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# R.F. CAVITY DESIGN FOR THE NSLS

K. Batchelor, J. Galayda, and R. Hawrylak
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973

## Abstract

The r.f. cavity design for the Booster, VUV ring and X-ray ring of the NSLS is described together with the mechanical design of tuners, coupling and monitoring loops and the temperature control systems. The results of higher order mode measurements as compared with Superfish[1] calculations are also presented.

## Introduction

The radiofrequency system for the Booster, VUV and X-ray Storage rings is designed to perform the following functions:

a) In the Booster ring accelerate the 70 MeV beam from the Linac injector up to an energy of 700 MeV at a 1 sec cycle rate in order to allow transfer and storage of beams in both storage rings.

b) In the VUV Storage Ring, to accumulate up to 0.5 Amperes of beam current and store it for several hours.

c) In the X-ray Storage Ring, to accumulate, accelerate to 2.5 GeV energy and store a beam current of 0.5 Amperes.

In all of these processes systems to maintain correct amplitude, phase and frequency synchronism are provided as described in Reference 2.

## Radiofrequency Design Criteria

The basic requirement of the storage ring radiofrequency systems is to maintain an adequate phase stable region in the presence of beam loading due to radiation losses and beam/cavity interactions. Factors such as the quantum lifetime, maximum energy deviation in the r.f. bucket, standard energy deviation and overvoltage factor required for stable operation are given in references 3 and 4 and are reproduced in Table I

TABLE 1. VUV AND X-RAY RING DESIGN PARAMETERS

| STORAGE RING | GAP VOLTAGE | ENERGY ($E_0$) | STANDARD FRACTIONAL ENERGY DEVIATION $\left(\frac{\sigma_\epsilon}{\epsilon_0}\right)$ | MAXIMUM FRACTIONAL ENERGY DEVIATION $\left(\frac{\epsilon_{MAX}}{\epsilon_0}\right)$ | OVER-VOLTAGE FACTOR | QUANTUM LIFETIME |
|---|---|---|---|---|---|---|
| VUV | 100 KV | 700 MeV | $4.24 \times 10^{-4}$ | $1.89 \times 10^{-2}$ | 9 | >>100 HRS |
| X-RAY | 500 KV | 700 MeV | $2.27 \times 10^{-4}$ | $1.45 \times 10^{-2}$ | 16.2 | >>100 HRS |
| X-RAY | 800 KV | 2500 MeV | $8.12 \times 10^{-4}$ | $1.5 \times 10^{-2}$ | 2.6 | >>100 HRS |

*For a cavity gap voltage at 700 MeV of 50 KV.

It is clear that the cavity voltages chosen assure adequate quantum lifetime in both storage rings and the beam lifetime will be limited by other factors such as beam instabilities or multiparticle effects (Touschek Lifetime). It is anticipated that the Touschek lifetime in the VUV ring and the X-ray ring at injection energy will be the dominant effect in determining the desired radiofrequency gap voltage. For the voltages used in computing the parameters given in Table 1 the Touschek lifetime is calculated to be 3 HRS in the VUV ring and 30 mins in the X-ray ring at Injection Energy.

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The synchrotron oscillation frequency, natural bunch length ($2\sigma_L$) and bunch time width ($2\sigma_t$) are also important parameters and are given in Table II for the radiofrequency parameters used in Table I.

Table II. Beam Parameters for VUV and X-ray Rings.

| Storage Ring | Gap Voltage | Beam Energy | Synchrotron Oscillation Frequency | Natural Bunch Length ($2\sigma_L$) | Bunch Time Width ($2\sigma_t$) |
|---|---|---|---|---|---|
| VUV | 100KV | 700MEV | 12.83 KHz | 7.4 cm | 0.25 nsec |
| X-ray | 50KV | 700MEV | 1.23 KHz | 5.7 cm | 0.19 nsec |
| X-ray | 800KV | 2.5GeV | 4.90 KHz | 10.1 cm | 0.34 nsec |

Having satisfied the quantum lifetime and bunch length requirements the remaining criteria relate to the power and beam loading requirements necessary for an effective cavity design. In reference 3 the methods and notation of Perry Wilson (5) have been used to investigate the power requirements and stability criteria. Here we design the radiofrequency feed system and coupling loop such that the radiofrequency drive system is "matched" to the cavity under the maximum beam current condition. Furthermore, we introduce a feedback system to keep the reflected voltage wave in the input line real during the filling and acceleration processes (i.e. cancel out the reactive component of the induced beam loading voltage). In satisfying these criteria we calculate the maximum tuning angle required as

$$\frac{\Delta f}{f_o} = -\frac{P_b}{2Q_o P_c}\tan\phi \qquad (1)$$

where $f_o$ is the natural resonant frequency of the cavity, $Q_o$ the unloaded Q value, $P_b$ the total beam power, $P_c$ the cavity excitation power and $\phi$ the synchronous phase angle. The beam power may be calculated from the average radiation loss rate and the cavity power from the total effective shunt impedance attained in the cavity design $P_c=V_c{}^2/R$ where R is the total effective shunt impedance of the cavity.

TABLE III. RADIO FREQUENCY DESIGN PARAMETERS

| | | | |
|---|---|---|---|
| OPERATING FREQUENCY ($f_o$) | 52.88 MHz | 52.88 MHz | 52.88 MHz |
| | 5 | 9 | 30 |
| EFFECTIVE SHUNT IMPEDANCE ($R_sT_0{}^2$) | 0.5 M | 2.20 M | 4.29 M |
| CAVITY Q VALUE | 5000 | 18,000 | 19,000 |
| PEAK CAVITY VOLTAGE ($V_c$) | 20 kV | 200 kV | 800 kV |
| SYNCHRONOUS PHASE ANGLE ($\phi$) | 60° | 83.6° | 51.0° |
| BEAM CURRENT ($I_0$) | 20 mA | 1 A | 1 A |
| ENERGY LOSS PER TURN WITHOUT WIGGLERS | 11.1 keV | 11.1 keV | 252 keV |
| ENERGY LOSS PER TURN WITH WIGGLERS | -- | 12.1 keV | 297 keV |
| MAXIMUM RADIATION POWER LOSS ($P_B$) | 220 Watts | 12.1 kW | 297 kW |
| CAVITY POWER DISSIPATION ($P_C$) | 800 Watts | 4.8 kW | 150 kW |
| OVERVOLTAGE $\left(\frac{eV}{V_c}\right)$ | 1.15 ' | 9 | 1.6* |
| TOTAL GENERATOR POWER ($P_G$) | 1 kW | 16.9 kW | 447 kW |
| POWER AVAILABLE FROM R.F. SOURCE | 3 kW | 50 kW | 500 kW |
| FREQUENCY DETUNING FOR "MATCH" ($\Delta f$) | 2.4 KHz | 33.0 KHz | 3.40 KHz |

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The Booster radiofrequency cavity does not have to satisfy the stringent beam lifetime and beam loading requirements imposed on the VUV and X-ray ring cavities because the residence time in the ring is <0.5 sec. It does have to be capable of accelerating the beam from 70 MeV to 700 MeV in less than 0.5 sec while maintaining a stable r.f. bucket. Thus there is a requirement for both frequency and amplitude control on the Booster cavity system.

The radiofrequency design parameters resulting from all of the above criteria are listed in Table III.

## Rf Measurements and Computations

Shunt impedance measurements of the fundamental and higher resonances in the VUV cavity span the range from 52 MHz to 1600 MHz. A metal sphere was pulled through the accelerating gap of the cavity on a nylon monofilament line while the shift in resonant frequency of the mode was measured using a Hewlett-Packard 5245L frequency counter, and a Hewlett-Packard 141T spectrum analyser system or a phase detector as the case required. A 19 mm diameter bend was used for most measurements, and a bend with 7 mm diameter was used to remeasure those modes for which the extra sensitivity of the larger bead could be forfeited. The most important parasitic resonances are listed along with the fundamental in Table IV. Of particular interest are the modes at 506 MHz and 579 MHz. The fields in the accelerating gap at these frequencies were investigated by measuring the resonant frequency with the bead at several locations off the geometric center of the cavity. The resulting field patterns imply that these modes are a mix of $TM_0$ and $TM_1$ harmonics, so both longitudinal and transverse impedances are listed in Table IV for these modes. The transverse impedances represent a rough estimate of the derivative of the transverse deflecting field with respect to displacement of the beam from the geometric center of the aperture. For a mixed mode, a transverse deflecting force is also created by a beam centered in the aperture.

TABLE IV. PARASITIC MODES IN THE VUV CAVITY

| RESONANT FREQUENCY (MEGAHERTZ) | LOADED Q VALUE | LONGITUDINAL IMPEDANCE (OHMS) | TRANSVERSE IMPEDANCE (KΩ/m) |
|---|---|---|---|
| 52.88 | 5300 | 130 | |
| 273.41 | 828 | 32 | |
| 506.94 | 20278 | 10 | 0.4 |
| 578.67 | 2184 | 7 | 0.3 |
| 859.41 | 5371 | 36 | |
| 1101.23 | 2831 | 11 | |
| 1153.19 | 8606 | 20 | |
| 1175.95 | 7304 | 9 | |
| 1282.08 | 3561 | 15 | |
| 1300.05 | 14723 | 16 | |
| 1365.31 | 3969 | 9 | |
| 1447.40 | 9295 | 43 | |
| 1478.11 | 8351 | 14 | |
| 1538.35 | 9615 | 43 | |

Investigation of ways to damp these modes continues. It has been found that the 273 MHz and 579 MHz modes can be damped to almost unmeasurable levels by inductively coupling to the modes with an antenna near the shorted end of the cavity. The 859 MHz, 1282 MHz, and 1447 MHz modes can be effectively damped by capacitive coupling to the field in the accelerating gap. A. Faltens[6] suggested that modes in the X-ray ring cavity above 1000 MHz be damped without disturbing the fundamental by connecting the cavity to a load through a waveguide. The ports available in the VUV ring cavity are not suited to this purpose.

SUPERFISH was used to set dimensions and estimate tolerances in the cavities. The resulting sensitivities to increases in dimension were: gap, +0.16 MHz/mm; cavity radius, -0.93 MHz/mm; length (gap fixed), -0.06 MHz/mm; center electrode radius, -0.14 MHz/mm. SUPERFISH predicted an unloaded Q of 18500 and R/Q of 131.2 for the fundamental, which agrees very well with the measured values of Q=17000 and R/Q=130. It gave satisfactory predictions of resonant frequency and R/Q for the 273 MHz, 859 MHz, 1153 MHz, 1447 MHz, and 1478 MHz modes, as well as some less important modes. The program also predicted an important mode at 579 MHz which may be related to the mixed mode measured at this frequency. The unloaded Q's of the higher modes as predicted by SUPERFISH are much higher (3x-10x) than any of the measured widths of these modes.

## Mechanical Designs

### Cavity

The basic configuration of the VUV and X-ray cavity is very similar. The X-ray version consists of two, 1/4 wave, capacitively loaded, open ended cavities joined together face to face as shown in Fig. 1. The VUV version is exactly one half of the X-ray cavity.

In order to achieve adequate rigidity, the tank is constructed of copper clad steel of total thickness of 7/16" with a copper layer 1/16" thick. The tank body is rolled out of flat stock and then butt welded to form a cylinder. The cover plate is reinforced with ribbing in order to minimize changes in the critical cavity accelerating gap dimension under vacuum conditions. With these ribs deflection is less than .015". One-half inch diameter water pipe has been welded onto the outside of the tank for cooling.

Each copper center electrode dissipates about 70 kW of RF power and the internal cooling passages accommodate the necessary water flow with as few welded joints as possible. The stem is made from an OFHC copper forging with longitudinal 3/8" square grooves machined on the outside, over which a 6-1/8" O.D. tube is shrunk fit to form eight feed and return cooling passages terminating in a manifold outside the tank. The other end is connected to appropriate radial grooves in the front plate, which has been formed of two 1-1/2" thick OFHC copper plates brazed

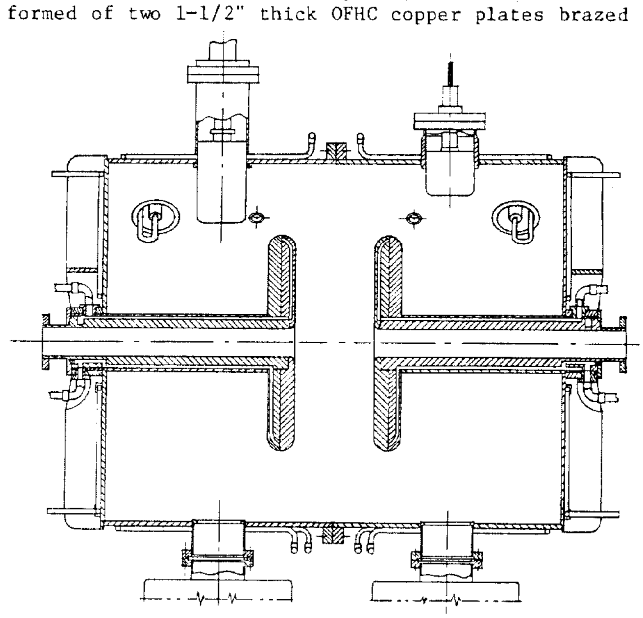

Figure 1. X-ray R.F. Cavity.

together. The rounded outside edge is electron beam welded as are the two water to vacuum joints on the center electrode. Each electrode is welded in the tank at the proper engagement depth required for the 58.88 MHz design frequency.

Both the X-ray and the VUV cavity have a 1 m diameter flanged joint. A soft aluminum wire gasket of 1/16" diameter is being used as a vacuum and rf sealing element. The joint is located at the node point where the current density is small.

## Tuner

The tuner (Fig. 2) is a movable water cooled cylinder copper plunger with all joints electron beam welded and has a tuning range of 160 KHz. It is driven by a stepping motor via an ACME screw and worm gear arrangement. There are no water to vacuum joints. There is a sliding contact between the plunger and the tank opening.

Similar tuners may be used in the VUV and X-ray rf cavity. However, in the X-ray cavity there may be problems with the sliding contact at the higher power levels so tuning may be provided by other means.

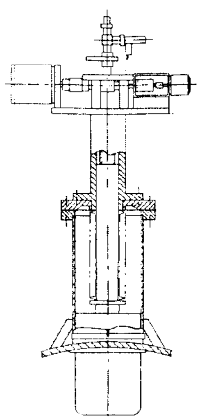

Figure 2. Tuner.

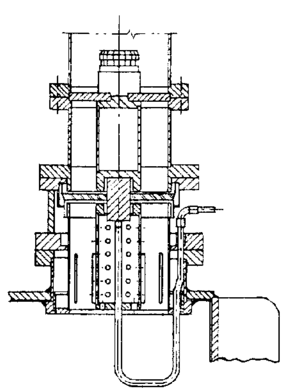

Figure 3. Coupling Loop and Vacuum Window.

## Coupling Loop and Vacuum Window

The coupling loop (Fig. 3) is a 2" wide water-cooled strip of copper bent into a rectangular configuration. It is connected to a 6" 50 ohm coaxial line passing through a 1 cm thick vacuum window of high alumina ceramic. The insulator is brazed to stainless steel sleeves on the O.D. and I.D. which facilitates welding the window to a flange. Cooling is provided on the outside by a water jacket and air can be blown onto the insulator on the air side.

The degree of coupling can be controlled by turning the loop at an angle to the longitudinal axis of the cavity thus varying the effective coupling area.

## Booster Cavity

The Rf cavity (Fig. 4) for the Booster Ring is a simple coaxial "Tee" structure with a gap at each end of the straight run of the Tee. The coaxial line passes through a vacuum window made out of high alumina ceramic. The seal is achieved by using spring loaded, C-shaped alumninum gaskets installed on both sides of the insulator. One set effects the vacuum seal, and the other serves as a resilient cushioning

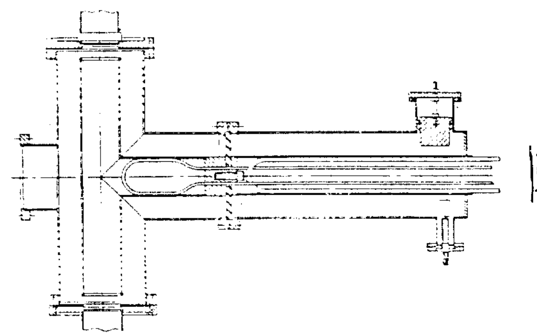


Figure 4. Booster RF Cavity.

## Temperature Control System

A stable temperature must be maintained in the VUV and X-ray cavities with an accuracy of <.1°C in order to keep a constant resonant frequency.

In the X-ray cavity a load of 200 kw requires 50 Gpm of cooling water at a $\Delta t$ of 15°C. An average water velocity of about 5 fps is maintained throughout the system. The necessary amount of demineralized and deionized water is being supplied by the house system and is being recirculated by a separate pump. Temperature control is achieved by modulating the flow of the makeup water using a RTD sensor, 62H-5E controller, and V4A control valve (All "Foxboro" components).

In the VUV cavity a relatively large water flow of about 20 Gpm is maintained, since the cooling passages are identical to those in the X-ray cavity. This results in a $\Delta t$ of only a fraction of °C, thus assuring a fast response to the control action. The water circulating system is similar to the X-ray version, except here most water is being recirculated and only a small part supplied by the house system for the cooling action and in order to maintain the proper resistivity of the water. Rough temperature control is achieved by a modulating valve, controlling the makeup water, with a vapor bulb controler. ("Trerice" Mod. 91400) Fine tuning is obtained by using a thermistor controlling an electric heater.

## Conclusions

The VUV and Booster cavity have both operated under vacuum and high power at the design frequency and power level without circulating beam.

## Acknowledgments

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