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Beam Bunch Space Manipulation in RHIC

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There are many scenarios for increasing the number of populated buckets in RHIC from the original 57 bunches planned. All of them impact the hardware, some more than others. Most of these schemes involve the use of one or more "fast" kickers.

The scenario described herein avoids the "fast" kicker problem and offers the real possibility of not only going to 114 populated buckets but of populating 171 or even 342 of the available r.f. buckets.

In an overview, the idea is to move beam bunches from the Booster to the AGS and ultimately to RHIC with the standard center-to-center spacing of 224 nsec. These beam bunches are then slid together in RHIC by manipulating rf voltages on a magnet porch (no acceleration).

The rf system envisions two cavities, 1) a "High Q" cavity which is powered at a fixed voltage and serves to hold the beam bunches in place after they are manipulated, and 2) a "Low Q" cavity which is pulsed on and off and moved in phase to accomplish the desired manipulation. Both of these cavities operate at the same 28.6 MHz frequency.

The drive power to the "Low Q" cavity is switched "On" at the end of the last populated rf cycle as shown in figure 1. The beam will see the sum of the voltages in these two cavities and the plan is to keep this sum approximately constant while advancing the phase through 360^{o}. To do this the rf phase and amplitude of the voltage developed on the "Low Q" cavity must be controlled to be that shown in the vector diagram of figure 2. The voltage and drive phase on the "Low Q" cavity are given by

$$\text{"Low Q" cavity voltage} = \frac{V_o \sin \Theta}{\sin\left(\frac{\pi-\Theta}{2}\right)}$$

where Θ = phase angle of the resultant
V_o = constant magnitude of the resultant

$$\text{phase} = \frac{\pi + \Theta}{2}$$

The length of the rf pulse train on the "low Q" cavity will be determined by the number of bunch populations being moved at one time, e.g. 1, 3 or 12. Three full cycles (Θ moving through 360^{o}) are required to shorten the interbunch spacing from 224 nsec to 112 nsec., the spacing needed for the acceleration of 114 bunches. One additional cycle will reduce the spacing to 75 nsec. that required for 171 bunches and the last cycle populates all the rf buckets and permits the acceleration of a full complement of 342 bunches. A careful examination of the "Turn-on" transient of the "Low Q" cavity voltage is necessary to determine, if these last two steps are possible.

For constant drive power the turn-on transient is determined by the Q of the cavity, the lower the Q the faster the voltage rise. The 1/e time of the turn-on envelope is Q/π number of cycles. The cavity design illustration given later has a Q of 3 and I will use this Q to compute the turn-on wave shape. These wave shapes can be generated by a computer by summing two sine waves just as the beam bunch does. The first wave is fixed at unit magnitude and reference phase. The second wave is given by the algorithm stated and modified by the turn-on exponential described. The results are shown in figure 3 as six progressive snapshots. Each snapshot shows the resulting sum voltage and that developed across the "Low Q" cavity. During this illustration the start point is fixed at 360 degrees which is just after the completion of the first full rf cycle. This rf bucket is assumed to be populated. The second label gives the phase of the resultant vector relative to the fixed reference voltage. This parameter varies from zero to 360 degrees during a complete cycle. The "snap" for 360 degrees is not shown since it is the same as that for zero degrees. The first "snap" (upper left hand corner) shows no voltage on the "Low Q" cavity which is the beginning and ending state of the process. I have placed a dot on the assumed populated buckets to aid in following the bucket motion. Figure 4 contains the same information with the 1/e time shortened to 1/4 rf periods. This is done to make it easier to follow the illustration of bucket motion but I doubt that switch-on transients this fast are practical.

Two cases are illustrated. First, indicated by the dots, assumes that we have populated buckets two rf periods apart and wish to move them so that every rf bucket is occupied. This is the last step in the process and is the most difficult to accomplish. Looking at figure 4 this convergence is clearly indicated as the rf cycle between the two populated rf waves is squeezed out. The amplitude of the second populated rf wave is reduced by about 10% during this process. The overall rf amplitude could be increased to offset this loss, if necessary. If we look instead at figure 3, we see the rf wave holding the second populated bunch is reduced much more in amplitude and becomes distorted. In fact when the phase reaches 180 degrees (center right) the original positive-going crest has almost disappeared and surely some of the beam has spilled over this crest and is trapped by the earlier positive-going wave. However, in the next "snap" these waves have merged pushing the spilled beam back together. Some amplitude correcting is again necessary.

A second process is indicated by the slash-mark. This process moves beam bunches initially separated by three rf waves down to two. In this case there is little distortion but amplitude loss can be observed which will need correction.

The actual "Low Q" cavity transient will lie somewhere between the two cases illustrated. An rf power amplifier is not limited to a constant power turn-on process but can deliver much more power during the turn-on transient. The final wave shape must be determined experimentally.

This phase motion must proceed adiabatically so that the occupied bucket area does not grow. The time required to complete a cycle of this process is not known but can be determined through computer study. The unit of time for an adiabatic process is the radial period of the synchrotron motion. This is determined among other things by the rf voltage. The cavity design illustrated develops a 10 KV crest. For this voltage the synchrotron frequency is 2.98 Hz and the radial period is 53.4 millsec. If 10 radial periods does not stir up the beam area too much, the time for a motion cycle is about a half-second. More radial periods may be required, lengthening the time for the total cycle. However, the radial period can be shortened by increasing the rf voltage. This can be done by changing the design and using more power or by using more than one cavity, two or three cavities would not be unreasonable.

Figure 5 contains a concept design for a cavity that will perform as described for the "Low Q" function. The assumptions used in generating this design are listed. The cavity is tuned but dampened to have the "Low Q" required by an external resistor which should be distributed around the gap and not lumped as shown in the simplified schematic. The 50 pf total capacity used to tune the cavity is assumed to be the total value after summing the gap capacity plus all strays and tube capacities. The ferrite dissipation was limited to 0.25 watts/cm^3 which I believe is conservative. The ferrite core needed to have an air gap which helps to stabilize the inductance although with this "Low Q" tuning drifts should not be a problem. In the end the driving power became 150 KW which is high but manageable. Careful design will be required to get the lead inductances low enough and therefore a prototype model and laboratory test are necessary to get the desired performance, but I don't see any fundamental obstacle in this approach.

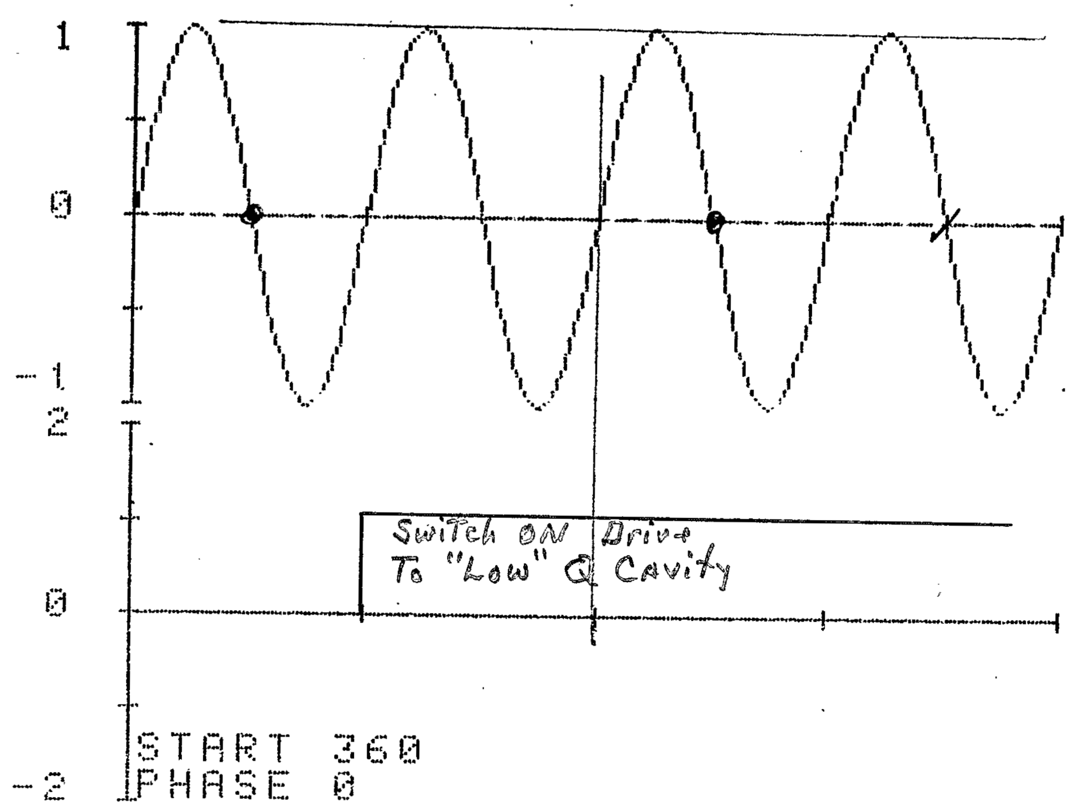


Fig. 1

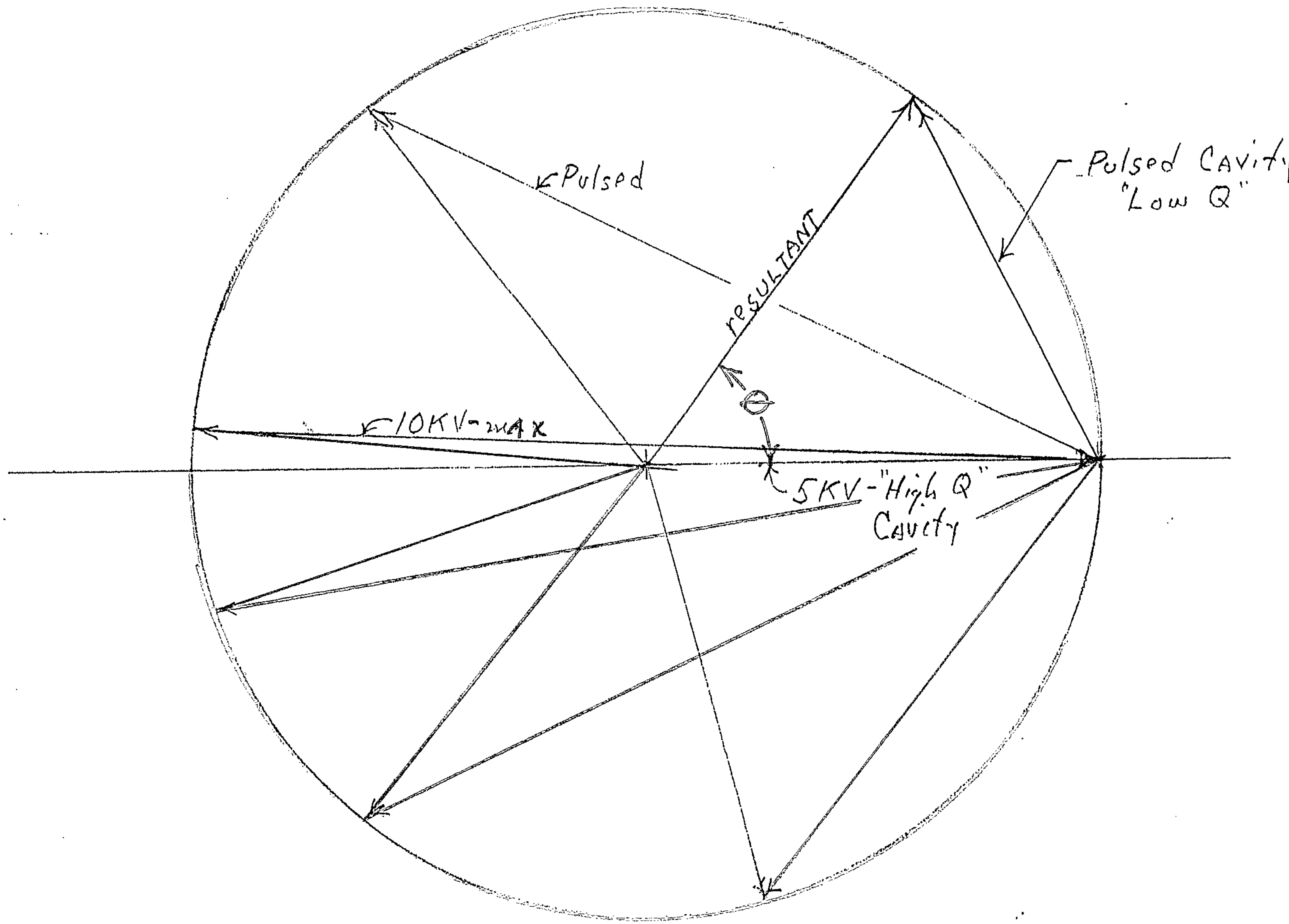

Pulsed
Pulsed Cavity
"Low Q"
RESULTANT
Θ
10KV-max
5KV-"High Q"
Cavity

Fig. 2

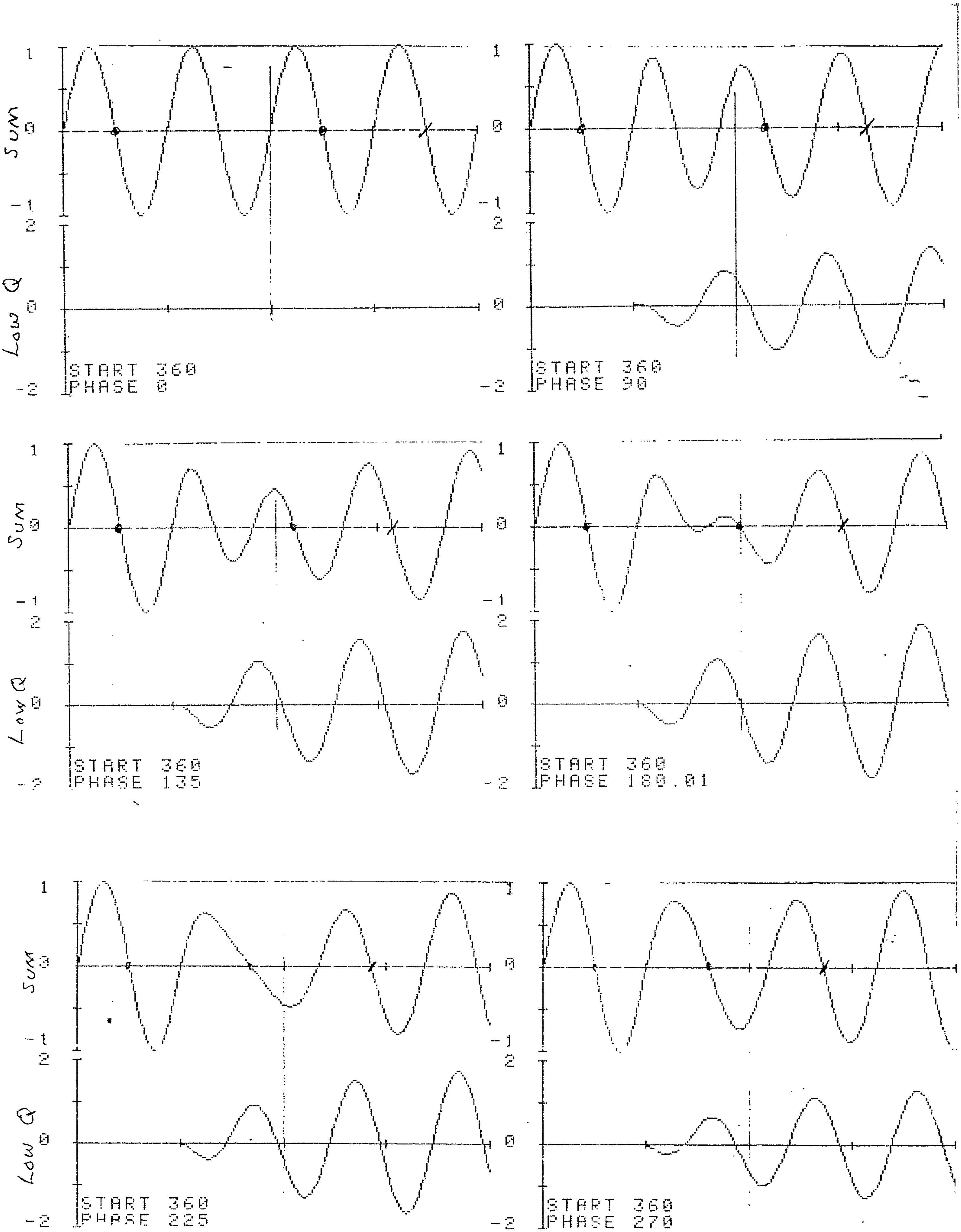

Sum
Low Q
1
0
-1
2
0
-2
START 360
PHASE 0
START 360
PHASE 90
START 360
PHASE 135
START 360
PHASE 180.01
START 360
PHASE 225
START 360
PHASE 270

Fig. 3

λ = ¼ cycle

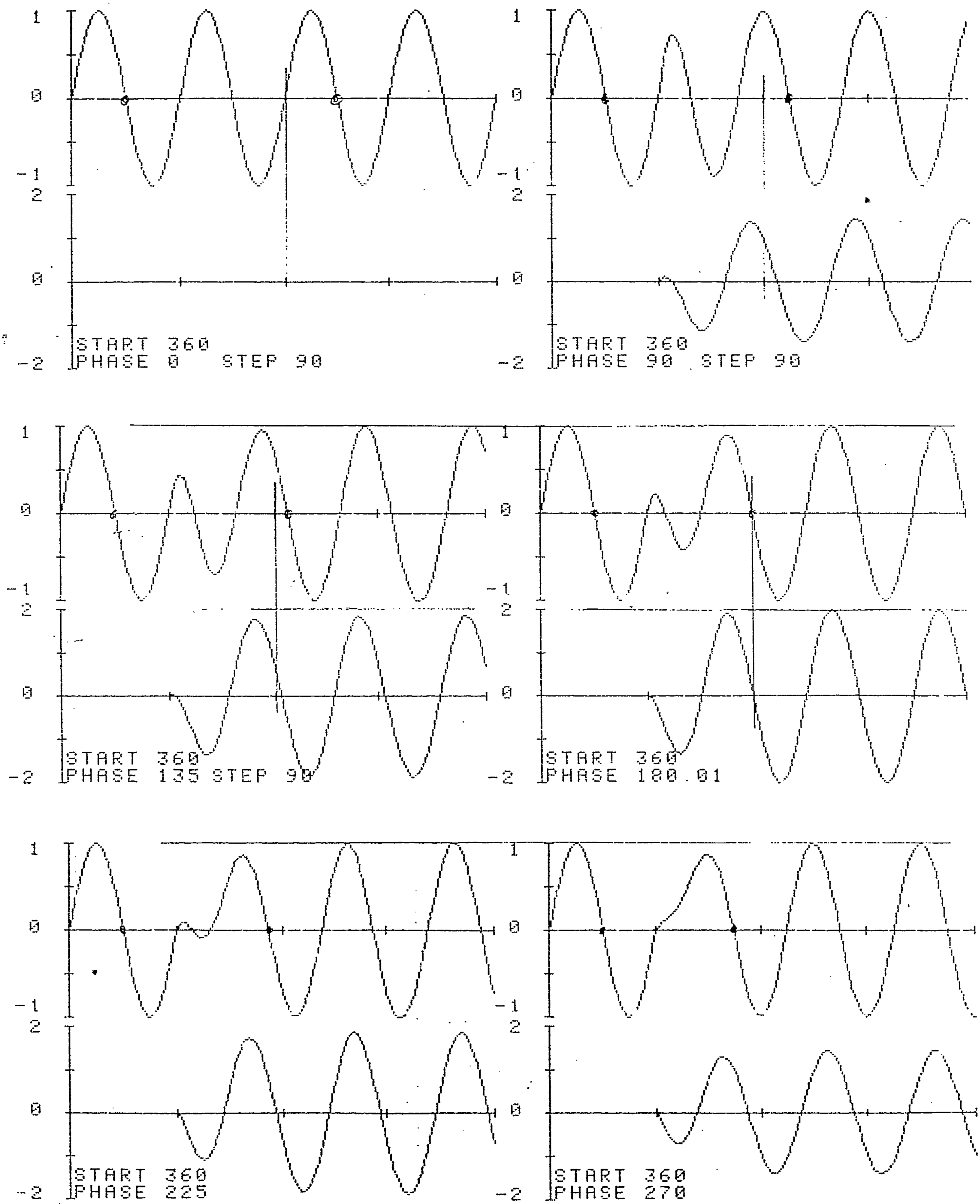
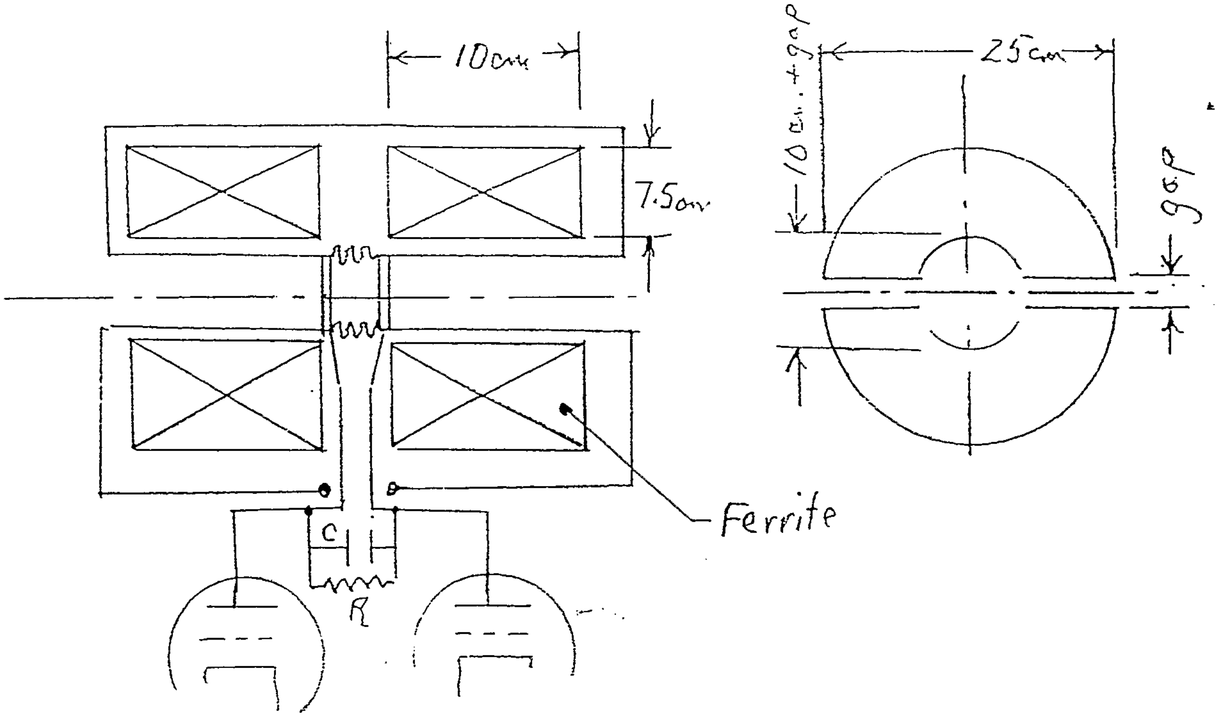


Fig.4



Assumptions

Ferrite $\mu_o = 100$

$\frac{\tan\delta}{\mu_o} = 200 \times 10^{-6}$

Ferrite Heat density
= 0.25 watts/cm^3

Total Cavity + stray
+ tube capacity = 50 pf

Ferrite Density 4.6 gm/cm^3

freq 26.8 MHz

Design

Peak Voltage = 10 KV

B max 43.2 gauss

freq = 26.8 MHz

Ferrite Vol. = 8247 cm^3

Ferrite diss = 2 KW

Ferrite Wt = 85 lbs

Air gap = 1.7 cm total

R = 360 ohms

Power = 150 KW

Loaded Q = 3

Fig. 5