THE ALPHA FERRITE-LOADED COAXIAL RESONATOR CAVITY*

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Abstract

The Advanced Electron Photon Facility (ALPHA) [1] is a joint collaboration between the Indiana University Center for Exploration of Energy and Matter and the Crane Naval Surface Warfare Center. The ALPHA storage ring will serve as a debuncher in single pass mode of operation. With a set of two gradient damping wigglers, the storage ring can also accumulate to achieve high charge density beams. In this report, we present the design, fabrication, and testing of the 15 MHz ferrite-loaded quarter-wave rf coaxial resonator cavity that will be utilized in the ALPHA storage ring. Topics pertaining to beam lifetime, radiation damping, ferrite-loaded transmission lines, and key cavity parameters will be discussed.

INTRODUCTION

In addition to serving as a radiation effects testing facility, the low energy electron storage ring will be an ideal laboratory to study the Touschek effect as well as beam dynamics near transition energy (i.e. quasi-isochronous condition) with the ability to vary the momentum compaction [2].

Table 1: Design Parameters of the ALPHA Storage Ring

Parameter	Value
Circumference	20 m
Energy	50 MeV
Dipole	2 m, $\rho = 1.273$ m
Edge Angle	12°
ν_x, ν_z	1.75, 0.75

CAVITY DESIGN

Due to space limitations, only 16.6 in (42.2 cm) of length was available for the 15 MHz rf cavity operating at harmonic number $h = 1$. The Toshiba M_4C_{21A} ferrite rings were used in the cavity to increase the effective magnetic permeability of the resonating medium, thereby enabling the construction of a compact low frequency structure. The ferrite rings have an inner diameter of 5 in (12.7 cm) and outer diameter of 8 in (20.3 cm). The cavity will be capacitively tuned with a 8-650 pF motor-controlled vacuum capacitor across the gap and rf power will be inductively coupled into the structure. The accelerating gap consists

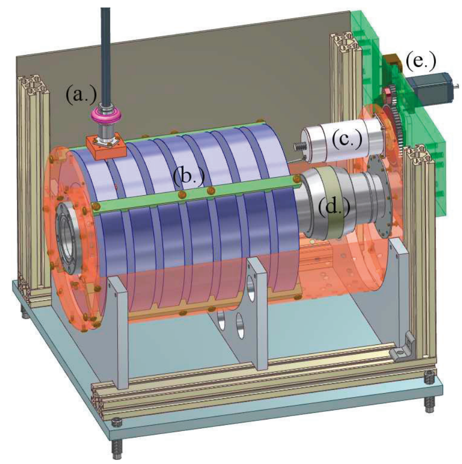

Figure 1: Cross-sectional drawing of the cavity design. (a.) rf drive point, (b.) M_4C_{21A} ferrite rings, (c.) vacuum capacitor, (d.) ceramic gap, (e.) capacitor tuning motor.

of a high-purity alumina ceramic cylinder welded in place with low-expansion Kovar fittings giving a gap length of 0.75 in (1.9 cm). The cavity design efforts were guided by ferrite-dominated transmission line theory and the Poisson-SUPERFISH [4] static field simulator. Required input rf power and cavity accelerating gap voltage will be determined by the physics of radiation damping and large-angle intrabeam scattering.

Beam Lifetime

In low energy storage rings, the mechanism which dominates the lifetime of stored beam is Touschek scattering. The Touschek effect involves two particles interacting through large-angle Coulomb scattering, transferring transverse momentum into longitudinal momentum resulting in closed orbit shifts where the particles are lost. A well-known expression [7, 8] summarizes the effect,

$$\frac{1}{\tau_T} = \frac{r_e^2 cq}{8\pi e\gamma^3\sigma_s}\frac{1}{C}\oint \frac{F(\xi)}{\sigma_x(s)\sigma_z(s)\sigma_{x'}(s)\delta_{acc}^2(s)}\,\mathrm{d}s \quad (1)$$

where the function $F(\xi)$ is defined to be

$$F(\xi) = \int_0^1 \left(\frac{1}{u} - \frac{1}{2}\ln\left(\frac{1}{u}\right) - 1\right) e^{-\xi/u}\,\mathrm{d}u \quad (2)$$

and $\xi = (\delta_{acc}(s)/\gamma\sigma_{x'}(s))^2$. Here σ_x, σ_z, $\sigma_{x'}$, σ_s, and δ_{acc} are defined as the rms transverse beam widths, dispersion correction term, rms bunch length, and momentum acceptance, respectively. The design of the storage ring

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was intended to have a Touschek lifetime dominated by rf momentum acceptance. When the damping wiggler bending radius is $\rho_w = 2\,\mathrm{m}$, corresponding to the horizontal damping partition number $\mathcal{J}_x \to 0$, the horizontal radiation damping time approaches a maximum of about 50 min before crossing the threshold of instability. A minimum cavity gap voltage of 1 kV will be chosen to mitigate particle loss and utilize radiation damping. See Figure 2.

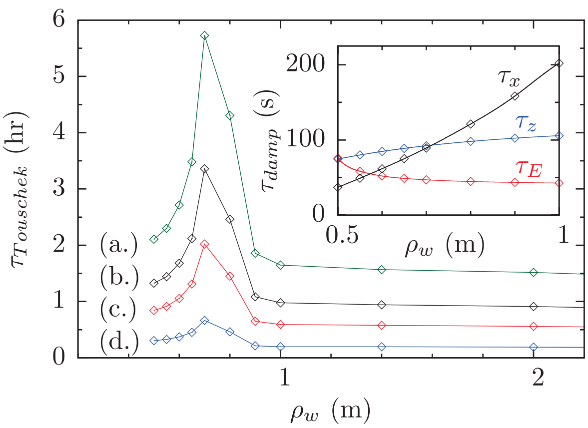

Figure 2: (a.) through (d.) are Touschek lifetimes varying with ρ_w and V_{gap} of 2 kV, 1 kV, 0.5 kV, and 0.1 kV, respectively. The subplot presents radiation damping times in the region of operational interest.

Transmission Line Theory

There exist literature pertaining to the topic of ferrite-dominated cavities [3]. Those models will be revisited with slight modifications to account for the specific geometry of the structure. The M_4C_{21A} ferrite rings have relative permittivity and permeability measured to be $\epsilon_r = 13.0$ and $\mu_r = 53.4$ at 25.0° C [6]. The effective ϵ and μ were approximated by averaging over the air gaps separating the ferrite rings,

$$\epsilon_e = \frac{\epsilon}{k + \epsilon\,(1-k)}\,\frac{d_1}{d_1+d_2} \tag{3}$$

$$\mu_e = (1 + k\,(\mu - 1))\,\frac{d_1}{d_1+d_2} \tag{4}$$

where $k = \ln(r_3/r_2)/\ln(r_4/r_1)$ and d_1, r_2, r_3, d_2 are the ferrite thickness, inner and outer radius, and air-gap length. The capacitance and inductance per meter are given as

$$C = \frac{2\pi\epsilon_e\epsilon_o}{\ln\left(\frac{r_4}{r_1}\right)}, \qquad L = \frac{1}{2\pi}\mu_e\mu_o \ln\left(\frac{r_4}{r_1}\right) \tag{5}$$

where r_1 and r_4 are the inner and outer radius of the structure and thus the wave velocity ν and the characteristic impedance Z_o can be computed. Suppose an external capacitor was placed across the gap thereby adding capacitance, where $C_{gap} = C_{cav} + C_{ext}$. Such a capacitor can be used to tune the resonance frequency of the structure governed by the transcendental expression,

$$\frac{1}{\omega_o C_{gap}} = Z_o \tan\left(\frac{\omega_o \ell}{\nu}\right) \tag{6}$$

where ℓ is the effective cavity length. Since the natural resonance frequency of the structure was well beyond the range for which an operational solution exists, the ferrite rings must be loaded to further lower the resonance frequency. The predictions made by transmission line theory given the final geometry are summarized in Figure 3.

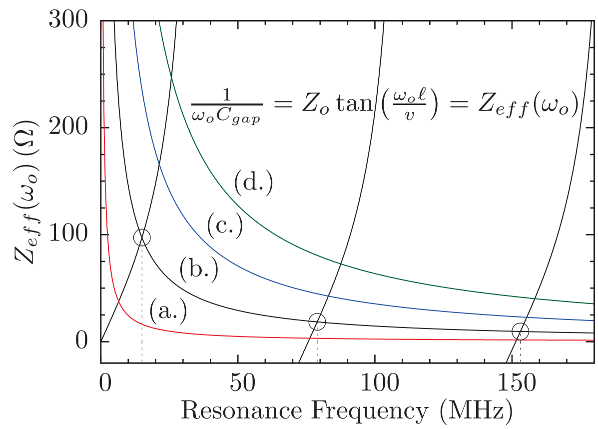

Figure 3: (a.) through (d.) corresponds to C_{gap} of 650 pF, 109 pF, 65 pF, and 25 pF, respectively. The solution with fundamental resonance frequency of 15 MHz exists when $C_{gap} = 109$ pF.

Poisson-SUPERFISH Simulations

The length and the inner diameter of the cavity are well-constrained. An exhaustive study utilizing Poisson-SUPERFISH was carried out to find geometries and ferrite configurations where resonance within the tuning range of the external gap capacitor can be achieved. These parameters will be summarized in Table 2 and field contours of the final structure at 25°C in Figure 4.

Table 2: Final Design Parameters for the Cavity

Parameter	Value
Length	37.31 cm
Inner Radius	5.56 cm
Outer Radius	10.93 cm
Ferrite Air Gap	0.93 cm
Ferrite Loaded	7

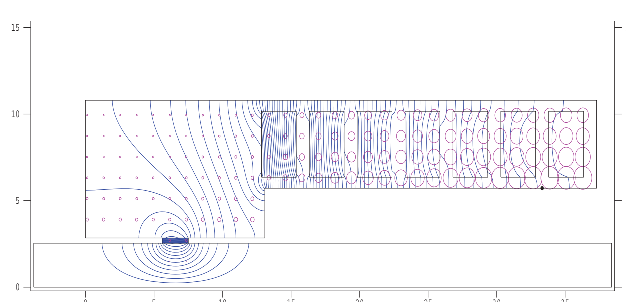

Figure 4: SUPERFISH simulation results with axis in units of cm. Resonance frequency of 30.296 MHz at $\mu_r' = 53.4$.

Single-stub Matching

Due to the compact nature of the structure and internal space limitation imposed by the loading of ferrite rings, an ideal driving point cannot be easily attained and thus matching techniques must be employed for the coupling of rf power. A simple shorted single-stub matching technique was used with the stub length to be 1.943 m corresponding to a capacitance of 145.35 pF and stub location 1.219 m from the load. The result was empirically verified to yield a SWR of 1.07 in low-power tests. All measurements hereafter will be through this matching network.

CAVITY MEASUREMENTS

Since the cavity is ferrite-dominated, the low-power and high-power measurements will differ by ferrite properties that are strongly dependent on temperature. The increasing μ', resulting from increasing ferrite temperatures, leads to a downward shift in cavity resonance frequency and increases loss in the ferrite (μ'') to further complicate matters. The results of low-power measurements will be summarized and high-power measurements discussed in this section.

Low-power Test

The cavity was characterized at low-power using an Agilent 8753D Vector Network Analyzer. Furthermore, an Agilent 8648B signal generator was used to characterize the cavity pick-ups with direct measurement of the gap with high-impedance probes. The results are summarized in Figure 5 and Table 3. Note that all low-power tests were carried out with ferrite temperature at 25°C.

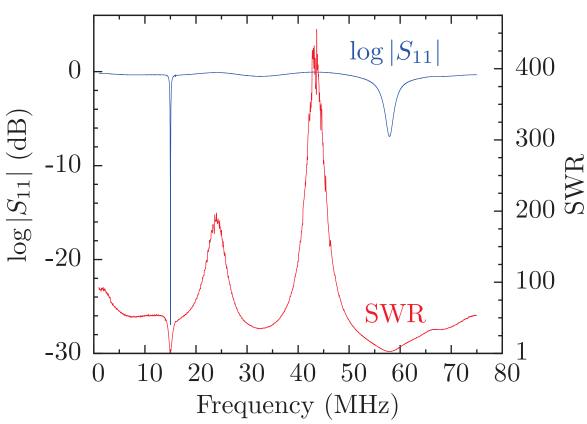

Figure 5: Cavity characterization with vector network analyzer where the SWR was measured to be 1.07 at 15 MHz.

Table 3: Results of Low-power Cavity Tests

Parameter	Value
Q_{loaded}	65.4
R_{shunt}	5564.5 Ω
$[R/Q]$	42.5
Freq. Tuning Range	6.9-27.6 MHz
Max RF Power	1.0 kW

High-power Test

As more rf power is fed into the cavity, the ferrite temperature will increase, changing its properties and ultimately altering the characteristics of the cavity. The temperature dependency of the M_4C_{21A} ferrite has been extensively studied in past longitudinal microwave instability inquiries [5, 6]. The cavity will be extensively tested at various rf input power levels with active tuning to maintain resonance condition. The ferrite temperature will be measured from the ferrite ring closest to the rf driving point, thus in the region of highest B-field, yielding the ceiling temperature of the seven ferrite rings.

CONCLUSION

Commissioning of the cavity at high-power is currently being carried out along with beam storage and damping. Results will be presented in future proceedings. Phase two of the rf cavity design will see upgrades to increase input rf power as well as optimization of the shorted single-stub for high-temperature applications. A cavity of harmonic number $h = 6$ has been proposed in near future to further shorten the bunch length for application in the inverse-Compton x-ray phase of the project.

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REFERENCES

[1] S. Y. Lee, P. E. Sokol et al., *The ALPHA Project at IU CEEM*, IPAC'10, Kyoto, Japan, May 2010, p. 268.

[2] S. Y. Lee, J. Kolski, Z. Liu, X. Pang, C. Park, W. Tam, F. Wang, *Low Energy Electron Storage Ring with Tunable Compaction Factor*, Rev. Sci. Instrum. 78, 075107, July 2007.

[3] I. S. K. Gardner, *Ferrite Dominated Cavities*, CAS, Oxford, UK, April 1991, p. 349.

[4] K. Halbach, R. F. Holsinger, *SUPERFISH - A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry*, Particle Accelerators, 1976 Vol 7, p. 213-222.

[5] K. Y. Ng, *Physics of Intensity Dependent Beam Instabilities*, Fermilab-FN-0713, Batavia, IL, 2002.

[6] C. Beltran, *Study of the longitudinal instability of the ferrite inductive inserts in the Los Alamos proton storage ring*, Ph.D. Thesis, Indiana University, 2003.

[7] J. Le Duff, *Single and multiple Touschek effects*, CAS, Berlin, Germany, 1987, P. 573.

[8] A. Streun, *Momentum Acceptance and Touschek Lifetime*, SLS-TME-TA-1997-0018.

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