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# PHYSICAL BASIS OF RF HYPERTHERMIA FOR CANCER THERAPY: SPATIAL DISTRIBUTION OF ABSORBED POWER FROM CIRCULAR OR CYLINDRICAL COILS

(hyperthermia/RF heating/inductive heating)

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The power dissipation in the material inductively heated by coils having various shapes was calculated: Heating effect at depth is improved 1) when the radius of the coil is large, 2) when the height of the coil is enlarged, 3) when the coil is placed away from the body, 4) with use of a cylindrical coil rather than a pancake-type coil which has the same radius as the cylindrical one, and 5) by revolving the coil around the central axis rather than by scanning uniformly over the same region. It is impossible to reduce the absorbed power at all points on the entire surface of the material, even if the electric currents in the coils are driven in opposite directions in order to offset the induced current at the surface of the material.

## INTRODUCTION

Various heating methods have been proposed for hyperthermia (1-10). Inductive heating has been attracting special attention for the following reasons; a smaller amount of absorbed power is distributed in the fat layer(11), it ensures heating at considerable depth (12), it can be performed without contact with the material(13), and the equipment can be easily adjusted (14). We calculated the distribution of absorbed power using coils with various shapes and their combination(15), and the results are described here.

## THEORY

### Magnetic field induced by a circular coil

Assume that a circular coil with a radius of $r_0$, in which a current $I = I_0 \sin \omega t$ flows, is placed in a heating material with permeability of $\mu$ and an electric conductivity of $\sigma$, as shown in Fig. 1. The axis of the coil is set on the Z axis, and the element of the coil at the point $P(x_0, y_0, z_0)$ is denoted by $d\mathbf{a}$. We consider the point $Q(x, y, z)$ on a circle which has radius r and the axis of which agrees with the Z axis.

According to the law of Biot-Savart, the z component of the magnetic field, Bz(r), at the point Q(x, y, z) may be expressed as follows:

$$Bz(r) = Bz_0(r) \sin \omega t \qquad (1)$$

$$Bz_0(r) = \int_0^{2\pi} \frac{\mu I_0 r_0}{4\pi} \times \frac{r_0 - x\cos\theta - y\sin\theta}{\{(x-r_0\cos\theta)^2 + (y-r_0\sin\theta)^2 + (z-z_0)^2\}^{3/2}} \, d\theta \qquad (2)$$

### Thermogeneration by the alternating magnetic field

The power dissipated at $r = r_1$ is obtained by the following method. Faraday's law of induction gives the relation between the magnetic field $\mathbb{B}$ and the electric field $\mathbb{E}$:

$$\nabla \times \mathbb{E} = -\frac{\partial \mathbb{B}}{\partial t} . \qquad (3)$$

Equation (3) is expressed, with the aid of Green's theorem, as

$$\oint \mathbb{E} \cdot d\mathbb{S} = -2\pi \frac{\partial}{\partial t} \int_0^{r_1} B_Z(r)\ r\ dr . \qquad (4)$$

Here, dS is the element of the circle with the radius $r_1$. From this, the following equation is obtained:

$$\mathbb{E} = -\frac{\omega \cos\omega t}{r_1} \int_0^{r_1} Bz_0(r)\ r\ dr . \qquad (5)$$

Absorbed power W per unit volume is:

$$W = \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} \sigma E^2 dt \tag{6}$$

$$= \frac{\sigma\omega^2}{2r_1{}^2}\left[\int_0^{r_1} Bz_0(r)\ r\ dr\right]^2 . \tag{7}$$

Thermogeneration by a cylindrical coil

Assume that a cylindrical coil of the height $\ell$, the axis of which is placed on the Z-axis, has two bases at $z = z_1$ and $z = z_1 - \ell$, and that the surface current of $Is = Is_0 \sin \omega t$ flows uniformly over the coil, as shown in Fig. 2. Under these conditions, equation (2) becomes:

$$Bz_0(r) = \int_{z_1-\ell}^{z_1} dz \int_0^{2\pi} \frac{\mu Is_0 r_0}{4\pi} \times \frac{r_0 - x\cos\theta - y\sin\theta}{\{(x-r_0\cos\theta)^2+(y-r_0\sin\theta)^2+(z-z_0)^2\}^{3/2}}\, d\theta . \tag{8}$$

## RESULTS OF CALCULATION

Calculation of the distribution of absorbed power was made for the case of 10MHz, $\mu = \mu_0$ and $\sigma = 0.6$S/m. Thermogeneration by an electrostatic potential and the reduction of the magnetic field due to heating material were ignored. Unless otherwise specified, $Is_0$ was 10A/cm.

Radius of the coil

Figs. 3-5 indicate the relationship between the radius of the coil and the distribution of dissipated power. In each figure, there is no dissipation along the axis, but the power increases in proportion to the distance from the axis, reaching the maximum at the distance of $r_0$, it then decreases linearly with distance from the axis. These figures show that the larger coil improves the heating effect at depth. These figures also show that the main feature of the pattern of the power distribution does not depend on the size of the coils.

Height of the coil

Fig. 6 shows the distribution of absorbed power, where the calculation is accomplished under the condition that the height of the coil $\ell$ is small compared with that in Fig. 4. A comparison between Fig. 4 and Fig. 6 shows that diminution in the height is accompanied by reduction of the power absorbed at depth.

Position of the coil

Fig. 7 shows the distribution of absorbed power when the coil is placed at $z_1$ = -5cm. When the material to be heated is placed apart from the coil, the reduction of the power absorbed at depth is slight in comparison with cases where the material is placed in contact with the coil, as in Fig. 4.

Offset of the magnetic fields produced by two coils

Figs. 8-12 show changes in the distribution of absorbed power under the condition that the current of the coil, which has a radius of 6cm and is placed at $z_1$ = -5cm, is changed from -40A/cm to -80A/cm, but the current of another coil, which has a radius of 10cm and is placed at $z_1$ = 0cm, is kept at 10A/cm. As shown in Fig. 11, the power absorbed near the surface ( z = 1cm ) can be reduced at y = 10cm, but can not be reduced over the whole area near the surface.

Pancake-type coil

Fig. 13 shows the distribution of absorbed power when a pancake-type coil consisting of three circular coils, which have a height of 0.5cm and a radius of 3, 4.3 and 5.8cm, respectively, is placed at $z_1$ = -3.75cm and is supplied with the current $Is_0$ of 2A/cm. The distribution of absorbed power agrees with that reported by Guy et al(16). A comparison of Fig. 13 with Fig. 7 shows that a cylindrical coil produces more power absorption at depth than the pancake-type coil in which the diameter of the outer coil is equal to that of the cylindrical one.

Offset of magnetic fields inside the coils

Fig. 14 shows the distribution of absorbed power when the material to be heated in a columnar shape is inserted in the two coils which are placed at the same $z_1$, but have different radii. In this case, the magnetic fields may be offset on the surface of the material by making the current in the coils flow in opposite directions. Thermogeneration on the surface of the material can be locally suppressed, but not over the whole surface.

### Uniform scanning of the coil

Fig. 15 shows the distribution of absorbed power when the axis of the coil with $r_0$ = 6cm is uniformly scanned over the circle with a radius of 12cm. The amount of absorbed power is maximized on the axis of the circle, and the amount of absorbed power at depth is significantly improved.

### Revolution of the coil

Fig. 16 shows the distribution of absorbed power when the axis of the coil revolves at a radius of 12cm around the central axis. The absorbed power at z = 1cm reaches maximum at a distance of 6.3cm from the axis. The comparison with Fig. 15 demonstrates that the absorbed power at depth is further improved.

## CONCLUSION

The distribution of absorbed power in the heated material was calculated for various types of circular and cylindrical coils. The absorbed power at depth can be increased when a large area is irradiated by magnetic field from a large coil. It is possible to reduce the power absorbed at a specific area on the surface when some coils are combined, but it is impossible to reduce the absorbed power at every point on the surface.

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## LEGENDS

Fig.1. Schematic representation of the circular coil.

Fig.2. Schematic representation of the cylindrical coil.

Fig.3. Distribution of absorbed power from a cylindrical coil.

Fig.4. Distribution of absorbed power from a cylindrical coil.

Fig.5. Distribution of absorbed power from a cylindrical coil.

Fig.6. Distribution of absorbed power from a circular coil.

Fig.7. Effect of positioning of the coil on the distribution of the absorbed power.

Fig.8. Offset of the magnetic fields by two coils with different radii. The phases of the electric currents applied to the two coils are shifted relatively by 180°.

Fig.9. Offset of the magnetic fields by two coils with different radii. The phases of the electric currents applied to the two coils are shifted relatively by 180°.

Fig.10. Offset of the magnetic fields by two coils with different radii. The phases of the electric currents applied to the two coils are shifted relatively by 180°.

Fig.11. Offset of the magnetic fields by two coils with different radii. The phases of the electric currents applied to the two coils are shifted relatively by 180°.

Fig.12. Offset of the magnetic fields by two coils with different radii. The phases of the electric currents applied to the two coils are shifted relatively by 180°.

Fig.13. Distribution of absorbed power from a pancake-type coil.

Fig.14. Insertion of the material to be heated into two coils which have different radii and have current flowing in opposite direction.

Fig.15. The axis of the coil with $r_0$ = 6cm is uniformly scanned over a circle with a radius of 12cm.

Fig.16. Distribution of the absorbed power when the axis of the coil revolutes at a radius of 12cm around the central axis.

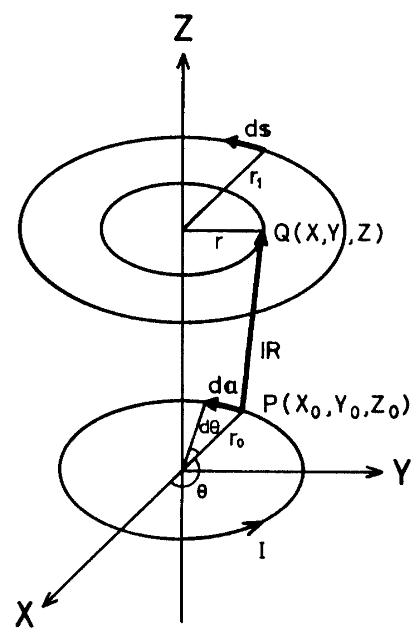



Fig.1

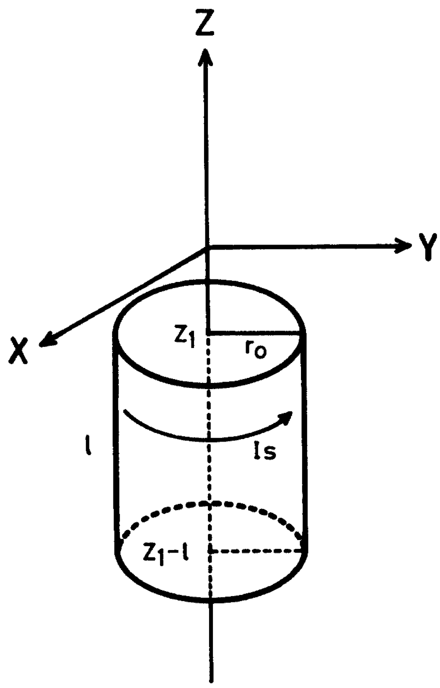
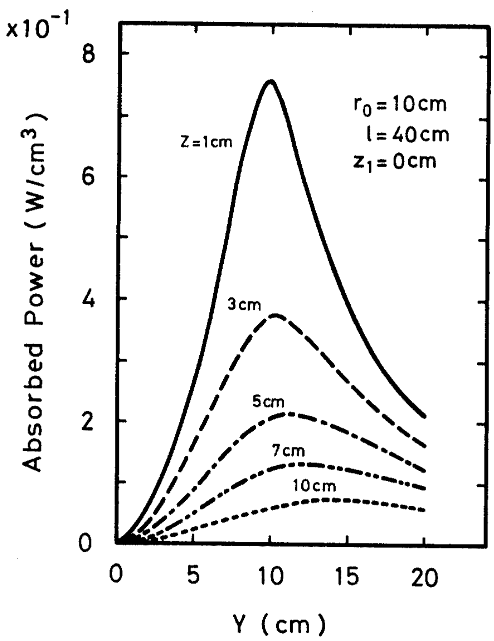



Fig.2

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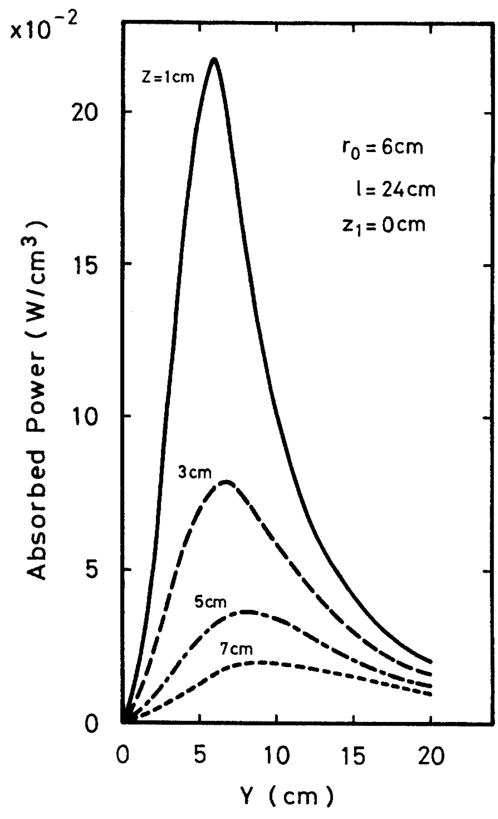


Fig.4

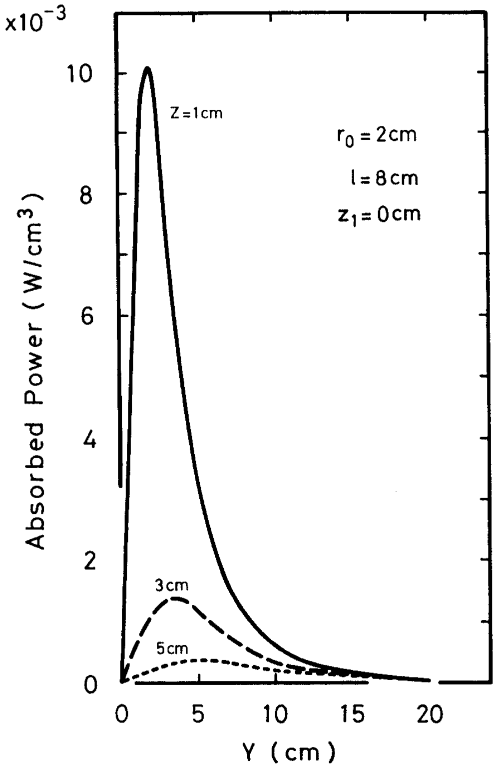


Fig.5

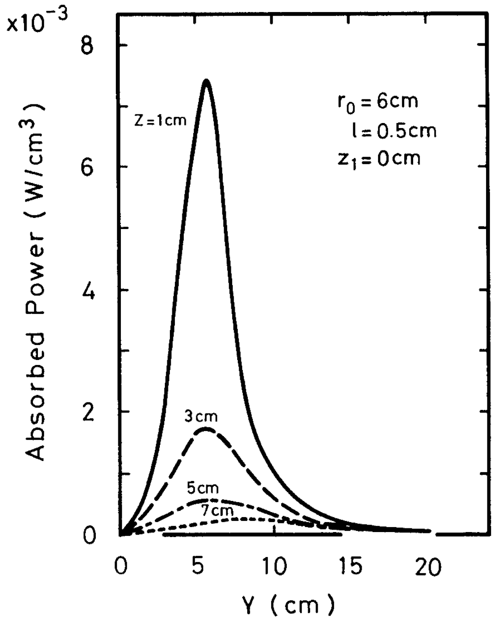


Fig.6

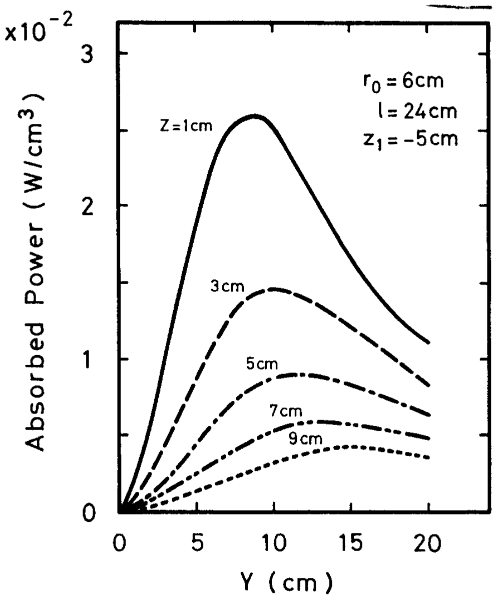


Fig.7

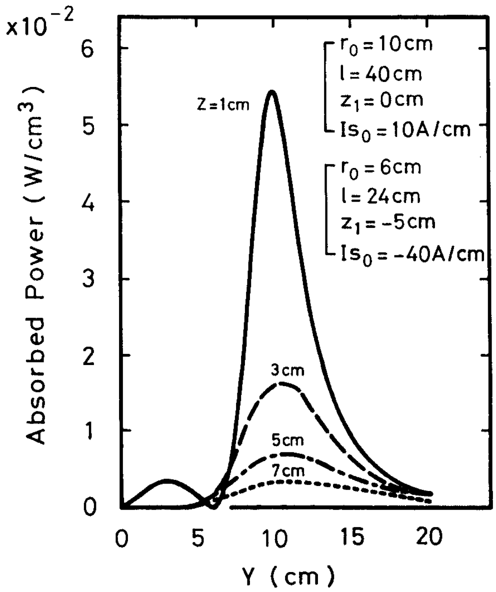


Fig.8

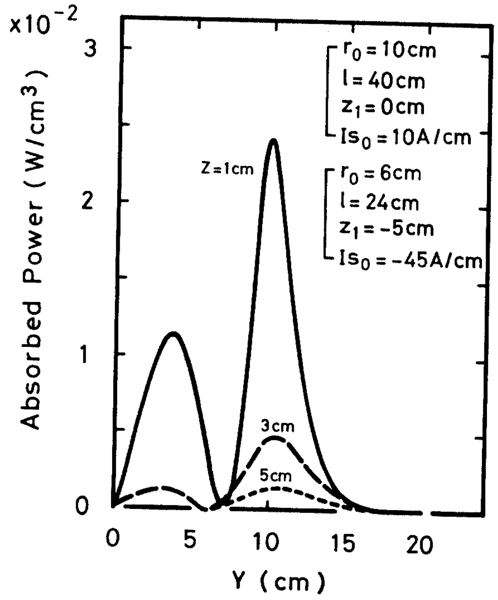


Fig.9

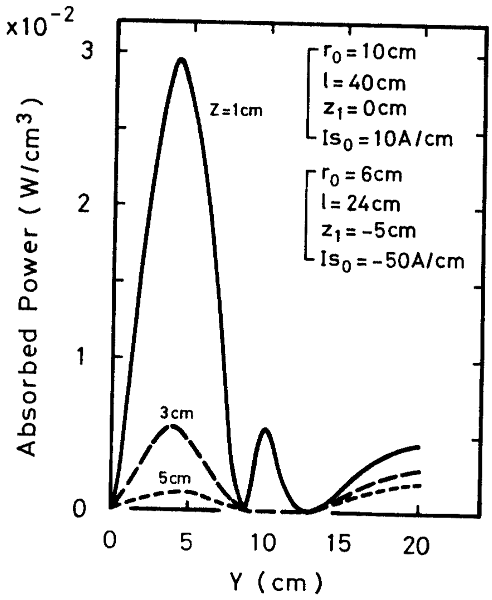


Fig.10

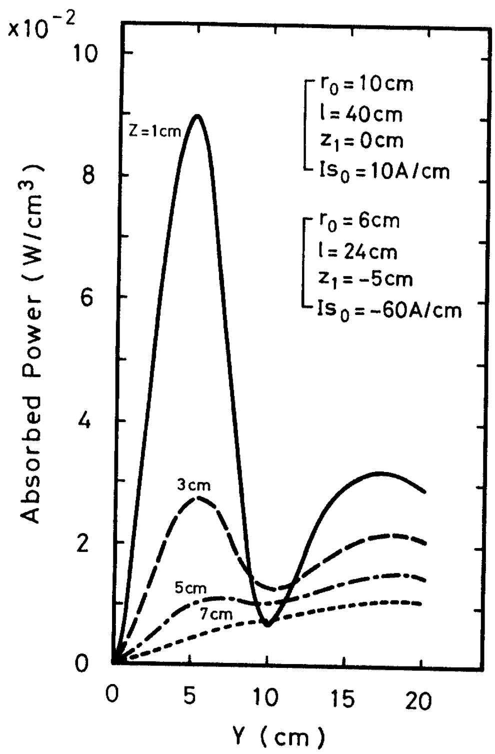


Fig.11

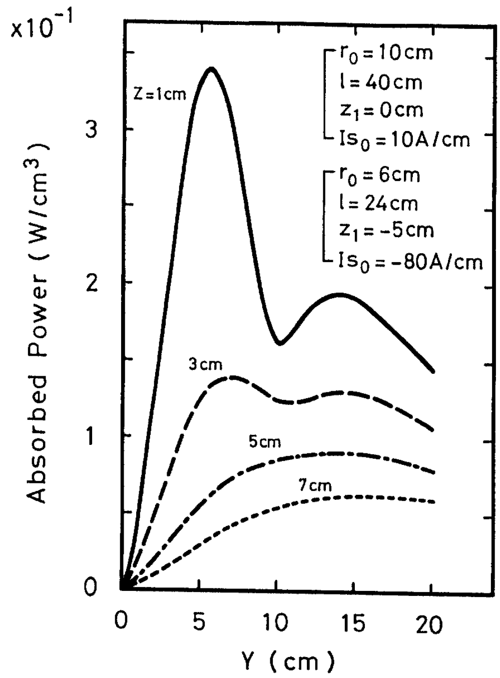


Fig.12

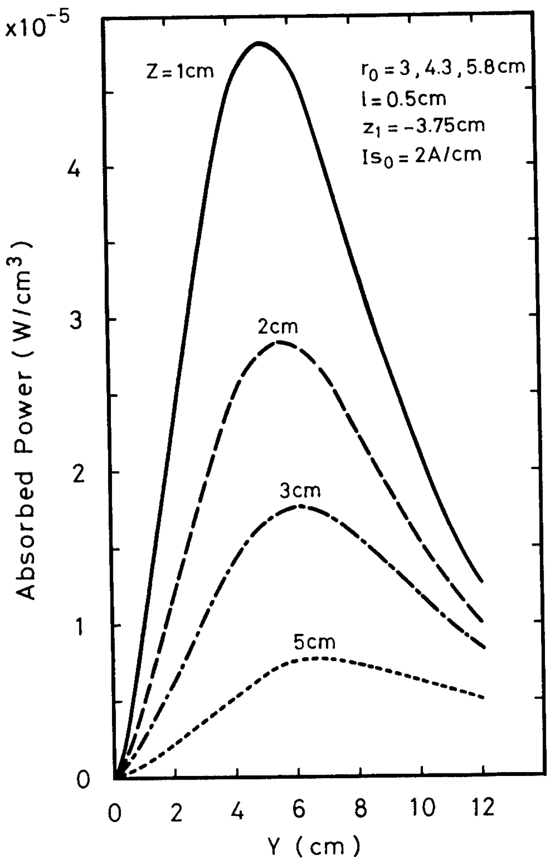


Fig.13

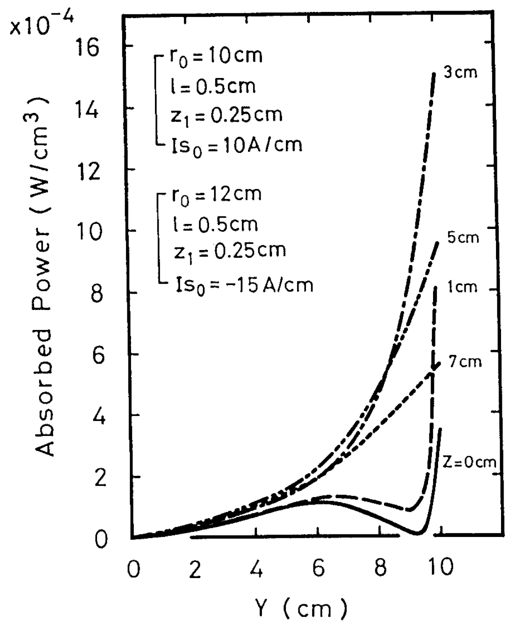


Fig.14

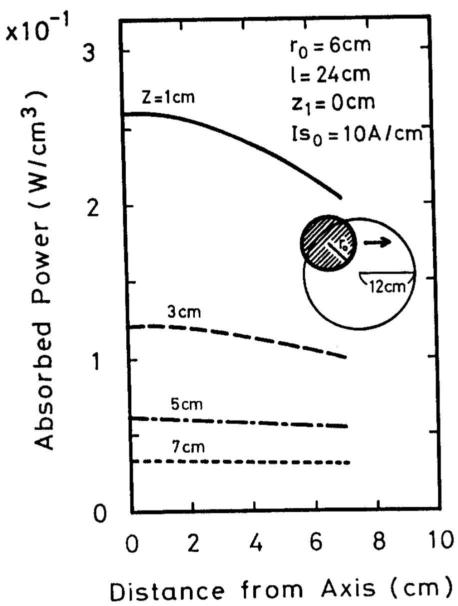


Fig.15

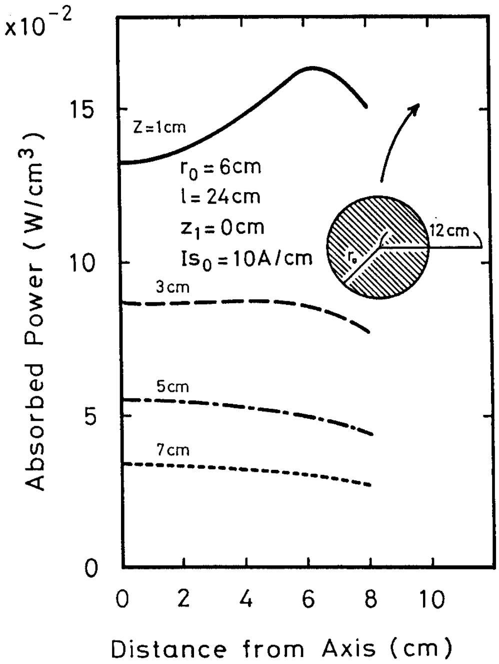


Fig.16