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TITLE THEORY AND MODELING OF A RELATIVISTIC KLYSTRON AMPLIFIER WITH HIGH SPACE CHARGE FOR MICROSECOND APPLICATIONS

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Theory and modeling of a Relativistic Klystron Amplifier with high space charge for microsecond applications

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ABSTRACT

We discuss basic Relativistic Klystron Amplifier physics. We show that in the intense space-charge regime the maximum power extraction does not coincide with the maximum harmonic bunching. In addition, we show that as the beam is bunched, the additional power stored in the Coulomb fields does not add significantly to the overall power extraction. Because of these effects, the power extraction at 1.3 GHz for a 500 kV, 5kA beam with reasonable beam-to-wall spacing is limited to around 35%.

1. INTRODUCTION

We will review basic Relativistic Klystron Amplifier (RKA) theory, with emphasis on effects due to intense space charge. In addition, we will include numerical simulations done with a self-consistent particle-in-cell (PIC) code to demonstrate these effects. In particular, we want to study the physics of harmonic bunching of the beam current and power extraction of the electron beam into microwaves at 1.3 GHz for our 500 kV, 5 kA beam. We will see that the ability to both bunch and extract power will degrade as the space charge is increased. The harmonic current can be somewhat increased by inductively tuning the idler cavity, with a loss of tube gain. Often, though, maximum power extraction will occur at the lesser harmonic current. Since only the beam's kinetic energy can contribute to the rf power, we want to maximize the difference between the beam's initial kinetic energy and the minimum value it can be. For a given injection voltage V_{inj}, as the beam current I_o is increased, its potential energy must also increase, thereby reducing its kinetic energy. As a result, there is a trade-off between harmonic current and extraction of kinetic energy. This can be seen in the simple expression for beam energy to microwave efficiency formula,

$$\eta = \frac{m_o c^2 (\Delta\gamma) I_1}{e V_{inj} I_o} \kappa \ ,$$

where m_o is the electron rest mass, $\Delta\gamma$ is the maximum decrease in the relativistic factor as the electrons are decelerated, I_1 is the fundamental harmonic current, and κ is related to the efficiency of extraction, usually better than 0.9. We will see that as we try to increase I_1, $\Delta\gamma$ will decrease (nonlinearly), providing a distinct optimum operation condition. If the space charge is too high, the potential energy fields can contain most of the initial beam energy. Unfortunately, usually only a few percent of the potential energy is in the mode we want. The rest is in higher order modes, and that energy is useless.

We will break this paper into five parts. First, we will discuss the basic RKA physics, including the definition of harmonic current and power extraction. Next, we will review the basic physics of intense space-charge beams, emphasizing the partitioning of energy due to the space charge. Then we will discuss the generation of the beam harmonic current in both the space-charge dominated and ballistic regimes. In the fourth section, we will explicitly show the mode distribution of the potential-energy fields for typical beam bunching. The last section will include PIC simulations, demonstrating these intense space-charge effects. There will be a series of runs showing the dependence of harmonic current on beam current and idler cavity tuning. Other runs will show the effect of a nonresonant output cavity, as well as how the extracted microwave power depends on the harmonic current.

2. RKA MICROWAVE PHYSICS

In Fig. 1, we see a schematic of an RKA. An annular, intense (5 kA), mildly relativistic (500 keV) electron beam passes through three cavities. The first cavity is externally driven and impresses an axial momentum variation on the initially uniform beam. Current modulation grows as the beam travels, as the momentum variation causes variations in the beam's axial density. We can describe the beam current in terms of its Fourier components

$$I(t,z) = I_o + I_1(z)\cos(\omega t + \phi_1) + I_2(z)\cos(2\omega t + \phi_2) + \ \ldots \tag{1}$$

The product $I_1 V_o$ is often referred to as the beam rf power, where V_o is the beam kinetic voltage. The fundamental current component, I_1, is typically on the order of $0.05 I_o$ at the idler cavity. This cavity is driven by the harmonic current, modeled in Fig. 2. We see that the cavity's gap voltage is given by

$$V_{gap} = Z_{cav} I_{ind} \tag{2}$$

where Z_{cav} is the cavity impedance and I_{ind}, the induced current, is the harmonic current times a coupling factor close to one. The gap voltage induced in the idler cavity is typically near the beam kinetic voltage. This high gain results from the large harmonic current (250 A or so). The idler cavity rf fields further modulate the beam momentum and provide harmonic current at the output cavity close to the DC beam current. The maximum harmonic current possible, for a delta function bunch of current, is twice the DC current. The harmonic current is typically around 1.4 I_o for conventional klystrons. For an RKA, the harmonic content is usually $\leq$1.0. The output cavity is tuned resonantly, so the rf fields induced in it decelerate the beam. Ramo's theorem[1] gives the microwave power which is extracted from the beam,

$$P(t) = \int_V \vec{J}(\vec{r},t) \cdot \vec{E}(\vec{r},t) dV \tag{3}$$

where $\vec{J}$ is the beam current density and $\vec{E}$ is the rf electric field. We see from Eq. (3) that only the beam's kinetic energy can be extracted; and since $E \sim e^{j\omega t}$, we can only extract power from the fundamental harmonic component. It is clear that we must simultaneously maximize I_1 and extract the maximum kinetic energy from the beam in order to have the highest microwave power.

For our 2.5 GW beam, our goal is 40% extraction, modest by conventional klystron standards. We will see that this is very aggressive for an intense RKA; 35% is about the best we can hope for with our nominal parameters. We might be able to reach 40% if we increase the beam voltage to 700 kV, lower the current to 3 kA, or have some combination of higher voltage and less current.

In Fig. 2, we see the output cavity model, where the cavity driven by the induced current

$$I_{ind} = \frac{\int_V \vec{J} \cdot \vec{E} dV}{V_{gap}} \quad .$$

In order to keep the rf fields low enough not to stop the beam completely and form a virtual cathode, the cavity R_o must be kept low. Unfortunately, since cavity Q is related to R_o, it also has a tendency to become small. If it becomes too small, the cavity is no longer resonant, and much of the power extracted is in unwanted modes. For practical purposes, we require $Q > 2$ and want it as high as possible, since the energy lost in the unwanted modes is inversely proportional to cavity Q.

The desired beam induced cavity voltage is αV_o, where α is the modulation parameter, typically 1.2, and V_o is the beam kinetic voltage. For harmonic currents of 3 kA and induced currents of two thirds that, we need a shunt impedance of about 300 Ω. A convenient way of matching the cavity design to this total shunt impedance is by calculating the geometrical quantity

$$\frac{R_o}{Q_l} = \frac{\left(\int E(r=0)dz\right)^2}{\omega\epsilon_o \int |E|^2 dV}$$

and the loaded cavity Q (included the port to an output waveguide), Q_l. For a fixed cavity geometry, the ratio of $\frac{R}{Q}$ is the same for various output waveguide couplings. In Fig. 3 we see a cavity with $\frac{R}{Q} = 100$ Ω, which matches the desired shunt impedance when the output coupling is adjusted for a loaded cavity Q of 3

3. INTENSE-SPACE CHARGE BEAM PHYSICS

The maximum extraction power is largely dominated by the space-charge physics. The amount of kinetic energy that can be extracted is given by the depressed kinetic voltage of the bunched beam due to its space charge depression minus the minimum voltage required to transport the bunched current.

For a given injection diode voltage, the voltage associated with an annular beam's kinetic energy is less since some potential energy is required to set up the Coulomb fields within the cylindrical pipe. The potential of an annular beam injected at a radius r_b with initial gamma γ_{inj} into a conducting cylinder of radius r_w must satisfy[2]

$$\phi(r) = \frac{I_o}{2\pi\epsilon_o v_o}\log\frac{r}{r_w} \qquad r_b < r < r_w$$

$$\phi(r) = -\frac{I_o}{2\pi\epsilon_o v_o}\log\frac{r_w}{r_b} \qquad r \le r_b$$

where the beam velocity is

$$v_o = \frac{c}{\sqrt{1-\left(\gamma_{inj}-\frac{e\phi(r_b)}{m_o c^2}\right)^{-2}}} \quad .$$

The beam potential at $r = r_b$ must thus satisfy ($\phi_b = \phi(r_b)$)

$$\frac{e\phi_b}{m_o c^2}\sqrt{1-\left(\gamma_{inj}-\frac{e\phi_b}{m_o c^2}\right)^{-2}} = \frac{e}{2\pi\epsilon_o m_o c^3} I_o \log\frac{r_w}{r_b} = \frac{I_o}{8.5\text{kA}}\log\frac{r_w}{r_b} \quad .$$

The left-hand side of the above equation is commonly known as $F(\phi_b)$. We can define a convenient normalized threshold current I_s to be

$$I_s = \frac{2\pi\epsilon_o m_o c^3}{e\log\frac{r_w}{r_b}} = \frac{8.5\text{kA}}{\log\frac{r_w}{r_b}} \quad .$$

The conservation of energy becomes (where the small circles denote the DC beam energy)

$$\gamma_{inj} = \gamma_o + \frac{I_o}{I_s\beta_o} \quad .$$

The function $F(\phi_b)$ is largest (and also the beam current I_o is largest) for a beam potential energy increase and kinetic energy decrease (recall we defined the pipe wall to be at ground) of

$$e\phi_b = \left(\gamma_{inj} - \gamma_{inj}^{1/3}\right) m_o c^2$$

and the corresponding largest current permissable is then

$$I_{max} = \frac{2\pi\epsilon_o m_o c^3}{e}\frac{\left(\gamma_{inj}^{2/3}-1\right)^{3/2}}{\log\frac{r_w}{r_b}} \quad . \tag{4}$$

We see that the kinetic energy drop is not the injection voltage and that there is residual kinetic energy. One would think that since some kinetic energy remains, additonal current can be pushed through the cylinder. However removal of any additional kinetic energy drops the beam velocity v_o, which in turn increases the charge density and requires more increased potential energy from the beam than was given by the drop in the kinetic energy. The nonlinear slowing of the bunch as it forms ads its growth[3]. If the beam current is near the threshold current I_{max} and is increased slightly, a significant reduction in the beam's kinetic energy (and velocity) is possible.

The ratio of beam kinetic energy to potential energy is also worth calculating. As the beam is bunched, some amount of the DC potential energy is converted to rf potential energy. The beam's kinetic energy at the threshold current is

$$KE = \left(\gamma_{inj}^{\frac{1}{3}} - 1\right) m_o c^2$$

and the potential energy is

$$PE = \left(\gamma_{inj} - \gamma_{inj}^{\frac{1}{3}}\right) m_o c \quad .$$

For all $\gamma_{inj} > 1$, $KE < PE$. In Fig. 4, we see the ratio $\frac{KE}{PE}$ as a function of the injection energy, γ_{inj}. We see that for practical values of the injection voltage (γ_{inj} around 2), the beam's potential energy is three times the kinetic energy (and three quarters the total energy). In Fig. 5 we see the partitioning of the total energy into kinetic and potential energy parts as a function of the injection gamma, γ_{inj}, and $\frac{I_b}{I_{max}}$.

A more useful version of Eq. (4) for space-charge limited current can tell us the maximum amount of kinetic energy we can extract. Solving for the minimum potential and kinetic energy we get

$$\gamma_{min}^{\frac{2}{3}} = \left(\frac{PE + KE}{m_o c^2}\right)^{\frac{2}{3}} = \left(\frac{I_{peak}}{8.5\mathrm{kA}} \log \frac{r_w}{r_b}\right)^{\frac{2}{3}} + 1 \quad . \tag{5}$$

For a given peak current, I_{peak}, the difference between γ_{inj} and γ_{min} is the available kinetic energy for conversion to microwaves. The maximum power extraction is

$$P_{out,max} = \frac{1}{2} I_1 (511\mathrm{kV})(\gamma_{inj} - \gamma_{min}) \quad .$$

In Table 1, we list γ_{min} and the available kinetic voltage as a function of beam current and radius for an injection voltage of 500 kV.

Table 1

γ_{min}	ΔKE_{avail}(kV)	I_{peak}(kA)	r_b(cm)	r_w
1.47	260	10	3.2	3.65
1.80	90	10	3.2	4.25
1.67	165	10	3.4	4.25
1.28	350	5	3.2	3.65
1.18	410	5	3.4	3.65

We would expect an effective wall radius of 4.25 cm when the beam is at the center of the 2 cm cavity gap. Although these formulas are strictly only for DC beams, they give us qualitative criteria. Also, depending on the potential depression, the cavity fringe fields can extract useful additional power, without the beam seeing the large cavity aperture.

We can write the maximum extraction efficiency in terms of the maximum available kinetic energy, V_{AKE}:

$$\eta = \frac{1}{2} \frac{I_1}{I_o} \frac{V_{AKE}}{V_o} \quad .$$

From Table 1, we see that decreasing the beam to wall spacing drastically increases the available kinetic energy.

4. HARMONIC BUNCHING

The growth of the beam harmonic current can either be space charge dominated or ballistic, depending on the current, the ratio of the wall radius to the beam radius, and the modulation voltage. For small momentum modulation, the bunching is the effect of space-charge compression waves initiated by the cavity. The current modulation from this effect is well known[3] and is given by

$$\frac{i_1}{I_o} = \frac{eV_{gap}M}{m_o c^2} \frac{1}{\beta_o \gamma_o^3 \alpha\mu} \sin\left(\frac{z\omega\delta\alpha\mu}{v_o}\right)$$

where M is the transit time factor,

$$M = \frac{\sin\left(\frac{\omega d}{2v_o}\right)}{\left(\frac{\omega d}{2v_o}\right)}$$

for a gap of length d and

$$\alpha = \frac{I_o}{I_s \beta_o \gamma_o^3} \quad ,$$

$$\alpha\mu = \left(\alpha^2 + \frac{\alpha}{\gamma_o^2}\right)^{\frac{1}{2}} \beta_o \quad ,$$

and

$$\delta = \frac{\beta_o^2}{\beta_o^2 - \alpha} \quad .$$

The maximum harmonic modulation occurs at an axial distance from the cavity of

$$z_b = \frac{\pi v_o}{2\omega\delta\alpha\mu} \quad .$$

The modulation decreases as we increase the potential depression, although the bunching distance becomes shorter.

One way to increase the harmonic current is to raise the gap voltage. For large voltages, the space charge forces can be ignored, and the motion is ballistic with faster particles overtaking slower ones. Ballistic motion is well known for the short-gap, nonrelativistic limit[1]. For a relativistic beam without space charge, the harmonic current in the limit of small gap voltages is

$$I_1 = 2I_o J_1(\chi)$$

and

$$\chi = \frac{MV_{gap}c}{m_o c^2 \gamma(\gamma^2 - 1)} \frac{\omega}{v_o} z \quad .$$

The harmonic current has a maximum of 1.164 I_o at $\chi = 1.84$.

In Fig. 6, we see the current modulation for a relativistic, intense beam as a function of the gap voltage. We see as the space charge increases, the maximum harmonic current decreases. The maximum harmonic current never reaches 1.164 I_o because of space charge and because the gap has finite length. As the space charge is increased, the gap voltage must be increased to reach the maximum harmonic current. This reduces the distance to the maximum bunching and makes the gap appear relatively longer. Eventually, a space charge is reached at which the required gap voltage is greater than the available kinetic voltage.

From the definition of I_s, we see that the easiest way to increase the harmonic current in the space charge dominated regime is to reduce the beam to wall spacing.

5. POTENTIAL FIELD MODE DISTRIBUTION

We will show in this section that the power in the potential fields stored in the fundamental mode is typically very small, only a few percent or less of the DC power. A simple output cavity structure cannot both resonantly extract power from the particles' kinetic energy and extract the potential fields. Therefore, if power is transferred from the kinetic energy to these fields, it cannot be extracted. If the fields did have most of the initial DC power in the fundamental mode, they could be simply stripped off the beam and transported down an extraction waveguide

We will consider a case with heavy potential depression from space charge. For the space-charge limiting current at γ_{inj}=2, Fig. 4 indicates that 75% of the total beam energy is in the Coulomb fields. Since $r_w - r_b \ll \frac{2\pi c}{\omega}$, we can use Gauss' law to describe the TEM field pattern. Let us also assume we have bunched the beam to a thickness δ, with no current between bunches. We want to find out what the mode distribution is as a function of δ. The electric field between the beam and wall is now

$$E_r = \frac{I_{peak}}{2\pi\epsilon_0 r}$$

at the bunch location and zero elsewhere. The stored energy between the bunch and the wall per unit length is

$$\varepsilon = I_0^2 A^2$$

where the constants have been collected in A. The power in the fields is

$$P_{PE} = \frac{\varepsilon}{v_0} \quad .$$

We wish to write the fields in a Fourier decomposition,

$$E_r = E_{DC} + E_1 \cos(\omega t + \theta_1) + \ldots$$

where

$$E_n = 2B\frac{\omega}{2\pi}\int_{-\pi}^{\pi} I\cos(\omega nt)dt$$

$$= 2B\frac{1}{2\pi}\int_{-\frac{\delta}{2}}^{\frac{\delta}{2}} I_{peak}\cos(\omega nt)d(\omega t) \quad .$$

The constant B is geometrically related to A. The peak current is

$$I_{peak} = \frac{I_0 2\pi}{\delta}$$

and we get

$$E_n = 2\frac{\sin\left(\frac{\delta n}{2}\right)}{\frac{\delta n}{2}} I_0 B \quad .$$

The total rf power is

$$P_{total} = \left(\frac{I_0 B 2\pi}{\delta}\right)^2 \frac{\delta}{2\pi} \quad .$$

The ratio of power stored in any given mode to the total power is

$$\frac{E_n^2}{E_r^2} = 4\frac{\sin^2\frac{\delta n}{2}}{\left(\frac{\delta n}{2}\right)^2}\frac{\delta}{2\pi} \quad .$$

The ratio for E_1 is a maximum at $\frac{\delta}{2} = 1.166$ and is

$$\left(\frac{E_1}{E_r}\right)^2_{best} \quad \frac{1}{4\pi^2} \cdot 0.23$$

If we assume we have 60% of the injection energy in the potential fields, then 14% of the initial energy is in the fundamental mode.

However, when $\delta = 0.1$ (the length of a typical bunch, shown in Figs. 12 through 17), then less than 2% of the injection energy is in the fundamental mode.

Let us also calculate the field power if the current has a sinusoidal distribution,

$$I = I_o(1 + \cos(\omega t)) \quad .$$

The radial electric field distribution is also approximately

$$E = E_o(1 + \cos(\omega t))$$

and the ratio of field power in the fundamental mode to the total power is

$$\left(\frac{E_1}{E_r}\right)^2 = \frac{1}{3} \quad .$$

In this case, less of the injection energy is on average in the potential fields, and there is less than 10% of the DC power in the fundamental mode.

6. PIC SIMULATIONS

In this section, we will provide PIC simulations to illustrate the above physical effects. We use the fully relativistic, self-consistent Los Alamos PIC code ISIS. First, we will show the relative decrease in harmonic current as the beam current is increased. Then we will show how it increases as the idler cavity is inductively tuned. Next, a couple of simulations with various amounts of output cavity Q will be shown. Finally, the dependence on output extraction on beam harmonic current for various beam current and beam-to-wall spacings will be presented.

6.1. Harmonic current versus beam current

In Fig. 7, we have plotted the decrease in fundamental harmonic current as the beam current is increased for a nominal 500 keV, 5 kA electron beam with radius r_b=3.2 cm. The input cavity drive was adjusted to have the maximum harmonic current at the location of the output cavity for all cases. We see a strong reduction in the harmonic current as the space charge depression is increased.

6.2. Harmonic current versus idler cavity tuning

In Fig. 8, we have plotted the harmonic current at the location of the output cavity as we have changed the idler cavity tuning. We see that as the cavity becomes more inductive, we can increase the harmonic current from 70% to nearly 120%. The gain of the idler cavity decreases and is compensated by driving the input cavity harder. This may in practice exceed the maximum drive, in which case a second idler cavity could be used to restore the gain.

6.3. Nonresonant output cavity

In Fig. 9, we show a nonresonant output cavity and the fields in the extraction waveguide. In the top figure we show the device r,z geometry and the beam in it at a snapshot in time. In the lower figure, we have plotted the radial electric field in the output waveguide as a function of time. A Fourier decomposition of this field shows that only 20% of the extracted power is in the fundamental 1.3 GHz mode. In Fig. 10, we lowered the cavity $\frac{Q}{2}$. The Q has then been increased to match the cavity shunt impedance. We see that the field in the output waveguide is primarily in the fundamental mode; only 20% of the extracted power is now lost.

6.4. Extraction versus harmonic current

In Fig. 11, we plot extraction efficiency as a function of beam fundamental harmonic current for 5 kA and r_b=3.2 cm. We see that the maximum extraction, 25%, occurs at a paltry fundamental current component of only 70%, far below the maximum current we can generate.

As we saw earlier, by inductively tuning the idler cavity, we can bunch the beam to harmonic contents of around 1.0. In Fig. 12, we see the beam profile and longitudinal phase space at a snapshot in time for r_b=3.2 cm. Plotted is the axial momentum $\gamma\beta_z$ for each particle followed. We see that the bunch before extraction has $\gamma\beta_z \sim 1.0$, or only about 200 keV of available kinetic energy for extraction. This is confirmed in Fig. 13, where we see the bunch after extraction, with $\gamma\beta_z \sim 0.5$. This results in the low output power of 0.4 GW. Note the shape of the output cavity leads to a low $\frac{R}{Q}$ in order to maintain reasonable cavity resonance while not over modulating the output cavity. Recall that the minimum gamma, γ_{min}, included the required potential beam energy. The momentum in the figures is just the kinetic motion and does not include the potential part. Therefore, we expect to see a lower minimum energy than we predict for power extraction.

The optimum current modulation for r_b=3.2 cm is about 0.65, resulting in a power output of about 0.55 GW. In Fig. 14, we see appropriate bunch formation, with very little potential depression. The maximum theoretical extraction possible is about

$$\eta = \frac{1}{2}(0.65)(0.75) = 24\% \quad ,$$

close to the 22% calculated. In Fig. 15, we see the bunch's kinetic energy after extraction, $\gamma\beta_z \sim 0.25$.

In the final configuration, Fig. 16, we move the beam closer to the wall to decrease the effect of space charge, r_b=3.4 cm. For this case, the optimum bunching is 0.75. We see better bunch formation, corresponding to a power output of 0.70 GW (=28%). We expect a maximum extraction of

$$\eta = \frac{1}{2}(0.75)(0.82) = 30\% \ .$$

In Fig. 17, we can confirm that the minimum kinetic energy is about 50 keV.

In the last two cases, we used the DC current and the beam wall size because we get extraction extending into the fringe fields in the beam pipe beyond the cavity gap.

7. CONCLUSION

We have reviewed basic RKA microwave and intense-beam physics. We have discovered that the overall beam power to microwave efficiency depends on the combination of harmonic current content and how much kinetic energy we can extract from the beam. We have also seen that the power in the potential energy fields is mostly lost; very little of it is in the fundamental mode we desire.

In conventional klystrons, output cavities typically extract over 95% of the beam rf power. However, because of differences in an RKA's beam, it is hard to exceed even 70% extraction efficiency. This is because of two effects. First, due to the large harmonic current (3 to 5 kA) and the relatively small beam kinetic voltage (500 kV), the cavity shunt impedance is limited to around 100 Ω. Since cavity R/Q is a geometric constant, reducing R also tends to reduce cavity Q. If the Q is too low, the fields in the cavity are no longer resonant, and much of the extracted power is lost in unwanted modes. The other reason for poor extraction in an intense modulated electron beam is that in order to maintain the Coulomb fields of the slower space charge, the beam kinetic energy is transferred to potential energy as the bunch is decelerated. Since this transfer of energy from kinetic to potential is highly nonlinear when the beam current is close to the space charge limit, this reduces the efficiency of the extraction both by reducing the kinetic energy and by increasing the energy spread of the bunch. Some gain can be obtained by doing the final extraction in the cavity fringe fields in the beam pipe and by letting the electrons debunch.

The main consequence of the above effects is that the maximum conversion to microwaves does not occur with maximum beam harmonic bunching. Also, for reasonable beam-to-wall spacings, it is hard to exceed 35% extraction for a 5 kA, 500 keV electron beam. Also, we have seen that the extraction can be improved most by moving the beam closer to the wall.

8. REFERENCES

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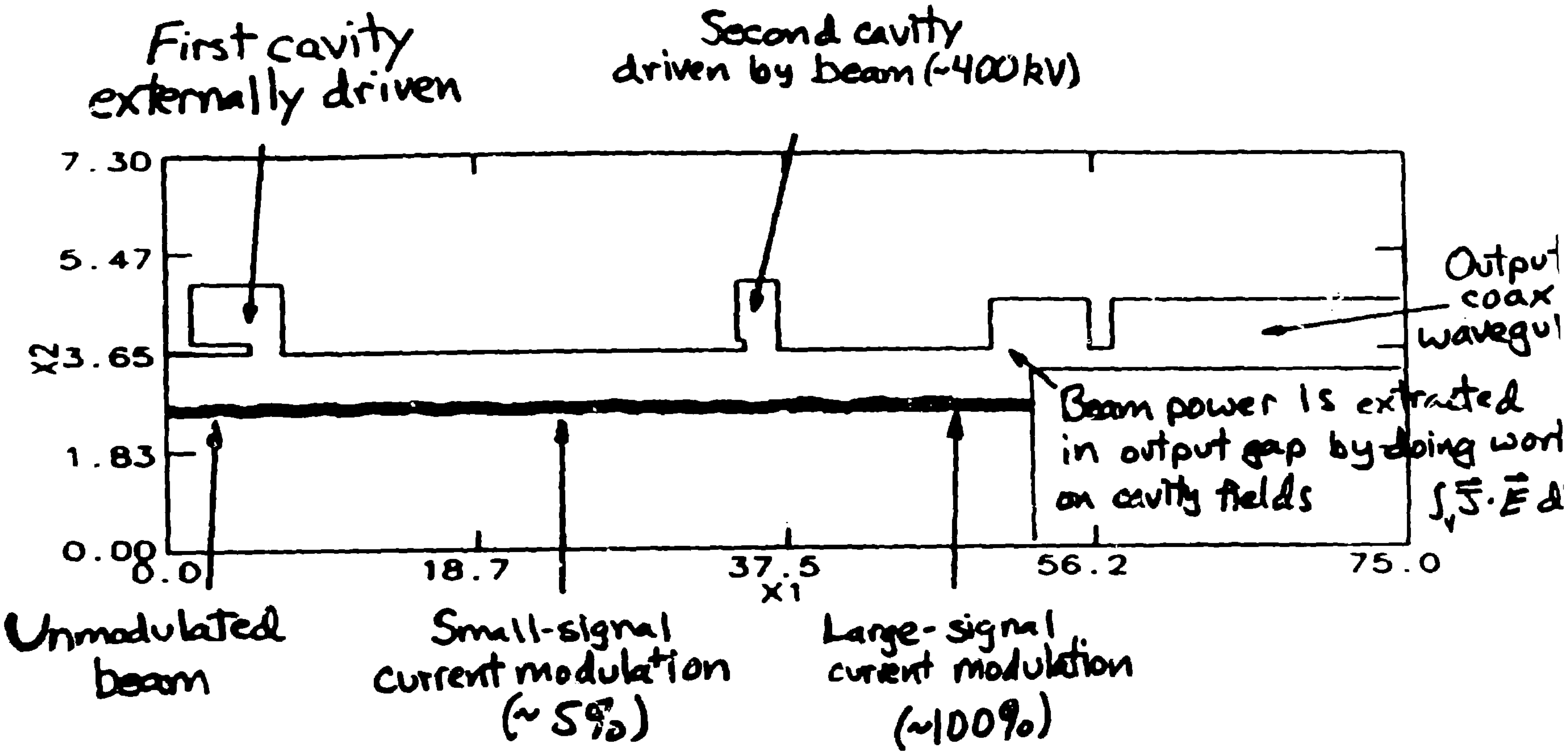
Figure Captions

1. Nominal 500 kV, 5 kA RKA, with pipe radius 3.65 cm.
2. Beam-cavity interaction model.
3. 1.3 GHz cavity with R/Q=100Ω.
4. Ratio of kinetic energy to potential energy for maximum current transmission for different injection energies.
5. Partitioning of injection energy for different injection energies and beam current.
6. Maximum current modulation versus gap voltage for different beam currents.
7. Harmonic current at the output cavity as a function of beam current, for resonantly tuned idler cavity.
8. Increase in harmonic current at output cavity as idler cavity is inductively tuned.
9. RKA geometry and electric field in output waveguide for nonresonant output cavity.
10. RKA geometry and electric field in output waveguide for resonant output cavity.
11. Extraction efficiency for a 500 kV, 5 kA RKA versus harmonic current with $\frac{r_w}{r_b}$=1.14. Best extraction is for 65% harmonic current.
12. RKA geometry and axial momentum $\gamma\beta_z$ at a snapshot in time with bunch before output cavity, for 100% harmonic current and r_b=3.2 cm.
13. RKA geometry and axial momentum $\gamma\beta_z$ at a snapshot in time with bunch after output cavity, for 100% harmonic current and r_b=3.2 cm.
14. RKA geometry and axial momentum $\gamma\beta_z$ at a snapshot in time with bunch before output cavity, for 65% harmonic current and r_b=3.2 cm.
15. RKA geometry and axial momentum $\gamma\beta_z$ at a snapshot in time with bunch after output cavity, for 65% harmonic current and r_b=3.2 cm.
16. RKA geometry and axial momentum $\gamma\beta_z$ at a snapshot in time with bunch before output cavity, for 70% harmonic current and r_b=3.4 cm.
17. RKA geometry and axial momentum $\gamma\beta_z$ at a snapshot in time with bunch after output cavity, for 70% harmonic current and r_b=3.4 cm.

RKA Description



Nominal RKA parameters:

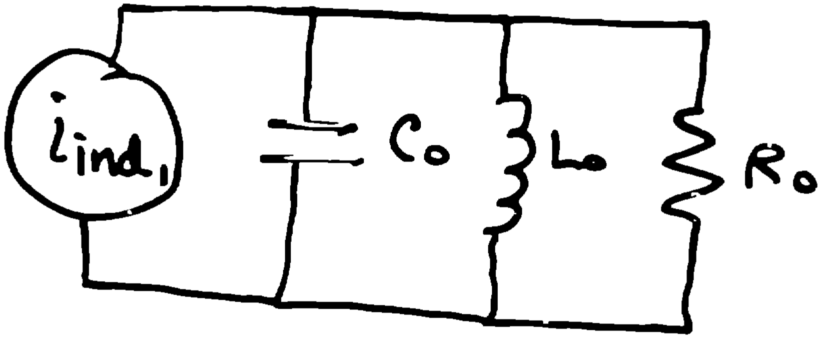
5 kA

500 kV

50% extraction power

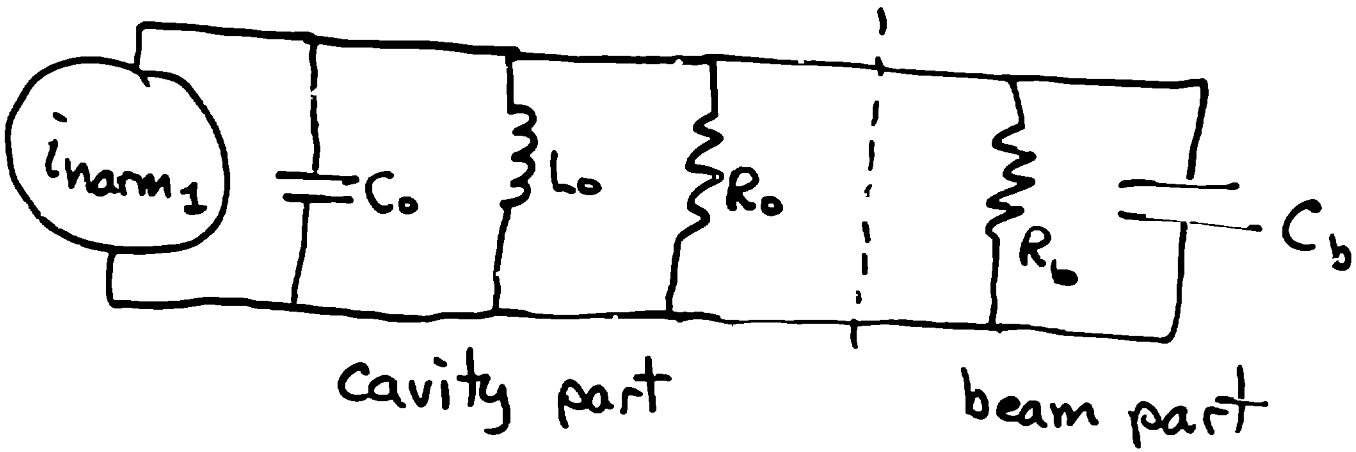
Beam Interaction in Output Cavity

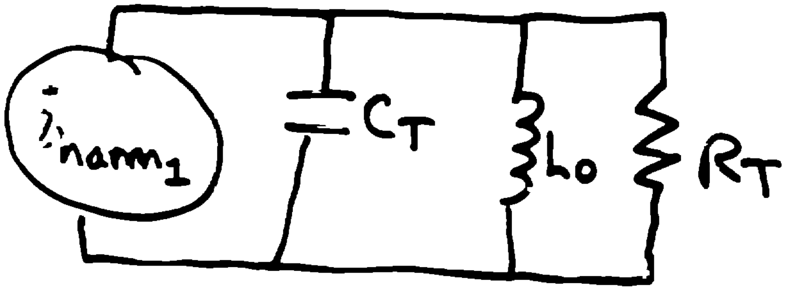
fig 2



Cavity driven by induced current

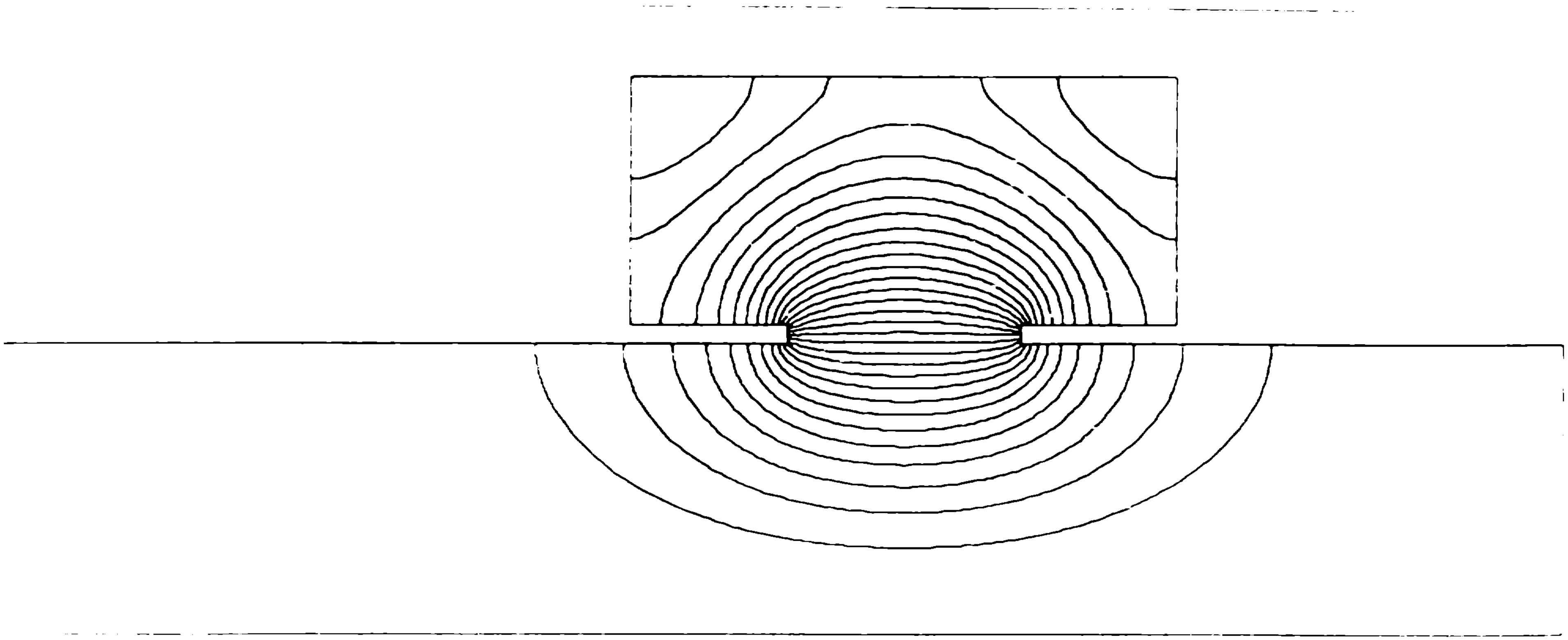
Alternative view:





$$\frac{1}{R_T} = \frac{1}{R_0} + \frac{1}{R_b}$$ Must match R_T

fig 2



name = [illegible] input cavity 1300 Friedman

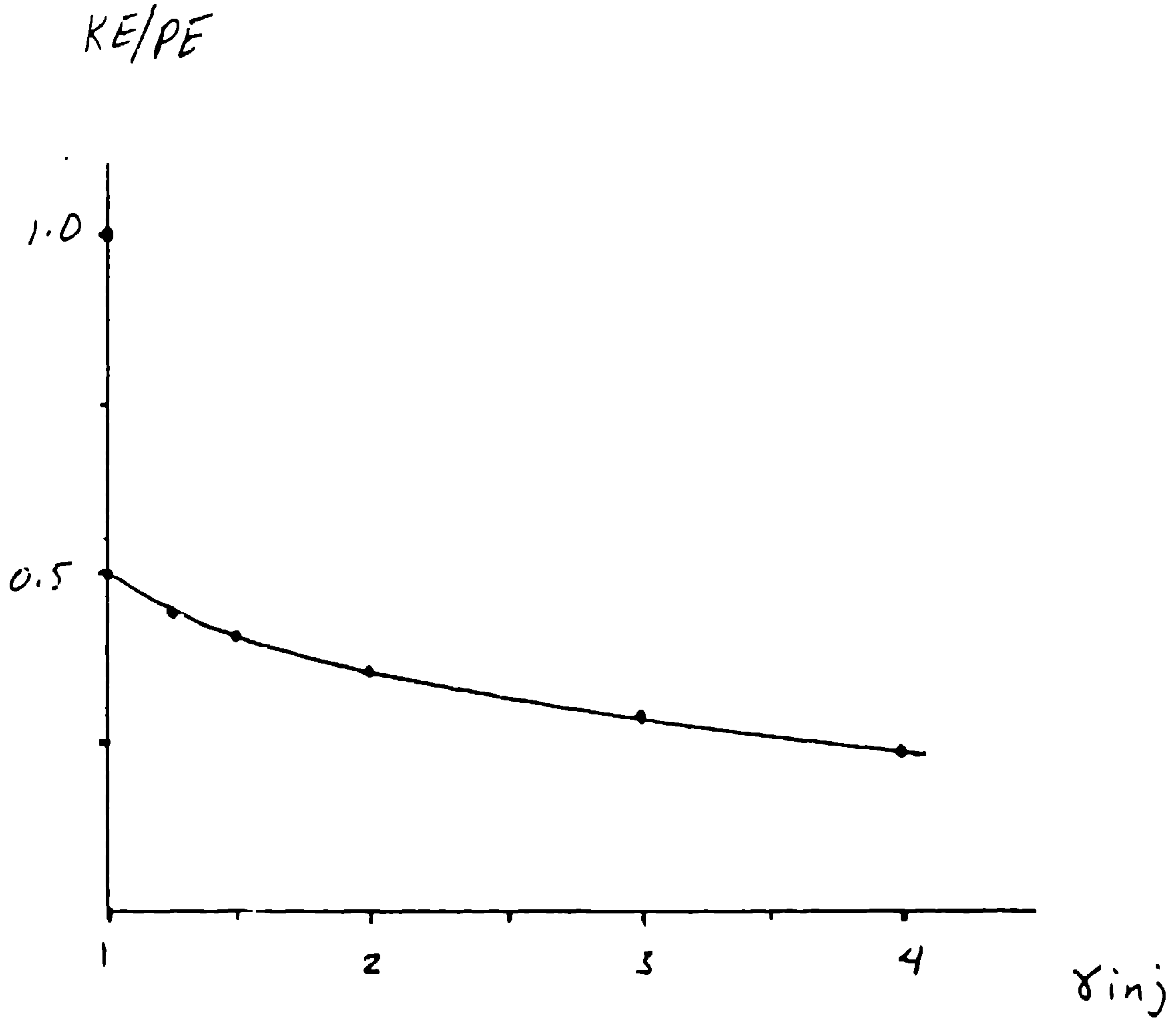
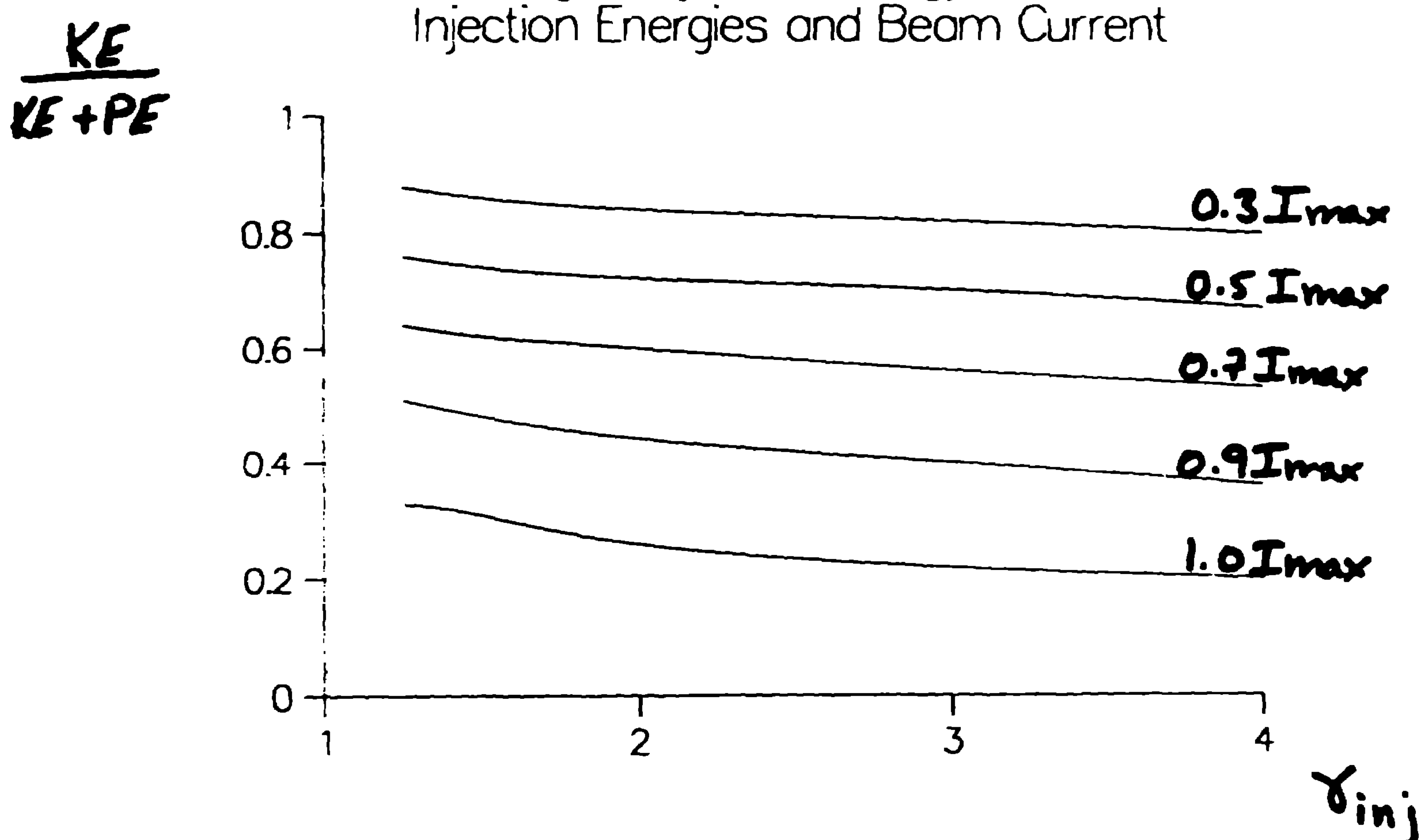


Fig 4 Ratio of Kinetic Energy to Potential Energy for Maximum current transmission for different Injection Energies

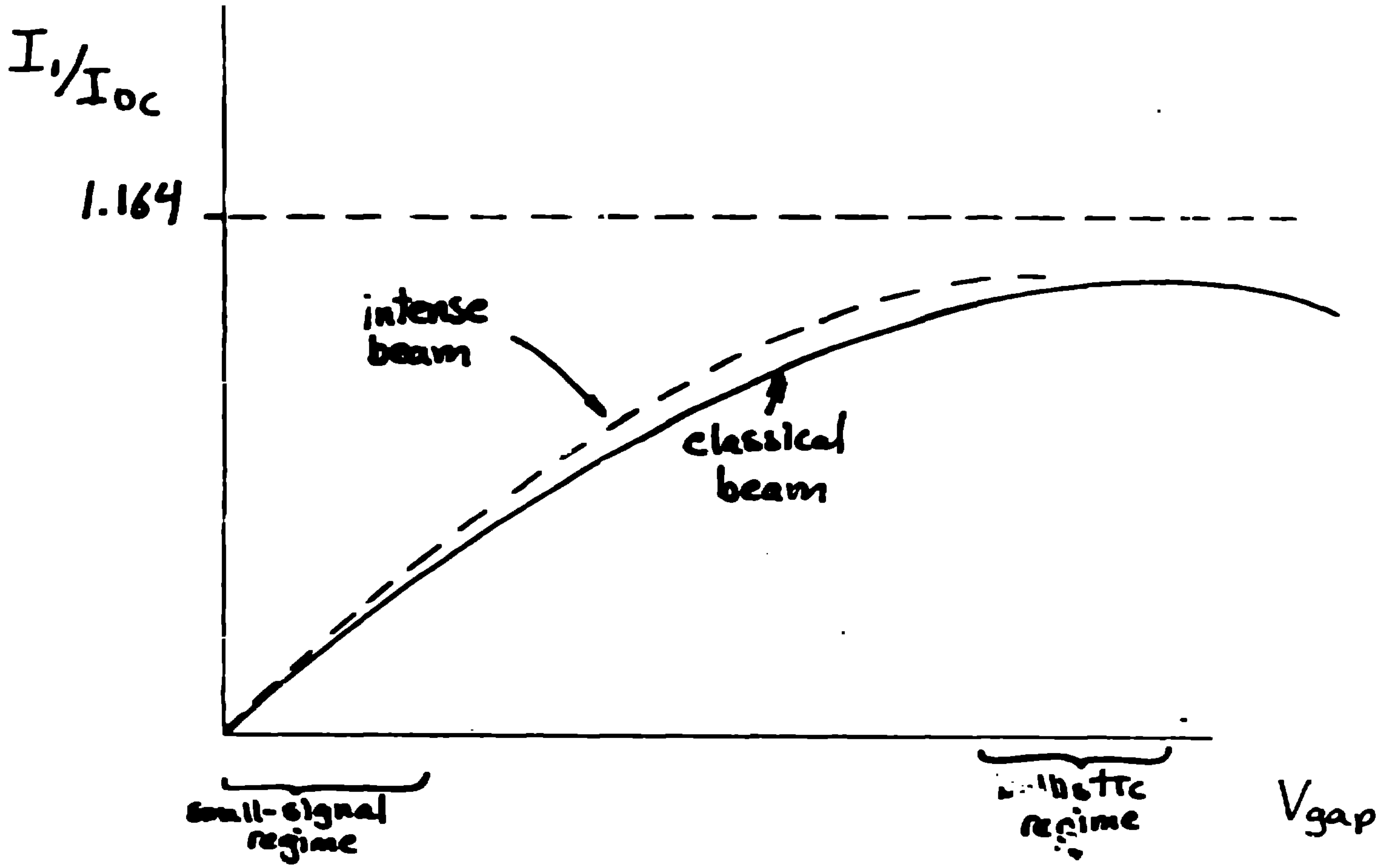
Partitioning of Injection Energy for Different Injection Energies and Beam Current



Power in potential (Coulomb) fields lost – mosty harmonics

Want to keep >90% of power in kinetic motion

Maximum Current Modulation versus Gap Voltage



Current modulation always less than 1.164 if beam has space charge

We want to operate in the ballistic regime

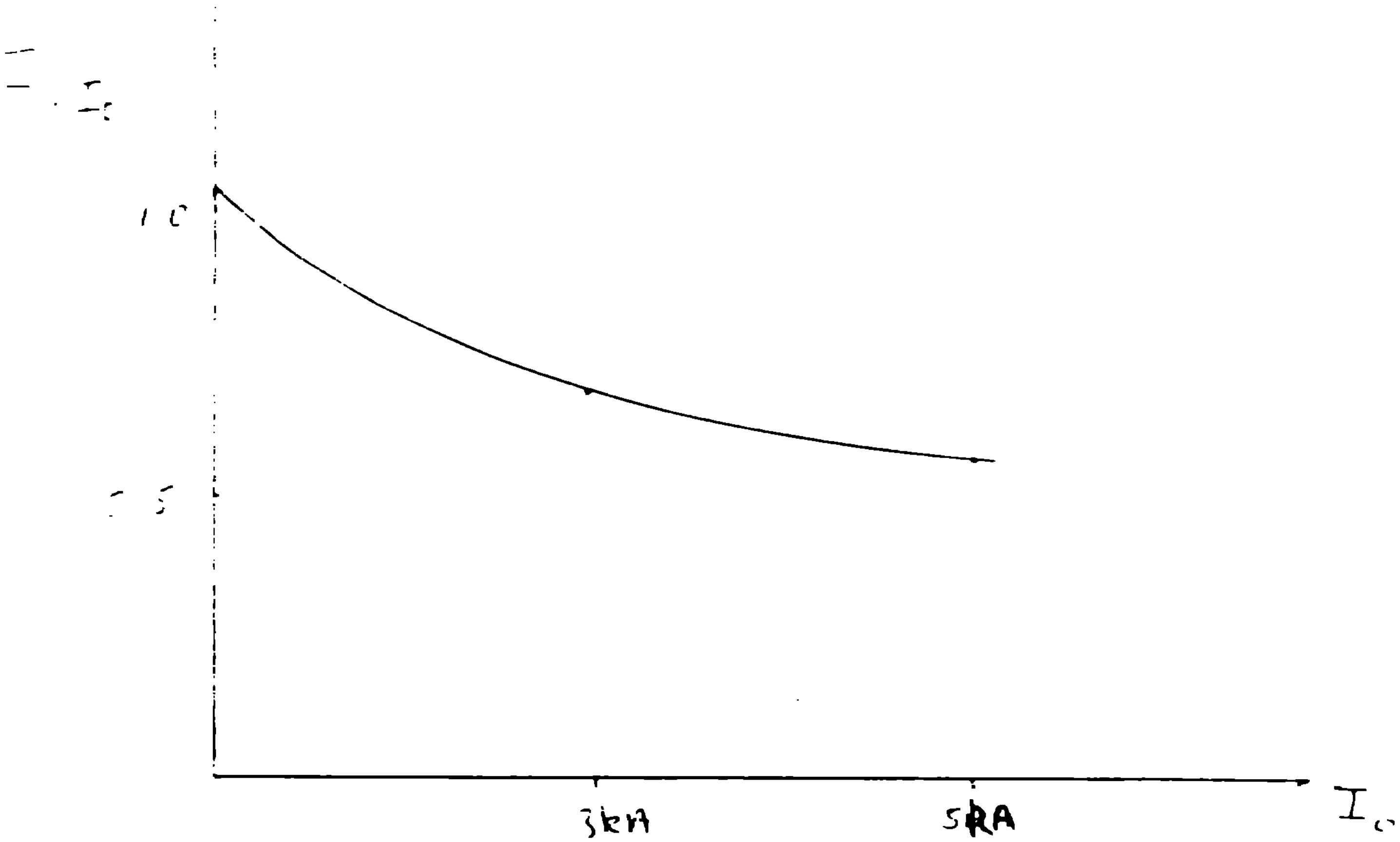


Fig 7 Harmonic Current at the output cavity as a function of beam current, for resonantly tuned idler cavity

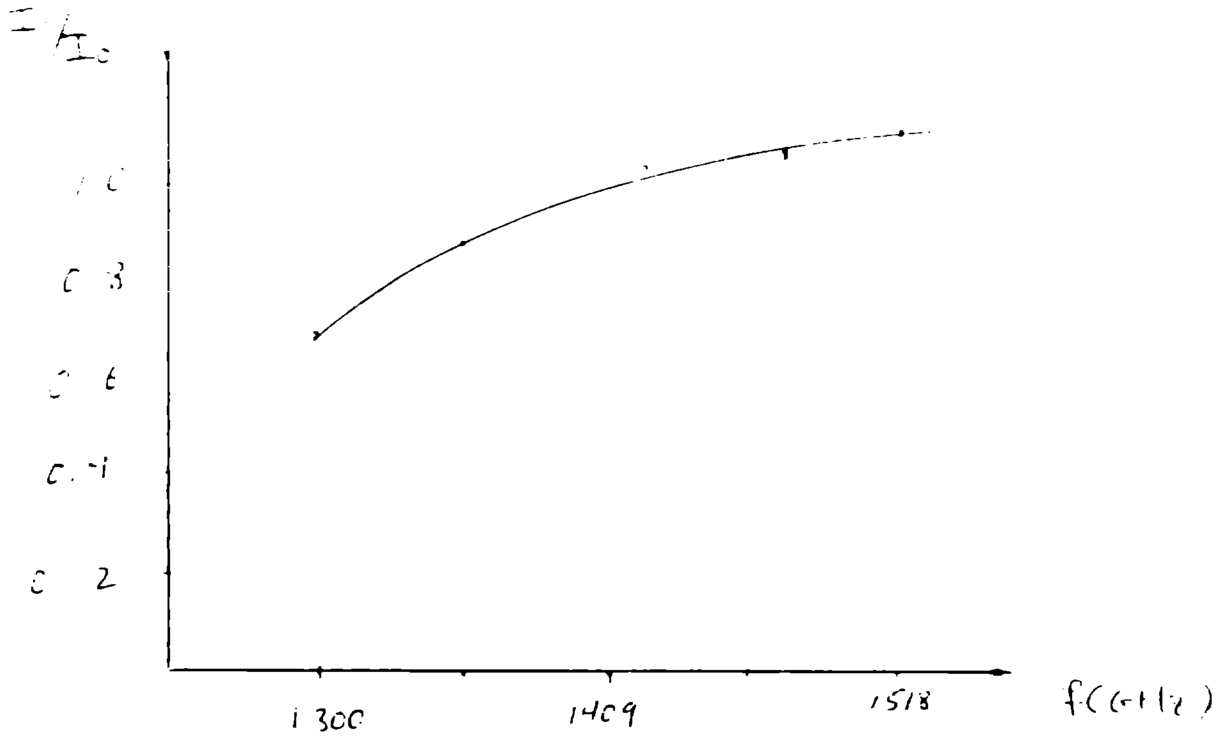
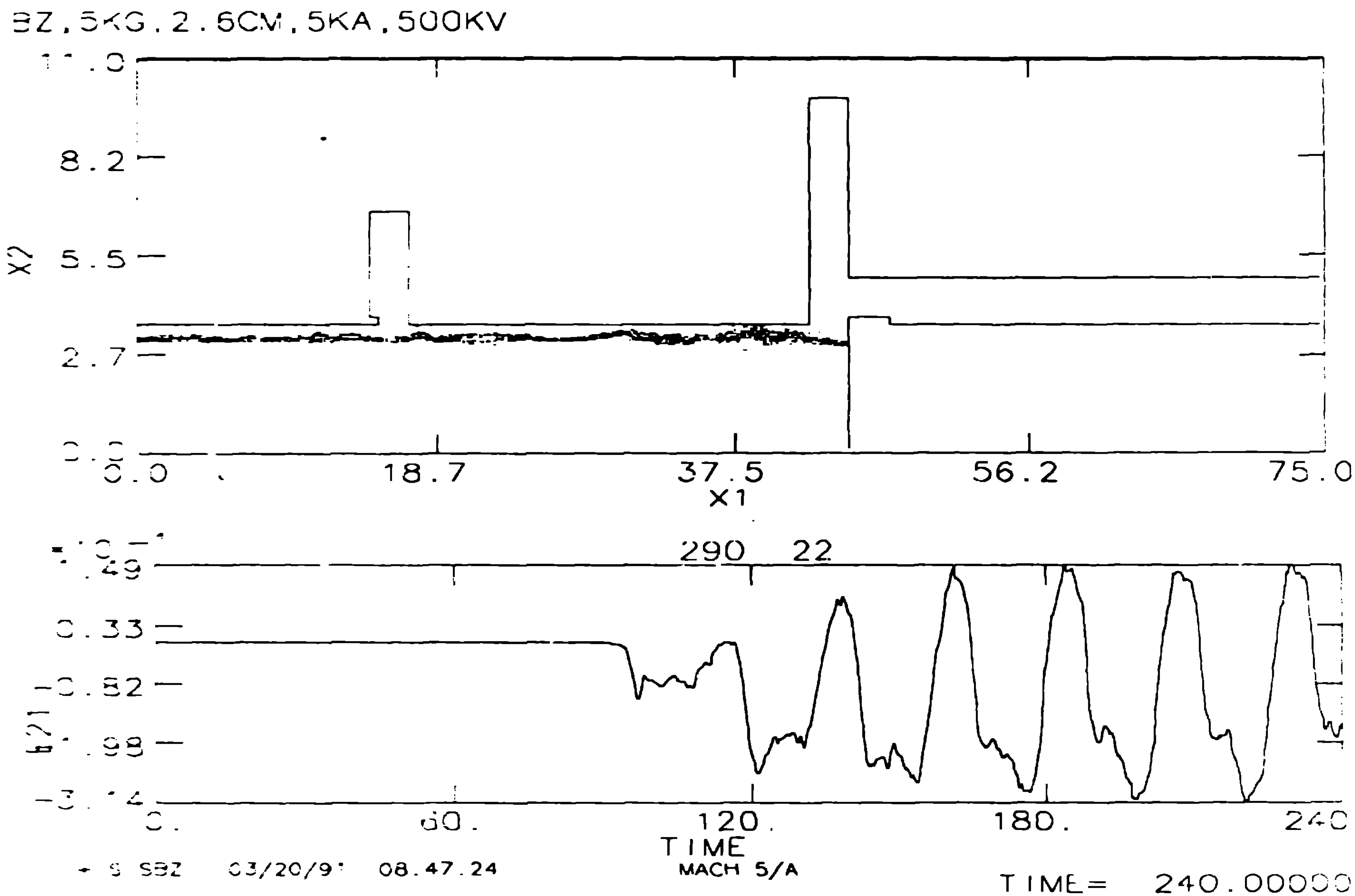
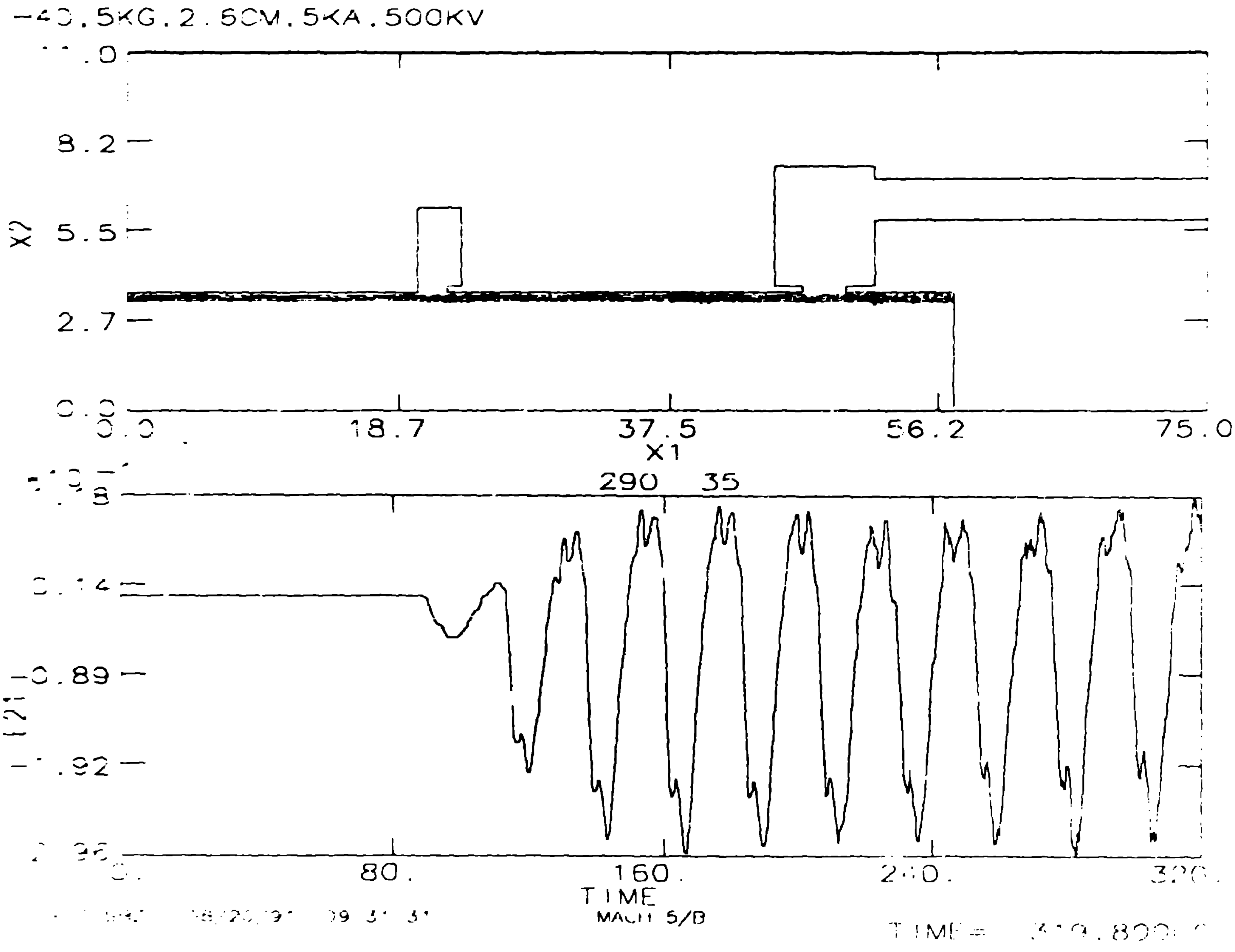


Fig 8 Increase in harmonic current at output cavity as idler cavity is inductively tuned


BZ,5KG,2.6CM,5KA,500KV
8.2
5.5
2.7
X2
0.0
18.7
37.5
56.2
75.0
X1
290 22
0.33
-0.82
-1.98
TIME
0.
60.
120.
180.
240.
03/20/91 08.47.24
MACH 5/A
TIME= 240.00000



.5KG.2.6CM.5KA.500KV
8.2
5.5
2.7
X2
18.7
37.5
56.2
75.0
X1
290
35
80.
160.
TIME
MACH 5/B

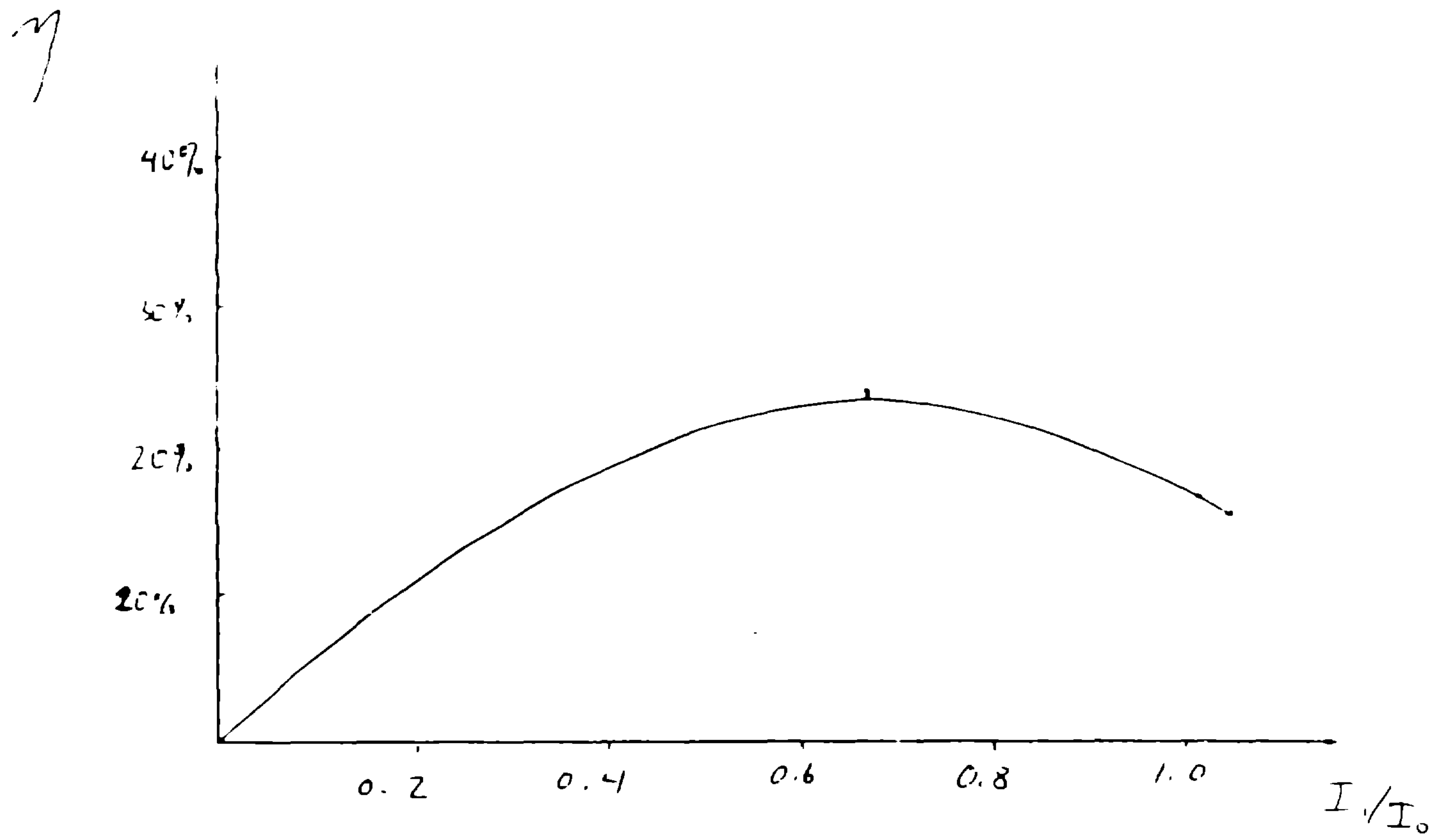
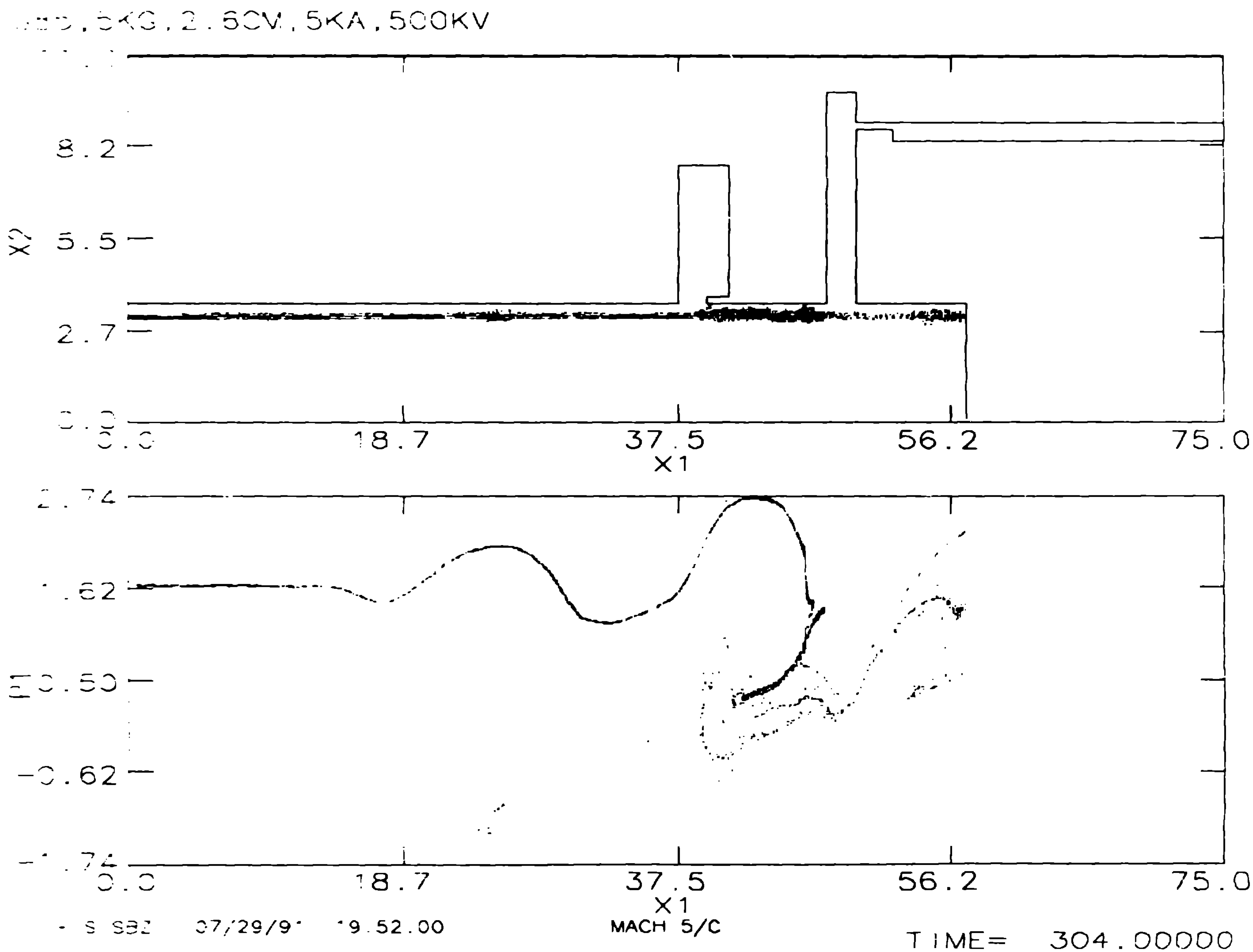
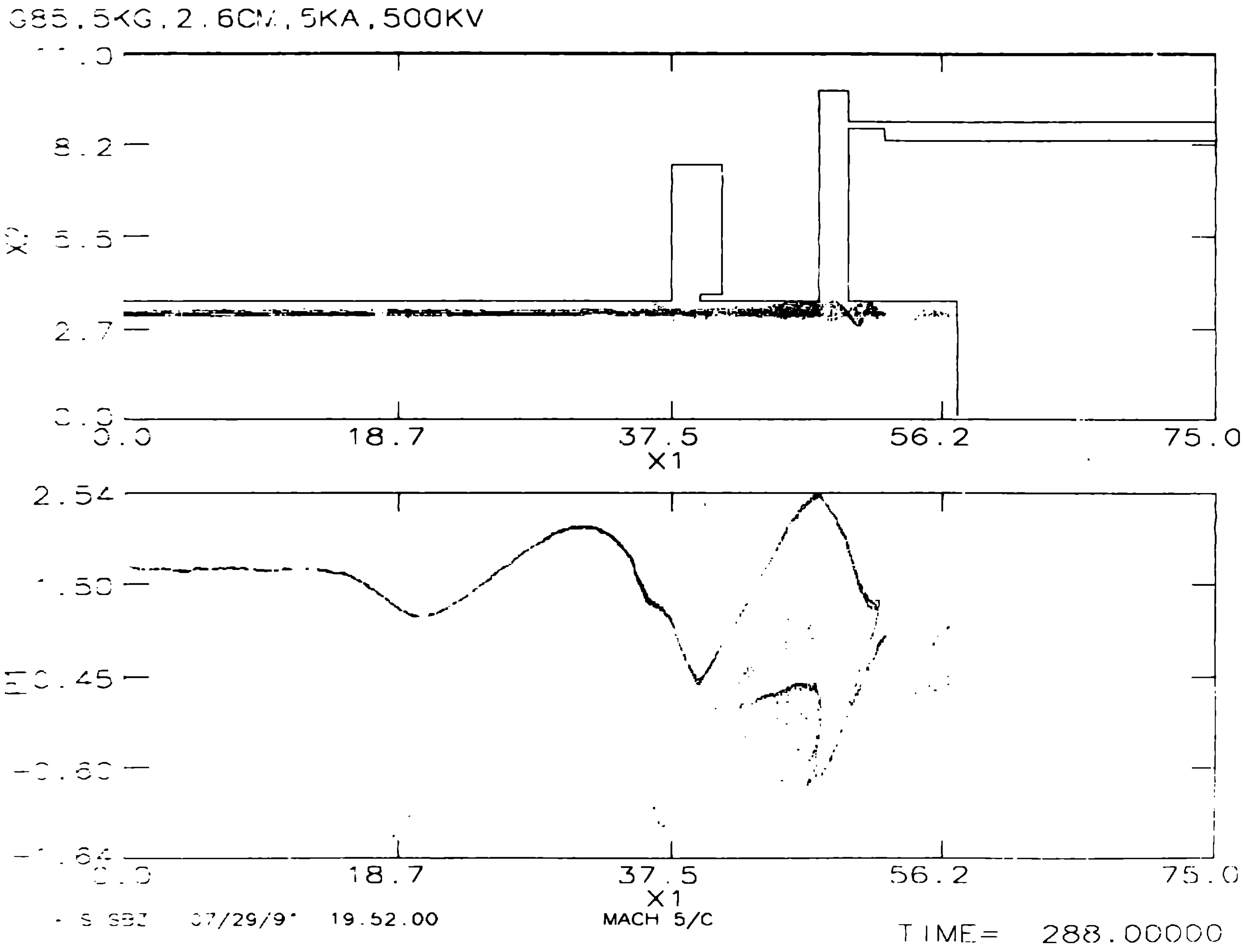
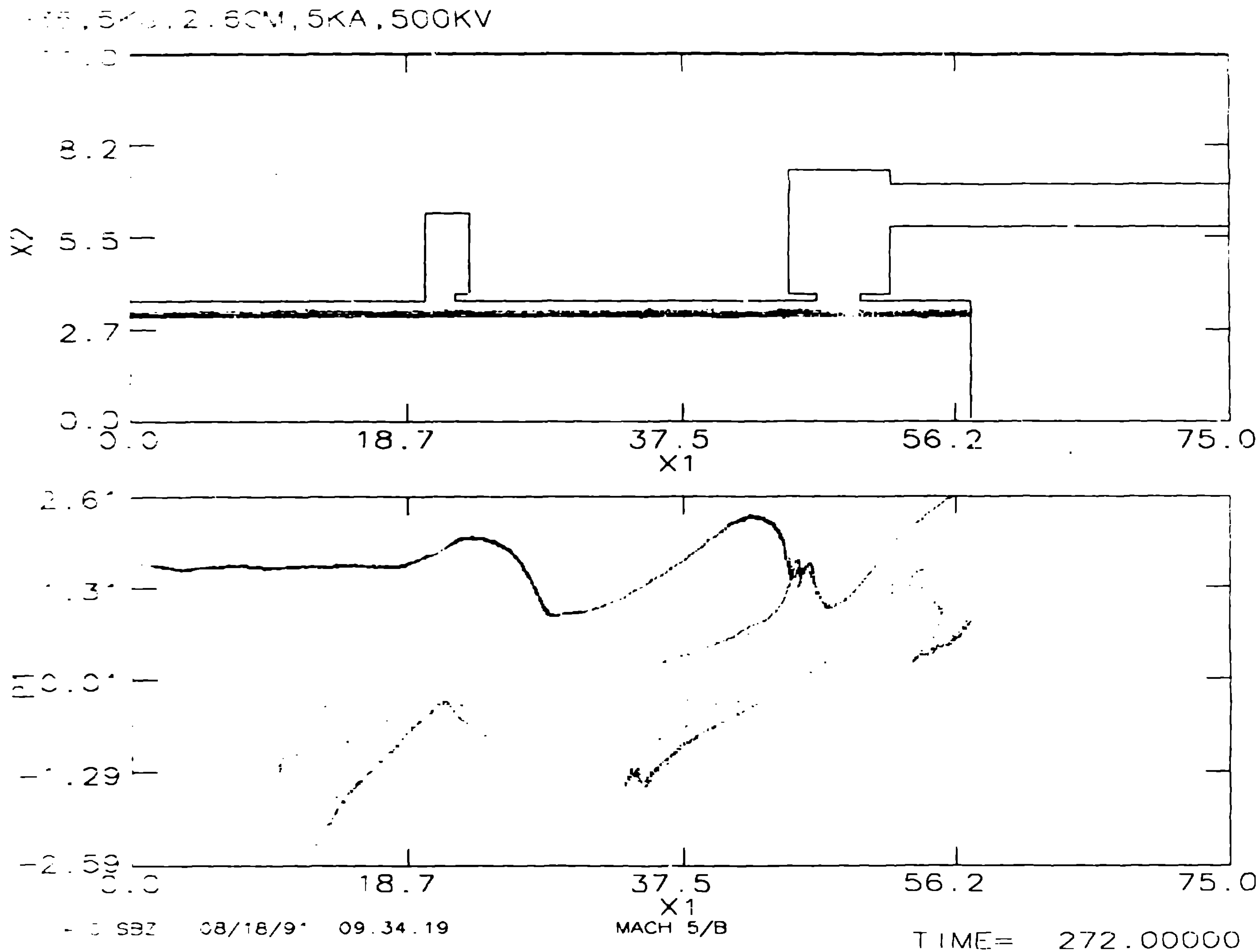


Fig. 11 Extraction efficiency for a 500 kV, 5 kA RKA versus harmonic bunching with $r_w/r_b = 114$. Best extraction is for 65% harmonic current

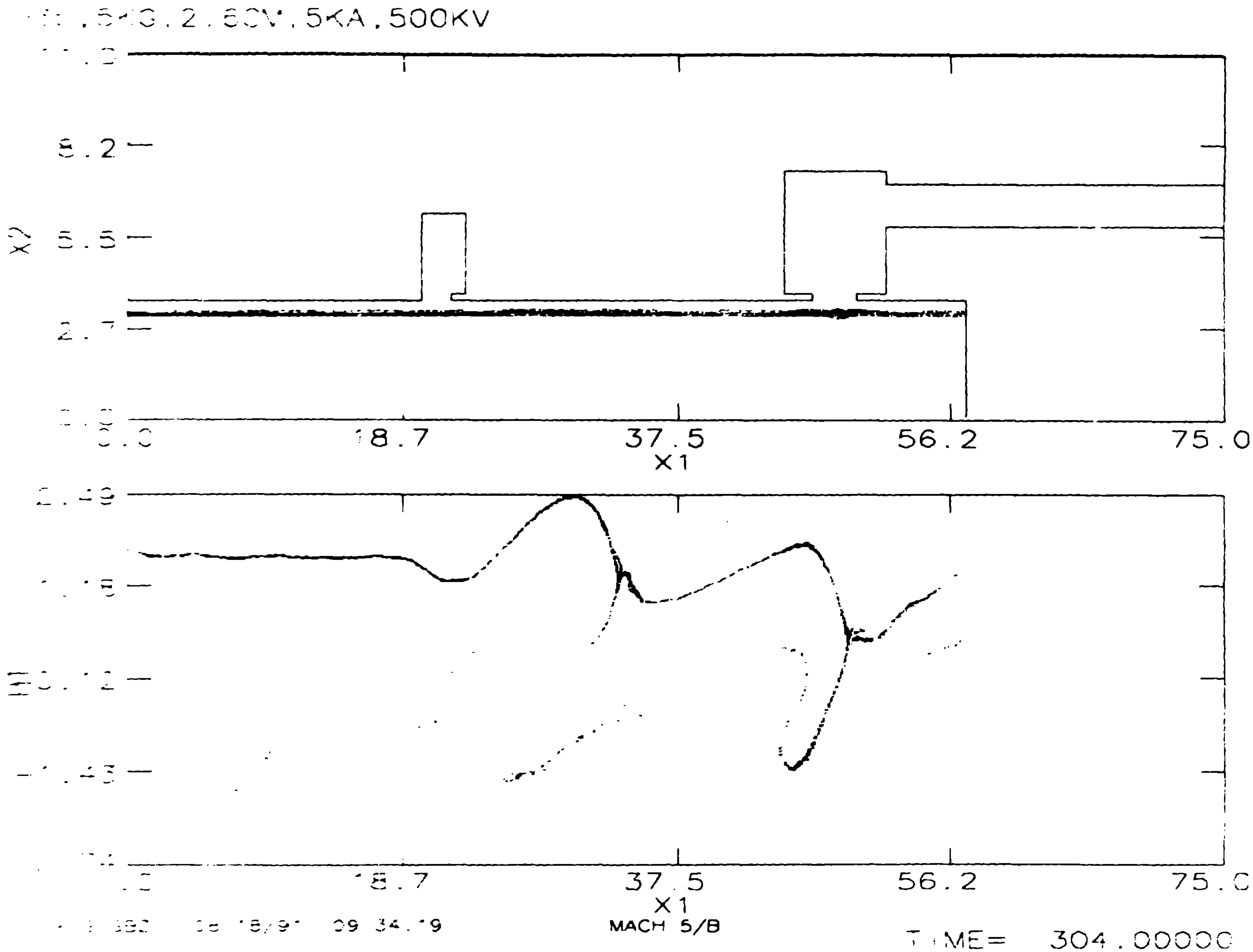

5KG, 2.6CM, 5KA, 500KV
8.2
X2
5.5
2.7
18.7
37.5
56.2
75.0
X1
1.62
-0.62
18.7
37.5
56.2
75.0
X1
19.52.00
MACH 5/C
TIME= 304.00000



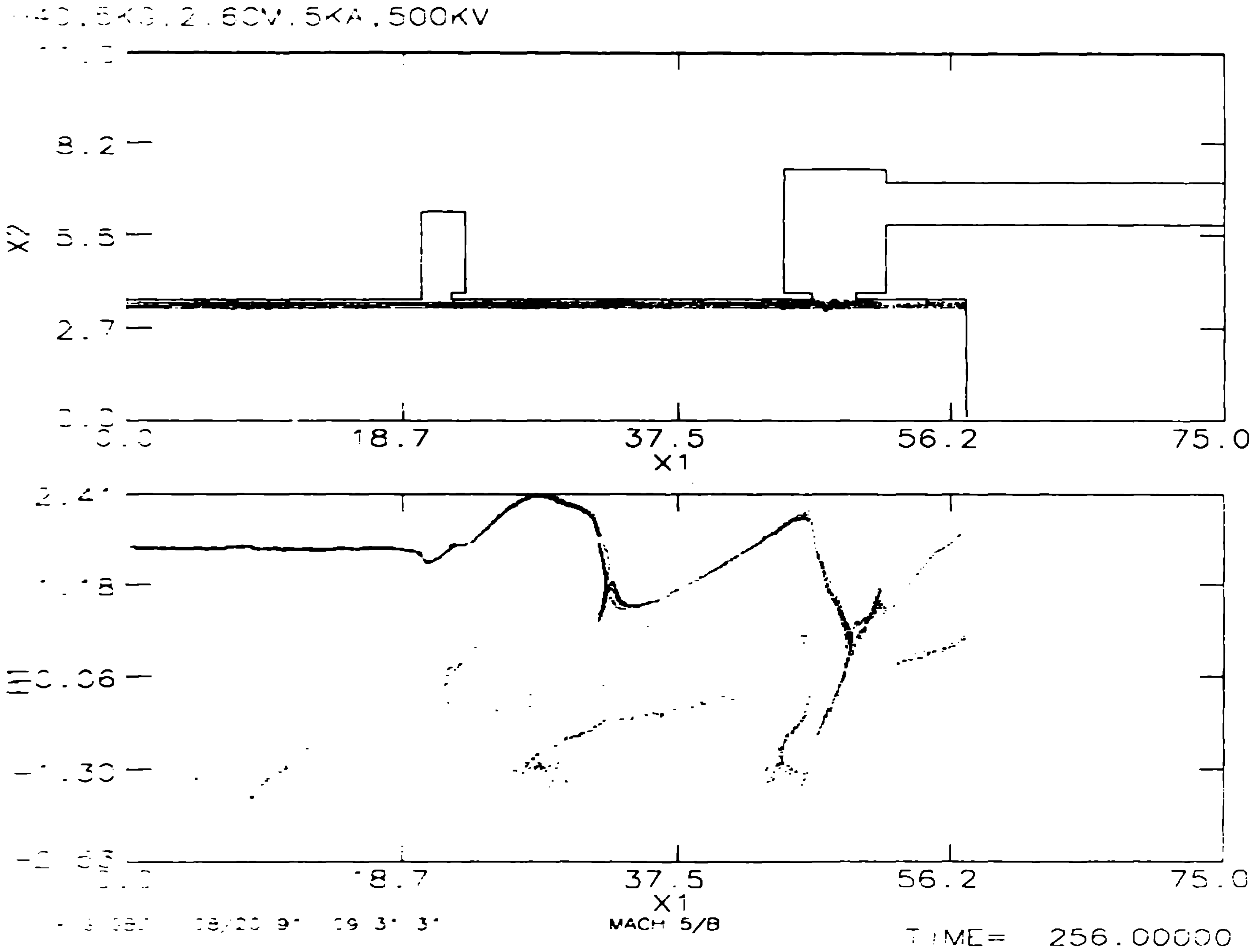
G85.5KG.2.6CM.5KA.500KV
8.2
5.5
2.7
0.0
18.7
37.5
56.2
75.0
X1
2.54
1.50
0.45
-0.60
18.7
37.5
56.2
75.0
X1
07/29/9
19.52.00
MACH 5/C
TIME= 288.00000



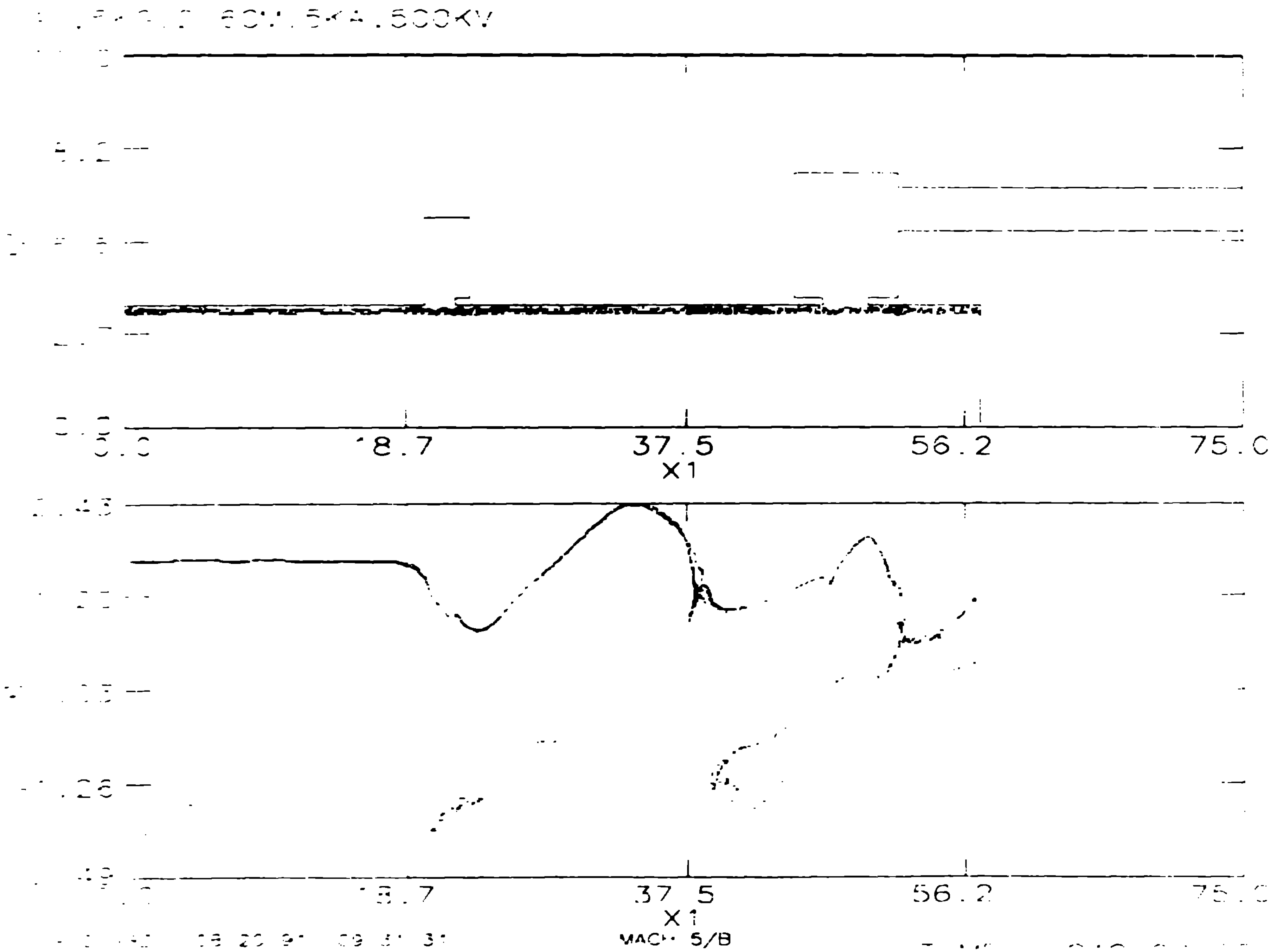
,5KA,500KV
8.2
5.5
2.7
X2
0.0
18.7
37.5
56.2
75.0
X1
-1.29
-2.59
X1
SBZ 08/18/9 09.34.19
MACH 5/B
TIME= 272.00000



.5KG.2.6CM.5KA.500KV
8.2
5.5
2.7
X2
18.7
37.5
56.2
75.0
X1
18.7
37.5
56.2
75.0
X1
MACH 5/B
TIME= 304.00000



.5KG.2.6CV.5KA.500KV
8.2
5.5
2.7
X2
18.7
37.5
56.2
75.0
X1
1.18
0.06
-1.30
18.7
37.5
56.2
75.0
X1
MACH 5/B
TIME= 256.00000


60M.5KA.500KV
18.7
37.5
56.2
75.0
X1
18.7
37.5
56.2
X1
MACH 5/B