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Proton cycle for the Booster

J. G. Cottingham

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J. G. COTTINGHAM

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ACCELERATOR DEVELOPMENT DEPARTMENT
Brookhaven National Laboratory
Upton, N.Y. 11973

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The main dipole and quadrupole electrical characteristics are as follows:

	Dipole	Quad
Number of Magnets	36 + 1	48 + 2
Inductance per magnet, henries	0.0032	0.00035
Total Inductance, henries	0.1184	0.0175
Injection field, tesla	0.1563	—
Injection current, amperes	635	635
1.5 GeV current, amperes	2220	2220
Total magnet resistance, ohms	0.044	0.050

There are four processes that consume a fixed quantity of time which must be inserted into the basic repetition period. These processes are as follows.

Transition from Rectify to Invert

When the rectifier timing is shifted from rectify to invert the rectifier output follows the last rectify sine wave down to the point of the first invert commutation. This elapsed time is less than a full half sine wave time because the invert process must be triggered ahead of the voltage crossover point (see Fig. 1). Before the voltage cross-over is reached two things must happen: 1) the extinguishing rectifier must have recovered its voltage hold-off ability. This time is specified by the manufacturer for the SCR rectifier and is typically 400 microseconds for rectifiers of this class although "fast recovery" units are available at a premium price. 2) Sufficient time must be allowed for the current to commutate from one rectifier to the next. This current transfer time is a function of the transformer commutating reactance and the potential difference between the commutating phases. To estimate the commutation time a transformer reactance of 6% is assumed which is about the lower limit for rectifier transformers of this class. Under this assumption the commutation time is 32.2° or .0015 seconds. (Note — the time required for this process is already slightly greater than the phase spacing for a 12-phase rectifier, 30°. For this reason going to a rectifier with more phases does not reduce the raw ripple voltage.) The sketch shown in the top of Fig. 1 illustrates this process. The time between rectifier firings during this changeover process is 139.2° or 6.4 ms.

Filter Recovery

The dipole rectifier system must contain a ripple filter with a minimum attenuation at the fundamental ripple frequency of 10. An attenuation of 30 would give more margin against excess (unexpected) raw ripple, but in the interest of minimizing the time lost to the filter recovery process the filter requirements have been cut to a minimum in this analysis.

Both filter designs are shown in Fig. 2. Filter "A" has an attenuation of 30 while "B" has only the required minimum value of 10. The response of these filters to a step input is also shown. The recovery time using filter "B" is about 6 ms.

Regulator Recovery

If we require that each pulse be independent of any preceding pulse then the magnet current must be under regulation prior to injection, thus correcting any variation caused by the preceding pulse. A time interval is required for this correction. The primary disturbance that must be corrected by this regulation process is that resulting from variations in line voltage. Brookhaven operates with a 5/8 % line voltage tap changer and we should plan to correct for two of these steps or 1.25%. If injection needs current control to 0.05% then a regulator correction of 25 is required. This takes 3.2 correction intervals, if each interval reduces the error by e. The correction interval is limited by the response of the filter and the commutation time of the rectifier. These times are respectively 1.7 and 1.3 ms for a total correction interval of 3.0 ms. Thus the correction time becomes 10 ms. (Note — this time has been reduced to near the theoretical limit.)

Injection Under-Shoot

During the filter recovery and while the regulator is correcting for errors produced by the preceding pulse, the injection magnet voltage must be applied to the magnet. Magnet current is, therefore, rising during this time interval, and thus must have started from a current below the desired injection value. The invert ramp must carry the current to this reduced value and the time to do this must be planned.

Once a repetition period is assigned and these "dead" times are subtracted the remaining time can be proportioned between the rectify and invert parts of this cycle. The current in the invert part of the cycle can be ramped downward limited only by power supply capability. But the rising current in the rectify part of the cycle must be controlled to preserve the accelerating bucket area. If the field rises too fast the accelerating bucket area is reduced. Conversely, if the field rises too slowly too much time is wasted in a very crowded time cycle.

The accelerating bucket area can be computed as follows [1] [2]

$$\textit{accelerating bucket area} = \frac{8C}{\pi c h}\,\alpha(\phi_s)\sqrt{\frac{eVE_o\gamma}{2\pi M h\,|\,n\,|}}$$

where:

$$\beta^2 = 1 - \frac{{E_o}^2}{E^2}$$

$$\gamma = \frac{E}{E_o}$$

$$\eta = \frac{1}{{\nu_h}^2} - \frac{1}{\gamma^2}$$

and

E_o = rest energy of protons
E = T + E_o
M = ratio - mass/charge
ν_h = horizontal ν (4.82)
$\alpha(\phi_s)$ = ratio bucket area/bucket area at 0° stable phase angle [3]
c = velocity of light

T = kinetic energy at injection
V = rf crest voltage
h = harmonic no.
ϕ_s = stable phase angle
C = machine circumference 201.78 meters
e = electronic charge

Using a selected accelerating bucket area the computing process proceeds as follows:

(1) For a set of machine inputs the desired value of $\alpha(\phi_s)$ was determined.

(2) From the value of $\alpha(\phi_s)$ the stable phase angle ϕ_s is obtained.

(3) From the stable phase angle the energy gain per turn is computed.

(4) From the energy gain per turn (per unit of time) the rate of magnet field rise is computed.

(5) This process is iterated to generate the field-time function. 2.4 ms steps were used in this integration.

The results are plotted in figure 3 for an rf accelerating crest voltage of 90 kV. Figure 4 displays the same information as given in figure 3 except it is plotted as dB/dt vs. time. Since the inductance of the dipole system is known, a voltage scale can be added to this plot.

The shortest possible acceleration time to reach 1.5 GeV is accomplished by following these constant bucket area curves. However, voltages near 10 kV would be required. Fortunately the times indicated are shorter than necessary. Figure 5 shows the trial and error solution fitting the whole pulse cycle into the 133.3 ms repetition period. A dipole magnet power supply having a maximum rectify voltage of 4500 volts is indicated. The accelerating cycle follows the constant bucket area curve until the power supply reaches its top voltage, after which the power supply voltage is held constant and the cycle is slowed. An energy of 1.5 GeV is reached in 62 ms as opposed to the 54 ms it would have taken if the constant bucket area curve had been followed all the way.

References

[1] Area and Bunching Factors of Partially Filled Buckets, Cole and Morton, LRL, University of California, UCID 10130 AS/Theoretical, (Sept. 21, 1984).

[2] Booster R. F. Program for Heavy Ions, BNL/RHIC-AP-17, Ruggiero and Young, (May 31, 1985).

[3] A Selection of Formulae and Data Useful for the Design of the A. G. Synchrotrons, CERN/MPS-SI/Int. D1/70/4, Bovet, Gouiran, Gumowski and Reich, (April 23, 1970).

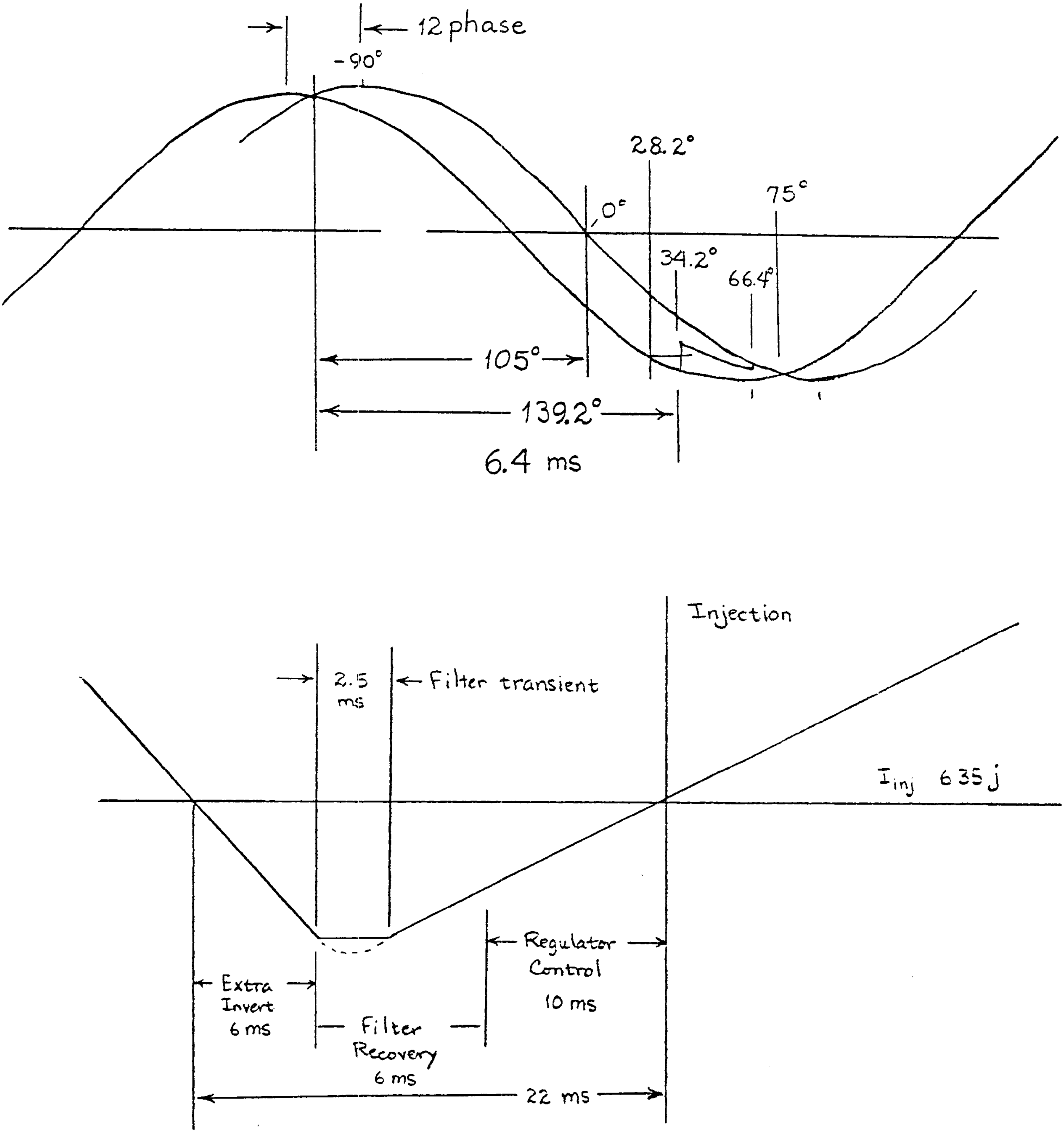
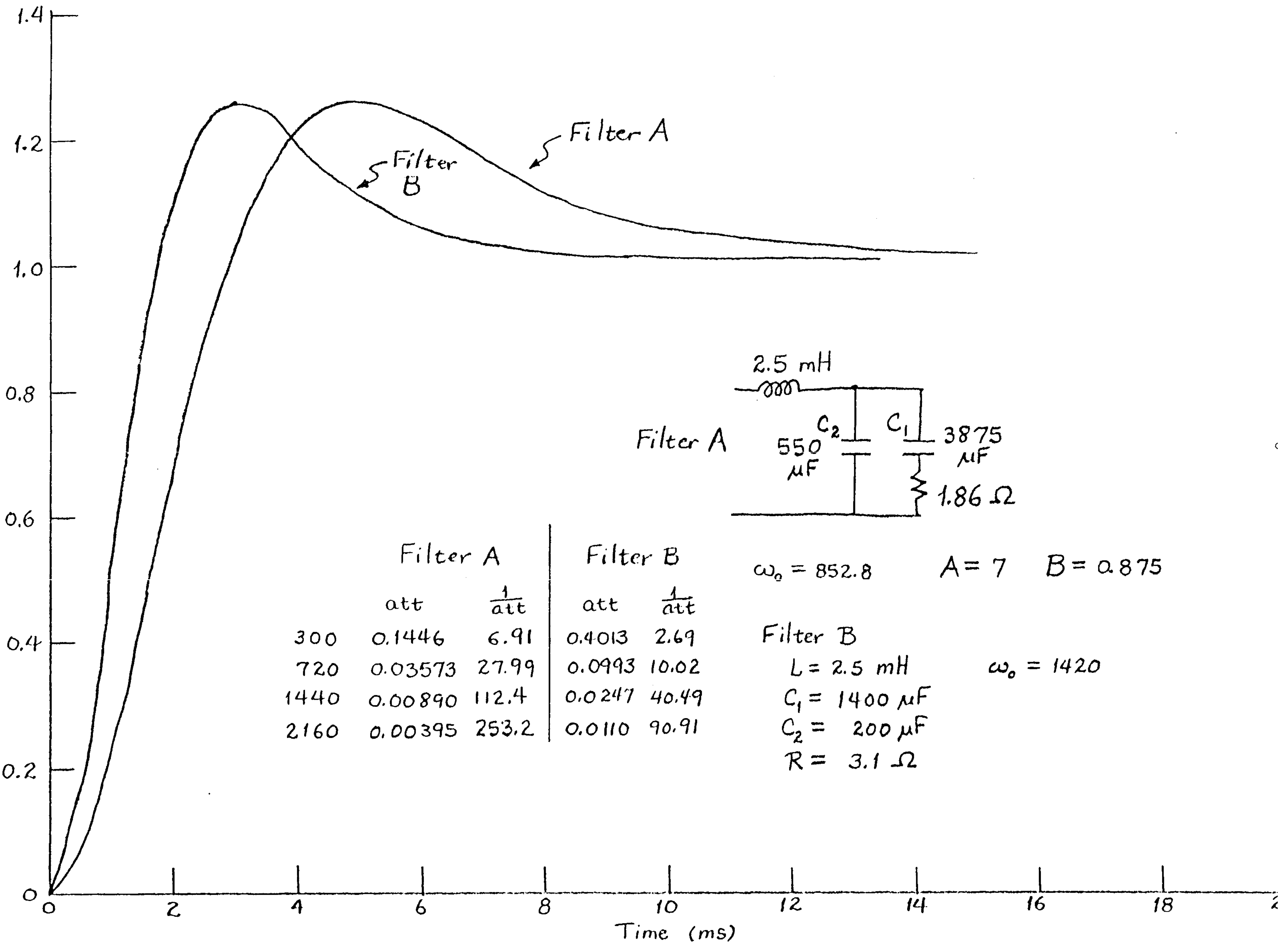


FIG. 1 COMMUTATION OVERLAP and INJECTION UNDERSHOOT PROCESS



	Filter A		Filter B	
	att	$\frac{1}{att}$	att	$\frac{1}{att}$
300	0.1446	6.91	0.4013	2.69
720	0.03573	27.99	0.0993	10.02
1440	0.00890	112.4	0.0247	40.49
2160	0.00395	253.2	0.0110	90.91

$\omega_o = 852.8$ $A = 7$ $B = 0.875$

Filter B

$L = 2.5$ mH $\omega_o = 1420$

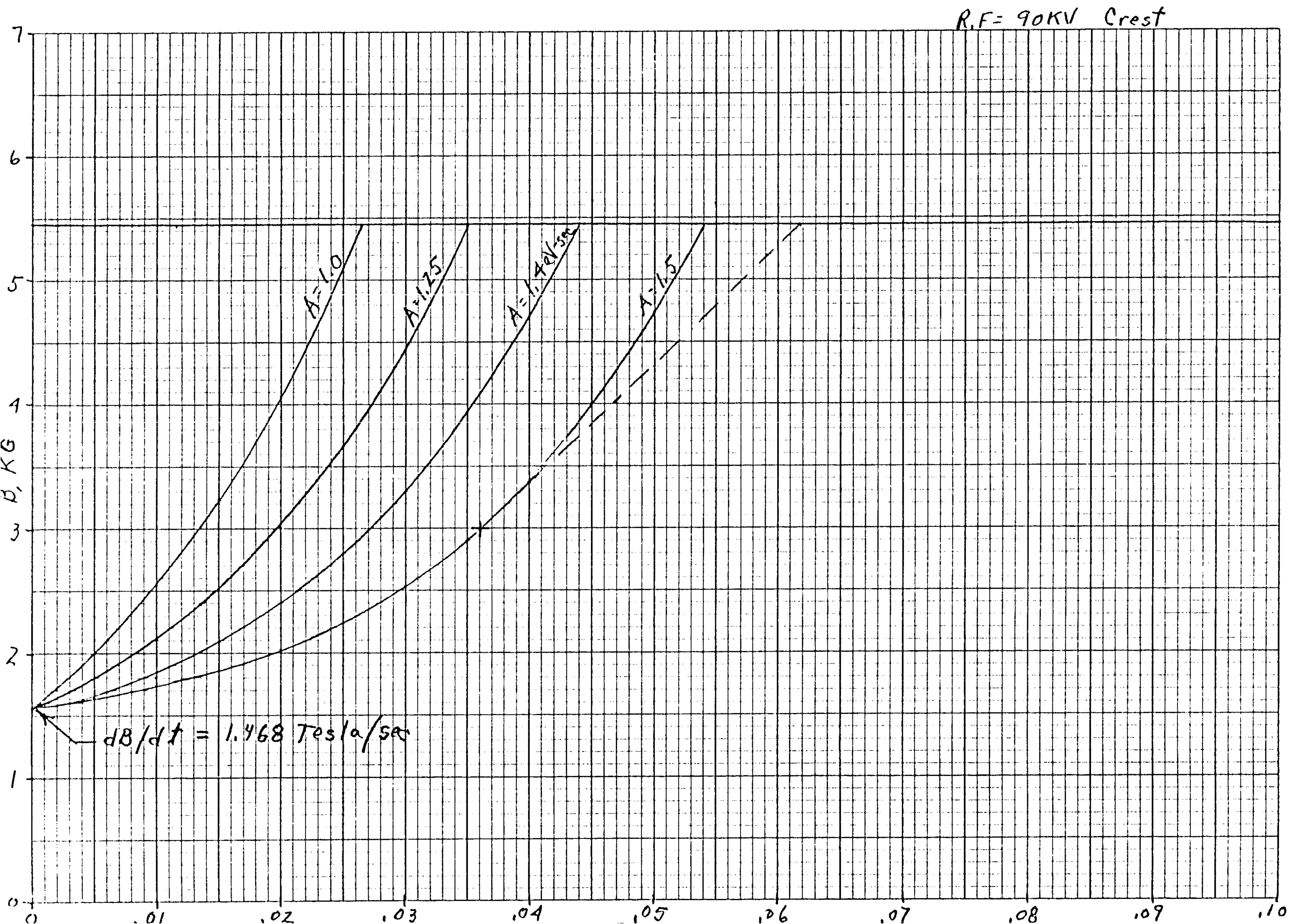
$C_1 = 1400$ μF

$C_2 = 200$ μF

$R = 3.1$ Ω

FIG. 2 RIPPLE FILTER RECOVERY TRANSIENT

FIG. 3 MAGNET FIELD vs. TIME FOR A CONSTANT ACCELERATING BUCKET AREA OPERATING WITH AN R.F. CREST VOLTAGE OF 90 KV.



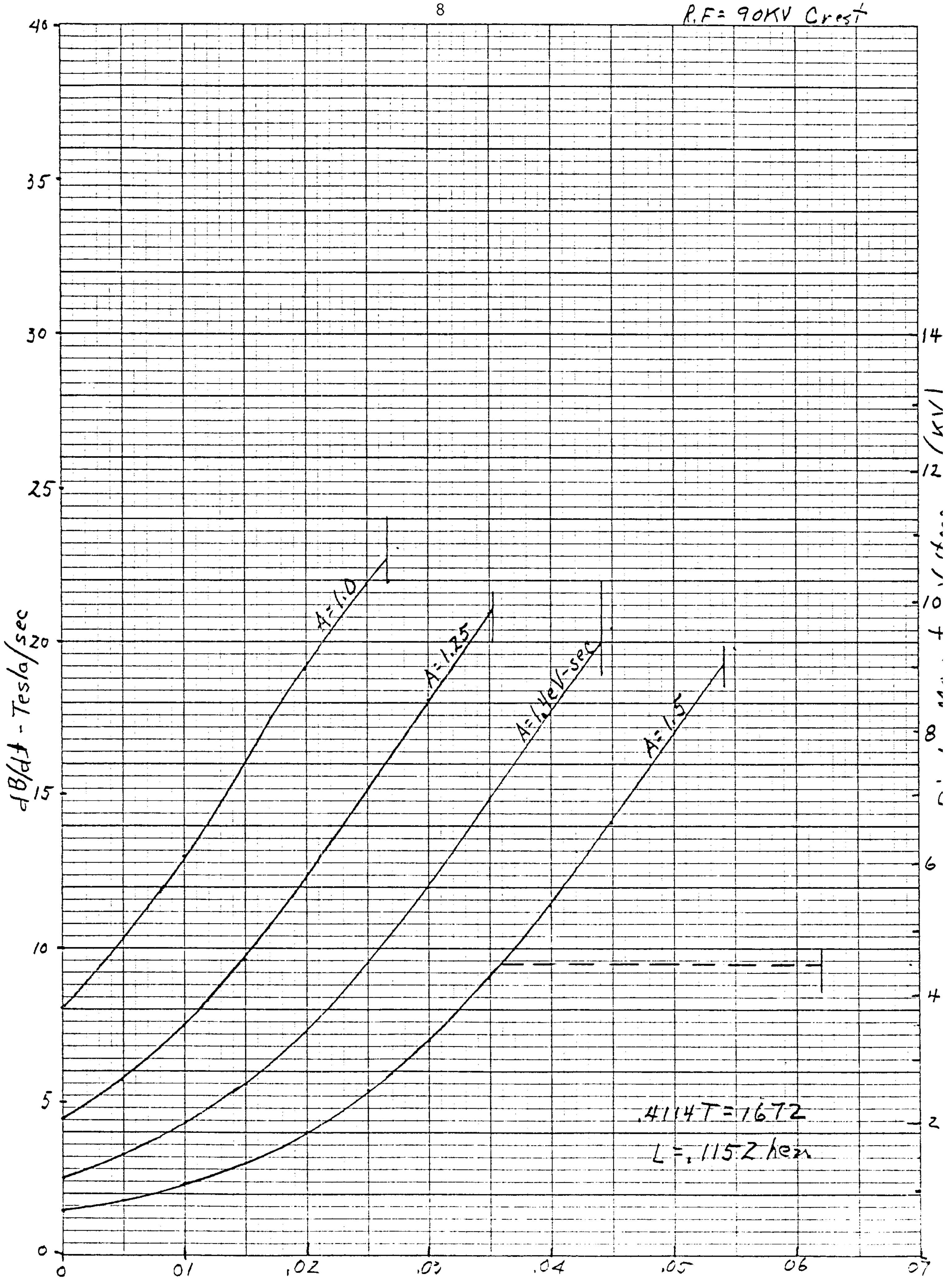


FIG. 4 MAGNET FIELD dB/dT FOR A CONSTANT ACCELERATING BUCKET AREA OPERATING WITH AN R.F. CREST VOLTAGE OF 90 KV.

FIG. 5 DIPOLE VOLTAGE AND CURRENT vs. TIME FOR A 0.133 SEC. REPETITION PERIOD.