RF ACCELERATING CAVITIES FOR AGS CONVERSION*

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Summary

The RF accelerating cavities at the Brookhaven AGS are of the balanced, coaxial type, filled with ferrite to allow permeability tuning. The basic limitation in such a cavity is heat dissipation in the ferrite.

It is the purpose of this paper to study the behavior of such a cavity as dc bias is applied to the ferrite. It will be shown that RF flux density is inversely proportional to radius only at zero bias; as the bias current increases, the flux density approaches a nearly uniform distribution, resulting in nearly uniform heating.

The results are applied to the problem of increasing the operating voltage of the present AGS cavities as well as to the design of a new cavity for the AGS conversion project.

Basic Considerations

The AGS accelerating cavities are of the balanced, reentrant type, as shown in Fig. 1. Since only the TEM mode is excited, the cavity may be treated as a pair of short-circuited coaxial transmission lines, with the open ends facing each other. The accelerating voltage is applied across the gap in the center conductor. The cavity is much less than $\lambda/2$ in length so that axial variations in flux density can be ignored. An external capacitance resonates the cavity just below the accelerator injection frequency.

If the cavity is short and ferrite permeability $\mu >> 1$, it may also be assumed that the stored energy in the cavity is nearly all magnetic and entirely in the ferrite. Cavity voltage is then given by

$$V = \frac{\partial\varphi}{\partial t} = \omega \int_{r_1}^{r_2} B(r)\, \ell dr \qquad (1)$$

The flux density B is usually assumed to vary as r^{-1} in a coaxial structure. This is true <u>only</u> if μ is constant with radius, i.e. if the dc bias $I_{dc} = 0$ (or in the trivial case of infinite bias where μ approaches 1).

Then

$$B(r) = B(r_1)\frac{r_1}{r} = B_1 \frac{r_1}{r} \qquad (2)$$

and

$$V = \omega\ell\, B_1\, r_1\, \ell n\, (r_2/r_1) \qquad (3)$$

where B_1 is the flux density at inner radius r_1.

Dissipation in ferrite is directly proportional to frequency and B^2, and inversely with μQ. However, it is found that μQ also decreases with increasing flux density, typically as B^{-1}. Thus, under zero bias conditions, power density in the ferrite varies approximately as r^{-3} and results in a hot spot at the inside radius. Cavity voltage is then limited by the maximum power density one permits at the hot spot. The above discussion also indicates that cavity power is roughly proportional to V^3.

Considerably higher voltages might be permitted if it were possible to design around an <u>average</u> power density, rather than around a hot spot. It will next be shown that as I_{dc} increases, flux distribution becomes nearly uniform, and that average power density considerations can indeed be used.

Flux Distribution Under Bias Conditions

If I_{dc} is not zero, μ is no longer constant. Continuity of tangential H requires that B(r) vary directly as $\mu(r)$. Combined with r^{-1} variation for coaxial structure,

$$B(r) = B(r_1)\left(\frac{r_1}{r}\right)\left[\frac{\mu(r)}{\mu(r_1)}\right]$$

$$= B_1\left(\frac{r_1}{r}\right)\left(\frac{\mu}{\mu_1}\right) \qquad (4)$$

Now for a given axial dc bias current I_{dc},

$$H_{dc} = \frac{NI_{dc}}{2\pi r} \qquad \text{(In AGS cavities N = 1.)}$$

The relationship between μ and H_{dc} can be determined empirically. For most well-behaved ferrites suitable for high power RF use, μ decreases monotonically with H_{dc}. If a unipolar dc supply is used, maximum μ has a remanent value μ_R which is somewhat lower than the initial μ. To a fair approximation μ can be assumed independent of frequency and RF flux density.

Since $\mu = \mu(H_{dc}) = \mu\,(I_{dc}, r)$,

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$$B(r) = \frac{B_1 r_1}{r} \, \frac{\mu(I_{dc}, r)}{\mu(I_{dc}, r_1)} \qquad (5)$$

and

$$V = \omega\ell \int_{r_1}^{r_2} \frac{B_1 r_1}{r} \, \frac{\mu(I_{dc}, r)}{\mu(I_{dc}, r_1)} \, dr$$

$$= \frac{\omega\ell \, B_1 r_1}{\mu(I_{dc}, r_1)} \int_{r_1}^{r_2} \mu(I_{dc}, r) \, \frac{dr}{r} \qquad (6)$$

then

$$B(r) = \frac{V \, \mu(I_{dc}, r)}{\omega\ell \, r \int_{r_1}^{r_2} \mu(I_{dc}, \rho) \, \frac{d\rho}{\rho}} \; . \qquad (7)$$

Qualitatively it may be seen that μ decreases with H_{dc} and H_{dc} varies as r^{-1}; then for a given I_{dc}, μ increases with radius. This tends to compensate for the r^{-1} variation of B.

Equation (7) forms the basis for design of the new AGS accelerating cavities as well as for the utilization of the present cavities at higher voltages. Since this equation involves empirical data, it can best be solved numerically. A simple Fortran program was written to accomplish this. Given the dimensions r_1, r_2 and ℓ, peak RF voltage, frequency, dc bias current and a set of points describing the μ-H_{dc} characteristic, the program computes RF flux density B versus radius r, as well as the inductance of the cavity L.

The present AGS cavity serves as an example to illustrate the procedure. The μ-H_{dc} characteristic for Ferroxcube 4H is shown in Fig. 2. The cavity inductances are calculated at a fixed frequency for various values of dc bias. Using a specific value of tuning capacitance, the actual resonant frequencies are calculated for each value of dc bias. The flux distributions are then computed at the proper frequency for each I_{dc}. The results are shown in Fig. 3. The leveling of RF flux density by dc bias is evident. In fact, in the AGS cavities flux density is essentially uniform above 200 A bias.

Experimental Results

To determine the effect of flux leveling on power dissipation, one of the existing AGS accelerating stations (Fig. 1) was run CW with no bias (resonant frequency approximately 1.1 MHz) at various RF voltages, starting at the present operating level of 8 kV peak. Thermal run-away occured at 9 kV. With only 100 A bias (1.5 MHz) the run-away point rose to 10 kV. Table I summarizes these results. Note that just below the run-away point the cavity was able to dissipate about 20% more power at 100 A bias than at zero bias. In the latter case run-away evidently occurred due to local overheating at the point of greatest flux density, resulting in a slow degradation of the cavity Q.

Table I

CW Performance Data for AGS Accelerating Station

Frequency - MHz:	1.1	1.5	1.8
Bias current - A dc:	0	100	150
Dissipation - kW @:			
8.0 kV peak	24.5	22.4	23.0
8.5	29.5	27.0	24.6
9.0	*	30.7	30.3
9.5		35.2	33.0
10.0		*	35.8

*Onset of thermal run-away.

In actual operation frequency is swept from approximately 1.3 to 4.5 MHz, the bias sweeping from 0 to 1000 A dc. If one wished to operate the cavities at, say, 10 kV, one might simply add some capacitance to lower the resonant frequency of the cavities and then sweep the bias from 200 to 1200 A. This would avoid the zero bias condition altogether. Fortunately, most of the sweep is traversed during the first 100 ms of an acceleration cycle, remaining nearly constant at 4.5 MHz for the remaining 900 ms. The flux density distribution is therefore virtually uniform over better than 90% of an RF pulse. The severe local heating occurs only at the very beginning of the pulse and its effect is therefore small.

Table II summarizes the performance of an AGS accelerating station at zero bias when the RF is pulsed. The present RF duty factor is about 50%. This would allow operation at 10 kV even with zero bias. Although the present data are incomplete it is expected that the combination of flux leveling and a duty cycle of about 50% will permit operation of the cavities at up to 12 kV peak. This will be verified when a suitable power amplifier becomes available in the near future.

Table II

Pulsed Performance Data for AGS Accelerating Station

Frequency - MHz:	1.1	1.1	1.1
Bias current - A:	0	0	0
Duty Factor:	100%	75%	50%
Peak Dissipation - kW @:			
8.0 kV peak	24.5	23.2	24.5
8.5	29.5	28.5	29.0
9.0	*	33.5	33.5
9.5		*	39.0
10.0			47.0
10.5			*

*Onset of thermal run-away.

Design Procedure and Application to AGS Conversion

The present AGS cavities are expected to stand duty during the Interim Phase of the AGS Conversion Project. For the Final Phase new cavities will be required, as outlined by Tranis et al. elsewhere in these Proceedings.[1]

The following basic specifications have been set:

Frequency range - 2.5 - 4.5 MHz

Number of accelerating stations - 8

Voltage per station - 48 kV peak

Length available per station - 8 ft

Minimum ID ferrite - 20 cm

An even number of gaps per station is desired for ease of biasing. The electrical length of each cavity should again be less than 30° for efficient utilization of ferrite. This consideration immediately rules out a two-gap structure and dictates four cavities per station. Thus, the cavity specifications are briefly:

Voltage - 12 kV peak

Frequency range - 2.5 - 4.5 MHz

Electrical length - < 30°

Minimum ID ferrite - 20 cm

Maximum length ferrite - 40 cm

From thermal considerations it is desired to keep power densities in ferrite below 0.3 W/cm^3.

The next step is to find a suitable ferrite material and, ultimately, a manufacturer capable of manufacturing it in large rings. (The latter consideration need not prevent one from doing calculations, however.) The ferrite must have low loss in the frequency range of interest and must have a reversible magnetization characteristic. (Some ferrites suffer permanent loss of Q upon magnetization.)

Three basic equations are pertinent. If flux leveling is assumed, flux density is independent of radius, and is given by

$$B = \frac{V \times 10^8}{2\pi f \ell \, (r_2 - r_1)} \tag{8}$$

where B is in gauss and dimensions in centimeters.

Power density is given by

$$\text{P.D.} = \frac{fB^2 \times 10^{-6}}{40 \, \mu Q} \quad \text{W/cm}^3 \tag{9}$$

$$\text{Total power } P = \text{P.D.} \times \text{Volume watts.} \tag{10}$$

To minimize ferrite costs one would choose as high a flux density as possible. One would therefore search for a ferrite with the highest possible μQ product at a given frequency f_o and flux density B_o. From a worst-case point of view this data should be taken at remanence. Call this reference value $(\mu Q)_o$. Assuming μQ varies as B^{-1} but is independent of H_{dc} at any particular frequency,

$$\mu Q(B) = (\mu Q)_o \frac{B_o}{B} \quad .$$

Using (9) and specifying 0.3 W/cm^3, one obtains a design flux density given by

$$B \approx 344 \left[\frac{(\text{P.D.}) \, (\mu Q)_o \, B_o}{f_o} \right]^{1/3}$$

$$= 230 \left[\frac{(\mu Q)_o \, B_o}{f_o} \right]^{1/3} \quad . \tag{11}$$

Dimensions can then be determined from (8). Approximate power can be calculated using (9) and (10).

One can now return to (7) and compute more accurately the actual flux distribution in a cavity of the dimension found above. A similar numerical analysis of power densities and total power can be made, but it requires extensive data of μQ vs. B vs. H_{dc}.

It should be mentioned that for most of the ferrites under consideration (as well as the Ferroxcube 4H currently in use) the μQf product remains constant or increases slightly as bias is applied and the frequency is swept at constant RF voltage. Since from (8) and (9) it is seen that power density is inversely proportional to μQf, power will not vary a great deal during a sweep. The worst case generally occurs at the low-frequency end.

Note that the design procedure is based on the observation that flux density, and to a good approximation, power density, are uniform throughout the cavity at moderate bias levels. It then becomes practical to design cavities with large OD/ID ratios.

Returning to the AGS conversion example, consider a cavity 20 cm ID, 40 cm long, operating at 12 kV peak at 2.5 MHz. A possible choice of ferrite is Ferroxcube 4C4 whose μQ at 2.5 MHz and 100 gauss (at remanence) is approximately 5000. From (11) the average flux density is found to be 136 gauss. The outer radius is found from (8) to be 24 cm. The flux distribution analysis was carried out for an outer radius of 25 cm and a tuning capacitance of 600 pF. The results are plotted in Fig. 4. The approximate power for this configuration is 19 kW per cavity or about 76 kW per station. For the assumption of uniform flux density to hold, operation would have to be confined above 200 or 300 A bias. In any event, swept frequency operation will again keep the cavity at high bias over better than 90% of the RF pulse.

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Reference

1. A. Tranis, V. Kovarik, J.W. Spinner and J.G. Cottingham, "The AGS Conversion RF System," to be published in the Proceedings of this Conference.

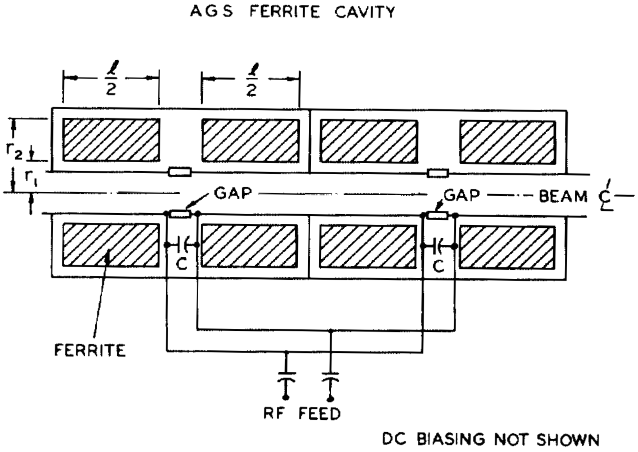

Fig. 1. AGS ferrite cavity—schematic representation.

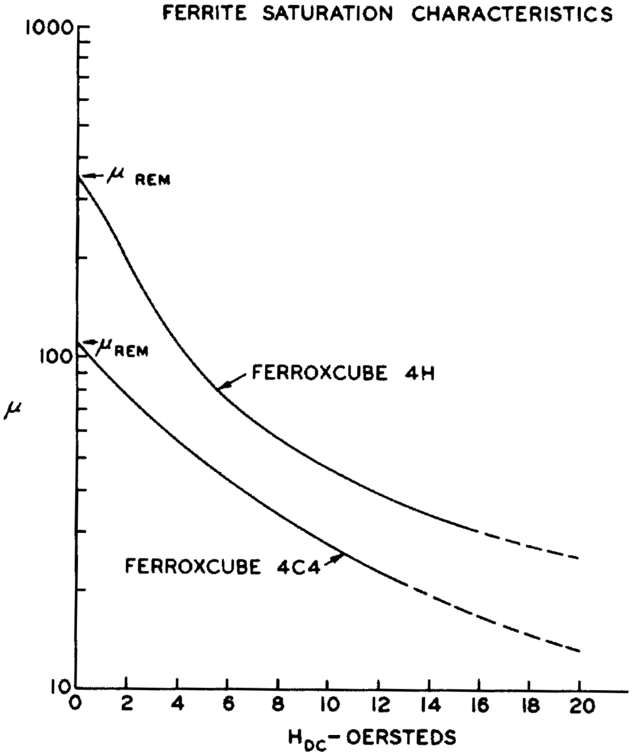

Fig. 2. Typical ferrite saturation characteristics starting from remanence.

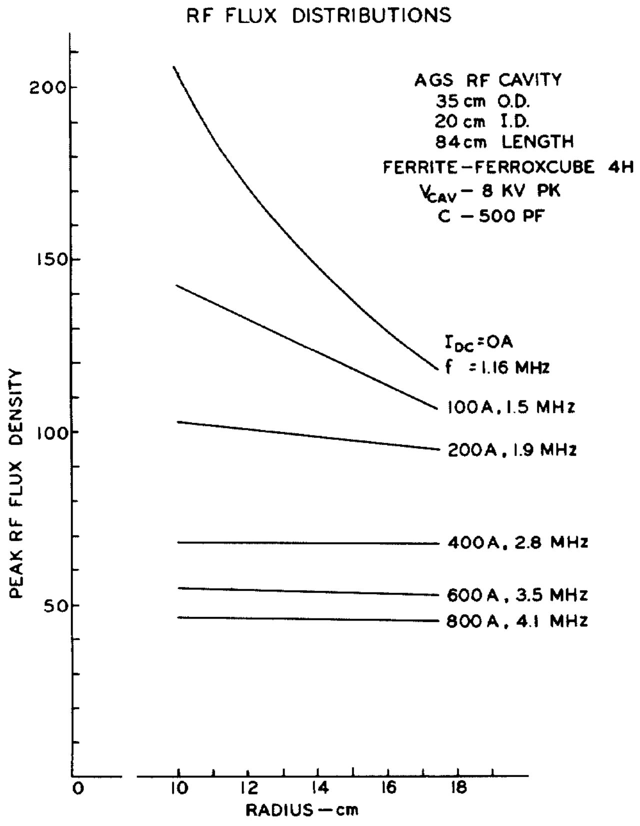

Fig. 3. RF flux distributions in present AGS cavities.

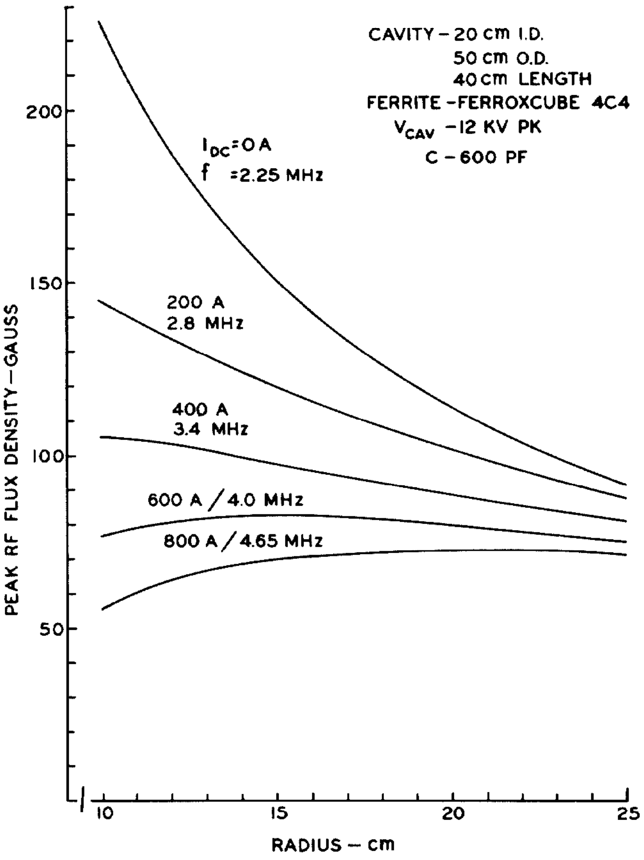

Fig. 4. RF flux distributions in Ferroxcube 4C4 cavity.