THE NSNS RF SYSTEM

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Introduction

The National Spallation Neutron Source includes an accumulator ring with a circumference of $C = 220.7$m that is designed to accumulate 2×10^{14}, 1 GeV kinetic energy protons, via charge exchange injection of H^-, in 1 ms. After the beam is accumulated it will be extracted in one turn using a kicker magnet. A 280ns gap is required to allow for the kicker rise time and the NSNS base line design calls for a radio frequency (rf) system to maintain the gap. Previous work [1] has established that a dual harmonic rf system with $h = 1$ and $h = 2$ has significant advantages over a single frequency system. A barrier bucket rf system is even better but there are unresolved issues, such as beam loading, which require more R&D. Therefore, the base design for the NSNS rf system is a dual harmonic system running with $h = 1$ and $h = 2$. The possibility of upgrading to a barrier cavity system is considered

1 Beam Dynamics Considerations

The change in the NSNS lattice design [2] had a marginal, beneficial impact on the rf parameters. The base design has a rf amplitude of 40 kV at $h = 1$ and 20 kV at $h = 2$ with the voltages phased so that the small amplitude synchrotron frequency vanishes. The relevant parameters are summarized in Table 1. Along with the zero current calculations, longitudinal dynamics simulations have been done. The code assumes perfect rf feedback so that the net cavity voltage and phase remain ideal. Standard algorithms were used for everything but the impedance related forces which were handled using a particle-particle algorithm. In this part of the algorithm the impedance induced voltage is of the form $V(t) = -RI(t) + (Z_{sc}/\omega_0)dI/dt$ where ω_0 is the angular revolution frequency of an ideal particle and the beam current is given by

$$I(t) = \sum_{k=1}^{N_p} \frac{Q}{\tau_p}(1 + 4|t - t_k|/\tau_p)\exp(-4|t - t_k|/\tau_p), \qquad (1)$$

where N_p is the number of macro-particles, t_k is the arrival time of the kth macro particle, Q is the charge of a macro particle, and τ_p is the equivalent duration of a macro-particle. Figure 1 shows the simulation results.

parameter	symbol and value
General parameters	
circumference	$C = 220.668$ m
transition energy	$\gamma_T = 4.933$
h=1 voltage	$V_1 = 40$ kV per turn
h=2 voltage	$V_2 = 20$ kV per turn
space charge	$Z_{sc} = i120\Omega$ at $h = 1$
wall resistance	$R = 20\Omega$
proton energy	1 GeV kinetic
bunch length	561 ns
gap length	280 ns
protons at extraction time	2.08×10^{14}
Zero current parameters	
bucket area	$A_{max} = 17$ eV − sec
bunch area	$A_b = 10$ eV − sec
Simulation parameters	
input	
LINAC energy spread	$\Delta E_L = 5.6$ MeV half width at base
chopped bunch length	$\tau_c = 480$ ns
macro-particle length	$\tau_p = 50$ ns equivalent length
macro-particles added per turn	10
number of turns	1280
output	
peak beam current	$I_{peak} = 88$ Amps
bunching factor	$I_{avg}/I_{peak} = 0.45$
gap length	$\tau_g = 280$ ns
energy spread in ring	$\Delta E = 9.4$ MeV half width at base

Table 1: Beam Dynamics Parameter List for 2 MW

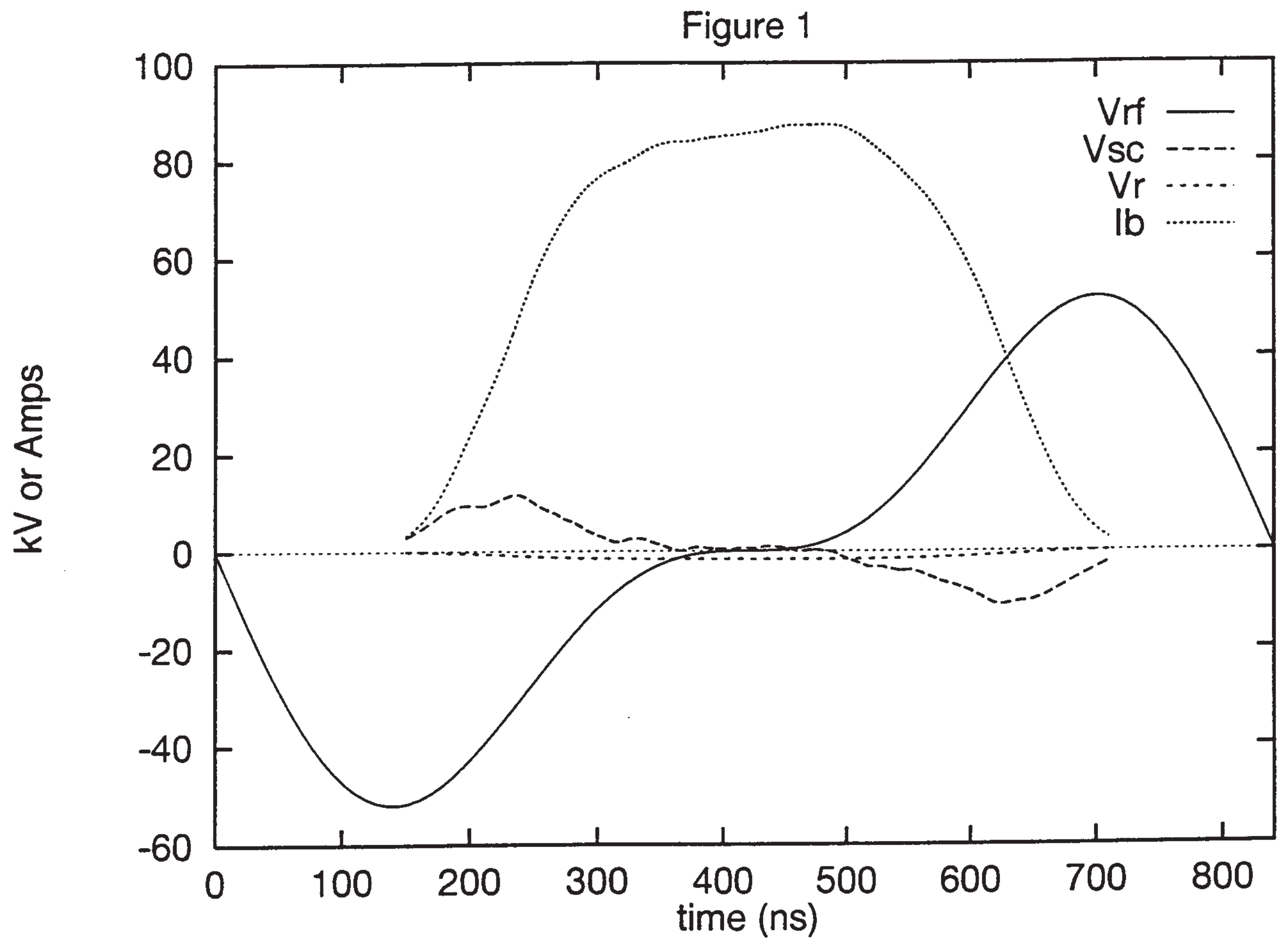

Figure 1: Simulation results: Rf voltage (Vrf), space charge induced voltage (Vsc), wall resistance induced voltage (Vr), and beam current (Ib)

2 Cavity Design

The harmonic numbers of one and two imply cavity frequencies of 1.26 MHz and 2.52 MHz. A variability of ±5% will be built into the cavities to accommodate changes in beam energy. This would be a slow mechanical adjustment, probably turning a knob on a variable capacitor, and would be very infrequent.

The AGS cavities and the AGS Booster Band III cavities are essentially prototypes of what we need here. They operate in the same frequency range and have the same voltage capability. The beam current is a factor of ten higher in the NSNS than in the AGS Booster, but on the other hand all the beam loading is reactive in the NSNS since the beam is not accelerated. The implication is that we can virtually copy the design of the AGS cavities [3]. However, the Booster Band III ferrite (Philips 4M2) will be used. Very little R& D is required here.

The gap voltage in the Booster Band III is 22.5 kV while it is 10 kV in the AGS. However there are four gaps in an AGS cavity while the Band III cavity has two. Both cavities fit in a 10 foot straight section. For the NSNS, $h = 1$ system we expect to use three cavities, with two gaps per cavity and 6.7 kV per gap. There will be one power amplifier per cavity to compensate the heavy beam loading. The NSNS voltage per gap is lower than either the AGS or the AGS Booster, since the heavy beam loading leads to a large generator current and the average power is very large. The NSNS $h = 2$ rf system will consist of one cavity with two gaps at 10 kV per gap, driven by a single power amplifier.

3 Design of the Power Amplifier

The design of the power amplifier is driven by beam loading requirements. From Fourier analysis of Figure 1 the beam current is given by

$$I_b(t) \approx \bar{I}_b(t)\,[1 + a_1 \cos(\omega_0 t) + a_2 \cos(2\omega_0 t)] \tag{2}$$

where $a_1 = 1.3$, $a_2 = .1$, and $\bar{I}_b(t) = 40t$ Amp ms^{-1}. To minimize the number of active components the cavity resonant frequency ω_r is assumed fixed throughout the cycle. Dynamic tuning of the cavity is also possible, and will be considered later.

The harmonic amplitudes of the beam current rise from zero to $a_1\bar{I}_{max} = 52$ Amps and $a_2\bar{I}_{max} = 4$ Amps for harmonics 1 and 2, respectively. The base line design requires the power amplifier to fully compensate these currents while providing the necessary quadrature component to drive the gap voltage. In some sense this may be pessimistic but the consequences of this assumption to the overall system cost are not great, whereas the benefits for system performance and reliability are very valuable.

Figure 2 shows the equivalent circuit of the cavity, beam, power amplifier, and bias supply. In the limit that the blocking capacitor and the inductance of the plate choke are very large, the gap voltage ($V_g(t)$) and anode voltage ($V_a(t)$) are related via $V_g(t) = V_a(t) - V_p$ where V_p is the constant voltage due to the plate supply. In the same approximation the current supplied by the power amplifier, which generates the voltage across the gap is $I_g(t) = -I_a(t) + I_p$, where I_p is current flowing through the plate supply. With this approximation the gap voltage, grid drive voltage $V_d(t)$, and the generator current are related via $I_g(t) = -I_a(V_g(t) + V_p, V_d(t)) + I_p$. The relationship $I_a = I_a(V_a, V_d)$ is usually expressed graphically as constant current characteristics, which are supplied by the manufacturer.

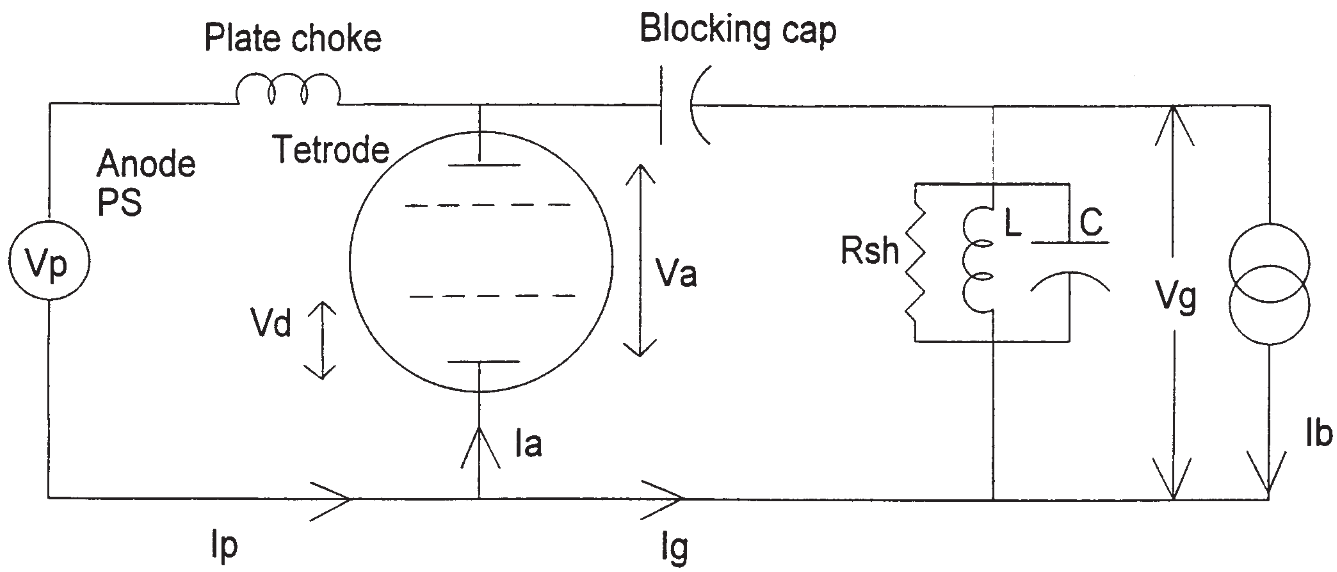

Figure 2: equivalent circuit made by beam cavity and power amplifier

For a power amplifier supplying n_g accelerating gaps in parallel, the voltage across a single gap is given by

$$V_g(t) = \int_0^\infty W(\tau)(I_b(t-\tau) + I_g(t-\tau)/n_g)d\tau, \tag{3}$$

where $W(\tau)$ is the wake potential of the unloaded cavity and it is assumed that the ferrite is not saturated. The wake potential is related to the cavity impedance via

$$W(\tau) = \frac{1}{2\pi}\int d\omega Z(\omega)e^{-i\omega\tau}. \tag{4}$$

For a single resonance the impedance is

$$Z(\omega) = \frac{R_{sh}}{1 + iQ(\omega_r/\omega - \omega/\omega_r)} \tag{5}$$

where R_{sh} is the shunt impedance per gap of the unloaded cavity, ω_r is its resonant frequency and Q is the unloaded quality factor.

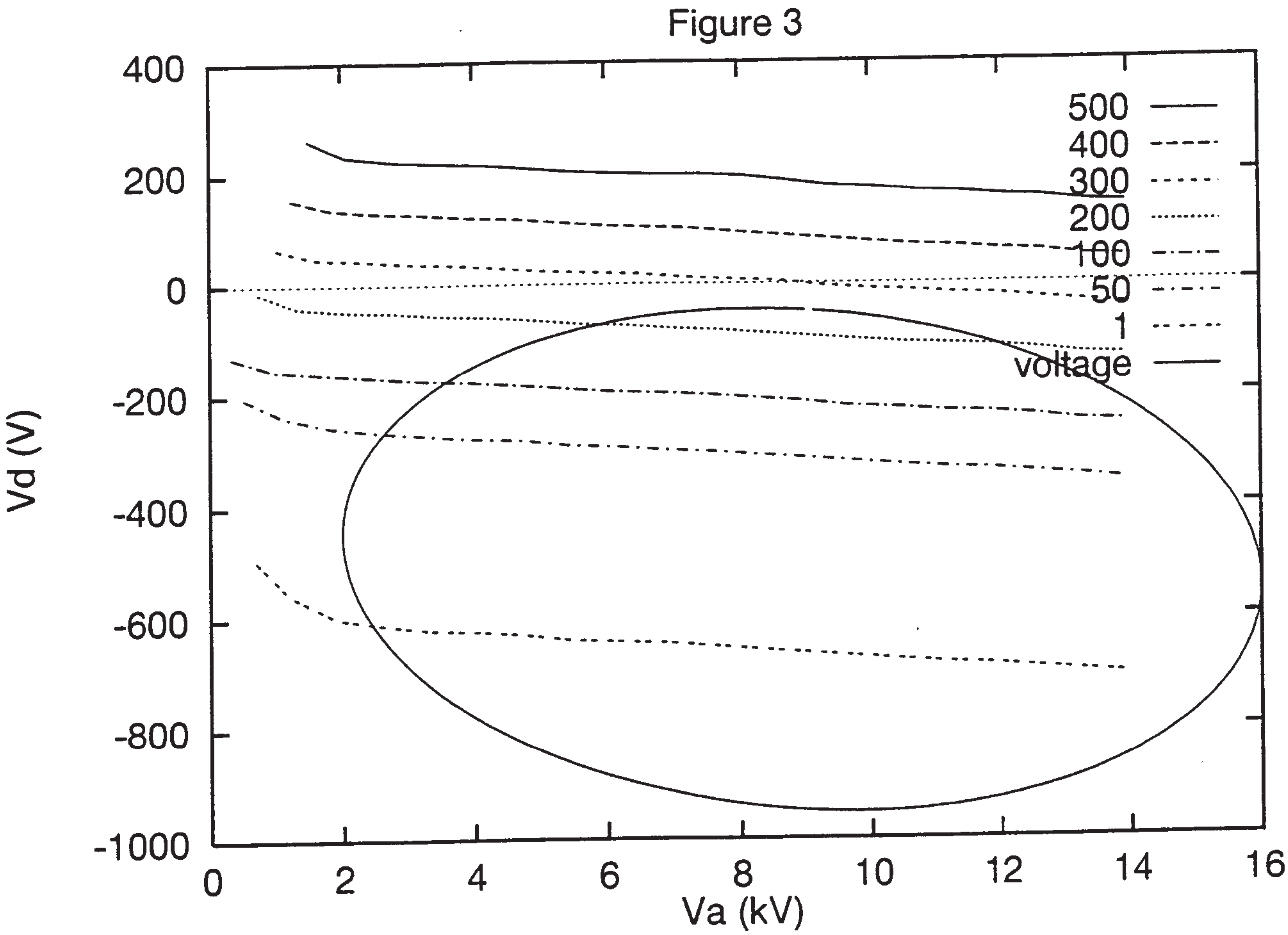

Figure 3: Current characteristics of TH558 and load line for $h = 1$

The control grid of the amplifier will be driven by a voltage of the form $V_d(t) = \bar{V}_d + \Delta V_d \sin(\omega t + \phi_d)$. The anode voltage is given by $V_a(t) = \bar{V}_a + \Delta V_a \sin(\omega t)$ where $\Delta V_a = V_g$ for direct coupling. By plotting these parametric equations on a graph of the tube characteristics one obtains the anode current $I_a(t, \bar{V}_d, \Delta V_d, \phi_d, \bar{V}_a, \Delta V_a)$. Assume $\omega = \omega_r$ so that the net current through the cavity is in phase with the voltage across the cavity. For the tube to fully compensate the beam current one must have $I_a(t) = \bar{I}_a - a\bar{I}\cos(\omega t) + I_0 \sin(\omega t) +$ higher harmonics, where $-a\bar{I}$ compensates the beam current and I_0 drives the cavity. For the $\omega = \omega_r$ case $I_0 = \Delta V_a / R_{sh}$ where R_{sh} is the shunt impedance of the cavity alone, which is dominated by losses in the ferrite. The problem is to find $\bar{V}_d, \Delta V_d, \phi_d$ and $\bar{V}_a$ so that the tube current has the required form. If we take $R_{sh} = 10\text{k}\Omega$, then $I_0 = 1$ Amp, which is irrelevant compared to $a_1\bar{I} = 52$ Amp. For $n_g = 2$ we have 104 Amp for the peak harmonic amplitude of the power amplifier current at $h = 1$.

Figure 3 shows constant current characteristics for a Thompson (TH558) tetrode amplifier along with an anode voltage of $V_a(\omega t) = 9\text{kV} + 7\text{kV}\sin(\omega t)$ and a grid drive voltage of $V_d(\omega t) = -500 + 450\cos(\omega t) - 53\sin(\omega t)$ Volts. The constant current characteristics are for a screen grid voltage of 2kV. The manufacturers data goes to an anode voltage of $V_a = 14$kV, these were extended to 16kV by fitting straight lines to the current charateristics in the region $3\text{kV} < V_a < 14\text{kV}$ and extrapolating

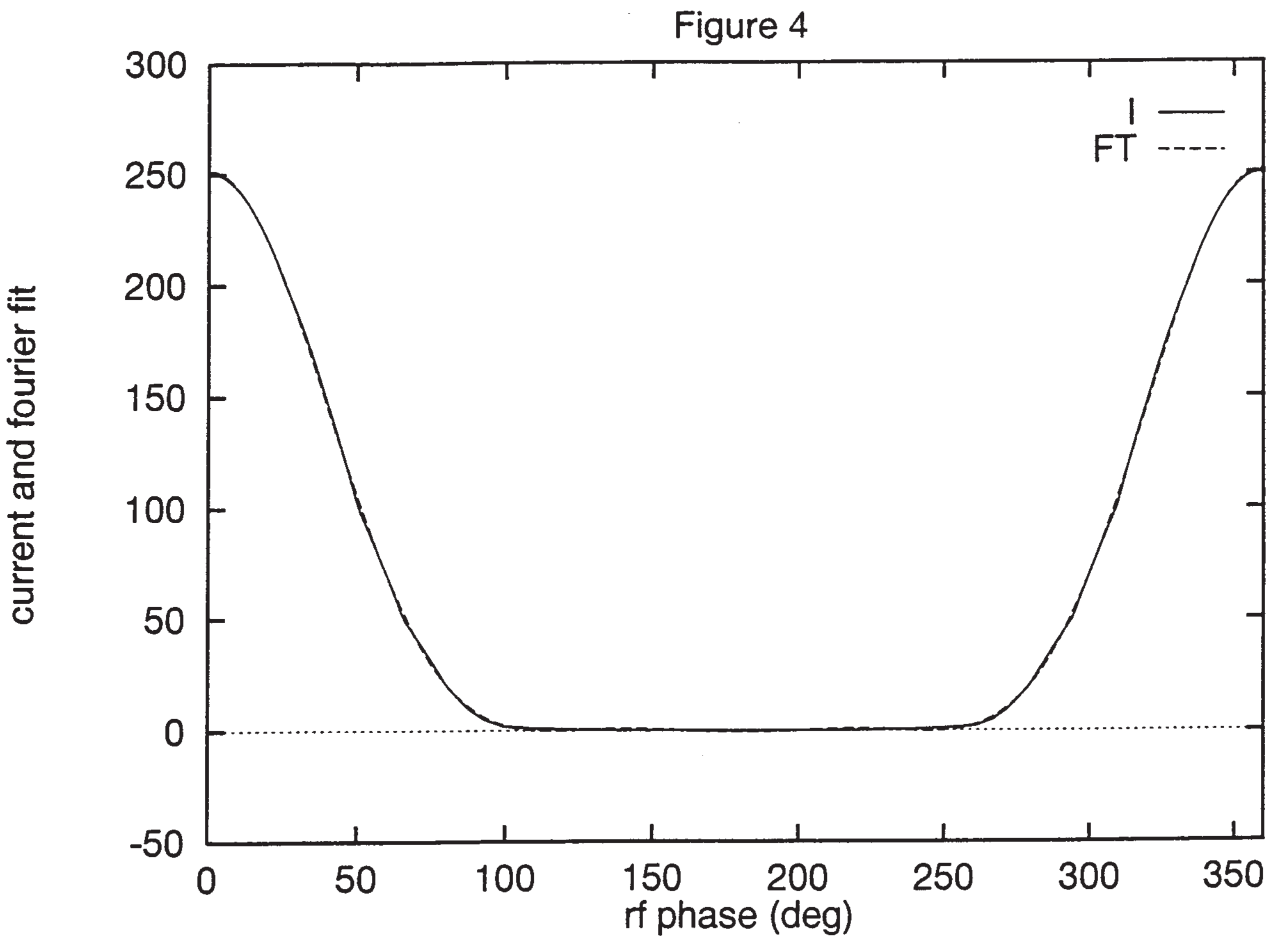

Figure 4: Anode current (I), and its Fourier reconstruction with $h = 0, 1, 2, 3, 4$ (Ft).

with the lines. It is worth mentioning that all the constant current lines were of the form

$$V_a/1000 + (0.132 \pm 0.002)V_d = \text{constant},$$

where there was no significant trend in the errors. Therefore, the anode current in the region of interest was assumed to satisfy $I_a = I_a(V_a/1000 + 0.132V_d)$, which reduced the dimensionality of the problem and made programming much easier.

The resulting current pulse and its Fourier series using dc through fourth harmonic are shown in Figure 4. The Fourier amplitude of the $h = 1$ harmonic is 107 Amps, and the average power dissipated over an rf cycle in the tetrode is $< I_a V_a >= 585$ kW. The TH558 tetrode is rated at 600 kW so with six gaps at $h = 1$ it is possible to compensate the beam loading while supplying the necessary voltage and never exceeding the manufacturer's specifications. Since the rf will operate for ~ 2 ms of the 16.7 ms NSNS cycle, the peak power the tube can supply will be larger than the manufacturers specification, but running the system in this way will stress the tube leading to a shorter operating life.

For $h = 2$ we will run both gaps with an rf amplitude of 10 kV. Using $a_2 = 0.1$ and compensating the beam current leads to a power dissipation $< I_a V_a > \approx V_p n_g a_2 \bar{I} = 104$ kW, which is small compared to the 600 kW rating of the tube.

4 Dynamic tuning of the cavity resonant frequency

Optimal tuning of the cavity resonant frequency reduces the required tetrode current. Consider a steady state, with no coherent oscillations and only a single harmonic component. The voltage across the gap $V_g(t) = \hat{V}_g \exp(ih\omega_0 t)$ is related to the beam current $I_b(t) = \hat{I}_b \exp(ih\omega_0 t)$ and the generator current $I_g(t) = \hat{I}_g \exp(ih\omega_0 t)$ via $\hat{V}_g = Z_c(\hat{I}_b + \hat{I}_g)$ where Z_c is the impedance of the cavity and all numbers are complex. Assume negligible synchronous phase and take $\hat{V}_g$ to be purely real. Then, $\hat{I}_b$ is pure imaginary. By optimal tuning of the cavity resonant frequency, via biasing the ferrite, one can change the phase of Z_c and minimize $|I_g|$, [4]. For optimal conditions $I_g = V_g/R_{sh}$ where R_{sh} is the cavity shunt impedance. At first glance this seems to imply that an rf system supplying ~ 1 kW would be sufficient to power the NSNS but requiring the system to be stable to pertubations changes the picture [4]. There are also complications owing to the fact that the permeability of the ferrite rings in the accelerating cavity are difficult to change on a ~ 1 ms time scale.

Ignore the variation in the total beam current for the moment. Even in this case determining the stability of a dual harmonic rf system is a complicated matter [6] and we will not attempt to address this problem here. For a rule of thumb consider the relative beam loading parameter $Y = I_b R_\ell / V_g$, where R_ℓ is the shunt impedance of the cavity and amplifier tetrode taken in parallel. We will consider only the $h = 1$ system.

The quantity R_ℓ depends on both the amplifier tetrode and the beam current. Using the load line shown in Figure 3 we calculate the admittance of the power amplifier as a function of rf phase. The resulting plot of

$$\frac{dI_a}{dV_a} \equiv \left. \frac{\partial I_a(V_a, V_d)}{\partial V_a} \right|_{V_d}$$

for this load line is shown in Figure 5. The average value of the admittance is 0.00266mho and corresponds to a resistance of $R_g = 375\Omega$. Since the tetrode drives $n_g = 2$ gaps, the resistance in parallel with a single gap is $n_g R_g = 750\Omega$. The cavity shunt impedance is of order 10 kΩ so $R_\ell \approx R_g$, at least at extraction time. Hence, the beam loading parameter for the uncompensated cavity is $Y = I_b n_g R_g / V_g = 5.6$.

For a dynamically tuned cavity the anode current is reduced and R_g increases, leading to an increase in Y. In principle this is not a show stopper since the actual stability criteria is given by Robinson's criteria $0 \leq \sin(2\phi_z) \leq 2/Y$. The detuning angle ϕ_z is given by

$$\phi_z = \tan^{-1}\left[Q\left(\frac{\omega_r}{h\omega_0} - \frac{h\omega_0}{\omega_r}\right)\right],$$

where ω_r and Q are the resonant frequency and quality factor of the cavity and amplifier tetrode in parallel. Note that $\phi_z \equiv 0$ in the base design. In a design employing cavity compensation ϕ_z would vary smoothly from 0 to $\approx \pi/2$ as the proton beam accumulated. The engineering difficulty comes from varying ϕ_z smoothly. The change in ϕ_z is brought about by creating a dc magnetic field in the ferrite rings of the accelerating cavities, thus changing their permeability μ. However, the μ of a ferrite depends on its past history and there is a time delay between changing the bias field and changing μ. Therefore, it seems unlikely that a closed loop tuning system will be possible for the NSNS. It might be possible to vary the ferrite permeability in a repeatable way every cycle which would compensate the cavity. If this is pursued then the cycle to cycle variability of *e.g.* the harmonic amplitudes due to the beam, will decide the power requirements for the rf system. The role of dynamic tuning on

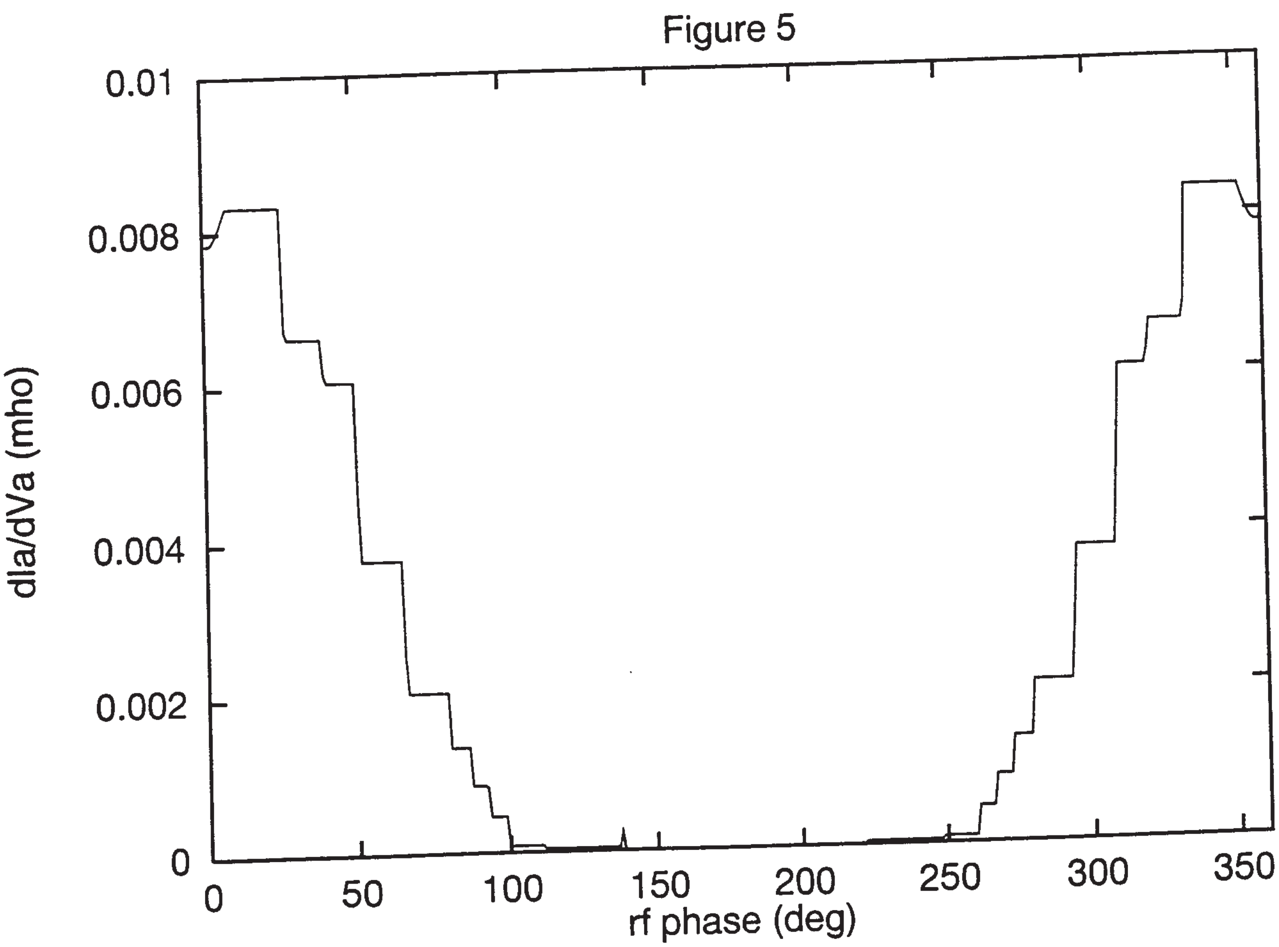

Figure 5: Admittance of the amplifier tetrode for the load line in Figure 3.

this time scale is a fertile are of R & D. Since the success of that R& D cannot be guaranteed the present design is not contingent on dynamic tuning. Also, if a smaller tetrode was used Y would be significantly larger. Experience and numerical analysis [7] has shown that stability of the complete rf system, including beam control and tuning loops could be compromised if $Y > 1$, where the value of R_ℓ includes the effects of the loops. In principle the system could be made stable with enough feedback but conservative engineering dictates the more robust design.

5 Rf feedback

The beamloading parameter defined in the previous section did not include the effect of rf feedback. When feedback is included the effective resistance of the cavity and power amplifier (R_ℓ) is reduced. The normal beam control feedback loops, such as a phase loop and automatic level control, will operate on the low level drive signal that is applied to the cavity power amplifiers (V_d). These loops are necessary at any beam intensity and do not address the beam loading problem since they do not fundamentally alter the cavity response to the beam current. In order to avoid the high current Robinson instability the effective R_ℓ must be reduced. The options are; direct rf feedback, one-turn-delay feedback, and feedforward beam current cancellation. There are pros and cons for each technique [8].

Although direct rf feedback is the most powerful technique it is not the best choice here. The main disadvantage being that a high power driver stage must be installed in the tunnel with very close proximity to the cavity and power amplifier. This is a serious disadvantage in the radiation environment close to the ring. The main advantage of direct rf feedback is that it is automatically adaptive to change in frequency or beam conditions. These features are more relevant to a synchrotron than the accumulator ring.

One-turn-delay feedback operates only on the low level drive signal and does not require any additional equipment in the tunnel. Although it does not have the bandwidth attainable with direct rf feedback, it does give impedance reduction at each revolution harmonic and restores stability for high beam current. The investment here is some rather sophisticated fast digital circuitry, one set for each cavity. The key feature is the long term operational stability that follows from the feedback nature of the system. This is the preferable choice and is taken as the base line plan at this stage in the design.

The feedforward beam current cancellation method is regarded as a contingency at this time. This technique will do the job but has the drawback that such a system will require frequent expert attention to maintain optimal performance since it is feedforward, not feedback. As the power tube ages or power supplies drift with time or as the beam parameters vary, the gains and time constants of the feedforward system for each cavity will require touch-up. These adjustments besides requiring special expertise may comprimise the up-time availability of the machine because cavities will have to be switched off in order to make the adjustments.

It should be noted that none of these techniques alter the power requirements from the power amplifier. Basically they all amount to obtaining the best possible drive signal to apply to the power amplifier. The amplifier still has to deliver the current at voltage.

Even with beam loading compensation working effectively it is still essential that the synchronization signal for the LINAC chopper be derived from the vector sum of the actual gap voltages of the cavities. This assures that even though there will be phase shifts between the low-level drive signal and the actual gap voltages the freshly injected beam will always be deposited in the center of the bucket. The consequences of this slowly varying phase during the macro pulse on beam loading in the LINAC should be considered.

6 Barrier Cavity Upgrade

It is possible that the hardware used for the conventional rf system can be upgraded to a barrier cavity system without significantly changing the high power components. With 8 rf gaps and 10 kV per gap the beam dynamics appears feasible [1]. Using the hardware of the conventional system for the barrier cavity would require a peak power amplifier current of $I_{peak} = n_g V_g Q/R_{sh}$ [5] where $V_g \approx$ 10kV and Q is the quality factor of the cavity. For a cavity operating at $h = 1$, $R_{sh}/Q = \sqrt{L/C} = 45\Omega$ per gap, where L is the inductance of the ferrite and C is the gap capacitance. For barrier cavity operation the capacitance will be reduced so that the resonant frequency $\omega_r = 1/\sqrt{LC}$ is approximately doubled. This will double R_{sh}/Q, so in barrier cavity mode $R_{sh}/Q = 90\Omega$ per gap. For a gap voltage of 10 kV, the peak power amplifier current is $I_{peak} \approx 200$ Amp. Roughly, the tube current will be a square wave with a base value of zero amps for half the revolution period, and rise to a value of about two hundred amps for the rest of the revolution period. In actual operation, the current pulse will be smooth and losses in the cavity will need to be compensated. Figure 6 shows a more realistic situation. This figure gives the cavity voltage and the tetrode current for one gap with $R_{sh}/Q = 90\Omega$, $Q = 10$, and $f_r = 2.33$ MHz. The peak tetrode current per gap is 142 Amp which yields 284 Amps for the peak tetrode current with $n_g = 2$. From Figure 3 one can see that this current is well within the capability of the tube. The tetrode will need to dissipate $< I_a V_a > \approx 0.5 * 284\text{A} * 13\text{kV} = 1.8$ MW for ~ 2 ms of the 16.7 ms cycle time. This leads to an average power dissipation of 220 kW, well within the tube specification. Possible deleterious effects on the tetrode reliability and lifetime due to the large peak power and the problem of beam loading in a barrier cavity system are currently under investigation.

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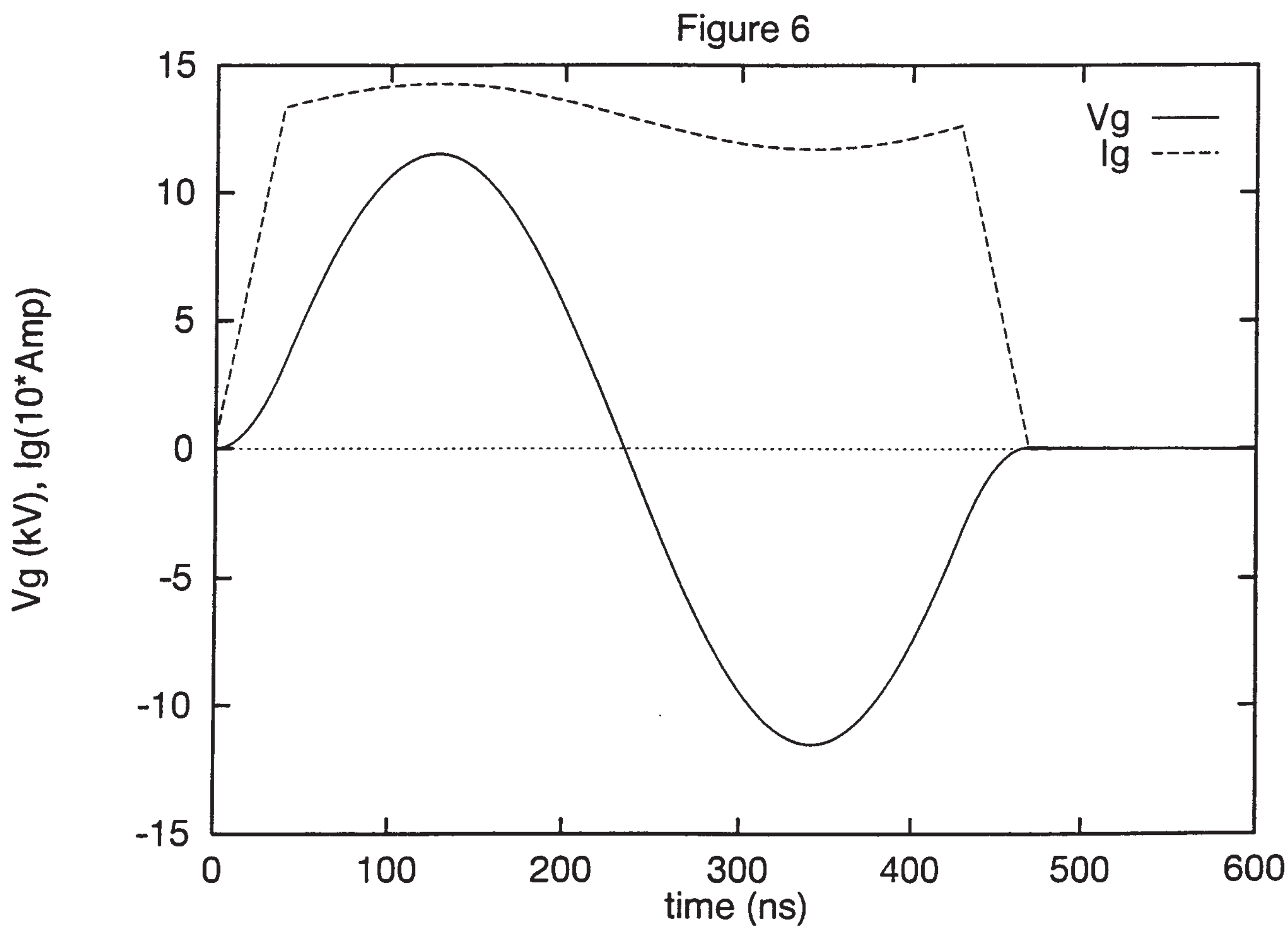

Figure 6: Voltage and tetrode current across one gap in barrier cavity mode.