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SPALLATION NEUTRON SOURCE/PROPOSED RF SYSTEM*

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September 30, 1993

BNL Interdepartmental Study of a Spallation Neutron Source

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* Worked performed under the auspices of the U. S. Dept. of Energy.

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✓ BNL-49655
Informal Report

SNS-4

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Introduction

The RF system for the synchrotrons of the spallation neutron source is designed to accelerate 1.4×10^{14} protons/pulse to an energy of 3.6 GeV. Injection energy is 600 MeV. The synchrotron repetition frequency is 30 Hz, with a 50% duty factor. The choice of operating frequency is somewhat arbitrary. We propose a low frequency of 1.3 to 1.6 MHz, which is the second harmonic of the revolution frequency. The advantages of such a low frequency system are: 1) there will be two bunches in the machines and the time between bunches will be sufficiently long to allow for the rise time of the extraction kicker. No missing bunches will be necessary, which simplifies injection, and transient beam loading problems are avoided. 2) With only two bunches there are no unstable coupled-bunch modes of longitudinal instability. 3) In multi-gap low frequency cavities the transient time factor is essentially unity because the rf wavelength is much longer than the cavity dimensions. 4) Cavities in this low frequency range are basically lumped-element type structures, where the sources of the inductance and capacitance are clearly identified. This allows effective control of higher order mode impedances in such cavities. 5) Ferrite-loaded low-frequency cavities are necessarily low impedance structures; ferrites are lossy. This low impedance makes it possible to achieve system stability without large amounts of feedback in a heavily beam loaded system. 6) We here at BNL have a good deal of experience in building rf systems in this range of frequency, voltage, and power level.

This report outlines the essential parameters of a practical rf system for the synchrotrons of the Spallation Neutron Source. The design uses materials, ferrites and vacuum tubes, that

are commercially available and with which we have recent experience.

The major RF system parameters are listed in Table I. The system configuration showing the cavity cross-section and the RF excitation is given in Figure 1. Four ferrite water-cooled stacks are arranged to form two gaps. The gaps are connected in parallel, with external bus bars. The bus bars are also used in the bias circuit, feeding the ferrite tuning current. This is shown in Figure 5. A figure-eight winding couples two stacks within a gap to balance the gap voltage, equalizing the RF voltage across each stack.

Cavity Design

The cavity uses Philips (Ferroxcube) 4M2 ferrite. Small sample loss measurements of this ferrite are available in the range of 2.5 MHz to 4.2 MHz. Figure 2 gives this data. This ferrite is used in the AGS Booster Band III cavity. This data has been projected to a frequency of 1.3 MHz. The RF injection frequency (1.3 MHz) determines the maximum RF flux density, hence the required volume of ferrite.

The design value for peak flux density is limited by the maximum heat loss that can be accommodated with water cooling. Experience limits water-cooled ferrite to an average dissipation of 200-250 mw/cc; or 400-500 mw/cc for a 50% duty factor. The projected ferrite loss at 1.3 MHz would allow a flux density of 400 Gauss. For a conservative design the flux density is limited to 300 Gauss. Ferrite ring sizes are consistent with rings that have been

RF Specifications

Intensity	1.4×10^{14} protons/ring/pulse
Harmonic Number	2
RF Frequency at Injection	1.31 MHz
RF Frequency at Extraction	1.62 MHz
Repetition Rate at Extraction	30 Hz
Duty Factor	50%
Peak Voltage	800 kV
Beam Current (dc component) (rf component)	18.1 Amperes 28.3 Amperes
Peak Power to Beam	7 MW
Peak Power Dissipated in Ferrite	1 MW
Total Peak Power	8 MW
Number of Cavities	8
Gaps per Cavity	2
Length of Cavity	360 cm
Peak Voltage	100 Kv/Cavity 50 Kv/gap
Number of Amplifiers per Cavity	1
Amplifier Peak Power	1 MW
Robinson Resistance	45.7 K ohms/ring 5.7 K ohms/cavity

TABLE I
RF SYSTEM SPECIFICATIONS

previously utilized, i.e. the AGS Booster uses 23 x 50 x 2.7 cm rings and the AGS uses 20 x 50 x 2.8 cm rings. The design parameters and heat loss calculations are given in Table II. The costs estimate is based on a cost of \$1500 per Booster ring.

The electrical parameters of the cavity are given in Table III. The tuning capacitance is to a large extent determined by the volume of ferrite and cannot be arbitrarily selected. The adequacy of a gap capacitance of $650\mu\mu\text{F}$ is determined by evaluating the transient beam loading. The injection of an impulse of current with a moment that is equivalent to the charge per bunch ($11.2\mu\text{ Coul}$), retards the RF voltage by 19° . By comparison injection from the Booster into the AGS produces a phase retardation in the RF voltage of 25° to 30° . The equivalent steady-state beam loading, measured by the stress on the tuning loop, is evaluated in terms of the fractional detuning of the resonant circuit. The fractional detuning of .043 is 20% of the cavity tuning current needed to follow the rf sweep. The detuning of the cavity is less than one half of the loaded cavity bandwidth.

Lacking measured data on Ferrite loss in the frequency range of 1.3 - 1.6 MHz a conservative design is employed. If, based on future loss measurements in this frequency range, a larger value of flux density can be employed than the volume of ferrite can be reduced. This will increase the value of gap capacitance and also reduce the cost of ferrite.

This value of gap capacitance, $650\mu\mu\text{F}$, is adequate.

Ferrite Rings

Material:		Philips 4M2
OD	=	50 cm
ID	=	20 cm
Ferrite Thickness	t =	2.8 cm
Cooling Plate Thickness (edge cooling)	=	0.3 cm
Number of Plates per Stack		25
Length of Stack	=	77.8 cm
2 Stacks per Gap		
4 Stacks per Cavity		
Total Length of Stacks	=	311.2 cm
Volume of Ferrite	=	450,000 cm ³
Weight of Ferrite	=	2245 kg
Estimated Cost of Ferrite		\$168,000

Performance

Maximum Voltage	50 KV/Gap 100 Kv/Cavity
Flux Density Maximum	300 Gauss
Peak Dissipation	200 <u>Milliwatts</u> cm ³
Average Dissipation	100 <u>Milliwatts</u> cm ³
Peak Dissipation in Cavity	90 KW
Tuning Range of Cavity	1.3 to 1.6 MHz
Unbiased Value of μ	140
Initial Value of μ	92
Final Value of μ	60

TABLE II
Cavity Design Parameters and Heat Loss Calculations

Inductance	22.9 $\mu\text{H/gap}$ ($v = 50 \text{ Kv}$) 45.8 $\mu\text{H/cavity}$ ($v = 100 \text{ Kv}$)
Tuning Capacitance	650 pF/gap ($v = 50 \text{ Kv}$) 325 pF/cavity ($v = 100 \text{ Kv}$)
Ferrite Loss Resistance	27.8 K $\frac{\text{Ohms}}{\text{gap}}$ 55.6 K $\frac{\text{Ohms}}{\text{Cavity}}$
Unloaded Q of Cavity	(Ferrite losses) 183
Loaded Q of cavity	(Ferrite losses, amplifier with 10 db of feedback) 10.4
Transient Beam Loading	$\Delta Q = (\text{Charge per Bunch}) = 11.2 \mu\text{Coul}$ $C = 325 \text{ pF}$ $V = 100 \text{ Kv}$ $\frac{\Delta Q}{CV} = .344$
Induced Phase Shift	19° - impulse 12.1° - half wave sinusoid
Steady State Beam Loading	Beam Current 28.3 A (peak rf) ΔC 28 pF/Cavity Fractional Detuning $\frac{\Delta F}{F} = .043$

TABLE III
Electrical Parameters of Cavity

RF LINK CABLE: Rowe Industries

High Voltage Silicon Lead Wire
RCB 1030-4-1

Figure 1
System Configuration
Cavity Cross-Section and RF Excitation

2.77 cm OD

DATA 4/21/87
4/20/87

$\uparrow P_0/V$

WATT/CM³)

B_{PEAK}
RF

(GAUSS)

Figure 2
Ferrite Loss Measurement (2.5 - 4.5 Mhz)
and Projection to 1.3 Mhz

MA GOLDEN
H. ZHANG

RF Design

Each cavity is excited by a one-tube Class AB₁ power output stage. The tube is link coupled to the cavity through a one-turn transformer formed between the beam pipe and the plate lead. The RF link runs through the annulus formed between the beam pipe and the ferrite rings as in shown in Figure 1. The RF flux magnetically couples the link with the beam pipe. Other than a RF bypass capacitor, no additional RF components are required.

The insulation of the plate lead is stressed only by the DC plate supply voltage, 27.5 KV. Silicon insulated leads rated at 60KV DC are available with an OD of 1 cm.

The power tube is a tetrode EIMAC 8973. With water cooling of the anode, the tube is rated to dissipate 1 MW. The tube operating voltages and calculated electrode currents and dissipation are given in Table IV. These values are compared with their rating. The plate circuit is designed on an average basis, while the grid and screen are designed on a peak basis. The plate thermal time constant, 200 milliseconds, is much greater than the cycle on time, 16.7 milliseconds. The grid and screen thermal time constants are comparable with the cycle on time. The grid drive power is estimated on a configured bandpass filter coupling the driver to the output stage. The design is conservative; the tube is operated well within rating.

The RF load line is constructed on the constant current characteristics of the tube, Figure 3. The RF phase is indicated as a running parameter on the load line. The dynamic plate resistance r_p is calculated as a function of RF phase from the tube characteristics. Each value of r_p contributes to the tube's output resistance R_{eq} as a function of the value of voltage swing or RF phase. This calculation is summarized in Table V.

The calculated value of R_{eq} is combined with the ferrite dissipation to give the output

resistance R_{out} and is compared with the Robinson resistance. These results are given in Table V. Since the output resistance R_{out} is greater than the Robinson resistance negative voltage feedback must be employed to keep the resistance below the threshold for beam-loading instabilities. As a minimum 4.8 db of feedback (gain reduction) is required. Practically 10 db of global feedback should be employed.

		<u>Tube Rating</u>
Plate Voltage	27.5 Kv	30 Kv
Screen Voltage	1.5 Kv	2.5 Kv
Grid Voltage	-400 Volts	
Peak Grid Drive Voltage	370 Volts	
Grid Drive Power	500 Watts	
Zero Signal Plate Current	10 A	
Peak Plate Current	180 A	
# Average Plate Current (Peak)	62 A	
* (Averaged)	36 A	110 A
Peak Load Power	1000 KW	
# Plate Dissipation (Peak)	705 Kw	
* (Averaged)	490 Kw	1000 Kw
P _{BB} - Plate Power Supply	1800 Kw	
# Peak Screen Current	10 A	
# Average Screen Current	1 A	
# Screen Dissipation	1.5 kW	7.5 Kw

* Averaged Basis, Tube on time 16.7 millisec.

Plate thermal time constant 200 milliseconds

Peak Basis

Averaged during tube on time

TABLE IV
Tube Parameters EIMAC 8973, Class AB₁ Operation

BEAM DAMPING

Ring

Beam Power	7 MW
Accelerating Voltage	800 Kv
Number of Cavities (stations)	8
Robinson Resistance	45.7 K ohms
	5.71 <u>K ohms</u> station

EIMAC 8973

From Load Line

$$\frac{1}{Req} = \frac{1}{3} \left[\frac{.067}{r_p(15^\circ)} + \frac{0.5}{r_p(15^\circ)} + \frac{0.933}{r_p(75^\circ)} \right]$$

Req = 759Ω at 25 kV level

referred to 100 kV level 12.14 KΩ

R_{ferrite} 55.6 KΩ

R_{out} = 9.96 KΩ

requires negative voltage feedback

Minimum Gain Reduction 1.75
(4.8 db)

Design for 10 db of Feedback

TABLE V
Beam Damping for EIMAC 8973

Figure 3

Load Line Construction
1 MW Class AB₁ Power Amplifier

Alternate RF Design

An alternate RF design employing a classical push-pull amplifier is given in Figure 4A. This arrangement employs two water cooled tubes operated Class AB₂ and rated for a plate dissipation of 300KW/tube. To match the voltage ratings of the tube and gap, each ferrite stack is tapped at ½ the stack length. The tube operating voltages and calculated electrode currents and dissipation are given in Table VI. The output resistance of the amplifier is calculated and compared with the Robinson resistance Table VII. To provide adequate damping 16 db of global feedback should be provided for the alternate configuration.

A second configuration, matching the voltage rating of the tube and gap, utilizes four gaps. The ferrite rings are divided into 8 stacks, two stacks per gap. The value of tuning capacitance is doubled (1300 $\mu\mu\text{F}$ /gap). This arrangement is shown in Figure 4B. The cavity design shown in Figures 4A and 4B are driven by the same power stage. The designs shown in Figure 4 are balanced and do not require a figure-of-eight RF winding.

To a large extent the output resistance of the cavity is dependent on the squares of the voltage ratio between cavity and tube. The plate resistance of tubes in this power range have relatively similar values of r_p at the same current level, i.e., the tube are designed with the same value of perveance. For the level of beam loading encountered in this application, the Robinson criterion cannot be satisfied with an open-loop amplifier. Negative voltage feedback must be employed. To minimize the quantity of feedback required tubes with the largest rated value of plate voltage should be employed.

The large value of gap voltage employed might require that the cavity be immersed in a dry inert gas under a few atmospheres of pressure. This will increase the sparking potential

within the cavity structure by a factor that is approximately proportional to the pressure. Based on experience with the AGS Booster cavity (45 kV per cavity) an increase in the sparking potential by a factor of 2.25 is known to be sufficient.

The low value of output resistance required for this application can be achieved with a cathode follower. Two characteristics of the cathode follower render this configuration unsuited for the application. With the bandwidth requirement of 300 KHz and an input capacitance to the tube of 1000 $\mu\mu\text{F}$, the RF drive power is comparable with that of the final stage. The drive power is estimated as 400 KW. In addition the cathode follower driving a resonant load can be unstable. At frequencies where the load appears capacitive, the configuration is that of a Colpits oscillator.

Cavity Bias and RF Balance

A scheme for tuning the cavity is shown in Figure 5. The bias or tuning current is directed through the cavity by employing the bus bars, beam pipe, and cavity body with two DC breaks as a continuous loop. The net flux encircled by the loop within the cavity structure of four ferrite stacks is zero. The loop encircles the flux contained within the bus bar structure. A balanced low pass filter isolates the residual magnetic flux from the tuning loop. Otherwise this flux would induce voltages within the loop and bias supply.

A figure-eight winding balances the gap voltage, equalizing the dissipation in each half of the ferrite stacks. The beam does not respond to an unbalance of the gap voltage. The beam is accelerated by the net gap voltage. Balance of the gap voltage minimizes dissipation within the ferrite and voltage stress within the cavity. This winding is optional and it's inclusion must be evaluated in terms of the final design numbers.

		<u>Tube Rating</u>
Plate Voltage	15 kV	20 kV
Screen Voltage	2 kV	2 kV
Grid Voltage	-500 Volts	
Peak Grid Voltage	560 Volts	
Zero Signal Plate Current	5 A	
Peak Plate Current	180 A	
Peak Plate Dissipation	430 KW	
Average Plate Dissipation (50% Duty Factor)	252 KW	300 KW
Average Plate Current CW Basis	62 A	
50% Duty Cycle	36 A	50 A
P _{BB} - Plate Supply	900 Kw/Tube	2 required
Average Screen Current	2.2 A	
Screen Dissipation CW Basis	4.4 Kw	6 Kw
50% Duty Cycle	2.2 Kw	
Average Grid Current	1 A	
Grid Driver Power for Two Tubes	1500 Watts	
Grid Dissipation	60 Watts	2 Kw

Can use Thomson TH 573

TABLE VI
Tube Operation (alternate design) EIMAC 4CM300,000
Class AB₂ Operation

Using 4CM 300,000
2 Tubes

$r_p = 400\Omega/\text{Tube}$ from Booster studies

Class B = 800Ω at 12.5 KV level

Referred to 100KV level 51.2 Kohms
Tube

2 Tubes 25.6 K Ω

R_{ferrite} 55.6 K Ω

R_{out} 17.5 K Ω

Requires negative voltage feedback

Minimum Gain Reduction 3.06 (9.7 db)

Design for 16 db of feedback

TABLE VII
Beam Damping for Alternate Design

$$C = 650 \mu\text{H}$$

EMAC 4CM 300,000

2 PER STATION

CLASS AB₂

Push Pull Operation

Figure 4A

Alternate Design

Figure 4B

4-Gap Cavity
2 - Tube Driver

Figure 5
Ferrite Bias Scheme Using Bus Bars and Cavity Structure

Arrows Indicate Bias Current

Conclusion:

The design of an rf system for the synchrotrons of the Spallation Neutron Source is described. The system works at a low frequency using the second harmonic of the revolution frequency. A system based on a 1 MegaWatt tetrode, link coupled to a two-gap cavity, is shown to be superior and more conservative to other schemes using two 300 KiloWatt tetrodes coupled to two or four-gap cavities. The designs are based on straightforward extensions of techniques recently employed in the AGS Booster and AGS rf system upgrade.

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