Temperature Anisotropy and Rotation Upgrades to the ICRF Modules in SNAP and TRANSP

by

David N. Smithe
MISSION RESEARCH CORPORATION

Presented at:
ICRF Modelling and Theory Workshop
Princeton Plasma Physics Laboratory
Princeton, NJ 08543
August 17-18, 1992

Work supported by DOE Contract #DE-FG05-91ER54129.
Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
OVERVIEW

Two new physics capabilities have been added to the RF modelling modules in SNAP and TRANSP, (and also the stand alone RF modelling code).

The new features are: Temperature Anisotropy ($T_\perp$ and $T_\parallel$), and Plasma Rotation ($V_z$).

TFTR diagnostics have the ability to measure these quantities, and SNAP and TRANSP included these effects in their transport calculations but the RF modules did not use them until now.

2&3D RF modelling codes

SNAP
STAND_ALONE
ARCH_SNAP

ICRF_HEATER
(SHOOT)
r: shooting method
$\theta$: mode expansion

TRANSP

FPP
SPRUCE
r: finite difference
$\theta$: psuedo-spectral

Information Exchange between transport and RF modelling codes

$P_{rf}, U_{rf\perp}, U_{rf\parallel}$

$\rho, T_\perp, T_\parallel, V_z$
OBJECTIVE

Fokker-Plank and transport codes have significantly better velocity-space treatment of the plasma than do the RF deposition models:

- FPP uses a 2 or 3D velocity space calculation,
- TRANSP uses Monte-Carlo particles, e.g., 3D in velocity space,
- Many 2 and 3D spatial RF deposition codes are based on Maxwellians, with a single velocity-space parameter, i.e., the isotropic temperature.

The ultimate goal of this effort was to provide the deposition codes with better velocity-space physics. For ICRH heating on TFTR, two important physics issues are velocity-space anisotropy (because of high energy tails), and plasma rotation (because of simultaneous NBI-RF heating). In addition, these two physical effects are among the suite of experimentally measurable quantities, and most of the required new formulas already exist in the literature.

IMPORTANCE OF TEMPERATURE ANISOTROPY

From the linear dielectric:

- Width of resonance zone depends on $T_{\parallel}$ only.
- 2nd harmonic term is proportional to $T_{\perp}$ only [for $(k_{\perp} \rho_{L})<1$].

In RF heated plasmas with high energy tails $T_{\perp}/T_{\parallel}=10^3$.

IMPORTANCE OF ROTATION

- In unbalanced co- or counter- NBI heated plasmas, $V_{\text{rot}} \approx V_{\text{therm}}$.
- When $V_{\text{rot}} \approx V_{\text{therm}}$, the resonance zone is shifted right or left by approximately its own thickness, for fixed $k_z$. But the shift is in the opposite direction for the opposite sign of $k_z$, so the full-spectrum resonance zone thickness approximately doubles or triples in size.
Splitting and Widening of Resonance Layer for Rotating Plasma

Resonance with $V_e=0$

Resonance with $V_e \neq V_{\text{therm}}$
FORMULAS

Formulas for the upgraded linear plasma dielectric exist in at least two sources:
1) "Hot Plasma in a Cylindrical Waveguide," by D. Gary Swanson, *Physics of Fluids* 10 (1967), pg. 428, and
These two references agree, to within a single typo...see next pages.

COMPUTATIONAL ISSUES

Manipulations allow formulas to be put in a relatively simple form, which uses a similar factor for all tensor elements. In general, the form chosen is that of Swanson, since it is more compact, and does not assume anything about the direction of $k_L$. Some manipulations were also performed to prevent forms which produced cancellations of large terms in a sum.

SPRUCE IMPLEMENTATION

Because SPRUCE is married to the FPP Fokker-Plank code, it only provides a raw power deposition profiles (FPP does the stored-energy calculation). Hence, only the linear dielectric tensor subroutines needed to be changed.

ICRF_HEATER (SHOOT) IMPLEMENTATION

Unlike TRANSPI, the RF deposition code in SNAP must also calculate the stored energy. It performs a STIX slowing-down calculation, as in *Nuclear Fusion* 15, 1975, pg. 737. New features added include:

1) Estimate of perpendicular-to-parallel energy in the tail based on $\tau_{\text{pitch}}/\tau_{\text{slow}}$.
2) Mirror-force conversion of $U_\perp$ to $U_\parallel$, for SNAP pressure balance,
3) Trapped-particle effects (restricted poloidal extent) for feature #2.
ANISOTROPIC TEMPERATURE EXAMPLES

Plasma: \( n_e = 5 \times 10^{13} \text{ cm}^{-3} \)
3\% H - 97\% D
\( T_{\text{plasma}} = 5 \text{ keV} \)
\( P_{\text{rf}} = 3 \text{ MW} \)
\( f_{\text{rf}} = 47 \text{ MHz} \)
\( \delta_{\text{shaf}} = 15 \text{ cm} \)
\( q = 1 \rightarrow 5. \)

Figure 1: Without Anisotropy, Inside Resonance.
- \( U_\perp/U_\parallel = 2. \)
- Stored energy contributes an additional peak of 1 keV to \( T_{\text{plasma}}. \)

Figure 2: With Anisotropy, Inside Resonance.
- Narrower profile, because \( U_\perp \) does not contribute as much to \( T_\parallel. \)
- Narrower profile, also means that stored energy contributes an additional peak of 5 keV to \( T_{\text{plasma}}. \)
- \( U_\perp/U_\parallel = 1000 \) at the resonance layer, but \( U_\perp/U_\parallel = 15 \) when poloidally averaged to take into account the mirror force conversion of \( U_\perp \) to \( U_\parallel. \)

Figure 3: With Anisotropy, Outside Resonance.
- No mirror forces, \( U_\perp/U_\parallel = 700 \) for hydrogen, since energy stored in trapped particles at their banana tips.
- But \( U_\perp/U_\parallel = 2 \) for small Deuterium tail, though, because at low energies \( \tau_{\text{pitch}} \) and \( \tau_{\text{slow}} \) are comparable.

ROTATION EXAMPLE

Same plasma as above, except with a rotation velocity \( V_z = V_{\text{therm}} \),
and single \( k_z = +7 \text{m}^{-1}. \)

Figure 4: With and Without Rotation.
- Resonance layer is shifted by roughly its own thickness.
Figure 1. A typical run without the anisotropic temperature upgrade.

Exactly Z for an isotropic plasma.

The ratio of $U_{\text{step}}$ (plot (b)) to $U_{\text{prf}}$ (plot (c)) is $\frac{U_{\text{step}}}{U_{\text{prf}}}$.

(c) radial profile of parallel stored energy.
(b) radial profile of perpendicular stored energy.
(a) contour plot of R-wave deposition.
Figure 2. Same run as in Figure 1, but with anisotropic temperature.

a) contour plot of RF wave deposition,  
b) radial profile of perpendicular stored energy,  
c) radial profile of parallel stored energy.

The ratio of $U_{\text{perp}}$ (plot b) to $U_{\text{par}}$ (plot c) is raised for an anisotropic plasma.

The power deposition profile is narrower because the effective tail parallel temperature is not artificially raised as in the isotropic case.
Figure 3. Run similar to Figure 2, except that the resonance is placed outside the magnetic axis.

a) contour plot of RF wave deposition,
b) radial profile of perpendicular stored energy,
c) radial profile of parallel stored energy.

The ratio of $U_{\text{perp}}$ (plot b) to $U_{\text{par}}$ (plot c) is greatest for resonance outside the magnetic axis, since there is little mirror effect to convert $U_{\text{perp}}$ to $U_{\text{par}}$.

The 2nd harmonic deuterium tail is very nearly isotropic because the small amount of power absorbed leads to low tail temperatures with nearly identical pitch angle scattering and slowing down collision rates.
Figure 4. Two runs showing the effect of plasma rotation with $\Lambda = z \Lambda_0$ in (b) without rotation, and $\Lambda$ with (a) rotation. The resonance layer is shielded by roughly its own thickness.
CONCLUSIONS

- Temperature Anisotropy and Rotation have been added to the RF packages in SNAP and TRANSP.

- Test runs to verify the physics have been performed.

- The SNAP model distributes the tail stored energy based on slowing-down and pitch-angle scattering rates.

- The SNAP model also includes mirror-force and trapped particle effects, to properly distinguish between inside and outside location of the resonance layer.