Rf Power Considerations for Beam Loading Compensation During Slip Stacking in the Main Injector

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Introduction

In order for slip stacking to be effective, the beam loading voltage in the rf cavities must be reduced to an acceptable value. The beam loading problem is severe because of the high beam current (twice the nominal Main Injector beam) and the need to use low rf voltages (around 50 kV) to slip and coalesce the two Booster batches. Transient beam loading effects are important for two reasons: there are gaps in the beam (in the simplest case two Booster batches are combined for antiproton production) and the rf beam current is modulated (at about 1 kHz) as the two beams slip past each other. The purpose of this note is to describe the requirements on the final power amplifiers used by the Main Injector rf system.

Tube Specifications

All calculations are performed using the characateristic curves shown in the Appendix. The screen voltage for these curves is fixed at 1 kV. Calculations were performed by a computer program using discrete data points obtained from the graph and by interpolation and extrapolation of the points.

Input Power Limitation

The most important limitation of the rf system is the anode power dissipation in the modulator. At injection, the tuner can withstand a maximum rf voltage of 9 kV. In order to insure that the maximum rf voltage is not exceeded, the power amplifier anode voltage is limited to 9 kV. Consequently , the modulator tube must drop the 25 kV anode power by 16 kV to achieve 9 kV at the power amplifier anode. Since the average (dc) currents in the modulator and the power amplifier are the same, the power amplifier input power is limited to 9/16 of the maximum power disipation of the modulator. For the Y-567B tubes used (for both the modulator and the power amplifier) the maximum input power to the power amplifier tube is $9/16\times150$ kW=84 kW.

It is probably worth noting that the input power limit could be increased to 150 kW if the voltage on the power amplifier were increased to 12.5 kV. However, the average power amplifier tube current (the more relevant quantity) would increase from 9.4A to 12A. If this option were used, it would be necessary to develop an alternative mechanism to avoid exceeding 9 kV of rf voltage at the tuners.

Gain linearity

We plan to use rf feedback to compensate the beam loading voltage. In order to operate a high gain feeedback system, it is important to have the gain of the rf system (and the power amplifier in particular) to be as linear as possible. This generally means that one wants to run the power amplifier at Class A (with some d.c. current in the absence of any rf drive). This mode of operation is less efficient than Class C operation (where no rf current flows in the absence of an rf signal). Since the rf beam current varies between 0 and twice the single beam current in slip stacking, it seems necessary for the power amplifier tube to operate at least a little bit into Class A and to require the power amplifier and modulator to dissipate the necessary power.

Rf Amplifier Load

The cavity is assumed to have an R/Q=62.5 Ω and a transformer (voltage step-up) ratio of 12:1. At injection the Q is about 3500 so the shunt impedance is Rs=219 KΩ. Since beam loading dominates most of the considerations, the shunt impedance of the cavity is largely irrelevant. The cavity is also assumed to be tuned to resonance although the cavity tuning is also largely irrelevant (but see discussion below).

Calculated Input Power

Figure 1 shows the required input power for an rf cavity voltage of 0.1 kV* as a function of grid bias. The different curves correspond to 3 different beam currents. The calculation is done for a full rf cycle assuming steady state conditions (beam in every bucket). An intensity of 6×10^{10} per bunch (5.04×10^{12} per Booster batch) yields an rf current of 1.02 A assuming that the rf current is twice the dc current. Two beams is a current of 2.04 A (when they are phased so that the currents add constructively). Assuming a voltage step-up ratio of 12:1, 1 A of rf beam current appears as 12 A at the power amplifier. The power requirements for a partially filled ring can be made using the appropriate beam currents with the appropriate duty factors. Some of the waviness in the curves may be caused by the difficulty of reading the graphical data accurately.

In the absence of any beam, the tube starts to conduct at a grid bias of about –300 V and has a significant conduction by the time it reaches –200 V. For the case where the beam current is non-zero, the power required is insensitive to the grid bias until about –200 V after which it increases rapidly. The result of the calculation for a rf cavity voltage of 100 kV is shown in Figure 2. The curves are quantitatively similar except that some input power is required even when there is no beam current. It would appear that it is possible to operate the power amplifier at around –200 V to maintain some tube conduction at zero beam current without too big a penalty in total power dissipation.

* This rf voltage is essentially the same as zero. It was chosen to avoid problems with some quantities that become undefined as the rf voltage approaches zero.

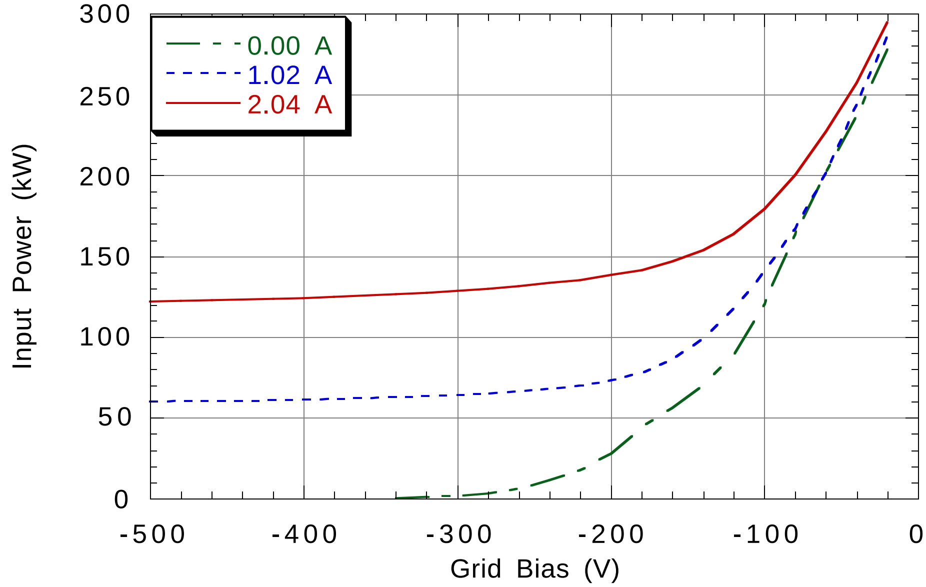

Figure 1. Input power required to generate 0.1 kV rf at the cavity gap for 3 beam currents. The cavity is not detuned.

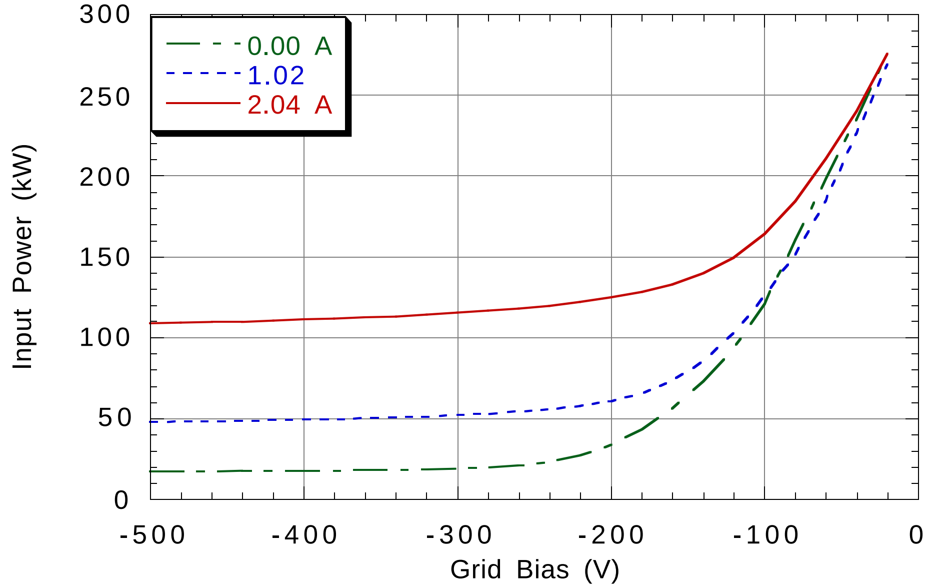

Figure 2. Input power required to generate 100 kV rf at the cavity gap for 3 beam currents. The cavity is not detuned.

Power dissipation in the grid and the screen

The power dissipated in the grid is shown in Figure 3. The grid power is minimized by operation at a grid voltage of around –120 V, but no where does it approach the maximum dissipation value of 500 W. Grid power dissipation is therefore not a concern.

The power dissipated in the screen is essentially zero except when the rf voltage causes the plate to swing towards zero voltage. For the rf voltages and beam currents considered above, the maximum screen dissipation was 500 W†, much less than the 1750 W rating of the tube. The screen dissipation can be virtually eliminated if the rf voltage is slightly reduced or if the anode voltage is slightly increased.

† This is for the case of 100 kV cavity voltage with a grid bias of –20 V. The screen dissipation decreases to about 350 W at a grid bias of –200 V.

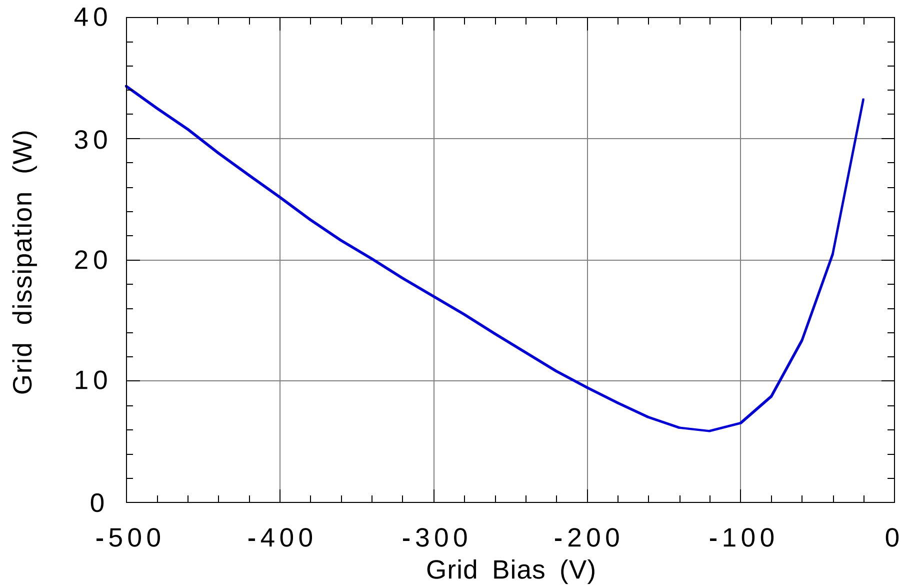

Figure 3. Grid power dissipation 100 kV cavity voltage at a beam current of 2.04 A.

Duty Factor Considerations

When slip stacking a single batch, the beam current is present at the rf cavities 1/7 of the time each revolution period. Neglecting the effect of transients, the power dissipation is approximately 1/7 of the power with beam current plus 6/7 times the power with no beam current. For the grid bias of -200 V, the power dissipation would be 34 kW for an rf beam current of 1.02 A and 44 kW for the rf beam current of 2.04 A. These values appear to be well within the power rating of the tube.

Slip stacking a full ring is more demanding since it requires a peak value of 138.2 kW. However, the rf current is only briefly at its peak value. The rf current varies between 0 and 2.04 A according to $1-\cos(2\pi ft)$, where f=1.2 kHz. The average power required is approximately the same as for a steady current of 1.02 A beam current, namely 73 kW. At the completion of the slipping process, the beams are combined and the full beam current of 2.04 A will require compensation. However, at this point, the rf voltage can be raised rapidly and the power requirements can be reduced by detuning the cavities.

Gain

The tube gain is shown in Figure 4. The gain is defined as the change in output voltage (kV) per change in drive voltage (V). The curve is somewhat noisy because of the difficulty of taking derivatives of numerically. In particular, the curves used are continuous, but derivatives (like the gain) are not required to be continuous. Nonetheless, it appears that the gain will be constant to within about ±50% if the tube is operated at a bias of −200 V.

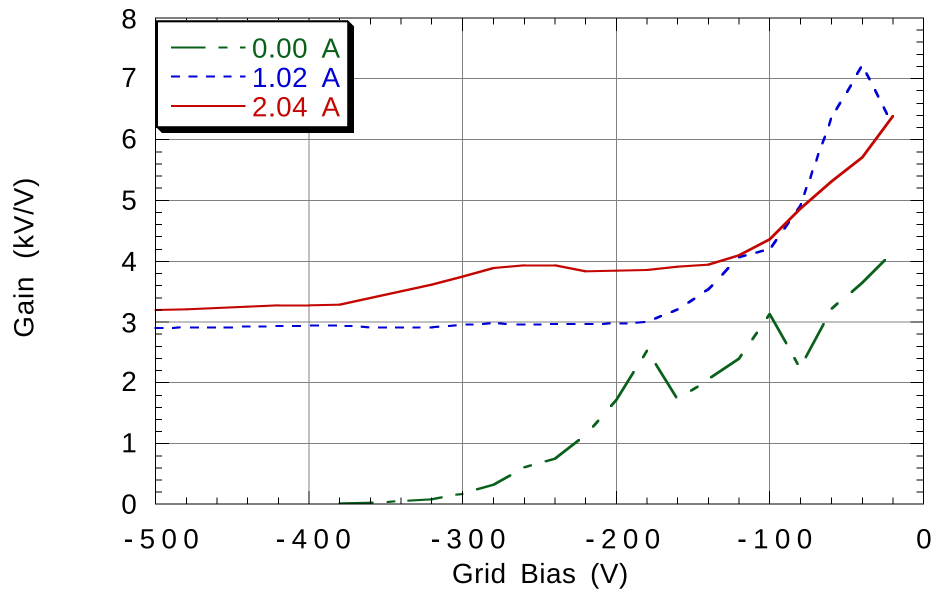

Figure 4. Tube gain as a function of grid bias for various beam loading currents.

Matching by Cavity Detuning

The large power dissipation is a result of the mismatch of the cavity to the load. If the rf current were constant the load could be better matched to the amplifier by detuning the cavity. If the generator current is in phase with the cavity voltage and if the beam is not being accelerated, the power required for a given rf voltage would be independent of the beam current.

However, practical considerations limit our ability to match to the beam load. To achieve 2 kV at the cavity the cavity must be detuned by 89.7°. This detuning angle corresponds to a change is resonant frequency of 2.6 MHz. This detuning is well beyond the range of the cavity tuner (a maximum of about 0.6 MHz including 0.3 MHz needed for acceleration) and furthermore could not be achieved with sufficient accuracy (with the current tuning loop) to permit a good match.

A more fundamental limitation arises from the beam transients. Cavity detuning can be used to match to some level of beam current–perhaps the average current –but the power amplifier has to accomodate the flucuations. At best, we could hope to reduce the current requirements by 50%.

Detuned Cavity

As an example of how the Main Injector system would operate with a detuned cavity consider the case of 100 kV per cavity with a synchronous phase angle of 20°. These parameters roughly approximate tube operation at the beginning of acceleration. The input power calculations are shown in Figure 5 assuming an anode voltage of 9 kV. The beam loading (for acceleration) is about 17 kW/A.

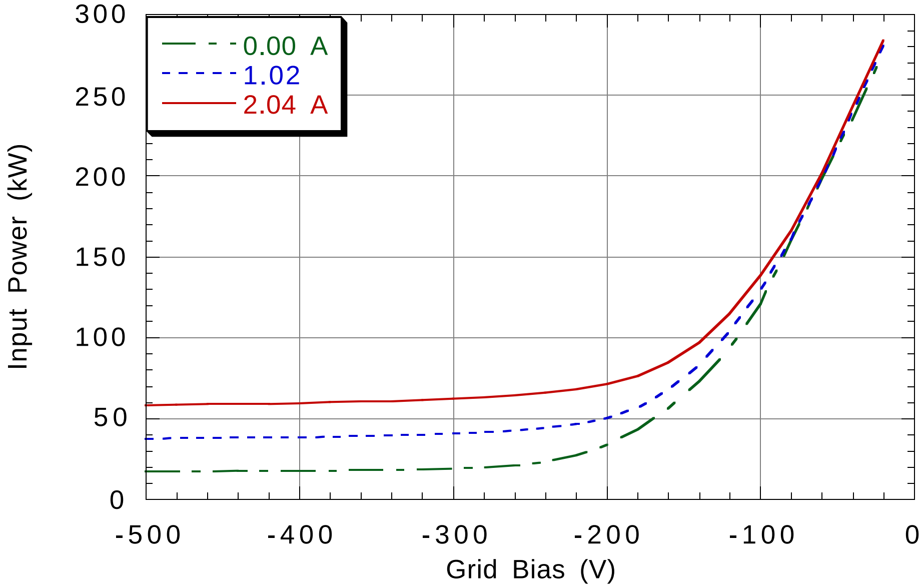

Figure 5. Input power required to generate 100 kV rf at the cavity gap for 3 beam currents at a synchronous phase of 20°. For 0, 1.02, and 2.04 A of rf beam current the cavity is detuned by 0, 73° and 81°, respectively.

Stability Issues

The rf system is heavily beam loaded and is susceptible to high current Robinson Instabilities if the cavities are even slightly detuned (by less than 0.5˚ for 2 kV per cavity). The intensity independent Robinson instability, however, requires some detuning of the cavities (in the absence of feedback). We hope to be able to operate the rf cavities with some detuning to provide damping of the intensity independent Robinson instability. One of the goals of the beam loading compensation systems will be to increase the threshhold of the high current Robinson instability. The beam compensation system will have to provide most of the rf current required to cancel the beam current so that the generator current (that part that is independent of the beam current) can provide the necessary phase focussing. Some of the formulas relevant to these instabilities are given in the appendix.

Conclusion

The rf system planned for the Main Injector appears to be capable of handling slip stacking for a single batch. Slip stacking the full ring may be within the power capabilities of the tube, but it certainly approaches the limit. However, slip stacking the full ring will certainly not be required (or desired) in the early part of Run II.

APPENDIX

Graphical Data

Figure 6 is the digitized graph of the power tube characteristics referred to and used for the calculations described in the main text.

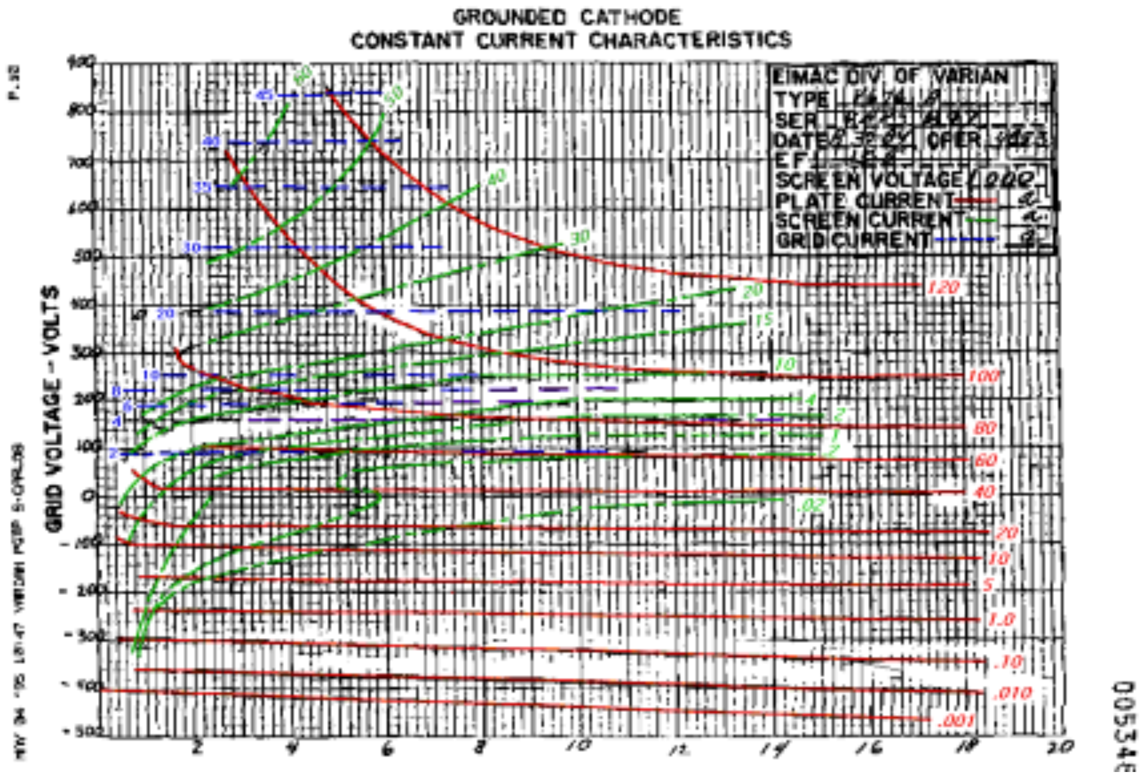

Figure 6. Power tube characteristic curves. The graph was obtained by scanning a poor quality photocopy and "colorizing" the curves for clarity.

Stability Criteria

The Robinson stability criteria apply to rf systems in the absence of feedback loops. The current independent criteria is that the detuning angle be positive, namely

$$\phi_d > 0$$

The detuning angle can be defined in terms of the cavity impedance

$$Z(\omega_{rf}) = R_s \cos\phi_d e^{-i\phi_d}$$

where $Z(\omega_{rf})$ is the cavity impedance at the rf frequency and R_s is the shunt impedance. The high current criterion is that the detuning be smaller than

$$\sin 2\phi_d < 2\left|\frac{V_{rf}}{i_b R}\right| \cos\phi_s$$

where V_{rf} is the rf voltage, i_b is the beam current, and ϕ_s is the beam loading angle (0 if there is no acceleration). At low rf voltages and high beam currents the amount of detuning is severely limited in the absence of beam loading compensation.