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Capture and acceleration on heavy ions

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CAPTURE AND ACCELERATION OF HEAVY IONS

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The injection, capture and acceleration process consists of five steps which are as follows:

1. Spiral injection
2. R.F. voltage switch on - "snap ON"
3. Growth or step change of the r.f. voltage to the desired electrical bucket size with zero stable phase
4. Continued growth of the r.f. voltage with the stable phase advancing to match the onset of a rising magnet field. This process is tailored to keep the electrical bucket area constant.
5. Acceleration to final energy at a constant dB/dt.

These processes are illustrated in Fig. 1 and are analyzed using as inputs the information summarized in Table 1.

SPIRAL INJECTION

The heavy ion beam is injected into the Booster using a multi-turn injection process filling the available phase space. This creates a d.c. ribbon beam with a very small energy width.

R.F. VOLTAGE SWITCH ON

The energy width of this ribbon beam is so small that to adiabatically capture it would take excessive time. The alternate is to "snap on" an r.f. voltage creating an electrical bucket centered on the beam energy. In a few synchrotron cycles the beam will roll up and fill this bucket. Figure 2 relates the r.f. crest voltage to the capture bucket area for the various heavy ion species.

R.F. VOLTAGE GROWTH

Once the bucket is filled the r.f. voltage can be increased slowly to create a beam populated region inside a larger electrical bucket. Again this growth process cannot be done adiabatically and some beam area growth will result from the practical growth rates that must be used. If the time used to measure these growth rates is normalized to the reciprocal of the synchrotron radial frequency, then comparisons can be made. Figure 3 shows this reciprocal as a function of r.f. voltage and ion species. As the r.f. voltage grows the synchrotron frequency changes and therefore the unit of time for measuring the growth rates change creating a picture difficult to present graphically. Nevertheless, I find this a useful way to normalize results.

Before starting acceleration one would like to contain the beam populated region inside a somewhat larger electrical bucket so that small errors in manipulation will not result in beam loss. The ratio of these two bucket area sizes is a function of time and the rate of r.f. voltage increase is shown in Figure 4. In making this figure time is measured as a count of radians of synchrotron frequency and the rate of r.f. voltage growth is measured as a fraction (percent) increase per radian of synchrotron frequency.

The following is an example of the use of these two figures. Let us assume that we would like an electrical bucket with an area 1.5 times that of the beam populated region. Also assume that the "snap-on" voltage was 140 volts and the ion being accelerated is gold. From Figure 2 we read that the "snap on" bucket area is 0.02 eV-sec. and, therefore, the desired ending area is 0.03 eV-sec. The beginning and ending r.f. voltages are then read to be 140 and 320 volts and the mean voltage is 230 volts. One radian of synchrotron frequency for gold and 230 volts of r.,f. is 0.785 millisec. as read from Figure 3. This becomes the unit of time. The number of these units is determined from Figure 4 once an acceptable r.f. growth rate has been selected. Acceptable growth rate must be determined experimentally since compromises are involved, but for this example let me chose a growth rate of 3%/radian. Under this choice 27.5 units of time are required to reach the desired bucket growth factor of 1.5 for a total lapse time of 21.59 millisec.

Faster processes can be found to make this voltage growth. If the growth rate is increased the process is shortened with some additional beam loss. The compromise between the productivity gain for shortening this capture step and the beam loss must be determined experimentally.

Another time saving process is the one described by Y. Y. Lee in Booster Technical Note 52 in which the r.f. voltage is stepped to the higher value after ¼ of a synchrotron period. This process also looses some beam, i.e. some of the beam is still near the edge of the bucket and may be lost during later manipulation of the r.f. bucket.

ONSET OF ACCELERATION

Once the r.f. electrical bucket has grown in area to the specified size acceleration can begin. This acceleration process should preserve the area of this last electrical bucket, a requirement key to this calculation.

Figure 5 shows the relationship between the r.f. bucket area, the r.f. voltage growth rate and the elapse time for the process to reach a selected dB/dt. Figure 5 was prepared using gold reaching a dB/dt of 4.5 Tesla/sec. The variations in the information shown in Figure 5 are small for other species of ions as illustrated in Figure 6 which shows gold vs. carbon for one electrical bucket area, 0.03 eV-sec. Similarly, the lapse time is not a strong function of the selection of the final dB/dt value, since dB/dt grows very rapidly near the end of the process, see Figure 7. Because of the above, Figure 5 can be in general used for all ion species and all ending dB/dt values. The time interval to reach the final fixed dB/dt is approximately 42.5 millisec. and may be slightly less if a lower final dB/dt is desired.

ACCELERATION AT FINALdB/dt to FULL ENERGY

The choice of the maximum value for the final dB/dt is related to the magnet power supply compatibilities. And since a common power supply designed to handle the proton and heavy ion acceleration is envisioned, this interaction must be reviewed. The proton acceleration cycle requires a magnet power supply capable of 4500 volts and 2220 amps., see Booster Technical Note 49. This power supply is planned to be built in two halves which can be seried for proton acceleration and parallel connected for operation with heavy ions. Thus, the voltage and current capabilities for the two operating mode must be related by the proper factor of two. The suggested solution is shown in the following table.

	Requirement		Design		
	Volts	Current Peak	Volts	Current Peak	Power
Protons	4500V	2220A	4500V	2800A	12.6MW
Heavy Ions	1500	5600	2250	5600	12.6MW

To make this compromise the power supply will be built to have more current than necessary in the proton operating mode and more voltage than necessary for operation with heavy ions.

If the power supply is designed to have 2250 volts in the heavy ion operating mode as indicated in the table than the maximum dB/dt that the power supply can force on the magnet is 4.67 Tesla/sec. This is higher than need be to complete the full cycle in one second. But, because of this the charts and figures used in this note have been developed to go to this high dB/dt.

Figure 8 shows the relationship between the bucket area, the r.f. crest voltage and the ion species for a magnetic field rise rate of 4.5 Tesla/sec. If the r.f. system is to be sized compatible with the magnet current power supply then the r.f. crest voltage of 20 kv. is required for gold at a bucket area of 0.05eV-sec. I would suggest that we plan for a somewhat larger bucket area and that 24kv. might be a better choice for the maximum r.f. crest voltage.

TABLE 1

ION	CHARGE Φ	MASS M	ν/c β	KENETIC ENERGY T (Mev)
Deuterium	1	2	.1767	30
Carbon	6	12	.1262	90
Sulfur	14	32	.1000	150
Copper	21	63	.0782	180
Iodine	29	127	.0595	210
Gold	33	197	.0478	210

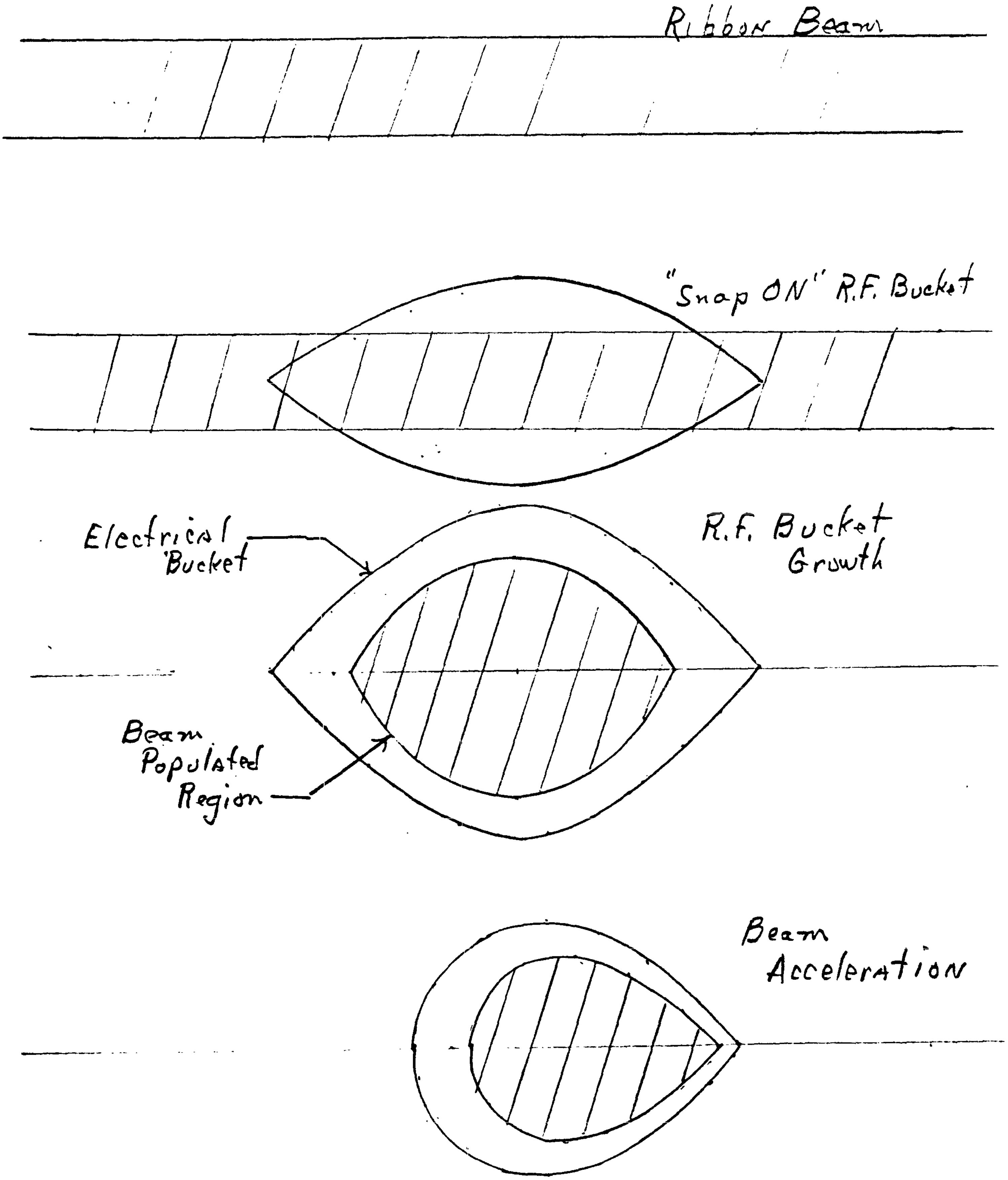
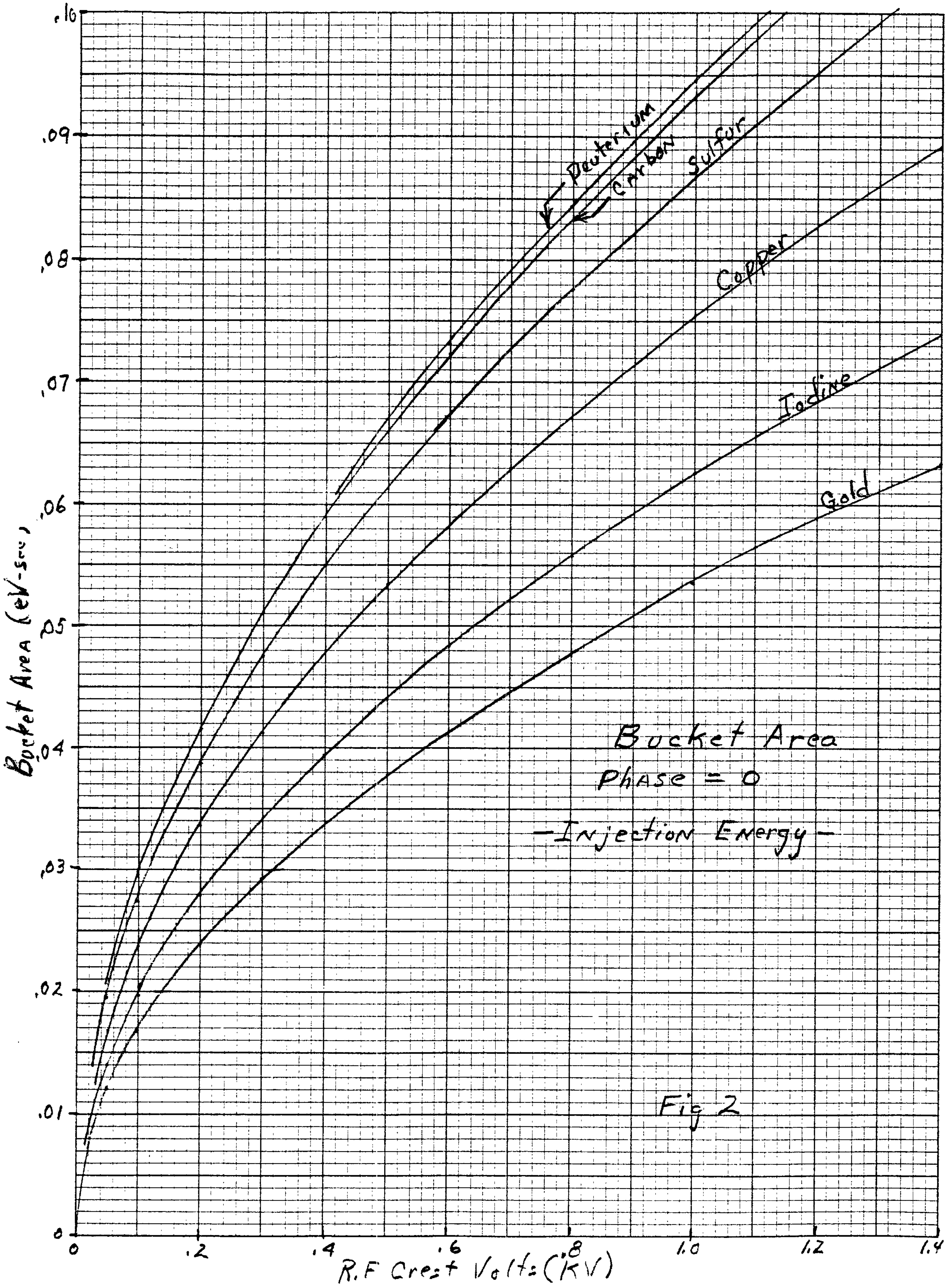
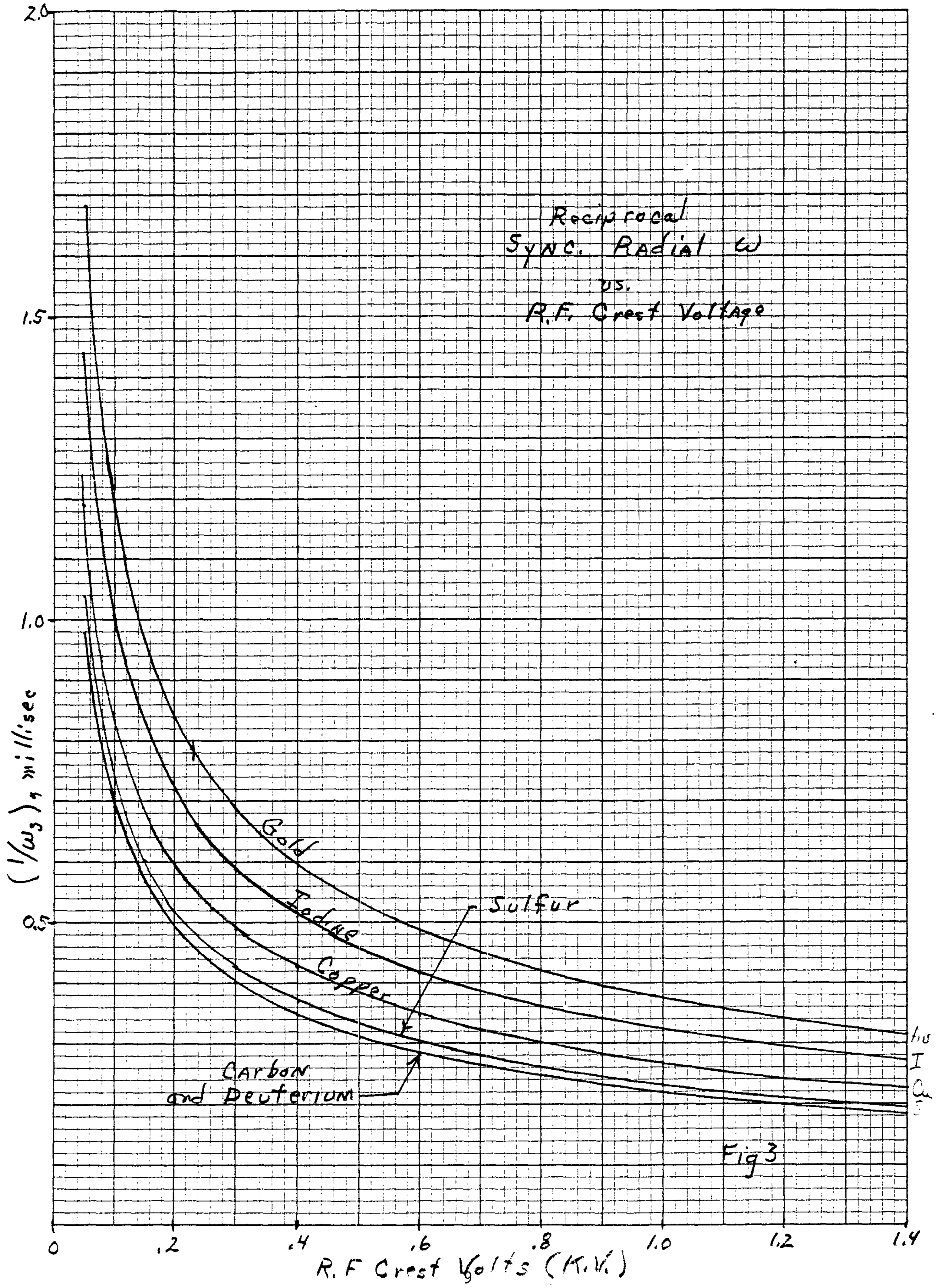

Ribbon Beam
"Snap ON" R.F. Bucket
Electrical Bucket
R.F. Bucket Growth
Beam Populated Region
Beam Acceleration

FIGURE 1



Bucket Area
Phase = 0
-Injection Energy-

Fig 2



Reciprocal
Sync. Radial ω
vs.
R.F. Crest Voltage

Fig 3

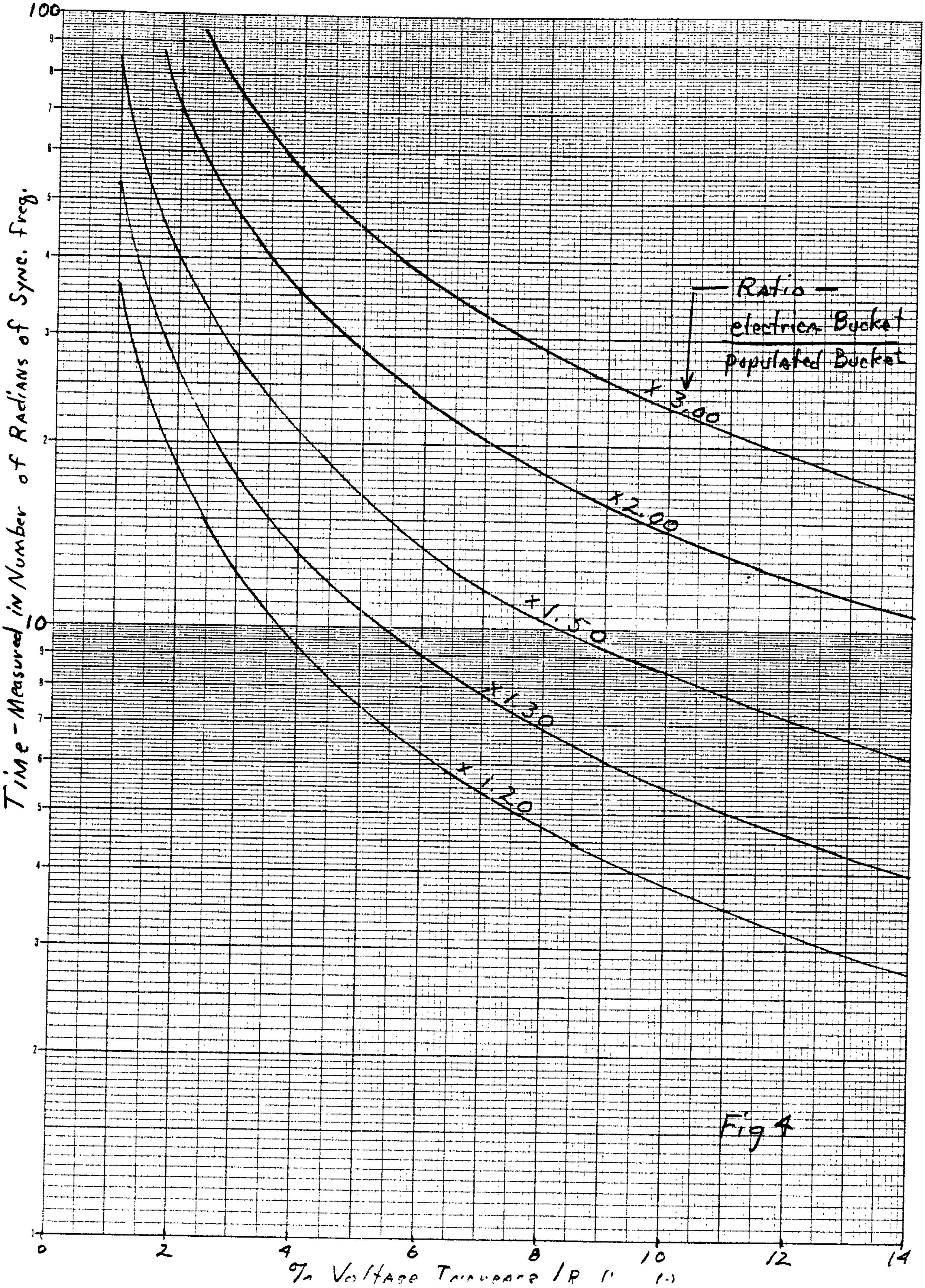

100
9
8
7
6
5
4
3
2
10
9
8
7
6
5
4
3
2
1
0
2
4
6
8
10
12
14
Time - Measured in Number of Radians of Sync. freq.
% Voltage Increase / R
— Ratio —
electrical Bucket
populated Bucket
× 3.00
× 2.00
× 1.50
× 1.30
× 1.20

Fig 4

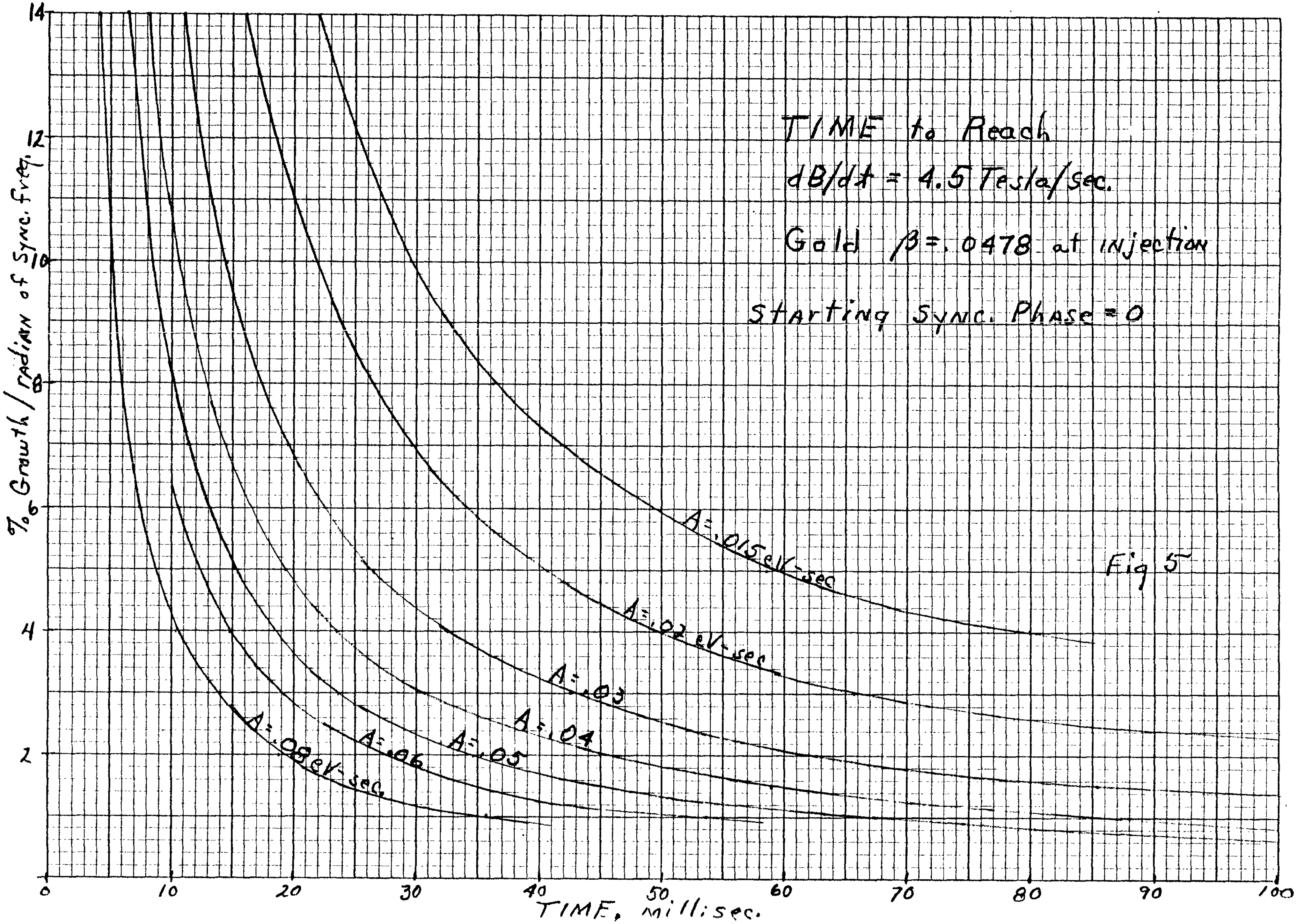

TIME to Reach
dB/dt = 4.5 Tesla/sec.
Gold β = .0478 at injection
Starting Sync. Phase = 0
A = .015 eV-sec
A = .02 eV-sec
A = .03
A = .04
A = .05
A = .06
A = .08 eV-sec
% Growth / radian of Sync. Freq.
14
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
100
TIME, millisec.

Fig 5

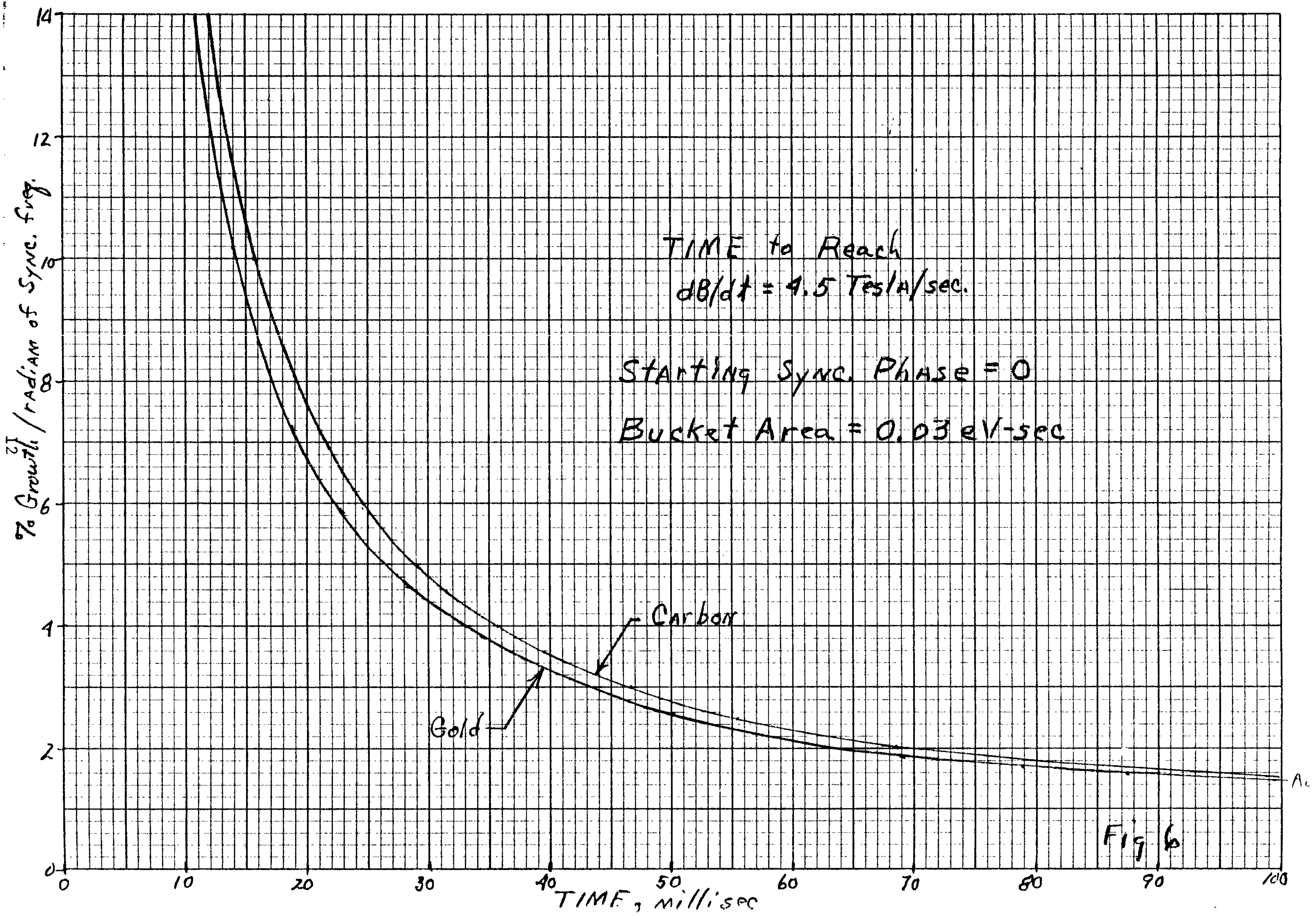

TIME to Reach
dB/dt = 4.5 Tesla/sec.
Starting Sync. Phase = 0
Bucket Area = 0.03 eV-sec
Carbon
Gold
Ac
% Growth / radian of Sync. freq.
TIME, millisec
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
80
90
100

Fig 6

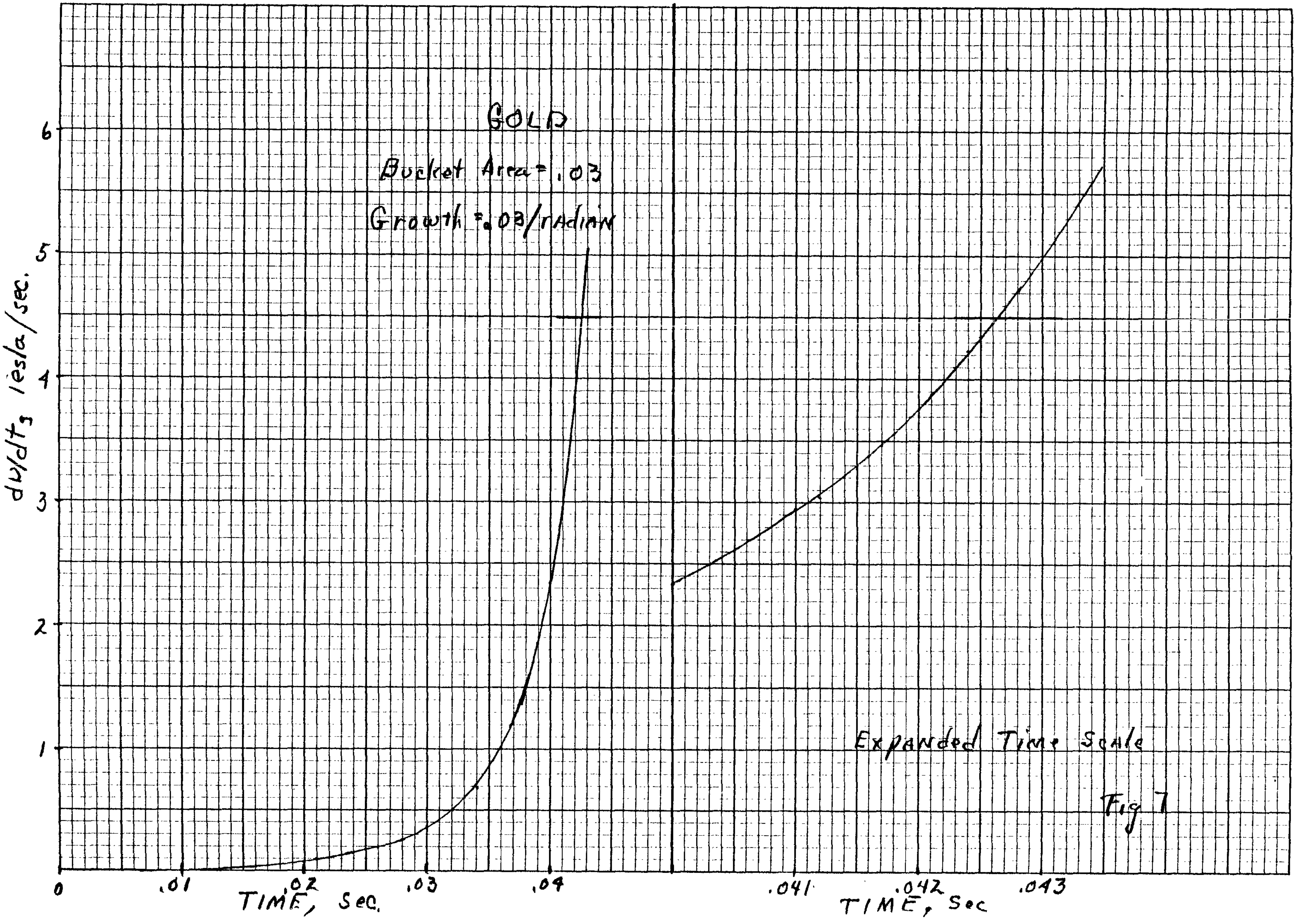
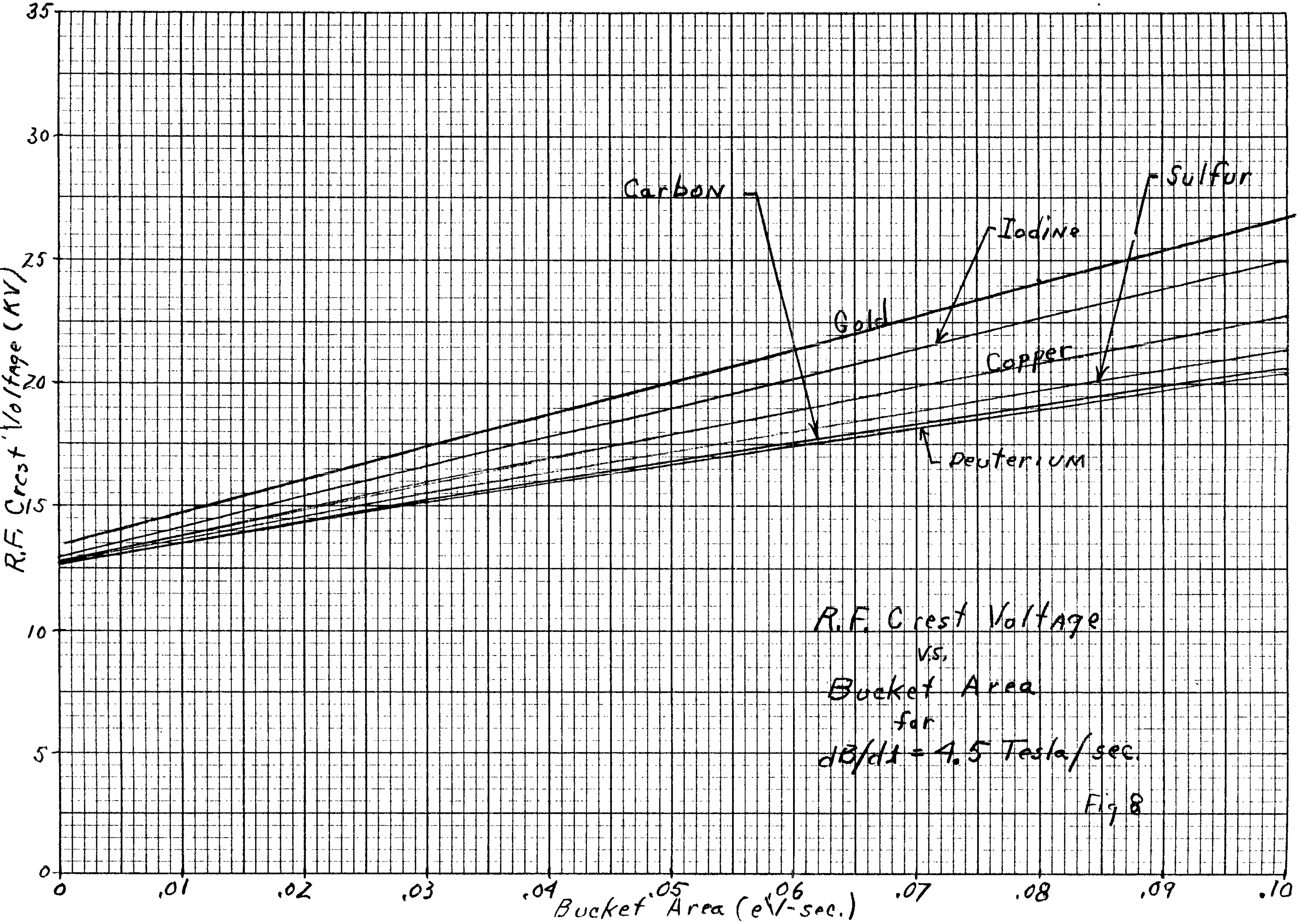

GOLD
Bucket Area = .03
Growth = .03/radian
dv/dt, Tesla/sec.
0
1
2
3
4
5
6
0
.01
.02
.03
.04
TIME, Sec.
.041
.042
.043
TIME, Sec
Expanded Time Scale

Fig 7



R.F. Crest Voltage
vs.
Bucket Area
for
$dB/dt = 4.5$ Tesla/sec.

Fig 8