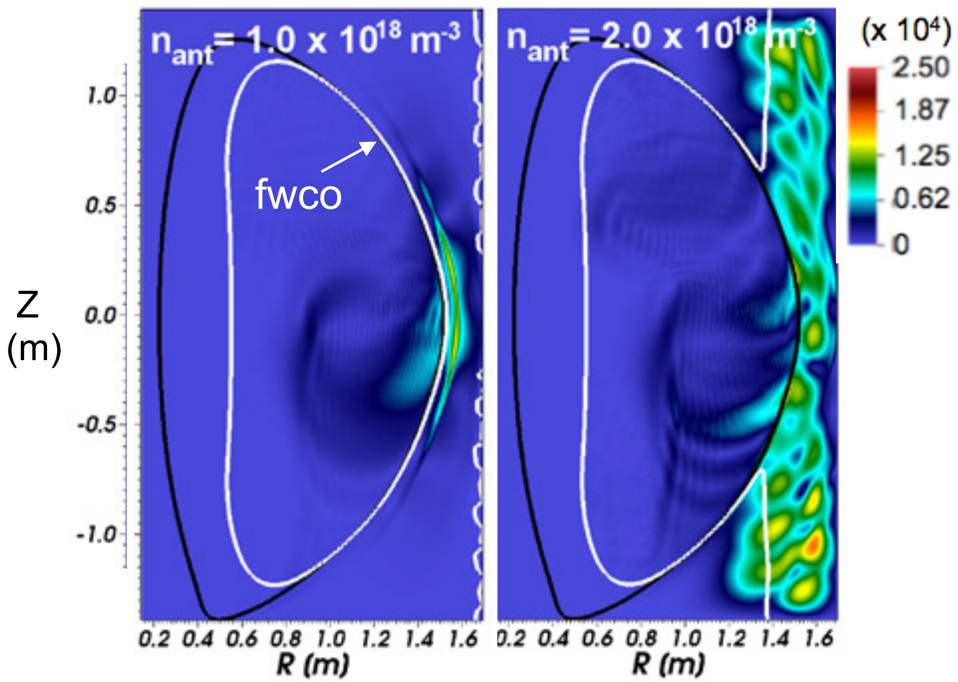
Surprising RF power loss to divertor via SOL observed

Camera view of RF heat spirals



R.J. Perkins, et al., *Phys. Plasmas* **22**, 042506 (2015)

AORSA modeling of RF fields vs density at antenna for $n_{\phi} = -21$

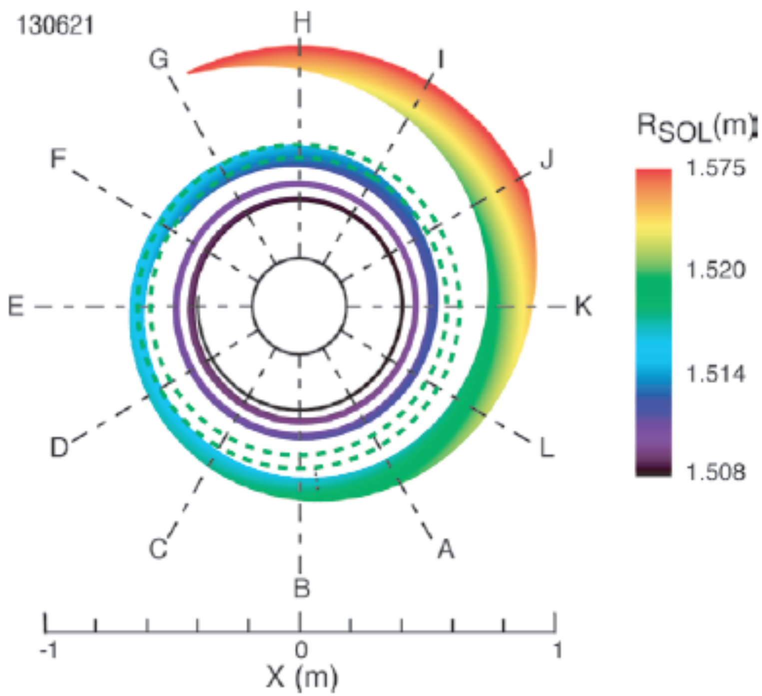


N. Bertelli, et al., *Nucl. Fusion* **54**, 083004 (2014)

- Spiral heat patterns are consistent with enhanced FW RF fields predicted in the SOL with AORSA when the density in front of the antenna exceeds the fast wave cutoff density

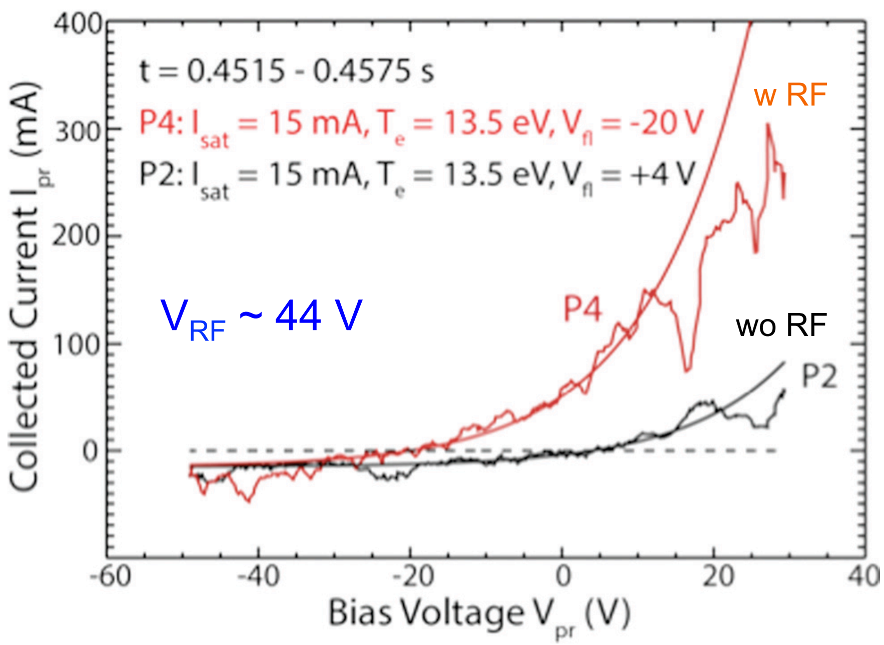
Far RF field rectification at magnetic field strike points appears to be responsible for energy deposition at the divertor spiral

RF heat spiral follows strike points for field lines in front of antenna across the SOL



R.J. Perkins, et al., *Nucl. Fusion* **53**, 083025 (2013)

RF far field rectification is indicated by the negative voltage shift of the I-V probe characteristic under the spiral



R.J. Perkins, et al., *Phys. Plasmas* **22**, 042506 (2015)

(141899 P_{RF} = 1.3 MW)

Summary

- A historical perspective of advances in understanding ICRF coupling and heating over the past 5 decades on devices at PPPL has been outlined for the C- stellarator, ST, PLT, TFTR and NSTX
  - Some key contributions from modeling, experiments and technology have been emphasized

- Going forward we plan to quantify the far field RF rectification contribution to the deposition on the divertor on NSTX-U by measuring the RF field directly

- We also plan to begin design of more optimized antennas to minimize SOL losses overall
  - Designs of particular interest are
    - ✧ The field aligned antenna on C-mod
    - ✧ The three strap antenna on ASDEX-U