Performance and Stability of Non-equilibrium MHD Disk Generators

by

Bor-Chyuan Lin

B.S., Mechanical Engineering
National Taiwan University (1981)
M.S., Mechanical Engineering
San Jose State University (1984)

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Signature of Author ....
Department of Aeronautics and Astronautics
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Certified by ....
Professor Manuel Martinez-Sanchez
Thesis Supervisor

Accepted by ....
Professor Harold Y. Wachman
Chairman, Departmental Graduate Committee

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Abstract

Non-equilibrium MHD disk generator operating at high Hall coefficient is prone to the formation of non-uniformities in plasma. The general effect of the existence of non-uniformity in plasma is an increase in the internal impedance of generator. Once the size of non-uniformity is comparable to the characteristic length of generator, the generator output may become unsteady.

In non-equilibrium MHD disk generators, the ionization instability has been found to be quite sensitive to the inlet stagnation temperature. At low stagnation temperatures, an ionization relaxation region near the inlet exists and this relaxation region absorbs energy due to the existence of reversal electrical field in this region. This energy absorption can induce the generator to operate in a mixed mode: absorbing power near the inlet and producing power downstream. Under these circumstances, an instability can develop. This type of instability can influence the whole channel and result in fluctuations in generator output. This type of instability is evaluated and characterized by a one-dimensional computer simulation.

The stability of non-equilibrium disk generators is studied and the resultant influence in performance is also discussed. Two schemes of stabilizing this generator instability are evaluated: 1) by operating a short inlet section open circuited and 2) by boosting the magnetic field over the same length. Both solutions are examined by the same computer simulations and the results show that the generator can be stabilized and the performance is also improved.

Thesis Supervisor: Manuel Martinez-Sanchez
Title: Professor of Aeronautics and Astronautics

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Nomenclature

B	magnetic flux density
c	sonic speed
E	electric field
e	electron charge
e^-	electron
g	statistical weight of the ground state
h	Plank's constant, channel height
I	current
j	current density
K_r	recombination coefficient
$\bar{K}$	Saha coefficient
k	Boltzmann's constant
m	particle mass
n	species number density
p	pressure
Q	collision cross-section
R	electrical resistance, gas constant
r	redius, spatial coordinate, radial direction
SF	seed fraction

T	temperature
t	time
U	flow velocity
α	degree of ionization
δ	collision loss factor
ϵ	ionization potential
θ	spatial coordinate, azimuthal direction
ν	collision frequency
ρ	mass density
σ	electrical conductivity
$\omega\tau$	Hall coefficient

Subscripts

a	working fluid, anode
c	cathode
e	electron
g	heavy component(neutrals and ions)
ia	ion of working fluid
is	ion of seed
j	species
L	external load of generator
o	stagnation condition
r	radial direction
θ	azimuthal direction

Superscripts

$+$	ion species
$\cdot$	time rate change

Chapter 1

Introduction

1.1 General Background

In close cycle MHD generators in which a noble gas, with a small amount of alkali metal as seed, is the working fluid non-equilibrium ionization occurs due to the fact that the currents flowing in the plasma preferentially heat the electrons causing the electron temperature to be much higher than that of the background gas. The elevation of the electron temperature above the gas temperature takes care of sufficient ionization of the seed and high conductivity can be reached. The high conductivity of plasma has very important consequences for MHD power generation: 1) it allows the generator to achieve high power densities with more moderate electric and magnetic fields, and 2) the generator can extract a large fraction of the inlet enthalpy over a relative short length.

The short length implies a small magnet, and therefore a low capital cost since the magnet has been found to be a dominant capital cost in MHD power generation systems. The disk generator is attractive relative to the linear one because of simplicity of construction and further reduced costs. Also, the non-equilibrium disk generators have experimentally demonstrated to extract a large portion of total flow enthalpy ($\sim 20\%$).

However, the development of the ionization instability under non-equilibrium conditions will influence the behavior of generator. The stability of the two-temperature plasma with respect to wave-like perturbations of the electron temperature and electron density was first studied by Kerrebrock [1]. He showed, using linear perturbation analysis, that under non-equilibrium conditions the argon-cesium plasma is unstable if the Hall coefficient exceeds a certain critical value. The critical value of the Hall coefficient is a function of the plasma properties and is found to be between 1 and 2 for many noble gas plasmas of interest [2, 3].

The performance of non-equilibrium MHD disk generators requires them to operate at values of Hall coefficient appreciably larger than one but for values below the threshold of appreciable ion slip. At such high Hall coefficients, the ionization instability is prone to develop. The growth rate of ionization instability is fast and fluctuations in several plasma parameters grow. The fluctuations of plasma properties, through interation with the local electric and magnetic fields, can result in the formation of large scale non-uniformities. Mechanism for the creation of non-uniformity in plasma has been extensively discussed by Louis [4]. These non-uniformities increase the internal resistance of the generator and may result in some fluctuations in the current output of the generator. Once the scales of non-uniformities are large comparable to the characteristic length of the generator, the fluctuations in the output may become violent. Consequently, the formation of non-uniformities in plasma seriously influences the performance of the generator. One example is the streamers observed experimentally in the linear Faraday generators. Large fluctuations can be seen in the voltage output of those electrodes connected by the streamers.

In non-equilibrium MHD generators, the ionization instability has been found to be quite sensitive to the inlet stagnation temperature [3], to the seed concentration, and to the loading situation [5, 6] of the generators. It is now well known theoretically and experimentally [7, 8] that the ionization instability does not significantly grow when the seed is close to full ionization. When the inlet stagnation temperature is high enough, a level of ionization close to full seed ionization can be maintained through the generator and stable operation can be reached. Whereas, at lower stagnation temperatures, an ionization relaxation region near the inlet exists. This relaxation region, characterized by a reversal of local electric field, absorbs the energy of ionization. This energy absorption can induce the generator to operate in a mixed mode: absorbing power at the inlet and producing power downstream. Under these circumstances, an instability of the device can develop. This type of instability can influence the whole channel, enhance the unsteadiness of output current ,and reduce the total power generation.

Therefore, the overall stability of non-equilibrium MHD generators depends not only on the stability of the bulk of plasma but most importantly on the operation of the ionization relaxation region under very strigent conditions.

1.2 Present Work

A one-dimensional time-dependent simulation of the non-equilibrium disk generator is first developed to evaluate and characterize the generator instability associated with the existence of reverese electric field in the relaxation zone. The model solves the unsteady equations for both electron and working gases. The important assumptions made are low magnetic Reynolds number, quasi-neutrality of the plasma, negligible ion slip effect, and insignificant radiation losses.

Configurations to eliminate the instability are also evaluated. The configurations are designed to obtain a high level of ionization at the entrance of the generator. The first configuration operates the inlet relaxation zone as an open-circuited device with maximum dissipation. The second configuration increases the magnetic field over the relaxation region to provide a local high rate of dissipation.

Both solutions are investigated using the simulation and they are found to eliminate the generator instability under the right conditions and to improve the overall performance of the generator.

1.3 Working Fluid

Noble gases have been widely accepted as the working fluid for non-equilibrium MHD power generation due to their high ionization potentials and small values of the collision loss factor. This small collision loss factor helps the elevation of electron temperature above gas temperature. Because of lower cost and ready availability, helium or argon has been exclusively considered as a working fluid. The main difference between argon and helium plasma derives from the atomic weight and from the Ramsauer effect in argon which results in very small momentum cross-section for collisions with low energy electrons. Therefore, the electron mobility is much larger in argon than in helium particularly for low seed concentration at temperatures of 2000 K and below. However, as the electron temperature increases, the degree of ionization increases and Coulomb collisions become important. Under these conditions, the mobility in helium and in argon converges. For example, the mobilities of helium and argon seeded with 0.5 % cesium are almost equal at an electron temperature in excess of 3500 K. The most typical electron temperature range in a non-equilibrium MHD generator is between 3000 to 5000 K.

Due to the light weight of helium, if Mach number and stagnation conditions are the same, a helium plasma can produce higher power density compared with an argon plasma. Fig.1.1 [9] indicates the much improved performance of helium generators over argon generators. This high power density makes a helium gas generator very compact and thus reduces its cost.

The comparison of Fig.1.2 with Fig.1.3 from reference 4 indicates that helium

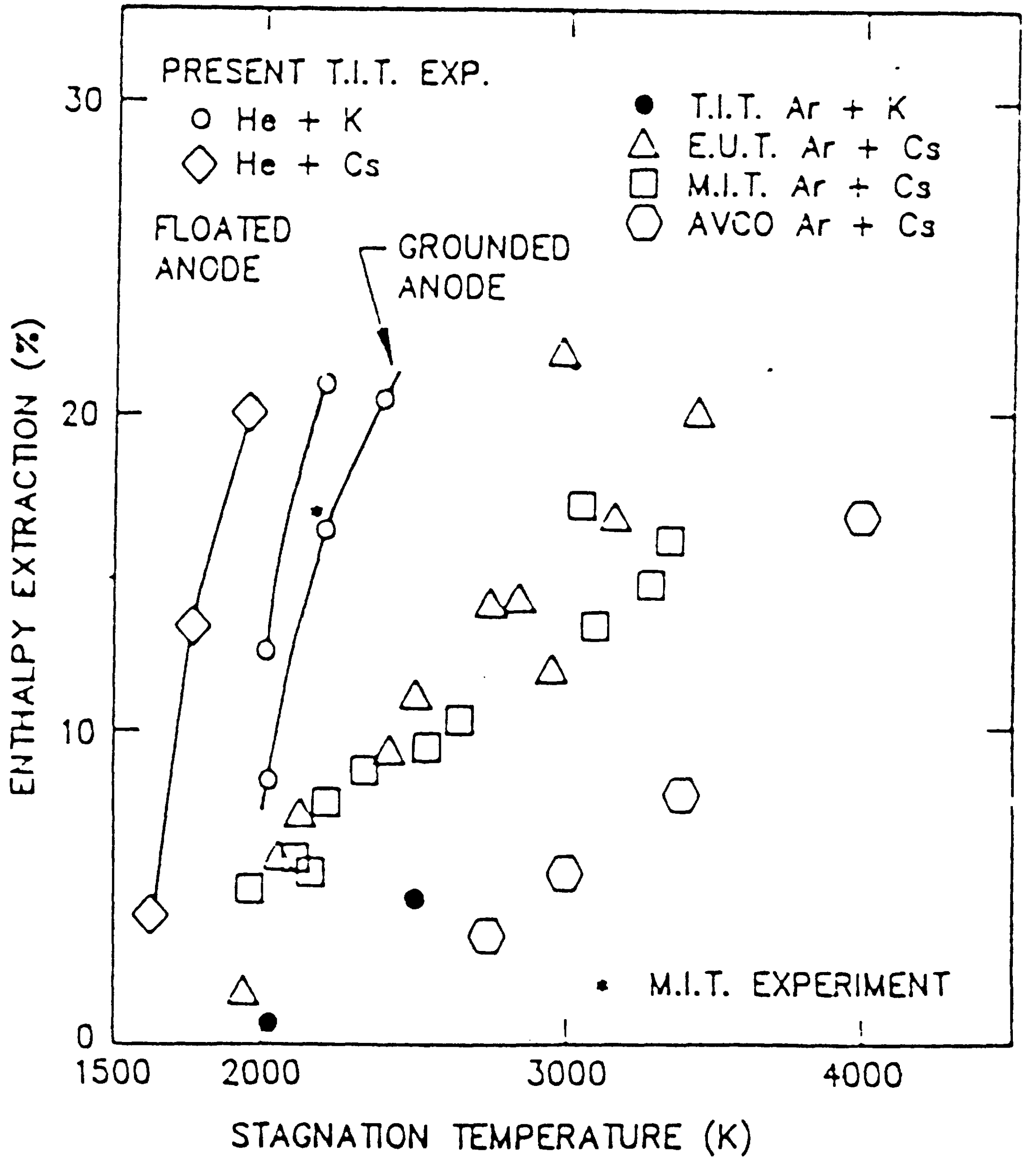

Figure 1-1: Progress in energy extraction - disk generator

can provide wider range of electron temperature for plasma stability than argon when the seed material is close to full ionization. The use of helium also avoids the occurence of the static instability which will occur in argon when $T_e > 3/2T_g$ and the degree of seed ionization is high [2].

Based on these facts, helium-cesium plasma seems to be a promising choice as a working fluid for non-equilibrium MHD power generation. We will use this plasma in our study.

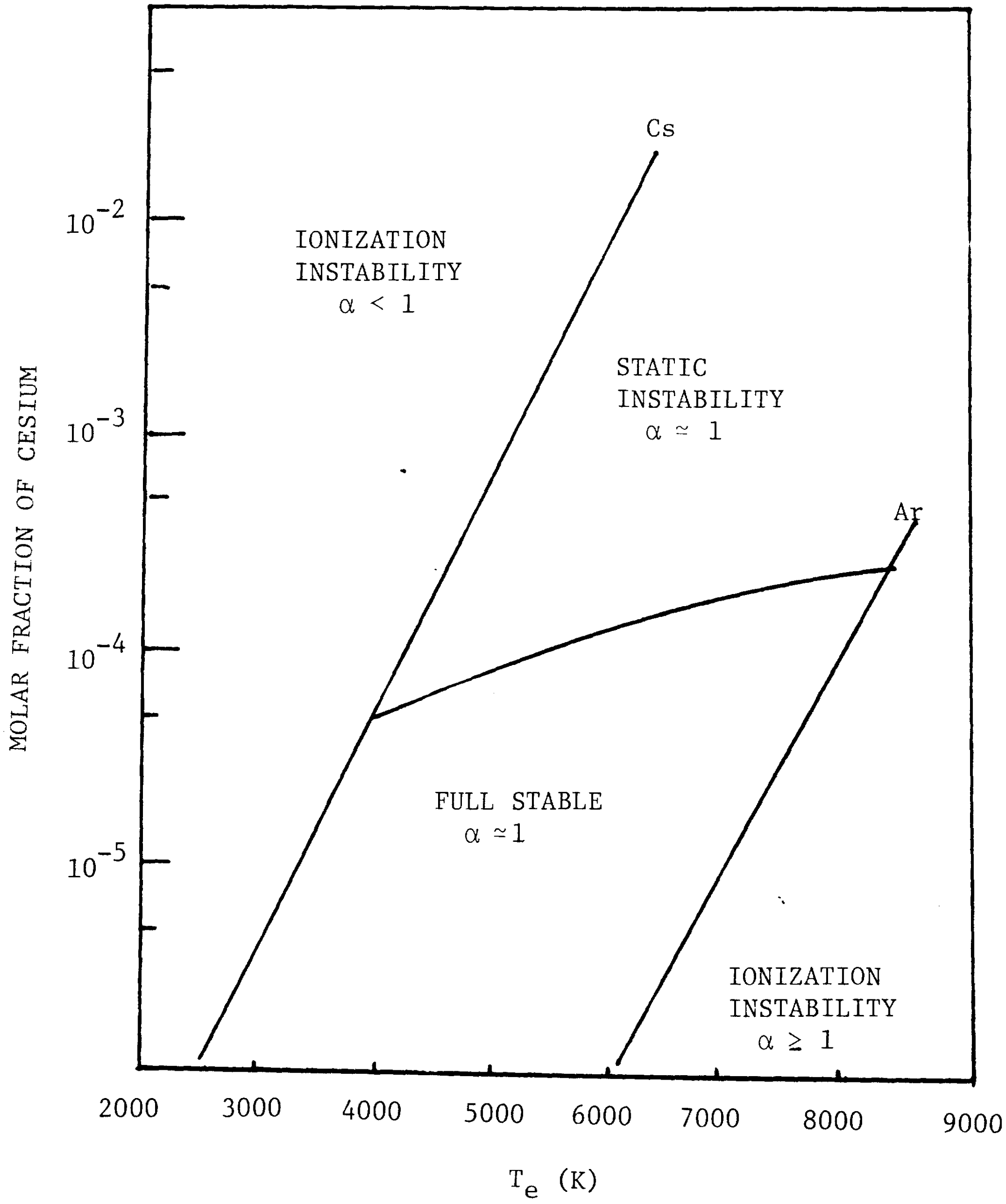

Figure 1-2: Stability map of argon-cesium plasma

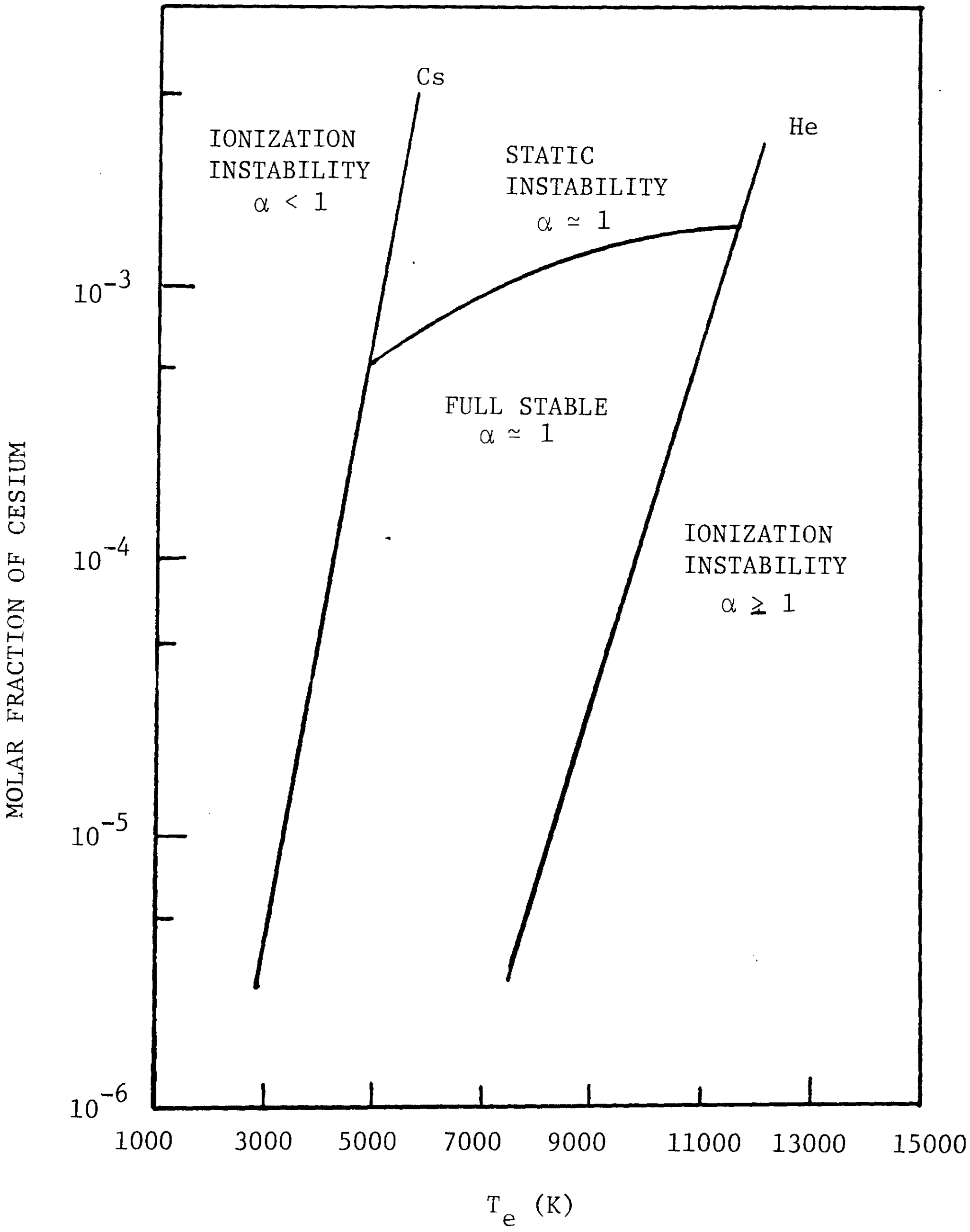

Figure 1-3: Stability map of helium-cesium plasma

Chapter 2

Stability of Non-equilibrium Disk Generators

2.1 Non-uniformity and Instability of Generators

The nature of non-uniformities in non-equilibrium generators has been extensively discussed by Louis [4, 10]. These non-uniformities basically result from the fluctuations of plasma properties, which are themselves due to the existence of any instability developed in the plasma or of an externally applied disturbance, through interactions with the local electric and magnetic fields. The general effect of the existence of non-uniformities is an increases in dissipation and an increase in the average internal resistance of the generator. Of particular concern is the size of the non-uniformity, that is, if the size of the non-uniformity is large enough to become comparable with the characteristic length of the generator, the output voltage of the generator can be unsteady and the performance can be influenced seriously.

A computer experiment was performed by Lin and Louis [11] to see the formation of a large-scale non-uniformity resulting from an externally created hot spark spot in an initially uniform plasma. The results shown in Fig.2.1 indicate that a large fraction of the surrounding current flows into the spot and that eddy currents driven by the Hall effect further increase the current flow into the spot. It can be seen that the non-uniformity has grown and the current streamlines are disturbed over the whole channel height. This large scale non-uniformity significantly reduces the generator output as shown in Fig.2.2 where X is the distance along the flow direction and J_y is the Faraday current density in the infinite-segmented linear generator considered.

Among the different kinds of plasma instabilities being examined in closed-cycle MHD power generation, the ionization instability has been found to contribute significantly to the instability problem of generators. To avoid the occurence of ionization instability, operation near full seed ionization has been proposed and stable plasma conditions have been experimentally reached [7, 8]. The total degree of ionization remains constant over a range of electron temperature in which the seed is fully ionized. In this full ionization range, the plasma is stable as long as the electron temperature fluctuations are limited in amplitude and the seed fraction is low enough to avoid Coulomb collision dominated conditions, under which the plasma may be subject to a static instability. Therefore, the stability concern favors operating a generator with low seed fraction ($10^{-5} \sim 10^{-4}$). The use of such a small amount of alkali seed provides conductivities in excess of 100 mho/m when full seed ionization is reached for an electron temperature around 4000 K with cesium seed. At that condition, the bulk of plasma can be stable and uniform in the generator for most cases.

However, according to the analysis of Louis in reference 4, for a singly loaded disk generator, a Hall generator, operating with a stable fully ionized plasma, the generator was found to be relatively unstable to a change in total current or to a small variation in the inlet ionization level because that Joule dissipation goes through a minimun for a local load coefficient corresponding to the load short circuit condition. The generator can revert from a stable mode to a mixed

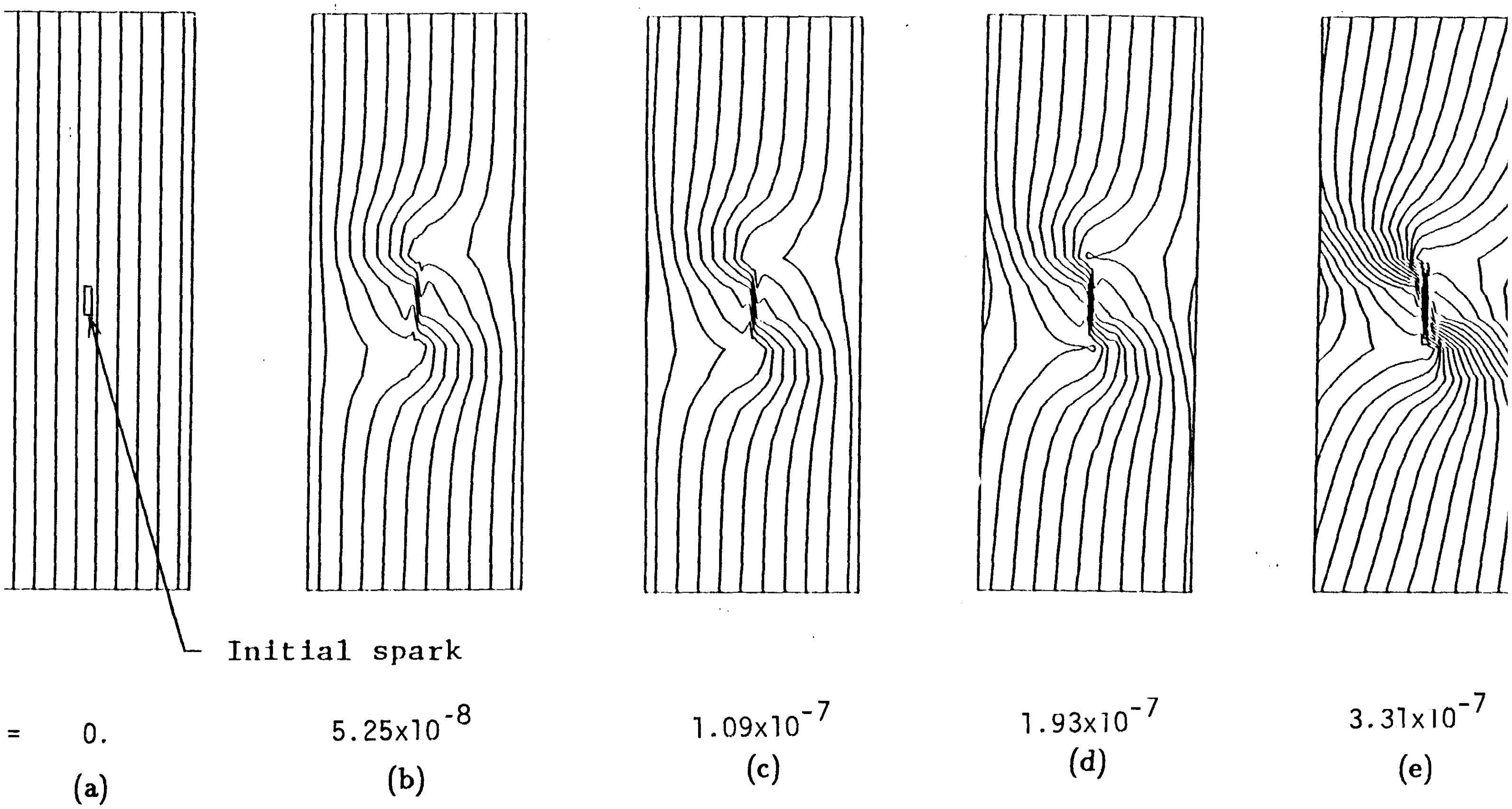

Figure 2-1: The development of current streamline ($\Delta\Phi = 46\frac{A}{m}$). Time=(a) 0. (b)0.53 (c)1.09 (d)1.93 (e)3.31 $\times 10^{-7}$ sec

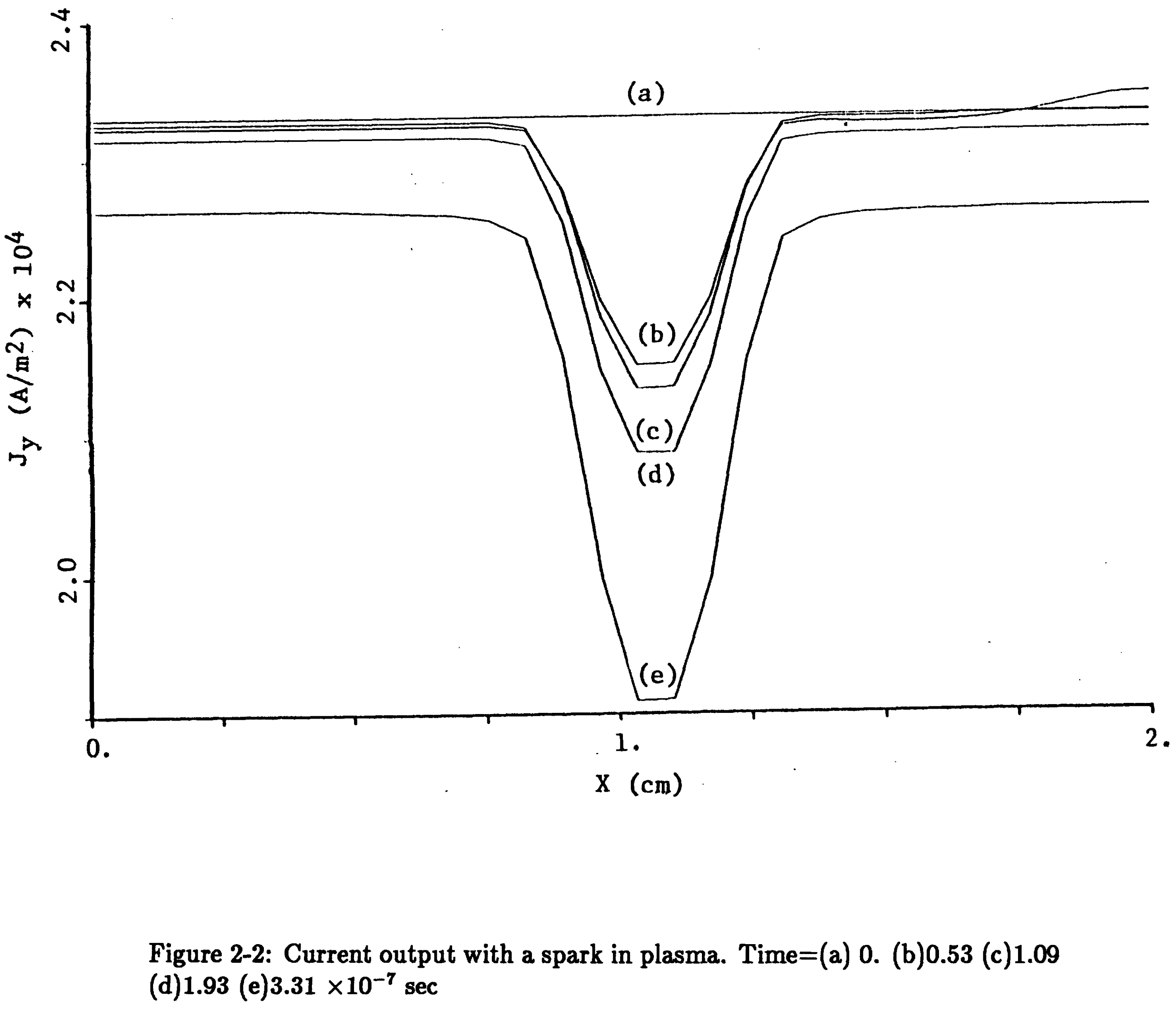

Figure 2-2: Current output with a spark in plasma. Time=(a) 0. (b)0.53 (c)1.09 (d)1.93 (e)3.31 $\times 10^{-7}$ sec

mode in which the inlet absorbes power. Experimental data [3] shown in Fig.2.3 confirm the possibility of conversion between two modes. This type of instability influences the whole generator and may be cyclic under some circumstances.

Therefore, although it is now well known that the bulk of the plasma can be stable when it reaches full seed ionization, it remains to be demonstrated that the devices as a whole can be made stable under more stringent conditions.

The stability of the generator as a whole can be influenced by the existence of an ionization relaxation zone located at the entrance of the disk generator. In the relaxation zone, the ionization process goes unstable and the non-equilibrium ionization is found to be non-uniform. Under the influence of non-uniformities, the plasma is more resistive and the relaxation length is longer than it would have been in the absence of non-uniformities. However, the characteristics and the interrelations between the formation of non-uniformities the existence of a inlet relaxation zone are still not well understood so that the relaxation length can not be predicted with reasonable accuracy at this time.

2.2 Stability Schemes

To eliminate this generator instability caused by the existence of reverse electric field in the relaxation region, the basic idea is to obtain a high level of ionization at the generator entrance in order to relax the plasma in a shorter distance. Three different ways are proposed to stabilize the disk generator:

1) by increasing the inlet temperature which raises the inlet level of ionization considerably and reduces the impedance and the length of the relaxation region;

2) by operating the inlet section of generator open-circuited and by moving the anode downstream of the relaxation region;

3) by boosting the magnetic field over the relaxation region in order to reach full seed ionization fast.

The first scheme has been experimentally demonstrated [3] and some of the

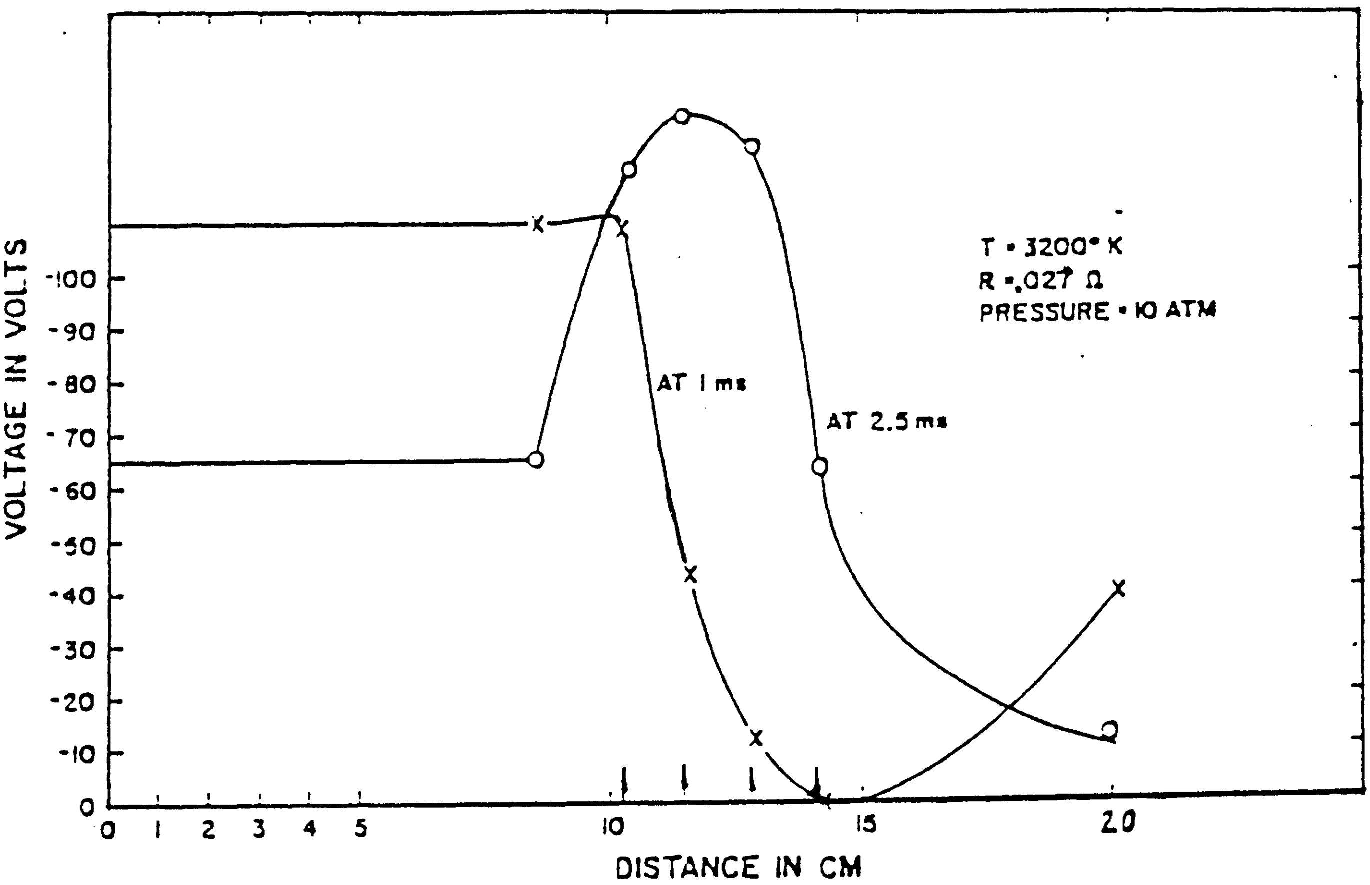

Figure 2-3: Radial voltage distributions at 2 moments

results are shown in Fig.2.4. The data indicate that for stagnation temperatures of 2720 K and below, the electric field at the inlet is positive indicating that energy is being absorbed within the ionization relaxation zone, whereas for high stagnation temperatures of 3600 and 3100 K, the device operates as a generator over the active length. It was also found in the same experiment that electric field and electron density fluctuations are very large when energy is absorbed in the inlet relaxation region in constrast to very small fluctuations when the device operates in a single generator mode.

The second scheme is to open circuit the inlet of the disk generator (no local radial current) so that the Joule heating is maximum and equal to $\sigma U_r^2 B^2$. This condition promotes the rapid relaxation to full seed ionization. The anode will have to be located downstream of this relaxation region.

In conventional disk generators, the electrical field reverses in the inlet region and at the point where the electric field is zero the Joule heating is $\frac{\sigma U_r^2 B^2}{1+\omega\tau^2}$ which indicates that for $\omega\tau \simeq 3$, the Joule heating is one order of magnitude smaller than for the open circuit condition and obviously it will be difficult for plasma to relax under these circumstances.

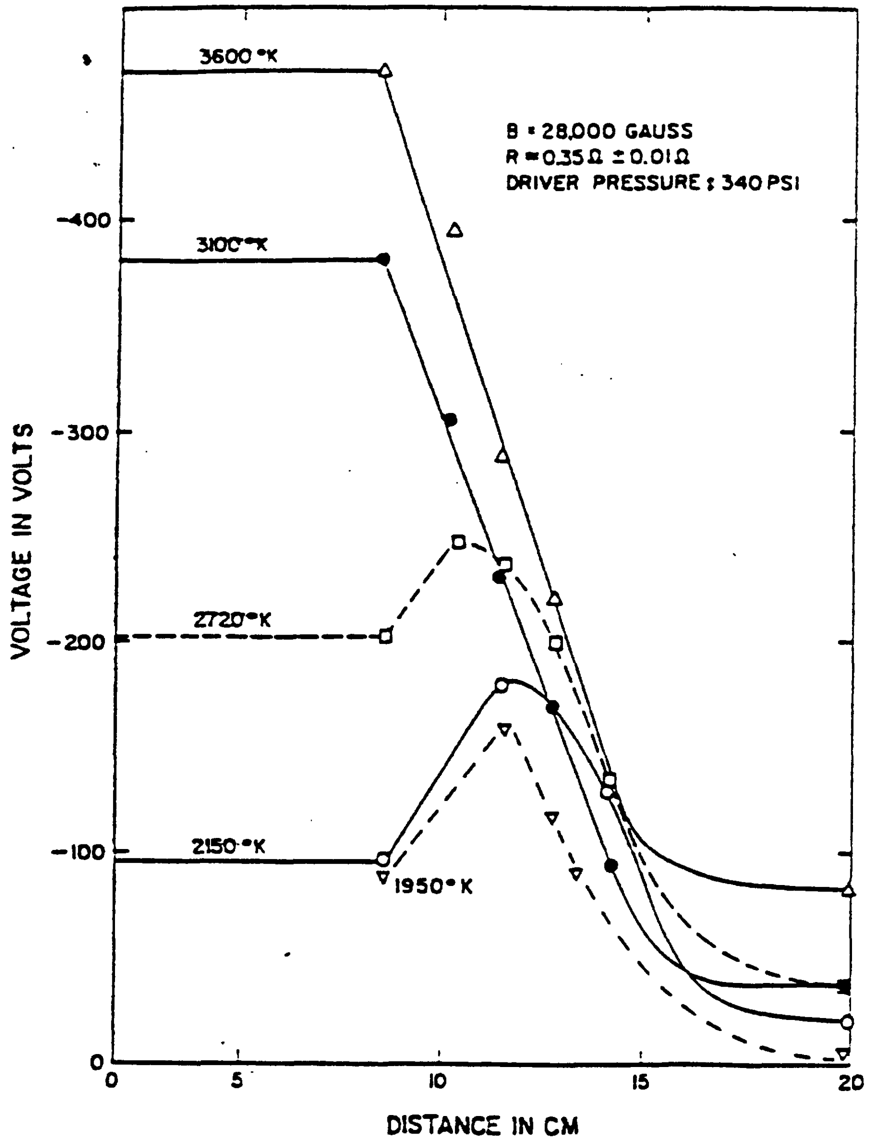

Figure 2-4: Radial voltage distribution for different stagnation temperatures (load=0.35 ohm)

Chapter 3

Mathematical Description of Non-equilibrium MHD Disk Generators

The non-equilibrium MHD disk generator is modeled by using the two-temperature mode in a time dependent quasi-one-dimensional scheme. The helium-cesium plasma is primarily composed of electrons, ions (Cs and He), and neutrals (Cs and He). The electron temperature is different from the temperature of heavy components (ions and neutrals).

3.1 Channel Model and Important Assumptions

The channel of the disk generator for calculation is shown in Fig.3.1. In the calculation, the disk channel is taken to have 15 cm as the inlet radius, 10 cm the channel length, and 5 cm the channel height even though the channel height can be variable along the radial direction.

The important assumptions made in the model are low magnetic Reynolds number, charge neutrality, negligible ion slip, and insignificance of radiative

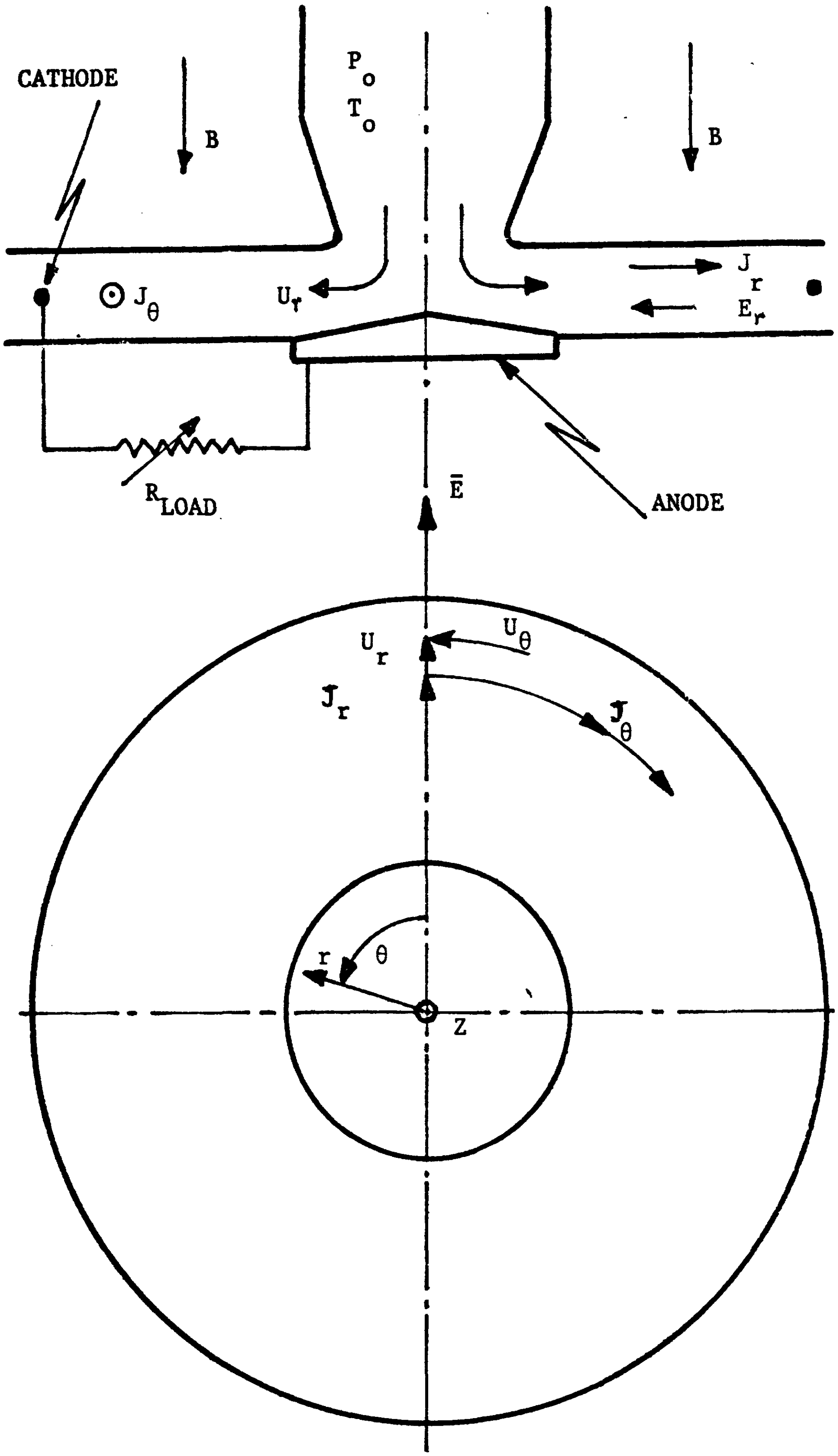

Figure 3-1: Schematic of a radial flow MHD disk generator

losses. A constant seed fraction is used and homogeneous mixing between seed and working gas throughout the channel is assumed. The magnetic field perpendicular to the calculating surface is uniform and constant in time. The external load is also fixed through the calculation. All the plasma properties are varied only along the radial direction in the one-dimensional model.

3.2 Formulation

The governing equations can basically be classified into the equations which determine the electrical properties and the equations which determine the gasdynamic properties. The former include Ohm's law, Maxwell equations, conservation of charge, the kinetic equation for the production of each species of charged particles, and the electron energy balance without radiation effects; while the latter include the general continuity, momentum and energy conservation equations with MHD effects, and the state equation. All these equations can be written in the one-dimensional form as follows:

conservation of radial current and charge

$$I = 2\pi r h J_r \tag{3.1}$$

$$n_e = n_{ia} + n_{is} \tag{3.2}$$

continuity of ion species

$$\frac{\partial n_{ia}}{\partial t} = -U_r \frac{\partial n_{ia}}{\partial r} - n_{ia}\frac{\partial U_r}{\partial r} - \frac{n_{ia}U_r}{h}\frac{\partial h}{\partial r} - \frac{n_{ia}U_r}{r} + \dot{n}_{ia} \tag{3.3}$$

$$\frac{\partial n_{is}}{\partial t} = -U_r \frac{\partial n_{is}}{\partial r} - n_{is}\frac{\partial U_r}{\partial r} - \frac{n_{is}U_r}{h}\frac{\partial h}{\partial r} - \frac{n_{is}U_r}{r} + \dot{n}_{is} \tag{3.4}$$

Ohm's law

$$E_r = (\omega\tau\, J_\theta + J_r)/\sigma - BU_\theta \tag{3.5}$$

$$J_\theta = -\sigma U_r B + \omega\tau\, J_r \tag{3.6}$$

electron energy

$$\frac{J_r^2+J_\theta^2}{\sigma} = (\frac{3}{2}kT_e+\epsilon_a)\dot{n}_{ia}+(\frac{3}{2}kT_e+\epsilon_s)\dot{n}_{is}+\frac{3}{2}\delta n_e m_e k(T_e-T_g)\sum_j \frac{\nu_{e-j}}{m_j}, \quad j=a,ia,s,is \tag{3.7}$$

and the general gasdynamic equation including MHD effect

$$\frac{\partial \rho}{\partial t} = -U_r\frac{\partial \rho}{\partial r} - \rho\frac{\partial U_r}{\partial r} - \frac{\rho U_r}{r} - \frac{\rho U_r}{h}\frac{\partial h}{\partial r} \tag{3.8}$$

$$\frac{\partial U_r}{\partial t} = -U_r\frac{\partial U_r}{\partial r} + \frac{U_\theta^2}{r} - \frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{1}{\rho}J_\theta B \tag{3.9}$$

$$\frac{\partial U_\theta}{\partial t} = -U_r\frac{\partial U_\theta}{\partial r} - \frac{U_r U_\theta}{r} - \frac{1}{\rho}J_r B \tag{3.10}$$

$$\frac{\partial T_g}{\partial t} = -U_r\frac{\partial T_g}{\partial r} - \frac{2}{3}T_g(\frac{\partial U_r}{\partial r} + \frac{U_r}{r} + \frac{U_r}{h}\frac{\partial h}{\partial r}) + \frac{2}{3\rho R}\frac{J_r^2+J_\theta^2}{\sigma} \tag{3.11}$$

where

$$\sigma = \frac{n_e e^2}{m_e \nu_e} \tag{3.12}$$

$$\omega\tau = \frac{eB}{m_e \nu_e} \tag{3.13}$$

$$\nu_e = \nu_{e-a} + \nu_{e-s} + \nu_{e-ia} + \nu_{e-is} \tag{3.14}$$

$$\nu_{e-j} = n_j Q_j \sqrt{\frac{8kT_e}{\pi m_e}} \quad j=a,s,ia,is \tag{3.15}$$

In our analysis, the collision cross section Q_j's are chosen as (in MKS unit)[13]

$$Q_a = 5.4 \times 10^{-20}\ m^2 \ \text{(for He)} \tag{3.16}$$

$$Q_s = 400 \times 10^{-20}\ m^2 \ \text{(for Cs)} \tag{3.17}$$

$$Q_{ia} = Q_{is} = 5.85 \times 10^{-10}\frac{\ln \Lambda}{T_e^2}, \tag{3.18}$$

where $\Lambda = 1.24 \times 10^7 n_e^{-\frac{1}{2}} T_e^{\frac{3}{2}}$ [14] and Q_a and Q_s are assumed to be constant in the range of electron temperature which the generator operates.

The ionization kinetics are assumed to be dominated by three-body recombination reactions of the form

$$\mathrm{Cs} + \mathrm{e}^- \rightleftharpoons \mathrm{Cs}^+ + \mathrm{e}^- + \mathrm{e}^- \tag{3.19}$$

$$\mathrm{He} + \mathrm{e}^- \rightleftharpoons \mathrm{He}^+ + \mathrm{e}^- + \mathrm{e}^- \tag{3.20}$$

That is, helium and cesium are considered ionizable while electrons are assumed as the third body. The rate equations, $\dot{n}_{ia}$ and $\dot{n}_{is}$, then become

$$\dot{n}_{ia} = K_r n_e (\bar{K}_a n_a - n_{ia} n_e) \tag{3.21}$$

$$\dot{n}_{is} = K_r n_e (\bar{K}_s n_s - n_{is} n_e) \tag{3.22}$$

where $\bar{K}$ and K_r are the Saha and the recombination coefficients respectively. They are calculated as

$$\bar{K}_a = \frac{2g_{ia}}{g_a} \left(\frac{2\pi m_e k T_e}{h^2}\right)^{\frac{3}{2}} \exp\left(-\frac{\epsilon_a}{kT_e}\right) \tag{3.23}$$

$$\bar{K}_s = \frac{2g_{is}}{g_s} \left(\frac{2\pi m_e k T_e}{h^2}\right)^{\frac{3}{2}} \exp\left(-\frac{\epsilon_s}{kT_e}\right) \tag{3.24}$$

and

$$K_r = 1.09 \times 10^{-20} T_e^{-4.5} \; m^6/s \tag{3.25}$$

where ϵ_a and ϵ_s are the ionization potentials of helium and cesium gases, h is Plank's constant, g_a, g_s, g_{ia}, and g_{is} are the statistical weights of the ground state of helium atom, cesium atom, helium ion, and cesium ion respectively.

Also noted is that in the derivation of the electron energy equation, the spatial gradients and the the temporal change of electron temperature are neglected [15].

The electromotive potential produced by the channel should be equal to the potential drop across the external load, i.e.

$$IR_L = -\int_{r_a}^{r_c} E_r \, dr \tag{3.26}$$

By substituting equations (3.1),(3.5) and (3.6) into (3.26),we can calculate the total current in terms of the plasma properties as

$$I = \frac{\int_{r_a}^{r_c} (\omega\tau B U_r + B U_\theta) \, dr}{\int_{r_a}^{r_c} (1 + (\omega\tau)^2)/(2\pi r h \sigma) \, dr + R_L} \tag{3.27}$$

The problem is now formulated in terms of 10 state variables n_e, n_a, n_{ia}, n_s, n_{is}, ρ, U_r, U_θ, T_e, T_g and 3 electrical variables J_θ, E_r, and I. The equations to solve these variables are equations (3.2) to (3.11) with (3.26) and 2 additional definitions for mass density

$$\rho = \sum_j m_j n_j \quad j = a, s, ia, is \tag{3.28}$$

and seed fraction

$$SF = \frac{n_a + n_{ia}}{n_s + n_{is}} \tag{3.29}$$

The whole system is then closed. As for the radial current density J_r, it can be determined from the current conservation equation (3.1) after the total current is found and the geometry of the channel is specified.

3.3 Calculating Process

3.3.1 Initial Condition (time=0)

At time = 0^-, the gasdynamic expansion of the working fluid through the channel is assumed to follow the isentropic relationship and the gasdynamic properties can be decided after the geometry of the channel and stagnation conditions are assigned. At this moment, there is no azimuthal flow and the plasma is considered to follow Saha equilibrium relation.

3.3.2 Duration of MHD Interaction (time>0)

At time $= 0^+$, the non-equilibrium ionization begins and the MHD efects are included in the determination of gasdynamic properties. The calculating process is advanced by a time scale limited by

$$\Delta t \leq \frac{\Delta r}{U_r + c}, \left(\frac{\partial \dot{n}_j}{\partial n_j}\right)^{-1} \quad j = ia, is, e \tag{3.30}$$

for each step. At each time step, the system of formulas described in the preceding section are applied to find the new value for each variable. Nevertheless, at the channel inlet point, the gasdynamic properties are kept constant and Saha equilibrium is also used.

Chapter 4

Results

4.1 Single Load Disk Generator

The results given in Fig.4.1(a) are the temporal fluctuations of current output of a He-Cs generator. The operating conditions for this generator are stagnation temperature 2000 K, stagnation pressure 5 atm, inlet Mach number 1.6, B field 1.5 T, Seed fraction 1×10^{-4}, and a single external load 1.0 ohm. Fig.4.2 shows the corresponding radial distributions of Hall potential at different times in a current output period chosen from Fig.4.1(a). The appearance of the negative Hall potential region which absorbs energy shows that the generator is operating in a mixed mode. The current output in Fig.4.1(a) turns out to be cyclic after a starting time of 0.25 ms. The period of this cyclic behavior is close to the flow time through the relaxation length.

Figs.4.3 and 4.4 give the radial distribution of the electron and gas temperatures at different times. Large electron temperature fluctuations are found at the inlet of the generator. Both electron and gas temperature waves are found to travel at the gas velocity downstream through the generator.

Fig.4.5 shows the time dependent radial distribution of electron density. It indicates large electron fluctuations at the generator inlet while the downstream

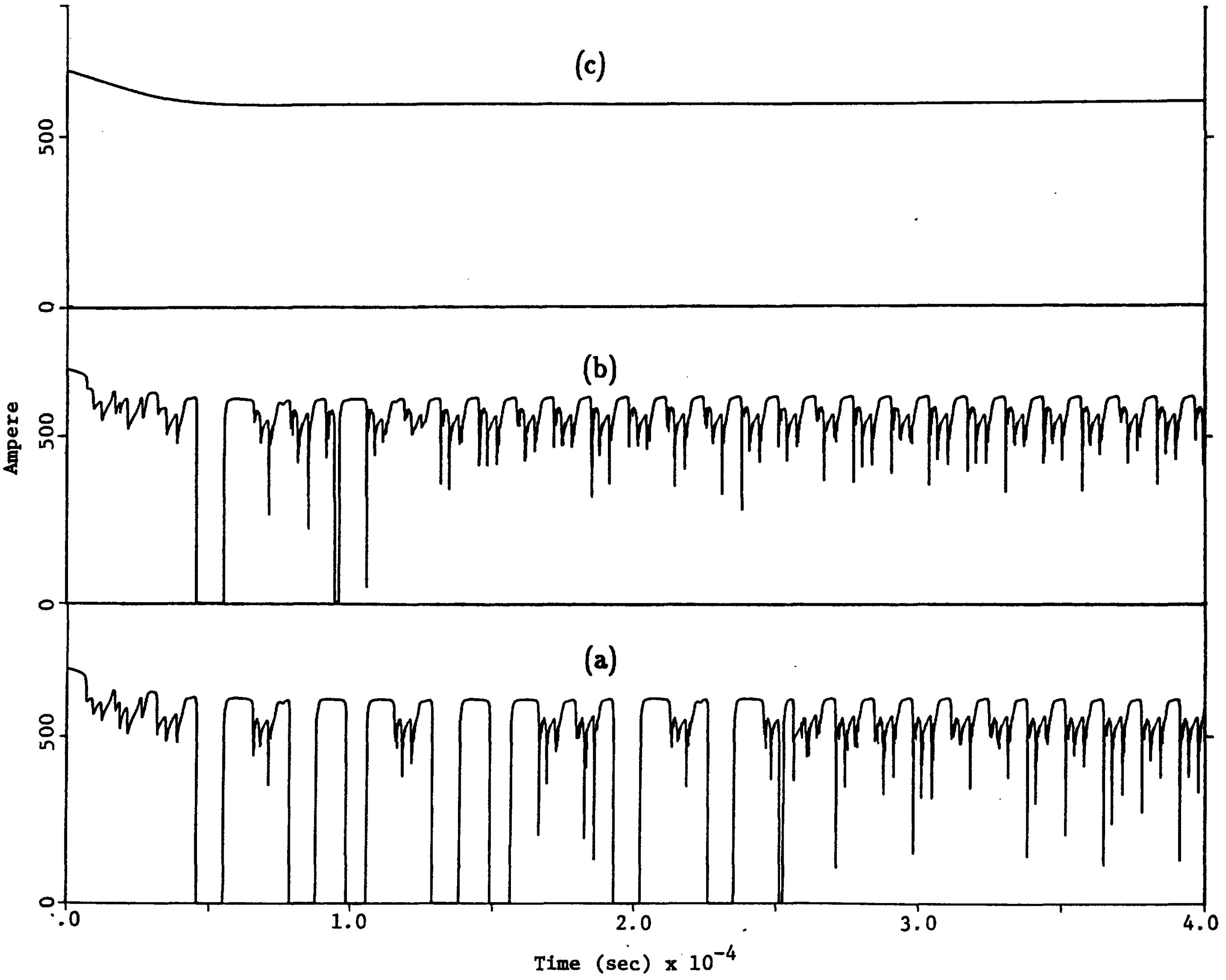

Figure 4-1: Temporal fluctuations of current output. Open-circuited inlet length (a) 0 (b) 5% (c) 10% of the channel length

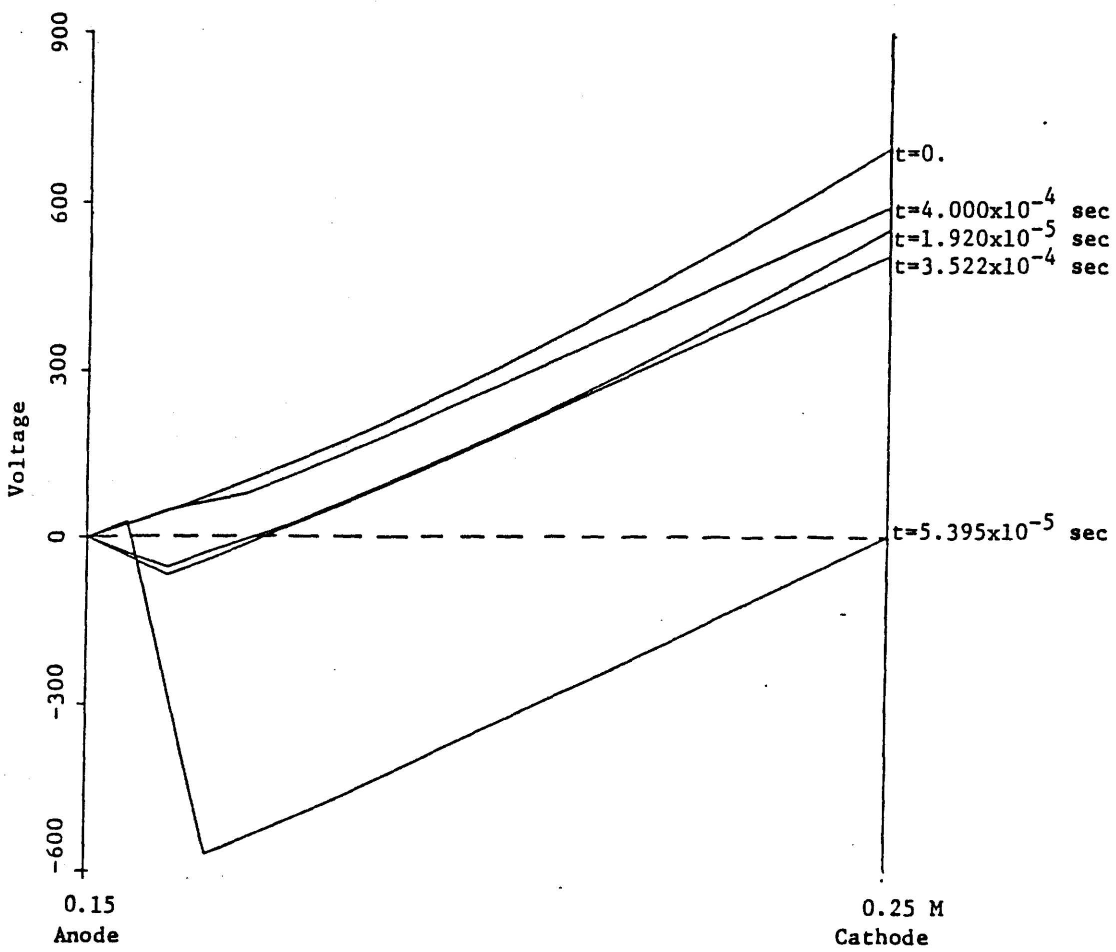

Figure 4-2: Hall potential distribution at different times in case (a) of Fig.4.1

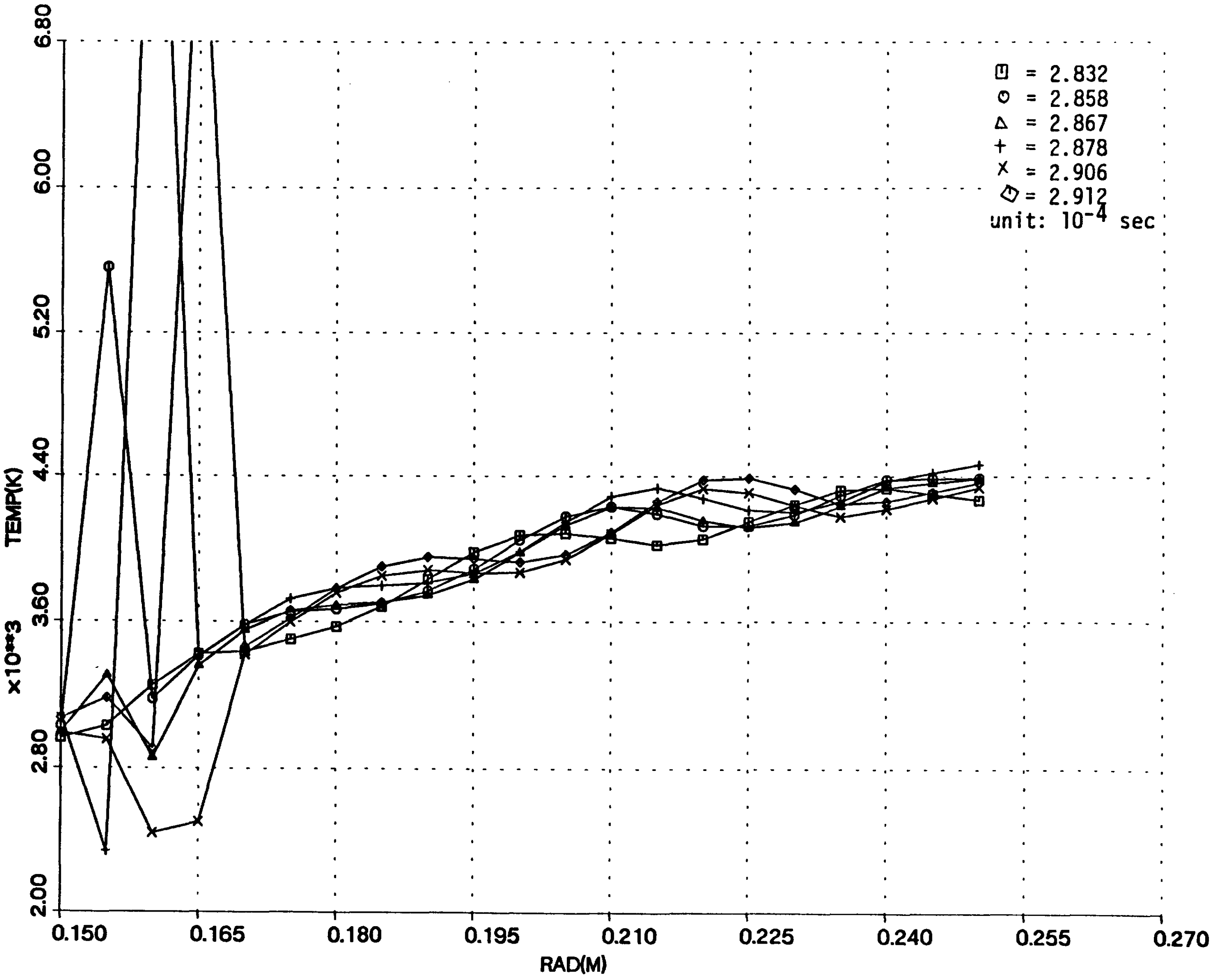

Figure 4-3: Radial electron temperature distribution at different times in case (a) of Fig.4.1

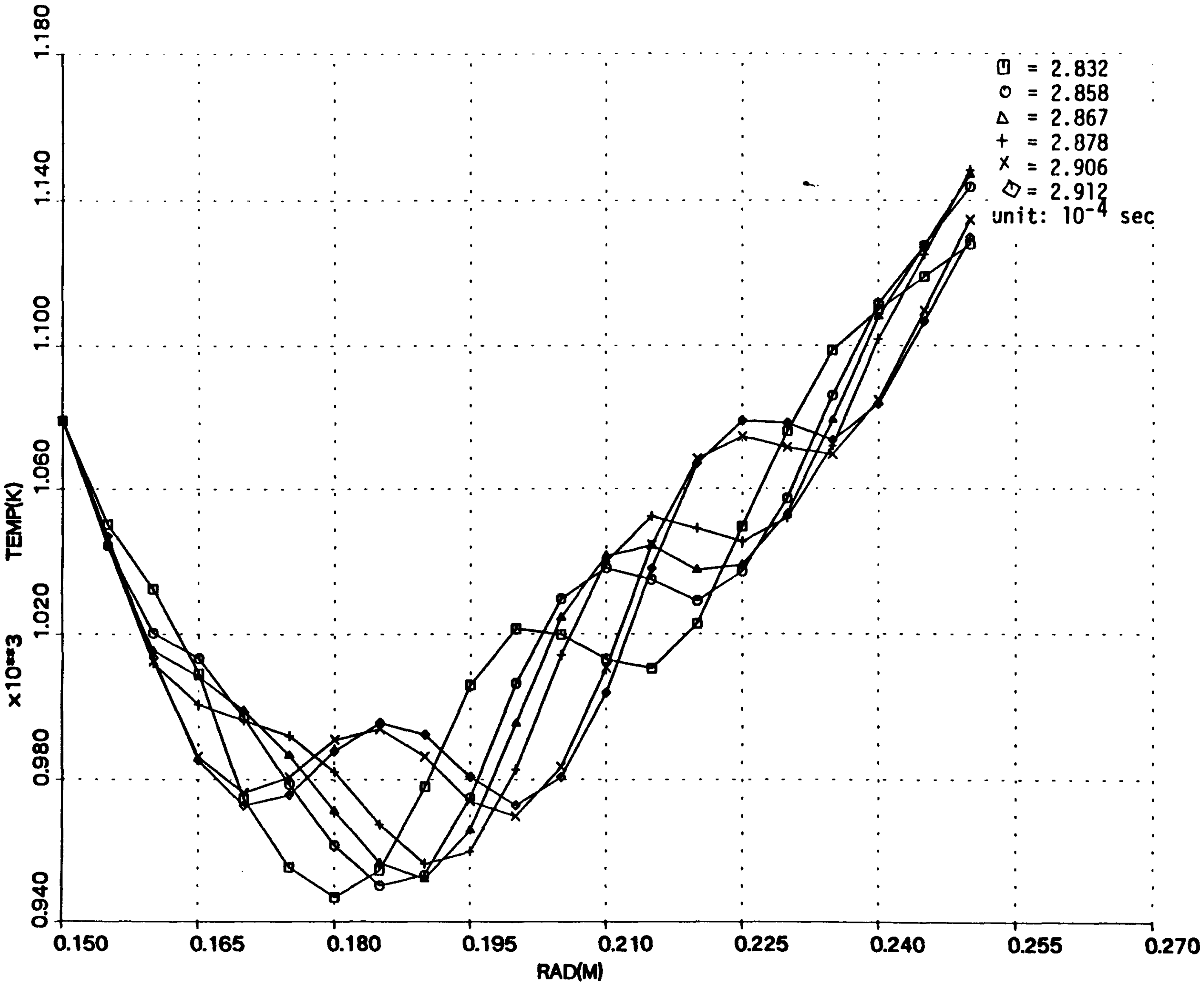

Figure 4-4: Radial gas temperature distribution at different times in case (a) of Fig.4.1

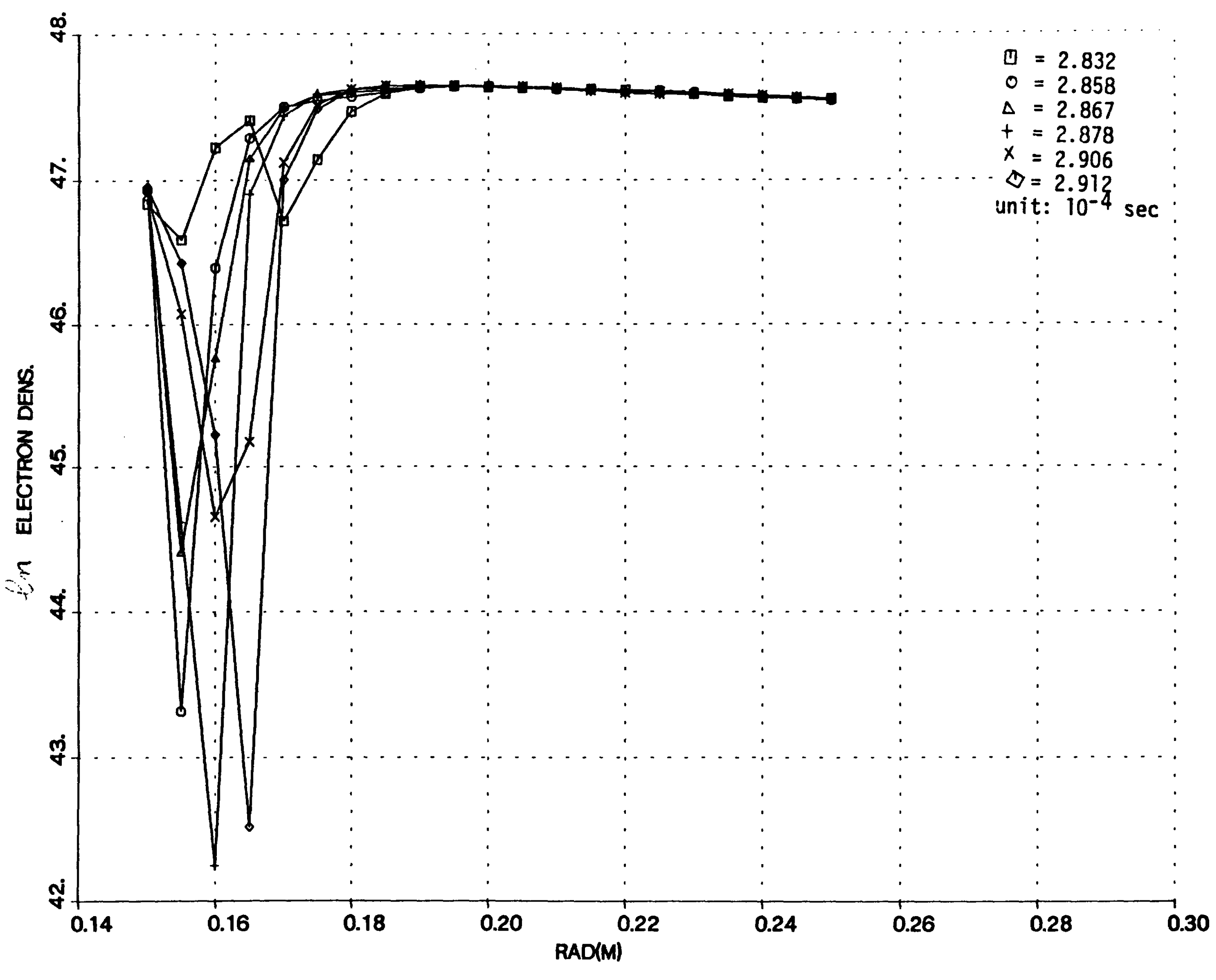

Figure 4-5: Radial electron density distribution at different times in case (a) of Fig.4.1

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section operates with a steady level of ionization close to full seed ionization.

4.2 Effect of Stable Configurations

Stable operation of the single load radial disk generator requires a high level of ionization at the inlet of the generator as given in reference 4. Operation with high inlet stagnation temperature can satisfy such conditions and it has been found experimentally to provide stable generator operation.

A configuration in which the inlet section is open-circuited has good possibility to provide the needed level of ionization at the entrance of generator. To prove this, two cases are considered and the results are shown in Fig.4.1 (b) and (c) for the same operating conditions as (a) except that 5% and 10% of the channel length are open-circuited at the inlet in (b) and (c) respectively. The external loads are reduced by the ratios of 0.966 and 0.929 respectively in order to operate both cases with the same initial current as (a). Fig.4.1 indicates that the level of fluctuations in total current are reduced in case (b) and totallly eliminated in case (c). Fig.4.6 compares the temporal fluctuations in the relaxation length (length covered by negative Hall field, where energy is absorbed). Even though the volume of the generator is reduced by 3.81% and 7.75% respectively, the average power over a period of 0.4 ms increases 23.4% and 51% for cases (b) and (c) when compared to (a). The power gains are in qualitative agreement with the experimental results of ref.9 which tested a helium driven disk generator with both grounded and floating anodes.

The grounded anode case of Fig.1.1 corresponds to the case with significant power absorption in the inlet section of the generator whereas the floated anode case corresponds to operation of the generator with an open circuited section at the inlet. The comparison of the power output of the floated versus grounded case for helium with potassium seed corroborates the above results from our calculation.

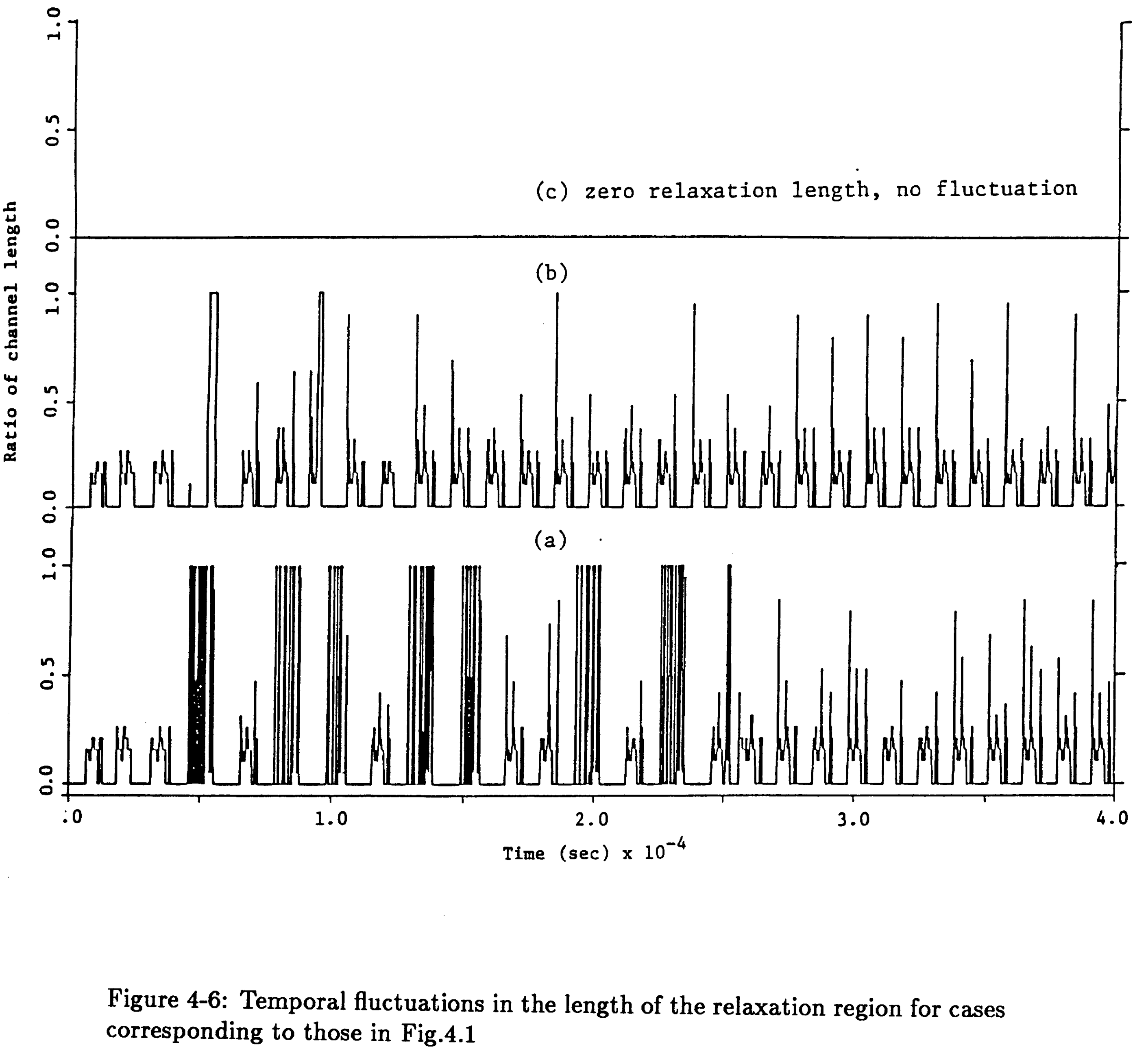

Figure 4-6: Temporal fluctuations in the length of the relaxation region for cases corresponding to those in Fig.4.1

The second configuration under consideration operates the inlet of the generator with a higher magnetic field. Two cases are considered by boosting the magnetic field to 1.7 T and 2.0 T at the inlet over 10% of the channel. Fig.4.7 (b) and (c) indicate that the fluctuations are sharply reduced in (b) and even totally eliminated in (c). The average power gains over a period of 0.4 ms are 33.7% and 55.8% for cases (b) and (c) respectively.

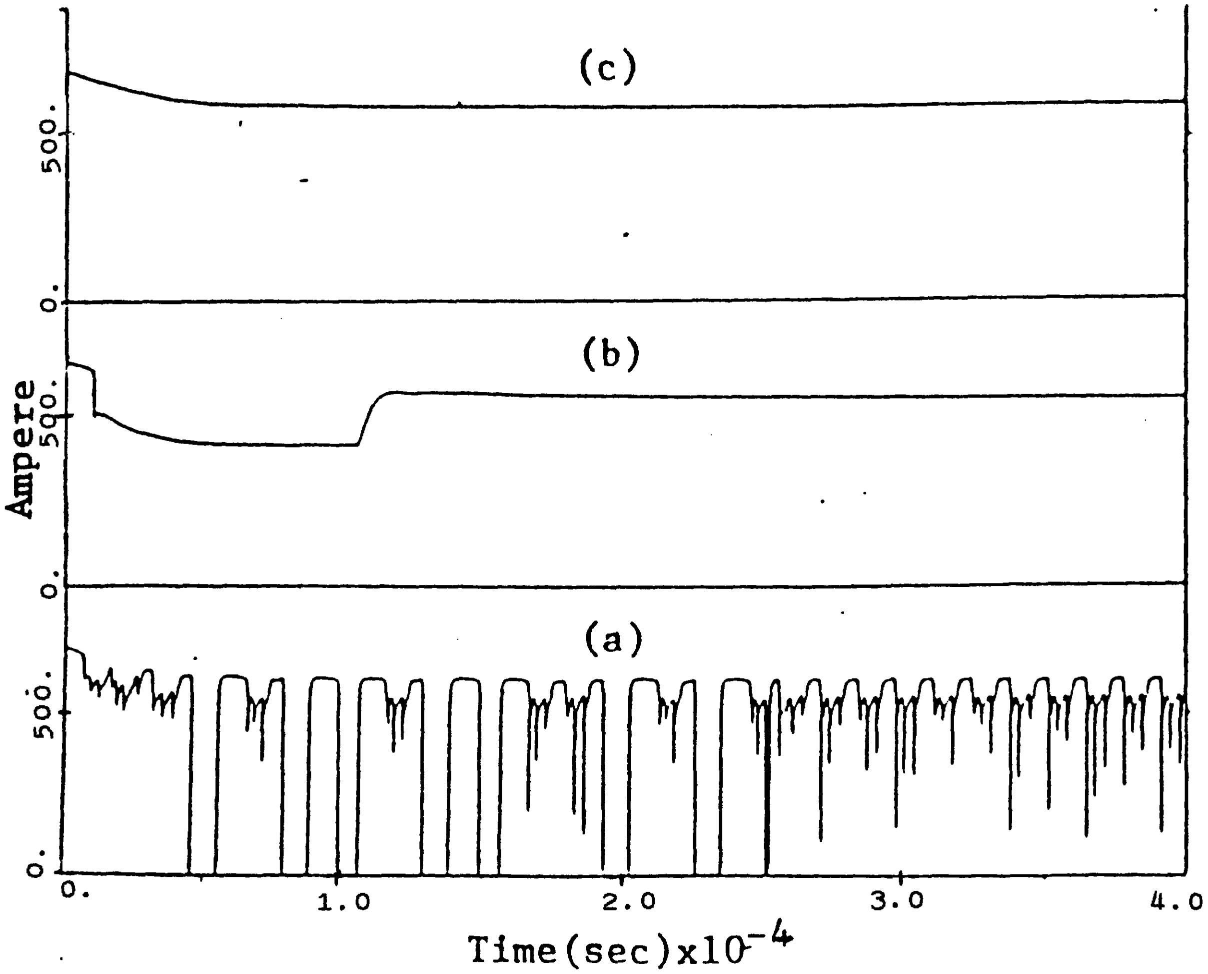

Figure 4-7: Temporal fluctuations of current output. Magnetic field near the inlet is boosted to 1.7 T in (b) or 2.0 T in (c).

Chapter 5

Conclusions

1. Non-uniformities in non-equilibrium generators basically result from the existence of any instability developed in the plasma or of an externally applied disturbances. The general effect of these non-uniformities is an increase in the internal impedance of the generator. If the size of non-uniformity grows comparable to the characteristic length of the generator, the output voltage can be unsteady. This reduction of generator performance due to the existence of plasma non-uniformity has been confirmed by the results of a computer experiment associated with an externally applied high intensity point perturbation.
2. The time dependent solutions of a mathematical model confirm the qualitative description of the generator instability associated with the existence of reversing electric field in the ionization relaxation zone and indicate that a radial disk MHD device operating with a relaxation region which absorbs energy is unstable.
3. The radial disk MHD generator can be made stable by leaving the inlet relaxation length open-circuited. It is found that by leaving the first 10% of generator length open-circuited, the generator becomes stable and the power output is increased by 51%. The effect of this stabilizing scheme is

corroborated with Japanese experiments by floated anode.

4. The radial disk MHD generator can also be made stable by boosting the magnetic field in the relaxation region. For example, it is found that by boosting the magnetic field from 1.5 T to 2 T in the first 10% of the channel length not only stabilizes the generator but also increases its power output by 55%.

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