RAPIDLY TUNED BUNCHER STRUCTURE FOR THE LOS ALAMOS PROTON STORAGE RING (PSR)*

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Summary

In the PSR's short-bunch operating mode, accumulated beam currents are intense and change rapidly. The resonant frequency of the 503.125-MHz buncher used in this mode must be rapidly adjusted through a 100-kHz range to maintain the correct 90° phase relation between cavity voltage and beam current. Modulation rates are up to 3 kHz/μs. Each structure consists of two side-coupled buncher cavities, resonantly coupled to a ferrite-loaded tuner cavity. The needed frequency change Δf in the buncher cells is produced by a $50 \times \Delta f$ change in the tuner, accomplished by varying a magnetic field applied to the ferrite perpendicular to the rf magnetic field. Fast modulation of this bias is provided by a low-inductance ferrite-core magnet excited by a special function generator. The resonantly coupled multicavity structure configuration allows buncher and tuner cells to be independently optimized for their specific functions.

This paper describes the buncher design, ferrite selection, and test results from a prototype ferrite-loaded tuner cavity. The tests have demonstrated the tuning scheme's feasibility, showing that the necessary 5-MHz range can be attained with only 12% of the tuner cell filled with ferrite, and that losses in the ferrite are small throughout this frequency interval.

Introduction

The PSR is a high-current accumulator ring[1] designed (in one of its two operating modes) to convert long (110-μs) proton pulses from the 800-MeV LAMPF linear accelerator into ultra-short (1-ns) high-intensity bunches that are ideally suited to driving a pulsed neutron source for nuclear physics experiments. The ring accumulation and extraction cycle is repeated at 120 Hz, the linac macropulse rate. In each cycle, six 1-ns bunches are simultaneously accumulated during the first 110 μs; these are then extracted singly at 1.4-ms intervals until the ring is empty. The short bunch-length is preserved by a system of eight cylindrical rf cavities operating in the TM_{010} mode at 503.125 MHz. This is the 180th harmonic of the ring circulation frequency, 2.795 MHz.

The 503.125-MHz component of the stored beam-current frequency spectrum drives the cavities resonantly, inducing an rf voltage in phase with the beam current; at completion of injection, this is much larger than the applied generator voltage. The vector sum of the beam-induced voltage and the generator voltage (the cavity voltage) must be manipulated so that it always lags the beam current by 90°, maintaining bunching action without beam-energy gain or loss. This can be achieved if the buncher-cavity resonant frequency is increased, relative to the generator frequency, by an amount proportional to the circulating beam current. In these circumstances no variation in the generator phase or amplitude is required, and the generator remains matched to the cavity-beam system.[2]

Because the beam current varies from zero to maximum in 110 μs during injection, with similarly rapid changes occuring during extraction, the buncher frequency must be variable at rates up to 3 kHz/μs. Because the buncher cavity Q is high the maximum frequency shift is small. Coupled with the need for low rf losses, these considerations produced a unique rapidly tunable buncher-structure design that uses the properties of high-frequency ferrite biased perpendicular to the rf magnetic fields.

Ferrite Tuning Scheme with Perpendicular Bias

As conventionally used in accelerator rf cavities, ferrite is magnetically biased parallel to the rf magnetic field and is not saturated. Typically it has a relatively high permeability and saturation magnetization, and its useful frequency range is below 100 MHz. The permeability is adjusted by the bias to vary the resonator frequency. The ferrite fills a large fraction of the cavity, both to obtain a large frequency variation and to reduce the resonator size. Because the material is unsaturated, the rf fields trace out sizable hysteresis loops and losses are large. Most of the rf power ends up in the ferrite.

In the present tuning scheme the rf frequency is much higher, but the required variation is very small. It is therefore possible to use an entirely different approach. A small fraction of the resonator is filled with high-frequency ferrite biased well above saturation in a direction perpendicular to the rf magnetic fields, and use is made of the material's magnetic resonance properties exhibited in this field configuration.[3] These produce large enough permeability changes to obtain the desired tuning, with the concurrent advantage of very low rf losses.

Resonantly Coupled Ferrite-Tuned Buncher Structure

The 503.125-MHz buncher system is composed of four identical structures, located in pairs on diametrically opposite sides of the PSR. Each pair is fed through a 90° hybrid by a 55-kW commercially supplied UHF television transmitter. Each structure consists of two bunching cells, side-coupled in the $\pi/2$ mode, with a ferrite-loaded tuner cavity resonantly coupled to one of them. A typical unit is shown in Fig. 1. The latter coupling is chosen so that the tuner contains only about 2% of the rf energy stored in the buncher cells. To obtain the 100-kHz frequency swing needed in the buncher cavities, it is necessary to adjust the tuner-cell frequency by 5 MHz.

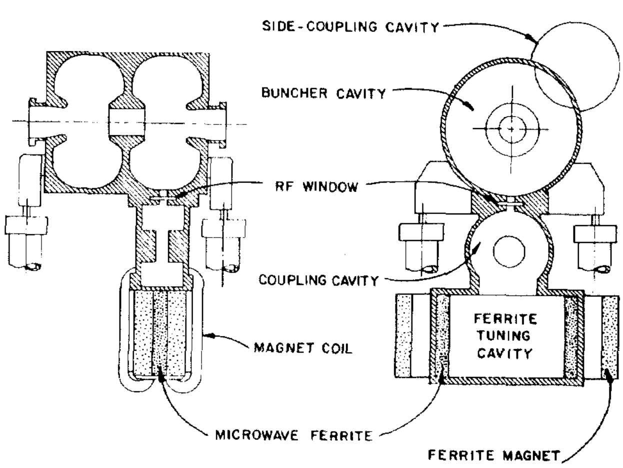

Fig. 1. Buncher structure, showing resonantly coupled, ferrite-loaded tuner.

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The clean separation of tuning and bunching functions in this multicavity structure provides several advantages. The buncher cavities can be optimized for interaction with the beam, the ferrite can be placed in a region of low rf-power density where cooling is straightforward, and the geometry of the tuner cell can be chosen for convenient application of the magnetic bias. Resonant coupling permits precise control of the rf amplitude ratio between buncher and tuner cells and reduces detuning-related amplitude variation in the cavities to a second-order effect.

Cavity Design

Both the buncher and tuning cavities were designed using the computer program SUPERFISH. The buncher-cell geometry is similar to that of the cavities used in the LAMPF 805-MHz linac, except for the very large beam aperture. Design parameters are given in Table I. Bracketed numbers refer to a single cell; unbracketed numbers refer to the whole buncher system.

TABLE I

BUNCHER SYSTEM AND TUNING PARAMETERS

Peak buncher voltage	1.8(0.225) MV
Buncher frequency	503.125 MHz
Shunt impedance/unit length	43 MΩ/m
Buncher-cell length	0.251 m
Total buncher length	2.008 m
Buncher shunt impedance	86(10.75) MΩ
Transit-time factor	0.785
Buncher unloaded Q	31 000
Power dissipated in buncher	37.7(4.71) kW
Maximum beam at 503.125 MHz	415 mA
Maximum generator current	41.9 mA
Maximum tuning angle	84.2°
Maximum buncher tuning range	100 kHz

The tuner cell is a narrow rectangular cavity operating in the TE_{101} mode. Figure 2 depicts a cross section through half of a tuner, showing the microwave ferrite inside, and one (of two) bias field magnets. The ferrite is in the form of rectangular slabs placed near the tuner-cell side walls where the rf magnetic fields are strongest. The cell is narrow (1.25 in.) to permit positioning the ferrite between the poles of the elongated C-magnets. Cavity design was accomplished using recently introduced SUPERFISH options that allow calculation of TE cutoff modes for a rectangular geometry, and that can handle problems containing materials with relative permeability and/or permittivity >1. The cavity cross section is uniform along its length, so the resonant frequency can be calculated from the cutoff-mode frequencies produced by the computation. Tuner parameters are listed in Table II. As before, bracketed and unbracketed quantities refer respectively to individual cells and the entire system.

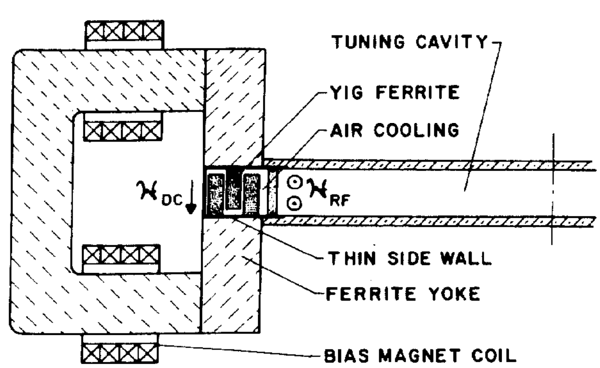

Fig. 2. Schematic section through half of tuner cavity, showing orientation of dc and rf magnetic fields.

TABLE II

TUNER CELL AND FERRITE PARAMETERS

Cavity dimensions (w x ℓ x h)	18 x 13 x 1.25 in.
Maximum tuner-cell range	5 MHz
Ferrite-loaded tuner Q (prototype)	4700
Unloaded tuner-cell Q (prototype)	5300
Power dissipated in tuner cells	5(1.25) kW
Power dissipated in ferrite	550(137.5) W
Total ferrite volume (12%)	2300(575) cm^3
Power density in ferrite	0.24 W/cm^3
Ferrite type	Trans-Tech G-810
Saturation magnetization	800 G
Spin-wave line width	1.50 Oe

The magnetic bias field H_{dc} applied to the ferrite saturates the material in the direction normal to the cavity rf magnetic fields. Figure 3 shows how, in this field configuration, the real and imaginary parts of the ferrite rf permeability vary with H_{dc}. The real part μ' decreases from μ_0 to large negative values as H_{dc} increases, swings to large positive values at the magnetic resonance field H_{res}, and then declines gradually toward μ_0 at large H_{dc}. The imaginary part μ'', corresponding to rf losses in the ferrite, is large near resonance but decreases to small values for large H_{dc}. The bias point for the tuner is chosen to place H_{dc} in the ferrite far above the magnetic resonance field for 503.125 MHz, between H_1 and H_2. Here μ' is small ($1.5 \rightarrow 6\ \mu_0$) but can be varied enough by moderate changes in H_{dc} to easily provide the needed frequency shift in the tuner. In this region the rf losses in the ferrite are much smaller than the hysteretic losses of parallel-bias ferrite applications.

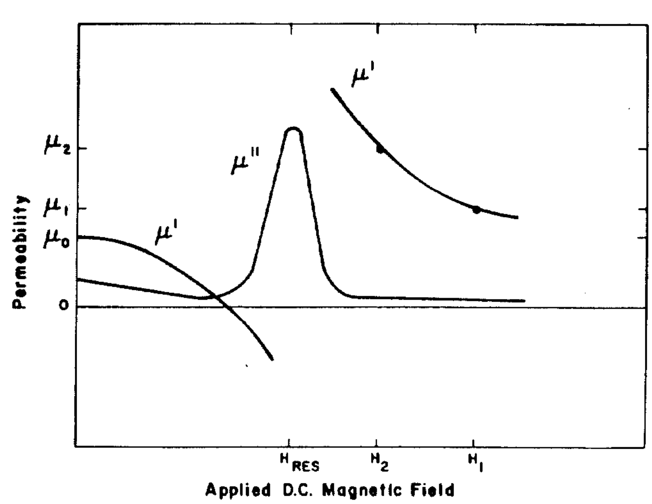

Fig. 3. Real and imaginary parts of ferrite rf permeability as a function of bias field.

An rf window is located between the tuner cell and the adjoining buncher cell. This allows vacuum to be maintained in the buncher while forced-air cooling is applied directly to the ferrite slabs. At design power levels, rf losses in the ferrite are not expected to exceed 500 mW/cm^3. Design of the tuner cell is complicated by the need for fast modulation of the magnetic bias field. The core of the bias magnet itself is constructed of high-permeability ferrite (Stackpole Ceramag 24B). It has a low-inductance winding (60 μH) so that it can be modulated at the required rate by a low-voltage solid-state driver. The cavity wall enclosing the tuner ferrite slabs must be thin and constructed of high-resistivity material, except for an interior copper plating, to permit the rapidly changing bias field to penetrate the ferrite without attenuation from eddy currents. The cavity wall in this area is 0.5-mm-thick stainless steel.

Prototype Tuner Cavity Measurements

A prototype tuner cell was built to select an appropriate ferrite and to investigate the tuning method using perpendicular bias field. References 4 and 5 present examples of cavity tuning using perpendicular bias but operating below H_{res} rather than above. To our knowledge, the PSR cavity-tuning scheme is the first to use a bias field far above H_{res}, the method that provides lowest possible ferrite losses.

To minimize losses and maximize the tuner cavity Q in the above-resonance region, a ferrite with a small spin-wave line width is needed. Aluminum-doped garnets satisfy this criterion and also have a low saturation magnetization, from 200 to 800 G. Several materials were tested, including calcium-vanadium-garnet (CVG) and aluminum-doped yttrium-iron-garnet (YIG). The YIG exhibited the smallest loss for a given tuning range in the prototype tuner cavity. Near 500 MHz, the best materials permitted a range of 40 MHz with the cavity Q remaining near 5000.

Figures 4 and 5 indicate the results of low-power measurements made in the tuner-cavity prototype on Trans-Tech G-810, the ferrite finally selected. They show the dependence of cavity resonant frequency and Q on applied magnetic field strength B_{dc}, with ferrite filling 12% of the cavity volume. Figure 5 reveals that rf losses are so low above B_{dc} = 1000 G that the loaded cavity Q approaches 90% of the unloaded Q. Figure 4 demonstrates that the required 5-MHz frequency change can be easily attained at this bias level by a variation in B_{dc} of <100 G. The unloaded

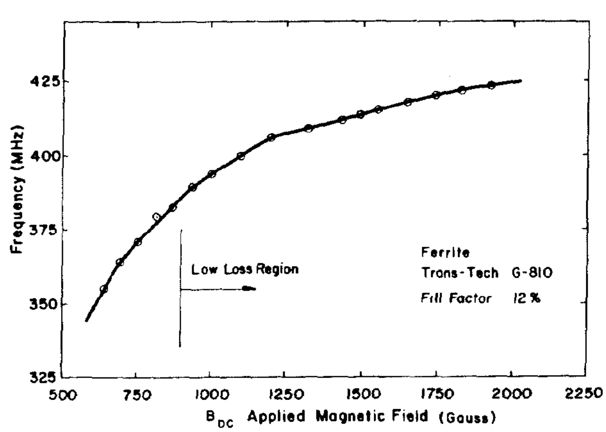

Fig. 4. Prototype tuner cell resonant frequency versus applied magnetic field strength.

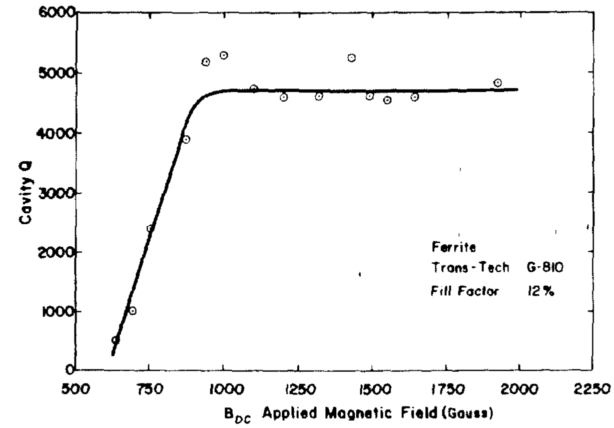

Fig. 5. Prototype tuner cell loaded Q versus applied magnetic field strength.

test cavity had a frequency of 488.7 MHz and a Q of 5300. Bias was applied by two steel-core C-magnets. The measurements were repeated at rf power levels up to 40-W cw and 1000-W pulsed with no observable reduction in available tuning range or cavity Q. Peak rf power levels are expected to be comparable to the latter value in the final PSR buncher system.

Complete Structure Prototype

A complete aluminum model structure consisting of two 503.125-MHz buncher cells, a tuner cell, and coupling cells has been fabricated. It is being used to check SUPERFISH calculations for cavity shapes, to determine appropriate coupling constants, to verify calculated coupled-cavity mode frequencies, and to confirm predicted tuning behavior of the complete buncher system, all at low rf power. Following these cold tests, a complete copper structure will be fabricated and tested at full power, with the tuner cavity bias field modulated at design speeds. Results should be available by winter, 1983-84.

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