ICRF Heating of Plasmas in the New JET Divertor Configuration

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ABSTRACT

A new ICRH system has been installed at JET for the pumped divertor configuration:

- Four antennas consisting each of four straps which can be phased independently.
- The main experiments have used 0π0π phasing (dipole) in a D(H) scenario in which the best heating results are observed.
- The coupling on the inner straps is lower compared to the coupling on the outer straps.
- Using dipole phasing the ICRH power to the plasma was raised to 13 MW in combination with 13 MW of NBI power in Elmy H-mode plasmas.

1. INTRODUCTION

The new ICRH system has been used to study a wide variety of reactor relevant Fast Wave heating and Current drive scenarios (see Fig.1). It has the following specifications [1]:

- Each strap is fed by a 2 MW tetrode amplifier.
- With four antennas this gives a total generator power of 32 MW.
- The frequency range is between 25 MHz and 55 MHz.
- The $k_{//}$ spectrum is narrower by a factor of 2-3 compared to the previous ICRH system.
- Real time automatic tuning on the frequency, line length and stub length.
- Feedback on the plasma position to maintain a requested coupling resistance.

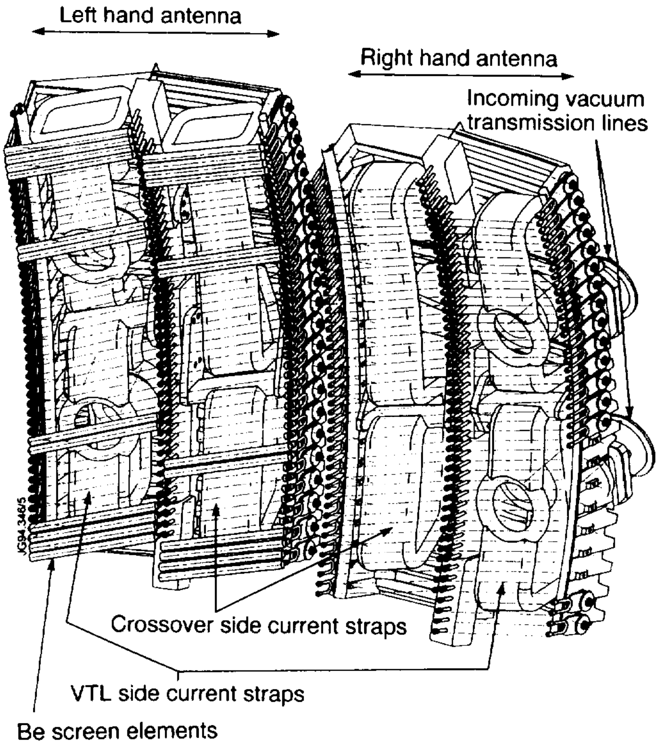

Fig. 1: The new four strap, A2 antenna at JET.

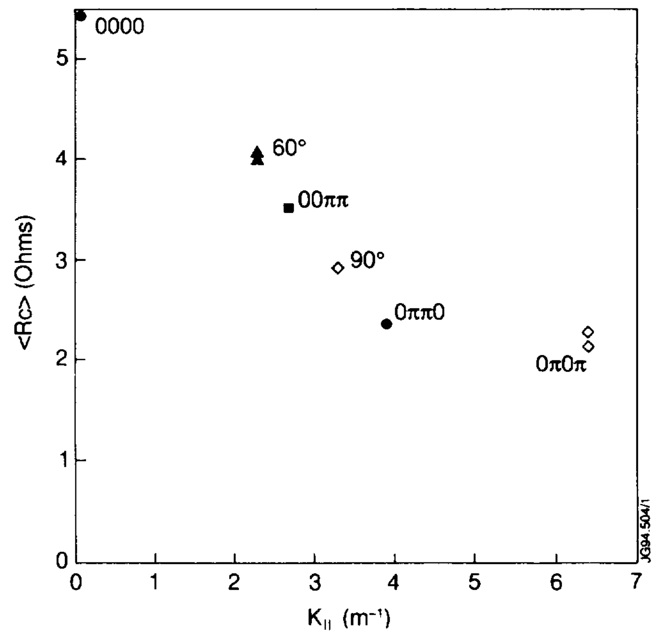

Fig.2: Coupling at different phasing.

2. ICRF COUPLING AND PHASING STUDIES

Coupling of the new antennas has been studied in detail (Fig.2) [2,3]:

- The highest coupling is observed for monopole phasing, a factor two lower coupling for dipole.
- A coupling imbalance between the outer and inner straps for all antenna phasings.
- The occurrence of hot spots on the poloidal limiters when phasing other than dipole is used.

The observed coupling imbalance has been studied over the frequency range of the RF amplifier:

- The average coupling resistance increases with frequency (Fig. 3) and the coupling imbalance decreases with frequency.

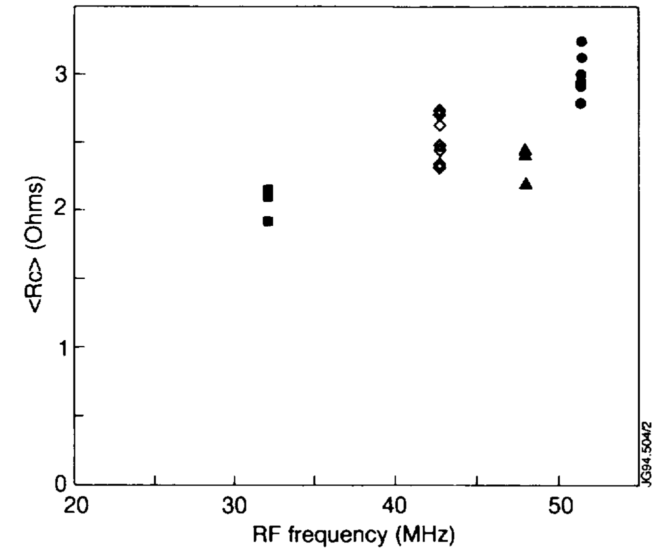

Fig.3: Average coupling vs. Frequency.

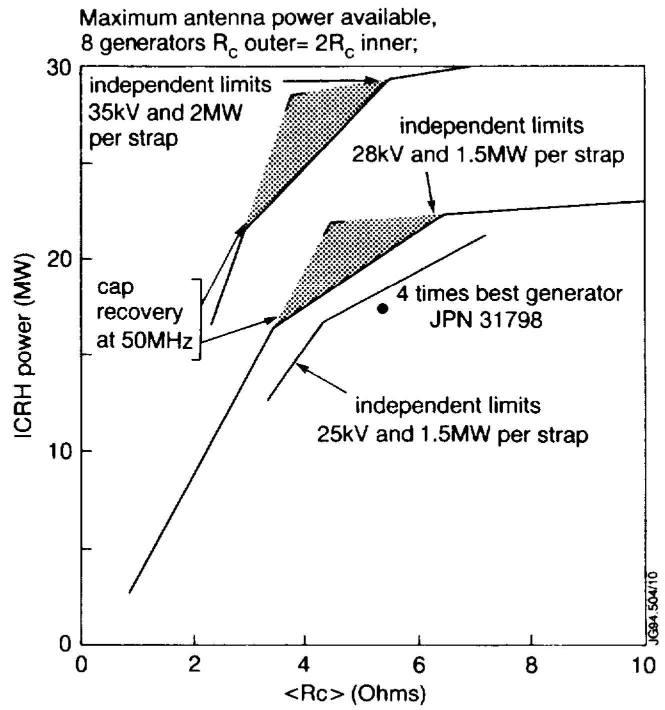

Fig.4: Power capabilities of the ICRH system.

Detailed studies of the coupling imbalance:

- Measurements of the scattering matrix reveal that observed imbalance is inherent to the design of the antenna and not caused by the loading of the plasma.
- The cross-over strap connecting the inner strap to the transmission line has a too high characteristic impedance degrading the coupling of the straps. This shifts the regime of equal coupling of all four straps to around 60 MHz.

To outline the performance of the ICRH system in the following section, two JET pulses are used:

⇒ Pulse 31795, 1MA/2.8T, high $\beta_{pol.}$ Discharge with 13 MW of ICRH and 13 MW NBI [4].

⇒ Pulse 31808, 3MA/2.8T, fast current rise study with early ICRH heating.

3. ICRF AT HIGHEST POWER LEVELS

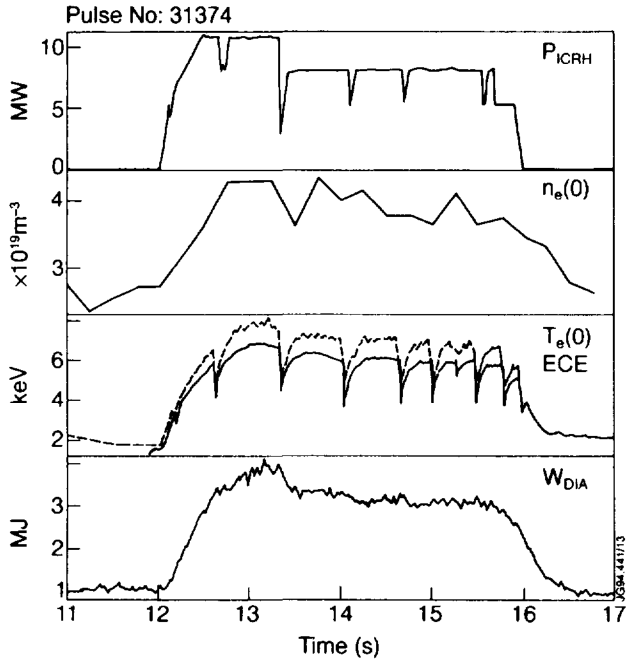

Fig.5: High power at 2MA/2.8T with ICRH only.

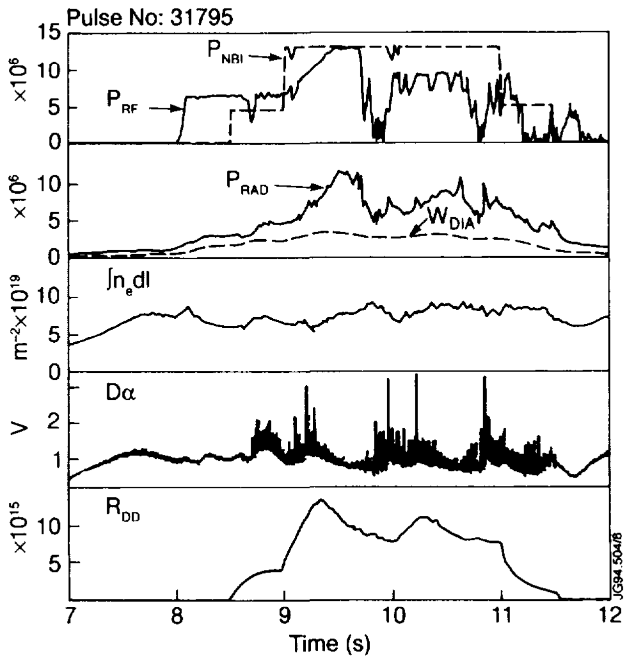

Fig.6: 13MW of ICRH combined with 13MW NBI at 1MA/2.8Tesla.

The JET experiments have concentrated on optimising the ICRH heating in dipole to maximise heating. The results are:

- Power imbalance between the four straps can be used to maximise the available power with respect to the observed coupling imbalance.
- The coupling increases with q_{95} (lower plasma current/higher toroidal field).
- The change of plasma loading during 'Grassy' ELMs can be tolerated by the transmitter. Under these conditions the coupling increases significantly. At 'Giant' ELMs the systems trips.
- 11 MW of ICRH has been coupled at 2MA/2.8T with 15 MW of NBI (Fig. 5), and 13 MW has been coupled to a 1MA/2.8T plasma with 13 MW of NBI (Fig. 6).

- Recently the first RF only H-mode of the present campaign was obtained in a 1MA/2.8T discharge. The power level was 9MW using dipole phasing at 42MHz. The average coupling resistance before the H-mode was 3 Ohm which dropped to 1.8 Ohm during the 100ms ELM-free phase, this caused tripping of some of the amplifiers. The distance from the antenna at the onset of H-mode was 2 centimetres.

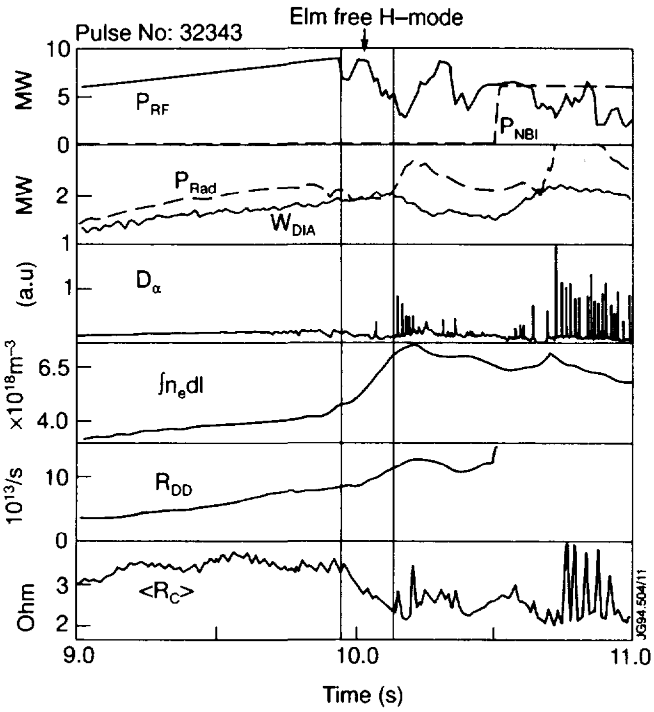

Fig.7: First RF H-mode at 1MA/2.8T.

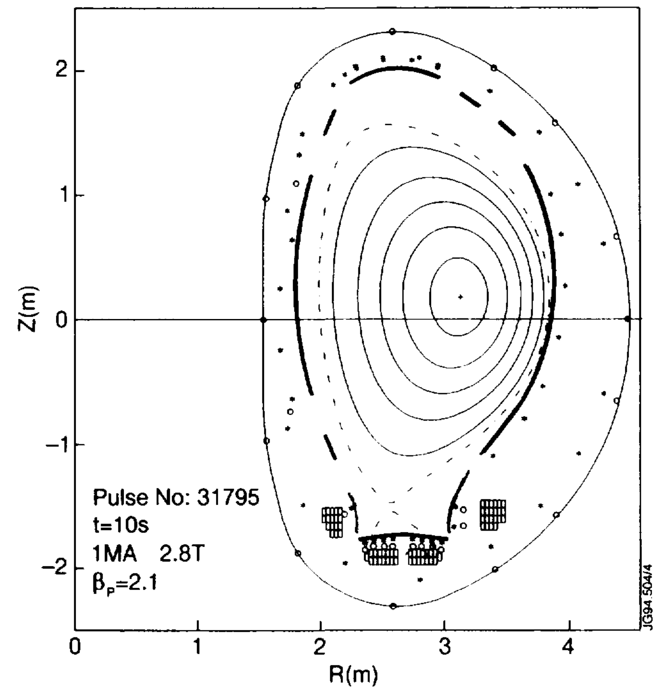

Fig.8: Configuration with high combined heating power at 1MA.

4. PLASMA SHAPING AND PLASMA POSITION CONTROL

The antenna design with respect to the shape of the Last Closed Flux Surface is as follows (Fig. 9):

- Discrete poloidal limiters are installed on each side of the antenna.
- The position of the screen is 20 mm behind the front surface of the Carbon tiles of the poloidal limiter, the straps are 36 mm behind the front of the screens.
- The Be-screen bars are aligned for a field line helicity obtained at low edge q (q_{95}=2.3 for 5MA/3.4T).

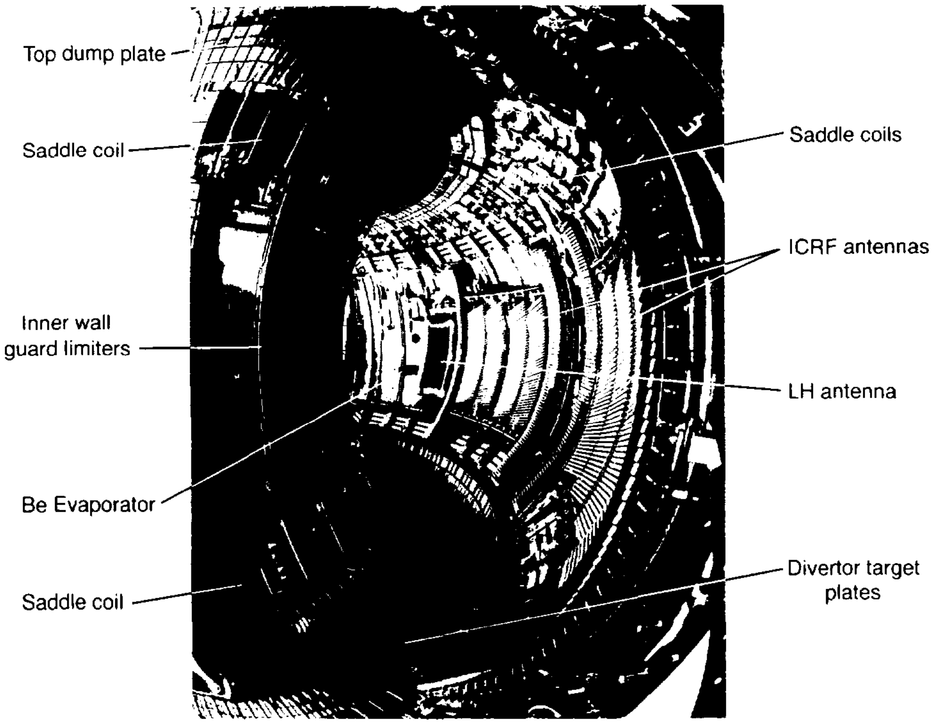

Fig.9: Poloidal view of the antenna.

⇒ Position feedback control (Fig. 10):

The feedback on the vertical field at JET can be used to maintain a requested coupling resistance since the coupling depends almost linearly on the plasma radial position [2]. During this feedback the fast real time boundary reconstruction monitors distances from the LCFS to the antenna:

- To define an inner limit for the radial position under coupling resistance feedback.
- To define an outer limit for the radial position under coupling resistance feedback. This to keep the plasma from moving into the limiter when the coupling request can not be achieved.
- To define a radial position when the ICRF system trips completely.

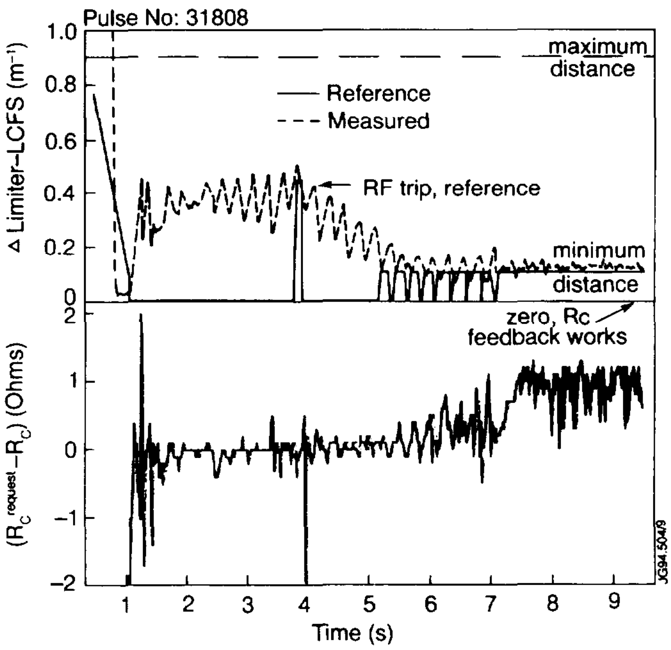

Fig.10: Plasma position feedback.

⇒ **Shape of the LCFS (Fig. 11 and Fig. 8):**

The ICRH coupling is related to the alignment of the LCFS to the shape of the antenna:

- A well aligned LCFS gives 1 Ohm better coupling compared to the so called standard Fat plasma in JET (Figures 11a and 11b compare the two shapes for equal conditions). However the well aligned LCFS is difficult to maintain due to variations in plasma inductance and beta.
- When the LCFS has a much smaller radius of curvature compared to the poloidal limiters the field lines are allowed to penetrate into the antenna screen raising the density in front of the strap.
- Under this condition it is observed that the coupling is improved again compared to a standard JET configuration. Only in this configuration the coupling is even further improved with the application of NBI (Fig. 8).

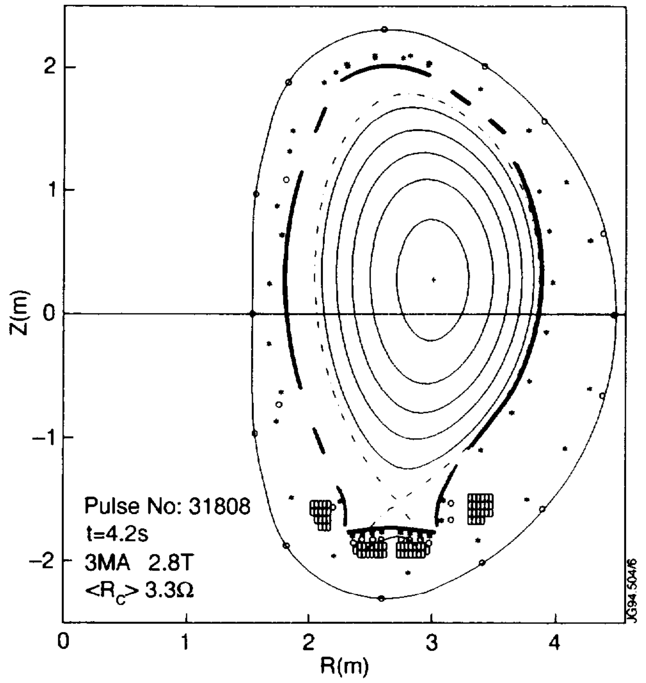

Fig. 11(a): Well aligned LCFS.

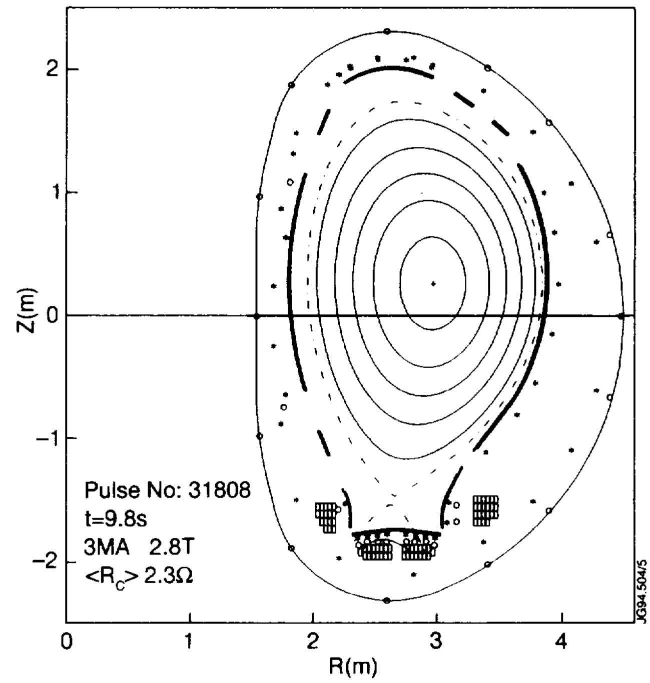

Fig. 11(b): Standard Fat plasma.

5. FUTURE EXPERIMENTS AND POSSIBLE ANTENNA UPGRADES

In view of the results presented above the following modification the ICRH system are being prepared:

Problems	Remedies and potential power gain
Bad heating efficiency and hot spots in monopole phasing.	Bumper limiter between inner straps and shield ends of antenna (1995 shutdown). Move plasma away from antenna (to be assessed). Power gain: factor 2.
Coupling imbalance between inner and outer straps.	Replace or change cross-over strap. Work at highest frequencies (this campaign). Power gain: factor 1.25.
Crowbars due to ELMs or rapid change at the plasma edge.	Trombones in Outer Transmission lines and improve trip identification system. No power gain but system more reliable (under study).
Electronics generate side bands which limit the power generation for low coupling.	New electronics (starting from October 1994). Power gain: factor 1.5 for low coupling, factor 1.2 for high coupling cases.

- The use of the ICRF antenna test bed will be crucial in the development of these modifications.

6. REFERENCES.

[1] Wade, T., et al, to be published in Fusion Engineering and Design, 1993.
[2] Bures, M., Proceedings of 21st EPS, Montpellier, 1994.
[3] Rimini, F., et al, IAEA-CN-60/A3/5-P-7, Seville, 1994.
[4] Gormezano, C., et al, IAEA-CN-60/A-5-I-3, Seville, 1994.