SIMULATION OF A SWP (SURFACE WAVE COUPLED PLASMA) USING OOPIC

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(Surface Wave Coupled Plasma)
using OOPIC

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Abstract

SWP(Surface Wave coupled Plasma) is simulated by using the OOPIC (Objected Oriented Particle-In-Cell) simulation code. Comparison is made between simulation results and experimental data for electron density distribution and electric field distribution in an Ar discharge.

Good qualitative agreements among these discharge properties have been obtained. It is found that both distributions decay exponentially along the x direction, perpendicular to the dielectric line. This decay rate indicates that the plasma distribution corresponds to the field distribution. It is also found that the standing waves along the dielectric line create a high density plasma with corresponding peaks; the microwaves are strongly coupled to the plasma.

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Naoki Matsumoto was a visitor with our Plasma Theory and Simulation Group here in Berkeley from January through July, 1996. He was here to learn and to apply our 2d3v EM code OOPIC to the Surface Wave Plasma reactor now operating at Sumitomo Metals Industries, in Amagasaki, Japan. His results are presented in this report. We found this simulation to be very challenging.

Prof. C. K. Birdsall July 1996

1 Introduction

SWP has currently been developed for etching processes, resist stripping processes, and so on. Recently SWP has attracted much attention because it was reported [8] that plasma with an electron density more than 10^{12} cm^{-3} can be generated, making SWP a candidate for high density plasma sources.

The configuration is shown schematically in Fig 1. The device is composed mainly of a dielectric line and a vacuum chamber with a vacuum window. Microwave power at 2.45GHz is launched into the dielectric line from the waveguide and propagates in the z direction while depositing energy into the plasma. There is a reflecting plane at the right side, which sets up a standing wave.

Experimental measurements of the electron density and the electric field in the plasma were made [4], [5] by using a Langmuir probe and a loop antenna. OOPIC is employed to assist in understanding how this surface wave coupled plasma evolves towards high density. Simulation can be compared with experimental data because OOPIC can simulate electromagnetic waves such as microwaves. The aim of simulating the SWP is to observe the control of the plasma by the dimensions, pressure, and power and then to design the optimum configuration.

2 Experiment

A single Langmuir probe (planar type with 2mm diameter) method and a loop antenna method were employed to measure the electron density distribution and the electric field distribution, respectively. Measurements using both methods were made between the position of 10mm and that of 80mm along the x direction, where x=0mm is located at the underside of the vacuum window. With the loop antenna, we measured only the TM(transverse magnetic) mode because the surface wave has an electric field Ex component and an Ez component. Actually, we did not detect the TE(transverse electric) mode in the cavity on our experiments.

The conditions for these measurements were: Ar gas pressure, 0.1Torr and microwave power, 300W. The size of the experimetal chamber was: the z direction, 200mm and the x direction, 100mm and all boundaries except an exhaust were metal boundaries. Both the probe and the antenna were inserted through the exhaust.

3 Model

The simulation model for SWP is shown in Fig.2. Although this model is not exactly the same as the laboratory experiment, we can assume this model in order to simplify the configuration and to understand the basic behavior of SWP. This assumption says that even a vacuum window made of ceramic can be the dielectric waveguide in a laboratory system.

In Fig.2, all boundaries except the incoming wave port are ideal conductors. The length of this model is 200mm in the z direction, 100mm in the x direction and there are 50 cells in the z direction, 25 cells in the x direction, respectively. These cells are spatially uniform. Microwave power at 2.45GHz is launched from the incoming wave port.

In order to guatantee the numerical stability of the electromagnetic field, we operate at $c\frac{\Delta t}{\Delta x,\Delta y} \approx 0.5$, Courant condition; here Δx,Δy is the grid spacing, Δt is the time step, and c is the speed of the light in vacuum. This equation means that a light wave will propagate through a half cell per timestep. Taking a larger timestep, over the Courant limit, produces poor results. The particle Courant condition, $v_{particle} \frac{\Delta t}{\Delta x,\Delta y} \ll 1$ is well satisfied because the electron thermal velocity in SWP is small compared to the speed of light.

As an initial plasma condition, electron energy and ion energy are set to be 1eV and 0.026eV (room temperature), respectively; the initial plasma density is uniform (n_e=n_i), set to be 10^8cm^{-3} using 36,000 simulation particles at t = 0. Ar is the discharge gas and the neutral gas pressure is set to be 0.1Torr uniformly for the entire simulation, that is, no gas flow.

4 Results

The electron density profile and electric field profile are shown in Fig.3 and Fig.4, with experimental data and simulation results, respectively. These simulation results produce good agreement with the experimental data.

In Fig.3, the electron density, starting from an initial uniform density of 10^8 cm^{-3}, has been observed to evolve to the order of 10^{11}cm^{-3} just below the dielectric line. The profile of electron density shows roughly an exponential decay along the x direction as measured in our experiments. This profile means that these electrons just below the dielectric line gain the most of the microwave energy, with enough heating to ionize, hence increase rapidly in number.

In Fig.4, the electric field without plasma, is also shown as a reference. Comparison between with plasma and without plasma makes us understand that microwaves are absorbed in the high density plasma because electric field with plasma decays more rapidly than that without plasma just below the dielectric line. The simulation data with plasma almost follows experimental data .

The simulation with plasma ran to t=60 nsec, which is 150 microwave cycles, 10^4 simulation time steps, taking about 3 hours on a DEC Alpha $200^{4/233}$ workstation.

Other preliminary results, obtained from simulation, are shown in Fig.5 - Fig.10. In Fig.5, JdotE, which is the time averaged power density deposited into the electrons, represents the heating. This heating results in the increase of the plasma density. Therefore, the peaks of JdotE are corresponding to the peaks of plasma density as seen in Fig.6 and Fig.7. The heating is not uniform in the z direction as there are standing waves along the dielectric line. That is, there are peaks and valleys of electron density along the z direction. These periodic patterns were also observed experimentally just below the dielectric line in the SWP system

As compared with Fig.8 and Fig.9, the peak value of electric fields around the high density plasma regions in Fig.8, is about 20 times higher than that in Fig.9. Electric field in Fig.9 demonstrates just microwave propagations without plasma. An accumlation of charged particles creates these peak regions. This means only electrons below the dielectric line are constrained by electromagnetic fields, which are dominant near the dielectric line. However, away from the dielectric line, electriostatic fields will be dominant.

As seen in Fig.10, this simulation has not achieved an equilibrium state yet because the number of computer particles is continuing to increase, exponentially in time. Running much longer time, it was observed that the simulation program eventually collapsed due to a numerical instability. Further work on controlling the numerical instability will be required.

5 Conclusion

A comparison was made between simulation results and experimental data containing an electron density distribution and an electric field distribution in Ar discharge. Good qualitative agreements of these discharge properties were obtained.

It was found that both distributions decayed exponentially along the x direction, perpendicular to the dielectric line. This meant the plasma distribution corresponds to the field distribution. It was also found that standing waves in the dielectric line made high density plasma and localized plasma distribution without external magnets, that was, the microwaves were strongly coupled plasma. We revealed the possibility to predict the behavior of the SWP source and to be able to design the optimum configuration by using OOPIC.

Further, we will make a comparison with other property of SWP such as distribution of electron temperature, ion energy and the dependence of pressure, gas species.

6 Acknowledgments

The author greatly appreciates useful discussions with Dr.J.Verboncoeur, Dr.V.P.Gopinath, K.Cartwright, D.Cooperberg and Prof.C.K.Birdsall at EECS Dept in University of California, Berkeley.

The author would also like to thank T.Akahori, Dr.K.Komachi, T.Ebata, Dr.Hinotani, Dr.Sato and Dr.S.Kobayashi of Sumitomo Metal Industries, Amagasaki, Japan, for supporting his visit to Berkeley, January - July 1996.

7 Reference

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8 Figure Captions

Fig.1 Schematic configration of SWP

Fig.2 SWP model for OOPIC, including initial plasma conditions

Fig.3 Distribution of plasma density Ne (at 0.1Torr Z=75mm)

Fig.4 Distribution of electric field Ex (at 0.1Torr Z=75mm)

Fig.5 Spatial profile of power deposited in the plasma by the fields

Fig.6 Number density of electrons

Fig.7 Number density of ions

Fig.8 Spatial profile of Ex with plasma

Fig.9 Spatial profile of Ex without plasma

Fig.10 Temporal evolution of the number of PIC electrons and ions

Fig.11 Poynting vector

Fig. 12 OOPIC input file

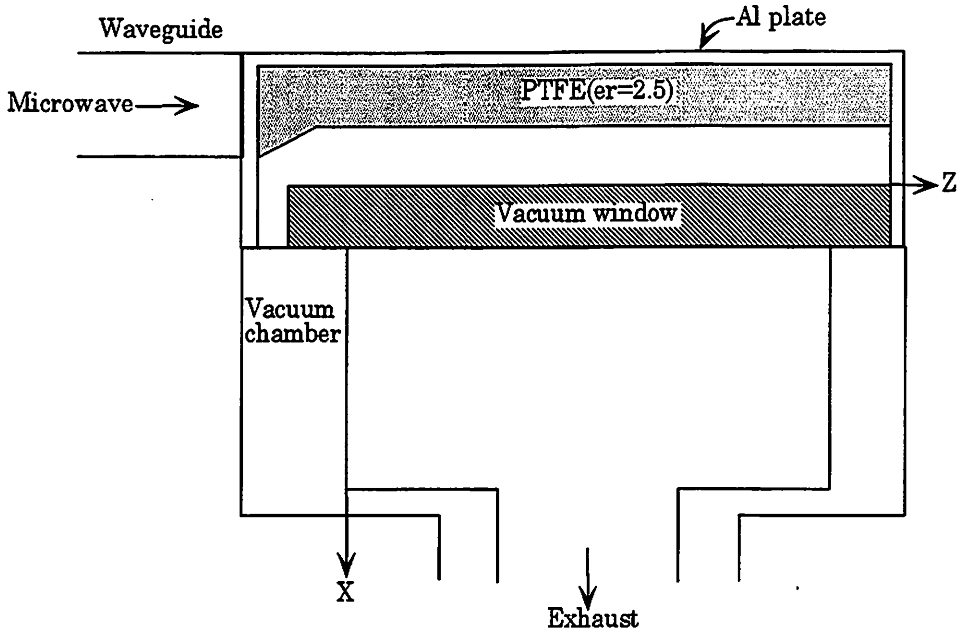

Fig1 Schematic configuraton of SWP

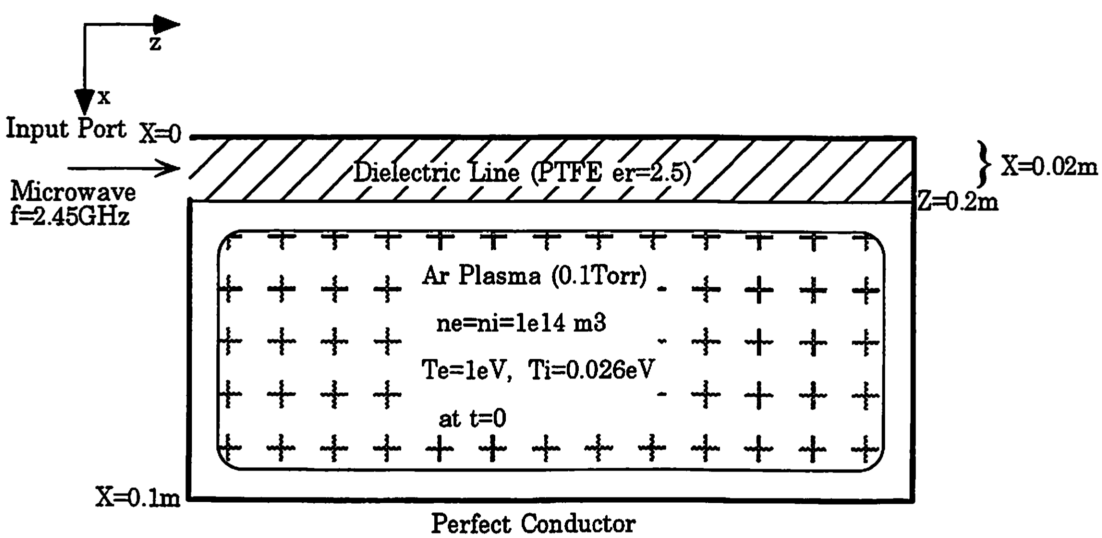

Fig2 SWP Model for OOPIC

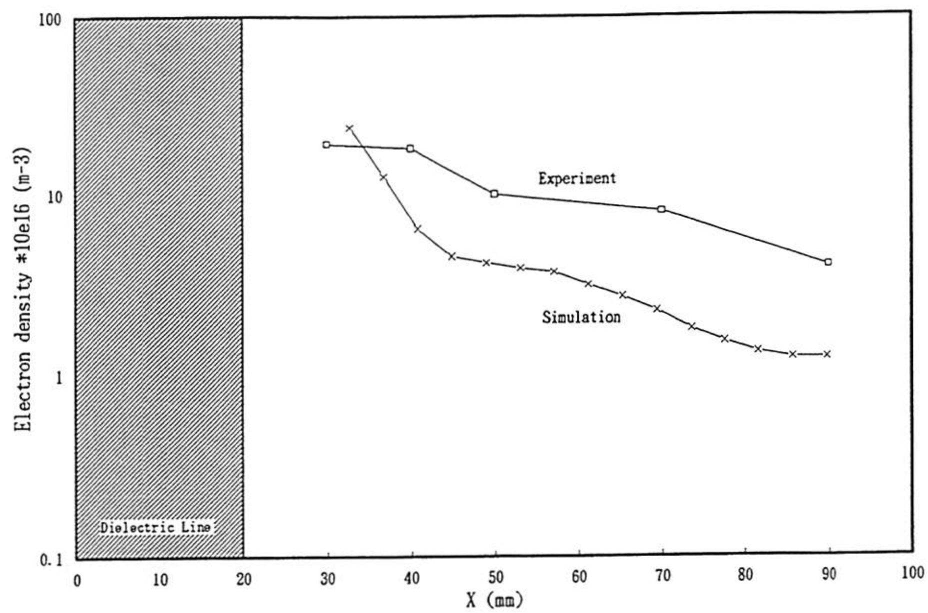

Fig.3 Distribution of plasma density Ne (at 0.1Torr Z=75mm)

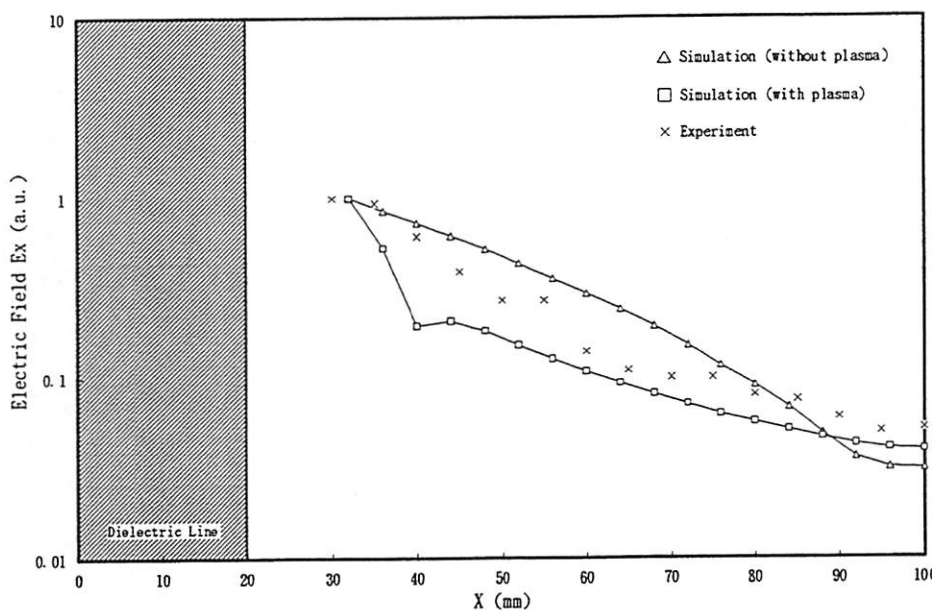

Fig.4 Distribution of electric field Ex (at 0.1Torr Z=75mm)

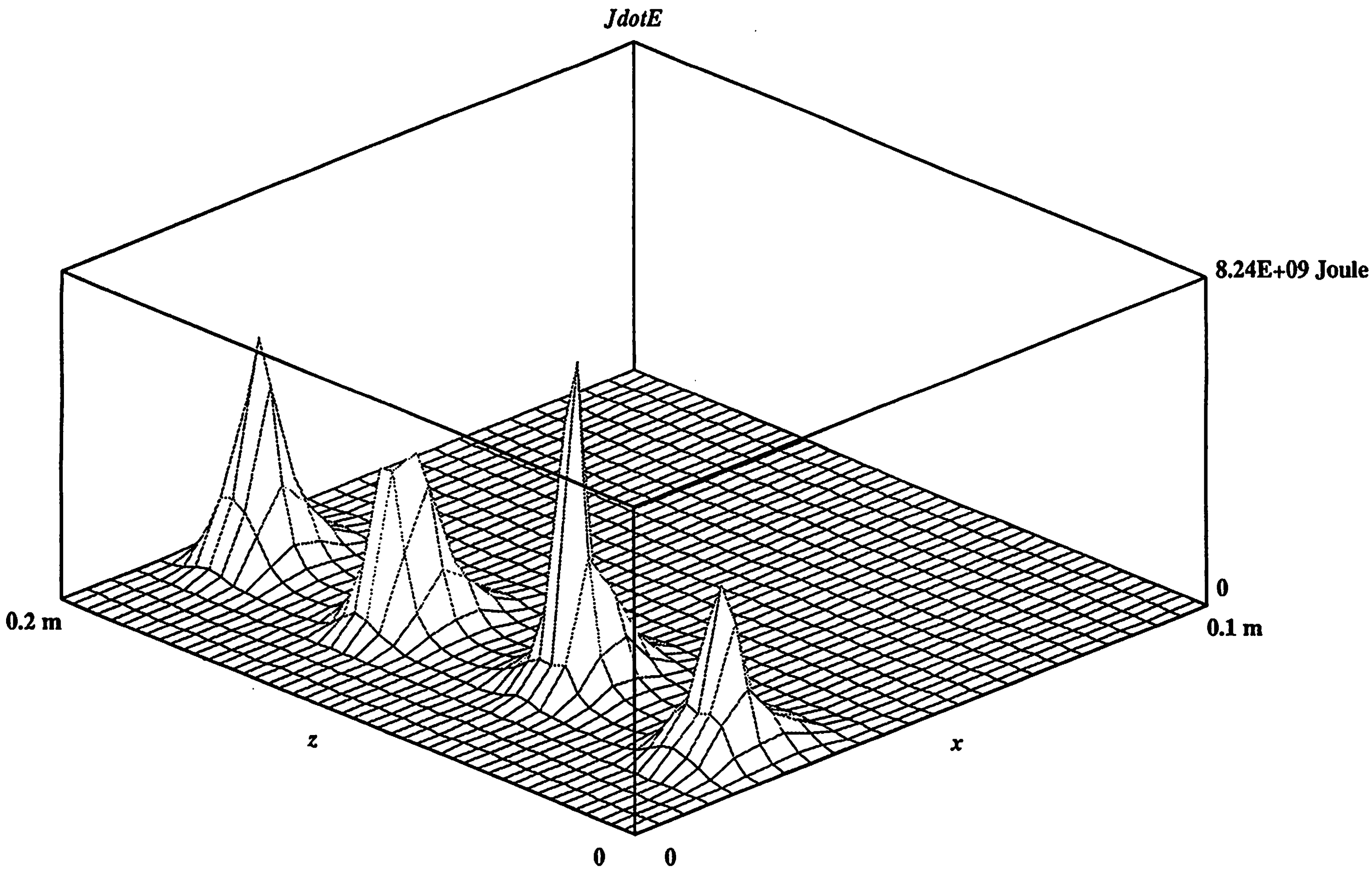

Fig.5 Spatial profile of power deposited in the plasma by the fields

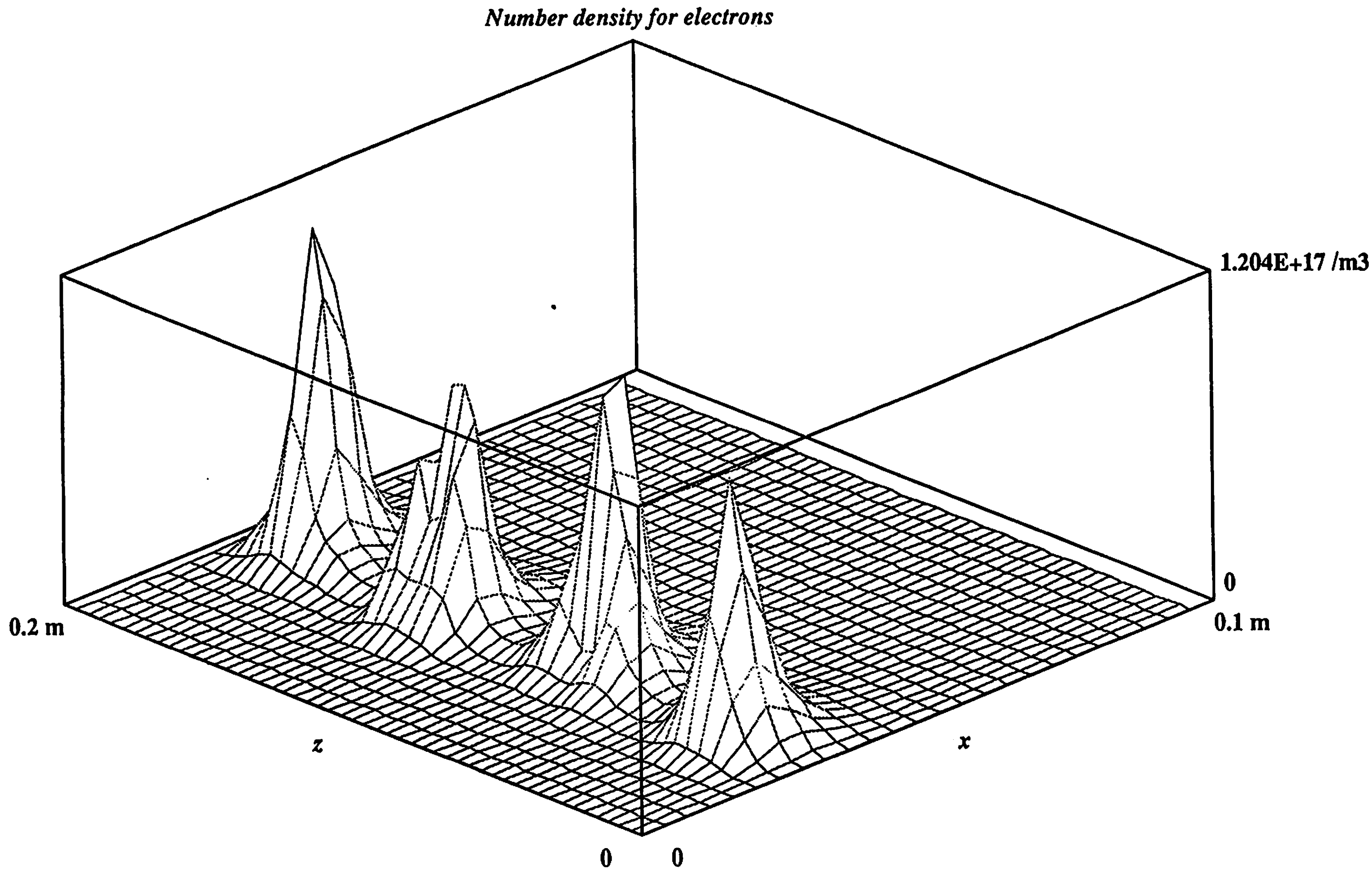

Fig.6 Number density of electrons

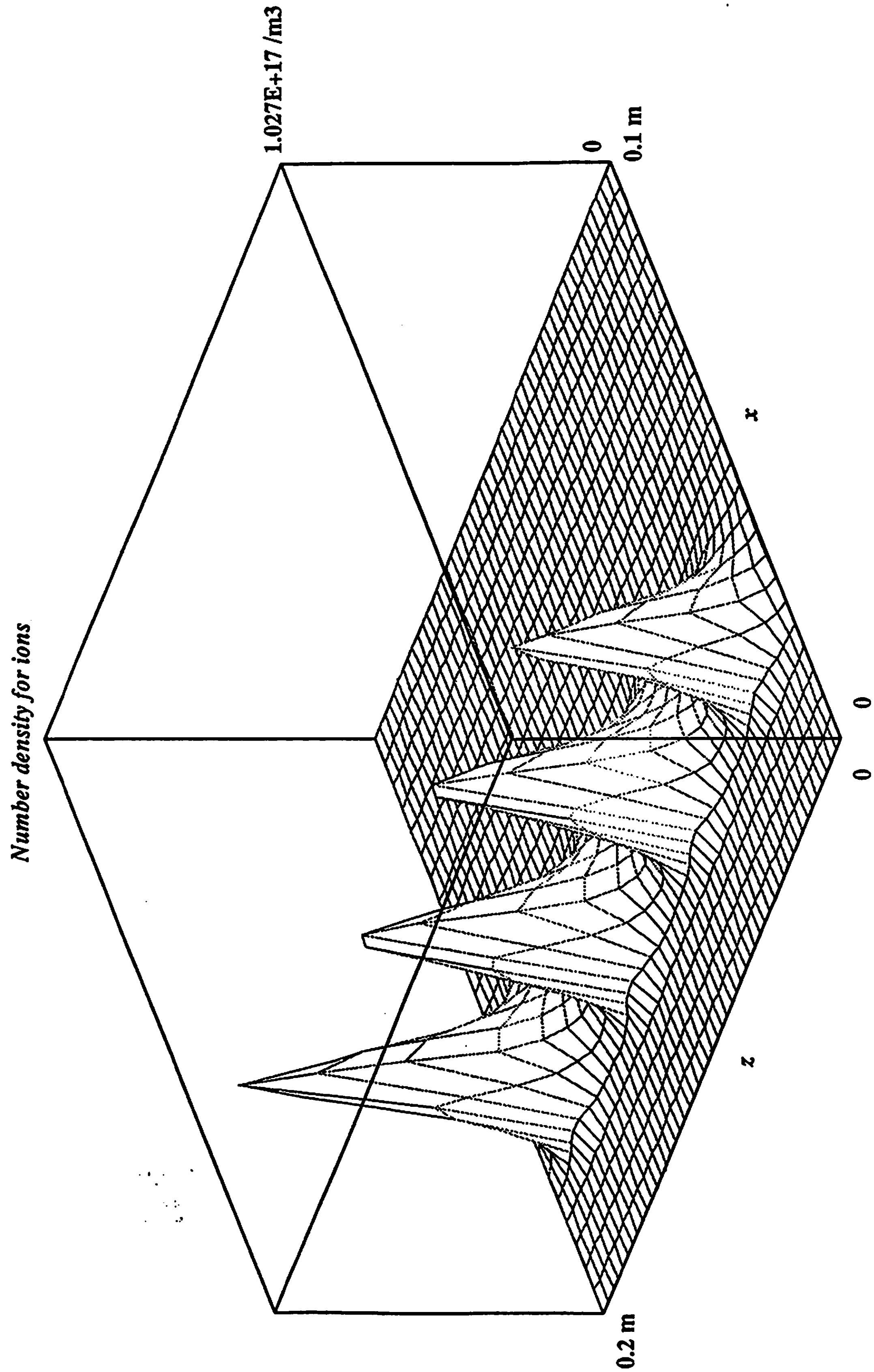

Fig.7 Number density of ions

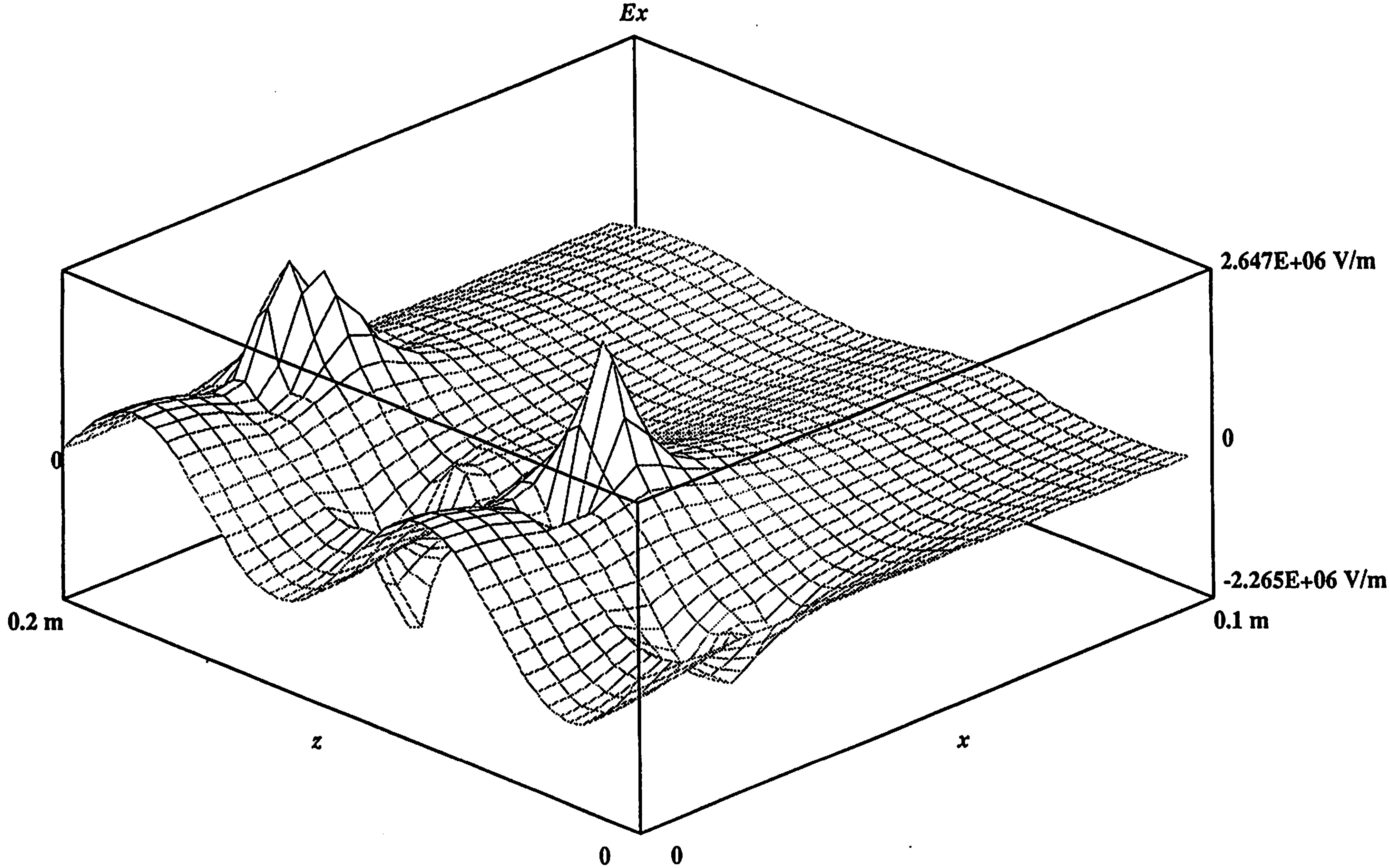

Fig.8 Spatial profile of Ex with plasma

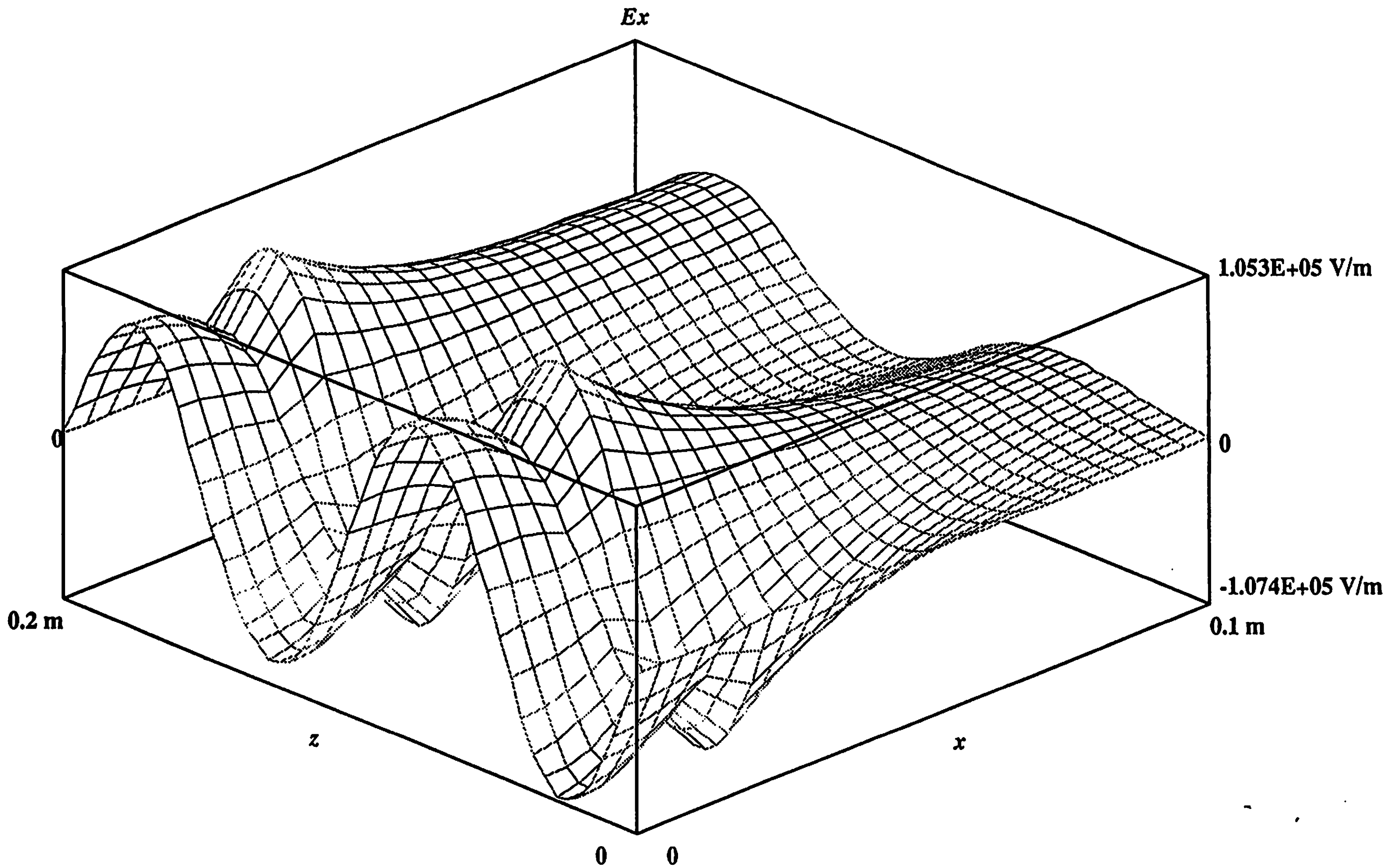

Fig.9 Spatial profile of Ex without plasma

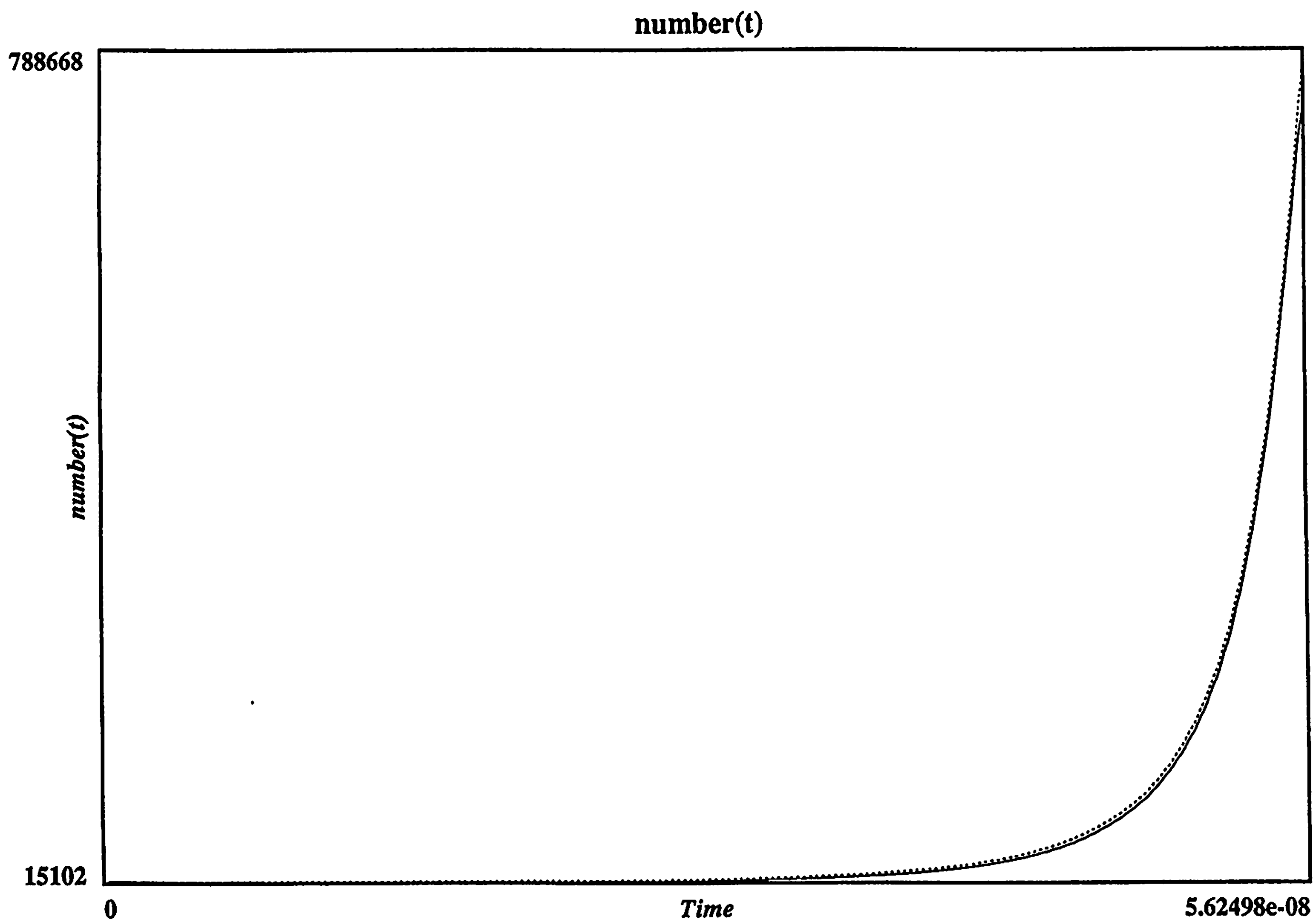

Fig.10 Temporal evolution of the number of PIC electrons and ions

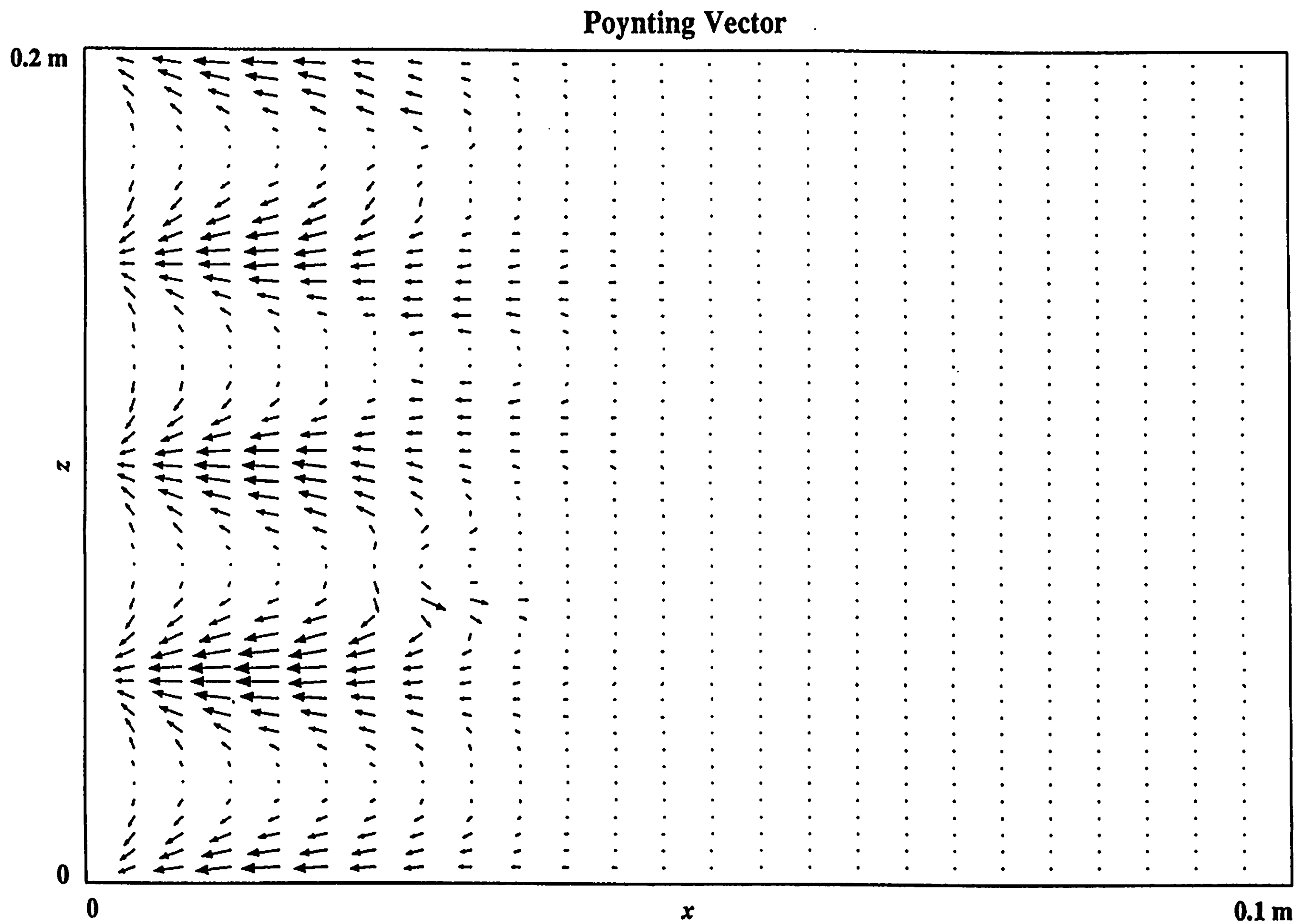

Fig.11 Poynting vector

Fig. 12 OOPIC input file

```
default
{
Simulation of Surface Wave coupled Plasma
}
Grid
{
        J = 25
        x1s = 0.0
        x1f = 0.10
        n1 = 1.0
        K = 50
        x2s = 0.0
        x2f = 0.20
        n2 = 1.0
        Rule
        {
         Limit
         n1 < 0.25
         Fatal -- n1 < 0.25 grid spacing too nonuniform to ensure accuracy
        }
        Rule
        {
         Algebra
         J * K > 10000
         Warning -- J*K >= 10000 may mean memory problems!
        }
        Geometry = 1
}
Control
{
        dt = 6e-12
        ElectrostaticFlag = 0
        gasPressure = 0.1
        eCollisionalFlag = 1
        iCollisionalFlag = 1
        FieldSubFlag = 25
        emdamping = 0
}
Species
{
        name = electrons
        m = 9.11E-31
        q = -1.6e-19
}
Species
{
        name = ions
        m = 6.626e-26
        q = 1.6e-19
}
Load
{
        speciesName = electrons
        zMinMKS = .020
        zMaxMKS = .1
        rMinMKS = .0
        rMaxMKS = .20
        vrdrift = 0
        vzdrift = 0
        vthdrift = 0
        temperature = 4.2e5
        cutoff = 0
        density = 1e14
        np2c = 1e8
}
Load
```

```
{
        speciesName = ions
        zMinMKS = .020
        zMaxMKS = .1
        rMinMKS = .0
        rMaxMKS = .20
        vrdrift = 0
        vzdrift = 0
        vthdrift = 0
        temperature = 2.5e2
        cutoff = 0
        density = 1e14
        np2c = 1e8
}
Diagnostic
{
        Comb = 1
        Ave = -1
        HistMax = -1
        title = JdotE
        j1 = 1
        k1 = 1
        j2 = 24
        k2 = 49
        VarName = JdotE
        x1_Label = X
        x2_Label = Y
        x3_Label = JdotE
}
Gap
{
        j1 = 0
        k1 = 0
        j2 = 5
        k2 = 0
        normal = 1
        frequency = 2.45e9
        A = 3e3
        C = 0
        EFFlag = 1
        name = Gap
}
DielectricRegion
{
        j1 = 0
        k1 = 0
        j2 = 5
        k2 = 50
        er = 2.5
}
Conductor
{
        j1 = 5
        k1 = 0
        j2 = 25
        k2 = 0
        normal = 1
}
Conductor
{
        j1 = 0
        k1 = 0
        j2 = 0
        k2 = 50
        normal = 1
}
```

```
Conductor
{
        j1 = 0
        k1 = 50
        j2 = 25
        k2 = 50
        normal = -1
}
Conductor
{
        j1 = 25
        k1 = 0
        j2 = 25
        k2 = 50
        normal = -1
}
```