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ON THE OPTIMIZATION OF $Q_{\rm ext}$ UNDER HEAVY BEAM LOADING AND IN THE PRESENCE OF MICROPHONICS

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ABSTRACT

We have derived expressions for the optimum setting of cavity parameters (loaded Q, coupling coefficient and static detuning) when operating under heavy beam loading and in the presence of microphonics. When applied to the IRFEL, we find that the optimum loaded Q for the Injector is 2×10^6. For the IRFEL linac, with 4 kW klystrons (unsaturated) and energy recovery, an optimum $Q_{\rm ext}$ of 4×10^6 allows operation at 8 MV/m in the presence of microphonics of 370 Hz p–p. For 625 μA single pass operation and the same $Q_{\rm ext}$ of 4×10^6 the maximum tolerable amount of microphonics is 180 Hz p–p. If the $Q_{\rm ext}$ is reoptimized to 6×10^6 the controllable amount of microphonics is 220 Hz p–p. We also have determined the sensitivity with respect to beam phase errors.

1. INTRODUCTION

Microphonic noise in the IRFEL cavities is expected to be of higher amplitude than in the CEBAF linac because of two reasons. Firstly because of the different requirements for the cooling of the HOM loads, and secondly because of the closer proximity of the FEL site to the CHL.

Heavy beam loading and higher microphonics, require careful optimization of the external Q of the Injector cavities. For the linac cavities, the external Q must be optimized to deal with the higher microphonics and energy recovery, as well as the 625μA single pass operation during the "First Light" stage. An additional constraint to the above optimization is that we have to use CEBAF's present rf control system and ensure reliable and robust performance.

In this note we first present the loaded Q (Q_L) optimization for the Injector cryounit. Then we present the calculations that lead to the Q_L optimization for the linac cavities, first with respect to tuning, then with respect to coupling. Finally we perform sensitivity studies to quantify the phase and beam current error margins the system can tolerate for a given amplitude of microphonic noise and klystron power.

2. INJECTOR CAVITIES

This section presents the calculation which leads to the optimization of the loaded Q of the cryounit cavities, assuming they are operated at 10 MV/m, and heavy beam loading resulting from the acceleration of 5mA, 20^0 off crest, in the presence of microphonic noise of 100 Hz amplitude.

The generator power required for acceleration of average beam current I_0, at a phase Ψ_b with respect to the rf crest, to a cavity voltage V_c, is given by [1],

$$P_g = \frac{V_c^2}{R_L}\frac{(1+\beta)}{4\beta}\left\{\left[1+\frac{I_0R_L}{V_c}\ \cos\Psi_b\right]^2+\left[\tan\Psi-\frac{I_0R_L}{V_c}\ \sin\Psi_b\right]^2\right\} \quad , \tag{1}$$

where R_L is the loaded shunt impedance defined by

$$R_L = (R/Q)Q_L \quad , \tag{2}$$

(R/Q) is 480 Ohm for CEBAF cavities, and Q_L is the loaded quality factor given by

$$Q_L = \frac{Q_0}{1+\beta} \quad . \tag{3}$$

Here β is the cavity coupling coefficient and Q_0 is the cavity intrinsic quality factor. Ψ is the tuning angle defined by

$$\tan\Psi = -2Q_L\frac{\delta f}{f_0} \tag{4}$$

where δf is the total amount of cavity detuning in Hz, including static detuning and microphonics.

If we define the parameter b as

$$b \equiv \frac{I_0\,(R/Q)\,Q_0}{V_c}\cos\Psi_b \quad , \tag{5}$$

the ratio of the power absorbed by the beam and the power dissipated in the cavity walls, then the ratio of generator power and power dissipated in the cavity walls, P_c, is rewritten as

$$\frac{P_g}{P_c} = \frac{1}{4\beta}\left\{(1+\beta+b)^2 + [(1+\beta)\tan\Psi - b\tan\Psi_b]^2\right\} \quad . \tag{6}$$

To optimize the generator power with respect to coupling we differentiate P_g with respect to β and set the derivative to zero. This gives,

$$\beta_{\text{opt}} = \sqrt{(b+1)^2 + \left[\frac{2\delta f}{\Delta f_0} + b\tan\Psi_b\right]^2} \tag{7}$$

where Δf_0 is the intrinsic bandwidth of the cavity, and the ratio of minimum generator and cavity power is

$$\frac{P_{g,\text{opt}}}{P_c} = \frac{1}{2}\left\{(b+1) + \sqrt{(b+1)^2 + \left[\frac{2\delta f}{\Delta f_0} + b\tan\Psi_b\right]^2}\right\} \quad . \tag{8}$$

For on crest operation, 5mA of beam current, 10 MV/m gradient, 100 Hz amplitude of microphonics, the optimum Q_L is 2×10^6 and the required power is 25.5 kW per cavity. For 20^0 off crest operation the optimum Q_L is 1.85×10^6 and the required power is 25.8 kW per cavity, assuming no optimization with respect to tuning. A plot of P_g (eq. (1) as function of Q_L, for 0^0 and 20^0 off crest beam phase, is shown in Fig. 1. For the IRFEL Injector cavities, beam loading and not microphonics is the major effect that determines the optimum Q_L.

3. LINAC CAVITIES

The linac cavities are expected to operate at a gradient of 8 MV/m. Power is fed in each cavity by its own 5 kW klystron, however we would like to restrict the operation of these klystrons to their linear regime which extends to 4 kW.

During energy recovery, according to the most recent bunching scenario [2], the 5 mA beam is accelerated 12.5^0 off crest, and decelerated -171.4^0 off crest when the FEL is off, resulting in a beam current vector of 340 μA magnitude and 100.55^0 phase. When the FEL is on, the phase of the decelerating beam is -170^0 and the beam vector has magnitude equal to 218 μA and phase 101.25^0.

As a consequence of the off–crest operation, the linac cavities must be detuned off–resonance by a constant detuning Δf_0, in order to minimize the generator power. We first obtain the condition for optimum tuning. It turns out that the amount of detuning *in Hz* required to minimize power is independent of coupling. Once we optimize generator power with respect to tuning, we calculate the maximum amount of microphonics the system can tolerate for a fixed (4 kW) amount of incident power, in the presence of beam loading. Next we optimize the coupling coefficient for this maximum amount of microphonics. In the zero current limit of the equations for $\beta_{\rm opt}$ and the corresponding power, we recover J. Delayen's previously derived results [3]. Finally, the optimum coupling is calculated for 625μA single pass, on crest operation.

3A. Optimization with respect to tuning for energy recovery

Let us start with the general power equation, eq. (6),

$$\frac{P_g}{P_c} = \frac{1}{4\beta}\left\{(1+\beta+b)^2 + [(1+\beta)\tan\Psi - b\tan\Psi_b]^2\right\} \quad . \tag{9}$$

The total amount of detuning, $\tan\Psi$, is given by

$$\tan\Psi = -2Q_L\frac{\delta f_0 + \delta f_m}{f_0} \tag{10}$$

where δf_0 is the static detuning and δf_m is the microphonic detuning.

The ratio of generator and cavity power is then

$$\frac{P_g}{P_c} = \frac{1}{4\beta}\left\{(1+\beta+b)^2 + \left[\frac{2\delta f_0}{\Delta f_0} + \frac{2\delta f_m}{\Delta f_0} + b\tan\Psi_b\right]^2\right\} \quad . \tag{11}$$

Minimizing the amount of generator power requires a static detuning given by

$$\delta f_0 = -\frac{\Delta f_0}{2} b\tan\Psi_b \tag{12}$$

which is independent of β, the coupling constant.

With the FEL on (I_0=218 μA, $\Psi_b = 101.25^0$) and $V_c = 4$ MV, the optimum detuning δf_0 is -19.2 Hz. With the FEL off ($I_0 = 340$ μA, $\Psi_b = 100.55^0$) the optimum detuning is -30 Hz. The ratio of generator and cavity power at optimum tuning, in the absence of microphonics, is given by

$$\frac{P_g}{P_c} = \frac{1}{4\beta}(1+\beta+b)^2 \quad . \tag{13}$$

3B. Optimization with respect to coupling for energy recovery

In the presence of microphonics of amplitude δf_m, the ratio of generator and cavity power at optimum tuning is

$$\frac{P_g}{P_c} = \frac{1}{4\beta}\left\{(1+\beta+b)^2 + \left[\frac{2\delta f_m}{\Delta f_0}\right]^2\right\} \quad . \tag{14}$$

By differentiating this expression with respect to β and setting the derivative to zero we find the condition for optimum coupling,

$$\beta_{\rm opt} = \sqrt{(b+1)^2 + \left(\frac{2\delta f_m}{\Delta f_0}\right)^2} \quad . \tag{15}$$

The ratio of minimum generator power and cavity power at $\beta_{\rm opt}$ is then given by

$$\frac{P_g}{P_c} = \frac{1}{2}\left[(b+1) + \sqrt{(b+1)^2 + \left(\frac{2\delta f_m}{\Delta f_0}\right)^2}\right] \quad . \tag{16}$$

Now if the maximum available power is 4kW, $V_c = 4$ MV, $Q_0 = 5\times10^9$, with energy recovery, the above equation gives that the maximum amplitude of microphonics the system can control is close to 185 Hz and the optimum loaded Q from eq. (15), is 4×10^6.

In the absence of beam ($b=0$) the above expressions become:

$$\beta_{\rm opt} = \sqrt{1 + \left(\frac{2\delta f_m}{\Delta f_0}\right)^2} \tag{17}$$

and

$$\frac{P_g}{P_c} = \frac{1}{2}\left[1 + \sqrt{1 + \left(\frac{2\delta f_m}{\Delta f_0}\right)^2}\right] \tag{18}$$

in agreement with J. Delayen's earlier results [3].

3C. Optimization for 625 μA single pass operation

During the first stages of the IRFEL project, single pass operation at maximum beam current of 625 μA is planned, in order to produce "first light." For these operating conditions (on crest and on resonance and heavier beam loading) we find, using eqs (15) and (16) that the maximum amount of microphonics that 4 kW klystrons can control is 110 Hz and the optimum loaded Q_L is 6×10^6. If we do not optimize Q_L for "first light" but use a value of 4×10^6 which is optimum for energy recovery, then the maximum amount of microphonics that can be controlled is 90 Hz. Stub tuners will need to be inserted in the waveguides to provide the tuning flexibility required to change Q_L from 4×10^6 to 6×10^6.

4. SENSITIVITY ANALYSIS

In the previous section we calculated that the maximum amplitude of microphonics the system can control with 4 kW klystrons is around 185 Hz. In this section we assume that the amplitude of the noise is 150 Hz and determine the magnitude of beam phase error allowed assuming the 4 kW klystrons. We have assumed that cavities are detuned by −25 Hz which may not be the optimum in all cases.

Case 1. First assume that the phase of the accelerating beam Ψ_1, has an error, but the difference between accelerating and decelerating phases remains constant, equal to its nominal value, $12.5^0 - (-170^0) = 182.5^0$. This could happen if the linac cryomodule was misphased but the path length around the recirculating arc was set properly. Figure 2 shows P_g as function of Ψ_1 for 150 Hz and 185 Hz microphonics, which demonstrates that P_g is insensitive to errors in Ψ_1, as long as $(\Psi_1 - \Psi_2)$ remains constant.

Case 2. We assume that $\Psi_1 = 12.5^0$ but Ψ_2 has an error. This could happen if the path length was set wrong. Here we found that an error of -6^0 consumes the power budget. Notice that this is true only for one sign of Ψ_2, and it is mainly due to the term in quadrature which is not entirely compensated by proper detuning. Figure 3 shows P_g as function of Ψ_2 for 150 Hz and 185 Hz microphonics.

Case 3. We took the worst case error in Ψ_2 of -6^0 and perturbed Ψ_1 by $\pm5^0$ from the 12.5^0 nominal, to see how much more power is required. This would be a case of badly phased linac and badly set up path length. We found that for $\delta\Psi_1 = 3.5^0$ and $\Psi_2 = -176^0$, one needs 500 W of extra power.

Case 4. Finally we assumed that phases are correct and varied I_0. Figure 4 shows the dependency of power on I_0 with the FEL on and off. Notice that P_g varies slowly with I_0 due again to the absence of optimization with respect to tuning.

5. CONCLUSIONS

The optimum Q_L for the IRFEL Injector cavities has been calculated to be 2×10^6. The optimum Q_L for the linac cavities has been calculated to 4×10^6 for energy recovery, and 6×10^6 for 625 μA single pass operation. The linac cavities need to be detuned by approximately -25 Hz in order to minimize power requirements during energy recovery. With the above parameters CEBAF's control system with 4 kW klystrons should be able to reliably control microphonic noise of amplitude up to 185 Hz during energy recovery and up to 110 Hz during single pass operation.

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REFERENCES

[1] Lia Merminga, RF Cavity Equations: Steady–state, CEBAF TN-95-019, July 1995.

[2] George Neil, private communication.

[3] Jean R. Delayen, Phase and Amplitude Stabilization of Superconducting Resonators, Ph.D. Thesis, 1978.

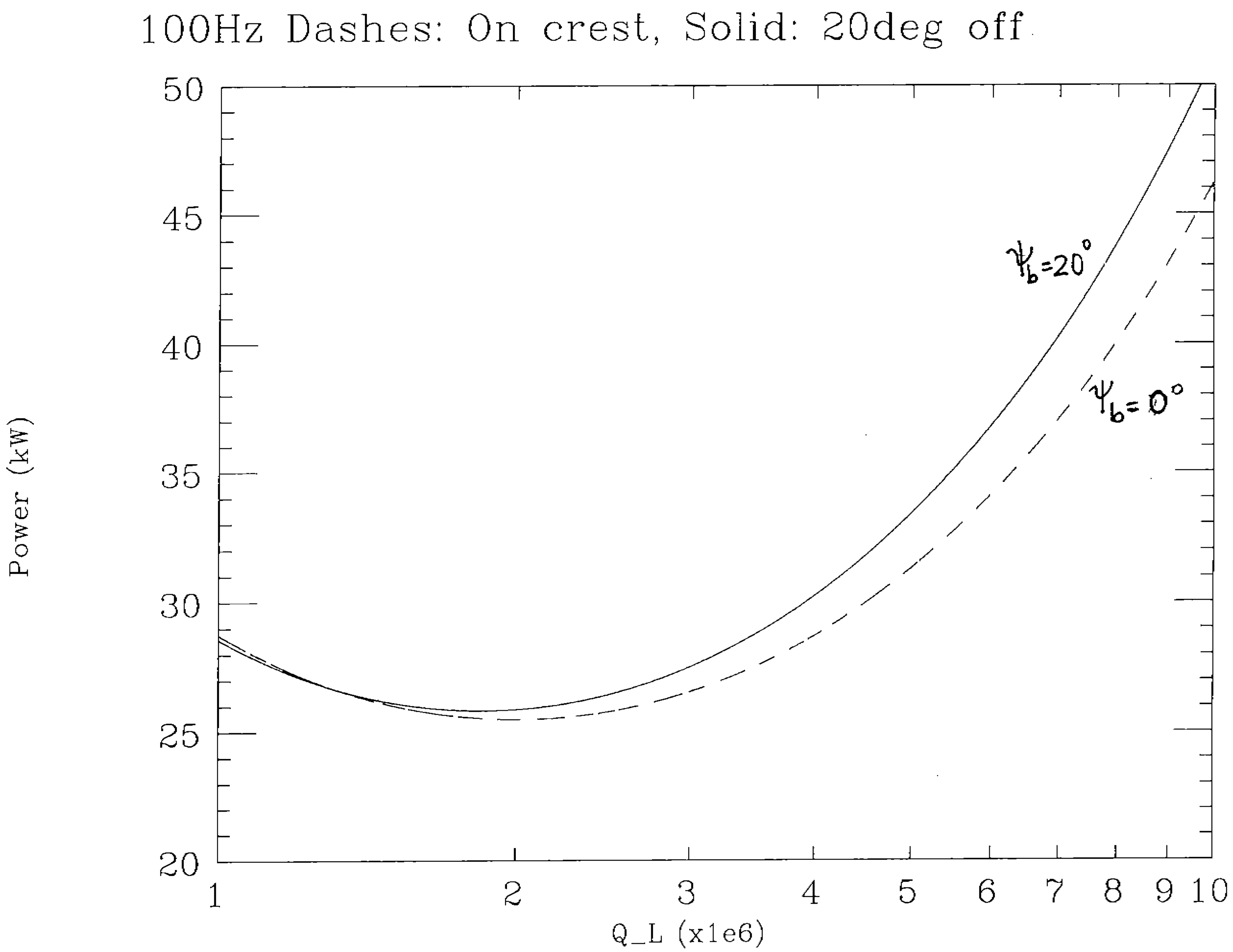
100Hz Dashes: On crest, Solid: 20deg off
Power (kW)
Q_L (x1e6)
50
45
40
35
30
25
20
1
2
3
4
5
6
7
8
9
10
$\psi_b=20^\circ$
$\psi_b=0^\circ$

Figure 1.

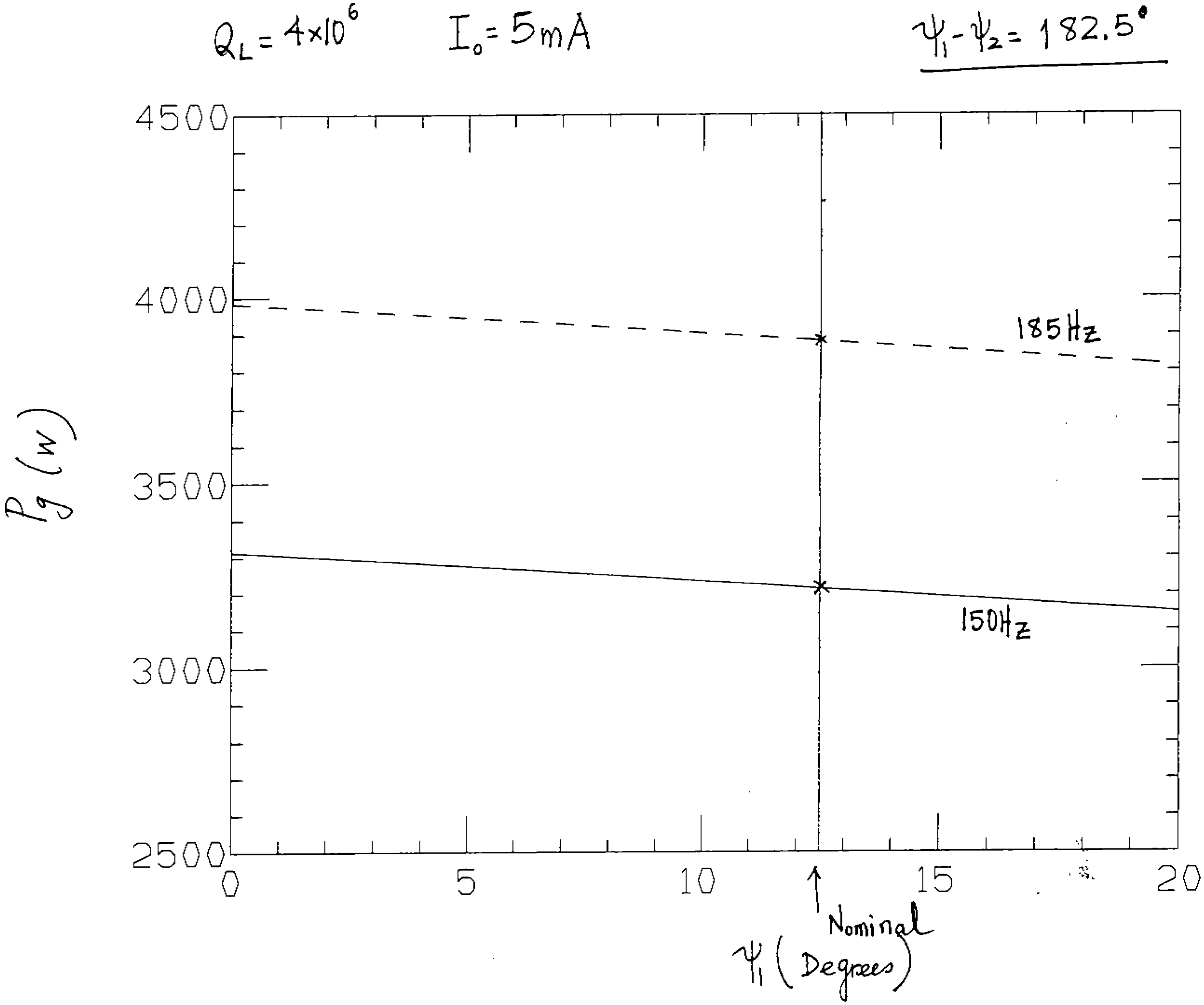

Figure 2.

p 7, top

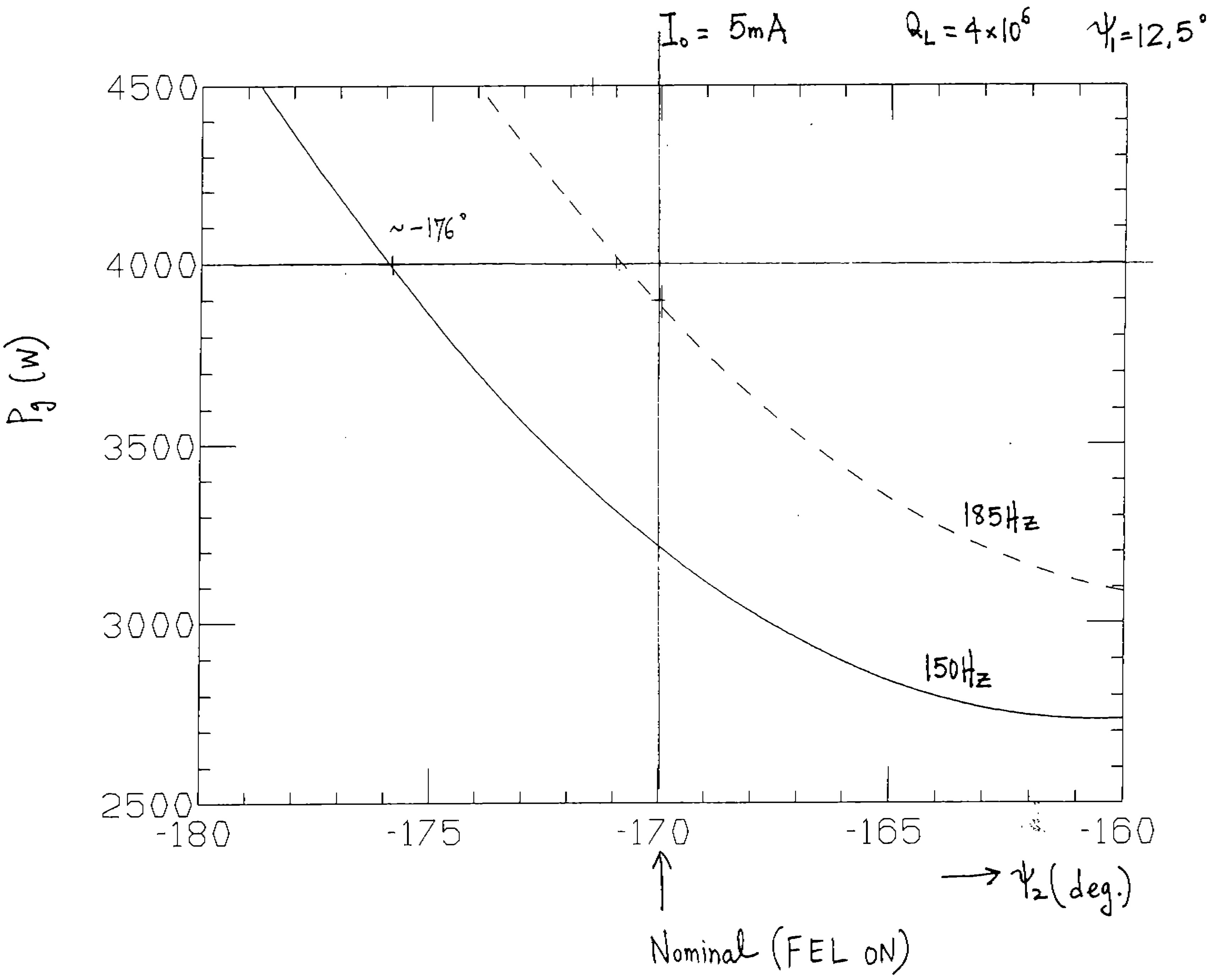

Figure 3.

p1.top

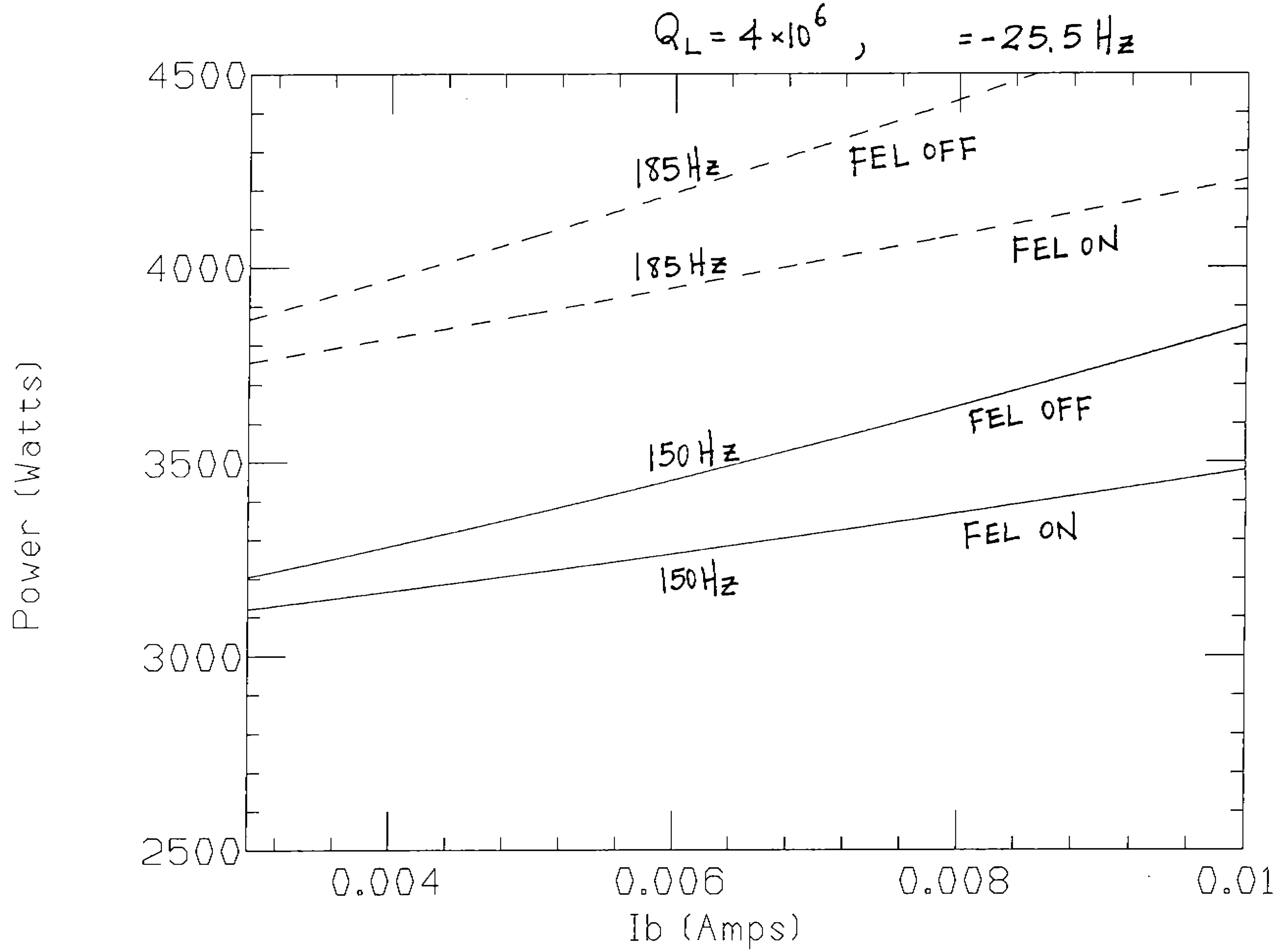

Figure 4.

f1. top