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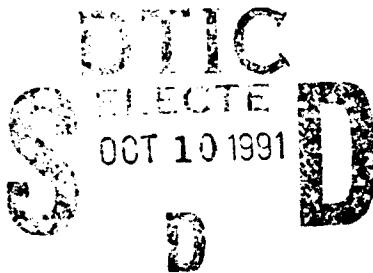
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Further Studies on Beam Breakup Growth Reduction by Cavity Cross-Couplings in Recirculating Accelerators: Effects of Long Pulse Length and Multiturn Recirculation

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Cavity cross-coupling was recently found to reduce beam breakup (BBU) growth in a recirculating accelerator known as the Spiral Line Induction Accelerator (SLIA). Here, we extend the analyses in two respects: long beam pulse lengths and a SLIA upgrade geometry which accelerates a 10 kA, 35 ns beam to 25 MeV via a 70-cavity, 7-turn recirculation.

We found that when the beam pulse length τ exceeds the beam's transit time τ' between cross-coupled cavities, BBU growth may be worsened as a result of the cross-couplings among cavities. This situation is not unlike other long pulse recirculating accelerators where beam recirculation leads to beam breakup of a regenerative type. Thus, the advantage of BBU reduction by cavity cross-coupling is restricted primarily to beams with $\tau < \tau'$, a condition envisioned for all SLIA geometries.

For the 70-gap, 7-turn SLIA upgrade, we found that cavity cross-coupling may reduce BBU growth up to factors of a thousand when the quality factor Q of the deflecting modes are relatively high (like 100). In these high Q cases, the amount of growth reduction depends on the arrangement and sequence of beam recirculation. For $Q \leq 20$, BBU growth reduction by factors of hundreds is observed, but this reduction is insensitive to the sequence of beam recirculation. The above conclusions were based on simple models of cavity coupling that have been used in conventional microwave literature. Not addressed is the detail design consideration that leads to the desired degree of cavity coupling.

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CONTENTS

FURTHER STUDIES ON BEAM BREAKUP GROWTH REDUCTION BY CAVITY CROSS-COUPLINGS IN RECIRCULATING ACCELERATORS: EFFECTS OF LONG PULSE LENGTH AND MULTITURN RECIRCULATION

I.   Introduction

In a previous paper,[1] we reported on the possible reduction of BBU growth by cross-couplings between cavities in the spiral line induction accelerator (SLIA).[2] These calculations applied only to a 2-turn, 20-cavity Proof-of-Concept Experiment (PoCE) where there are five cavities in each of the four arms A. B. C. D (Fig. 1). Cross-coupling occurs, for example, between the accelerating cavities in arm A with those in arm C, as both arms are situated within the same accelerating unit. This cross-coupling leads to the sharing of deflection mode energy in one cavity, which the beam momentarily occupies, with another cavity to which the former cavity cross couples. This sharing of deflecting mode energy is thought to be the main reason for BBU reduction. For the PoCE. the beam's pulse length is sufficiently short that, at any moment, the beam passes through only one of the cross-coupled cavities. For this reason, the reduction in growth was found to prevail, regardless of the phase of the electrons between the cross-coupled cavities.[1] Thus, we concluded that PoCE would very likely accelerate a 10 kA beam to several MeV (8.5) without risk of losing it to the walls because of BBU.

It is natural to inquire whether the projected advantages of cross-coupling would also be observed in a SLIA upgrade, where there would be many recirculations. It is also natural to inquire whether the advantages of cross-coupling would exist in a long pulse beam. This paper attempts to address these questions.

For the SLIA upgrade, the parameters of the beam and of the cavities are chosen to be the same as in Ref. 1. The pulse length is 35 ns, the accelerating cavities increase the beam energy by 300 keV after each gap crossing and the cavities are grouped in units of five on each straight

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arm. Neighboring gaps on the same arm are separated by 35 cm. The bend joining two arms is 350 cm long. The upgrade which we consider in this paper consists of a 7-turn, 70-cavity system which should bring the beam energy to about 25 MeV (Fig. 2). Several issues are considered in this paper.

First, in our previous work,[1] results were reported for a beam pulse length less than or equal to the beam transit time between coupled cavities. Beam overlap may in fact occur in PoCE and the question is to investigate the effects of beam pulse length in that case. Beam overlap may increase BBU growth, since the tail of the beam may be excited by the cross-coupled cavities that lie ahead, in addition to the excitation by the cavity through which the beam tail currently passes.

A more important question we wish to investigate is the effect of adding many more turns (or many more cavities) to the previous system when cavity cross-couplings are present (Fig. 2b,c). Since the beam goes around the accelerator the problem of beam paths around the cavity needs to be addressed. The beam can recirculate in many different ways when there are multiple paths within the same accelerating unit (Fig. 2b,c). For example, it can go around sequentially from one arm to the neighboring one, or by skipping arms (see for example Fig. 8 below). There is also the possibility of having a center arm (Fig. 2c).

In Section II, we investigate the question of beam pulse length in PoCE. In Section III, the 7-turn, 70-cavity upgrade is considered, first without a center arm, then with a center arm. The results are summarized in the Abstract. They are further discussed in the last section.

II. Pulse length variation

It is well-known that BBU growth depends on pulse length both in linear and cyclic accelerators. In this section, we investigate the case of variable pulse length going from short to long, with the beam present in the cross-coupled cavities. In PoCE, there may actually be such a slight beam overlap, that is the pulse length τ is slightly longer than the transit time between cavities τ'. The problem of pulse length variation was investigated for the PoCE geometry only, because of the limitations on the numerical scheme that will be mentioned later. Nevertheless, we may draw certain conclusions from such studies.

As mentioned above, PoCE is a two-turn, 20-cavity accelerator with a 10 kA, 35 ns beam going through sets of 5 cavities separated by 35 cm each, and bends of 350 cm long between each set of accelerating cavities. In this configuration, each cavity N is cross-coupled to the (N±10)th cavity. The dimensionless coupling coefficient is denoted by κ and results have been presented where BBU growth was reduced for $\kappa \neq 0$.

Numerical considerations

The code used in Ref. 1 was designed only for a beam with pulse length less than or equal to the transit time around one turn. It cannot be used when beam overlap occurs. Although the equations do not change, the previous code took advantage of the fact that all the effects of the preceding cavities are carried by the beam when it enters a new cavity. So, the calculation can be broken up at each cavity. When beam overlap takes place, this splitting according to cavities is not possible anymore since the beam in cavity (N+10) for example will affect the field in cavity N, which in turn modifies the beam deflection in cavity N and that

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deflection determines beam deflection for all subsequent cavities, including cavity (N+10). Because of this very strong coupling, the only way of computing the beam transverse displacement at any instant of time is to compute all the fields and all the beam displacements in all of the cavities at each new time step.

In fact, this feedback of BBU on itself makes it regenerative and contributes to the intuitive notion that cross-coupling may be destabilizing.[3-10] This new approach requires much more computer memory than previously and this is the reason why this calculation was performed for PoCE only. A new code was rewritten entirely for this problem of pulse length variation and before any run was made, it was benchmarked against the previous code for $\tau < \tau'$. We fix $\omega_0 \tau' = 204$, $\omega_0 = 2\pi \times 1 \text{GHz}$ and then vary $\omega_0 \tau$, from 40 up to 340, where ω_0 is the frequency of the breakup mode.

Results

Results are shown in Figs. 3 to 5 for a given cross-coupling coefficient κ for several values of Q and for varying beam pulse length τ. The BBU growth for large Q cavity (=100) drops as a function of $\omega_0 \tau$ and then stabilizes up to $\omega_0 \tau = 340$. It takes some time for cross-coupling to be felt for large Q cavities and the fluctuations which are observed at longer τ may be due to the beatings which appear in the solution for such a value of the cross-coupling coefficient. The case for Q=4 does not show any reduction for small beam pulse length. This case can be understood since the time-scale for energy exchange is small. However, when $\tau > \tau'$, feedback between cavities becomes important and the BBU growth increases with τ beyond the level of $\kappa = 0$. The case for Q=20 is intermediate between

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these two cases and is the most complex. It behaves like the large Q case for $\tau < \tau'$ and like the low Q one for $\tau > \tau'$.

It is instructive to show the deflecting mode amplitude in cavities for the low Q case since it is not obscured by beatings. For $\omega_0\tau = 340$, Figs. 6 and 7 show the deflecting mode amplitudes in cavities 1, 5, 6, 11, 16 and 20 as a function of time. The noticeable feature is that there are three spikes in each cavity until the beam exits the system. The first spike is due to the beam entering cavity N. The second spike occurs when the beam enters the coupled cavity N+10. At that time, cavity N is excited again and gives a side kick to the beam. When that portion of the beam reaches the cavity N+10, it excites cavity N again through the coupling, giving rise to the third spike. This echo illustrates well the back-coupling between cavity and beam. It is also responsible for BBU growth for long pulses.

To conclude, a small overlap ($\tau \gtrsim \tau'$) will not adversely affect BBU growth reduction by cavity cross-coupling. As the beam's pulse length increases further, the BBU growth worsens and the beam deflection may reach higher levels than would have been without cross-coupling. Regenerative BBU growth will occur in those cases. The time it takes for regenerative growth to occur increases with Q, according to the data collected so far.

III. Seventy cavity upgrade SLIA

Results up to now have been obtained for the PoCE geometry (2-turn, 20-cavity configuration). An extension of the system to a 7-turn, 70-cavity configuration has two main purposes. It answers two main questions:

    1. Is the BBU growth further reduced for a larger number of cross-coupled cavities?

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2. Does the reduction depend on the way the beam passes through the multiple arms?

The first question is very straightforward and most fundamental since, if there is no further reduction, the effects of cross-coupling can be viewed with some suspicion. The second question requires some explaining. Since the beam is to go through all 7 arms of each accelerating unit, the results may depend on the order in which the beam goes through the arms. In this section, we reserve the word gap for the actual place where the beam crosses the cavity and unit as the accelerating unit (which consists of 7 arms). An analogy can be made with a thread (beam) going through a button (unit) with many holes (gaps). Will the button be better secured to the garment depending on the path of the thread through the various holes or not? Is BBU growth more limited depending on the beam path threading through the unit or not? The main conceptual difference between button sewing and SLIA upgrade is that the beam goes through each gap only once instead of several times for the thread through each button hole.

Two main types of configurations will be examined for SLIA upgrade: first, configurations in which there is no center arm (Fig. 2b) and second, configurations with a center arm (Fig. 2c). These two types of configurations will be examined in different subsections. The center arm configurations are more complicated to study as we shall see later since they introduce more parameters which reflect the lack of symmetry in the gap coupling between the center arm and the peripheral arms (Fig. 2c). However, as mentioned before, only beam pulse length less than τ' will be considered in the remainder of this paper.

a) Configurations without a center arm (Fig. 2b).

Three types of configurations are examined in the following section
and displayed in Fig. 8. On the various graphs are shown the possible
sequences of beam paths through the seven arms in a unit. In configuration
I, the beam goes through each arm in adjacent order. In configuration II,
the beam goes through gaps by skipping the adjacent arm after each turn.
In configuration III, the beam goes through the gaps by skipping two arms
at a time around the periphery. Furthermore, it is assumed that each gap
is cross-coupled directly to its two neighbors (that belong to two adjacent
arms) only through the cross-coupling coefficient κ and that the κ's are
the same for all cross-couplings [Fig. 2c]. Thus, corresponding gaps in
neighboring arms are coupled through κ by definition. Weaker coupling
between two cavities would result if they are separated by more than one
arm, as gaps separated by one arm are coupled, at first sight, through κ^2.
From this simple argument, it would seem that configuration I is the worst
since the beam will enter the unit on its second turn in one of the two
gaps which has just been cross-excited by the previous beam's passage. In
the same line of thought, configuration III would seem to be the best since
on its second turn, the beam enters the gap which is the furthest away from
the gap directly excited by the beam's first passage. As we shall see, the
true situation is more complicated than this intuitive argument would
indicate.

The beam parameters are the same as for PoCE: beam current $I=10$ kA,
relativistic factor $\gamma=17$, transverse impedance $Z_{\perp}/30Q=0.416\Omega$, and BBU
coupling coefficient $\varepsilon=0.0144$. The normalized focusing strength $\Omega=\omega_o/\omega_c$,
Q and κ are specified in the various figures. Beam transport between
cavities are described by 2x2 matrices. Note that $Z_{\perp}/30Q$ does not change

when Q i⁻ ..anged. Initial conditions are the same as in Ref. 1, i.e., the deflecting mode amplitude in the first gap is set to f_o at t=0 while all other quantities are set to 0 at t=0.

The equations for configuration I in Fig. 8 are given below to illustrate the structure of the governing equations. If we define L as the following operator,

$$L \equiv \frac{d^2}{dt^2} + \frac{\omega_o}{Q}\frac{d}{dt} + \omega_o^2,$$

then equations for coupled gaps 1 through 61 are:

$$Lf^1 = \kappa(f^{61} + f^{11}) + \varepsilon h^1 x^1 \qquad (1)$$

$$Lf^{11} = \kappa(f^1 + f^{21}) + \varepsilon h^{11} x^{11} \qquad (2)$$

$$Lf^{21} = \kappa(f^{11} + f^{31}) + \varepsilon h^{21} x^{21} \qquad (3)$$

$$Lf^{31} = \kappa(f^{21} + f^{41}) + \varepsilon h^{31} x^{31} \qquad (4)$$

$$Lf^{41} = \kappa(f^{31} + f^{51}) + \varepsilon h^{41} x^{41} \qquad (5)$$

$$Lf^{51} = \kappa(f^{41} + f^{61}) + \varepsilon h^{51} x^{51} \qquad (6)$$

$$Lf^{61} = \kappa(f^{51} + f^1) + \varepsilon h^{61} x^{61} \qquad (7)$$

where $h^i(t)$ is a function of time which is 1 when the beam is present at the gap and 0 at all other times. Note that in this system of equations the energy of the beam can change from its initial value (3.5 MeV) to its final value (25 MeV), resulting in a change in ε, the BBU coupling constant and Ω the normalized focusing strength. Both quantities are inversely proportional to γ. The BBU coupling constant decreases with γ, since as γ increases, the beam becomes stiffer and the transverse beam displacement for the same mode amplitude decreases. The normalized field strength decreases since the betatron frequency decreases. It is well-known that

these two effects cancel each other out[11] as far as BBU growth is concerned.

The code structure is the same as for PoCE except that now, all the mode amplitudes in the coupled gaps are solved for at every gap. This procedure was followed to insure that all the gaps are cross-coupled to each other whenever the beam passes any cross-coupled gap.

Results

A typical example of deflecting mode amplitude and beam displacement as a function of gap number and time is shown in Figs. 9 and 10 for $\kappa = 0.1$, $Q = 20$ and $\Omega = 0.51$. The deflecting mode amplitudes in each gap reflect clearly the beam's passages especially for the first 4 or 5 turns when the deflecting mode amplitude has not grown too much and has not overshadowed the results at earlier times. The beam displacement can be shown to grow steadily along its path and beatings between the various cavities can be seen from these graphs. A summary of the results appear on Figs. 11 to 13. On Fig. 11, the BBU growth for the three different configurations is shown as a function of κ for a coasting beam (constant $\gamma = 17$) for $Q = 100$, $\Omega = 0.8$. Several remarks can be made :

1. The maximum reduction reaches a factor of 1000 for configuration II for $\kappa = 0.1$

2. For $\kappa < 0.04$, configuration I seems to show a larger reduction than configuration II and III, contrary to intuition.

3. For $\kappa > 0.04$, configuration II and III show less BBU growth than configuration I, with III better at small κ and II taking over for $\kappa = 0.08$.

Figure 12 shows the results for Q=20, Ω=0.8 and the comparison between a coasting and an accelerating beam. The differences between the various configurations are not shown since they are small for that value of Q, due to the importance of damping. The interesting features of the results are once more the further reduction in BBU growth with increasing κ. The reduction in these cases reaches factors of approximately a hundred. The similarity of the results between the coasting and accelerating beam corroborates the findings in Ref. 11 that the exponent for BBU growth is proportional to ε/Ω, which is independent of γ for solenoidal focusing. It seems that there are enough cavities for the scaling to hold. Figure 13 shows results for Q=4, Ω=0.515 for both coasting and accelerating beams. Once more, the differences between configurations are completely negligible. Note that the BBU growth for this 7-turn system is only a factor of about 3. Even for this low value of Q, BBU growth is reduced but the variations in the configurations do not make much difference (if at all).

In conclusion to this subsection, it has been shown that the scaling of PoCE to 7-turn, 70-cavity has confirmed the reduction of BBU growth due to cross-coupling, that the most sensitive parameter (besides the system parameters which are assumed to be fixed) is the cross-coupling coefficient and that for the larger Q cases, the path of the beam around the coupled cavities is a significant factor. For low Q cases, the threading of the beam through the unit does not make any difference, at least within the assumptions of the model presented here.

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b)   Configuration with center arm (Fig. 2c)

In the final configurations, the beam goes through a center pipe on one of its passages. This case is much more complicated than the previous one as numerous configurations can be envisioned. Two most extreme cases will be considered among the many possible ones and are shown in Fig. 14. In the first one which we shall call configuration IV, the beam goes through the center arm first before going around the peripheral arms in adjacent order. In the second case, which we shall call configuration V, the beam goes through the center arm last after having gone through the peripheral arms in adjacent order. Once more, on the basis of simple-minded intuition, it seems that case IV should be the worst one since the center arm is connected to all the other arms and its excitation on the first turn will excite the gaps in all the other arms. But from what we have learned in the previous section, the differences between these two cases are not expected to be very important as Q is lowered.

Before going any further, several assumptions must be made. In this new geometry, a gap in each peripheral arm is excited by three gaps, two from the neighboring peripheral arms and one in the center arm [Fig. 2c]. The degree of excitation by the peripheral arm is measured by the coupling constant κ and that by the center arm by κ'. The center arm is excited by all the peripheral arms and that degree of excitation is measured by κ''. There is no reason to assume κ, κ', κ'' to be equal. Thus, in this model, the breakup modes in gaps 1 and 11 in configuration IV [Fig. 14] evolve according to

$$Lf^1 = \kappa''[f^{11} + f^{21} + f^{31} + f^{41} + f^{51} + f^{61}] + \varepsilon h^1 x^1 \qquad (8)$$

$$Lf^{11} = \kappa' f^1 + \kappa[f^{21} + f^{61}] + \varepsilon h^{11} x^{11} \qquad (9)$$

Similar equations for f^{21}, f^{31}, ...f^{61} can be constructed.

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The coupling coefficients κ, κ' and κ'' cannot be chosen arbitrarily. The first question which must be addressed is the condition which must be satisfied by these coefficients in order that the system of cross-coupled gaps undergoes only stable oscillations in the absence of any beam. Considerable algebra involving a 7x7 determinant leads to the simple condition:

$$\kappa'\kappa'' > - \kappa^2/6. \tag{10}$$

This inequality shows that any set of positive coupling constants leads to a stable mode of oscillations.

Because of the many possibilities introduced by three coupling parameters, some simplifying but rather arbitrary assumptions are made. κ and κ' are assumed to be equal. This seems to be physically plausible because the distance between two peripheral gaps and that one between the central gap and any peripheral one are the same for this special case of 7 turns (6 gaps on the outside, 1 in the center). The second assumption sets κ to be equal to $\kappa/\sqrt{2}$. This is motivated by the observation that any peripheral gap is connected to 3 neighboring gaps whereas the central gap is connected to 6 peripheral gaps. From energy considerations, one may venture that the central gap shares its energy with twice as many gaps as any peripheral one. This ratio was then changed to study the sensitivity of the results, as reported below.

The results are shown in Figs. 15 to 17 for Q=100, Ω=0.8, then for Q=20, Ω=0.8 and for Q=4, Ω=0.515 as was done for configurations I to III. First of all, the results present the same kind of characteristics as those without a center arm and the reduction factors are very similar. If we look at the results in more detail, we see that configuration V is

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consistently better than configuration IV for the large Q case, but not by much. So, our simple-minded guess turns out to be correct but not in a striking fashion. Also, configuration II seems to give the best reduction factor for $\kappa=0.1$ but that may depend on the choice of the ratio κ''/κ for the last two configurations. Both configurations IV and V show a sharp drop in BBU growth as a function of κ, followed by a plateau starting at $\kappa \simeq 0.05$. This feature was also shared by a 2-turn, 20 -cavity system[1], but not by the results of Fig. 12.

The test concerning the ratio of κ'' to κ is shown in Figs. 15 and 17. For $\kappa=0.05$, κ'' was changed from its value of $\sqrt{2}/2$ to 0.3 and to 1. For the larger κ'' value, the BBU growth is less severe, in agreement with the fact that more coupling will reduce BBU growth (for $\tau < \tau'$). For the lower κ'' value, BBU growth becomes more severe. This test reinforces the conclusion that increased cross-coupling reduces BBU growth.

IV. <u>Conclusion</u>

It has been shown in this work that cross-coupling between cavities reduces BBU growth for non-overlapping beams ($\tau < \tau'$). For a 7-turn, 70-cavity SLIA upgrade, more reduction is achieved for larger cross-coupling coefficients. For higher values of Q ($Q \gtrsim 100$), the type of configuration chosen for the beam path through the accelerating unit may make some difference, whereas for lower values of Q ($Q \lesssim 20$), the type of configuration does not make much difference. It is possible that for optimization purposes and for a specific case, one configuration may be better than the others but a simulation would be required with a more complete model.

The addition of a pipe in the center of the accelerating unit adds to the number of free parameters and to the complexity of the solution without yielding much additional insight. The only two advantages associated with this geometry seem to be that the presence of a central gap reduces BBU growth consistently and that no further reduction is observed beyond a relatively small value of κ. But once more, in view of the increase in the number of free parameters, these conclusions are tentative, since many other possibilities have not been considered. The parameter and configuration spaces have only been surveyed rather coarsely.

Reduction of BBU amplitude by a factor of 1000 have been simulated in a 7-turn, 70-cavity SLIA upgrade. Even in this case, we made a conservative assumption in assigning a constant value of $Z_\perp/Q=12.5\Omega$, regardless of the values of Q used. The practical value for $Z_\perp/Q$ may be lowered for carefully designed shielded gaps.[12]

Other assumptions which may affect the solution in unknown ways are the transit time factor where the gap width cannot be assumed to be small. Nor have we considered the coupling between the BBU and the beam's corkscrew motions.[13] Perhaps the most important problem that has not been addressed is the cavity design that can lead to the desirable cross-coupling coefficients (κ). If the conventional microwave literature may be used as a guide, coupling coefficients of a few per cent have been routinely considered, e.g., in klystron oscillators.[14]

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Acknowledgments

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SLIA PROOF-OF-CONCEPT EXPERIMENT
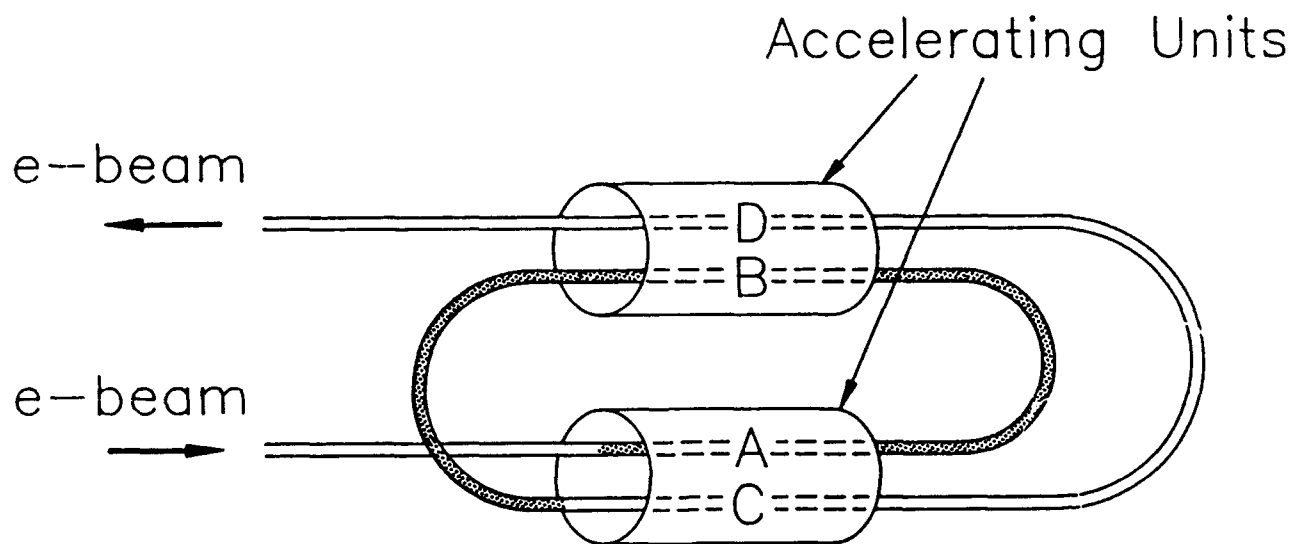
Fig. 1 Schematics of Proof-of-Concept Experiment for the Spiral Line
Induction Accelerator.

SLIA Upgrade
7 turn – 70 Cavities
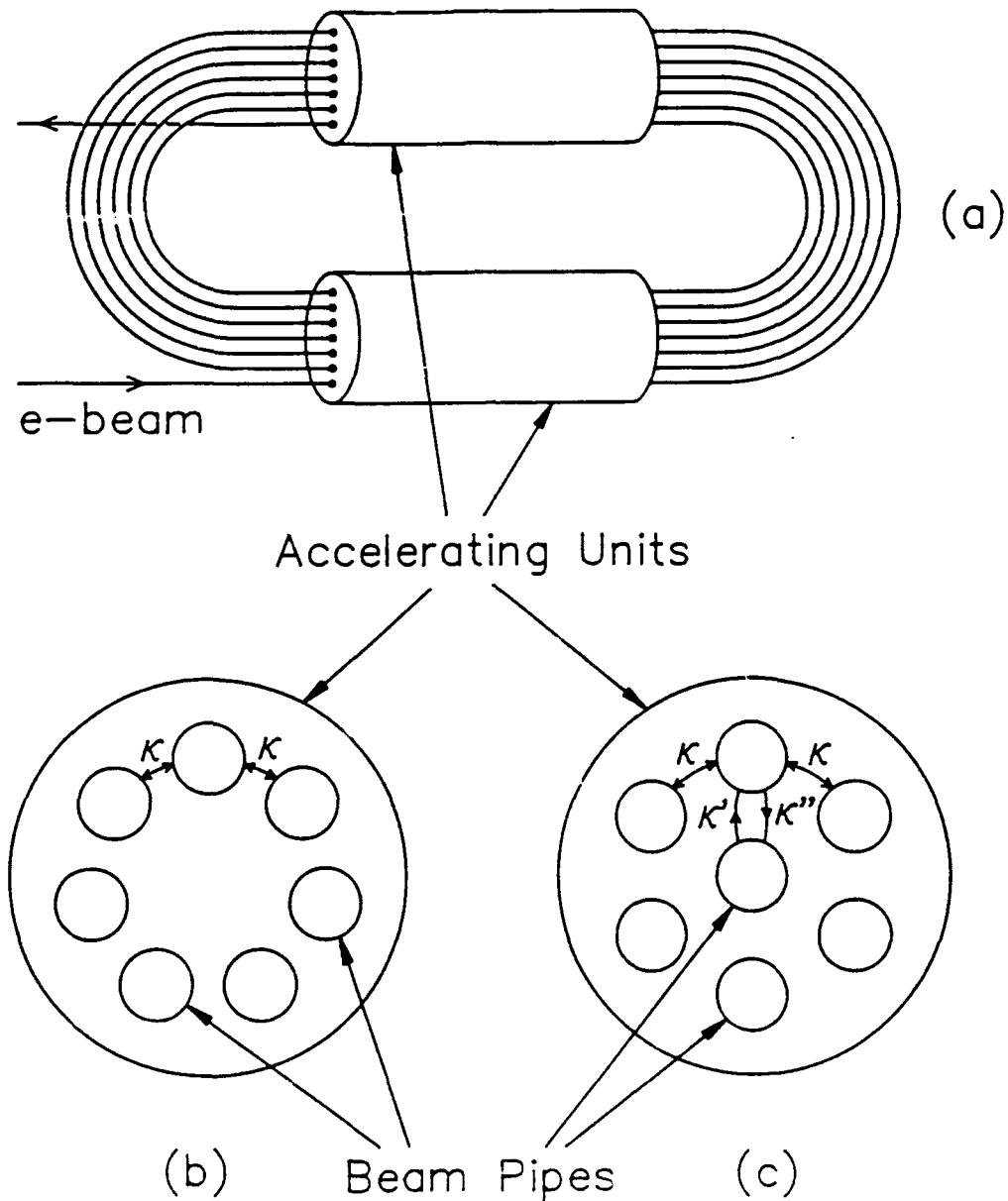
Fig. 2 Schematics of SLIA upgrade showing the 7 turns (a) and the cross
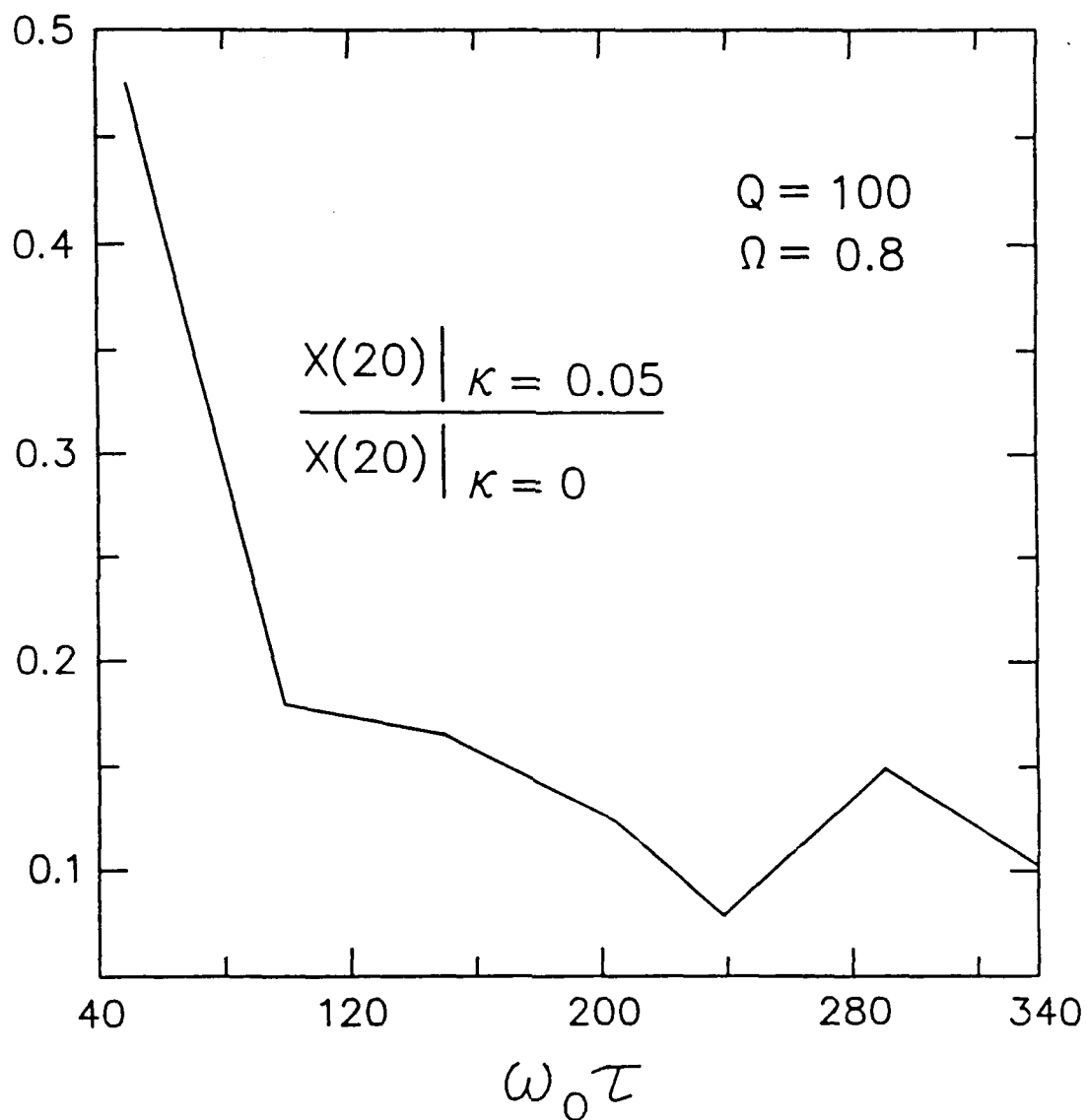
sectional views of different beam pipe arrangements (b, c).

Fig. 3 Influence of beam pulse length on BBU growth for PoCE for Q=100, Ω=0.8 and κ=0.05. The graph plots the ratio of the final beam displacement with (κ=0.05) to that one without cross-coupling.

$$\frac{X(20)\big|_{\kappa = 0.05}}{X(20)\big|_{\kappa = 0}}$$

$Q = 4$

$\Omega = 0.14$
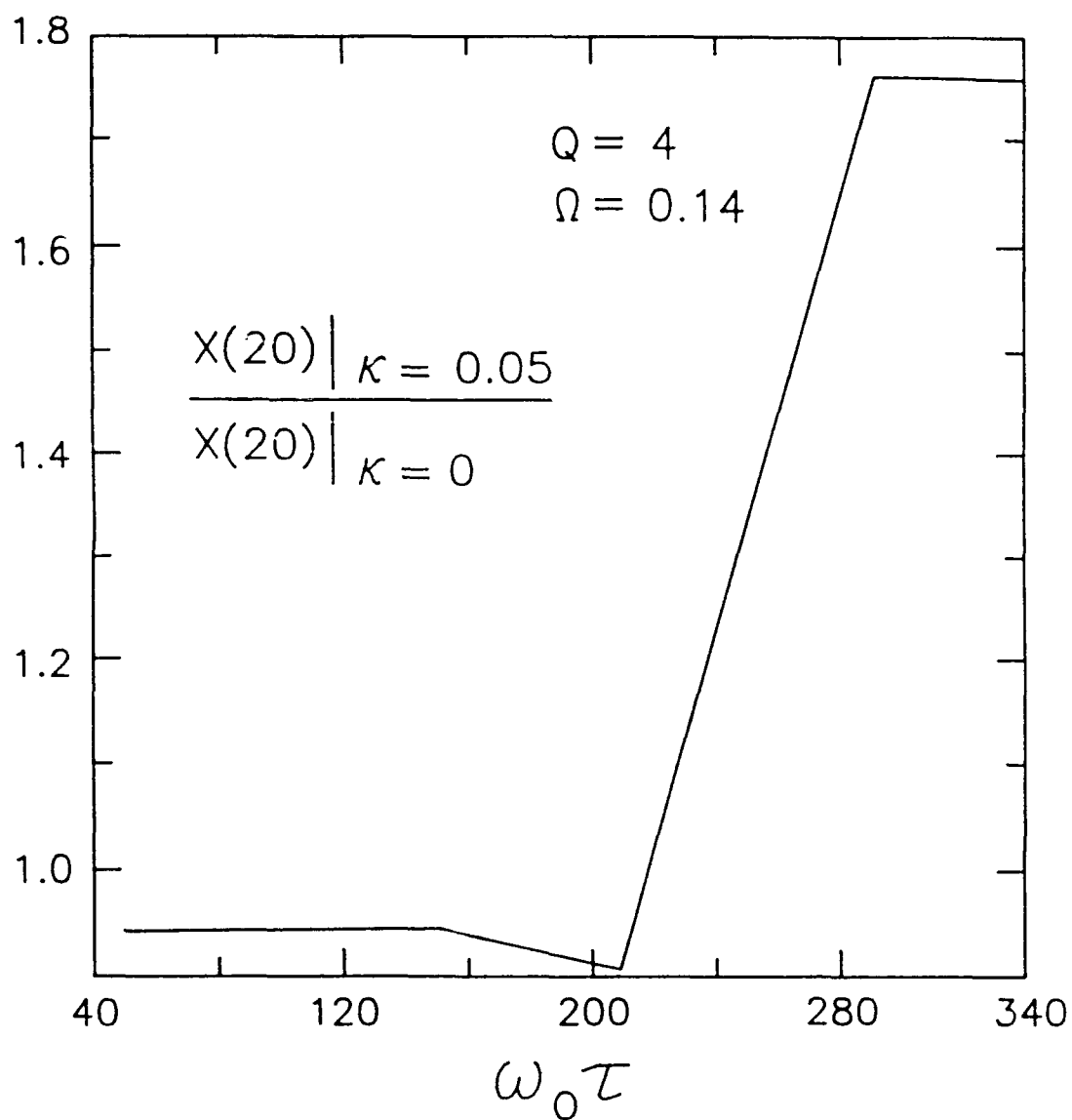
Fig. 4   Same as Fig. 3 for Q=4, Ω=0.14.

$$\frac{X(20)\Big|_{\kappa = 0.05}}{X(20)\Big|_{\kappa = 0}}$$

$Q = 20$
$\Omega = 0.28$
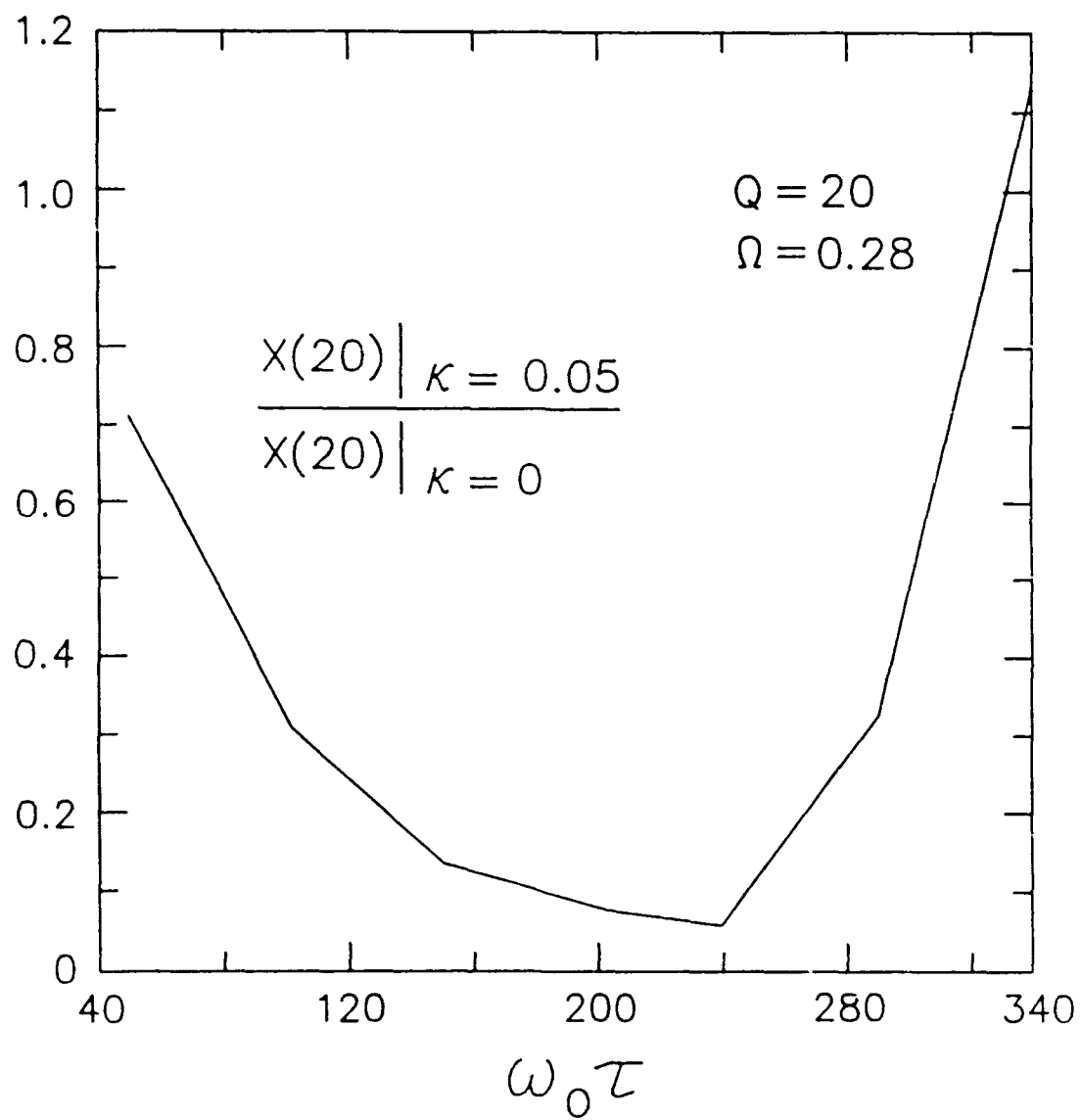
Fig. 5   Same as Fig. 3 for Q=20, Ω=0.28

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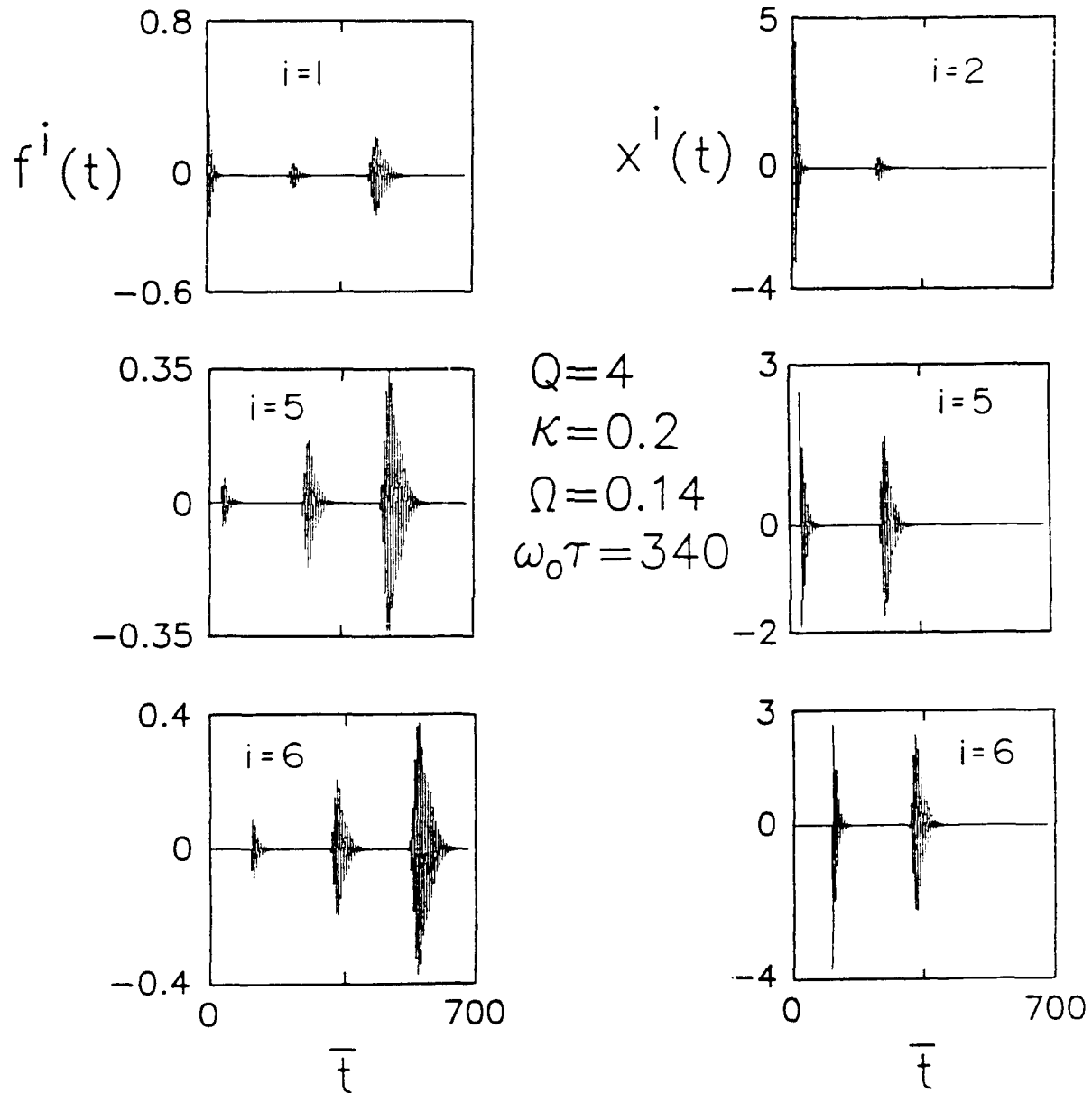
Fig. 6 Time history (normalized units) of deflecting mode amplitude (left)
and beam transverse displacement (right) at cavities 1, 5 and 6 for
PoCE for the case Q=4, Ω=0.14 and κ=0.2. The coordinates have
linear scales.

$f^i(t)$

0.8

0

−0.6

i=11

0.6

0

−0.6

i=16

1

0

−1

i=20

0

700

$\overline{t}$

$x^i(t)$

10

0

−10

i=11

16

0

−16

i=16

30

0

−30

i=20

0

700

$\overline{t}$

$Q=4$
$\kappa=0.2$
$\Omega=0.14$
$\omega_0\tau=340$
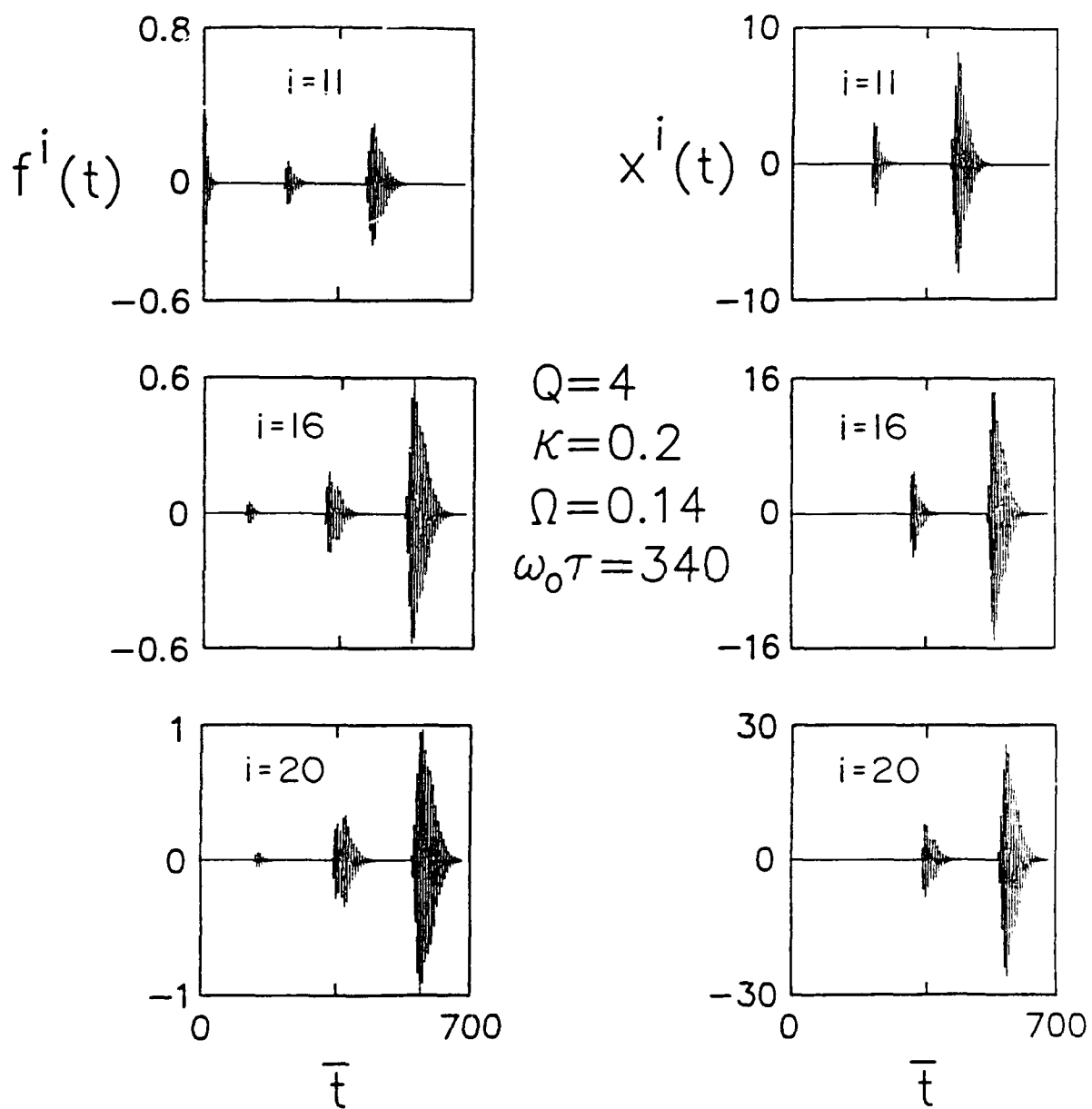
Fig. 7 Same as Fig. 6 for cavities 11, 16 and 20.
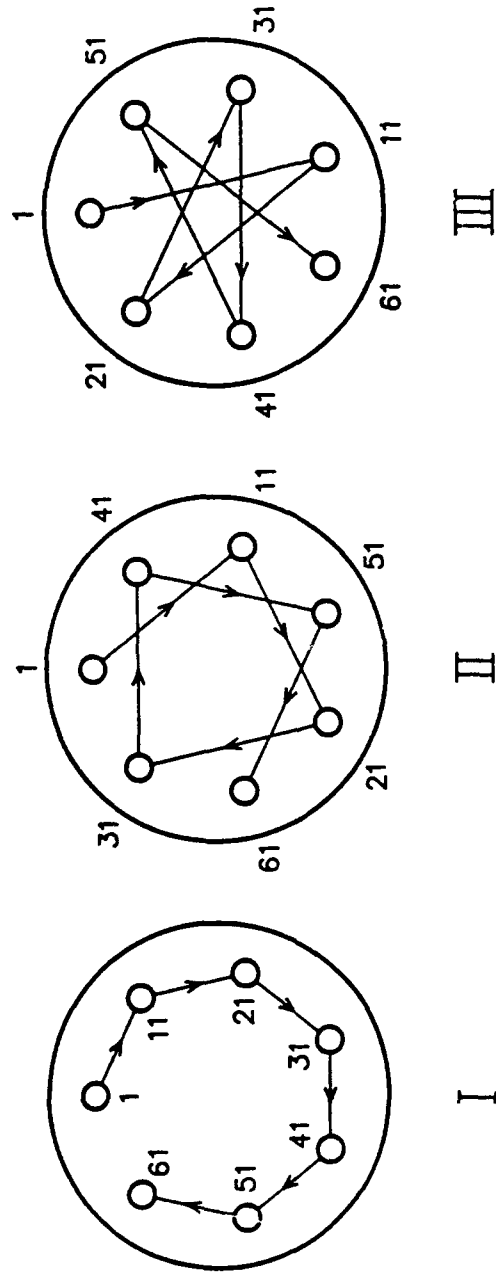
Fig. 8 Various configurations for the beam path around the first coupled
cavity for a 7-turn, 70-cavity SLIA upgrade. Note that the numbers
indicate the gap number in the order that the beam sees them.
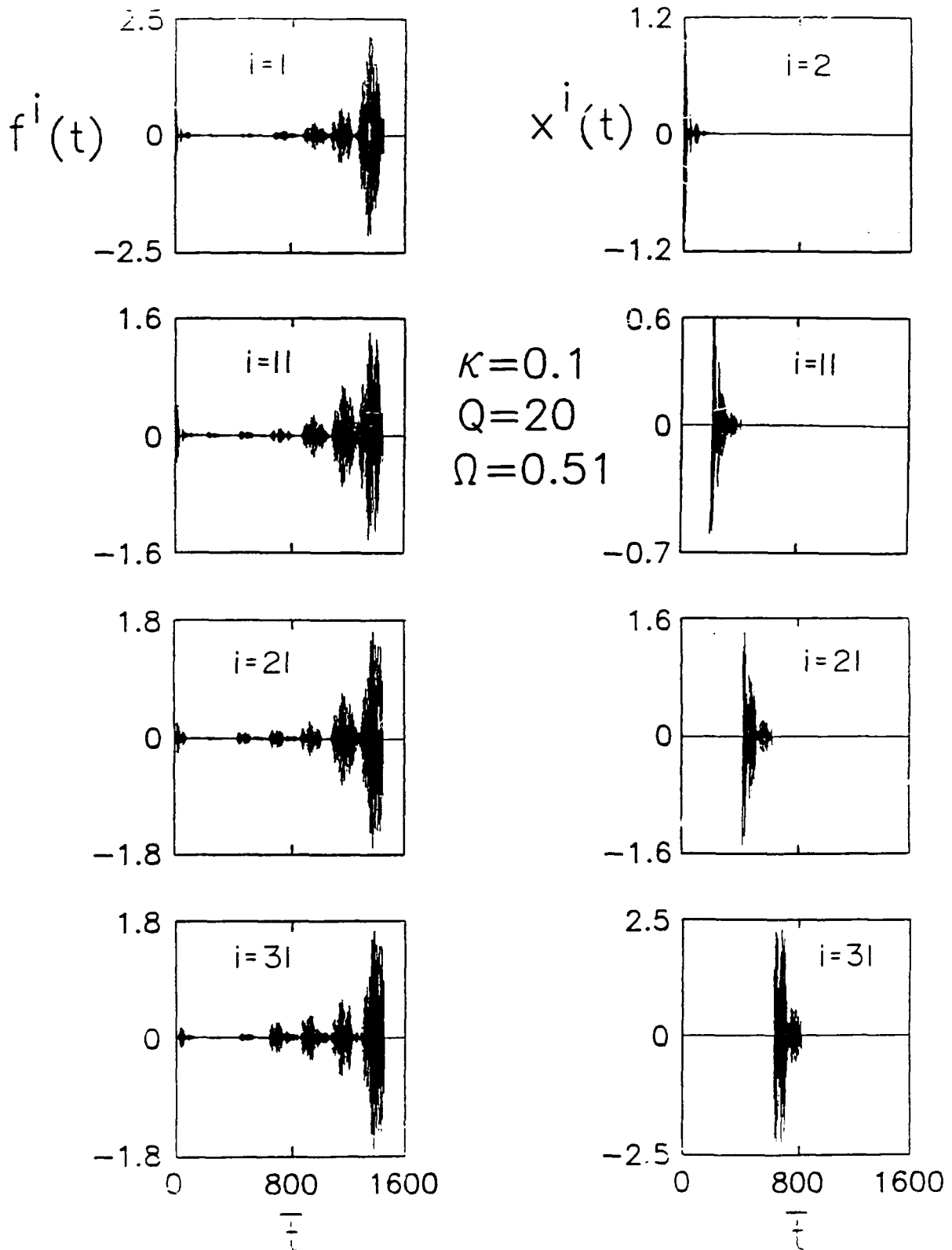
Fig. 9 Typical time history for deflecting mode amplitude (on the left) and beam transverse displacement at cavities 1, 11, 21 and 31 for SLIA upgrade for the case Q=20, Ω=0.51 and κ=0.1. The coordinates have linear scales.

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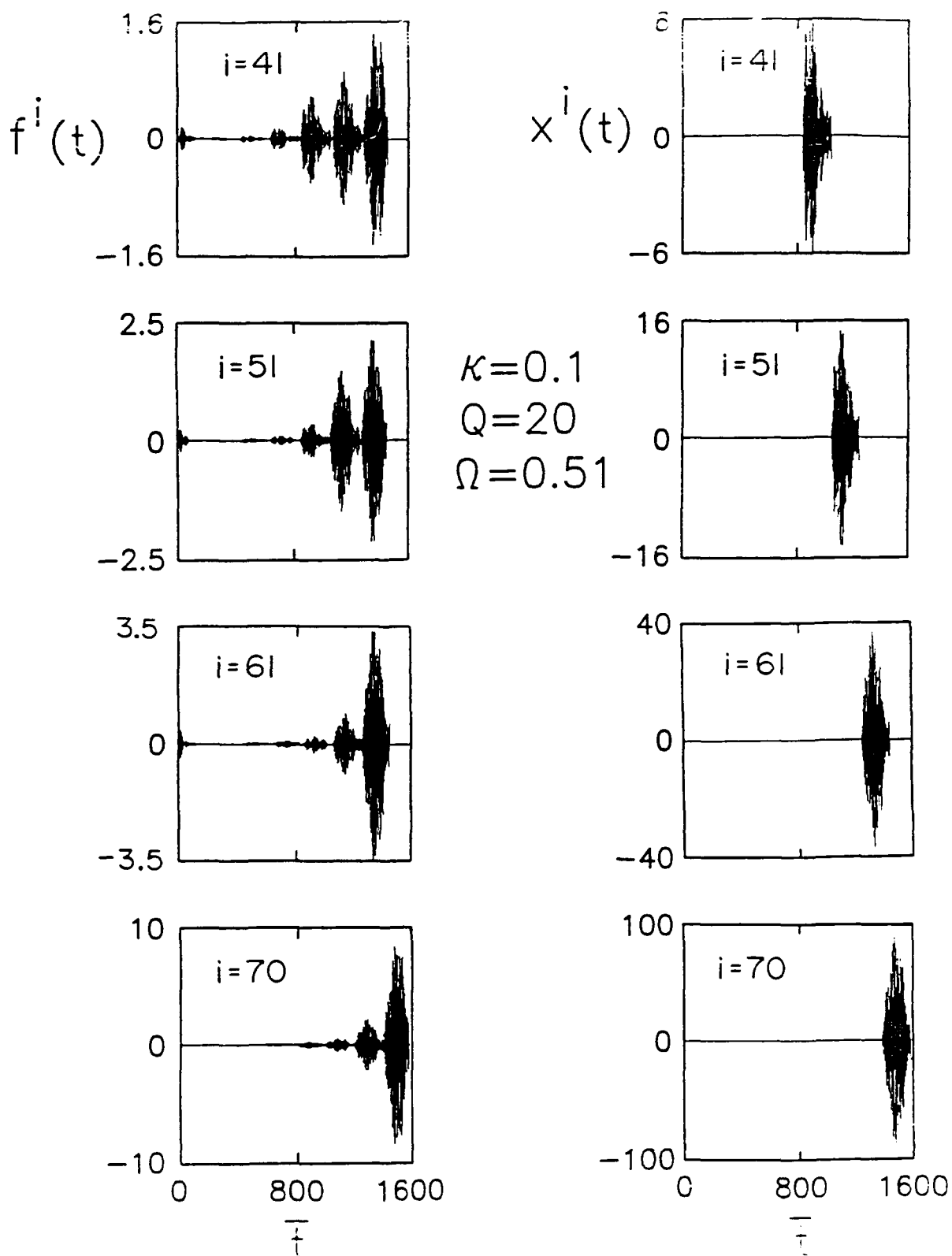
Fig. 10 Same as Fig. 9 for cavities 41, 51, 61 and 70.

27
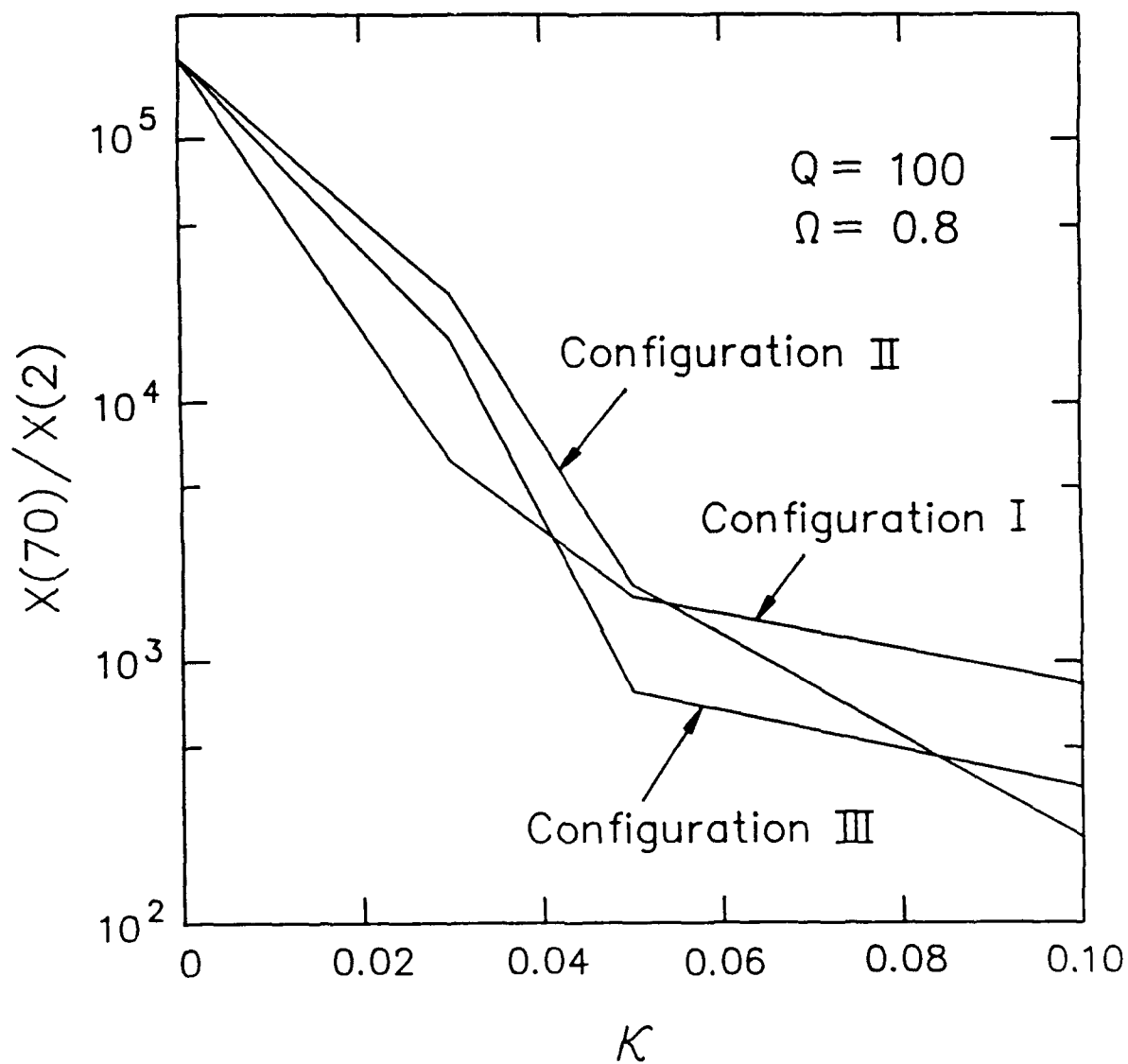
Fig. 11 BBU growth as measured by ratio of final displacement over initial displacement for various configurations for 7-turn SLIA upgrade for Q=100, Ω=0.8 as a function of cross-coupling coefficient κ (coasting beam only).
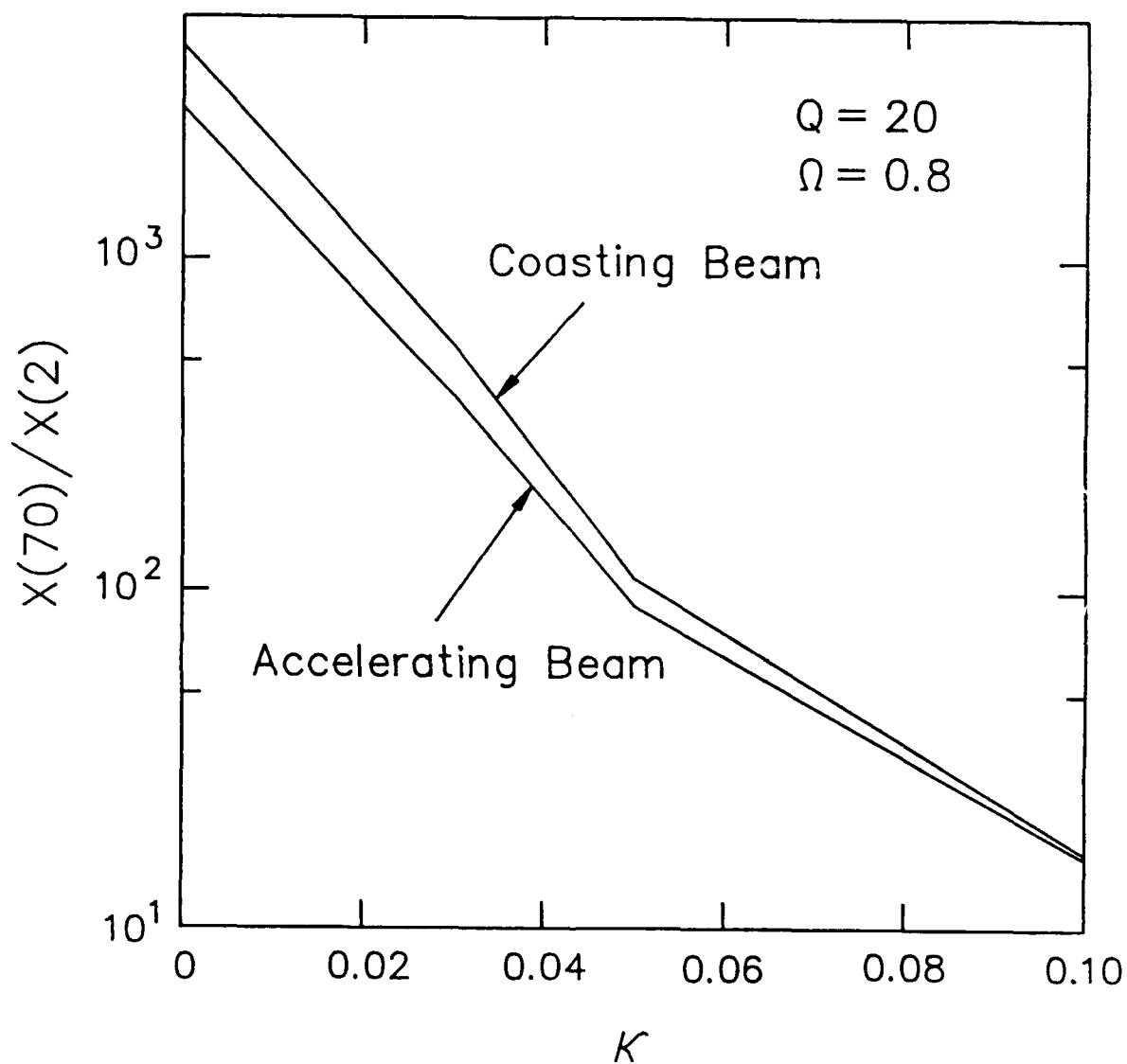
Fig. 12 Same as Fig. 11, except that the results are shown for a coasting and an accelerating beam for Q=20, Ω=0.8. The dependence on the various configurations is not shown because it is small.
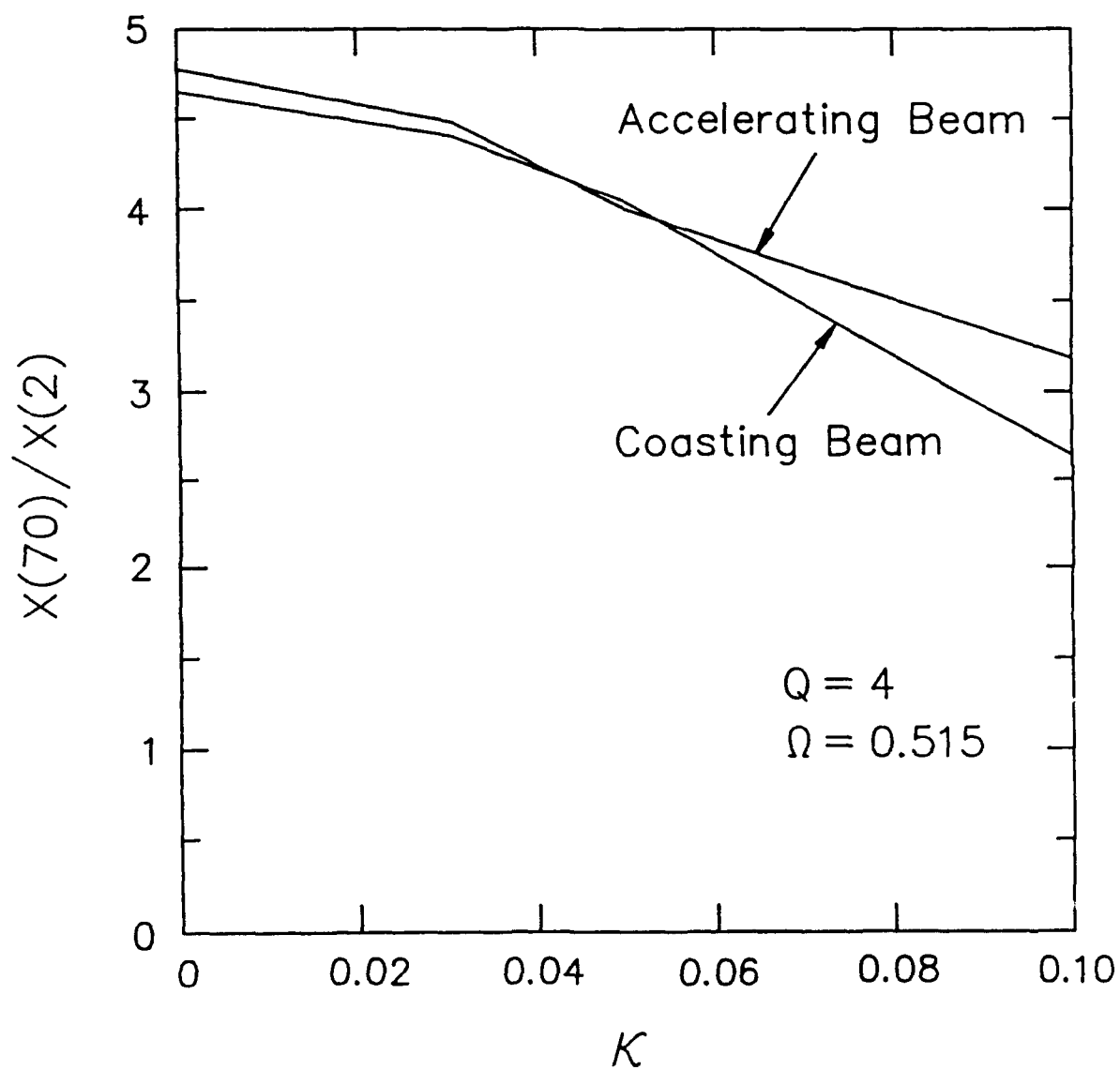
Fig. 13 Same as Fig. 12 for Q=4 and Ω=0.515. The results for the various
configurations are indistinguishable for this case.
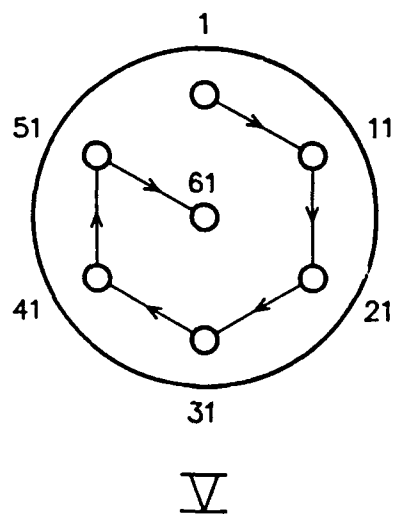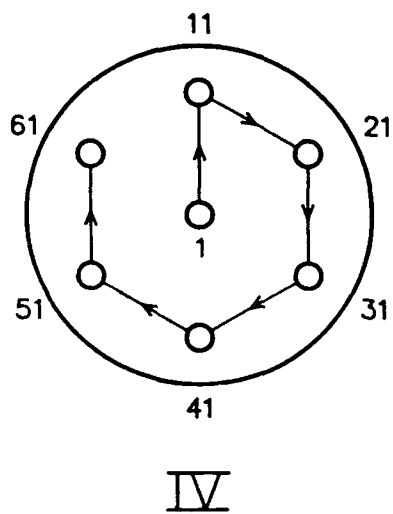
Fig. 14 Various configurations for the beam path around the first coupled cavity when a central gap is included. Note that only cases with continuous path around the periphery have been included.
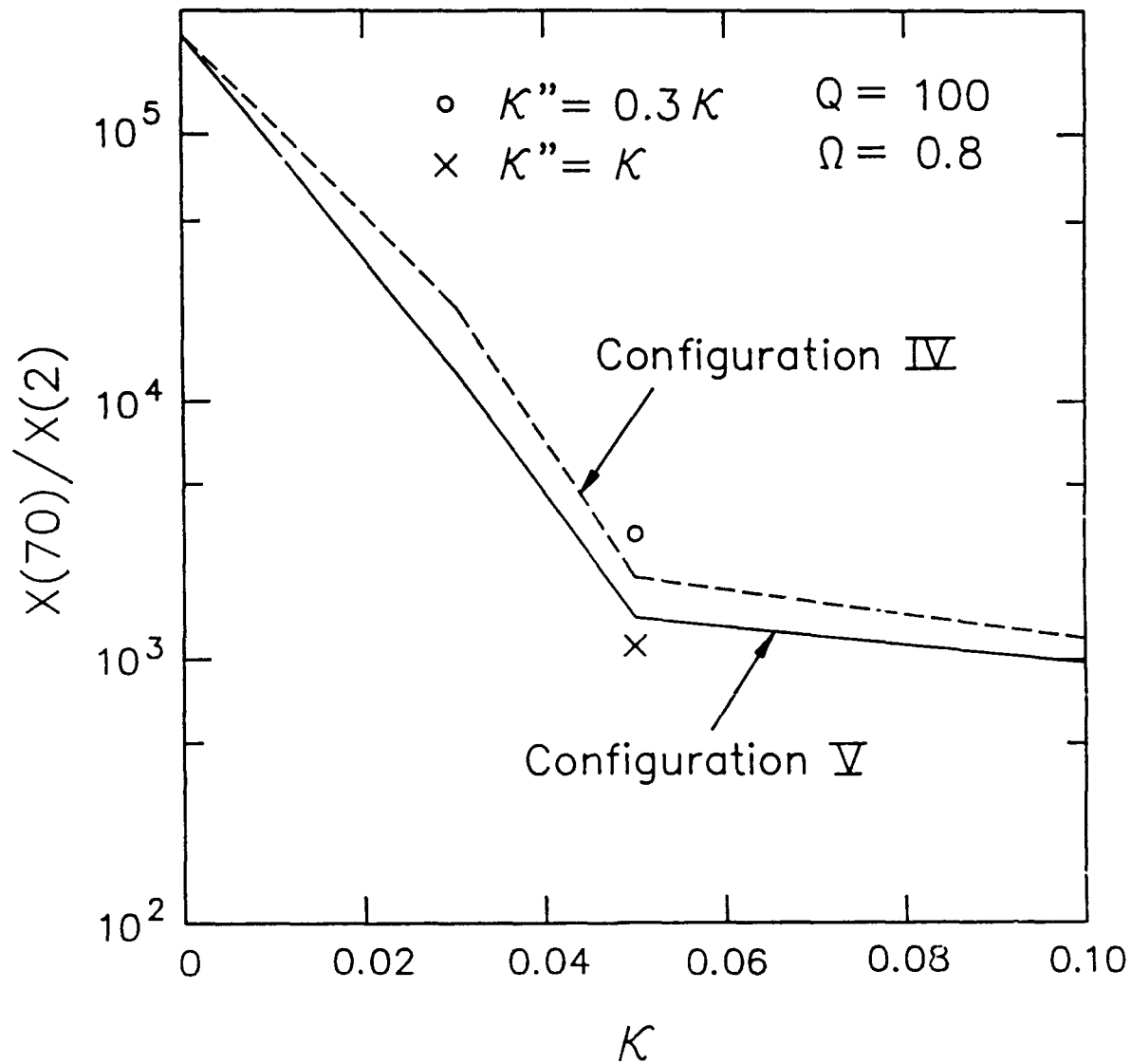
Fig. 15 BBU growth as measured by ratio of final displacement over initial
displacement for configurations IV and V for 7-turn SLIA upgrade
for Q=100, Ω=0.8 as a function of cross-coupling coefficient
(coasting beam). Note the two extra points at κ=0.05 where κ'' has
been changed to 0.3 κ and κ respectively for configuration IV only.
All other results have been obtained for κ''= 0.707 κ.

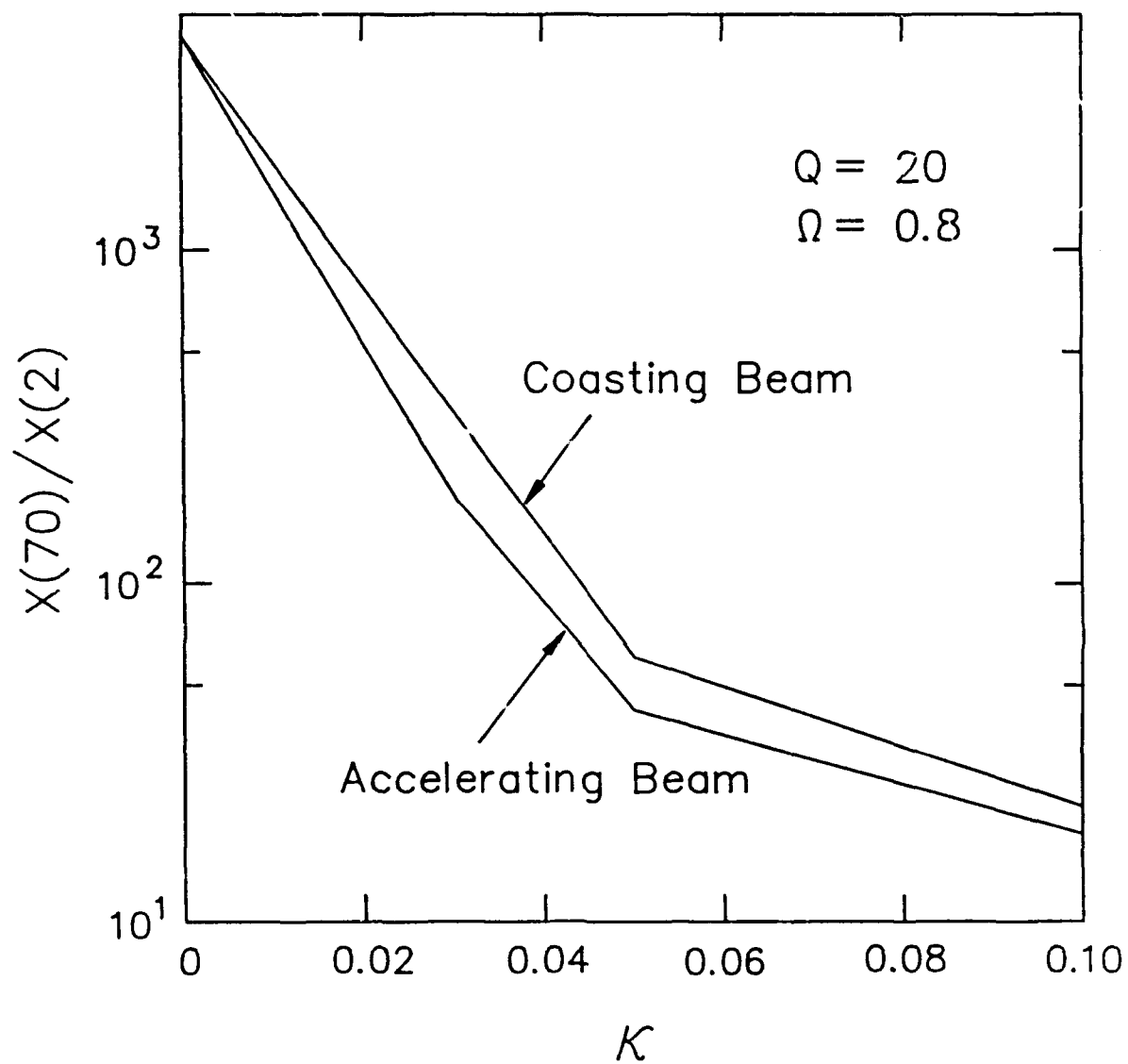Fig. 16 Same as Fig. 15 for Q=20, Ω=0.8 for a coasting and an accelerating
beam. The results for configurations IV and V are not shown
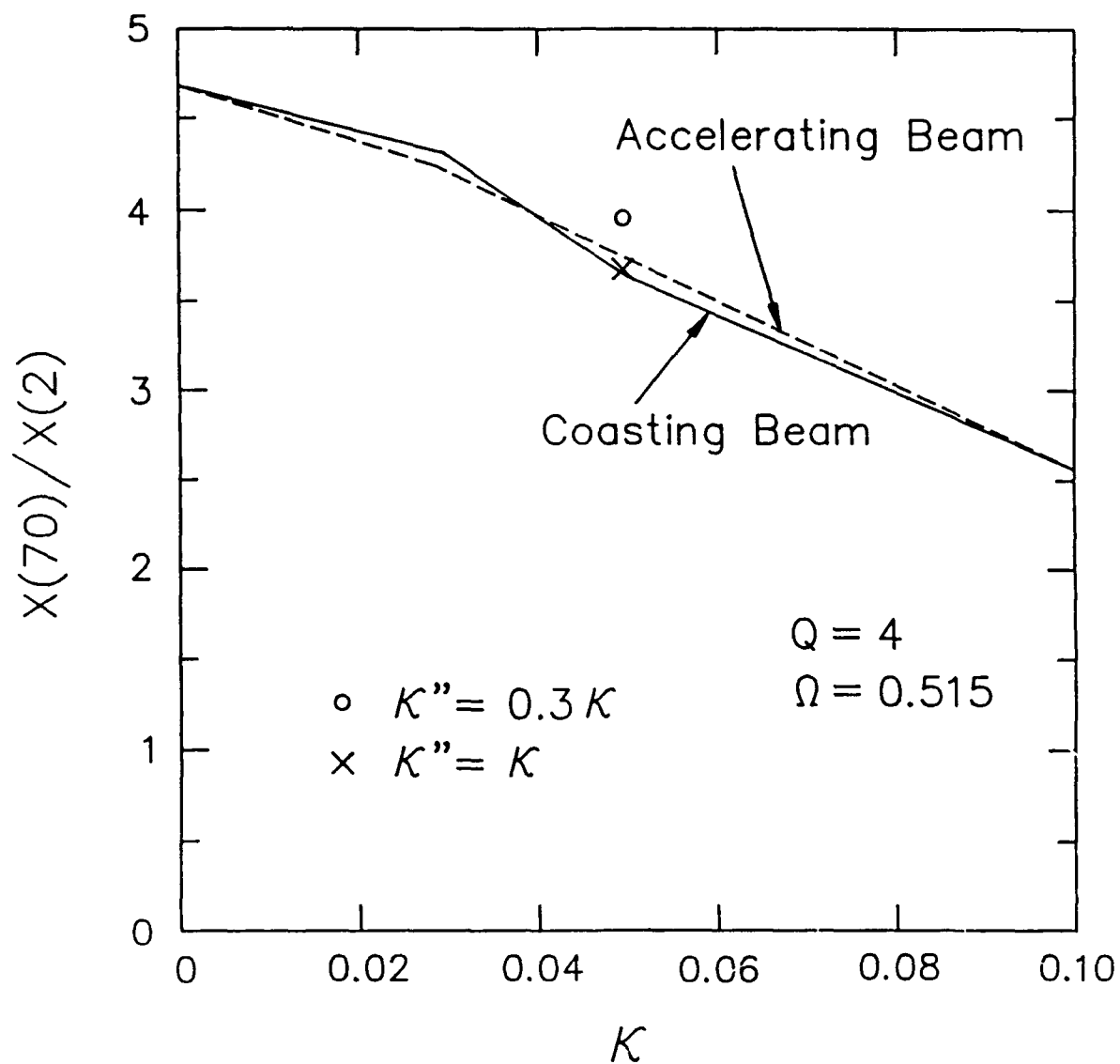separately because the difference is small.

Fig. 17 Same as Fig. 16 for Q=4, Ω=0.515. As in Fig. 15, dependence of results with κ" is shown for the coasting beam case.