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PHASE TRANSITION FOR AGS UPGRADE

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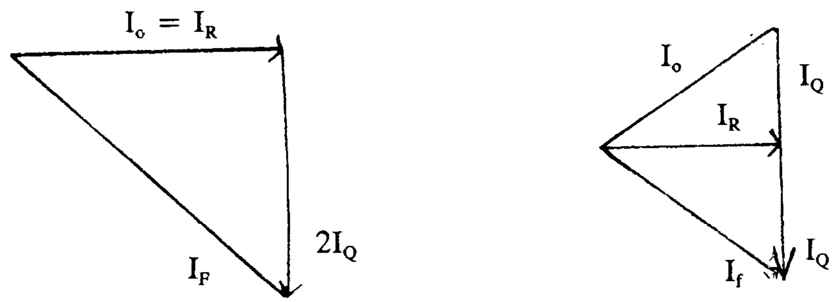
Introduction

Phase transition for the AGS RF Upgrade can require the power amplifiers to handle very large reactive currents, resulting in the power output tube being driven into the positive-grid region (class AB_2 operation) or even current limited. Normally, the cavity is non-resonant. The reactive component of beam current resonates with the cavity and provides a tuned or resonant load for the power amplifier. At phase transition the reactive component of beam current changes abruptly from lead to lag; from an equivalent capacitance to an equivalent inductance. The power output tube must provide a current that in addition to a fixed real component (beam power, ferrite loss) has a reactive component, which is equal to the full change of beam current. Normally the reactive component of beam current is larger than its real component.

By operating the cavity at resonance just prior to phase transition the tube current before and the tube current after transition are (complex) conjugate. The absolute value of tube current is significantly less than would be required by utilizing the former scenario. The difference between the two scenarios is illustrated by the phase diagrams of Figure 1.



$$I_f = 2I_Q\sqrt{1 + \frac{I_R^2}{4I_Q^2}}$$

$$I_o = I_f = I_Q\sqrt{1 + \frac{I_R^2}{I_Q^2}}$$

1A - Resonant Load

1B - Resonant Cavity

Figure 1
Phasor Diagram of Cavity Current Before and After Phase Transition

I_R = Real Component of Cavity Current
I_Q = Reactive Component of Beam Current
I_O = Cavity Current Before Transition
I_f = Cavity Current After Transition

PARAMETERS

The parameters employed for this study are:

$N = 9 \times 10^{13}$ protons per pulse
(includes a 50% safety factory)

RF Frequency = 4.45 MHz
Cavity Voltage = 40 kV
Accelerating Voltage = 23.5 kV
Beam Power = 126 KW/cavity
Ferrite Dissipation = 65 KW/cavity
Synchronous Phase Angle = 36°

The real and quadratune components of beam current are calculated as:

$I_R^1 = 6.29$ A
$I_Q = 8.66$ A

The cavity current due to ferrite dissipation is calculated as:

$I_R^{11} = 3.25$ A

thus

$I_R = I_R^1 + I_R^{11} = 9.54$ A

The maximum cavity current for the two scenarios described are calculated as

for A (resonant load) = 19.77 A
for B (resonant cavity) = 12.88 A

Referred to the plate of the output tube, the fundamental component of current has a peak value of

for A = 79.1 A
for B = 51.5 A

For class B operation the peak value of plate current is approximately

for A = 190 A
for B = 120 A

The load impedance phase angle after transition is calculated as

for A = 61.2°, lag
for B = 42.2°, lag.

SYSTEM DESCRIPTION

It is proposed that the amplifier load be detuned prior to reaching transition energy. A pulse is applied to the phase-shifter within the cavity tuning loop. The pulse width is selected to approximate the loop settling time. The pulse amplitude is chosen to advance the phase (in the steady-date) by 42.2°, corresponding to the load impedance angle for maximum beam intensity. At transition energy the phase is retarded and terminates as a lag angle that is dependent on the beam intensity. The lag angle is less than 42.2°. Table I gives the lag angle after transition as a function of beam intensity. Following transition the tuning loop retunes the cavity, phase angle of 0°. Figure 2 gives the load impedance phase angle for a beam intensity of 9 x 10^{13} and 5.4 x 10^{13}. For this figure it is assumed that the cavity tuning loop settling time is 1.5 milliseconds. Transition energy is at time γ_T.

N x10^{13}	BEAM CURRENT		BEFORE TRANSITION		AFTER TRANSITION	
	I_1 (Amp)	I_Q (Amp)	Lead Angle	Tube Current (Amp)	Lag Angle	Tube Current (Amp)
0	0	0	42.2°	17.5	-42.2°	17.5
1.8	2.14	1.73	42.2°	24.4	- 8°	18.3
3.6	4.30	3.48	42.2°	31.2	16.8°	24.2
5.4	6.45	5.22	42.4°	38	30°	32.5
7.2	8.56	6.93	42.4°	44.7	37.5°	41.7
9.	10.7	8.66	42.2°	51.5	42.2°	51.5

TABLE I

Tube Current, Amplitude and Phase, at Transitron

I_1 = Beam Current
I_Q = Reactive Component of Beam Current

All currents are given by peak value of fundamental.

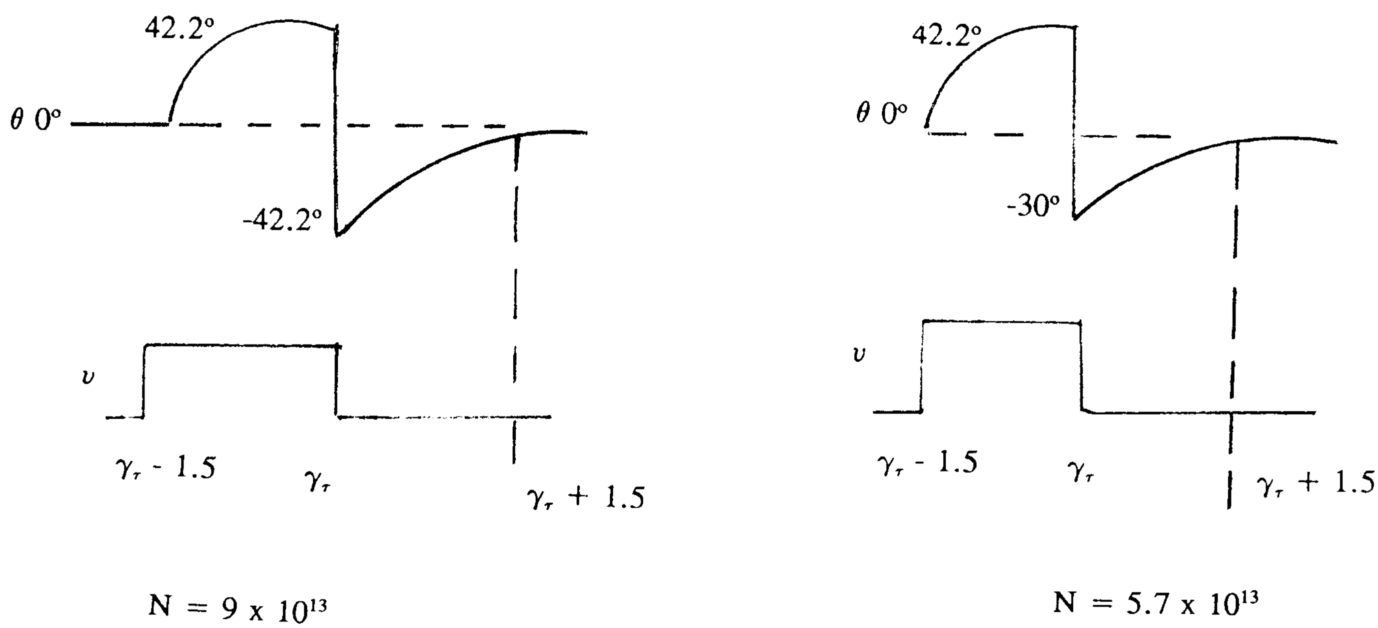


Figure 2
Load Impedance Phase Angle

Output Stage

The design of the power amplifier output stage is based on the current and power required at phase transition. Using the detuning scenario of Figure 1B and the Thomson-CSF 573 tetrode operating as a class AB_1 amplifier the "load line" or locus of operation was developed. This development required a number of iterations correcting for the 3/2's power law of tube current and correcting for the phase shift between plate current and grid voltage. The locus is a rotated ellipse on the tube's constant-current characteristic and is given in Figure 3.

The tube is biased at:

$$E_{bb} = 12 \text{ Kv}$$
$$E_{c2} = 1500 \text{ volts}$$
$$E_{c1} = -380 \text{ volts}$$

resulting in a quiescent plate current of 5 amperes. The operating locus is given by the parametric equation

$$e_b = 12\text{-}10 \sin wt \quad \text{Kv}$$
$$e_c = -380 + 380 \sin (wt + 35°) \quad \text{volts.}$$

The current waveform is given in Figure 4 and is compared to a sinusoid. Harmonic analysis of the current-waveform gives a fundamental component of

$$i_b = 53.7 \sin (wt + 42°) \quad \text{Amperes.}$$

and an average value of 32.7 Amperes. The load voltage is 10 sin wt in Kv. The load-impedance phase angle is 42° lead and the load power is 200 KW.

The locus was analyzed and the electrode current and dissipation calculated. The results are given in Table II and compared with the tube ratings. Table II also contains an estimate of these parameters for maximum acceleration.

	Phase Transition	Maximum Acceleration	Tube Limit
Peak Plate Current	125A	80A	400A
Average Plate Current	32.7A	24A	
Plate Dissipation	193KW	93KW	300KW
Peak Screen Current	3A	3	
Average Screen Current	.45A	.7A	
Screen Dissipation	665W	1034W	5000W
Grid Drive Voltage	380 Volts	330 Volts	
Peak Grid Current	0	0	
Grid Dissipation	0	0	2000W

Table II

Summary of Tube Operating Parameters

$$E_{bb} = 12 \text{ Kv}$$
$$E_{c2} = 1500 \text{ volts}$$
$$E_{c1} = -380 \text{ volts}$$

Thomson - CSF 573

CONSTANT-CURRENT CHARACTERISTICS
Vg2 = 1500 V

- anode current (A)
- control-grid current (A)
- screen-grid current (A)

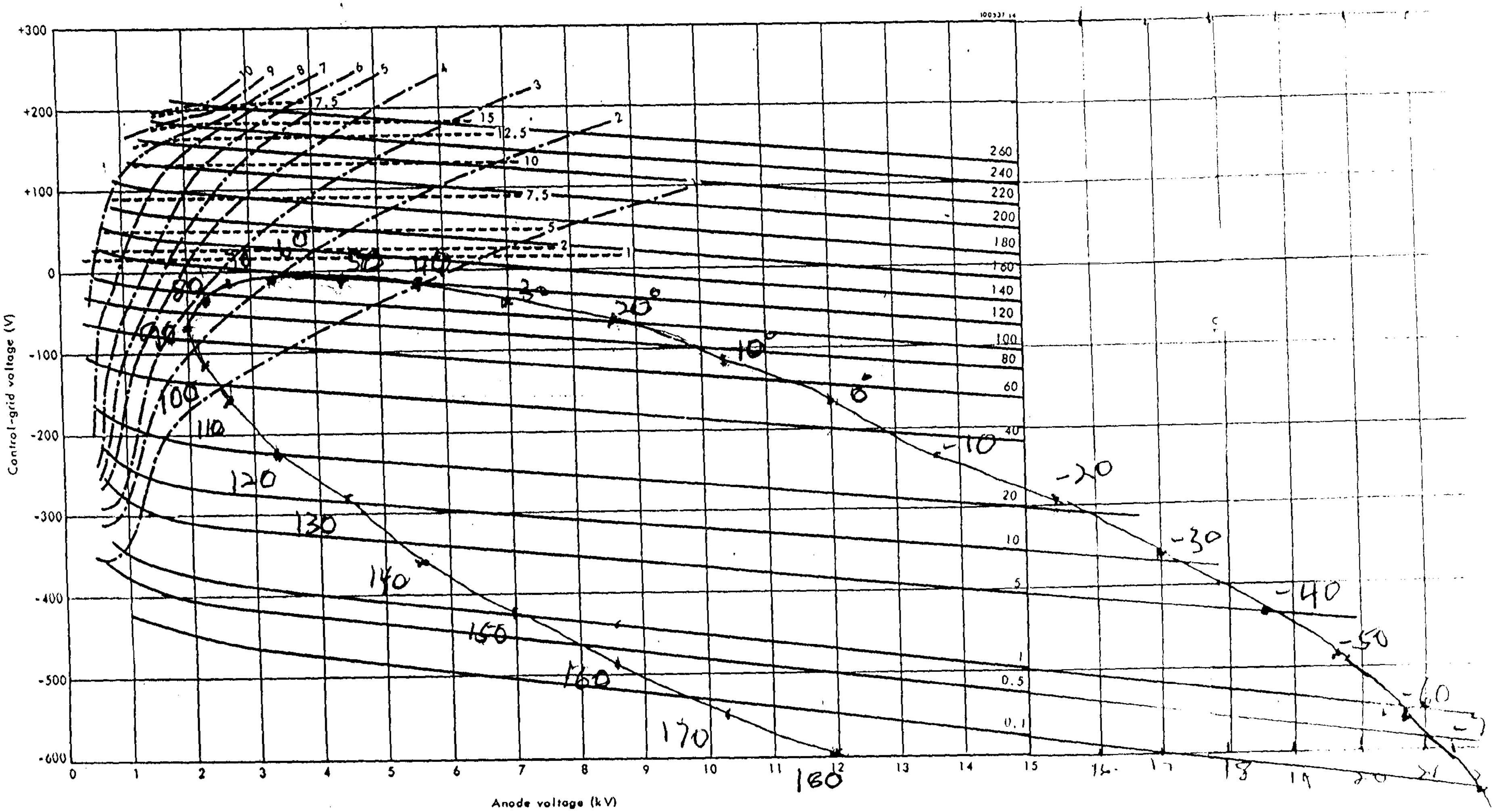


Figure 3

Phase Transition

E_{c2} = 1500 V
E_{c1} = -380 volts
Grid Drive = 380 volts

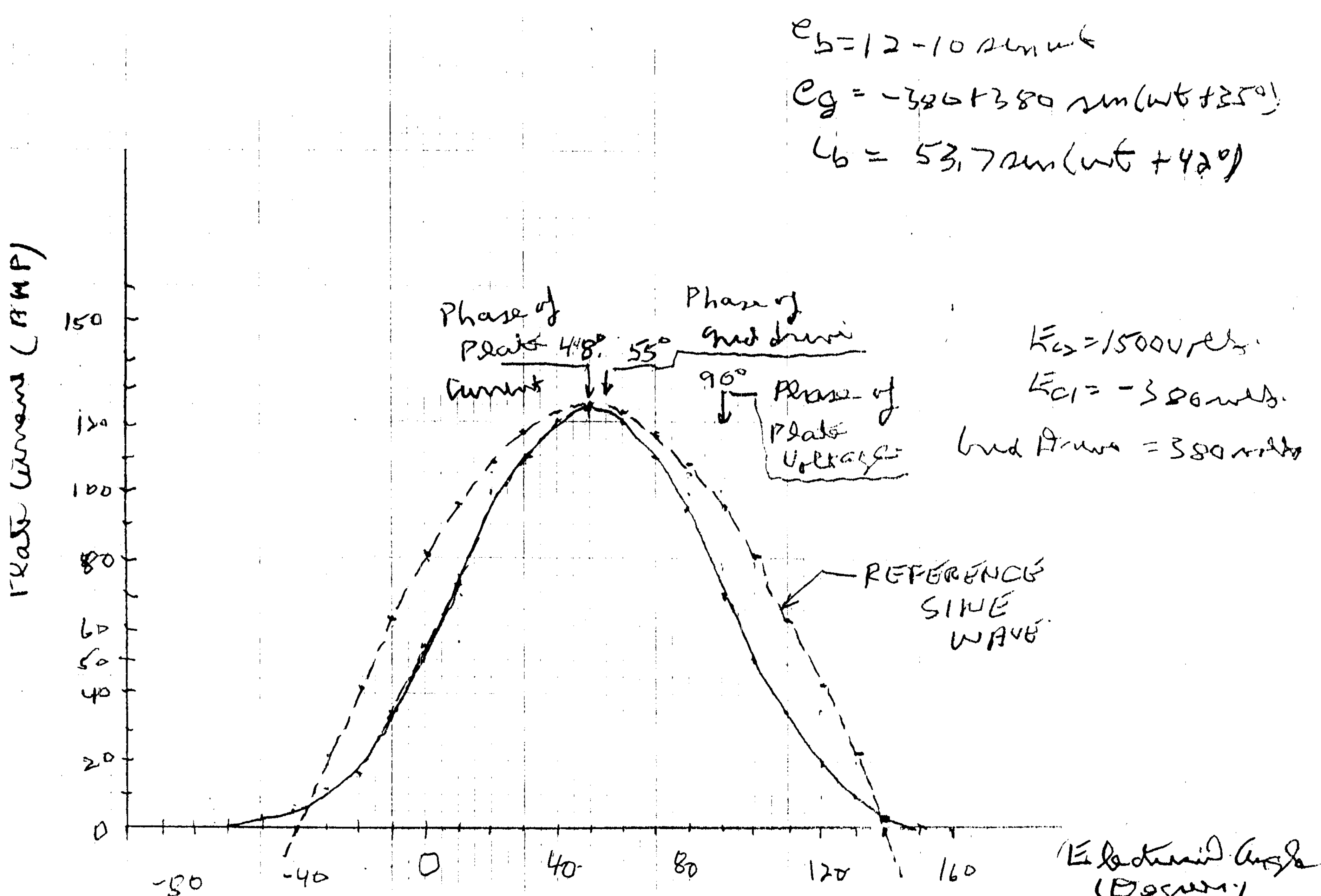


Figure 4

Tube Current at Phase Transition