HIGH LEVEL RF FOR THE SNS RING*

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Abstract

A high level RF system (HLRF) consisting of power amplifiers (PA's) and ferrite loaded cavities is being designed and built by Brookhaven National Laboratory (BNL) for the Spallation Neutron Source (SNS) project. It is a fixed frequency, two harmonic system whose main function is to maintain a gap for the kicker rise time. Three cavities running at the fundamental harmonic (h=1) will provide 40 kV and one cavity at the second harmonic (h=2) will provide 20 kV. Each cavity has two gaps with a design voltage of 10 kV per gap and will be driven by a power amplifier (PA) directly adjacent to it. The PA uses a 600kW tetrode to provide the necessary drive current. The anode of the tetrode is magnetically coupled to the downstream cell of the cavity. Drive to the PA will be provided by a wide band, solid state amplifier located remotely. A dynamic tuning scheme will be implemented to help compensate for the effect of beam loading.

1 INTRODUCTION

Main tasks of the HLRF system for the SNS ring is to capture proton beam during 1 ms injection from the 1GeV linac and to maintain a gap for the rise time of the extraction kicker. The HLRF system consists of three harmonic one cavities running at 1.05 MHz and one harmonic two cavity at 2.1 MHz.

The HLRF will be required to operate at wide dynamic ranges of the gap voltage (20 dB) and from no beam loading at the beginning of the cycle to the heavy beam loading (75 Amps peak current) at the end.

This paper will describe all the key components of the HLRF system with the emphasis on the ways to cope with the heavy beam loading.

2 SYSTEM PARAMETERS

High beam loading and reliability of the system are determining factors for the system configuration and parameters. Table 1 is a tabulation of the RF parameters:

To achieve these requirements, a set of parameters was developed. These parameters take into consideration beam loading, reliable high voltage design, availability of components (ferrites, tubes, etc.), space in the ring and maintainability.

Table I

Parameter	*Value*
Circumference	248 m
Total h=1 voltage	40 kV
Total h=2 voltage	20 kV
Space charge Z/n	i200 Ω
Proton kinetic energy	1Gev
Injection bunch length	610 ns
Injection energy spread	+/- 3.8 MeV, full
Protons at extraction time	2.08×10^{14}
Maximum bunch length	650 ns
Peak beam current	75 Amps

System parameters are tabulated in Table II.

Table II

RF system type	Dual harmonic
Cavity length	2.3 m
Accelerating gaps per cavity	2
Harmonic 1 frequency	1.058 MHz
Number of harmonic 1 cavities	3
Harmonic 1 total voltage	40 kV
Harmonic 2 frequency	2.115 MHz
Number of harmonic 2 cavities	1
Harmonic 2 total voltage	20 kV
Beam loading compensation	Dynamic tuning and feed forward
Harmonic 1 cavity shunt impedance	800 Ω

3 CAVITY AND POWER AMPLIFIER

Reliability, conservative design and easy maintainability were the prime consideration in the development of the SNS RF system. From past experience in the AGS and AGS Booster, we learned that the most optimized and conservative voltage across the gap is 10 kV. To keep the gap voltage at or below 10 kV, and keep flux density as well as power dissipation at reasonable levels, a two gap RF cavity was designed. In this design, two gaps are single ended and ferrite loaded. Gaps are interconnected by buswork, which, for symmetry, and to reduce inductance, are in front and in the rear of the cavity.

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Small samples, as well as full size ferrite rings, were evaluated for power dissipation, permeability and instabilities. The best choice for the ferrite for this application was Philips 4M2. The highest flux density is at the lowest frequency and on the inner surface of the ferrite ring. Each gap consists of 21 rings, and each ring measured 50cm O.D x 25cm I.D. x 2.72cm thick.

$$V_{gap} = 2 \cdot \pi \cdot f \cdot B_{rf} \cdot l \cdot a \cdot \ln(b/a)$$

$$B_{rf\ \max} = \frac{10^4}{6.28 \cdot 1.05MHz \cdot 21 \cdot .0272 \cdot .125 \cdot \ln\frac{50}{25}} = 310 \cdot Gauss$$

Tests of the ferrite showed no instabilities at flux density in excess of 400 Gauss.

The ferrite power dissipation is taken care of by water cooling. A cooling coil was constructed from dual rectangular copper conductor wound in a spiral shape. Double disk grinding of the coils on both sides provided the flatness and finish necessary for efficient heat transfer between ferrite rings and the cooling plates without the use of thermal conductive grease.

To reduce the beam loading, the R/Q should have the lowest possible value. One way to achieve this is to increase the gap capacitance. In our design, four capacitors of 750 pF each provide a total gap capacitance of 3 nF. Our calculations show that, for f_{rf} = 1.05 MHz the required inductance is 7.7 uH. To attain it, the initial permeability of 145 should be reduced to 90 by the dc bias current. Because removing 3 capacitors from the h=1 cavity will convert it to h=2 cavity, we are able to utilize the same cavity for both systems.

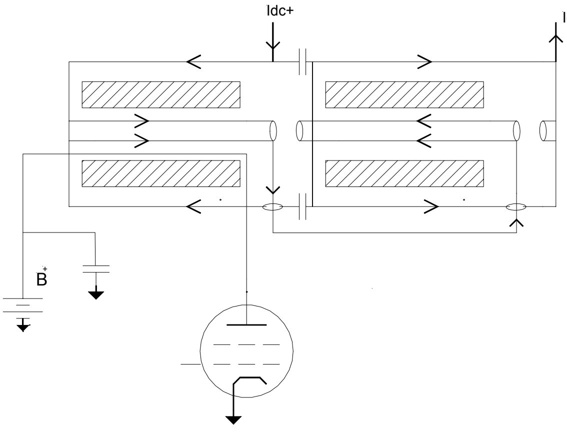

Figure 1

Figure # 1 shows a functional diagram of the RF cavity and the PA. Ferrite rings are dc biased whereas the outer can, beam pipe and the gap connecting buswork form a single turn bias winding. Because two halves of the cavity are in series to the dc bias, but in parallel to the RF drive, the RF will be cancelled (figure eight).

Cavity is excited by a single tube class AB1 power output stage. The amplifier is magnetically coupled to the cavity. B^+ link is inserted along the beam pipe. This technique eliminates the need for a plate choke.

The power tube is a tetrode (Thomson TH558) chosen for it's high plate dissipation (500 kW) and relatively low plate resistance (2kΩ). This type of tube and its smaller version has been used in the BNL AGS RF system for almost 10 years and it have proven to be very reliable.

The feedback (grid to plate) capacitance of the TH558 is 7pF, and has to be neutralized for stable operation. Because the cavity is single-ended, it was impossible to use the gap pick-up as a source of the inverted signal, required for neutralization. To circumvent this difficulty, an input transformer with a center tap was used to provide both the inversion and a 2:1 step-up for the drive signal. (see figure 2)

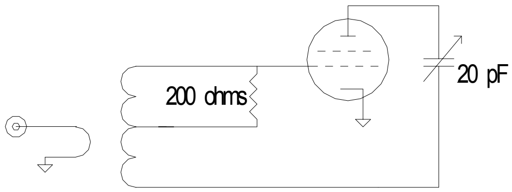

Figure 2

4 DYNAMIC TUNING

The beam current in the accumulator ring is in quadrature with the generator current. During the accumulation the average beam current increases from 0 to 35 amperes. The peak amplitude of the first harmonic component is 50 amperes per gap with total 100 amperes per cavity.

$$I_b = 2 \cdot 10^{14}\, ppp = 35Adc = 55Apk$$

By optimizing the resonant frequency of the cavity, the PA current may be reduced to the unloaded value.

Set the gap voltage to $V(t) = V_{rf}\sin(\omega t)$ and the PA current to $I_{pa}(t) = \left(\frac{V_{rf}}{R}\right)\sin(\omega t)$.

The beam current is $I_B = I_b\cos(\omega t)$.

The total driving current is the sum of the beam and PA contribution and is equal to the sum of the currents in the resistor, capacitor and inductor of the cavity.

$$\frac{V_{rf}}{R}\sin(\omega t) - I_b\cos(\omega t)$$

$$= \frac{V_{rf}\sin(\omega t)}{R} + \left(\omega C - \frac{1}{\omega L}\right)V_{rf}\cos(\omega t)$$

so, $I_b = V_{rf}\left(\frac{1}{\omega L} - \omega C\right)$

The inductance is varied according to:

$$-\frac{\Delta L}{L}=\frac{(R/Q)\cdot I_b}{V_{rf}+(R/Q)\cdot I_b}\quad \text{where}\quad \left(R/Q \;=\; \frac{1}{\omega C}\right)$$

$$\frac{\Delta L}{L}=.35=35\%$$

$$\frac{\Delta f}{f}=-\frac{1}{2}\left(\frac{\Delta L}{L}\right)=17\%$$

At 1.05 MHz it would represent 170 kHz frequency difference between the drive frequency and the resonant frequency of the cavity. The loaded Q of the cavity is 50 at tube quiescent current of 5 amperes, and drops to 38 at 10 amperes.

To simulate this mistuned condition the frequency was swept from 1.05 MHz to 1.22 MHz, while keeping the cavity tuned at the 1.05 MHz by the constant tuning current. AGC kept the voltage on the gap constant at 7 kV. (Figure 3)

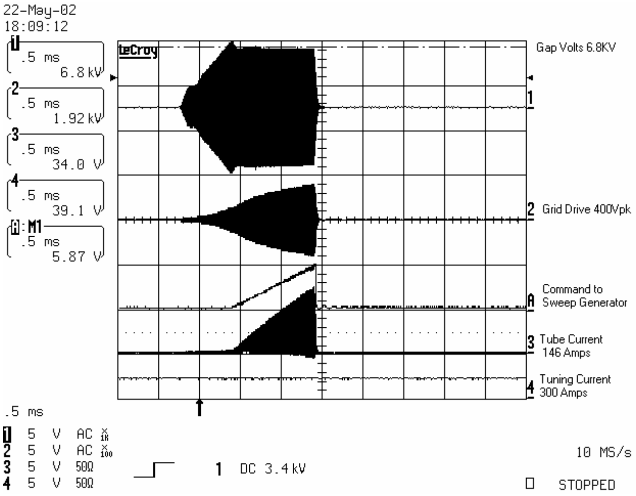

Figure 3

To tune the ferrite at the rate of 150 kHz in 1 ms (450 amperes/ ms) would require a rather sophisticated transistor bank with at least 10 kHz bandwidth.

Dynamic tuning is a feed forward correction, which is perfect for the SNS application since the repetition rate of the machine is 60 Hz, and the beam intensity doesn't change from cycle to cycle. Tuning current will be changing at 60 Hz (or multiple of it) +/- 450 amperes peak around the dc component needed to tune the cavity without the beam loading.

It was first tried on the test (2 ferrite ring) cavity. In this test we used two separate tuning supplies: one to provide the dc component to tune cavity to the resonance frequency, and second to resonate with external cap bank at 60 cycles. The results were great, and a full power tuning supply was built to test the final cavity.

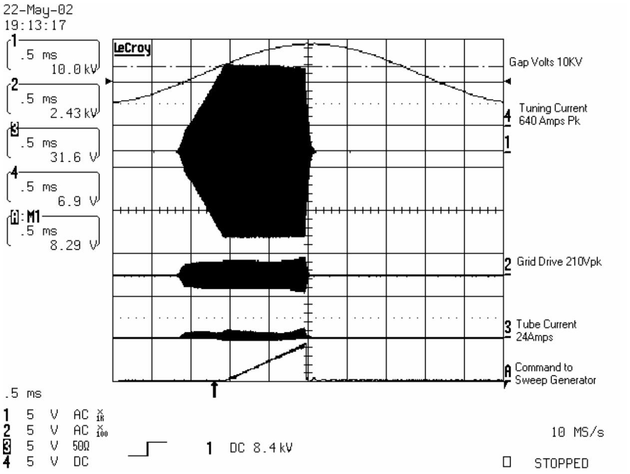

Figure 4

Fig. 4 shows a dynamically tuned cavity: 10 kV on the gap with the tube current less then 30 amperes. As you can see the tube current and the grid drive are drastically reduced.

As an upgrade to this concept we combined both power supplies functions, and to reduce the maximum tuning current increased the frequency of the ac component from 60 to 180 Hz.

5 CONCLUSIONS

First, the cavity and power amplifier were rigorously tested and operated at BNL at the gap voltages exceeding the design values. The system was designed conservatively with an eye on reliability, ease of operation and troubleshooting in a high radiation environment. All the components used were rated with comfortable safety margins.

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