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ICRF-Induced Fusion Product Loss in TFTR,*

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Abstract

When ICRF power is applied to plasmas in which there is no externally-supplied minority species, an enhanced loss of DD fusion products results. The characteristics of the loss are consistent with particles at or near the birth energy having their perpendicular velocity increased by the ICRF such that those near the passing/trapped boundary are carried into the first orbit loss cone. A rudimentary model of this process predicts losses of a magnitude similar to those seen. Predictions based upon this data for hypothetical ICRF ash removal from reactor plasmas suggest that the technique will not be energy efficient.

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There are several ICRF configurations on TFTR

- 4 antennae
- Up to 12 MW available
- 47 MHz (1992) (now 43 & 64 MHz)

Modes of operation:

•H-minority

-B_T= 3.4 T

- 1–5% H in D or ^{4}He plasmas

-Resonance layer on axis

• ^{3}He minority

-B_T= 4.6 T

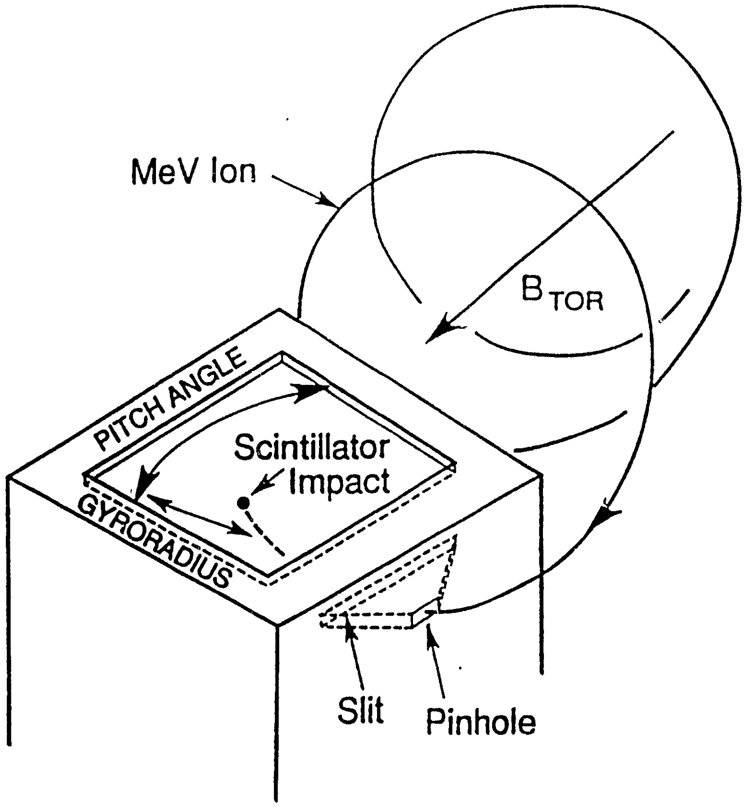
- 1–5% ^{3}He in D plasmas

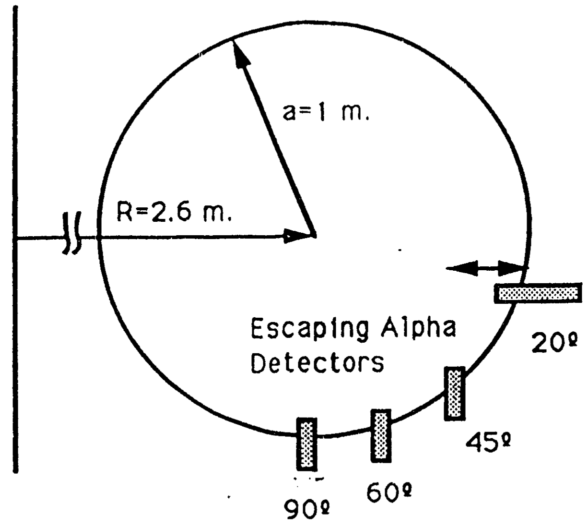
-Resonance layer on axis

•No minority species

-Same as ^{3}He minority condition, but no ^{3}He injected

"Escaping Alpha" detectors can measure ICRF tail ion loss and ICRF-induced fusion product loss





•Detectors below midplane at 20°, 45°, 60°, & 90°

•Detectors act as magnetic spectrometers, dispersing fast ions by gyroradius (energy) and pitch angle onto scintillator

•Photomultipliers and intensified videocamera record magnitude and characteristics of loss

•Thin foils over apertures (except 20° probe) set lower limit on energy accepted: $E \geq 300$ keV for H, D, or T; $E \geq 900$ keV for ^{3}He or α

Fusion Product Loss is Enhanced by ICRF

•Observations made during experiment to use ICRF waves to heat electrons

Plasma conditions:

$R = 2.62$ m
$I_p = 1.8$ MA
$B_T = 4.4$ T
$P_{NBI} = 22$ MW
$f_{ICRF} = 47$ MHz
$P_{ICRF} = 0$—3 MW
$S_{neut} = 2\times10^{16}$ n/sec
no injected minority species

•Resonances for bulk ions (D) and naturally-occurring impurities are well off-axis

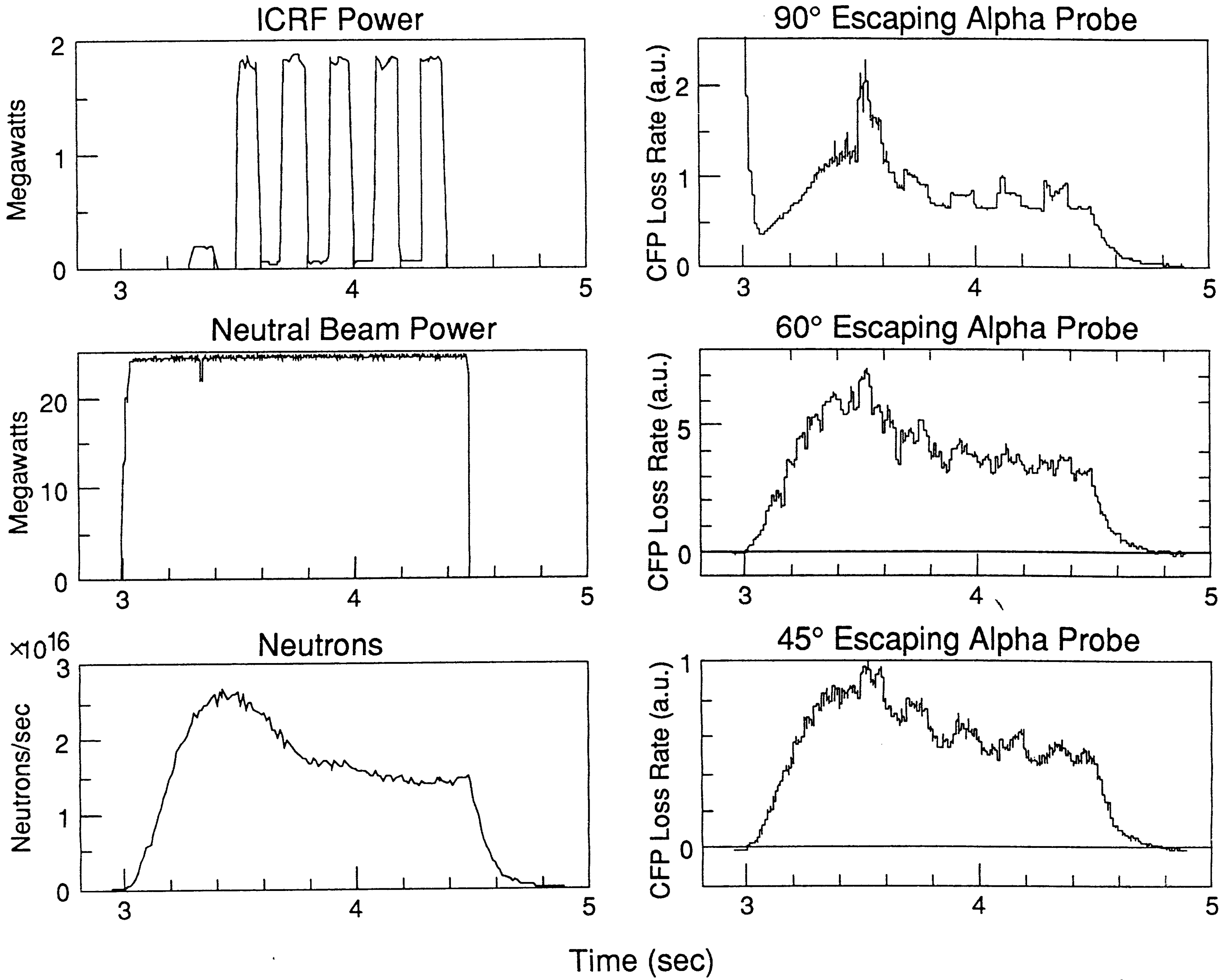
•DD fusion products*can* interact with ICRF waves throughout much of plasma volume:

1 MeV T: $2\Omega_T$ resonance at R=2.59 m

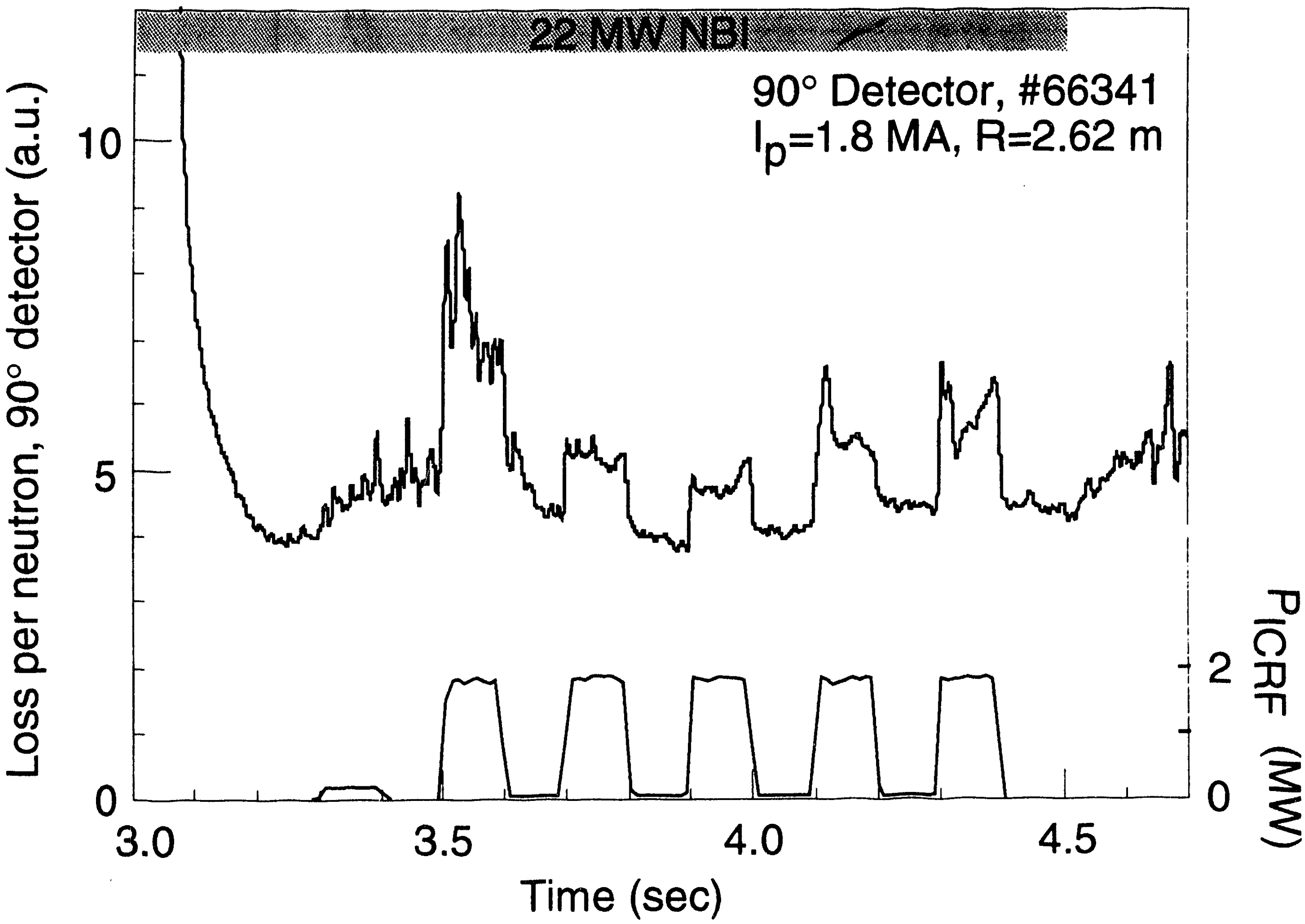
3 MeV p: No resonance layer within plasma, but wave-particle interaction possible across entire plasma, due to large $k_{||}v_{||}$ shift

•Modelling indicates that ICRF can have significant effect upon fusion products

DD Fusion Product Loss During Modulated ICRF Heating



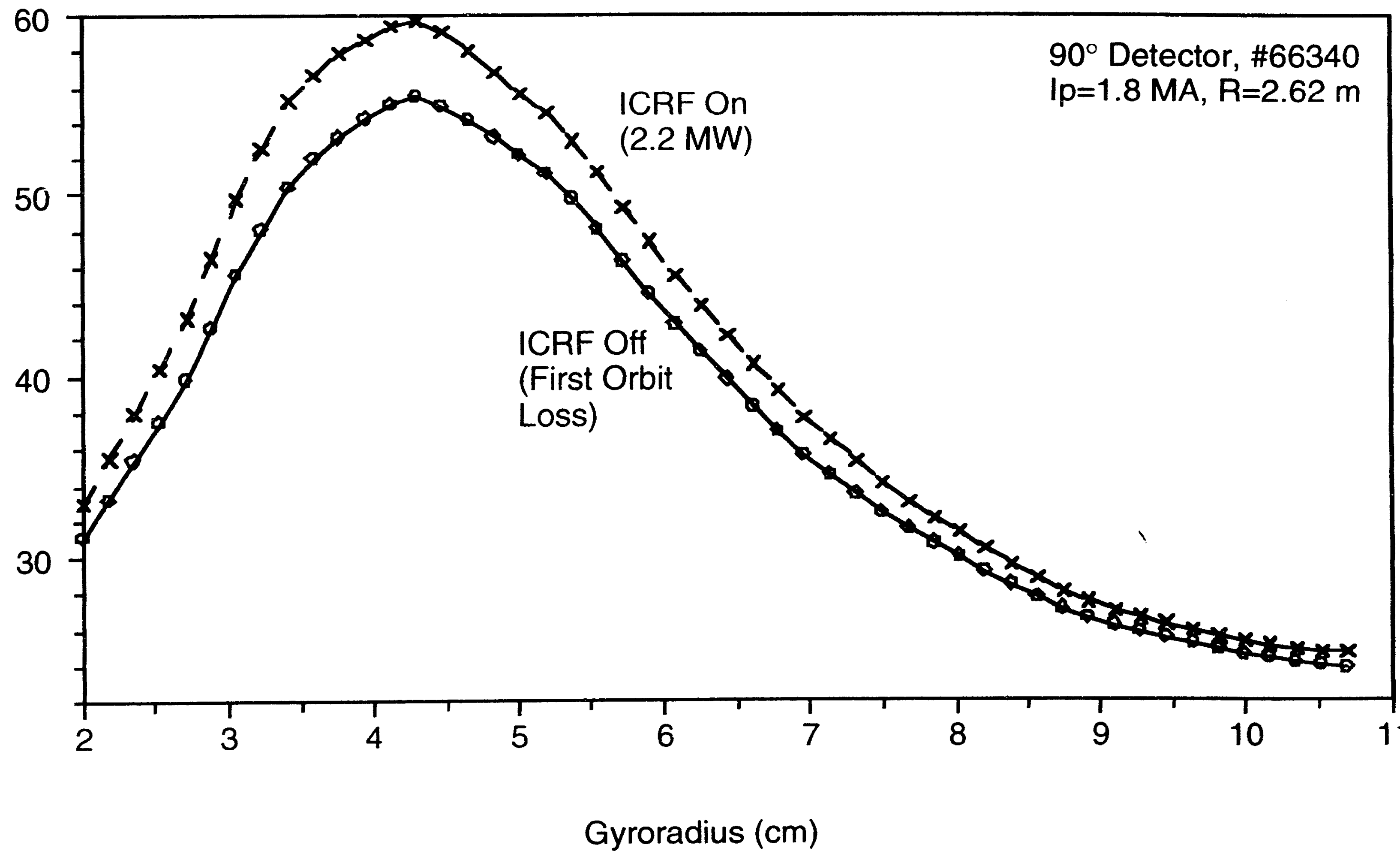
Modest ICRF Power Results in Significant Increase in Fusion Product Loss Rate



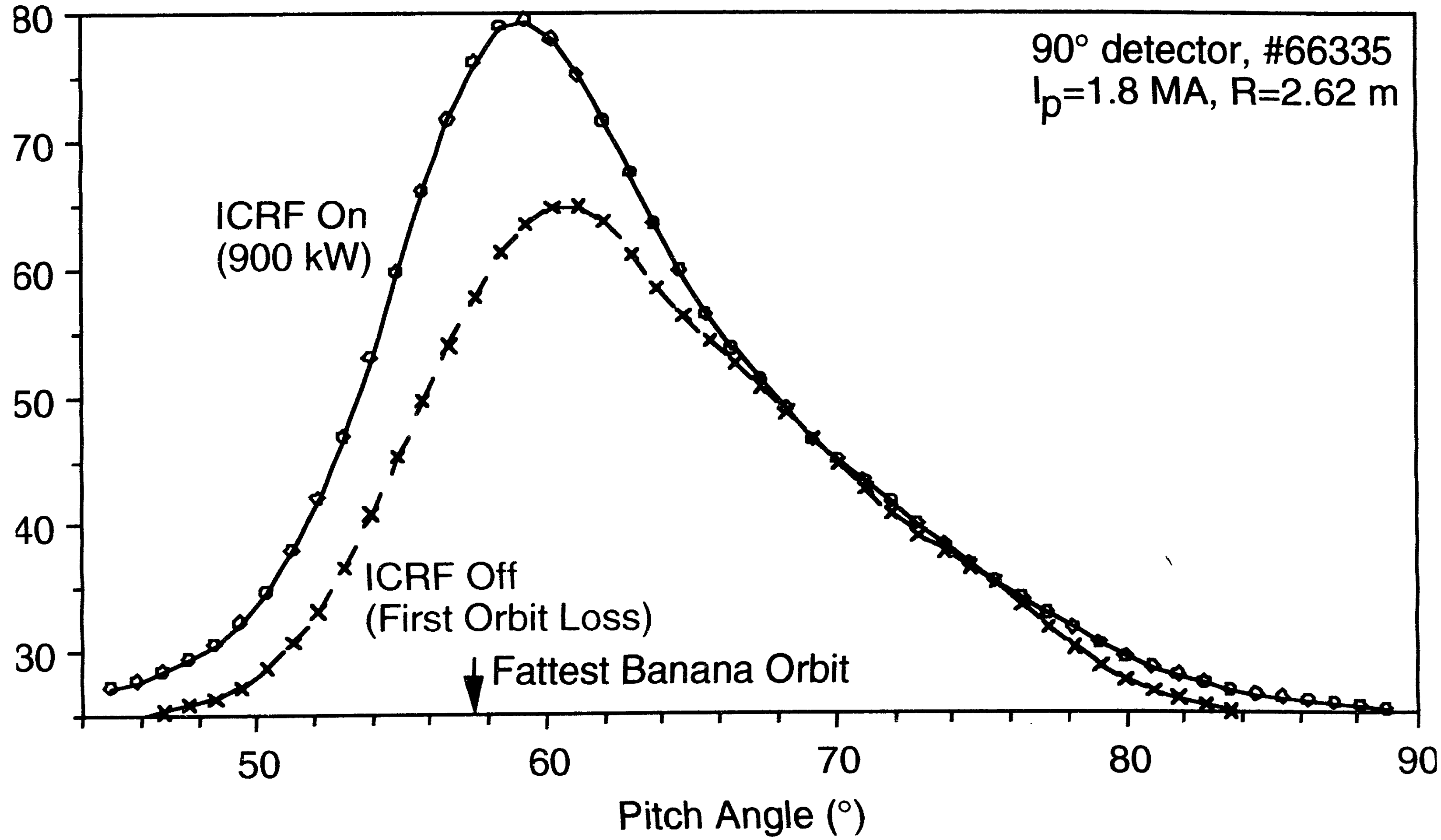
- Loss rate increases by ≥25% with application of 1.8 MW ICRF

- Loss turns on and off very rapidly with application of RF fields

Gyroradius Distribution of Lost Fusion Products is Not Measurably Altered by ICRF

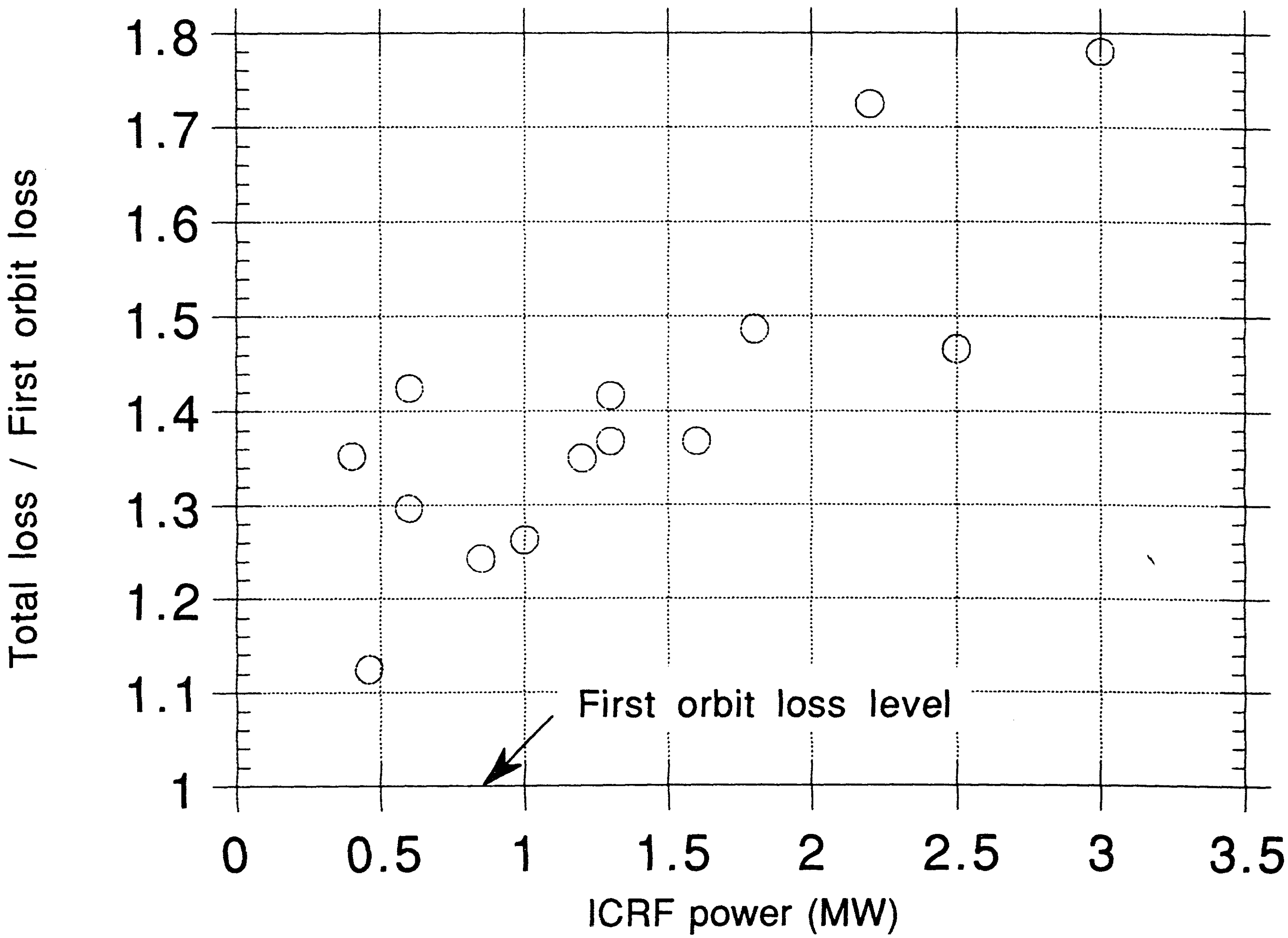


ICRF-Induced Loss Is at Passing/Trapped Boundary



• A broad instrumental function spreads the apparent loss

ICRF Loss Increases with Power



Results Indicate Loss is Conversion of Passing to First-Orbit Lost Particles

•Loss added by ICRF is at the fattest banana orbit (first orbit loss cone)

•Loss starts rapidly when ICRF turns on and stops rapidly at turn-off

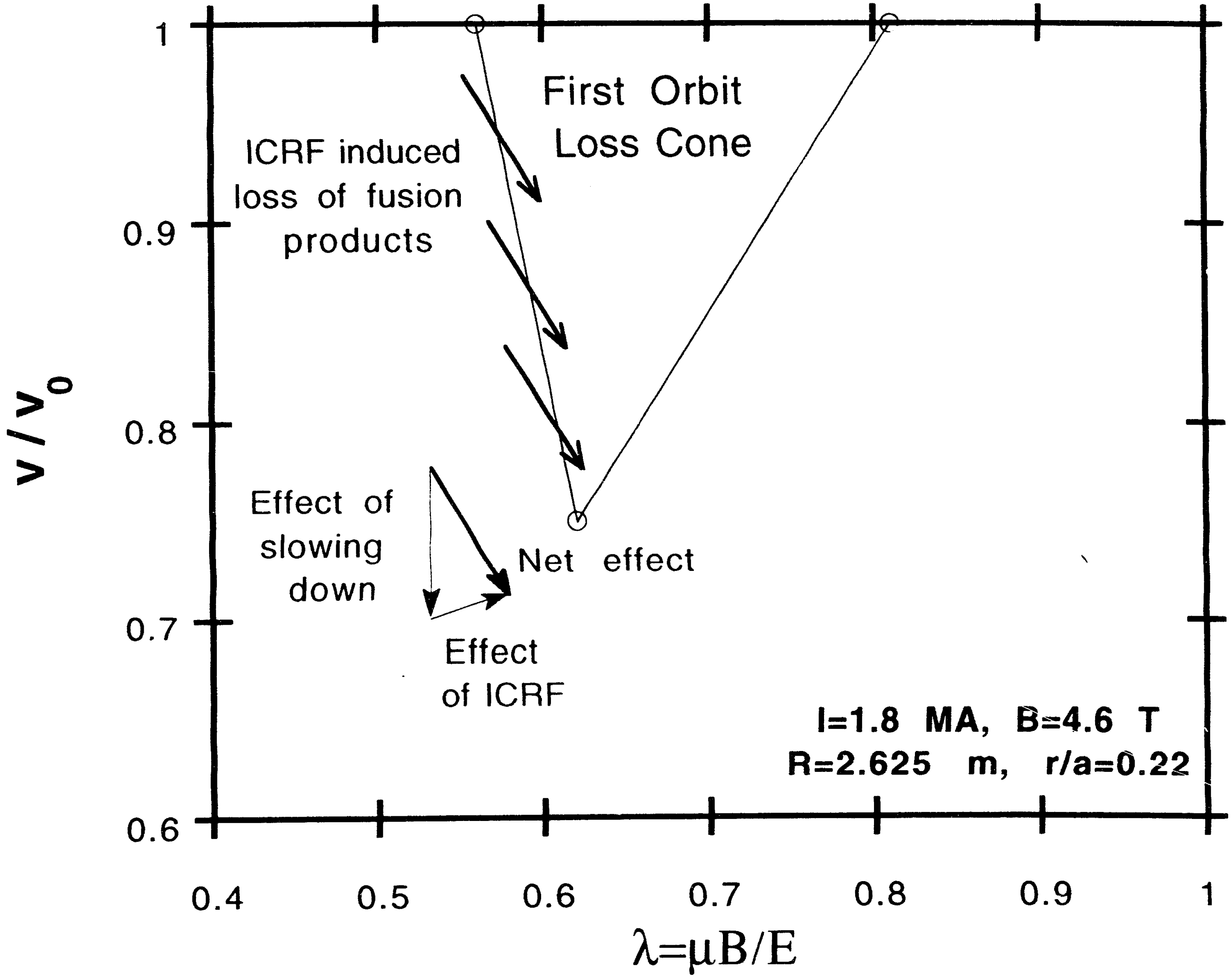
Two processes are theoretically possible:

(1) Direct increase in particles' $v_\perp$ by RF, which carries barely-passing particles into loss cone (C. S. Chang, *Phys. Fluids* **28**, 3598 (1985))

(2) Spiralling, due to repeated cycles of ICRF acceleration and collisional slowing down, of barely-passing particles outward in minor radius until they mirror at high-field side of orbit (C. S. Chang, et al. *Phys. Fluids B* **3**, 3429 (1991))

•The second process is, according to theory, far slower than the first, so only modeling of the first has been attempted

Mechanism of DD Fusion Product Loss During ICRF



Theoretical Estimate of Loss Rate is Comparable to Observed Loss

(C. S. Chang, *Phys. Fluids* **28**, 3598 (1985))

- Rate of particle transport in velocity space is, in simplest approximation,

$$\frac{d\lambda}{dt} \approx \nu_{RF}$$

with $\nu_{RF} \approx \frac{p_{abs}}{m_f n_f v_f^2}$ and $\lambda = \frac{\mu B}{E}$

where:

p_{abs} = absorbed RF power density
m_f = fast ion mass
n_f = fast ion density
v_f = fast ion velocity

For the results quoted here, p_{abs} is from modelling with the ORNL PICES code.

- On a given flux surface, there is a minimum energy, E_{min}, below which ions cannot enter the loss cone. A fast ion will be lost only if its birth λ is close enough to the passing/trapped boundary that it can be swept into the loss cone before slowing below E_{min}. Hence, the range of λ at birth is given by

$$\Delta\lambda_{RF} = \frac{d\lambda}{dt}\Delta\tau_{min},$$

where $\Delta\tau_{min}$ = time for fast ion to slow from birth energy to E_{min}

•The width of the first orbit loss cone, at the birth energy, is $\Delta\lambda_{FO} \approx 0.25$. Hence the loss of tritons during ICRF should increase by the ratio

$$\frac{\Delta\lambda_{RF}+\Delta\lambda_{FO}}{\Delta\lambda_{FO}}$$

•Calculations of these parameters for the dischage observed (66341) are given in table below:

	1 MeV tritons	3 MeV protons
v_f (at birth)	8.0×10^{6} m/sec	2.4×10^{7} m/sec
n_f	2.5×10^{16} m^{-3}	2.5×10^{16} m^{-3}
p_{abs}	20 kW/m^3 (PICES result)	20 kW/m^3 (assumed)
ν_{RF}	2.5 sec^{-1}	0.83 sec^{-1}
E_{min}	0.57 MeV	1.7MeV
$\Delta\tau_{min}$	0.28 sec	0.039 sec
$\Delta\lambda_{RF}$	0.70	0.032
$(\Delta\lambda_{FO}+\Delta\lambda_{RF})/\Delta\lambda_{FO}$	3.8	1.1

•Actual increase in loss rate is by a factor of ~1.25

•Theoretical estimate for enhanced proton loss is close to that observed.

•Since tritons comprise ~30% of detector signal, the predicted increase would raise total detector signal by a factor of ~1.85; this is markedly larger than observed increase.

Development of an Improved Model is Planned

- Present model considers only one flux surface, but a range of surfaces contribute to detector signal. Also, not all lost particles from the surface considered strike the particular detector used.

- A detailed calculation of the loss is being developed, which will integrate the ICRF-induced loss flux over the parts of velocity and real space which are accessible to the detector:

$$\Gamma = 2\pi \int d\theta dr \int dv \; \nu_{RF}(v) \; \eta \; v^3 \frac{df_0}{dv}$$

where

f_0 = slowing down distribution of tritons

η = geometric and velocity space factors $\sim O(1)$.

Loss Can Be Large, But is Unlikely to Extrapolate to Energy-Efficient Ash Removal

Positives:

- Fractional increase of loss above first orbit level can be large (×1.8 seen with 3 MW)

- Present detectors cannot identify escaping ion species; if only T interacts with ICRF, loss in 3 MW case is ~3.7× first orbit loss. If same ratio holds for all flux surfaces, this implies ~11% loss rate for T, which is significant.

- This loss depends upon the existence of a first-orbit loss cone. For ITER, loss cone will be tiny in the plasma core, and so ICRF-induced loss of central α's is likely to be small. However, loss cone grows quite large in regions near edge. Here ICRF might enhance substantially ash removal.

Negatives:

- Fusion products are expelled at or near their birth energy, meaning that they have not heated the plasma much.

- Energy efficiency of the process in this experiment is poor: ~80 kW of absorbed ICRF power expels fusion products whose total kinetic energy is 400 W!

- Configuration in reactor would be more complex, since α's would be in resonance at same location as deuterium ions (hence *not* minority heating).

An Experiment is Planned for the TFTR DT Phase to Investigate ICRF-Induced Loss of α's

(XP DT 29)

•Experiment will vary harmonic number, fusion product type, and resonance layer location in an effort to understand how these affect the loss.

•Experiment will also attempt to clarify effect of $k_{||}v_{||}$ shift.

•Conditions to try:

-$2\Omega_T$ on 1 MeV T & 3 MeV p: repetition of above conditions

-Fundamental α heating: resonance layer at R=2.28 m (off-axis); wider resonance possible due to $k_{||}v_{||}$ shift

-No α harmonics in plasma: a more direct test for effects of $k_{||}v_{||}$ shift

-$2\Omega_\alpha$: for comparison with fundamental heating

Under most of these conditions, B_T will be varied to assess effect of resonance position and $k_{||}v_{||}$ shift

•Experiment presently scheduled for mid-August 1994

Summary

- ICRF-induced loss of fusion products has been observed in the absence of resonant minority species

- The enhanced loss of fusion products occurs by the transport of passing ions into the first orbit loss cone through heating to increase $v_{\perp}$

- ICRF-enhanced loss of fusion products can be appreciable: 1.8 times first orbit loss with 1.8 MW ICRF

- This process expels fusion products near birth energy, and is very energy-inefficient. Considerable improvement would be needed before it would be applicable to ash removal in ignited devices

- Experiments on ICRF-induced loss of α's are planned for TFTR

END

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