BNL-105170-2014-TECH

Booster Technical Note No. 126;BNL-105170-2014-IR

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August 1988

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U.S. Department of Energy

USDOE Office of Science (SC)

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INTRODUCTION

This note summarizes the preliminary design study of the RF power amplifier for the upgraded AGS. The keystone in this study is the utilization of the present RF cavities for the upgraded AGS. Contrary to the present configuration, the power amplifier will be installed in the tunnel adjacent to the cavity. Each amplifier has its own driver and is electronically isolated from the other nine amplifiers.

In many ways the amplifier requirements are similar to those of the AGS Booster. This could have been predicted on the common beam in the two machines. The cavity voltages are similar: 45kV for the Booster and 40 kV for the AGS. The significant difference is in the number of gaps per cavity: 4 for the AGS and 2 for the Booster. The Booster cavity is coupled to the power amplifier through a 2:1 step - down auto transformer. To utilize a similarly designed power amplifier the AGS cavity must be coupled to the amplifier through a 1:1 transformer. For both cases the effective voltage transformation from the amplifier to the cavity terminal is 4:1. This is illustrated in Fig. 1A for the Booster and in Fig. 1B for the upgraded AGS.

In principle, the upgraded AGS cavity can be excited directly from the power amplifier as illustrated in Fig. 1C. However, the 8:1 transformation requires that the amplifier tube have an extremely large current capability (better than 200 A peak) and a very low output resistance (less than 100 ohms). The match between the anode's volt ampere characteristics and the transformed load is impractical.

The major problem in the AGS upgrade is the low value of gap capacitance. Due to an increase in beam intensity, beam loading is increased and will manifest itself as a transient phase shift during injection of a formed beam from the Booster. The present AGS cavities are tuned with 328$\mu\mu$F/gap and requires an increase to a value of 830 $\mu\mu$F/gap or better. This requires modification of the present cavity.

This report is organized into, and treats, four major aspects of the development program.

1. Electrical specification
2. Design of the power amplifier
3. Design of the output transformer
4. Modifications of the cavity for an increase of gap capacitance.

ELECTRICAL SPECIFICATION

The RF system specifications are based on a proton beam of 6×10^{13} particles per pulse. Based on a design-safety factor of 1.5, the electrical system is designed to accommodate a proton beam of 9×10^{13} particles per pulse. The design parameters are given in Table I.

Beam Intensity	6×10^{13} particles/pulse
Design	9×10^{13} particles/pulse 0.75×10^{13} particles/bunch 1.2×10^{-6} coul/bunch
Frequency	4.1 - 4.5 MHz
Beam Current	
Based on a half - sinusoidal distribution	
Average	4.92A to 5.40 A.
Peak	15.45 to 16.96 A.
Fundamental (Peak Values) I_1	7.72 to 8.48 A.
Voltage	
Based on a $\dot{B}$ max of 33×10^3 Gauss/sec.	
Maximum energy gain	220 KeV/turn 22 KeV/cavity 5.5 KeV/gap
Cavity voltage (peak value)	10 Kv/gap 40 Kv/cavity
Beam Power	
Maximum	29.7 KW/gap 118.8 KW/cavity
Cavity Loss (principally in the ferrite)	
10 Kv gap voltage	28 - 35 KW
Amplifier Power	
Peak	154 KW
Robinson Resistance	
Ring	67.2 KΩ
Cavity	6.72 KΩ

TABLE I

DESIGN PARAMETERS FOR THE RF SYSTEM

Ferrite losses in the cavity have been previously measured and curves of cavity dissipation are reproduced in Fig. 2.

These specifications are reduced to required cavity feed current during various machine phases. The three machine phases that limit the amplifier and cavity performance are:

a) Injection Phase

At injection three formed bunches are injected from the Booster such that the centroid of each bunch is in quadrature with the gap voltage. The AGS operates in a storage mode while the Booster performs a second acceleration cycle and injects three additional bunches into the AGS. This continues until 12 bunches are injected. The beam induces a current and voltage in the cavity that is in quadrature with the cavity voltage, detuning the cavity. The stable phase angle is on the positive slope of the accelerating voltage, resulting in a current that leads the voltage by 90^{o}. See Fig. 3A. The transient response is depicted in Fig. 3B. At injection, the capacitor is charging from the inductor. The inductor current is i_L. The induced beam current i_b reduces the charging current

$$\frac{dv}{dt} = \frac{i_L - i_b}{C}$$

resulting in a slope reduction and delay of the gap voltage. Numerical evaluation and significance of the delay is discussed in section 4, Cavity Modification.

b) Phase Transition

At phase transition the centroid of the beam jumps from its stable phase angle on the positive slope of the accelerating voltage to the same angle on the negative slope, see Fig. 4. The quadrature component of beam current jumps from lead to lag. Until the cavity is retuned by the AFC loop the amplifier will supply the net change of reactive current.

c) Maximum Acceleration

During the maximum acceleration phase, the frequency loop tunes the system to resonance, and the amplifier again feeds a resonant load. The tube dissipation and current is minimized.

During the injection phase and at phase transition, the tube dissipation and current are a maximum, characteristic of tuned amplifiers feeding a non-resonant load.

The cavity feed current is given in Table II for the three machine phases.

MACHINE PHASE	CAVITY CURRENT	BEAM CURRENT IN PHASE	BEAM CURRENT QUADRATURE PHASE	TOTAL CURRENT
INJECTION	5.6	0	30.42	$31.42 \lfloor 79.7^{\circ}$
TRANSITION	7	23.8	± 24.16	$57.30 \lfloor -57.48^{\circ}$
MAXIMUM ACCELERATION	7	23.8	24.16	$30.8 \lfloor 0$

$\Psi_B = 44.5^{\circ}$

TABLE II

CAVITY DRIVE CURRENT PER STATION (4 GAPS)

CURRENT: PEAK VALUE OF FUNDAMENTAL (AMPS)

DESIGN POWER AMPLIFIER

The initial design concept of two different circuit arrangements have been studied. Both circuits utilize a single tube class AB_1, driver, employing the EIMAC 4CM300,000G tetrode. The tube is employed in the Booster RF power amplifier and is described in detail in AD Booster Tech. Note 92. The performance and configuration of the three amplifiers are quite similar.

For the first circuit a 1.3:1 step-down transformer couples into the existing AGS cavity, consisting of 4 gaps wired in parallel, see Figure 5. The gross tube performance including plate current, dissipation, and beam damping resistance is given in Table III. The tube operates class AB_1, with a zero signal plate current of 5A. Since the load line and current swing matches the Booster amplifier an average plate resistance of 200 ohms is used in developing the table; 186 ohms was calculated for the Booster power amplifier. The transformer configuration provides push-pull or symmetrical excitation for the cavity.

The load lines (locus) for this circuit are given in Figures 6A and 6B. Figure 6A is for maximum beam acceleration and a resonant load; Figure 6B is for transition and a non-resonant load.

The second circuit is used with two independent stations in each cavity. Each station consists of two gaps, wired in parallel. The station voltage is 40 Kv peak; the gap voltage, 20 Kv peak. This configuration is utilized to increase the cavity capacitance by a factor of 2, which is required to decrease beam loading. However, the gap voltage also increases by a factor of 2 and the ferrite dissipation by a factor of 4. Ferrite dissipation is discussed in section 4 of this report.

The circuit diagram is given in Figure 7 and the tube performance is given in Table IV. The amplifier is coupled to each station through a 2:1 step-up auto transformer. Unbalance of the gap voltage due to single-ended excitation of the cavity introduces a common mode voltage across the gap. By phasing the excitation symmetrically in space, as shown in Figure 7, and exciting the amplifiers push-pull the common mode response of the two stations are out of phase and thus cancel.

Unbalance of the gap voltage due to single-ended excitation depends on the Q of the cavity, excluding the damping provided by the power amplifier. The unloaded Q of the cavity is 48; with beam loading 18.5. The unbalance is ± 2.7% and will be cancelled by the cavity drive configuration.

Tube Performance	MACHINE PHASE			Tube Absolute Rating
	Injection	Transition	Max. Accel.	
Cavity Feed Current	31.47	57.3 A	30.8 A	
(Peak Valve of Fundamental)				
E_{BB}	15 kV	15 kV	15 kV	20 kV
E_{C2}	1 kV	1 kV	1 kV	2 kV
E_{C1}	-280 V	-280 V	-280 V	
Peak Plate Current	48.3A	88.2A	47.4A	260 A
Average Plate Current (Short Term Average)	15.4A	28.1A	15.1A	50 A
Peak Grid Current	0	0	0	
Peak Screen Current	2 A	3.5A	2 A	
P_{BB}	231 kW	421. kW	227 kW	
Plate Dissipation	203 kW	267 kW	73 kW	
P_L	28 kW	154 kW	154 kW	
Beam Power	0	119 kW	119 kW	
Ferrite Dissipation	28 kW	35 kW	35 kW	
Average Quantities				
Plate Dissipation				
50% Duty Cycle	97kW			300kW
Tube Resistance Reflected:				
Across Cavity	3.8 KΩ			
Beam Damping	3.23 KΩ			

TABLE III

SUMMARY OF TUBE PERFORMANCE

CIRCUIT OF FIGURE 5

Tube Performance	MACHINE PHASE Injection	Transition	Max. Accel.	Tube Absolute Rating
Cavity Feed Current (Peak Valve of Fundamental)	17.86	30.67	18.9	
E_{BB}	12kV	12 kV	12 kV	20 kV
E_{C2}	1.2kV	1.2 kV	1.2 kV	2 kV
E_{C1}	-320	-320	-320	
Peak Plate Current	71.44A	122.7A	75.6A	260 A
Average Plate Current (Short Term Average)	22.74A	39 A	24.06A	50 A
Peak Grid Current	0	0	0	
P_{BB}	272.9kW	468.7kW	288 kW	
Plate Dissipation	217.1kW	279.7kW	99 kW	
P_L	56 kW	189 kW	189 kW	
Beam Power	0	119 kW	119 kW	
Ferrite Dissipation	56 kW	70 kW	70 kW	
Average Quantities Plate Dissipation 50% Duty Cycle	100kW			300kW
Tube Resistance Reflected:				
Across Cavity	6.4 KΩ			
Beam Damping	4.1 KΩ			

TABLE IV

SUMMARY OF TUBE PERFORMANCE

CIRCUIT OF FIGURE 7

TRANSFORMER DESIGN

The transformer coupling the power amplifier to the cavity has a turn ratio of 1.3:1 and should be electrically transparent. The major electrical problems introduced by the transformer are:

1. An introduction of phase-shift from amplifier to cavity due to its leak inductance.

2. Detuning of the cavity and a stress on the tuning loop due to its output inductance shunting the ferrite.

To minimize both effects the transformer must be designed for an extremely small value of leakage inductance. The magnetizing inductance must be limited in value, resulting in a high value of flux density and core loss. The design is a compromise between core loss, cooling and leakage inductance. The transformer must be tightly wound with the excitation winding approximating a current sheet.

To quantify the design the equivalent circuit of the transformer, amplifier and cavity is given in Figure 8. The parameters are defined as:

r is the output resistance of the amplifier

$$r = 400\Omega \left(\frac{1}{1.3} \right)^2$$

C is the input capacitance of 4 gaps.
L is the inductance of 4 gaps.
R_T models the losses in the transformer.
R models the ferrite losses.
L_p is the primary inductance of the transformer.
σ is the leakage inductance of the transformer

$$\sigma = (1 - k^2)\ L_p \approx 2\ (1-k)\ L_p$$

The system operates with a gap voltage of 10,000 volts and a cavity feed current of 32A. We arbitrarily limit the phase shift in the transformer to 2^o, thus the voltage drop across the leakage inductance, σ, is 349 volts. The value of σ is calculated as 0.44 μhy.

The transformer is wound on AGS cavity ferrite rings 4L2. The initial permeability is larger than 200. Without corrections for geometry

$$k \geq 1 - \frac{1}{200} = .995$$

and with reasonable control of the leakage reluctance $k \geq .998$. Thus the primary inductance can be between 44 and 110μH. The net change of tuning inductance lies between 2.5% and 1%, which are acceptable values.

The transformer is wound on the AGS ferrite rings 4L2, dimensions of the ring are:

OD = 50 cm
ID = 20 cm
Thickness = 2.8cm

The measured ferrite loss is given in Figure 9. For a turns ratio of 1.3 each ring is wound with an 8 turn primary and a 6 turn secondary, approximating a current sheet.

With a single ring the inductance is 37μH. The ferrite power dissipation density with an RF duty cycle of 50% is 263mw/cm^3. The transformer design is developed by using a multiple number of rings and series connecting the windings. The results are given in Table V.

The 3 or 4 ring design can be cooled with forced air. The 1 or 2 ring design requires circulating water and cooling plates, as used in the cavity; another possibility is the immersion of the transformer in a bath of a radiation resistant coolant. The design requires construction and measurement of the leakage inductance and heat transfer characteristics.

CAVITY MODIFICATIONS

The present AGS cavity consists of 4 gaps driven in parallel, the capacitance is 328 $\mu\mu$F/gap or 82 $\mu\mu$F/cavity. Transient beam loading manifests itself as both amplitude and phase modulation of the gap voltage. At injection, the formed beam from the Booster introduces a phase delay. Though injected in quadrature, the transient induced phase delay decelerates the beam. Appendix A summarizes the transient analysis. The phase shift induced by the sequential injection of three bunches is approximated by

$$\Delta\theta_0 = \frac{\pi}{8} \left\{ \frac{Q}{c} \right\} \frac{1}{v}$$

$$\Delta\theta_1 = \left\{ \frac{Q}{c} \right\} \frac{1}{v} \left[\frac{\pi}{8} + \frac{\pi}{4} e^{-\pi Q_o} \right]$$

$$\Delta\theta_2 = \left\{ \frac{Q}{c} \right\} \frac{1}{v} \left[\frac{\pi}{8} + \frac{\pi}{4} e^{-\pi/Q_o} \left[1 + e^{-\pi/Q_o} \right] \right]$$

where $\Delta\theta_0$, $\Delta\theta_1$, $\Delta\theta_2$ are the induced phase shifts during the injection of the first, second and third bunch.

Q = charge per bunch
C = capacitance per gap (or cavity)
V = peak voltage per gap (or cavity)
Q_0 = the Q (quality factor) of the cavity

These functions are weakly dependent on the Q_0 of the cavity and are tabulated in appendix A. The energy loss per unit of charge is the product of $\Delta\theta$ and V and is a function primarily of the Q/C ratio of the machine. For the present cavity configura-

NO. OF RINGS	INDUCTANCE μH	CW DISSIPATION F=4.1MHz mw/cm^3	CW DISSIPATION F=4.5 MHz mw/cm^3	50% DUTY CYCLE DISSIPATION mw/cm^3	TOTAL DISSIPATION WATTS
1	37	450	600	263	1214
2	74	110	160	68	628
3	111	46	70	29	402
4	148	25	40	17	314

TABLE V

PRELIMINARY DESIGN OF FERRITE RING TRANSFORMERS

tion and with

$C = 82\mu\mu F$/cavity
$Q = 1.2 \times 10^{-6}$ coul/bunch
10 cavities/turn

the energy loss varies from 203KeV/turn to 267KeV/turn as Q_0 varies from 10 to 50. The energy loss is independent of the magnitude of the gap voltage.

In addition, a phase shift (delay) is developed. The phase shift is inversely dependent on the magnitude of the gap voltage. Typically, at acceleration, the gap voltage is 10Kv and at injection 5Kv. The phase shift is calculated as a function of Q_0 during the injection of the three bunches, see Table VI.

TABLE VI
PHASE DELAYS AT INJECTION

$V = 5$ Kv/gap $C = 328\mu\mu F$/gap
$Q = 1.2 \times 10^{-6}$ coul/bunch

Q_o	$\Delta\theta_o$	$\Delta\theta_1$	$\Delta\theta_2$
10	16.4°	40.3°	58.1°
20	16.4°	44.4°	68.1°
50	16.4°	47.2°	76.5°

These phase delays are approaching the limits of stability, 90°. The phase shifts can be decreased by increasing the value of gap capacitance. Limiting the phase angle to 30° the value of C must increase to 830 $\mu\mu F$/gap or 207 $\mu\mu F$/cavity. The phase shift can also be decreased by feedback or feed forward. But the response time of the loops must be faster than 0.48 μsec (2 RF periods).

The gap capacitance can be increased only by decreasing the cavity inductance. The inductance can be decreased by:

1. increasing the bias current to reduce the permeability
2. decreasing the volume of ferrite in the cavity
3. a combination of the above.

If the volume of ferrite is decreased by removing ferrite rings from the cavity structure the magnetic flux density in the rings increases, which in turn increases the dissipation within the cavity. The ferrite dissipation has been studied as a function of the number of rings within the cavity. As presently structured, each cavity consists of 4 gaps. Each gap is constructed from 14 ferrite rings; material is 4L2. Dimensions of the rings are:

OD = 50 cm
ID = 20 cm
Thickness = 2.8 cm

The loss measurements for 4L2 are given in Figure 9. The results of this study for a 4 gap cavity is summarized Table VII.

Water cooling of ferrite rings can handle a power dissipation density of 250 - 300 mw/cm^3. For power handling capabilities, the time average dissipation with 50% duty cycle limits the ferrite volume. In principle, if 7 rings per gap were utilized, the inductance would be halved and the gap capacitance would double to approximately 648 $\mu\mu$F. The bias current would further decrease the inductance, such that the gap capacitance increases to 830$\mu\mu$F/gap or 207$\mu\mu$F/cavity.

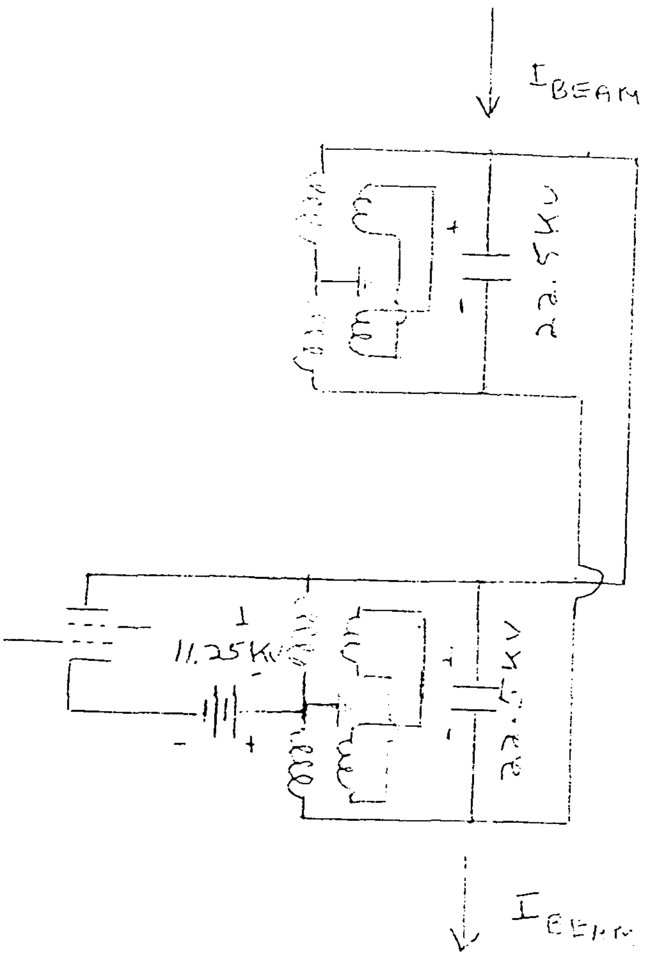
As an alternative approach and to keep the cavity structure as it is presently assembled, 2 gaps would be used in each cavity as an RF accelerating station. Each cavity would contain 2 accelerating stations, each excited by its own power amplifier, as shown in Figure 7. The station capacitance is 164 $\mu\mu$F and would be increased to 207 $\mu\mu$F by an increase of bias current. For this modification, the gap capacitance remains at 328 $\mu\mu$F but the gap voltage is increased from 10Kv to 20Kv. The stored energy per station doubles.

This modification can be considered only if the cavity is capable of operating at 20 Kv. This must be determined by a series of voltage breakdown measurements of the cavity.

Rings Per Gap	Gap Voltage (kV)	B (Gauss)		cw Power Dissipation Density mw/cm3		AV Power Dissipation Density mw/cm3 50% Duty Cycle	Power Dissipation Per Cavity (kW)/50% Duty Cycle
		F =4.1 MHz	F =4.5 MHz	F =4.1 MHz	F =4.5MHz		
14	10	65.9	60	72	110	45.5	11.76
12	10	76.9	70	110	165	68.8	15.25
10	10	92.3	84	180	235	104	19.21
8	10	115.3	105	300	370	168	24.83
7	10	132	120	500	600	275	35.56
6	10	153.7	140	650	800	362	40.12
14	20	132	120	500	600	275	35.56* 71.12**

* for 1 station/2 GAPS
** for 2 stations/4 gaps

TABLE VII
POWER DISSIPATION STUDY OF FOUR GAP CAVITY AS A FUNCTION OF THE NUMBER OF RINGS



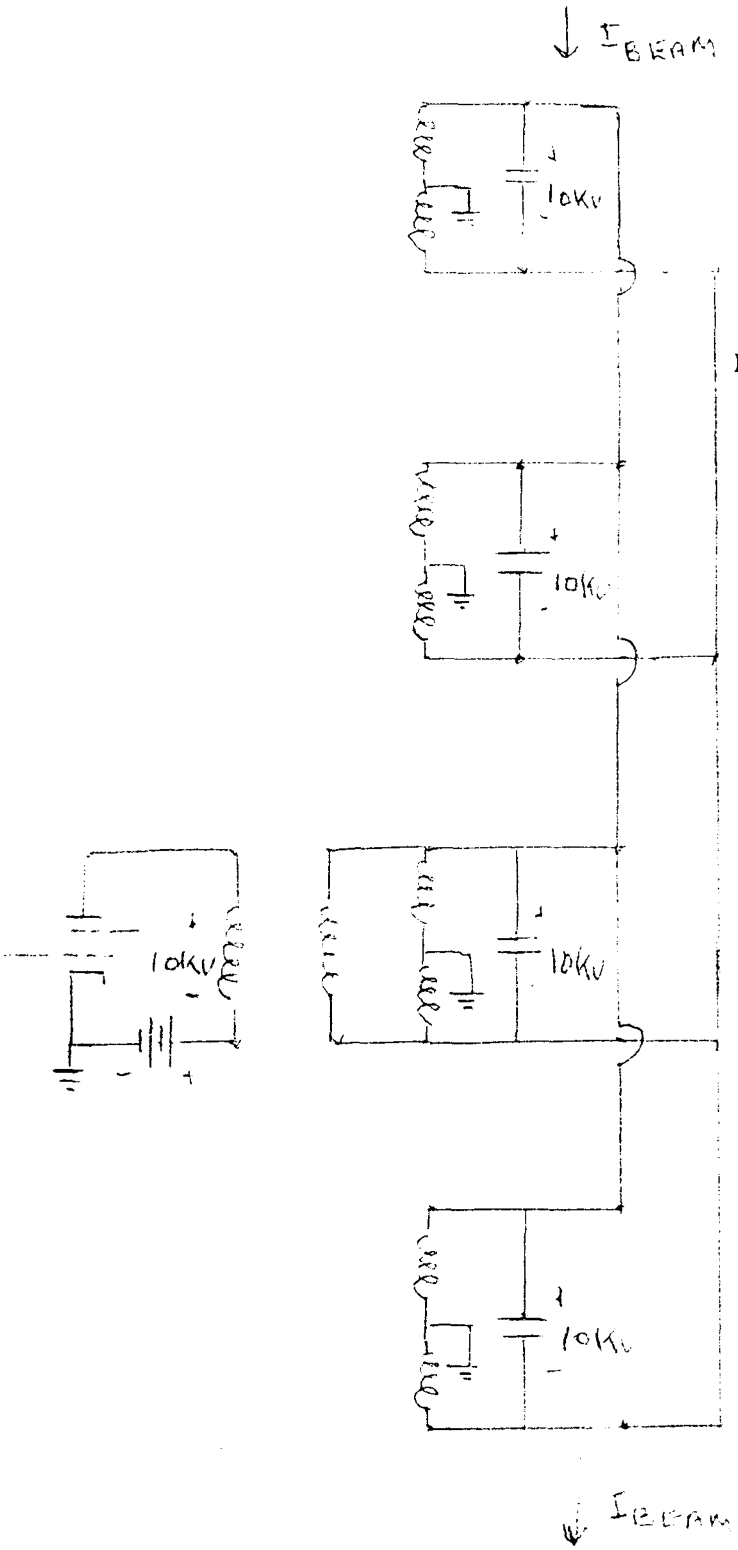
Beam sees two capacities in series

Cavity voltage = 45 Kv

Transformation from plate to cavity = 1:4.

FIGURE 1-A

CAVITY CONFIGURATION AND DRIVE FOR BOOSTER



Beam see four capacitors in series

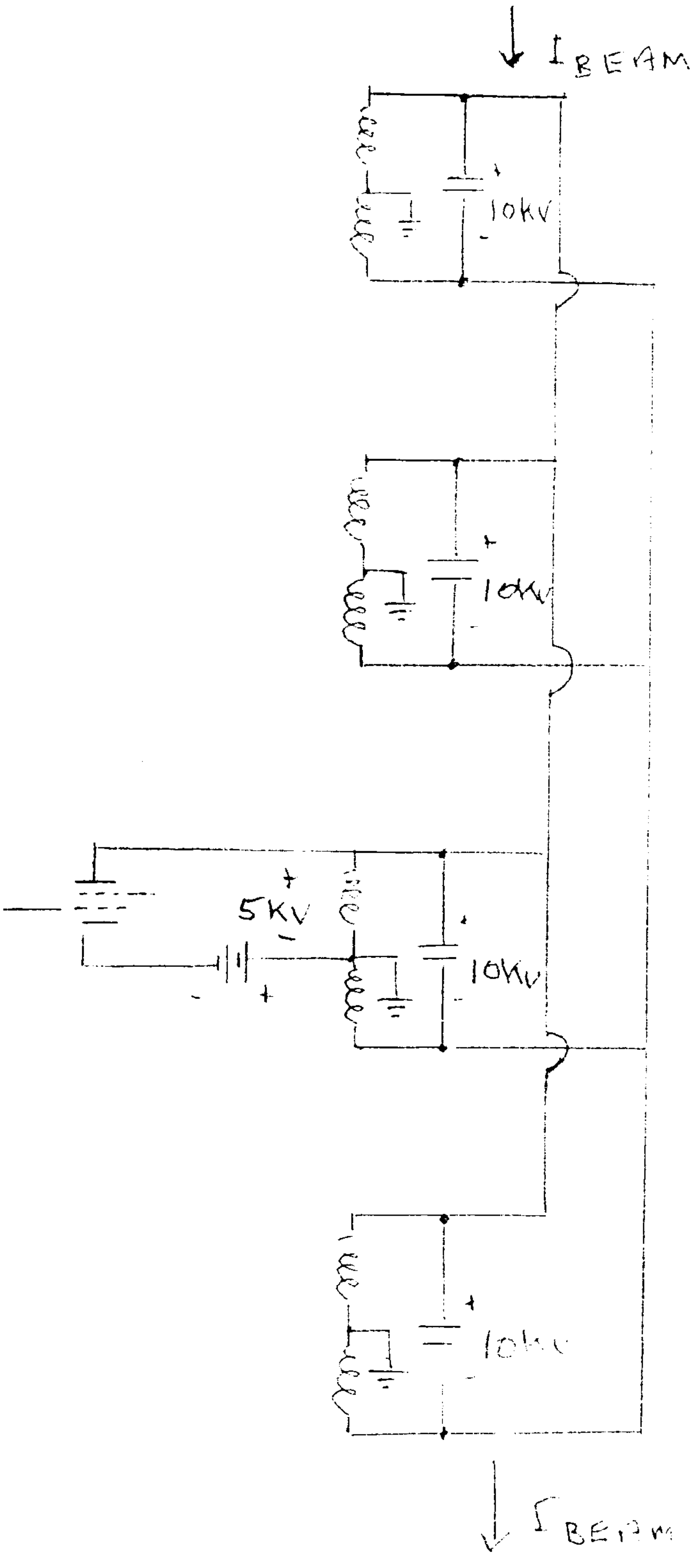
Cavity voltage = 40 Kv.

Transformation from plate to cavity = 1:4.

FIGURE 1B

CAVITY CONFIGURATION AND DRIVE FOR UPGRADED AGS

WITH TRANSFORMER



Beam sees four capacitors in series

Cavity voltage = 40 Kv

Transformation from plate to cavity = 1:8.

FIGURE 1C

CAVITY CONFIGURATION AND DRIVE FOR UPGRADED AGS

WITHOUT TRANSFORMER

46 1320

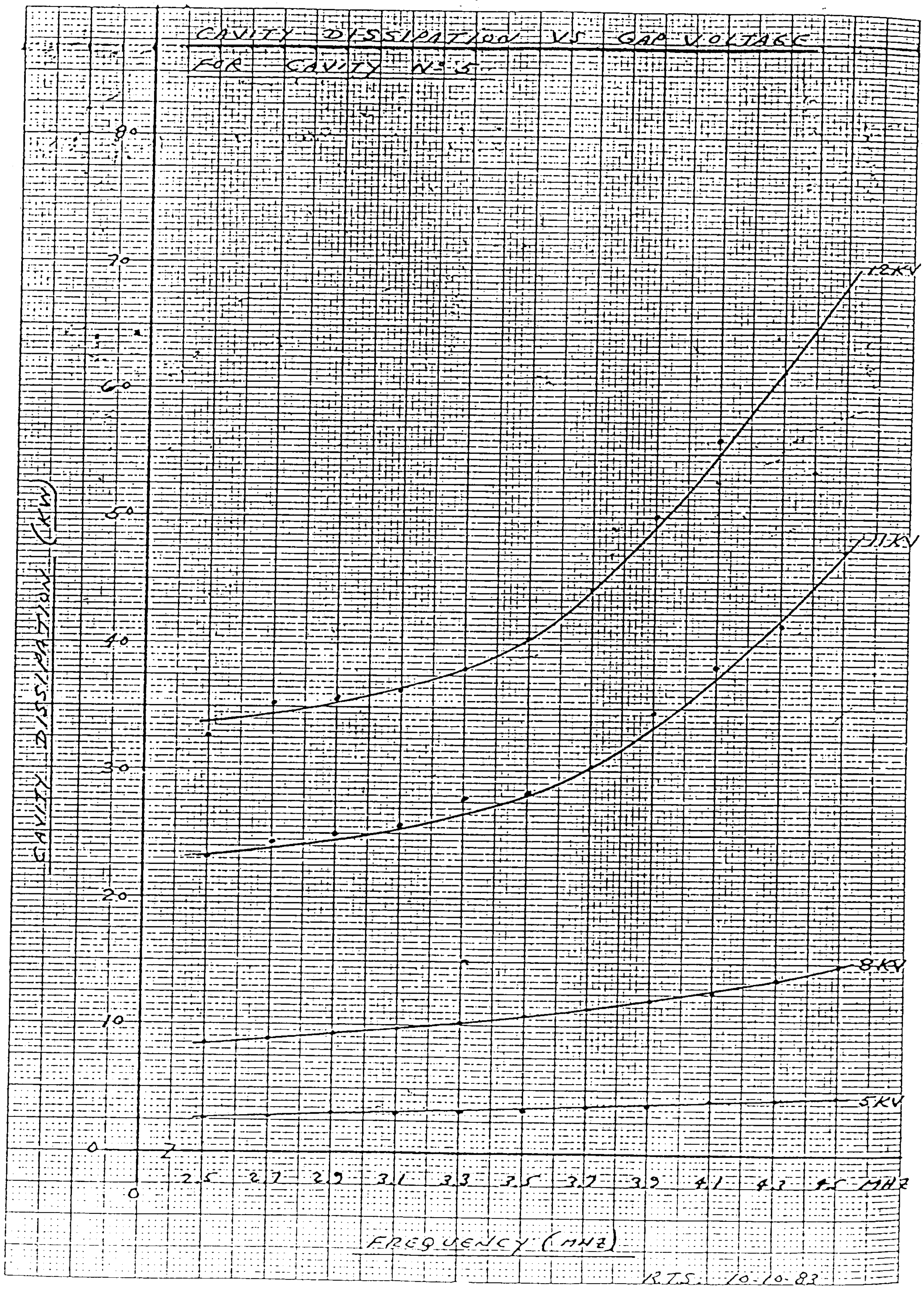


FIGURE 2