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DESIGN OF FERRITE-TUNED ACCELERATOR CAVITIES USING PERPENDICULAR-BIASED HIGH-Q FERRITES

by

Klaus Kaspar

ABSTRACT

Microwave ferrites with dc bias fields perpendicular to the rf fields exhibit magnetic and dielectric quality factors 1 order of magnitude above that of ferrites used in ferrite-tuned synchrotron accelerating cavities built in the past. For the LAMPF II project, these ferrites appear to allow the design of synchrotron cavities with high gap voltages and high efficiency. A simple coaxial quarter-wave-resonator geometry, first considered only as a model for preliminary studies, turned out to be a good basis for the solution of most technical problems such as generation of the bias field, cooling of the ferrites, and installation of a generous high-voltage gap design. Two quarter-wave resonators combined to form one accelerating unit of about 2.5-m length and 0.6-m diameter should be capable of delivering 120 kV of accelerating voltage in the tuning range 50-60 MHz, up to 200 kV in the range 59-60 MHz. The main advantage of the given resonator design is its full rotational symmetry, which allows calculation and optimization of all electrical properties with maximum reliability.

I. INTRODUCTION

Synchrotron cavities have been built for more than 30 years and for more than 20 synchrotron facilities. Among the various methods tried for controlling the resonant frequency of the cavities, only dc bias fields with field lines parallel to the magnetic rf field lines have been used. Many of the difficulties and limitations of these ferrite-tuned cavities can be reduced or avoided if the dc bias field is applied perpendicular to the magnetic rf field.¹⁻³ After model measurements* were performed at Los Alamos, we studied

*This information was supplied by R. D. Carlini, Los Alamos National Laboratory (1984) and W. R. Smythe, Denver, Colorado (1984).

how the bias-field method can be used to design the accelerating system for the proposed LAMPF II facility.

II. THE rf REQUIREMENTS FOR THE LAMPF II FACILITY

The plan for the LAMPF II project consists of a fast-cycling booster and a main ring. The relevant parameters for the rf accelerating systems are listed in Table I.

In both machines, maximum rf voltage per cavity is required to reduce the number and cost of the accelerating stations needed. For the booster, the voltage per cavity is a factor of 2 higher than the voltages used in the most powerful comparable cavities [FNAL (Fermi National Accelerator Laboratory) booster]. For the main ring, similar values to those in the FNAL main ring are used. The number of accelerating stations is quite large even with the design voltages per cavity as specified.

III. REVIEW OF THE PROPERTIES OF PARALLEL-BIASED FERRITES

In existing synchrotron cavities, the ferrites are usually operated from near initial permeability to near saturation, which means that the region of

TABLE I
PARAMETERS FOR THE DESIGN OF THE LAMPF II rf SYSTEM

	<u>Booster</u>	<u>Main Ring</u>
Energy range (GeV)	0.800-9.000	9.000-45.00
Repetition rate (Hz)	60	30
Rise time of cycle (ms)	10	50
Accelerating frequency (MHz)	50.60-59.70	59.70-60.00
Energy gain per revolution (keV)	2000	5000
Required peak rf voltage (kVp)	4000	10000
Number of accelerating cavities	34 + 6	72 + 8
Peak voltage per cavity (kVp)	120	140
Maximum proton intensity (p/s)	$2 \cdot 10^{13}$	$4 \cdot 10^{13}$
Average beam current (A)	1.6	1.6
Current at accelerating frequency (Ap)	3.2	3.2
Beam loading per cavity (kWp)	180	180

motion at domain boundaries is included in the tuning cycle. There are two reasons: (1) the requirements for the generation of a high dc bias field are lowered, and (2) using the full permeability range of the ferrite is probably the only way to vary the resonant frequency of accelerating cavities by factors of 3 and more. The highest efficiency of the dc bias field is obtained when the bias field uses the same closed magnetic circuit as does the rf magnetic field; this means the bias field is parallel to the rf field.

The capabilities of ferrite-tuned cavities are determined and limited by the properties of the ferrite material. Some of the characteristic properties are the following:

- low magnetic-quality factors, $Q_{\text{mmat}} = 5-200$;
- low dielectric-quality factors, $Q_{\text{emat}} = 10-30$;
- strong dependence of the material properties on operating conditions such as rf amplitude, temperature, and tuning speed^{4,5};
- limited reproducibility of the ferrite data;
- cooling problems resulting from poor thermal conductivity and high losses in the material;
- nonlinear effects⁶;
- limitation of the rf amplitude by the so-called Q-loss effect or high-loss effect^{4,5,7}; and
- possible time dependence of the response to the bias field.⁸

Some of the effects are not fully understood and/or cannot be reproducibly controlled.

IV. PROPERTIES OF PERPENDICULAR-BIASED FERRITES

Ferrites with dc bias are used in various microwave applications such as phase shifters, controlled attenuators, and modulators. Most of the problems and restrictions known from synchrotron cavities seem not to exist in these applications. The reasons for the very different ferrite properties can, on the one hand, be explained by the special compositions of and the more refined production methods used for these materials. On the other hand, it is assumed that the main differences are due to the fact that the ferrites are operated near saturation and with the dc bias field perpendicular to the rf magnetic fields. Under these conditions the ferrites show the following properties:

- very high magnetic Q values, $Q = 1000-5000$;
- very high electric Q values, $Q = \sim 1000$, and
- low dependence of the material properties on rf amplitude, tuning speed, and other operating conditions.

For the LAMPF II project it has been proposed to use microwave ferrites and the perpendicular bias method for the design of the accelerating cavities.¹⁻³ Model measurements with several microwave ferrite types in the range 60-80 MHz exhibited the same advantageous ferrite properties known at microwave frequencies.* Whereas the measurements give evidence of considerably higher magnetic Q values, we use as a basis a "worst-case" magnetic Q value of $Q_{\text{mat}} = 1000$ over the whole frequency range.

V. SIMPLE QUARTER-WAVE-CAVITY CONCEPT FOR LAMPF II

The following studies are based on the discussion of the simplest case of a coaxial quarter-wave resonator as shown in Fig. 1. On the one hand, this geometry is sufficient to describe the transmission-line formalism used for calculation and to discuss most of the technical problems arising from the perpendicular bias of the ferrites. On the other hand, this simple geometry offers several advantages over more complicated systems. We consider it for the final cavity design as well.

*This information was supplied by R. D. Carlini, Los Alamos National Laboratory (1984) and W. R. Smythe, Denver, Colorado (1984).

Fig. 1. Coaxial quarter-wave resonator.

To calculate the rf properties of the given resonator geometry, we treat it as a combination of two homogeneous transmission-line sections. Inhomogeneities appearing around the transition from the tuner to the ferrite-free line section and also in the gap region are neglected. Also, the gap capacity is neglected, which means that the calculated lengths of the ferrite-free line section must be shortened by a length corresponding to the gap length. The results obtained in this way are considered as a first approximation. The transmission-line relations used to calculate the given case, as well as more complicated resonator geometries, are assembled in the Appendix.

Table II shows the data calculated for two cavity examples with the same radial dimensions but with different lengths for the tuner sections. The first column describes the design proposed for the LAMPF II booster cavities; the second column describes the resonator proposed for the main ring.

Both examples are calculated to have the same permeability, $\mu_{\text{mat}} = 2.0$ at 60 MHz. As a result, at 60 MHz and with the same gap voltage, the maximum rf currents and the maximum magnetic power densities are nearly the same in both cases. The permeability and bias-field variation required to tune the cavities from 60 to 50 MHz would be considerably larger for the short tuner version. The advantages of the longer tuner for large frequency variations are evident. However, an increase of the tuner length to more than 600 mm leads to a relatively small length of the ferrite-free line section. The space around this section is useful for installation of a sufficiently long ceramic gap insulator and is better reserved for this purpose.

In both examples the magnetic and the electric Q values are put at very pessimistic values. Probably both values can be assumed to be at least a factor of 2 larger.

In the case of very small frequency variations, as in the main ring, the shorter tuner is adequate. With the high bias fields required for 60 MHz, larger magnetic Q values are relatively certain. It seems possible to run the given main-ring cavity design to gap voltages above the 100-kV peak per quarter-wave resonator, though only 70 kV are assumed in Table II. The shorter tuner has the advantage that the ferrite stays completely out of the high electric-power-density region; on the other hand, it provides additional space to install a longer ceramic gap insulator if that is needed.

TABLE II
CALCULATED DATA FOR COAXIAL CAVITY^a

<u>Cavity dimensions</u>	<u>Booster</u>	<u>Main Ring</u>
Cavity outer diameter (mm)	400	400
Cavity inner diameter (mm)	120	120
Ferrite outer diameter (mm)	398	398
Ferrite inner diameter (mm)	300	300
Length of tuner (mm)	600	200
Length of free line (mm)	500	1000
Operating frequency (MHz)	50.0-60.0	59.5-60.0
Gap voltage (kV)	60.0-60.0	70.0-70.0
Transformation (V_{gap}/V_t)	1.16-1.24	3.17-3.27
Max. tuner rf current (A)	0.85-0.98	0.97-0.97
<u>Ferrite material data</u>		
Material permeability (μ_{mat})	5.56-2.00	2.24-2.00
Material permittivity (ϵ_{mat})	14.0-14.0	14.0-14.0
Magnetic quality factor (Q_{mmat})	1000-1000	1000-1000
Electric quality factor (Q_{emat})	100-100	100-100
<u>Maximum power densities</u>		
Magnetic, point A (W/cm^3)	0.54-0.38	0.55-0.50
Magnetic, point B (W/cm^3)	0.18-0.12	0.50-0.45
Electric, point B (W/cm^3)	0.13-0.14	0.03-0.03
<u>Total peak power losses</u>		
Magnetic losses in tuner (kW)	9.63-6.78	4.28-3.98
Losses in cavity walls (kW)	1.10-1.60	2.40-2.40

^aCalculated data for the coaxial cavity with different tuner lengths. The additional space required for ferrite cooling has been neglected. Inhomogeneities between the tuner and the ferrite-free line section and in the gap region have been neglected as well. All power data are peak values without considering duty factor.

VI. GENERATION OF THE PERPENDICULAR dc-BIAS FIELD

It is assumed that the dc bias field H_{dc} needed to realize a certain ferrite permeability μ_{mat} can be calculated from the material's saturation magnetization $4\pi \cdot M_s$:*

$$\mu_{mat} = 1 + 4\pi \cdot M_s / H_{dc} \quad .$$

Microwave ferrites with saturation magnetizations as low as $4\pi \cdot M_s = 300$ -600 G are available from several firms. Samples with $4\pi \cdot M_s = 600$ have been measured at Los Alamos and seem to satisfy all requirements.** For these samples one obtains

$$H_{dc} = 16\text{-}48 \cdot 10^3 \text{ A/m} \quad \text{for} \quad \mu_{mat} = 4.0\text{-}2.0 \quad .$$

It is difficult to calculate how much the applied external magnetic field will be reduced by polarization of the ferrite, inhomogeneous field distribution, and other effects. Therefore, the above value is multiplied by a safety factor of two and a maximum value of $H_{dc} = 10^5$ A/m is used for further discussion. It seems possible to realize this bias field by means of a water-cooled high-current solenoid enclosing the ferrite tuner as shown in Fig. 2. A rough estimate leads to the data given in Table III.

*This information was supplied by W. R. Smythe, Denver, Colorado (1984).

**This information was supplied by R. D. Carlini, Los Alamos National Laboratory (1984).

Fig. 2. The dc bias windings in the perpendicular-biased cavity.

TABLE III
EXPECTED MAXIMUM ELECTRIC DATA FOR THE PERPENDICULAR-BIAS SYSTEM

Length $\times$ diameter of solenoid	0.7 m $\times$ 0.45 m
Cross section of conductor	2 $\times$ 20 mm $\times$ 20 mm
Number of windings	10
Maximum dc bias field	100 000 A/m
Resistance of winding	0.32 m Ω
Maximum dc current	8000 A
Maximum dc voltage drop	3.0 V
Maximum dc power dissipation	24 kW
Maximum self-inductance	100 μ H
Maximum tuning rate (booster)	3.20 MHz/ms
Maximum bias field rate	12 500 A/m $\cdot$ ms
Maximum bias current rate	1000 A/ms
Maximum dc voltage	65 V

The results look extreme at first glance but are comparable with the bias requirements for parallel-biased cavities. For example, each FNAL booster cavity is biased by a 60-kW (30-V/2000-A) bias supply,⁹ and Ref. 10 describes a bias supply method delivering 70 V at the beginning and 5 V/20 000 A at the end of the cycle for a fast-cycling synchrotron cavity. Compared with these, the data in Table III seem surprisingly low. The reason is that the ferrites discussed here have been selected for low-saturation magnetization values.

With the bias windings mounted outside the rf resonator, one of the main problems occurring in most parallel-biased cavity designs (decoupling of the bias circuit and the rf resonator) is optimally solved. Instead, the question arises whether the rapidly varying dc bias field can penetrate the resonator walls without unacceptable losses or disturbance by eddy currents. It is expected that problems of this kind can be avoided by building the outer conductor of the cavity of stainless steel sheet with a thickness less than the skin depth at the maximum-bias field frequency. At 20 kHz the skin depth in stainless steel is about 2.3 mm. With 0.5- to 1.0-mm stainless cavity walls plated on the inside with about 0.02-mm copper, eddy-current effects are probably negligible.

It seems desirable to use some kind of magnetic yoke for the magnetic field outside the cavity. The advantages can be lower (or not higher) bias currents, better homogeneity of the field inside the ferrite, and reduction of the magnetic stray field outside the cavity. Yoke segments consisting of laminated iron or some cheaper ferrite material assembled around the cavity as indicated in Fig. 3 would be useful for this purpose.

VII. COOLING OF PERPENDICULAR-BIASED FERRITES

The large magnetic and electric quality factors available in microwave ferrites with perpendicular bias reduce the rf losses drastically. However, this advantage is mostly lost by raising the gap voltage per resonator and leads to the point at which ferrite losses are no longer negligible.

Due to the relatively low thermal conductivity of ferrites, the power losses inside the material lead to temperature gradients. The $1/r^2$ distribution of the magnetic and dielectric power densities in a coaxial cavity normally produces high radial temperature gradients. In a coaxial cavity with parallel bias, the dc-bias field goes with $1/r$ and the resulting power-density distribution becomes nearly constant with the radius.¹⁰ It is not clear whether a similar compensating effect exists or can be generated in a cavity with a perpendicular-bias field.

Fig. 3. Possibility of realizing a magnetic yoke around the bias solenoid. The dc-bias solenoid consists of 20 single-turn windings connected outside the yoke to form a 10-turn solenoid winding.

Large temperature gradients cause large mechanical stresses and may break the ferrite elements. Large local temperatures produce large changes of the magnetic and electric material properties and can lead to thermal instability of the whole system.⁷ Mean power densities of about 0.3 W/cm^3 are considered maximum values for stable operation¹¹; however, higher values have been used without problems.

In existing cavities the tuner section always consists of a stack of ferrite rings cooled by water-cooled copper disks or by an air flow passed through gaps between the rings.

The usual and most effective solution, using water-cooled copper disks between the ferrite rings, has to be excluded from a perpendicular-biased system because of eddy currents induced in the cooling discs. It seems possible to overcome this problem in the same way as for the outer conductor of the cavity, using cooling disks made of thin stainless sheet. Cooling rings using extremely thin (0.1-mm) stainless membranes have already been discussed at GSI (Gesellschaft für Schwerionen Forschung) for other reasons; such rings would expand under the pressure of the cooling water to give optimum thermal contact with the ferrite surfaces.

Calculations on the rf field distribution in a ferrite stack with inserted cooling plates^{*} revealed considerable, probably unfavorable, deviations from the field distribution without cooling plate. The CERN booster cavities are one of the few designs using air cooling. My own calculations, using published data⁷ and assuming $Q_{\text{mat}} = 200$ for the CERN ferrites, lead to peak power densities of 0.6 W/cm^3 for these cavities. The peak power densities given in Table II, calculated for relatively pessimistic assumptions for Q_{mat} , could be kept below this value. Air cooling is considered to be the simplest and most adequate cooling method for the perpendicular-biased cavity design.

VIII. DESIGN OF THE ACCELERATING GAP

The design of the ceramic gap seal is one of the most severe problems and may turn out to be the main limitation for the attainable gap voltages. The cavity design considered here provides enough radial and longitudinal space for a generous layout of the gap geometry. The risk of sparkovers can

^{*}This information was supplied by R. D. Carlini, Los Alamos National Laboratory (1984).

probably be kept low by careful design of the gap, corona rolls, and a sufficiently long ceramic gap seal.

If the usual technique is used, with metal joints brazed to the ends of the ceramic seal, it has to be kept in mind that rf currents in the order of several hundred amperes have to pass over this brazing region, possibly leading to considerable rf losses and overheating problems.

The operating conditions of the cavities are similar to those of the FMAI cavities, where initial problems with the gaps seem to be entirely solved.^{12,13}

The air cooling proposed for the ferrites will probably be useful for cooling the gaps as well.

IX. COMBINATION OF TWO QUARTER-WAVE RESONATORS IN ONE CAVITY

With the bias windings completely separate from the rf fields, there is no technical necessity to combine pairs of resonators in each cavity unit, as is the case in nearly all parallel-biased cavities. However, by combining two quarter-wave resonators in each accelerating station, the number of rf and control systems can be reduced by a factor of 2. Figure 4 shows two resonators coupled to the tuner ends.

For maximum energy gain of the particles, the distance from gap center to gap center should be $\beta \cdot \lambda/2 = 2.5$ m. With the dimensions given in Table II and with both resonators in closest connection, this distance will be about 2.0 m or 140° . The reduction in energy gain would then be about 10%. In this

Fig. 4. Combination of two quarter-wave resonators in one accelerating unit.

case it would be useful to move the two resonators apart by the missing distance and provide additional space for rf coupling and air cooling.

X. COMPARISON WITH MORE COMPLEX CAVITY GEOMETRIES

In the preceding sections I have tried to show that most of the critical problems in the LAMPF II cavities can be solved technically based on a simple coaxial quarter-wave resonator geometry. The question arises whether better or more economical solutions can be obtained by means of a more complex cavity geometry.

A drift-tube cavity design with the ferrites assembled in several smaller separate tuner units similar to the FNAL booster cavities has been studied in more detail. The following advantages are expected in this geometry: (1) The dimensions of the ferrite elements can be chosen independent of the beam-tube dimensions and thus matched to other requirements. (2) Smaller tuner diameters facilitate the generation of the perpendicular bias field. (3) As indicated in Fig. 5, there is an attractive solution for closing the bias-field flux by means of an external yoke. (4) It seems possible to submerge the whole tuner assembly in a cooling bath or to use flood cooling with an appropriate cooling liquid.

Calculations with the dimensions given in Fig. 5 and two double tuner units containing a ferrite volume similar to the coaxial booster cavity led to ineffectively low drift-tube lengths. A larger number of tuner units are necessary. Studies on this geometry were not continued; the simple transmission-line model used is probably not sufficient to get reliable data on similarly complex geometries. A more elaborate investigation was not possible in the time available but would be indispensable for a final judgment.

Compared with the drift tube and other structures considered, the coaxial cavity has one important advantage. The transmission-line calculations described in this report are only approximate in this case. However, due to its rotational symmetry, the simple coaxial geometry is the only case that allows application of much more precise calculational methods such as SUPERFISH or other field-distribution programs. This feature allows calculation of most electric properties, reliable investigation of higher resonance modes, and of possibilities to influence these with a precision and reliability that can never be achieved in a less symmetric design.

Fig. 5. Schematic of a drift-tube cavity with separate smaller tuner units.

XI. BEAM LOADING IN THE LAMPF II CAVITIES

In every accelerator, beam loading becomes important when the power taken up by the beam becomes larger than the power dissipated in the cavity. A look at Tables I and II shows that beam loading will be a fundamental problem in LAMPF II.

One solution is to raise the power dissipation in the cavity to a level comparable to the power given to the beam. With the perpendicular-biased cavities, there would still be the advantage of the feasibility of larger gap voltages per cavity than in conventional systems. The losses would no longer appear in the ferrites but could be concentrated on components of the cavity that are easier to cool. Additional losses can be realized by building the cavity walls, especially the inner conductor, out of stainless steel or more lossy material. The given inner-conductor diameter allows 100-mm aperture diameter and 10-mm wall thickness for cooling channels, etc. However, because of its poor electric efficiency, this method should be avoided if possible.

The extent to which closed-loop control methods can be used instead of or in combination with additional loading of the cavity needs thorough study. It is expected that high quality factors, which mean a decreased time constant and response time of the cavities, raise the chances of solving the beam-loading problems by control methods.

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APPENDIX

APPROXIMATION FOR THE DESIGN OF THE ACCELERATING CAVITIES

The general case of a coaxial ferrite-tuned quarter-wave resonator can be described with the resonator geometry shown in Fig. A-1. It consists of two basic units, a foreshortened piece of coaxial line (section A-B) partly filled with ferrite material and a second open-ended piece of coaxial line (section B-G) containing no ferrite. Both units can be treated with known transmission-line formulae. All ferrite-tuned accelerating cavities used in synchrotrons to the present can be understood as a combination of one or more of these basic units.

The tuner section (section A-B) of the cavity can be treated as a foreshortened piece of transmission line filled entirely with a dielectric with average properties μ_{eff} and ϵ_{eff} . The electric parameters of the tuner are then given by the following expressions:

Effective permeability:
$$\mu_{eff} = (\mu_{mat} - 1) \cdot \phi + 1$$

Effective permittivity:
$$\epsilon_{eff} = \frac{\epsilon_{mat}}{\phi + (1 - \phi) \cdot \epsilon_{mat}}$$

Fig. A-1. Schematic section through a ferrite-tuned coaxial quarter-wave resonator.

Filling factor: $\phi = \frac{\ln(D_{F2}/D_{F1})}{\ln(D_{C2}/D_{C1})}$

Wavelength on tuner: $\lambda_T = \lambda_{vac} / (\mu_{eff} \cdot \epsilon_{eff})^{1/2}$

Characteristic tuner impedance: $Z_{cT} = (\mu_{eff}/\epsilon_{eff})^{1/2} \cdot 60 \cdot \ln(D_{C2}/D_{C1})$

Current on the tuner: $I_T(x) = I_T(0) \cdot \cos(\theta_T \cdot x)$

Voltage on the tuner: $U_T(x) = j \cdot Z_{cT} \cdot I_T(0) \cdot \sin(\theta_T \cdot x)$

Maximum tuner current: $I_T(0) = -j \cdot \frac{U_T(L_T)}{Z_{cT} \cdot \sin \theta_T \cdot L_T}$

Impedance of the tuner: $X_T(L_T) = -j \cdot Z_{cT} \cdot \tan(\theta_T \cdot L_T)$

Magnetic field: $H_T(x, r) = \frac{I_T(x)}{2\pi \cdot r}$

Magnetic power density: $dP_m/dV = \frac{\omega_r \cdot \mu_{mat} \cdot \mu_0 \cdot H_T(x, r)^2}{2 \cdot Q_{mmat}}$

Voltage across the ferrite: $U_{Fe}(x) = \frac{\epsilon_{eff}}{\epsilon_{mat}} \cdot U_T(x)$

Electric field in ferrite: $E_{Fe}(x, r) = \frac{U_{Fe}(x)}{r \cdot \ln(D_{OF}/D_{IF})}$

Electric power density: $dP_e/dV = \frac{\omega_r \cdot \epsilon_{mat} \cdot \epsilon_0 \cdot E_{Fe}(x, r)^2}{2 \cdot Q_{emat}}$

The electric parameters of the ferrite-free section B-C, when calculated from the open end G toward point C, are given by the following expressions:

Voltage distribution: $U_L(x) = U_G(x_G) \cdot \cos(\theta_L \cdot x) ; \theta_L = 2\pi/\lambda_{vac}$

Current distribution:

$$I_L(x) = j \cdot \frac{1}{Z_{cL}} \cdot U_G(x_G) \cdot \sin(\theta_L \cdot x)$$

Impedance of open line:

$$X_L(x_B) = -j \cdot Z_{cL} \cdot \cot(\theta_L \cdot L_L)$$

The gap capacitance has been neglected here. It can be taken into account by increasing the free line length L_L by a certain length ΔL . For resonance of the whole system, the ferrite permeability μ_{mat} has to be varied to fulfill the condition $X_T(L_T) = -X_L(L_L)$.